Institution: University College London (UCL)
Unit of Assessment: 9 Physics

1. Unit context and structure, research and impact strategy

1.1 Overall context and aims

We aim to attract the most talented researchers and provide an exceptional environment in which they can flourish to perform outstanding physics research. We achieve this through: targeted use of our funds to pump-prime new initiatives and support early-career researchers; making the most of UCL's interdisciplinary ethos and low barriers to collaboration; supporting staff to take international leadership roles; and close involvement in the development of transformative techniques and instrumentation. The evidence below shows we have:

- Recruited and retained outstanding staff, who have made seminal contributions to the subject;
- Formulated and implemented a clear vision for the discipline;
- Maintained excellent infrastructure and support to allow our researchers to thrive;
- Promoted inter-disciplinary collaborations;
- Achieved exceptionally wide engagement with research users and the wider public.

1.2 Overall research strategy

UCL has one of the largest concentrations of physics research in the UK and we aim for the highest levels of excellence across the subject. Our portfolio ranges from the fundamental constituents of matter to the large-scale structure of the universe, the frontiers of quantum technologies and the complexities of condensed-phase and biological systems.

During the coming years our strategy is to

- Build on the broad excellence in our research;
- Increase the diversity of our staff cohort;
- Grow the interface between physics and data science;
- Contribute to fundamental research advances and their societal impact;
- Make full use of the connectivity and opportunities for collaboration in central London, while mitigating the inevitable space constraints by locating appropriate activities elsewhere;
- Develop further the priority areas highlighted below in the descriptions of individual research fields.

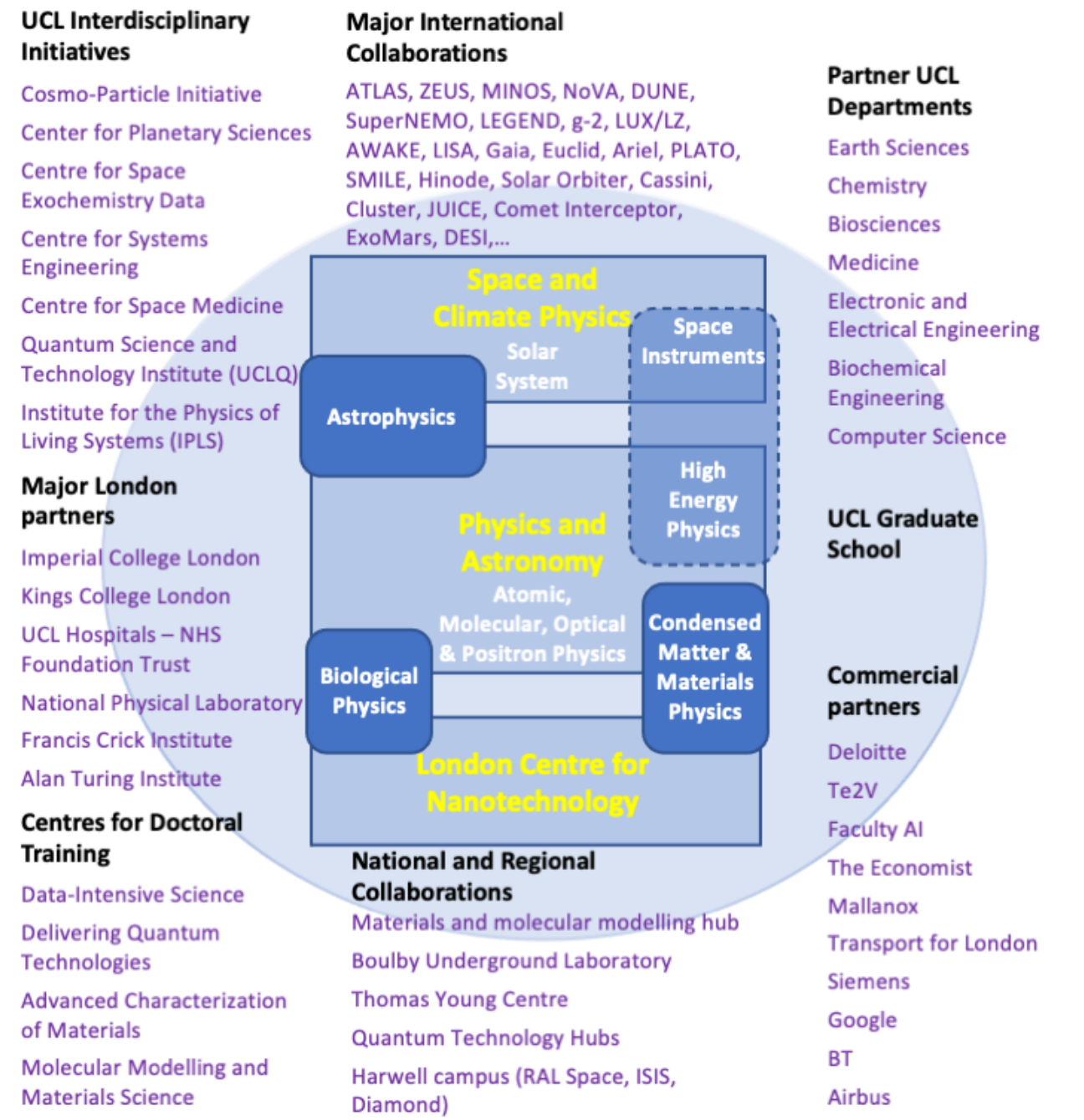

Figure 1: UCL physics research and its environment of major research and training partnerships within and beyond UCL.

1.3 Structure and management

1.3.1 Departments

Physics at UCL is structured into three departments (see Figure 1, yellow text) within the Faculty of **M**athematical **A**nd **P**hysical **S**ciences (MAPS), which is in turn part of the BEAMS School (**B**uilt Environment, **E**ngineering **A**nd **M**athematical and Physical **S**ciences). This maintains broad research excellence across the discipline while seizing opportunities in particular technology areas.

- **Physics & Astronomy** (P&A) is the main undergraduate teaching department and the largest unit (68.9 FTE academic staff excluding LCN joint appointments – see below, 87 FTE research staff, 272 postgraduate research students). Research covers the full breadth of the subject and is structured into five main groups: Astronomy and Astrophysics (**Astro**), Biological Physics (**BP**), High-Energy Physics (**HEP**), Condensed Matter and Materials Physics (**CMMP**) and Atomic, Molecular, Optical and Positron Physics (**AMOPP**). The

department is based on UCL's central Bloomsbury campus, and also occupies space at the Royal Institution and the Harwell Science and Innovation Campus. It runs UCL's flourishing undergraduate physics programme (annual intake rose from 149 to 250 over the period).

- **Space & Climate Physics** (SCP) is located at the Mullard Space Science Laboratory (MSSL), near Dorking in Surrey (25.4 FTE academic staff, 33 FTE research staff, 51 research students) and also has offices in Bloomsbury. The MSSL site includes a 19th-century country house, and purpose-built laboratories and cleanrooms that would be difficult to accommodate in Bloomsbury. It is focused on the opportunities in astrophysics and solar system science afforded by space missions. A team of 85 specialist engineers constructs spacecraft-borne instruments, working closely with scientific research groups defining the missions and exploiting the data. The department actively transfers expertise in project management and systems engineering to the private sector via CPD courses and MSc apprenticeships.
- The **London Centre for Nanotechnology** (LCN) is an interdisciplinary research department, centred in a purpose-built building adjacent to P&A, having joint academic staff with P&A (CMMP and BP groups), Electronic & Electrical Engineering, Computer Science, Chemistry, Biological Sciences, Biochemical Engineering, Medicine, and Earth Sciences. LCN returns 17.2 FTE staff in this UoA, mostly joint with P&A but including one with Computer Science; there are 18 FTE associated research staff, while physics-related students are included in the numbers for P&A above. The LCN also forms a cross-London collaboration with Imperial and (in a new strategic initiative during the period) King's College London – staff submitted by home institutions. Its mission is to pursue opportunities offered by the tools of modern nanoscience across a range of science and technology areas, focusing on information technology, healthcare and the environment, and to make those tools available to the widest possible community.

Each department has a management group, with representation across its portfolio, that advises its head on strategic and operational issues. The heads meet regularly to agree the overall research vision for physics, and have monthly one-to-one meetings with the Dean of MAPS. Five-year strategic plans for each department are approved annually by the Dean and feed into the Faculty's own objectives. An interdisciplinary LCN stakeholder group brings together the Deans/Heads partner faculties/departments; the LCN Directors from UCL, Imperial and King's also meet regularly to coordinate cross-institutional strategy. The Heads of Department and the Dean are all active researchers, and UCL has always been clear that they are expected to act as scholars first and managers second.

1.3.2 Cross-cutting Centres and Institutes

UCL dynamically forms centres and institutes to address both major research questions and critical societal needs. Alongside their established participation in the LCN, UCL physicists play a prominent role in several such groupings.

- The **UCL Quantum Science and Technology Institute** (UCLQ) brings together researchers in the rapidly developing area of quantum technologies across UCL. Led from the LCN, it includes groups from P&A, Electrical & Electronic Engineering, Computer Science and Chemistry (33 academic staff, 15 in UoA9).
- The **Centre for Planetary Sciences** (CPS) brings together the planetary science groups in P&A, SCP and Earth Sciences along with Birkbeck College (45 academic staff, 18 in UoA9).
- The new UCL **Centre for Space Exochemistry Data** (CSED) in the Harwell Space Cluster brings together researchers from the Astro and AMOPP groups, Computer Science and RAL Space, promoting collaborations between astrophysical science, AI, industry, public sector organisations and SMEs.
- The **Cosmoparticle Initiative** (CPI) links the Astro, HEP and AMOPP research groups in P&A with SCP, with a core of 13 academic staff. Its focus is on the overlap between cosmology and astro-particle physics, with a focus in areas such as dark matter, early-universe physics and neutrino physics.
- The **Thomas Young Centre** (TYC) links researchers from UCL, Imperial, King's and QMUL interested in the theory and simulation of materials across length- and time-scales. UCL's

participation is led from the P&A CMMP group (7 staff), and covers the LCN, Chemistry and Earth Sciences as well as engineering and biomedical departments. The centre hosts an active visitor programme and organises regular 'soirées' presenting contrasting views of current research.

- The **Institute for the Physics of Living Systems** (IPLS) brings together researchers from P&A, the LCN, the Division of Biosciences, the Laboratory of Molecular Cell Biology (all at UCL) and the Francis Crick Institute (25 academic staff, 5 from UoA9). Supported by major investment from the Provost's Strategic Development Fund, it tackles fundamental questions in the physics of biological matter including cell and tissue mechanics.

1.4 Overview of our research

Physics research at UCL covers a full spectrum from the largest to the smallest length-scales.

