Institution: University of Nottingham

Unit of Assessment: 9

a. Overview

Research activity in the School of Physics and Astronomy is structured across 6 research groups, made up of the 57 Category A staff listed below (cf. 46 Category A staff returned in RAE2008). This group comprises 22 Professors, 12 Associate Professors/Readers, 6 Lecturers, 15 Research Fellows (9 with proleptic lectureships) and 2 Principal Research Officers. Since RAE2008 the School has undergone planned expansion through investment of £11.2M in new infrastructure and the appointment of 16 new academic staff. The School's current research grant portfolio is £38.6M.

Astronomy (*Astro*): Profs. Almaini, Aragón-Salamanca, Conselice, Merrifield; Drs. Bamford*[E], Bolton*[E], Dye[E], Gray*, Hatch*[E], Pearce

Cold Atoms & Quantum Optics (*ColdAtoms*): Prof. Krüger; Drs. Hackermüller[E] and Fernholz

Condensed Matter Theory (*CMTh*): Profs. Fromhold, Garrahan, Jungwirth, Lesanovsky; Drs. Armour, Dunn, Li*[E], Olmos*[E], Powell[E], Swift

Experimental Condensed Matter & Nanoscience (*ECMN*): Profs. Beton, Eaves, Gallagher, Henini, Horsewill, Kent, Moriarty, Patanè, Owers-Bradley (50%); Drs. Akimov[†], Campion[†], Edmonds, Hill*[E], Makarovsky[E], Notingher, O'Shea, Rushforth*[E], Smith*[E], Stannard*[E]

Magnetic Resonance Imaging (*MRI*): Profs. Bowtell, Gowland, Morris, Owers-Bradley (50%); Drs. Brookes[E], Francis, Köckenberger, Mullinger*[E]

Particle Theory (*PTh*): Prof. Copeland; Drs. Avgoustidis*[E], Burrage*[E], Green, Moss[E], Padilla*, Saffin, Skordis*[E].

Above, *E* = Early Career Researcher (ECR); * = Research Fellow; † = Principal Research Officer.

b. Research Strategy

b1) Achievement of Strategic Aims Stated in RAE2008

- **Expansion of the Cold Atoms & Quantum Optics Group**

The group, founded in 2007, has grown through the appointment to lectureships of experimentalists *Fernholz* (2008, from QUANTOP Copenhagen) and *Hackermüller* (2009, from the Max-Planck Institute for Quantum Optics, Munich). These posts were funded by a £5.2M EPSRC and HEFCE Science and Innovation (S&I) award (EP/E036473/1, 2007-2013) plus £1.9M from the University, which underpinned the formation of the Midlands Ultracold Atom Research Centre (MUARC). MUARC is a joint initiative with the University of Birmingham, who also recruited two lecturers, to deliver co-ordinated activity with critical mass in cold quantum matter. The Nottingham node of MUARC now includes 5 postdoctoral research associates (PDRAs), 2 with personal fellowships, and 7 PhD students. Areas of focus are atom-chip sensors, quantum communication, and quantum simulators. New theory lectureship appointments (*Lesanovsky* 2009, *Powell* 2013) and fellowships (*Li*, *Olmos*) in quantum optics and cold atoms link closely to the *CMTh* group.

- **Growth of the Particle Theory Group**

Growth anticipated in RAE2008 has been realised by appointing *Padilla*, *Skordis* and *Burrage* to proleptic lectureships, doubling the number of academic staff in the group. All three hold Royal Society University Research Fellowships (RS URF), which started in 2008, 2010 and 2013, respectively. *Moss* was appointed to a lectureship in 2012 as part of the expansion of the Midlands Physics Alliance Graduate School and *Avgoustidis* won a Nottingham Research Fellowship (NRF) in 2013. A further strategic aim identified in RAE2008, to strengthen links to major international facilities, has been achieved through membership of the Dark Energy Survey (*Copeland*) and of the Euclid (*Avgoustidis*, *Burrage*, *Skordis*) and Planck (*Moss*) consortia. The group is now well-established, with 10 PhD students and 4 PDRAs. It is supported by an STFC Consolidated Grant, and by the Leverhulme Trust, Royal Society and European Union (EU).

- **Expansion of the Midlands Physics Alliance Graduate School (MPAGS)**

A major success arising from our strategy for developing regional partnerships has been the expansion of MPAGS, which was established by a £4M award from the HEFCE Strategic Development Fund to the Universities of Birmingham, Nottingham and Warwick. This provided funds to deliver a co-ordinated programme of postgraduate (PG) training in EPSRC-related science, with the first annual cycle of module delivery and summer schools being completed in 2008. A second HEFCE award (£3M) in 2010 was used to extend MPAGS to the areas of astronomy and particle physics, to fund student placements in industry, and to enable other regional Universities (Keele, Leicester, Loughborough and Nottingham Trent) to access MPAGS

training. The HEFCE awards were used to appoint a total of 12 academic staff, including 4 in Nottingham, of whom 3 (*Dye*, *Lesanovsky*, *Moss*) have been appointed since 2008.

- **Promotion of Interdisciplinary Collaborations (see also Section e1)**

Two centres embedded in the School, the Sir Peter Mansfield Magnetic Resonance Centre (SPMMRC) and the Nottingham Nanoscience and Nanotechnology Centre (NNNC), form foci for collaboration with chemists, life scientists, engineers, NHS clinicians and industrial partners.

The facilities at the SPMMRC support the *MRI* group in a broad programme of collaborative research, including studies of gastrointestinal function, kidney and liver disease, multiple sclerosis and Parkinson's disease, plus the application of novel MRI developments in neuroscience. This research has been underpinned by consecutive 5-year MRC Programme Grants (£4.2M total) in the REF period, and close collaboration with industry, notably with Philips Healthcare.

