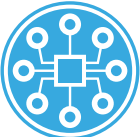
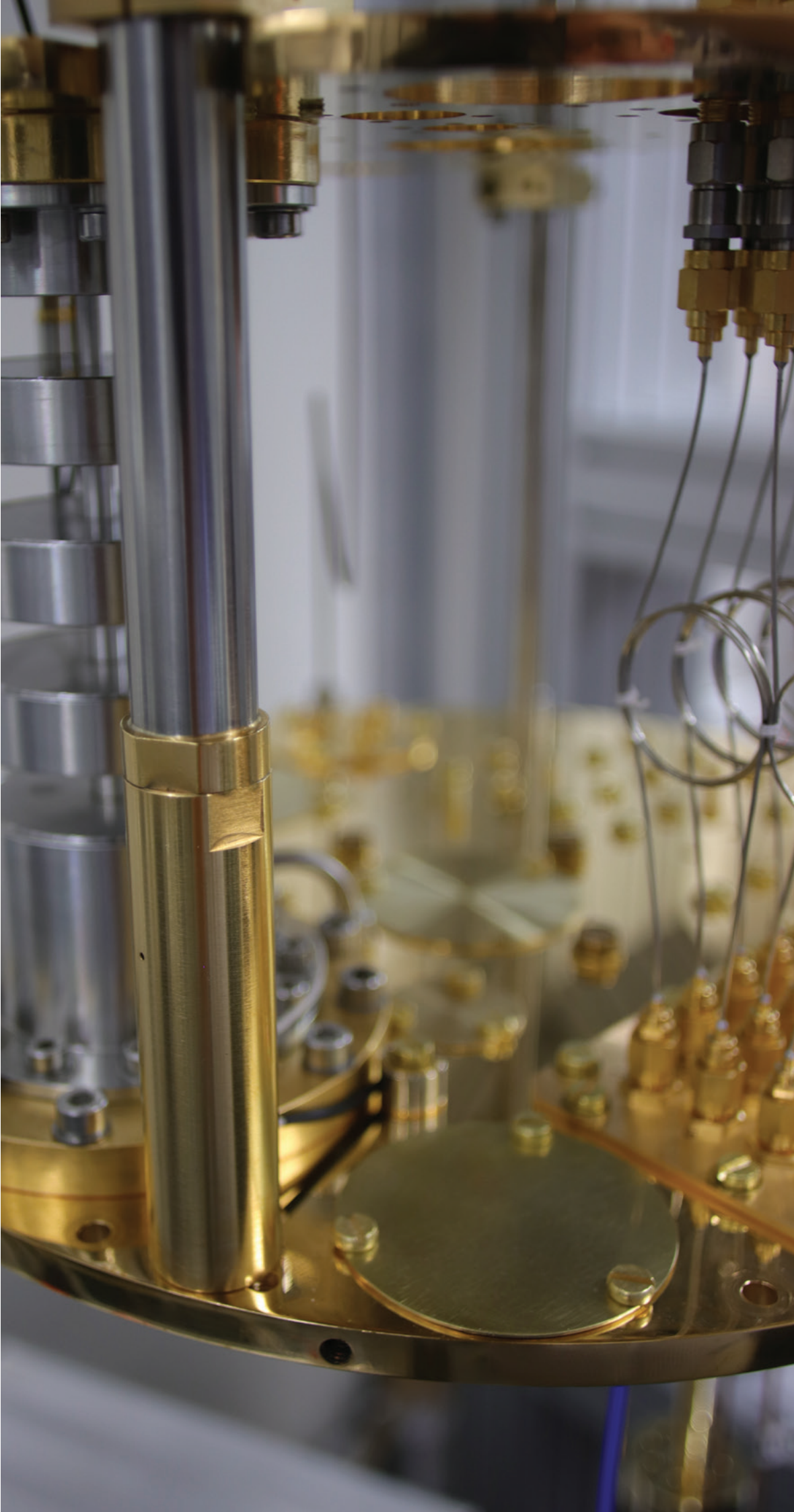


ANNUAL  
REPORT  
**2020**



**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**

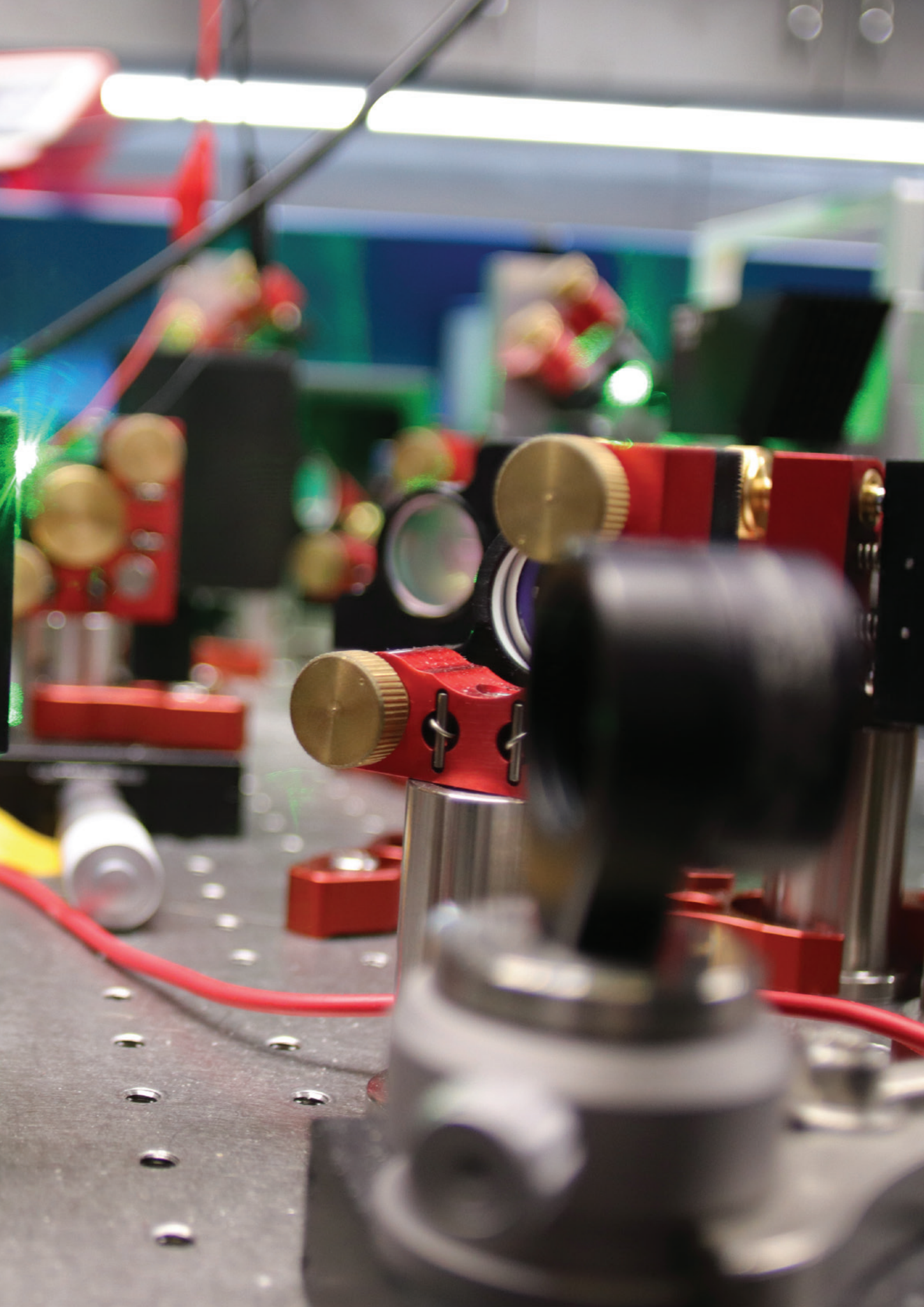
EQUS acknowledges the Traditional Owners of Country throughout Australia and their continuing connection to lands, waters and communities. We pay our respects to Aboriginal and Torres Strait Islander cultures and to Elders past and present. We honour and respect the long tradition of knowledge-making, including in the STEM disciplines of science, technology, engineering and mathematics, of First Nations People.

**Cover image**

Dilution fridge in the Superconducting Quantum Devices lab

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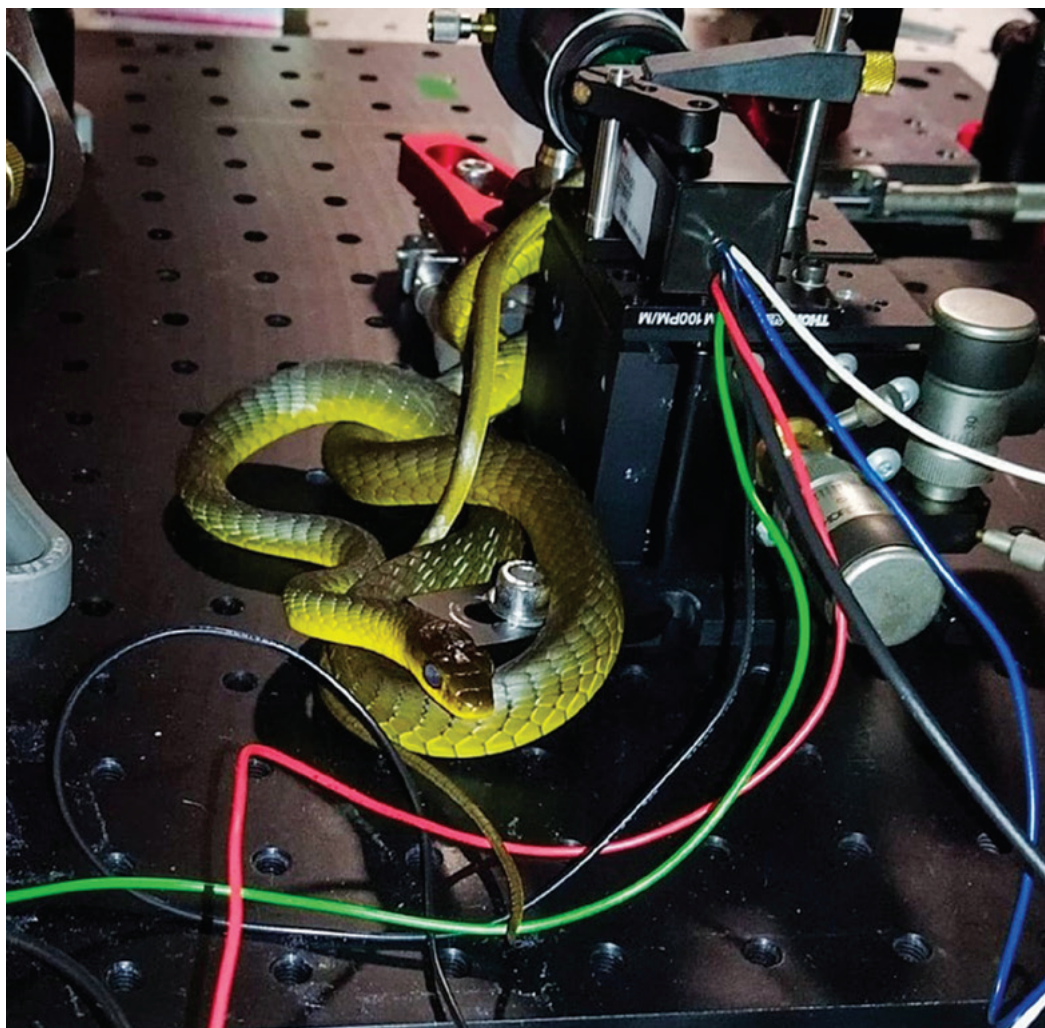


## Executive summary

Quantum technologies use the properties of quantum mechanics for practical applications. They are found in our everyday lives, for example, in smart phones and cars, and in industrial applications in manufacturing, engineering and imaging.

Today's technology captures only a small fraction of the potential of quantum physics. New developments in research and engineering mean a new generation of technologies. These technologies have potential in fields such as health, telecommunications and finance, and will benefit business and society.

The Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS) is a seven-year investment of more than \$40 million by the Australian government in quantum technologies. EQUS is solving the most challenging research problems at the interface of basic quantum physics and engineering, working with partners in industry to translate discoveries into practical applications and devices, and training a new generation of scientists in cutting-edge research, innovation and entrepreneurialism.



**Far left**  
Inside the  
Queensland  
Quantum  
Optics lab

**Left**  
Surprise visitor  
in the Diamond  
Nanoscience lab

## Director's update

Well, that was ... quite a year.

Twelve months ago we were witnessing catastrophic bushfires, and their devastating effects, across Australia. The effects on the Centre ranged from severe air pollution at many of our nodes, through to the last-minute cancellation of our long-anticipated workshop for high-school teachers as part of STEM X Academy. (We look forward to running that under better conditions in the future!)

Once the flames died down we were looking forward to another quantum-filled, but otherwise uneventful, year...

As it did for everyone we know, the global pandemic of 2020 presented many challenges for EQUUS<sup>1</sup>. What made these challenges bearable was the spirit and verve with which our colleagues met and overcame them all. Nearly everyone worked from home at some stage: experimenters locked out of their labs conducted numerical and design research while catching up on their paper backlogs; despite forgoing their normal caffeine haunts, our theorists had an amazingly productive year; and our professional team kept the Centre's body and soul going while maintaining their sense of humour. We all got to see each other's homes, families and amusing choice of Zoom backgrounds.

We have been very lucky to come through relatively unscathed: we have friends and family around the world who have seen severe health and livelihood impacts. Members of the Centre became part of the dialogue surrounding the global #BlackLivesMatter movement and the #ShutDownSTEM #ShutDownAcademia initiative, which reminded us of the long-standing inequities and injustices that our BIPOC colleagues face daily, and the continuing barriers to equity and inclusion in STEM fields and society.

A definite silver lining of 2020 has been the increased public interest and engagement in evidence-based interventions, and in scientific consultation. New Chief Investigator Sally Shrapnel's background as both medical practitioner and data scientist saw her leading a large-scale COVID-19-related study.

On the quantum front, CSIRO launched a report—*Growing Australia's Quantum Technology Industry*—on Australia's current quantum technology ecosystem and provided a roadmap to the creation of 16,000 jobs and \$4 billion annual revenue by 2040. (These figures are admirably conservative: we believe the impact on jobs and revenue will be much greater.) As our community evolves an inspiring

<sup>1</sup> To top it off, EQUUS researchers demonstrated that paradox-free time travel is theoretically possible, meaning that even if we could go back in time, there'd be no way to prevent the year's events.

## Director's update

approach to rally around, and truly aspirational goals, we see the potential to grow an industry sector that will make a significant contribution to Australia's economy and society.

EQUUS is contributing to this growth on many fronts. Our internal programs continue to provide our researchers with the necessary technical knowledge, communication skills and entrepreneurial spirit. Some programs had to be scaled back or postponed because of the pandemic, but we look forward to a full program of events in 2021.

Our research continues to be recognised as world-class. Some highlights include:

- Development of a new way to measure a tiny force known as the Casimir force and to use it to manipulate and control objects
- Publication of a major review of the thermodynamics of clocks
- Experimental verification of a counterintuitive idea from quantum theory, that ignorance of the whole does not necessarily imply ignorance of the parts.

We developed two new flagship research programs, the 1kQubit Flagship and the Quantum Clock Flagship, which will enhance collaboration and build on the Centre's existing strengths to develop quantum technologies that will benefit society. The Translational Research Program inaugurated research translation programs for our members and awarded funding to five projects.

2020 saw us welcome two new Chief Investigators, Dr Jacqui Romero and Dr Sally Shrapnel, and we are looking forward to welcoming six more from 1 January 2021. We also fondly farewelled three Chief Investigators, Professor Jason Twamley, Professor Steven Flammia and Dr John McFerran, as well as our founding Chief Operations Officer, Lisa Walker. We wish them the very best as they move on to new challenges!

I am proud to say EQUUS folk were recognised by prestigious prizes, including:

- Professor Stephen Bartlett was elected a Fellow of the American Physical Society
- Professor Warwick Bowen was awarded the Barry Inglis Medal from Australia's National Measurement Institute
- Dr Jacqueline Romero was named as one of the 40 Under 40 Most Influential Asian-Australians
- Dr Matt van Breugel was awarded a Stanford Australia Foundation-CSIRO scholarship
- Dr Ben McAllister was awarded the EQUUS Director's Prize.

Now, let's try this again. All the best for the year ahead...

**Professor Andrew White, Director**  
**Professor Tom Stace, Deputy Director**

**Left**  
Inside the Quantum  
Technology lab

# Governance

## ADVISORY COMMITTEE

The Advisory Committee contributes to the development of strategies and vision for the Centre's future and supports links between academia, industry and government. Professor Vicki Sara stepped down as Chair of the Advisory Committee at the end of 2019; the role has been taken over by Professor Christine Williams. The committee met virtually in August 2020.

**Right**  
Professor  
Christine  
Williams

**Far right**  
Professor Sir  
Peter Knight



## SCIENTIFIC

## ADVISORY COMMITTEE

The Scientific Advisory Committee advises the Centre Director on the strategic direction of current and future scientific research. The Scientific Advisory Committee met virtually as part of the EQUUS Annual Workshop in December 2020.



The Advisory Committee consists of:

- **Professor Christine Williams (Chair)**, Chair at Life Sciences Queensland, Chair of the Women in Economics Network in Queensland, former Queensland Chief Scientist
- **Dr Gregory Clark ac**, Chair at KaComm Communications
- **Dr Bronwyn Evans**, Director at GME, CEO at Engineers Australia
- **Dr Ben Greene**, CEO at Electro Optic Systems
- **Dr Anthony Szabo**, Research Leader, Spectrum Sensing and Shaping, Cyber and Electronic Warfare Division, Defence Science and Technology Group
- **Professor Jim Williams AM FAA FTSE**, Emeritus Professor, Department of Electronic Materials Engineering, Australian National University

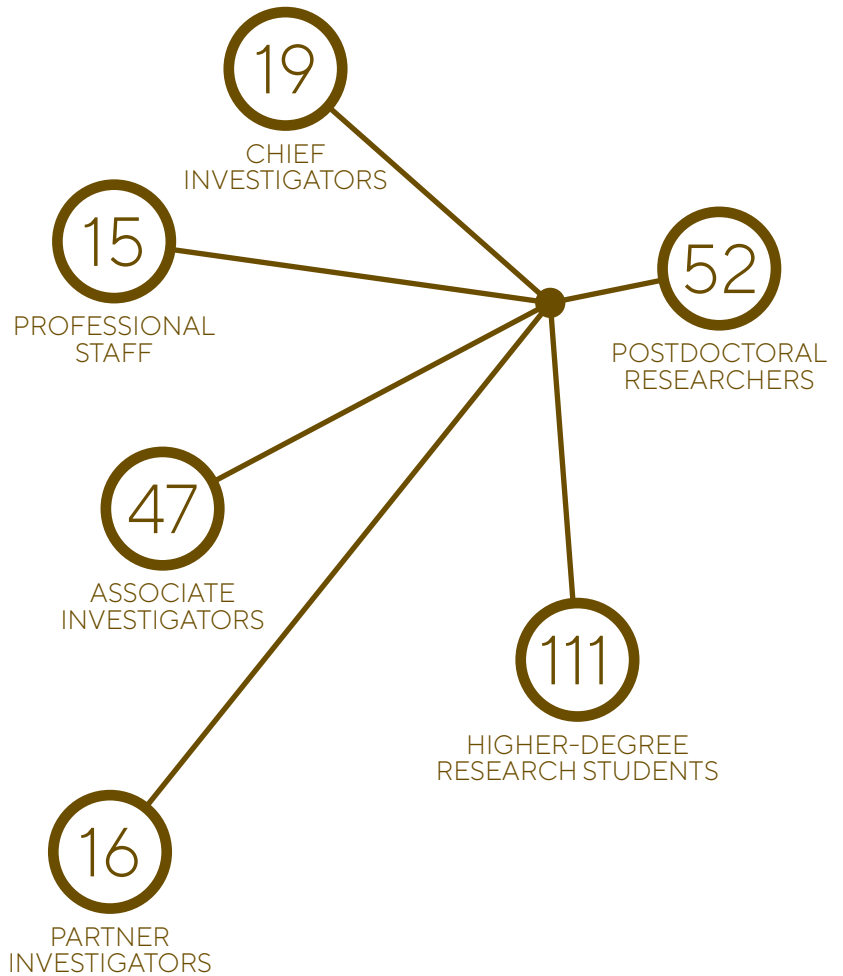
The Scientific Advisory Committee consists of:

- **Professor Sir Peter Knight FRS (Chair)**, Emeritus Professor at Imperial College London, principal of the Kavli Royal Society International Centre, former president of the Institute of Physics and the Optical Society of America
- **Professor Alain Aspect**, Laboratoire Charles Fabry, Institut d'Optique
- **Professor Rainer Blatt**, Institute of Experimental Physics, Universität Innsbruck
- **Professor John Clarke**, Department of Physics, University of California, Berkeley
- **Professor Birgitta Whaley**, Whaley Research Group, University of California, Berkeley

# Team

## CHIEF INVESTIGATORS

Andrew White *UQ*  
Tom Stace *UQ*  
Arkady Fedorov *UQ*  
Daniel Shaddock *ANU*  
David Reilly *USYD*  
Gavin Brennen *MQ*  
Gerard Milburn *UQ*  
Halina Rubinsztein-Dunlop *UQ*  
Jacqui Romero *UQ*  
Jason Twamley *MQ*  
John McFerran *UWA*  
Matthew Davis *UQ*  
Michael Biercuk *USYD*  
Michael Tobar *UWA*  
Sally Shrapnel *UQ*  
Stephen Bartlett *USYD*  
Steven Flammia *USYD*  
Thomas Volz *MQ*  
Warwick Bowen *UQ*



## PROFESSIONAL STAFF

Angela Bird *UQ*  
Belinda Wallis *MQ*  
Cheryl Stephenson *UQ*  
Christina Dobson *UQ*  
Deb Gooley *USYD*  
Kristen Harley *UQ*  
Linda Barbour *UWA*  
Lisa Walker *UQ*  
Michael Harvey *UQ*  
Sareh Rajabi *ANU*  
Satpal Sahota *USYD*

