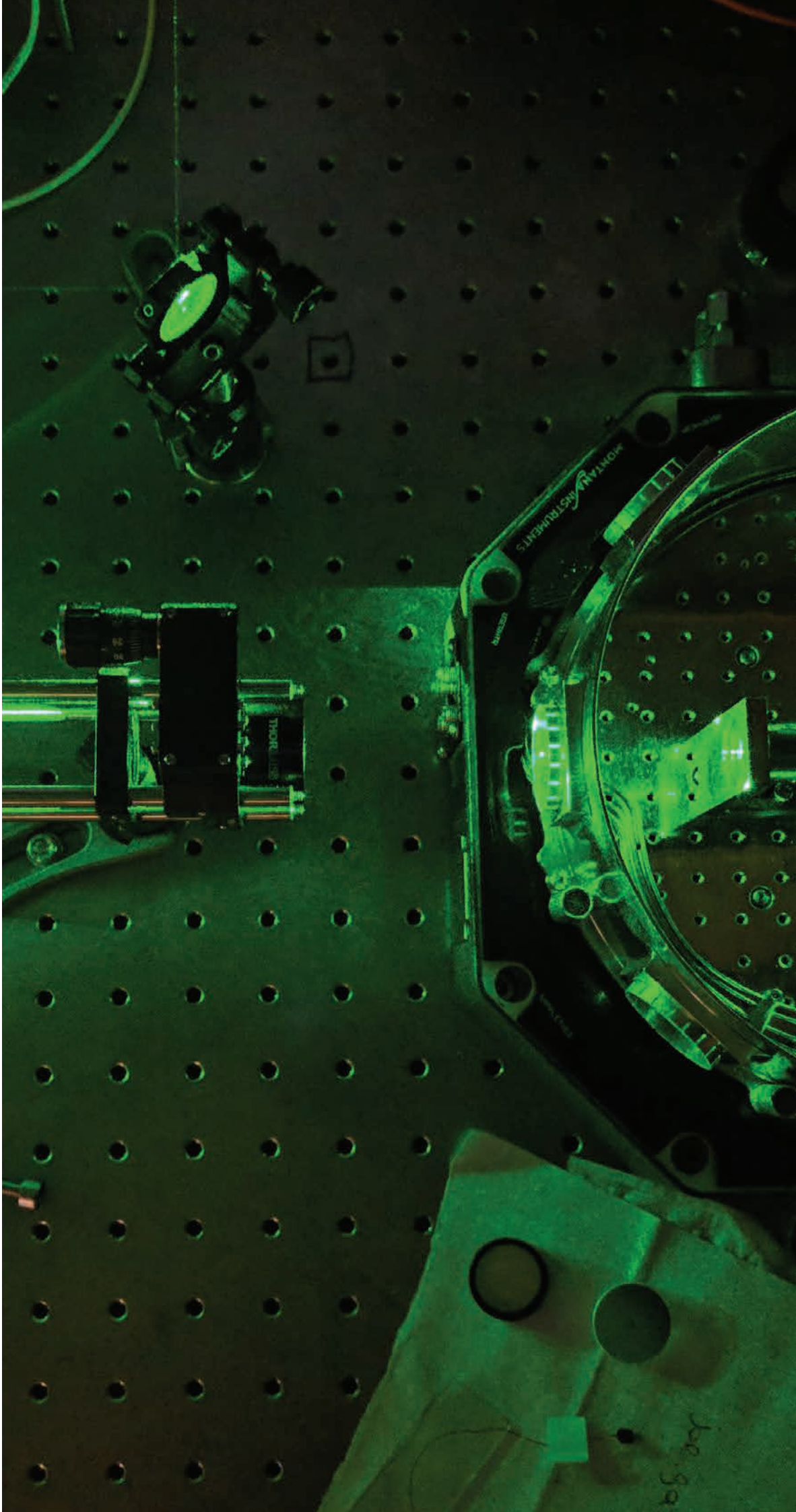
ANNUAL REPORT 2018



EQUS

Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

EQUS acknowledges the support of the Australian Research Council

Australian Government
Australian Research Council

We also acknowledge the financial and in-kind support provided by our collaborating organisations

The University of Queensland Australia
The University of Sydney
Macquarie University Sydney · Australia
The University of Western Australia
Australian National University

Cover image
Opening the cryo-chamber
Photo by Matthew van Breugel

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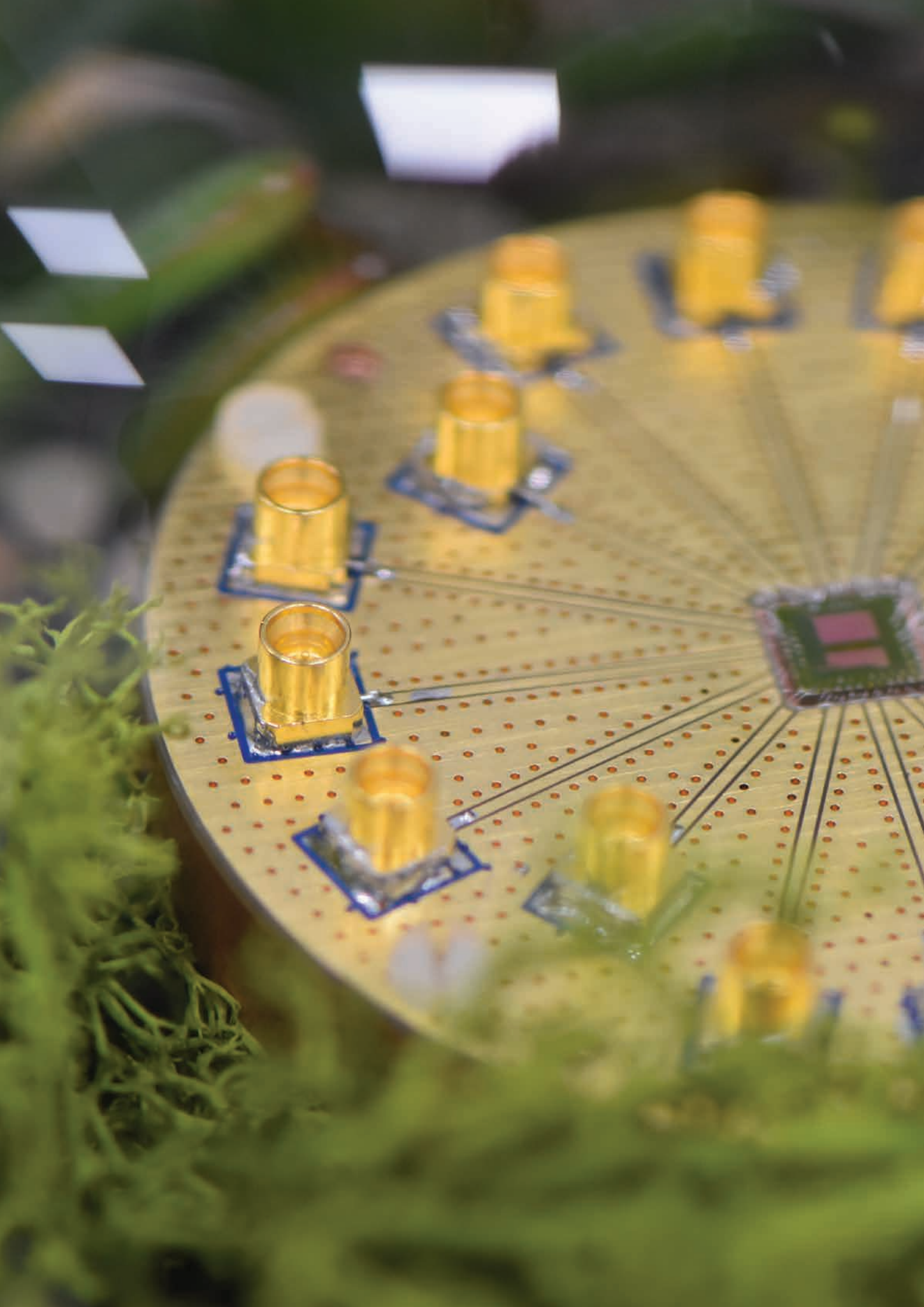
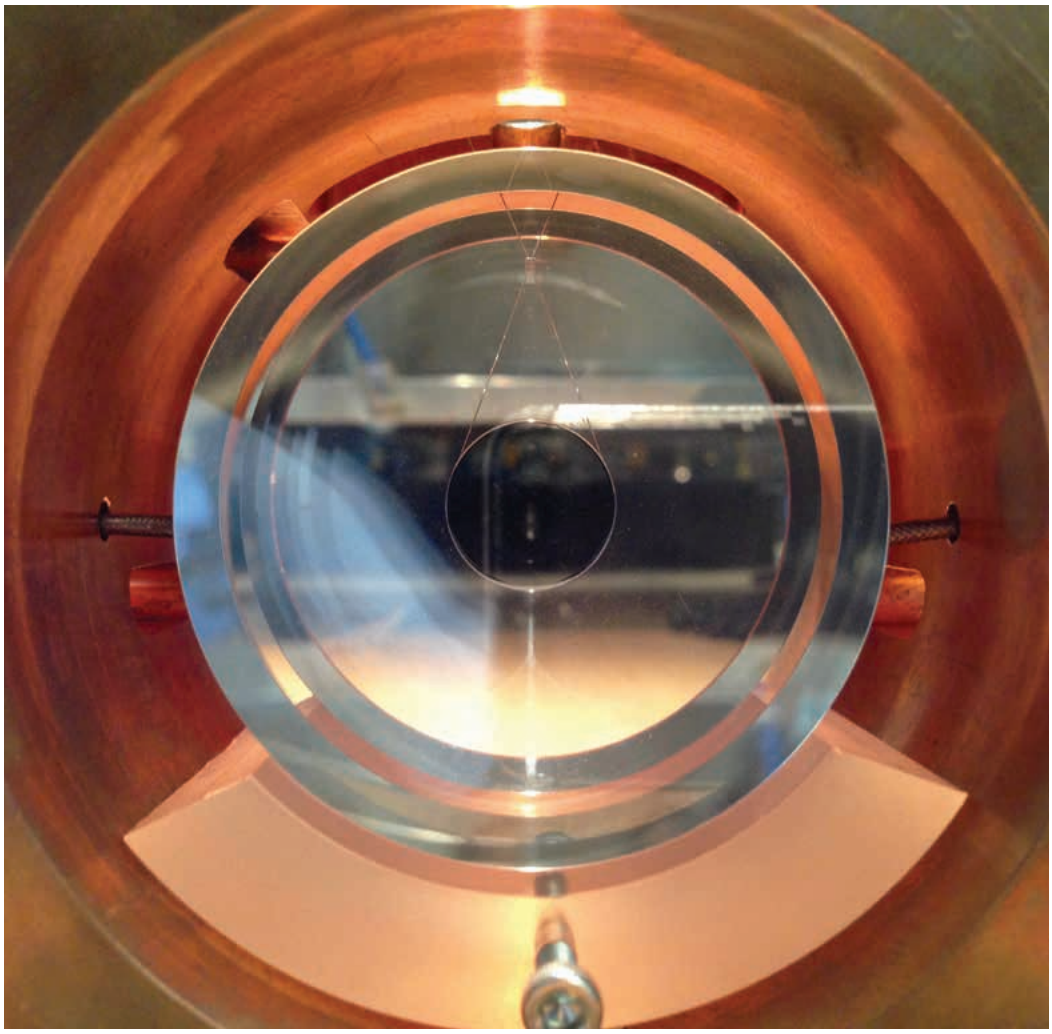


Executive summary

It is a good time to be a quantum physicist in Australia, where more than two decades of support for quantum engineering, science and technology has paved the way for significant scientific outputs and exciting translation efforts.

Quantum technologies will play an increasing role in future technologies. The next decade will see an explosion of activity in quantum engineering, which our Centre is well placed to steer through our three research programs, collaboration with industry partners and our Translational Research Laboratory.

The release of this Annual Report marks the conclusion of the first year of our new Australian Research Council Centre of Excellence. In 2018, we established new research projects across each of our five nodes, engaged existing and new stakeholders in industry and policy, and began to deliver on our equity and diversity, communication and outreach, and mentoring objectives.



Far left
Classical cryogenic electronics for supporting the operation of qubits at cryogenic temperatures
Photo by Steven Waddy

Immediate left
A dumbbell-shaped sapphire crystal, suspended by a thin niobium wire
Photo by Jeremy Bourhill

Director's update

The first year of EQUS has seen a successful start across the Centre. Our new research programs are focussed on engineering multi-component quantum systems to build quantum machines for practical applications. Quantum machines are engineered devices that use quantum phenomena — such as superposition or entanglement — to produce effects and capabilities that are not achievable with classical techniques. With advances in both hardware and software, and progress across a range of key milestones, EQUS leads Australia's efforts in these disruptive technologies. On pages 18 to 23 we discuss some of the research highlights from 2018.

I'd like to thank Professor Andrew Doherty for all his hard work over the last three years as Deputy-Director, and with only a twinge of envy wish him good fortune during his two-year leave-of-absence working for quantum industry in Silicon Valley. We look forward to hearing all about it when you return next year! I also wish to thank Professor Tom Stace for taking over as Deputy; it's a vital role and we'd be lost without you there.

This year saw a slew of student-initiated initiatives, including a workshop on Axion Physics in Sydney organised by students from our University of Western Australia node, a cross-country outreach trip from Sydney to Perth organised by our students at Macquarie University (in which they ran workshops for over 150 students in New South Wales and Victorian schools) and early in 2019 a workshop on Python programming for quantum applications organised by our students at the University of Sydney. I continue to be amazed and humbled by the energy and organisation of our students.

In 2018, we were successful in attracting new Australian government funding to develop quantum machines for defence applications, with Chief Investigators Professor Warwick Bowen and Professor Halina Rubinsztein-Dunlop — both at our University of Queensland node — each being awarded three-year grants from Defence Science and Technology via the DST Next Generation Technology scheme. In addition, our internal funding from Defence saw the successful completion of two projects, by Chief Investigators Professor Daniel Shaddock and Professor Michael Tobar, respectively at our Australian National University and University of Western Australia nodes.

Director's update

Our Chief Investigator Professor Michael Biercuk continued to grow QCtrl, the company he spun out from his EQUS research, with successful multi-million dollar seed capital rounds and a slew of media articles focussed on the company. Chief Investigator Daniel Shaddock's company, Liquid Instruments, has seen millions of dollars of sales and a $11M investment last month. And, of course, our Chief Investigator Professor David Reilly oversaw the establishment of Microsoft's research program at our University of Sydney node, including world-class silicon fabrication capabilities. All three companies have been hiring our students and are a great example of the varying paths from idea to product.

In August—with support from three other Centres of Excellence—we ran Island Physics 2018, a workshop held at Magnetic Island to bring together researchers and industry representatives. In November, EQUS supported a Parliamentary Friends of Science event in Canberra to provide a forum on quantum technologies for scientists, technologists, parliamentarians, and policymakers. The event signalled the need for a national plan for the sector, and we look forward to participating—with our colleagues from across academia, government and industry—in its development this year. I'd particularly like to thank our communications officer, Tara Roberson, for the two years of work that went into making the Parliamentary breakfast happen.

EQUS has portfolios for equity and diversity, communications and outreach, and mentoring and career development. Decisions in each portfolio are made by an enthusiastic committee consisting of students, early-career researchers, and Chief Investigators. All portfolios were very active this year. For example, our EQUIP committee (Equity in Quantum Physics), established two award programs, one for primary carers, one for researchers re-entering an academic career following extended career breaks; they also ran several successful and well-received equity and diversity events across all five EQUS nodes. Further highlights from the portfolios can be found starting on page 50.

Finally, it is with pleasure and pride that I report that our researchers were recognised by slew of awards in 2018, with Ben McAllister winning the University of Western Australia Three-Minute Thesis (3MT) competition and being selected as one of ten finalists from among 58 competitors at the 2018 Asia-Pacific 3MT in September. Dr Jacquiline Romero won the Ruby Payne-Scott Award for excellence in early-career research in physics, was selected as one of the fifteen International Rising Talents of 2019 Awardees in the L'Oréal-UNESCO International Awards for Women in Science and was one of the two 2018 Westpac Research Fellows. Professor Halina Rubinsztein-Dunlop was appointed an Officer of the Order of Australia, and she and her team won the 2018 Eureka Prize for Excellence in Interdisciplinary Scientific Research. For details, see pages 18 to 23.

We are looking forward to another busy, exciting, year!

Professor Andrew White, Director
March 2019

Left
Moisture condensing in the neck of the nitrogen cold trap of a dilution refrigerator
Photo by Steven Waddy

Centre Strategy

OUR MISSION

is to engineer the quantum future.

OUR VISION

is to conduct world-leading research to exploit the potential of quantum science and develop a range of transformational technologies that will benefit society.

AUSTRALIA'S QUANTUM FUTURE

Quantum technologies use the properties of quantum mechanics for practical applications.

Quantum technologies can be found in our everyday lives, from smart phones and cars to industrial applications in manufacturing, engineering and imaging.

Today's technology only captures a small fraction of the potential of quantum physics. New developments in research and engineering mean a new generation of technologies are being created. These technologies have potential uses in a range of fields including health, telecommunications and finance, and will impact across business and society as a whole.

The Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS) is a seven-year investment of over $40 million by the Australian government in quantum technologies. EQUS researchers are conducting world-leading research into building quantum machines, with programs to develop the Designer Quantum Materials, Quantum-enabled Diagnostics and Imaging, and Quantum Engines and Instruments at the heart of these machines.

WE WILL ACHIEVE THIS THROUGH DISCOVERY AND EDUCATION

Discovery: Foster leading-edge research and engineering of quantum physics and quantum machines for the social and economic benefit of our community.

Education: Create a quantum-literate ecosystem by training a generation of quantum engineers and scientists within a program of focussed research, as well as engagement with community.

THE VALUES THAT GUIDE OUR PERFORMANCE

Discovery: Our research transforms technology.

Innovation: Our ideas shape the quantum future.

Collaboration: Our partnerships with all parts of society translate research into application.

Communication: Our research must be shared.

Centre Strategy

WHAT IS A QUANTUM MACHINE?

Quantum machines are next-generation technologies that use the principles of quantum physics.

Possible applications include: quantum sensors that are potentially cheaper, lighter and more sensitive than classical sensors; quantum imaging systems, such as cameras that visualise gas leaks or see through smoke; and quantum communication technologies for ultra-secure communications and storage of data.

WE ARE COMMITTED TO FOUR STRATEGIC OBJECTIVES

1 Building quantum machines by engineering multi-component quantum systems

Support ground-breaking research in quantum physics with programs to develop quantum designer materials, quantum-enabled diagnostics and imaging, and quantum engines and instruments.

Grow research collaboration across different physics platforms to build integrated quantum technologies.

Strengthen and grow national and international research collaboration to ensure we leverage the breadth of our research to make significant contribution to global quantum research.

2 Developing practical quantum technologies with societal impact

Build capacity in translational research through industry partnerships, strategic recruitment, developing prototyping ability and the involvement of scientific partners in research activities.

Establish cross-disciplinary collaboration to help identify societal needs that may benefit from the new possibilities in quantum research.

Maintain a strong commitment to responsible research and innovation.

Provide workshops to encourage the development of skills in entrepreneurship, innovation, and collaboration, which will enable us to find better ways to translate discoveries into social and economic benefits.

3 Growing Australia's world-leading research community in quantum engineering

Actively pursue strategic and high-quality international collaborations, partnerships, and networks.

Attract, retain and nurture research talent by providing access to mentoring, skill building and talent development programs.

Build research capacity through strategic funding to improve national and international engagement of researchers by nurturing links with globally-leading academic and industry partners.

Uphold equity and diversity as core drivers of research.

4 Training a new generation of versatile and knowledgeable quantum engineers

Facilitate access for our researchers to world-class technologies, capabilities, and services that will support high-quality research endeavour.

Support the development and technical capabilities of our researchers through professional development workshops, fellowships, study visits, industry internships and international student exchange programs.

Build capacity and technical capabilities through graduate programs to meet the rising need for scientifically trained engineers.

Our focus on research excellence will create a thriving ecosystem where research and engineering of quantum machines is integrated across industry, the public sector and the research community

Governance

SCIENTIFIC ADVISORY COMMITTEE

The Scientific Advisory Committee advises the Centre Director on the strategic direction of current and future scientific research. It is comprised of eminent researchers from the United States of America, the United Kingdom and elsewhere. The Scientific Advisory Committee met at the EQUS Annual Workshop in December 2018.

Below Professor Sir Peter Knight

The Scientific Advisory Committee consists of:

- Professor Sir Peter Knight, FRS (Chair), The Kavli Royal Society International Centre and Imperial College London, UK
- Professor Alain Aspect, École Polytechnique and Institut d'Optique, Graduate School, France
- Professor Rainer Blatt, Institute for Quantum Optics, University of Innsbruck, Austria
- Professor John Clarke, University of California, Berkeley, USA
- Professor Birgitta Whaley, Whaley Research Group, University of California, Berkeley USA.