The interdisciplinary facilities within the NNNC enhance the strong links between the *ECMN* and *CMTh* groups and the Schools of Chemistry and Pharmacy. These include collaborations involving *Beton*, *Garrahan, Moriarty, O'Shea*, and *Patanè* on two-dimensional supramolecular assembly, biocompatible quantum dots, photo-electron spectroscopy, and sub-molecular resolution atomic force microscopy (AFM). The *ECMN* group's interdisciplinary links have also grown through new activity in magnetoscience, and the application of Raman microscopy to cancer screening and stem cell sorting (£0.7M National Institute for Health Research [NIHR] award). Since 2008, we have strengthened these areas via £2M CIF investment, the appointment of *Hill* (2010; EPSRC Career Acceleration Fellow [CAF]), and by recruiting *Smith*, who was awarded a RS URF in 2012.

b2) Evolution of Research Strategy during the REF Assessment Period

Since RAE2008 we have developed our research strategy to identify and pursue opportunities arising from our research successes and changes in the external research landscape.

- **Supporting Fellowship Applications from Early Career Researchers (ECRs)**

We have introduced new strategies to increase the number of ECR fellows hosted by the School, with the aim of expanding our research portfolio, enhancing internal and external collaboration, and mentoring the best ECRs through the transition from fellowships into permanent positions, thus ensuring the long-term sustainability of our research. Strategies include providing targeted support for fellowship applications from external candidates, as well as mentoring and training at all stages of the application process. This has led to a total of 30 ECR fellowship awards: 18 have been funded externally by STFC, EPSRC, the Royal Society, the Leverhulme Trust and the Marie Curie scheme, while 11 were won through the University-funded Anne McLaren Fellowship (AMF) and Nottingham Research Fellowship (NRF) schemes.

- **Formation of a Strategic Advisory Board (SAB)**

The SAB was established in 2011 to provide external input into our strategy for research, teaching, knowledge transfer and outreach. Current membership includes industrialists from e2v, Experian, Hitachi, Huawei, Pfizer and Rolls Royce, plus representatives from RCUK and major research organisations/facilities, including the British Geological Survey, the Diamond Light Source and STFC. The SAB offers advice on research opportunities, the skills that employers require from our undergraduates and postgraduates, and commercialisation of our research.

- **Strategic Partnership with e2v Technologies**

In 2011, e2v (a UK company with more than 1500 employees and a £200M turnover) committed £1M to establish and operate a research and manufacturing centre within the School, based on collaborative activity with the *ECMN* and *CMTh* groups. The centre manufactures semiconductor devices and develops new concepts for high-frequency (GHz/THz) electronic devices in a 90 m^2 dedicated cleanroom space within our nanofabrication facility. Our partnership with e2v has stimulated new collaborative research on THz devices, nitride semiconductors, and tunnel devices, funded in part by a Knowledge Transfer Partnership (KTP) from the Technology Strategy Board.

- **Major New Research Activities Established since RAE2008**

Graphene We have developed a new integrated programme of growth, experimental study, and modelling of graphene-based structures, including tunnel transistors, which involves *ECMN* and *CMTh* staff, *Beton*, *Eaves*, *Fromhold*, *Makarovsky* (appointed in 2010) and *Patanè*, working with 2 PDRAs and 6 PhD students. A new dual-chamber, molecular beam epitaxy (MBE) system, funded by a recent £1.3M EPSRC grant (EP/K040243/1), will be used to grow graphene/boron nitride heterostructures. This will underpin major expansion of graphene research beyond 2014.

Theory of Quantum Non-Equilibrium Systems This new research programme, which now involves 6 Category A staff, 5 PDRAs and 7 PhD students, focuses on complex emergent dynamics and non-equilibrium phases of quantum many-body systems, ranging from fundamental theory to applications in diverse systems of experimental interest. The programme builds on our expertise in statistical physics (*Garrahan*), cold atoms (*Lesanovsky*) and condensed matter (*Armour* and *Powell*), and integrates with parallel experiments in MUARC. It is supported by £1.5M EPSRC funding and by the award of University-funded fellowships to *Li* (NRF) and *Olmos* (AMF). This activity will further benefit from *Lesanovsky*'s €1.5M ERC Starting Grant (from January 2014).

Astronomical Survey Science With large international survey projects becoming vital to future progress in the understanding of galaxy evolution, we have invested £0.6M of University and CIF funding since 2009 to secure leading roles in key survey programmes. Members of the *Astro* (*Aragón-Salamanca* and *Gray*) and *PTh* (*Copeland*) groups have joined the Dark Energy Survey to explore aspects of galaxy formation and cosmology. *Conselice* leads our involvement in the low-frequency radio astronomy project, LOFAR, which will provide access to new data on high-redshift galaxy formation. *Aragón-Salamanca* and *Merrifield* recently became members of the Sloan Digital Sky Survey IV, with major involvement in the Mapping Nearby Galaxies (MaNGA) project that will provide full spectral observations of a large sample of galaxies, allowing the mapping of their kinematics and stellar populations.

Magnetoencephalography (MEG) The installation of a 275-channel MEG system, completed in 2008, facilitated a major programme of physics-based research on new techniques for source localisation and measurement of brain connectivity. This now underpins a substantial programme of collaborative research focused on the dynamics of brain networks in psychiatric disorders, especially schizophrenia, which is supported by a joint grant portfolio in excess of £5M from the MRC. *Brookes*, who was instrumental in much of this development, was appointed to a lectureship in 2013, on completion of his Leverhulme Early Career Fellowship.

Metal/Semiconductor Spintronics: Theoretical work by *Jungwirth* (*CMTh*), who received a €2.5M ERC Advanced Grant in 2011, has highlighted the advantages of metallic and semiconductor antiferromagnets for spintronic materials and devices, leading to a strategic shift in the focus of our spintronics research. New experimental work on these materials has been facilitated by the award of a £1M EPSRC CAF to *Rushforth (ECMN).*

b3) Future plans

- **Strategic Plans for the School**

Our plans are tailored to delivering a programme of cutting-edge research which is of high international standing, and ranges from curiosity-driven research to applications-led work. We highlight the following strategic priorities and plans:

Establishing new interdisciplinary research programmes: for example by strengthening research in biophysics, and building new activity in geophysics. This will open up opportunities for further industrial collaboration and the potential for increased NERC and BBSRC funding. To develop activity in geophysics, we have established new collaborations with the British Geological Survey (BGS) on geophysical imaging and gravity sensing, in alignment with a University strategy of developing closer links with the nearby BGS Keyworth site. We will also exploit synergies between the research of our *PTh* and *ColdAtoms* groups and the Quantum Gravity group in the School of Mathematical Sciences through a joint lectureship, recently approved by the University.