## POSTDOCTORAL RESEARCHERS

Adil Gangat *UQ*  
Adrian Chapman *USYD*  
Aidan Strathearn *UQ*  
Alexis Jouan *USYD*  
Andreas Sawadsky *UQ*  
Andrew Groszek *UQ*  
Andrew Wade *ANU*  
Arghavan Safavi-Naini *UQ*  
Ben Brown *USYD*  
Ben McAllister *UWA*  
Christina Giarmatzi *UTS*  
Christopher Baker *UQ*  
Cornelius Hempel *USYD*  
Cyril Laplane *MQ*  
David Tuckett *USYD*  
Deniz Stiegemann *UQ*  
Elizabeth Bridge *UQ*  
Fabio Costa *UQ*  
Glen Harris *UQ*  
Igor Marinkovic *UQ*  
James Bennett *UQ*  
James Witt *USYD*  
Joshua Combes *UQ*  
Lars Madsen *UQ*  
Lewis Williamson *UQ*  
Lorenzo Scarpelli *MQ*  
Lyle Roberts *ANU*  
Magdalena Zych *UQ*

## Team

Marcelo Pereira de Almeida *UQ*  
Marcus Appleby *USYD*  
Markus Rambach *UQ*  
Matthew van Breugel *MQ*  
Mattias Johnsson *MQ*  
Nathan McMahon *UQ*  
Nicolas Mauranyapin *UQ*  
Paul Altin *ANU*  
Prasanna Pakkiam *UQ*  
Raditya Weda Bomantara *USYD*  
Ramil Nigmatullin *MQ*  
Reece Roberts *MQ*

Robert Wolf *USYD*  
Robin Harper *USYD*  
Sarath Raman Nair *MQ*  
Tara Roberson *UQ*  
Terry Farrelly *UQ*  
Till Weinhold *UQ*  
Ting Rei Tan *USYD*  
Torsten Gaebel *USYD*  
Walter Wasserman *UQ*  
Xin (Eric) He *UQ*  
Yauhen (Eugene) Sachkou *UQ*  
Zijun (Cindy) Zhao *UWA*

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### TECHNICAL AND SUPPORT STAFF

Eric Howard *MQ*  
Peggy Atkinson *UWA*

Steven Osborne *UWA*  
Yuanyuan Yang *USYD*

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### PHD STUDENTS

Aaron Quiskamp *UWA*  
Abithaswathi Muniraj Saraswathy *UQ*  
Akram Youssry *UTS*  
Alejandro Gómez Frieiro *UQ*  
Alex Pritchard *UQ*  
Alex Terrasson *UQ*  
Alexander Rischka *USYD*  
Alistair Robertson Milne *USYD*  
Amy van der Hel *UQ*  
Anatoly Kulikov *UQ*  
Andrés Rosario Hamann *UQ*  
Andrew Wood *MQ*  
Art Harol *USYD*  
Arkin Tikku *USYD*  
Benjamin Dix-Matthews *UWA*  
Bradley Mommers *UQ*  
Brendan Harlech-Jones *USYD*  
Carolyn Wood *UQ*  
Catxere Casacio *UQ*  
Chao Meng *UQ*  
Christiaan Bekker *UQ*  
Dat Thanh Le *UQ*

Edgar Tanuarta *USYD*  
Elija Perrier *UTS*  
Elisabeth Wagner *MQ*  
Emily Rose Rees *ANU*  
Erick Romero Sanchez *UQ*  
Felix Thomsen *USYD*  
Fernando Gotardo *UQ*  
Graeme Flower *UWA*  
Guillaume Gauthier *UQ*  
Hamish Greenall *UQ*  
Harshit Verma *UQ*  
Iftekher Chowdhury *MQ*  
Ignazio Cristina *USYD*  
James Spollard *ANU*  
James White *MQ*  
Jason Pillay *UQ*  
Jemy Geordy *MQ*  
Jihun Cha *UQ*  
Jobin Thomas Valliyakalayil *ANU*  
Jovian Delaforce *UQ*  
Juliette Soule *USYD*  
Kaumudibikash Goswami *UQ*

# Team

Kemian Qin *UQ*  
Kwan Goddard-Lee *UQ*  
Larnii Booth *UQ*  
Larry Cohen *USYD*  
Leo Sementilli *UQ*  
Leonardo Morais *UQ*  
Lewis Howard *UQ*  
Lirandë Pira *UTS*  
Mahdi Qaryan *UQ*  
Maria Quadeer *UTS*  
Mark Webster *USYD*  
Michael Kewming *UQ*  
Miles Malone *UQ*  
Ming Su *UQ*  
Nor Azwa Zakaria *UQ*  
Parth Girdhar *USYD*  
Paul Sibley *ANU*  
Paul Webster *USYD*  
Pradeepkumar Nandakumar *UQ*  
Prahlad Warszawski *USYD*  
Raphael Abrahão *UQ*

Raymond Harris *UQ*  
Riddhi Gupta *USYD*  
Rob Harris *UQ*  
Rohit Navarathna *UQ*  
Sam Smith *USYD*  
Samuel Bartee *USYD*  
Samuel Elman *USYD*  
Soroush Khademi *UQ*  
Stefan Forstner *UQ*  
Steven Waddy *USYD*  
Thomas Boele *USYD*  
Thomas Smith *USYD*  
Timothy Evans *USYD*  
Tyler Jones *UQ*  
Varun Prakash *UQ*  
W. Y. Sarah Lau *UQ*  
William Campbell *UWA*  
William Pol *USYD*  
Yasmine Sfindla *UQ*  
Zach Cristina *USYD*  
Zhonghua Ma *UQ*

---

## MASTER'S STUDENTS

Catriona Thomson *UWA*  
Cong Yi *UWA*  
Elrina Hartman *UWA*  
Jay Mummery *UWA*  
Lyra Cronin *MQ*

Nabomita Roy-Mukty *MQ*  
Omar Muhieddine *MQ*  
Tim Wohlers-Reichel *USYD*  
Timothy Newman *USYD*

---

## HONOURS STUDENTS

Anthony O'Rourke *USYD*  
Benjamin Field *USYD*  
Callam Manning *UQ*  
Callum Sambridge *ANU*  
Cameron Jones *USYD*  
Evan Hockings *USYD*  
Fatemeh Mohit *UQ*  
Germain Tobar *UQ*

Jack Berry *USYD*  
Lauren McQueen *UQ*  
Liam Bond *UQ*  
Lilani Toms-Hardman *UWA*  
Mackenzie Shaw *USYD*  
Nicholas Fazio *USYD*  
Simeon Simjanovski *UQ*  
Timothy Harris *UQ*

# Team

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## PARTNER INVESTIGATORS

Alessandro Fedrizzi *Herriot-Watt University*

Alexia Auffeves *Institut Néel*

Andreas Wallraff *ETH Zürich*

Fedor Jelezko *Ulm University*

Holger Mueller *UC Berkeley*

Ian Walmsley *University of Oxford*

Jörg Schmiedmayer *TU Wien*

Lorenza Viola *Dartmouth College*

Markus Aspelmeyer *University of Vienna*

Michael Wouters *National Measurement Institute*

Oriol Romero-Isart *IQOQI*

Pascale Senellart-Mardon *CNRS*

Peter Wolf *CNRS*

Peter Zoller *IQOQI*

Robyn Starr *CNTS*

Wolfram Pernice *Universität Münster*

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## ASSOCIATE INVESTIGATORS

Alán Aspuru-Guzik *University of Toronto*

Alexei Gilchrist *MQ*

Arne Grimsmo *USYD*

Behnam Tonekaboni *Griffith University*

Ben Baragiola *RMIT University*

Chris Ferrie *UTS*

Clemens Müller *ETH Zürich and IBM*

Daniel Burgarth *MQ*

David Gozzard *UWA*

Felix Miranda *NASA*

Ian Manchester *USYD*

Isaac Kim *USYD*

Ivan Kassal *USYD*

Jacinda Ginges *UQ*

Jennifer Ogilvie *University of Michigan*

Jingbo Wang *UWA*

Joan Leach *ANU*

John Bartholomew *USYD*

Jonathan Home *ETH Zürich*

Kae Nemoto *NII Tokyo*

Kavan Modi *Monash University*

Lachlan Rogers *University of Newcastle*

Lawrence Lee *UNSW*

Lute Maleki *OEWaves Inc.*

Marco Tomamichel *UTS*

Mark Baker *UQ*

Martin Ringbauer *Universität Innsbruck*

Matt Woolley *UNSW*

Maxim Goryachev *UWA*

Maxime Richard *CNRS*

Michael Hush *USYD*

Michael Vanner *Imperial College London*

Nathan Langford *UTS*

Nicholas King *USYD*

Peter Lodahl *University of Copenhagen*

Peter Rohde *UTS*

Robert Casson *University of Adelaide*

Salah Sukkarieh *USYD*

Samantha Hood *Imperial College London*

Sascha Schediwy *UWA*

Sujatha Raman *ANU*

Terence Rudolph *Imperial College London*

Tyler Neely *UQ*

Victor Flambaum *UNSW*

Vladimir Kruglov *UQ*

William Munro *NTT Basic Research Laboratories*

Yuval Sanders *MQ*

## COMPLETIONS

### PHD

Anatoly Kulikov UQ

*In situ quantum control over superconducting qubits*

Andrew Wood MQ

*Exploring the physics of mechanically tunable microcavity polaritons*

Christiaan Bekker UQ

*Integrated cavity opto-electromechanics: electrical tuning and control of optomechanical systems*

Erick Romero Sanchez UQ

*Phononics: engineering and control of acoustic fields on a chip*

Ignazio Cristina USYD

*Initialisation, control and simulation of spin systems*

Jason Pillay UQ

*Matrix product state study of strongly-interacting systems and quantum phase transitions*

Prahlad Warszawski USYD

*Quantum trajectories for, and as, understanding*

Raphael Abrahão UQ

*Frontiers of quantum optics: photonics tolls, computational complexity, quantum metrology, and quantum correlations*

Riddhi Gupta USYD

*Robotic control and machine learning for the characterization and control of qubits*

Sarath Raman Nair MQ

*Engineering room-temperature quantum magnetic sensors with fibre cavity diamond lasers*

Zach Cristina USYD

*Tailoring surface codes: improvements in quantum error correction with biased noise*

### MASTER'S

Cong Yi UWA

*Performance limits of synchronous frequency-to-voltage converter*

Elrina Hartman UWA

*Dark matter search: towards new methods of cryogenic WIMP detection*

Nabomita Roy-Mukty MQ

*Super absorption of light in spin ensembles*

Omar Muhieddine MQ

*A room-temperature diamond maser*

Timothy Newmann USYD

*Hardware and methods for scaling up quantum information experiments*

### HONOURS

Anthony O'Rourke USYD

*Towards modelling noise in the GKP quantum error-correcting code*

Benjamin Field USYD

*Simulation of measurement by a novel optical very long baseline intensity interferometer*

Callam Manning UQ

*Looking for the superfluid fountain effect in a Bose-Einstein condensate*

Callum Sambridge ANU

*The weak signal limit of coherent laser ranging*

Cameron Jones USYD

*Protected Clifford gates for Majorana zero modes using adiabatic evolutions*

Evan Hockings USYD

*Scalable Clifford noise characterisation*

Felix Thomsen USYD

*Decoding correlated errors with topological codes for quantum computing*

Jack Berry USYD

*Exploitation of symmetry to find optimal quantum codes and decoders*

Liam Bond UQ

*Robust state preparation in the Dicke model*

Lilani Toms-Hardman UWA

*Isotope shift spectroscopy with atomic clock transitions*

Mackenzie Shaw USYD

*Hardware-efficient scheme for Clifford circuits in GKP superconducting qubits*

Nicholas Fazio USYD

*Thinking about magic; universal quantum computing in the NISQ regime*

Timothy Harris UQ

*Many-body dynamics of a dipolar quantum simulator*

## Life after EQUUS

### ALUM UPDATE

#### DR RIDDHI GUPTA

Dr Gupta is a research staff member in the Quantum Group at IBM, based in Sydney, working on demonstrations of quantum computing theory and applications. She is helping to bring near-term applications of quantum computing to reality by considering open research problems in quantum error correction, chemistry and finance.



Her PhD—completed in 2020 under the supervision of Chief Investigator Professor Michael Biercuk and Professor Andrew Doherty at USYD—brought together insights from classical control engineering and robotics to develop algorithms to address decoherence in quantum computing hardware. Dr Gupta proposed techniques for characterising classical noise correlations and performance variations in near-term quantum devices using single-qubit projective measurements, focusing on the

central tasks of qubit state estimation and prediction for measurement sequences that are either temporally or spatially correlated.

As a PhD student, Dr Gupta was involved in EQUUS' Equity in Quantum Physics and Mentoring and Career Development committees. She represented EQUUS at Soapbox Science and was awarded the 2019 Director's Prize for exceptional contributions to the Centre.

Dr Gupta said that EQUUS provided a great opportunity to meet physicists who have come into the field with a range of different experiences and outlooks. "It was a great experience to work with others on how to strive for betterment as part of an institution we cared about. EQUUS was a great source of support and learning so thanks for a wonderful experience!"

# Life after EQUUS

## PROFILES



**Professor Steven Flammia**

### **Amazon Web Services Center for Quantum Computing**

Chief Investigator Professor Steven Flammia left EQUUS in May 2020 for Pasadena, California, where he works at the Amazon Web Services Center for Quantum Computing.



**Professor Jason Twamley**

### **Okinawa Institute of Science and Technology Graduate University**

Chief Investigator Professor Jason Twamley left EQUUS in June 2020 to lead the Quantum Machines Unit at the Okinawa Institute of Science and Technology Graduate University in Japan.



**Dr W. Y. Sarah Lau**

### **Finisar**

After completing a PhD, Dr W. Y. Sarah Lau joined Finisar's Brisbane office as an optical engineer.



**Dr Andrew Wood**

### **Hypercube Scientific**

After completing a PhD, Dr Andrew Wood joined Hypercube Scientific as a scientific consultant, based in Sydney.



**Peggy Atkinson**

### **Australian Bureau of Meteorology**

After working as a research assistant, Peggy Atkinson moved from Perth to Melbourne to work as a duty forecaster at the Australian Bureau of Meteorology.



**Liam Bond**

### **Centrum Wiskunde & Informatica**

After completing Honours, Liam Bond moved to the Netherlands to do a PhD with EQUUS alumna Dr Arghavan Safavi-Naini at Centrum Wiskunde & Informatica (CWI).

# Collaborators

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



## Research

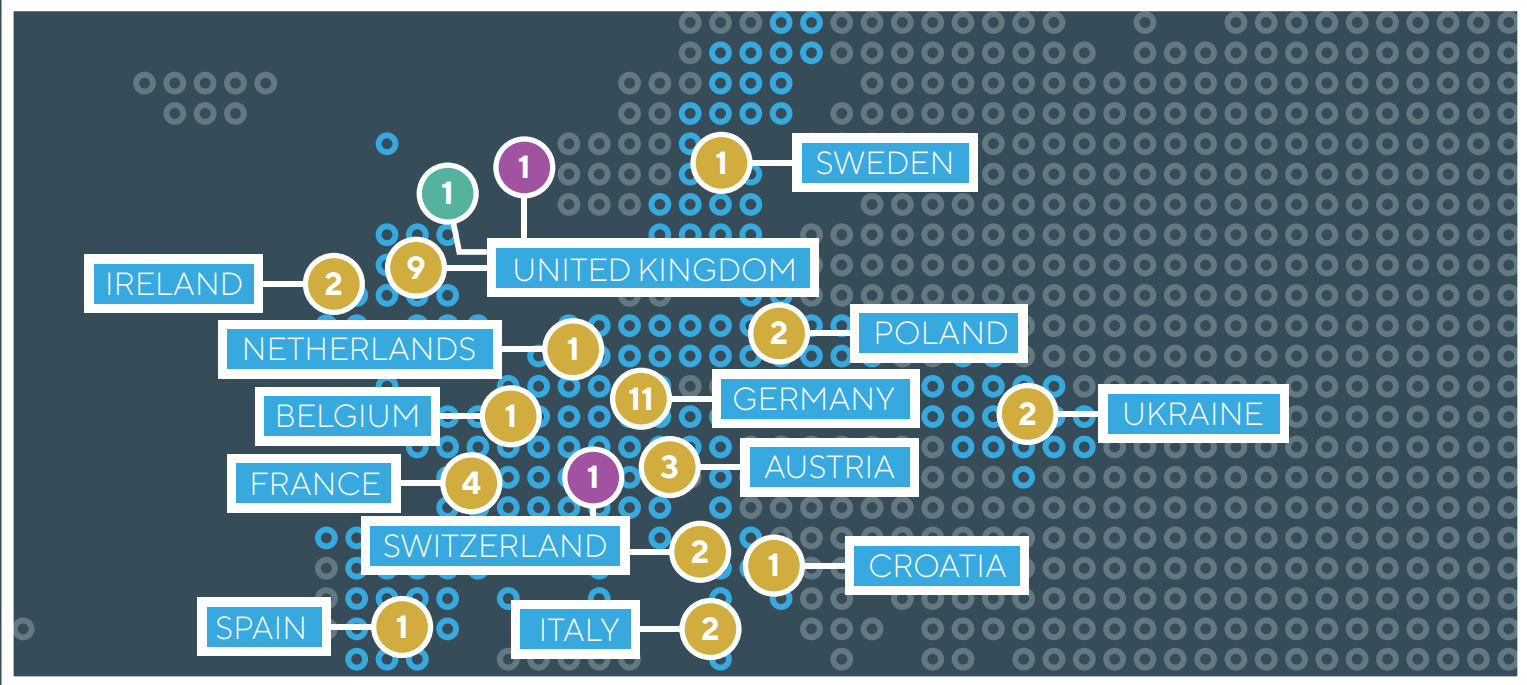
We are actively collaborating with researchers across the globe. In 2020 EQUS researchers collaborated with researchers from 97 institutions in 27 countries.

## Industry

In 2020 we partnered with eight organisations to continue our work in scientific discovery and technology development.

## Impact

EQUS contributes to Australia's economy, security and environment. In 2020 we provided briefings, support, outreach and/or advice to 18 national and international bodies.



## 2020 highlights

### NATIONAL QUANTUM STRATEGY

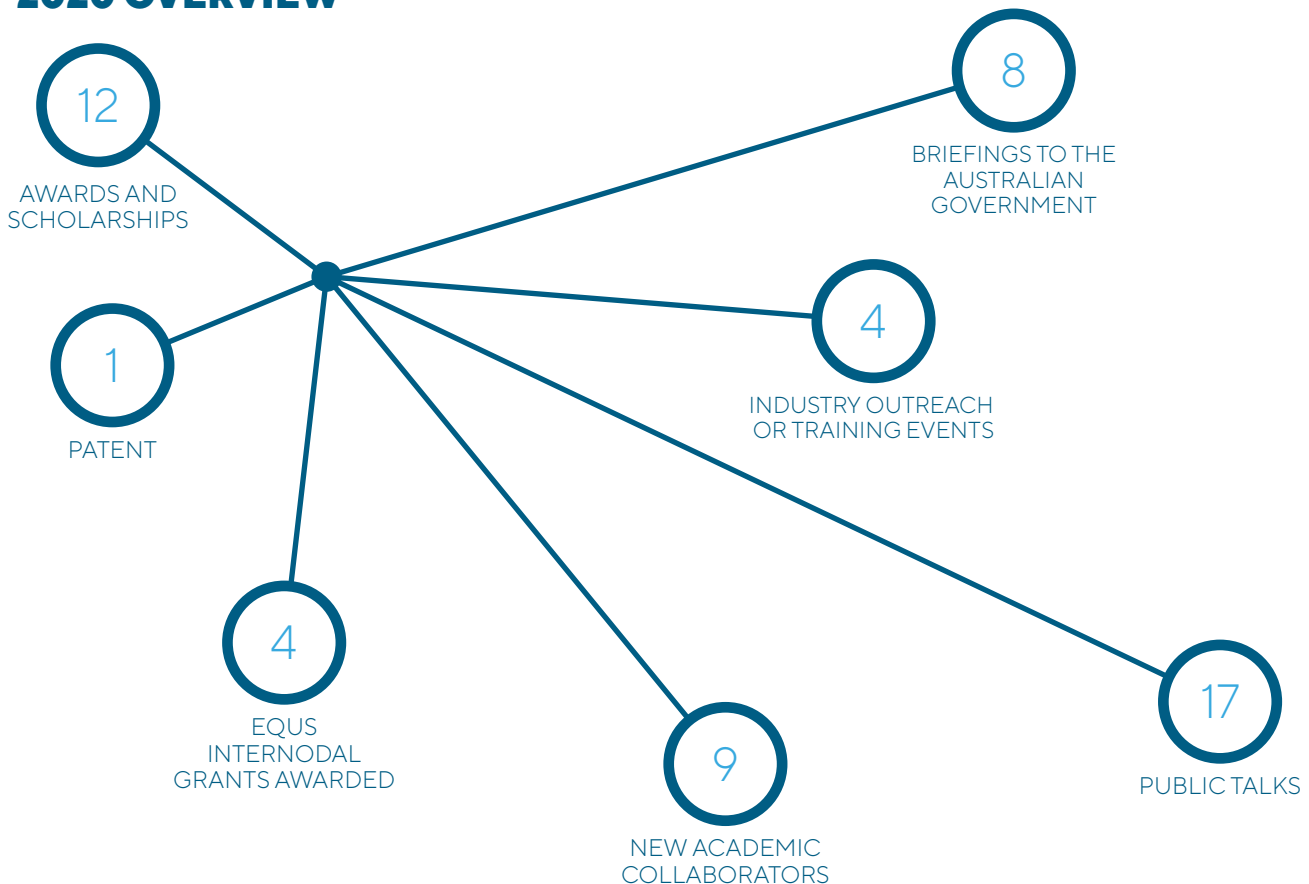
In May, CSIRO released *Growing Australia's Quantum Technology Industry*, outlining the opportunities that quantum technology can unlock for Australia. The report, an idea conceived by EQUS, was the result of almost a year's worth of research and stakeholder consultation.

The report provides a snapshot of Australia's current quantum technology ecosystem and outlines a vision for the industry for the next 20 years. It conservatively estimates that, by 2040, Australia's quantum technology industry

could generate more than \$4 billion in revenue and 16,000 new jobs. It also sets out a series of broad recommendations intended as a roadmap for achieving these outcomes.

The roadmap was launched at a webinar event on 22 May, chaired by CSIRO Chief Scientist Dr Cathy Foley. Centre Director Professor Andrew White (UQ) and Chief Investigator Professor Michael Biercuk (USYD) were part of the panel of experts who provided insights into the roadmap.

