Annual Report 2022

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

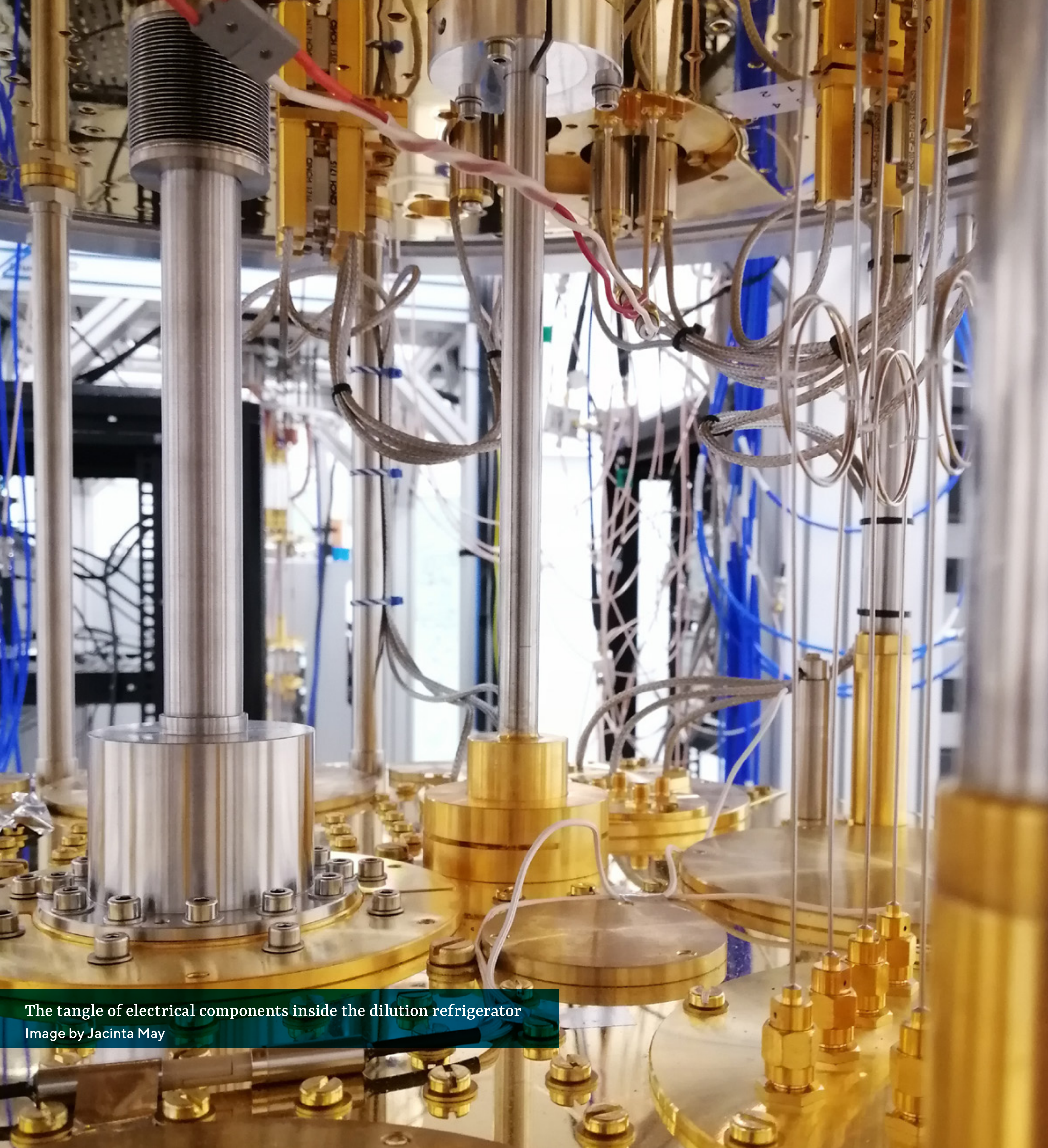
EQUS acknowledges the Traditional Owners of Country throughout Australia and their continuing connection to lands, waters and communities. We pay our respects to Aboriginal and Torres Strait Islander cultures and to Elders past and present. We honour and respect the long tradition of knowledge-making,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

Cover image

Optical sorting of bright nanodiamond using a 532-nm laser.

Image by Zixin Huang

Contents



The tangle of electrical components inside the dilution refrigerator
Image by Jacinta May

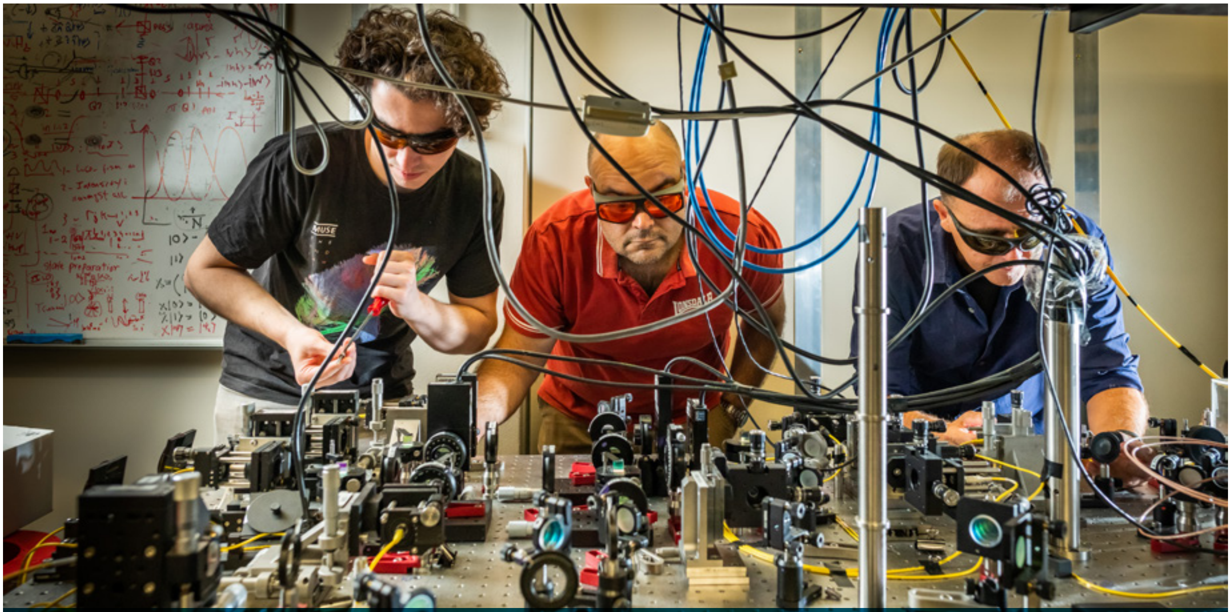
Executive summary

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.

This annual report covers EQUS activities for the 2022 calendar year. It forms part of our official reporting and accounting requirements to the Australian Research Council. Centre activities encompass research, research translation, equity, diversity and inclusion, mentoring and career development, outreach and education, operations and finance.



EQUS PhD Student Sebastian Malewicz, EQUS Research Fellow Dr Marcelo Almeida and EQUS Director Professor Andrew White
Image by Xavier Montaner, Photogenia

Director's update

2022 proved to be as eventful as the prior two years, with impacts from the unusually wet year in Australia and the associated flooding, the war in Ukraine and subsequent economic crisis, and adapting to the new normal post-COVID. Despite the disruptions and challenges, there were still many reasons for EQUS to celebrate: we saw the return of in-person events; domestic and international travel restrictions were lifted; and EQUS researchers continued to deliver high quality research outcomes. We also celebrated Professor Alain Aspect, one of the founding members of our Scientific Advisory Committee, winning the Nobel Prize in Physics!

As has become the trend, the Centre excelled across our three Research Programs and two Flagships with results ranging from new methods to image stars using quantum error correction, through to the development of a superconducting chip-sized microwave circulator, to the first substantive search for axions by the ORGAN Experiment. Many more projects are detailed in the pages of this report, and I highly recommend reading it cover to cover.

Last year the federal government established Australia's first National Quantum Advisory Committee, of which I was privileged to become a member – in no large part due to the reputation that the EQUS has developed as international research leaders in quantum technology. EQUS hosted prestigious visitors—including Australia's Chief Scientist, Dr Cathy Foley AO, and the Shadow Assistant Minister for Communications & Cyber Security, the Hon Tim Watts, MP—providing us with an excellent opportunity to showcase EQUS research. We also hosted a visit by members of the Queensland Department of Tourism, Innovation, and Sport, who were impressed by EQUS' successes with our Translational Research Program.

After years of lockdowns and travel restrictions, it was great to finally reconnect with colleagues in-person at a variety of events, starting the year with the Quantum Australia conference and ending it with our Annual Workshop, held in Newcastle, NSW. The inaugural Quantum Australia conference was hosted by the Sydney Quantum Academy at Jones Bay, providing an eagerly awaited opportunity to catch up with EQUS colleagues from across various states and territories. This was also a valuable opportunity to gain input from the university, commercial, and government sectors, which helps guide our strategic goals and raise awareness about the importance of investing in the emerging quantum technology industry in Australia.

One of the Centre's 2022 highlights was the inaugural inSTEM conference, a networking and career development event for early-to-mid-career researchers from marginalised or underrepresented groups in STEM, and their allies. The conference was a huge success with 150 researchers in attendance, learning from leading experts on a range of topics that facilitate career development and progression. The conference also featured speakers and panels that discussed how both universities and industry can create change that improves access, supports retention, and champions success in STEM for researchers from marginalized or underrepresented groups. For me it was inspiring to see how an idea conceived by two of our early career researchers was brought to life through the will and determination of the EQUIP (equity in quantum physics) Committee.

Another Centre highlight was the National Quantum & Dark Matter Road Trip, an initiative of the EQUS Public Engagement & Outreach Committee that was run for the first time, in partnership with the ARC Centre of Excellence for Dark Matter Particle Physics. The QDM Road Trip was an extraordinary undertaking by the organising committee and the 25 scientists who volunteered their time to participate in this activity. The Road Trippers travelled from Brisbane to Perth over three weeks and 7,000 km, visiting 25 schools and hosting 14 community events, in rural and regional towns. It's estimated the Road Trip engaged with around 2000 people in all things quantum and dark matter. I am extremely proud of our staff and students for taking on this epic outreach activity, bringing quantum physics out of the labs into the world.

In October, Dr Michael Harvey, our Translational Research Program Manager, Dr Russell Manfield of UQ's Business School, and I travelled to Washington DC to attend the Quantum World Congress and deliver a boot camp on 'Quantum Technologies for Decision Makers'; a precursor for our upcoming MOOC of the same name which will be launched in partnership with the UQ Business School.

Our outstanding performance—in both our research and our portfolios—is, as always, due to the hard work and commitment of our people. I would like to extend a sincere thank you to all our members and partners for your continued engagement and contribution to the Centre; it is a privilege to work with such brilliant and generous people.

I hope you enjoy reading about all of this, and more, in our 2022 Annual Report.

Professor Andrew White
Director, ARC Centre of Excellence for Engineered Quantum Systems

Governance

ADVISORY COMMITTEE

The Advisory Committee contributes to the Centre's strategic direction and supports links between academia, industry and government.

Professor Christine Williams

The Advisory Committee consists of:

- **Professor Christine Williams (Chair),** Chair of the Board of Life Sciences Queensland, Executive Director of the Women in Economics Network Queensland, Member of the Innovation Advisory Council, Activator at SheEO, Adjunct Professor at The University of Queensland
- **Dr Gregory Clark AC FAA FTSE,** Chair at KaComm Communications
- **Dr Bronwyn Evans HonFIEAust FTSE CPEng,** Chair at Building 4.0 CRC, Director at GME, Fellow at Australian Academy of Technological Sciences and Engineering, Honorary Fellow at Engineers Australia
- **Dr Ben Greene,** Founder and Head of Innovation at Electro Optic Systems
- **Professor Jim Williams AM FAA FTSE,** Emeritus Professor, Department of Electronic Materials Engineering, Australian National University

SCIENTIFIC ADVISORY COMMITTEE

The Scientific Advisory Committee provides independent scientific expertise and advice regarding the Centre's research program. The committee met in December at the conclusion of the EQUS 2022 Annual Workshop.

Centre Director Andrew White with three of our Scientific Advisory Committee Members at the 2022 EQUS Annual Workshop: (left to right) Professor Andrew White, Professor John Clarke, Professor Sir Peter Knight and Professor Rainer Blatt
Image by Her Atelier

The Scientific Advisory Committee consists of:

- **Professor Sir Peter Knight FRS (Chair),** Emeritus Professor at Imperial College London, Fellow of the Royal Society and Chair of the UK National Quantum Technology Programme Strategic Advisory Board
- **Professor Alain Aspect ForMemRS,** Laboratoire Charles Fabry, Institut d'Optique
- **Professor Rainer Blatt ForMemNAS,** Institute of Experimental Physics, Universität Innsbruck
- **Professor John Clarke FRS,** Department of Physics, University of California, Berkeley
- **Professor Birgitta Whaley FAPS,** Whaley Research Group, University of California, Berkeley

CENTRE EXECUTIVE AND DIRECTORATE

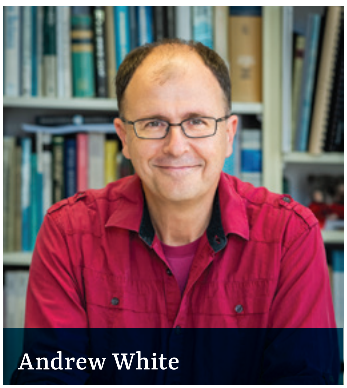
The Centre Executive includes the Centre Director, Deputy Directors, Chief Operating Officer, Node Directors and Translational Research Program Director. The Executive meets monthly and is responsible for the development and execution of the Centre's strategic direction. The Executive also provides leadership and direction to the Centre's operations, ensuring the Centre is managed responsibly and successfully.

The Executive consists of:

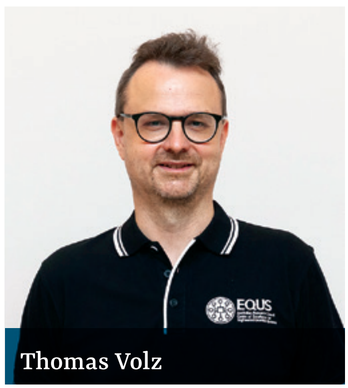
- **Professor Andrew White FAA (Chair),** Director
- **Associate Professor Sally Shrapnel,** Deputy Director
- **Professor Thomas Volz,** Deputy Director, Node Director (MQ)
- **Katrina Tune,** Chief Operating Officer
- **Dr John Bartholomew,** Node Director (USYD)
- **Associate Professor Kirk McKenzie,** Node Director (ANU)
- **Professor Michael Tobar FAA,** Node Director (UWA)
- **Professor Halina Rubinsztein-Dunlop AO FAA,** Translational Research Program Director


Professor Sir Peter Knight

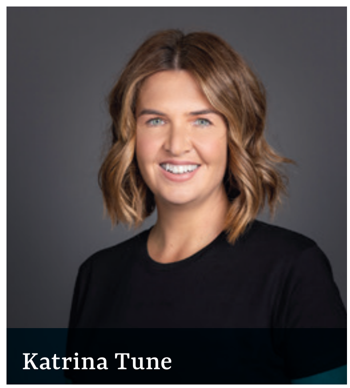
The Centre Directorate, which comprises the Centre Director, Deputy Directors and Chief Operating Officer, meets weekly to discuss priority operational issues that may be progressed without Executive approval.


