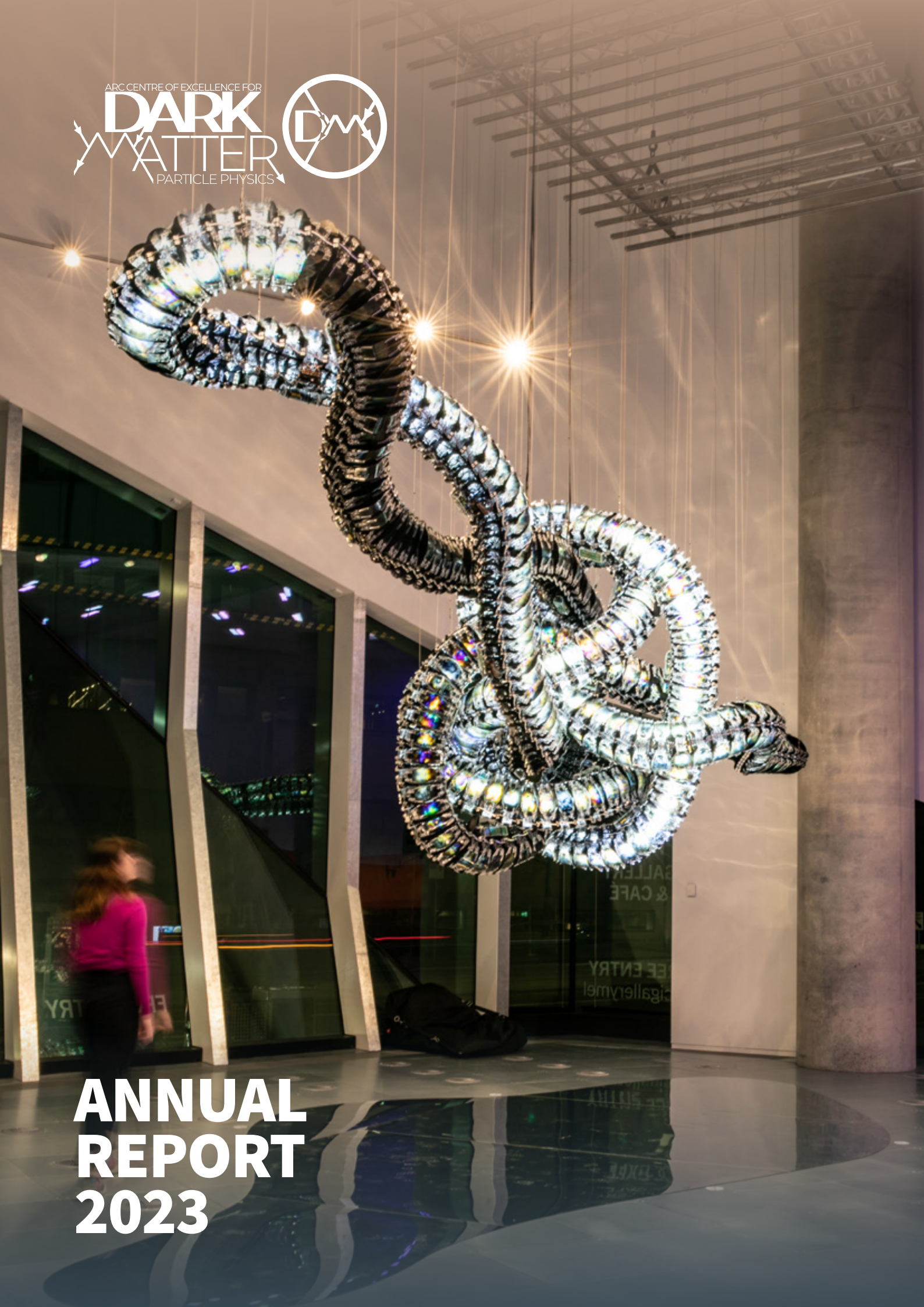
ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS



ANNUAL REPORT 2023

acknowledgements

The ARC Centre of Excellence for Dark Matter Particle Physics (Dark Matter Centre) acknowledges the support of the Australian Research Council.

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

Australian Government
Australian Research Council

COLLABORATING PARTNERS

The University of Adelaide
Australian National University
The University of Melbourne
Swinburne University of Technology
The University of Sydney
The University of Western Australia
Australian Government ANSTO
Australian Government Department of Defence

INTERNATIONAL PARTNERS

INFN
Caltech
MIT
Stockholm University
HZDR Helmholtz Zentrum Dresden Rossendorf
The University Of Sheffield.
University of Washington
Uni Freiburg
UvA Universiteit van Amsterdam

The Dark Matter Centre acknowledges the Traditional Custodians of the lands and waters on which we work. We acknowledge and pay respects to the Elders and Traditional Owners of the land on which our Australian nodes stand. We pay our respects to their Elders, past, present, and emerging.

The Dark Matter Centre acknowledges **AVGD** for design services provided for the production of this Annual Report.

Cover photo: Installation view of Chroma V by Yunchul Kim in Science Gallery Melbourne's DARK MATTERS. Photography: Alan Weedon, 2023.

advisory board chair message

In 2023 the ARC Centre of Excellence for Dark Matter Particle Physics continued to mature into its role as a Centre of Excellence. With its collaborations producing high levels of research, its development of the next generation of physicists and engineers, its outreach and education programs, it is being recognised internationally as a key player in the search for dark matter.

I am pleased to see that there have been many opportunities for Centre members to collaborate with each other and also with international colleagues throughout the year, with travel almost back to pre-pandemic levels. There was a good range of plenary talks given by the Centre's researchers at various conferences, sharing the research of the Centre internationally.

I was fortunate to attend one of the Chief Investigator meetings in November in Melbourne where almost all the participants were able to be there in person and I led some robust discussions around the future directions of the Centre. The meeting emphasised the importance of the team getting together and being prepared to discuss key issues.

Outreach and education have always been a strong part of the Centre's portfolio of activities and this was represented by another successful National Quantum & Dark Matter Road Trip, additions to the list of regional partner schools, progress in the education space, and the hugely successful DARK MATTERS exhibition at the Science Gallery Melbourne, in collaboration with Arts at CERN, was a real highlight, featuring a true merging of arts and science.

The students and Early Career Researchers in the Centre hit their stride in 2023, with a successful ECR workshop, funding provided to a range of fantastic initiatives in the Special Initiatives ECR funding round, and training and development opportunities including the IdeaSquare terraforming activity at CERN. This energetic and talented group are well on their way to becoming the scientific leaders of the future.

The research theme section of this report provides a comprehensive overview of the research undertaken across the Centre in 2023 and I urge you to read about all the fantastic work of the students and researchers. SABRE South was a strong focus of the Direct Detection program in 2023 and its delivery remains one of the most important research projects of the Centre.

The ARC Mid-Term Review happening in early 2024 presents an opportunity to reflect on what we've achieved so far as a Centre and map out the ways that we can improve in the next few years. I will be providing my full support of the Centre during this process and will work through the Advisory Board to provide guidance on the implementation of the panel's recommendations.

I have enjoyed reading this report and congratulate everyone on their many achievements in the various activities of the Centre including research, outreach and translation. I look forward to what is to come in 2024.

Aidan Byrne

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www. centredarkmatter.org

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@CDMPP.org

ARC Centre of Excellence for Dark Matter Particle Physics

@arc_cdmpp

acronyms and abbreviations

Institutions:

ANSTO: Australian Nuclear Science and Technology Organisation

ANU: Australian National University

Caltech: California Institute of Technology

DSTG: Defence Science and Technology Group

HZDR: Helmholtz-Zentrum Dresden-Rossendorf

INFN: Istituto Nazionale di Fisica Nucleare (Italian National Institute for Nuclear Physics)

LNGS: Laboratori Nazionali del Gran Sasso

MIT: Massachusetts Institute of Technology

SUT: Swinburne University of Technology

Stockholm: University of Stockholm

UoA: University of Adelaide

UAmst: University of Amsterdam

UFreib: University of Freiburg

UoM: University of Melbourne

UoS: University of Sydney

USheff: University of Sheffield

UWA: University of Western Australia

UWash: University of Washington

General:

AI: Associate Investigator

CDM: Centre for Dark Matter (abbrev for ARC Centre of Excellence for Dark Matter Particle Physics)

Centre: ARC Centre of Excellence for Dark Matter Particle Physics

CERN: European Organization for Nuclear Research

CI: Chief Investigator

COO: Chief Operating Officer

ECR: Early Career Researcher

EDI: Equity, Diversity and Inclusion

KPIs: Key Performance Indicators

LHC: Large Hadron Collider

ORGAN: Oscillating Resonant Group AxioN experiment

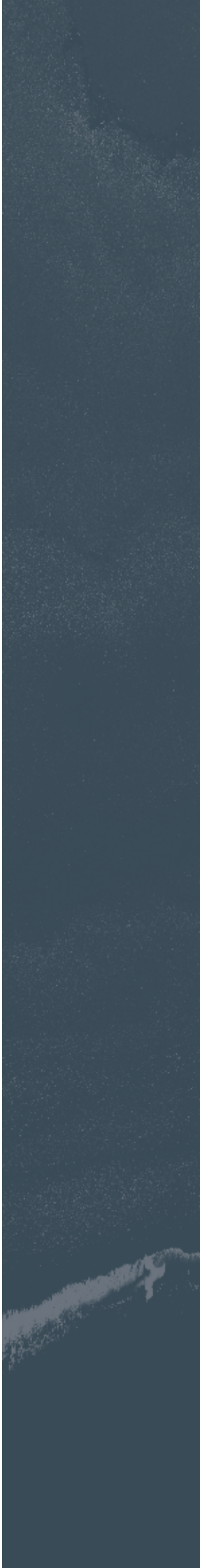
PI: Partner Investigator

Postdoc: Postdoctoral Researcher or Postdoctoral Research Associate

SABRE: Sodium Iodide with Active Background Rejection Experiment

SUPL: Stawell Underground Physics Laboratory

XLZD Consortium: Xenon, Lux-Zeplin, Darwin



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director's message

In 2023, the ARC Centre of Excellence for Dark Matter Particle Physics saw significant progress, marked by increased opportunities for Centre members to collaborate and notable advancements in our research on dark matter.

Discovering the nature of dark matter is a 'big science' question and it requires a collaborative effort across institutions to do what no single person or group could achieve alone. A successful collaboration hinges on effective communication and the cultivation of a safe, inclusive environment for all Centre members. Embracing diverse perspectives, problem-solving approaches, and cultural backgrounds is vital, as they serve as valuable assets that we must nurture and celebrate.

For International Women's Day, I was asked how I have been able to #inspireinclusion. Our Centre has taken proactive steps to promote gender equity by seeding women-only academic positions in physics, such as Irene Bolognino' s appointment in Adelaide in 2023. These positive actions contribute to increasing the representation of women in our discipline. There is still much work to be done to address gender imbalance and support underrepresented groups. We can all play a role in fostering inclusivity by challenging gender stereotypes, speaking out against discrimination and unacceptable behaviour, highlighting bias, and actively promoting inclusion.

Role models play an important part in inspiring and empowering individuals, particularly in underrepresented fields like physics. By showcasing women at the forefront of science and normalising the presence of women in physics, we help break down barriers and encourage more diversity in STEM. It is often said that you cannot aspire to be what you cannot see, which is why highlighting the achievements of female Chief Investigators (CIs) in the media and promoting their contributions to science is important. Additionally, our Centre members actively engaged in outreach activities throughout the year, further promoting diversity and inclusion in STEM.

In June, I had the privilege of visiting CERN, where I had the opportunity to witness our students' presentations during the two-week pilot terraforming program at IdeaSquare. I was thoroughly impressed by the quality of their presentations that were engaging, detailed, and comprehensive, addressing complex issues with professionalism. Their creatively produced videos added a touch of humour to the proceedings.

Five of our PhD students participated in this program, working alongside people from diverse backgrounds in multidisciplinary teams. Together, they explored the intriguing question: What if humanity could start everything from scratch – what would we do differently?

I was pleased to see the practical application of research originating from our dark matter research. Alan Duffy's presentation at the AusIMM Mine Waste and Tailings Conference 2023 showcased how a new muon detection platform can be used to scan large structures at BHP's Prominent Hill mine site. Developed by mDetect, a start-up created by Centre members, this platform also utilises software developed by the SABRE South project.

Our students, ECRs and academics had many opportunities to attend local and international conferences and collaborate with international colleagues. The Centre has gained significant exposure, with its members delivering plenary, keynote, and parallel talks at numerous international conferences, covering a wide range of research themes and topics.

Our research program is gaining strength, driven by the initiative of our ECRs and fuelled by fresh ideas across all research themes. A notable achievement of our Centre ECRs was securing substantial ARC LIEF funding for CELLAR, an underground cryogenic facility located in SUPL. This initiative marks a new direction in dark matter searches within the Centre. Particularly pleasing, the project is led by ECRs, highlighting their talent and leadership within our research community. The ambitious SABRE South program continues to make steady progress, with the installation of the large muon system at SUPL scheduled for January 2024. Our world-class research program and associated publications are presented later in this report.

The initial round of funding from DSTG has been allocated, and all approved projects provide support to ECRs. Additionally, we have completed the first round of Special Initiatives funding specifically designated for ECRs, with six projects receiving funding across a broad spectrum of research areas and Centre portfolios.

The DARK MATTERS exhibition, a collaborative effort between Science Gallery Melbourne, Arts at CERN, and our Centre, delved into the fundamental essence of dark matter, conveying to the community the sense of wonder and mystery that drives our research. The exhibition was exceptionally successful, drawing a record number of visitors (about 40,000) to explore the works created by artists from all over the world, some of whom collaborated with Centre researchers.

The highly popular National Quantum & Dark Matter Road Trip, organised in collaboration with EQUS, was also very successful this year. The road trip covered an impressive 4,640 km, hosting events in 24 cities and towns. This initiative provides our researchers with a valuable opportunity to engage with regional Australia, inspire a new generation of physicists, and foster connections among Centre members.

I am immensely proud of our dynamic, enthusiastic, and driven cohort of students and ECRs, a sentiment that was palpable at both the ECR workshop and the Annual Workshop. The Annual Workshop also exuded a notably positive atmosphere, where we introduced innovative initiatives in the diversity sphere, many of them spearheaded by our ECRs. The cultural challenge brought a sense of camaraderie and excitement to the workshop. I appreciate the hard work that has gone into all these amazing events, and the goodwill of Centre members, particularly the ECRs, who generously volunteered their time to ensure their success. Witnessing our Centre come together in such a cohesive manner, surpassing individual contributions to collectively inspire new generations and engage the wider public, fills me with pride.

For more detailed insights into the Centre's progress and accomplishments throughout 2023, I encourage you to delve into the comprehensive report. As we approach the Centre's Mid-Term Review and the second phase of our journey, I am eager to continue enhancing our activities and making even greater strides in 2024.

I look forward to the year ahead,

Elisabetta Barberio

strategy

The ARC Centre of Excellence for Dark Matter Particle Physics brings together experts from across Australia and internationally to unlock the secrets of dark matter, while also fostering the science and engineering leaders of the future. These objectives will be realised in the following ways in 2024:

1. Research Program – To transform our knowledge of the universe

- Undertake research to advance the Centre's theoretical and experimental goals (for full details see Research Program sections and Research Activity Plan for 2024)
- Provide the legacy of a world-class underground physics facility that takes full advantage of Australia's southern hemisphere location
- Install and commission SABRE South in SUPL
- Develop new theoretical ideas for what dark matter can be, and the theory underpinning novel strategies to test those ideas with laboratory experiments or astrophysical observations
- Extend the dark matter discovery potential of ORGAN and continue taking data
- Expand the dark matter searches with the ATLAS experiment at the CERN LHC and prepare equipment to upgrade the experiment for the High-Luminosity LHC era

2. Outreach and Education – Inspire a new generation of scientists and engineers

- Education program with special emphasis on regional schools and expanding the school partners and outreach and education activities that promote diversity and inclusion
- Build international collaborations in Outreach through IPPOG and overseas connections
- Run National Quantum and Dark Matter Road Trip during National Science Week
- Continue collaboration with Science Gallery Melbourne and associated activities
- Engage with educators through professional development and teacher associations

3. Foster and develop the emerging scientific leaders of the future

- Run second round of Special Initiatives funding for students and ECRs
- Provide diverse training opportunities to Centre members
- Renew CoE Mentorloop platform membership and actively promote mentoring opportunities and training for students and ECRs
- Provide leadership opportunities for ECRs across the operations and research activities of the Centre

4. Develop new ideas, technologies and facilities for the next generation of dark matter experiments

- New theoretical ideas and vigorous R&D and prototyping for future dark matter experiments based in Australia and overseas including liquid Xenon detectors (XLZD/DARWIN), gas detectors for directional detection (CYGNUS-Oz), Axion detectors, superfluid, optomechanics and quantum technologies (see Research Program sections and Research Activity Plan for 2024)
- Develop new low background screening techniques for dark matter direct detection

5. Translate the new technologies to industry, defence and the public

- Provide training in innovative thinking to help translate discoveries into social and economic benefits
- Run the second round of funding for Centre members to apply for DST Group funding

6. and do so in a cohesive national and international environment with a strong EDI program

- Strengthen national and international collaborations by continuing and expanding common projects and personnel exchanges with our partners
- Review and implement the Equity, Diversity and Inclusion action plan
- Roll out positive changes to the working environments for Centre members
- Update EDI resources on the Centre website
- Run training for EDI committee and Centre members

timeline

2019

28 August 2019
Centre awarded

2020

14 August 2020
Centre commenced

2021

22 September 2021
Centre launch

2022

2023

2024

March 2024
Current day

11 June 2024
ARC Mid-term review site visit

2025

2026

2027

13 August 2027
Centre end date

governance

The Centre is hosted by the University of Melbourne, the largest research university in Australia. An overview of the management structure is provided below and is designed to support a coordinated program of research and activities to deliver the Centre's objectives.

Operation and Management

The Centre Director, Chief Investigator Elisabetta Barberio, is responsible for the overall strategic direction and operation of the Centre, with advice from the relevant Centre committees.

The Director is supported by the Chief Operating Officer (COO), Anita Vecchies, who oversees the day-to-day operational matters of the Centre and also provides strategic advice to the Director. The COO oversees the Central Operations Team of professional staff who are responsible for the Centre's financial management, human resources, outreach and education programs, event management, media and communications and preparation of annual reports and budget documents. Internal communications include fortnightly meetings and an enewsletter.

The Centre has six nodes, the University of Adelaide, the Australian National University, the University of Melbourne, Swinburne University of Technology, the University of Sydney and the University of Western Australia. Each node has a Node Manager, who is a member of the Centre's Executive Committee. The Central Operations Team works in collaboration with the node administrative team to ensure a coherent and coordinated approach to Centre-wide activities, financial management and reporting requirements.

Executive Committee

The Dark Matter Centre Executive Committee manages node interaction and cooperation and Centre resources. It also oversees the activities of the various portfolios with a particular interest in the sustantial gender equity, education, and outreach activities conducted by the Centre.

Led by the Centre Director, the Centre Executive Committee comprises Node Managers and the COO. One postdoctoral researcher from the Early Career Researcher Committee also attends the Executive Committee but does not have voting rights.

The Executive Committee is comprised of:

- Chair - Elisabetta Barberio (Director)
- Cedric Simenel (Deputy Director)
- Anthony Williams (Deputy Director and node leader, UoA)
- Celine Boehm (Node leader, UoS)
- Darren Croton (Node leader, SUT)
- Andrew Stuchbery (Node leader, ANU)
- Michael Tobar (Node leader, UWA)
- Raymond Volkas (Node leader, UoM)
- Anita Vecchies (COO)
- Jayden Newstead (ECR representative UoM)

Research Committee

The role of the Research Committee is to oversee research at the Centre. It is responsible for the Centre's scientific goals and performance indicators, and for building and maintaining the cross-node scientific research collaborations. The four Research Programs each have one Research Program Leader, with the exception of the Direct Detection Program which has two co-leaders due to the number and variety of experiments to be conducted. The Research Committee comprises the Centre Director, the Deputy Director and the Research Program Leaders.

The Research Program Leaders are drawn from a mixture of senior and midcareer researchers, as part of our ongoing succession planning strategy. During the course of the Centre it is foreseen that junior researchers exhibiting strong research leadership are mentored to gradually replace the more senior of the program leaders.

The Research Committee is comprised of:

- Chair - Elisabetta Barberio (Director)
- Cedric Simenel (Deputy Director)
- Anthony Williams (Deputy Director)
- Phillip Urquijo and Michael Tobar (Direct Detection Leaders)
- Steve Tims (Precision Metrology Leader)
- Nicole Bell (Theory Leader)
- Paul Jackson (LHC Leader)
- Ellen Sirks (ECR representative, postdoc - UoS)
- Ferdos Dastgiri (ECR representative, PhD student - ANU)

*correct as at 31 December 2023

Advisory Board

The Centre's Advisory Board assists the Centre Director by contributing to the development of strategies and vision for the future and by serving as a vehicle for creating better linkages between academia, industry, and government.

The Advisory Board is comprised of:

- Chair – Aidan Byrne (University of Queensland Provost, Past CEO of the Australian Research Council)
- Sue Barrel (former Chief Scientist at the Bureau of Meteorology)
- Campbell Olsen (CEO of Arete Capital Partners; major shareholder of Stawell Gold Mine)
- Len Sciacca (Enterprise Professor, Defence Science & Technology, University of Melbourne)
- Robyn Williams (ABC science journalist and presenter)
- Justin Zobel (Pro Vice-Chancellor, Graduate & International Research, Chancellery (Research and Enterprise), the University of Melbourne)

International Scientific Advisory Committee (ISAC)

The role of the International Scientific Advisory Committee is to mentor the Director, the Executive Committee and the Research Management Committee on the scientific program and directions of the Centre. It provides advice to the Director on important emerging new directions in the field of the Centre and on the highest priorities for the allocation of Special Initiatives funds each year.

The International Scientific Advisory Committee is comprised of:

- Chair – Nigel Smith (Director, SNOLAB)
- Tom Browder (University of Hawaii, USA Spokesperson of Belle II)
- Stephen Buckman (Australian National University)
- Aaron Chou (Leader of axion dark matter group at Fermilab, USA)
- Priscilla Cushman (University of Minnesota; Spokesperson of SuperCDMS-SNOLAB)
- Dan Hooper (University of Chicago)
- Ian Shipsey (Head of Particle Physics at Oxford University, UK)

Equity, Diversity and Inclusion (EDI) Committee

The role of the EDI Committee is to "PROCLAIM":

P: Propose EDI targeted initiatives such as seminars and fellowships

R: Report on EDI activities of the Centre for the annual report

O: Organise EDI events such as training and dedicated workshops

C: Communicate through the website and presentations at Centre events

L: Listen and be a point of contact

A: Advocate EDI best practices via outreach and social media

I: Identify EDI challenges in the Centre and the Dark Matter scientific community

M: Monitor the evolution with respect to the KPI of the Centre

The Equity, Diversity and Inclusion Committee is comprised of:

- Chair – Martin White (UoA)
- Deputy Chair – Jade McKenzie (UoM)
- Emily Filmer (UoA)
- Michaela Froehlich (ANU)
- Teresa Früth (UoS)
- Renee Key (SUT)
- Harish Potti (UoA)
- Zuzana Slavkovska (ANU)
- Michael Tobar (UWA)
- Phillip Urquijo (UoM)
- Yi Yi Zhong (ANU)

Mentoring & Careers Committee

Established to coordinate mentoring and training opportunities for early and mid-career researchers in the Centre, the Mentoring & Careers Committee is comprised of:

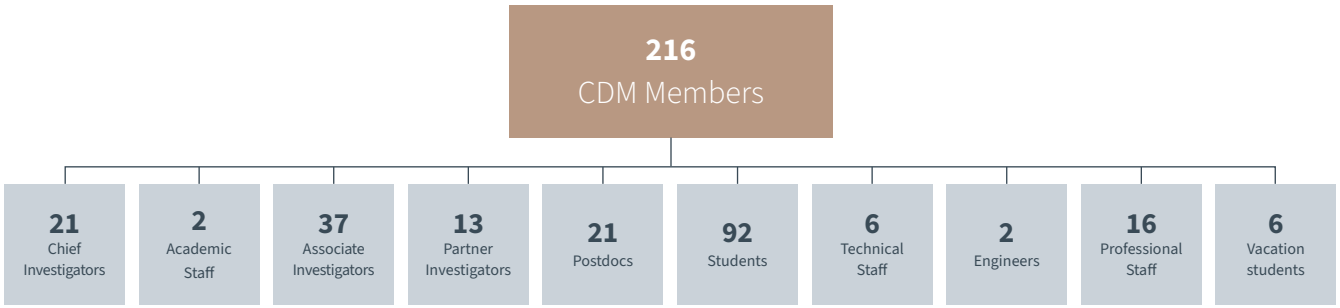
- Chair – Darren Croton (SUT)
- Deputy Chair - Michaela Froehlich (ANU)
- Irene Bolognino (UoA)
- Maxim Goryachev (UWA)
- Chiara (Maria) Lisotti (UoS)
- Jayden Newstead (UoM)

Early Career Researcher Committee

Established in order to allow Early Career Researchers (ECRs) to provide input into the Centre, the ECR committee is elected by the Centre's ECRs and is reviewed annually. The Committee members sit in on the Executive and Research Committees (as outlined above), help coordinate activities targeted to ECRs including the annual ECR workshop, provide regular updates to key committees/groups of the Centre and also represent their peers by seeking their input via surveys and other methods of communication. In 2023 the members were:

- Jayden Newstead (UoM)
- Ellen Sirks (UoS)
- Ferdos Dastgiri (ANU)

centre membership snapshot



These numbers include people were Centre members during 2023. Members will be counted in in multiple categories if their role in the Centre changed during the year.

centre members

The following people were Centre members during 2023. Members may appear in multiple categories if their role in the Centre changed during the year.