Enhancing collaboration between research groups: for example by prioritising staff and fellowship appointments that link the new *ColdAtoms* group to the *ECMN*, *MRI* and *CMTh* groups, thus opening up new research directions at the interface between different fields. Fertile areas for collaboration include gravitational and magnetic field sensing, condensate-surface interactions, imaging and quantum information.

Internationalisation of research: building on our broad existing portfolio of international collaborations, which includes active projects with 36% of the overseas universities in the Top 100 of the Academic Ranking of World Universities (Shanghai Jiao Tong University), we will take further leadership roles in global alliances with emerging centres of excellence and strengthen links with leading institutions in Europe, Asia and the US (described in Section e1). For example, the *MRI* group has worked with the Faculty of Engineering to establish a research unit at the University of Nottingham's China campus. This builds on a new collaboration with a Chinese MRI scanner manufacturer (Ningbo Xin Gaoyi Magnetism) and links with Zhejiang University. We will also build

on collaborations with leading Brazilian research centres involving *ColdAtoms* and *MRI*. These have recently been supported by pump-priming funding (£110k) from a joint FAPESP-(Fundação de Amparo à Pesquisa do Estado de São Paulo)-Nottingham-Birmingham initiative.

- **Group Plans to Build on Research Strengths, Recent Investments and Opportunities**

Astro will continue its focus on the formation and evolution of galaxies, aligned with STFC's Roadmap Science Challenge A:5. This will involve a wide range of observational and theoretical programmes that blend our established activities with newer projects that exploit our investment and leading roles in facilities (see Section b2). The group is also preparing for involvement in the next generation of surveys by, for example, contributing extensively to the development work for the European Space Agency's Euclid mission, drawing on expertise in both *Astro* and *PTh* groups.

CMTh will build on its recent success and unique combination of expertise by expanding research activity in complex quantum systems, with emphasis on non-equilibrium dynamics, the cold-atom/condensed matter interface, and hybrid classical-quantum systems (superconducting quantum circuits and nanoelectromechanics). Another key theme will be non-linear dynamics, including classical critical phenomena and high-frequency electronics in graphene-based devices.

ColdAtoms will focus increasingly on the fusion of cold atoms and condensed matter to develop new hybrid quantum systems. The group will expand existing collaborations on low-dimensional quantum gases and open systems, integrated light-atom interfaces and memories, atom interferometers, and portable sensors of rotation and gravitational/electromagnetic fields.

ECMN priorities include the MBE growth, and experimental/theoretical study (with *CMTh*), of graphene-based heterostructures and devices; projects on wide-band gap nitride semiconductors and high-frequency electronics with e2v; resonant photo-electron spectroscopy of adsorbed molecules; the quantum dynamics of small molecules in fullerene cages; force mapping of complex molecules and molecular machines; two-dimensional polymers and metal-organic frameworks. Priorities in biophysics include the exploitation of composite nanoparticles in cell-targeting and *in-vivo* fluorescence imaging, extension of Raman skin cancer screening to other cancer types, and biological imaging by tip-enhanced Raman microscopy. This diversification of research is well matched to EPSRC funding priorities, and positions the group to take advantage of the new soft X-ray beam line at Diamond and neutron scattering facility upgrades at the Insitut Laue-Langevin.

MRI will use its unique infrastructure as a platform for new interdisciplinary studies underpinned by physics-led developments and close links with industry. For example, the group will prioritise developments in ultra-high field MRI, neuroimaging of children and multi-modal imaging, which align with the recommendations of the 2012 Report of the EPSRC/MRC Medical Imaging Technology Working Group. In the area of hyperpolarised technologies, work with *CMTh* on the dynamics of coupled spin systems is a priority, along with *in vitro* studies of protein folding.

PTh will prioritise: the study of the cosmological constant in relation to dark energy; new tests to discriminate between modified gravity and general relativity; methods for directional detection of dark matter; the nature and origin of the baryon asymmetry. The group's strategic membership of the Dark Energy Survey and Euclid consortium will provide the data required to develop and validate models of dark energy and matter, thus opening up new directions in this field.

c. People

c1) Staffing Strategy and Staff Development

- **Appointment of 16 New Academic Staff**

Since 2008, 4 academic staff have retired or left the School, and we have appointed 16 new academic staff at Lecturer level (9 with proleptic appointments) as part of our planned expansion. In the same period there were 24 promotions to Professor or Associate Professor/Reader level.

The strategic expansion of the *ColdAtoms* and *PTh* groups has been realised through 6 new staff appointments (discussed in Section b1). *CMTh* group activities have been enhanced through the appointment (2009) of *Lesanovsky* (promoted to Reader in 2011 and then Chair in 2013), whose theoretical expertise complements the experimental *ColdAtoms* group research. The *CMTh* group has been further strengthened by the appointment of *Powell* (2013) to a lectureship and fellowship awards to *Li* (NRF) and *Olmos* (AMF). These appointments have catalysed new collaborative activity in quantum optics, atomic physics and Bose-Einstein condensates.

The *ECMN* group has been strengthened by the appointment of *Makarovsky,* who brings expertise in nanostructures and graphene, and by proleptic appointments for *Rushforth* and *Hill*, who hold

EPSRC CAFs and lead new activities in spintronic materials and magnetoscience, respectively. In addition *Smith* (RS URF) has established new activity in colloidal fluids, linking to research in magnetoscience and granular materials. The appointment of Principal Research Fellow *Akimov* strengthens our expertise in ultrafast optics and THz spectroscopy.

Research in MEG, a strategic priority for the *MRI* group, has been enhanced by the appointment of *Brookes* to a lectureship in 2013. In addition, the award of an AMF in 2012 to *Mullinger* opened up research opportunities in multi-modal imaging and led to a new interdisciplinary partnership with the University of Birmingham's Behavioural Neuroscience Group. This collaborative link was subsequently strengthened by the establishment of a joint lectureship between our School and the School of Psychology in Birmingham. *Mullinger* has very recently been appointed to this position.