Andrew White

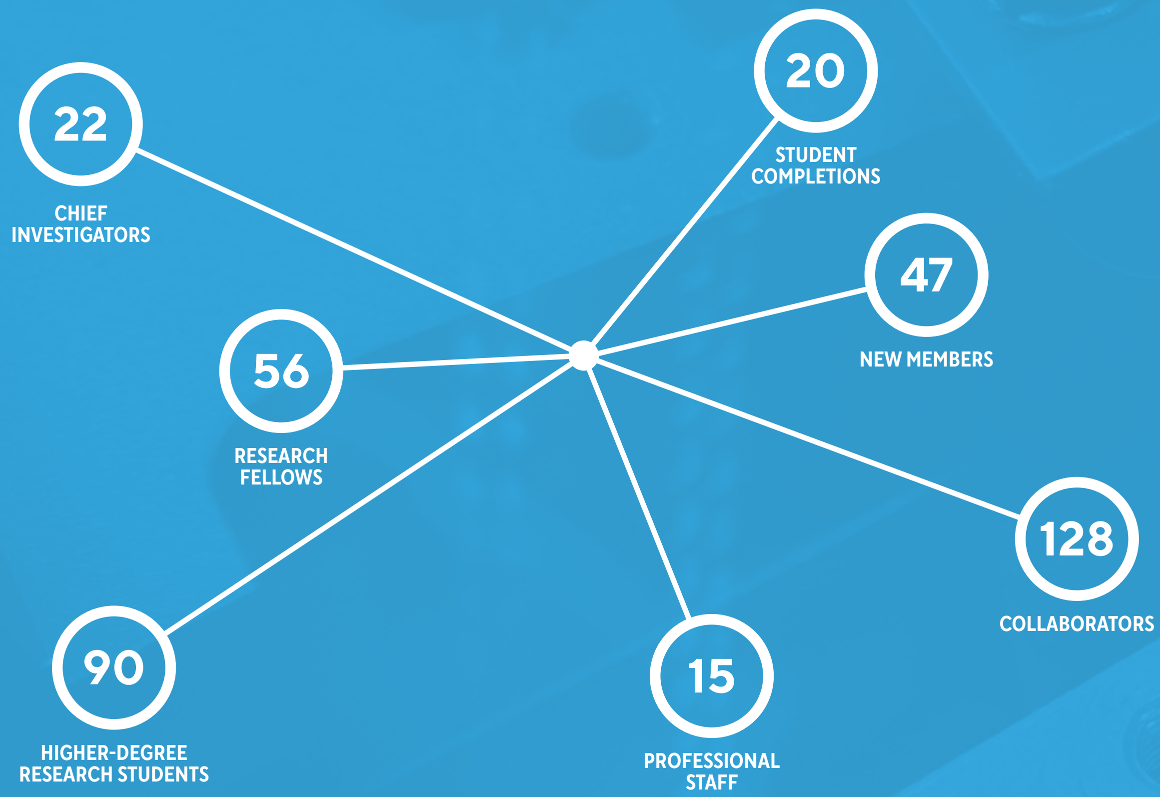

Sally Shrapnel



Thomas Volz


Katrina Tune

Our people: Overview



EQUS, led by Laureate Professor Andrew White, is a collaborative research endeavour, comprising researchers from five leading Australian universities, 16 Partner Organisations across Australia, North America, the United Kingdom and Europe, and various other national and international organisations.

Our strength, without a doubt, lies in our people: talented researchers who are passionate about using quantum physics to develop technologies that will benefit society; professional staff that support and enable our research success; and an Advisory Committee and Scientific Advisory Committee who help guide and shape our strategic direction.

Our people: Awards and recognition

In 2022, several EQUS members were recognised for their contributions to quantum science and technology.


Peter Knight

Peter Knight was awarded the 2022 President's Medal by the Institute of Physics for services to physics, in particular his leadership and championing of the value of physics and quantum technology to society, nationally and internationally.

Halina Rubinsztein-Dunlop was awarded the 2022 Moyal Medal from Macquarie University in recognition of her outstanding contributions to Physics; especially laser-enhanced ionisation spectroscopy, laser micro-manipulation including cooling and trapping of atoms, the transfer of angular momentum from light to microscopic particles, as well as biomedical applications.

Emily Rose Rees was awarded Australian National University's John Carver Prize for her talk on Gravity Sensing using Inter-spacecraft laser interferometry.

Ryan MacDonell was awarded the 2022 Miller Prize - International Symposium on Molecular Spectroscopy.

John Bartholomew received a 2022 University of Sydney Supervisor of the Year Award.

Dominic Williamson was named Australia's top researcher in the field of mathematical physics by The Australian's Research Magazine, based on the number of citations for papers published in the top 20 journals in each field over the past five years.

Ben McAllister received a 2022 Aspire Award for research excellence.


Professor Tim Colmer (left) presents the UWA Aspire Award to Dr Ben McAllister.

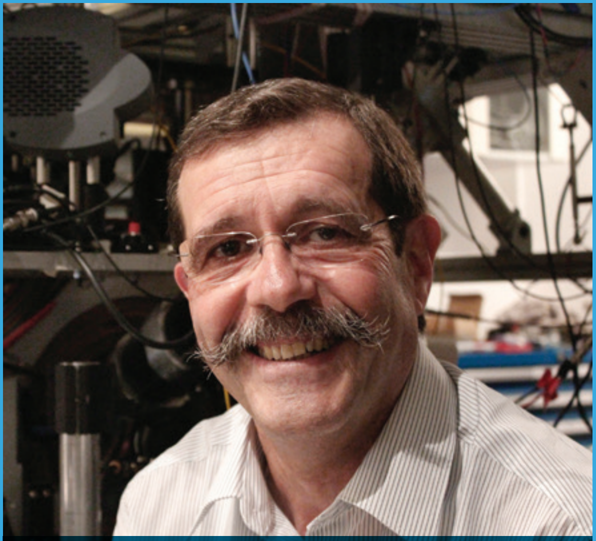
Alain Aspect, a member of the EQUS Scientific Advisory Committee, was awarded the **2022 Nobel Prize in Physics.** Since 1901, Nobel prizes have been awarded in October to researchers who, 'have conferred the greatest benefit to humankind through their inventions, discoveries and improvements in various fields of knowledge'. Alain, along with American John Clauser and Austrian Anton Zeilinger, won the prize for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science.

One of the most remarkable traits of quantum mechanics is that it allows two or more particles to exist in what is called an entangled state. What happens to one of the particles in an entangled pair determines what happens to the other particle, even if they are far apart. In 1981–1982, Alain Aspect conducted ground-breaking experiments using entangled particles of light: photons. These and other experiments confirm that quantum mechanics is correct and pave the way for quantum computers, quantum networks and quantum encrypted communication.

EQUS Director Andrew White said that entanglement is at the heart of EQUS' quest to build quantum machines.

"Entanglement has the same role in quantum technologies as does heat in an engine or electricity in a light bulb," he said.

"Alain showed that entanglement between two photons persists even if the orientation of the polarisers that analyses the photons is changed during the photons' flight.



Alain Aspect

"This means that nature defies description in terms of a local—that is, light-speed-limited—'hidden variable' theory."

Hidden-variable theories are useful in physics, with one such example being thermodynamics.

"Thermodynamics hides the velocities of trillions of individual atoms behind a theory with only a handful of parameters, such as pressure, volume and temperature," Professor White said.

"Einstein felt that quantum theory must also be a hidden-variable theory, and of course follow the limitations of relativity in having no aspects faster than the speed of light."

"What Aspect, Caluser and Zeilinger's work shows is that Einstein was incorrect—nature is inherently non-local, non-realist or both, and we need to understand its rules to engineer the quantum technologies of the future."

Our people: EQUS awards

DIRECTOR'S MEDAL

Jeremy Bourhill

Jeremy Bourhill receiving his Director's Medal from EQUS Director Andrew White
Image by Her Atelier

The Director's Medal is presented to the researcher who not only exhibits the spirit of collaborative enquiry required to advance research in quantum physics but also goes above and beyond to assist with service activities within the Centre.

Jeremy Bourhill is a Research Fellow in the Quantum Technologies and Dark Matter Laboratory at UWA. His research focuses on spin ensembles in solids and novel microwave techniques to interact with them for the purposes of designing quantum protocols. Jeremy is also interested in designing and constructing new experiments to search for dark matter that will circumvent many of the current hurdles facing the global effort. Jeremy is an EQUS Node Representative and an active mentor and supervisor of EQUS students. He became a Mental Health First Aid Officer to better support his colleagues at the UWA Node, is a member of the EQUS Public Engagement & Outreach Committee and participated in the 2022 National Quantum & Dark Matter Road Trip.

CENTRE CITIZEN

Timothy Hirsch

Timothy Hirsch receiving his Centre Citizen award from EQUS Director Andrew White
Image by Her Atelier

The Centre Citizen Award is presented to an EQUS member who best represents the aspirations of the Centre through their passion and commitment to the Centre's culture.

Timothy Hirsch is a PhD student in the Quantum Optics Laboratory at UQ, where his research aims to develop a nanomechanical computing architecture, which uses mechanical vibrations (phonons) instead of electricity to store and transmit information. The motivation is to create a computer with high radiation tolerance and low energy consumption. Tim is an EQUS Node Representative. As a member of the EQUS Public Engagement & Outreach Committee, Tim was a part of the 2022 National Quantum & Dark Matter Road Trip, he is on the Quantum Art Competition sub-committee and is the EQUS judge for the 2023 Quantum Shorts Film Festival. As a member of the EQUS EQUIP Committee, Tim was an integral part of the inaugural inSTEM Conference both as a member of the organising committee and the conference event crew.

BEST TEAM PROJECT

Emily Rose Rees, Andrew Wade and **Andrew Sutton** for their work developing a technique to readout the laser frequency needed for the next GRACE mission. Working closely with CEA Technologies and NASA-JPL they demonstrated the technique at the JPL campus in Pasadena in October 2022. The project has resulted in two journal articles.

BEST STUDENT-LED PROJECT

Mark Webster for his paper on the XP Stabiliser Formalism. Besides creating a new class of quantum stabiliser codes, the paper has techniques for better understanding existing codes.

BEST COLLABORATIVE PAPER

Aaron Quiskamp, Ben McAllister, Paul Altin, Eugene Ivanov, Maxim Goryachev and **Mike Tobar** for The ORGAN Experiment, Australia's first major contribution to dark matter detection.

BEST PROFILE-RAISING EVENT OR ACTIVITY

The **inSTEM Conference,** conceived by the EQUS EQUIP Committee and led by EQUS in its inaugural year, brought together 150 early-to-mid-career researchers from underrepresented and marginalised groups in STEM to network and hear from leading experts on topics and strategies that support career development and progression.

BEST CONTRIBUTION TO PUBLIC DEBATE

Tara Roberson for her leadership in responsible innovation; research concerned with the responsible development and use of quantum technologies.

THREE-MINUTE THESIS COMPETITION

First place: **Christophe Valahu**
Second place: **Lirandë Pira**
Third place: **Ben Field**

POSTER COMPETITION

First place: **Simeon Simjanovski**
Second place: **Cory Aitchison** and **Vanessa Olaya Agudelo**
Third place: **Ali Fawaz**

PITCH COMPETITION

First place: **Kyle Clunies-Ross**

EQUS award recipients at the EQUS Annual Workshop (left to right) Tim Newman, Marcus Rambach, Jeremy Bourhill, Cory Aitchison, Ben Field, Lirandë Pira, Kyle Clunies-Ross, Ali Fawaz, Timothy Hirsch, Simeon Simjanovski, Ben McAllister, Vanessa Olaya Agudelo and Aaron Quiskamp
Image by Her Atelier

Our people: Team

CHIEF INVESTIGATORS

Andrew White *UQ*
Sally Shrapnel *UQ*
Thomas Volz *MQ*
Andrew Doherty USYD
Arkady Fedorov *UQ*
Arne Grimsmo *USYD*
Daniel Burgarth *MQ*
David Reilly *USYD*
Gavin Brennen *MQ*
Gerard Milburn *UQ*
Halina Rubinsztein-Dunlop *UQ*
Jacqui Romero *UQ*
John Bartholomew *USYD*
Kirk McKenzie *ANU*
Magdalena Zych *UQ*
Matthew Davis *UQ*
Maxim Goryachev *UWA*
Michael Biercuk *USYD*
Michael Tobar *UWA*
Stephen Bartlett *USYD*
Tom Stace *UQ*
Warwick Bowen *UQ*

PARTNER INVESTIGATORS

Alessandro Fedrizzi *Herriot-Watt University*
Alexia Auffèves *Institut Néel*
Andreas Wallraff *ETH Zurich*
Fedor Jelezko *Ulm University*
Holger Müller *UC Berkeley*
Ian Walmsley *University of Oxford*
Jörg Schmiedmayer *TU Wien*
Lorenza Viola *Dartmouth College*
Mark Baker *UQ*
Markus Aspelmeyer *University of Vienna*
Michael Wouters *NMI*
Oriol Romero-Isart *IQOQI*
Pascale Senellart-Mardon *CNRS*
Peter Zoller *IQOQI*
Peter Wolf *CNRS*
Robyn Starr *MOG Laboratories*
Wolfram Pernice *Universität Münster*

Alexia Auffèves presenting at the 2022 EQUS Annual Workshop.
Image by Her Atelier

ASSOCIATE INVESTIGATORS

Alán Aspuru-Guzik *University of Toronto*
Alexei Gilchrist *MQ*
Andrew Sutton *ANU*
Behnam Tonekaboni *CSIRO*
Ben Baragiola *RMIT University*
Ben McAllister *UWA*
Benjamin Dix-Matthews *UWA*
Chris Ferrie *UTS*
Christina Giarmatzi *UTS*
Clemens Müller *Zurich Instruments*
Cornelius Hempel *Paul Scherrer Institute*
Cyril Laplane *MQ*
Daniel Shaddock *ANU*
David Gozzard *ICRAR*
Eugene Ivanov *UWA*
Felix Miranda *NASA Glenn Research Centre*
Ian Manchester *USYD*
Ivan Kassal *USYD*
Jacinda Ginges *UQ*
Jennifer Ogilvie *University of Michigan*
Jingbo Wang *UWA*
Joan Leach *ANU*
Jonathan Home *ETH Zurich*
Joshua Combes *UQ*
Kae Nemoto *National Institute of Informatics*
Kavan Modi *Monash University*
Lachlan Rogers *University of Newcastle*
Lawrence Lee *UNSW*
Lute Maleki *OEwaves*
Marco Tomamichel *National University of Singapore*
Martin Ringbauer *Universität Innsbruck*
Matthew Woolley *UNSW*
Maxime Richard *CNRS*
Michael Hush *Q-CTRL*
Michael Vanner *Imperial College London*
Mikolaj Schmidt *MQ*
Nathan Langford *UTS*
Nicholas King *USYD*
Peter Lodahl *University of Copenhagen*
Peter Jacobson *UQ*
Peter Rohde *UTS*
Robert Casson *University of Adelaide*
Ryan MacDonell *USYD*
Sahand Mahmoodian *USYD*
Salah Sukkarieh *USYD*
Sascha Schediwy *UWA*
Sujatha Raman *ANU*
Susan Coppersmith *UNSW*
Terence Rudolph *Imperial College London*
Till Weinhold *Defence Science and Technology Group*
Tyler Neely *UQ*
Victor Flambaum *UNSW*
Vladimir Kruglov *UQ*
William Munro NTT *Basic Research Laboratories*
Yuval Sanders *MQ*
Zixin Huang *MQ*

RESEARCH FELLOWS

Aidan Strathearn *UQ*
Alexander Stilgoe *UQ*
Andreas Sawadsky *UQ*
Andrew Groszek *UQ*
Andrew Wade *ANU*
Angela Karanjai *USYD*
Ben Brown *USYD*
Benjamin Carey *UQ*
Byron Villis *USYD*
Charles Woffinden *UQ*
Christopher Baker *UQ*
Daniel Peace *UQ*

Dat Thanh Le *UQ*
Deniz Stiegemann *UQ*
Elizabeth Marcellina *USYD*
Fabio Costa *UQ*
Glen Harris *UQ*
Graeme Flower *UWA*
Guillaume Gauthier *UQ*
Hyma (Harish) Vallabhapurapu *MQ*
Igor Marinkovic *UQ*
James Bennett *UQ*
James Witt *USYD*
Jeremy Bourhill *UWA*
Jue Zhang *ANU*
Kerstin Beer *MQ*
Kun Zuo *USYD*
Laura Henderson *UQ*
Lewis Williamson *UQ*
Lorenzo Scarpelli *MQ*
Lyle Roberts *ANU*
Marcelo Pereira de Almeida *UQ*
Markus Rambach *UQ*
Mattias Johnsson *MQ*
Nathaniel Bawden *UQ*
Nicolas Mauranyapin *UQ*
Paul Altin *ANU*
Paul Webster *USYD*
Prasanna Pakkiam *UQ*
Raditya Bomantara *USYD*
Ramil Nigmatullin *MQ*
Reece Roberts *MQ*
Robert Harris *UQ*
Salini Karuvade *USYD*
Sarath Raman Nair *MQ*
Tara Roberson *UQ*
Terry Farrelly *UQ*
Torsten Gaebel *USYD*
Xin (Eric) He *UQ*
Yauhen (Eugene) Sachkou *UQ*
Zijun (Cindy) Zhao *UWA*