Director

Elisabetta Barberio (UoM)

Chief Investigators

Elisabetta Barberio (UoM)
Nicole Bell (UoM)
Celine Boehm (UoS)
Darren Croton (SUT)
Matthew Dolan (UoM)
Alan Duffy (SUT)
Maxim Goryachev (UWA)
Gary Hill (UoA)
Paul Jackson (UoA)
Greg Lane (ANU)
Jeremy Mould (SUT)
Cedric Simenel (ANU)
Andrew Stuchbery (ANU)
Geoffrey Taylor (UoM)
Steve Tims (ANU)
Anthony Thomas (UoA)
Michael Tobar (UWA)
Phillip Urquijo (UoM)
Raymond Volkas (UoM)
Martin White (UoA)
Anthony Williams (UoA)

Academic Staff

Irene Bolognino (UoA)
Theresa Früth (UoS)

Associate Investigators

Paul Altin (ANU)
Laura Baudis (University of Zurich)
Geoffrey Brooks (SUT)
Ben Buchler (ANU)
Frank Calaprice (Princeton)
Zhenwei Cao (SUT)
Peter Cox (UoM)
Darren Croton (SUT)
Sara Diglio (CNRS France)
Caterina Doglioni (CNRS France)
Zengwei Ge (SICCAS)
Eugene Ivanov (UWA)
Ayse Kizilersu (UoA)
Dominik Koll (ANU and HZDR)
Shanti Krishnan (SUT)
Grace Lawrence (UCL)
Justin Leontini (SUT)
Ian McArthur (UWA)
Victoria Millar (UoM)
Francesco Nuti (UoM)
Ciaran O'Hare (UoS)
Chris Power (UWA)
Peter Quinn (UWA)
Pat Rajeev (SUT)
Marc Schumann (Ufreib)
Edward Taylor (SUT)
Andrea Thamm (UoM)
Christine Thong (SUT)
Claudia Tomei (INFN Roma)
Marurizio Toscano (UoM)
Jan Van Driel (UoM)
Christian Weiser (Ufreib)
Yajing Xing (IMT Atlantique)
Shihai Yue (SICCAS)
Cindy Zhao (UWA)
Yong Zhu (SICCAS)
Madeleine Zurowski (University of Toronto)

Partner Investigators

Gianfranco Bertone (UAmst)
Marcella Diemoz (INFN)
Richard Garrett (ANSTO)
Philip Hopkins (Caltech)
Michael Hotchkis (ANSTO)
Aldo Ianni (INFN)
Karl Jakobs (UFreib)
Damian Marinaro (DSTG)
Gray Rybka (UWash)
Tracy Slatyer (MIT)
Neil Spooner (USheff)
Anton Wallner (HZDR)
Frank Wilczek (Stockholm)

Postdoctoral Researchers (Funded)

Michael Baker (UoM)
Lindsey Bignell (ANU)
Irene Bolognino (UoA)
Jeremy Bourhill (UWA)
Giorgio Busoni (ANU)
Graeme Flower (UWA)
Michaela Froehlich (ANU)
Matthew Gerathy (UoM)
Robert James (UoM)
Ben McAllister (UWA/SUT)
Peter McNamara (ANU)
William Melbourne (UoM)
Robert Mostoghiu Paun (SUT)
Jayden Newstead (UoM)
Francesco Nuti (UoM)
Harish Potti (UoA)
Federico Scutti (SUT)
Dipan Sengupta (UoA)
Ellen Sirks (UoS)
Zuzana Slavkovska (ANU)
Xuan-Gong Wang (UoA)

Postdoctoral Researchers (Affiliated)

Rebecca Allen (SUT)
Adam Batten (SUT)
James Webb (UoM)
Alexander Woodcock (UoA)

Students

PhD

Raghda Abdel Khaleq (ANU)
Ramtin Amintaheri (UoS)
Victoria Bashu (ANU)
William Campbell (UWA)
Isabel Carr (UoM)
Ferdos Dastgiri (ANU)
Aman Desai (UoA)
Mitchell Dixon (SUT)
Matthew Fewell (UoA)
Emily Filmer (UoA)
Gangyong Fu (UoM)
James Gallagher (UoA)
Kenn Goh (UoA)
Charles Grant (UoA)
Matthew Green (UoA)
Minh Tan Ha (UoA)
Cameron Harris (UoA)
Elrina Hartman (UWA)
Maaz Hayat (UoM)
Fredrick Hiskens (UoM)
Liam Hockley (UoA)
Tyler Hughes (SUT)
Nicholas Hunt-Smith (UoA)
Wasif Husain (UoA)
Vanshika Kansal (SUT)
Sharry Kapoor (UoS)
Renee Key (SUT)
Albert Kong (UoA)
Navneet Krishnan (ANU)
Judith Kull (UoA)
Grace Lawrence (SUT)
Kyle Leaver (UoA)
Nicholas Leerdam (UoA)
Jesper Leong (UoA)
Ben Li (UoS)
Maria Chiara Lisotti (UoS)
Bill Loizos (UoA)
Emily McDonald (UoM)
Lachlan McKie (UoA)
Peter McNamara (UoM)
William Melbourne (Dix) (UoM)
Michael Mews (UoM)
Giulia Milana (SUT)
Lachlan Milligan (UoM)
Markus Mosbech (UoS)
Shiryo Owa (UoA)
Hitarthi Pandya (UoA)
Thu Le Ha (Joni) Pham (UoM)
Aaron Quiskamp (UWA)
Alex Ritter (UoM)
Tristan Ruggeri (UoA)
Matthew Rumley (UoA)
Steven Samuels (UWA)
Iman Shaukat Ali (UoM)
Alexander (Alexei) Sopov (UoM)
Nathan Spinks (ANU)
Owen Stanley (UoM)
Catriona Thomson (UWA)
Edmund Ting (UoA)
Adam Ussing (SUT)
Peter Verwayan (UoS)
Michael Virgato (UoM)
Scott Williams (UoM)
Joshua Wood (UoM)
Yiyi Zhong (ANU)
Madeleine Zurowski (UoM)

MPhil

Nathanael Botten (UoA)
Meera Deshpande (UoA)
Joshua Gill (UoA)
Duncan McClay (UoA)
Georgy Sanamyan (UoA)
Sam Thompson (ANU)

Masters

Vishal Ayyagari (UoM)

Sen Sam Chhun (UoM)

Samarth Paraskum Gohel (UoM)

Jack Irving-Dinsdale (UoM)

Zhaoguo Meng (UoM)

Aphisit Nanphakdi (UoM)

Jeongoh Park (UoM)

Aspen Reardon (UoM)

Kieran Rule (UoM)

Neal Salan (SUT)

Nimrod Shapir (UoM)

Lucia Stockdale (UoM)

Michael Verde (UoM)

Jinyi Wu (UoM)

Ho Man Yim (UoM)

Honours

Robert Crew (UWA)

Michael Hatzon (UWA)

Haylea Purnell (UoA)

Emma Paterson (UWA)

Thomas Venville (SUT)

Technical Staff

Scott Collins (SUT)

Chris Kafer (ANU)

Padric McGee (UoA)

Daniel Tempra (ANU)

Raffaele Timpano (SUT)

Tom Tunningley (ANU)

Craig Webster (SUT)

Engineers

Tiziano Baroncelli (UoM)

Giulia Milana (SUT)

Professional Staff

Jackie Bondell (Education and Outreach Officer)

Linda Barbour (UWA Administration)

Emily Campbell (UoA Administration)

Sharon Johnson (UoA Administration)

Aline Lorieri (Administration Officer)

Jade McKenzie (Database Administrator)

Fleur Morrison (Communications and Media Officer)

Mary Odlum (Finance Manager)

Simon Parsons (SUT Administration)

Petra Rickman (ANU Administration)

Rebecca Rossi (Administration Officer)

Kathryn Ryan (UoM Administration)

Hannah Sainty (Communications and Media Officer – temporary backfill)

Silvana Santucci (UoA Administration)

Anita Vecchies (Chief Operating Officer)

Martina Velandi (Administration Officer)

Vacation students funded by the Centre

Ben Carew (UoS)

Matthew Green (UoA)

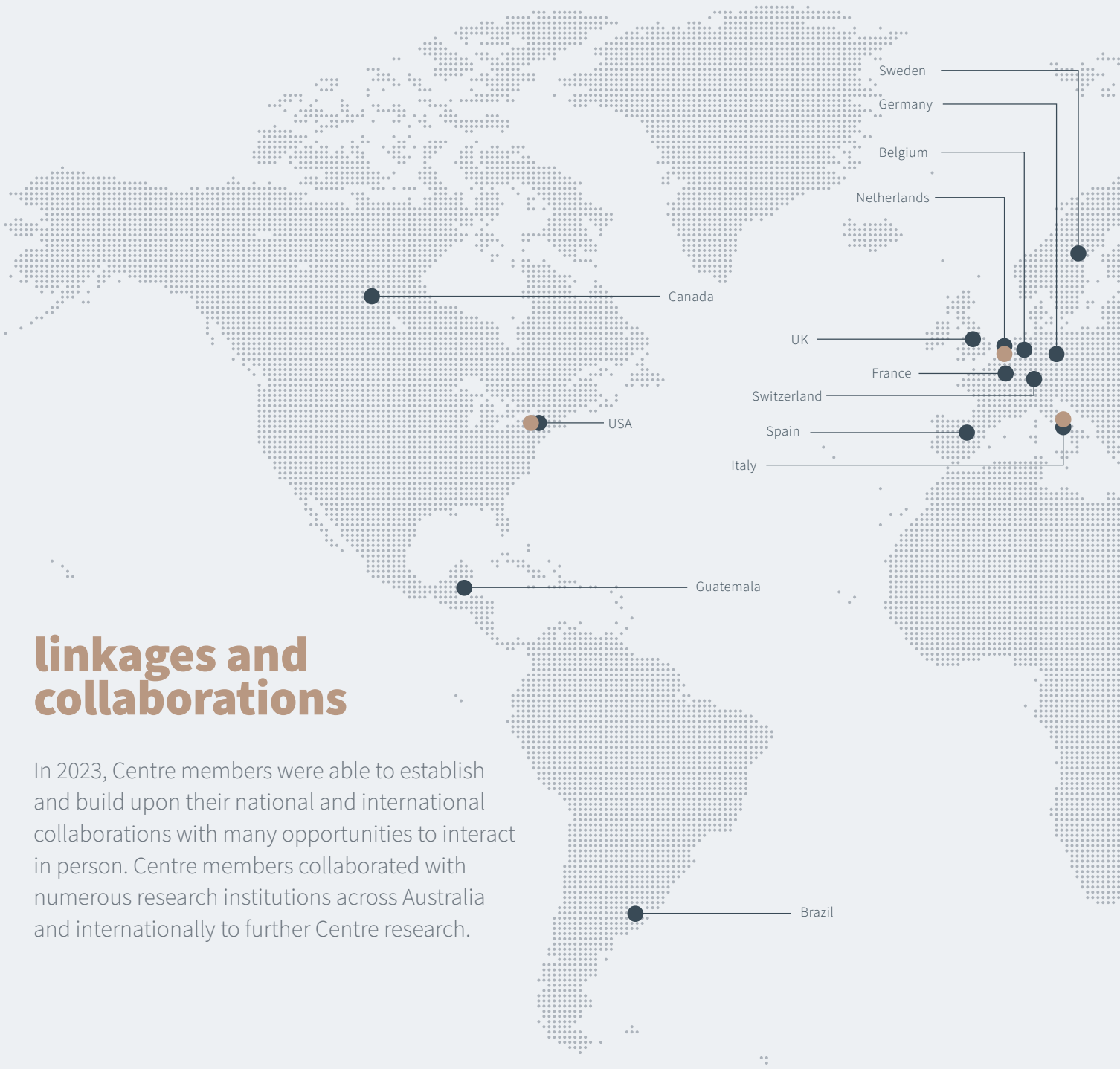
Mia Horsfall (SUT)

Hank Hua (UoM)

Ashley Johnson (UWA)

Isabelle Savill-Brown (ANU)

Centre members at the CDM Annual Workshop in Glenelg, SA

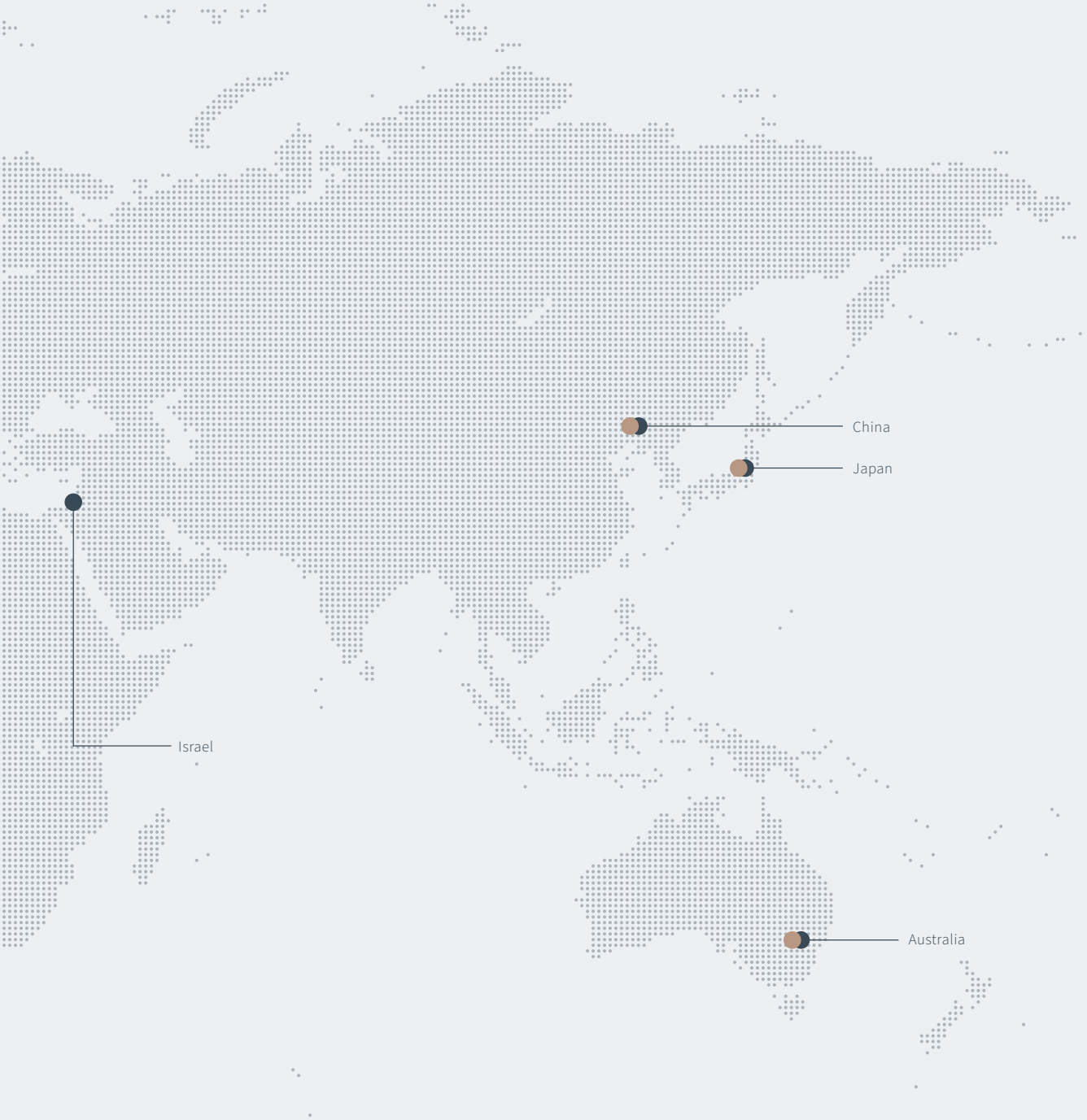


linkages and collaborations

In 2023, Centre members were able to establish and build upon their national and international collaborations with many opportunities to interact in person. Centre members collaborated with numerous research institutions across Australia and internationally to further Centre research.

Research Organisations

Argonne National Lab, USA
Australian Nuclear Science and Technology Organisation (ANSTO), Australia
Berkley University, USA
California Institute of Technology (Caltech), USA
California State University, Fresno, USA
Cambridge University, UK
CEA, Saclay, France
Centre national de la recherche scientifique (CNRS), France
CERN, Switzerland*
Cruzeiro do Sul, Brazil
Defence Science and Technology Group (DSTG), Australia
Deutsches Elektronen-Synchrotron DESY, Germany*
FEMTO-ST Institute, France
FermiLab National Accelerator Laboratory, USA
Grand Sasso Science Institute, Italy
Helmholtz-Zentrum Dresden Rossendorf (HZDR), Germany
Illinois Institute of Technology, USA
IMT Atlantique, France
Institute of High Energy Physics (IHEP), China*
Istituto Nazionale di Fisica Nucleare (INFN) Roma, Italy
Japanese High-Energy Accelerator Research Organization (KEK), Japan
Kobe University, Japan
KTH Stwockholm, Sweden
Laboratorio Nazionali del Gran Sasso, Italy
Langzhou University, China*
LANL, New Mexico, USA
Lawrence Livermore National Laboratory, USA
Los Alamos National Laboratory, USA
Lund University, Sweden
Massachusetts Institute of Technology (MIT), USA
Oxford University, UK
Pacific Northwest National Lab (PNNL), USA
Princeton University, USA
Queen Mary University of London, UK*
Sorbonne University, France*
Stockholm University, Sweden
Thomas Jefferson Lab (JLab), USA
TRIUMF, Canada
UCAS, China



UNESP, Brazil
University College London, UK*
Universita degli Studi di Milano, Italy
University of Amsterdam, Netherlands
University of California Irvine, USA
University of California, Los Angeles (UCLA), USA
University of California, Merced, USA
University of California, San Diego, USA
University of Florida, USA
University of Freiburg, Germany
University of Geneva, Switzerland
University of Göttingen, Germany
University of Hawaii, Manoa, USA
University of New Mexico, USA
University of Ottawa, Canada
University of Queensland, Australia
University of Sheffield, UK
University of South Florida – St Petersburg, USA
University of Tsukuba, Japan*
University of Toronto, Canada
University of Washington, USA
University of Zaragoza, Spain
UNSW, Australia
Washington University in St. Louis, USA
Yale University, USA

Industry linkages and collaborations

mDetect, Australia
RMD A Dynasil Company, USA
Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS), China
Stawell Gold Mines, Australia (through SUPL Ltd)
Swagelok, Australia and New Zealand
WT Partnership, Australia

Research Organisations
Industry Organisations

*New in 2023

partnership with DSTG and new projects

The Defence Science Technology Group (DSTG) develops innovative technologies that can be delivered by industry and transitioned into Defence capability and shapes innovation, science and technology within Defence across the nation.

As a partner of CDM, DSTG provides funding to support research that is of interest and relevance to Defence. This funding can support PhD students, internships and seed funding for pilot projects.

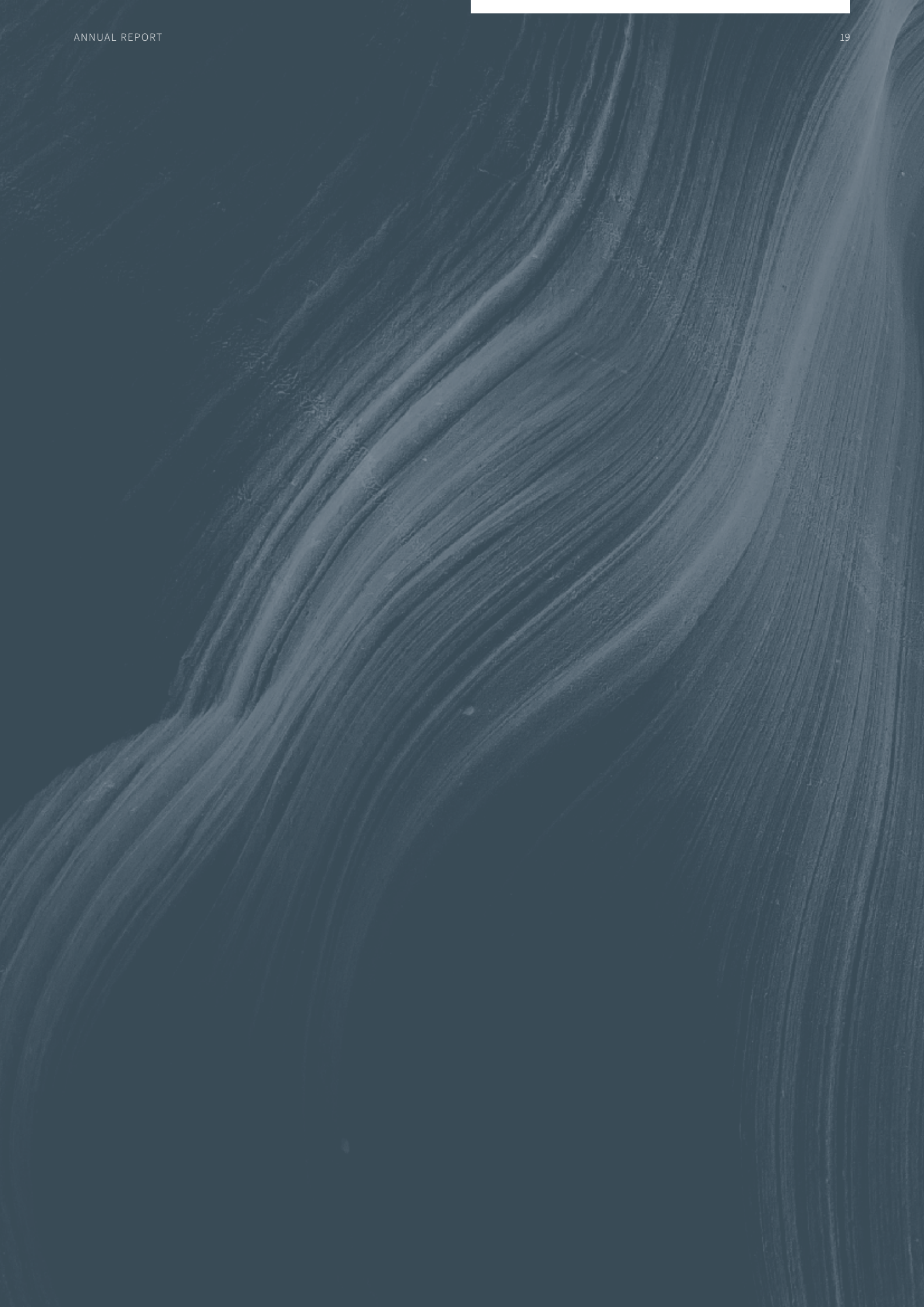
In 2023, CDM worked with DSTG to run the first open competitive call for applications and outlined an initial set of research priorities for Defence to which projects could be aligned.

The following projects were funded:

- Directional Neutron Detection using a Micropatterned Gas Time Projection Chamber – Lindsey Bignell and co-applicants from ANU.
- Monitoring nuclear reactor burnup via coherent scattering of neutrinos – Jayden Newstead and Alex Ritter from UoM
- Simulation of a nested neutron spectrometer – Phillip Urquijo and Lachlan Milligan from UoM

We were fortunate to have DSTG PI Damian Marinaro attend our Centre Annual Workshop and he delivered a talk which gave an overview of the Defence program and areas of Research and Development, some examples of R&D projects and outlined some radiological defence priority themes. He also talked about career opportunities within Defence for interested Centre members and provided some practical advice on the application process and key requirements.

A new set of priorities will be provided by DSTG for the next round of funding in the first half of 2024.



research program overview

The Centre's research program covers a wide mass range of potential dark matter candidates. CDM research is organised in four integrated Research Program areas:

Program 1: Direct Detection
(6 nodes, 40 researchers, 22 students)

The Centre's program covers a wide range of putative dark matter particle masses with Australian based experiments using above-ground precision quantum techniques at UWA and deep underground experiments in SUPL. The ORGAN experiment (UWA) is already producing data and the SABRE experiment (SUPL) is in the construction and installation phase. The Centre is producing new detection technologies to extend our dark matter searches via our robust R&D program.

Program 2: Precision Metrology
(2 nodes, 9 researchers, 5 students)

Selecting ultra-pure materials for the underground experiments requires the development of excellent ultra-low background radioactivity measurements. The Centre is leveraging ANU and ANSTO Accelerator Mass Spectrometry (AMS) to develop ultra-sensitive radioactivity measurement techniques for lead 210. UWA will develop ultra-precise measurements frequencies needed for sub eV dark matter searches.

Program 3: Large Hadron Collider Searches
(2 nodes, 8 researchers, 16 students)

Dark matter searches with Run3 data at the ATLAS experiment at the Large Hadron Collider at CERN (Switzerland) are expanding our experimental reach to dark matter masses and interactions in regions where the direct detection experiments have less sensitivity.