### 2020 OVERVIEW



## 2020 highlights

### EQUS WELCOMES TWO NEW CHIEF INVESTIGATORS

In 2020, EQUS welcomed Dr Jacqui Romero (UQ) and Dr Sally Shrapnel (UQ) as new Chief Investigators.

Dr Romero works in the field of experimental quantum information. Her research is helping to increase information security, using the shape of light as a carrier of quantum information.

In 2020, Dr Romero was recognised as one of the 40 Under 40 Most Influential Asian-Australians. This prestigious award celebrates Dr Romero's numerous achievements and recognises her as a young leader in the field of science.

In 2019, she was awarded a Westpac Research Fellowship, and globally was one of just 15 recipients of the L'Oréal-UNESCO For Women in Science International Rising Talent award. In 2018, she won the Ruby Payne-Scott Medal from the Australian Institute of Physics and a Young Tall Poppy Award, and in 2017, she was one of four L'Oréal-UNESCO For Women in Science Fellows in Australia.

Dr Shrapnel works at the interface of causality and machine learning. Her research aims to infer causal relationships from different types of data and to build models that can be used to predict the effects of clinical and other interventions. She is also a registered medical practitioner.

In 2020, Dr Shrapnel led a large-scale COVID-19-related study. The team of researchers and clinicians collated and analysed data from around 370 hospitals across 53 countries. They analysed data from the most critically ill patients in the COVID-19 pandemic to provide clinicians with real-time insights into this new disease.

Dr Romero and Dr Shrapnel also collaborated with Centre Director Professor Andrew White and PhD student Michael Kewming on an experiment that showed that quantum physics provides a way to hide ignorance. Doing so required controlling and measuring quantum systems of up to nine dimensions. This achievement has implications for the security of future quantum-based encryption. The results were published in *Physical Review Letters* in June.



**Far left**  
Jacqui Romero

**Left**  
Sally Shrapnel

## 2020 highlights

### EQUS TO INTRODUCE NEW FLAGSHIP PROGRAMS

In 2020, EQUS developed two new flagship research programs—the 1kQubit Flagship and the Quantum Clock Flagship. These flagships are project-oriented, and align with the Centre’s existing Designer Quantum Materials and Quantum Engines and Instruments research programs, respectively.

The 1kQubit Flagship aims to develop the theoretical foundations for a useful fault-tolerant quantum processor. Such a device requires around 1,000 logical qubits to be built, using around 1,000 physical qubits and based on technology that is expected to be available in the next five to ten years.

The Quantum Clock Flagship aims to develop the hardware, architecture and

theoretical foundations for improved clock technologies. New clock and microwave synthesis hardware and quantum-information-inspired characterisation techniques will enable improved qubit performance metrics and clock-characterisation routines.

EQUS is excited to welcome five new Chief Investigators from 1 January 2021 to drive the flagships. Dr Daniel Burgarth (MQ) and Dr Arne Grimsmo (USYD) will drive the 1kQubit Flagship. Dr John Bartholomew (USYD), Dr Maxim Goryachev (UWA) and Dr Magdalena Zych (UQ) will drive the Quantum Clock Flagship. The flagships will be delivered over four years (2021–24).

#### Below

New flagship drivers (left to right): Daniel Burgarth, Arne Grimsmo, John Bartholomew, Maxim Goryachev and Magdalena Zych



### EQUS RESEARCHERS NAMED STEM AMBASSADORS

Dr Ben McAllister (UWA) and Dr Tara Roberson (UQ) were named STEM Ambassadors by Science & Technology Australia. They will work with their local MPs to help bridge the gap between science and government in Australia.

The STEM Ambassador program encourages the involvement of science in Australian politics and aims to put science and evidence-based policy

on the national agenda. It does so by creating relationships between MPs and STEM professionals and increasing the profile and value of STEM among decision-makers.

Dr McAllister is paired with the MP for Perth, Patrick Gorman. Dr Roberson is paired with the MP for Ryan, Julian Simmonds.

## 2020 highlights

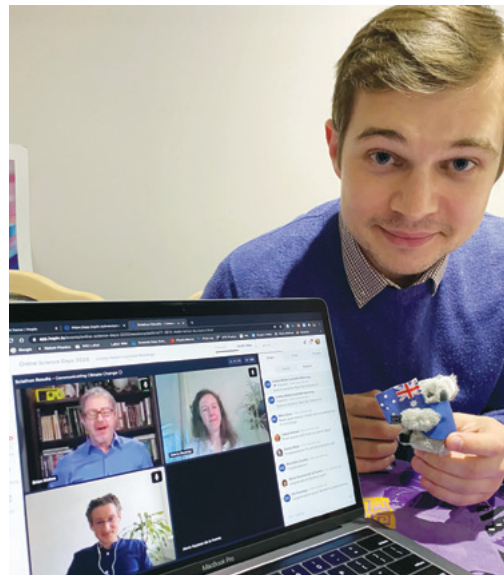
### EQUS RESEARCHERS SELECTED TO REPRESENT AUSTRALIA AT THE 70TH LINDAU NOBEL LAUREATE MEETING

PhD student W. Y. Sarah Lau (UQ) and postdoctoral researcher Dr Yauhen (Eugene) Sachkou (UQ) were selected to represent Australia at the highly prestigious 70th Lindau Nobel Laureate meeting. The meeting, which was to be held in Germany, has been postponed to 2021 as a result of the pandemic. However, both attended Online Science Days 2020, which was held in lieu of the postponed meeting.

In addition, Dr Sachkou was part of the winning team in the 'communicating climate change' category of Online Sciathon 2020—the first online version of a 48-hour science marathon run each year by the Lindau Nobel Laureate Meetings.

The team looked at how to make action against climate change fashionable by engaging social-media influencers.

Dr Sachkou said that working on the climate change problem showed him how physicists can contribute to solving global issues, even without having particular experience in those areas.



**Left**  
Eugene Sachkou after the announcement of the results of the 'communicating climate change' section of Online Sciathon 2020.  
*Photo by Eugene Sachkou*

### EQUS RESEARCHER AWARDED JOINT EQUS–CSIRO FELLOWSHIP

Dr Tara Roberson (UQ) was awarded a joint EQUS–CSIRO fellowship to study the societal impacts of quantum technologies.



Dr Roberson's project aims to assess sentiment towards responsible innovation in the research community and to establish a baseline for public perspectives of quantum technology.

It will lay the groundwork for exploring the benefits and issues associated with possible quantum futures and provide recommendations for responsible innovation for emerging technologies.

**Left**  
Tara Roberson

## 2020 highlights

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### EQUS CHIEF INVESTIGATOR ELECTED FELLOW OF THE AMERICAN PHYSICAL SOCIETY

Professor Stephen Bartlett (USYD) was elected a Fellow of the American Physical Society for pioneering theoretical research in quantum information, including the theory of

quantum computational phases of matter and classical simulation methods for quantum circuits.

Professor Barry Sanders—Director of the Institute for Quantum Science and Technology at the University of Calgary, Canada, and one of Professor Bartlett’s sponsors for his election—said: “Stephen’s theories of quantum computational phases of matter and simulating quantum circuits elucidate what exactly the power behind quantum computing is and how to achieve it.”

Professor Bartlett’s election follows his appointment earlier in 2020 as the Lead Editor of *PRX Quantum*, a new journal in the *Physical Review* series.

**Below**  
Stephen Bartlett



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### EQUS CHIEF INVESTIGATOR AWARDED BARRY INGLIS MEDAL

Professor Warwick Bowen (UQ) was awarded the Barry Inglis Medal from Australia’s National Measurement Institute for his role in the development of quantum technologies and innovative practical solutions to the benefit of measurement science.

The award recognises Professor Bowen’s work developing ground-breaking sensors, enabling the study of individual molecules, medical imaging and mineral exploration. It further recognises his partnership with Australian industry to commercialise these technologies, and outstanding contributions to health, industry and fundamental research.

This is the third consecutive year that an EQUS researcher has received one of the two prizes awarded by the National Measurement Institute each year on World Metrology Day.

**Right**  
Warwick Bowen



## 2020 highlights

### EQUS RESEARCHER AWARDED ENTREPRENEURIAL SCHOLARSHIP

Dr Matt van Breugel (MQ) was awarded a Stanford Australia Foundation–CSIRO scholarship through CSIRO’s ON Accelerate program. The scholarship will allow Dr van Breugel to take up an executive education program at the Stanford Graduate School of Business in California, USA.

Dr van Breugel is the CEO and co-founder of Redback Systems, a deep-tech startup by a team of researchers from EQUS and other Macquarie University labs. The

team participated in ON Accelerate as part of their journey to commercialise a compact, affordable and robust high-resolution spectrometer. In addition to Dr van Breugel’s scholarship, the Redback Systems team was awarded a \$25,000 runway booster prize to help them get their spectrometer to market sooner.

The team’s efforts were enabled by EQUS’ Translational Research Program, which awarded them \$50,000 in 2019.



**Left**  
Matt van Breugel

## 2020 highlights

### AUSTRALIAN QUANTUM VORTEX TEAM NAMED FINALISTS FOR EUREKA PRIZE

**Below**

The Australian Quantum Vortex team (left to right): Mark Baker, Mark Reeves, Thomas Bell, Guillaume Gauthier (seated), Oliver Stockdale, Yauhen (Eugene) Sachkou (seated), Chris Baker, Matthew Davis, Halina Rubinsztein-Dunlop, Warwick Bowen, Tyler Neely and Glen Harris

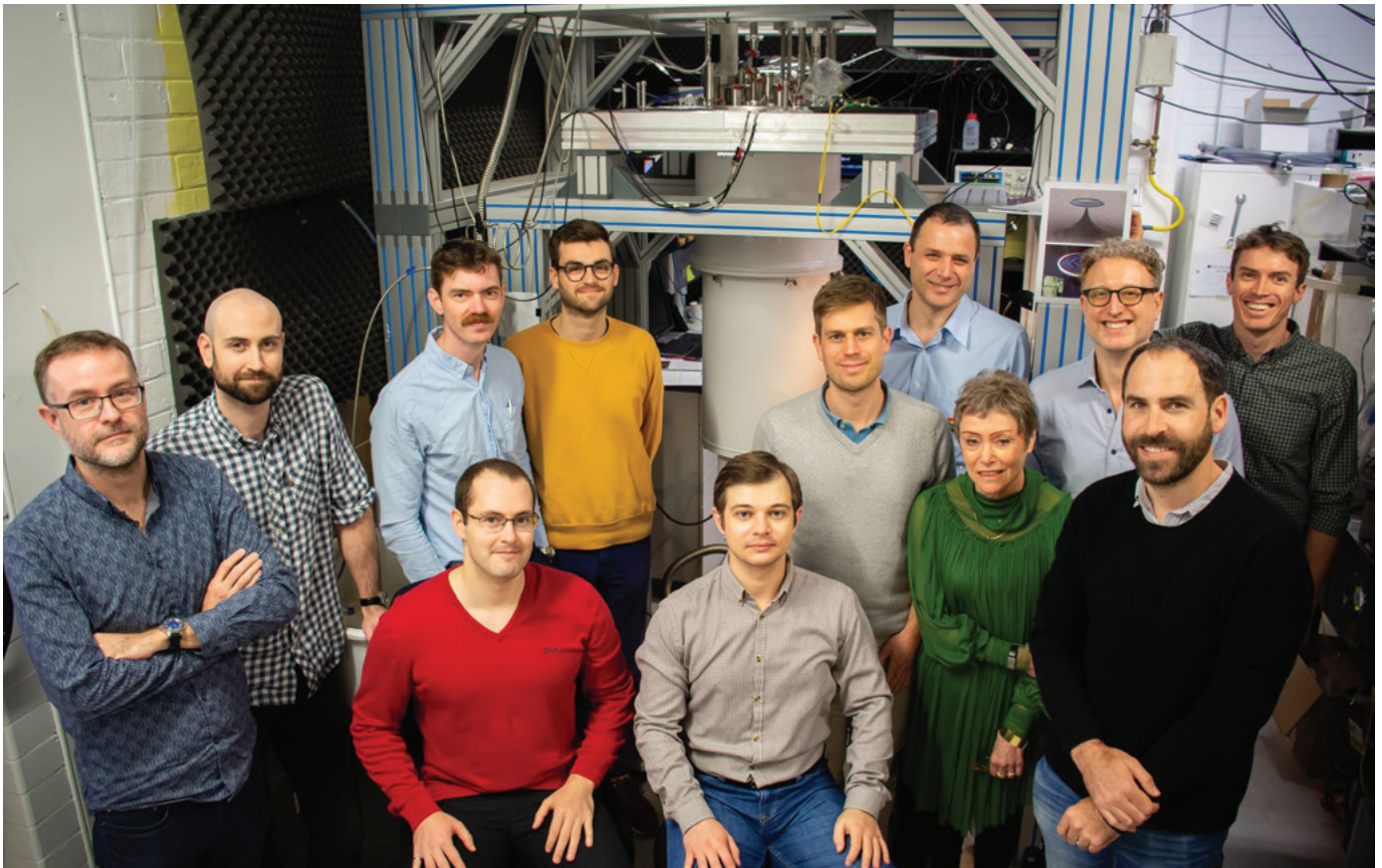
Chief Investigators Professor Warwick Bowen (UQ), Professor Matthew Davis (UQ) and Professor Halina Rubinsztein-Dunlop (UQ), and Associate Investigators Dr Mark Baker (UQ) and Dr Tyler Neely (UQ) were part of the 21-member Australian Quantum Vortex team named as one of three finalists for the 2020 Eureka Prize for Scientific Research.

The team developed laser technologies to observe the microscale origins of large-scale structures in quantum turbulence for the first time. Their results verify 70-year-old predictions that vortices

emerge in quantum fluids and have implications for the design of future quantum technologies such as precision inertial sensors.

The Australian Quantum Vortex team represents a collaboration between three Australian universities—UQ, Monash and Swinburne—and two ARC Centres of Excellence—EQUS and the ARC Centre of Excellence in Future Low-Energy Electronics Technologies.

The discovery is captured in three key 2019 publications in *Science*.



## 2020 highlights

### EQUS DIRECTOR'S PRIZE

The 2020 EQUUS Director's Prize for exceptional contributions to the Centre was awarded to postdoctoral researcher Dr Ben McAllister (UWA). Dr McAllister works on axion dark-matter detection at the Quantum Technologies and Dark Matter Laboratory with Chief Investigator Professor Michael Tobar.

The Director's Prize recognises the EQUUS member or group who has contributed most to the Centre in a given year, by enriching the research culture of the Centre and/or through Centre-wide activities such as outreach or mentoring. Dr McAllister's award highlights that he is an exemplary EQUUS member, contributing new ideas and leadership to EQUUS' world-class research, and contributing equally impressively to the overall life of the Centre.

Dr McAllister is a talented early-career researcher, with an H-index of 8 and 271 citations just over a year out from PhD conferral. He recently acquired a prestigious Forrest Prospect Fellowship to work on EQUUS-aligned research, bringing resources and collaborations to the Centre. He currently supervises three EQUUS PhD students and has previously supervised six EQUUS Honours students.

He is very involved in Centre-wide activities. He has co-chaired the Public Engagement committee since 2019 and is a member of the Quantum for Educators

committee. In 2018, he spear-headed the organisation and chairing of the EQUUS Axion Dark Matter Incubator. He has also received two EQUUS collaboration awards, with Dr Paul Altin at ANU (which has become a lasting collaboration) and with Dr Glen Harris at UQ (delayed owing to COVID-19).



**Left**  
Ben McAllister

He is an ambassador for EQUUS in various spaces, appearing regularly on radio and podcasts, and giving talks at schools and to the public. His TEDx talk about the ORGAN Experiment, part of EQUUS' research program, has been viewed on YouTube nearly 6,000 times.

# Centre strategy: Update

## OUR MISSION

... is to engineer the quantum future by building quantum machines that harness the quantum world for practical applications.

## 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.

### BUILDING QUANTUM MACHINES BY ENGINEERING MULTICOMPONENT QUANTUM SYSTEMS

1

#### 2020 ACHIEVEMENTS

Experimental and theoretical work across the Centre's three research themes saw numerous successes (pages 26-49)

The Centre's national and international collaborations continued to grow (pages 14-15)

#### 2021 PLANS

Research to advance the Centre's theoretical and experimental goals (pages 50-53)

Research towards the goals of the new 1kQubit and Quantum Clock flagship programs (pages 50, 53)

### DEVELOPING PRACTICAL QUANTUM TECHNOLOGIES WITH SOCIETAL IMPACT

2

#### 2020 ACHIEVEMENTS

Collaboration with CSIRO in responsible innovation is underway following the launch of the CSIRO Quantum Technologies Roadmap for Australia (pages 16, 19)

EQUS' Translational Research Program funded five projects (page 55)

#### 2021 PLANS

Further funding by the Centre's Translational Research Program to support projects that translate EQUS research into new quantum technologies and applications

Participation in national review into university technology translation



**Left**  
Data acquisition during the French winter at the French space agency (CNES) in Toulouse  
Image by Sascha Schediwy

## GROWING AUSTRALIA'S WORLD-LEADING RESEARCH COMMUNITY IN QUANTUM ENGINEERING

3

### 2020 ACHIEVEMENTS

The Mentoring and Career Development portfolio supported EQUUS early-career researchers and students through mentoring and workshops (pages 62-63)

EQUUS welcomed two new Chief Investigators, to promote and support a new generation of Australian quantum science (page 17)

### 2021 PLANS

Development of EQUUS alumni network to enhance collaboration and mentoring opportunities

Addition of six new Chief Investigators, to further promote and support a new generation of Australian quantum science

## TRAINING A NEW GENERATION OF VERSATILE AND KNOWLEDGEABLE QUANTUM ENGINEERS

4

### 2020 ACHIEVEMENTS

The Mentoring and Career Development portfolio funded four grants to support collaborations between EQUUS nodes and researchers (page 62)

Four industry outreach or training events were delivered (page 60)

### 2021 PLANS

Participation in national review of Australia's readiness for a quantum industry

Collaboration with science teachers to provide curriculum-aligned content on quantum physics for Australian classrooms

## Research overview

A quantum machine is a device constructed from specialised materials, engines and sensors to fulfil a specific application. It involves a complex array of electrical, mechanical and optical components, brought together by sophisticated engineering and control.

EQUS is building quantum machines to harness the quantum world for practical applications. Our research encompasses theory and experiment, and is organised within three carefully crafted research programs that each consolidate multiple individual projects.

The three research programs are:

- 1 Designer quantum materials**, harnessing quantum many-body physics and exquisite control of individual quantum systems to create quantum materials from which quantum machines can be built
- 2 Quantum-enabled diagnostics and imaging**, developing prototypes of the sensing and imaging components required for a quantum machine to interact with its environment
- 3 Quantum engines and instruments**, understanding quantum engines and instruments so that quantum machines with tens or hundreds of individual components can be designed and manipulated.

# Research programs

## Research Program 1

DESIGNER QUANTUM MATERIALS

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## Research Program 2

QUANTUM-ENABLED DIAGNOSTICS AND IMAGING

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## Research Program 3

QUANTUM ENGINES AND INSTRUMENTS

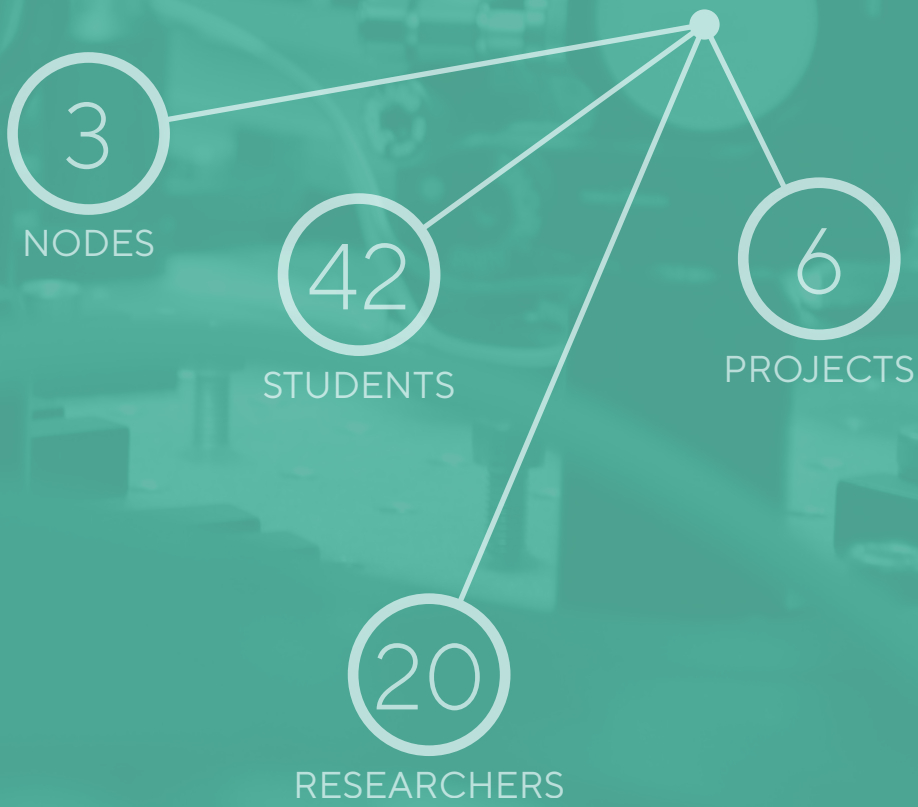
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# DESIGNER QUANTUM MATERIALS

**The Designer Quantum Materials 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



# A STITCH IN TIME: HOW A QUANTUM PHYSICIST INVENTED NEW CODE FROM OLD TRICKS

## ScienceDaily<sup>1</sup>

Building large-scale quantum computers will require suppression of errors. EQUUS postdoctoral researcher Dr Ben Brown has used a neat trick to apply powerful 3D error-suppression codes in a 2D architecture. He has achieved what one quantum industry insider described as “something that many researchers thought was impossible”.

Dr Brown has developed a type of error-correcting code for quantum computers that will free up more hardware to do useful calculations. It also provides an approach that will allow companies like Google and IBM to design better quantum microchips.

He did this by applying already known code that operates in three-dimensions to a two-dimensional framework.

“The trick is to use time as the third dimension,” Dr Brown said. “I’m using two physical dimensions and adding in time as the third dimension. This opens up possibilities we didn’t have before.