The appointments of *Bamford* (working on galaxy morphology with leading involvement in the Galaxy Zoo), *Dye* (Herschel science, gravitational lensing in the study of mass distribution and galactic structure), *Bolton* (numerical modelling of the intergalactic medium), and *Hatch* (early evolution of galaxy clusters) have strengthened and broadened the *Astro* group's research. *Bamford, Hatch* and *Bolton* have proleptic positions and hold STFC fellowships or RS URFs.

- **Staff Development**

Since 2008, the University has promoted 8 of the School's academic staff to Chair and 13 to Associate Professor or Reader. There have also been 3 promotions to Principal Research Fellow (Associate-Professor-equivalent). Advice on career progression is provided through annual Personal Development and Performance Review (PDPR), in which significant achievements are rewarded by enhanced salary awards. In the spirit of the *Concordat to Support the Career Development of Researchers* (henceforth *Concordat*), this scheme is applied uniformly to research and academic staff. All staff are invited annually to submit promotion applications.

The School has introduced several other schemes to support the career development of all staff (academic, research and technical) involved in research, and to promote opportunities for staff to develop new research directions. For academic staff, a priority is to balance the demands of teaching, administration and research. To this end, we operate a workload allocation model, which ensures an equitable distribution of teaching and administrative work, while taking account of research commitments. A study leave scheme, introduced in 2008 to support the development of new research initiatives, has allowed 13 academic staff to take sabbatical leave (11 for two consecutive semesters; 2 for one semester). Outcomes include the award of the School's first Knowledge Transfer Partnership, and a new collaboration between the *CMTh* and *Astro* groups on asteroid formation. A 'shadow' lecturer scheme provides cover for teaching duties, releasing staff to undertake international visits or to give invited talks at major international conferences.

Our Staff Development Committee promotes career development opportunities, monitors attendance at courses offered by the University's Professional Development Service (including courses on project management and research ethics), and organises School-specific training events, for example on routes to deriving impact from our research. New lecturers are supported through specific courses on teaching, research and postgraduate supervision, and have a teaching workload that ramps linearly to a full load over four years. Further support for new staff is provided through mentoring and priority access to PhD studentships and pump-priming grants.

Our research is supported by 25 technical staff who provide specialist expertise in fine-machining, cryogenics, electronics, ultra-high vacuum (UHV) techniques, electron microscopy and nanofabrication. To ensure the long-term provision of these services, we have supported apprenticeship schemes, taking on 3 trainee technicians since 2008.

The School's Research Staff Committee (RStC) provides a forum for discussion between 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 Diversity, 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. Following discussions at the RStC, we have organised a series of training events, followed by personal mentoring, on preparing fellowship applications. Since 2008, this has led to 20 successful fellowship applications by our research staff and newly-graduated PhDs to EU, Leverhulme, RCUK, Royal Society, and

University of Nottingham schemes. Of these fellowships, 15 are held in Nottingham, enhancing both the career progression of the fellowship holders (11 are Category A staff), and also our research portfolio. Since 2008, 20 of our research staff or PhD students have moved to permanent academic posts elsewhere in Europe, America and Asia.

- **Staff with Personal Fellowships: 27 Category A Staff and 16 Postdoctoral Fellows**

All staff are encouraged, via PDPR and mentoring, to seek personal research fellowships and are supported throughout the application process by, for example, mock interviews and the commissioning of advice from external consultants. The success of this process is evident from the inclusion in our return of 27 Category A staff who currently hold, or have held, personal fellowships since 2008, including 20 new awards. These span several schemes: 7 Royal Society URFs (*Almaini, Bolton, Burrage, Edmonds, Padilla, Skordis, Smith*), 4 STFC Advanced/Rutherford Fellowships (*Bamford, Gray, Green, Hatch*), 5 EPSRC AF/CAFs (*Armour*, *Garrahan*, *Hill*, *Patanè*, *Rushforth*), 1 EPSRC Leadership Fellowship (*Moriarty*), 1 STFC/PPARC Senior Fellowship (*Merrifield*), 2 Royal Society Leverhulme Trust Senior Fellowships (*Copeland, Köckenberger*), 2 Leverhulme Early Career Fellowships (*Brookes, Stannard*), 1 ERC Advanced Grant (*Jungwirth*); 5 Nottingham-funded fellowships won in open competition (*Avgoustidis*, *Li*, *Mullinger*, *Olmos*, *Stannard*). In addition, an ERC Starting Grant (*Lesanovsky*) will start on 1 January 2014.

We have also hosted 16 postdoctoral researchers (in addition to the 27 Category A staff) with competitively awarded personal fellowships since 2008. These include EPSRC and STFC Postdoctoral Fellows, as well as Humboldt and Marie Curie Fellows.

- **International Appointments, Recruitment, and Visiting Scholars**

Staff held 9 overseas appointments and professorships, including: *Copeland*, Visiting Professor, AstroParticule et Cosmologie Laboratoire, Paris (since 2009) and Visiting Fellow, Kavli Institute for Cosmological Physics, Chicago (2013); *Edmonds*, Visiting Professor, Institute of Semiconductors, Chinese Academy of Sciences, Beijing (2010-2011); *Fromhold*, Visiting Professor, University of Melbourne (2010). Senior overseas visitors include: Prof. J. Brodie, University of California Santa Cruz (to *Astro* 2012, 2013); Prof. D. Chandler, Berkeley (*CMTh* 2008, 2009); Prof. L. Pogosian, Simon Fraser University (*PTh* 2010); Dr L. Gross, IBM Zurich (to both *ColdAtoms* and *ECMN* 2008, 2011, 2012, 2013); Dr S. Robinson, National Institutes of Health, Bethesda, US (*MRI* 2013).

The School led the *Quantum Technologies* strand of the University's EPSRC Global Engagements grant (EP/K003941/1, £0.5M) developing *CMTh*, *ColdAtoms*, *ECMN* and *MRI* collaborations via 34 exchange visits with 24 institutions in India, South Korea, and the US. MUARC's programme of exchange visits and collaborations, funded partly by the S&I award, links *ColdAtoms*, *CMTh* and *ECMN* with key groups including the École Normale Supérieure, Paris; Max-Planck Institute for Quantum Optics, Munich; Universities of Innsbruck and Trento.