Program 4: Dark Matter Theory
(5 nodes, 17 researchers, 12 students)

The Centre's theory program unites and underpins the experimental programs. If dark matter is discovered, this program will develop the theoretical framework to describe dark matter particles and their interactions, incorporating dark matter into a new fundamental theory of nature. It informs and helps interpret the Centre's experimental results, drives future searches and fosters strong particle-astrophysics links.

direct detection research program

WIMP direct detection

SABRE South

Nodes involved: ANU, SUT, UoA, UoM, UoS

Chief investigators: E. Barberio, G. Hill, G. Lane, J. Mould, A. Stuchbery, G. Taylor, P. Urquijo, A Williams

Academic Staff: I. Bolognino, T. Früth

Postdocs: L. Bignell, M. Froehlich, M. Gerathy, R. James, P. McNamara, W. Melbourne, F. Nuti, F. Scutti, Z. Slavkovska

Engineers: T. Baroncelli, G. Milana

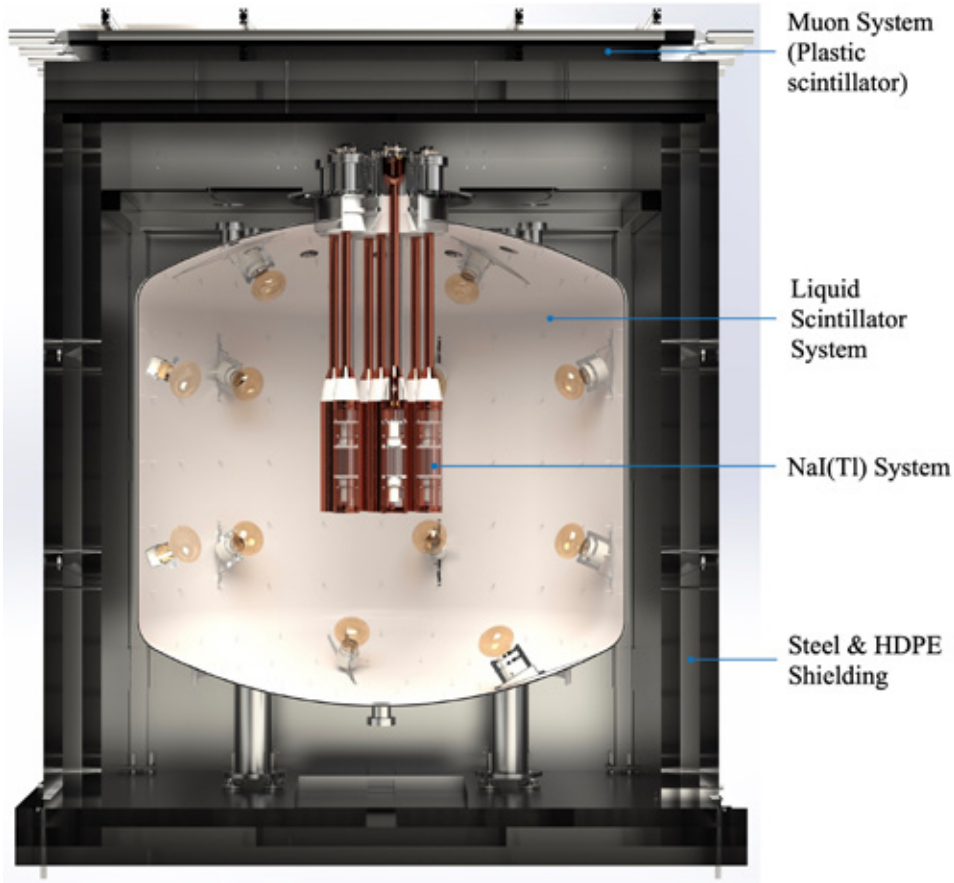
Associate Investigators: G. Brooks, C. O'Hare, M. Zurowski

Students: S. Chhun, F. Dastgiri, G-Y. Fu, H. Hua, J. Irving-Dinsdale, K. Leaver, M. Mews, L. McKie, L. Milligan, K. Rule, N. Spinks, O. Stanley, M. Tan Ha, J. Wu, Y-Y. Zhong

Professional and technical staff: J. McKenzie

Introduction

The SABRE experiments are a unique pairing of similarly designed detectors with sodium iodide crystal targets that are to be operated in laboratories in the northern and southern hemispheres, where seasonal background will be opposite in phase. The SABRE South experiment is designed to have additional active background rejection from a liquid scintillator veto and will be located in the Stawell Underground Physics Laboratory (SUPL). The SABRE North experiment in LNGS will use the same target and crystal detector concept, without the liquid scintillator.



A cross-sectional view of the SABRE South detector is shown. The experiment is made up of three subdetector systems: (i) the NaI(Tl) crystal detector system, (ii) the linear alkylbenzene liquid scintillator system, and (iii) the EJ200 plastic scintillator muon detectors. Together, the liquid scintillator and muon detectors act as an active veto system.

SABRE South is designed to be the most sensitive NaI(Tl) detector built to date and is expected to overtake its nearest competitors within two years after commencing operation. Combined with the dual Northern and southern hemisphere perspectives, the SABRE experiments should be able to confirm or refute the DAMA/LIBRA excess by around 2027/2028. SABRE South has begun installation with the muon and data acquisition systems already in SUPL, and will be mostly completed in the coming year. A large number of off-site activities have been underway in the past year, described in more detail below.

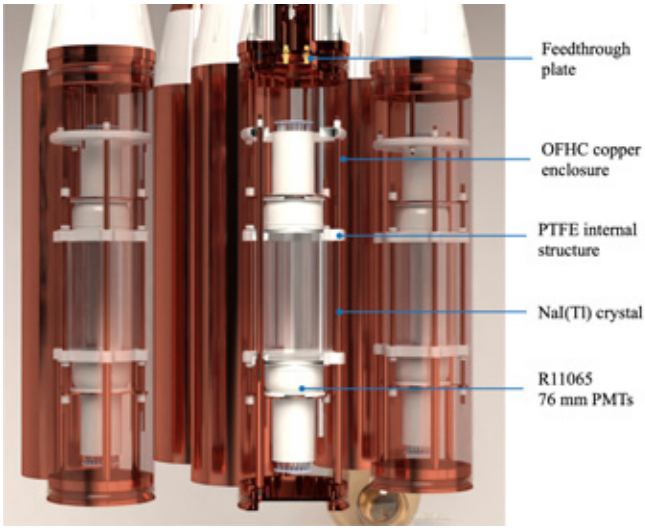
The SABRE South Collaboration was officially formed through the establishment of the SABRE South Collaboration Board by the member institutions. The collaboration is strongly supported by working groups, led by early- to mid-career researchers from each participating institution. These working groups meet regularly and have representation across the relevant nodes of the Centre. SABRE South was well represented at many international conferences in 2023, particularly by early- to mid-career researchers in the collaboration.

The SABRE South Technical Design Report (TDR) was written in 2023. This 200-page report contains details of all aspects of the experiment's design, assembly procedures, operational considerations, computing, software, and physics sensitivities. The latter is based on a publication on the simulation and background in SABRE South. The TDR was presented to an international scientific review committee comprised of experts from other dark matter experiments and underground laboratories. The committee wrote a report on recommendations, submitted to the Deputy Vice-Chancellors Research of the participating universities, which has since helped guide work in SABRE South.

The largest component of the whole experiment, the 100-tonne steel shielding cube, was put out for tender by a UoM project management team. A preferred supplier was identified from the external steel fabrication companies that submitted tenders. They will construct the shielding in 2024. It will be deployed in two stages in 2024 and 2025. This is a major milestone that sets the schedule for the assembly and commissioning of the experiment in the coming year.

NaI(Tl) Detector

Seven NaI (Tl) crystals will be grown using NaI astrograde powder obtained from Sigma Aldrich (Merck), known for its minimal potassium content. These crystals will be housed in oxygen-free copper enclosures measuring 570mm in length. With dimensions of approximately 150-200 mm in length and 110 mm in diameter, each crystal will weigh about 7 kg, resulting in a total crystal mass of approximately 50 kg. To detect dark matter, each crystal will be equipped with two highly sensitive 76mm Hamamatsu R11065 photomultiplier tubes (PMTs) designed for ultra-low noise detection.



Crystal production

Crystal production is the most critical item for the success of SABRE South. The crystals are target volume and the leading source of background is from crystal impurities. Two producers have been engaged to use crystal growth procedures developed by SABRE: RMD and SICCAS. Several prototype crystals have been produced with RMD using astrograde powder and a Bridgman-Stockbarger growth procedure, with world-best radioactive contamination levels. These have been tested at LNGS and with ICP-MS and were found to satisfy the crystal requirements for the final experiment. These requirements include 39K, 210Pb, 129I contamination level limits, as well as light yield, resolution, and good crystal structure.

Despite the good results, it was identified by SABRE North colleagues that further improvements to the contamination levels can be achieved from the use of zone refining in the production process. In 2023 a zone refining oven was set up for the RMD production line by collaborators at Princeton and INFN. We expect to begin production with this process in 2024.

The second production line involves Centre AIs from SICCAS who have used a modified Bridgman method with a double-walled platinum crucible technique. This method has been demonstrated to work in earlier prototypes with astrograde powder and was reproduced in 2023. An MoU between UoM and SICCAS was put in place, which has supported the work on achieving the growth of 7 kg high-purity crystals in 2023, and is a major milestone for SABRE South. It is expected that the production line with astrograde powder with SICCAS will be ready by mid-2024 after final surface treatment studies.

Enclosure, glove box and insertion system engineering

Within the copper enclosure, the crystals are mounted directly to the PMT using high purity copper and PTFE (teflon) parts. The design of the enclosure is complete, and prototypes of the copper end-cap plates have been tested to ensure good seals for handling high-purity nitrogen and to ensure no leakage from the liquid scintillator.

The nitrogen-flushed glovebox for assembly of these detectors has been purchased. It was chosen to have good capability in maintaining minimal humidity, radon, and dust ingress. The crystal insertion system has been designed, manufactured, and ready for integration with the fluid/gas handling system.

PMT Characterisation

The isolation of dark matter signatures is challenging due to the low-energy signatures involved. At room temperature this can be swamped by PMT induced background. An excellent understanding of low energy background, and single photon performance is therefore crucial. The Melbourne group commissioned a new dark room facility for PMT characterisation in 2022 and continued to carry out PMT analyses throughout 2023. The tests for the crystal PMTs have focused on the single photo-electron response, quantum efficiencies, gain and stability over time, as well as dark rate and its temperature dependence. Machine learners have been developed to mitigate PMT noise with promising outcomes, and a publication on the topic is being prepared for submission.

Crystal Characterisation and Analysis

Several high purity crystals from RMD have continued to be analysed at LNGS for characterisation and development of the crystal detector assembly process. SABRE South members were directly involved in the setup of these tests at LNGS. The data acquisition and analysis used the SABRE South developed DAQ and software frameworks. The light yield, resolution, and 210Pb levels were measured.

The leading background contributions to SABRE are twofold: (i) PMT and electronics induced noise, and (ii) radioactive decay and neutrons from spallation. In both cases, machine learning algorithms were developed and trained on data from the PMT test bench, NaI35 run at LNGS, the HIAF at ANU, and in the future it will utilise new algorithms developed in 2023 to simulate detector and electronics effects. The latter is key to reach the low thresholds needed to understand the DAMA/LIBRA signature.

Veto detectors, calibration systems and shielding

Liquid scintillator veto

The liquid scintillator vessel is made of stainless steel and lined with lumirror reflector film. It is approximately 3.3 m tall with a 2.6 m diameter and designed to hold 12 kL of liquid scintillator. The main top-flange has seven smaller flanges for the insertion of the crystal enclosures. The upper torispherical section has 12 flanges for cabling, gas flow, and callibration systems. The liquid scintillator is a mixture of linear alkylbenzene (LAB) and fluorophores PPO and Bis-MSB. The vessel is instrumented nominally with 18 204mm Hamamatsu R5912 PMTs with oil-proof electronics bases to detect veto signals with very low energy thresholds.

Full characterisation tests of all R5912 PMTs have been performed in the Melbourne test bench. This work studied efficiencies, single photo-electron responses, noise as a function of temperature and gain, and afterpulse background. Machine learning techniques were developed for noise mitigation and particle identification using a prototype liquid scintillator system and laser test bench data.

In late 2023 a further 16 PMTs were donated by IHEP from the decommissioned Daya Bay experiment. Work was undertaken to characterise these PMTs, some of which will also be used in the SABRE vessel.

With the vessel already built, the current effort is focused on LAB transport, PMT and Lumirror mounting, cleaning, and fluid handling. In 2021, 17 kL of LAB was procured from Nanjing via the IHEP JUNO group. It was developed to meet the tighter requirements of JUNO, with excellent photon attenuation and radioactive contamination properties. The storage tank has been hosted by the Australian Synchrotron and a facility in Ballarat. The LAB is expected to be transported to SUPL in a smaller transport vessel. The fluorophores have also been procured ready for mixing. Significant efforts in 2023 were to develop Lumirror templates and PMT assembly procedures, which present a challenge due to the confined spaces.

Fluid handling systems

Another major effort is the design and fabrication of the systems that manage the flow and monitoring of the high purity nitrogen used in the veto and crystal detectors, and the handling of the liquid scintillator.

The ANU group lead the assembly of this system which was largely completed in 2023.

Calibration systems

Three calibration systems have been built or designed for SABRE: (i) a radioactive source-based system to be deployed via tubes inserted into the LS for the crystal and veto systems designed in 2022, (ii) a pulsed optical system to test the LS system designed in 2023, and (iii) a radioactive source based system for the muon detectors built in 2022/2023. The latter was deployed to SUPL in early 2024. The calibration systems are designed to correct for performance changes over time, which is crucial for a well-understood annual modulation measurement.

Muon detector

On top of the vessel is the EJ200 plastic scintillator muon detector, made up of eight 3.0 m x 0.4 m x 5 cm assemblies. The muon detector is designed to stably measure muon rates over long periods and to provide an additional veto in tandem with the LAB detector. This is the first major system to be installed in SUPL since its opening. We expect to use the system to perform angle-dependent flux and flux modulation measurements in 2024 until its integration with the full SABRE detector in 2025. In 2023 the performance of the muon detectors was thoroughly studied for efficiency, energy scale, timing, and spatial resolution. Long-term stability studies have been performed to understand gain shifts that may affect performance.

In addition to providing a much more statistically powerful muon flux measurement, it will be used to measure the angular distribution of muons incoming to SUPL. Transport of this equipment to SUPL will provide invaluable experience in the logistics of transporting large, heavy and delicate equipment through SGM.

Practicing and testing the installation of lumirror reflector film and mock 3D printed PMTs in the SABRE vessel at SUT

Shielding

The vessel is surrounded by a shielding system made of an 100 mm layer of polyethylene sandwiched between two 80 mm layers of steel. The steel is sourced from manufacturing processes that use minimal amounts of recycled steel content. The sandwich system is designed to shield gamma rays with steel and neutrons with polyethylene. The efficiency of the shielding has been fully simulated, to ensure background in the crystal detectors is less than 10\% of the total expected. The total mass of steel is around 110 tonnes. The design had to take into account weight limitations for truck cartage to SUPL of around 4 tonnes, and is therefore pre-assembled in 4 tonne modules.

Data Acquisition, Monitoring and Control systems

DAQ infrastructure

The data acquisition (DAQ) system is primarily composed of a CAEN VME crate with CAEN 500 MS/s and 3.2 GS/s digitisers with onboard firmware for digital pulse processing and zero suppression. A trigger logic unit is used to control data rates by triggering on coincidences within and between subdetector systems. The system is read out via optical links to DAQ server units. The PMT high-voltage (HV) system is a CAEN mainframe controlled by EPICS (Experimental Physics and Industrial Control System) with three 24 channel HV boards. The hardware of the system is complete. An EPICS based system has been stably deployed for the muon run at SUPL, DAQ run control at LNGS, HV control and monitoring, PMT testbench studies, and for detector calibration runs. Versions of the software have been developed for calibration and control of each of the detector subsystems. It has been integrated with slow control and environmental monitoring systems.

Online computing infrastructure

The local SUPL computing infrastructure for SABRE was procured using UoM funding and partially deployed in early 2024. This comprises three 24 core DELL Xeon Gold server units for direct data acquisition, a high-capacity storage and processing server with 56 Xeon Gold cores and 66 TB of storage. Two 16 core Xeon Gold server units were procured and are used for run control and monitoring data processing. The entire system is backed up by a smart UPS which also acts to smooth the power input to the HV systems.

Software and offline computing

There are three main projects in development for SABRE. The GEANT4 based full simulation of the experiment was developed and published in 2023. Detector digitisation and resolution effects were introduced to fully mimic waveform data acquired by the readout system. This is being used to develop more advanced analysis algorithms in all subsystems.

The python based data processing and analysis framework (Pyrate) that processes data from either the DAQ system or from the GEANT4 simulation went through further development. It supports a wide range of ongoing calibration and machine learning based pulse shape analysis studies. Recent developments include new event builders that use sophisticated algorithms to combine data from all the detector channels in SABRE.

The final main project is on offline computing. The conditions database is crucial for managing calibration data and to correlate environmental conditions into data analysis. Major progress has been made on the database in 2023. The offline storage for SABRE is provided by UoM. It is currently 30 TB of fast disk and 150 TB of long term storage and will ramp up as required in the future. All collaborators have access to the SABRE data, and can process it on the UoM Spartan HPC system. The data link from SUPL to UoM was set up for continuous data transfer and remote control of detector systems, and has been successful in supporting large data transfers of muon detector data.

R&D CYGNUS-Oz

Nodes involved: ANU, UoA, UoM, UoS

Chief Investigators: N. Bell, C. Boehm, G. Hill, P. Jackson, G. Lane, A. Stuchbery, A. Thomas, M. White, A. Williams

Postdocs: L. Bignell, I. Bolognino, P. McNamara, J. Newstead, Z. Slavkovska

Students: V. Bashu, F. Dastgiri, K. Leaver, C. Lisotti, L. McKie

Associate Investigators: C. O'Hare

Introduction

The development of directional detection technology for dark matter searches is motivated by the approaching existential crisis for conventional dark matter detection known as the 'neutrino fog'. Next generation experiments will observe solar neutrino interactions: these are impossible to shield and are indistinguishable from a genuine dark matter signal, so will constrain these experiments' ability to search for dark matter.

This problem can be overcome by using a detector that records the direction of the nuclear recoils. While solar neutrinos point back to the Sun, dark matter signals point in the direction of the solar system's galactic orbit: towards the constellation Cygnus. The development of directional capability is therefore necessary to see into the neutrino fog. Directionality is also the best means to identify a galactic dark matter signal. Importantly, any dark matter discovery claimed by a non-directional detector will require a follow-up directional measurement to unambiguously confirm it is genuinely dark matter.

The international CYGNUS Consortium is aiming to build a large-scale experiment using the only detection technology capable of achieving the required directional performance -- the gas Time Projection Chamber (TPC). A decadal CYGNUS goal is to build a several large directional experiments, located at underground facilities in the CYGNUS collaborator host countries (Australia, Italy, Japan, UK, US). The combined exposure of these detectors would give sufficient sensitivity to search for dark matter into the neutrino fog, while also probing other fundamental physics problems.

CYGNUS-Oz

Australian efforts towards this international effort are co-ordinated through the CYGNUS-Oz collaboration, formally constituted in 2022. The collaboration features a mix of experimentalists and theorists from the Centre.

A number of significant research milestones were reached in 2023. The ANU node is leading the experimental activities, with the CYGNUS-1 prototype directional TPC. The past year saw the first directional measurements in the detector. Measurements included the track inclination angle and the 'head-tail', or vector sense, of the track. Both are essential features for a future dark matter search. CYGNUS-1 also measured electron drift velocities as they transit through the detector's electric field – a key input for the design of a future experiment's gas mixture – and compared the scintillation light and ionisation charge signals from particle events, as a means of assessing the viability of these detection channels for a large detector. The experimental measurements are supported by simulation modelling to understand the stopping of particles and transport of charges through the gas-filled detector volume, and electrostatic field modelling.

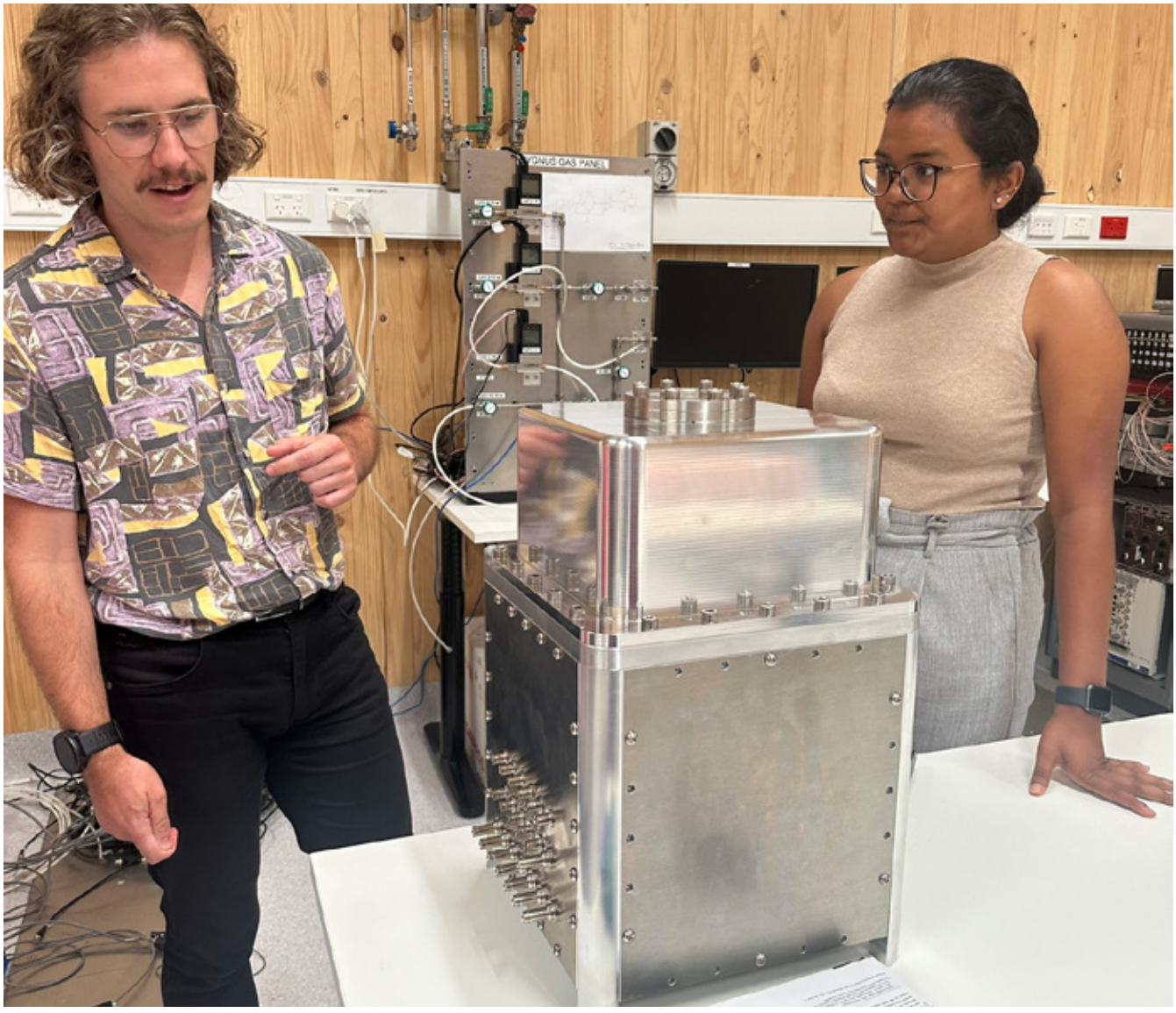
2023 also saw the ANU purchase new equipment using funding from the ANU's Major Equipment program and Defence Science and Technology Group funding administered through the Centre. This equipment has culminated in the development of a new prototype, CYGNUS-n, which features an improved mechanical design over CYGNUS-1 and an intensified camera readout. The intensified camera will be the first micro-patterned readout to be used by the group, and will allow CYGNUS-n to observe low-energy directional tracks, including from neutrons. There is strong interest in directional neutron detection as a means of translating our detector technology to uses in defence and other areas.

We have deepened our collaborations with our international partners over the past year, publishing our first joint experimental study [arxiv:2312.07720] with collaborators in the UK and Japan. This study examined a molecular sieve radon filtration system, which is essential for removing radon backgrounds from a future large experiment. The outstanding performance of the radon filter has inspired a new ANU-led initiative to explore the use of these radon filters for radon reduction in other applications (such as at SUPL) and to develop a radon emanation measurement capability.

Another joint study with international CYGNUS collaborators was led by UoS theorists Chiara Lisotti and Ciaran O'Hare. Together with experimentalists from ANU, Italy, and the US, this work examined the measurement possibilities of solar neutrino-electron scattering in a directional detector. The study found that an appreciable neutrino event rate could be measured in a relatively small 10 m^3 detector, and that the full-scale CYGNUS experiment could constrain the important and difficult-to-observe CNO neutrino flux in a way that is complementary to existing neutrino observatories.

Our collaborative activities have been supported by number of visits from Centre students (V. Bashu, F. Dastgiri, L. McKie) and CI Greg Lane, as well as visits to the ANU laboratory by Dinesh Loomba (US), Alasdair McLean (UK), Neil Spooner (UK, Centre PI), and Tom Thorpe (US). As discussed in the 'Events' section, the University of Sydney hosted the CYGNUS Workshop on Directional Recoil Detection in December 2023, in which all groups involved in the CYGNUS Consortium shared their latest results.

Finally, the experimental work received a boost at the end of 2023, being given a new laboratory space in the recently opened state-of-the-art physics building at ANU. The 8 m x 8 m space gives ample room for the next phase on our experimental roadmap: the CYGNUS Experimental Tile (CYGNET). CYGNET will be a 72 L directional detector that will settle the remaining technical questions on our path to scaling up to a large experiment, while itself acting as an ideal test-bed to explore translational applications of directional neutron detection.



PhD students Lachlan and Victoria in the new ANU Dark Matter Detector Laboratory with the CYGNUS-n prototype. CYGNUS-1 prototype in the background.

XLZD

Nodes involved: UoM, UoS

Chief investigators: E. Barberio, N. Bell, C. Boehm, P. Urquijo

Academic Staff: T. Früth

Postdocs: R. James, J. Newstead

Associate Investigators: S. Diglio, C. O'Hare, M. Schumann, Y. Xing

Students: O. Stanley

Dual-phase liquid xenon time-projection chambers have been leading the search for mid to high-mass WIMP-like dark matter particles for many years now. In 2022, the Centre joined the international effort to build a next-generation liquid xenon detector. The XLZD consortium combines the leading experiments (XENONnT and LZ) with large-scale R&D efforts (DARWIN). The consortium is planning a 60-80 tonne detector with sensitivity into the neutrino fog, where neutrinos become a significant background to the dark matter search.

In 2023, the Centre's efforts on XLZD have been growing. Researchers at UoS, UoM, and the partner institute Subatech have met monthly to discuss updates and plans, including experimental contributions to the program. They also conducted two online software tutorials on simulation and statical inference primarily aimed at the PhD students on the project. Centre researchers have started to get involved in various tasks on XLZD, including simulation geometry, light collection efficiency, sensitivity studies, and editing the forthcoming detector design report. The team includes four shared PhD students between the University of Melbourne and Subatech (France).