“It’s a bit like knitting. Each row is like a one-dimensional line. You knit row after row of wool and, over time, this produces a two-dimensional panel of material.

“Because quantum information is so fragile, it produces a lot of errors—a lot of dropped stitches.”

Reducing errors in quantum computing is one of the biggest challenges facing scientists before they can build machines large enough to solve useful problems.

Dr Michael Beverland from Microsoft Quantum said: “This paper explores an exciting, exotic approach to perform fault-tolerant quantum computation, pointing the way towards potentially achieving universal quantum computation in two spatial dimensions without the need for distillation, something that many researchers thought was impossible.”

Dr Naomi Nickerson, Director of Quantum Architecture at PsiQuantum, California, said: “This result ... has the potential to ... bring practical quantum computing closer.”

### Below

Error suppression opens up a pathway to universal quantum computing



<sup>1</sup> BJ Brown. **A fault-tolerant non-Clifford gate for the surface code in two dimensions.** *Sci. Adv.* 6:eay4929 (2020)

# QUANTUM PHYSICS PROVIDES A WAY TO HIDE IGNORANCE

## Scienmag<sup>1</sup>

Students can hide their ignorance and answer questions correctly in an exam without their lack of knowledge being detected by teachers—but only in the quantum world.

EQUUS researchers have verified this counterintuitive concept in the lab, using a quantum alphabet based on the shapes of individual particles of light.

According to classical intuition, ignorance can be traced to a source—if a student’s knowledge of a book is incomplete, a teacher can design a test to probe which parts of the book are unknown to the student.

EQUUS PhD student Michael Kewming said that this wasn’t always the case in the quantum world.

“Let’s say the student is sitting an exam that covers two topics, and although they haven’t studied they’ve been given a single hint by a knowledgeable friend.

“In the classical situation, this hint can only be so helpful—providing information about only one topic—and the teacher can still uncover which topic the student is ignorant of.

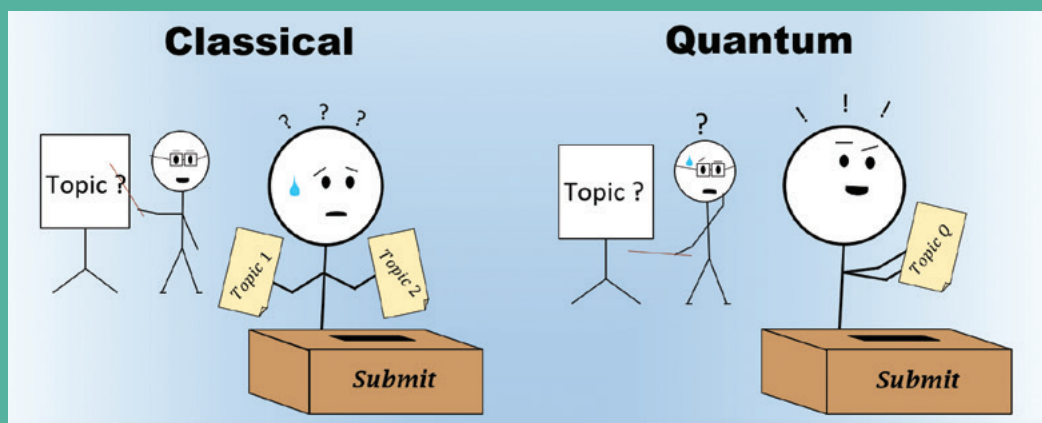
“But a hint written using our quantum alphabet could simultaneously contain information about both topics, despite appearing to be about only one.

“As a result, the teacher cannot determine the source of the student’s ignorance because the hint is always useful to the student.”

Chief Investigator Dr Jacqui Romero said the team’s findings would be important when evaluating security in quantum encryption.

“We have shown that what is true for classical hints is not true for quantum hints.”

Unfortunately for students preparing for exams, quantum hints won’t be available outside the lab anytime soon.



### Left

In the classical world, the student’s ignorance is revealed by the teacher’s questions. In the quantum world, the student hides their ignorance using hints written in a quantum alphabet.

Illustration by Michael Kewming

<sup>1</sup> MJ Kewming, S Shrapnel, AG White and J Romero. **Hiding ignorance using high dimensions.** *Phys. Rev. Lett.* 124:250401 (2020)

## Science updates

### LONG-RANGE ENTANGLEMENT IN AN ION CRYSTAL

Chief Investigator Biercuk's group have demonstrated the first signatures of spin-spin entanglement in a trap across arrays of more than 100 ions. This was made possible by a major technical

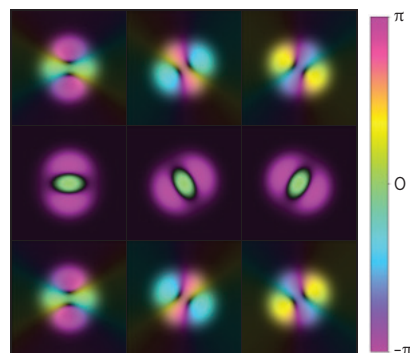
upgrade of a Raman laser system, which delivers beams with adjustable position inside the room-temperature bore of a superconducting magnet.

### NEW QUBITS

Following the introduction of the new dualmon qubit, Chief Investigator Stace extended the Hilbert space available for qubit encoding into the lowest Bloch band of existing transmon qubits<sup>1</sup>, which are immune to the relaxation induced by

typical noise sources. Chief Investigator Stace's group have also been developing theoretical tools for analysing new gates in these qubits, based on Majorana modes in electronic circuits.

### QUANTUM INFORMATION IN LIGHT



**Right**  
A quantum alphabet, made using the shape of light

Chief Investigator Romero and Centre Director White showed violation of higher-dimensional entropic inequalities, with up to 14-dimensional qudits encoded in the transverse shape of photons<sup>2</sup>. Chief Investigator Romero also demonstrated the distribution of qutrit entanglement over telecommunication fibres<sup>3</sup>.

### QUANTUM CODES

Chief Investigator Bartlett continued to make substantial progress in the theory of quantum error correction tailored to realistic noise sources. Building on past achievements, Chief Investigator Bartlett's group have now made the codes fault-tolerant, meaning that they include

the effect of imperfect measurements. The group's most recent results offer the highest fault-tolerant thresholds for quantum computing yet discovered<sup>4</sup>.

- 1 DT Le, JH Cole & TM Stace. **Building a bigger Hilbert space for superconducting devices, one Bloch state at a time.** *Phys. Rev. Res.* 2:013245 (2020)
- 2 MJ Kewming, S Shrapnel, AG White & J Romero. **Hiding ignorance using high dimensions.** *Phys. Rev. Lett.* 124:250401 (2020)
- 3 H Cao *et al.* **Distribution of high-dimensional orbital angular momentum entanglement over a 1 km few-mode fiber.** *Optica* 7:232-237 (2020)
- 4 DK Tuckett, SD Bartlett, ST Flammia & BJ Brown. **Fault-tolerant thresholds for the surface code in excess of 5% under biased noise.** *Phys. Rev. Lett.* 124:130501 (2020)

## LIGHT-MATTER INTERACTION AND CONTROL

Chief Investigator Volz's team has continued their efforts to engineer strong photon-photon interactions in an exciton polariton fibre-cavity system. Chief Investigators Volz and Brennen<sup>1</sup> made further progress towards a theoretical understanding of the photon correlations under off-resonant pumping and subsequent filtering of the emitted light.

Associate Investigator Woolley developed a theory of quantum-state control in lattices of oscillators using both coherent (Hamiltonian) and dissipative (reservoir engineering) control for the generation of multipartite entangled states (for example, cluster states). This is applicable to trapped ions, circuit

quantum electrodynamics systems and optomechanical systems<sup>2</sup>. Given the relevance to optomechanical lattices, this may provide a further contribution towards demonstrating classically forbidden motional states of a macroscale system, in the form of multipartite entangled motional states. It also potentially provides a theoretical basis for the generation of entanglement over a quantum network.

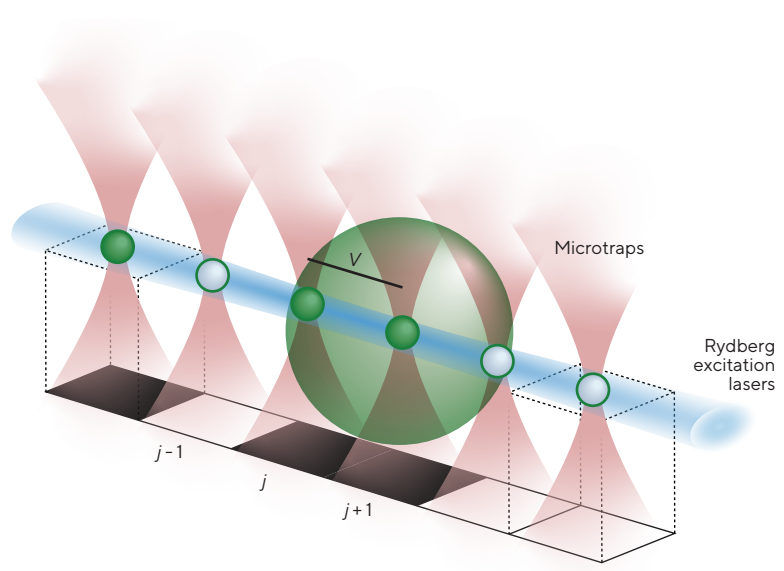
Chief Investigators Stace and Brennen have made progress on the theory of holographic quantum error-correcting codes<sup>3</sup>, and have found improved error-correcting thresholds using exact, efficient tensor-network decoders.

### Below

Physical platform for quantum cellular automata based on arrays of Rydberg atoms (with nearest-neighbour interaction strength  $V$ )

## QUANTUM CELLULAR AUTOMATA

Chief Investigator Brennen and Associate Investigator Gilchrist have developed the theory of quantum simulation with quantum cellular automata<sup>4</sup>, showing how to generate non-unitary quantum cellular automata rules in trapped Rydberg atoms in microtrap arrays using controlled dissipation to steer a register to a gigahertz state.



1 S Schutz *et al.* **Ensemble-induced strong light-matter coupling of a single quantum emitter.** *Phys. Rev. Lett.* 124:113602 (2020)

2 S Ma, MJ Woolley, IR Petersen & N Yamamoto. **Linear open quantum systems with passive Hamiltonians and a single local dissipative process.** *Automatica* 125:109477 (2021)

3 RJ Harris, E Coupe, NA McMahon, GK Brennen & TM Stace. **Decoding holographic codes with an integer optimization decoder.** *Phys. Rev. A* 102:062417 (2020)

4 TM Wintermantel *et al.* **Unitary and nonunitary quantum cellular automata with Rydberg arrays.** *Phys. Rev. Lett.* 124:070503 (2020)

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# QUANTUM- ENABLED DIAGNOSTICS AND IMAGING

**Sensors are ubiquitous in modern technology, enabling examination of human bodies, the environment, galaxies and more. The Quantum-Enabled Diagnostics and Imaging program uses quantum mechanics to engineer new probes, sensors and techniques to enhance capabilities across a range of applications, including medical imaging and navigation.**

## Research Program 2



# A FORCE FROM NOTHING USED TO CONTROL AND MANIPULATE OBJECTS

## The National Tribune<sup>1</sup>

A collaboration between researchers from The University of Western Australia and The University of California Merced has provided a new way to measure tiny forces and use them to control objects.

The research was jointly led by Chief Investigator Professor Michael Tobar and Dr Jacob Pate from the University of Merced.

Once thought to be of only academic interest, a tiny force known as the Casimir force is now drawing interest in fields such as metrology (the science of measurement) and sensing.

“If you can measure and manipulate the Casimir force on objects, then we gain

the ability to improve force sensitivity and reduce mechanical losses, with the potential to strongly impact science and technology,” Chief Investigator Tobar said.

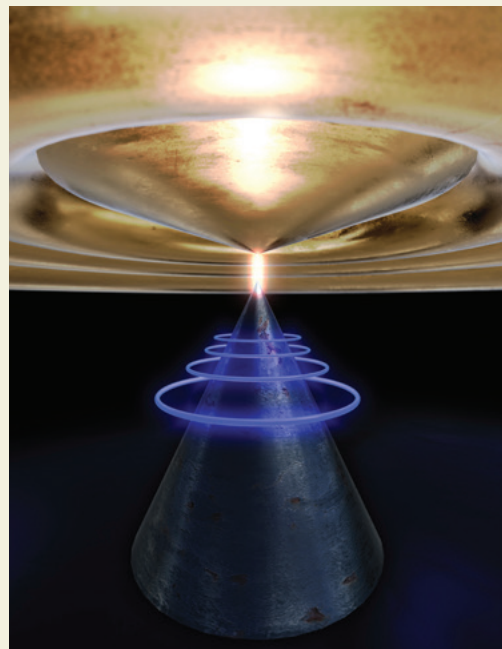
“To understand this, we need to remember that in reality a perfect vacuum does not exist—even in empty space at zero temperature, virtual particles, like photons, flicker in and out of existence.

“These fluctuations interact with objects placed in vacuum and are actually enhanced in magnitude as temperature is increased, causing a measurable force from ‘nothing’—the Casimir force.

“We’ve now developed precision technology that allows us control and manipulate objects with this force.”

The researchers were able to measure the Casimir force and manipulate the objects through a precision microwave photonic cavity, known as a re-entrant cavity, at room temperature, using a setup with a thin metallic membrane separated from the re-entrant cavity, exquisitely controlled to roughly the width of a grain of dust.

“This allowed orders of magnitudes of improvement in force sensitivity and the ability to control the mechanical state of the membrane,” Chief Investigator Tobar said.



### Right

Depiction of the clamping device and how it works  
Image by Jake Pate,  
UC Merced

<sup>1</sup> JM Pate, M Goryachev, RY Chiao, JE Sharping & ME Tobar. **Casimir spring and dilution in macroscopic cavity optomechanics.** *Nat. Phys.* 16:1117–1122 (2020)

# NEED TO BE IN TWO PLACES AT ONCE? IT MAY BE POSSIBLE

## Get STEM<sup>1</sup>

Quantum physics has demonstrated that tiny particles can exist in multiple places at once, but a new method may prove that it is possible for larger, visible objects to also exist in multiple places.

Physicists have been investigating this possibility for almost a century, and now an EQUUS-led international collaboration has suggested that a tiny heat-seeking tool may finally provide the answer.

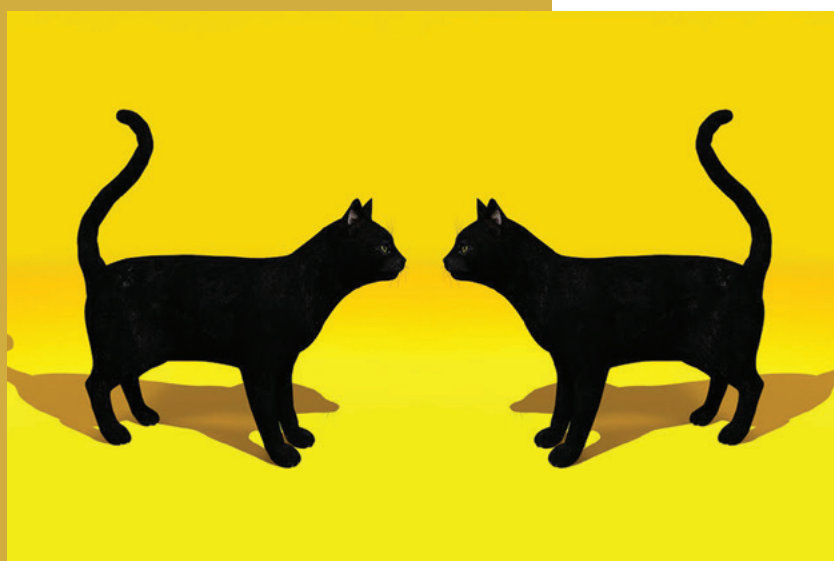
EQUUS postdoctoral researcher Dr Stefan Forstner said the result could turn our understanding of physics on its head.

“Quantum superposition—where particles exist concurrently in multiple places—has been thought to apply only to tiny, subatomic particles,” Dr Forstner said.

“But superposition of larger, visible objects may in fact be possible, unless—as theory suggests—a background noise field exists, which would simultaneously prevent such macroscopic quantum states and create tiny amounts of heat.

“Detecting this heat could be a smoking gun, ruling out larger-scale superposition—but for the last century we haven’t observed this evidence.

“By using a recently developed nanometre-sized resonator—which is essentially insensitive to the environmental temperature—together with a clever measurement strategy, we can avoid these problems.”



Chief Investigator Professor Warwick Bowen said debate between physicists about this quantum phenomenon led Schrödinger to develop his famous example of the cat, which could be alive and dead at the same time.

“When you look at the known laws of physics, there’s no fundamental mechanism to stop us from creating quantum states of larger and larger objects, or even living beings,” Dr Forstner said.

“So we have to ask the question—as we advance our technological abilities, can we hope or fear to one day make Schrödinger’s cat a reality?”

“It’s a finding that would make us all question our reality.”

**Above**  
Is it possible to be in two places at once?

<sup>1</sup> S Forstner, M Zych, S Basiri-Esfahani, KE Khosla & WP Bowen. **Nanomechanical test of quantum linearity.** *Optica* 7:1427-1434 (2020)

### CONVENTIONAL QUANTUM OPTOMECHANICS

Chief Investigator Bowen and Associate Investigator Vanner have discovered a new regime in which non-classical states may be conditioned at room temperature via measurements with much lower experimental requirements than previous techniques<sup>1</sup>. They have made classical demonstrations of the effect in the laboratory and are now gearing up for a full quantum demonstration. Chief Investigator Bowen's team also showed that interfacial defects arising from lattice mismatch introduce additional dissipation when growing crystalline thin films, such as silicon carbide. By engineering the geometry of the resonators and removing the defective interfacial layer, the team achieved quality factors of more than 1,000,000 in silicon carbide trampoline resonators at room temperature, five times higher than those achieved without the removal of the interfacial defect layer<sup>2</sup>.

Chief Investigator Tobar demonstrated piezoelectric excitation—not requiring mode-spectra engineering or external optical microwave signals—of bulk phononic frequency combs at 20 millikelvin<sup>3</sup>. Strong Duffing nonlinearity was observed below the generation threshold, suggesting that the system is a phononic analogue to Kerr frequency combs excited in monolithic optical microresonators. The ultralow-power regime provides a way of integrating this phononic system with quantum hybrid

systems such as impurity defects and superconducting qubits.

In a collaboration with Professor Ray Chiao, Chief Investigator Tobar demonstrated a method for realising a Casimir spring and engineering dissipation dilution in macroscale optomechanics, by coupling a metallic silicon nitride membrane to a photonic re-entrant cavity<sup>4</sup>. This provides a way of manipulating phonons via thermal photons, leading to in situ reconfigurable mechanical states, of reducing loss mechanisms and of creating additional types of acoustic nonlinearity—all at room temperature.

Chief Investigator Tobar demonstrated—for the first time—optomechanical resonator structures that meet the loss requirements for a white-light signal-recycling interferometer with strain sensitivity below  $10^{-24}$  Hz<sup>-1/2</sup> at a few kilohertz<sup>5</sup>. Experimental data for two resonators were combined with analytic models of four-kilometre interferometers similar to LIGO, with sensitivity enhancement across a much broader band of neutron-star coalescence frequencies than dual-recycled Fabry-Perot Michelson detectors. Either membrane or bulk acoustic-wave resonators could be implemented as add-on components to existing detectors.

1 C Meng, GA Brawley, JS Bennett, MR Vanner & WP Bowen. **Mechanical squeezing via fast continuous measurement.** *Phys. Rev. Lett.* 125:043604 (2020)

2 E Romero *et al.* **Engineering the dissipation of crystalline micromechanical resonators.** *Phys. Rev. Appl.* 13:044007 (2020)

3 M Goryachev, S Galliou & ME Tobar. **Generation of ultralow power phononic combs.** *Phys. Rev. Res.* 2:023035 (2020)

4 JM Pate, M Goryachev, RY Chiao, JE Sharping & ME Tobar. **Casimir spring and dilution in macroscopic cavity optomechanics.** *Nat. Phys.* 16:1117-1122 (2020)

5 MA Page *et al.* **Gravitational wave detectors with broadband high frequency sensitivity.** *Commun. Phys.* 4:27 (2021)

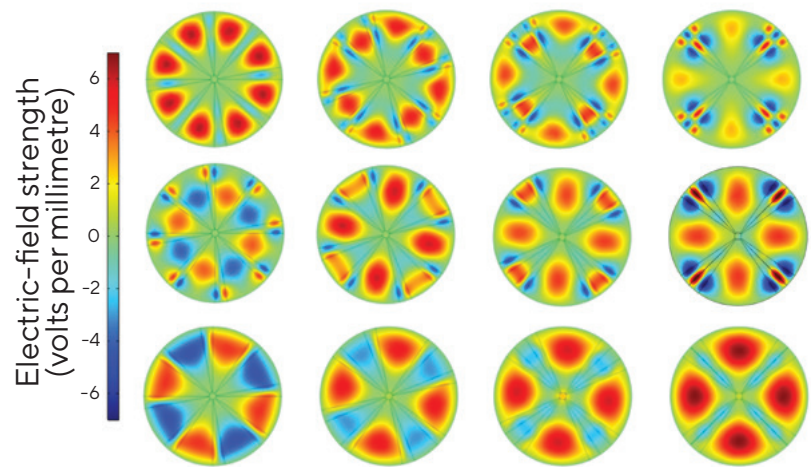
## Science updates

Chief Investigator Volz has started to implement feedback cooling of levitated nanospheres and has implemented a more compact trap design based on parabolic mirrors, which will enable easy integration of fibre cavities. Although

a large part of this project is funded by Lockheed Martin, the cooling technology and the new trap will be highly relevant for the levitated nanoparticle clocks within the new Quantum Clock Flagship.

### DARK-MATTER DETECTION

Chief Investigator Tobar developed a way to undertake broadband low-mass axion detection, by implementing a new precision technique with conducting wires<sup>1</sup>. In addition, Chief Investigator Tobar's team undertook a study of a resonant-cavity haloscope design for application to high-mass axion searches (above approximately 60 microelectronvolts)<sup>2</sup>. Results showed a significant increase in axion sensitivity.