1.4.1 Astrophysics and Space Science (44.1 FTE staff)

Research in astrophysics and space science at UCL covers an exceptionally broad range including cosmology, extra-galactic, galactic and stellar astrophysics, exoplanets, solar physics, space plasma physics, and planetary science. Its key strength is in **integrating theoretical and computational developments** in each area **with observational expertise and leadership**, including on many large international collaborations. This position is based on an exceptional community, including an unusually large cohort of specialist engineers; the synergies between different areas, and the numerous leadership positions we occupy, provide outstanding opportunities for UCL researchers.

We build on this broad programme by developing and exploiting instrumentation for both ground-based facilities and space missions, by making new connections between cosmology and particle physics, and through leveraging leadership roles. Following our earlier success proposing and scientifically leading the ESA Cryosat mission, the **three** most recent space science missions approved by the European Space Agency (ESA) were **all** proposed by (and are now under the science leadership of) UCL staff, an unprecedented concentration of space research leadership in a single university. Figure 2 highlights our involvement in space missions during the REF period, and our leadership in upcoming major missions; leads form consortia, coordinate proposals against fierce competition, work with agencies to deliver the missions, and lead the science after launch. We have strategically developed science programmes alongside our leadership in instrumentation and management.

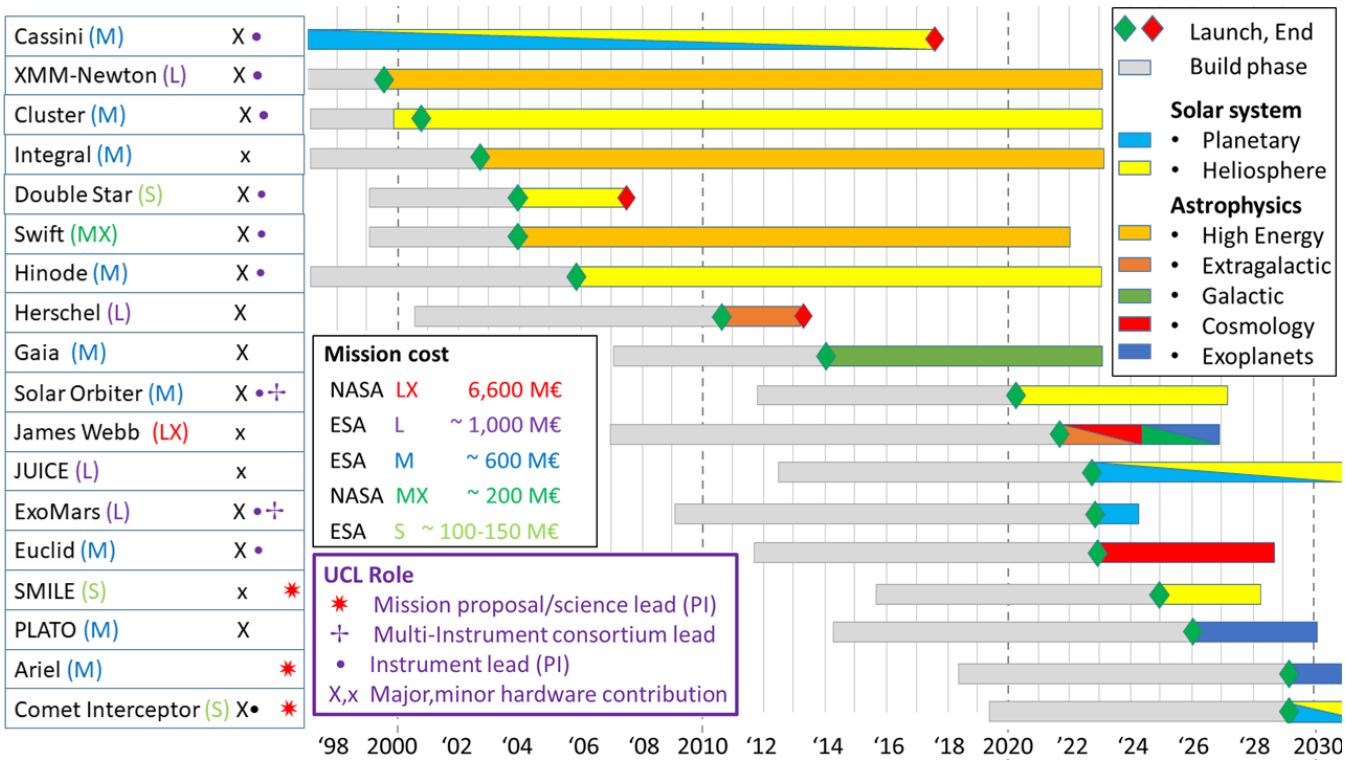

Figure 2: UCL hardware development and leadership roles in major space missions operated or approved by the worldwide space agencies since 2000. Grey bars denote build phase and thick coloured bars the (currently funded) mission duration. Data analysis and exploitation generally continues long after operations end.

Our research achievements demonstrate vitality across the sub-fields.

- **Cosmology and large-scale structure**: we were founding members of the ground-based **Dark Energy Survey** (DES, 2013-19, data analysis continuing) and **Dark Energy Spectroscopic Instrument** (DESI, 2019-), combining critical instrumentation contributions with scientific leadership. The first year DES data demonstrated the power of the "multi-probe" approach followed by all subsequent dark-energy projects. We have successfully exploited data taken by **Planck** (ESA mission 2009-2019) to test models of cosmic structure, and shared in two Breakthrough Prizes in Fundamental Physics (in 2015 to the Supernova Cosmology Project, in 2018 to the WMAP Consortium). We lead one of the two instruments on **Euclid** (ESA M2 mission, 2022 launch) aimed at understanding dark energy and dark matter, and have a senior leadership role in its scientific consortium.
- **Extragalactic and galactic astrophysics, and stellar evolution:** We participated in the reconstruction of a supermassive black-hole image by the Event Horizon Telescope team, contributing modelling of general relativistic radiation transfer (sharing a further 2020 Breakthrough Prize). Using a UCL-built and led telescope on NASA's **Swift** satellite, we discovered unexpectedly intense ultraviolet emission from the first merger of binary neutron stars to be observed via gravitational waves. We are major contributors to the **Gaia** mission (launched 2013), which measures position and radial velocity of about 1.7 billion stars in our galaxy and the local group; UCL calibrated the detector chains and made a major contribution to the Radial Velocity Spectrometer alongside involvement in the analysis. We made a range of discoveries (e.g. dust in the reionization era, structures of tori around active galactic nuclei) using the Atacama Large Millimeter Array (ALMA). We have PI leadership and management roles in the James Clerk Maxwell Telescope. We compared the effects of star formation and super-massive black holes on galactic evolution by exploiting data from the **Herschel** mission (where UCL had a strong role in the **SPIRE** instrument) throughout the review period. We also lead the e-MERLIN radio astronomy legacy project **COBRaS**, surveying massive star and binary populations in the Galaxy.
- **Exoplanets**: we reported the first discovery of water in the atmosphere of a small planet in the habitable zone. We have **science PI leadership in the Ariel mission** (ESA M4

mission, 2029 launch) which will characterize the chemical composition and thermal structure of transiting exoplanet atmospheres). We lead front-end electronics development and sensor characterisation for **PLATO** (ESA M3 mission, 2026 launch) which will search for Earth-like rocky exoplanets in the habitable zone) and lead two work-packages in the science consortium.

- **Solar system physics**: we have **science PI leadership in the Comet Interceptor** mission (ESA/Japan F1 mission, 2029 launch with Ariel) and expect to be PI for its EnVisS instrument (final selection in progress). We also have the European **science co-PI leadership in the SMILE mission** (ESA/China, 2024 launch), which will measure the Earth's magnetosphere's global response to solar wind and geomagnetic variations. We lead the Solar Wind Analyser instrument suite for Solar Orbiter (the ESA/NASA M1 mission, launched 2020) and uniquely have a major hardware role in a second instrument, the Extreme Ultraviolet Imager. We are PI for the PanCam panoramic camera for the **Exomars Rosalind Franklin Rover** (to launch 2022). We also lead the Extreme Ultraviolet Imaging Spectrometer for **Hinode**, which has yielded a wealth of information about solar physics and solar flares, and the Electron Spectrometer sensor of the Cassini Plasma Spectrometer (CAPS- ELS) in the **Cassini-Huygens** mission which unexpectedly discovered complex negative ions in the atmosphere of Titan. UCL is PI for the PEACE electron analysers on the **Cluster II** multi-spacecraft mission (ESA/NASA, launched 2000), which produced data contradicting the standard substorm current wedge model during the review period.
- **Theoretical and computational astrophysics and cosmology**: we brought together simulation and analytic studies to analyse cosmological and galactic surveys, yielding high-profile results including the most powerful test of cosmic isotropy to date. Our numerical codes led to award-winning insights into phase transitions in the early Universe. Our work on chemistry in the interstellar medium and in exoplanetary atmospheres links with the ExoMol molecular line-lists project, which has been reviewed as Europe's largest contribution to Exoplanet Science and connects the Astrophysics and AMOPP groups.

During the assessment period

- We invested in **new space at Harwell** to support CSED and the Ariel project team in close proximity to RAL Space, where the Ariel instrument will be tested and assembled;
- We refurbished space in Bloomsbury for a relocation of the Astrophysics Group and the establishment of the **Cosmoparticle Initiative** (see Section 1.3.2);
- We made four new appointments to expand research in **exoplanets** and to support Ariel and PLATO (Waldmann – ERC Starting Grant, Van Eylen, Kama and Pinilla – to start in 2021);
- We appointed Ellis (ERC Advanced Grant) and Feeney (RS-URF with proleptic Lectureship) to strengthen **observational and computational cosmology**, Schoenrich and Sanders (RS-URF with proleptic Lectureships) in **galactic astrophysics**, Long, Verscharen (both proleptic STFC-ERFs) and Reid in **space plasma and solar physics**.

In the coming period we plan major developments in

- **Gravitational waves and time-domain astronomy**, including multi-messenger observation of compact object mergers. UCL recently jointed LISA; we are currently making an appointment in this area, and actively supporting applicants for fellowships;
- **The dark universe**, including exploitation of the data from the DESI survey (observations from 2020), the Euclid mission, and the LSST survey;
- **Laboratory cosmology,** exploiting connections to quantum technologies for the detection of gravitational waves and dark matter, and quantum simulations of the physics of the early universe and black holes within condensed-matter systems or cold atomic gases, supported by the Cosmoparticle Initiative (see Section 1.3.2);
- **Extra-solar planets**, with frontier areas including the determination of atmospheric compositions and the search for life, and preparation for launches of PLATO and Ariel. Alongside the CSED, we are also pioneering a new commercial approach to create

opportunities for cutting-edge science satellites through a UCL start-up, Blue Skies Space Ltd.