PHD STUDENTS

Aaron Quiskamp *UWA*
Abhinash Roy *MQ*
Abithaswathi Muniraj Saraswathy *UQ*
Alex Terrasson *UQ*
Alexander Hahn *MQ*
Alistair Robertson Milne *USYD*
Amy Navarathna *UQ*
Anirban Dey *MQ*
Arjun Rao *USYD*
Arkin Tikku *USYD*
Ben Field *USYD*
Bradley Mommers *UQ*
Brendan Harlech-Jones *USYD*
Callum Sambridge *ANU*
Carolyn Wood *UQ*
Cassandra Bowie *UQ*
Catriona Thomson *UWA*
Chun-Ching Chiu *UQ*
Dan George *MQ*
Elija Perrier *USYD*
Elisabeth Wagner *MQ*
Elrina Hartman *UWA*
Emily Rose Rees *ANU*
Evan Hockings *USYD*
Fatemeh Mohit *UQ*
Felix Thomsen *USYD*
Fernando Gotardo *UQ*
Gargi Tyagi *USYD*
Guang-Qi Zhao *USYD*
Hamish Greenall *UQ*
Jemy Geordy *MQ*
Jihun Cha *UQ*

Jobin Thomas Valliyakalayil *ANU*
Joseph Pham *USYD*
Juliette Soule *USYD*
Kwan Goddard-Lee *UQ*
Kyle Clunies-Ross *UQ*
Larnii Booth *UQ*
Larry Cohen *USYD*
Lauren McQueen *UQ*
Leo Sementilli *UQ*
Leonardo Assis Morais *UQ*
Lirandë Pira *UTS*
Lyra Cronin *MQ*
Maarten Christenhusz *UQ*
Mackenzie Shaw *USYD*
Maria Quadeer *UTS*
Marino Lara Alva *UQ*
Mark Webster *USYD*
Maverick Millican *UQ*
Ming Su *UQ*
Namisha Chabbra *ANU*
Nicholas Fazio *USYD*
Nouédyn Baspin *USYD*
Omprakash Chandra *USYD*
Pradeepkumar Nandakumar *UQ*
Raji Bhaskaran Nair *MQ*
Rakesh Saini *MQ*
Raymond Harrison *UQ*
Riddhi Ghosh *MQ*
Rohit Navarathna *UQ*
Samuel Bartee *USYD*
Samuel Elman *USYD*
Samuel Smith *USYD*
Sayantan Das *UQ*
Sebastian Malewicz *UQ*
Simeon Simjanovski *UQ*
Soroush Khademi *UQ*
Stefan Zeppetzauer *UQ*
Stefanus Edgar Tanuarta *USYD*
Steven Waddy *USYD*
Thomas Boele *USYD*
Timothy Evans *USYD*
Timothy Hirsch *UQ*
Timothy Newman *USYD*
Timothy Harris *UQ*
Tyler Jones *UQ*
Varun Prakash *UQ*
Varun Srivastava *MQ*
Walter Wasserman *UQ*
William Campbell *UWA*
Xiaoya (Tina) Jin *UQ*
Yun-Chih Liao *UQ*
Zach Degnan *UQ*
Zachary Kerr *UQ*
Zsolt Szabo *MQ*

MASTER'S STUDENTS

Ali Fawaz *MQ*
Bryn Roughan *UWA*
Haider Zulgiqar *UQ*
Mackenzie Shaw *USYD*
Mahdi Qaryan *UQ*
Maria Carol Villavedra *MQ*
Robert Limina *UWA*
Timothy Harris *UQ*
Tim Wohlers-Reichel *USYD*
Zhonghua Ma *UQ*

OPERATIONS TEAM

Katrina Tune *UQ*
Angela Bird *UQ*
Belinda Wallis *MQ*
Cheryl Stephenson *UQ*
Debra Gooley *USYD*
Kristen Harley *UQ*
Linda Barbour *UWA*
Michael Harvey *UQ*
Sarah Allen *UQ*
Sareh Rajabi *ANU*
Satpal Sahota *USYD*

RESEARCH PROFESSIONAL STAFF

James Lavis *UQ*
Marcus Goffage *UQ*
Rodrigo Bruni *UQ*
Steve Osborne *UWA*

RESEARCH AFFILIATES

Adesh Kushwaha *USYD*
Alice Jeffrey *USYD*
Anthony O'Rourke *USYD*
Campbell Millar *UWA*
Chintan Mistry *USYD*
Cory Aitchison *USYD*
Deepali Rajawat *UWA*
Deepesh Singh *UQ*
Eric Howard *MQ*
Haoyuan (Jacky) Huo *USYD*
Ishaan Goel *UWA*
Jacinta May *USYD*
Juan Pablo Bonilla Ataides *USYD*
Justin Brown *USYD*
Matthew Choi *USYD*
Matthew van Breugel *MQ*
Michael Ma *USYD*
Michael Robinson *USYD*
Mitchell Field *UQ*
Robert Wolf *USYD*
Steven Samuels *UWA*
Tina Jin *UQ*
Ting Rei Tan *USYD*
Tomas Navickas *USYD*
Vanessa Olaya Agudelo *USYD*
Xanda Kolesnikow *USYD*

COMPLETIONS

PhD

Abdallah el Kass *USYD*
Milli-Kelvin Electronics at the Quantum-Classical Interface

Alejandro Gómez Frieiro *UQ*
Protecting superconducting quantum circuits from measurement back-action and ionizing radiation

Alex Pritchard *UQ*
Rotational and superfluid dynamics of multi-component Bose-Einstein condensates

Chao Meng *UQ*
Optomechanical state preparation via strong measurement

Dat Thanh Le *UQ*
Engineered quantum systems for quantum computation with superconducting circuits

Graeme Flower *UWA*
Improving Axion Dark Matter Detection Experiments with a focus on the use of Magnonic Systems

James Spollard *ANU*
Digitally Enhanced Coherent Optical Metrology

Nor Azwa Zakaria *UQ*
Exploring engineered solid-state single-photon emitters as multi-photon sources

Yasmine Sfendla *UQ*
Catching waves: superfluid and light on a silicon chip

Master's

Bryn Roughan *UWA*
Electric Vector Potentials in Non-conservative Electrodynamics

Mackenzie Shaw *USYD*
Quantum Computation with Gottesman-Kitaev-Preskill Codes: Logical Gates, Measurements, and Analysis Techniques

Mahdi Qaryan *UQ*
Encoding and measuring information in high-dimensional quantum states

Robert Limina *UWA*
Non conservative electrodynamics – Generating electromotive force and exploring Faraday's paradox

Honours

Cory Aitchison *USYD*
No Strings Attached: Defects and boundaries with the Cubic Code mode

Danny Chacko *USYD*
Quantifying measurement noise in SiMOS quantum dots

Justin Brown *USYD*
Optical Coupling to High Q/V Resonators for Erbium Quantum Technologies

Konstantin Lakic *UQ*
Implementing multi-qubit gates in larger Hilbert spaces for superconducting circuits

Michael Ma *USYD*
Towards efficient ground-state laser cooling of ytterbium ion chains in a linear Paul trap using electromagnetically induced transparency

Steven Samuels *UWA*
Implementation of JPA in Invisible Axion Detection Experiments

Tina Jin *UQ*
Computing with Mechanical Motion

Our people: Life after EQUS

NOR AZWA ZAKARIA

Nor Azwa Zakaria joined EQUS in 2015, working with Professor Andrew White on the Quantum Technology Laboratory at The University of Queensland.

During her time at EQUS she received an International Scholarship from The University of Queensland and was a member of the EQUS Equity in Quantum Physics (EQUIP).

Nor's research focused on developing single-photon sources where she worked with quantum dots devices:

"The quantum dots are respectively embedded in passively and actively controlled microvillar cavities. The first-generation device produced a high brightness of 14% at the output of the single-mode fibre while demonstrating a long stream of photons exhibiting high HOM interference. The second-generation device successfully produced an event-ready entangled photon pairs via Type-II fusion gate operation. It allows a single-photon source to be converted into an event-ready source of polarisation-entangled photon pairs with as much brightness as was possible at that time. This is a scalable architecture for producing entangled photons, important for quantum processing and a fundamental test of quantum mechanics."

Nor has been appointed Assistant Professor at the Photonics and Quantum Centre (iPQC) at the International Islamic University Malaysia (IIUM). She works in the field of photonics and quantum technology and explores fibre laser technologies, fibre optic devices, and quantum communication technologies.

"Being a part of iPQC, I hope to produce technologies and know-how that can be commercialised in the technology market while creating a sustainable future for the establishment. Also, I hope to bridge communication between the university and other institutes, and assist the feasibilities research conducted in Malaysia. In the bigger picture, I hope to be a part of the quantum community and contribute to developing quantum computing in potential application sectors such as finance, healthcare, and information technology", she said.

Andreas Sawadsky

Quantum Brilliance

After completing a postdoctoral fellowship at the University of Queensland in the Quantum Optics Laboratory Andreas took up a position with Quantum Brilliance as a Strategic Talent Partner.

Chao Meng

University of Copenhagen

After completing his PhD scholarship at the University of Queensland under the supervision of CI Warwick Bowen, Chao moved to Denmark to take up a Postdoctoral Research Fellowship at the Niels Bohr Institute.

Lorenzo Scarpelli

Delft University of Technology

After a three-year research fellowship at the Macquarie University Node, Lorenzo has now taken up a new postdoctoral research fellowship at TU Delft in the Netherlands.

Lyle Roberts

Advanced Navigation

A former Research Fellow at the Australian National University Lyle is now Head of Photonics at Advanced Navigation after the company acquired the spin-out he established with colleague James Spollard, Vai Photonics.

Reece Roberts

Knox Grammar School

After working as a postdoctoral fellow at Macquarie University under EQUS Chief Investigator Professor Thomas Volz, Reece is now a science teacher at Knox Grammar School.

James Bennett

Griffith University

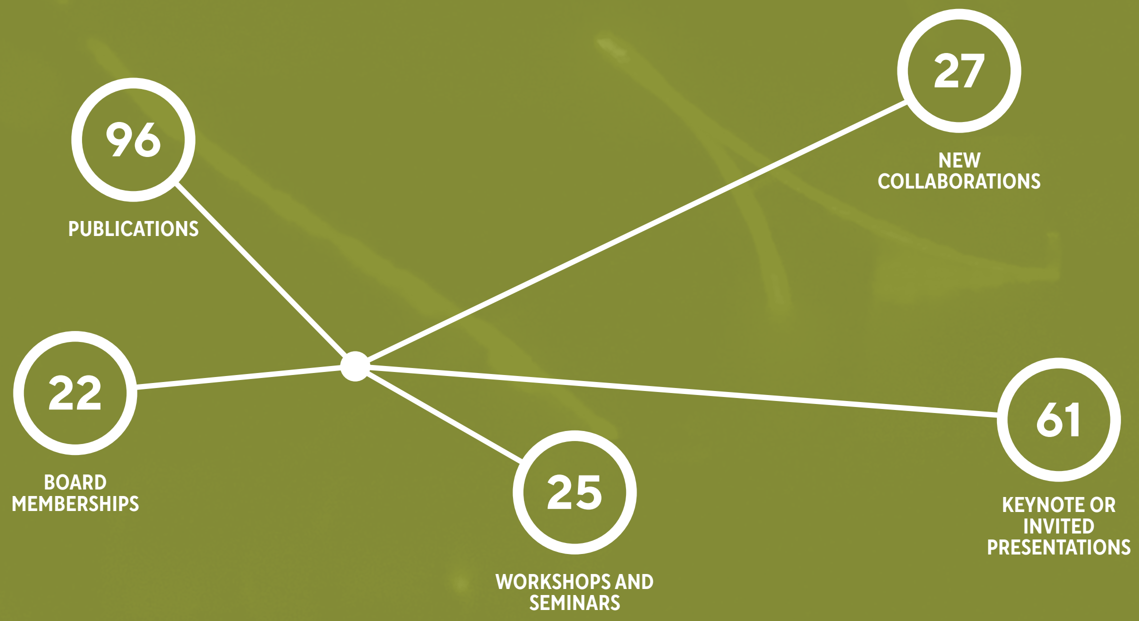
After completing a postdoctoral fellowship at the University of Queensland in the Quantum Optics Laboratory, James accepted a position as a Lecturer in the School of Environment and Science at Griffith University.

Our research: Overview

EQUS is engineering the quantum future by building quantum machines that harness the quantum world for practical applications. We are solving the most challenging research problems at the interface of basic quantum physics and engineering.

Our research encompasses theory and experiment, and is organised around the following research programs:

1. **Designer quantum materials**
2. **Quantum-enabled diagnostics and imaging**
3. **Quantum engines and instruments**
4. **1kQubit flagship**
5. **Quantum clock flagship**



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

Quantum-enabled diagnostics and imaging

Developing prototypes of the sensing and imaging components required for a quantum machine to interact with its environment

Quantum engines and instruments

Understanding quantum engines and instruments so that quantum machines with tens or hundreds of individual components may be designed and manipulated

1kQubit flagship

Developing the theoretical foundations for a useful fault-tolerant quantum processor

Quantum clock flagship

Developing the hardware, architecture and theoretical foundations for improved clock technologies

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.

2022 HIGHLIGHTS

In 2022, EQUS researchers made substantial progress in this program across a wide range of topics, including quantum chemistry, quantum information and networks, light-matter interaction and control and superconducting qubits.

Key advances are as follows:

Experimental platforms

- Demonstrated an algorithm that efficiently characterises evolving quantum states, even in the presence of substantial noise, using qudits encoded in shape of light (see page 25).
- Developed a cryogenic quantum control platform that allows classical control of quantum systems while dissipating little power: the circuits are the most complex devices to ever operate at this temperature.
- Observed giant Rydberg excitons—with diameters as large as 1 micron—in the semiconductor cuprous oxide. These couple strongly to cavity photons offering a promising route to a new platform for quantum technologies.

Theoretical advances

- Identified a technique to perform analogue quantum simulations of ultrafast chemical dynamics using trapped ions (see page 26).
- Formulated a unifying theory for superconducting qubits interacting with the electromagnetic field: from cavity through to waveguide QED.
- Developed a simple model to understand and model solid-state defect systems and to preserve quantum states in noisy environments.

EFFICIENT QUANTUM STATE TRACKING IN NOISY ENVIRONMENTS[1]

EQUS researchers have experimentally demonstrated an algorithm that efficiently characterises evolving quantum states, even in the presence of substantial noise.

Quantum state tomography is essential for quantum computation and communication applications. However, current techniques scale notoriously badly with dimension and are generally not capable of following evolving states dynamically. Methods that overcome these issues have been proposed theoretically, but there have been very few experimental demonstrations.

The research team experimentally implemented an efficient way to describe quantum states that change in time, with high fidelity, using a machine learning technique known as matrix-exponentiated gradient tomography. They did this using photonic qutrits (three-dimensional quantum systems) in the presence of substantial environmental noise up to 20× higher than the actual signal. Such an efficient algorithm paves the way to describing large, evolving systems (greater dimensions and/or larger numbers of quantum carriers), for which the current standard quantum state tomography techniques perform poorly.

FUN FACT

It took the EQUS team almost two years from first data acquisition to putting the paper on the arXiv. So, to any students out there who feel stuck and like nothing ever changes: there is something at the end of the tunnel that will be worth all the effort.

Moving forward, the team would like to extend the scheme to higher dimensions and/or more photons. They encourage other EQUS members to get involved by trying the scheme in their systems, such as ions or superconducting qubits. It would also be interesting to see whether the underlying theory could be used in closely related fields such as Hamiltonian identification and continuous learning.