### QUANTUM BIOIMAGING

Chief Investigator Bowen's team made two major breakthroughs. The first breakthrough showed that quantum-limited particle tracking enables an increase in the speed of fluid viscosity measurements by four orders of magnitude compared to previous techniques<sup>3</sup>. This enables the rich physics of out-of-equilibrium biology to be studied in new ways, without averaging over the interesting dynamics. The second breakthrough demonstrated absolute quantum advantage in microscopy for the first time, by building a state-of-the-art stimulated Raman microscope that

uses quantum correlations to evade otherwise unavoidable photodamage in a biological sample, enabling imaging of molecular vibrations with 200-nanometre resolution<sup>4</sup>.

**Above**  
Simulated transverse magnetic modes in an eight-sapphire-wedge cavity, used to detect axions, as the wedges move together (left to right)

1 ME Tobar, BT McAllister & M Goryachev. **Broadband electrical action sensing techniques with conducting wires for low-mass dark matter axion detection.** *Phys. Dark Universe* 30:100624 (2020)

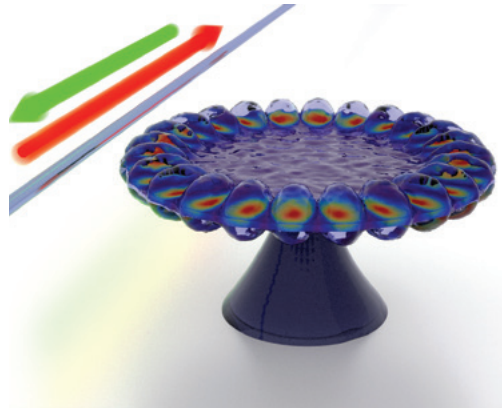
2 AP Quiskamp, BT McAllister, G Rybka & ME Tobar. **Dielectric-boosted sensitivity to cylindrical azimuthally varying transverse-magnetic resonant modes in an axion haloscope.** *Phys. Rev. Appl.* 14:044051 (2020)

3 LS Madsen *et al.* **Ultrafast viscosity measurement with ballistic optical tweezers.** *arXiv* 2007.03066 (2020)

4 CA Casacio *et al.* **Quantum correlations overcome the photodamage limits of light microscopy.** *arXiv* 2004.00178 (2020)

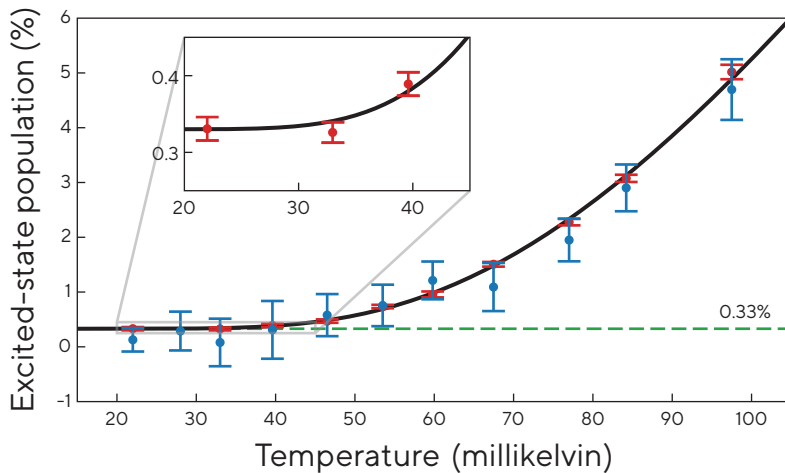
## SUPERFLUID CIRCUITRY

**Right**  
Artistic representation of a large-amplitude superfluid Brillouin acoustic wave  
Image by Chris Baker



Chief Investigator Bowen's team scaled the circuitry developed in 2018–19—simple silica devices on a silicon chip with a superfluid helium film self-assembled onto them—into a silicon-on-insulator platform. The team is now able to build complex photonic circuits and integrate them with optics. With this silica architecture, they have demonstrated optomechanically driven acoustic lasing with a record low threshold<sup>1</sup>.

## TEMPERATURE MEASUREMENT



Using circuit quantum electrodynamics, Chief Investigator Fedorov measured qubit temperature with up to 0.01% accuracy, using correlations between two sequential measurements<sup>2</sup>. Unlike other techniques, Chief Investigator Fedorov's method does not require high-fidelity readout and does not involve the excited levels of the system outside of the qubit subspace. The high accuracy allowed Chief Investigator Fedorov to perform 'temperature spectroscopy' of the qubit, shedding light on sources of decoherence.

**Above**  
Temperature measurement of qubits with (red) and without (blue) a Josephson parametric amplifier

## METROLOGY WITH CORRELATED PHASE AND LOSS

Chief Investigator Stace worked with experimentalists at the University of Bristol to develop the theory of parameter estimation in situations where the parameter affects phase shift and absorption<sup>3</sup>. The archetypal example of this situation is optical thermometry, in

which the absorption and phase shift of light passing through a warm vapour both depend on temperature. Accounting for both effects in the theory enables improved parameter estimation.

<sup>1</sup> X He *et al.* **Strong optical coupling through superfluid Brillouin lasing.** *Nat. Phys.* 16:417–421 (2020)

<sup>2</sup> A Kulikov, R Navarathna & A Fedorov. **Measuring effective temperatures of qubits using correlations.** *Phys. Rev. Lett.* 124:240501 (2020)

<sup>3</sup> PM Birchall *et al.* **Quantum optical metrology of correlated phase and loss.** *Phys. Rev. Lett.* 124:140501 (2020)

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### FORCE AND POSITION SENSING

Associate Investigator Woolley has been working on new approaches to force sensing in quantum optomechanical systems, combining time-dependent control with non-classical state preparation<sup>1</sup>. In joint theoretical and experimental work with Professor Mika Sillanpää (Aalto University), Associate Investigator Woolley has shown that it

is possible to evade the limitation on measuring the position of an oscillator by measuring it without backaction, by constructing one effective oscillator from two physical oscillators<sup>2</sup>. Associate Investigator Woolley has developed theoretical analyses of stability of linear open quantum systems<sup>3</sup>.

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### STATES FOR QUANTUM SENSING

Chief Investigator Brennen, in collaboration with Chief Investigator Volz and Associate Investigator Burgarth, introduced a method for generating large, entangled states ideal for quantum sensing<sup>4</sup>. Their method uses geometric phase gates that act on a collection of spins, and requires only global rotations on the spins and dispersive coupling to a shared bosonic mode, be it mechanical, microwave or photon. This method has built-in dynamical decoupling, providing

robustness to dephasing. It uses Grover-style amplitude amplification to minimise error due to mode decay. Chief Investigator Brennen is investigating how to implement the model using trapped-ion registers—for Dicke states with up to 70 spins—in collaboration with former EQUUS postdoctoral researcher Dr Arghavan Safavi-Naini (now at CWI, Amsterdam), Chief Investigator Davis and Associate Investigator Hempel.

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### TESTS OF FUNDAMENTAL PHYSICS

Chief Investigator Bowen and postdoctoral researcher Dr Magdalena Zych have developed a new approach to test spontaneous-collapse models using nanoscale optomechanics<sup>5</sup>.

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1 DN Bernal-García, H Vinck-Posada & MJ Woolley. **Nonstationary force sensing under dissipative mechanical quantum squeezing**. *Phys. Rev. A* 102:053515 (2020)

2 LM de Lépinay, CF Ockeloen-Korppi, MJ Woolley & MA Sillanpää. **Quantum-mechanics free subsystem with mechanical oscillators**. *arXiv* 2009.12902 (2020)

3 MF Emzir, MJ Woolley & IR Petersen. **Stability analysis of quantum systems: a Lyapunov criterion and an invariance principle**. *arXiv* 2008.01534 (2020)

4 MT Johnsson, NR Mukty, D Burgarth, T Volz & GK Brennen. **Geometric pathway to scalable quantum sensing**. *Phys. Rev. Lett.* 125:190403 (2020)

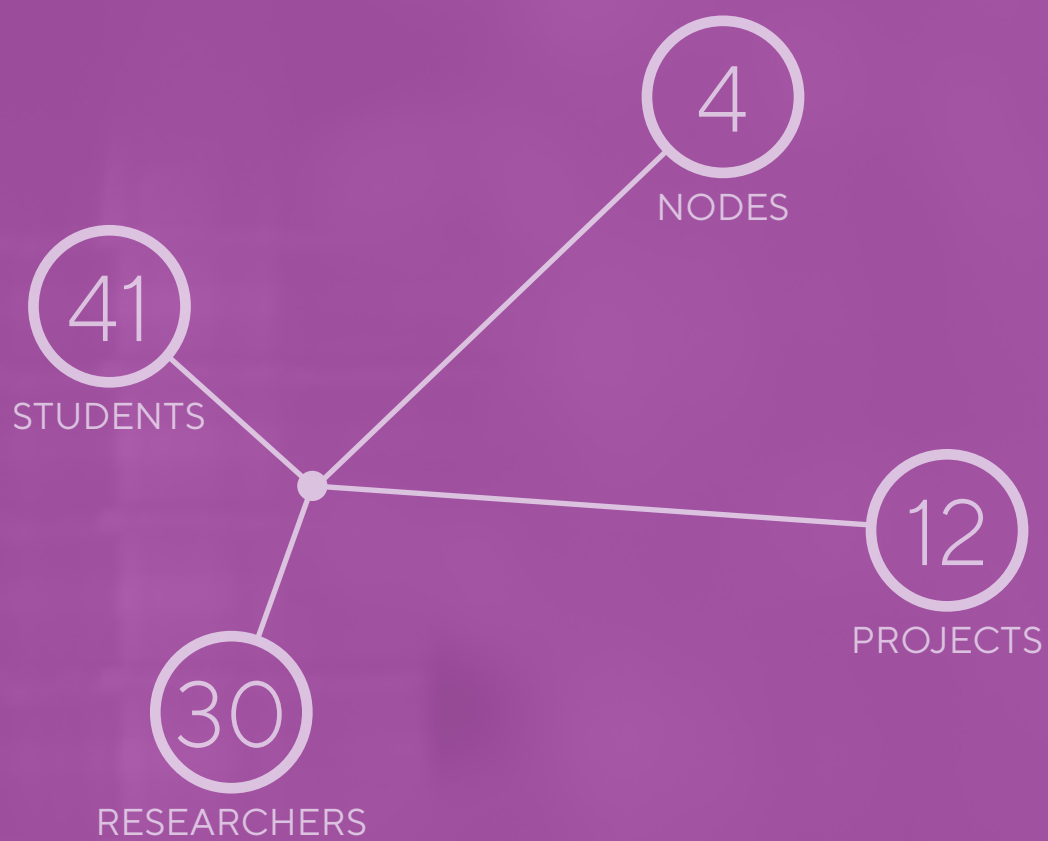
5 S Forstner, M Zych, S Basiri-Esfahani, KE Khosla & WP Bowen. **Nanomechanical test of quantum linearity**. *Optica* 7:1427-1434 (2020)

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# QUANTUM ENGINES AND INSTRUMENTS

**The Quantum Engines and Instruments program develops tools and design approaches that enable complex quantum machines to be pieced together from disparate components. It aims to pioneer a new generation of instruments tailored to the demanding requirements of quantum science, including precision clocks, oscillators and time bases, and high-speed cryogenic electronics.**

## Research Program 3



# SCIENTISTS DEVELOP FIRST QUANTUM ALGORITHM TO CHARACTERISE NOISE ACROSS LARGE SYSTEMS

## The Quantum Daily<sup>1</sup>

Quantum systems are notoriously prone to errors and noise. To overcome this and build a functional quantum computer, physicists should ideally understand the noise across an entire system.

That has been out of reach until now, with EQUS postdoctoral researcher Dr Robin Harper and colleagues developing the first system-wide quantum algorithm to characterise noise.

Noise is the main obstacle to building large-scale quantum computers. To tame the noise (interference or instability), scientists need to understand how it affects an entire quantum system.

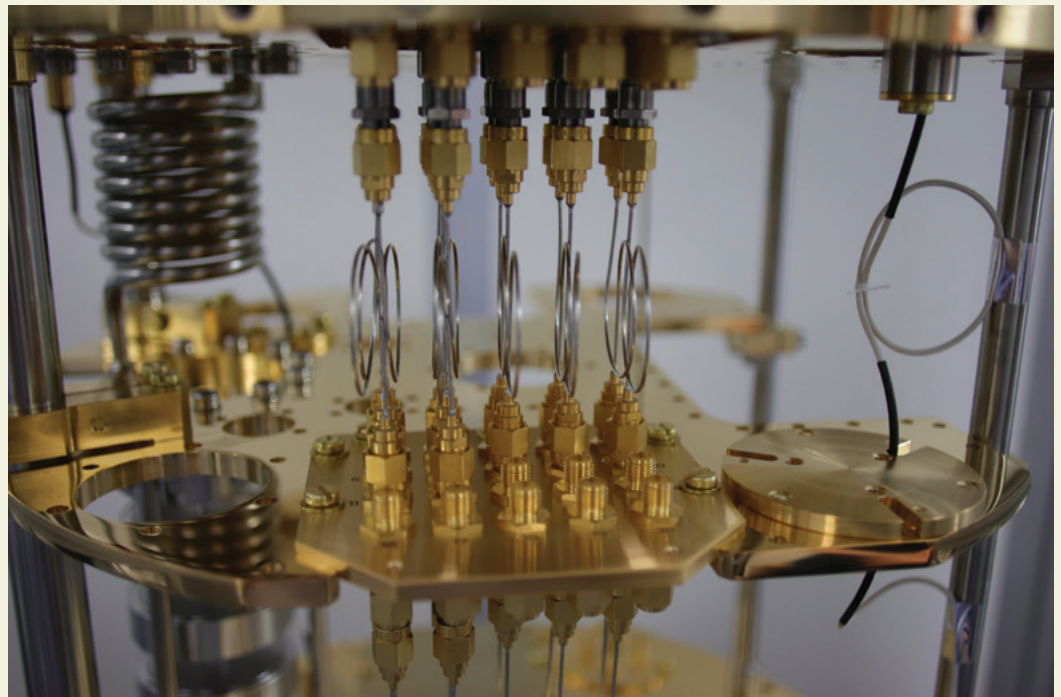
Until now, this information was only available for very small devices or subsets of devices.

Work by Dr Harper and colleagues develops algorithms that will work across large quantum devices.

They demonstrate this by diagnosing the noise in an IBM Quantum Experience device, discovering correlations in the 14-qubit machine not previously detected.

Dr Harper said, "The results are the first implementation of provably rigorous and scalable diagnostic algorithms capable of being run on current quantum devices and beyond."

**Right**  
Researchers used the IBM Quantum Experience to conduct their experiments



<sup>1</sup> R Harper, ST Flammia & JJ Wallman. **Efficient learning of quantum noise.** *Nat. Phys.* 16:1184-1188 (2020)

# QLD SCIENTISTS FIND PARADOX-FREE TIME TRAVEL IS THEORETICALLY POSSIBLE

Stuart Layt, *The Age*<sup>1</sup>

Mathematical modelling by Queensland scientists has sent accepted time-travel theory for a loop, proving that paradox-free time travel is theoretically possible.

EQUS Honours student Germain Tobar and researcher Dr Fabio Costa have detailed the complex mathematical proofs that show a person travelling from the present to the past would still be able to act freely without creating paradoxes.

The most famous time-travel paradox is the grandfather paradox: what happens if you travel back in time and kill your own grandfather? If you do, you cease to exist, but if you cease to exist then you never existed to kill your grandfather.

“There is a lot of debate at the moment, a lot of physicists think closed time-like curves [where events from one point on a timeline affect things at a previous point in the timeline] can’t exist because of the possibility for these paradoxes,” Mr Tobar said.

The researchers use the example of someone travelling back in time to stop the current pandemic. Under the previous model, they would not be able to stop patient zero contracting the virus. They could under the new model outlined in the paper, but the pandemic would still occur through other means—a different person getting sick, the time traveller getting sick, or something else.



QI - Quite Interesting ✓

Yesterday at 9:00 PM · 🌐

Physicists have recently shown that time is self-healing - that if you did travel back in time, you would be unable to prevent the events that led you to travel back in time in the first place.

👍👎 2K

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👍 Like

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➦ Share

Dr Costa said it was heady stuff to think about, and their equations were about proving logical consistencies, rather than a way to allow physical time travel.

“We still don’t have a complete understanding of the laws of the Universe; especially in the realms where gravity plays an important role, we don’t know what the physics looks like,” he said.

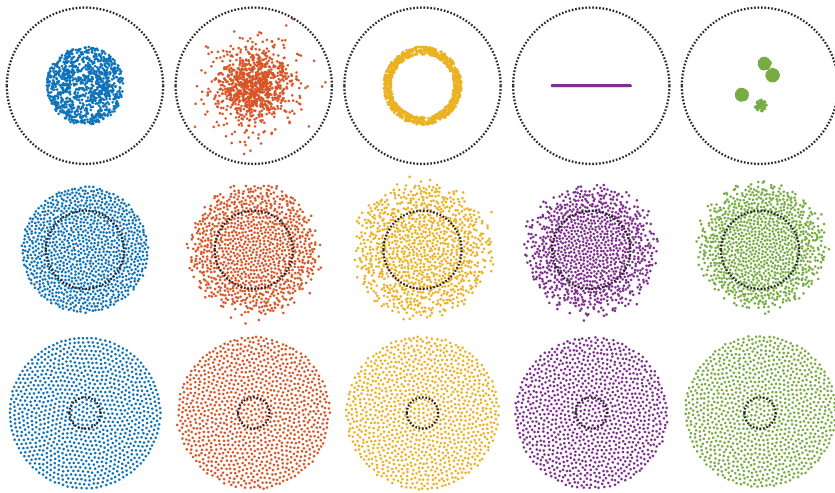
“We can’t say that time travel is physically possible, but what we have shown is that it is not impossible.”

**Top**  
Fabio Costa (left)  
and Germain  
Tobar (right)

**Above**  
Facebook post  
from @qikipedia

<sup>1</sup> G Tobar & F Costa. **Reversible dynamics with closed time-like curves and freedom of choice.** *Class. Quantum Grav.* 37:205011 (2020)

## ATOMTRONICS



Chief Investigator Rubinsztein–Dunlop and Associate Investigators Baker and Neely co-authored a commissioned review on atomtronics<sup>1</sup>, with EQUUS contributing to the chapters on optical trapping techniques and ring-trapped Bose–Einstein condensates. Associate Investigator Neely and Chief Investigators Bowen and Davis described a new universality class in dissipative superfluids<sup>2</sup>, showing that regardless of the initial distribution of same-sign vortices the long-time configuration obtains the profile of a Rankine vortex, which is forbidden in classical viscous fluids.

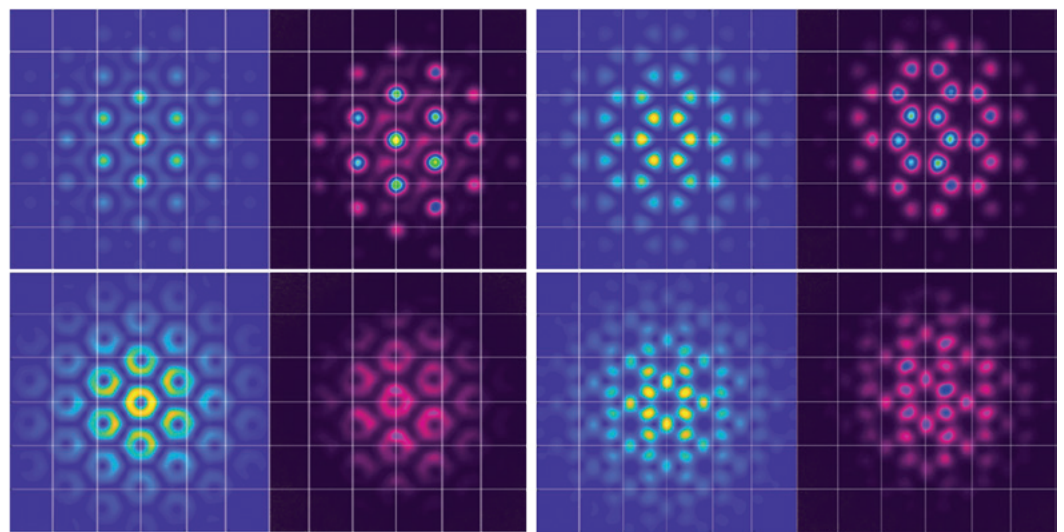
**Above**  
Simulated distribution of vortices (coloured dots) in a viscous superfluid over time (top to bottom), starting from five different configurations; the black dotted circles correspond to the same physical size in each row

**Right**  
Simulations (left) and measurements (right) of optical vortex beams

## OPTICAL PHASED ARRAYS

Chief Investigator Shaddock’s team demonstrated an optical phased array using solid-state laser-beam steering<sup>3</sup> at speeds of one megahertz, 100 times faster

than typical voice-coil steering mirrors. This optical phased array was used to generate optical vortex beams, with controllable orbital angular momentum<sup>4</sup>.



- 1 L Amico *et al.* **Roadmap on atomtronics.** *arXiv*2008.04439 (2020)
- 2 OR Stockdale *et al.* **Universal dynamics in the expansion of vortex clusters in a dissipative two-dimensional superfluid.** *Phys. Rev. Res.* 2:033138 (2020)
- 3 DR Gozzard, LE Roberts, JT Spollard, PG Sibley & DA Shaddock. **Fast beam steering with an optical phased array.** *Opt. Lett.* 45:3793–3796 (2020)
- 4 DR Gozzard, JT Spollard, PG Sibley, LE Roberts & DA Shaddock. **Optical vortex beams with controllable orbital angular momentum using an optical phased array.** *OSA Continuum* 3:3399–3406 (2020)

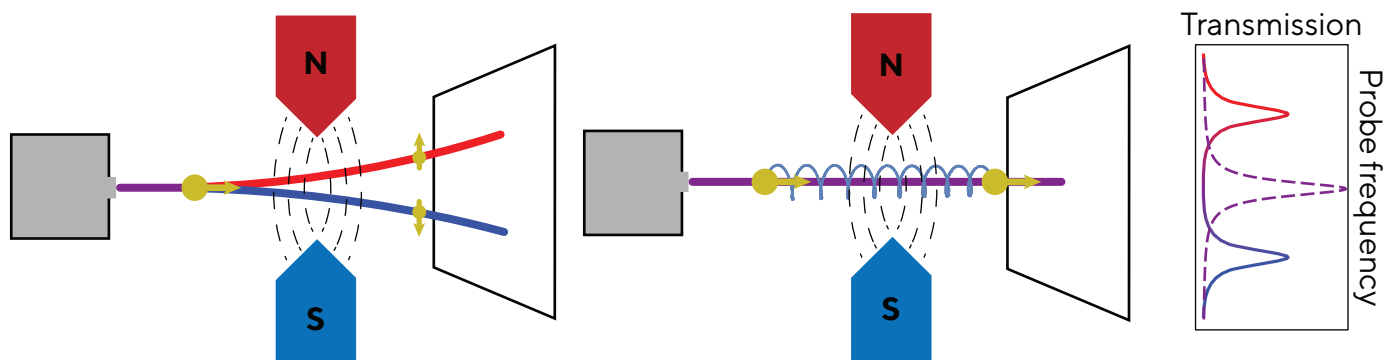
## BACKACTION-PROTECTED MEASUREMENT OF SUPERCONDUCTING QUBITS

Chief Investigator Fedorov used a superconducting qubit to test a new regime of continuous measurement named 'quantum rifling'.<sup>1</sup> Measurement of a rapidly evolving qubit returns the time-averaged expectation value of the measurement operator, erasing information about the initial state of the qubit and completely suppressing the measurement backaction. Using two superconducting qubits coupled to the

same probe field, Chief Investigator Fedorov demonstrated that quantum rifling enables measurement of either one of the qubits on-demand, while protecting the state of the other from measurement backaction. These results enable the implementation of selective readout multiplexing of several qubits, contributing to the efficient scaling up of quantum processors for future quantum technologies.