- **Helio-physics**: our instruments on Solar Orbiter recently joined those currently operating on Cluster and Hinode, contributing to the 'Grand Heliospheric Observatory' which will lead to very significant advances in solar, stellar, and space plasma physics over the next decade. We are seeking UKSA support to participate in SOLAR-C EUVST;
- **Space weather**, where we run training courses for Met Office forecasters, collaborate closely to improve accuracy, and are preparing the solar wind plasma instrument for the ESA Lagrange mission;
- The search for evidence of historical **life on Mars**, using the ESA ExoMars Rover;
- Studies of **planetary magnetospheres**, exploiting particle, field and imaging data from the ESA JUICE mission and planning Ganymede aurora observations from 2032;
- Support for all areas will be developed by enhancing **theoretical and numerical activities.** Cross-cutting areas including chemical complexity, astro-statistics and astro-informatics. Our CDT in Data Intensive Science (see below) will grow activities at the interface between astrophysics, space physics and data science, with further investment from the Provost's Strategic Development Fund.

1.4.2 Physics of Matter (45.8 FTE staff)

We see the substantial UCL activity across this area as a cohesive whole, spanning P&A's Atomic, Molecular, Optical and Positron Physics (AMOPP), Biological Physics, and Condensed Matter and Materials Physics (CMMP) groups as well as the LCN, because of the many interconnections. The period has seen a transformation of this area, with new unifying topics such as topological order, active matter, out-of-equilibrium dynamics, physics of information, and quantum technologies generating collaborations and connections to astronomy and elementary particle physics, as well as to engineering and life sciences. Our strategy is to exploit the exceptional research at UCL in life and medical sciences, our strength across quantum technologies (including links to engineering and computer science through UCLQ), synergies between experiment, theory, and modelling, and access to national and international facilities alongside local fabrication and measurement laboratories.

- **Topological matter and order:** we have seen important results in experimental realisation of fractionalised excitations, especially monopoles in spin ices and searches for so-called 'Kitaev matter' (Majorana fermion quasiparticles). We demonstrated the first topological spin insulator. The period also saw experimental verification of our 'order-by-disorder' picture of quantum phase transitions.
- **Far-from-equilibrium dynamics:** we have exploited the unprecedented time resolution of free-electron lasers to study dynamics of nanomaterials, developed new approaches to thermalisation, many-body localisation and time crystals, and continue to lead in the theory of out-of-equilibrium light-matter condensates in polariton systems. We also led the semiclassical study of new regimes in quantum interference and multiple ionization under intense laser fields.
- **Nanomaterials and interfaces:** we have developed new material types by the solution processing of fullerenes, graphene and other two-dimensional materials, and produced the first phosphorene nanoribbons. We gained key insights into the process of biomineralization, determining conditions for formation of defects in inorganic crystals templated on organic scaffolds. We demonstrated the phenomenon of negative capacitance in ferroelectric multilayers, and identified the sites for nucleation of ices on dust particles (with major implications for atmospheric science).
- **Physics of living systems:** our programme probing biological matter from molecular to cellular length scales yielded insights into functional and pathological self-assembly, e.g. the formation of nanopores by immune proteins and the formation and self-replication of amyloids and other protein fibrils. We established fundamental models of cell division and force transmission in the cytoskeleton, and made key contributions to quantum biology, highlighting the importance of non-classical vibrations in photosynthetic energy transfer under ambient conditions.

- **Physics of information:** we developed information-theoretic approaches to both the Second and Third Laws of thermodynamics. We demonstrated the computational power of non-local correlations and showed it can be quantified by contextuality, also that gauge colour codes can perform fault-tolerant error correction in quantum computers.
- **Cold atoms, molecules and hybrid systems:** we developed chip-based architectures manipulating cold Rydberg atoms and molecules, and demonstrated matter-wave interferometry with them — at ~500 nm, the largest objects for which interference has been observed. We realised a quantum interface between Rydberg atoms and superconducting circuits and demonstrated guiding and velocity selection of positronium in Rydberg states. We demonstrated instabilities in systems of cold atoms coupled to optical cavities and controlled resonant energy transfer in cold collisions using electric fields, and continued to lead the calculation of high-accuracy molecular line-lists (notably through the ExoMol project, key to the exoplanet field). We demonstrated cavity cooling control of levitated nanoparticles, realised new cooling schemes for mechanical oscillators using whispering-gallery modes, and developed sensors for acceleration and magnetic induction imaging based on nanoparticles and atomic gases.
- **Low-energy fundamental physics:** we proposed new experimental demonstrations of the quantum nature of gravity in the laboratory using entanglement, and proposed new gravity sensors using levitated nanoparticles. We identified significant disagreement with existing theory in the fine structure of positronium and are exploiting our matter-wave interferometry of Rydberg states to test the weak equivalence principle for antimatter.

During the assessment period

- With support (>£400k) from the Provost's Strategic Development Fund we met a target in the last REF through a **major development in biological physics**, appointing Saric (ERC Starting Grant and RS-URF) and Bannerjee (RS-URF) in theory, and transferring Llorente-Garcia (UCL-Crick fellow) to an academic position in experiment. We seized the opportunity presented by the Francis Crick Institute (FCI), appointing Molodtsov and Hadjivasiliou (after the period) as joint group leaders at the physics-biomedicine interface (transferring fully to UCL in 2025 and 2027); we also appointed (after the period) Michaels to a further theory position.
- We strengthened connections with **central facilities science** by the appointments of Kruger (joint with ISIS) and Johnson in X-ray and neutron scattering of multiferroics and quantum materials.
- The appointments of Pal (ERC Starting Grant) in many-body localisation and thermalisation and Rosta in novel atomistic simulations further broadened our strengths in **condensed matter theory**, chemical and biological physics, also catalysing a major (£6M) EPSRC programme grant held in the LCN by Pepper (returned in UoA12).
- We transferred Yurchenko to an academic position, strengthening the ExoMol project team and connections to exoplanet science.
- Fulfilling targets in the last REF we grew connections through new joint appointments, to fundamental **computer science** through the LCN and Computer Science (Masanes, returned in UoA9), and to **device physics** through LCN and Electronic & Electrical Engineering (Lombardo, returned in UoA12).
- We consolidated our leading position in quantum technologies across UCLQ with the award and renewal of the successful EPSRC **Centre for Doctoral Training in Quantum Technologies (£5.0M, £6.2M)**, a **Skills Hub in Quantum Systems Engineering (£3.6M)**, a major expansion of our equipment base supported by the **largest capital grant (£8M)** from the National Quantum Technologies Programme, participation in the **Quantum Computing and Simulation Hub** (**£2.5M**, with UCL equipment/estates investment of £323k) and a **Prosperity Partnership in quantum software with Google (£2M)**.

In the coming period we see particular opportunities through:

- Extending our work on **topological materials** to thin films and exploiting connections with spintronics;

- Exploiting new **X-ray sources and free-electron lasers** to study the early dynamics of emerging complex orders;
- Studying increasingly **complex biological systems** and mechanisms;
- Bringing **quantum technologies** including quantum information processors and quantum sensors to wider use;
- Opening a new era of **precision measurements**, including low-energy tests of fundamental physics, through a frequency comb laser;
- A new LCN programme exploiting **novel liquid ion sources** for nanofabrication (Perez Martinez, UKRI Fellow);
- Combining our unique expertise in trapping cold hydrogen isotopes with neutrino physics through a **new measurement of the absolute neutrino mass** using atomic tritium.

1.4.3 Elementary Particle Physics (21.6 FTE staff)

We have a broad leadership in both accelerator-based and non-accelerator particle physics, with numerous spokesperson or analysis coordination roles, and strong integration between theory and experiment. Our strategy is to continue exploitation of the rich data from the Large Hadron Collider (LHC) while leading searches for new physics in non-accelerator-based experiments.

- **Energy frontier physics**: UCL led the first measurement of the most common Higgs decay ($H \to b\bar{b}$) as well as the search for resonant and non-resonant Higgs Pair production ($HH \to b\bar{b}b\bar{b}$), measured the four-lepton line-shape, and contributed to other important searches and measurements. We led initiatives to reinterpret measurements for the widest sensitivity to physics beyond the Standard Model. We provided the UK ATLAS PI and the overall ZEUS spokesperson during the period. We are recognised as leading analysts of the parton distribution functions underpinning hadron collider physics; through key CERN committee PDF4LHC, we guide information exchange between theory and experiments, maximising the information from precision measurements. We jointly led theoretical advances (involving the MINLO perturbation technique) underpinning new precision simulations, e.g. for the observation of $H \to b\bar{b}$, and provide the most accurate simulation of the main LHC Higgs production channel, vital to determinations of Higgs properties. We make leading contributions to the phenomenology of neutrino masses at colliders.
- **Lepton physics:** We play a major role in determining **neutrino mass parameters** and hence in understanding the origins of matter-antimatter asymmetry, with leading contributions to both theory and experiment. Our long-standing leadership in neutrino oscillations involved data analysis for MINOS+ and NOvA experiments, and development and construction of the next-generation DUNE and CHIPS projects. We provided spokespersons for MINOS+ and CHIPS (which we initiated), and conveners for the oscillation, cross-section, beam simulation and calibration working groups in NOvA. We have a strong presence in leadership and analysis at SuperNEMO (providing the spokesperson, constructing and installing tracker modules in a joint HEP-SCP project), securing UK presence in **searches for neutrinoless double beta-decays** evidencing Majorana neutrinos, and pioneered UK involvement in the next-generation LEGEND experiment (providing the chair of its Institutional Board). We have recognised leadership in the theory of neutrino masses and lepton number violation, and the phenomenology of double beta-decay searches. We have a presence, unique in the UK, in the balloon-borne ANITA experiment searching for new cosmic-ray and neutrino physics. We also **initiated UK involvement in the muon** $(g-2)$ **experiment**, providing the overall spokesperson during the period, as well as in the lepton flavour-violating $\mu 2e$ and $\mu 3e$ decay searches, leading contributions to data acquisition systems and physics studies.
- **Dark matter searches**: We have a leadership role in the current direct dark matter searches using liquid xenon detectors (LZ experiment in South Dakota). We led the UK effort in the LUX experiment (providing the UK PI), setting world-leading constraints on WIMP dark matter during the period. We are leading proposals for the next (third) generation of experiments having ground-breaking sensitivity, definitively testing the WIMP hypothesis and extending direct searches to previously inaccessible yet equally well-motivated models of thermal relic dark matter. Our measurements of missing energy at ATLAS continued to extend limits on WIMP production. This work has close contacts with

astrophysical studies of dark matter and dark energy through the CPI – see Section 1.3.2. The UCL group has **established the Boulby underground laboratory as a world-leading facility** for low-background studies, underpinning leadership in international dark-matter projects and also environmental, geophysical and biological studies.