1 M Rambach, A Youssry, M Tomamichel & J Romero **Efficient Quantum State Tracking in Noisy Environments,** *Quantum Science and Technology 8(1).* 015010 (2023)

ANALOGUE QUANTUM SIMULATIONS OF CHEMICAL DYNAMICS

EQUS researchers have devised a scheme for performing analogue quantum simulations of ultrafast chemical dynamics using existing quantum systems.

One of the areas in which quantum computing is expected to offer substantial advantage over classical computing is chemistry, enabling tractable simulations of complex molecular dynamics and chemical reactions. To achieve this, laboratory-based systems need to be engineered that behave in the same way, and have the same properties, as the vibrational and electronic properties of molecules.

The team — including Research Fellow Ryan MacDonell, PhD student Claire Edmunds, Chief Investigator Mike Biercuk, and Associate Investigators Cornelis Hempel and Ivan Kassal — devised a scheme for simulating ultrafast chemical reactions using currently available technology. They showed that certain quantum technologies, such as trapped ions or superconducting circuits, can be used as analogue quantum simulators for molecular dynamics. After developing the initial proposal with two electronic states and two vibrational modes, the main challenges were to determine whether the idea could be scaled up to larger molecules and what additional effects could be simulated.

As a demonstration, they showed how the non-adiabatic dynamics (through a conical intersection) of pyrazine could be simulated using a single trapped ion. Their approach allows the dynamics to be slowed relative to the molecule, enabling the study of phenomena that would be difficult or impossible to study with molecules and ultrafast lasers. It also scales to large molecules in complex environments, potentially beyond the capabilities of classical computers, and enables the implementation of realistic bath-system interactions.

The team are now working to implement their simulator using trapped ions. They are also looking into further extensions, such as taking measurements to produce and characterise molecular absorption spectra and engineering anharmonic effects in vibrational modes. They hope the method will enable classically intractable chemical dynamics simulations in the near term.

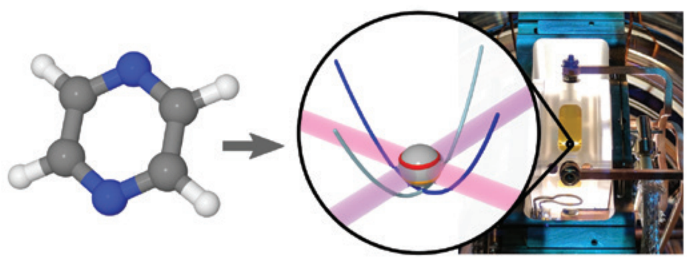


Image demonstrating the mapping of molecular dynamics, onto a trapped-ion system containing qudits (quantum d-level systems) and bosonic modes (ion's vibrational motions).

Designer quantum materials

2023 ACTIVITY PLAN

- Incorporate colour centres into high Q, low mode-volume optical resonators for light-matter interfacing.
- Develop a single-ion-addressing scheme for the 2D ion trap platform.
- Demonstrate a topological photon-qubit edge state which spatial wave-function distribution can be changed in-situ by the qubit frequency.
- Perform experiments on high-dimensional quantum-logic gates using multi-plane light conversion.
- Integrate arrays of quantum dots with resonators and cryo-control.
- Modelling of superconducting circulators.
- Construct a low-temperature optical fibre-cavity microscope to allow imaging of cuprous oxide Rydberg exciton-polaritons.

Quantum-enabled diagnostics and imaging

The quantum-enabled diagnostics and imaging program seeks to exploit quantum mechanics to engineer new probes, sensors and techniques that enhance capabilities across a range of applications, ranging from diagnosis and detection in medical imaging to the accuracy of navigation.

2022 HIGHLIGHTS

In 2022, EQUS researchers made substantial progress in this program in the development of engineered optomechanical devices, the use of quantum physics for probing biological systems, many-body spin states for sensing and new approaches to tests of fundamental physics.

Key advances are as follows:

Experimental platforms

- Developing optomechanical systems to search for dark matter and test quantum gravity (see page 29).
- Demonstrated resonant pushing of nanodiamonds in a microfluidic environment.
- Demonstrated enhancement of microwave magnetic fields through grape dimers, observing a clear enhancement of optically detected magnetic resonance in NV nanodiamonds.

Theoretical advances

- Proposed an experimentally feasible protocol for quantum imaging of stars by storing star light in widely separated quantum memories, which can then be measured to determine the location and intensity distribution of the stellar source (see page 30).
- Demonstrated enhanced parameter estimation in a model for non-linear quantum sensing based on quantum Raman memories in opto-mechanical systems.
- Quantum entanglement of two macroscopic objects, model by EQUS investigators, part of a team chosen as the 2021 Breakthrough of the Year by Physics World.

SPECTRAL SENSITIVITY OF DISSIMILAR ELECTROMAGNETIC HALOSCOPES TO AXION DARK MATTER AND HIGH-FREQUENCY GRAVITATIONAL WAVES[1]

EQUS researchers have devised a universal way of comparing the sensitivity of the many different types of axion detector, without needing specify the signal type.

Understanding the composition of dark matter is one of the greatest challenges facing modern fundamental physics. In the past 5 years, many dark matter searches (for axions in particular) have been proposed and developed. These detectors are sensitive not only to axions, but also gravitational waves, such as those detected by LIGO–VIRGO from collisions between black holes and neutron stars. The only difference is that we're dealing with 1,000,000 times higher-frequency gravitational waves and thus much smaller objects that produce them. Do these objects exist in the Universe? We won't know unless we look for them.

The only thing we're certain about is that the standard model of particle physics is incomplete. Theoretical physicists have proposed a great number of novel particles to look for, such as quark nuggets, domain walls, WIMPzillas and primordial black holes.

These objects will leave traces of gravitational waves very different to axion dark mater, so the sensitivities of proposed detectors cannot be directly translated and compared.

We used a systematic technique to compare the many different axion detectors in terms of their sensitivity to high-frequency gravitational waves, independent of their form.

The many differences in the small details of each experiment, and the need to take into account the different assumptions used in each, make it very difficult to compare experiment sensitivity. Our work enables detectors to be compared irrespective of the details of the diverse types of signal they could detect.

Our result is important for the emerging field of high-frequency gravitational-wave detection and for dark matter searches, both of which could be compared to the "Wild West" of proposals. Our work does not deal with any particular realisation or instrument in detail, but rather sets the rules of the playground for the field where various quantum instruments could be directly compared. In a way, it could be compared to the early days of gravitational-wave searches, where it took a few decades and the emergence of the field of optomechanics to construct a universal technique to compare very different instruments.

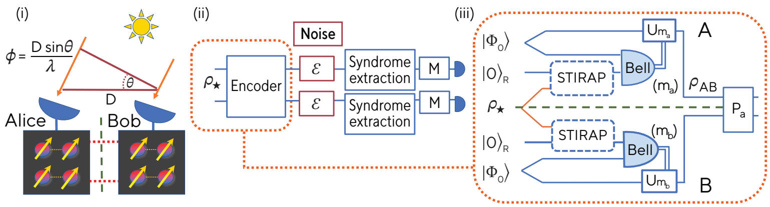
It is a universal trend to use quantum technologies, including superconducting particle detectors, levitated nanosystems, superfluids and single-photon sources, in fundamental physics searches. We encourage other EQUS members to look at how their quantum technology could be used in this field. You might be surprised at how much impact it can have!

1 ME. Tobar, CA. Thomson, WM. Campbell, A Quiskamp, JF. Bourhill *et al.* **Comparing Instrument Spectral Sensitivity of Dissimilar Electromagnetic Haloscopes to Axion Dark Matter and High Frequency Gravitational Waves.** *Symmetry 14* 10, 2165 (2022)

IMAGING STARS WITH QUANTUM ERROR CORRECTIONS[1]

EQUS researchers have proposed a quantum error-correction protocol that corrects for loss and noise when imaging stars and thus enhances imaging resolution.

The performance of an imaging system is limited by diffraction, which means that the resolution is constrained by the size of the system's light collectors and the wavelength of the source radiation. For astronomy, the holy grail would be optical interferometers roughly the size of Earth. However, the development of large optical interferometers is hindered by loss, noise and the physical weight of the instrument.



Overview of the error correction protocol

The EQUS team have proposed a general, experimentally feasible protocol for storing star light in widely separated quantum memories, which can then be measured to determine the location and intensity distribution of the source. To mimic a large optical interferometer, the light must be collected and processed coherently. We propose to use quantum error correction to mitigate errors due to loss and noise in this process.

Quantum error correction is a rapidly developing area, focused mainly on enabling scalable quantum computing in the presence of errors. Our proposal applies quantum error correction to an imaging task where the signal has not been prepared by the experimenter. Our scheme represents an application for near-term, intermediate-scale quantum devices that may increase imaging resolution beyond what is feasible using classical techniques.

By using STIRAP (stimulated Raman adiabatic passage), we developed a general quantum code for coupling an arbitrary string to the starlight, despite the light-matter interaction Hamiltonian being fixed. We showed that even a small code offers substantial protection against noise during imaging.

Our work has implications for the quantum and astronomy communities because it lays the foundation for developing the next generation of quantum-enabled optical telescopes. An optical interferometer the size of Earth's diameter would be powerful enough to image small planets around nearby stars, details of solar systems, kinematics of stellar surfaces, and potentially details around black-hole event horizons, none of which can be resolved by currently planned projects.

We're now developing the framework into multi-mode networks, and working with experimentalists (include EQUS Deputy Director Thomas Volz) to perform a proof-of principle demonstration.

1 Z Huang, GK. Brennen & Y Ouyang **Imaging Stars with Quantum Error Correction.** *Phys.Rev.Lett. 129* 21, 210502 (2022)

Quantum-enabled diagnostics and imaging

2023 ACTIVITY PLAN

- Investigate the performance of error corrected sensing with symmetric states in the presence of realistic errors in control gates.
- Investigate the sensitivity of the milli-Kelvin maser system to various external effects for sensor applications.
- Use precision optomechanics to test fundamental physics.
- Realise a compact NV maser platform and explore its use as a magnetic-field sensor and precision oscillator.
- Apply sophisticated signal processing tools to solid-state sensing platforms capable of detecting forces beyond conventional quantum limits.

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.

2022 HIGHLIGHTS

In 2022, EQUS researchers made progress in this program in areas such as atomtronics, superconducting and optical systems and devices, nuclear spin isomer characterisation, benchmarking tools, quantum thermodynamics and engines, and dark-matter detection.

Key advances are as follows:

Experimental platforms

- Developed new digital codes showing improved crosstalk suppression for digitally-enhanced optical interferometry.
- Demonstrated a high-efficiency, high availability, quantum memory for storing and recalling quantum information encoded in photons (see page 33).
- Measured nuclear spin isomers of molecular hydrogen using a combination of Raman spectroscopy and microwave cavities and oscillators.

Theoretical advances

- Investigated the link between the thermodynamics of learning machines and the idea of average learning error, finding that optimal learners minimise the power dissipated as they minimise error rate (see page 34).
- Developed benchmarking tools for the next generation of two- and three-qubit devices in silicon.
- Developing a resource theory for quantum measurements, finding new distances measures and bounds.

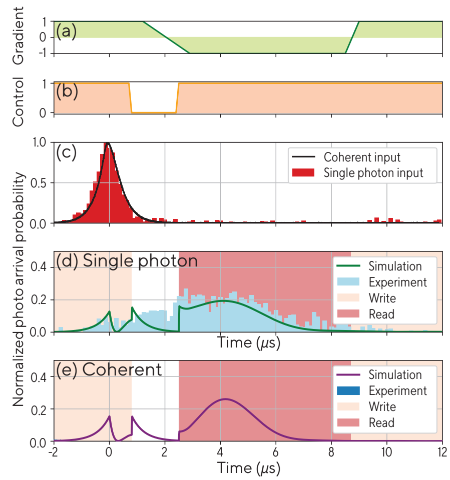
EFFICIENT, EVER-READY QUANTUM MEMORY AT ROOM TEMPERATURE FOR SINGLE PHOTONS[1]

EQUS researchers have demonstrated a quantum memory that stores and recalls information with comparable performance to the current best laboratory demonstrations, operates continuously, and may be implemented with minimal technical effort.

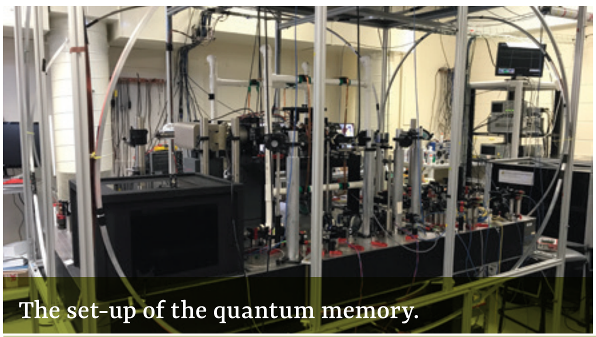
Quantum technologies have the potential to revolutionise our society, but creating the networks of quantum resources to support these future technologies is challenging. One potential solution is a quantum repeater with a quantum memory. Many high performing quantum memories have been demonstrated under laboratory conditions, but these memories are not suitable for large-scale use.

The EQUS team have demonstrated a simple, readily usable quantum memory, which operates continuously, at room temperature and without vacuum, and can store and recall quantum states with comparable performance to the laboratory demonstrations. We used hot rubidium gas in a glass cell as our memory medium, and single particles of light (photons) as the quantum states.

With this set-up, we successfully stored photons and could recall them 84% of the time — comparable to the current best quantum memories. However, because our memory does not require any state preparation steps, it operates continuously. Moreover, because it operates outside of a vacuum and at room temperature, it can be implemented with minimal technical effort for quantum technology applications. This is in contrast to other quantum memories, which require long preparation times between operation, and complex, expensive technology for implementation.



Memory operation and storage results: timing for the magnetic field gradient (a) and control field switching (b); and experimental coincidence data of the input states (c), and of a single photon state (d) and corresponding coherent state (e) stored and recalled after 4μs, overlaid with simulated results.



The set-up of the quantum memory.

Looking forward, we hope to implement our quantum memory in a quantum communication channel to synchronise communication between two stations and extend feasible communication distances. Specifically, communication to satellites suffers from a Doppler shift because of the movement of the satellite, which creates a problem when linking to different ground stations. Our memory has a proven capability of changing the frequency of the stored light and we're looking to use it to compensate for the Doppler shift.

1 AC. Leung, WYS Lau, AD. Tranter, KV Paul, M Rambach *et al.* **Efficient, ever-ready quantum memory at room temperature for single photons.** *e-Print: 2203.12108* (2022)

THE PHYSICS OF LEARNING MACHINES[1]

The planet is full of learning machines and, consequently, of minds. All animals equipped with a brain are, among other things, physically constrained learning machines, optimised by evolution and experience to exploit limited thermodynamic resources. What physical principles underlie this? How might they be used to make artificial learning agents?

We investigated the link between the stochastic thermodynamics of elementary learning machines and the information-theoretical idea of average learning error. We showed that optimal learners minimise the power dissipated as they minimise error rate. This is true for classical (thermal) and quantum learning machines. As far as we are aware, there are no naturally occurring learning machines based on quantum effects—surely a contingent feature of our particular place in the cosmos.

The biggest challenge we had to overcome was to reformulate stochastic thermodynamic relations so that they can be extended to the fully quantum regime where the temperature is very low. These are quantum generalisations of the classical Crookes and Jarzynski equalities. Once found, we defined a class of quantum learning machines driven by quantum noise, such as quantum tunnelling, rather than by the thermal noise typical of electrochemical systems.

The discovery of the link between learning optimisation and optimal power consumption motivated a further question: if thermodynamic principles drive the emergence of learning machines, then why are artificial machine learning algorithms so energy inefficient?

Our work suggests that this inefficiency is a result of the history of machine learning and the wide availability of inexpensive CMOS processors. Deep learning has its roots in attempts to numerically simulate a 1960s-level understanding of mammalian neurosystems. It has come of age recently as a result of the rapid increase in training data and fast chips on which to run the simple models of neural networks. By redirecting our view to physical learning machines and away from algorithms, substantial improvements in terms of energy dissipation should be possible.