Currently, the School hosts 70 PDRAs/Fellows; 10 were recruited from outside the EU, 22 from the EU (non-UK), and 38 from the UK. These include 12 personal fellowship holders recruited from overseas. Of the 23 new Category A staff, 11 joined us from institutions located outside the UK.

- **Equality and Diversity**

The School established a Diversity Committee in 2007, with representatives from all job families. This committee has worked to develop practices that promote equality and diversity in the School. These include: (i) operation of a transparent workload model; (ii) changes to promotion procedures to avoid over-reliance on self-driven applications; (iii) introduction of a new study leave system (discussed above); (iv) support for staff who wish to work part-time through flexible timetabling; (v) the introduction of 'keeping-in touch days' to streamline the return from maternity leave. These changes were informed by feedback from annual anonymous staff surveys. The School received an *Athena Swan Silver* award in 2010, and contributed to the University's successful application for an institutional Silver award in 2013. The School runs biennial equality and diversity training events for all staff. New staff also complete on-line diversity training during their induction.

We have been very successful in supporting applications to the Anne McLaren Fellowship scheme (University-funded scheme targeted at outstanding female ECRs in science, technology, engineering and medicine). Since 2008 the School has hosted 8 AMFs. Of these, *Burrage* and *Hatch* subsequently won Royal Society and STFC fellowships, and were appointed to proleptic lectureships. Of our returned staff, 2 Professors, 4 Associate Professors/Readers, and 5 Lecturers /Research Fellows are female.

c2) Research Students

- **PG Recruitment and Funding**

Our research student cohort stands at 131. Since 2008 we have awarded an average of 28 PhDs per year, a 65% increase compared with RAE2008. More than half of our returned outputs have PhD student co-authors. Studentships are funded by EPSRC, MRC and STFC doctoral training accounts, the MPAGS HEFCE grant, EU Initial Training Networks (ITNs), the EPSRC-funded Integrated Magnetic Resonance Centre for Doctoral Training, BBSRC and STFC project studentships, and by direct industrial support including CASE studentships. In addition, the School/University fund 3-4 studentships each year, which are allocated strategically, to leverage additional funding, and to support ECRs or new research programmes. We have been extremely successful in winning EU Marie Curie awards, which have provided 16 PhD studentships since 2008, funded by 6 separate awards; there are currently 18 EU (non-UK) PhD students in the School. Approximately one third (46) of our PhD students are international (non-EU), with many funded by national governments or international scholarships. A summer internship scheme to help attract PhD students of the highest quality provides 10-15 research placements each year for top-class undergraduates; 17 internees have gone on to study for a PhD with us since 2008.

- **Training and Support**

MPAGS (now directed by *Garrahan*) provides a platform for high-quality, wide-ranging, postgraduate teaching. Access Grid nodes, installed at each site, allow lectures delivered at one site to be transmitted live to students at partner institutions, and facilitate interactions between the remote audiences and the lecturer. Modules typically involve 10 hours of lectures, taught over 5 weeks, complemented by one-day workshops held at the end of each teaching block. In the first phase of MPAGS, the focus was on EPSRC-related physics, but a second HEFCE award in 2010 extended MPAGS to the astronomy and particle physics areas. Around 40 modules, from a total portfolio of 68, are now delivered annually through MPAGS, and 180 students are currently registered on courses. Workshops and summer schools are also organised through MPAGS, with several events run each year. MPAGS currently provides a platform for the training elements of 3 EU ITNs (total value €11M, 39 students) that are co-ordinated by our staff: ACRITAS - Actuation and Characterisation at the Single Bond Limit (co-ordinated by *Moriarty*), HiMR - Ultra-High Field Magnetic Resonance Imaging (*Gowland*) and QTea - Quantum sensor technologies and applications (*Fernholz*).

Each PhD student in the School has two academic supervisors and access to pastoral support from two Postgraduate Tutors. In addition to subject-specific training, the University's Graduate School provides diverse generic skills training for PhD students (including *Interpersonal and Communication Skills* and *Leadership and Management*), and each research group organises weekly research seminars. Monthly colloquia by leading (often overseas) researchers ensure that students and staff are exposed to topics outside their field. There are many opportunities for PhD students to present their work at regular group meetings and, funded by the School, at international conferences.

- **Progress and Monitoring**

Student progress is monitored by formally-recorded monthly meetings and viva examination of reports produced at the end of the 1st and 2nd years of study. This process provides students with valuable exposure to the mode of assessment used for a PhD. Students are required to take 35 credits of taught modules, typically comprising MPAGS modules (5 credits for 10 hours of lectures) combined with generic training.

d. Income, Infrastructure and Facilities

d1) Infrastructure and Facilities

The School's research infrastructure and facilities have been enhanced by £11.2M investment over the REF period, including £2.4M CIF funding. Our research infrastructure is clustered thematically in three buildings, which are in close proximity and house the research groups as follows:

MRI is based in the 1500 m^2 Sir Peter Mansfield Magnetic Resonance Centre (SPMMRC), which accommodates the UK's first 7T human MRI scanner. This is one of only two such systems in the UK and about 40 worldwide. The SPMMRC also houses a 275-channel MEG scanner, a 3T Philips scanner and a 9.4T NMR microscope, mainly used for studies of hyperpolarisation. The *MRI* group also manages a 1.5T human scanner, based in the School of Psychology. In 2008, a £0.5M Wolfson Foundation Grant was used to develop two new laser laboratories for optical polarisation

research, and a magnet laboratory housing a dual-centre prototype dynamic nuclear polarisation imaging system, constructed in collaboration with Oxford Instruments as part of an EPSRC-funded project (EP/C534786/1, £0.75M). In addition, *Morris* was PI on an EPSRC grant (EP/G003076/1, £1.3M), which, along with a University contribution, funded a new £1M lung imaging facility based around a 1.5T MRI scanner sited in the nearby Queen's Medical Centre.

Astro* and *PTh are co-located in the 650 m^2 Centre for Astronomy and Particle Theory (CAPT). Since 2008, 150 m^2 of new office space has been created to accommodate a 25% increase in the number of academic staff, fellows, students and visitors. The University has made long-term investments in these groups by continued support for the Southern African Large Telescope, and has allocated £0.6M (£0.4M CIF plus £0.2M University funding) for computing facilities and membership of: the Low Frequency Array (LOFAR); the Dark Energy Survey; the Sloan Digital Sky Survey IV (SDSS-IV).