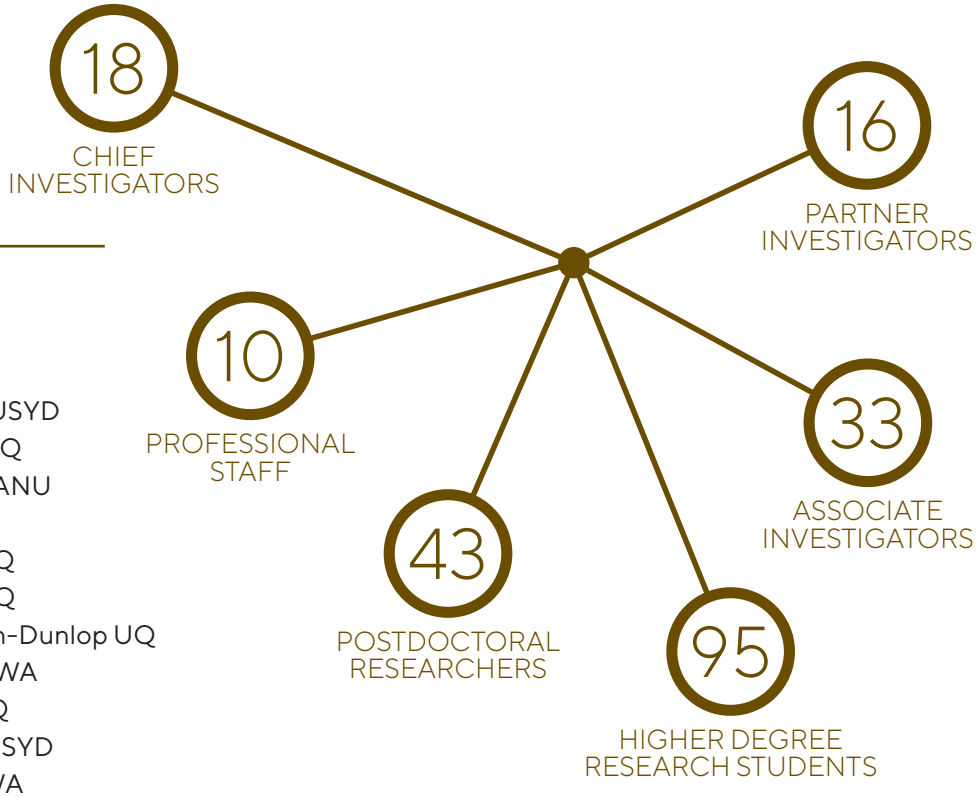
ADVISORY COMMITTEE

The Advisory Committee contributes to the development of strategies and vision for the Centre's future and supports linkages between academia, industry and government. The committee is comprised of influential people from business and government. The committee met once in 2018.

The Advisory Committee includes:

- Professor Vicki Sara FAA FTSE (Chair), respectively former-CEO of the Australian Research Council; Director of the Australian Institute of Commercialisation; Director of the Australian Centre for Plant Functional Genomics; and Chancellor of the University of Technology Sydney
- Dr Bronwyn Evans, current CEO of Standards Australia; Chair of the Growth Centre for Medical Technologies and Pharmaceuticals; Member of the Australia-Japan Foundation; and is the VP (Finance) of the International Standards Organisation, ISO
- Professor Jim Williams, former Director of the ANU Research School of Physical Sciences and Engineering; and Director of UWA, Centre for Atomic, Molecular and Surface Physics (CAMSP)
- Dr Alex Zelinsky, Chief Defence Scientist and head of Defence Science and Technology (DST); and former Group Executive for Information Sciences at the CSIRO
- Dr Ben Greene, the founder and CEO of Electro Optic Systems (EOS); and Chief Executive Officer of the Space Environment Research Centre (SERC).

Team



CHIEF INVESTIGATORS

Director Andrew White UQ
Deputy Director Tom Stace UQ
Chief Investigator Andrew Doherty USYD
Chief Investigator Arkady Fedorov UQ
Chief Investigator Daniel Shaddock ANU
Chief Investigator David Reilly USYD
Chief Investigator Gavin Brennen MQ
Chief Investigator Gerard Milburn UQ
Chief Investigator Halina Rubinsztein-Dunlop UQ
Chief Investigator John McFerran UWA
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Chief Investigator Michael Biercuk USYD
Chief Investigator Michael Tobar UWA
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Chief Investigator Jason Twamley MQ

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Murray Kane UQ
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Joyce Wang UQ
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Maxim Goryachev UWA
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Robin Harper USYD
Glen Harris UQ
Cornelius Hempel USYD
John Hornibrook USYD
Markus Jerger UQ
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Benjamin Kaebe UWA
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Kamil Korzekwa USYD
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Nathan McMahon MQ
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Tyler Neely UQ
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Lyle Roberts ANU
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Arghavan Safavi UQ
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Sally Shrapnel UQ
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Till Weinhold UQ
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Benjamin Dix-Matthews UWA
Claire Edmunds USYD
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Virginia Frey USYD
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Jemy Geordy MQ
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Parth Girdhar USYD
Kwan Goddard-Lee UQ
Alejandro Gomez Frieiro UQ
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Hamish Greenall UQ
Josh Guanzon UQ
Thomas Guff MQ
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Rob Harris UQ
Xin He UQ
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Bradley Mommers UQ
Leonardo Morais UQ
Sebastian Murk MQ
Hakop Pashayan USYD
Sebastian Pauka USYD
Jason Pillay UQ
Varun Prakash UQ
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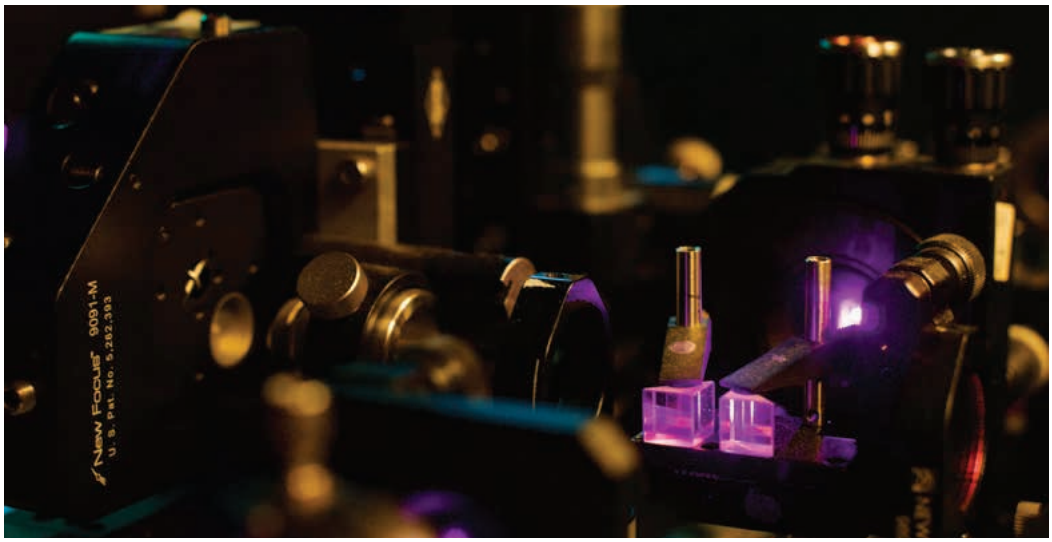
Team



Left
Tiny prism-like mirrors emit fluorescent purple light just for fun. They also reflect single photons.
Photo by Christina Giarmatzi

Kemian Qin UQ
Sarath Raman Nair MQ
Reece Roberts MQ
Sam Roberts USYD
Alistair Robertson Milne USYD
Erick Romero Sanchez UQ
Andres Rosario Hamann UQ
Yauhen Sachkou UQ
Yasmine Sfendla UQ
Paul Sibley ANU
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Natasha Taylor UQ
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David Tuckett USYD
Matthew van Breugel MQ
Harshit Verma UQ
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Prahlad Warszawski USYD
Paul Webster USYD
James White MQ
Andrew Wood MQ
Carolyn Wood UQ
Nick Wyatt UQ

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Graeme Flower UWA
Scott Hardie UWA
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Brett Leask UWA
Campbell McLauchlan USYD
Timothy Newman USYD
Alan Robertson USYD
Nabomita Roy-Mukty MQ
Mushfiq Shah UWA
Raymon Watson UWA

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Nicholas Bosch USYD
Eric Huang USYD
Ashwin Singh USYD
Jordan Smith ANU
Calida Tang USYD
Catriona Thomson UWA
Matthew Winnel USYD

Team

NEW STUDENTS' THESIS TITLES

PHD

James Spollard
Optical phased array as an enabler for free space QKD

Leonardo Assis Morais
Generation of single photons at room temperature

Yasmine Sfendla
Quantum optomechanics with macroscopic systems

Larnii Booth
Optical biosensing, plasmonics, and biophysics

Chao Meng
Optical measurement and control of electron lattices on superfluid films

Ming Su
Experimental exploration of quantum causality

MASTERS

Graeme Flower
Axion dark matter direct detection experiments

Scott Hardie
Bulk acoustic wave quartz resonators and gravitational wave astronomy

HONOURS

Jordan Smith
Ground-to-satellite quantum key distribution (QKD)

Kwan Goddard-Lee
Dynamics of vortices in a Bose-Einstein condensate

Joshua Guanzon
Non-equilibrium thermodynamics with quantum gases

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Heriot-Watt University

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Pascale Senellart-Mardon
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Lorenza Viola
Dartmouth College

Andreas Wallraff
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Michael Wouters
National Measurement Institute

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Robert Casson
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Alexei Gilchrist
MQ

Nicholas King
USYD

Joan Leach
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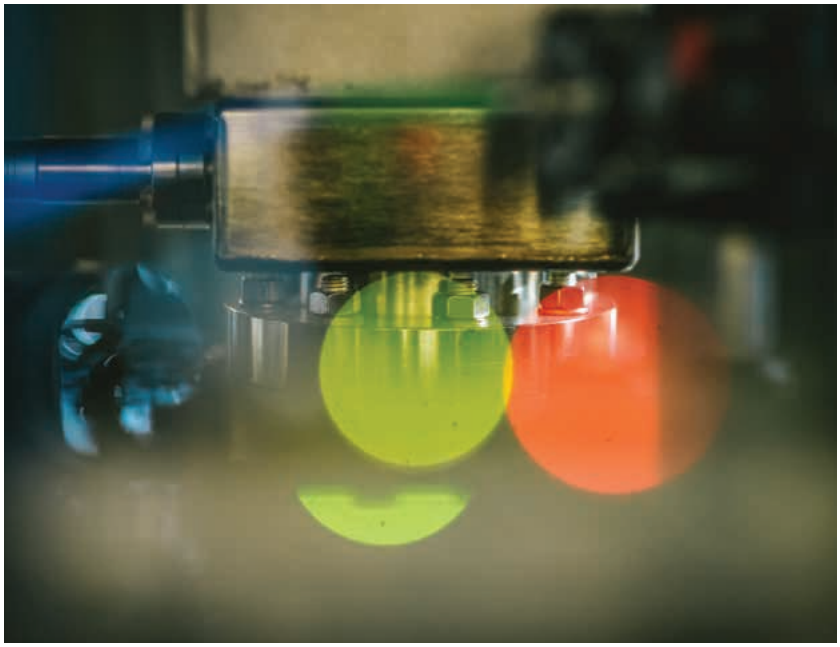
Lawrence Lee
University of NSW

Ian Manchester
USYD



Above
A #quantumsnap
by Patrick Self

Jacqui Romero
UQ

Salah Sukkarieh
USYD

Marco Tomamichel
University of Technology Sydney

Jacinda Ginges
UQ

Clemens Mueller
ETH and IBM, Zurich

Samantha Hood
Imperial College, London

Sascha Schediwy
UWA

Ivan Kassal
USYD

Matt Woolley
University of NSW

Nathan Langford
University of Technology Sydney

Jingbo Wang
UWA

Life after EQUS

COMPLETIONS

HONOURS

Nicholas Bosch
Cooper Doyle
Eric Huang
Ashwin Singh
Jordan Smith
Calida Tang
Catriona Thomson
Matthew Winnel

POSTGRADUATE STUDIES

Harrison Ball
Fionnan Reynolds
Babatunde Ayeni
Behnam Tonekaboni
Geoffrey Gillett
Nicolas Mauranyapin
Muhammad Waleed
Akhter Hosain
David Waddington

EQUS ALUMNUS RECEIVES AWARD FOR EXCELLENCE IN MEASUREMENT RESEARCH

Congratulations to EQUS alumnus and Associate Investigator Michael Vanner who was awarded one of two young researcher prizes for excellence in measurement research by the Australian Government's National Measurement Institute (NMI).

Dr Michael R Vanner, a former EQUS postdoctoral research fellow, was awarded Australia's National Measurement Institute Prize for his outstanding contributions to precision measurement in the emerging new field of cavity quantum optomechanics.

After working at EQUS, Dr Vanner moved to the UK and is now principal investigator of the Quantum Measurement Lab at Imperial College London. He remains a close collaborator with EQUS.

Assistant Minister for Science, Senator the Hon. Zed Seselja, said that this work demonstrated the ongoing relevance of measurement science.

"There is almost no aspect of modern life that does not depend on, or at least benefit from, consistent, reliable measurement," Senator Seselja said.

"Today, the NMI has recognised leaders in measurement who have made valuable contributions to our wellbeing, to industry and to fundamental research."

Life after EQUS

PROFILES

Dr Samantha Hood

Imperial College, London UK
After completing her PhD, Dr Samantha Hood moved to London to work as a postdoctoral research fellow at Imperial College.

Dr Markus Rambach

Heriot-Watt University, Edinburgh, UK
After completing his PhD, Dr Markus Rambach moved to Edinburgh to work as a research associate at Heriot-Watt University.

Dr Geoffrey Gillett

Quantum Valley Ideas Laboratories, Waterloo, Canada
After completing his PhD, Dr Geoff Gillett moved to Canada to work in industry as a senior scientist for Quantum Valley Ideas Laboratories.

Dr Juan Loredo

CNRS France
After completing his PhD, Dr Juan Loredo moved to France to work as a postdoctoral research fellow at CNRS.

Dr Ewa Rej

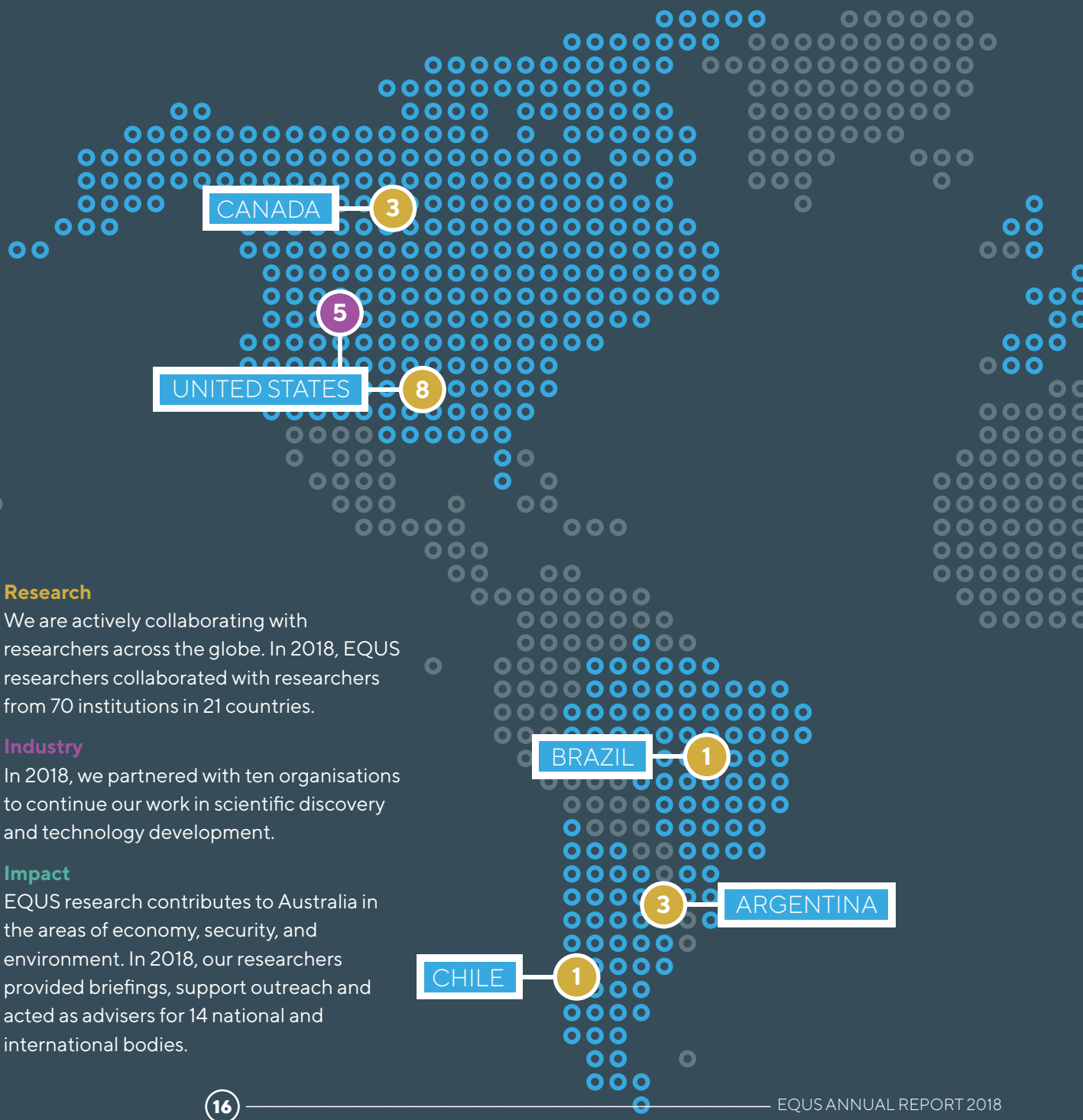
Caltech (California Institute of Technology), USA
After completing her PhD, Dr Ewa Rej moved to the United States of America to work as a postdoctoral scholar at Caltech.

Dr Nora Tischler

Griffith University Australia
After completing her PhD, Dr Nora Tischler moved from Sydney to Brisbane to work as a postdoctoral research fellow at Griffith University.

Collaborators

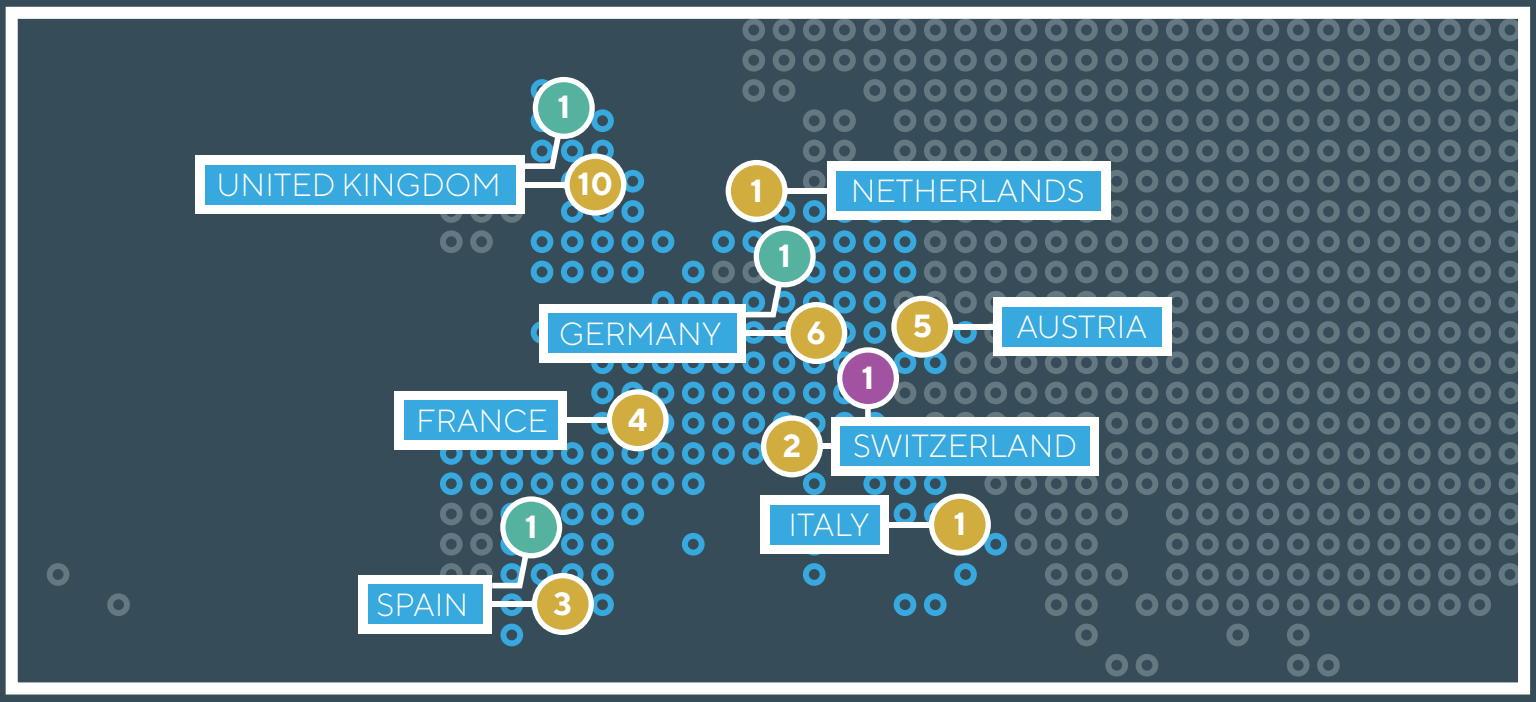
EQUS is continuously developing national and international connections to foster a world-leading research community and drive the development of quantum machines through collaborations with industry and society at large



Research
We are actively collaborating with researchers across the globe. In 2018, EQUS researchers collaborated with researchers from 70 institutions in 21 countries.

Industry
In 2018, we partnered with ten organisations to continue our work in scientific discovery and technology development.

Impact
EQUS research contributes to Australia in the areas of economy, security, and environment. In 2018, our researchers provided briefings, support outreach and acted as advisers for 14 national and international bodies.