### Below

Quantum rifling in a Stern-Gerlach setup: a spin (yellow) prepared in a superposition state is deflected by the magnetic field during measurement (red and blue), whereas a spin driven strongly during measurement ('quantum rifling') is undisturbed (purple)



## HYBRID CAVITY-MAGNON SUPERCONDUCTING SYSTEMS

Chief Investigator Tobar and Associate Investigator Dr Maxim Goryachev conducted the first characterisation of 3D-printed niobium<sup>2</sup>, successfully measuring its transition temperature while developing a new way of characterising small superconducting samples. They also engineered a hybrid cavity-magnon system in the dispersive regime, enabling

characterisation of the magnetic field trapped in a superconducting cavity<sup>3</sup>, and continued to characterise the properties of magnon samples<sup>4</sup>.

1 D Szombati *et al.* **Quantum rifling: protecting a qubit from measurement back action.** *Phys. Rev. Lett.* 124:070401 (2020)

2 BT McAllister *et al.* **Characterisation of cryogenic material properties of 3D-printed superconducting niobium using a 3D lumped element microwave cavity.** *IEEE Trans. Instrum. Meas.* 70:6002007 (2021)

3 G Flower, BT McAllister, M Goryachev & ME Tobar. **Determination of niobium cavity magnetic field screening via a dispersively hybridized magnonic sensor.** *Appl. Phys. Lett.* 117:162401 (2020)

4 J Krupka *et al.* **Resonances in large ferrimagnetic YIG samples – electrodynamic analysis.** *J. Magnetism Magnetic Mater.* 521:167536 (2021)

### COMMUNICATION THROUGH FULLY NOISY CHANNELS

Classically, no information can be transmitted through a depolarising channel. Centre Director White and Chief Investigator Romero showed that by combining a depolarising channel with another channel in an indefinite causal order—that is, where there is a superposition of the order that the

two channels are applied—it becomes possible to transmit substantial amounts of information<sup>1</sup>. When one channel is fully depolarising and the other is a known unitary, the ideal limit is communication of up to one bit; experimentally, Centre Director White and Chief Investigator Romero achieved  $0.64 \pm 0.02$  bits.

### EFFICIENT NOISE DETECTION

Chief Investigator Flammia developed a protocol to efficiently learn quantum noise, detecting correlations within arbitrary sets of qubits. The protocol constructs a quantum noise correlation

matrix to allow easy visualisation of correlations between all pairs of qubits, enabling the detection of long-range two-qubit correlations in a 14-qubit superconducting device.

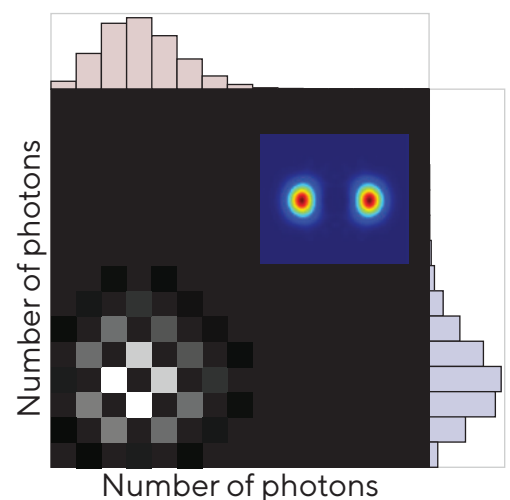
### FUNDAMENTAL PHYSICS

Chief Investigators Stace and Tobar have been co-supervising PhD student Graeme Flower (UWA) to develop the theory for a new class of microwave

photon counter designed to detect anomalous photons from axion-photon conversion in superconducting axion detectors.

### MACHINE LEARNING

Chief Investigators Shrapnel and Milburn, in collaboration with PhD student Michael Kewming, showed the origin of the quantum advantage in dissipative learning machines at very low temperature<sup>2</sup>, by studying a coherent Ising machine using a parametrically Kerr nonlinear optical system. This insight is now being developed to understand the physical constraints of quantum noise on optical and nanomechanical neuromorphic machine learning architectures<sup>3</sup>.



**Right**  
The joint photon number distribution (main panel) for two entangled cavities exhibits highly non-Gaussian cat-like states (inset), indicative of strong non-classicality

1 K Goswami, Y Cao, GA Paz-Silva, J Romero & AG White. **Increasing communication capacity via superposition of order.** *Phys. Rev. Res.* 2:033292 (2020)

2 MJ Kewming, S Shrapnel & GJ Milburn. **Quantum correlations in the Kerr Ising model.** *New J. Phys.* 22:053042 (2020)

3 MJ Kewming, S Shrapnel & GJ Milburn. **Designing a physical quantum agent.** *Phys. Rev. A* 103:032411 (2021)

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### EXTENSION OF RESOURCE THEORY OF QUANTUM MEASUREMENT OUTCOMES

Associate Investigator Gilchrist has been further developing the resource theory of quantum measurement outcomes to attempt to find a smaller complete set of resource monotones (the currently known set is uncountably infinite in size). A complete set of monotones would predict the partial ordering of measurement resources and give a notion of the quality of a measurement. Although

standard notions of information gain are monotones, more are needed for a partial order, but presumably not an infinite number of them. In addition, Associate Investigator Gilchrist has been working with Chief Investigator Volz to develop a method for generating entangled light from two-photon stimulation of hot rubidium gas.

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### BENCHMARKING TOOLS

Chief Investigator Bartlett, in collaboration with Professor Andrew Dzurak's group (UNSW, CQC<sup>2</sup>T), has

continued to develop benchmarking tools for the next generation of two- and three-qubit devices.

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### QUANTUM CLOCKS

Chief Investigator Milburn continued research on the physical constraints of classical and quantum clocks, publishing a major review of the thermodynamics of clocks<sup>1</sup>. In collaboration with Chief Investigator Fedorov, Chief Investigator Milburn is developing an experimental scheme for a low-temperature quantum clock in a superconducting system. In

collaboration with PhD student Leo Assis (UQ), Chief Investigator Milburn is developing a scheme for a quantum optical clock using coherent feedback in two coupled nonlinear cavities. This theory can also be applied to clock designs under investigation at UWA (led by Associate Investigator Dr Maxim Goryachev).

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### SUPERCONDUCTING CIRCULATORS

Chief Investigators Stace and Fedorov have continued working on the theory of circulators. Recent theoretical calculations show regimes of high performance and approaches to optimising circulator parameters using standard optimisation methods. As a means to engineer larger systems with

chiral, non-reciprocal modes, this result could help to realise on-chip microwave components with new capabilities, built from exotic quantum materials.

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<sup>1</sup> GJ Milburn. **The thermodynamics of clocks.** *Contemp. Phys.* 61:69-95 (2020)

## DESIGNER QUANTUM MATERIALS

### Theory

Chief Investigator Bartlett's team will focus on developing low-density parity-check codes for quantum computing and further advancing the state-of-the-art with decoders. Chief Investigators Brennen and Stace will continue to collaborate on holographic quantum error-correction codes, concentrating on implementations in optical and ion systems, and on how to perform encoded gates.

Chief Investigators Bartlett, Brennen and Stace will continue working on new, robust qubits for the 1kQubit Flagship, motivated by new results for Gottesman-Kitaev-Preskill-based encodings reported at the EQUUS-sponsored Byron Bay Quantum Workshop. Chief Investigator Brennen will continue work on quantum cellular automata for measuring information transport.

### Experiment

Chief Investigator Biercuk has begun experiments examining spin squeezing as a signature of spin-spin entanglement due to a single-axis-twisting Hamiltonian. He will benchmark spin-spin entanglement in large two-dimensional ion crystals, benchmark ultrasensitive force detection using large ion crystals, and develop ground-state cooling of ion motion in one dimension.

Chief Investigator Volz will resume measurements on resonant and off-resonant probing of exciton polariton fibre-cavity systems and develop modelling of photon correlations in an off-resonantly pumped fibre-cavity polariton system.

### 1kQubit Flagship

The 1kQubit Flagship aims to develop the theoretical foundations for a useful fault-tolerant quantum processor. Such a device requires around 1,000 logical qubits to be built, using around 1,000 physical qubits and based on technology that is expected to be available in the next five to ten years.

New Chief Investigators Burgarth and Grimsmo will drive the 1kQubit Flagship, with Chief Investigators Bartlett, Brennen and Stace also focusing their research efforts towards it.

The extensible QECSIM package, funded by EQUUS' Translational Research Program, integrates quantum error-correcting codes into a unified framework. To be released in early 2021, this package is a core part of the 1kQubit Flagship. It will form the basis for future opportunities to collaborate with relevant Australian and international groups on new methods in quantum error correction and to develop 'quantum error correction as a service' to quantum industries. Theoretical research into robust qubits will also be a key component of the 1kQubit Flagship.

## QUANTUM-ENABLED DIAGNOSTICS AND IMAGING

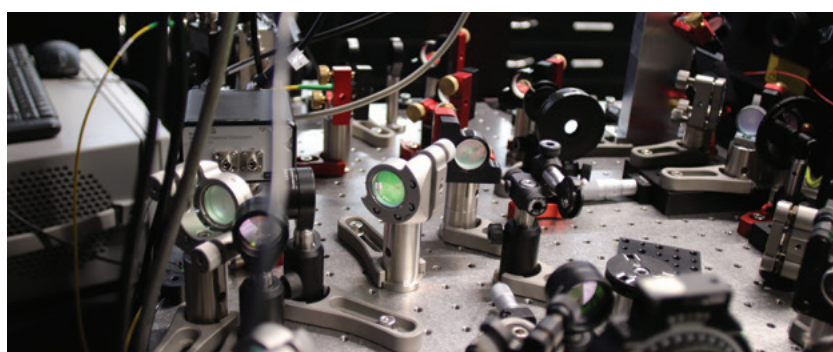
### Theory

Chief Investigator Brennen will continue work on the quantum-sensing projects initiated in 2020. In a new collaboration with Dr Yingkai Ouyang (University of Sheffield), Chief Investigator Brennen will investigate practical methods for combining quantum error correction with quantum sensing, with a focus on using Gottesman–Kitaev–Preskill-encoded states in continuous-variable systems. Chief Investigators Stace and Tobar will continue to research single-photon counters to greatly improve the sensitivity of axion dark-matter detection.

### Experiment

Chief Investigator Fedorov’s temperature measurement hints at interconnection between two-level fluctuators and quasiparticles. In 2021, he plans to detect quasiparticle generation events directly and to develop novel shielding for superconducting quantum circuits. Chief Investigators Fedorov and Bowen have begun a collaboration to test the possibility of spontaneous collapse using qubit-coupled mechanical resonators and to answer basic questions about the effect of mechanical vibrations on the decoherence of superconducting qubits.

Chief Investigator Bowen has begun a collaboration with Professor Jelena Vučković (Stanford University) that aims to realise mechanical quality factors above ten billion. If successful, this will be a major enabling step towards getting deep into the quantum regime. The main goal is to condition via measurement a



**Above**  
Inside the  
Bose–Einstein  
Condensation lab

quantum state of a mechanical resonator at room temperature for the first time.

In superfluid physics, Chief Investigator Bowen plans to exploit the new silicon-on-insulator platform to: (1) push the confining scales down to hundreds of nanometres, introducing strong nonlinearities; (2) observe quantised vortices in thin superfluid films for the first time; and (3) use superfluid optomechanics to build a photon-number-resolving detector. In quantum microscopy, Chief Investigator Bowen will extend quantum Raman microscopy to enable quantum-enhanced multispectral Raman imaging.

In 2020, Chief Investigator Tobar finished a two-year run of rotating quartz oscillators to test Lorentz invariance. In 2021, he will analyse the data to put new limits in the minimal sector and in the higher-dimensional sector. The oscillators are now being used to search for scalar dark matter. In addition, the UWA team is configuring optomechanical systems to undertake precision tests of fundamental physics, such as the search for scalar dark matter, tests of quantum gravity and searches for high-frequency gravitational waves.

## 2021 research plan

### QUANTUM ENGINES AND INSTRUMENTS

#### Theory

Associate Investigator Gilchrist and new Chief Investigator Burgarth will work on generalising the theory of quantum measurement to include backaction as a resource, with direct application to quantum control.

Chief Investigator Bartlett will initiate two new Quantum Characterization of Intermediate Scale Systems (QCISS) grants—focused largely on developing characterisation methods for quantum error correction and fault tolerance—and will continue to collaborate with UNSW and Quantum Benchmark.

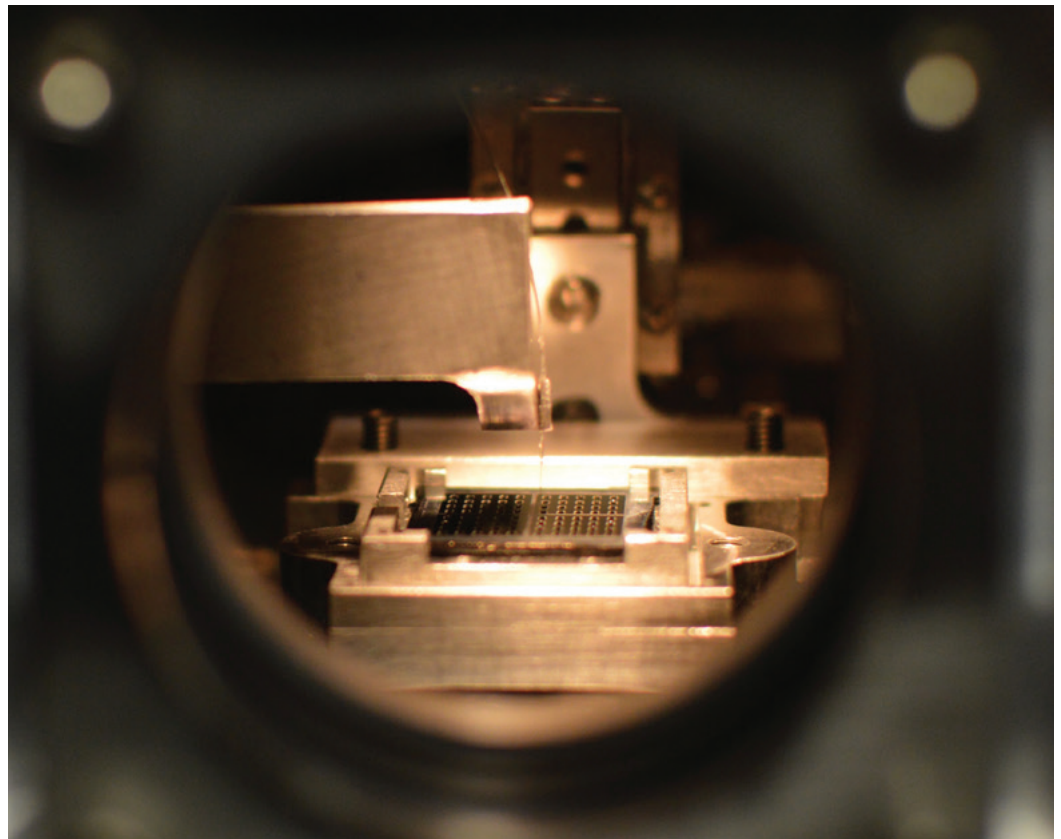
Chief Investigator Stace will continue theoretical development of and

an experimental collaboration on superconducting circulators, with a view to rapid translation.

Associate Investigator Woolley and Dr Natalia Ares (Oxford University) will seek to explain observed experimental phenomena in the dynamics of a nanomechanical oscillator operated as a single-electron transistor. Quantum thermodynamics provides a potential future research direction once an appropriate theoretical toolkit has been developed. In the longer term, this toolkit could contribute towards the demonstration of a many-body heat engine that approaches quantum-limited efficiency.

#### Right

Silicon chip with hundreds of single-crystal silicon carbide resonators inside a vacuum chamber  
*Photo by Erick Romero*



### Experiment

Chief Investigators Fedorov and Stace will work on realising a superconducting circulator based on Josephson junctions, which will be fully compatible with the fabrication of superconducting quantum bits. This circulator will be crucial for scaling up superconducting qubits.

Chief Investigator Tobar and new Chief Investigator Goryachev will continue to develop quantum hybrid instruments and their components, focusing on operation in large magnetic fields and the use of new shapes through 3D printing.

Chief Investigator Rubinsztein-Dunlop and Associate Investigators Baker and Neely will move into new space provided to EQUUS at UQ. They will conduct projects to investigate the instability that occurs at the interface of two rapidly counter-flowing superfluids and the tunnelling of quantised vortices. They will also look for the hydrodynamic analogue of the edge states of the fractional quantum Hall effect. They will demonstrate arbitrary matter waves through amplitude and phase imprinting and benchmark rotation-sensing schemes.

Chief Investigator Shaddock will continue to develop a coherent LiDAR system, focusing on performance limits at ultralow optical power. He will develop an ultralow-optical-power phase-tracking testbed, including frequency-stabilised lasers. In preliminary tests, this system resulted in the lowest-power beam to ever be tracked, three times lower than the previous record.

Associate Professor Kirk McKenzie has been recruited from NASA's Jet Propulsion Laboratory to take over as Chief Investigator and ANU node leader, and to assume supervisor responsibility for Chief Investigator Shaddock's research team, while he focuses on his start-up, Liquid Instruments.

### Quantum Clock Flagship

EQUUS has strengths in low-noise oscillators, signal processing and quantum information. The Quantum Clock Flagship includes several new research directions that consolidate EQUUS' strengths.

The Quantum Clock Flagship aims to develop: (1) a microwave qubit-clock synthesis chain; (2) a hybrid oscillator that couples solid-state qubits to oscillators; and (3) the theory for autonomous quantum clocks and relativistic noise in oscillators.

It builds on research by Chief Investigators Bowen, Milburn, Stace, Tobar and Volz, and will be driven by new Chief Investigators Bartholomew, Goryachev and Zych. Chief Investigator Milburn will collaborate with Chief Investigators Bowen and Volz, and new Chief Investigator Goryachev to produce quantum theories of the clocks under development in those groups, using the method of quantum trajectories.

## Research translation

EQUS' major impacts come through a focus on translating research outcomes and knowledge into new quantum technologies and applications. The Centre is building a culture of innovation, translation and commercialisation among Australia's quantum science researchers and technologists.

The Translational Research Program designs and delivers activities to see applications of EQUS research realised as practical prototypes. It bridges the innovation gap between laboratory discoveries and new technological developments, with a collection of programs and events to provide: (1) the means to undertake translational research and prototyping; (2) the means to gain translation experience and interact with industry; and (3) direct experience with local and international quantum industry participants and events.

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### EQUS START-UPS

In 2020, EQUS saw the formation of four start-up companies:

- 1 **Elemental Instruments**, high-uniformity controllable magnetic field devices
- 2 **Kyro Labs**, coherent random modulation for LiDAR
- 3 **Opacity Quantum**, software as a service for quantum computing diagnostics
- 4 **Redback Systems**, compact precision spectrometers

**Right**  
The Redback  
Systems team



## NEW FUNDING ROUTES FOR RESEARCH TRANSLATION

In 2020, the Translational Research Program introduced three primary funding routes to support research translation—HDR Translation Stipends, Translation Fellowships and Facilitation Projects.

HDR Translation Stipends give higher-degree research students the opportunity to gain experience in research translation. Four were awarded in 2020.

Translation Fellowships let early-career researchers experience what it's like to lead research translation and to engage with industry and wider society. One was awarded in 2020.

Facilitation Projects fund prototyping, proof-of-principle, end-use application investigations or other work required to mitigate risks and translate research outcomes towards deployable packages appropriate for industry and end-user engagement. Four were awarded in 2020.

The following five projects were funded in 2020:

**Error mapping for quantum computers.** This project takes a Bayesian approach to learning a Hamiltonian for quantum computers and has led to the formation of a start-up company, Opacity Quantum. USYD, 1 Facilitation Project, 2 HDR Translation Stipends.

**Compact superconducting microwave circulator.** This project is designing a compact and integrated

superconducting microwave circulator able to be manufactured using simple deposition techniques on silicon wafers. UQ, 1 Facilitation Project, 1 HDR Translation Stipend.

**Phase-stable clocks for 5G communications.** This project is implementing EQUUS research on precision timekeeping to improve the performance of 5G base stations. UWA, 1 Facilitation Project, 1 HDR Translation Stipend.

**Optical communications ground station demonstrator.** This project is demonstrating an advanced optical communications ground station using atmospheric-noise-suppression technology, capable of amplitude- and phase-stabilised coherent communications to low-altitude and stratospheric aircraft, and of receiving signals from spacecraft between low-Earth orbit and the surface of the Moon. UWA, 1 Facilitation Project.

**Field-deployable precision magnetometer.** This project is building a proof-of-principle room-temperature, miniaturised magnetometer based on cavity optomechanical devices, which will be integrated on-chip and include a new scheme for suppressing laser phase noise. UQ, 1 Translation Fellowship.