CMTh*, *ColdAtoms* and *ECMN are housed in the main Physics Building, which occupies 6000 m^2. Since 2008, a 200 m^2 area has been converted into state-of-the-art laboratories for the *ColdAtoms* group through an investment of £1.6M from the University, CIF and the S&I award for MUARC. This suite houses a meeting area, optics and electronics testing facilities, and four fully-equipped laboratories with close temperature control and vibration-damped optical benches, plus separate control rooms allowing fully-automated computer control of four experiments.

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. The NNNC provides access to scanning and transmission electron microscopy, X-ray photo-electron spectroscopy, and Raman spectroscopy. Our infrastructure has been enhanced by the acquisition of: two low-temperature UHV AFM/STMs and a variable temperature UHV AFM/STM; field cycling and ultra-low temperature NMR facilities; a new large-bore cryogen-free 19T magnet, located in a refurbished laboratory, for magnetoscience; a combined Raman spectrometer and AFM with associated cell biology facilities; a confocal microscope for imaging nanoparticles and exfoliated layered compounds; a cryostat with vector magnetic field capability for use in spintronics research.

Within the Physics Building there is a helium liquefier and mechanical, vacuum, and electronics workshops (including facilities for UHV construction and fine-machining), which are operated by specialist technicians in support of the *ColdAtoms*, *ECMN* and *MRI* groups.

Nanofabrication and Epitaxial Growth: The Physics Building houses a large cleanroom suite [ISO Class 7 (Class 10000), 300 m^2], accommodating 3 MBE systems, which grow III-V heterostructures, spintronic and nitride semiconductors (a new dual-chamber MBE system, funded by a £1.3M EPSRC award, will be delivered in 2014 and used to grow graphene multilayers), electron beam lithography, plasma etching and metallisation facilities. This equipment is used for fundamental studies of growth and to fabricate nanostructures for *ECMN* and *ColdAtoms*. Since 2008 this facility has been upgraded by installing plasma processing equipment for etching silicon, aluminium gallium arsenide, gallium nitride and graphene, and a plasma-enhanced chemical vapour deposition system for depositing 'hard' masks for etching. A 6-source magnetron sputtering system was purchased in 2011, to enable sequential growth of metals, oxides and, via transport to the MBE systems, semiconductors. A 90 m^2 ISO Class 7 cleanroom was constructed in 2011 for lease to e2v. Partnership with e2v has enhanced our in-house processing techniques and expertise, benefiting our collaborative programme of research, development and manufacturing.

High Performance Computing (HPC) infrastructure: The School makes extensive use of the University's HPC facilities, established with £3M SRIF/CIF investment, which provide over 2,000 computer cores running at over 20 teraFLOPS. In 2013, these facilities were upgraded as part of EPSRC's investment of £3M in the MidPlus Centre of Excellence for Computational Science, Engineering and Mathematics; Nottingham is one of the four MidPlus partners. Since 2005, *Pearce* has served on the University HPC Management Committee, playing a leading role in developing the case for HPC facilities and in their procurement.

£11.2M investment in infrastructure since 2008: This is made up of £5.4M for converting and equipping new laboratories (£1.6M for *ColdAtoms*; £0.5M for the e2v cleanroom; £1.4M for the MEG facility; £0.9M for magnetoscience; £1M for the lung imaging centre), £2.3M for refurbishing laboratories and office space (£1M for *ECMN* cleanrooms; £0.7M for *ECMN* nanoscience; £0.5M Wolfson award for *MRI*; £0.1M for CAPT offices), £1.9M for purchasing new strategic equipment

(£1M for two low-temperature and one variable temperature UHV STM/AFM systems; £0.9M for an X-ray diffractometer), £1M for University HPC facilities, and £0.6M for membership of international telescope consortia.

Planned School/University infrastructure investments in 2014 include: a £0.8M upgrade of our helium liquefier to provide an enhanced University facility for supplying internal and external users; 70 m^2 office refurbishment for *CMTh* collaboration with the School of Mathematical Sciences on complex quantum systems; creation of 40 m^2 cleanroom space for our new graphene MBE machine; 60 m^2 new nanofabrication facilities to expand our manufacturing capability with e2v.

d2) Research Funding Portfolio

The value of current (31 July 2013) awards is £38.6M including £27.3M from RCUK (EPSRC, STFC, MRC and BBSRC), £5.4M from the EU, £3.2M from charities, £1.2M from industry, and £0.9M from the Department of Health/NIHR. The group funding profiles are:

Group	Active portfolio	Key awards
Astro	£4.3M	£1.8M STFC Consolidated Grant, PI *Aragón-Salamanca*
CMTh	£2.6M	£0.7M EPSRC grant on Non-equilibrium Dynamics of Open Systems, PI *Garrahan*
ColdAtoms	£6.8M	£5.2M EPSRC/HEFCE Science and Innovation award joint with the University of Birmingham
ECMN	£13.5M	£1.7M EPSRC Leadership Fellowship, PI *Moriarty*; £1.0M EPSRC Career Acceleration Fellowship, PI *Rushforth*
MRI	£5.9M	£2.4M MRC Ultra-high field MRI Programme Grant; PI *Morris*
PTh	£2.3M	£0.4M STFC Consolidated Grant; PI *Copeland*
School	£3.2M	Doctoral training grants from BBSRC, EPSRC, MRC, STFC

Our Research Committee co-ordinates the School's response to funding opportunities, negotiates University support for major applications, and monitors our research portfolio. The *Astro* and *PTh* groups have continuously held rolling/consolidated grants since 2006 and 2008, respectively, successfully bridging the transition from PPARC to STFC funding, and the *MRI* group has been awarded three successive 5-year MRC Programme Grants. Our EPSRC-related activities are well aligned to the EPSRC Grand Challenges in Physics and to their Healthcare and Energy themes. Since 2008, we have strategically targeted EU and European Research Council funding, leading to an increase in EU income of 60% from 2009 to 2013.