- **New instrumentation and accelerators**: in addition to developing the CHIPS experiment for neutrino detection and the Boulby laboratory (see above), UCL was a **founding member of**, and provides the deputy spokesperson for, **the AWAKE collaboration**, which has produced transformative results in plasma wakefield acceleration during the review period, and is also developing detectors for quality assurance of proton therapy beams, such as the new **proton therapy accelerator** currently being installed at UCL Hospitals.

During the period we appointed Chislett to strengthen our leadership in muon physics, transferred Scanlon (RS-URF) to a proleptic Lectureship to reinforce our leadership in Higgs physics at ATLAS (he also plays a major role in our CDT for Data Intensive Science), and welcomed Dobson (dark matter) and Agostini (neutrino physics) as new Ernest Rutherford Fellows, putting UCL in a leading position in the LEGEND experiment. After the period we also welcomed Malik (RS-URF), strengthening links between phenomenology, experiments, and quantum technologies. In the coming period, we foresee major developments through

- Preparing the ATLAS trigger upgrade for the **high-luminosity LHC**, full exploitation of LHC Run 3 ATLAS data, and leadership in strategic development for future colliders;
- **Novel phenomenology**, including novel high-precision parton shower simulations, increased precision and an understanding of theory uncertainties in parton distributions;
- In the neutrino sector, participation in the international **DUNE** experiment (where UCL contributed the highly successful purity monitor), leading contributions to the **LEGEND** double-beta experiment, as well as further development of CHIPS, measurements from the NOvA experiment, applications of quantum technologies to determine **absolute neutrino masses**, and experimental data-driven methods to improve theory predictions of double beta-decay;
- Leading searches for **dark matter** and related areas, including exploitation of the Boulby facility, and extending searches to ultra-light candidates using quantum technologies;
- Measurement of $(\boldsymbol{g-2})$ for muons, and testing lepton flavour violations in $\mu 2e$ and $\mu 3e$ experiments;
- Development of **plasma wakefield acceleration** as a usable technology for high-energy physics;
- Collaboration with UCL Medical Physics and Bioengineering and the NHS UCL Hospitals Trust to develop and exploit **proton therapy technologies**.

1.5 Impact strategy

We aim to bring about impact from our research in the broadest sense.

- **Commercial impact:** UCL Business (UCLB) is a wholly owned subsidiary of UCL responsible for negotiating technology transfer arrangements, both licensing and spin-outs. It works closely with UCL Innovation and Enterprise, which holds institutional-level partnerships and includes a dedicated Engineering, Technology and Built Environment team. Through them, researchers in our departments have been awarded **> £925k of EPSRC/STFC impact acceleration and HEIF funding** during the review period. These central teams are supplemented by specialist faculty advisers responsible to Vice-Deans for Enterprise; in addition to the MAPS team, the LCN (as a cross-faculty entity) also accesses the team in the Faculty of Engineering Science.
- **Consultancy:** UCL Consultants (UCLC) arranges UCL-related consultancy arrangements, providing legal support, billing, and allowing staff to use the UCL name. 23 staff from the UoA performed consultancy during the REF period, with **total value of £10.3M**, for organizations ranging from the European Space Agency to major energy, aerospace and pharmaceutical companies.
- Outward-facing **training and professional development:** we run bespoke professional courses in project management and systems engineering for external clients (e.g. Teledyne e2V) based on expertise developed for the exceptional demands of space missions. We

also run courses for corporate clients (e.g. Santander PLC) on quantum technologies. SCP has initiated a successful MSc apprenticeship scheme.

- The **media and the general public**: UCL Culture has a dedicated public engagement unit promoting activities including 'Bright Club' stand-up evenings and UCL's participation in national initiatives such as the 'pint of science' scheme and the Cheltenham Science Festival. P&A hosts a dedicated physics outreach coordinator (co-funded since 2017 by the Ogden Trust). We make full use of our central London locations with public tours and school visits at the UCL Observatory, and an annual 'Your Universe' science festival in Bloomsbury; we also run regular open days and outreach activities at MSSL. Our staff have exceptional media and science communication profiles – they include a regular presenter of *The Sky At Night* and authors of prizewinning popular science books for both adults and children.
- **Advocacy and advice to policymakers**: the UCL Vice-Provost's Office for Research has a dedicated team helping UCL researchers communicate policy advice, including written and oral evidence to the Science & Technology Select Committee enquiry on Quantum Technologies in 2018.
- Finally, we encourage our **students** to engage with the highly entrepreneurial London business scene, through cross-entrepreneurship events run by UCL Innovation and Enterprise but also through physics-focused activities such as involvement with our doctoral training programmes and industry-sponsored hackathons.

1.6 Open access

UCL is fully committed to open access to scientific information. Full texts of all publications are made available through *UCL Discovery* – indicative of the success of this approach, **98.68% of *all* publications** from our departments accepted after 1 April 2016 (not just those submitted in REF2) either have full-text uploaded or have a REF open-access exception.

We have consistently taken initiatives to ensure **raw data from experiments** are placed online for analysis by all, advocating strongly for this within large collaborations.

- In **particle physics**, the Rivet (Robust Independent Validation for Experiment and Theory) software platform originated at UCL, and a UCL researcher developed the recently adopted ATLAS (and CERN-wide) policy on data preservation. UCL contributes a representative to the HEPDATA steering committee, advising on data archiving for non-LHC experiments, and the MINOS/MINOS+ collaboration (led by a UCL spokesperson) published its entire sterile-neutrino analysis dataset online.
- In **astrophysics**, we led the current policy within DES (and DESI) that all raw data are made public the year after being taken. We provided Cassini-Huygens CAPS-ELS to the ESA planetary science archive, and are preparing with ESA to release ExoMars PanCam pictures immediately after reception. We provide all Cluster and Double Star PEACE calibrated science data to the ESA Cluster Science Archive. Data from our Solar Orbiter SWA instrument will be publically available 90 days after reception.

UCL has established *UCL Discovery* as a publicly searchable database of UCL-created data. Butterworth is a member of the steering group for the UCL Office for Open Science.

Many **physics software projects** are available open-source, including the CONQUEST linear-scaling electronic structure package (led by Bowler) and the POWHEG toolbox for corrections to leading-order amplitudes in collider processes (modules by Hamilton). We lead development of the widely-used PYNBODY simulation analysis suite which has been acknowledged in >220 publications across astrophysics. We recently published the *tangos* platform for sharing simulation data (The Agile Numerical Galaxy Organization System). All codes created through CSED are open source, available on GitHub (https://github.com/ucl-exoplanets/) and widely used (over 4,000 installations of TauREx3 PyPi toolkit, 44,000 downloads of PyLightcurve and Iraclis).

1.7 Research integrity

UCL fully supports the *UK Concordat to support Research Integrity* and has adopted a 4-level training framework; Level 2 (Understanding Research Integrity) is required before research

students transfer to PhD status. Training is tailored to physical sciences and starts at induction; students and supervisors sign an 'integrity agreement' pledging high standards and demonstrating understanding of misconduct. Students attend UCL's central training course, with participation monitored through our electronic log, and are encouraged to use a 'dilemma game' integrity tool. UCL has been a leader in the development of research integrity policy, and from 2014 hosted the UK's National Hub for Responsible Research and Innovation (RRI), combining researchers, policymakers, industry and the public. All staff and students are made aware of the routes to raise concerns about research practices (first the Head of Department, then the Research Integrity unit within the Office for the Vice-Provost, Research).

2. People

People are our most important resource: the largest single contribution to our research environment is the dynamism of our research community, across all career stages.

2.1 Equalities

In developing this community, we aim to be driven by scientific excellence. We aspire to give opportunities, to both staff and students, on the basis of merit, irrespective of gender, race, orientation or other protected characteristics. We aim to provide a supportive and positive environment to our researchers, recognising that science is a demanding and sometimes discouraging field in which to work.

2.1.1 Approach to equalities in the REF submission

All HESA category 3 (academic research and teaching) staff, and all HESA 2 (research) staff meeting the independence criterion, were submitted. Female HESA 2 staff were less likely to be submitted than male HESA 2 staff, because fewer currently hold independent fellowships. We proactively encourage female research staff to apply for fellowships and 27% of those holding fellowships during the period were female; of these, 75% now hold academic or proleptic appointments and are therefore classified as HESA 3. The data did not allow us to draw conclusions about selection of BME or disabled HESA 2 staff.

Outputs were initially selected, from lists submitted by individuals, by a group of senior staff including HoDs and the P&A departmental board. All staff involved in the selection of outputs received training in equal opportunities. The provisional list was approved by a specially convened panel with an external chair, chosen to have an approximately equal gender balance, who were provided with data on the overall gender and ethnicity balance of the staff, and the corresponding outputs. Results by gender, ethnicity and age are shown in Table 1.

Table 1: summary of staff population and output profile against three characteristics.

Characteristic	Category	Proportions	
		Selected staff (headcount)	Output attributions
Gender	Male	78.6%	76.2%
	Female	21.4%	23.8%
Ethnicity	White	77.8%	75.6%
	BME	12.0%	13.9%
	Unknown	10.3%	10.6%
Age	Under 45	49.6%	56.6%
	45 or above	50.4%	43.4%

2.1.2 Equality charters and the working environment

We participate enthusiastically in the UK equality charters for higher education. These schemes are designed for departmental units so our departments participate separately, and have inevitably reached different stages. P&A and SCP lie within the IoP's Project Juno: P&A has 'Juno champion' status (renewed in 2019) and an associated Athena SWAN Silver Award, while SCP received 'Juno practitioner' status in 2020. As an interdisciplinary centre with significant focus outside physics, the LCN applies directly to Athena SWAN and received a Bronze Award in 2019. All three departments run their own staff and student surveys to complement UCL-wide surveys; we use these to gather information on points of concern and to target action plans.

Juno and Athena SWAN concentrate on action for gender equity. The current gender balance of staff and students is shown in Table 2.

Table 2: gender distribution in staff and (research) student headcount across the UoA.

Staff group	Male	Female	Total	% Male	% Female
Academic staff	99	28	127	78.0%	22.0%
Research staff	128	31	159	80.5%	19.5%
Postgraduate research students	251	78	329	76.3%	23.7%
Professional services staff (non-technical)	33	47	80	41.3%	58.8%
Technical staff	63	8	71	88.7%	11.3%

In the undergraduate intake, female students rose from 21% in 2012-13 to 32% in 2019-20; for postgraduate research students they were 27% in 2019-20. Our senior female academics are role models for gender equity: Nguyen won the flagship Rosalind Franklin Award from the Royal Society in 2019, recognising an outstanding contribution to any STEM area and supporting the promotion of women in STEM (our second winner, following the LCN's McKendry, returned in UoA1 in 2014).