UNITED KINGDOM
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NETHERLANDS
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GERMANY
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AUSTRIA
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FRANCE
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SWITZERLAND
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ITALY
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SPAIN
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RUSSIA
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SOUTH KOREA
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JAPAN
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CHINA
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TAIWAN
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AUSTRALIA
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NEW ZEALAND
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2018 highlights

AUSTRALIA'S QUANTUM FUTURE

Australia is brimming with potential according to leading experts in quantum science and technology, and the time to capitalise on this potential is now.

Scientists, technologists, Parliamentarians, policy makers and senior members of the STEM sector met in Canberra for the Parliamentary Friends of Science in November with a focus on quantum technologies.

Co-chaired by Minister for Industry, Science and Technology, the Hon. Karen Andrews MP, and the Shadow Minister for Defence, the Hon. Richard Marles MP, the event brought together leading experts from across the nation and was supported by the ARC Centre of Excellence for Engineered Quantum Systems (EQUS).

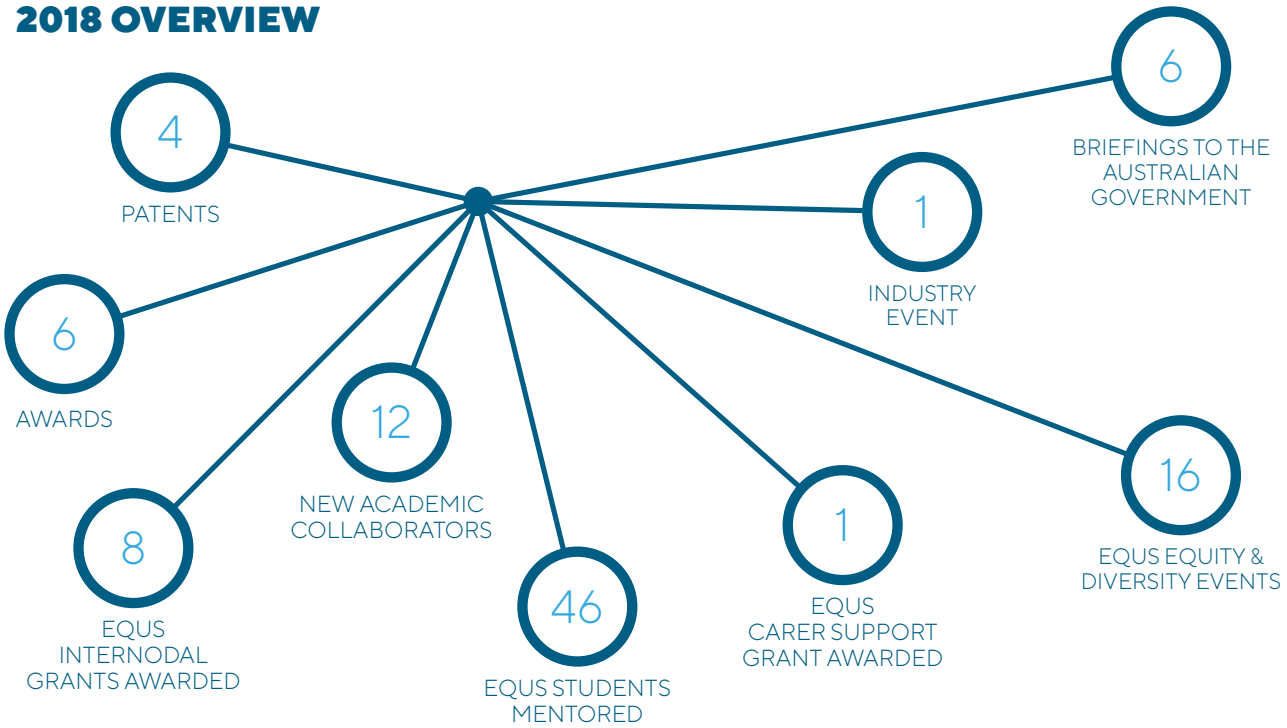
2018 Australian of the Year, Professor Michelle Simmons, highlighted the value of the Centres of Excellence program in Australia and providing an overview of how quantum physics would transform the way technology is developed.

EQUS Director, Professor Andrew White, signalled the need for a national plan for the sector, to help unify efforts across the discipline.

"Australia catalysed this latest revolution in quantum technology and we are well positioned to ride the global wave of momentum," Professor White said.

"We began this revolution, and now it's time to benefit from it."

2018 OVERVIEW



2018 highlights

QUANTUM TECHNOLOGY-THEMED PARLIAMENTARY FRIENDS OF SCIENCE

On November 28, EQUS supported a quantum technology-themed Parliamentary Friends of Science event at Parliament House, Canberra.

The event introduced parliamentarians, policymakers, and other stakeholders to recent advances and applications in quantum technology and highlighted Australian efforts in the field.

Eighteen EQUS representatives attended. They were Chief Investigators, Early Career Researchers and PhD candidates from each of the Centre's nodes.

The parliamentarians and policymakers who attended the event included:

- Hon. Karen Andrews MP, Minister for Industry, Science and Technology
- Hon. Richard Marles MP, Shadow Minister for Defence
- Nick Champion, Shadow Assistant Minister for Manufacturing and Science
- Dr Mike Freelander MP
- Dr David Gillespie MP
- Ross Hart MP
- Peter Khalil MP
- Senator David Smith
- Tim Watts MP
- Trent Zimmerman MP
- Dr Cathy Foley, CSIRO
- Jane Urquhart, Department of Industry, Innovation, and Science
- Sarah Chapman, Education Queensland.

Also represented were advisers to Senator Kim Carr, Senator Pauline Hanson, Senator Ian Macdonald and the Hon. Michael Keenan MP.

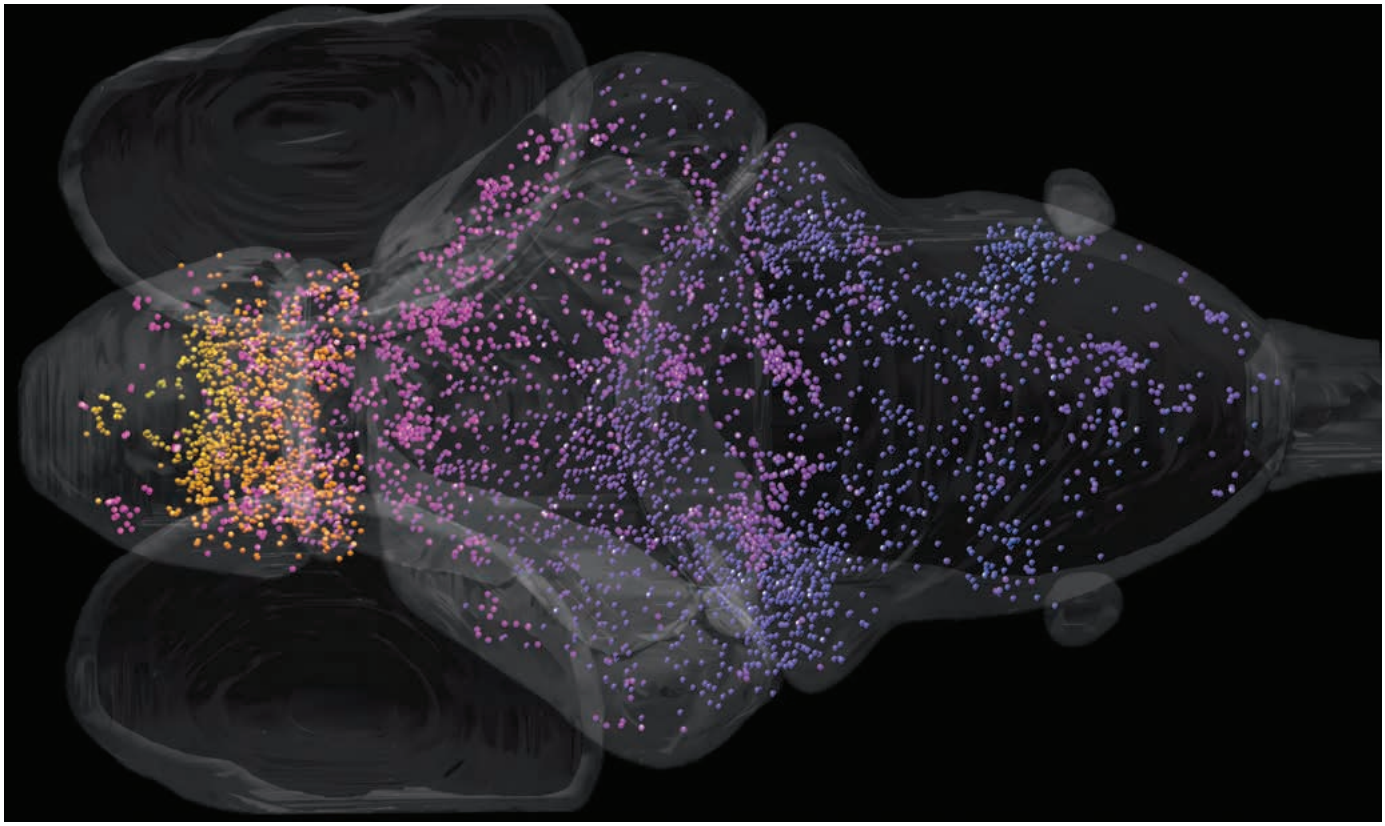
Above
Left to right: Michael Kewming, Gavin Brennen, Thomas Volz, Ben McAllister, Jingbo Wang, Arkady Fedorov, Halina Rubinsztein-Dunlop, Tara Roberson, Claire Edmunds, Riddhi Gupta, Andrew White, Lisa Walker, Sally Shrapnel, Matt Davis, David Gozzard, Sarah Lau, Tom Stace. Not pictured: Daniel Shaddock.

Left
Left to right: Science & Technology Australia CEO Kylie Walker, Hon. Richard Marles, Hon. Karen Andrews, Australian of the Year Professor Michelle Simmons and EQUS director Andrew White

2018 highlights

OPTICAL PHYSICS AND NEUROSCIENCE RESEARCH WINS EUREKA PRIZE FOR INTERDISCIPLINARY RESEARCH

Working between optical physics and neuroscience has brought positive results for a team of researchers, including EQUS Chief Investigator Halina Rubinsztein-Dunlop.



Above
Using optical physics techniques, researchers were able to study a 'moving' brain that was totally stationary

Working with zebrafish, they used a new technique based on the physics of optical trapping to study the cells and circuits in the brain that are responsible for motion processing for the first time.

Chief Investigator Rubinsztein-Dunlop said, "In our interdisciplinary project, using the physics technique of optical trapping, we've used a laser to move the ear stones in zebrafish model, producing a sensation of movement and eliciting behavioural adjustments, all without moving the animal.

"By tricking an animal into thinking it's moving while the brain remains stationary, we can now use advanced microscopy to study the cells and circuits across the brain responsible for motion processing for the first time."

The researchers were awarded the UNSW Eureka Prize for Interdisciplinary Research at the "Oscars of Australian science."

Without the use of laser micromanipulation it would have been impossible to "trick" the fish into thinking it was moving.

2018 highlights

EQUS CHIEF INVESTIGATOR AWARDED ORDER OF AUSTRALIA

Congratulations to EQUS Chief Investigator Professor Halina Rubinsztein-Dunlop who has been made an Officer in the General Division (AO) of the Order of Australia for distinguished service to: laser physics and nano-optics as a researcher, mentor and academic, the promotion of educational programs, and women in science.

Chief Investigator Rubinsztein-Dunlop is recognised internationally for her achievements over the past four decades in physics, specifically in laser micro manipulation and atom optics.

At the University of Queensland, her team produced one of the first Bose-Einstein condensates, the coldest states of matter in the known universe, in the Southern Hemisphere. Her research team has also designed and built "atomic circuits" using cold atoms. These are the atomic analogue of modern electronic devices and will be important in future quantum machines.

In 2002, Chief Investigator Rubinsztein-Dunlop became the first female Professor of Physics in Australia.

Below
Professor Halina Rubinsztein-Dunlop

EQUS POSTDOC AWARDED YOUNG SCIENTIST PRIZE IN ITALY

Congratulations to EQUS researcher Dr Maxim Goryachev on being awarded the European Frequency and Time Forum (EFTF) Young Scientist Award 2018 at the 32nd European Frequency and Time Forum in Turin, Italy.

The EFTF Young Scientist Award is conferred in recognition of a personal contribution that demonstrated a high degree of initiative and creativity and led to already established or easily foreseeable outstanding advances in the field of time and frequency metrology.

Maxim was chosen as an award recipient for his work on the development of cryogenic Bulk Acoustic Wave (BAW) technology, and application to precision oscillators, fundamental physics tests and quantum measurements.

Maxim's pioneering work in measuring quartz BAW oscillators at cryogenic temperatures first began with his PhD work at the Institute FEMTO-ST, École Nationale Supérieure de Mécanique et des Microtechniques (ENSMM), in Besançon, France.

Since joining EQUS, Maxim has gone on to adapt the technology for precision quantum and frequency measurement, the results of which are seen as a major achievement of the Centre.

2018 highlights

CENTRE PRIZES

EQUS launched new Centre Prizes in 2018. These prizes are presented each year at the Annual Workshop in recognition of excellence in: research, communication and outreach; engagement and impact; and exceptional contributions made to the Centre.

Director's prize for exceptional contributions to the Centre

This prize recognises an EQUS researcher or team that has contributed to the Centre on a whole. This might be through Centre-wide activities, such as communication initiatives or mentoring, or by enriching the research culture of the Centre. In 2018, this prize was awarded to EQUS PhD candidate **Matthew van Breugel** from Macquarie University.

Centre prize for impact and engagement

This prize recognises the work that a researcher has engaged in to promote and/or foster the impact of their research outputs. In 2018, this prize was awarded to EQUS PhD candidate **Michael Kweming** from the University of Queensland.

Centre prize for communication and outreach

This prize recognises an EQUS researcher or team for their involvement in significant communication and/or outreach initiatives in the broader community. In 2018, this prize was awarded to EQUS PhD candidate **Ben McAllister** from the University of Western Australia.

Below
Participants in the 2018 EQUS Workshop
Photo by Lachlan Rogers

2018 highlights

Centre prize for best paper by a student

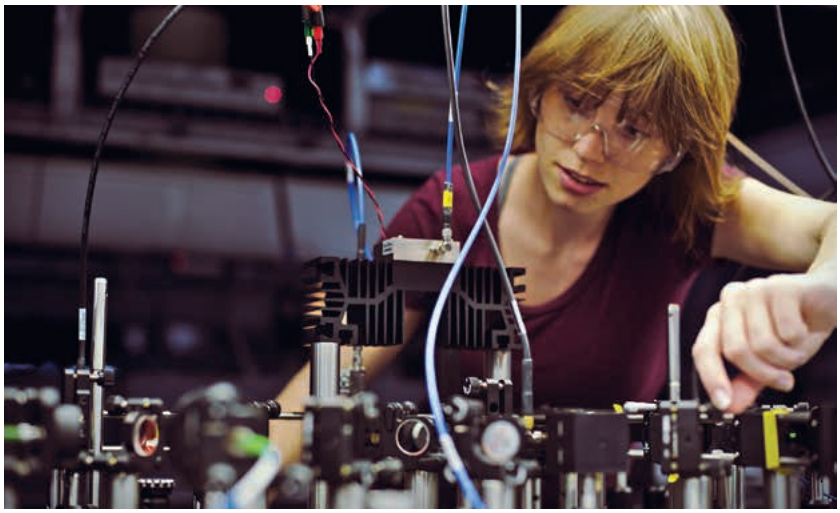
This prize is awarded to the student who is judged to have produced the most outstanding research publication. In 2018, this prize was awarded to PhD candidate **David Tuckett** from the University of Sydney.

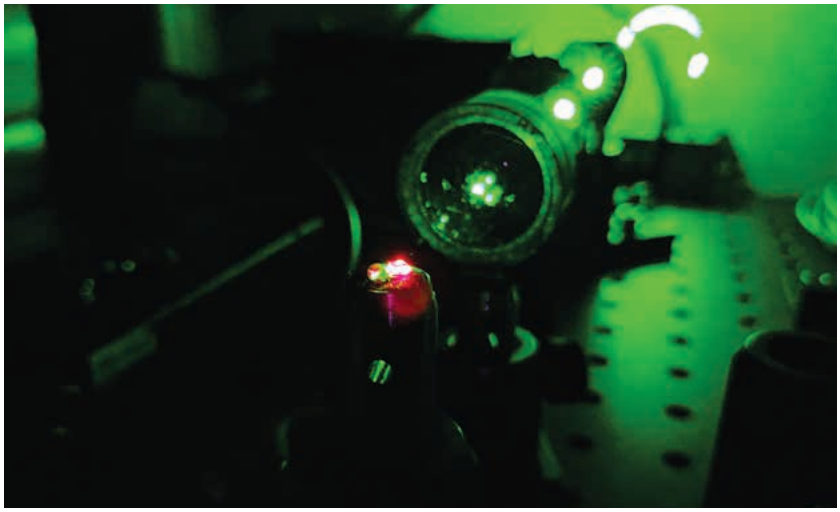
Centre prize for best posters

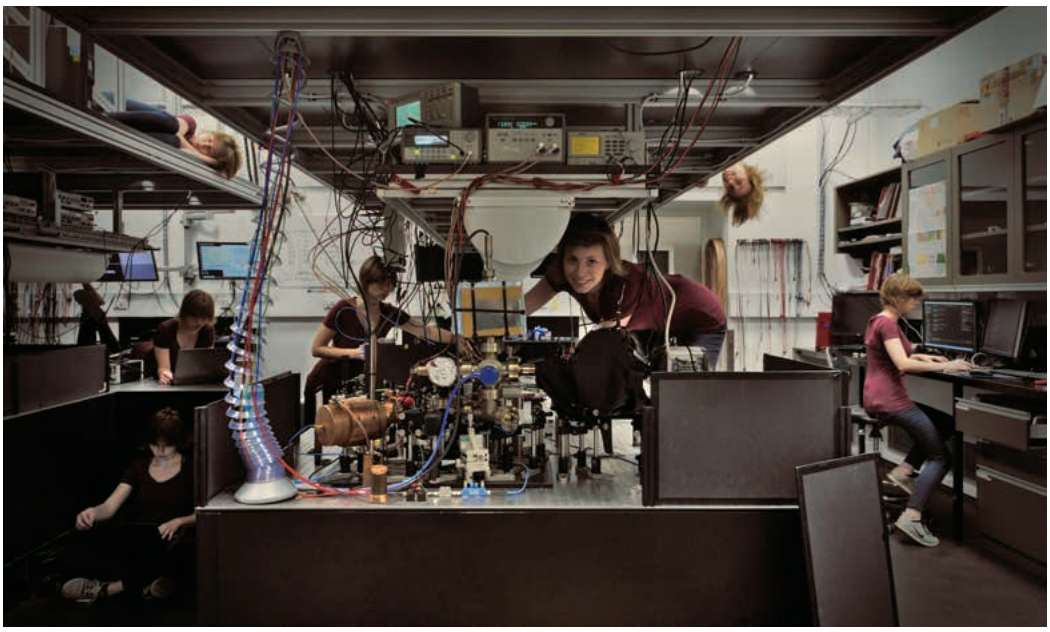
This prize is awarded to the student who is judged to have produced the best research poster at the EQUS Annual Workshop. In 2018, this prize was awarded to PhD candidate **Christiaan Becker** from the University of Queensland.

Quantum Snaps

This biennial photo competition looks for images that represent our researchers and their work. In 2018, the winning photo (used for the cover of this report) was submitted by PhD candidate **Matthew van Breugel**. The runner-up photo was submitted by PhD candidate **Virginia Frey**.







Top
Therapeutic fibre coupling
Photo by Virginia Frey

Above
A diamond fluoresces red from defects within the lattice
Photo by Matt van Breugel

Left
A day in the lab
Photo by Virginia Frey

Research overview

EQUS is building sophisticated quantum machines to harness the quantum world for practical applications. Our research is evenly split between theoretical advances and experimental developments, in seven different physical architectures: neutral atoms, superconducting electronics, trapped ions, optomechanics, photonics, polaritonics and quantum dots.

Our research is conducted in three programs:

1. the **Designer quantum materials** program, to create new phases of quantum matter from which quantum machines can be built;

2. the **Quantum-enabled diagnostics and imaging** program, to develop prototypes of the sensing and imaging components required for a quantum machine to interact with their environment; and

3. the **Quantum engines and instruments** program, to develop understanding of quantum engines and instruments so that we can design and manipulate quantum machines that have tens or hundreds of individual components.

