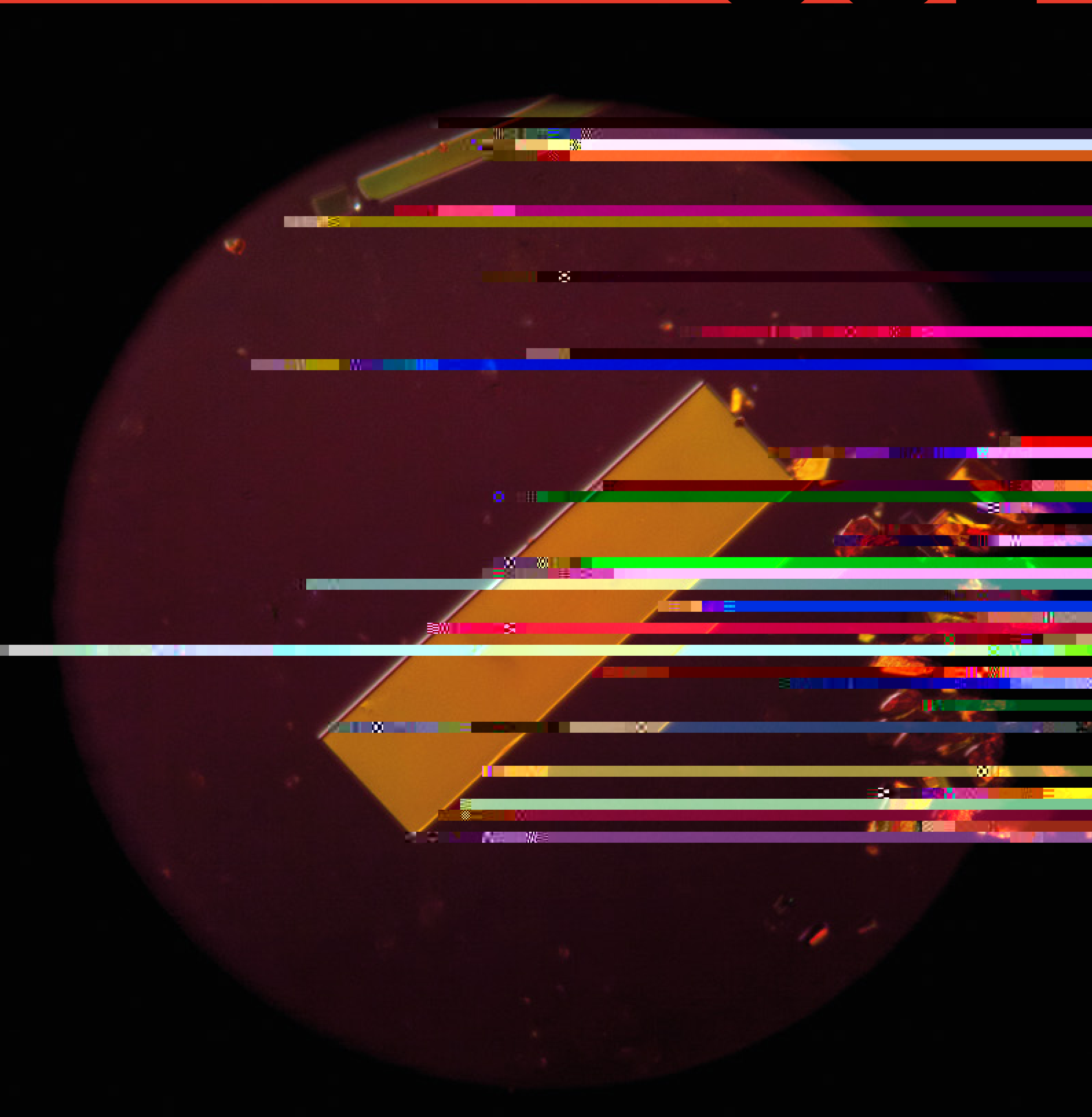
UCL DEPARTMENT OF PHYSICS AND ASTRONOMY

UCL



PHYSICS AND ASTRONOMY
ANNUAL REVIEW 2013–14

Cover image:
Optical microscope image (50x magnification) of single crystals of the C60 derivative [6,6]-phenyl-C61-butyrric acid methyl ester (PCBM), an electron transporting organic semiconductor widely used in organic solar cells.
Credit: Giuseppe Maria Paternó.

Image page 2:
Credit: UCL Media Services.

Image page 11:

Welcome

Welcome to another edition of our Annual Review. 2013 was a busy and eventful year; the Department has continued to grow and we have made a large number of outstanding academic appointments, some of them jointly with our neighbours, the London Centre for Nanotechnology (LCN). Many of the appointees hold prestigious personal fellowships from UK research councils or the Royal Society; it is exciting to see the great science they are already producing as they settle into the Department. Page 12 of this Review introduces each member of staff and briefly describes their research.

“ … 2013, … ”

On the teaching side, the Institute of Physics updated its accreditation of our degree programmes and we also underwent an Internal Quality Review. I am very pleased to report that both were successful and served to validate our approach to teaching. All three undergraduate laboratories have now been refurbished and this year has seen some technological innovations to our teaching programmes. Page 9 describes just a few of these changes. Thanks to **Raman Prinja** in his role as Director of Teaching for spearheading these advances.

2013 has also seen the retirement of two key members of academic staff; **Tony Harker** served as the Deputy Head of Department for nine years. He made a huge contribution to the Department and I am extremely grateful to Tony for the support he has given me, particularly when my tenure as Head of Department began. He not only served as the de facto Head of Department for one year, to enable me to continue my research at CERN working with the Large Hadron Collider, but his essential contribution continued when I returned. Raman Prinja has now taken over as the Deputy Head of Department, and I am grateful to Raman and to **Hilary Wigmore**, Departmental Manager, for ensuring a smooth transition after Tony's departure. **Ian Furniss**, who in his capacity as Programme Tutor has supported many undergraduate students, also retired this year, and I wish him all the very best in his retirement.