Quantum switches dissipate the least power compared to classical switches. We devised quantum learning machines based on networks of quantum switches that promise the ability to engineer very energy-efficient quantum learning agents that are fundamentally different from unitary, gate-based coherent quantum computing.

Spiking neural nets have a greater learning capability. We came up with quantum spiking neural nets based on quantum nanomechanical resonators. A surprising consequence of these models is that they suggest that all spiking learning models may be reduced to networks of coupled clocks. Our future work will develop practical spiking neural net devices for optical implementation.

Our predictions may be implemented in several EQUS technologies, including, superconducting circuits, optomechanics, ion traps and single photonics.

1 GJ Milburn & S Basiri-Esfahani **The physics of learning machines.** *Contemp.Phys. 63* 1, 34-60 (2022)

Quantum engines and instruments

2023 ACTIVITY PLAN

- Further develop random benchmarking schemes.
- Develop efficient extraction of microwave photons from an erbium ensemble using Purcell enhancement.
- Investigate nonequilibrium steady states, quantum gas engines, and quantum advantage in many-body quantum heat engines.
- Investigate how system improvements can yield higher precision, self-calibrating ultra-cold atom rotation sensors.
- Develop quantum approaches to machine learning algorithms using optical modes.
- Develop techniques to 3D print produce novel materials and shapes for quantum technologies.

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.

This theory-focused flagship, which emerged from the Designer Quantum Materials research program, launched at the start of 2021. It has three main streams:

1. Next-generation qubits
2. Practical high-rate codes and fault-tolerant logic gates
3. High-threshold efficient decoders

2022 HIGHLIGHTS

- Introduced key result for low-overhead quantum computing, demonstrating that a local 'pre-decoder' can address problems of bandwidth and latency that arise with prior approaches to quantum error correction as code sizes increase.
- Developed error bounds for the rotating wave approximation, both for the semi-classical light-matter interaction and for the full quantum treatment.
- Generalised the construction of stabiliser codes to arbitrary tensor networks, allowing for the systematic construction of an essentially infinite number of new codes: "doped" codes, in analogy with semiconductor impurity doping (see page 37).

2023 ACTIVITY PLAN

- Enable automated discovery of bias-preserving gates and their most robust drive sequences by finalising software to perform optimal control in the presence of structured noise.
- Develop mechanisms for non-local gates between spins using interactions mediated by a bosonic mode.
- Investigate applications of LDPC codes for realistic physical hardware models and further develop local autonomous decoders.

THE XP STABILISER FORMALISM[1]

EQUS PhD Student, Mark Webster, has been investigating ways of efficiently representing general quantum states that cannot be simulated using classical computing.

Representing a general quantum state requires an amount of information that grows exponentially with system size. One way to describe quantum states more compactly is using the Pauli stabiliser formalism. States within this formalism demonstrate some aspects of quantum behaviour, such as superposition and entanglement; however, these behaviours can also be simulated using a classical computer.

We have been working on a generalisation of the Pauli stabiliser formalism called the XP stabiliser formalism, which allows us to represent a wider range of states. These states cannot always be simulated classically, suggesting the formalism captures some of the advantages we expect from quantum computing.

The new formalism may have applications in producing robust quantum memories, creating resource states that help to realise universal quantum computers and in condensed matter physics. There are still many interesting open questions.

Possible research directions include:

- Finding good error-correction protocols,
- Determining which topological phases may be represented in the new formalism, and
- Developing useful quantum codes (which could be applied, for instance, in quantum memories or magic state distillation).

“A key challenge for me was that it took a long time to be able to read and understand papers in this field! I had been away from university for a long time, and it was really helpful to talk with young researchers in my group. This informal mentoring—often over a few beers—really accelerated my development,” Mark explained.

“I also found that coding up examples in Python made things much more concrete and easier to understand. This also helped me to quickly come up with hypotheses and test them ahead of proving them mathematically. I’ve now released the code as a package for others to use and explore the new formalism. It would also be great to talk with others in EQUS about possible applications and implications of the work.”

1 MA Webster, BJ. Brown & SD. Bartlett **The XP Stabiliser Formalism: a Generalisation of the Pauli Stabiliser Formalism with Arbitrary Phases.** *Quantum 6* 815 (2022)

Quantum clock flagship

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.

This flagship, which emerged from the Quantum Engine and Instruments research program, launched at the start of 2021. It has three main streams:

1. Development of a microwave qubit-clock synthesis chain
2. Investigation of hybrid oscillators based on optomechanical platforms coupled to strain-controlled defects
3. Theoretical exploration of coherent quantum feedback based on incommensurate observables for new oscillator designs

2022 HIGHLIGHTS

- Observed milliKelvin "freeze-out" of hopping conductivity in specially treated cylindrical isotopically pure silicon samples, critical to goal of building a hybrid oscillator based on a variety of optomechanical platforms coupled to strain-controlled defects.
- Irradiated small silicon samples: by doping high purity samples with only one type of electron spin impurity, aim to observe exceptionally narrow optical bandwidths.
- Constructed Bulk Acoustic Wave resonators from High Resistivity Float Zone silicon.
- Theoretically analysed the nuclear spin stability of europium and erbium systems as a function of magnetic field, preparatory to realising quantum hard drives for VLBI.
- Detailed modelling for atomic beam clock experiments, enabled quasi-analytic calculation of the velocity averaged response for a thermal atomic beam interrogated by a Ramsey-Bordé clock transition in alkali atoms.
- Investigated mass-energy effects in freely propagating composite particles (see page 39).

2023 ACTIVITY PLAN

- Engineer a strong interaction between two low-loss systems, e.g. an electromagnetic whispering gallery mode and an electron spin resonance.
- Construct a 1550 nm optical cavity to interrogate silicon Bulk Acoustic Wave resonators.
- Improve the noise performance microwave amplifiers by implementation of interferometric techniques.

QUANTISED MASS-ENERGY EFFECTS IN AN UNRUH-DEWITT DETECTOR

EQUS researchers have shown that mass–energy equivalence must be incorporated into the traditional model of a quantum particle interacting with an external environment to represent realistic scenarios in which particles such as atoms interact with, for example, light.

The traditional model of a particle interacting with, for example, light is known as the Unruh–DeWitt model, and is widely used in theoretical physics. This simple model consists of a point-like particle with internal energy levels, which interacts with a quantum field but travels on a classical trajectory (that is, there is no quantum uncertainty in its position or momentum). If the particle 'detects' energy from the field, then it absorbs that energy and is excited to a higher internal energy level (like when an atom absorbs a photon and its electrons move to higher energy levels). Alternately, the particle may emit energy to the field and drop to a lower energy level. However, researchers have recently begun to include a quantum centre of mass for the detector in an effort to create a model that, while still simple, more closely resembles a real quantum particle.

We incorporated Einstein's mass–energy equivalence (which also gives us $E = mc^2$) into the traditional model. In our new model, the internal energy levels of the particle have an associated mass, and exchanging energy with the field alters not only the energy but also the mass of the detector — as required by relativity. To understand the implications of this, we investigated the role mass has in our model and in previous models that assume a fixed mass.

Although effects of mass–energy equivalence would usually be considered negligible in the low-energy limit, we found that, surprisingly, not only are they present in that regime, but they are of the same order of magnitude as the energy of the centre of mass of the detector. This means that anyone wishing to adapt the Unruh–DeWitt model to realistic quantum particles (such as atoms) must include the mass–energy equivalence.

Our approach strengthens the connection between the research areas of quantum field theory, relativistic quantum information and atomic physics. Besides showing that mass–energy equivalence cannot be neglected even in the regime previously assumed to be fully non-relativistic, the incorporation of mass–energy equivalence into the model opens new possibilities for testing the interplay between quantum physics and gravity.

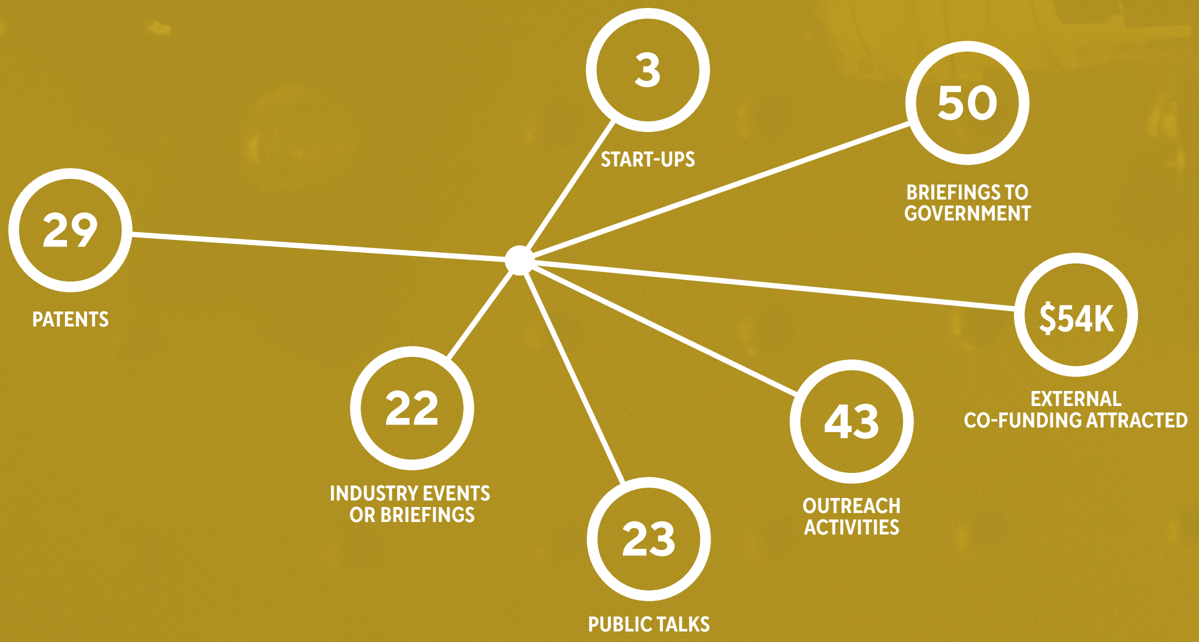
This project is only just beginning, and we will continue to explore the consequences of including mass–energy equivalence in this model.

Our impact: Overview

To complement our cutting-edge research programs, EQUS delivers broad impact through the following:

1. **Research translation**
2. **Equity, diversity and inclusion**
3. **Mentoring and career development**
4. **Outreach and education**

Our capacity-building programs are training a new generation of scientists in cutting-edge fundamental research, innovation and entrepreneurialism. The EQUS team works with partners in government and industry to translate research discoveries into practical applications and devices. We have programs to develop resources for students and teachers, and to inspire future quantum scientists and engineers. We aim to be equitable and inclusive across all our programs, creating an environment that promotes and celebrates diversity and individuality.



Research translation

Translating research outcomes and knowledge into new quantum technologies and applications

Equity, diversity and inclusion

Building a vibrant, engaged, diverse and inclusive community of knowledge leaders for academia and industry

Mentoring and career development

Creating a quantum-literate ecosystem by training a generation of quantum scientists and engineers

Outreach and education

Engaging and educating diverse audiences in quantum science and technology and its potential for our future

Research translation

EQUS is building the foundations for an innovative, advanced economy in Australia. We aim to bridge the innovation gap for the translation of quantum science to quantum technology development, through links with end-users in government, local small-to-medium enterprises and global technology giants.

2022 SUMMARY

The following translation projects were funded in 2022:

Microwave Helical Cavity UWA

EQUS researchers at UWA invented a new class of microwave devices. The resonating microwaves in such a device possess many unique properties owing to the unique geometry of the cavity design, which introduces a coupling of previously transverse mode polarisations. Such properties include a high rate of frequency tuning of high frequency modes (>15 GHz) my mechanical actuation, something difficult to achieve in traditional resonators, and with application for filtering in telecommunications. The modes also exhibit intrinsic "handedness" or helicity, which is unique to these new devices. Never observed before polarisation of microwave radiation may have numerous applications for chiral media e.g. right and left molecules, important for drug and chemical manufacturing processes. These devices could also be important for high-dimensional entanglement between microwave frequency photons. The funded project will design and optimise prototype devices and benchmark their performance for potential applications.

Optophoresis for Particle Sorting and Diagnostics MQ

Optical tweezers and solar sails both harness the momentum of light to move solid objects. EQUS researchers at Macquarie University have demonstrated that the optical forces on nanoparticles can depend strongly on their optical activity i.e., their absorption and fluorescence. This project will extend this finding to a microfluidic device that can sort nanoparticles in a viscous medium using only the force of light. The technology developed will enable sorting and evaluation of particles by optical properties, size and shape, and eventually using functionalised particles to detect the presence of one or more analyte in a micro-volume of solution. By using only light the cost of analysis will be reduced substantially, meaning applications for this technology are possible from environmental monitoring to point-of-care diagnostics in health settings.

2023 ACTIVITY PLAN

EQUS will continue to encourage and support research translation activities in 2023. Projects expected to receive funding include:

High Performance Fibre Bragg Grating Filters **USYD**

EQUS researchers in collaboration with the Australian National Fabrication Facility have developed extremely high-performance fibre Bragg grating filters. Originally conceived for use in quantum computing and quantum memory experiments, these devices may be useful in communications, sensing and diagnostics, and a range of instrumentation applications. Next steps will include packaging the devices, so they are stable and robust as well as adding the ability to tune them while in use.

Wideband Tuneable Low Phase Noise Oscillators for Communications **UWA**

This project will build a wide band tuneable low phase noise oscillator based on quantum hybrid systems technology developed at UWA. The prototype is targeted at use in 5G mobile networks to improve data rates, range, and power consumption. By using a new type of frequency reference and reducing phase noise using interferometric feedback these devices will be robust and low cost.

Optical Levitation Gravitometer **MQ**

EQUS researchers at Macquarie University have developed expertise in levitating small particles using only light and using these to measure very small forces or displacements. This project will adapt this technology to the particular use case of measuring small variations in gravity for sensing purposes.

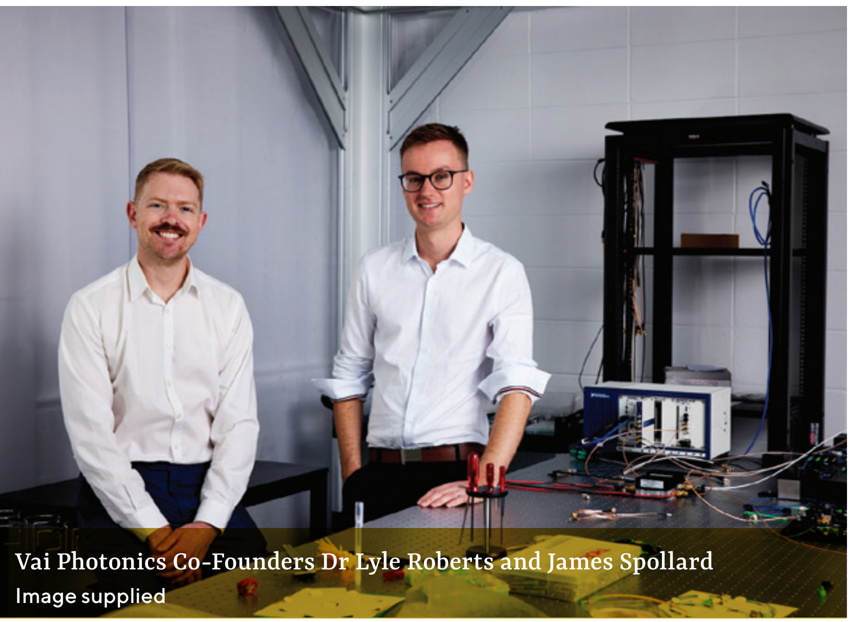
Reef Water Monitoring **UQ**

EQUS researchers are devising a detection system capable of long-term, in situ monitoring of water for agricultural runoff contaminants.

SHAPING THE FUTURE OF PHOTONIC SENSING

In 2021, the EQUS Translation Research Program awarded Dr Lyle Roberts a TRL Fellowship. This funding enabled him to build a proof-of-concept device to generate data on the capability and performance of navigation Doppler LiDAR.