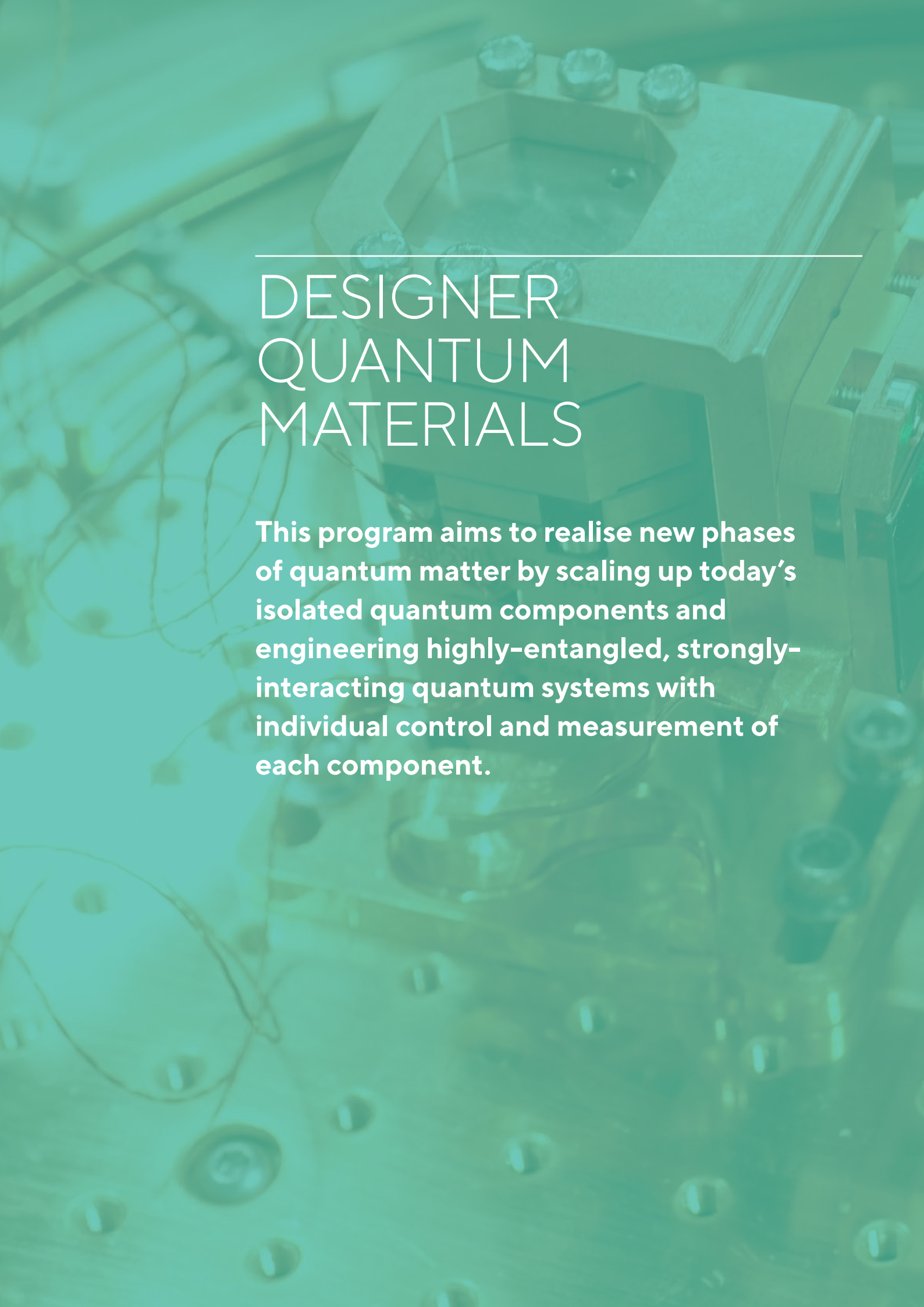
Research programs

EQUS research is organised around carefully crafted research themes and individual projects

Research Program 1
DESIGNER QUANTUM MATERIALS

Research Program 2
QUANTUM-ENABLED DIAGNOSTICS AND IMAGING

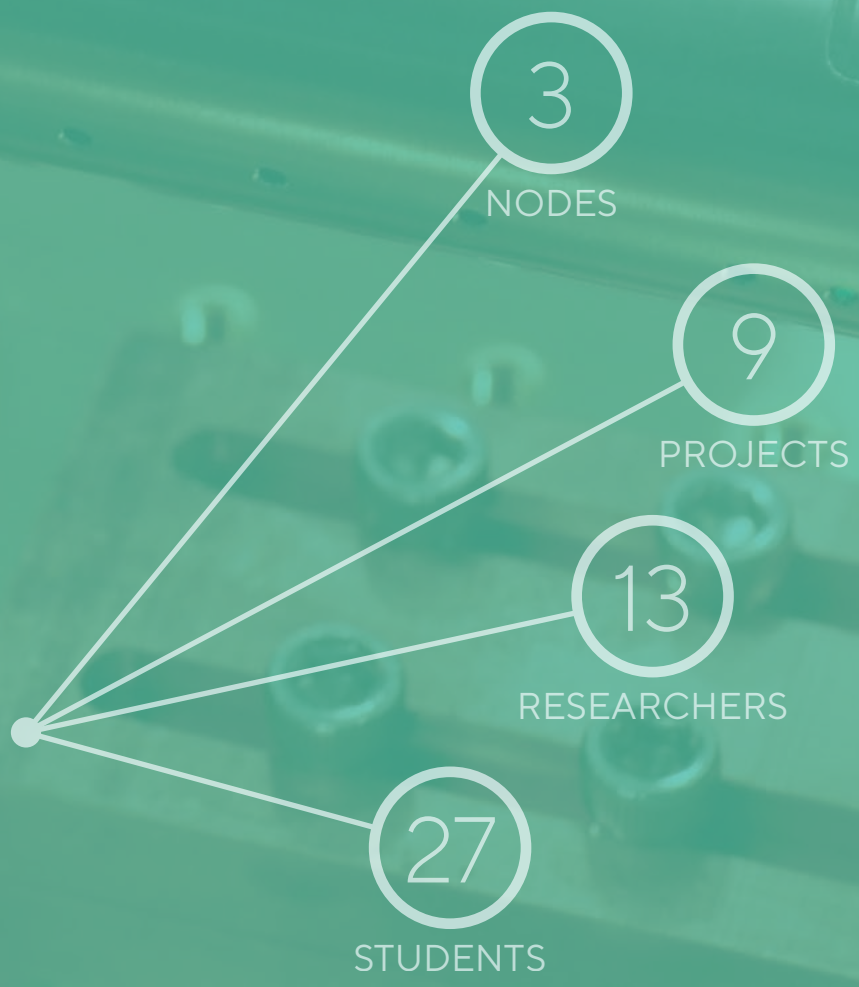
Research Program 3
QUANTUM ENGINES AND INSTRUMENTS



DESIGNER QUANTUM MATERIALS

This program aims to realise new phases of quantum matter by scaling up today's isolated quantum components and engineering highly-entangled, strongly-interacting quantum systems with individual control and measurement of each component.

Research Program 1



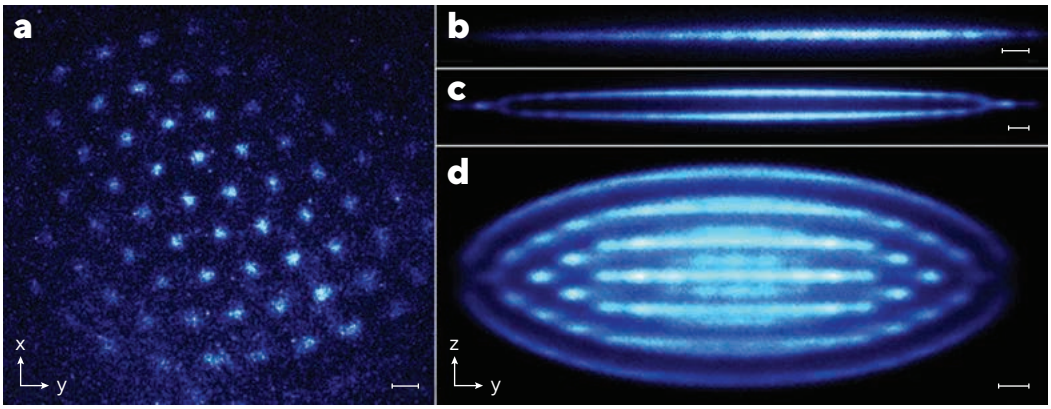
TRAPPED IONS

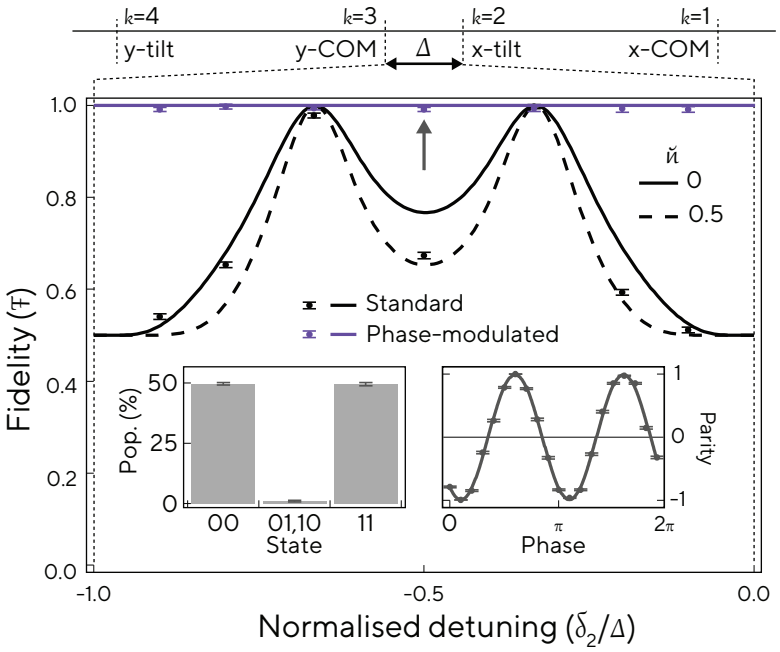
Chief Investigator Biercuk's lab saw two major experimental systems brought fully online for this program — a Penning trap used for quantum simulation experiments with large two-dimensional ion crystals, and an Innsbruck-style "Blade" Paul trap for experiments with linear ion crystals. Both systems are focussed on hardware development and the development of control techniques.

In a major research result for 2018, our research in the Paul trap experimentally demonstrated a new class of error-robust phase-modulated entangling gates using trapped ions in the presence of multi-mode spectra[1]. The robustness of these gates was experimentally verified against both static and time-varying noise in the drive frequencies and the effect of a tailored operator-construction was demonstrated to systematically reduce sensitivity to noise. Data showed good agreement with a new theoretical model developed in the filter function framework to capture the influence of time-dependent noise. These results constitute a major first step towards entangling operation to achieve totally new regimes of interacting spin systems.

Right
Ions in the newly commissioned ion trap at USyd

Below
Fidelity versus engineered errors, for different control protocols





1 AR Milne, CL Edmunds, C Hempel, V Frey, S Mavadia and MJ Biercuk *arXiv 1808.10462* (2018)

Research highlights

SPINS IN SEMICONDUCTORS

The Quantum Nanoscience Lab of Chief Investigator Reilly at the University of Sydney, together with industry partner Microsoft, have made significant progress towards the milestone of controlling arrays of coupled semiconductor quantum dots. Advances in 2018 in this area include:

1. taping-out a suite of ASIC chips based on cryo-CMOS circuits, for scaling-up quantum control;
2. implantation of many-channel readout methods, based on LTE, WiFi orthogonal frequency domain multiplexing approaches; and
3. the design, fabrication and cryogenic test of a prototype device comprising several hundred electrostatic gates, for the parallel control and readout of ~50 quantum dots.

QUANTUM CONTROL

The University of Sydney theory group of Chief Investigators Bartlett, Doherty and Flammia continued collaborative work with experimental spin qubit teams at Copenhagen (Marcus, Kuemmeth) and Harvard (Yacoby) to develop quantum control for high-fidelity qubit coupling in semiconductor quantum devices, and have experimentally demonstrated how a mediating large-dot coupler can give ultra-fast long-range coupling of spin qubits, as is needed for the design of topologically ordered quantum materials[1].

QUANTUM PHOTONICS AND POLARITONICS

In the lab of Chief Investigator Volz at Macquarie, the quantum polaritonics team carried out further theoretical and experimental work on the effect of polariton blockade in GaAs-based fibre-cavity polariton system. Intrinsic material properties of the system are now well understood. Together with Associate Investigator Maxime Richard and Partner Investigator Alexia Auffeves, both from Institut Néel in Grenoble, photon correlation data from off-resonant excitation was analysed theoretically.

Centre Director White and international collaborators carried out theoretical and experimental studies on multipartite quantum correlations, which are a powerful resource that underpins applications from quantum metrology to quantum computing. They observed genuine multi-time correlations in a sequence of three generalised measurements on a single photon: the correlations cannot be reproduced by any spatial quantum state of equal dimension. Their work lays the foundation for the exploration of temporal correlations arising in quantum networks for quantum information applications.

1 FK Malinowski *et al.*, *Physical Review X 8, 011045* (2018)

Research highlights

THEORETICAL ADVANCES

Theoretical teams in EQUS have made several breakthroughs in the underlying quantum physics of Designer Quantum Materials.

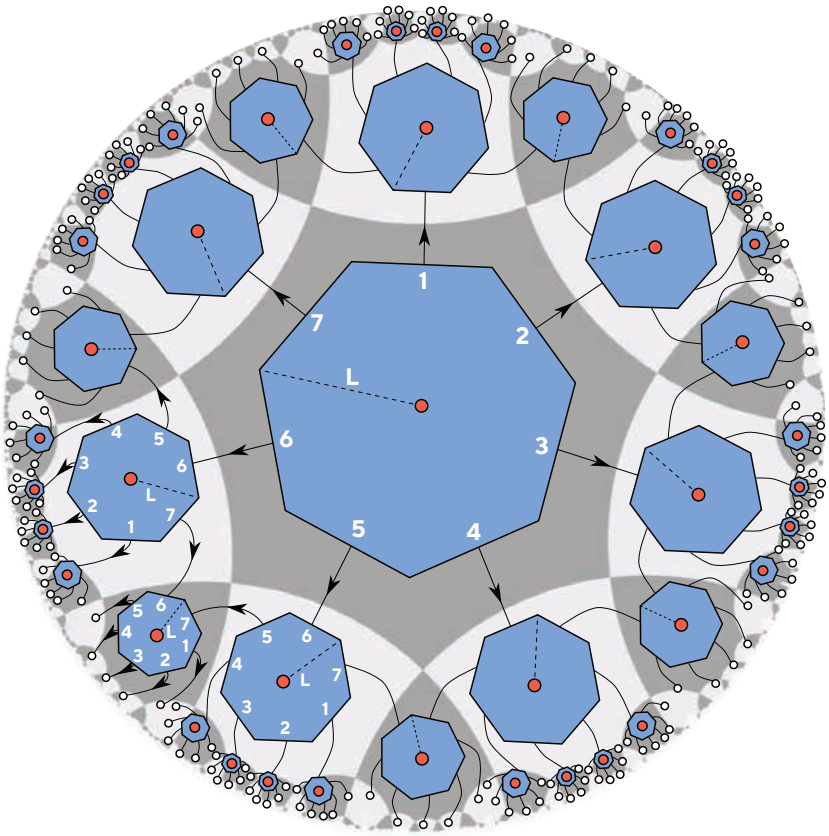
Chief Investigators Stace and Brennen developed a new class of engineered Holographic Codes. This research was inspired by cosmological models of quantum gravity. The codes are generated by a hyperbolic tiling of negatively curved space. Their research opens up a wide class of similar codes. They have demonstrated an erasure threshold of around 1/3 and a Pauli threshold around 5%. This work has recently attracted research funding from the US Air Force for three years.

Chief Investigators Bartlett and Flammia have continued to investigate the use of topologically-ordered designer quantum materials to function for robust quantum memories and information processors. With PhD student David Tuckett, they demonstrated a strikingly high threshold for the well-studied surface code against common experimental noise[1].

PhD student Sam Roberts and Chief Investigator Bartlett have shown how symmetry consideration can lead to a self-correcting quantum memory in a variety of 3D topological models; a paper is under consideration at PRX[2].

PhD student Chris Chubb and Chief Investigator Flammia have had a major success in studying the effects of correlated noise on the threshold for topological codes[3].

Below
A tessellation of 7-qubit seed tensors to construct a holographic code, mapping logical qubits (red) to physical qubits (white)



1 DK Tuckett, SD Bartlett and ST Flammia *Physical Review Letters 120, 050505* (2018)

2 S Roberts and SD Bartlett *arXiv 1805.01474* (2018)

3 CT Chubb and ST Flammia *arXiv 1809.10704* (2018)

PLANS FOR 2019

Experiment

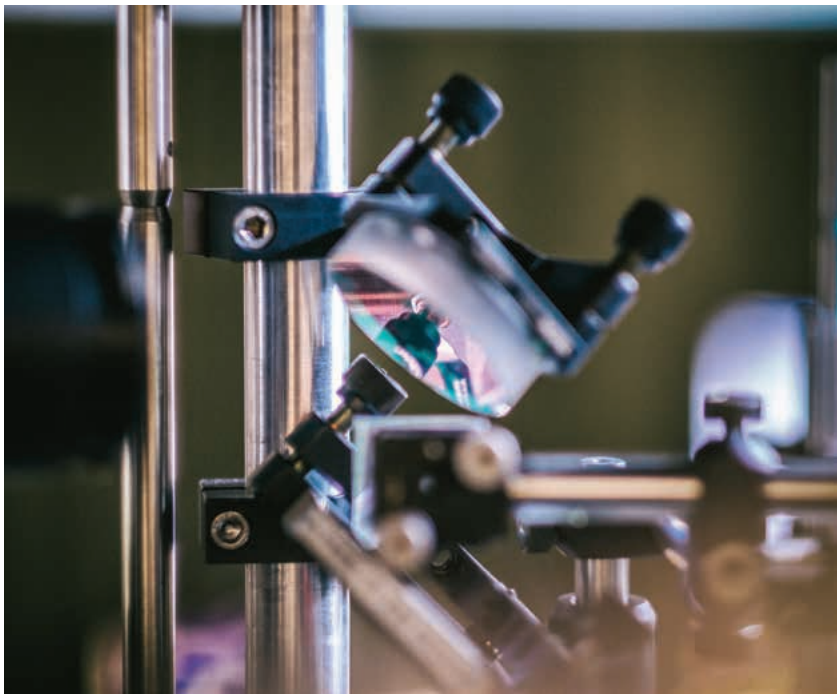
Chief Investigator Biercuk will add single-ion addressing to the linear trap for single-qubit unitaries gates, and explore how phase-modulation can be used to control the underlying spin-spin Hamiltonian. Chief Investigator Fedorov will measure relaxation and dephasing of cavity coupled transmon systems. Chief Investigator Reilly and the Microsoft team will address scaling up quantum systems for control and readout 1000s of quantum dots. Chief Investigator Tobar will improve the free space stabilisation technique; set new limits on Lorentz-Invariance violating coefficients; develop quantum technology for the Oscillating Resonant Group Axion (ORGAN) axion Haloscope. Chief Investigator Volz will install new superconducting detectors in off-resonant photon systems, and initiate novel CdTe cavity designs. Centre Director White will continue to work on programmable event-ready entanglement from quantum-dot photon sources.

Theory

Chief Investigators Bartlett and Flammia will develop new tailored codes to mitigate correlated noise in experimentally relevant systems and explore how topological symmetries emerge naturally, rather than being enforced. Chief Investigators Brennen and Stace will continue research in holographic codes.

Chief Investigator Brennen will complete research on symmetry fractionalisation in tensor networks to identify gapless symmetry protected topological phases and the role of emergent gauge symmetry.

Below
In the Bose Einstein Condensate Lab



A NEW QUANTUM DEVICE DEFIES THE CONCEPTS OF 'BEFORE' AND 'AFTER'

Science News, Emily Conover, August 23[1]

One thing leads to another. It sounds obvious, but in the quantum realm, the saying doesn't always ring true. A new quantum device can jumble up a sequence of two events so that they take place in both orders simultaneously, researchers report in a paper in press in Physical Review Letters.

"In everyday life, we are used to thinking of events having a definite order," says physicist Jacqui Romero of the University of Queensland in Australia. For example, in the morning, you might brush your teeth before washing your face, or vice versa. But in the quantum realm, both can be true simultaneously.

The device, known as a quantum switch, works by putting particles of light through a series of two operations – labelled A and B – that alter the shape of the light. These photons can travel along two separate paths to A and B. Along one path, A happens before B, and on the other, B happens before A.

Right Quantum weirdness in 'chicken or egg' paradox

Which path the photon takes is determined by its polarisation, the direction in which its electromagnetic waves wiggle – up and down or side to side. Photons that have horizontal polarisation experience operation A first, and those with vertical polarisation experience B first.

But, thanks to the counter-intuitive quantum property of superposition, the photon can be both horizontally and vertically polarised at once. In that case, the light experiences both A before B and B before A, Romero and colleagues report.

The results mark "the first steps toward controlling a new regime of quantum physics," says physicist Giulio Chiribella of the University of Oxford and the University of Hong Kong, whose team came up with the quantum switch idea but who was not involved with the experiment.

The quantum switch could potentially be useful in quantum communication and quantum computing. One weird new superpower that the quantum switch provides is the ability to communicate through channels where any information that goes in is scrambled, Romero and colleagues report in a paper posted on July 19 at arXiv.org.

1 K Goswami, C Giarmatzi, M Kewming, F Costa, C Branciard, J Romero and AG White *Physical Review Letters 121, 090503* (2018)

AUSTRALIAN SCIENTISTS ARE LEADING THE WAY IN QUANTUM CHEMISTRY, TOO

Gizmodo, Rae Johnston, July 25[1]

Quantum computing is still a baby, really. We are still working out exactly what problems quantum computers will be able to solve (although we know they'll be able to do it fast, obviously).

Quantum chemistry is tipped to benefit hugely. Because right now, anything but the most simple chemical processes are beyond the capacity of the biggest and fastest supercomputers.

With quantum computing, however, our understanding of the complicated bonds and reactions of molecules using quantum mechanics will go through the roof. Scientists say they will be able to unlock lower-energy pathways for chemical reactions, allowing the design of new catalysts.

We're talking huge implications for industries like fertiliser production.