There have been many exciting science highlights over the past year, some of which are featured in this Review: the data from the Planck satellite on the cosmic microwave background was cited by Physics World as one of the top ten breakthroughs of the year (page 14); Peter Higgs (an ex-lecturer in UCL Mathematics and now a UCL Honorary Fellow) won the Nobel prize with François Englert for the discovery of the Higgs boson at the Large Hadron Collider – a project several of us worked on here at UCL (page 13). The Jupiter Icy Moons mission (JUICE) was approved by European Space Agency (ESA), with major participation from the Department and the Mullard Space Science Laboratory (MSSL) (page 26), and funding was recently approved for the UCLH proton therapy unit, an exciting development in which we have a strong research interest.

This Review serves to highlight some of our most significant successes and challenges during 2013, as well as showing an appreciation towards staff and students; many of whom have made a notable contribution not only to science, but also to the life of the Department.

Professor Jonathan Butterworth
Head of Department

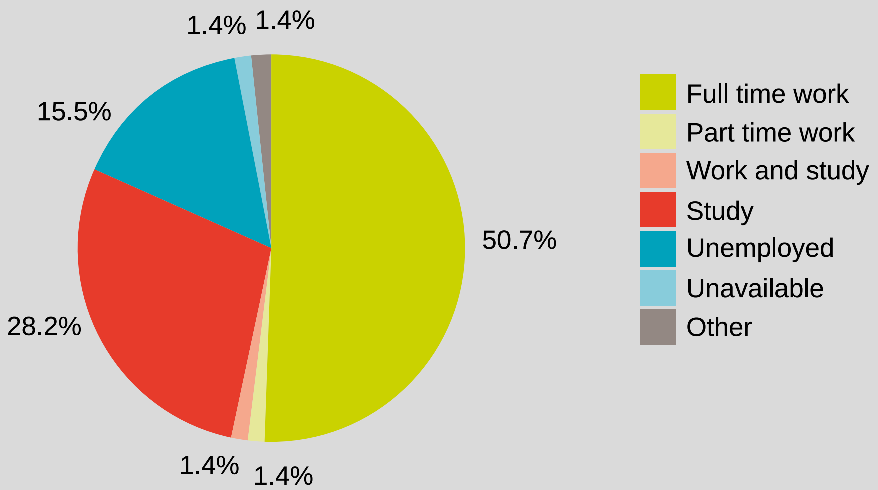
Community Focus

BSc/MSci: 144

Total Number of Graduates: 112

Response Rate: 83.32%

Median Salary: £28,000
(full time employment)



Adam Davison

Data Scientist, MSci Physics (2006), PhD Physics and Astronomy (2011)

I joined UCL as an undergraduate Physics student in 2002. The combination of interesting people and great research opportunities led me to stay for a PhD and subsequent position as Research Associate. My research at UCL was focussed on the much publicised search for the Higgs boson with the ATLAS experiment at CERN. Being involved in such a high profile international enterprise brought opportunities to travel the world and work with some fantastically smart people. The intense public interest also meant that explaining what you do for a living in the pub, often turned into a fifteen minute Physics lecture!

In 2013 I decided it was time to move on to something new. Luckily, it turns out that some of the problems high energy physicists have spent the last twenty years solving, such as how to analyse data when it arrives at a rate of about one CD per second, are now being faced

After completing my joint honours degree in Physics and Chemistry, I spent several years as a PhD research student, first in the High Energy Physics (HEP) team and later the thermodynamics group in the Chemistry Department. I never wrote up my PhD – after meeting my partner Pete Fitch, also a member of Physics and Astronomy, and the birth of our daughter Zoë (aka “the Fitchlet”, thanks to

The first Physics and Astronomy Gala Dinner was held on the 25th of October 2013. It was an unprecedented opportunity for some thirty undergraduate and postgraduate students, thirty-six Alumni and twenty members of staff plus guests to come together for the Awards Ceremony. The evening began with a drinks reception, followed by the Gala Dinner and concluded with the ‘After Dinner Speaker’, which had been a feature of the previous annual alumni dinners.

It was an extremely uplifting experience to learn of the tremendous achievements of our students and to witness the Award Ceremony, with several awards and postgraduate studentships having been funded by our Alumni. Academics of my generation have perhaps an unspoken suspicion that we were much better behaved in our day. As I related in my introduction to Charlotte Nichol (née Waterhouse), our ‘After Dinner Speaker’; in 1959, a certain Dr Peter Higgs was appointed as a temporary junior lecturer in the UCL Mathematics Department. He was asked to teach the mysteries of Lagrangian Mechanics to second year physics students and subsequently became the target of lighted paper darts aimed in his direction. At the end of the academic year, he accepted with alacrity a position at Edinburgh, where his work in 1964 won him this year’s Nobel Prize in Physics, shared with Françoise Englert!

As the Alumni Co-ordinator, I was extremely pleased by the high attendance of Alumni in spite (or because) of the changed arrangements. Charlotte, accompanied by husband **Dr Ryan Nichol** and their remarkably well behaved six month old daughter, Evelyn, gave a wonderful speech describing life at the “White Board Face,” as Deputy Head and physics teacher at an inner London state high school.