This work was the basis for establishing Vai Photonics, a start-up co-founded by Dr Roberts and EQUS PhD Student James Spollard. Vai Photonics built sensors that enable vehicles to navigate with precision and confidence when GPS is unavailable or unreliable. Built on more than a decade of R&D in electro-optic sensor technology, Vai Photonics' breakthrough navigation Doppler LiDAR delivers a step change in navigation performance that reduces dependence on the Global Navigation Satellite System (GNSS).



Vai Photonics Co-Founders Dr Lyle Roberts and James Spollard
Image supplied

In 2022 the start-up was acquired by Advanced Navigation in a deal worth up to $40 million. Dr Lyle Roberts and James Spollard are looking forward to working with Advanced Navigation, one of the world's most ambitious innovators in AI robotics and navigation technology, to commercialize their photonics-based navigation technology.

"It's a huge win for us—together with Advanced Navigation, we're able to bring our product to market much faster than originally planned," Dr Roberts said.

"We were fortunate to receive early backing in the form of seed funding from EQUS, which allowed us to develop prototypes and conduct regular field tests" Dr Roberts said.

"More than anything, EQUS provided support and encouragement to translate our research into a commercial product.

"While funding is integral, the incredible culture and mentorship inspired and motivated our research to become what it is today.

EQUS Director Professor Andrew White applauded the initiative and determination shown by Lyle and James.

"Lyle and James are perfect examples of researchers achieving useful outcomes by utilising the funds, mentoring and guidance available through EQUS' Translation Research Program, to help pursue the real-world impacts that our research can deliver," he said.

"These two are what Australia's research future looks like."

EQUS STARTUP ENABLING QUANTUM COMPUTERS

EQUS start-up Analog Quantum Circuits (AQC) received an investment of $3 million from Uniseed, Australia's longest running venture fund, to enable the development of key components required for the scale up of quantum computing.

AQC was founded by EQUS Chief Investigators Professor Tom Stace and Associate Professor Arkady Fedorov, who will drive the development to meet the needs of the internationally growing quantum computing industry. AQC's ground-breaking, patented technology miniaturises and integrates microwave circulators, critical hardware components that quantum computers need to route signals to and from the qubits. This invention is an important step in the future of large-scale quantum computing.

AQC's inaugural CEO, Tom Stace, said, "AQC develops core microwave technologies for superconducting quantum computers, which are one of the most promising platforms being pursued globally. We are very pleased to be partnering with Uniseed to bring this to market."

AQC builds on research funded by the Australian Research Council (ARC), through EQUS and Future Fellowships held by the founders.

EQUS Director Andrew White said, "Tom and Arkady have been working on this technology for over 5 years, and it is fabulous to see EQUS' fundamental research being translated to address real needs in the sector."

Professor Halina Rubinsztein-Dunlop AO, Director of EQUS' innovative Translational Research Program (TRP), said "the TRP provided the research team with translation funding and expert support to help turn this promising research into the business we are seeing launched today."

AQC will provide significant funding, through a contract research agreement, to the EQUS laboratories at The University of Queensland to complete critical experimental and developmental work.

AQC is the first quantum hardware start-up in Queensland, and the first superconducting quantum hardware start-up in Australia. Building on the founders' research at UQ, AQC is developing fundamental microwave electronics to enable the scale up of superconducting quantum computers.

Hon. Meaghan Scanlon MP, AQC Chief Scientific Officer Associate Professor Arkady Fedorov, Hon. Ed Husic MP and ACQ CEO Professor Tom Stace.
Image by Jenny Cuerel Photography

Equity, diversity and inclusion

EQUS is committed to improving equity, diversity and inclusion within the Centre and the wider quantum physics community. We aim to foster a safe, welcoming and inclusive environment that allows all EQUS members to achieve success and to feel respected and supported.

2022 SUMMARY

Centre activities in 2022 related to equity, diversity and inclusion include:

- Hosting the inaugural inSTEM Conference (see page 47).
- Creation of the EQUS Participation & Inclusion Award which will supersede the EQUS Primary Carer Award. This new Career Support Award is designed to provide support to members that may be primary carers or have responsibilities that may limit their ability to access career development opportunities or progress their careers at the expected rate.
- Sponsorship of LGBTQIA+ and First Nations scholarships for Science & Technology Australia's Science meets Parliament.
- Training an EQUS member at each node as a mental health first aid officer.
- Running the EQUS 2021/2022 Summer Research Program in conjunction with the EQUS Mentoring and Career Development Committee. The 2021/2022 Program round was specifically for Aboriginal and/or Torres Strait Islander students and students from other underrepresented groups in STEM. Eight scholarships awarded ($24,000 in funding).

The following initiative began in 2021 and is ongoing:

- Development of an EQUS grievance management process.

2023 ACTIVITY PLAN

In addition to continuing ongoing activities in 2023 the Centre plans to start work on the following initiatives:

- Creation of the EQUS EDI PhD Student Top Up Scheme to provide support for PhD students who are experiencing financial hardship.
- Sponsorship of LGBTQIA+ and First Nations scholarships for Science & Technology Australia's Science meets Parliament.
- Sponsorship of the 2023 inSTEM Conference.
- Training an EQUS member at each node to be an EQUS contact officer.
- Running the EQUS 2023/2024 Summer Research Program in conjunction with the EQUS Mentoring and Career Development Committee.

inSTEM CONFERENCE

The inSTEM Conference was conceived by members of the 2021 EQUS EQUIP (equity in quantum physics) committee who shared the challenges they experienced trying to establish a network as a woman in physics. Networking is a key strategy for career progression, yet research has found that women's networks are less powerful than men's and that women are typically less equipped to leverage the networks they do have when it comes to their career. Furthermore, the research found that this issue is not specific to women but is indicative of the experiences of marginalised and underrepresented groups in general.

The EQUIP committee agreed that EQUS should establish a conference that shared insights from leading experts on topics and strategies that supported career development and progression; in a safe environment, where attendees from marginalised or underrepresented groups, and their allies, could meet, make connections and build relationships with other researchers.

We approached the STEM-focussed ARC Centres of Excellence to gauge their interest in our idea. We received overwhelming support and the inaugural inSTEM Conference was born. Led by EQUS with the support of the Department of Defence, eight ARC Centres of Excellence and one ARC ITTC (see list at right).

The inSTEM Conference, held in Meanjin/Brisbane on the 20th– 21st of July 2022, had 150 early-to-mid-career researchers in attendance. Researchers heard from presenters and panellists on topics such as networking, CV design, interview skills, LinkedIn and mentoring. In-person attendees also had a chance to practice their networking skills and get feedback on their cover letters and CVs during speed drop-in sessions.

A second conference stream focused on how to create change that improves access, supports retention and champions success in STEM for individuals from marginalised or underrepresented groups. Panellists shared their perspectives and lived experience as people from underrepresented and/or marginalised groups, how they have navigated their own careers, and the challenges and successes they had along the way.

The success of this event was without a doubt due to our sponsors and the many individuals who volunteered their time as part of the inSTEM organising committee or event crew. The feedback from attendees and presenters was so positive that the event will take place again in 2023 this time held in Naarm/Melbourne and led by the ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS). Please head to www.instem.io to find out the latest information about future conferences.

inSTEM partners

Mentoring and career development

EQUS provides mentoring and career development opportunities for our higher-degree research students and early career researchers; with the aim of advancing their research and technical skills, and broader knowledge of the field. Training opportunities also aim to build knowledge and skills in the areas of entrepreneurship and commercialisation, leadership, and media and communications. EQUS members also have access to guidance and support through the Centre's mentoring program.

2022 SUMMARY

2022 saw a return of a number of training and development activities that had been postponed in 2020 and 2021 due to covid impacts. Centre activities in this portfolio included:

- Online training sessions: Building your profile as a researcher (Kylie Ahern), So you're graduating your PhD in a pandemic. What next? (Professor Inger Mewburn) and Planning your research career (Hugh Kearns)
- EQUS – FLEET Idea Factory (see page 49)
- Python Workshop
- EQUS Collaboration Grant Round. Four grants awarded ($11,147 in funding)
- Running the EQUS 2022/2023 Summer Research Program in conjunction with the EQUS EQUIP (equity in quantum physics) Committee. For the second year running the program was open to Aboriginal and/or Torres Strait Islander students and students from other underrepresented groups in STEM. Eight scholarships awarded ($24,000 in funding)

2023 ACTIVITY PLAN

In 2023, EQUS is aiming to deliver the following training and development activities:

- New online training sessions
- EQUS – FLEET Idea Factory
- Summer School
- EQUS Collaboration Grant Round
- Running the EQUS 2023/2024 Summer Research Program in conjunction with the EQUIP (Equity in Quantum Physics) Committee
- Transition the EQUS Mentoring Program to the ARC Centre of Excellence Mentorloop Platform, enabling a more diverse program that supports mentor/mentee matches across a number of different Centre's of Excellence.

2022 EQUS – FLEET IDEA FACTORY

The Idea Factory has been a regular EQUS workshop, initially aimed at assisting early career researchers in the practicalities of writing strong research proposals. Since 2018, it has been run in collaboration with the ARC Centre of Excellence for Future Low-Energy Electronics Technologies (FLEET).

In 2022, we were able to gather in person for this event, in Caloundra; the first time in three years. This year the focus was on research translation, and how to think about the impact of your research beyond the confines of academia. Some of the skills developed will be useful for participants considering applying for funding in either the EQUS or FLEET research translation schemes. The program was facilitated by Jonathan Lacey and Emily Chang from Cruxes Innovation.

Almost 30 participants from EQUS and FLEET learnt about how important it was to be solving a problem that was actually important for stakeholders and end-users, rather than a problem you think they might have, and how the solution needed to have massive (rather than incremental) impact. Topics such as Gaddie pitches and testing assumptions with stakeholder interviews were covered. Participants were asked to get in touch with potential stakeholders during the workshop, and finished on the last day with a presentation of their own compelling impact story.

Across the workshop, there were plenty of opportunities to network with other participants, including at the ten-pin bowling plus pizza feast on the first night, followed by the extravagant Thai feast at the workshop dinner.

The participants all appeared to enjoy the workshop, with many expressing their opinion that it opened their eyes to how their research and skills could make a difference in the world beyond universities. Several were inspired to start preparing applications for the Centre research translation programs.

Idea Factory

We look forward to seeing the results over the next few months!

EQUS PhD Student, and Idea Factory attendee Tim Hirsch said: "The Idea Factory was intense. 27 of us PhD students and postdocs travelled north to Caloundra to learn how to make real-world impact with our research. Everyone coming to the workshop had to bring with them a research translation idea, which we would develop over the three days under the tutelage of our start-up sensei's Jonathan and Emily.

The expectation of being insulated from any real consequence was shattered on the first day, when Jonathan and Emily assigned us homework: by the next morning, we had to talk to five people about our idea—and three of them couldn't be family or people in the room. Aah! In hindsight, I think pushing us to take real steps was a big strength of the workshop: research translation involves a lot of unsolicited communication, which I find scary and therefore probably wouldn't have done for the first time on my own initiative.

This became one of my biggest takeaways from the Idea Factory—talking to people about your translation and commercialisation ideas is both the first thing you need to do, and the thing you need to keep doing continuously, if you are going to successfully translate your research.

I'm grateful to be doing my PhD within a larger ARC centre that provides opportunities like the Idea Factory. I think everyone participating came out with good contacts, good experience, and more confidence that they could produce impact. I recommend anyone with at least a passing interest in research translation to apply for next year's Idea Factory."

2022 EQUS ANNUAL WORKSHOP

The EQUS Annual Workshop is a key forum for collaboration and exchange of ideas between EQUS members. The 2022 workshop, the first whole-of-centre event in-person in three years, was held in Newcastle, NSW.

The workshop was attended by 158 EQUS members including members of the Scientific Advisory Committee; Professor Sir Peter Knight, Professor Rainer Blatt and Professor John Clarke.

Highlights of the workshop included:

- Invited talks by Professor Alexia Auffèves (CNRS MajuLab), Lisa Annese (Chief Executive Officer of Diversity Council Australia), Assistant-Professor Yvonne Gao (National University of Singapore) and Dr Jess Wade (Imperial College)
- Research and portfolio updates from 26 EQUS members
- Pitch, poster and three-minute thesis competitions
- Awarding of EQUS prizes (see pages 12–13).

Professor Alexia Auffèves is Research Director at the CNRS International Research Lab MajuLab (Singapore) and an EQUS Partner Investigator. In her keynote, Alexia presented the recently launched quantum energy initiative— *quantum-energy-initiative.org*—which aims to develop a holistic understanding of the energetic footprint and efficiencies of quantum technologies. To consider these impacts QEI has established a transverse, interdisciplinary and international research line connecting quantum thermodynamics, quantum information science, quantum physics and engineering.

Lisa Annese, CEO of Diversity Council Australia, delivered a keynote on diversity and inclusion (D&I) in the workplace and the ability for effective D&I policies and strategies to retain a satisfied workforce resulting in greater profitability, innovation and organisational performance.

Dr Yvonne Gao is a Principal Investigator in the Centre for Quantum Technologies and Presidential Young Professor in the Department of Physics at the National University of Singapore. Yvonne's presentation, Quantum information processing with bosonic modes: a story of cats, cavities and coherence, explored how stored multiphoton states are promising candidates for long-lived quantum memories and for logical qubits that can be protected against environmental noise.

Dr Jess Wade, a Research Fellow from the Department of Materials, Imperial College London, shared both her research on chiral molecular materials and their potential to offer a more sustainable and efficient solution for preparing, controlling, storing and reading-out quantum states. Jess also shared the many science communication, outreach activities and diversity initiatives she has been involved in; and why she believes it is the responsibility of STEM researchers to take an active role in trying to address the many inequities that exist in the current academic workforce.

Edgar Tanuarta presenting their poster "Finite-bandwidth gyrator for protected superconducting qubit" at the 2022 EQUS Annual Workshop Poster Session

The 2022 EQUS Annual Workshop participants

The workshop also provided the opportunity to hear from each of the 21 EQUS research projects and five portfolio committees. EQUS Students and early-career researchers also had the opportunity to share their research in a poster or three-minute thesis (3MT) format or to pitch their research to hypothetical investors, Associate Professor Jacqui Romero, Professor Kirk McKenzie (ANU) and Professor Tom Stace (UQ). Prizes were awarded to the top presenters in each category.

The awards dinner was another highlight of the workshop, providing the Centre Executive with an opportunity to acknowledge the outstanding performance of our members and recognise the contributions they make to EQUS.

Outreach and education

EQUS continues to engage the community in quantum and its potential for the future of society. We aim to engage and educate the wider community by promoting our research through media releases, the EQUS website and social media. The Centre and its members also participate in public events and activities, collaborations with science teachers and consultations with government and industry.

2022 SUMMARY

In 2022, communication and outreach activities included:

- The National Quantum & Dark Matter Road Trip (see page 53)
- The EQUS Quantum Art Competition
- Sponsorship of and participation in the National Science Quiz
- Sponsorship of and participation in Quantum Shorts

2023 ACTIVITY PLAN

In 2023, EQUS is aiming to deliver the following communication and outreach activities:

- The National Quantum & Dark Matter Road Trip (Qld & Vic)
- The Quantum Alphabet museum exhibit (legacy activity)
- EQUS outreach Fellowships/Scholarships
- The EQUS Quantum Art Competition
- The Clear as Quantum podcast (Season 2)

QUANTUM AND DARK MATTER ROAD TRIP

The National Quantum & Dark Matter Road Trip saw 24 members of EQUS and the ARC Centre of Excellence for Dark Matter Particle Physics drive from Brisbane to Perth over National Science Week, 8–26 August. The team visited 25 regional schools and delivered 14 public events during the trip, engaging members of the public at schools, pubs and committee hubs in all things quantum and dark matter.