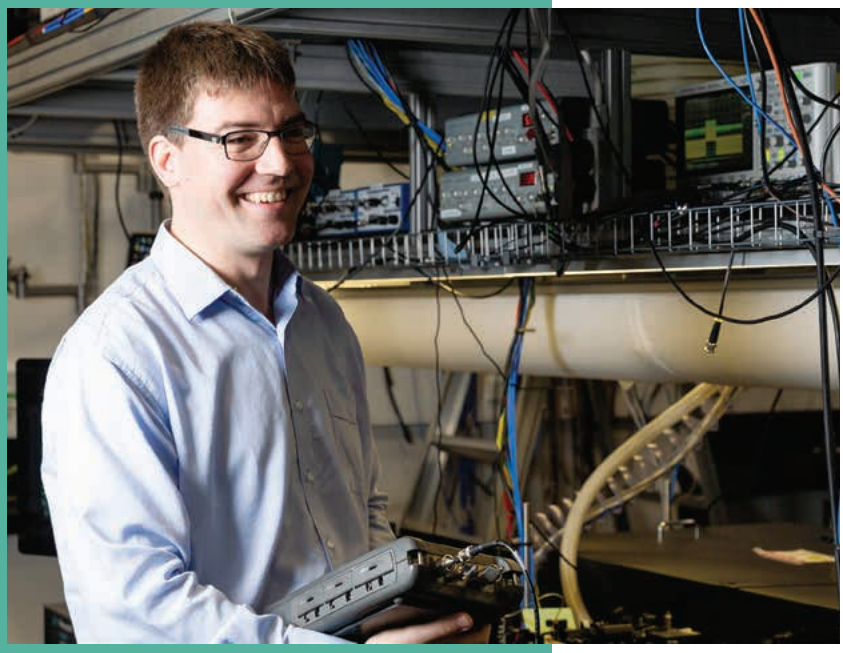
Now, an international group of researchers (led by an Australian Scientist, of course) have achieved the world's first multi-qubit demonstration of a quantum chemistry calculation performed on a system of trapped ions, one of the leading hardware platforms in the race to develop a universal quantum computer.

The research, headed up by University of Sydney physicist Dr Cornelius Hempel, explores a promising pathway for developing effective ways to model chemical bonds and reactions using quantum computers.

"Even the largest supercomputers are struggling to model accurately anything but the most basic chemistry. Quantum computers simulating nature, however, unlock a whole new way of understanding matter. They will provide us with a new tool to solve problems in materials science, medicine and industrial chemistry using simulations." Dr Hempel said.

Other possible uses include the development of organic solar cells and better batteries through improved materials and using new insights to design personalised medicines.

Below
Dr Cornelius Hempel



1 C Hempel, C Maier, J Romero, J McClean, T Monz, H Shen, P Jurcevic, BP Lanyon, P Love, R Babbush, A Aspuru-Guzik, R Blatt and CF Roos *Physical Review X, 8, 031022* (2018)

QUANTUM-ENABLED DIAGNOSTICS AND IMAGING

Sensors are ubiquitous in modern technology: from examining our bodies, through our local environments, to the galaxy and beyond. This program seeks to exploit quantum mechanics to engineer new probes, sensors and techniques that enhance capabilities across a range of applications, from diagnosis and detection in medical imaging to the accuracy of navigation.

Research Program 2

Research highlights

SENSING WITH QUANTUM DEFECTS

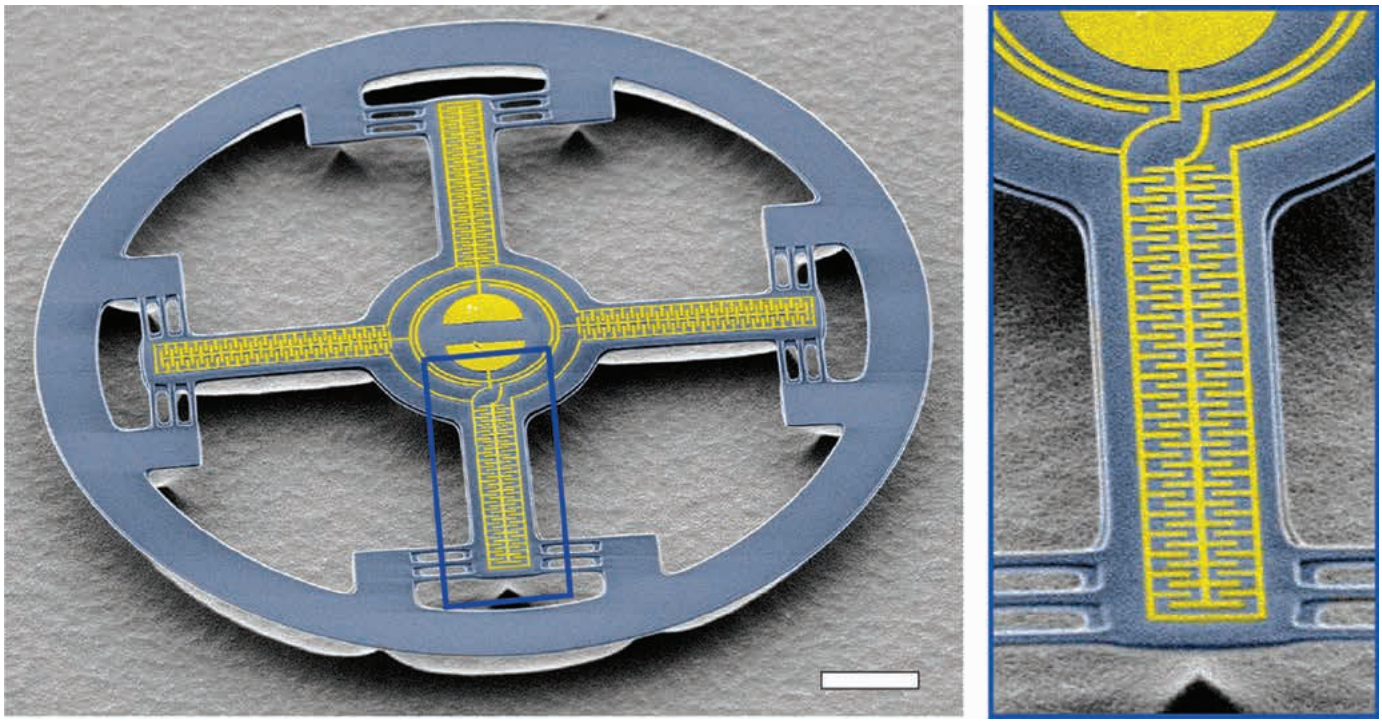
Quantum defects offer a combination of nanoscale size, allowing the environment of the sensor to be probed with unprecedented resolution, and the ability to quantum control them with light and microwaves even at room temperature. EQUS researchers have developed a new understanding of collective effects due to the interaction of multiple defects that can be used to boost interactions between defects and light (Chief Investigators Volz and Brennan), proposing new diagnostic techniques taking advantage of blinking effects (Chief Investigators Volz and Associate Investigator Gilchrist), and developing new approaches to magnetic resonance imaging based on hyperpolarisation and dynamic nuclear polarisation[1].

OPTOMECHANICAL SENSORS AND DEVICES

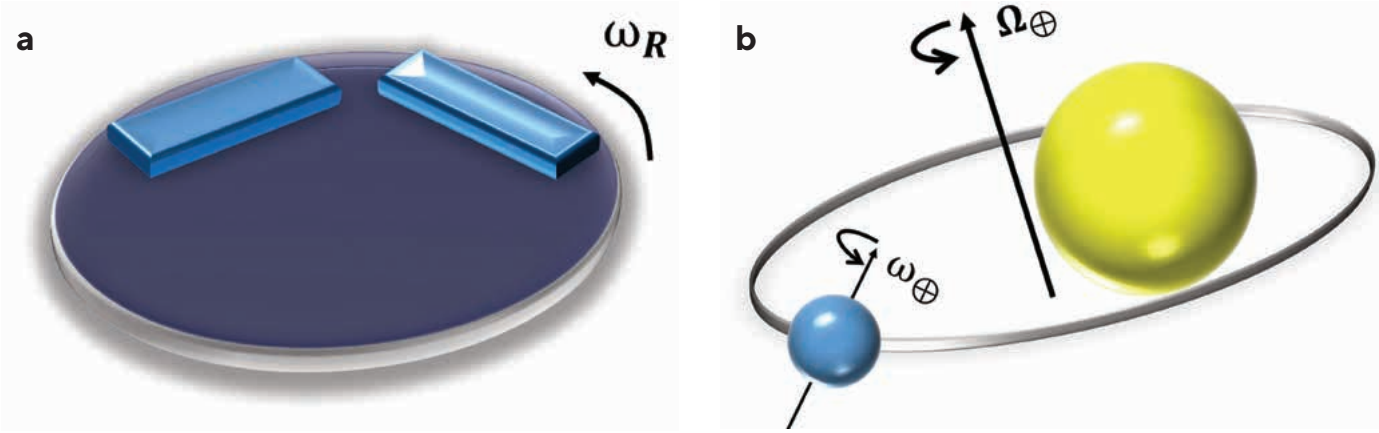
Micro- and nano-fabricated optomechanical systems have recently reached the regime where quantum interaction between the mechanical element and light (or microwaves) used to probe it is evident. This opens up the prospect to study quantum physics in massive systems of previously unobtainable size and to build new quantum-engineered machines and sensors.

Associate Investigator Woolley, in collaboration with the Sillanpää laboratory at Aalto University, demonstrated the first

Below Optical double-disk resonator with integrated capacitive electrodes for wavelength tuning developed by CI Bowen and his team using the new nano-fabrication facilities at UQ



1 DEJ Waddington, T Boele, E Rej, DR McCamey, NJC King, T Gaebel and DJ Reilly *arXiv 1709.01851* (2017)



Above
Quartz bulk-acoustic wave Lorentz Invariance tests of CI Tobar and his team

stabilised entanglement of two massive mechanical oscillators[1]. This technology is an important enabling step towards forces sensors that evade the usual back action introduced by observation in quantum mechanics, and for distribution of quantum states within microwave quantum systems.

Chief Investigator Bowen, with the Andersen laboratory at Denmark Technical University, demonstrated the first optomechanical sensor enhanced using quantum correlated light, showing that it was possible to improve both sensitivity and bandwidth in optomechanical magnetometry[2]. Chief Investigator Bowen's team also developed the first high quality on-chip optical microcavities capable of electrical tuning to an arbitrary resonant wavelength[3]. This is a key technological capability for building networks of optical devices on a chip for quantum photonics and also for classical applications such as coherent radar and high bandwidth optical buses in next generation computer architectures.

Chief Investigator Tobar's team improved their record-breaking phononic Lorentz Invariance tests by a factor of 100 using quartz bulk acoustic wave resonators[4] and proposed a new (recently patented) approach to optomechanical gradiometry[5].

Despite excellent recent progress, the preparation of mechanical quantum superposition states remains an outstanding challenge due to weak coupling and thermal decoherence. Centre Director White and his team — together with international collaborators — introduced a novel optomechanical scheme that significantly relaxes these requirements allowing the preparation of quantum superposition states of motion of a mechanical resonator by exploiting the non-linearity of multi-photon quantum measurements[6]. They experimentally demonstrated this multi-photon-counting technique on a mechanical thermal state in the classical limit and observe interference fringes in the mechanical position distribution

1 CF Ockeloen-Korppi *et al. Nature 556, 478* (2018)

2 B-B Li *et al. Optica 5, 850* (2018)

3 C Bekker, CG Baker, R Kalra, H-H Cheng, B-B Li, V Prakash and WP Bowen *arXiv 1808.01908* (2018).

4 M Goryachev *et al. IEEE Trans. on UFFC 65, 991* (2018)

5 AV Veryaskin, JF Bourhill, EN Ivanov and ME Tobar *WO 2018/071993* (2018)

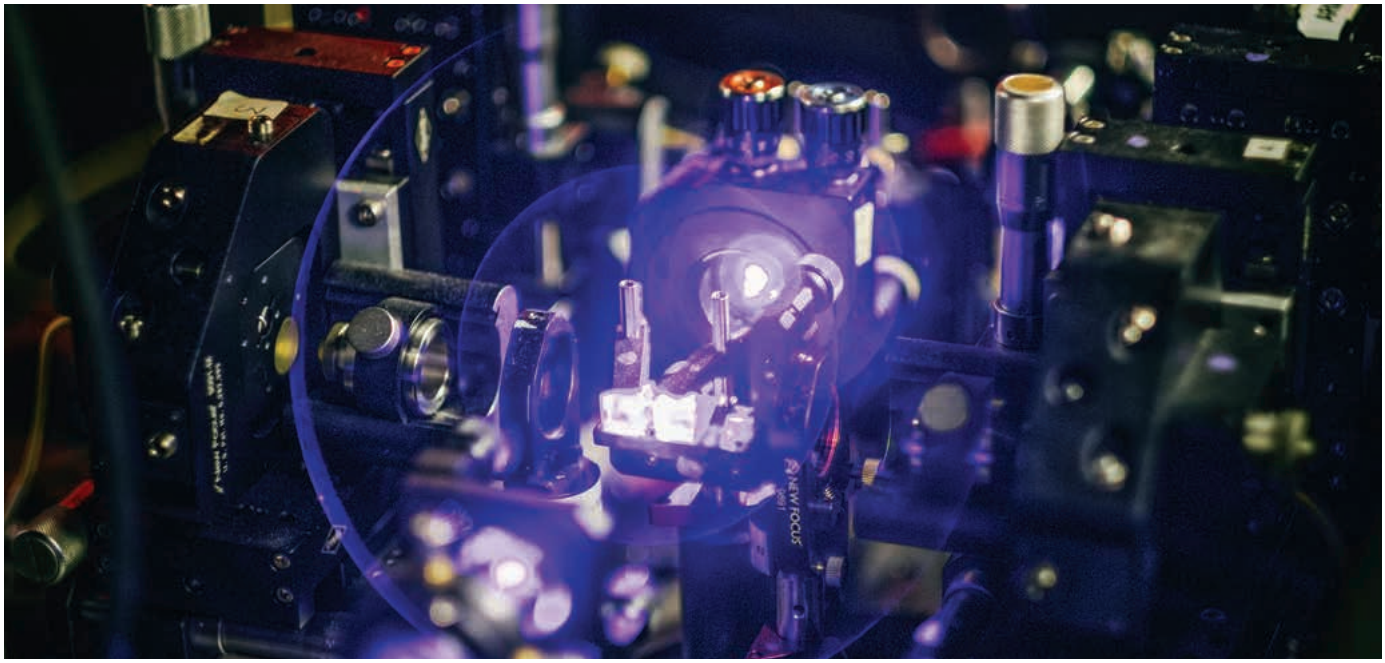
6 M Ringbauer, TJ Weinhold, LA Howard, AG White and MR Vanner *New Journal of Physics 20, 053042* (2018)

that show phase super-resolution. They also introduced hypercube states, a class of continuous-variable quantum states generated as orthographic projections of hypercubes in phase space[1]. Hypercube states exhibit phase-space features much smaller than Planck's constant, making them sensitive to perturbations at extremely small scales. Theoretically they show that the sensitivity of these states is surprisingly robust, making them a practical resource for sensing applications. In a high-temperature proof-of-principle experiment they observe, and match to theory, the signature outer-edge vertex structure of hypercube states.

QUANTUM DIAGNOSTICS

Centre Director White and international collaborators (EQUS alumni Dr Michael Vanner (Oxford) and Dr Martin Ringbauer (Heriot-Watt)) undertook a comprehensive analysis of multilevel coherence[2], which acts as the single-party analogue to multipartite entanglement, developing the theoretical and experimental groundwork for characterising and quantifying multilevel coherence. They verified and lower-bounded the robustness of multilevel coherence by performing a semi-device-independent phase discrimination task, implemented experimentally with four-level quantum probes in a photonic setup. Their results demonstrate the key role multilevel coherence plays in enhanced phase discrimination — a primitive for quantum communication and metrology — and suggest new ways to reliably and effectively test the quantum behaviour of physical systems.

Below
Developing a single photon source
Photo by Patrick Self



1 LA Howard *et al. arXiv 1811.03011* (2018)

2 M Ringbauer et *al. Physical Review X 8, 041007* (2018)

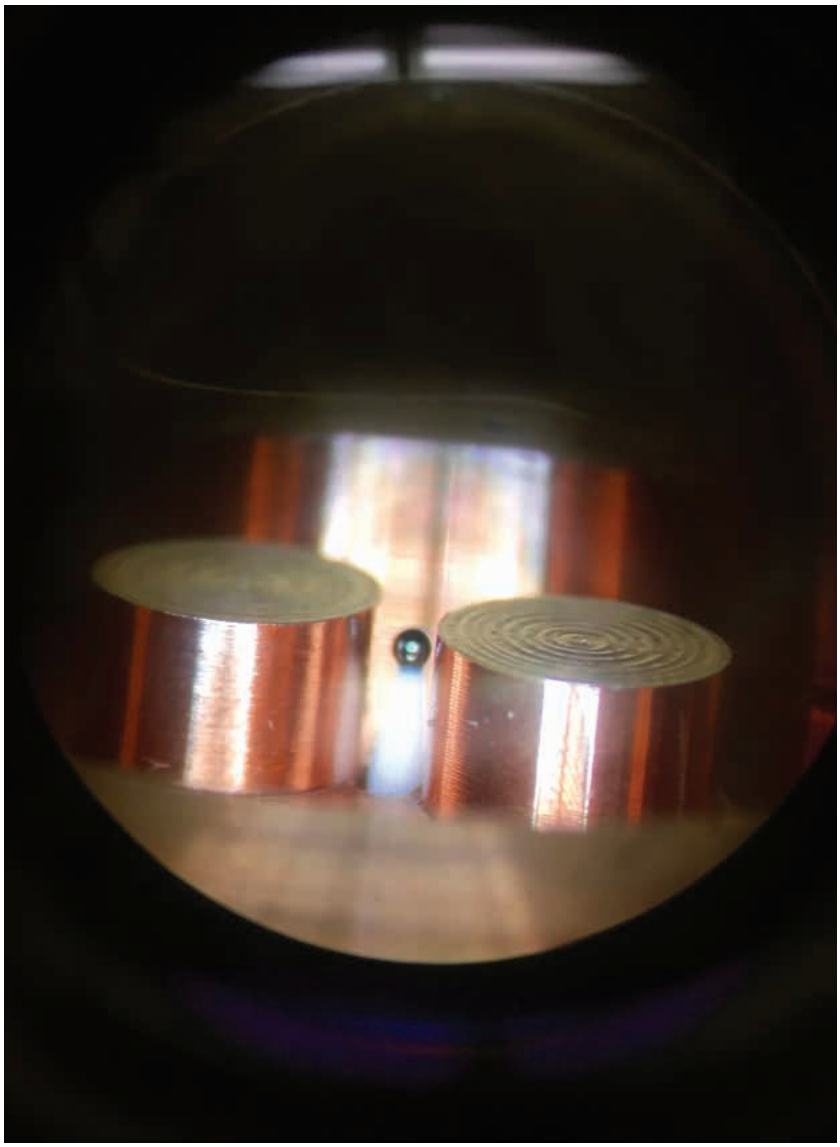
PLANS FOR 2019

Theory

Chief Investigator Bartlett will develop theory to support a new generation of experiments that couple 4 spin qubits to a common mediator, to enable supercoherence. Chief Investigator Twamley will investigate Unruh radiation and optical backaction in optomechanical systems (with Chief Investigator Bowen). Associate Investigator Woolley will investigate continuous-variable Bell inequalities in electro- and optomechanics; quantum-limited, travelling-wave electromechanical and optomechanical amplifiers.

Experiment

Chief Investigator Bowen will make first direct measurements of vortex quantisation in 2D helium; Chief Investigator Bowen will show strong radiation pressure coupling optically and electrically. Chief Investigator Reilly will validate whether spins in nanoparticles sense and image electric fields, pH, field gradients, fluid flow. Chief Investigators Rubinsztein-Dunlop and Davis will characterise rotation of quantum fluids to study effective drag forces between fluid components; increase vertical BEC confinement, to study the quantum properties of bosonic transport and Bose-Hubbard trimers. Chief Investigator Volz will measure temperature dependence of superradiance in diamond colour centres. Centre Director White will demonstrate optimal remote sensing by photon counting of detected fields.



Above
This hybrid system might one day be used to transfer and store quantum information
Photo by Jeremy Bourhill

CAN A QUANTUM DRUM VIBRATE AND STAND STILL AT THE SAME TIME?

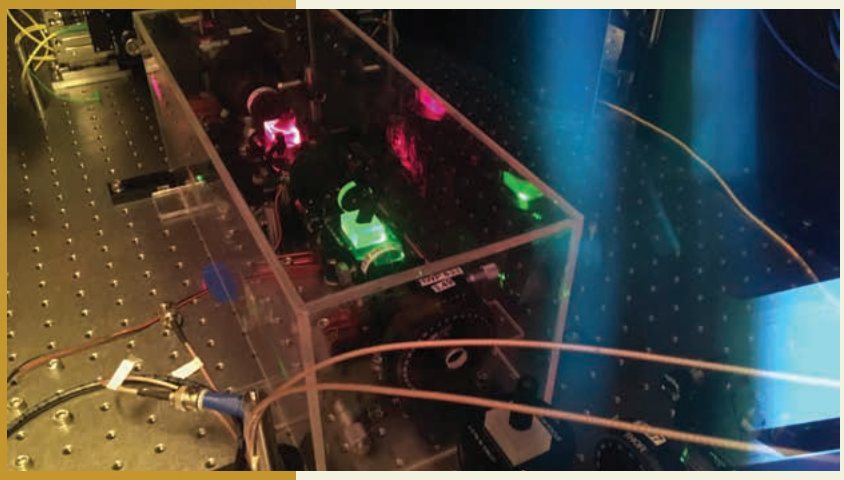
Techexplorist, Pranjal Mehar, May 18[1]

In quantum mechanics objects can behave like both particles and waves. The objects can be here and there at the same time. Such counter-intuitive behaviour is typically confined to the microscopic realm, which begs the question "why don't we see such behaviour in everyday objects?"