We increasingly focus also on equity related to other protected characteristics; all three departments have transformed their Athena SWAN/Juno working groups into broader Equality, Diversity and Inclusion (EDI) committees. Of the 108 HESA 3 staff where data are available (84 male, 24 female), 86 identify as white and 15 as BME (13.9%) with 7 identifications unknown; the corresponding numbers for 115 HESA 2 staff are 82 white and 15 BME (13.0%), with 14 identifications unknown and 4 withheld. Approximately 2% of our HESA 2 staff and none of our HESA 3 staff are known to identify as disabled. Our research student intake identifying as 'non-white' rose from 22% in 2013-14 to 39% in 2019-20.

We are keenly aware that physics (at UCL, as elsewhere) remains predominantly white and male; while working to change this, we recognise this is a long-term project and in the meantime we must make the environment a welcoming one for women and other currently under-represented groups. We recognise challenges can arise in academic environments through power imbalances in close working relationships (e.g. between senior staff and junior staff or students), and UCL was the first Russell Group university to ban personal relationships between staff and students for whom they are directly responsible. We are proud of the work done by our staff to highlight equalities: for example, P&A is currently led by its first BME Head, who is also a member of the UCL-wide Equality Charters Group, and a Professor from P&A is the MAPS Faculty's first Vice-Dean for EDI. UCL has a consciously welcoming attitude to LGBTQ+ staff and students, and was proud to be among the Stonewall Top 100 Employers in 2018 (the only UK university to earn a place while having both an Athena SWAN silver institutional award and a Race Equality Charter Mark).

Members of P&A proposed a high-level UCL Preventing Sexual Misconduct Strategy Group, which led to improvements in culture across UCL. They were instrumental in delivering an institution-wide 'Report + Support' tool, launched in February 2019, which reformed how reports are handled,

removing barriers (allowing anonymous reporting where necessary) and providing improved support. We enthusiastically embrace the '*Where Do You Draw the Line?'* workshops, co-developed by UCL with Cambridge, Manchester and Oxford, that focus on the boundaries between acceptable and unacceptable behaviour in academic contexts and encourage a culture of active by-standing; we run sessions in all three departments (9 since 2017) co-facilitated by the HoDs and UCL's EDI team. Supplementary *Taking the Lead* workshops target staff with leadership responsibilities, focussing on effective interventions and creating a positive environment.

2.2 Staffing strategy

2.2.1 Academic staff

We appoint our academic staff on the basis of open, international searches with the widest possible reach. Recognising that the primary limit on our appointment of currently under-represented groups is the numbers who apply, our practice is actively to reach out to individuals within these groups and encourage applications. The vast majority of first-choice applicants accept our offers (18 out of 19 advertised posts appointed to in the review period, plus all three appointed subsequently). Long-term fellowships (particularly from UKRI, Research Councils, and the Royal Society) provide an important route to academic posts; where a fellow works in an area with a strategic need for an academic appointment, they may be interviewed for a proleptic appointment with the same criteria as an open competition. We hosted 40 long-term (5 years +) career development fellows during the REF period; of these, 27 now have academic or proleptic appointments at UCL, and 9 moved to academic research/teaching appointments elsewhere.

Of the 110.5 FTE staff returned in REF2014, 25 have left (not all full time): 7 retirements, 7 to positions at other UK universities, 2 to UK industry or national laboratories, 8 to international positions (one continues part-time at UCL), one death. We have made 21 new full-time appointments and now return 112.5 FTE. Two recruitments were interrupted by the Covid-19 pandemic; UCL re-started these to sustain long-term investments in key areas (biological physics, experimental condensed matter) although the start dates now fall after the REF census date. Annual appraisals encourage career development and support staff to apply for promotion when ready; 79 academic promotions occurred during the period (43 to Reader/Associate Professor and 36 to Professor), including 20 female promotions (24% of all senior promotions and 100% of female candidates put forward). From 2018 the grades of Senior Lecturer and Reader were combined into Associate Professor, but staff could retain previous designations.

All academic staff are expected to be both teachers and researchers unless bought out by external funds. The teaching departments (P&A and SCP) have formal workload management systems; probationary staff carry a reduced load, and we also make reductions in recognition of particular personal circumstances. Increased flexibility has been afforded over the period by the appointment of a cohort of dedicated Teaching Fellows (now 7.8 FTE, with career grades of Lecturer, Associate Professor and Professor (Teaching)), providing leadership in teaching practice and taking around 20% of the undergraduate teaching load.

2.2.2 Research and support staff

Our postdoctoral research, technical support and engineering staff are critical: we currently have 159 postdoctoral and 169 support staff (the LCN total includes all supporting physics-related research there – some also support other UoAs). We see career development of both groups as an important responsibility; they have the opportunity to select a mentor separate from their line manager for broader career development. Annual appraisals ensure regular reviews of progress and opportunities and we systematically encourage postdoctoral staff to consider submitting fellowship applications. UCL fully implements the *Concordat to support Career Development of Researchers*, and postdoctoral researchers are employed on open-ended contracts. Research staff are encouraged to apply for promotion through UCL's careers framework: 13 were promoted to Senior Research Associate/Fellow (77%:23% male:female), and 5 to Principal or Professorial Research Associate/Fellow over the period.

We support the development of 'communities of practice' linking technical and IT staff across UCL; several of our staff are group coordinators. Technical staff have the opportunity to transfer to research roles where appropriate, providing further opportunities for promotion.

2.2.3 Staff development and recognition

All new staff have a probationary period: three years for academic staff (unless they have substantial teaching experience) and nine months otherwise. Regular meetings with the line manager ensure that probationary objectives are met; new academic staff are assigned a mentor (usually a senior academic from the same research group) to help with initial familiarisation, establish departmental connections and support career development (including advice on teaching and grant funding).

UCL offers a comprehensive programme of staff development (see REF5a). We encourage staff to take advantage of these opportunities and to undertake roles that will further their careers. UCL's Academic Promotions Framework (for academic and research staff) provides expectations across research, teaching, impact and institutional citizenship. All non-Professorial academic staff are considered for promotion annually against these criteria. Staff in research environments frequently go beyond their formal job requirements, and all three departments have award schemes to recognise these contributions.

2.2.4 Leave and part-time working

We enthusiastically implement UCL's policies on parental leave, carers' leave, and requests for part-time working, and see this as an important mechanism to retain skilled staff with family responsibilities. 5 of our staff have taken shared parental leave during the period (including senior academic staff) and we make extensive use of part-time and flexible working (e.g. >50 SCP staff).

2.2.5 Returners

All three departments support staff returning from periods of leave to travel or receive training, and academic staff are given one year free of administrative and teaching commitments to re-establish their research.

2.2.6 Sabbatical leave

UCL offers academic staff opportunities to apply for sabbatical leave for (one term for every three years of service), and 29 staff have taken a sabbatical during the period, with 18 spending time at an international institution. We use sabbaticals strategically to refresh our portfolio in the light of international developments and many staff have identified opportunities in new areas. For example, A Green developed new topics at the interface between many-body quantum physics and machine learning, Doel focused on the delivery of the 4MOST spectrograph, Hoogenboom shifted his biophysics research towards immunology, and Thorne incorporated electroweak corrections into parton distributions (underpinning the forthcoming definitive 'global fit' of the standard model).

2.3 Our students and research training

Our most important legacy is the scientists we train. 'Integration of Research and Education' is a theme of UCL's 2034 strategy, and we make it a priority to develop research culture in all students, undergraduate and postgraduate. During the period, 442 students obtained undergraduate Masters (MSci) degrees in physics-related disciplines, and 592 MSc degrees; all these carry out a significant research project (nominally 300 hours for the MSci, 600 hours for the MSc).

Research students are initially registered for the MPhil, and normally transfer to PhD registration early in their second year of research after writing a report and defending it at interview with a supervisory panel. With recruitment to our recently funded CDTs the total number of research students is currently 329, and 350 PhD degrees were awarded in the period (50 per year, up from 33 in REF2014); we moved from 3-year to 4-year PhD funding over the period and >90% of PhD theses are submitted within five years (based on the four most recent cohorts for which data are available). An electronic logbook system tracks supervisor engagement, completion of training courses, and overall progress.

2.3.1 Centres for Doctoral Training (CDTs) and doctoral training partnerships

UCL was an early and enthusiastic proponent of centres for doctoral training (CDTs), especially where there is a large concentration of research in one location, because of the benefits to students of a cohort-centred approach. P&A and LCN host the EPSRC CDT in Delivering Quantum Technologies (awarded 2014, renewed 2019), and our joint CDT in Data Intensive Science (P&A and SCP) was top-ranked in the inaugural STFC competition (2017) and A-ranked in the review (2019). Both cohorts undertake general study aimed at acquiring both transferable research skills and specialist (often interdisciplinary) knowledge relevant to their field, then pursue a PhD programme in one of the participating research groups, benefiting throughout from whole-cohort training activities, support and collaborative networks.

We also host student projects from other EPSRC CDTs, notably Advanced Characterisation of Materials (held within the LCN, jointly between Imperial and UCL, awarded 2014 and renewed 2019), and M3S (Molecular Modelling and Materials Science, held in UCL Chemistry, awarded 2009 and renewed 2014). Our staff are involved in the supervisory pool for the NERC London Doctoral Training Partnership, whose themes include atmospheric and ocean processes, environmental physics and mathematical modelling. In total 114 students from these CDTs or partnerships embarked on research degrees with physics supervisors during the period, and 63 of our Category A staff are members of the supervisory pools for one or more of these centres.

Training innovations introduced through the CDTs included: a 'mystery sample challenge', research case studies surveying open problems in rapidly developing areas, case studies on start-ups in quantum technologies, the opportunity to pitch to a panel including venture capital representatives for commercialisation funding, presentation skills training incorporating lessons from the performing arts, and group research projects addressing challenges presented by partners. The first-ever **STFC Machine Learning Summer School** was organised at UCL in 2018, attended by ~120 students from across the UK, with much of the training delivered by industry partners. These programmes have been particularly successful at bringing commercial and government partners to work with our students through placement opportunities and the provision of joint training. All the students on our CDT in Data Intensive Science have **joint projects with partners**, and over 30 students and PDRAs have undertaken **placements with partners** since 2017. Partners include Intel, ASOS, Mellanox Technologies, Faculty AI, The Economist, UKAEA, TfL, Babylon Health, Hitachi, NPL, DSTL, Joint Biosecurity Centre, Keysight, Siemens, BT, Huawei and Google.