## Research translation

### CASE STUDY: TOWARDS THE STABILISATION OF STRATOSPHERIC AND LOW-EARTH-ORBIT COHERENT OPTICAL LINKS

**Right**  
Optical terminal for point-to-point phase-stabilised optical-frequency transfer

In 2019, EQUUS' Translational Research Program awarded \$39,000 to a project to develop a device that mitigates the effects of atmospheric turbulence on free-space optical links. The project was a collaboration between UWA, the French space agency (CNES) and the SYRTE observatory in Paris.

The successful transfer of optical-frequency signals over free-space laser links, such as between ground stations and satellites, is currently hindered by atmospheric turbulence, which induces phase perturbations of the optical signals.

This project saw the creation of the first phase-stabilised, coherent, optical-frequency transfer system designed to work over a true point-to-point free-space link. The funding was used to construct two compact, field-deployable systems capable of actively suppressing the zeroth-order phase noise and the first-order beam-wandering effects of the atmosphere.

In February 2020, the system was deployed over a 265-metre free-space



optical link, between two buildings at the CNES campus in Toulouse. This demonstration achieved a record for the most stable optical-frequency transfer—being an order of magnitude more stable than state-of-the-art optical atomic clocks. The technology is thus suitable for future space-to-ground atomic-clock comparisons, which may be used to test fundamental physics theories such as general relativity and dark matter.

The project has led to an ongoing collaboration with CNES. The next steps for the team will be a proof-of-principle demonstration over a vertical link to an unmanned aerial vehicle.

The project involved EQUUS researchers Associate Investigator Dr Sascha Schediwy, PhD student Benjamin Dix-Matthews, Associate Investigator Dr David Gozzard and Chief Investigator Professor Michael Tobar.

**Below**  
Benjamin Dix-Matthews, Sascha Schediwy and Michael Tobar (left to right)

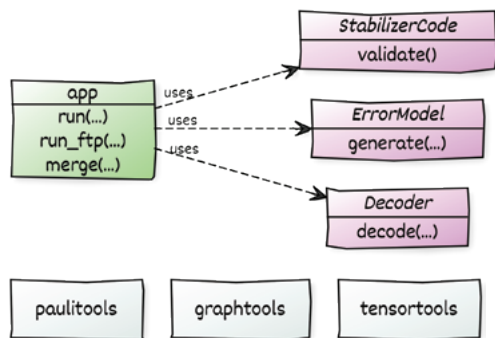


## CASE STUDY: TRANSLATING SOFTWARE FOR QUANTUM ERROR CORRECTION

In 2019, EQUUS' Translational Research Program provided \$25,000 to fund a project to develop a software library to construct, optimise and test quantum error-correction solutions. The project was a collaboration between USYD, MQ and UQ, led by EQUUS postdoctoral researcher Dr David Tuckett (USYD).

Quantum computers have the potential to solve problems that are intractable using classical computers, with benefits in areas such as medicine, energy-efficient processes and machine learning. Quantum error correction is expected to have a key role in protecting the fragile quantum states on which computers are based, enabling quantum computers to realise their full potential.

This project saw the release of new open-source software, called QECSIM (Python quantum error correction simulator). Originally developed as a personal research tool, the funding



```
# run [OPTIONS] CODE ERROR_MODEL DECODER ERROR_PROBABILITY...
qecsim run -r50 "toric(3,3)" "generic.bit_flip" "toric.mwpm" \
0.05 0.1 0.15

>>> from qecsim import app
>>> app.run(code, error_model, decoder, 0.05, max_runs=50)

{"code": "Toric 3x3", "error_model": "Bit-flip",
 "decoder": "Toric MWPM", "error_probability": 0.05,
 ..., "logical_failure_rate": 0.03, ...}
```

enabled the software to be packaged and documented ready for public use.

QECSIM enables key metrics of quantum error-correction codes and decoders to be evaluated in the presence of experimentally realistic error models<sup>1,2,3</sup>. It includes a fully documented command-line interface and application programming interface (API), which facilitate simulations on high-performance computing clusters and prototyping in notebooks. It is optimised and has a modular design for ease of extension.

QECSIM has already been used by EQUUS<sup>4</sup> and non-EQUUS researchers for new projects. It will hopefully lead to new simulation workflows and contribute to the realisation of large-scale reliable quantum computation. Dr Tuckett shared his experiences of and best practices for developing open-source software at the 2020 EQUUS Annual Workshop.

### Above

Examples of QECSIM's command-line interface and application programming interface

### Left

Modular design of the core application (green), extensible models (purple) and optimised services (grey)

1 DK Tuckett, SD Bartlett & ST Flammia. **Ultra-high error threshold for surface codes with biased noise.** *Phys. Rev. Lett.* 120:050505 (2018)

2 DK Tuckett, AS Darmawan, CT Chubb, S Bravyi, SD Bartlett & ST Flammia. **Tailoring surface codes for highly biased noise.** *Phys. Rev. X* 9:041031 (2019)

3 DK Tuckett, SD Bartlett, ST Flammia & BJ Brown. **Fault-tolerant thresholds for the surface code in excess of 5% under biased noise.** *Phys. Rev. Lett.* 124:130501 (2020)

4 JP Bonilla Ataides, DK Tuckett, SD Bartlett, ST Flammia & BJ Brown. **The XZZX surface code.** *arXiv* 2009.07851 (2020)

## Equity and diversity

**EQUS is committed to improving equity, diversity and inclusion within the Centre, at the five collaborating institutions and in the wider quantum physics community. The Centre aims to foster a safe, welcoming and inclusive environment that allows all EQUS members to achieve success, and to feel respected and supported.**

In 2020, EQUS delivered several events and initiatives to help educate and support EQUS members.

On 10 June, EQUS participated in the #ShutDownSTEM initiative—part of the global #BlackLivesMatter movement. EQUS members were provided with resources on practising anti-racism, and several research groups took time to reflect on racism in academia and quantum.

In July, EQUS launched a virtual journal club to discuss current research surrounding equity and diversity in STEM and how it applies to the Centre. The meetings consist of an overview of the selected literature and group discussion. The club gathered four times in 2020.

EQUS is in the process of introducing guidelines for EQUS job advertisements to ensure that the Centre attracts the best researchers. The guidelines are based on material provided by Dr James Millen, King's College London—who was an invited speaker at the 2020 EQUS Annual Workshop—and derived from extensive research by various organisations.

EQUS continues to sponsor events and activities that promote equity, diversity and inclusion in STEM. In 2020, EQUS sponsored Soapbox Science Sydney and a workshop on equity, diversity and inclusion at the 14th Pacific Rim Conference on Lasers and Electro-Optics.

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### LGBTSTEM DAY

In recognition of LGBTSTEM Day, EQUS organised a series of short talks by people working in STEM who identify as LGBTQIA+, including EQUS researcher Dr Tara Roberson (UQ). The talks provided insights into the experience of LGBTQIA+ scientists and into practical changes that can be made to ensure a more inclusive workplace culture. 45 members of EQUS, the ARC Centre of Excellence in Future Low-Energy Electronics Technologies and/or associated institutions attended the event.

**Right**  
LGBTSTEM  
Day biscuit  
*Photo by  
Yasmine Sfendla*



## Equity and diversity

### WIKIPEDIA EDIT-A-THON

To coincide with National Science Week, EQUUS ran a Wikipedia edit-a-thon. The aim of the event was to increase the visibility of people from under-represented groups in STEM and help to ensure that the diversity of the STEM community is reflected on Wikipedia.

The event involved 25 members of EQUUS and/or the ARC Centre of Excellence in Future Low-Energy Electronics Technologies from 7 institutions (ANU, UQ, USYD, UWA, Monash, RMIT and UNSW). The attendees collectively improved 23 Wikipedia pages for people from under-represented groups in STEM and created two new ones.

### DEBORAH JIN FELLOWSHIPS

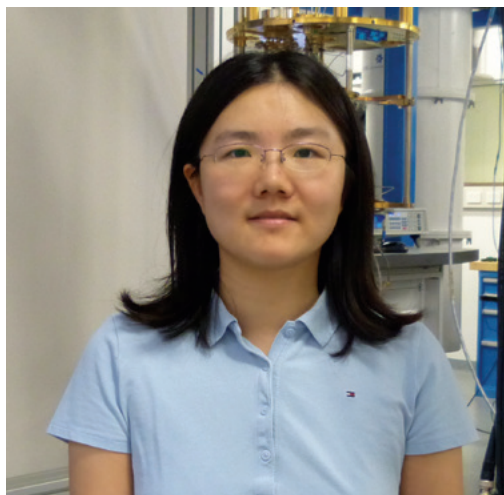
Two postdoctoral researchers joined EQUUS in 2020 as the inaugural Deborah Jin Fellows. Dr Elizabeth Bridge (UQ) is working with Chief Investigator Bowen and Dr Zijun (Cindy) Zhao (UWA) is working with Chief Investigator Tobar.

Dr Bridge works with optomechanical sensors. For example, she's developing magnetic sensors that can be used as communication devices deep in underground mines. Dr Bridge shared some of her experiences as a researcher in EQUUS' Q&ARC episode.

Dr Zhao researches quantum technologies to test fundamental physics

and search for dark matter. For example, she's working towards uncovering new physics using precision measurements of crystals in cryogenic environments. Dr Zhao presented some of her research at the 2020 EQUUS Annual Workshop.

EQUUS' Deborah Jin Fellowship program aims to increase the proportion of women at EQUUS and in quantum physics through targeted recruitment. The program has subsequently been used as a template at UQ for targeted hiring in the School of Mathematics and Physics and for establishing a university-wide policy for inclusive and diversity-centric recruitment.



**Far left**  
Zijun (Cindy) Zhao

**Left**  
Elizabeth Bridge

## Communication and outreach

### Below

Still from Schrödinger's Cat Burglar, the winning entry to Quantum Games

### Bottom left

Associate Investigator Dr Jacinda Ginges talking to students at the Queensland Academy for Science, Mathematics and Technology at their Lunch With A Scientist networking event

### Bottom right

Deputy Director Professor Tom Stace appeared on the children's science show Scope

**EQUS continues to engage diverse audiences with quantum science and technologies. The Centre promotes new research, public events, and other activities and achievements through media releases, the EQUS website and social media on an ongoing basis.**

In 2020, communication and outreach activities were substantially affected by the catastrophic bushfires and then the COVID-19 pandemic. Most notably, a quantum masterclass for Australian science teachers, to be delivered as part of the STEM X Academy in Canberra in January, had to be cancelled at the last minute as a result of the bushfires. In addition, plans for a Quantum Roadtrip and public showcasing of the winning Quantum Games at World Science Festival Brisbane were cancelled as a result of the pandemic.

Nevertheless, EQUS organised or participated in several virtual outreach activities in 2020.

The Centre was once again a scientific partner for the Quantum Shorts competition, an initiative of the Centre for Quantum Technologies at the National University of Singapore.

The 2019–20 Quantum Games competition concluded, with first prize going to Martin Binfield-James. Martin's game—Schrödinger's Cat Burglar—is a puzzle-based game that incorporates several ideas inspired by quantum physics.

EQUS' Translational Research Program delivered several workshops and events related to research translation or quantum in business and industry. It also coordinated submissions to government and was invited to consult on various research translation and commercialisation matters by state and federal government bodies.

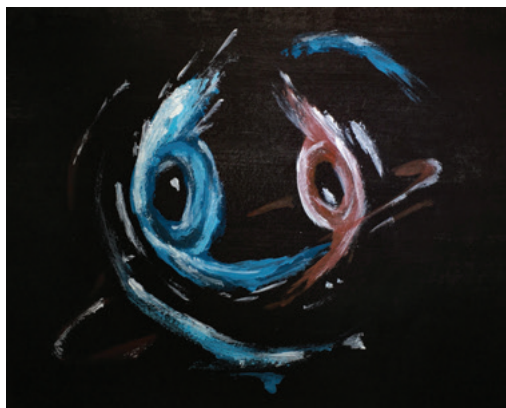


## Communication and outreach

### QUANTUM ART

To coincide with National Science Week, EQUUS ran a quantum art competition. The competition was open to anyone outside EQUUS and the scope was purposely broad to encourage a wide variety of artforms and interpretations of 'quantum art'.

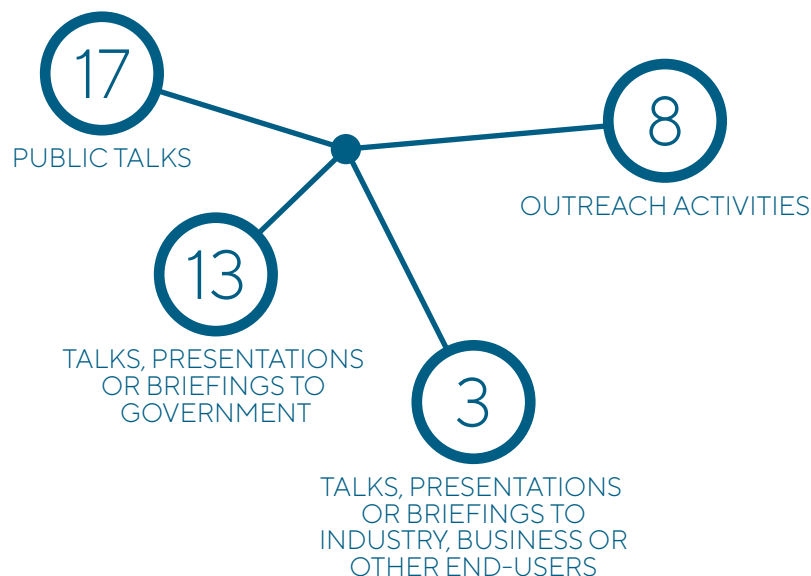
The winning entry was a suite of five quantum-themed poems by Jackson Used, an interdisciplinary artist from Perth. Chief Investigator Professor Gerard Milburn—former EQUUS Director and one of the judges—said: "The poems were elegant and lyrical. They relate physical concepts to human emotions, not an easy thing to do."



Runner-up prizes were awarded to Jess Hill and Amy Treloar, high-school students from Canberra, and Pramodh Senarath Yapa and Guy Whittall-Scherfee, higher-degree research students at the University of Alberta, Canada. Jess and

### Q&ARC VIDEO SERIES

EQUUS participated in a video series—called Q&ARC—with other ARC Centres of Excellence. EQUUS' video features Chief Investigator Dr Jacqui Romero (UQ), Deborah Jin Fellow Dr Liz Bridge (UQ)



Amy's video entry takes the audience on a journey through a young physicist's discovery of quarks, in their finite variety. Pramodh and Guy's entry uses the medium of hip-hop to introduce the audience to low-temperature physics and explain how fermions pair up to form Bose-Einstein condensates.

The People's Choice Prize went to Toby Davis, a high-school student in Canberra. Toby's entry is an abstract rendition of a particle-antiparticle pair in the process of annihilation.

Other judges included Jennifer Burns, artworker on the science journal *Nature*, and Tilly Boleyn, curator at Science Gallery Melbourne. Tilly summed up the competition perfectly: "I found all the entries fascinating and partially bamboozling—so very spot on for what I would expect from a quantum art competition!"

and PhD student Jemy Geordy (MQ) talking about their research and what it's like to be a researcher at an ARC Centre of Excellence. The full series is available on the ARC's YouTube channel.

**Left**  
Winning entry for the People's Choice Prize, by Toby Davis

## Mentoring and career development

**EQUS provides training and mentoring for higher-degree research students and early-career researchers to support the advancement of their research skills and broader knowledge of the field. Training opportunities also address skills that will assist EQUS members in their academic and industry careers.**

Owing to disruption by the COVID-19 pandemic, several activities relating to mentoring and career development became virtual or were deferred. Most notably, the 2020 EQUS Summer School and Idea Factory were postponed to 2021. Despite this, EQUS successfully delivered several programs and events to support EQUS members.

The EQUS mentoring program provides career-oriented support for higher-degree research students and early-career researchers. The program continued successfully in 2020, with 55 mentees matched with 46 mentors. Through EQUS' collaboration grant scheme, four early-career researchers were collectively awarded \$10,500 in funding to support new collaborations between EQUS researchers.

The EQUS summer research program provides an opportunity for current and recent undergraduate students to get a taste of scientific research and develop skills and knowledge for careers in quantum science and technology. The program was expanded in 2020, with 16 students awarded scholarships. These students receive a stipend of \$400 per week for up to six weeks.

The EQUS webinar series continued and expanded, with 18 webinars being presented by EQUS members across all levels. In lieu of the postponed Idea Factory, EQUS ran a smaller event at which previously successful DECRA fellows within EQUS shared their experience and advice.

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### PYTHON WORKSHOP

The Python workshop aims to provide participants with an introduction to the Python programming language, confidence and capability in writing reliable and understandable code, and a connection to the large community of

researchers and industry professionals creating research-grade code.

Owing to the COVID-19 pandemic, the 2020 Python workshop was run virtually in a scaled-down format, with no invited speakers, only 40 participants and over two instead of four days. Nevertheless, the workshop received very positive feedback from attendees.

The workshop was led by EQUS alumnus Dr Alan Robertson (USYD) and Associate Investigator Dr Yuval Sanders (MQ). In addition to achieving the stated aims, the workshop provided valuable insights into running successful virtual workshops.

**Right**  
Python-themed  
EQUS logo,  
designed by  
Christina Dobson



# Mentoring and career development

## SCIENCE COMMUNICATION WORKSHOP SERIES

In September, EQUUS ran a series of virtual workshops for EQUUS members on science communication. The first—science communication fundamentals—was led by postdoctoral researchers Dr Ben McAllister (UWA) and Dr Tara Roberson (UQ). The second—science communication online—was led by Australian science communicator Lee Constable. The third—science

communication and the media—was led by UK science journalist Richard Hollingham from Boffin Media.

Attendees developed and refined their elevator pitches, learned how to use social media as a science communication tool and picked up tips for doing radio and TV interviews during a pandemic.

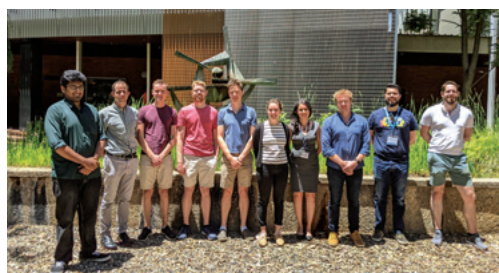
## ANNUAL WORKSHOP

The EQUUS Annual Workshop is the primary forum for collaboration and exchange of ideas between EQUUS members. The 2020 workshop ran as a hybrid event, with talks streamed to venues in Brisbane, Canberra, Perth and Sydney, as well as to online attendees.

The workshop was attended by roughly 150 people, including students, early-career researchers, Chief Investigators and members of the Scientific Advisory Committee.

Highlights of the event include:

- Invited talks by Dr Naomi Nickerson, Director of Quantum Architecture at PsiQuantum, and Dr James Millen, Lecturer in Advanced Photonics at King's College London
- Talks on research commercialisation by Associate Investigator Dr Sascha Schediwy (UWA), on public good, artificial intelligence and the COVID-19 pandemic by Chief Investigator Sally Shrapnel (UQ), and on developing shareable and reusable software by postdoctoral researcher Dr David Tuckett (USYD)
- Awarding of the Director's Prize to Dr Ben McAllister



**Left**  
Attendees at the Annual Workshop  
Top to bottom:  
Brisbane,  
Canberra,  
Perth and  
Sydney

## Publications

- Y Yang, K Das, A Moini & DJ Reilly. **A cryo-CMOS voltage reference in 28-nm FDSOI.** *IEEE Solid-State Circuits Lett.* 3:186–189 (2020)
- BJ Brown. **A fault-tolerant non-Clifford gate for the surface code in two dimensions.** *Sci. Adv.* 6:eaay4929 (2020)
- NA McMahon, S Singh & GK Brennen. **A holographic duality from lifted tensor networks.** *npj Quantum Inform.* 6:36 (2020)
- JS Bennett, LS Madsen, H Rubinsztein-Dunlop & WP Bowen. **A quantum heat machine from fast optomechanics.** *New J. Phys.* 22:103028 (2020)
- T Farrelly. **A review of quantum cellular automata.** *Quantum* 4:368 (2020)
- MK Vijayan, AP Lund & PP Rohde. **A robust W-state encoding for linear quantum optics.** *Quantum* 4:303 (2020)
- RS Gupta, CL Edmunds, AR Milne, C Hempel & MJ Biercuk. **Adaptive characterization of spatially inhomogeneous fields and errors in qubit registers.** *npj Quantum Inform.* 6:53 (2020)
- TC Bartolo, JS Smith, B Muralidharan, C Müller, TM Stace & JH Cole. **Aharonov-Bohm interference as a probe of Majorana fermions.** *Phys. Rev. Res.* 2:043430 (2020)
- G Muñoz-Matutano, M Johnsson, J Martinez-Pastor, D Rivas Gongora, L Seravalli, G Trevisi, P Frigeri, T Volz & M Gurioli. **All optical switching of a single photon stream by excitonic depletion.** *Commun. Phys.* 3:29 (2020)
- SR Nair, LJ Rogers, X Vidal, RP Roberts, H Abe, T Ohshima, T Yatsui, AD Greentree, J Jeske & T Volz. **Amplification by stimulated emission of nitrogen-vacancy centres in a diamond-loaded fibre cavity.** *Nanophotonics* 9:4505–4518 (2020)
- J Lee, C Arenz, D Burgarth & H Rabitz. **An upper bound on the time required to implement unitary operations.** *J. Phys. A* 53:125304 (2020)
- DT Ralph, PA Altin, DS Rabeling, DE McClelland & DA Shaddock. **Automatic mode-matching of a Fabry-Pérot cavity with a single photodiode and spatial light modulation.** *J. Opt.* 22:105605 (2020)
- J Darulova, SJ Pauka, N Wiebe, KW Chan, GC Gardener, MJ Manfra, MC Cassidy & M Troyer. **Autonomous tuning and charge-state detection of gate-defined quantum dots.** *Phys. Rev. Appl.* 13:054005 (2020)
- S Puri, L St-Jean, JA Gross, A Grimm, NE Frattini, PS Iyer, A Krishna, S Touzard, L Jiang, A Blais, ST Flammia & SM Girvin. **Bias-preserving gates with stabilized cat qubits.** *Sci. Adv.* 6:eaay5901 (2020)
- ME Tobar, BT McAllister & M Goryachev. **Broadband electrical action sensing techniques with conducting wires for low-mass dark matter axion detection.** *Phys. Dark Universe* 30:100624 (2020)
- DT Le, JH Cole & TM Stace. **Building a bigger Hilbert space for superconducting devices, one Bloch state at a time.** *Phys. Rev. Res.* 2:013245 (2020)
- TM Roberson. **Can hype be a force for good? Inviting unexpected engagement with science and technology futures.** *Public Underst. Sci.* 29:544–552 (2020)
- JM Pate, M Goryachev, RY Chiao, JE Sharping & ME Tobar. **Casimir spring and dilution in macroscopic cavity optomechanics.** *Nat. Phys.* 16:1117–1122 (2020)
- J White, C Laplane, RP Roberts, LJ Brown, T Volz & DW Inglis. **Characterization of optofluidic devices for the sorting of sub-micrometer particles.** *Appl. Opt.* 59:271–276 (2020)
- A Chapman & ST Flammia. **Characterization of solvable spin models via graph invariants.** *Quantum* 4:278 (2020)
- SJ Pauka, K Das, JM Hornibrook, GC Gardner, MJ Manfra, MC Cassidy & DJ Reilly. **Characterizing quantum devices at scale with custom cryo-CMOS.** *Phys. Rev. Appl.* 13:054072 (2020)
- LE Roberts, RL Ward, C Smith & DA Shaddock. **Coherent beam combining using an internally sensed optical phased array of frequency-offset phase locked lasers.** *Photonics* 7:118 (2020)
- RW Bomantara & J Gong. **Combating quasiparticle poisoning with multiple Majorana fermions in a periodically-driven quantum wire.** *J. Phys. Condes. Matter* 32:435301 (2020)
- D Cohen, R Nigmatullin, M Eldar & A Retzker. **Confined nano-NMR spectroscopy using NV centers.** *Adv. Quantum Technol.* 3:2000019 (2020)
- M Umer, RW Bomantara & J Gong. **Counterpropagating edge states in Floquet topological insulating phases.** *Phys. Rev. B* 101:235438 (2020)
- PG Sibley, RL Ward, LE Roberts, SP Francis & DA Shaddock. **Crosstalk reduction for multi-channel optical phase metrology.** *Opt. Express* 28:10400–10424 (2020)
- RJ Harris, E Coupe, NA McMahon, GK Brennen & TM Stace. **Decoding holographic codes with an integer optimization decoder.** *Phys. Rev. A* 102:062417 (2020)
- MC Jarratt, SJ Waddy, A Jouan, AC Mahoney, GC Gardner, S Fallahi, MJ Manfra & DJ Reilly. **Detection of the quantum capacitance of a point contact via dispersive gate sensing.** *Phys. Rev. Appl.* 14:064021 (2020)