Now, a team of researchers from the UK and Australia has developed a technique that helps them understand the boundary between the quantum world and our everyday classical world.

The technique generates such behaviour in a motion of a tiny drum that cannot be seen with the naked eye.

Below Quantum drum setup



Dr. Michael Vanner from the Quantum Measurement Lab at Imperial College London, said, "Such systems offer significant potential for the development of powerful new quantum-enhanced technologies, such as ultra-precise sensors, and new types of transducers.

"Excitingly, this research direction will also enable us to test the fundamental limits of quantum mechanics by observing how quantum superpositions behave at a large scale."

Hitting drums produces vibrations. Hitting a drum with a drumstick causes it to rapidly move up and down. In the quantum world, a drum can vibrate and stand still at the same time. However, generating such quantum motion is very challenging.

Lead author of the project Dr. Martin Ringbauer from EQUS, said, "For this, you need a very special kind of drumstick in order to create quantum vibration."

"We adopted a trick from optical quantum computing to help us play the quantum drum. We used a measurement with single particles of light — photons — to tailor the properties of the drumstick."

"This provides a promising route to making a mechanical version of Schrodinger's cat, where the drum vibrates and stands still at the same time."

These experiments have made the first observation of mechanical interferences fringes, which is a crucial step forward for the field.

Scientists are now working hard to improve their technique and operate the experiments at temperatures close to absolute zero where quantum mechanics is expected to dominate.

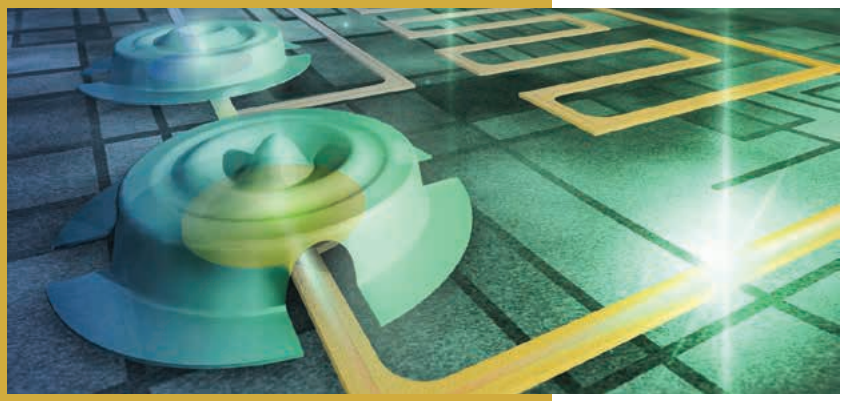
1 M Ringbauer, TJ Weinhold, LA Howard, AG White and MR Vanner *New Journal of Physics 20, 053042* (2018).

EXPERIMENT SHOWS EINSTEIN'S QUANTUM 'SPOOKY ACTION' APPROACHES THE HUMAN SCALE

The Conversation, April 26, written by Matt Woolley[1]

Quantum physics is often defined as the physics of the very small – think atoms, electrons and photons.

But we have managed to demonstrate one of the quirky features of quantum physics at a much larger scale. In a paper published today in Nature, we describe how we were able to create quantum entanglement of the motion of objects composed of many billions of atoms.



Above
An era of quantum machines is here

Why we did it

On the fundamental side, this demonstration gives us greater confidence that the laws of quantum physics do indeed apply to large objects.

But will this continue to hold true as the size and mass of the objects in such experiments is increased? We don't know.

Tabletop experiments with massive objects bring forth the possibility that such a question might one day be answered.

On the applied side, one may ask: what could mechanical quantum systems offer in this electronic age? But mechanical systems are more common than many people realise.

The humble quartz oscillator remains a crucial technology for clocks. Surfaces are imaged using the atomic force microscope, essentially a suspended cantilever that deflects light. Gravitational waves are observed by monitoring the motion of suspended mirrors using laser light.

While quantum control of mechanical systems conceivably offers an advantage in each of these scenarios, mechanical systems offer another advantage: they move and so they couple to both microwaves and light.

While the processing power of a future quantum computer might rely on microwaves in a low-temperature laboratory environment, quantum communications systems require light propagating through optical fibres or free space.

Mechanical systems can act as intermediaries between these worlds and thereby contribute to the realisation of a quantum internet.

While it is hard to say exactly where these experiments might ultimately lead, it is clear that the era of massive quantum machines has arrived, and is here to stay.

1 CF Ockeloen-Korppi *et al. Nature 556, 478* (2018)

QUANTUM ENGINES AND INSTRUMENTS

This program develops tools and design approaches that will enable us to piece together complex quantum machines out of their disparate components and aims to pioneer a new generation of instruments tailored to the demanding requirements of quantum science, from precision clocks, oscillators and time-bases to high-speed cryogenic electronics.

Research Program 3

Research highlights

PROJECT REPORTS

QUANTUM THERMODYNAMICS AND ENTANGLEMENT

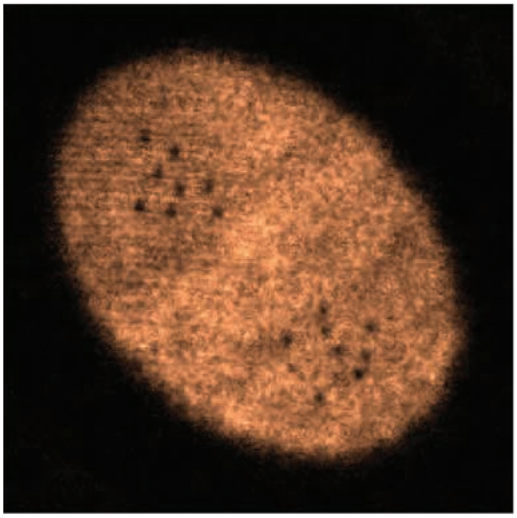
Chief Investigator Milburn and EQUS postdoctoral researcher Dr Sally Shrapnel developed a new realisation of causal interventions as measurement and control and showed how all interventions, classical or quantum, designed to test causal relations are necessarily restricted by thermodynamics. This work paves the way for a thermodynamic study of classical and quantum causal relation, and establishes that the most general causal correlations in classical and quantum mechanical systems require entropy gradients in order to be assigned a unique causal graph[1].

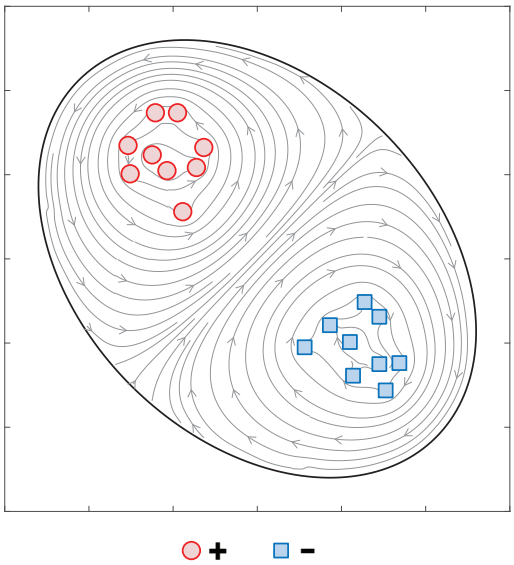
Quantised vortices in BECs present an ideal test-bed for 2D vortex physics, due to their isolation, control and close correspondence to a point vortex system. In experiment and supporting theory, Dr Tyler Neely and Chief Investigators Rubinsztein-Dunlop and Davis have produced negative temperature vortex states in a uniform and configured BEC, observing such a state for the first time and demonstrating their dynamic metastability over many seconds. This work establishes a direct connection between experimental fluids and Onsager's model of turbulence that had remained elusive in other classical and quantum fluid systems. It has been accepted in *Science*.

Dr Neely and collaborators (Murray Olsen, UQ and Ashton Bradley, Otago) have jointly analysed quantum transport in Bose-Hubbard trimers and theoretically investigated the transport properties of a Bose-Hubbard trimer consisting of three tunnel-coupled potential wells[2]. Surprisingly, the transport dynamics greatly depend on the particular quantum state of the system, with vastly different population dynamics depending on whether there was an initial coherent state or number state.

Immediate right
Image of BEC after stirring to induce vortices

Far right
Theory modelling of the same system, with clockwise and anticlockwise vortices in distinct colours





1 GJ Milburn and S Shrapnel *Entropy 20, 687* (2018)

2 M. Olsen, TW Neel, and A. S. Bradley *Phys. Rev Lett. 120, 230406* (2018)

Research highlights

QUANTUM ALGORITHMS

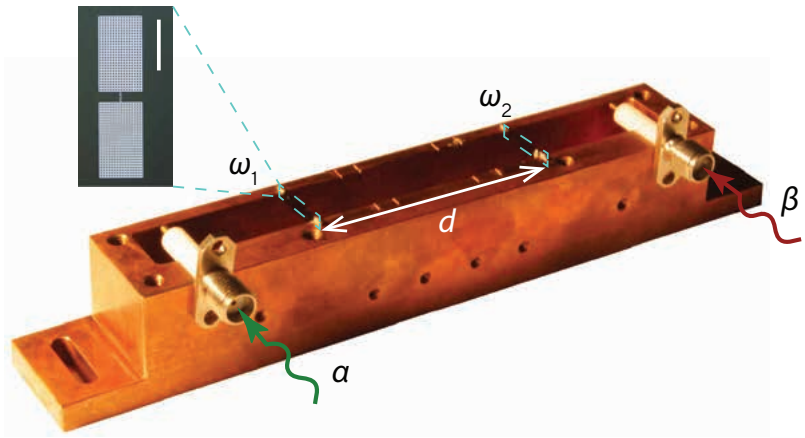
Currently, cryptocurrencies rely on the difficulty of solving inverse hashing problems as a "Proof of Work" in order to verify network transactions in a way that avoids double spending attacks and limits inflationary pressures on the currency. Chief Investigator Brennen and colleagues analysed whether quantum resources are a threat or benefit to blockchain technologies. They showed that quantum computers pose little threat to the Bitcoin mining. Furthermore, the Proof of Work can be modified to reduce the quantum complexity advantage. However, the cryptography used for digital signatures on transactions are threatened by a future quantum computer and should be changed to be quantum resistant[1].

Chief Investigator Twamley and Associate Investigator Wang have developed an algorithm to perform unstructured search using non-linear quantum mechanics. It is known that quantum computing utilising non-linear quantum mechanics can solve problems which are far harder than standard linear quantum mechanics, for example, #P problems in polynomial time, however very few explicit algorithms have been found. This work has led Associate Investigator Wang to develop further examples which are more powerful than standard quantum algorithms[2].

QUANTUM DEVICES AND INTERFACES

Chief Investigators Fedorov and Stace worked closely on the theory and first experimental demonstration of nonreciprocal scattering from two spatially separated superconducting qubits[3]. The nonreciprocity emerges from the quantum non-linearity and correlations of a collective quantum object, and opens a path to building passive quantum nonreciprocal devices.

Chief Investigator Stace has developed a new class of on-chip, superconducting circulators with Associate Investigator Mueller (IBM Zurich). A new, high-bandwidth circulator design that can be integrated on-chip in superconducting circuits was proposed. This proposal is now being implemented in Chief Investigator Fedorov's lab. Provisional patents based on this proposal have been filed through UQ[4].



Above
A copper waveguide with two 3D transmon qubits, used to demonstrate nonreciprocal scattering

1 D Agarwal, GK Brennen, T Lee, M Santha and M Tomamichel *Ledger 3, 68* (2018).

2 K de Lacy, L Noakes, J Twamley, JB Wang *Quantum Information Processing 17 (10), 266* (2018)

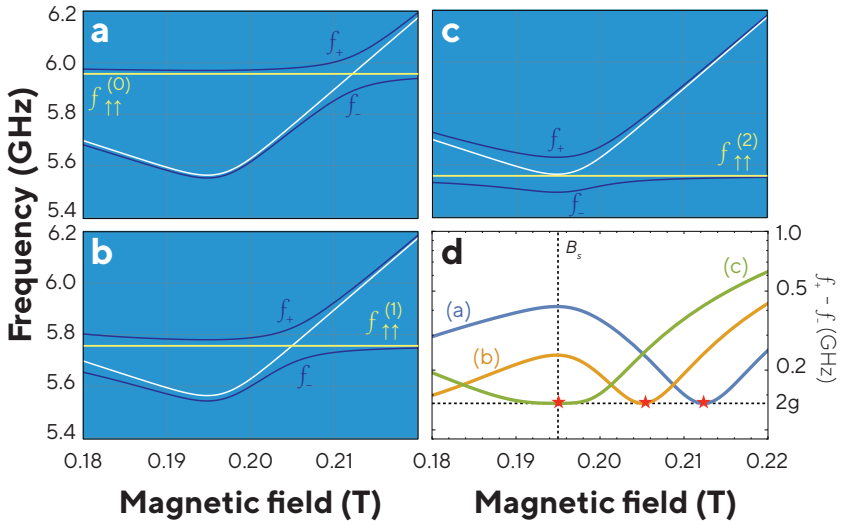
3 A Hamann *et al. Physical Review Letters 121, 123601* (2018)

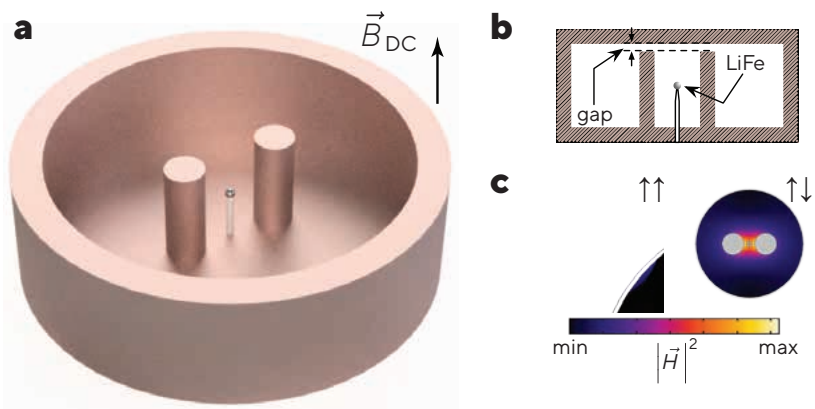
4 C Müller, S Guan, N Vogt, J Cole and TM Stace *Physical Review Letters 120, 213602* (2018)

Chief Investigator Shaddock has developed enabling technology for future ground-to-space quantum key distribution systems. In particular, his group is developing monolithic optical hardware for optical phased arrays, in combination with digitally enhanced interferometry firmware that utilises the phased arrays. This work will be ongoing throughout 2019.

Chief Investigator Tobar's group has shown that single crystal lithium ferrite spheres coupled to a 3D cavity allow strong coupling between the photon and magnon, with coupling strength of up to 250 MHz at 9.5 GHz. The photon-magnon coupling can be significantly improved and exceed that of the widely used yttrium iron garnet, due to higher spin density in LiFe. Magnon mode softening at low DC fields combined with the Zeeman effect creates magnon spin-wave modes that are insensitive to first-order magnetic-field fluctuations. This "double-magic point" clock transition could potentially be useful in cavity QED experiments[1].

Below Spectra of reentrant cavity coupled to LiFe spheres as a function of **b** field





Centre Director White's group constructed the narrowest linewidth cavity-enhanced single photon source ever demonstrated, spectroscopically locked to the 795 nm Rb linewidth. In addition to being a key element in quantum networks, this device exhibits mode-locked biphoton states with comb-like correlation functions. It emits both single photon pairs and two-photon NOON states, dividing the output into an even and an odd comb, respectively. With even-comb photons they demonstrated revivals of the typical nonclassical Hong-Ou-Mandel interference up to the 84th dip, corresponding to a path length difference exceeding 100 m[2]. With odd-comb photons they observe single-photon interference fringes modulated over even greater distances: twice the displacement range of the Hong-Ou-Mandel interference.

1 M Goryachev, S Watt, J Bourhill, M Kostylev and ME Tobar *Physical Review B 97, 155129* (2018)

2 M Rambach *et al. Physical Review Letters 121, 093603* (2018)

PLANS FOR 2019

Theory

Chief Investigators Bartlett and Flammia will work with Quantum Benchmark to develop platform-independent solutions for assessing near-term quantum devices; benchmarking 2-qubit gates with UNSW collaboration. Chief Investigator Davis will include effects of quantum correlations in BEC thermodynamics / engines. Chief Investigator Milburn will develop quantum agent models and account for quantum noise to assess quantum enhancements. Chief Investigator Twamley will develop quantum instruments based on distributed quantum networks.

Experiment

Chief Investigator Bowen will explore the thermodynamics of 2D superfluids. Chief Investigator Fedorov will study microwave bandgap photon bound states; experimentally realise new, on-chip superconducting circulator design (with Chief Investigator Stace). Chief Investigator Shaddock will use the optical fibre optical phased array to continue to develop aspects of the internally-sensed optical phased array architecture and demonstrate acquisition and tracking of targets and arbitrary wavefront manipulation. Centre Director White will investigate using comb photon source to create a measurement device for gravity-wave optomechanics (based on ideas of Prof. Heurs).

Below
Back to basics in the lab

SCIENTISTS INVENTED A REAL-LIFE FLUX CAPACITOR

Futurism, Kristin Houser, May 29[1]

Great Scott! A team of physicists just figured out how to make a flux capacitor.

No, it's not a real-life version of what was in the "Back to the Future" franchise (reminder: in the movies, the flux capacitor is the plutonium-powered device that makes time-travel possible). While the version proposed by these scientists won't let you traipse through time, it could do something almost as cool: help usher in the quantum computing era.

What the heck is this flux capacitor, anyway? Let's break it down. Capacitors are devices that store energy, and they're pretty common in the world of electronics. Flux, meanwhile, is the amount of something moving across a certain area. So in a flux capacitor, microwaves are the something, and the channel they move across is a central capacitor.

Ironically, while Doc and Marty didn't need roads where they were going, the best analogy for how the researchers' flux capacitor would work does involve traffic. The device forces microwaves to flow in just one direction around a centre area, just like cars in a roundabout. This is pretty remarkable because it breaks something called time-reversal symmetry—a theoretical law of physics that states that, if you reversed time, you'd see whatever just happened, happen exactly in reverse, like a mirror image.

The researchers propose two designs for their flux capacitor. One does resemble the Y-shaped device used in the movies, but is much more complicated than "Back to the Future" made it seem.

"In it, quantum 'tubes' of magnetic flux can move around a central capacitor by a process known as quantum tunnelling, where they overcome classically insurmountable obstacles," explains theoretical physicist Jared Cole.

The flux capacitor itself may be complex, but it's applications are clear. The device could help researchers precisely control signals, necessary to advance quantum computing. It could also help us improve the electronics we use today, everything from smart phones to radar systems.

Right
The "Back to the Future" flux capacitor

1 C Müller, S Guan, N Vogt, J Cole and TM Stace *Physical Review Letters 120, 213602* (2018)

WORLD'S GROUNDWATER STORES FALLS UNDER THE DEEP INSIGHT OF AN AUSTRALIAN PHYSICIST'S SPACE MISSION

ABC News, Ben Deacon, 23 June

An Australian physicist has developed satellite technology that measures the world's freshwater reserves from space.

The technology is at the heart of the NASA's Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission, which launched last month and follows the first GRACE mission which launched in 2002.

The launch was particularly stressful for Australian physicist Daniel Shaddock from the Australian National University, as 15 years of his work was on board the rocket.

"It was a little bit surreal," Professor Shaddock said.

"So many years of your life working on something – it was hard to believe it was actually happening and finally launching.

"It was very exciting when it finally went up and nothing blew up. And the most exciting part is still yet to come."

Professor Shaddock developed a retroreflector that uses lasers to measure the world's water reserves from space with unprecedented accuracy.

"It measures something that's really important; the presence of water – whether that's frozen form or liquid form – across the entire globe at once. And that's something you can only do from space.

"Any large body of water will generate gravity and that gravity can be picked up by GRACE."

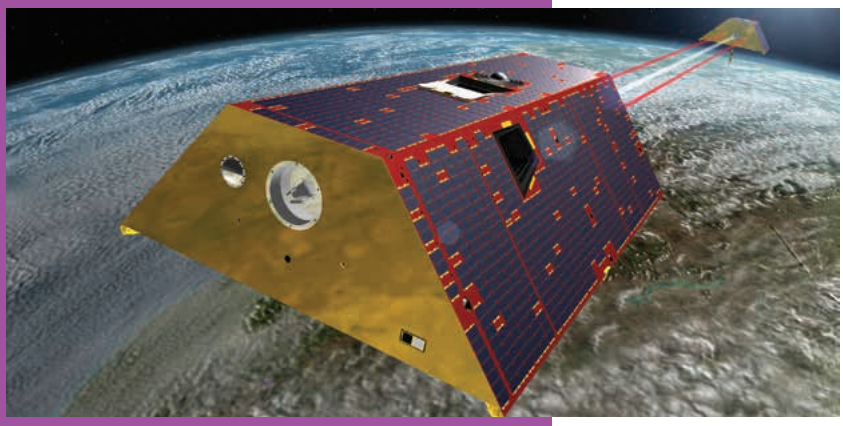
GRACE detects tiny changes in gravity caused by large masses of water on Earth, which then causes a pair of satellites to speed up or slow down.

Professor Shaddock's laser device measures these changes in speed.

"In the case of the Laser Ranging Interferometer, we can pick up changes in the separation of the spacecraft by ten nanometres. That's ten billionths of a metre – about the diameter of a virus."

Below left
Professor Daniel Shaddock

Below right
One of the twin GRACE-FO satellites



Research translation

EQUS is working to move our research beyond the lab towards practical prototypes and commercial applications.