AXION and WISP Direct Detection

Nodes involved: UWA, SUT, ANU, UoS

Chief Investigators: M Tobar, M. Goryachev

Postdocs: B McAllister, J. Bourhill, G. Flower

Students: A. Quiskamp, C. Thomson, W. Campbell, E. Hartman, S. Samuels

Associate Investigators: E. Ivanov, P. Altin, C. O'Hare, Z. Zhao

Partner Investigators: G. Rybka

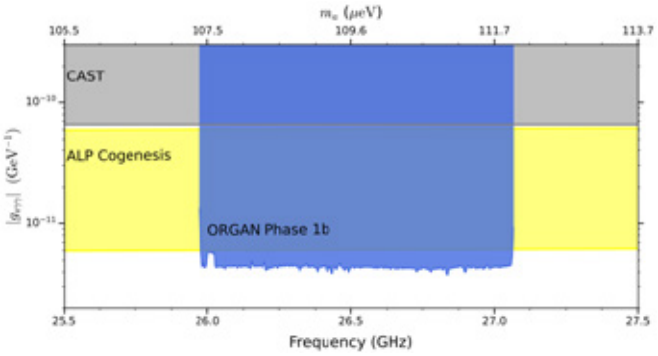
Research program overview

2023 has been a productive year within the centre for searching for axion and WISP dark matter. The Centre teams continued to progress on many fronts, with many highlights for 2023. This included:

- The successful completion of ORGAN phase 1b, which will be a large part of Aaron Quiskamp's PhD thesis at UWA, which is due for submission in 2024.
- The second successful room temperature run of UPLOAD using precision oscillators. Catriona Thomson awarded her PhD thesis for her work on UPLOAD and using precision oscillators to search for dark matter, her thesis was entitled "Techniques to Search for WISP and WIMP Dark Matter Using Frequency Metrology,"
- The first experimental run of ORGAN-Q, a 6 GHz haloscope, which implemented quantum technologies as part of the measurement process.
- New novel proposals to test for ultra-light axions using twisted resonators, and search for new axion coupling terms if high energy monopoles exist.
- Development of technologies to allow tuneable resonators to facilitate dark matter searches.
- The successful development of the MAGE high frequency gravitational wave detector, which is also "in principle" sensitive the scalar dark matter, the main topic of William Campbell's PhD thesis submitted for review.
- UWA was involved in international discussions on the next generation of axion dark matter detectors, with a summary article published [Int. J. Mod. Phys. A, 38, 33 & 34 (2023)].

ORGAN

The flagship axion program of the Centre is the ORGAN axion dark matter haloscope experiment, which uses a high Tesla background field to convert axions to microwave photons in a tuneable high-Q resonator. ORGAN targets the 15-50 GHz or 60-200 micro eV range in mass, where serious theoretical prediction suggests the axion exists. Last year we finished our second short, targeted scan, Phase 1b, and successfully excluded Axion Like Particle Cogenesis models between 25.9–27.1 GHz (107.4-111.9 micro eV) [Phys. Rev. Lett. 132, 03160 (2024)]. This was achieved through the design of a novel tuneable rectangular cavity [Phys. Rev. D 109, 015013 (2024)]. Furthermore, in 2023 we ran our off-shoot experiment, ORGAN-Q, which implements quantum technologies and novel resonant designs in the lower frequency (~6 GHz) range. This experiment just finished taking data in March 2024, and allowed the first use of quantum technologies for a UWA haloscope experiment. For Phase 2 we continue to investigate dielectrically loaded cavities with novel tuning and single photon detectors in our frequency range. Finally, the data from the ORGAN 1a experiment, was used to put limits on other types of dark matter, with results published in 2023 [Annalen der Physik, 536, 1 (2023)], ways to improve on some of these results were also outlined in [Annalen der Physik, 0594 (2023)].



Axion dark matter exclusion limits on the coupling parameter, $g_{a\gamma\gamma}$, set by the ORGAN experiment.

The AC Haloscope, UPconversion Loop Oscillator Axion Detector (UPLOAD)

The UPLOAD experiments use an AC background field as an excited high-Q mode in a microwave cavity resonator, which causes another high-Q readout mode to be excited, which may be read out to search for predicted frequency or power perturbations. The experiment is sensitive to axions where the mass matches the difference frequency between the two modes. In 2023 we published the second version of this room temperature experiment, which improved on our previous experiment by three orders of magnitude, by searching for power fluctuations rather than frequency fluctuations [Phys. Rev. D, 107, 112003 (2023)]. It is widely thought if the two modes approach degeneracy then one may search for ultra-light axions using this technique. However, practically this is impossible due to non-linear effects and feed through not allowing the simultaneous excitation of a mode, and the readout of another at nearly the same frequency. In 2023 the UWA group published a new way to do this in a single mode resonator with non-zero helicity [Phys. Rev. D, 108, 052014 (2023)]. The approach uses 3D printed twisted cavity resonators, which exhibit anyon rotational symmetry and have resonant bulk modes of non-zero helicity, which make them sensitive to ultra-light dark matter within the bandwidth of the resonator. The device was also patented because the microwave modes have non-zero angular momentum, and could be used for a variety of applications.

To further the sensitivity of these experiments we are now investigating possible cryogenic implementation of UPLOAD and UPLOAD-ANYON, which will require expanded collaborations with experts on 3D-printing and superconducting cavities.

Axion Dark Matter eXperiment (ADMX) Generation 1 and 2

The ADMX collaboration began run 1D in 2023 and is now running continuously. Centre researchers continue to work with ADMX researchers on cavity designs and simulations for the current run 1D experiment, as well as the future ADMX Extended Frequency Range. They are also heavily involved in the high resolution analysis which searches for cold flows. Recent work showed how the experiment could be improved using quantum technologies [Rev. Sci. Instrum., 94, 044703 (2023)]. and how the ADMX haloscope could be used to search for a cosmic axion back ground [Phys. Rev. Lett. 131, 101002 (2023)].

ADMX and ORGAN Low-Frequency

The ADMX and ORGAN collaborations have shown a growing interest in the lower-mass axion regime between 100-600 MHz – 0.41 to 2.5 micro eV, with cavities being built in the University of Florida and SUT. With the first prototype characterisation and sensitivity estimates calculated in 2023, recently published by the ADMX collaboration [Phys. Rev. D, 109, 042004 (2024)]. Centre researchers, Hartman and McAllister played a leading role in these calculations.

Low mass detectors for axions with LCR circuits

In collaboration with researchers from DESY, centre researchers conceived a new experiment using a high voltage capacitor to search for effects of heavy monopoles if the GUT-scale axion is shown to exist, or to simultaneously search for both the axion and the monopole at the same time, [Phys. Rev. D, 108, 035024 (2023)]. It was shown that QCD axion sensitivity would be relatively straight forward to attain. We are proposing to first undertake a prototype experiment as a step to achieving such sensitivity.

Scalar Dark Matter

The UWA group has been developing Bulk Acoustic Wave (BAW) technology, which is sensitive to a variety tests of fundamental physics, including scalar dark matter. The next experiments will use this technology to search for high frequency gravitational wave, through the Multi-mode Acoustic Gravitational wave Experiment, MAGE. An update describing the experiment was published in 2023 in, [Sci Rep 13, 10638 (2023)]. One of the important issues with many of these detection experiments, is the ability to tune two independent resonators to the same frequency, we devised a way of tuning these resonators by many linewidths by applying a DC voltage to the crystal, which may be useful in future experiments, [Appl. Phys. Lett. 122, 032202 (2023)].

precision metrology research program

Nodes involved: ANU, UWA

Chief Investigators: M. Goryachev, S. Tims, M. Tobar

Postdocs: M. Froehlich, Z. Slavkovska

Students: W. Campbell, F. Dastgiri, G. Flower, A. Quiskamp, C. Thomson

Associate Investigators: E. Ivanov, D. Koll

Partner Investigators: A. Wallner, M. Hotchkis

Improving the detection sensitivity for those radionuclides identified as most likely to impact dark matter detection capability remains the focus of the precision metrology program at ANU. Development of low phase noise oscillators for use as detectors continues at the UWA node. Details are provided in the AXION section.

Nuclear metrology

Characterisation of dark mater detector materials

The failure of a key component of the ANU accelerator, crucial for actinide measurements with the AMS system, delayed all actinide isotope measurements for most of the year. AMS activities were limited to optimizing the isotope extraction efficiency from the ion source that injects atom beams into the accelerator and AMS measurements performed on the VEGA accelerator at ANSTO. Nevertheless, significant progress has been made towards our efforts to quantify 210Pb in the NaI(Tl) detector crystal material. In collaboration with our PI institutions, HZDR and ANSTO, we have identified a source of lead material with extremely low 210Pb content that will enable 210Pb/(total Pb) determination in the requisite materials. Further, we have established and demonstrated measurement protocols and techniques that provide stable output beams from the ion source, and which allow determination of the 210Pb/(total Pb) ratio at levels almost two orders of magnitude below the ratio expected for the NaI(Tl) raw material with the VEGA accelerator. Further improvements, through methods that reduce interference in the AMS detection system and tests on other relevant materials used in construction of the dark matter detector, should be possible when the ANU accelerator capabilities are reinstated in April 2024.

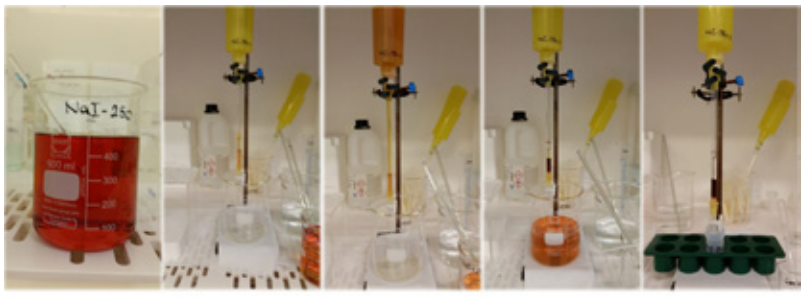
ICP-MS development

Progress on achieving measurement of 40K at low ppb levels with ALS Environmental, the commercial laboratory in Sydney, has been slow, and the sensitivity remains in the 10-100 ppb range. More testing is underway to reach the required sensitivity. Concern regarding the uniformity of the thallium concentration in the NaI(Tl) detector crystals, following trials of new purification steps in the manufacturing process, has seen the addition of the development of methods to extract and quantify thallium levels in astrograde NaI material using ICP-MS. Preliminary measurements are in preparation with results expected in mid 2024.

AMS capability improvements

Before the issues with the ANU accelerator, there was significant progress with efforts to improve the sensitivity of the AMS time-of-flight system. These included measurement automation with the isotope fast-switching system, and its use with the time-of-flight detector required for measurements of uranium and daughter product isotopes for samples with intrinsically low levels. Automated measurements of plutonium, uranium and protactinium isotopes have now been trialed with considerable success, leading to a reduction in the systematic error, improved statistical precision in the data, and a consequent improvement in the sensitivity for the measured isotopes. Verification of the new methods awaits the return of an operational gas stripper.

The temporary hiatus in actinide capabilities at ANU has provided an opportunity to commence the development of techniques that will be required to measure fission product isotopes with the AMS system. Significant parts of the early stages of this program, including assessments of optimal beam injection species, new detection methods and identification and minimisation of isotopic species likely to lead to interference in the detection system, all which can be performed without the gas stripper, has commenced. Specifically, an expansion of AMS capabilities at ANU to include spontaneous fission product isotopes has commenced with 90Sr, 93Zr and 99Tc, these isotopes have been selected as a low-level detection will have spin-off applications in radioactive waste management, reactor technologies and for medical isotope releases to the environment.



LHC research program

Nodes invovled: UoA, UoM

Chief Investigators: E. Barberio, P. Jackson, G. Taylor, M. White

Postdocs: H. Potti, J. Webb

Students: M. Amerl, I. Carr, A. Desai, M. Fewell, E. Filmer, J. Gallagher, C. Grant, M. Green, A. Kong, J. Kull, H. Pandya, J. Pham, H. Purnell, A. Reardon, T. Ruggeri, E. Ting, S. Williams

Partner Investigator: K. Jakobs

Associate Investigators: C. Doglioni

Collider Searches for Dark Matter: Large Hadron Collider - ATLAS experiment

The Centre provides an opportunity to search for Dark Matter direct production at one of the most notable and unique facilities in the world, namely the experimental environment provided by the world's highest energy particle collider - Large Hadron Collider at CERN in Geneva, Switzerland. At this laboratory, members of the Centre work on the ATLAS experiment, one of two multi-purpose detectors well equipped to search for evidence of dark matter production in proton-proton collisions. During 2023, the ATLAS experiment was recording data at a new world-record collision energy of 13.6 Tera Electron Volts (TeV). Centre researchers focus their attention on several aspects of the search for dark matter with ATLAS, understanding the reconstruction and calibration of hadronic jets of particles and missing transverse momentum (MET). The aim is to find direct evidence of Standard Model particles produced in conjunction with a signature of MET, which it is postulated would be carried away by the dark matter candidate(s).

Centre researchers have led analyses searching for evidence of hadronic jets that have been tagged as originating from charm-quarks. This signature has resulted in increased sensitivity to models of Supersymmetry or other beyond Standard Model theories that propose pair production of new particles that subsequently decay to massive particles that interact weakly with our detectors and leave a significant signal by their absence. This analysis work is close to completion with results to be published in early 2024.

In models where the Higgs boson decays to Dark Matter, we infer its presence by studying signals of invisible decays of the Higgs boson. Centre researchers have combining various production and decay mechanisms to increase the sensitivity to invisible decays of the Higgs boson and published these results in 2023.

DM searches with ATLAS data are underpinned by performance work and require a thorough understanding the objects that manifest in detector environments. Centre researchers are working to strengthen our understanding of hadronic jets by deploying advanced machine learning techniques and algorithms based on particle flow to extract greater precision. Efforts on calibration and tagging of jets is also prominent. Work on flavour tagging and new techniques in jet calibration has led to publications in 2023.

Beyond performance and physics analysis, it is important that we keep a keen eye on the long-term health and productivity of the detector. The next big transition in fundamental physics will come with the upgrade to the High-Luminosity LHC era (2026 and beyond) this will require a near complete refurbishment of the ATLAS detector. Centre researchers are focused on the construction, testing and deployment of modules for the inner tracker upgrade (ITK). Having passed review milestones at each site, module production will occur in Melbourne with modules then sent to Adelaide to perform a thermal cycling and rigorous testing procedure prior to them being shipped to CERN for assembly and ultimately deployment into the experiment.


VERTEX
Schelde Exotech
Hetehol

theory research program

Nodes involved: ANU, SUT, UoA, UoM, UoS

Chief Investigators: N. Bell, C. Boehm, D. Croton, M. Dolan, A. Duffy, C. Simenel, A. Thomas, R. Volkas, M. White, A. Williams

Postdocs: M. Baker, G. Busoni, J. Newstead, D. Sengupta, X-G. Wang

Students: R. Abdel Khaleq, F. Hiskens, N. Hunt-Smith, J. Gill, W. Husain, N. Krishnan, G. Lawrence, A. Ritter, I. Shaukat Ali, A. Sopov, M. Virgato, J. Wood

Associate Investigators: P. Cox, C. O'Hare

The overall aim of the theory program is to understand the nature of dark matter. This is accomplished by exploring ideas for what dark matter can be, and developing new or better ways to test those ideas with laboratory experiments or astrophysical observations. This is an activity that utilises the complementary skill set in the theory team, which spans particle, nuclear and astrophysics expertise. Ideas-generation is a key element of our research. This is true both of our work at the pure theory end of the spectrum and our work at the theory-experiment boundary. The former includes the development of theoretical models which incorporate dark matter and its interactions, while the latter includes the proposal of novel experimental approaches to detect dark matter, detailed simulations to compare the sensitivity of different approaches, and the development or refinement of the science case for major experimental or observational programs.

In 2023, we started the year with a Theory Program workshop held in February at the University of Adelaide, at which the full team of theory CIs, postdocs and AIs, engaged in many lively research discussions. Over the course of the year, Centre theorists have undertaken a diverse range of research projects. Links between the theory and experiment have also been strengthened, through involvement in the DARWIN, CYGNUS and LHC programs, and the development of novel ideas for the detection of low mass dark matter including the proposed Optomechanical Dark-matter INstrument (ODIN). Some highlights of theory research published in 2023 are described below; further projects are ongoing.

Impact of shell model interactions on nuclear responses to WIMP elastic scattering

Raghda Abdel Khaleq, Giorgio Busoni, Cedric Simenel and Andrew Stuchbery have performed a systematic nuclear shell model studies of ground-state structures of all nuclei involved in WIMP direct detection. The goal is to better understand and quantify the impact of nuclear structure on dark matter direct detection rates. Repeating the calculations with different shell model interactions allows uncertainty quantification. A subset of the results have been published in [SciPost Phys. Proc. 12, 062 (2023)] and a longer paper has been submitted.

Improving models for nuclear structure to probe their effect on direct detection

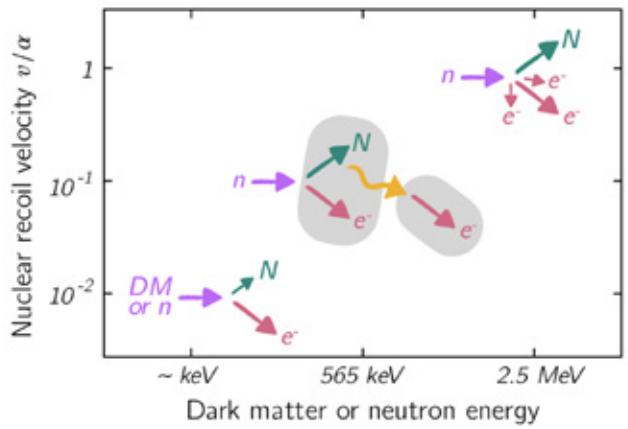
Current studies of the impact of nuclear structure on WIMP direct detection are based on the nuclear shell model. The latter is particularly well suited for spherical and near magic nuclei. However, many detectors use nuclei that are deformed and/or away from magicity, for which mean-field based models are better suited, providing that correlations (e.g., leading to ground-state deformation) are accounted for by symmetry breaking and restoration techniques. Cedric Simenel and his collaborator studied the ability of such techniques to account for correlations by comparing them with exact quantum Monte Carlo simulations of interacting fermions on a one-dimensional quantum ring [Phys. Rev. C 108, 054307 (2023)].

Dark Matter, neutrinos, and the matter-antimatter asymmetries of the universe

CI Ray Volkas and PhD student Alexei Sopov proposed and developed a model they termed "VISHnu". This model, which features the well-known dark matter candidate called the "axion", connects dark matter with both neutrino mass generation and an explanation of the matter-antimatter asymmetry of the universe. It does so in the context of a successful cosmology that utilises a period of exponential expansion known as "inflation", thus explaining why the universe has a flat spatial geometry and why the cosmic microwave background is isotropic to one part in 100,000 [Phys.Dark Univ. 42 (2023)].

Precise predictions for the Migdal effect

The scattering of neutral particles by an atomic nucleus can lead to electronic ionization and excitation through a process known as the Migdal effect. This process is of particular interest for the direct detection of low mass dark matter. Peter Cox, Matthew Dolan and collaborators improved upon previous calculations of the Migdal effect, using the Dirac-Hartree-Fock method to calculate the atomic wave functions, enabling robust results for higher nuclear recoil velocities than was previously possible. Their calculations provide the theoretical foundations for future measurements of the Migdal effect using neutron sources, and searches for dark matter in direct detection experiments [Phys.Rev.D 107, 3, 035032 (2023)].



Schematic representation of the different energy regimes for dark matter induced and neutron-induced Migdal processes

Detection of light dark matter

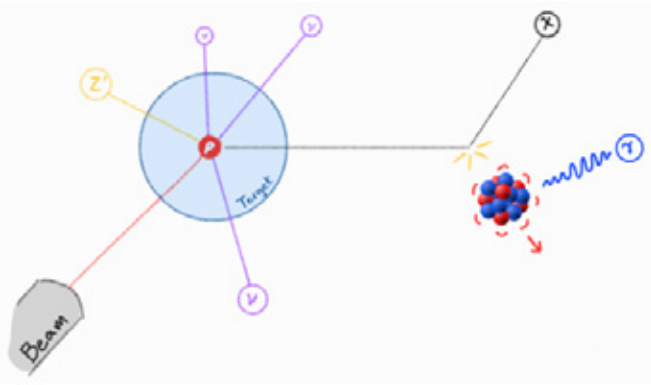
The detection of light dark matter is the subject of many ongoing research projects in the Centre. Most direct detection experiments lose sensitivity if the dark matter mass is less than a few GeV, since the nuclear recoil energy deposited by the elastic scattering of dark matter on the target lies below the energy threshold for detection.

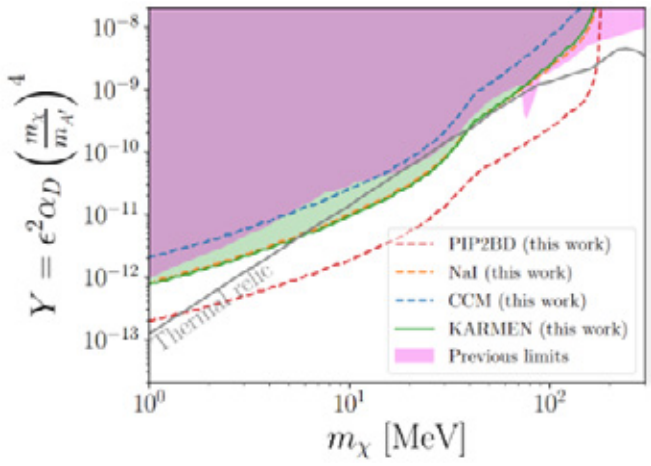
Nicole Bell, Peter Cox, Matthew Dolan, Jayden Newstead and Alex Ritter have considered the doping of liquid Xenon detectors with a lighter element such as hydrogen. This provides a target nucleus with better kinematic matching to light dark matter and, consequently, nuclear recoil energies above the detection threshold. Their results indicate that combining Hydrogen-doping with the Midgal effect improves the reach to low dark matter masses, particularly for spin-dependent proton scattering. This work has been submitted for publication.

Light dark matter particles would be more readily detectable if they could be produced with, or boosted to, higher energies. Nicole Bell, Jayden Newstead and Iman Shaukat Ali have considered scenarios in which galactic dark matter is boosted to relativistic energies by interactions with galactic cosmic rays. Dark matter can also be boosted to relativistic energies in the gravitational field of a neutron star. Nicole Bell, Giorgio Busoni, Michael Virgato and Sandra Robles have continued to study the capture of dark matter in neutron stars, and consequential observation signatures. These projects will be finalised and published in the coming year.

A new way to search for light dark matter using fixed-target experiments

Fixed-target experiments collide high-energy beams of particles into targets, potentially creating dark matter particles. This work developed a new and improved method for detecting these dark matter particles in nearby neutrino detectors – observing the decay of nuclei excited by the inelastic scattering of dark matter. This is in contrast to similar previous searches which used elastic scattering, and it proved to have significantly better sensitivity. Jayden Newstead and collaborators used existing data collected by KARMEN to set world-leading constraints on dark matter interacting via "dark photons" [Phys.Rev.Lett. 131, 11, 111801 (2023)]. With experimental improvements planned for the future, this new technique will become even more powerful. This is a significant step forward and suggests follow-up studies, including applying the method to cosmogenically boosted dark matter.

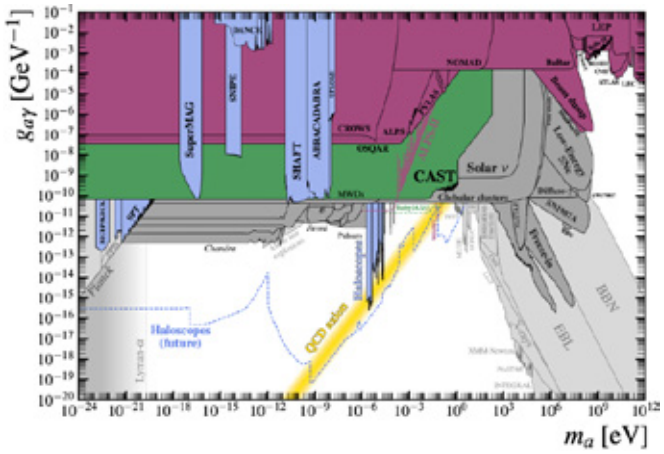




Top: Dark matter production in a "bump dump" and detection via inelastic scattering. Bottom: New limits on scalar dark matter.

Feebly Interacting Particles

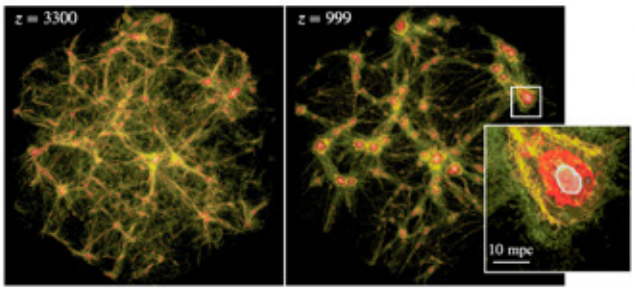
Light, Feebly-Interacting Particles (FIPs) may represent or be connected to the dark matter in the Universe. Celine Boehm and Ciaran O'Hare co-authored a report that gives an overview of effects to search for FIPs [Eur.Phys.J.C 83, 1122 (2023)]. A figure from the report, showing all current constraints on axion-type FIPs, is reproduced below.



Current constraints on axions coupled to photons, including laboratory, astrophysical and dark matter bounds.

Axion minivoids and implications for direct detection

A consequence of axion dark matter being produced after inflation is the formation of ultra-small-scale dark matter substructures called miniclusters. These small clumps pose a crisis for direct detection experiments looking for the axion on Earth because they would potentially imply a severely reduced dark matter flux in the solar neighbourhood. Ciaran O'Hare and collaborators performed realistic N-body simulations of the formation of axion miniclusters and concluded that the spaces between miniclusters, dubbed "minivoids" are not actually entirely devoid of axions. This result partially restores prospects for detection in the laboratory [Phys. Rev.D 107, 8, 083510 (2023)].



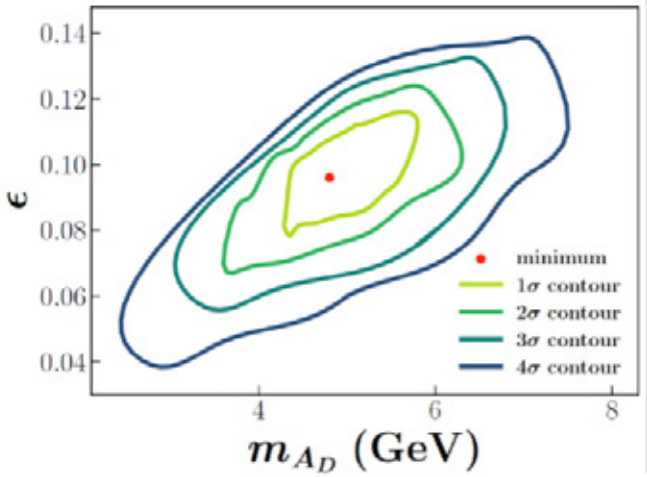
A result that partially restores prospects for detection in the laboratory [Phys.Rev.D 107, 8, 083510 (2023)].