2.3.2 Other student-centred training activities

Building on the success of our CDTs, we take an increasingly cohort-centred approach to research student training across the rest of our portfolio. We provide subject-specific advanced research training to appropriate groups of students:

- A high-level course on materials modelling, run through the Thomas Young Centre and including material on electronic structure techniques as well as a range of classical simulation methods;
- Advanced training in particle physics, including software carpentry, computing and statistics, an in-depth survey of the standard model, and advanced topics including detector techniques, neutrino physics, dark matter, and detector technologies;
- Training courses in high-performance computing, numerical methods, and software engineering (including peer-led courses in Python and C++ funded by the departments).

We also promote transferable skills including communication skills and groupwork, for example through a regular student-organised retreat at Cumberland Lodge in Windsor Great Park for students and early-career researchers in quantum technology and quantum physics (Qcumber – 5 held during the REF period), and through an annual 2-day Hackathon for students in physics and related quantitative subjects. Commercial participants as sponsors or judges have included Deloitte Digital, Quantcast and ASI Data Science (now Faculty AI) - one of London's leading machine learning consultancies, founded in 2014 by our former students and typifying the benefits of this approach.

2.3.3 Entrepreneurship for early-career researchers

We also follow up our placement opportunities and training with subject-specific schemes to promote entrepreneurship among early-career researchers. 31 of our students benefited from the first year of the new **SPERO entrepreneurship programme** run by UCL Innovation and Enterprise in 2019-20.

Additionally, **UCLQ Innovation Fellowships** support UCL researchers (postgraduate or postdoctoral) bringing a quantum technology to the protype stage before seeking licensing opportunities or venture capital funding. Projects funded by the scheme include new robust accelerometers based on levitated nanoparticles (the inventor also holds an RAEng Postdoctoral Fellowship) and a novel design of superconducting qubit.

2.4 Our people during the Covid-19 pandemic

Regular meetings and briefings from the Heads and Dean kept staff and students informed. We spoke openly about the challenges of remote working and made flexibility a priority for those with caring responsibilities. We reopened research facilities wherever possible consistent with staff and student safety (see §3.3) and supported students to apply for funding extensions where needed; UCL provided 3-month extensions for all funded final-year PhD students and increased its hardship fund to £3K per individual. We invested heavily in tools for online collaboration and remote control of experiments, purchased additional software licenses for those who cannot perform experiments, and shipped furniture and equipment to those working at home. We continued to run programmes of seminars and group meetings and seized the opportunity to invite speakers from distant locations. We have used always-open Zoom rooms and 'virtual coffee' to maintain informal contact with staff and students.

3. Income, infrastructure and facilities

3.1 Income

Research income is £162.3M over the REF period **(£23.2M per year, up from £18M per year in REF2014)**. UKRI and the research councils (including the Royal Society) are our most important funders (£108.5M), with STFC contributing £66.3M and EPSRC £28.8M; EU government bodies (including the ERC) contributed £31.1M and charities £3.7M. Research income in kind from the use of research facilities supported by UKRI is **£82.8M**, including £58.0M for particle physics, £15.7M for condensed-matter and optical sciences, £6.5M for telescope access (ground-based and satellite-borne), and £2.6M for computing (see summary in Table 3).

Table 3: summary of income in kind from use of UKRI- and UKSA-supported facilities.

Ground-based telescopes (e.g. ALMA, eMERLIN, ESO, William Herschel and Isaac Newton telescopes)	£4,153,275
Space-based telescopes (e.g. XMM-Newton, Hubble)	£2,371,340
Particle physics (CERN, T2K, LT)	£57,954,165
Condensed-matter and optical science (Diamond, ESRF and XMaS, ILL, ISIS, European XFEL, Central Laser Facility, EMFL)	£15,727,162
Computing (Dirac, ARCHER Materials Chemistry, UKAMOR and UKCP consortia)	£2,628,633
TOTAL	**£82,834,574**

In addition, we are substantial users of non-UKRI resources, through our success in international calls and participation in international collaborations. Examples (with estimated values) include: Keck 10m telescope (14.5 nights, ~£550k), additional Hubble time via US grant (64 orbits,

~£300k), Advanced Photon Source, USA (£2M), Pohang Light Source, China (£300k), SCALA X-FEL, Japan (£300k), Azure cloud computing (~£70k).

3.1.1 Research funding strategy

We have a comprehensive strategy in place to support research funding applications. A specialised team of Research Facilitators operates across the BEAMS School, who send a monthly newsletter identifying calls, celebrating successes and organising mock interviews for major grants and fellowships. Departments provide mentoring of early-career staff and review of their applications by senior colleagues, and targeted use of UCL and RCIF funds to support strategic equipment items (especially those with a wide user base). UCL's success in inter-disciplinary projects is underpinned by a pan-institutional set of Grand Challenges and Research Domains.

3.1.2 Personal grants and fellowships

An important indicator of our research vibrancy is success in highly competitive fellowships or personal grants from the European Research Council, UKRI and its member councils, and the Royal Society. During the review period our staff held seven ERC Advanced grants, six Consolidator grants and five Starting grants – see Table 4. They also held 23 Royal Society URFs, 12 STFC Ernest Rutherford Fellowships and 3 other STFC Fellowships, 11 EPSRC Fellowships, plus a UKRI Future Leaders Fellowship and Hawking Fellowship – see Table 5. Thomas won a Royal Society Research Professorship in 2020.

Table 4: European Research Council (ERC) individual awards held by members of UCL Physics staff during the REF period.

Advanced	Tennyson (2010-15), Lahav (2011-16), Ellis (2014-19), Barlow (2015-20), Thomas (2015-20), Viti (2018-23), Tennyson (2020-25).
Consolidator	Tinetti (2013-18), Michaelides (2013-18), Buitelaar (2014-21), Blumberger (2015-20), Hogan (2015-20), Pontzen (2018-23)
Starting	Bose (2012-17), Peiris (2012-17), Waldmann (2017-22), Saric (2018-23), Pal (2019-24)

Table 5: Major external fellowships held or won by Physics staff during the REF period.

Royal Society	**URFs:** Abdalla (2009-17), Arridge (2012-17), Backhouse (2017-21), Bannerjee (2018-23), Blumberger (2009-14), Feeney (2019-24), L Green (2012-18), Hesketh (2010-18), Holin (2012-18), Kitching (2012-20), Malik (2015-23), Nguyen (2009-14), Nichol (2006-14), Nurse (2008-21), Perry (2013-15), Pilkington (2013-17), Pontzen (2013-21), Saintonge (2013-21), Sanders (2019-24), Saric (2017-22), Scanlon (2014-21), Schoenrich (2017-22), Tinetti (2009-16). **Research Professorship:** Thomas (2020-).
STFC	**Ernest Rutherford Fellows:** Agostini (2020-25), De Looze (2019-24), Dobson (2018-23), Ercolano (2009-14), Facini (2016-22), Farihi (2013-17), Font Ribera (2016-21), Greve (2012-17), Joachimi (2013-18), Korn (2013-18), Long (2019-24), Verscharen (2017-22). **Innovation Fellows:** Jolly (2018-21), Tennyson (2018-21). **Public Engagement Fellow:** G Jones (2016-19).
EPSRC	**Career Acceleration Fellows:** Emmanouilidou (2009-15), Olaya-Castro (2008-14). Parish (2011-14), Schofield (2009-14). **Leadership Fellows:** A Green (2011-16), Pickard (2009-14). **EPSRC Fellows:** Fenton (2012-18), McMorrow (2016-21), Masanes (2018-23), Oppenheim (2013-21), Szymanska (2013-23).

NERC	**Independent Research Fellow:** Forsyth (2016-21)
UKRI	**Future Leaders Fellow:** Perez Martinez (2020-); **Stephen Hawking Fellow:** Younsi (2021-)

3.2 Infrastructure and facilities

Total expenditure in the three departments on equipment in the period was **£47.7M** (£6.8M per year – LCN spend benefits all disciplines represented there, not only physics); of this, £37.0M was from external grants, £5.5M from UCL's core funds, and £5.1M from other activities (e.g. facilities income). UCL invested £9.4M from its capital programme in estates projects wholly or largely benefiting physics research, including major laboratory refurbishments, and facility upgrades at both LCN and MSSL, plus a further £53M in two large campus projects with significant benefit to physics (refurbishment of the Kathleen Lonsdale Building and the Wilkins Terrace adjacent to the Physics Building).

3.2.1 Computing facilities and support

UCL hosts the national Tier 2 computing hub for Materials and Molecular Modelling (£4M EPSRC investment in 2016, a further £4.5M from 2019 – UCL committed £600k running costs plus >7 FTE years staff time); this project currently supports *Thomas* (~17,000 cores, 88TB RAM) and its replacement *Young* (23,000 cores, 116 TB RAM). The project is led from the CMMP group in P&A and closely associated with the Thomas Young Centre. A further machine *Michael* (project led from UCL Chemistry) provides >8000 cores and ~40 TB RAM dedicated to the battery materials work of the Faraday Institution. The *DiRAC* supercomputing initiative (originally UCL-led) is now supported by STFC as a national facility, with the project office based in UCL.

Physics researchers are among the largest users of UCL's central compute platforms: *Grace* (10400 cores, 40TB RAM with a high-bandwidth Infiniband connection, intended for large multimode parallel jobs) and its replacement *Kathleen* (7680 cores, 36TB RAM), and *Myriad* (a high-throughput cluster including GPUs for shared-memory jobs and data science, with 3816 cores and 31TB RAM), and the central Research Data Storage service. Additionally, during the earlier part of the period we benefited from *Legion* (a general-use cluster with 5800 cores), and shared access to *Emerald*, a GPU system hosted by STFC for the Science and Engineering South consortium. Smaller-scale departmental facilities include dedicated clusters for particle physics, astrophysics, cosmology, biological physics and materials simulation; these were refreshed with £140k of UCL RCIF investment during the period and currently total >6000 cores with 30TB RAM. All three departments have research computing staff (12 FTE in all) who manage local systems and supply subject-specialist support; they complement UCL's central team, which includes a highly regarded Research Software Development Group (founded in 2012 as the first of its kind, now with 24 software engineers) providing support to individual projects and key training including an MSc-level course in research software engineering taken by >1000 staff and students.

3.2.2 Nanoscience, nanofabrication and quantum technologies

Several major equipment upgrades provided testbeds for quantum devices and improved our nanofabrication facilities. The largest came from the multi-institutional QUES^{2}T initiative, led from UCL, in the National Quantum Technologies Programme capital call. This brought three new dilution refrigerators and a low temperature scanning probe system to the LCN, plus major upgrades to electron beam lithography and a new furnace for silicon devices. This £6M equipment investment at UCL was accompanied by a £3.2M estates project (UCL-funded) to enhance the LCN cleanroom (ISO6) and refurbish laboratories for the equipment. This project was associated with new laboratories for work on piezoelectric materials and negative capacitance, and for X-ray scattering, and an upgrade to the Optical Sciences Laboratory underpinning contributions to DESI and the 4MOST instrument at ESO (UCL investment £368k). Further quantum technology testbeds were funded by the ERC and through the Quantum Computing and Simulation Hub. We also upgraded the LCN's equipment in bio-nanoscience with new Atomic Force Microscopes, and a new LCN-led super-resolution fluorescence microscope.