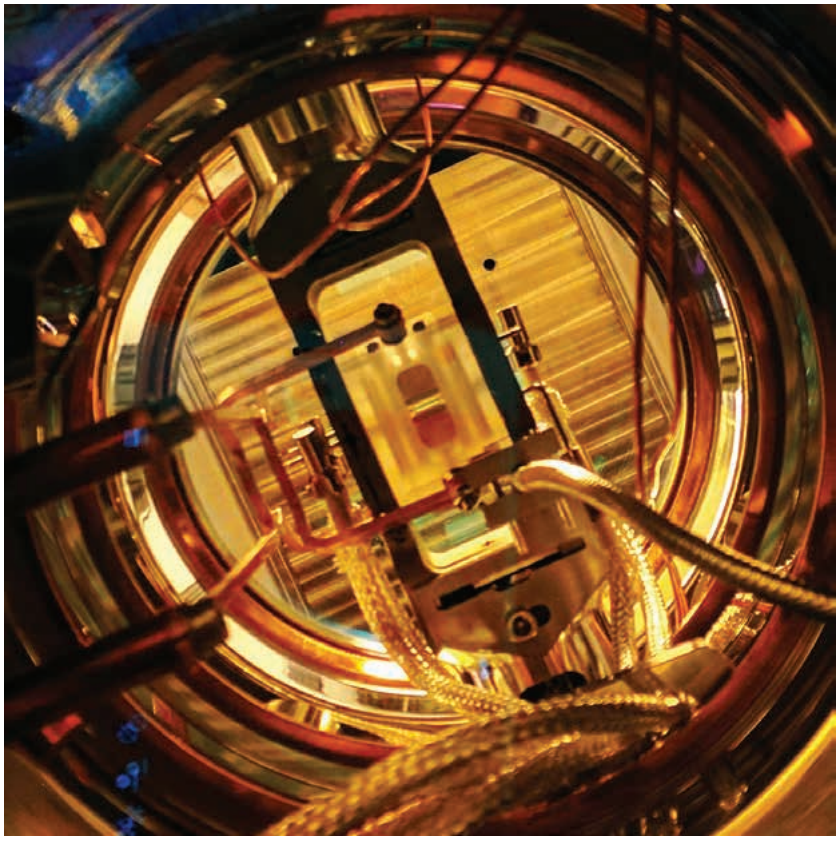
The Translational Research Laboratory is a flagship program within EQUS with the strategic objectives of: providing technical support and carrying out the feasibility studies required to see applications realised as practical prototypes, carrying out industry engagement activities to connect researchers with new partnerships; and building a culture of innovation and entrepreneurship in the Centre.

SUPPORTING A QUANTUM INDUSTRY IN AUSTRALIA

Australian quantum science researchers and industry representatives met for a four-day conference in August 2018 on Magnetic Island to lay out the future of Australia's emerging quantum industry.

The conference was led by the EQUS and sponsored by the ARC Centre of Excellence for Future Low-Energy Electronic Technology, ARC Centre of Excellence for Exciton Science and the legacy Centre of Excellence for Quantum-Atom Optics. Goals of the conference were to provide an overview of current quantum science research, strengthen relationships between industry and researchers, and lay out the future of quantum industry in Australia.

Below
A view through the ultra-high-vacuum chamber
Photo by Michael Biercuk



Conference participants discussed three key themes in relation to the establishment of a quantum industry in Australia. The themes were:

- Quantum science applications
- Potential for collaboration with industry sectors
- Emerging workforce needs.

In many ways, this discussion was well-timed as Australian research in quantum continues to go from strength to strength. Highlights from the past year or so include our 2018 Australian of the Year - quantum physicist Professor Michelle Simmons, who heads up one of four national research centres in this space. In the same period, Sydney universities have been working together to establish an academy for a new generation of quantum

engineers and quantum-based start-up companies have begun to emerge.

In brief, participants identified opportunities for researchers and industry to work together to advance blue sky research and technological applications for quantum science. They also highlighted the challenges influencing these collaborations and the emerging quantum industry.

A full report on the conference is available at equs.org/ip2018.

QUANTUM START-UP Q-CTRL LAUNCHES FIRST PRODUCT

CIO, George Nott, 4 December

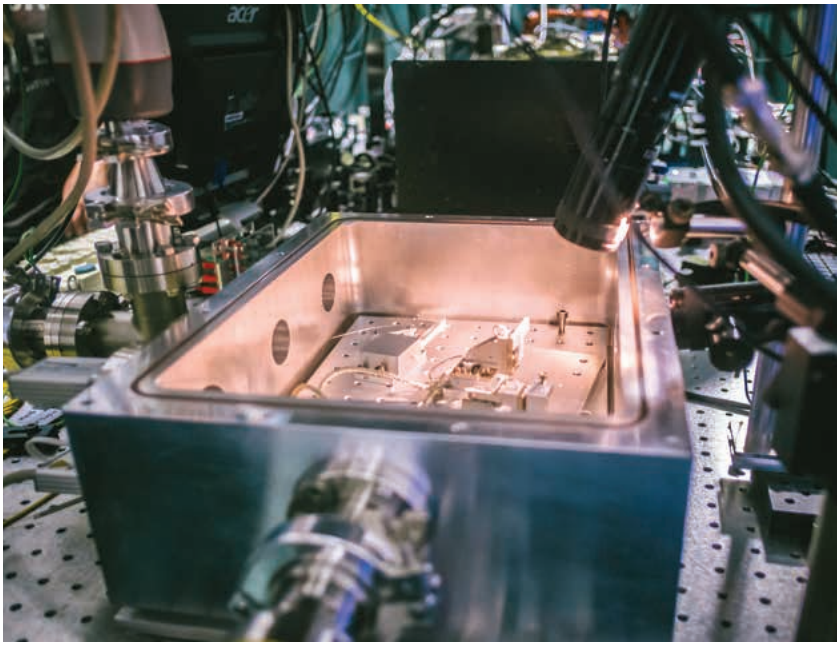
Sydney start-up Q-CTRL has launched its inaugural product — Black Opal — which it describes as "the world's first commercially available software suite designed to improve the performance of quantum computing hardware".

Quantum systems are highly susceptible to decoherence. The states of quantum bits, or qubits, in quantum computers are quickly randomised by interference from the environment.

Q-CTRL's toolkit help teams design and deploy control for their quantum hardware in order to suppress these errors.

"Quantum control has for a long time been thought of as a bit of a black art. Those of us who were deeply ingrained in it understood the capabilities it brings, but many others would only dip their toes in the water and that was enough," explains Q-CTRL founder, University of Sydney Professor Michael Biercuk.

"We're aiming to remove those barriers, remove the friction points that have prevented teams from taking advantage of everything that's possible," he adds.



Above
In the lab at EQUS

The controls in the toolkit were described by Biercuk as being able to "effectively turn back the clock" on decoherence. "So all the randomisation that occurs, unwinds; it's like unmixing the soup," he told Computerworld last year.

Q-CTRL launched in November 2017, the first spin-off company of the Australia Research Council Centre of Excellence for Engineered Quantum Systems.

Equity and diversity

Addressing issues of equity and diversity is a priority for EQUS. The Centre is underpinned by a commitment to equal opportunity and diversity. Centre members strive to treat everyone in an unbiased and inclusive manner, and to remove barriers of disadvantage for all members and the wider research community.

The Equity in Quantum Physics (EQUIP) Committee was established early in the Centre to help address equity and diversity issues. The Committee works across all five universities to address structural issues, and provide resources and activities to support students and researchers.

In 2018, the committee established a Centre Code of Conduct, which is publicly available on the EQUS website and are working on a Centre Equity and Diversity strategy. The committee also made a submission to the Australian Academy of Science Women STEM Decadal Plan working group.

INDIGENOUS ATTENDEES AT SCIENCE MEETS PARLIAMENT 2018

In partnership with Science & Technology Australia and the Australian Academy of Science, EQUS supported scholarships to STEM practitioners with an Indigenous background to attend Science meets Parliament in Canberra.

Three indigenous scientists were selected. The recipients were:

- Cardiovascular researcher Ms Amy Searle (Vic, Latji Latji Nation)
- Water scientist Mr Bradley Moggridge (ACT, Kamilaroi Nation)
- Data scientist Dr Kalinda Griffiths (NT, Yawuru Nation)

Science meets Parliament brings around 200 Australian scientists and technologists to Canberra for professional development, networking, and to meet face-to-face with MPs and Senators.

The scholarships covered travel, accommodation, meals and transfers, as well as full registration for the event including the gala dinner in the Great Hall at Parliament House. Financial assistance for childcare was also available upon application.

Below
Left to right: Melanie Bagg, Kylie Walker, Andrew White, Kalinda Griffiths, Bradley Moggridge, Andrew Doherty, Amy Searle, Anne-Maria Arabia

Equity and diversity

PRIMARY CARER SUPPORT

EQUS recognises that many students and researchers have caring responsibilities that may limit their access to opportunities for the development of their careers.

In 2018 EQUIP established a new program to help primary carers with the cost of carer management while pursuing their careers. $15,000 is available each year to support this program.

One primary carer grant was awarded in 2018 to support a postdoctoral fellow undertaking an overseas collaboration.

RE-ENTRY AWARDS

EQUS encourages re-entry of researchers who are on a significant (more than six months) career break from academia.

In 2018, EQUIP established a new Re-Entry Award program. Up to $10,000 per year is available for EQUS-affiliated researchers, or up to $7,000 for external researchers nominated by an EQUS Chief Investigator.

EQUIP EVENTS PROGRAM

The EQUIP committee coordinated events across all five EQUS nodes for days of significance related to equity and diversity. These included the International Day for LGBTIQA+ persons in STEM, the International Day of Women and Girls in Science, and Ada Lovelace Day.

Below
UWA LGBTIQA+ in STEM cakes

SPONSORSHIP

EQUS is an active and visible sponsor of STEM equity and diversity initiatives. In 2018, EQUS sponsored an event by the Australian Institute of Physics' Equity and Diversity group at the biennial AIP conference.

In addition, EQUS instituted a new policy which requires all requests for sponsorship to provide information on the diversity of invited speakers and organisation committees. This information is used to determine whether sponsorship will be granted.

Communication and outreach

EQUS researchers engaged diverse audiences with quantum science and technologies over the past twelve months.

The Centre promoted new research, public events and other activities and achievements through media releases, the EQUS website and on social media. Our researchers provided multiple briefings to government, industry and other end-user groups, and supported professional development opportunities for science teachers across Australia.

The following are selected highlights from 2018.

Below
Students at Hay War Memorial High School in western NSW

Bottom
The road trip team at Parkes

QUANTUM COAST TO COAST OUTREACH ROAD TRIP

EQUS researchers and students undertook a massive "physics in the outback" outreach road trip when they travelled from Sydney to Perth in late 2018.

Along the way, they ran workshops for over 150 students at schools in New South Wales and Victoria, and in a pub at Opal Inn in Cooper Pedy, South Australia.

> *In Ceduna, one person had a keen conversation with the team about physics because they noticed the Macquarie Physics Department stickers on our car. She was originally from Perth and had a friend who had studied physics at UWA. She was excited about our road trip and about the science engagement with outback Australia, and was keen to follow our trip on social media.*

Sponsored by EQUS and Macquarie University, the road trip gave the team a chance to practice their science communication skills while engaging rural communities and schools with quantum science.

In the workshops, school students were able to zoom into and measure individual atoms inside a diamond, took a virtual tour of a physics lab and learnt about what it's like to work as a physicist.

Communication and outreach

Several keen students from the schools followed the team's @diamondnansocience Instagram account to keep up to date with lab activities and research.

> *At a service station in WA the person behind the counter was excited to hear that we'd driven from Sydney. She had finished high school the year before and had loved physics! She had noticed our physics stickers on the MQ car.*

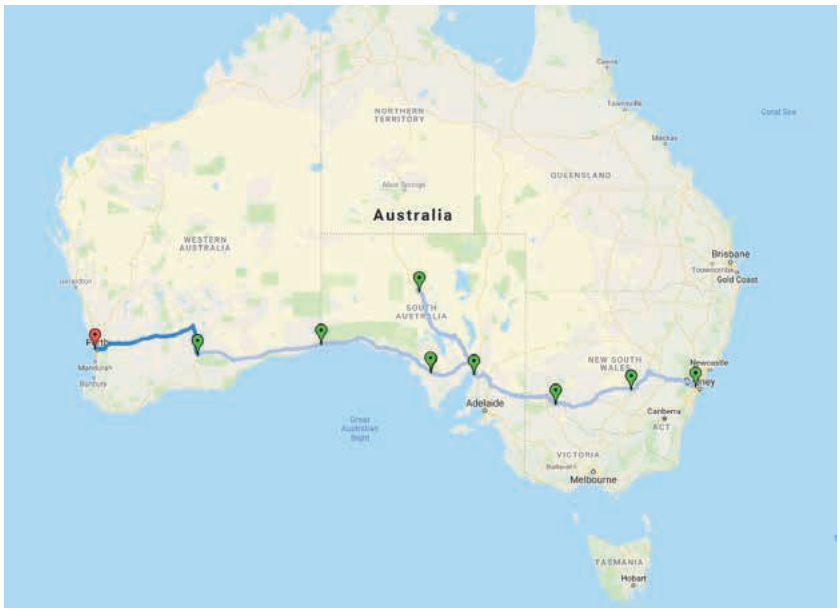
By the time the Macquarie physics car returned to Sydney it had completed a round trip of 10,493 km, making the trip more than a third of the total distance travelled by the car so far!

Well done to the Quantum Coast to Coast team!

- Lachlan Rogers
- Matt van Breugel
- Reece Roberts
- Sarath Raman Nair
- Jemy Geordy
- Tom Guff

Schools visited

- Orange High School, NSW
- Parks School, NSW
- West Wyalong School, NSW
- Hay War Memorial High School, NSW
- Robinvale College, Vic
- Red Cliffs Secondary School, Vic



Media coverage and recognition

- Central Western Daily newspaper article about visit to Orange School
- Newspaper journalist attended school visit n Robinvale
- Write-up in Macquarie University and Macquarie University's Faculty of Science newsletters
- Team awarded a Department of Physics service award at Macquarie University

Top
Their route of more than 10,000 km

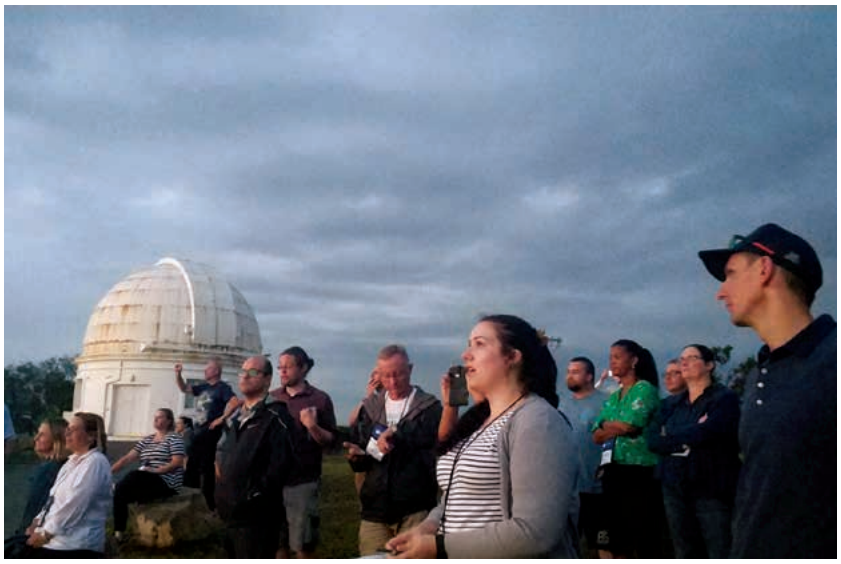
Above
Hay War Memorial High School in western NSW

Communication and outreach

EQUS SUPPORTS REGIONAL AND REMOTE SCIENCE TEACHERS

The National Youth Science Forum is a five-day professional development program for experienced and new secondary science teachers from across Australia. The program runs in Canberra and Brisbane each year. EQUS sponsored four science teachers to attend the program.

Below
The National Youth Science Forum in progress



Above
NYSF teachers at the Mt Coot-tha Observatory

Teacher feedback:

The 2019 NYFS National Science Teachers Summer School (NSTSS) was an excellent way to develop my resources and my broader network of experts and teachers, while also ensuring that I remain inspired about the breadth of ways science influences our lives and the diversity of scientific career paths.

The National Science Teachers Summer School was an amazing opportunity for me to network with other teachers and researchers and to see and experience cutting-edge science. I was able to interact with teachers to share ideas, perspectives and build relationships that I will take back to my school and will help develop me professionally.

This event provided access to the students who were taking part in the NYSF program and all of these showed a passion for science and level of maturity well beyond their years. These feelings were echoed by all the science teachers I spoke to and the success of the event is a credit to everybody involved, especially all the students who have taken time out of their holidays to be a part of this fantastic program.

Communication and outreach

PHYSICS DAY FOR INDIGENOUS STUDENTS

The University of Queensland Aboriginal and Torres Strait Islander Studies Unit (UQ ATSI) hosted a week-long program for Indigenous students called InspireU in January 2018.

EQUS Chief Investigator Tom Stace collaborated with UQ ATSIS to deliver a physics- and mathematics-centric day.

During the day, the students participated in hands-on activities, demos and discussions led by EQUS and UQ researchers. In the evening, UQ's David Moriarty and members of the amateur astronomical society ran an observation evening in which they saw the Dog Star.

QUANTUM GAMES

Chief Investigator Tom Stace coordinated this competition to developed quantum-themed computer games in 2017 and 2018. Developers submitted video game entries by January 2018 for shortlisting.

Shortlisted games were showcased at the World Science Festival Brisbane in March 2018 at the Queensland Museum. Approximately 5,000 people visited the Quantum Games stall and around 1,000 people played the games.

The prizes for the competition were awarded by quantum physicist and best-selling children's book author Dr Chris Ferrie, course coordinator for computer game development Dr Ross Brown, and games developer Olga Varlamova.

Above
Quantum Games exhibition at the World Science Festival Brisbane

Left
Prize ceremony for Quantum Games competition

Communication and outreach

EQUS STUDENT COMPETES IN 3MT ASIA PACIFIC AND FAMELAB NATIONAL FINALS

Above
EQUS PhD candidate Ben McAllister

EQUS PhD candidate Ben McAllister competed in the 3MT (three minute thesis) Asia Pacific finals in addition to the FameLab Australia national finals in 2018.

Entitled "The organ experiment: Shining a light on dark matter", Ben's talk dealt with the nature of dark matter and asked: how might we detect it and what can it be used for?

Read his full abstract below, or check out a video of his talk on Australia's Science Channel.

Abstract

We have known for decades that the regular matter that we understand composes less than 1/6th of all matter in the universe and that we are surrounded at all time by mysterious "dark" matter of unknown composition. Many believe it is composed of a particle known as the "axion", although this particle is yet to be conclusively observed.

I am building an experiment to detect dark matter axions. Detection, however, is only the first step. Think of what humanity has accomplished using only the small proportion of matter we understand. The potential benefits and impacts to society of a new type of matter that is five times as abundant are staggering and difficult to overstate. A deeper understanding of our universe invariably leads to progress in science, technology and wider society. We must always push at the boundaries of our knowledge.

The nature of dark matter is one of the greatest unknowns facing the scientific world today, and as such it presents a significant opportunity for discovery and progress.

Mentoring and career development

EQUS provides training for graduate students and Early Career Researchers across all five nodes. This training supports the advancement of their research skills and broader knowledge of the field. Training opportunities also address skills that will assist our students and researchers in their academic and industry careers.

In addition to running professional development events during 2018, EQUS established a new mentoring program to provide career-oriented support for students as well as Centre collaboration grants for postgraduate students and ECRs and summer projects for undergraduates.

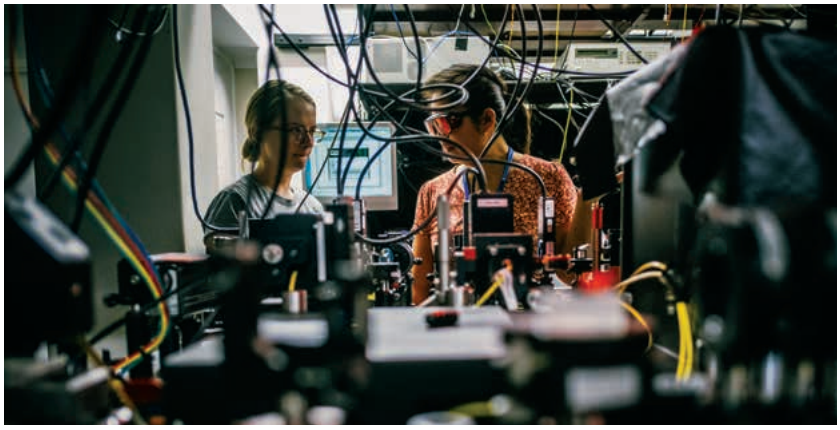
The following are highlights from 2018.

MENTORING PROGRAM

EQUS is committed to providing career-oriented support for all its students.

The field of quantum science is extremely dynamic at the structural level: new collaborations linking research groups and funding bodies across the academic and industrial sector continue to emerge at a prolific rate, and it is an exciting time to be developing a career in quantum science. This dynamism brings with it its own challenges. It is common for research students to focus almost exclusively on their projects while enrolled and to start thinking about the next stage of their career only once they are close to submitting, or after submitting their thesis. While this understandable, it is certainly not the best way to go about things.

Whether students plan to pursue a research career within the academic context, or go outside the academy into the wide world of industry, government and personal entrepreneurship (or in such a way that links them all!), the sooner they start addressing their career trajectory, the better. There are many ways to find out about these things, but the most efficient and interesting way is to get tailored support from someone who has already been down this path and who is deeply engaged in their field.