Evidence for the Existence of a Dark Photon

A key to understanding this dark matter could lie with the dark photon, a theoretical particle that may serve as a portal between dark-sector particles and regular matter.

In recent work - a collaboration between Nicholas Hunt-Smith, Anthony Thomas, Xuan-Gong Wang and Martin White and colleagues at Jefferson Laboratory - the potential effects of a dark photon on the interpretation of results from deep inelastic scattering experiments were studied.

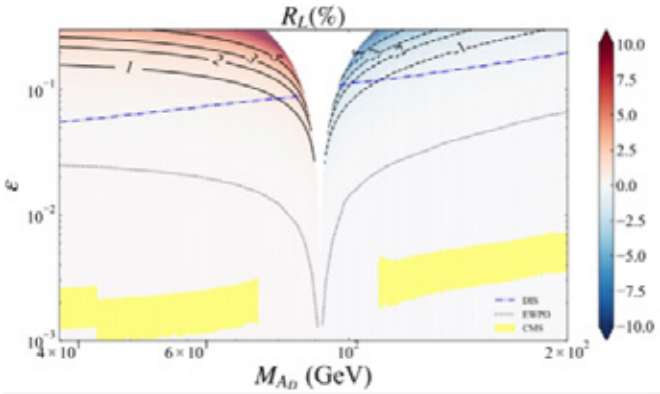
Specifically, the state-of-the-art Jefferson Angular Momentum collaboration (JAM) global analysis framework for parton distribution functions was modified to allow for the effect of a dark photon. It was found that the dark photon hypothesis is preferred over the Standard Model hypothesis at a significance of 6.5 sigma, which constitutes strong evidence, albeit indirect, for a dark photon [JHEP 09, 096 (2023)].



Profile likelihood showing preferred regions for the dark photon mass and mixing parameter derived from a global fit to the world's deep-inelastic scattering data.

Dark photon effect on the rare kaon decay

Rare kaon decays and analogous rare B meson processes are powerful tools to test the Standard Model (SM) and probe new physics. A light dark photon could potentially yield a significant contribution to these branching ratios, accounting for anomalies between experiments and the SM predictions. Xuan-Gong Wang and Anthony Thomas performed a systematic analysis of the dark photon contribution to rare kaon decays, focusing on the channel. The dark photon correction to this channel can be characterised by a factor RL. In contrast with naive expectations, RL is at most a few percent, corresponding to the case where the dark photon parameters approach the 'eigenmass repulsion' region. This effect is too small to be observed, given the experimental accuracy anticipated in the near future [J. Phys. G 50, 085001 (2023)].



Percentage correction to the branching ratio Br($K_L \to \pi^0 \nu\nu$) versus the mass and mixing parameter for the dark photon. Limits from the CMS experiment, deep-inelastic scattering and electroweak precision observables are also shown.

Constraining Dark Boson Decay Using Neutron Stars

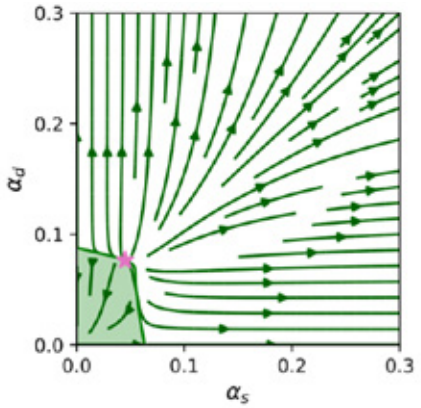
Wassif Hussain, Anthony Thomas and Dipan Sengupta performed an analysis of neutron lifetime anomaly and its consequences for neutron stars within a dark matter scenario. The neutron lifetime anomaly refers to the discrepancy of the measurement of the neutron lifetime using two different experimental techniques. A possible solution to the anomaly can be obtained if neutrons have a decay mode to dark sector states. However, this solution is strongly constrained by the dynamics of neutron stars. Hussian et al. outlined the parameter space where a light particle with an extremely long lifetime can potentially satisfy the neutron lifetime anomaly as well as be consistent with neutron star constraints [Universe 9, 7, 307 (2023)].

Graviton-photon production with a massive spin-2 particle

Joshua Gill, Dipan Sengupta and Anthony Williams performed a complex and intricate calculation in general relativity to show that a widely discussed paper published in Physical Review Letters (H. Cai et al, Phys.Rev.Lett. 128 (2022) 8, 081806) on a dark matter scenario with a massive spin-2 particle was erroneous in its entirety. Cai et al. claimed that there was a "so-called" chiral-enhancement in models with a massive spin-2 particle, which made it an excellent dark matter candidate. Gill et al. demonstrated, on general field theory grounds, that this was erroneous and showed how these calculations can impact other dark matter scenarios [Phys. Rev. D 108, 5, L051702 (2023)].

"Dark Quarks"

CI Ray Volkas and PhD student Alex Ritter explored a new idea for why the ordinary and dark matter densities in the universe today are so similar, a puzzle known as the "cosmological coincidence problem". The idea centres around the dark matter being identified as a baryonic bound state of particles called "dark quarks", mimicking how ordinary quarks bind into protons and neutrons. By making the dark matter similar to ordinary protons and neutrons, and exploiting the physics of how the strong nuclear forces changes strength with distance, they were able to find theories where the cosmological coincidence was reduced to a one-in-three chance, thus greatly reducing the mystery [Phys. Rev. D 107, 015029 (2023)].



Streamlines show how the strengths of the ordinary strong force (horizontal axis) and the dark strong force (vertical) axis vary with distance.

GAMBIT Dark Matter Results

The Global-and-Modular Beyond-the-Standard-Model Inference Tool (GAMBIT) collaboration is an international team of approximately 80 particle physicists, astrophysicists and statisticians who perform global statistical fits of dark matter theories. Using fast simulations of a large range of particle astrophysics experiments, Centre researchers are able to interrogate theories with over 30 years of accumulated data to determine which models remain viable, which can explain current hints of dark matter discovery, and which can be discovered in near future experiments.

Two GAMBIT papers in 2023 explored simplified models of dark matter. Simplified models provide a useful way to study the impacts of a small number of new particles on experimental observables and the interplay of those observables, without the need to construct an underlying theory. In the first study, indirect detection, direct detection and collider search data were used to investigate models in which a scalar or fermionic dark matter candidate couples to quarks via an s-channel vector mediator [Eur. Phys. J. C 83 3, 249 (2023)]. Large parts of the parameter space were found to survive for each model. In the case of Dirac or Majorana fermion dark matter, excesses in LHC monojet searches and relic density limits tend to prefer the resonance region, where the dark matter has approximately half the mass of the mediator. A combination of vector and axial-vector couplings to the Dirac candidate also leads to competing constraints from direct detection and unitarity violation.

In a second study, the work was extended to include a model with a vector dark matter particle that interacts with Standard Model particles via an s-channel vector mediator [Eur. Phys.J.C 83 8, 692 (2023)]. A new unitarity bound was derived to assist with the correct interpretation of missing energy searches at the LHC. Two parameter space regions emerged as consistent with all experimental constraints, corresponding to different annihilation modes of the dark matter. Although the models were found to be subject to strong validity constraints, they are currently most strongly constrained by measurements less sensitive to the high-energy behaviour of the theory. Understanding when these models cannot be consistently studied will become increasingly relevant as they are applied to LHC Run 3 data, raising important issues for the near future.

An alternative is to construct theories that are valid at high energy scales and explore their implications for lower-energy experimental measurements. The GAMBIT collaboration studied a Minimal Supersymmetric Standard Model with an eV-scale gravitino as the lightest supersymmetric particle, and the six electroweakinos as the only other light states [Eur. Phys. J. C 83 6, 493 (2023)]. Much of the parameter space was found to be excluded by current LHC searches, although there remain viable solutions which have a rich phenomenology. Crucially, these models feature multiple electroweakinos that would be within reach of the future LHC runs.

research activity plan for 2024

WIMP Direct Detection:

SABRE South:

- Fabrication of the shielding and commencement of its installation in SUPL
- Commissioning of the NaI(Tl) crystal handling glove box in a clean tent space at SUPL, and assembly of the first high purity crystal detector modules
- Continuous operation of the muon detectors for the analysis of flux and angular distribution of muons reaching SUPL
- Publications on photosensor characterisation, cosmic ray background, studies of induced annual modulation, and sensitivity studies for various types of dark matter candidates

R&D CYGNUS-Oz:

- Augmentation of CYGNUS-n prototype with intensified camera readout
- Translation applications with a focus on fast directional neutron detection
- Development of radon filtration and radon emanation measurement system

Current and next generation liquid xenon TPCs:

- Contributions to simulations XLZD design and sensitivity studies
- Contribution to detector monitoring sensors
- Transport and commissioning of the Xemis-1 prototype LXe system from Subatech Nantes, for studies of LXe - photosensor systems

AXION and WISP Direct Detection:

- R&D on quantum technologies and cavity resonators for ORGAN Phase 2
- Investigation of possible cryogenic implementation of UPLOAD and UPLOAD-ANYON, in a greater collaboration
- Continued investigation of low mass axion detection experiments to increase the range of axion masses covered, with the ADMX and ORGAN collaboration
- Continuation of ADMX sensitivity calculations, data analysis and simulations and modelling for future high and low mass extensions
- Continuation of improvements to existing Scalar DM detection experiments and extend their scope to search for WIMPs and gravitational waves

Precision Metrology (nuclear):

- Continued development of an AMS capacity to measure 210Pb at ANSTO accelerator
- Evaluation of the integrated fast isotope switching /time-of-flight detection systems
- Progression of ICP-MS measurement sensitivity and capability for 40K and other relevant naturally occurring radionucleotides
- Development of AMS capacity to measure fission product fragments

LHC:

- Completion of searches for final states with jets, flavour-tagged jets and missing transverse momentum
- Extension of analyses techniques for further novel searches for dark matter including using displaced vertices
- Improvement of hadronic jet measurements and algorithms to use global particle flow to better understand hadronic measurements
- Production and QC of the silicon detectors for the ATLAS inner tracker upgrade for High Luminosity LHC

Theory:

- Development of new techniques to probe low-mass dark matter
- Determine the impact of dark matter on neutron stars and other astrophysical systems
- Understand and quantify the impact of nuclear structure on dark matter direct detection rates
- Development of schemes to explain the dark matter mass scale in asymmetric dark matter models
- Perform global fits to dark matter direct detection data, incorporating nuclear, astrophysical and quenching uncertainties
- Determine constraints on and potential new signatures of well-motivated dark matter models.

SUPL update

2023 saw some exciting developments at SUPL with the appointment of a new SUPL Facility and Laboratory Manager. Kim Mintern-Lane manages the operations of the overall SUPL facility, with a major focus on safety, coordination of occupancy and access to the facility, and maintaining a close working relationship with Stawell Gold Mines.

Kim is based in Stawell, where she grew up and attended primary and secondary school and works closely with the SABRE South researchers and has coordinated training and the initial delivery of equipment to SUPL for the experiment.

Scientists received the first transmissions from a muon detector placed 1km underground in SUPL in late 2023 as part of a program to characterise the low-radiation environment inside SUPL. The muon detector records the amount of cosmic radiation that reaches the laboratory.

Muons are heavier versions of electrons that are made from the collision of cosmic rays with atoms in Earth's atmosphere. The muon detector records these collisions to determine levels of cosmic radiation.

It is crucial that low levels of radiation are recorded to ensure that the environment surrounding the SABRE South experiment, which will be transported to the laboratory in 2024, is as pristine as possible in order to detect dark matter particles.

In its first few days, the muon detector recorded about five detections per day, far lower than the 1.8 million or more interactions that would be expected above ground. This is an exciting milestone for the project as it shows that by building the laboratory 1km underground, it has significantly reduced the cosmic radiation that will reach the dark matter detector.

Sue Barrell, Chair of SUPL Ltd, said the milestone paved the way for scientific innovation into the future.

> *"SUPL is a unique facility, bringing together community interests and research objectives. It has been quite a journey to get to this point, but the ground is now set to deliver some world-class science outcomes."*

Mike Mews collecting data from the muon detector in SUPL

CDM PhD student Mike Mews was among the researchers who travelled into SUPL to set up the muon detector to communicate with computers above ground. Mike has also undergone training that will allow him to work underground for extended periods.

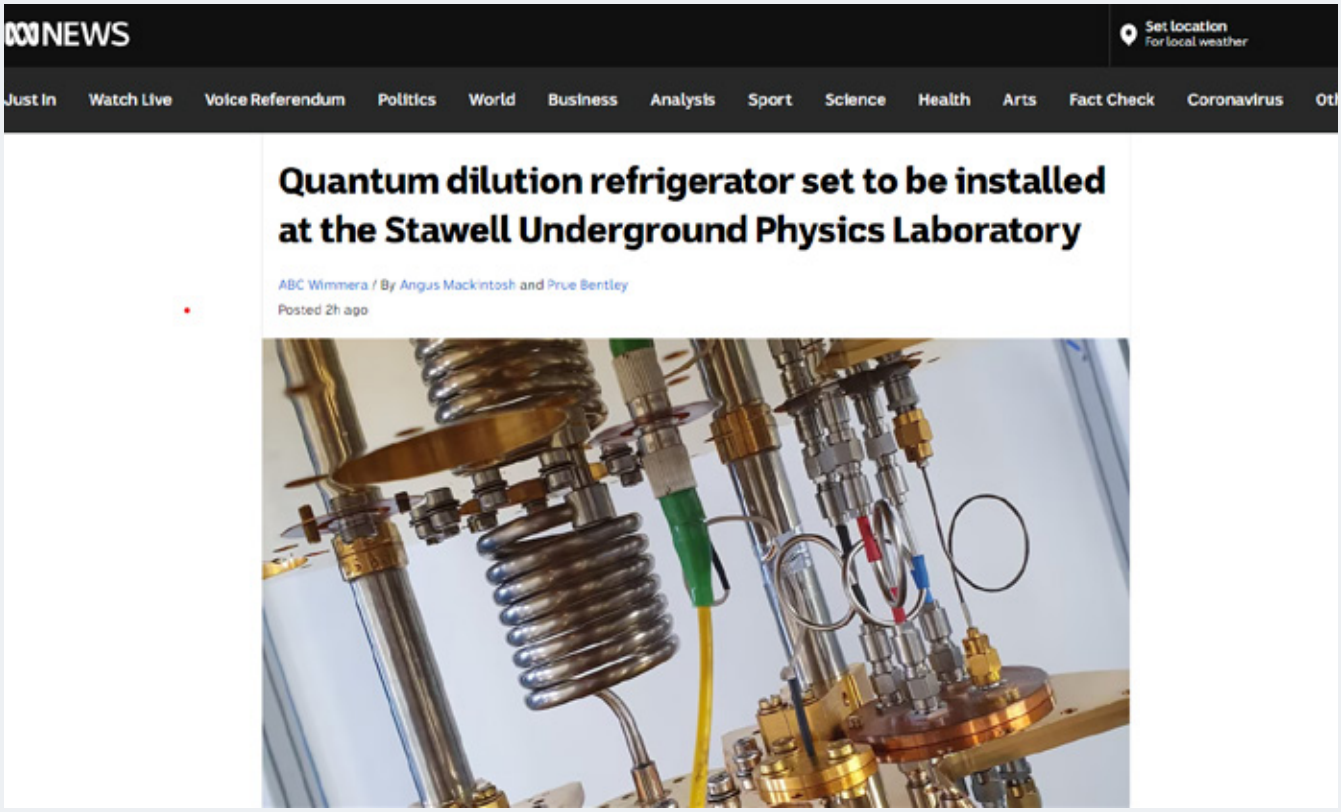
> *"It's really exciting that we can read the cosmic radiation levels deep underground while sitting at our desks at Melbourne University. I'm looking forward to travelling to SUPL more regularly as the project continues to progress and we create the ideal environment for the SABRE South experiment."*

Funding was awarded for a new facility, the Cryogenic Experimental Laboratory for Low-background Australian Research (CELLAR), which will be a huge boost for Australian research, attracting international and multidisciplinary collaborations, and advancing the growth of Australia's high-tech industry.

CELLAR will become a reality thanks to funding awarded to a collaboration of researchers from around Australia as part the ARC Linkage, Infrastructure, Equipment and Facilities (LIEF) funding scheme and will facilitate the purchase of two dilution fridges, one to be installed in SUPL and the other aboveground at Swinburne in 2024.

The team, led by Glen Harris from the University of Queensland and the ARC Centre of Excellence for Engineered Quantum Systems, includes CDM researchers from SUT, UoM and UWA. Glen Harris said, "Deep underground laboratories like SUPL are rare, with only a handful worldwide, and the number with high-tech cryogenic systems like CELLAR is even lower. We're very excited to be able to create this unique environment for world-class research here in Australia, enabling ultraprecise experiments for fundamental science, and new cutting-edge technologies."

The second fridge will enable comparative research between the surface and deep underground, allowing researchers to prototype experiments before deploying them in SUPL. This will be an open-access facility with unique capabilities, and the team expects CELLAR to attract strong international collaborations with multidisciplinary teams.



translation

Dark matter researchers attend CERN innovation program

Australian dark matter researchers boosted their innovative thinking with a pilot program at IdeaSquare, CERN in Switzerland.

Five CDM PhD students were selected to take part in the pilot at CERN's innovation lab, IdeaSquare, that aims to foster transformative thinking with the scientific and broader community using collaborative methodologies to innovate for the future of humankind.

Over two weeks Kenn Goh (UoA), Renee Key (SUT), Lachlan McKie (ANU), Hitarthi Pandya (UoA) and Owen Stanley (UoM) collaborated with innovation coaches and technical experts to build globally relevant innovation skills to expand their interdisciplinary thinking and employability skills.

In teams of between three and five they participated in a project challenge involving terraforming – imagining how they would adapt another planet for human life - as a method to apply scientific and technical knowledge in new ways to innovate for the good of the planet and its inhabitants.

CDM member and SUT's Design Factory Melbourne Academic Director Christine Thong said "This pilot program offers enormous benefits in both equipping dark matter researchers with the skills to bring an innovation mindset to their work, and to help create a culture of innovation within the wider scientific community."

> *"Now, more than ever, innovative thinking is crucial to helping us find new ways to tackle some of our most pressing scientific problems, from trying to understand the nature of dark matter to how we adapt to climate change."*

Owen Stanley said he decided to join the program because he wanted to get a better understanding on how the work that he has been doing can be translated to non-physics research.

"I'm hoping to be able to obtain a broader view of the world as well as connections with researchers I otherwise wouldn't have met." He said.

(Photo credit: Jimmy Poulaillon – CERN)

Renee Key said design and innovation techniques play an important role in her research.

"I'd previously expected that much of my research would build upon the work of others, but I've found myself needing to generate new techniques to reach our science goals, so I'm excited to learn more about innovation in science," she said.

> *"I'm especially interested in understanding keys to utilising current technology to build resourceful solutions to unexpected and emerging issues.*

"Also, I cannot wait to tour some of the departments at CERN, what a dream to be at one of the most influential facilities in physics!" she said.

Translation opportunity from search for dark matter

The search for dark matter can lead researchers in surprising directions, towards new information and unexpected discoveries. Postdoctoral researcher Jeremy Bourhill at UWA, has developed a device with the potential to drastically improve the efficiency of purifying chemicals for pharmaceutical manufacturing.

A large percentage of drug molecules are chiral; they exist as either left- or right-handed forms, referred to as enantiomers. They have the same mass and the same physical properties, and so are very difficult to separate from one another. However, there is a difference between the enantiomers when they interact with a similarly chiral system, such as the human metabolism.

When a drug molecule interacts with a human cell, it does so in a "lock and key" mechanism, and while one enantiomer will operate the lock and have therapeutic outcomes, the other will be ineffective or worse, can cause serious, unwanted side-effects. Purifying pharmaceutical products into their left- or right-handed forms is therefore an extremely important methodology.

The 3D-printed electromagnetic device Jeremy is developing creates a unique mixing of electric and magnetic fields, which can impart force on left- and right-handed molecules differently. This allows the two enantiomers to be separated from each other, and promises to improve the efficiency with which drugs can be purified.

Given the devices create this effect over a large volume, the filtering process, that currently costs the medical industry billions of dollars each year, can be carried out at a larger scale and more quickly, reducing costs and lowering the barrier for removing medical side-effects.

But Jeremy didn't develop this device with the pharmaceutical industry in mind, he was in fact looking for dark matter. The unique electromagnetic state generated inside the device actually makes it sensitive to the extremely light hypothetical dark matter particle called the axion. As he said in an interview with The West Australian:

"We wouldn't have invented this if we weren't looking for dark matter.

> *"You need to come up with new ways of looking at the universe and then naturally you can create new technology that has these unforeseen applications."*

He believes delving into the puzzle of dark matter calls for innovative solutions that often result in the creation of groundbreaking technologies that can be used for alternative means.

"It's the big reason to ask fundamental questions like, 'What is dark matter?' By the very nature of asking those questions, you require solutions that don't exist yet. If we don't know what dark matter is because no one's been able to see it, we need to come up with new solutions to see it."

case study

New device offers opportunities for mining and construction industries

The world-first use of a muon detector by the mining sector has highlighted the potential for blue-sky research to solve industry challenges.

Speaking at the AusIMM Mine Waste and Tailings Conference 2023, researchers demonstrated how a new muon detection platform had been used to scan large structures at BHP's Prominent Hill mine site, opening the way for these kinds of technologies to aid in monitoring stability.

Muons are heavier versions of electrons that are made from the collision of cosmic rays with atoms in Earth's atmosphere and can act as a kind of x-ray to visualise conditions within hundreds of metres of rock.

This characteristic of muons has been harnessed to provide mining and construction industries with the ability to 'see through' structures to detect weaknesses.

The platform was developed by mDetect, an innovative start-up comprising members of the Dark Matter Centre, including SUT CI Alan Duffy.

In an interview with Robyn Williams on The Science Show on ABC Radio National, Alan explained his joy at the translation of fundamental science to industry.

"It was a thrill to see something that came out of the most blue-sky, fundamental of research, to actually be used in the mining sector to try to safeguard these waste storage facilities; it was a wonderful moment."

He explained how the muon detector, developed with his cofounder and CDM AI Shanti Krishan, enclosed in a simple yellow protective case helped see through large structures to identify weaknesses.

"The origin of the muons is coming from space, or rather from our atmosphere … they travel down and they will punch through potentially hundreds of metres of rock before stopping.

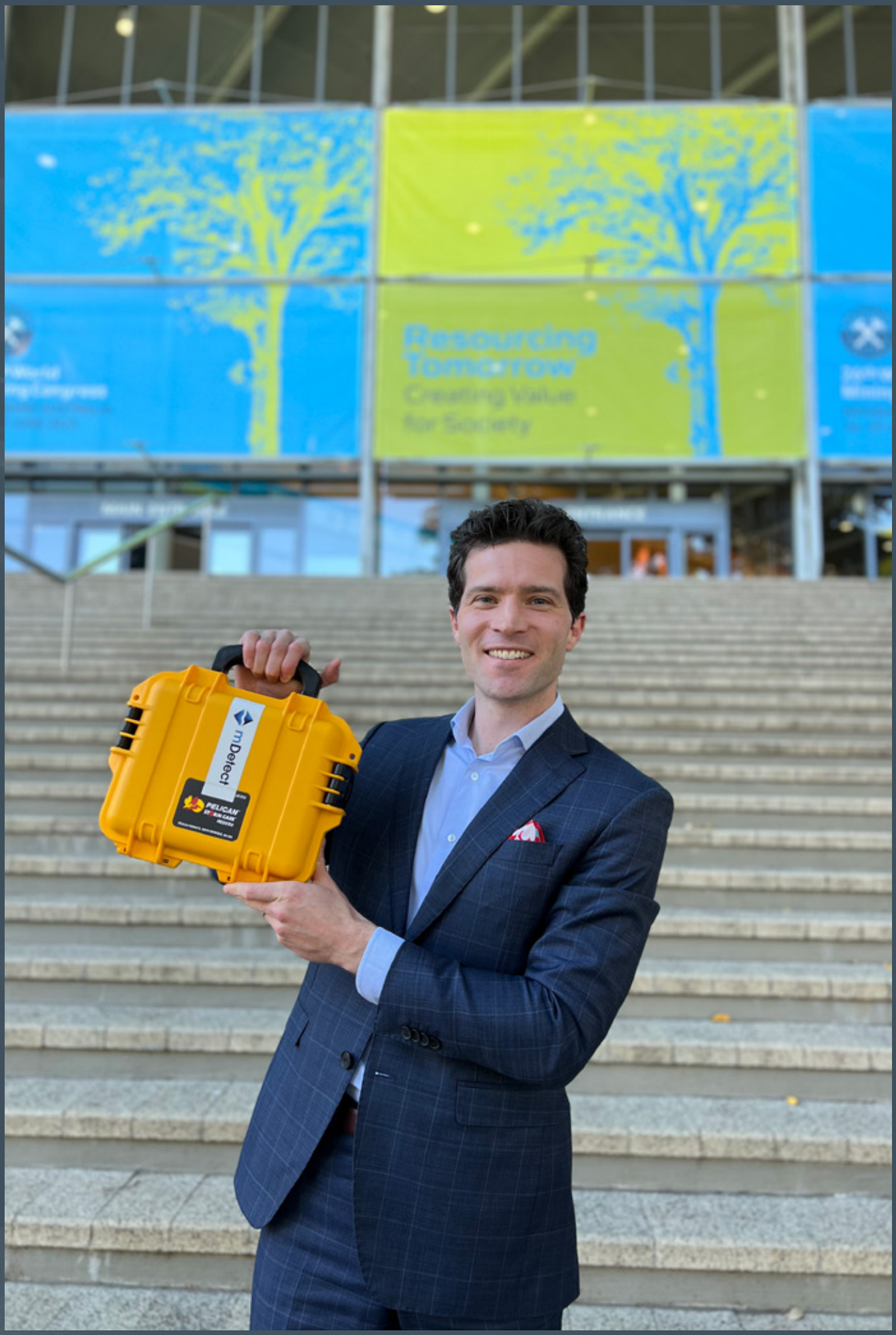
"If you put a detector such as this little yellow box underneath the area of interest the muons will pass through and if there is a dense structure they will get absorbed so you will get a shadow. If there is a crack or a large void you will have more arrive than you had anticipated and so that will be a hotspot.