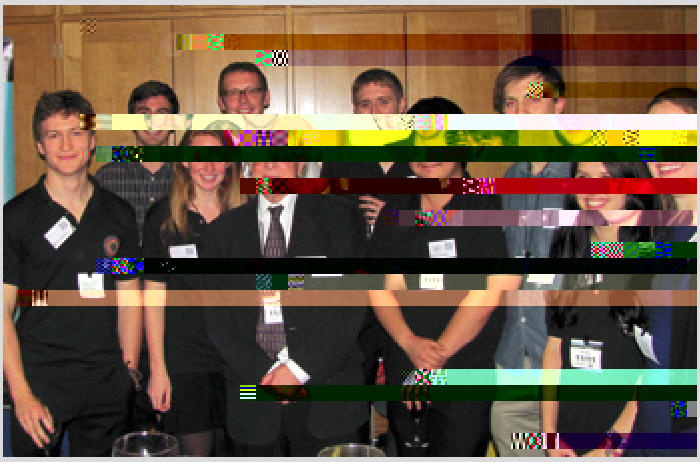
The After Dinner Speaker for the 2014 dinner will be Dr Chris Lintott, Chris graduated from UCL in 2006 with a PhD and is currently

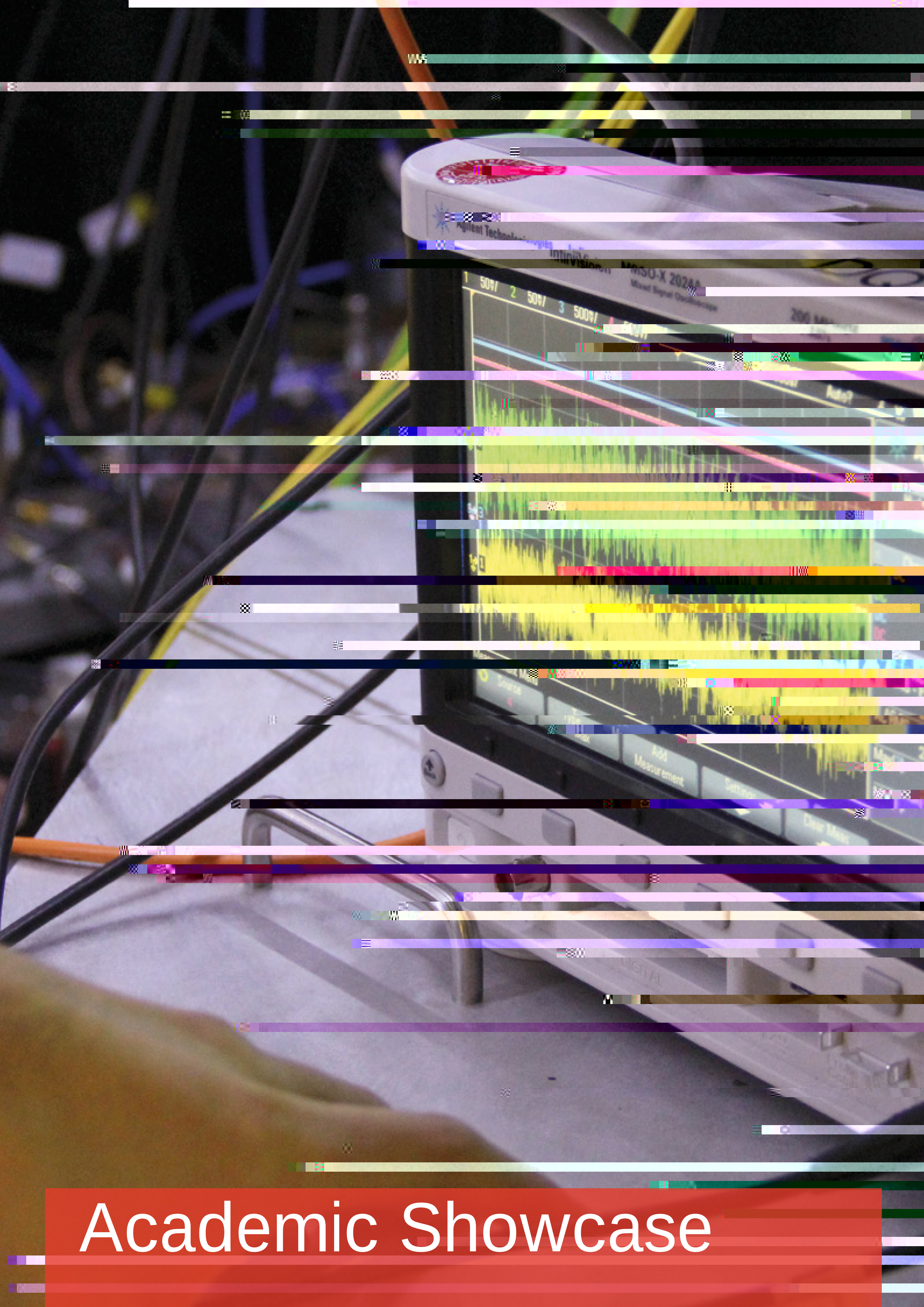
Team Teaching Fellows

Over the past 24 months, Physics and Astronomy has sought to expand its teaching repertoire through the appointment of four additional Teaching Fellows. The Department now boasts

‘**Collider**’ is a major new immersive exhibition at the Science Museum, which blends theatre, video and sound art to recreate a visit to CERN and explore the LHC. On Monday 11 November 2013, the Parliamentary Office for Science and Technology hosted a special event for Lords and MPs, with guest of honour Professor Peter Higgs, to celebrate the opening of this ground-breaking exhibition.

UCL members of staff, **Prof. Jon Butterworth** and **Dr Gavin Hesketh**, as well as PhD students from the High Energy Physics Group (HEP) were on hand to discuss the Large Hadron Collider (LHC), their exhibition stall included electronics designed at UCL for the LHC, which ensures the ATLAS detector stays synchronised with the proton-