3.2.3 Dark-matter searches

We have established a new mass spectrometry laboratory to support dark-matter searches, with £200k of RCIF funding; it has world-leading sensitivity to uranium and thorium as well as other isotopes relevant to low-background experiments. As well as dark matter searches, applications include the LEGEND neutrino mass experiment and detection of trace contaminants in drinking water.

3.2.4 Space science

UCL invested £150k in facilities at MSSL for assembly and testing of space instrumentation for ESA, NASA and JAXA missions. They now include 11 test chambers for vacuum testing, outgassing and contamination control, and two cleanrooms (ISO6 and ISO8). The facility includes CAD design, thermal analysis, sheet metal forming and electrical discharge machining, optical and plasma calibration; it is extensively used by external customers, including universities and commercial organizations. In addition, we have invested in space for Ariel mission coordination and the CSED at Harwell.

3.2.5 Workshops

Fulfilling a target in the last REF, we combined the MAPS Faculty workshop with the Biochemical and Chemical Engineering workshop to produce a single, state-of-the-art mechanical workshop for the BEAMS school with greater throughput and an operating budget >£400k pa. The larger user base has enabled significant capital investments (including £43k from P&A for a new computer-controlled machine. The facility is now equipped with modern machinery and infrastructure for design and delivery of complex components.

3.2.6 New laser laboratories and optical spectroscopy tools

The space vacated by the workshop rationalisation was developed into a new Photon Science Hub, including two quantum measurement laboratories for P&A, with investment by UCL of £3.8M. We also invested in a new optical frequency comb from UCL RCIF funds (£250k), which will be fibre-linked to the new laboratories and will underpin future experiments in quantum sensing and quantum optics, spectroscopy for exoplanet research, and table-top tests of physics beyond the Standard Model.

3.2.7 New office and collaboration spaces

We relocated the Astrophysics group into the Lewis Building and NW Wing on the Bloomsbury campus, two minutes' walk from the Physics Building. We provided new office and collaboration space for the core membership of the Cosmoparticle Initiative, as well as refurbishing space in the Physics Building for our CDTs.

3.3 Our facilities in the context of Covid-19

UCL moved entirely to remote working in March 2020 at the onset of the Covid-19 pandemic. All laboratories and experimental facilities were closed, with the exception of a very small number of long-running experiments which could be managed remotely and some Covid-related research in the LCN building. The Physics, LCN and MSSL buildings were among the first at UCL to reopen, in July 2020; they have since operated with maximum 25% occupancy and 2m distancing. We prioritise access to experiments and technical work that can only be done on-site; UCL policy is that all meetings currently take place online.

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

4.1 London collaborations

London is a major scientific centre and a significant draw for international talent. Major learned societies (including the Royal Society, Institute of Physics, Royal Astronomical Society) accompany exceptional scientific universities (e.g. Imperial, King's, QMUL) and research institutes (National Physical Laboratory, Francis Crick Institute, Alan Turing Institute). We make full use of this environment through the multi-university London Centre for Nanotechnology (with Imperial and

King's) and Thomas Young Centre (with Imperial, King's and QMUL). The Institute for the Physics of Living Systems links UCL with the Francis Crick Institute and we have links with Imperial, King's, Birkbeck, QMUL, and RHUL through our postgraduate training programmes; students from the DIS CDT take placements at the Turing Institute. We see the 'London factor' as key to the formation of partnerships; we have formed links with numerous London-based technology start-ups, helping them to expand their businesses and improve their competitive position.

4.2 International institutional collaborations

UCL's international strategy prioritises cross-institutional links with selected global partners, alongside 'bottom-up' collaborations in individual subjects. Strategic partners in Physics include Peking University (PKU) and the Chinese Academy of Sciences in China, Yale University in the US, the University of Toronto and McGill University in Canada, Tokyo Institute of Technology and National Institute for Materials Science (NIMS) in Japan, ASTAR in Singapore, and Seoul National University in South Korea. UCL invested £114k in seed-corn funding for physics collaborations during the period.

4.3 Collaborative research programmes

4.3.1 Formal collaborations

Especially in astrophysics, space science and particle physics, much of our work is structured around large collaborations. These include DES*, DESI*, Euclid*, ALMA, Gaia*, Ariel*, PLATO*, Comet Interceptor*, SMILE*, Exomars*, Solar Orbiter*, Hinode*, Cluster*, Lagrange*, Juice, LEGEND, LISA, LSST, ATLAS*, MINOS+*, CHIPS*, ZEUS*, Super-NEMO*, ANITA, NOVA*, *g*-2*, LUX-Zeplin*, AWAKE* and DUNE (* denotes major UCL PI/spokesperson or consortium-level leadership role).

4.3.2 Informal collaborations

Outside these formal structures, collaborations are central to our scientific productivity. In total, 1459 different national and international partner universities appear in joint publications in the review period. Over 6000 papers are joint with other UK institutions, over 4500 with US institutions, and over 3000 each with France and Germany, and almost 2000 with China. 80% of all our publications have at least one international co-author (still 68% excluding larger collaborations with >15 authors).

4.4 Interactions with users, beneficiaries and audiences

We aim not just to do excellent physics but to ensure that we connect both with wider society and with users of our research.

4.4.1 The general public

UCL is a public institution and the bulk of our research is publicly funded; therefore, we see a responsibility to maintain a dialogue with the public (not just to 'inform' or 'educate' them). Our central London location contributes significantly to our activities; the Ogden Trust has funded a Physics Outreach Coordinator within UCL since 2017. L Green regularly presents *The Sky at Night* on BBC1, Butterworth's blog *Life and Physics* was hosted by The Guardian in 2010-2018 and had ~50,000 visitors per month in that time, Coates' science articles on *The Conversation* have >1.2M reads, and Bramwell has made three appearances on BBC Radio 4's *In Our Time*. Prinja's *Planetarium* won both the American Institute of Physics Writing for Children Prize and the Royal Society's Young People's Book Prize in 2019, while Butterworth's *Smashing Physics* was shortlisted for the 2015 Royal Society Winton Prize. We have led several competitively selected exhibits at the annual Royal Society Summer Science Exhibitions, which typically attract 14,000+ visitors, including Quantum Biology (Olaya Castro) James Webb Space Telescope (Barlow), Aurora Explorer (Fazakerley), Ice Worlds (G Jones) and A Comet Revealed (G Jones).

The UCL discovery of water in the atmosphere of exoplanet K2-18b generated over 4000 media reports in 2019 (based on >60 media interviews). The first reconstructed image of a black hole (with UCL the only UK consortium member) attracted similar coverage, with Younsi's television and newspaper interviews reaching tens of millions, and >5 million views for videos featuring the work of Wu and Younsi. The launch of Solar Orbiter in February 2020 generated numerous media

appearances for Owen and Verscharen, with ESA 'first light' press and social media events generating international interest and reaching 600 million individuals by traditional media (up to 3 billion via social media). Diego's documentary *Seven Ages of Starlight* has been shown ten times, and Olaya-Castro's contribution to *The Secrets of Quantum Physics* eight times, on BBC4. Kitching proposed and participated in the BBC's *The Mystery of Dark Energy* which aired 7 times. Major science-art collaborations have been initiated by Peiris, Ghag, Kitching, Hoogenboom and Pontzen; our staff led a UCLQ quantum outreach day at Spitalfields Market and Ghag led the establishment of *Dark Matter Day* as a regular STFC event in London. L Green and Pontzen serve on the Advisory Panel for the Cheltenham Science Festival.

4.4.2 School and university students

Since 1997 P&A has hosted the UCL Science Centre, a weekly series of lectures targeted at sixth-formers (30,000 student visits during the review period). Each year we give >30 schools talks, organise regular Particle Physics masterclasses and events at the UCL Observatory in Mill Hill reaching over 1000 school pupils, alongside training events for newly qualified physics teachers. UCL's 3-day fundamental science festival *Your Universe*, held in Bloomsbury since 2009, celebrates particle physics and astronomy and generates a dialogue between the public and active physicists; the 8 events during the period were attended by ~2400 school pupils (and 1400 members of the general public).

A major new initiative during the review period is ORBYTS (**O**riginal **R**esearch **B**y **Y**oung **T**winkle **S**tudents). UCL early-career researchers visit schools and provide A-level students with university-level physics skills to work on real research. Over 300 students from 22 schools participated in 2019-20 (over 50% eligible for free school meals). We also coordinate a 'Hacking Science' coding project in Hackney schools and youth centres. Since 2017 UCLQ has organised a summer school in quantum technologies, targeted especially at under-represented groups and those from undergraduate backgrounds other than physics; >80 students benefited from this opportunity. SCP run an annual "space science week" work experience programme for 35-50 A-level students from diverse backgrounds and a 50:50 gender balance, with support from UCLs Widening Participation scheme.

4.4.3 Commercial and government beneficiaries

In addition to the examples in Impact Case Studies, and the training engagement through CDTs, Howard, Skipper and collaborators licensed their nano-inks technology to Linde, while UCLQ ran a series of quantum industry days in central London featuring quantum technologies across UCL. We ran professional development activities in systems engineering and project management (beneficiaries included Airbus, ESA, e2V) and also in quantum technologies (Santander). We led TYC seminars given to BP during 2019 through an Innovate UK project and established collaborations in electronic materials with Infineon Technologies and Applied Materials Inc. Our spin-out SpaceFlux facilitates big data analytics for space-based applications. Our collaboration with the Meteorological Office on space weather, and the success of the physics-based startup Quantemol Ltd, are described in Impact Case Studies.

4.5 Contributions to the research base

Our researchers published 7,968 papers during the review period; by the submission date these had been cited 230,803 times, with an h-index of 172. Of these, 425 (5.33%) were in the top 1% for citations based on their subject category, year, and document type.