> *"In other words, literally an x-ray using the highest energy particles we've ever recorded rather than your bog-standard x-ray machines."*

Alan said the innovation improved on existing techniques to efficiently and effectively determine the integrity of structures that could span kilometres.

"Certainly, you can use other probes and the challenge with anything to do with radiation detectors is that you have to use licenses and there are hazards of using that.

> "They prefer to use other techniques – surface scanning, they can even use satellite imagery to check the structural stability of these kilometers across enormous earthworks - but nothing gives you the ability to see quite like the superman-esque x-ray vision to see through the structure and reveal those areas of weakness. We really did provide something unique."


Resourcing
Tomorrow
Creating Value
for Society
mDetect
PELICAN

equity, diversity and inclusion

The Equity, Diversity, and Inclusion (EDI) portfolio exists to improve gender balance in STEM, support families and carers within the Centre, inspire a new, more diverse generation of STEM researchers, and build a culture of respect and inclusion.

The EDI committee includes willing representatives from each node. It has been very active in 2023, meeting on a frequent basis to prepare for Centre events and develop a strategic plan. In late 2022, we consulted Centre members about what training they would like in the future.

Based on the input of Centre members, we organised an in-person neurodiversity training session at the Annual Workshop. *Untapped Group* developed and led the session. This session involved lecture content on issues affecting neurodiverse workers. The lecture was followed by a brainstorming session, where Centre members were encouraged to reflect on how they could implement changes in their nodes to improve the working environment for neurodiverse individuals. The committee collated ideas from the brainstorming session. Now, they are using the ideas to make positive changes for 2024 and beyond. Some of the recommendations include a deliberate effort for more social scripts, improvements to meeting structures, and education on sensory experiences in a shared office.

There were additional initiatives that saw their debut at the Annual Workshop in 2023. The first was to invite participants to include a short cultural snippet in their talks and posters, allowing Centre members to learn about each other's cultural backgrounds, in addition to providing icebreakers for conversation at coffee breaks. Cultural dress was also encouraged for the workshop dinner. The second initiative was the creation of social scripts for workshop events, which are a recognised way of assisting neurodiverse participants. These proved to be very successful and will be repeated in future years of the Centre. Finally, we held an EDI afternoon tea, at which Centre members could meet the EDI committee in an informal setting and provide feedback and suggestions for future work.

"My impression is that this committee did an excellent job. The variety of initiatives and their innovative character worked well."

"I liked the inclusion of a social script…I can see how simply having an understanding of what to expect from the different aspects of the workshop could alleviate any forms of anxiety present in people who might be affected by that. For me, however, it was nice to have an understanding of what certain activities involved when otherwise it would not have been mentioned until the activity itself!"

As part of our work in supporting underrepresented STEM groups, the EDI committee sponsored the inSTEM Conference 2023, held at RMIT University in Melbourne. inSTEM is an initiative of the STEM-focused ARC Centres of Excellence. It is a networking and career development conference for higher degree research students and postdoctoral researchers from marginalised groups in STEM and their allies. The conference was attended by Centre members, including researchers Emily Filmer and Hitarthi Pandya.

The Centre continues to seed new tenure and tenure track positions within its nodes with a particular emphasis on hiring women, in line with its commitments outlined in the proposal. The University of Adelaide has now hired Dr Irene Bolognino, an established young leader in dark matter direct detection and neutrino physics. We are also actively exploring ways to increase the proportion of females and gender diverse people in the Centre student and postdoctoral researcher cohort. These activities have been supplemented by an increasing effort to address the Centre gender balance by ensuring that when new Centre members (eg. AIs and PIs) are added that gender balance is a key priority.

Ash Vance from Untapped Group giving a talk on neurodiversity to the room with curtains partly closed to reduce the level of bright light for participants with visual sensory sensitivities

media and communications

Through our Media and Communications activities, the Centre aims to develop and celebrate our members, highlight our research, promote diversity and inspire a future generation of researchers.

In 2023, the Centre's work and its members were actively promoted and featured across different platforms including radio, television, podcasts, social media, online and print media.

Promoting women in science

One of the aims of our media and communication activities is to help create a more diverse scientific community. This includes promoting the women in our Centre through the media to show students and potential scientists that they belong in the scientific community.

On International Day of Women and Girls in Science, we highlighted Nicole Bell's new role as Australian Institute of Physics President. Nicole was interviewed by Australian Associated Press and the article was syndicated across 219 titles including Canberra Times and SBS. Nicole was also interviewed on ABC Evenings with David Astle, and the story reached an international audience through Physics World and its podcast.

Zuzana Slavokovska was also interviewed on ABC Canberra on International Day of Women and Girls in Science, where she discussed her experience working in science.

During the National Quantum and Dark Matter Road Trip, Emily Filmer wrote about the need for greater diversity in science, and the importance of seeing the faces of diverse scientists. The article was published in Education Today, providing its audience of teachers with insight into the value of role models and outreach activities including the road trip.

Female Scientists no Longer in the Shadows

Scientist travelling around Australia to show girls the real face of science.

EMILY FILMER, ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS MEMBER
AUG 22, 2023

The face of science is changing.

Inspiring remote, rural and regional communities

The National QDM Road Trip was an opportunity to engage with regional, rural and metropolitan audiences, which is another way we are trying to promote science to diverse audiences. It was also an opportunity to share the excitement of our search for dark matter and featured on metropolitan radio stations, including ABC Melbourne, Perth, Brisbane and Victoria (statewide).

We worked to spread the message through the media coverage that science is for everyone, whether in the cities or the country towns we visited.

The road trip also provided an opportunity for students and Early Career Researchers from across the Centres' nodes to gain experience being interviewed by journalists, helping them develop media liaison and communication skills. These were low pressure opportunities as they were with local newspapers and radio stations. In preparation for interviews, ECRs spoke to the media officer about messaging and potential questions.

The EXPRESS

COMMUNITY & BUSINESS >

7 September, 2023

Road trip showcases science to students

ATHERTON and Dimbulah students had the opportunity to engage with leading Australian researchers during the National Quantum and Dark Matter Road Trip for National Science Week recently.

Students Chris Mentaiti, Chaz Nehow, Liam Hoskins, Jett Macfarlane, and Ben Howard, with road trippers Jesse Slim and Victoria Bashu, taking part in a gravity well demonstration.

Sharing the excitement of dark matter research

The Centre promoted its activities in order to highlight the value of fundamental research and generate an interest in science across Australia. We attracted media attention from ABC Breakfast TV and ABC Sydney when we transported muon detectors into the Stawell Underground Physics Laboratory.

We also highlighted Dark Matter Day among Victorian and ACT communities when our researchers spoke to ABC Canberra, ABC Melbourne and ABC Wimmera about our search for dark matter.


COSMOS

My Cosmos | Space | Tech | Nature | Earth | Histor
Biology | Chemistry | Engineering | Mathematics

Cosmos » Core Sciences

Dark matter lab in VIC gold mine detects first 'muons'

Stawell Underground Physics Laboratory launch. Credit: University of Melbourne.

October 27, 2023

Researchers at the Stawell Underground Physics Laboratory (SUPL) in

Building links with the community

While metropolitan media might reach larger audiences, we also value the interest of regional media in the search for dark matter. When we hold events or reach a milestone in our research, we engage local media, particularly in Stawell, to ensure we maintain a close relationship with the community. This ensures support for our research and the opportunity to reach rural and remote communities.

Social media

The Centre has a Twitter, Facebook, LinkedIn and Instagram account, and opened separate Instagram and Twitter accounts with EQUS to promote the National Quantum & Dark Matter Road Trip.

Through the Centre's social media channels we have showcased our researchers' work and successes, promote diversity and inspire future generations.

These channels also provide the opportunity to highlight our events and be involved in dialogue with the national and international academic and scientific communities.

Internal communications

The Dark Matters newsletter is distributed to Centre members every two months and features information about successes, opportunities and events throughout the Centre.

The newsletter not only provides information, but also helps build a sense of belonging within the Centre, especially in Cultural Snippet, Meet the Researcher and travel recounts. Engagement with the newsletter was high across the Centre, with the December edition opened 243 times. Popular articles include details on Annual Workshop registrations, media articles featuring Centre members and news about recent events.

Researchers communicate informally across the nodes via SLACK, using different channels for research, outreach and ECR activities. The Centre uses the Atlassian collaboration software Confluence to coordinate meeting agendas, store and share documents and technical information.

A Centre-wide meeting is held each fortnight, in which a member or invited guest provides information about their research, or other relevant topics.

media highlights and stats

Muon detector in SUPL on the ABC
572,958 views on ABC TV Breakfast and ABC News Sydney

The Dark Side of the Universe on Catalyst
Hosted by former CDM Advisory Board member Tamara Davis, a Catalyst special aired in April and available on ABC iview featured CDM scientists in the hunt for the dark universe.

X (Twitter) impressions

142,163

Twitter Followers

343 (2021)
725 (2022)
921 (2023)

Facebook impressions

10,700

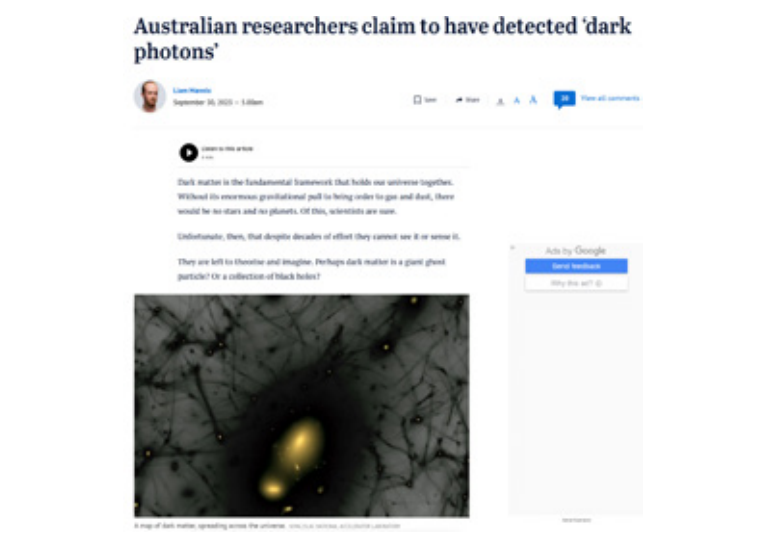
LinkedIn impressions

1,349 (2021)
10,518 (2022)
19,500 (2023)

LinkedIn Followers

139 (2021)
503 (2022)
756 (2023)

The Sydney Morning Herald profiled a scientific publication by UoA researchers on the modelling of dark photons.



Australian researchers claim to have detected 'dark photons'

In honour of International Women's Day, Nicole Bell and Celine Boehm featured in the COSMOS list of 50 women at the cutting edge of Science in Australia

COSMOS

My Cosmos | Space | Tech | Nature | Earth | History | Anthropology | Behaviour | Citizen Science | Culture

Cosmos » People

50 women at the cutting edge of science in Australia

Credit: Marc Blazewicz

March 7, 2023

Road Trip X (Twitter) impressions

19,500 (over a 2 month period)

Road Trip Facebook impressions

3,949 (organic)

23,713 (boosted)

outreach, education and engagement

The vision of the education and public outreach program of the Centre is to share the excitement and benefits of Australia's hunt for dark matter to inspire and train a new generation of innovative thinkers. In 2023, there were many oppotrunities for in person outreach and education activities and Centre members were able to interact with over 39 schools, visit and particpate in conferences and participate in over 27 public events.

Partner Schools:

In 2023, the CDM Regional Partner Schools program grew to add more partner schools in western Victoria, with schools in Ararat and Hamilton in addition to our original schools in Stawell and Warrnambool. The goal of this program is to cultivate long-term relationships with schools in areas traditionally underserved by science engagement programs.

In the first year of the partnership, CDM members led activities with all Year 7 classes at the school, as well as with any senior Physics students. In the second year, the lessons expand to those students as Year 8s in addition to the new Year 7s. This pattern continues with the goal of creating a longitudinal impact on student decisions to remain engaged with science and technology through their final secondary years and into tertiary education. The topics covered in these lessons not only include Dark Matter-related Physics topics such as gravitation, galaxies, and the Standard Model, but also broader understandings such as Scientific Inquiry, Experimental Investigations, and the evolution of Scientific Understanding.

Additionally, CDM offers engagement activities such as a student arts competition and science quiz games to better understand how they relate to the content they are learning!
The CDM is collaborating with the Faculty of Education at the University of Melbourne to assess the impact of these programs on regional student attitudes towards science and whether they change over time.

In 2023, the first observations in this study were completed and will continue through 2024. The CDM will be expanding this program to schools in regional New South Wales, providing opportunities for more centre members to directly work with students and schools, as well as developing professional development workshops for teachers from the partner schools.

Brauer College Extended Investigation Student projects:
In 2023, University of Melbourne CDM members Owen Stanley and Bill Melbourne mentored two Year 12 students from the CDM Regional Partner School Brauer College, a government school in Warrnambool, VIC. Secondary students Milo and Rain were identified by their Physics teacher during their Year 11 as students looking for an additional academic challenge. In conjunction with the Centre for Higher Education Studies, Milo and Rain undertook a year-long project focused on muon detection as part of a VCE Extended Studies course. In this course, they had to develop a research question, complete a literature review, take and analyse data, and report and document their findings in a short paper and presentation. CDM looks forward to expanding these opportunities to more students in partner schools closer to other nodes as we add more schools to the program.

case study

Engaging with Educators

One of the best ways to build student enthusiasm for learning science and, especially, Physics is to ensure teachers are well-supported to introduce exciting, contemporary topics such as Dark Matter into their classrooms.

Providing teacher professional development workshops broadens the reach of the Centre's outreach goals, by training the trainer. If teachers are supported with science content knowledge, curriculum-aligned lessons, and targeted activities, they can share their new understanding with students over many years. This philosophy has been at the core of the CDM outreach program since its inception and 2023 provided opportunities to build the CDM's education program for teachers.

The CDM targets local, state, and Australia-wide science teacher conferences to deliver workshops on how teachers can incorporate Dark Matter topics into their classrooms. Local and state-level events in Victoria, Queensland, and Tasmania ensured connecting with teachers across a diverse geographic area. A highlight of 2023 was (the Australian Science Teachers Association Annual Conference (CONASTA) conference hosted by the South Australian Science Teachers Association (SASTA). The CDM workshop 'Detecting the Unseen: Dark Matter from the Lab to the Classroom' was fully attended by the participants with teachers not only learning about CDM science but also playing the role of students by participating in the accompanying classroom activities. The session was very highly regarded and CDM's Jackie Bondell was invited to turn the session into an article for the SASTA Journal. The article was published in SASTA's double, year-end issue in November and was a testament ot the evolution of the CDM's teacher professional development programs.

Girls In STEM:

2023 once again provided great opportunities to engage with diverse student audiences across Australia. A highlight was an invitation to host two workshops as part of #STEMLIKEAPATSGIRL, an annual event for girls from around Far North Queensland hosted by St. Patrick's Townsville. At this day-long event, girls from Years 4 - 9 from local schools engaged in workshops related to science, technology, and maths. The Dark Matter workshop introduced the girls to the basics of dark matter science, including evidence for dark matter and what CDM scientists are doing to help understand what it could be. One of the activities that the students most enjoyed was the Dark Matter Mystery Boxes, which made them think about how people learn about things they cannot see! CDM has been invited back to this event again in 2024 and looks forward to bringing new activities and science updates to the students.

IPPOG: Meetings, presentations, Future Collaborations (Masterclasses)

2023 marked the first full year of CDM serving as the Australian host organisation for the International Particle Physics Outreach Group (IPPOG). IPPOG, headquartered at CERN, recently celebrated its 25th anniversary and is the preeminent international organisation of professionals and scientists focused on particle physics outreach. IPPOG has two yearly meetings, in which representatives from around the world gather to learn about best practices in physics outreach, share success stories from their home countries and labs, meet in working groups to advance projects such as physics masterclasses, and create new collaborations for future projects. In May 2023, CDM Senior Education and Outreach Manager Jackie Bondell attended the IPPOG meeting in Sofia, Bulgaria as the Australian representative. The meeting provided opportunities to learn more about the breadth of physics outreach programs supported internationally and to share with an international audience some of the core CDM programs such as the Regional Partner Schools Program and the National Quantum & Dark Matter Road Trip. Additionally, this meeting highlighted the opportunity to bring the Particle Physics Masterclass program to more students and teachers in Australia with new goals for 2024. Another key highlight of the meeting was a report of the early development of a dark matter Masterclass, with CDM joining in to pilot some of new activities with Australian students and teachers. IPPOG provides an essential conduit for CDM to be part of the broader international conversation on best practices for sharing Dark Matter science and research.

Public lectures

In addition to public lectures that formed part of broader events during National Science Week and as part of the National Quantum & Dark Matter Road Trip (detailed further below), Centre members gave a number of public lectures across the country.

- Elisabetta Barberio - *The Search for Dark Matter: Exploring the Universe a Kilometre Underground* for the July Lectures in Physics at the University of Melbourne
- Irene Bolognino - *The Hunt for Dark Matter in a Gold Mine in Australia* for the Astronomical Society of South Australia
- Nicole Bell – Detecting the Dark Universe for the Australian & New Zealand Association for the Advancement of Science
- Sara Diglio - *The search for Dark Matter and its implications for our understanding of the Universe* for the Alliance Francaise Apéro-Scientifique
- Alan Duffy (with Suzie Sheehy) – *How to Discover a Universe* during the 31st International Conference on Lepton-Photon Interactions

Quantum physics in the pub - Canberra

Following on from the success of Dark Matter in the Pub during National Science Week in 2022, Centre members Nicole Bell (UoM) and Navneet Krishnan (ANU) participated in Quantum Physics in the Pub. Nicole talked to members of the public about neutrinos and how these quantum shape shifters were essential to forming the Universe and Navneet talked about his dark matter research. This event was run by Phil Dooley (ANU & Phil Up On Science) and coincided with the ANU Summer School.

Dark Matter Day at ANU

To celebrate the day of the mysterious substance called dark matter, researchers from the ANU and the University of Sydney met with dark matter enthusiasts and curious minds on October 30, 2023. It was an exciting in-person event with a range of interactive demos on display and presentations about one of nature's biggest mysteries and offered the participants the opportunity to delve into the enigmatic world of dark matter. The event was a great success!

Suzie Sheehy and Alan Duffy at the Lepton Photon public lecture.

Caption: Dark Matter Day at ANU: Ferdos Dastgiri (ANU), Zuzana Slavkovska (ANU), Lindsey Bignell (ANU), Ciaran O'Hare (UoS), Ellen Sirks (UoS)

Spooktacular at Swinburne

To celebrate Halloween, Dark Matter Day, and the return of the Swinburne CAS Public Lecture series, CDM partnered with OzGrav to host a Halloween Spooktacular.

The theme for the evening was 'Things That Go Bump in the Dark', and featured three short-form talks by Professor Matthew Bailes, Yuanming Wang and Renee Key on topics ranging from a new gravitational wave interactive VR tool, discovering luminous pulsars, and making tiny black holes in the universe. A short panel session after the talks allowed the audience to ask any burning questions that came to mind, like 'What would happen if a black hole flew past Earth?'.

Swinburne students hosted VR games and a virtual sky tour for attendees after the lecture. The event was held on campus at Swinburne and drew a diverse crowd of science enthusiasts and students. It was the best display of Halloween costumes in the Greater Melbourne district. Notable mentions of costumes go out to Schrodinger's Cat (Jackie Bondell - pictured), Science Barbie, and the crew from Adventure Time.

The Spooktacular event was a huge success, and the short-form talk format was a hit with the audience, as it allowed for a more engaging and interactive experience and helped the audience gain a broad perspective of the varied science between CDM and OzGrav.

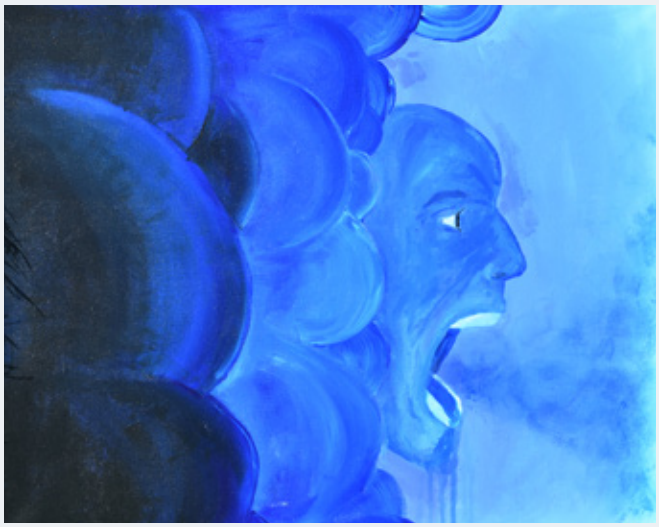
By Renee Key (SUT)

dark matter art

High School Art Competition

In our annual high school art competition, students used what they learnt from the web and visits to their schools by the Centre to create unique and original artworks, representing their interpretation of a dark matter particle. Competition winners received a certificate and gift voucher from the Centre.

Y7-9 category – winner – Taylor, Monivae College, Hamilton
Into the Dark - What inspired me to create this was that we don't know. We don't know what Dark matter is so I painted my interpretation of Dark matter.



DARK MATTERS – Unseen & Unknown

The partnership between the Science Gallery Melbourne and CDM was very active in 2023, culminating in the free exhibition DARK MATTERS. The exhibition was a collaboration between the Science Gallery, Arts at CERN and the CDM, and was co-curated by Head of Arts at CERN, Monica Bello, and Head of Curatorial at Science Gallery Melbourne, Tilly Boleyn, in collaboration with a curatorial panel of young people.

The exhibition aimed to explore the fundamental essence of life and the universe, and how so much of it remains a mystery to us. DARK MATTERS through local and international experimental projects – some developed in conversation with our scientists and researchers – explored life and all the dark matter that flows through it, under it and collides with it.

The centrepiece of the exhibition was Chroma V by South Korean artist and electronic music composter Yunchul Kim (featured on the front cover of this report). Other exhibits included:

In this room. Everywhere – by Alicia Sometimes & Andrew Watson featured contributions from Alan Duffy, Ben McAllister and Grace Lawrence.

Scientific Dreaming – by Suzanne Treister (pictured below) featured contributions from Elisabetta Barberio, Jeremy Mould, Ray Volkas and Theresa Fruth.

A book created as a complement to the exhibition is titled 'Sight Unseen' and features images from SUPL on its cover. The book is available through Perimeter books and features a contribution from Elisabetta Barberio.

Inspired by the first image of a supermassive black hole in 2019, the book considers phenomena in our universe and once hidden from human sight, now made visible through the combined efforts and outputs of artists and scientists. It is a collection of essays and images that draws on Western and First Nations knowledge systems to ask readers to see together.


DARK MATTERS
UNSEEN & UNKNOWN
05.08.23—02.12.23
IN COLLABORATION WITH ARTS AT CERN
FREE ENTRY
DARK MATTERS is an exhibition created in collaboration with Arts at CERN and the ARC Centre of Excellence for Dark Matter Particle Physics exploring the fundamental essence of life and the universe, and how so much of it remains a mystery to us.
CONTENT WARNING:
ARTISTS, RESEARCHERS AND COLLABORATORS:
Alan Bogana, Professor Alan Duffy, Alicia Sometimes, Andrew Watson, Anne Pfeifer, Dr Ben McAllister, Bernhard Kreutzer, David Hochgatterer, Dom Chambers, Professor Elisabetta Barberio, Grace Lawrence, Emeritus Professor Jeremy Mould, Jesse Wolpert, Joe Gerhardt, Jon Butt, Julijonas Urbonas, Lawrence Leung, Marc Vilanova, Patricia Domínguez, Professor Phillip Urquijo, Professor Raymond Volkas, Robert Andrew, Ruth Jarman, Semiconductor, Suzanne Treister, Dr Theo Papatheodorou, Dr Theresa Fruth, Dr Vyom Sharma, Yunchul Kim.
DESIGN:
Studio Peter King, Forde + Nicol
MAKERS AND SHAKERS:
Aaron C Carter Carpentry, Bollinger+Grohmann, Brennan & Hemmings Constructions, Flys Alone Painting, Focused Fire Engineering, Get Rigged, Image Box, Reveal Productions, Steve Watson & Partners, Studio Tops, Substraight.
Science Gallery Melbourne is part of the Museums and Collections Department at the University of Melbourne.
This exhibition is only possible as a result of the brains, spark, good humour and excellent work of this team of human delights.
TOYOTA
DCFI
Arts at CERN

dark matters in numbers:

41,910	**A record total visitors to the gallery**
14	**artworks from local and international artists, scientists, and research collaborators**
12	**public programs including Friday night socials and National Science Week**
481	**attendees to the opening launch event**
75,827	**muons detected**
89%	**of visitors were satisfied with their visit**
85%	**of visitors were first time visitors to science gallery**

During National Science Week, over 700 school students from 30 schools participated in DARK MATTERS tours and hands on STEAM workshops. Some highlights of events that Centre members participated in included:

- **Kids vs Science** with local children aged 8-16 interviewing leading scientists from across Victoria
- **STEMx Speed Networking** – for women and gender diverse people working in STEM
- **STEAM Careers Forum** – Innovation & Future Industries
- **Supporting two First Nations artist residencies** – Jackie Sheppard and Tyler Willay

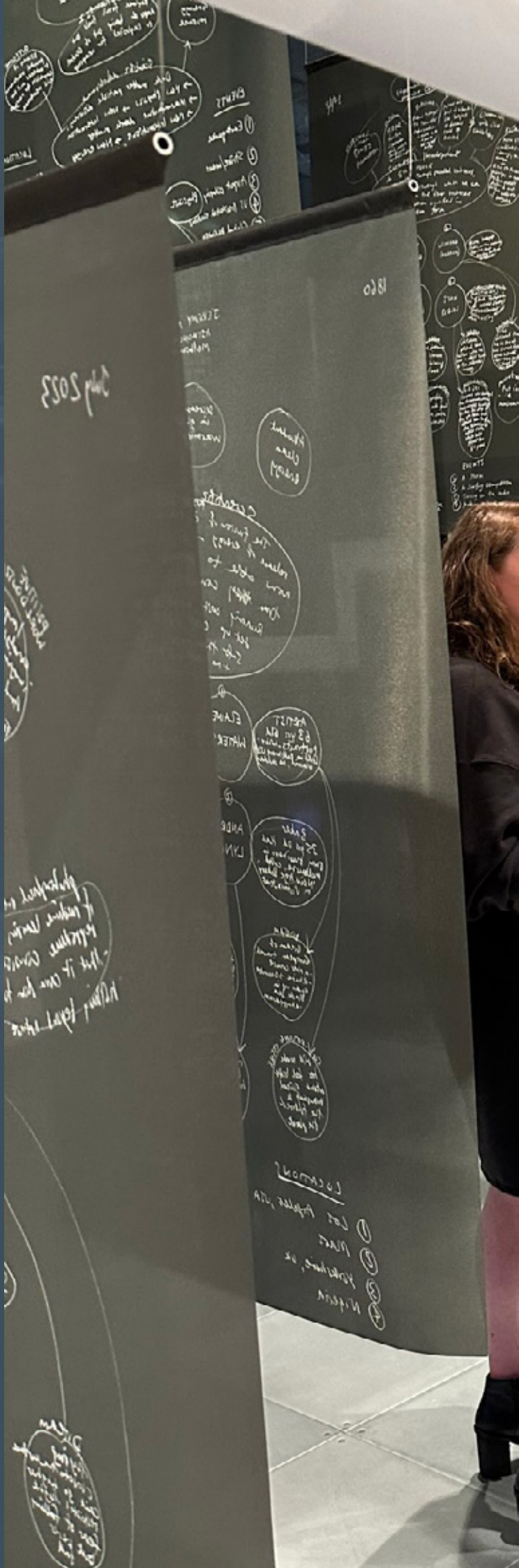


Photo credit: Jacinta Keefe Photography

national science week

Centre members participated in a range of activities to promote science to students and the wider community during and around National Science Week 2023.