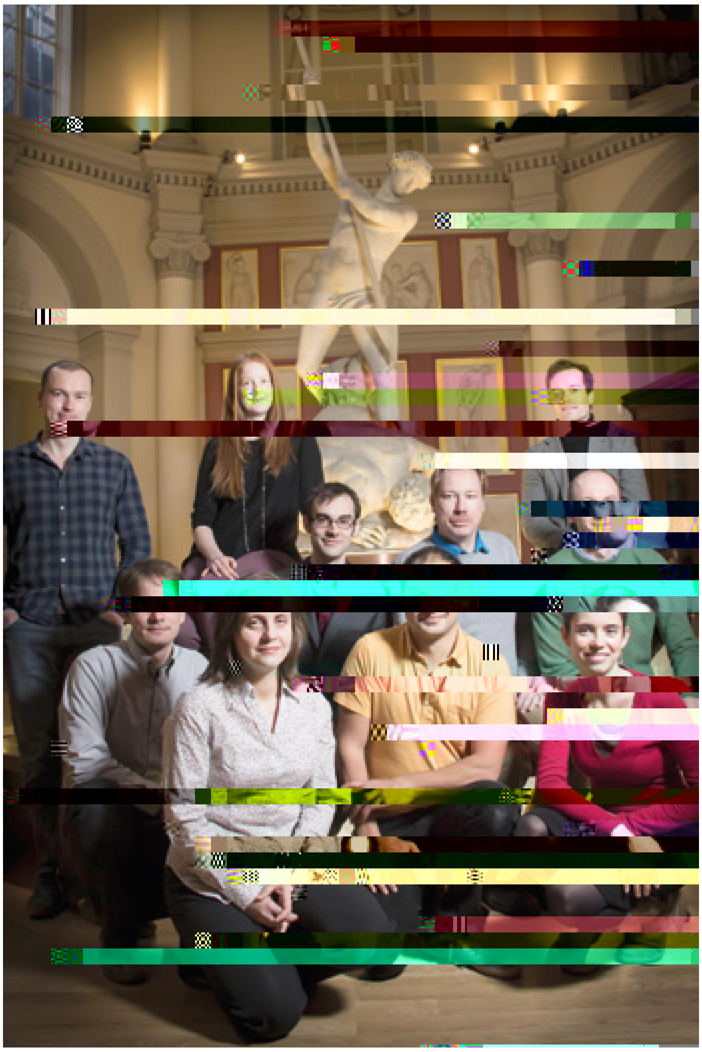




Academic Showcase

Academic Appointments

2013 has been an extremely successful year in terms of recruitment, with a large number of outstanding researchers having joined the Department as permanent academic members of staff. Recruitment is a two way process, and a measure of the continuing success of the Department can be evidenced through the ability to attract highly esteemed academic members of staff. Each member of staff compliments and enhances the high-profile research portfolios of both the individual research groups and the Department as a whole.



(Left to right) back row – 1 [illegible] A [illegible] , A G [illegible]

Agapi Emmanouilidou (AMOPP):
Specialises in attosecond and strong-field science and interaction of matter with free-electron lasers, an EPSRC Research Fellow from UCL.

Jay Farihi (Astro):
Specialises in exoplanetary systems and the frequency and composition of extrasolar asteroids, from Cambridge University.

Thomas Greve (Astro):
Specialises in galaxy formation and evolution, an STFC Research Fellow from UCL.

Keith Hamilton (HEP):
Specialises in precision predictions for the LHC, from CERN Theory Division.

Christopher Howard (CMMP):
Specialises in experimental (nano)materials physics, from UCL/Linde LLC.

Benjamin Joachimi (Astro):
Works on large-scale structure cosmology with a focus on gravitational lensing and intrinsic galaxy alignments, from Edinburgh University.

Andreas Korn (HEP):
Specialises in ATLAS exotic searches and tracker upgrade, from the University of Edinburgh.

Isabel Llorente Garcia (AMOPP):
Specialises in magnetic traps for Biophysics, from Oxford University.

Gerd Materlik (CMMP/ LCN):
Professor of facilities science, applications and sources of synchrotron radiation and free electron lasers, from Diamond Light Source.

Andrew Pontzen (Astro):
Specialises in cosmology, from Oxford University.

Amélie Saintonge (Astro):
Specialises in galaxy evolution, from the Max Plank Institute for Extraterrestrial Physics.

Marzena Szymanska (AMOPP/ CMMP):
Specialises in quantum coherence in non-equilibrium light-matter systems, from Warwick University.

Pierre Thibault (CMMP):
Specialises in high-resolution X-ray imaging, from TU Munich.

Pavlo Zubko (CMMP/ LCN):
Specialises in complex-oxide thin films and heterostructures, from University of Geneva.

Higgs boson: the post-discovery era

Just over a year after the announcement of its discovery, the Higgs boson continues to dominate the headlines in particle physics.

Two major new results were announced in 2013: firstly, the spin and other intrinsic properties of the Higgs were measured. These determine the angular orientation of its decay products and were found

Daiwa Anglo-Japanese Foundation: Daiwa Adrian Prize

Awarded to **Professor Alex Shluger, Dr Peter Sushko and collaborators from the Tokyo Institute of Technology.**

For their work on the “Exploration of active functionality in abundant oxide materials utilising unique nanostructure: discovering novel properties of traditional materials and addressing the limited availability of technologically important elements through curiosity driven-driven research.”

Research Degrees

Doctor of Philosophy (PhD)