4.5.1 Leadership of conferences and research training schools

Our staff were leads or organisers of more than 135 national and international conferences, including membership of the organising committee for ICHEP (Konstantinidis). We gave over 500 invited talks in the UK and over 1100 internationally, including major plenary/highlight talks at: APS April Meeting (Feeney); Solvay Conference 2015 (Ellis); COSMO-14 and COSMO-18, Texas Symposium on Relativistic Astrophysics (Peiris); EWASS (Saintonge, Savini); IAU General Assembly (Long); European Biophysical Society (Saric), Biophysical Society (Hoogenboom, Molodtsov); American Society for Cell Biology (Molodtsov); German Physical Society (Robinson); E-MRS (Shluger, Zubko); MRS (Shluger); ACS (Schofield, Perez Martinez, Viti); APS March meeting (Michaelides x 3, Saric, Schofield, Johnson, Olaya-Castro, Szymanska, Oppenheim);

ECOSS (Michaelides); ICPEAC (Laricchia); Gordon Conferences (Michaelides, Szymanska, Bose, Faria); SPIE Photonics West (Barker); QIP (Oppenheim); International Conference on Magnetism (Kruger); Neutrino 2016 (Agostini, Waters); EPS High Energy Physics Meeting (Butterworth, Konstantinidis); ICHEP (Konstantinidis, Nurse, Saakyan); Recontres du Blois (Deppisch, Peiris), du Vietnam (Deppisch) and de Moriond (Campanelli). We organised training schools including: STFC Solar and CASRA Radio Schools (Reid); Essential Cosmology for the Next Generation (Font Ribera); STFC School in Machine Learning (McEwen); Mott Physics Beyond the Heisenberg Model (McMorrow); EPSRC/IoP Physics by the Lake Condensed Matter Theory School (Fisher, Szymanska).

4.5.2 Strategic direction of the field

Our staff play a major role in formulating science policy and setting the directions of their research fields. Saakyan co-authored the double beta decay report for the Astro-particle Physics European Consortium (APPEC) and Lahav sits on its advisory committee, Waters is a member of the STFC UK Dark matter review, Coates, Lahav and McMorrow have all sat on the STFC Science Board, Butterworth was a member of the UK CERN committee and of the European Particle Physics Strategy Group. Peiris is a member of STFC Council (Butterworth will join in 2021). Fisher was a member of the EPSRC Physical Sciences SAT, McMorrow chairs the Scientific Advisory Committee for ESRF. Further details are given in Table 7.

4.5.3 Named lectures

Named lectures included the Carnegie Centennial Lecture at St Andrews and the Brinson Lecture at Chicago (Ellis), the Svein Rosseland Lecture in Oslo (Peiris), and the Gordon Lecture at Cornell (Saintonge); in 2020, **all three** of the RAS named lectures were given by UCL researchers (Darwin Lecture – Lahav, Whitrow Lecture – Pontzen, Dungey Lecture – Matthews). The Whitrow and Dungey lecturers in 2014 and 2017 were Lahav and Owen.

4.5.4 Awards, fellowships and prizes

Our staff have won highly competitive fellowships from major funders, including ERC, EPSRC, STFC, UKRI and the Royal Society (see Table 4, Table 5); Thomas recently won a highly prestigious Royal Society Research Professorship. Ellis, Tennyson, and Thomas (elected 2017) are Fellows of the Royal Society (FRS). Major awards to UoA staff are shown in Table 6. In addition, Sir Michael Pepper FRS (returned in UoA12, joint appointment in LCN) won the 2019 Newton Medal and Prize of the IoP – the Institute's premier award, and a significant additional indicator of our environment's vitality. Ellis and Michaelides were named in the Clarivate international 'highly cited researchers' list for 2019, and Thorne is the senior of three authors for the authoritative 'structure functions' section of the biennial Review of Particle Physics. Bramwell was awarded an Honorary Doctorate by the University of Uppsala.

Table 6: major prizes and awards won by UCL Physics staff in the review period.

Recipient	Prize	Awarding body	Date
Individual awards			
Thomas	Fellow of the Royal Society (FRS)	Royal Society	2017
Nguyen	Rosalind Franklin Award		2019
Materlik	Glazebrook	Institute of Physics	2014
Pickard	Rayleigh		2015
Olaya-Castro	Maxwell		2016
L Green	Lise Meitner		2017
Thomas	Michael Faraday		2018
Peiris	Fred Hoyle		2018
Ellis	Michael Faraday		2020

Shluger	David Tabor		2020
Michaelides	Corday-Morgan	Royal Society of Chemistry	2016
Pontzen	Fowler Award	Royal Astronomical Society	2016
Saintonge	Fowler Award		2018
Waldmann	Fowler Award		2019
Cropper	Service Award		2018
Ellis	Carl Sagan Memorial Prize	NASA	2017
Robinson	Gregori Aminoff Prize	Royal Swedish Academy	2015
Hoogenboom	Medal for Scanning Probe Microscopy	Royal Microscopical Society	2016
Peiris	Göran Gustafsson Prize	Göran Gustafsson Foundation	2020
Major group awards			
Ellis	Breakthrough Prize (Supernova Cosmology Project)	Breakthrough Prize Board	2015
Peiris	Breakthrough Prize (WMAP Consortium)		2018
Younsi	Breakthrough Prize (Event Horizon Telescope)		2020
Younsi	Einstein Medal (Event Horizon Telescope)	Einstein Society	2020
Peiris, Pontzen	Buchalter Cosmology Prizes (with collaborators)	American Astronomical Society	2014, 2018
Harra, Matthews	Daiwa-Adrian	Daiwa Anglo-Japanese Foundation	2016
Lucie Green, Matthews	Group Achievement (Geophysics, Hinode EIS collaboration)	Royal Astronomical Society	2015
Feeney, McEwen, Peiris, Savini	Group Achievement (Astronomy, Planck collaboration)		2018
Fazakerley and colleagues	Group Achievement (Geophysics, Cluster Science and Operations team)		2019
Cropper and colleagues	Sir Arthur Clarke Award for Scientific Achievement (UK Gaia team)	British Interplanetary Society	2017
Coates	Sir Arthur Clarke Award for Scientific Achievement (UK Cassini team)	British Interplanetary Society	2018
Feeney, McEwen, Peiris, Savini	Gruber Cosmology Prize (Planck collaboration)	Gruber Foundation	2018

4.5.5 Other evidence of national and international leadership

We encourage our staff to play leading roles in the physics community and this is reflected in the positions of responsibility that they hold (see Table 7 for a selection) including an exceptionally large number of leadership roles (PI, Spokesperson or equivalent) in major collaborations. Our staff examined at least 676 PhD theses during the review period.

Table 7: major leadership activities by UCL Physics staff in the review period.

Leadership positions in major collaborations	**European Space Agency (ESA):** PI of Ariel (Tinetti) and Comet Interceptor (G Jones); European co-PI of SMILE (Branduardi-Raymont); Euclid Consortium Board and Science Lead, VIS instrument (Cropper); PI of PanCam for ExoMars Rosalind Franklin Rover and CAPS electron spectrometer for Cassini (Coates); PLATO council member (Smith); PI of SWA sensor suite for Solar Orbiter (Owen); PI of Hinode EIS (Matthews); PI of Cluster PEACE and Double Star PEACE (Fazakerley) Spokesperson, ZEUS collaboration and Deputy Spokesperson, AWAKE (Wing); co-Spokesperson of super-NEMO (Waters); ATLAS-UK chair (Konstantinidis); Spokesperson, MINOS+ and PI, CHIPS Collaboration (Thomas); UK PI of LUX and Chair of Dark Matter UK Consortium (Ghag); co-Spokesperson, Muon *g*-2 collaboration (Lancaster); co-PI of PFS instrument, Subaru telescope (Ellis); co-Chair, DES Science Committee and Chair of DES:UK (Lahav); PI of COBRaS consortium (Prinja); PI of EPSRC Materials and Molecular Modelling Hub (Michaelides) and AMOR consortium (Tennyson); Chair of CCPQ (Monteiro).
Editorial positions and boards	**Editorial positions:** Editor in Chief, Solar Physics (Van Driel-Gesztelyi); Guest Editor for Planetary and Space Science (Coates) and Space Science Reviews (Wicks); Topical editor for Annales Geophysicae (Owen); Editorial Board, volume editor, Geophysical Monograph Series (Forsyth), Journal of Chemical Physics (Michaelides), and special issue editor, Nanoscale (Nguyen). **Editorial Boards:** Annual Reviews of Astronomy and Astrophysics (Van Driel-Gesztelyi); Contemporary Physics (Ellis, Fisher); Contemporary Science (L Green); J Phys B (Laricchia); Journal of Astrophysics and Advances in Astronomy (Ghag); Journal of Molecular Spectroscopy (Yurchenko); J Phys Cond Matt (Bowler); J Roy Soc. Interface (Bowler), Surface Science (Michaelides), European Physical Journal D (Cassidy), Physical Biology (Hoogenboom), Scientific Reports (Renzoni)
Committees and conference leadership (international)	CERN European Particle Physics Strategy Group (Butterworth) and LHC Committee (Waters); ERC grant panels (Font-Ribera, Michaelides, Peiris); NASA selection panels (Coates, G Jones, Matthews, Wicks); Vice-President, Solar Physics Division, European Physical Society (L Green); ESA Space Planning Committee (Smith); Chair of Executive Committee, Canon Foundation (Fisher); Academy of Finland panel chairs (Coates, Owen, Van Driel-Gesztelyi). **Advisory Committees:** Simons Observatory and Aspen Centre for Physics (Peiris); Hamburg Quantum Excellence Cluster (Butterworth); Flatiron Institute (Peiris); Astro-Particle Physics European Consortium (Lahav); Chair of Science Advisory Committee, ESRF (McMorrow); MARVEL National Competence

	Centre, Switzerland (Michaelides); Max-Planck Society Training School (Monteiro); SNOLab (Ghag).
Committees and conference leadership (national)	Vice-President and President, Society for Popular Astronomy (Coates), RAS Vice-President (Peiris), Council (Matthews) and Chair of International Committee (Wu); chair of review committee for Institute of Astronomy, Cambridge (Lahav); UK CERN Committee (Butterworth); UK Board member, James Clerk Maxwell Telescope (Greve). **Science and Technology Facilities Council (STFC):** Council (Peiris); Science Board (Coates, Lahav, McMorrow); 21st Century Challenges Committee (Lahav); Astronomy Grants Panel subpanel chairs (Coates – planetary, Matthews - solar); Chair, Particle Astrophysics Advisory Panel (Ghag); Projects Peer Review Panel (Campanelli, Konstantinidis, Savini, Wicks); STFC Long Baseline Neutrino Experiments Strategic Review Panel (Thorne); Particle Physics Grants Panel theory Vice-Chair and experimental Vice-Chair (Thorne, Wing); Particle Physics Advisory Panel (Thorne, Wing); chair of Computing and Particle Physics Evaluation Panels (Lahav); Consolidated Grant Committee (Font-Ribera); ELT Steering Committee (Smith); KMOS and MOONS Oversight Committees (Cropper); Boulby Underground Laboratory Advisory Committee (Ghag). **Engineering and Physical Sciences Research Council (EPSRC):** Physical Sciences Strategic Advisory Team (Fisher).

4.6 Conclusion

The awards won by our researchers are a tribute to the role UCL is playing in the development of modern physics. The leadership by our senior staff is broad and extends across the whole subject. UCL's collaborative and informal ethos helps this to translate to an exceptional environment for our students and early-career staff. That environment is geared to what they will achieve next.