These included a public lecture in Stawell, a national road trip partnering with the ARC Centre of Excellence for Engineered Quantum Systems (EQUS) and various events at the Science Gallery Melbourne (mentioned above). Centre researchers at all of these events engaged with schools and the community to educate, inspire and spread the word about dark matter.

Public lecture in Stawell

As part of National Science Week, Centre Chief Investigator Phillip Urquijo travelled to Stawell to present a talk at the Town Hall. The talk covered the basics of dark matter and why Centre researchers have built an underground laboratory in Stawell Gold Mines, provided an update on the project, and discussed similar projects around the world.

The Stawell community asked questions that ranged from the role of religion in the Big Bang to the implications of finding dark matter.

They also asked about whether the Stawell Underground Physics Laboratory would be used for other research in the future. While the SABRE South experiment will be the initial major research carried out in the laboratory, it is planned that further research – whether in the areas of geology, biology or other fields – will be located on the site.

Professor Urquijo said the discovery of dark matter would solve a great mystery of the universe, and potentially lead to unknown scientific breakthroughs.

His talk was supported by SUPL Laboratory and Facilities Manager Kim Mintern-Lane.

The Centre is committed to partnering with the Stawell community in the SABRE South project, through its community and school outreach work.

National Quantum & Dark Matter Road Trip

The 2023 National Quantum & Dark Matter Road Trip has once more been deemed a huge success, visiting 18 schools and delivering 12 public events across Australia.

During the road trip, which was part of National Science Week, ARC Centre of Excellence for Engineered Quantum Systems (EQUS) and the ARC Centre of Excellence for Dark Matter Particle Physics (CDM) members visited regional and remote Victoria, New South Wales and Queensland.

Pop-up events including public talks, pub trivia, demonstrations and a workshop were also held in capital cities across the country as part of the road trip.

Promoted via a dedicated website and social media as well as the National Science Week website, by the end of the event, road trippers had reached more than 1,600 people at schools, universities, pubs and community hubs across the country.

Feedback from students, teachers, public event attendees and road-trippers was overwhelmingly positive.

Road trippers also enjoyed the opportunity to inspire a new generation of scientists living in rural and remote parts of Australia.

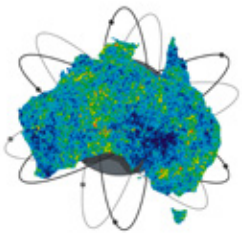
Highlights of the event included a Town Hall with MP Monique Ryan, a science/art workshop and public lectures in Adelaide, Melbourne, Sydney, Perth and Brisbane.

The school visits were well-received by students and teachers, with 81% of students reporting they learnt something new from the session, 65% would recommend the experience to others, and 69% feeling that the session was a good way to learn about physics.

The response to public events was also positive, with participants describing the pub trivia and public talks as, ‘amazing’, ‘engaging’ and ‘interesting’.

Road trip organiser and participant, Ben McAllister said this year’s road trip was a rewarding experience.

> *“I continue to be pleasantly amazed by the questions students have. By far my favourite question of the trip was, ‘Where does wind come from?’ It was clearly something the student had been thinking about for a while but needed the opportunity of having eight scientists in the room to satisfy his curiosity.”*



NATIONAL
Quantum & Dark Matter
ROAD TRIP

Road tripper and PhD student Victoria Bashu, said she appreciated the opportunity to meet students and share her experience.

“The trip was full of highlights. One of them was a student coming up to me and asking what path I took to be a scientist. A few years back, I was a high school student and today I, alongside the full team, am inspiring these young minds. That was very special.”

The scientists came from eight universities, representing theorists, experimentalists, physicists and engineers. They also had diverse backgrounds in tems of gender, ethnicity and research interests.

The CDM members who joined the trip were: Victoria Bashu (ANU), Jackie Bondell (UoM), Emily Filmer (UoA), Ben McAllister (SUT), Peter McNamara (ANU), Hitarthi Pandya (UoA), Steven Samuels (UWA) and many others across the Centre participaing in the public lectures, pub quizes and demo day.

Our early career researchers were provided with opportunities to be interviewed for print and radio media and practice their science communication skills with new participants being trained and mentored by experienced participants and the CDM Media Officer.

This year’s road trip was funded by EQUS, CDM, a National Science Week Grant awarded to EQUS and CDM, and DTAC Wangaratta.

Thank you to all the road trippers, communities and schools who participated in the event for your enthusiasm and passion for sharing the excitement of science.

Road trip stats

34	scientists and science communicators
16	CDM members across the nodes
20	days of road tripping activities on the odometer
9,511	kilometres on the odometer
18	school visits
12	public events
24+	cities & towns
2000+	items of merch
1600+	people engaged
900	students
160	pub goers
120	attendees at other public events
1	30th Birthday

Winton State School, QLD

Mallacoota College, Victoria

Lavington Library art science workshop – Albury, Victoria

Djarragun College, Qld

Public lecture – Swinburne University of Technology, Victoria

Pub trivia – Wangaratta, Victoria

Road trippers – Vic/NSW leg

ECR report

Early Career researchers are the lifeblood of research, and the Centre is heavily invested in providing development and opportunities for ECRs. To facilitate this goal, the Centre elects representatives to form an ECR Committee each year, with two representatives on the Centre's Research Committee, and one on the Executive Committee.

In 2023 the ECR Committee consisted of Ferdos Dastgiri, Ellen Sirks (Research Committee) and Jayden Newstead (Executive Committee).

The ECR committee began work around June 2023, with a focus on implementing feedback given by the ECRs in previous surveys. The main feedback was that ECRs wanted more internode collaboration and exposure. The main goal of the committee has been to provide informative sessions to the ECRs, that will also run outside of the annual workshops.

The annual ECR workshop was a great success, receiving very positive feedback from across the Centre and was organised and attended only by ECRs. When planning the workshop, the committee took steps to address previous feedback, including: making the social activity more inclusive, including a social script, having some unstructured time, holding focus sessions with practical advice and adding more ECR talks (however some of these ended up being included in the main workshop).

One of the focused sessions was on mental health and wellbeing. Working with the EDI committee to provide an opportunity for the ECRs to develop mental resilience, especially in the context of academia, we decided a mental health and wellbeing session was best delivered during the ECR Workshop. While covering this topic was generally appreciated and recognised as important, we received feedback that suggested improvements such as more practical suggestions and tips. In 2024, we plan to have more regular, targeted sessions focusing on this important issue and leveraging opportunities such as the CDM fortnightly meetings.

The other focused session provided career advice with the aim of building the confidence of ECRs and provide tangible advice which can help them stand out to future employers. The session included a panel discussion with a seasoned academic (Professor Martin White) and an industry expert in a hiring position (Emma James, Funds South Australia). This session had very positive feedback and as a follow up, the ECR committee created a public Confluence page with job advertisements. The engagement with the Slack channel has also been increased and encouraged, to allow for quick communication of this information and discussion. In the future we aim to empower ECRs to build and make use of the professional networking opportunities available through the Centre and provide more resources for ECRs finishing their studies or current work.

> *"The workshop exceeded my expectations. The organisers…did a great job organising everything, including little details as well as delivering the workshop. An ECR survey assured that the participants were satisfied with the workshop agenda and allowed people to express any wishes how to make them more comfortable, resulting in several improvements like the information whether a session was interactive or not, the implementation of a social script and more.*

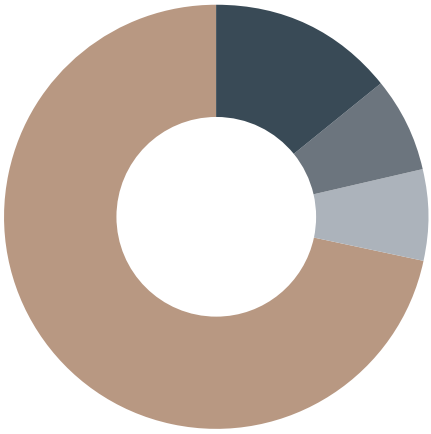
My favourite part was the interactive design challenge "Build your own detector" led by Theresa Fruth, in which my team proposed to build a laboratory deep down under the ocean. Several other highlights of the workshop include the academic job advice session, the networking session in a cocktail lounge and the lecture on presenting plots from Ciaran O'Hare. The latter has influenced my view on plot making and motivated me to care more about the little details on my plots! – Zuzana Slavkovska"

Following the annual workshop a survey was circulated to get anonymous feedback from all attendees. Some selected comments:

"I really enjoyed this meeting. It was well organised, well moderated and I appreciate your effort, Ellen, Ferdos and Jay!"

"I really enjoyed the ECR workshop this year and it was very well organised. Thank you for putting so much effort. A huge shout out to you three :)"

"Very successful event, amazing job!"



Satisfaction with the ECR workshop.

- Very satisfied (71.4%)
- Somewhat satisfied (14.3%)
- Neither satisfied nor dissatisfied (7.1%)
- Somewhat dissatisfied (7.1%)

Trivia night social event

special initiatives ECR funding round

2023 saw the first funding round of ECR Special Initiatives. Students and ECRs could apply for funding for projects to promote collaborative visits between the nodes or to international laboratories and to pursue their own new collaborative research ideas.

Special Initiatives funding can support all aspects of Centre activities including research, mentoring, outreach, equity, diversity & inclusion, and translation.

Six projects were funded and a summary of the projects and progress achieved in 2023 is outlined below.

Establishing a computing subgroup – Jayden Newstead (UoM) and Matthew Green (UoA)
The goal is to bring together Centre members from all research themes, nodes and levels to meet and discuss advancements in computing, share their skills and experience, and foster internode collaboration. The first event will be run in February 2024 – a 3 day workshop aimed at improving the computing skills of ECRs across the Centre.

Dark Matter Centre colouring book – Theresa Fruth (UoS) and
Theresa Fruth and a team of ECRs across the Centre have started to produce a dark matter themed colouring book aimed at school children (8+). The aim is to highlight the research happening in the centre, by explaining basic concepts of dark matter and the experimental search for it. There will be four topics: Astronomy, direct detection, colliders, and wave-like dark matter. Each topic has a group of ECRs assigned to it, who are currently coming up with drawing and puzzle ideas, as well as suitable artists.

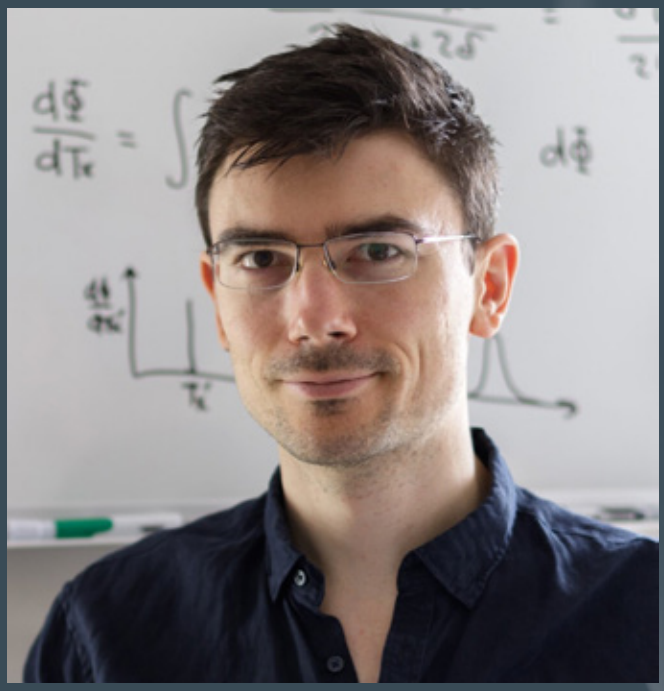
New Low Mass Axion Detection Program – ORGAN Low Frequency – Ben McAllister (SUT), Aaron Quiskamp (UWA) and Elrina Hartman (UWA)
This funding supports the purchase of various pieces of critical equipment for a new axion detection experiment within the Centre, complementary to existing searches. Specifically, the project is a low frequency/low mass axion detection program which can be viewed as an extension of the ORGAN program. It will leverage and strengthen the collaboration between the SUT and UWA nodes and will be housed in the 3T MRI machine at SUT.

Particle meets quantum, fostering collaboration with a muon detector for use with precision quantum experiments – Peter McNamara (ANU) and co-applicants at SUT, UoM, UoA and UWA
This project aims to foster collaboration between particle and quantum physicists working within the centre, leading to cross pollination of ideas and expertise. Funding will support the construction of a small muon detector to measure the cosmic ray flux in coincidence with precision quantum experiments at UWA such as MAGE and ORGAN. The purpose of this is to understand how cosmic rays might interact with these experiments, potentially causing spurious signals. This detector is intended to be the first phase of muon detectors to be used with quantum experiments. Future applications can include using these muon detectors in conjunction with qubit coherence measurements to understand how cosmic rays can limit quantum devices.

The Universe Makers – Ellen Sirks (UoS) and collaborators at SUT
The aim is to produce an outreach demo similar to the Universe Makers exhibit of Durham University. The exhibit contains interactive demonstrations allowing participants to run simulations of the Universe which are then projected as holograms. The demo will be adapted to be more focused on the research in the Centre, demonstrating for example the effects of different dark matter models. All the mechanical and software plans have now been shared, and so they can start adapting the software, and build the first demo.

Super-SIMS to characterize ultra-low 40K concentrations in NaI crystals – Dominik Koll (ANU/HZDR) and Zuzana Slavkovska (ANU)
One of the main radioactive contaminants in low-background experiments is the primordial radionuclide 40K. Inductively-coupled plasma mass spectrometry (ICP-MS) is regularly used to quantify potassium (K) concentrations, though suffers from molecular interferences and dilution effects. This is an exploratory project to quantify the contaminant K in sodium iodide (NaI) using the alternative mass spectrometric technique of secondary ion mass spectrometry (SIMS) and combining it with an accelerator mass spectrometry (AMS) system. This new Super-SIMS is installed at HZDR and has the potential to be superior compared to other techniques due to the inherent destruction of molecular interferences and the use of solid samples with no dilution.

member profiles



"I wanted to have an opportunity to provide ECRs with experiences and training which would not just support their journeys in academia but also continue to foster a feeling of community within the centre. So far, I have enjoyed the experience; it's much tougher than I expected but also very rewarding."

Jayden Newstead

Jayden Newstead's contribution to the Centre spans beyond the research he is undertaking close to the interface of theory and experimental particle physics.

He is involved with the DARWIN and CYGNUS-Oz collaborations, but also in providing valuable development opportunities for Early Career Researchers (ECRs).

For more than 12 years, Jayden has been part of the DARWIN collaboration, working to set goals for the experiment, determine the effect of neutrino backgrounds and determine what could be learned about neutrinos using the experiment.

More recently, he joined the CYGNUS-Oz collaboration, working on the simulation of physics signals and forecasting the experiment's sensitivity.

"The prospect of bringing this ambitious direct detection experiment to Australia is very exciting," he said.

"I'm particularly interested in exploring the Migdal effect in gaseous detectors and looking at non-standard directional signals of dark matter and how they can be discriminated."

In a publication last year, Jayden explored the detection of light dark matter with fixed-target experiments. This work developed a new and improved method for detecting dark matter particles in nearby neutrino detectors by observing the decay of nuclei excited by the inelastic scattering of dark matter.

This method significantly improved on similar previous searches which used elastic scattering.

Alongside his research, Jayden is dedicated to supporting ECRs through his role as a member of the ECR committee, which meets to discuss different ways of improving the experience of researchers at a range of events throughout the year.

With the help of a Special Initiatives Grant, he implemented a computing workshop to provide a crash course to research computing that would teach PhD students some of the basics and hopefully save them time in the future.

mentoring committee report

It has been an exciting year for mentoring and personal development within the Centre. 2023 welcomed a new mentoring committee, which included Darren Croton (chair) from SUT, Michaela Froehlich (co-chair) from ANU, Irene Bolognino (UoA), Maxim Goryachev (UWA), Jayden Newstead (postdoc representative) from UoM, and Chiara Lisotti (student representative) from UoS. This new committee met several times across the year to plan events and coordinate with the other committees within the Centre.

The standout mentoring event of 2023 was the launch of Mentorloop, a joint initiative between 12 ARC Centres of Excellence, including the Dark Matter Centre. Launched on June 7th by ARC Deputy CEO Dr Richard Johnson, the ARC Mentorloop platform offers Centre members a unique way to engage with mentors and mentees both within and beyond the Dark Matter Centre community. With ~40 active participants already engaged among a larger pool of ~350 members across all Centres, Mentorloop presents a valuable opportunity for researchers, professional staff, and industry experts to cultivate meaningful mentoring relationships. Beyond fostering connections, the program provides tailored insights, advice, and career advancement opportunities, shaping a collaborative environment conducive to personal and professional growth.

To further promote Mentorloop and mentoring within the Centre, on October 18th, the mentoring committee conducted an online seminar titled "*How to get the most out of your mentoring experience to accelerate your career*," for both the Dark Matter Centre and ASTRO 3D. The session provided general guidance on mentoring, preparation, expectations, and various tips and tricks, followed by a panel discussion featuring experienced mentors, including Centre Director Elisabetta Barberio. The session allowed time for questions and discussion and, was recorded for future reference by mentors and mentees.

Following this, on October 26th, the Dark Matter Centre and ASTRO 3D again collaborated to organise an online speed mentoring event using the Twine platform. The event, designed to be both fun and informative, allowed mentees to quickly gather broad career advice from a diverse array of mentors. The hour-long session brought together 18 participants for a series of rapid 4-minute conversations, resulting in a total of 56 connections and 224 minutes of valuable dialogue. The fast-paced nature of the event created an energetic atmosphere, making it an engaging and effective networking opportunity for all involved.

Finally, speed networking was extended to an in-person event at the Dark Matter Centre Annual Workshop, held from November 29th to December 1st. With approximately 50 participants, networking sessions were structured in rounds of 5 minutes, fostering a vibrant (and often chaotic!) atmosphere in the room. The event garnered enthusiastic engagement from attendees. Feedback from both mentors and mentees was overwhelmingly positive, highlighting the value of the experience. Some international AIs, initially hesitant, expressed excitement about implementing similar networking events at their respective universities after witnessing the success firsthand.

training and development

CDM is committed to the development all of its members. In 2023, the Centre offered a range of formal and informal training activities, many with a strong focus on equity, diversity and inclusion.

These included:

- A Neurodiversity seminar and workshop - Untapped Group (CDM annual workshop)
- Future Science Talks – Science Comedy Program
- IdeaSquare Terraforming at CERN
- Working in confined spaces – training to work in the SABRE South vessel
- Refresher training, working in confined spaces and at heights
- Formal induction training at the Stawell Gold Mine to work in SUPL
- Online mentoring training seminar
- Grant writing tips – online seminar
- Academic Job Advice (ECR workshop)
- How to make a plot (ECR workshop)
- Mental Health and Wellbeing Session - Student Wellbeing and Access, University of Adelaide (ECR workshop)
- Sharing your Science - Outreach workshop (ECR workshop)
- ExperiTECH from Lab to Market – a practical workshop run by Swinburne Design Factory Melbourne for Innovation + Enterprise services

CERN Innovation program reflection by Hitarthi Pandya

Attending the Terraforming program at Innovation Lab was an incredibly fun, immersive and introspective experience. Most days we would work on a different problem (or analyse a different angle to a past problem) and work through ideas as a team.

Because the problems were always so complex, it was always fascinating to see how the rest of the team interpreted the problem, which aspects they wanted to focus on and what types of concerns were brought up to discuss further.

With such a diverse team, exciting aspects were always raised, which always took us on wild detours that were really enjoyable.

An important thing I learned was that solutions to problems don't only have a positive impact; sometimes there are negatives, and they may outweigh the positives. Especially with complex problems, solutions will rarely have only positive impacts. Thus, its crucial to scrutinise a solution from every angle to make sure all possibilities are known.

I also learned a lot about myself through this experience in terms of how I work and resolve issues. In a team-based environment, it is critical to be able to communicate and listen to ideas, build upon them and come to a final conclusion; and it's not always easy. But I think I am much better at these aspects than before.

"I really enjoyed the two weeks I spent at Innovation Lab, and the whole experience is filled with memories I will never forget!"

CDM Vacation Studentships

Over the 2022/23 summer vacation period, CDM supported six vacation studentships across each node of the Centre. Students underwent a competitive application process and were selected to undertake a 4-8 week dark matter research project.

Mia Horsfall undertook a studentship at Swinburne University under the supervision of Darren Croton and Robert Mostoghiu Paun. She had completed second year of undergraduate physics at UoM and her project was to investigate the assumptions invoked in the Standard Halo Model (SHM) and analyse the implications of any differences found within values calculated from our assumptions and commonly quoted values of SHM.

Mia reflected "*My time at Swinburne and with the Centre for Dark Matter has been the most rewarding and dynamic experience I have had in my two years at university.*

> *It is not an exaggeration to say that I feel as though I have learnt more about practical application of theory in these 6 weeks than I have in any single subject in my course. I am incredibly grateful to the Centre, Professor Croton, Doctor Mostoghiu Paun and all the other Swinburne staff for accommodating me during this time and opening my eyes to what a career in research may look like."*

During his studentship at UoM, Hank Hua developed a machine learning-based technique of cleaning up and reducing noise in the photomultiplier tubes (PMTs) that will instrument the SABRE South veto detector.

By making use of a machine learning algorithm called a boosted decision tree (BDT), Hank combined a number of variables describing the properties of a PMT signal (including a novel Fourier transform based variable he developed himself) in order to distinguish between a single photon "signal" data-set and a dark "noise" data-set. Where dark, in this case, refers to the fact that there is no light incident on the PMT i.e. no external signal.

Whilst some noise sources are expected to look near identical to the single photon signals (like the PMTs inherent thermionic noise), other sources of noise (such as electronic/RF noise) could perhaps be identified by Hank's algorithm. After developing, testing, and verifying his machine learner, the results indicated that it is indeed possible to discriminate between single photon signals and some forms of noise. See Figure 1 which shows how often the learner correctly identifies signal events, and falsely identifies signal events, based on the threshold placed on the BDT score (Figure 2). Noticeably, performance improves when Fourier transform variable (FFT) is included, implying some noise might be RF-like.

Whilst some additional work needs to be performed to understand the noise sources we're discriminating against, Hank's work is nearing publication and will be of use to the wider SABRE South experiment as a tool to clean up the datasets from unwanted noise and background.

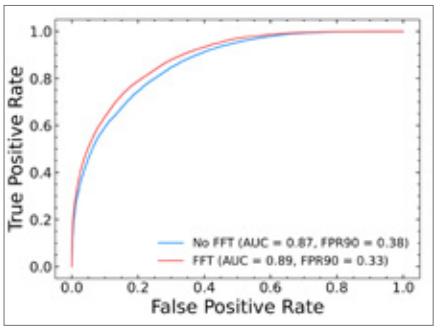


Figure 1

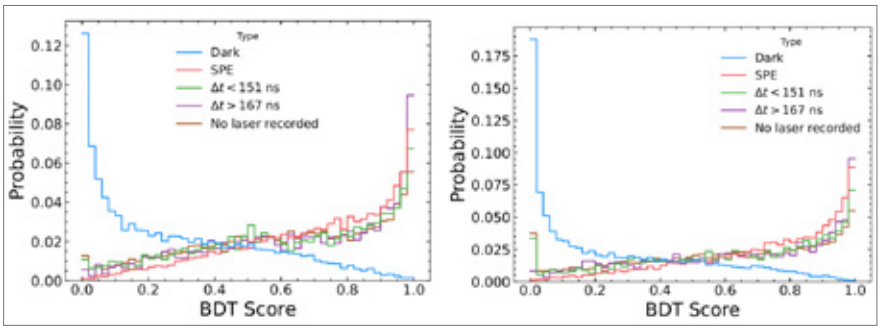


Figure 2 – each plot corresponds with one of the plot lines in Figure 1

member profiles

"It's been very enjoyable getting to know women in STEMM from all over the world."