- **Access to major non-RCUK Facilities not included in RA4: £3.0M**

Staff secured access to the following international facilities: MAX-lab synchrotron, Sweden (£2M, 196 days access, *O'Shea*); BESSY synchrotron, Germany (£0.1M, 10 days, *Edmonds*); Advanced Light Source synchrotron, USA (£0.1M, 12 days, *Edmonds*); European Synchrotron Radiation Facility, France (£0.1M, 6 days, *Edmonds*); European Magnetic Field Laboratory (£0.2M, 116 hours, *Patanè*); telescope time (£0.5M, 146 hours, *Astro* collectively).

e. Collaboration or Contribution to the Discipline or Research Base

e1) Collaborations and Interdisciplinary Activities

During the census period, staff collaborated with 265 international groups in 41 countries. This includes partnership in 30 EU/ESF projects (with our staff co-ordinating 17 of these, including 5 ITNs) with a total value of £76.7M (funding of £7.8M to the School).

Expansion of interdisciplinary activities, highlighted as a priority in RAE2008, has been achieved and there are now ongoing collaborations with all Schools in the University of Nottingham Faculty of Science (Biosciences, Chemistry, Computer Science, Mathematical Sciences, Pharmacy and Psychology) and with other faculties (particularly Engineering and Medicine and Health Sciences).

Astro leadership roles in major international observational projects include the Planetary Nebulae Spectrograph (PN.S) project, which probes galactic kinematics (*Merrifield* UK leader, 17; here, the quoted numbers indicate total number of refereed publications since 2008); a multi-wavelength study of the Abell 901/2 multiple cluster system, STAGES (*Gray* PI, 7), leading to a new European Southern Observatory (ESO) large programme (PI *Aragón-Salamanca*); the ESO distant cluster survey, EDisCS (*Aragón-Salamanca* UK leader, 27); the Hubble Space Telescope (HST) Near Infrared Camera and Multi-Object Spectrometer (NICMOS) survey (*Conselice* PI, 12); the Ultra-deep Survey of the UK Infrared Deep Sky Survey, UKIDSS, and associated ESO large programme (*Almaini* PI, 8). We also lead gas-physics simulations in the Virgo Consortium (*Pearce*, 10).

ColdAtoms has a major collaboration with the University of Birmingham on sensors and matter-wave interferometers, and other national links developed, for example, through the EPSRC-funded UK Network for research at the interface between cold-atom and condensed matter physics, led by *Fromhold* (*CMTh*). International collaborators include Copenhagen (non-classical squeezed states), U Mass Amherst (non-linearity in quantum gases), the International School for Advanced Studies (SISSA) Trieste (superfluid dynamics), and Technical University Vienna (one-dimensional quantum gases). *Fernholz* leads the €4.2M QTea ITN.

CMTh key collaborations include: *Garrahan* with theorists in Berkeley, Geneva, Michigan and Paris on glasses and dynamic arrest; *Swift* with the Max Planck Institute for Dynamics and Self-organization; *Armour* with theorists and experimentalists in Bordeaux, Dartmouth (US) and Grenoble on nanoelectromechanical systems; *Fromhold* with the Faculties of Engineering and Medicine on cold-atom quantum sensors; *Lesanovsky* with scientists at Dresden and Vienna on hybrid quantum optical systems, and with Mainz and Innsbruck on quantum information processing in trapped ions. Since 2008, the group has been active in five EU networks (co-ordinating two of value €4.2M), including two ITNs.

ECMN has many interdisciplinary links with chemists, engineers and life scientists (33% of *ECMN* REF outputs have co-authors from other disciplines) including work on two-dimensional supramolecular organisation and polymers, colloidal semiconductor nanoparticles, and on the growth of metal-organic frameworks funded by an EPSRC Programme Grant (EP/I011870/1, £4.2M). Collaborations with chemists in Nottingham and Oxford provide access to novel materials such as conjugated polymer nanorings. *O'Shea* collaborates with the MAX-lab synchrotron to develop new resonant photo-emission techniques. *Horsewill* is a founder member of a consortium, including Columbia, Kyoto, and Southampton, studying endohedral fullerenes synthesised using 'molecular surgery'. *Notingher*'s work on cancer screening using Raman spectroscopy has stimulated extensive links with medics in Nottingham and Derby. *Eaves* and *Hill*'s EPSRC Basic Technology project (EP/G037647/1, £0.6M) brings together researchers from *CMTh* (*Swift*), the Engineering Faculty, and the Schools of Biosciences and Pharmacy, to study biological systems and granular media in zero gravity. *Eaves* and *Makarovsky* have established a new collaboration with the Manchester Graphene group on tunnel transistors.

MRI research is highly interdisciplinary and collaborative: of the 25 MRI-related outputs returned for REF, 16 have co-authors from outside the School (6 have clinical co-authors and 8 have co-authors from other institutions). Operation of the 7T scanner as a National Facility has generated new collaborations with UCL and the Universities of Birmingham, Cambridge, Leicester and Oxford. This scanner was also part of the *Euro-BioImaging* research infrastructure project of the European Strategy Forum on Research Infrastructures Roadmap. Gowland leads the €3.6M HiMR ITN, which brings together 8 EU sites that have human scanners operating at 7T or above, plus Philips, Siemens and GE, to train the leaders of future research in ultra-high field MRI. *Morris* leads the University's Biomedical Imaging Priority Group.

PTh key collaborations include those on the cosmological constant, dark energy and modified gravity between *Burrage*, *Copeland*, *Moss*, *Padilla*, *Saffin*, *Skordis* and theorists in Bologna, Saclay, Orsay, Geneva, Cape Town, Barcelona, DESY, UBC and the Perimeter Institute in Canada, and UC Davis; constraints on the direct detection of dark matter between *Green* and theorists in Madrid; B mode signatures from cosmic (super) strings between *Avgoustidis*, *Copeland* and *Moss* and theorists in APC Paris, Arizona State University, UBC Canada and SFU Canada; the nature of string inflation, gravitational radiation from solitons, and electroweak baryogenesis between *Copeland*, *Saffin* and theorists in CERN, Tufts, Heidelberg, Auckland and Stavanger.