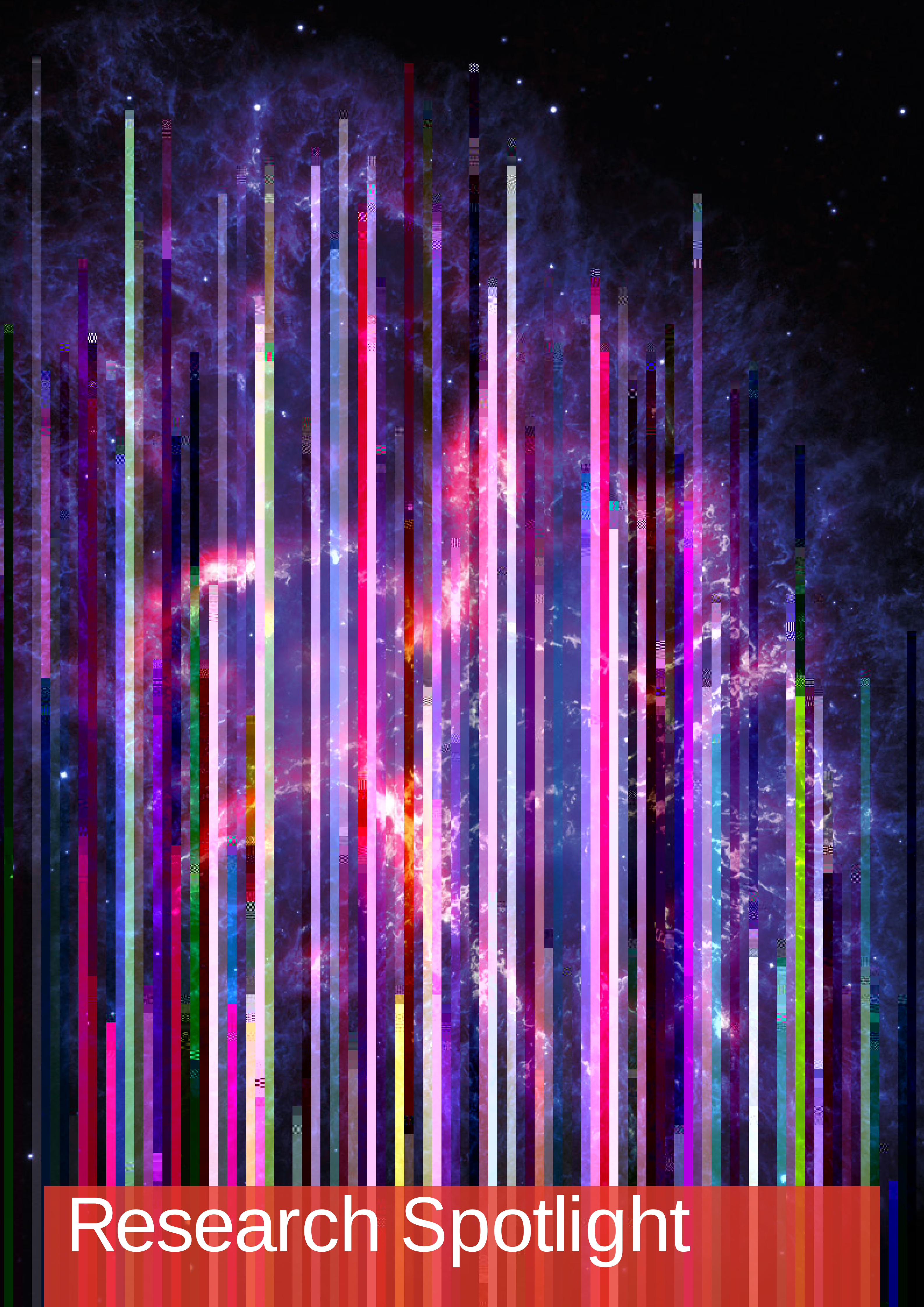
Ala'a Azzam
A linelist for the hydrogen sulphide molecule
(Supervisor Professor J. Tennyson)

Sarah Baker
Studies of jets, subjets and the Higgs search with the ATLAS detector
(Supervisor Professor J. Butterworth)

Richard Bean
Domain structure imaging by Bragg geometry x-ray ptychography
(Supervisor Professor I. Robinson)

Stephen Bieniek
Two b or not two b-jets: measurement of inclusive and dijet b-jet differential cross-
s A

0 Bo/7 1 Tf0 Tc 0 Tw 80 Td( )Tj7.71 1 Tf-7.31.32 Td.7Spr cg8.121 (h 4TJ0.0B)0.7 (e)-14(c)-1.4a 10jTnJ0.008Tc 5(e A)9(T)-15C(y)]TOue 0B10j9(m)2-5(&(n)-37(t o)-5(f)]TJ9(r)

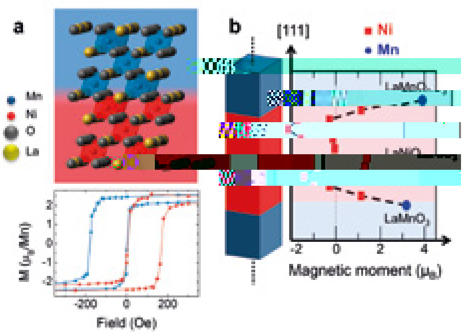


Research Spotlight

Artificially layered oxides

Complex oxides are an exciting class of materials that exhibit incredibly diverse functional properties including high-temperature superconductivity, ferroelectricity, and exotic magnetism. The structural compatibility between many different materials in this class means that they can be assembled, like LEGO bricks, into complex artificially layered heterostructures, with a high degree of crystalline perfection. This opens up a seemingly endless set of possibilities for the creation of novel and highly multifunctional materials and gives us access to the fascinating new physical phenomena that appear in oxides which are engineered at the nanoscale.

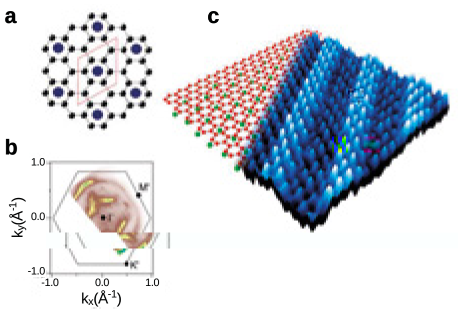
One interesting and technologically important category of oxides, is the family of perovskite ferroelectrics. Among their many useful properties, their high dielectric permittivities are utilised in various types of capacitors, whilst their defining characteristic, the switchable spontaneous polarisation, is exploited in ferroelectric random access memories. Improvements in data storage capacity, as well the realisation of new devices such as ferroelectric tunnel junctions, requires the downscaling of ferroelectrics to thicknesses of just a few nanometres, motivating intense research on ferroelectricity in the so-called ultrathin limit. Dr Pavlo Zubko, together with colleagues



Another exciting aspect of research on artificially layered oxides is that the properties of a heterostructure can often be very different from those of its individual constituents. Interfaces between chemically different compounds violate the symmetries of the bulk materials and allow for the emergence of new phenomena. For example, when ultrathin layers of ferromagnetic $LaMnO_3$ are interleaved with paramagnetic $LaNiO_3$ in superlattices grown along a specially chosen crystallographic direction (figure 2), electrons are transferred across the interface from the manganite to the nickelate layers. This modifies the magnetic interactions between the interfacial Ni and Mn ions, giving rise to a new magnetic structure within the nominally paramagnetic $LaNiO_3$ layers and leading to the appearance of exchange bias, manifested as a shift of the ferromagnetic magnetisation-field loop. Heterostructures involving other members of the rare-earth nickelates family which already exhibit magnetism and metal-insulator transitions in bulk should have even more interesting properties, as the bulk phases will compete with interface-induced effects.