Road trippers hanging out in Coffs Harbour ...


and Kalgoorlie

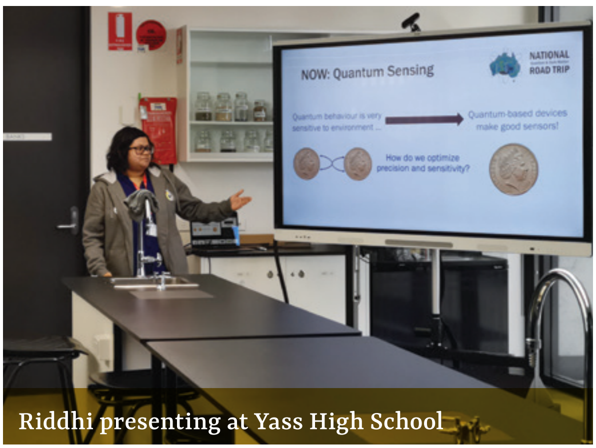
Overall, the road trip was a huge success. The feedback so far has been really positive, especially from students, teachers and attendees at our public events, but also from the road-trippers.

Ben McAllister – road trip organiser and participant, and co-chair of EQUS' Public Engagement Committee – said: "The road trip was a fantastic opportunity to get out into regional and rural areas and talk to school students and people who wouldn't typically get that kind of engagement. The students had some fantastic questions—there was so much curiosity about the nature of the Universe, at all levels, which was really encouraging to see."

In total, the team engaged around 2,000 people at schools, pubs and community centres in quantum technologies and dark matter, including around 1,400 high-school students. We also received a huge amount of media coverage, including 11 unique print and/or online media stories (syndicated across roughly 120 titles), 15 radio spots and a feature on WIN News Toowoomba (syndicated across Queensland).

Stefan presenting to students at Stawell High School

Graeme presenting at Cunderdin District High School

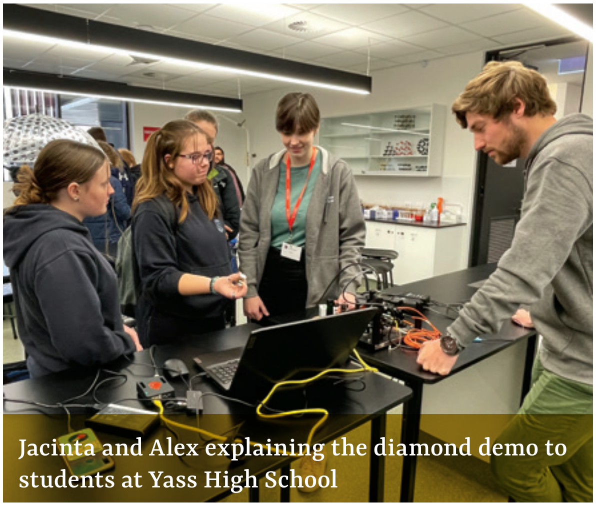


Riddhi presenting at Yass High School

As well as being great promotion for the road trip and EQUS, it provided EQUS members with the opportunity to practice their science communication. In particular:

- Ben McAllister was interviewed by ABC Goulburn Murray, ABC Wimmera, ABC Mildura–Swan Hill, 2GB/3AW and ABC Statewide, Bendigo HIT FM, quoted in the Yass Valley Times
- Cyril Laplane was interviewed by ABC Newcastle
- Jacinta May was interviewed by and quoted in the Bendigo Advertiser
- Jeremy Bourhill was interviewed by Noongar Radio and ABC Midwest & Wheatbelt, and quoted in Western Australian articles
- Maverick Millican was interviewed by WIN News.

Ben giving a public talk to an audience of 100 at Stawell Town Hall



Jacinta and Alex explaining the diamond demo to students at Yass High School

Ben said that the road trip was exhausting, but also a tonne of fun, with the pub quizzes being a person highlight. "As well as being great fun, the pub quizzes proved to be great conversation starters. People seemed genuinely interested in quantum and dark matter—we spent hours after each quiz chatting to people and answering their questions," he said.

The EQUS members who joined the trip were:

- Ben McAllister
- Kristen Harley
- Cyril Laplane
- Fatemeh Mohit
- Lauren McQueen
- Maverick Millican
- Alex Hahn
- Elisabeth Wagner
- Jacinta May
- Riddhi Ghosh
- Stefan Zeppetzauer
- Tim Hirsch
- Will Campbell
- Elrina Hartman
- Graeme Flower
- Jeremy Bourhill

ROAD TRIP STATS

24 scientists and science communicators

11 EQUS members
5 EQUS and CDM members
8 CDM members

12,372 km on the odometer

7115km Car 1 Brisbane to Perth
3656km Car 2 Brisbane to Adelaide
1601km Car 3 Kalgoorlie to Perth

22 days of road-tripping activities

25 schools
14 public events
40+ cities and towns

2000ish people engaged

1400 school students
120 pub goers
165 public talk or lecture attendees
315 attendees at other public events

3000ish items of merch

2000 stickers
270 bags of jelly beans
200 fridge magnets
30 seed packets
500 EQUS/CDM merch items

3 car magnets lost on the highway
2 cancelled flights
2 fruit incidents
1 roadkill incident
1 COVID case
0 ghosts(?)

Publications

G Moody, VJ Sorger, DJ Blumenthal, PW Juodawlkis, W Loh, C Sorace-Agaskar, AE Jones, KC Balram, JCF Matthews, A Laing, M Davanco, L Chang, JE Bowers, N Quack, C Galland, I Aharonovich, MA Wolff, C Schuck, N Sinclair, RM Camacho. **2022 Roadmap on integrated quantum photonics.** *Journal of Physics: Photonics* 4(1), 012501 (2022)

C Becher, W Gao, S Kar, C Marciniak, T Monz, JG Bartholomew, P Goldner, H Loh, E Marcellina, KEJ Goh, TS Koh, B Weber, Z Mu, J-Y Tsai, Q Yan, T Huber, S Höfling, S Gyger, S Steinhauer & V Zwiller. **2023 roadmap for materials for quantum technologies.** *Materials for Quantum Technology* (2022)

F Costa. **A no-go theorem for superpositions of causal orders.** *Quantum* 6, 663 (2022)

M Bojer, Z Huang, S Karl, S Richter, P Kok & J von Zanthier. **A quantitative comparison of amplitude versus intensity interferometry for astronomy.** *New Journal of Physics* 24(4), 043026 (2022)

ER Rees, AR Wade, AJ Sutton & K McKenzie. **Absolute Frequency Readout of Cavity against Atomic Reference.** *Remote Sensing* 2022, Vol. 14, Page 2689, 14(11), 2689 (2022)

ME Tobar, RY Chiao & M Goryachev. **Active Electric Dipole Energy Sources: Transduction via Electric Scalar and Vector Potentials.** *Sensors* 2022 Vol. 22, Page 7029, 22(18), 7029 (2022)

S Walsh, A Frost, L Howard, DR Gozzard, DR Gozzard, S Karpathakis, B Dix-Matthews, CT Gravestock, A McCann & S Schediwy. **Angle-of-arrival variability of retroreflected lasers despite atmospheric reciprocity.** *Optics Letters* Vol. 47, Issue 8, Pp. 1920-1923, 47(8), 1920–1923. (2022)

L Parker & F Costa. **Background Independence and Quantum Causal Structure.** *Quantum* 6, 865 (2022)

C Doyle, WW Zhang, M Wang, BA Bell, SD Bartlett & A Blanco-Redondo. **Biphoton entanglement of topologically distinct modes.** *Physical Review A* 105(2), 023513 (2022)

DT Le, MP Almeida & NB An. **Certification of photon Fock states using second-order nonlinearity.** *Physical Review A* 106(6), 062608 (2022)

LF Reyes, S Murthy, E García-Gallo, M Irvine, L Merson, I Martin-Loeches, J Rello, FS Taccone, RA Fowler, AB Docherty, C Kartsonaki, I Aragao, PW Barrett, A Beane, A Burrell, MP Cheng, MD Christian, JP Cidade, BW Citarella & PL Olliaro. **Clinical characteristics, risk factors and outcomes in patients with severe COVID-19 registered in the International Severe Acute Respiratory and Emerging Infection Consortium WHO clinical characterisation protocol: a prospective, multinational, multicentre, observational study.** *ERJ Open Research* 8(1), 21 (2022)

JS Bennett. **Coherent Feedback Goes for a Spin.** *Physics* 15 (2022)

S Daryanoosh, A Gilchrist & BQ Baragiola. **Collisional-model quantum trajectories for entangled-qubit environments.** *Physical Review A* 106(2), 022202 (2022)

D Burgarth, P Facchi & R Hillier. **Control of Quantum Noise: On the Role of Dilations.** *Annales Henri Poincare* 1–23 (2022)

AB Stilgoe, TA Nieminen & H Rubinsztein-Dunlop. **Controlled transfer of transverse orbital angular momentum to optically trapped birefringent microparticles.** *Nature Photonics* 2022 16:5, 16(5), 346–351 (2022)

WW Wasserman, RA Harrison, GI Harris, A Sawadsky, YL Sfendla, WP Bowen & CG Baker. **Cryogenic and hermetically sealed packaging of photonic chips for optomechanics.** *Optics Express* Vol. 30, Issue 17, Pp. 30822-30831, 30(17), 30822–30831 (2022)

K Sahay & BJ Brown. **Decoder for the Triangular Color Code by Matching on a Möbius Strip.** *PRX Quantum* 3(1), 010310 (2022)

DJ Parker, M Savytskyi, W Vine, A Laucht, T Duty, A Morello, AL Grimsmo & JJ Pla. **Degenerate Parametric Amplification via Three-Wave Mixing Using Kinetic Inductance.** *Physical Review Applied* 17(3), 034064 (2022)

E Blumenthal, C Mor, AA Diringer, LS Martin, P Lewalle, D Burgarth, KB Whaley & S Hacohen-Gourgy. **Demonstration of universal control between non-interacting qubits using the Quantum Zeno effect.** *Npj Quantum Information* 2022 8:1, 8(1), 1–6 (2022)

A Quiskamp, BT McAllister, P Altin, EN Ivanov, M Goryachev & ME Tobar. **Direct search for dark matter axions excluding ALP cogenesis in the 63- to 67-μeV range with the ORGAN experiment.** *Science Advances* 8(27), 3765 (2022)

FA Bayocboc, MJ Davis & KV Kheruntsyan. **Dynamics of thermalization of two tunnel-coupled one-dimensional quasicondensates.** *Physical Review A* 106(2), 023320 (2022)

M Arnold & R Nigmatullin. **Dynamics of vortex defect formation in two-dimensional Coulomb crystals.** *Physical Review B* 106(10), 104106 (2022)

G Li Bassi, K Gibbons, JY Suen, HJ Dalton, N White, A Corley, S Shrapnel, S Hinton, S Forsyth, JG Laffey, E Fan, JP Fanning, M Panigada, R Bartlett, D Brodie, A Burrell, D Chiumello, A Elhazmi, M Esperatti & AOR Vazquez. **Early short course of neuromuscular blocking agents in patients with COVID-19 ARDS: a propensity score analysis.** *Critical Care* 26(1), 1–17 (2022)

P Iyer, A Jain, SD Bartlett & J Emerson. **Efficient diagnostics for quantum error correction.** *Physical Review Research* 4(4), 043218 (2021)

M Rambach, A Youssry, M Tomamichel & J Romero. **Efficient quantum state tracking in noisy environments.** *Quantum Science and Technology* 8(1), 015010 (2022)

LO Conlon, T Michel, G Guccione, K McKenzie, SM Assad & PK Lam. **Enhancing the precision limits of interferometric satellite geodesy missions.** *Npj Microgravity* 2022 8:1, 8(1), 1–10 (2022)

DJ George, YR Sanders, M Bagherimehrab, BC Sanders & GK Brennen. **Entanglement in quantum field theory via wavelet representations.** *Physical Review D* 106(3), 036025 (2022)

MJ Kewming & S Shrapnel. **Entropy production and fluctuation theorems in a continuously monitored optical cavity at zero temperature.** *Quantum* 6, 685 (2022)

D Gribben, DM Rouse, J Iles-Smith, A Strathearn, H Maguire, P Kirton, A Nazir, EM Gauger & BW Lovett. **Exact Dynamics of Nonadditive Environments in Non-Markovian Open Quantum Systems.** *PRX Quantum* 3(1), 010321 (2022)

G Rubino, LA Rozema, F Massa, M Araújo, M Zych, C Brukner & P Walther. **Experimental Entanglement of Temporal Orders.** *Quantum Information and Measurement (QIM) V: Quantum Technologies* Paper S3B.3, Part F165-QIM 2019, S3B.3 (2019)

Z Huang, SK Joshi, D Aktas, C Lupo, AO Quintavalle, N Venkatachalam, S Wengerowsky, M Lončarić, SP Neumann, B Liu, Ž Samec, L Kling, M Stipčević, R Ursin & JG Rarity. **Experimental implementation of secure anonymous protocols on an eight-user quantum key distribution network.** *Npj Quantum Information* 2022 8:1, 8(1), 1–7 (2022)

H Pashayan, O Reardon-Smith, K Korzekwa & SD Bartlett. **Fast Estimation of Outcome Probabilities for Quantum Circuits.** *PRX Quantum* 3(2), 020361 (2022)

DT Stephen, A Dua, J Garre-Rubio, DJ Williamson & M Hermele. **Fractionalization of subsystem symmetries in two dimensions.** *Physical Review B* 106(8), 085104 (2022)

CA Thomson, ME Tobar & M Goryachev. **Generation of bimodal solitons in a sapphire whispering-gallery-mode maser at millikelvin temperatures.** *Physical Review A* 105(3), 033511 (2022)

A Navarathna & WP Bowen. **Good vibrations for quantum computing.** *Nature Physics* 2022 18:7, 18(7), 736–738 (2022)

M Frembs, S Roberts, ET Campbell & SD Bartlett. **Hierarchies of resources for measurement-based quantum computation.** *New Journal of Physics* (2022)

S Singh, AS Darmawan, BJ Brown & S Puri. **High-fidelity magic-state preparation with a biased-noise architecture.** *Physical Review A* 105(5), 052410 (2022)

Z Huang, GK Brennen & Y Ouyang. **Imaging stars with quantum error correction.** (2022)

JT Spollard, LE Roberts, PG Sibley, CS Sambridge, DA Shaddock & K McKenzie. **Improved cross-talk suppression for digitally enhanced interferometry using Golay complementary pairs.** *Optics Letters* Vol. 47, Issue 7, Pp. 1570-1573, 47(7), 1570–1573 (2022)

DJ Armstrong, AB Stilgoe, TA Nieminen & H Rubinsztein-Dunlop. **Improved two-photon photopolymerisation and optical trapping with aberration-corrected structured light.** *Frontiers in Nanotechnology* 4, 75 (2022)

E García-Gallo, L Merson, K Kennon, S Kelly, BW Citarella, DV Fryer, S Shrapnel, J Lee, S Duque, YV Fuentes, V Balan, S Smith, J Wei, BP Gonçalves, CD Russell, L Sigfrid, A Dagens, PL Olliaro, J Baruch & LF Reyes. **ISARIC-COVID-19 dataset: A Prospective, Standardized, Global Dataset of Patients Hospitalized with COVID-19.** *Scientific Data* 2022 9:1, 9(1), 1–22 (2022)

PWF Forsyth, KS Hayward, LE Roberts, SF Cox, DA Shaddock & BJJ Slagmolen. **Large dynamic range, high resolution optical heterodyne readout for high velocity slip events.** *Review of Scientific Instruments* 93(6), 064503 (2022)

T Farrelly, DK Tuckett & TM Stace. **Local tensor-network codes.** *New Journal of Physics* 24(4), 043015 (2022)

LZ Cohen, IH Kim, SD Bartlett & BJ Brown. **Low-overhead fault-tolerant quantum computing using long-range connectivity.** *Science Advances* 8(20), 1717 (2022)

G Tobar, S Haine, F Costa & M Zych. **Mass-energy equivalence in gravitationally bound quantum states of the neutron.** *Physical Review A* 106(5), 052801 (2022)

JA Gross, BQ Baragiola, TM Stace & J Combes. **Master equations and quantum trajectories for squeezed wave packets.** *Physical Review A* 105(2), 023721 (2022)

S Borah, B Sarma, MJ Kewming, F Quijandría, GJ Milburn & J Twamley. **Measurement-based estimator scheme for continuous quantum error correction.** *Physical Review Research* 4(3), 033207 (2022)