e2) Industrial and User Input into Research Activity and Strategy

The shared access to equipment, and exchange of expertise, resulting from our partnership with e2v brings mutual benefits such as improved performance of semiconductor devices operating above 100 GHz, including receiver protectors (KTS and KTP grants, PI *Fromhold*). Collaborations with industry, medical practitioners and governmental organisations (including Agilent, Ambiental, Bruker UK, e2v, GSK, Oxford Instruments, Philips, Proctor & Gamble, Reckitt Benckiser, Rolls Royce, SABMiller, Unilever – see also our Impact Statement), together with user representation on the School's Strategic Advisory Board (see Section b2), provide broad industrial input to inform and refresh our research and impact strategies. For example, partnership with e2v led to major nanofabrication infrastructure investment for joint projects (see the associated Impact Case Study).

e3) Leadership in the Academic Community

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

Invited Talks and Keynote Presentations: staff gave 77 Plenary and 415 Invited talks at International (Int.) conferences, 105 Invited talks at national conferences, and 332 seminars at universities and research institutes (44% outside the UK). Highlights include: Opening review talk at CYGNUS 2009 Directional dark matter detection, MIT Boston (*Green*, 2009); Int. Conference on Electronic Properties of Two-Dimensional Systems, Kobe (*Jungwirth*, 2009); American Physical Society March Meeting, Oregon (*Hackermüller*, 2010); Invited review, Galactic nuclei and their connection to the environment, Int. Conference in Honour of Miriani Pastoriza, Gramado, Brazil (*Almaini*, 2012); Annual Meeting of the Organisation for Human Brain Mapping, Beijing (*Brookes*, 2012); 31st Int. Conference on the Physics of Semiconductors, ETH Zurich (*Patanè*, 2012).

Conference Organisation: staff chaired 35 international conferences and served as Programme Committee members on 149 more. Highlights include: Organisers of conference "Galaxy Evolution and Environment", Kuala Lumpur (*Gray*, *Merrifield*, *Pearce*, 2009); Programme Committee of The Int. Conferences on Electron Dynamics in Semiconductors, Optoelectronics and Nanostructures (*Patanè*, Montpellier 2009 and Matsue 2013); Programme Committee of the 30th Int. Conference on the Physics of Semiconductors (ICPS 2010), Seoul (*Eaves*, 2010); Co-Chair of the Int. Society for Magnetic Resonance in Medicine (ISMRM) Workshop on Ultra-High Field Systems and Applications, Lake Louise (*Bowtell*, 2011); *MRI* group members have served on the Annual Meeting Programme Committee of the ISMRM since 2008; Chairs of the "Tales of Lambda" Int. meeting on dark energy, Nottingham (*Padilla*, *Saffin*, *Skordis*, 2013).

Journal Editorship: staff served on 24 Editorial Boards including: Journal of Cosmology and Astroparticle Physics (*Green*, since 2006); Neuroimage (*Brookes*, since 2011); PloS ONE (*Garrahan*, since 2012); The Astrophysical Journal (*Conselice*, since 2010).

Awards and Prizes: Ten awards (in addition to fellowships, listed in Section c1) including: Royal Society Wolfson Merit Award (*Copeland*, 2008-2012); Philip Leverhulme Prize in Astronomy and Astrophysics (*Conselice*, 2009); International Society for the Study of the Lumbar Spine Prize (*Gowland*, 2009); Explicitly named in the citation for the 2012 Royal Astronomical Society 'A' Group Award to the UKIDSS project (*Almaini*, *Dye*); Humboldt Research Award (*Akimov*, 2013); IOP Tabor Medal and Prize (*Beton*, 2013); IOP Rayleigh Medal and Prize (*Copeland*, 2013).

Leadership in Learned Societies: Chair of IOP Conferences Committee (*Moriarty*, 2012-2015). Chair of IOP Simon Prize Committee (*Owers-Bradley*, 2011). IOP Group Chairs: Low-temperature (*Owers-Bradley*, 2008-2010); Nanoscale Physics and Technology (*Moriarty*, 2009-2012); Quantum Optics, Quantum information and Quantum Control (*Fromhold*, 2010-2014); Thin Films & Surfaces (*O'Shea*, 2010-2013); BRSG Magnetic Resonance (*Owers-Bradley*, 2013-2016). Hon. Secretary of the IOP Applied Physics & Technology Division (*O'Shea*, 2011-2012). Member of Sectional Committee 2 (Physics & Astronomy) of the Royal Society (*Eaves*, 2008-2010). Board Member of the European Physical Society Condensed Matter Division (*Patanè*, since 2011). ISMRM Study Group Chairs: High Field Systems & Applications (*Bowtell*, 2011); Brain Function (*Gowland,* 2012).

National and International Advisory Roles: staff contributed to scientific governance through membership of bodies to allocate and monitor resources in national and international research councils and facilities: for example by chairing 6 RCUK grant panels. Advisory roles include membership of: the RAE2008 and REF Physics sub-panels, the REF Impact Pilot Assessment Panel (*Eaves*) and the Clinical Medicine REF Sub-panel (*Morris*); Chair of the STFC European Extremely Large Telescope (E-ELT) Strategic Steering Committee (*Merrifield*, 2009); many international telescope time allocation committees, including the ESO (*Conselice*, 2009-2010; *Gray*, 2012; *Hatch*, 2013; *Merrifield*, Panel Chair, 2009-2010), Gemini (*Dye*, 2011-2012), HST (*Conselice*, 2010; *Gray*, 2011), Chandra X-ray Satellite (*Hatch*, 2012); Project scientist for the UKIRT Hemisphere Survey (*Dye*, since 2012); EPSRC Shaping Capability and Peer Review – Advice Stream (*Beton*, 2012; *Fromhold*, 2011-2012); Diamond beamtime allocation and user working groups (*Edmonds*, 2009-2013); Synchrotron SOLEIL beamtime Peer Review Committee (*O'Shea*, since 2011); Neutron scattering instrument review panel, Institut Laue-Langevin (*Horsewill*, 2011); President of the *European Magnetic Field Laboratory* user community (*Patanè*, since 2011); Leverhulme Trust Research Awards Advisory Committee (*Eaves*, 2008-2015); Advisory Board of the Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig (*Morris*, 2008-2014); STFC Particle Astrophysics Advisory Panel Member (*Green*, 2012-2015).