Chemically doping graphitic materials

The most structurally simple and widely studied two-dimensional material is graphene. Graphene is a honeycomb atomic crystal of carbon that is only one atom thick, which has an extraordinary combination of physical properties. For example, it is many times stronger than steel, a better conductor of heat and electricity than copper, and is almost transparent to light. Graphene therefore has numerous potential applications, from displays and touch screens to ultra-strong composite materials. World-wide, scientists are devoting huge efforts to understand and control the properties of this material, and to develop methods for physically incorporating it into applications.



Dr Christopher Howard and co-workers manipulate graphitic materials, a class which includes graphene that is stacked in layers (graphite) and rolled into tubes (nanotubes), by the process of chemical doping. This involves decorating the graphitic material with dopant atoms or molecules, for example simple metals. The highly tunable electronic structure of graphitic materials means they readily accept/donate electrons from/to the dopant species with the dopants then typically forming ordered arrays on the graphene surface (figure 3a), or between the sheets of graphite. Adding charge carriers in this way permits the tuning of properties for specific applications, and also enables the search for exotic electronic behaviour. In fact, people chemically dope graphite with lithium every day when a mobile phone battery is charged

At the highest electron concentrations, achieved by doping with calcium metal, graphite becomes a superconductor: once it is cooled below a critical temperature, T_C, it conducts electricity with no resistance.

The detailed electronic structure of this superconductor was measured using photoemission spectroscopy, a technique based on the photoelectric effect, with collaborators at Stanford University (figure 3b). The experiments illustrated the crucial role played by the electrons associated with the 2D arrays of calcium atoms in the superconducting mechanism. These results now lay down the framework to realising superconductivity in graphene itself, a major aim of the research group. Above T_C, Scanning Tunnelling Microscopy (STM) revealed that some of the electrons donated to the graphite spontaneously form striking nanometer-scale stripes (figure 1c). It was demonstrated that the stripes are a so-called charge-density wave. This is a novel electronic groundstate often found in low dimensional materials proximal to superconductivity, but it is the first time such a state was demonstrated in any graphitic material.

Key to harnessing the properties of graphene is developing industrially scalable methods to physically incorporate it into technological applications. For example, if graphite can be dissolved to form solutions of individual graphene sheets, such solutions can be used to efficiently paint graphene into thin films or embed it into composites. The stubborn insolubility of graphite can be overcome via chemical doping. Doping potassium atoms and ammonia molecules between graphite sheets expands the layer separation and weakens the interlayer attraction. The doped graphite then dissolves in organic solvents to form solutions of charged graphene. The presence of single-layer graphene in solution, was confirmed by neutron scattering conducted at the Institut Laue-Langevin in Grenoble (figure 4a) and corroborated by atomic force microscopy of dissolved graphene flakes dropped from solution onto a mica surface (Figure 4b).

Atomic, Molecular, Optical and Positron Physics (AMOPP)

Project in Focus

Quantum control of continuous variables

The AMOPP group perform high precision measurements, coupled with theoretical work, which is aimed at improving the understanding of fundamental processes. Their research can be applied to diverse areas such as the development and structure of the Universe, environmental change, and the behavior of biological systems. One relatively new and exciting area of research relates to quantum information and the development of quantum technologies. UCL hosts one of the UK's leading centres for research into quantum technologies and members of the AMOPP group investigate a wide

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range of research within the field of quantum information theory. Practical applications of quantum information theory are still in the development phase, but will harness the features of quantum mechanics and perform tasks which are hard, or impossible, with conventional technologies. Dr Alessio Serafini discusses progress in quantum technologies, as research is beginning to move towards experiments with a potential for practical impact.

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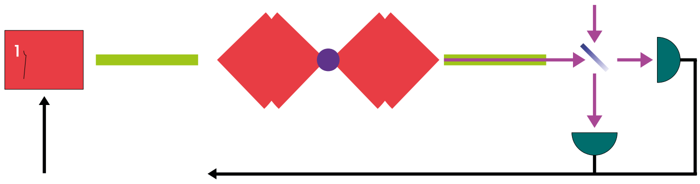
Quantum Control of Continuous Variables

Quantum systems hold considerable technological promise for a variety of applications such as information processing, secure communication and advanced sensing. However, decisive advances with quantum hardware will only be possible if the control of coherent quantum resources is achieved. As a

Focusing on the problem of the noiseless (Hamiltonian) controllability of continuous variable systems, they considered whether it would be possible to implement any arbitrary noiseless operation on the system. This was an unprecedented standpoint and by focusing only on a given a set of dynamical controls, with an always-on dynamic and restricting quadratic interactions, the problem was simplified to looking at the group of canonical transformations. Following this, through a connection between controllability and the property of recurrence (the fact that any initial state evolves back to itself up to an arbitrarily small error after a certain time), they have derived a necessary condition for the controllability of continuous variable systems under quadratic interactions. Quadratic interactions are sufficient to create squeezing and entanglement, and to cool down quantum systems.