Above
EQUS students in the lab
Photo by Patrick Self

The EQUS Mentoring Program is designed to address this. EQUS mentors are drawn from the outstanding range of researchers, collaborators and alumni (across both academia and industry) who are members of EQUS. Forty-six EQUS higher degree research students have been allocated a mentor and the relationships are developing well: all have had email correspondence, and most have had Skype conversations. Several have already met in person.

Mentoring and career development

SUMMER PROJECTS FOR UNDERGRADUATE STUDENTS

Above
How many physicists does it take to install a fragile, vacuum compatible optical fibre?
Photo by Nutsinee Kijbunchoo

EQUS advertised a work experience program for the 2018/2019 summer break, whereby undergraduate students can apply to work on a research project at any EQUS node for four to six weeks. The intent of this program is to grow the domestic pipeline of PhD students for the Centre. We received 20 applications and offered nine students the summer projects, three each at the University of Western Australia, University of Sydney, and University of Queensland.

COLLABORATION SUPPORT

Building on the Idea Factory, EQUS launched a Centre Collaboration Award scheme whereby PhD students and Early Career Researchers can apply for funding to support new research collaborations with affiliated EQUS researchers. A total of $28,900 was awarded to eight recipients, with grants ranging from $1,000 to $7,000. Six of the grants provided funding support for national collaboration and two for international travel support.

EQUS Collaboration Award report – Nathan McMahon

As part of the EQUS Centre Collaboration Award, I visited both Tobias Osborne's group at the Institute for Theoretical Physics at Leibniz university, Hannover and Hans Briegel's group at the Institute for Theoretical Physics at the University of Innsbruck for two weeks each during November of 2018. While visiting Tobias I presented the work that I had done during my PhD as an EQUS student, and engaged in many interesting discussions with his group and other members of the institute. These discussions resulted in three viable collaborations going forward with members of the group.

During the second half of my trip, visiting Hans Briegel's group at Innsbruck, I engaged in many interesting discussions with members of his group on their approach to machine learning via projective simulation. I again presented the work done during my PhD. However I am currently looking at applying for a fellowship which I heard about through this visit.

The EQUS centre collaboration award has offered me an opportunity to visit other groups and develop myself professionally as well as forming collaborations which would have been unlikely otherwise.

EQUS Collaboration Award report – Rob Harris

I used my EQUS Collaboration Award to visit Kavan Modi (EQUS Associate Investigator) and Felix Pollock at Monash University. We plan to start a collaboration based on my work on Randomised Benchmarking and their work on process tensors. I visited from November 12-28, 2018.

Randomised Benchmarking is an important tool for measuring the error rate of a set of quantum gates. In Randomised Benchmarking, we select a random sample from a gate set and implement this many times to find out how likely the final state is to be the expected final state. After implementation for different sequence lengths of gates, we can estimate the average error per gate.

The majority of previous work in Randomised Benchmarking has assumed an error independent of the particular gate, by modelling the implemented gate as the ideal gate followed by an independent noisy progress. Our recent work has developed an error model with the error term within the gate Hamiltonian for single qubit gates, leading to notable changes in characteristics.

The group at Monash has previously looked at modelling errors using process tensors. If a quantum circuit meets certain conditions we can separate the ideal process from the noise. This would allow us to model and analyse more complex noise models.

During the visit we found a process tensor that would be able to describe the error model we used in previous work. We also created a general model for a process tensor that we can use for all possible error models.

Based on the visit we are working on joint research papers. The first describes the particular process tensors. Once the analysis has been completed on different error models, we expect to write the second paper with these results.

Centre events

IDEA FACTORY

Below
The 30 participants in the Idea Factory were trained in scientific communications

EQUS ran the Idea Factory for the third time since 2016. This year, the workshop was co-sponsored by the ARC Centre of Excellence in Future Low-Energy Electronic Technologies (FLEET).

Co-sponsorship allowed Early Career Researchers from both Centres, to meet for the first time and encouraged cross-organisational collaboration.

Over three days, the 30 participants were trained in scientific communication by Dr Merryn McKinnon (The Australian National Centre for Public Awareness of Science) and given advice on how to develop grant applications by a range of senior researchers. They were divided into six teams who were tasked with developing a grant application from scratch and then pitching it to a judging panel. The judging panel was impressed with the presentations.

AXION INCUBATOR

A two-day research incubator entitled "Quantum Technologies for Axion Dark Matter Detection" was held in Sydney during September. The event provided an opportunity for EQUS researchers to get up to speed with the field of axion detection and provided an overview of Centre efforts to detect axions with the ORGAN experiment at the University of Western Australia. The goal of the incubator was to generate new ideas for axion detection experiments with a focus on utilising the wealth of quantum technology experience within the centre.

Right
Focussing on new ideas for axion detection

Centre events

SPRING SCHOOL

In September, EQUS held its annual spring school for students at Newport in NSW. The program was structured around interactive tutorial sessions and sessions were based upon Centre research topics.

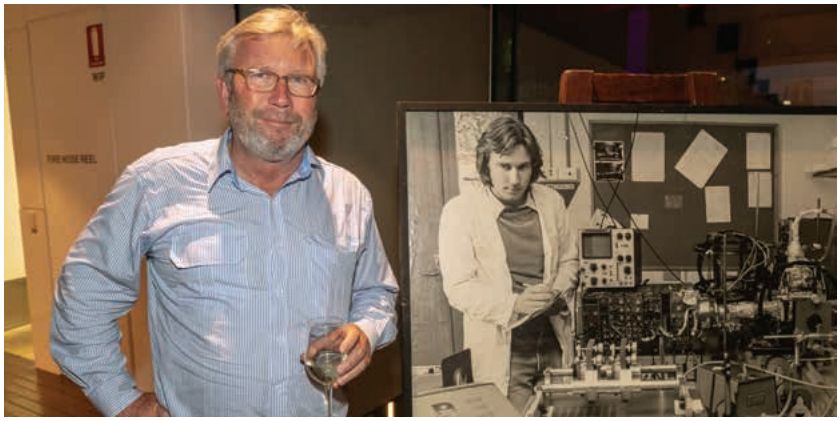
The Spring School program ran over three days covering three topics in quantum information science and one session on self-care during PhD. The scientific theme of the school this year was quantum computing, with two experimental and two theoretical lecturers. The speakers were:

- Dr Maja Cassidy (Microsoft Quantum, Sydney) *Experimental challenges for quantum computing*
- Dr Ivan Kassal (USyd) *Quantum algorithms and quantum simulation*
- Dr Arne Grimsmo (USyd) *Introduction to superconducting qubit*
- Dr Cornelius Hempel (USyd) *Quantum information processing with trapped ions.*

During the session on PhD self-care, students heard about self-help strategies to improve mental health, personal relationships and physical health. The school also included several social networking opportunities. Feedback indicated this was appreciated and these social events are recommended for future editions of the school.

QUANTUM GATES, JUMPS, AND MACHINES

This event was a celebration of the scientific career of EQUS founder Professor Gerard Milburn on his 60th birthday. The theme – Quantum Gates, Jumps and Machines – captured his contributions to the field in three broad areas: quantum information and computation, quantum measurement and dynamics, and engineered quantum systems.



Below
Professor Milburn stands beside a photo of himself at the Quantum Gates, Jumps and Machines event

ANNUAL WORKSHOP

The first Annual Workshop for the new Centre ran in Perth in December this year before the Australian Institute of Physics biennial conference. Over 130 delegates from Centre nodes and collaborators as well as members of our Scientific Advisory Committee attended.

Highlights from the event included:

- Presentations from international speakers including **Yiwen Chu** from Yale University, **Peter Wolf** from CNRS, **Alexia Auffeves** from the Institut Néel, **Joseph Emerson** from the University of Waterloo, and **Cathy Foley** from CSIRO.
- The announcement of the new Centre Prizes.
- Morning yoga sessions on the Scarborough beachfront.

Publications

MA Hosain, JM Le Floch, J Krupka and ME Tobar **'Aggregate frequency width, nuclear hyperfine coupling and Jahn–Teller effect of Cu 2+ impurity ion ESR in SrLaAlO 4 dielectric resonator at 20 millikelvin'** *Journal of Physics: Condensed Matter* vol 30 issue 1 10.1088/1361-648X/aa9a1e

NC Menicucci, BQ Baragiola, TF Demarie and GK Brennen **'Anonymous broadcasting of classical information with a continuous-variable topological quantum code'** *Physical Review A* vol 97 10.1103/PhysRevA.97.032345

M Goryachev, BT McAllister and ME Tobar **'Axion detection with negatively coupled cavity arrays'** *Physics Letters A* vol 382 issue 33 10.1016/j.physleta.2017.09.016

RJ Chapman, A Karim, Z Huang, ST Flammia, M Tomamichel and A Peruzzo **'Beating the classical limits of information transmission using a quantum decoder'** *Physical Review A* vol 97 10.1103/PhysRevA.97.012315

M Goryachev, S Watt, J Bourhill, M Kostylev and ME Tobar **'Cavity magnon polaritons with lithium ferrite and three-dimensional microwave resonators at milliKelvin temperatures'** *Physical Review B* vol 97 10.1103/PhysRevB.97.155129

M Ringbauer, TR Bromley, M Cianciaruso, L Lami, WYS Lau, G Adesso, AG White, A Fedrizzi and M Piani **'Certification and quantification of multilevel quantum coherence'** *Physical Review X* vol 8 10.1103/PhysRevX.8.041007

The BIGBell Collaboration **'Challenging local realism with human choices'** *Nature* vol 557 10.1038/s41586-018-0085-3

G Milburn and S Shrapnel **'Classical and quantum causal interventions'** *Entropy* vol 20 issue 9 10.3390/e20090687

K Korzekwa, S Czachórski, Z Puchała and K Życzkowski **'Coherifying quantum channels'** *New Journal of Physics* vol 20 10.1088/1367-2630/aaaff3

M Appleby, TY Chien, S Flammia and S Waldron **'Constructing exact symmetric informationally complete measurements from numerical solutions'** *Journal of Physics A: Mathematical and Theoretical* vol 51 issue 16 10.1088/1751-8121/aab4cd

M Frembs, S Roberts and SD Bartlett **'Contextuality as a resource for measurement-based quantum computation beyond qubits'** *New Journal of Physics* vol 20 10.1088/1367-2630/aae3ad

SP Harvey, CGL Bøttcher, LA Orona, SD Bartlett, AC Doherty and A Yacoby **'Coupling two spin qubits with a high-impedance resonator'** *Physical Review B* vol 97 10.1103/PhysRevB.97.235409

XG Croot, SJ Pauka, JD Watson, GC Gardner, S Fallahi, MJ Manfra and DJ Reilly **'Device architecture for coupling spin qubits via an intermediate quantum state'** *Physical Review Applied* vol 10 10.1103/PhysRevApplied.10.044058

C Bény, CT Chubb, T Farrelly and TJ Osborne **'Energy cost of entanglement extraction in complex quantum systems'** *Nature Communications* vol 9 10.1038/s41467-018-06153-w

S Mavadia, CL Edmunds, C Hempel, H Ball, F Roy, TM Stace and M Biercuk **'Experimental quantum verification in the presence of temporally correlated noise'** *NPJ Quantum Information* vol 4 10.1038/s41534-017-0052-0

M Ringbauer, TJ Weinhold, LA Howard, AG White and MR Vanner **'Generation of mechanical interference fringes by multi-photon counting'** *New Journal of Physics* vol 20 10.1088/1367-2630/aabb8d

M Rambach, WYS Lau, S Laibacher, V Tamma, AG White and TJ Weinhold **'Hectometer revivals of quantum interference'** *Physical Review Letters* vol 121 10.1103/PhysRevLett.121.093603

S Singh, N McMahon and GK Brennen **'Holographic spin networks from tensor network states'** Physical Review D vol 97 10.1103/PhysRevD.97.026013

K Goswami, C Giarmatzi, M Kewming, F Costa, C Branciard, J Romero and AG White **'Indefinite causal order in a quantum switch'** *Physical Review Letters* vol 121 10.1103/PhysRevLett.121.090503

M Goryachev, EN Ivanov, S Galliou and ME Tobar **'Inducing strong non-linearities in a phonon trapping quartz bulk acoustic wave resonator coupled to a superconducting quantum interference device'** *Applied Sciences* vol 8 issue 4 10.3390/app8040602

P Webster and SD Bartlett **'Locality-preserving logical operators in topological stabilizer codes'** *Physical Review A* vol 97 10.1103/PhysRevA.97.012330

Publications

R Swaroop Gupta and M Biercuk **'Machine learning for predictive estimation of qubit dynamics subject to dephasing'** *Physical Review Applied* vol 9 10.1103/PhysRevApplied.9.064042

MK Olsen, TW Neely and AS Bradley **'Mesoscopic dynamical differences from quantum state preparation in a bose-hubbard trimer'** *Physical Review Letters* vol 120 10.1103/PhysRevLett.120.230406

M Ringbauer, F Costa, ME Goggin, AG White and A Fedrizzi **'Multi-time quantum correlations with no spatial analog'** *NPJ Quantum Information* vol 37 10.1038/s41534-018-0086-y

A Rosario Hamann, C Müller, M Jerger, M Zanner, J Combes, M Pletyukhov, M Weides, TM Stace and A Fedorov **'Nonreciprocity realized with quantum non-linearity'** *Physical Review Letters* vol 121 10.1103/PhysRevLett.121.123601

LM Norris, D Lucarelli, VM Frey, S Mavadia, MJ Biercuk and L Viola **'Optimally band-limited spectroscopy of control noise using a qubit sensor'** *Physical Review A* vol 98 10.1103/PhysRevA.98.032315

F Rozpędek, T Schiet, LPhuc Thinh, D Elkouss, AC Doherty and S Wehner **'Optimizing practical entanglement distillation'** *Physical Review A* vol 97 10.1103/PhysRevA.97.062333

C Müller, S Guan, N Vogt, JH Cole and TM Stace **'Passive on-chip superconducting circulator using a ring of tunnel junctions'** *Physical Review Letters* vol 120 10.1103/PhysRevLett.120.213602

TA Bell, G Gauthier, TW Neely, H Rubinsztein-Dunlop, MJ Davis and MA Baker **'Phase and micromotion of Bose-Einstein condensates in a time-averaged ring trap'** *Physical Review A* vol 98 10.1103/PhysRevA.98.013604

SN Saadatmand, SD Bartlett and IP McCulloch **'Phase diagram of the quantum Ising model with long-range interactions on an infinite-cylinder triangular lattice'** *Physical Review B* vol 97 10.1103/PhysRevB.97.155116

BM Ayeni, RNC Pfeifer and GK Brennen **'Phase transitions on a ladder of braided non-Abelian anyons'** *Physical Review B* vol 98 10.1103/PhysRevB.98.045432

C Hempel, C Maier, J Romero, J McClean, T Monz, H Shen, P Jurcevic, B Lanyon, P Love, R Babbush, A Aspuru-Guzik, R Blatt and C Roos **'Quantum chemistry calculations on a trapped-ion quantum simulator'** *Physical Review X* vol 8 10.1103/PhysRevX.8.031022

MA Hosain, JM Le Floch, J Krupka and ME Tobar **'Rigorous ESR spectroscopy of Fe 3+ impurity ion with oxygen vacancy in ferroelectric SrTiO 3 crystal at 20 mK'** *Journal of Physics: Condensed Matter* vol 30 issue 29 10.1088/1361-648X/aacc05

SD Bartlett, GK Brennen and A Miyake **'Robust symmetry-protected metrology with the Haldane phase'** *Quantum Science and Technology* vol 3 10.1088/2058-9565/aa9c56

YY Lai, GD Lin, J Twamley and HS Goan **'Single-nitrogen-vacancy-center quantum memory for a superconducting flux qubit mediated by a ferromagnet'** *Physical Review A* vol 97 10.1103/PhysRevA.97.052303

FK Malinowski, F Martins, TB Smith, SD Bartlett, AC Doherty, PD Nissen, S Fallahi, GC Gardner, MJ Manfra, CM Marcus and F Kuemmeth **'Spin of a multielectron quantum dot and its interaction with a neighboring electron'** *Physical Review X* vol 8 10.1103/PhysRevX.8.011045

J Romero, R Babbush, JR McClean, C Hempel, PJ Love and A Aspuru-Guzik **'Strategies for quantum computing molecular energies using the unitary coupled cluster ansatz'** *Quantum Science and Technology* vol 4 10.1088/2058-9565/aad3e4

BT McAllister, G Flower, LE Tobar and ME Tobar **'Tunable supermode dielectric resonators for axion dark-matter haloscopes'** *Physical Review Applied* vol 9 10.1103/PhysRevApplied.9.014028

DK Tuckett, SD Bartlett and ST Flammia **'Ultrahigh error threshold for surface codes with biased noise'** *Physical Review Letters* vol 120 10.1103/PhysRevLett.120.050505

F Costa, M Ringbauer, ME Goggin, AG White and A Fedrizzi **'Unifying framework for spatial and temporal quantum correlations'** *Physical Review A* vol 98 10.1103/PhysRevA.98.012328

MA Hosain, JM Le Floch, J Krupka, JF Bourhill and ME Tobar **'Whispering gallery mode dielectric spectroscopy of SrLaAlO4 at milliKelvin temperatures'** *Journal of Applied Physics* vol 123 10.1063/1.5029941

Key Performance Indicators

	TARGET 2018	RESULT 2018
RESEARCH OUTPUTS AND SERVICE		
Peer-reviewed journal articles	30	41*
High impact publications (citations in top 20% most cited papers in fields of Physics)	5	4
International and national Advisory Boards in the research fields of Centre	2	5
Keynote and plenary addresses at international and national conferences	2	3
Editorial boards for international peer reviewed journals in the research fields of the Centre	2	2
Program Committees for international and national conferences	8	3
Invited talks/papers at international meetings	20	18
PEOPLE AND TRAINING		
Training courses held by the Centre	3	2
Workshops/conferences held/offered by the Centre	3	5
New postdoctoral researcher working on Centre research	10	8
New Honours supervised by Centre researchers	5	3
New PhDs supervised by Centre researchers	5	6
New Masters supervised by Centre researchers	0	2
New Associate Investigators	3	20
PhD completions	0	8
Honours completions	5	7
EQUS mentoring program	1	1
Delivery of EQUS induction program	1	1

* 25 of these publications did not use the funding code CE170100009

Key Performance Indicators

	TARGET 2018	RESULT 2018
COMMUNICATION AND OUTREACH		
Talks open to the public	5	6
Talks/presentations/briefings to government	2	6
Talks/presentations/briefings to industry/ business/end-users	2	2
Annual training for STEM teachers	60 teachers	4 teachers
Outreach activities for school students	12	13
Industry engagement events	1	1
NEW COLLABORATIONS		
New industry collaborative relationship	0	0
New academic collaborative relationship	0	12
EQUITY		
Female Higher Degree Research (HDR) students	15%	19%
Female postdoctoral researchers	10%	15%

Income and expenditure report

	2018 Actuals $	2019 Forecast $	2020 Forecast $
INCOME			
ARC Centre of Excellence Grant			
ARC Centre of Excellence Grant[1]	9,355,762	4,703,512	4,824,023
Administering and Collaborating Organisation Contributions			
The University of Queensland	538,160	538,160	538,160
The University of Sydney	365,555	365,555	365,555
Macquarie University	151,452	151,452	151,452
Macquarie University – Scholarships[2]	-	113,991	113,991
The University of Western Australia	142,207	142,207	142,207
The Australian National University[3]	65,784	39,470	52,627
Partner Organisation Contributions			
Defence Science and Technology	100,000	100,000	100,000
University of Ulm	4,688	4,688	4,688
TOTAL INCOME	**10,723,608**	**6,159,035**	**6,292,703**
EXPENDITURE			
Salaries	2,602,221	3,509,381	3,185,265
Scholarships	203,877	379,161	334,727
Equipment	367,227	402,400	350,500
Research Maintenance & Consumables	228,098	447,011	432,769
Travel	500,939	568,634	608,653
Admin, Operational & Other	239,416	466,678	471,678
TOTAL EXPENDITURE	**4,141,779**	**5,773,265**	**5,383,592**
ANNUAL SURPLUS/(DEFICIT)	**6,581,829**	**385,770**	**909,111**
BALANCE BROUGHT FORWARD FROM PREVIOUS YEAR	**0**	**6,581,829**	**6,967,599**
TOTAL CARRYFORWARD TO NEXT YEAR[4]	**6,581,829**	**6,967,599**	**7,876,710**

Notes:

1 ARC income in 2018 includes two years of ARC income due to the Centre delaying its commencement to 2018 instead of 2017. Consequently, there will always be a large carryforward into the next year. ARC income forecast for 2019 and 2020 is based on a 1.5% year-on-year indexation increase.

2 MQ has not disbursed funds for scholarships in 2018. MQ will, in accordance with Schedule 1 of the Participants Agreement, disburse funds to the total of $455,964 for scholarships over the remaining life of the Centre with the first disbursement of funds to commence in 2019.

3 ANU contributed an additional 25% of its 2019 cash contribution in 2018 ($13,157). Consequently, the 2019 forecast is reduced from $52,627 to $39,470.

4 The large carryforward from 2018 to 2019 is due to: $4,500,000 of the Centre's 2019 budget received in 2018 due to the Centre delaying its commencement to 2018 instead of 2017; $144,793 of 2018 ARC funds received in 2018 to be distributed to projects and portfolios in 2019 due to budget timing differences; $205,762 of ARC indexation for two years yet to be distributed; $1,718,117 of annual surplus funds in research projects, portfolios and Centre Strategic Funds; $13,157 prepayment of ANU contributions in note 3

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