G Flower, BT McAllister, M Goryachev & ME Tobar. **Determination of niobium cavity magnetic field screening via a dispersively hybridized magnonic sensor.** *Appl. Phys. Lett.* 117:162401 (2020)

AP Quiskamp, BT McAllister, G Rybka & ME Tobar. **Dielectric-boosted sensitivity to cylindrical azimuthally varying transverse-magnetic resonant modes in an axion haloscope.** *Phys. Rev. Appl.* 14:044051 (2020)

TB Smith, MC Cassidy, DJ Reilly, SD Bartlett & AL Grimsmo. **Dispersive readout of Majorana qubits.** *PRX Quantum* 1:020313 (2020)

C Müller. **Dissipative Rabi model in the dispersive regime.** *Phys. Rev. Res.* 2:033046 (2020)

H Cao, S-C Gao, C Zhang, J Wang, D-Y He, B-H Liu, Z-W Zhou, Y-J Chen, Z-H Li, S-Y Yu, J Romero, Y-F Huang, C-F Li & G-C Guo. **Distribution of high-dimensional orbital angular momentum entanglement over a 1 km few-mode fiber.** *Optica* 7:232-237 (2020)

CL Edmunds, C Hempel, RJ Harris, V Frey, TM Stace & MJ Biercuk. **Dynamically corrected gates suppressing spatiotemporal error correlations as measured by randomized benchmarking.** *Phys. Rev. Res.* 2:013156 (2020)

TJ Osborne & DE Stiegemann. **Dynamics for holographic codes.** *J. High Energy Phys.* 4:154 (2020)

ST Flammia & JJ Wallman. **Efficient estimation of Pauli channels.** *ACM Trans. Quantum Comput.* 1:3 (2020)

R Harper, ST Flammia & JJ Wallman. **Efficient learning of quantum noise.** *Nat. Phys.* 16:1184-1188 (2020)

E Romero, VM Valenzuela, AR Kermany, L Sementilli, F Iacopi & WP Bowen. **Engineering the dissipation of crystalline micromechanical resonators.** *Phys. Rev. Appl.* 13:044007 (2020)

S Schutz, J Schachenmayer, D Hagenmuller, GK Brennen, T Volz, V Sandoghdar, TW Ebbesen, C Genes & G Pupillo. **Ensemble-induced strong light-matter coupling of a single quantum emitter.** *Phys. Rev. Lett.* 124:113602 (2020)

K Goswami & J Romero. **Experiments on quantum causality.** *AVS Quantum Sci.* 2:037101 (2020)

DR Gozzard, LE Roberts, JT Spollard, PG Sibley & DA Shaddock. **Fast beam steering with an optical phased array.** *Opt. Lett.* 45:3793-3796 (2020)

P Webster & SD Bartlett. **Fault-tolerant quantum gates with defects in topological stabilizer codes.** *Phys. Rev. A* 102:022403 (2020)

DK Tuckett, SD Bartlett, ST Flammia & BJ Brown. **Fault-tolerant thresholds for the surface code in excess of 5% under biased noise.** *Phys. Rev. Lett.* 124:130501 (2020)

H Cao, C Radhakrishnan, M Su, MM Ali, C Zhang, Y-f Huang, T Byrnes, C-F Li & G-C Guo. **Fragility of quantum correlations and coherence in a multipartite photonic system.** *Phys. Rev. A* 102:012403 (2020)

H Pashayan, SD Bartlett & D Gross. **From estimation of quantum probabilities to simulation of quantum circuits.** *Quantum* 4:223 (2020)

C-C Chen, TM Stace & H-S Goan. **Full-polaron master equation approach to dynamical steady states of a driven two-level system beyond the weak system-environment coupling.** *Phys. Rev. B* 102:035306 (2020)

J Foo, S Onoe, M Zych & TC Ralph. **Generating multi-partite entanglement from the quantum vacuum with a finite-lifetime mirror.** *New J. Phys.* 22:083075 (2020)

M Appleby, S Flammia, G McConnell & J Yard. **Generating ray class fields of real quadratic fields via complex equiangular lines.** *Acta Arithmetica* 192:211-233 (2020)

J Bourhill, NC Carvalho, M Goryachev, S Galliou & ME Tobar. **Generation of coherent phonons via a cavity enhanced photonic lambda scheme.** *Appl. Phys. Lett.* 117:164001 (2020)

M Goryachev, S Galliou & ME Tobar. **Generation of ultralow power phononic combs.** *Phys. Rev. Res.* 2:023035 (2020)

MT Johnsson, N Roy-Mukty, D Burgarth, T Volz & GK Brennen. **Geometric pathway to scalable quantum sensing.** *Phys. Rev. Lett.* 125:190403 (2020)

MJ Kewming, S Shrapnel, AG White & J Romero. **Hiding ignorance using high dimensions.** *Phys. Rev. Lett.* 124:250401 (2020)

S Tan, RW Bomantara & J Gong. **High-fidelity and long-distance entangled-state transfer with Floquet topological edge modes.** *Phys. Rev. A* 102:022608 (2020)

CD Marciniak, A Rischka, RN Wolf & MJ Biercuk. **High-power spectral beamsplitter for closely spaced frequencies.** *Opt. Express* 28:11372-11379 (2020)

DEJ Waddington, T Boele, R Maschmeyer, Z Kuncic & MS Rosen. **High-sensitivity in vivo contrast for ultra-low field magnetic resonance imaging using superparamagnetic iron oxide nanoparticles.** *Sci. Adv.* 6:eabb0998 (2020)

## Publications

- F Wienholtz, K Blaum, J Karthein, D Lunney, S Malbrunot-Ettenauer, V Manea, M Mougeot, L Schweikhard, T Steinsberger & RN Wolf. **Improved stability of multi-reflection time-of-flight mass spectrometers through passive and active voltage stabilization.** *Nucl. Instrum. Methods B* 463:348–356 (2020)
- K Goswami, Y Cao, GA Paz-Silva, J Romero & AG White. **Increasing communication capacity via superposition of order.** *Phys. Rev. Res.* 2:033292 (2020)
- RS Gupta, LCG Govia & MJ Biercuk. **Integration of spectator qubits into quantum computer architectures for hardware tune-up and calibration.** *Phys. Rev. A* 102:042611 (2020)
- Y Wan, R Jördens, SD Erickson, JJ Wu, R Bowler, TR Tan, P-Y Hou, DJ Wineland, AC Wilson & D Leibfried. **Ion transport and reordering in a 2D trap array.** *Adv. Quantum Technol.* 3:2000028 (2020)
- A Kulikov, R Navarathna & A Fedorov. **Measuring effective temperatures of qubits using correlations.** *Phys. Rev. Lett.* 124:240501 (2020)
- C Meng, GA Brawley, JS Bennett, MR Vanner & WP Bowen. **Mechanical squeezing via fast continuous measurement.** *Phys. Rev. Lett.* 125:043604 (2020)
- BP Dix-Matthews, SW Schediwy, DR Gozzard, S Driver, KU Schreiber, R Carman & ME Tobar. **Methods for coherent optical Doppler orbitography.** *J. Geodesy* 94:55 (2020)
- S Forstner, M Zych, S Basiri-Esfahani, KE Khosla & WP Bowen. **Nanomechanical test of quantum linearity.** *Optica* 7:1427–1434 (2020)
- YY Atas, A Safavi-Naini & KV Kheruntsyan. **Nonequilibrium quantum thermodynamics of determinantal many-body systems: application to the Tonks–Girardeau and ideal Fermi gases.** *Phys. Rev. A* 102:043312 (2020)
- T Touloup, RW Bomantara, CH Lee & J Gong. **Nonlinearity induced topological physics in momentum space and real space.** *Phys. Rev. B* 102:115411 (2020)
- DN Bernal-García, H Vinck-Posada & MJ Woolley. **Nonstationary force sensing under dissipative mechanical quantum squeezing.** *Phys. Rev. A* 102:053515 (2020)
- CDB Bentley, H Ball, MJ Biercuk, ARR Carvalho, MR Hush & HJ Slatyer. **Numeric optimization for configurable, parallel, error-robust entangling gates in large ion registers.** *Adv. Quantum Technol.* 3:2000044 (2020)
- T Roberson. **On social change, agency, and public interest: what can science communication learn from public relations?** *J. Sci. Commun.* 19:Y01 (2020)
- DR Gozzard, JT Spollard, PG Sibley, LE Roberts & DA Shaddock. **Optical vortex beams with controllable orbital angular momentum using an optical phased array.** *OSA Continuum* 3:3399–3406 (2020)
- B Sarma, T Busch & J Twamley. **Optomechanical cooling by STIRAP-assisted energy transfer: an alternative route towards the mechanical ground state.** *New J. Phys.* 22:103043 (2020)
- BJ Brown & DJ Williamson. **Parallelized quantum error correction with fracton topological codes.** *Phys. Rev. Res.* 2:013303 (2020)
- AR Milne, CL Edmunds, C Hempel, F Roy, S Mavadia & MJ Biercuk. **Phase-modulated entangling gates robust to static and time-varying errors.** *Phys. Rev. Appl.* 13:024022 (2020)
- SFE Karpathakis, CT Gravestock, DR Gozzard, TR Pulbrook & SW Schediwy. **Phase synchronization system receiver module for the mid-frequency Square Kilometre Array.** *J. Astron. Telesc. Instrum. Syst.* 6:044002 (2020)
- DS Karpov, VY Monarkha, D Szombati, AG Frieiro, AN Omelyanchouk, E Il'ichev, A Fedorov & SN Shevchenko. **Probabilistic motional averaging.** *Eur. Phys. J. B* 93:49 (2020)
- H Triki & VI Kruglov. **Propagation of dipole solitons in inhomogeneous highly dispersive optical-fiber media.** *Phys. Rev. E* 101:042220 (2020)
- GI Harris, A Sawadsky, YL Sfindla, WW Wasserman, WP Bowen & CG Baker. **Proposal for a quantum traveling Brillouin resonator.** *Opt. Express* 28:22450–22461 (2020)
- AL Grimsmo, J Combes & BQ Baragiola. **Quantum computing with rotation-symmetric bosonic codes.** *Phys. Rev. X* 10:011058 (2020)
- MJ Kewming, S Shrapnel & GJ Milburn. **Quantum correlations in the Kerr Ising model.** *New J. Phys.* 22:053042 (2020)
- PM Birchall, EJ Allen, TM Stace, JL O'Brien, JCF Matthews & H Cable. **Quantum optical metrology of correlated phase and loss.** *Phys. Rev. Lett.* 124:140501 (2020)
- D Szombati, AG Frieiro, C Mueller, T Jones, M Jerger & A Fedorov. **Quantum rifling: protecting a qubit from measurement back action.** *Phys. Rev. Lett.* 124:070401 (2020)
- LJ Henderson, A Bejencia, E Castro-Ruiz, C Budroni, M Zych, C Brukner & RB Mann. **Quantum temporal superposition: the case of quantum field theory.** *Phys. Rev. Lett.* 125:131602 (2020)
- D Burgarth, P Facchi, H Nakazato, S Pascazio & K Yuasa. **Quantum Zeno dynamics through general quantum operations.** *Quantum* 4:289 (2020)

# Publications

- VI Kruglov & H Triki. **Quartic and dipole solitons in a highly dispersive optical waveguide with self-steepening nonlinearity and varying parameters.** *Phys. Rev. A* 102:043509 (2020)
- AN Pearson, KE Khosla, M Mergenthaler, GAD Briggs, EA Laird & N Ares. **Radio-frequency optomechanical characterization of a silicon nitride drum.** *Sci. Rep.* 10:1654 (2020)
- M Jafarzadeh, Y-D Wu, YR Sanders & BC Sanders. **Randomized benchmarking for qudit Clifford gates.** *New J. Phys.* 22:063014 (2020)
- SJ Pauka, JDS Witt, CN Allen, B Harlech-Jones, A Jouan, GC Gardner, S Gronin, T Wang, C Thomas, MJ Manfra, J Gukelberger, J Gamble, DJ Reilly & MC Cassidy. **Repairing the surface of InAs-based topological heterostructures.** *J. Appl. Phys.* 128:114301 (2020)
- G Tobar & F Costa. **Reversible dynamics with closed time-like curves and freedom of choice.** *Class. Quantum Grav.* 37:205011 (2020)
- C Cirstoiu, K Korzekwa & D Jennings. **Robustness of Noether's principle: maximal disconnects between conservation laws and symmetries in quantum theory.** *Phys. Rev. X* 10:041035 (2020)
- BP Dolan, A Hunter-McCabe & J Twamley. **Shaking photons from the vacuum: acceleration radiation from vibrating atoms.** *New J. Phys.* 22:033026 (2020)
- V Frey, LM Norris, L Viola & MJ Biercuk. **Simultaneous spectral estimation of dephasing and amplitude noise on a qubit sensor via optimally band-limited control.** *Phys. Rev. Appl.* 14:024021 (2020)
- VI Kruglov. **Solitary wave and periodic solutions of nonlinear Schrödinger equation including higher order dispersions.** *Opt. Commun.* 472:125866 (2020)
- P Warszawski, HM Wiseman & AC Doherty. **Solving quantum trajectories for systems with linear Heisenberg-picture dynamics and Gaussian measurement noise.** *Phys. Rev. A* 102:042210 (2020)
- X He, GI Harris, CG Baker, A Sawadsky, YL Sfindla, YP Sachkou, S Forstner & WP Bowen. **Strong optical coupling through superfluid Brillouin lasing.** *Nat. Phys.* 16:417–421 (2020)
- A Gonzales, D Dilley & M Byrd. **Sufficient conditions and constraints for reversing general quantum errors.** *Phys. Rev. A* 102:062415 (2020)
- S Roberts & SD Bartlett. **Symmetry-protected self-correcting quantum memories.** *Phys. Rev. X* 10:031041 (2020)
- T Boele, DEJ Waddington, T Gaebel, E Rej, A Hasija, LJ Brown, DR McCamey & DJ Reilly. **Tailored nanodiamonds for hyperpolarized C-13 MRI.** *Phys. Rev. B* 101:155416 (2020)
- P Girdhar & AC Doherty. **Testing generalised uncertainty principles through quantum noise.** *New J. Phys.* 22:093073 (2020)
- IH Kim, E Tang & J Preskill. **The ghost in the radiation: robust encodings of the black hole interior.** *J. High Energy Phys.* 6:31 (2020)
- G Alexander, RE Allen, A Atala, WP Bowen, AA Coley, JB Goodenough, MI Katsnelson, EV Koonin, M Krenn, LS Madsen, M Mansson, NP Mauranyapin, AI Melvin, E Rasel, LE Reichl, R Yampolskiy, PB Yasskin, A Zeilinger & S Lidstrom. **The sounds of science—a symphony for many instruments and voices.** *Physica Scripta* 95:062501 (2020)
- GJ Milburn. **The thermodynamics of clocks.** *Contemp. Phys.* 61:69–95 (2020)
- RA Kidd, A Safavi-Naini & JF Corney. **Thermalization in a Bose-Hubbard dimer with modulated tunneling.** *Phys. Rev. A* 102:023330 (2020)
- RW Bomantara. **Time-induced second-order topological superconductors.** *Phys. Rev. Res.* 2:033495 (2020)
- K Beer, D Bondarenko, T Farrelly, TJ Osborne, R Salzmann, D Scheiermann & R Wolf. **Training deep quantum neural networks.** *Nat. Commun.* 11:808 (2020)
- ZC Zhao, TJ Raeber, BJ Murdoch, JG Partridge, DG McCulloch & DR McKenzie. **Unifying the optical and electrical properties of amorphous carbon: application to hopping photoconductivity and memristance.** *J. Appl. Phys.* 128:215109 (2020)
- TM Wintermantel, Y Wang, G Lothead, S Shevate, GK Brennen & S Whitlock. **Unitary and nonunitary quantum cellular automata with Rydberg arrays.** *Phys. Rev. Lett.* 124:070503 (2020)
- OR Stockdale, MT Reeves, X Yu, G Gauthier, K Goddard-Lee, WP Bowen, TW Neely & MJ Davis. **Universal dynamics in the expansion of vortex clusters in a dissipative two-dimensional superfluid.** *Phys. Rev. Res.* 2:033138 (2020)
- BJ Brown & S Roberts. **Universal fault-tolerant measurement-based quantum computation.** *Phys. Rev. Res.* 2:033305 (2020)
- J Foo, S Onoe & M Zych. **Unruh-deWitt detectors in quantum superpositions of trajectories.** *Phys. Rev. D* 102:085013 (2020)
- D Cohen, R Nigmatullin, O Kenneth, F Jelezko, M Khodas & A Retzker. **Utilising NV based quantum sensing for velocimetry at the nanoscale.** *Sci. Rep.* 10:5298 (2020)

## Key Performance Indicators

	TARGET 2020	RESULT 2020
<b>RESEARCH OUTPUT AND SERVICE</b>		
Peer-reviewed journal articles	80	109
High-impact publications (in the top 20% most cited papers in fields of physics)	10	22
International and national advisory boards in the research field of the Centre	2	7
Keynote and plenary addresses at international and national conferences	2	3
Editorial boards for international peer-reviewed journals in the research field of the Centre	2	8
Program committees for international and national conferences	10	6
Invited talks or papers at international meetings	25	2
Training courses held or offered by the Centre	3	13
Workshops or conferences held or offered by the Centre	3	2
<b>PEOPLE AND TRAINING</b>		
New postdoctoral researchers working on Centre research	4	11
New PhD students supervised by Centre researchers	5	17
New Master's students supervised by Centre researchers	0	3
New Honours students supervised by Centre researchers	5	10
New Associate Investigators	3	4
PhD completions	10	11
Master's completions	0	5
Honours completions	5	13
Delivery of EQUUS mentoring program	1	1
Delivery of EQUUS induction program	1	1

# Key Performance Indicators

	TARGET 2020	RESULT 2020
<b>COMMUNICATION AND OUTREACH</b>		
Talks open to the public	8	17
Talks, presentations or briefings to government	2	13
Talks, presentations or briefings to industry, business or other end-users	2	3
Training for STEM teachers	60 teachers	0
Outreach activities for school students	12	8
Industry engagement events	2	0
<b>NEW COLLABORATIONS</b>		
New industry collaborative relationships	1	4
New academic collaborative relationships	1	9
<b>EQUITY AND DIVERSITY</b>		
Female higher-degree research students	20%	20%
Female postdoctoral researchers	15%	12%

# Income and expenditure report

	<b>2020 Actuals \$</b>
<b>INCOME</b>	
<b>ARC Centre of Excellence Grant</b>	
ARC Centre of Excellence Grant	4,862,561
<b>Administering and Collaborating Organisation Contributions</b>	
The University of Queensland	538,160
The University of Sydney	341,470
Macquarie University	151,452
Macquarie University – Scholarships <sup>1,2</sup>	-
The University of Western Australia	96,067
The Australian National University	52,627
<b>Partner Organisation Contributions</b>	
Defence Science and Technology	94,500
University of Ulm <sup>3</sup>	4,688
<b>TOTAL INCOME</b>	<b>6,141,525</b>
<b>EXPENSES</b>	
Salaries	3,363,801
PhD support	232,159
Equipment	431,230
Research maintenance and consumables	195,765
Travel	135,923
Administration and other	176,270
Education, outreach and communications	38,662
Workshops and conferences	64,683
<b>TOTAL EXPENSES</b>	<b>4,638,493</b>
<b>ANNUAL SURPLUS/(DEFICIT)</b>	<b>1,503,032</b>

## Notes:

- MQ will disburse funds to the total of \$231,207 for scholarships over the remaining life of the Centre.
- As at 31 December 2020, MQ funds of \$231,207 are recorded in a separate general ledger account at MQ. In accordance with the Participants Agreement, the funds are available to EQUUS Chief Investigators for international tuition fee scholarships. The amount of \$231,207 is represented by cash contributions for the three years to 31 December 2020 of \$341,973, less scholarship expense to the reporting date of \$110,766.
- Owing to travel restrictions in 2020, the contribution from University of Ulm was used for consumables towards the EQUUS research program.