This result on noiseless control can be applied to show surprising possibilities; given a one-dimensional chain of interacting quantum harmonic oscillators, these techniques demonstrate that any quadratic operation, anywhere on the chain, may be implemented by only two controls acting on any single oscillator of the chain. This is a classic partial control scenario, where direct access to the quantum system is severely restricted, but full controllability on the many body system may still be established. The sufficient controllability criterion of Genoni and co-workers is also necessary for a single degree of freedom. Dr Serafini's team is currently investigating whether this may stand for many degrees of freedom.

Dr Serafini's team are also developing the theory of optimal feedback control of continuous variables. In feedback control set-ups, the system is observed by a continuous TD[(aaTent anopessar,)a3ytvestigating whether this e8-3yste anputcomT[1ytve7 oe choice of future control operations on the system. This line pushes theoretical research past the relevant, but idealised noiseless scenario, and into the study of systems subject to realistic quantum noise. Furthermore, this kind of control focuses on target states rather than



High Energy Physics (HEP)

Project in Focus

High energy particle physics explores the most fundamental questions about the nature and evolution of the Universe, probing the most basic constituents of matter and how these elementary particles interact.

The Standard Model of particle physics has been remarkably successful at describing the visible Universe, and the unveiling of the Higgs boson at the Large Hadron Collider (LHC) last year, the cornerstone of the model, marked a crowning achievement. However despite its successes, the Standard Model does not readily provide a solution to the 80 year puzzle of ‘dark matter’.

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By measuring the motion of stars and galaxies, the presence of much more mass than is visible, or can be accounted for by regular baryonic material, is inferred. An incredible 85% of the mass content of the Universe is in the form of this dark matter, created in the early Universe shortly after the Big Bang. Though we can see its

The LUX experiment, housed 1.5 km underground in a former gold mine, is the largest detector of its kind, filled with 350 kg of liquid xenon and viewed by photosensors that record flashes of scintillation light produced when particles scatter in the detector. The xenon is held at -110 degrees Celsius in a titanium vessel, shown in Figure 2, and then immersed in a water tank. The detector was installed underground in 2012 and, following commissioning and calibration, the first WIMP search run began in April 2013, accruing 85 days of data.

A critically important area of analysis for dark matter experiments, in particular the first data taking campaigns, is establishing the detector's efficiency for WIMP detection. For LUX this is the responsibility of the 'Golden Group', led by UCL. Their work involves: identifying and characterising all the initial raw signals from the photosensors (figure 3), and selecting from these signals

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acomponents which contintute the ‘eyes’
aof the Planck High Frequency Intirument.
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athat the measurements taken in spaceand
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The Jupiter Icy Moons Explorer (JUICE)

In February 2013, the European Space Agency (ESA) announced which scientific experiments would make up the payload

Project in Focus

e Jupiter Icy Moons Explorer (JUICE)

Aim

Results to Date

UCL Involvement

Biological Physics (BioP)

The BioP group aims to undertake research in which physics of the highest academic quality is applied to address critical biological questions. It forms a network between experimental and theoretical physicists from different research groups in the Department, for whom biological problems are either the main focus and/or a significant application of their research activities.

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Working at the interface of physics, engineering and biology, **Dr Isabel Llorente-García** explains how ultrasensitive fluorescence-imaging detection, combined with magnetic force sensing, can be used to investigate how viruses enter cells. This work is in collaboration with Prof. Mark Marsh (LMCB, UCL), Dr Sonia Contera (Oxford Physics) and **Dr Phil Jones** (UCL Physics).

Understanding how viruses enter live cells

Molecular complexes that perform vital functions in live cells can be labelled with fluorescent tags, which emit light when illuminated by the appropriate excitation light. Fluorescence microscopy then provides valuable information about the location, number and arrangement of these complexes in the cell. When carried out in live cells (in vivo), it allows dynamic monitoring, maintaining the native biological context and functionality in the living cell.

In tailor-made magnetic trapping potentials, magnetic forces can be used to trap and manipulate micrometre-sized particles in solution. Prior to the magnetic trapping process, the particles can be functionalised and attached to the biological complexes of interest. The magnetic traps can then be employed to exert and measure forces relevant to the function of the molecular complexes in the cell. This enables live-cell force-spectroscopy experiments to be conducted at the single-molecule level.

Viral infections remain a serious threat to human health. For instance, HIV infects approximately two million people a year and kills a similar number. Viruses hijack fundamental cellular processes to replicate and cause infection. They exploit specific cell-surface receptor molecules to penetrate the cell-membrane barrier of new host cells, by mechanisms which are not well understood. Using HIV entry as a model system and applying the above mentioned biophysical techniques at the single-molecule level in live cells, will provide unparalleled insight into the mechanisms of viral infection.