C Meng, GA Brawley, S Khademi, EM Bridge, JS Bennett & WP Bowen. **Measurement-based preparation of multimode mechanical states.** *Science Advances* 8(21), 7585 (2022)

A Wade & K McKenzie. **Mirror coating-thermal-noise mitigation using multi-spatial-mode cavity readout.** *Physical Review A* 106(2), 023511 (2022)

LS Booth, EV Browne, NP Mauranyapin, LS Madsen, S Barfoot, A Mark & WP Bowen. **Modelling of the dynamic polarizability of macromolecules for single-molecule optical biosensing.** *Scientific Reports* 2022 12:1, 12(1), 1–15 (2022)

MT Johnsson, BQ Baragiola, T Volz & GK Brennen. **Modified coherence of quantum spins in a damped pure-dephasing model.** *Physical Review B* 105(9), 094308 (2022)

L Sementilli, E Romero & WP Bowen. **Nanomechanical Dissipation and Strain Engineering.** *Advanced Functional Materials* 32(3), 2105247 (2022)

M Bagherimehrab, YR Sanders, DW Berry, GK Brennen & BC Sanders. **Nearly Optimal Quantum Algorithm for Generating the Ground State of a Free Quantum Field Theory.** *PRX Quantum* 3(2), 020364 (2022)

TR Scruby, DE Browne, P Webster & M Vasmer. **Numerical Implementation of Just-In-Time Decoding in Novel Lattice Slices Through the Three-Dimensional Surface Code.** *Quantum* 6, 721 (2022)

D Burgarth, P Facchi, G Gramegna & K Yuasa. **One bound to rule them all: from Adiabatic to Zeno.** *Quantum* 6, 737 (2022)

DR Gozzard, R Craine, D Hickey, A Martin, W Shen & B Sones. **Optical couplers and step-index fibers fabricated using FDM 3D printers.** *Optics Letters* Vol. 47, Issue 19, Pp. 5124-5127, 47(19), 5124–5127. (2022)

U Zanforlin, C Lupo, PWR Connolly, P Kok, GS Buller & Z Huang. **Optical quantum super-resolution imaging and hypothesis testing.** *Nature Communications* 2022 13:1, 13(1), 1–9 (2022)

T Farrelly, N Milicevic, RJ Harris, NA McMahon & TM Stace. **Parallel decoding of multiple logical qubits in tensor-network codes.** *Physical Review A* 105(5), 052446 (2022)

CGL Bøttcher, SP Harvey, S Fallahi, GC Gardner, MJ Manfra, U Vool, SD Bartlett & A Yacoby. **Parametric longitudinal coupling between a high-impedance superconducting resonator and a semiconductor quantum dot singlet-triplet spin qubit.** *Nature Communications* 2022 13:1, 13(1), 1–10 (2022)

T Hillmann, F Quijandría, AL Grimsmo & G Ferrini. **Performance of Teleportation-Based Error-Correction Circuits for Bosonic Codes with Noisy Measurements.** *PRX Quantum* 3(2), 020334 (2022)

ME Tobar, BT McAllister & M Goryachev. **Poynting vector controversy in axion modified electrodynamics.** *Physical Review D* 105(4), 045009 (2022)

CE Wood & M Zych. **Quantized mass-energy effects in an Unruh-DeWitt detector.** *Physical Review D* 106(2), 025012 (2022)

D Burgarth, J Borggaard & Z Zimborás. **Quantum distance to uncontrollability and quantum speed limits.** *Physical Review A* 105(4), 042402 (2022)

J Foo, CS Arabaci, M Zych & RB Mann. **Quantum Signatures of Black Hole Mass Superpositions.** *Physical Review Letters* 129(18), 181301 (2022)

A Khoshaman, W Vinci, B Denis, E Andriyash & MH Amin. **Quantum variational autoencoder.** *Quantum Science and Technology* 4(1), 014006 (2019)

W-H Zhou, MK Vijayan, X-W Wang, Y-H Lu, J Gao, Z-Q Jiao, R-J Ren, Y-J Chang, Z-S Shen, PP Rohde & X-M Jin. **Reducing circuit complexity in optical quantum computation using 3D architectures.** *Optics Express* Vol. 30, Issue 18, Pp. 32887-32894, 30(18), 32887–32894 (2022)

ML Watson, DL Brown, AB Stilgoe, JL Stow & H Rubinsztein-Dunlop. **Rotational optical tweezers for active microrheometry within living cells.** *Optica* Vol. 9, Issue 9, Pp. 1066-1072, 9(9), 1066–1072 (2022)

K Orfanakis, SK Rajendran, V Walther, T Volz, T Pohl & H Ohadi. **Rydberg exciton–polaritons in a Cu_2O microcavity.** *Nature Materials* 2022 21:7, 21(7), 767–772 (2022)

O Raii, F Mintert & D Burgarth. **Scalable quantum control and non-abelian anyon creation in a honeycomb lattice.** *Physical Review A* 106(6), 062401 (2022)

AS Bradley, J Clarke, TW Neely & BP Anderson. **Scaling dynamics of the ultra-cold Bose gas.** *Physical Review A* 106(5), 053316 (2021)

J Foo, RB Mann & M Zych. **Schrödinger's black hole cat.** (2022)

VV Flambaum, BT McAllister, IB Samsonov & ME Tobar. **Searching for scalar field dark matter using cavity resonators and capacitors.** *Physical Review D* 106(5), 055037 (2022)

TA Nieminen, ML Watson, VLY Loke, AB Stilgoe & H Rubinsztein-Dunlop. **Spin–orbit interaction in non-paraxial Gaussian beams and the spin-only measurement of optical torque.** *Journal of Optics* 24(12), 124001 (2022)

D Burgarth, P Facchi & R Hillier. **Stability and convergence of dynamical decoupling with finite amplitude controls.** *Journal of Mathematical Physics* 63(11), 112206 (2022)

J Baruch, A Rojek, C Kartsonaki, BKT Vijayaraghavan, BP Gonçalves, MG Pritchard, L Merson, J Dunning, M Hall, L Sigfrid, BW Citarella, S Murthy, TO Yeabah, P Olliaro, A Abbas, SA Abdukahil, NN Abdulkadir, R Abe, L Abel & D Zucman. **Symptom-based case definitions for COVID-19: Time and geographical variations for detection at hospital admission among 260,000 patients.** *Influenza and Other Respiratory Viruses* 16(6), 1040–1050 (2022)

J Foo, S Onoe, M Zych & TC Ralph. **Telefilters, telemirrors, and causality.** *Physical Review A* 105(3), 033711. (2022)

Z Degnan, X He, AG Frieiro, YP Sachkou, A Fedorov & P Jacobson. **Ternary metal oxide substrates for superconducting circuits.** *Materials for Quantum Technology* 2(2), 025004 (2022)

MA Webster, BJ Brown & SD Bartlett. **The XP Stabiliser Formalism: a Generalisation of the Pauli Stabiliser Formalism with Arbitrary Phases.** *Quantum* 6, 815 (2022)

MT Reeves, K Goddard-Lee, G Gauthier, OR Stockdale, H Salman, T Edmonds, X Yu, AS Bradley, M Baker, H Rubinsztein-Dunlop, MJ Davis & TW Neely. **Turbulent Relaxation to Equilibrium in a Two-Dimensional Quantum Vortex Gas.** *Physical Review X* 12(1), 011031 (2022)

DR Gozzard, LA Howard, BP Dix-Matthews, SFE Karpathakis, CT Gravestock & SW Schediwy. **Ultrastable Free-Space Laser Links for a Global Network of Optical Atomic Clocks.** *Physical Review Letters* 128(2), 020801 (2022)

A Hahn, D Burgarth & K Yuasa. **Unification of random dynamical decoupling and the quantum Zeno effect.** *New Journal of Physics* 24(6), 063027 (2022)

P Webster, M Vasmer, TR Scruby & SD Bartlett. **Universal fault-tolerant quantum computing with stabilizer codes.** *Physical Review Research* 4(1), 013092 (2022)

M Wainstein, S MacDonald, DV Fryer, K Young, V Balan, H Begum, A Burrell, BW Citarella, JP Cobb, S Kelly, K Kennon, J Lee, L Merson, S Murthy, A Nicho, MG Semple, S Strudwick, SA Webb, P Rossignol & S Shrapnel. **Use of an extended KDIGO definition to diagnose acute kidney injury in patients with COVID-19: A multinational study using the ISARIC–WHO clinical characterisation protocol.** *PLOS Medicine* 19(4), e1003969 (2022)

D Gribben, A Strathearn, GE Fux, P Kirton & BW Lovett. **Using the Environment to Understand non-Markovian Open Quantum Systems.** *Quantum* 6, 847 (2022)

Key performance indicators

	2022 TARGETS	2022 ACTUALS
RESEARCH OUTPUT AND SERVICE		
Peer-reviewed journal articles	70	96
High-impact publications (in the top 20% most cited papers in fields of physics)	10	17
International and national advisory boards in the research field of the Centre	3	10
Keynote and plenary addresses at international and national conferences	2	13
Editorial boards for international peer-reviewed journals in the research field of the Centre	3	12
Program committees for international and national conferences	8	24
Invited talks or papers at international meetings	15	48
Training courses held or offered by the Centre	10	19
Workshops or conferences held or offered by the Centre	5	6
PEOPLE AND TRAINING		
New postdoctoral researchers working on Centre research	4	11
New PhD students supervised by Centre researchers	8	19
New Master's students supervised by Centre researchers	2	2
New Honours students supervised by Centre researchers	10	2
New Associate Investigators	6	6
PhD completions	10	9
Master's completions	0	4
Honours completions	10	7
EQUS mentoring program participants	60	66

	2022 TARGETS	2022 ACTUALS
COMMUNICATION AND OUTREACH		
Talks open to the public	5	23
Talks, presentations or briefings to government	10	50
Talks, presentations or briefings to industry, business or other end-users	10	22
Training for STEM teachers	25 teachers	50 teachers
Public outreach activities	20	43
Industry engagement events	1	1
Media mentions and appearances	50	28
NEW COLLABORATIONS		
New industry collaborative relationships	3	7
New academic collaborative relationships	1	27
EQUITY AND DIVERSITY		
Female higher-degree research students	25%	24%
Female postdoctoral researchers	15%	16%
Female associate investigators	5%	16%
Female chief investigators	20%	18%
Female partner investigators	20%	18%
Female advisory committee members (AC & SAC)	20%	27%
Centre EDI Training Sessions	1	2

Income and expenditure report

	2022 actuals
INCOME	
ARC Centre of Excellence grant	
ARC Centre of Excellence grant	$4,994,641
Administering and Collaborating Organisation contributions	
The University of Queensland	$538,160
The University of Sydney	$365,555
Macquarie University	$151,452
Macquarie University, scholarships[1]	
The University of Western Australia	$142,207
The Australian National University	$52,627
Partner Organisation contributions	
Defence Science and Technology Group (DSTG)	$100,000
University of Ulm[2]	$4,688
Other Contributions (InSTEM Sponsorship)	
ASTRO3D	$5,000
CIPPS	$5,000
CLEX	$5,000
CQC2T	$5,000
Exciton Science	$5,000
FLEET	$5,000
OzGrav	$5,000
TMOS	$5,000
Centre for COBOTICS	$2,500
Defence Science Technology Group (DSTG)	$10,000
Eventbrite (inSTEM Registrations)	$1,184
TOTAL INCOME	**$6,403,014**

	2022 actuals
EXPENSES	
Salaries	$3,400,795
PhD support	$216,758
Equipment	$1,462,322
Travel and visitor support	$350,347
Administration, management and other	$160,663
Education, outreach and communications	$146,701
Workshops and conferences	$317,709
TOTAL EXPENSES	**$6,055,295**
ANNUAL SURPLUS	**$347,719**

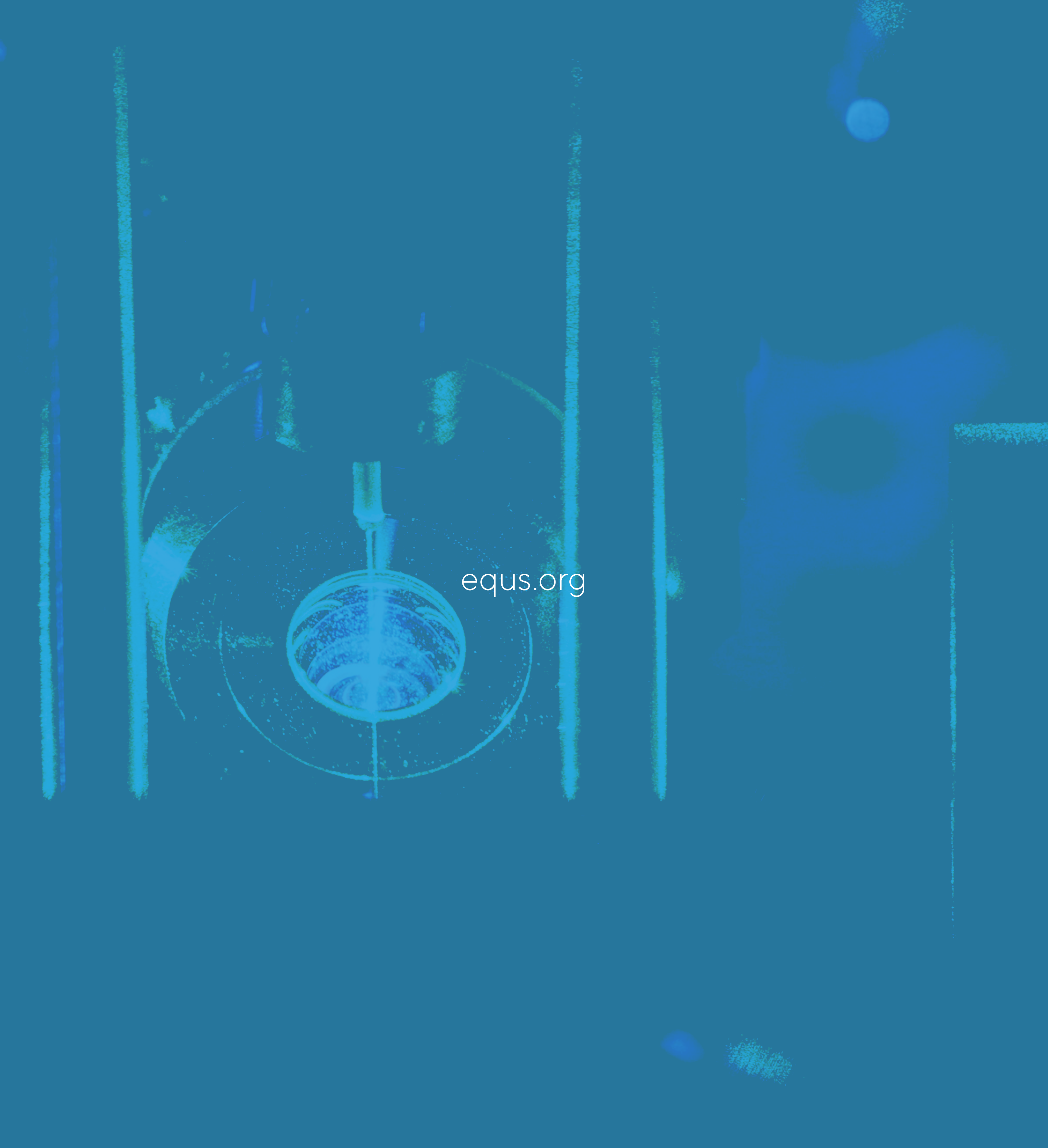
Notes:

1 As at 31 December 2022 Macquarie University funds of $167,513 are recorded in a separate general ledger account and held at Macquarie University. In accordance with the ARC CE EQUS Participants Agreement the funds are available to EQUS Chief Investigators for international tuition fee scholarships. The amount of $167,513 is represented by cash contributions for the five years to 31 December 2022 of $417,967 less scholarships expense to the reporting date of $250,454.

2 Cash held at University of Ulm and expended against consumables.

AUSTRALIAN RESEARCH COUNCIL
CENTRE OF EXCELLENCE FOR
ENGINEERED QUANTUM SYSTEMS

+61 7 3346 7429
comms@equs.org
equs.org
@ARC_EQUS


equs.org