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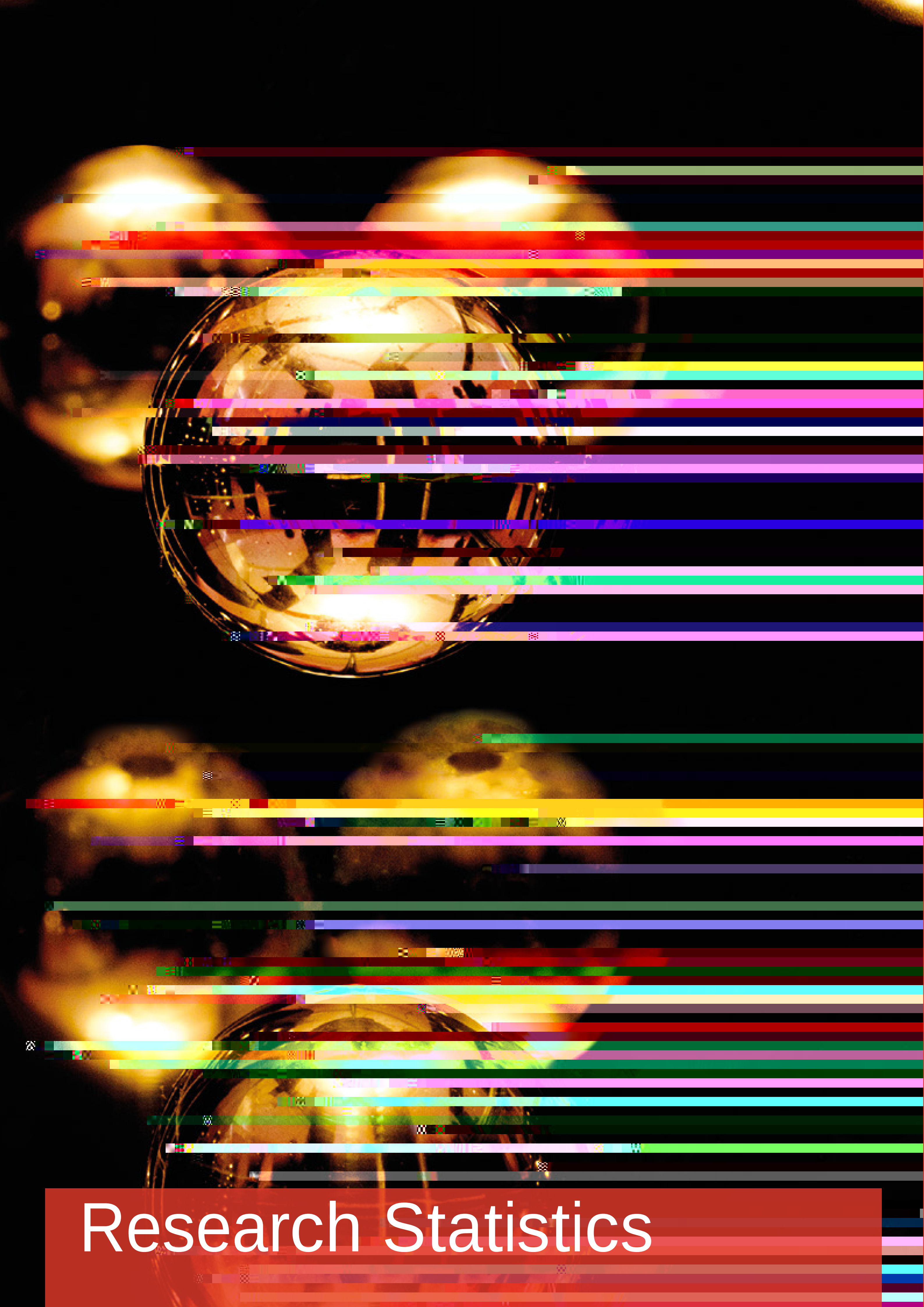
Project in Focus

Fluorescence microscopy, magnetic force sensing and manipulation for the study of receptor-mediated virus entry

Aim



Research Statistics

Publication Summary

Active Grants and Contracts

In the last financial year (Aug 2012 – Jul 2013), The MAPS faculty as a whole yielded £43,155,000, with the Department of Physics and Astronomy contributing £9,842,000 (23%) of the total research income for the MAPS faculty.

Astrophysics

Euclid Implementation Phase (UKSA) PI: Dr Filipe Abdalla, £545,348

University Research Fellowship (URF) (Royal Society) PI: Dr Filipe Abdalla, £504,594

UCL Astrophysics consolidated grant (STFC) PI: Dr Nick Achilleos, £52,668

Impact studentship: David Johnson – improving the representation of the thermosphere and ionosphere for space weather (UK Met Ofýce) PI: Dr Anasuya Aruliah, Ã31,627

ATMOP: advanced thermosphere modelling for orbit prediction (EU FP7) PI: Prof. Alan Aylward, Ã204,412

ESPAS: near-Earth space data infrastructures for e-science (European Commission FP7) PI: Prof. Alan Aylward, Ã197,306

UCL Astrophysics consolidated grant (STFC) PI: Prof. Michael Barlow, Ã52,889

COGS – capitalising on gravitational shear (EU FP7) PI: Prof. Sarah Bridle, Ã1,050,000

Large scale structure insights into the origins of cosmic acceleration (Royal Society) PI: Dr Sarah Bridle, Ã11,920

Another way of seeing – contemporary art responds to planetary science (STFC) PI: Dr Andrew Charlambous, Ã2,625

BigBoss UK development [illegible]LTU[illegible]

Comets as laboratories: observing and modelling commentary spectra (STFC) PI: Prof. Steve Miller, Ã185,912

The Miracle Consortium: modelling the Universe - from atomic to large scale structures (STFC) PI: Prof. Steve Miller, Ã557,483

Cosmic Dawn – understanding the origins of cosmic structure (EU FP7) PI: Dr Hiranya Peiris, Ã1,119,800

Cosmological constraints on the very early universe (Royal Society) PI: Dr Hiranya Peiris, Ã12,000

Detecting signatures of eternal in f ation using WMAP and Planck data (FQXi) PI: Dr Hiranya Peiris, Ã64,189

Philip Leverhulme Prize - Hiranya Peiris (Leverhulme Trust) PI: Dr Hiranya Peiris, Ã70,000

Travel for collaboration on exoplanets (FQXi) PI: Dr Hiranya Peiris, Ã3,047

RS Fellowship: Connecting physics and galaxy formation (Royal Society)

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Control of atomic motion with AC f elds (Royal Society) Ã12,000 PI: Prof Ferruccio Renzoni

Exploring stochastic thermodynamics with optical traps (Leverhulme Trust) PI: Prof Ferruccio Renzoni, Ã149,040

Magnetic sensor systems for the detection of metallic objects – identifying and characterising materials using magnetic f eld interrogation (Atomic Weapons Establishment) PI: Prof Ferruccio Renzoni, Ã141,070

Modelling condensed matter systems with quantum gases in optical cavities (EPSRC) PI: Prof. Ferruccio Renzoni, Ã806,753

COSMA – coherent optics sensors for medical applications (European Commission FP7) PI: Prof. Ferruccio Renzoni, Ã23,550

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HEP

Development and maintenance of atlas run time tester

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