Theresa Fruth

Collaboration is key to the work of researchers within the Centre and is at the heart of Theresa Fruth's work.

Theresa collaborates with a wide range of groups across different experiments and is part of an international group of female scientists working together to build a community and increase the presence of women in leadership in science fields.

She has been involved with the LUX-ZEPLIN (LZ) experiment (a currently running dark matter direct direction experiment searching for weakly interacting massive particles (WIMPs) since she began her PhD in 2015. In early 2023, she completed her tenure as simulations co-coordinator of the experiment.

Since then, she has shifted some of her focus to her role on the steering committee in the XLZD consortium, which is planning the ultimate liquid xenon observatory.

Theresa brings her experience working on LZ to the SABRE South experiment, for which she leads the PMT (photomultiplier tube) working group collaborating closely with colleagues at the University of Melbourne. She has also helped with the veto test installations led by Lindsey Bignell from the Australian National University.

"Getting involved in different aspects of SABRE has allowed me to get to know colleagues all over Australia better, which I have enjoyed a lot," she says.

Theresa is also involved in the Homeward Bound program, which aims to boost female leadership in science and will offer her the opportunity to travel with a group of women on a voyage to Antarctica.

"It's been an interesting journey of reflecting on leadership styles, my own thinking and behaviour, being a woman in STEMM, as well as large issues such as climate change.

Theresa is also leading the development of a colouring book that aims to ignite an interest in science in children.

events

Centre events offers members from across all nodes with the opportunity to collaborate to share information and skills that will assist students and researchers in their academic and industry careers.

In 2023, events went back almost entirely to being held in person with some opportunities for people to view presentations remotely.

The Centre's ECR and Annual Workshops were the main opportunity for the whole Centre and some international Centre members and guests to come together in person. Both are profiled in more detail in other sections.

There were also a nubmer of workshops, meetings and conferences organised by Centre members which are profiled below.

CDM also highlights days of significance on the scientific calendar in order to promote an understanding of dark matter and physics careers in the wider community, and to celebrate the work and achievements of members. These include National Science Week and Dark Matter Day, profiled in other sections of this report.

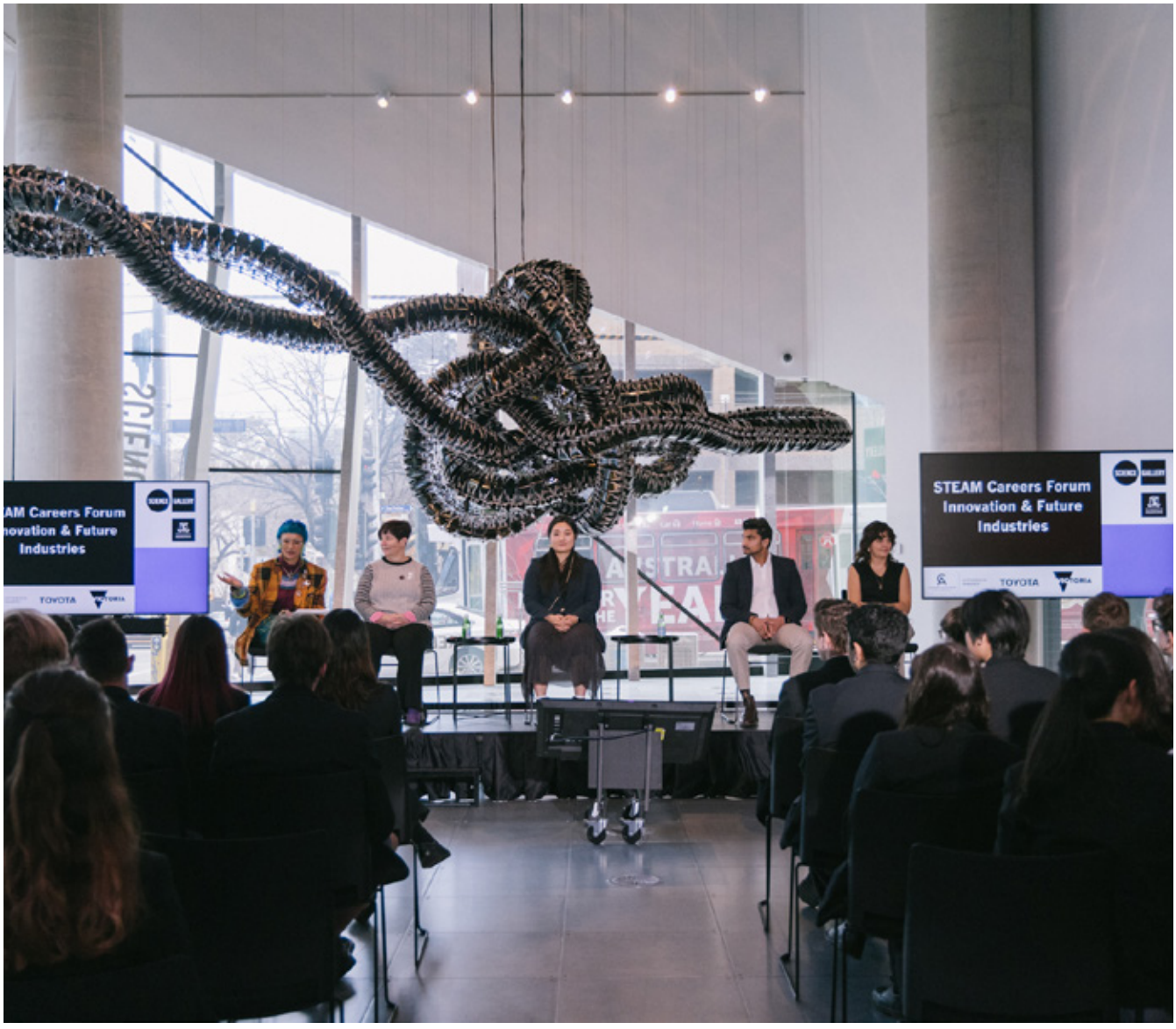
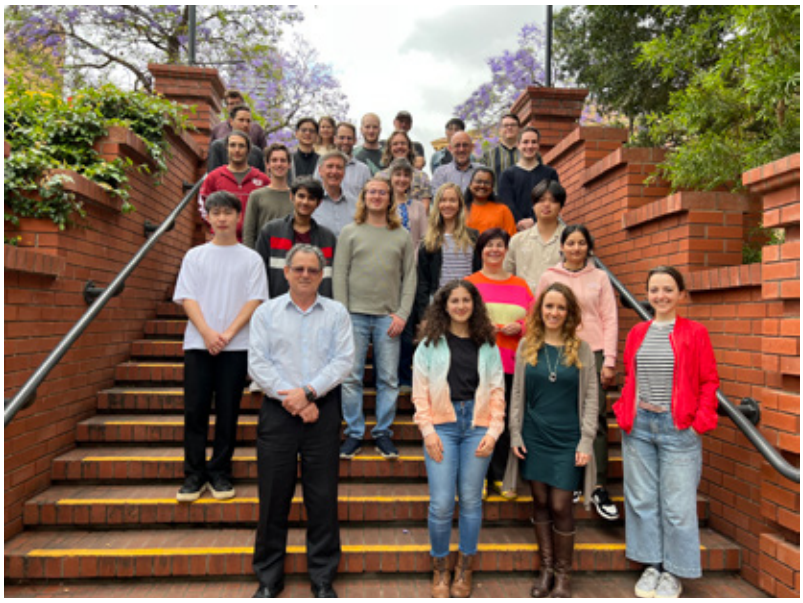


Photo credit: Jacinta Keefe Photography

Theory Workshop

Theory Chief Investigators and postdoctoral researchers from across the Centre gathered in Adelaide at the beginning of the year for a three-day workshop to discuss emerging dark matter theory research directions. The program contained a combination of full-group discussions, and smaller working group sessions focused on specific ideas. These activities played an important team-building role, and led to new projects on topics such as dark photons, dark matter in neutron stars, and novel experimental probes of dark matter.



SABRE South workshop

Centre members working on SABRE South met in Adelaide before the Centre's annual workshop for a two-day collaboration workshop. Participants from five of the Centre's nodes heard talks from academics, postdoctoral researchers and students updating them on the progress of each of the different work packages and systems of SABRE South. There were also talks from the project manager, SUPL facility and lab manager and CDM PI Aldo Ianni who attended online. It was a productive couple of days with opportunities for discussion and a social dinner.

CoE Operations Forum

Three ARC Centres of Excellence (Exciton Science, FLEET and CDM) organised and co-sponsored a COE Operational Staff Forum in Melbourne in February. Over 70 professional staff from 15 Centres of Excellence across Australia came together to network, share best practice, and have round table discussions on topics that spanned the operations activities of Centres.

CDM COO Anita Vecchies ran a speed networking session to start off the day, Jackie Bondell talked about starting an outreach program and Fleur Morrison talked about Dark Matter media engagement.

Jackie also organised an outreach expo where Centres were able to display and talk about their outreach activities and merchandise.

InSTEM

By Jade McKenzie

I attended the inSTEM conference from 19-21 September. The goal of inSTEM was to foster networking and career development for individuals from marginalised and underrepresented groups in STEM. Organised by RMIT University and STEM-focused ARC Centres of Excellence, the event addressed the realities and disparities of career progression and provided a safe space for attendees to connect and learn how they can create safe spaces for others.

Kicking off with a keynote presentation from Nicole Bell, leading experts shared invaluable insights on strategies for career advancement, emphasising the importance of effective networks and embracing diversity in the workplace. Some highlights included a presentation on unmasking imposter syndrome with Alison Shamir, panel discussions focused on neurodiversity, mental health, and chronic illness, and A/Prof. Alice Motion using music and performance as a way to teach scientific concepts and connect the sciences to the arts.

Drawing inspiration from inSTEM, let us commit ourselves to be catalysts for change. By doing so, we can forge a path towards a STEM community that not only embraces diversity but actively champions equal opportunities for all.

27th Canberra International Physics Summer School

About 60 undergraduate and graduate students (including six CDM students from ANU, UoA and UoM) attended the Canberra International Physics Summer School at ANU in 2023.

The summer school's theme was 'Fields and Particles' and provided Australian and international students with the opportunity to learn about cutting edge research in physical sciences.

Centre CI Cedric Simenel chaired the event, and other Centre members involved included Anthony Williams (Foundations of Quantum Field Theory), Giorgio Busoni (Standard Model) and Nicole Bell (Dark Matter). CDM was also one of the sponsors of the event.

There were many Centre researchers who helped organise, give talks, keynotes and plenary presentations at international conferences and workshops throughout the year. Some highlights are:

31st International Conference on Lepton-Photon Interactions

Centre members were among organisers, speakers, panelists and delegates at the Lepton Photon Conference 2023 at the Melbourne Convention and Exhibition Centre in July. CDM was also the main sponsor of the event.

Hosted by Monash University, the conference covered topics such as results from current experiments, R&D towards future facilities, theoretical developments, and contributions on inclusion, diversity, and public engagement.

CDM Director Elisabetta Barberio, Chief Investigators Nicole Bell and Gary Hill and Postdoctoral Researcher Harish Potti were plenary speakers, with nine other Centre members giving a range of research talks on dark matter topics Outreach and Education Coordinator Jackie Bondell and students Joni Pham and Emily Filmer presented during the Diversity, Inclusion, Equity and Outreach session.

In addition, 13 Centre members presented posters. Many other CDM members attended and there were opportunities to strengthen and seed new collaborations.

Irene Bolognino and Paul Jackson (UoA) were part of the organising committee for the event.

Irene reflects on her experience of the symposium:

> *"I attended the Lepton Photon conference with the aim of increasing my connections and starting new collaborations, as well as being updated on new analyses and technologies.*

I fully met my goals thanks to the intense and well-designed program. Moreover, being part of the organising committee facilitated this process because I found myself interacting with many people from different institutions.

I used every moment to improve some aspect of working life, my skills during the talks, relationships during the breaks and during the social dinner.

I was honoured to be the convenor of the session on Dark Matter, a plenary session, and on Diversity, Inclusion, Equity and Outreach, a very important section which, in my opinion, should always be present at every conference.

Personally, I found the locations fantastic as they both had a parent room, which was essential for a new mother as I am."

Harish Potti discusses mental health at Lepton Photon Conference

The recent Lepton Photon 2023 conference featured a plenary panel debate on "Mental Health in Particle Physics". Centre member Harish Potti was a panelist alongside Turner Institute for Brain and Mental Health at Monash university Professor Kim Kornish and Tezpur University in India's Dr Moon Moon Devi.

Dr Potti said, "As part of the ATLAS Early Career Scientist Board, we organise various types of events like induction days, soft skills workshops, tutorials, etc that are helpful to the Early Career Scientist (ECS) community. Among them, mental health workshops were the most popular types of event and the feedback showed a strong desire from the ECS community to raise awareness about work-related mental health challenges and having support networks at workplaces."

9th Symposium on Frequency Standards and Metrology and summer school

CDM CI Mike Tobar was the symposium chair of the international 9th Symposium on Frequency Standards and Metrology held in Kingscliff NSW. Other CDM personnel were part of the local organising committee and CDM was one of the sponsors of the event.

The symposium served as an international discussion forum on precision frequency standards throughout the electromagnetic spectrum, and associated precision and quantum metrology. It focuses on the fundamental scientific aspects of the latest ideas, results, and applications in relation to these frequency standards and measurement techniques. More than seven years after the last symposium, significant progress has occurred across all associated fields. With almost 200 attendees from across the globe, it included invited talks from world experts including CI Maxim Goryachev and AI Eugene Ivanov and more than 100 poster presentations.

The symposium was preceded by a Summer School on Frequency Standards, Precision and Quantum Measurement, held at the Gold Coast, Qld and was also chaired by Mike Tobar, sponsored by CDM and attended by students and postdocs from the UWA node.

8th CYGNUS Workshop on Directional Recoil Detection

The week-long CYGNUS Workshop on Directional Recoil Detection at the University of Sydney brought together world leaders in the construction of novel particle detection technologies to develop a clearer view of dark matter.

Delegates at the workshop included Sven Vahsen of the University of Hawaii, Elisabetta Baracchini of the Gran Sasso Science Institute, Italy, Kentaro Miuchi of Kobe University, and CDM Partner Investigator Neil Spooner of Sheffield University. Six Centre members gave presentations including a keynote from Nicole Bell.

Event organiser Ciaran O'Hare said the CYGNUS project could be a step towards discovering the identity of the mysterious dark matter.

"This workshop constitutes an important milestone in charting the future of research in dark matter detection," he said.

"For the first time since 2019, experts on this novel type of detector got together to have a serious discussion about where our field is going, and to devise a strategy to confront the major existential problem that threatens the future of all searches for dark matter around the world."

ANZCOP and Australian Institute of Physics (AIP) Summer meeting at ANU

A meeting showcasing the work of Australia and New Zealand's physics and photonics community was held at ANU. CDM was one of the sponsors and ten CDM students and ECRs from ANU, UWA, UoM and UoA gave talks during the week. It was great to see gender balance across our speakers with half being women.

18th International Conference on Topics in Astroparticle and Underground Physics (TAUP)

An International Conference on Topics in Astoparticle and Underground Physics was organised by the Institute of High Energy Physics of the Austrian Academy of Sciences, the University of Vienna, the Technische Universität Wien, the University of Innsbruck and the Comenius University Bratislava.

The biennial TAUP series covers recent experimental and theoretical developments in astroparticle physics. Nicole Bell gave a plenary presentation, Phillip Urquijo was a convenor of one of the dark matter and its detection sessions and two Centre members gave talks in the parallel sessions.

A selection of other keynote/plenary talks from Centre members in 2023 included:

- International Conference on High Energy Particle & Astroparticle Physics (ICHEPAP2023) – Nicole Bell, plenary titled, Physics Prospects of Future Dark Matter Searches
- Technology and Instrumentation in Particle Physics (TIPP) 2023 – Ben McAllister, keynote titled Axion Dark Matter Detection
- Rencontres du Vietnam: Windows on the Universe – Federico Scutti, plenary titled Status of DM detection with scintillators (COSINE, ANAIS, DAMA/LIBRA, SABRE)
- Third International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (3rd J-PARC HEF-ex WS) – Anthony Thomas, plenary titled Quark-Meson-Coupling model for hypernuclei and neutron stars
- Division of Astrophysics, Cosmology and Gravitation Annual Meeting – Raymond Volkas, plenary titled VISHv: flavour-variant DFSZ axion model for inflation, neutrino masses, dark matter and baryogenesis
- International symposium on cosmology and particle astrophysics - Raymond Volkas, plenary titled Flavours of dark matter

annual workshop

120 Centre members and international partners from across Australia and internationally attended the CDM's second in-person Annual Workshop "Collaboratively Striving for Success" over three days in Glenelg, Adelaide in late November.

The EDI committee sought feedback from Centre members to help shape the workshop (as detailed earlier) and the program organising committee also incorporated feedback from 2022 and suggestions collected during the COO's visit to some of the nodes to refine the program. This resulted in an engaging workshop with a balance of physics talks and other activities providing Centre members and visitors with an oversight of the research across the Centre and opportunities to network and build relationships.

Highlights of the event included:

- An engaging Welcome to Country given by Kaurna Elder, Uncle Rod O'Brien
- 27 research talks and keynotes from Centre members featuring research across the Centre and visitors including AI Marc Schumann (Freiburg), PI Damian Marinaro (DSTG), PI Richard Garrett (ANSTO), Dominique Thers (SUBATECH laboratory)
- A SUPL update from Sue Barrell
- An outreach and education update from various ECRs involved in these activities and a launch of the outreach node kits
- ECR update and highlights from ECRs in 2023
- A poster session with 32 posters presented by Centre students and ECRs (poster prize details below)
- The workshop dinner where Centre awards were presented by Advisory Board member and SUPL Ltd Chair, Sue Barrell (details below)
- An interesting and productive EDI training session and workshop on Neurodiversity
- Speed networking – an energy charged session with short 1:1 mentoring chats
- The first opportunity the Centre professional staff to all meet in person and do a team building activity
- And many opportunities to have fun

Responses collected in a post workshop survey were again very positive, satisfaction rates on the venue, overall workshop and program structure were all over 90%.

When asked "What did you like about the annual worshop?", in addition to the venue/location, the social aspect and overview talks, specific comments included:

"It was much more interactive than last year and had a wider diversity in talks."

"Opportunity to learn about the full spectrum of Centre research."

"Opportunity to meet and network with so many different people - different institutions, career stages, etc"

Raghda

Sharry

Victoria

Yajing (and Zuzana who organised the challenge)

Cultural challenge at the workshop

To celebrate the wide range of cultural diversity in the Centre, this year's Annual Workshop was enriched by a cultural challenge organised by Zuzana Slavkovska from the Centre's EDI committee.

The participants were challenged to include a cultural slide in their presentations and a cultural corner on their posters. Cultural clothes or any accessories were also encouraged during the workshop dinner. It was great to see how many participated and shared a bit of their home or culture. Best contributions were awarded at the end of the meeting.

Raghda Abdel Khaleq (ANU) from Palestine, Yajing Xing (Subatech) from China, Victoria Uttaree Bashu (ANU) from Bangladesh and Sharry Kapoor (UoS) from India earned the prize for the best cultural clothing, all of them wearing national dresses.

Harish Potti (UoA) presented the best cultural corner on a poster, showing kuchipudi, a traditional south Indian dance, and tambura, a classical Indian musical instrument.

There were three prizes awarded for the best cultural snippet in a presentation. Phillip Urquijo (UoM) with roots in the Basque Country, Australia, England and Ireland showed the stunning forest of Healesville and a delicious paella dish. Emily Filmer (UoA) played an impressive video of herself dancing a typical Scottish dance. Michaela Froehlich (ANU) from Austria showed not only the Wiener Riesenrad and a famous dessert Sachertorte, but also deers living in Austria instead of the Australian kangaroos.

CDM Collaboration and Centre Values Award recipient

Michaela Froehlich (ANU)

Michaela is a chemist that is part of the metrology team at the Australian National University. She is an excellent collaborator who has who has brought people together across the Centre and internationally. She has established international collaborations with Centre partner Helmholtz-Zentrum Dresden-Rossendorf and strengthened the collaboration with ANSTO. She has brought together scientists from across the globe with different backgrounds of expertise and various levels of experience. As deputy chair of the Mentoring Committee, Michaela has recommended and secured changes to the existing mentoring program and been instrumental in identifying a mentoring platform suitable for the Centre's needs. She also participates in mentoring programs beyond the Centre at ANU and also in the Curious Minds Program, mentoring female high school students and supporting them to explore opportunities in STEM.

CDM Outreach and Impact Award recipients

Jeremy Bourhill (UWA)

Jeremy is an experimental physicist and postdoctoral researcher at the University of Western Australia. He actively promotes the Centre and dark matter research by participating in a range of outreach activities. He has participated in in all three of the road trips over National Science Week and gave a public lecture and radio interview for the 2023 National Quantum and Dark Matter Road Trip. He has also given numerous public talks on dark matter physics and demonstrated innovation and novely in his projects. Jeremy is a generous and supportive leader, mentoring more junior Centre members in the outreach activities and research.

Emily Filmer (UoA)

Emily is a PhD student at the University of Adelaide working on the LHC research program. She regularly volunteers to particiapte in outreach opportunities and is heavily invested in the outreach activities of the Centre. She actively promotes the Centre and its research nationally through outreach activities and internationally, enhancing the Centre's impact. A fantastic role model, she actively encourages women and minority groups to participate in STEM through talks at schools and events. She has been a key contributor to the 2022 and 2023 road trips and wrote a motivational article in Education Today sharing her story as a woman in STEM. She has also presented a Diversity and Inclusion talk at the international Lepton Photon conference and promoting the Centre in her visits to CERN, TRIUMF, Berkeley Lab and SLAC National Accelerator laboratory.

L-R: Emily Filmer, Jeremy Bourhill and Michaela Froehlich

Best Poster Award (Panel vote)
Emily Filmer (UoA). For poster titled
"Searching for WIMPS with Long-Lived Particles at the ATLAS Detector"

Best Poster Award (Centre member vote)
Edmund Ting (UoA). For poster titled
"Reuse, Repurpose, Reinterpret: Making the Most of LHC Results"

awards and honours

Raghda Abdel Khaleq (ANU)
Robert & Helen Crompton Travel Award

awarded by the Australian National University

Michael Baker (UoM)
IPPP DIVA Award – for a visit to KCL and IPPP

awarded by the Institute for Particle Physics Phenomenology

Elisabetta Barberio (UoM)
appointed member of the ICFA: Instrumentation, Innovation and Development Panel

Nicole Bell (UoM)
appointed as President of the Australian Institute of Physics

This appointment recognises Professor Bell's leadership and contributions to the discipline.

In her two-year term as AIP president, she intends to promote the importance of fundamental research.

Nicole Bell (UoM)
Named one of the 50 Women at the cutting edge of science in Australia by Cosmos in honour of International Women's Day

Celine Boehm (USyd)
Named one of the 50 Women at the cutting edge of science in Australia by Cosmos in honour of International Women's Day

Jeremy Bourhill (UWA)
Defence West Aspire Award

awarded by Business Events Perth

Awarded to Western Australia's exceptional researchers, academics and professionals who represent the diversity of Western Australia's research and entrepreneurial strengths and exemplify the innovation that Western Australia is renowned for globally.

Geoffrey Brooks (SUT) (pictured)
2023 Bessemer Gold Medal for outstanding services to the steel industry

awarded by the Institute of Materials, Minerals and Mining (IOM3), United Kingdom

Emily Filmer (UoA)
Best Poster Prize for "Searches for BSM physics using challenging long-lived signatures with the ATLAS detector"

awarded at the Lepton Photon 2023 Conference

Michaela Froehlich (ANU)
Environmental Chemistry Medal

awarded by the Royal Australian Chemical Institute

Awarded annually for excellence in scientific work in Australia that has involved substantial environmental chemistry, or for service to Environmental Chemistry in Australia, over the past ten years.

Navneet Krishnan (ANU)
Dean's Commendation for Excellence in Tutoring or Demonstrating

awarded by the Australian National University for dedication to teaching and learning and support for the student experience in the College of Science.

Judith Kull (UoA)
Hans-Jürgen & Marianne Ohff Research Grant

awarded by the University of Adelaide to support postgraduate research students to undertake study and/or fieldwork at a German-speaking university or research institution.

Grace Lawrence (SUT)
Royal Society of Victoria Young Scientist Research Prize - Physical Sciences section
awarded by the Royal Society of Victoria

The awards aim to foster and recognise excellence in Victoria's early career researchers and offer prizes in Biomedical & Health Sciences, Biological Sciences (non-human), Earth Sciences and Physical Sciences. Dr Lawrence's PhD was titled, "Dark Matter within Simulated Milky Way Analogues and the Subsequent Direct Detection Possibilities on Earth".

At the presentation evening, Grace explained the search for dark matter and how her research aimed to support the direct detection of the mysterious substance.

Ben McAllister (SUT)
Swinburne Vice-Chancellor's Research Excellence Award (ECR)
awarded by Swinburne University of Technology

Ben McAllister (SUT)
ANFF Technology Ambassador Fellowship
awarded by the Australian Nanofabrication Facility

National Quantum and Dark Matter Road Trip
National Science Week Grants 2023 grant
awarded by the Department of Industry, Science, Energy and Resources

Robyn Owens (CDM Advisory Board member)
In the 2023 King's Birthday Honours was appointed a Member of the Order of Australia for "significant service to science in the fields of computer vision and mathematics"

Emma Paterson (UWA)
Most Interesting Poster for "Searching for Ultra-Light Axions with Twisted Cavity Resonators of Anyon Rotational Symmetry with Bulk Modes of Non-Zero Helicity"
awarded at the 9th Symposium on Frequency Standards and Metrology

Emma Paterson (UWA)
AIP Student Oral Presentation Award
awarded at the ANZCOP-AIP Summer Meeting

Andrea Thamm (UoM)
IPPP DIVA Award – for a visit to the University of Glasgow and IPPP
awarded by the Institute for Particle Physics Phenomenology

student completions

Honours:

Robert Crew (UWA)
Emma Paterson (UWA)
Haylea Purnell (UoA)
Thomas Venville (SUT)

Masters:

Jack Irving-Dinsdale (UoM)
Jeongoh Park (UoM)
Kieran Rule (UoM)
Nimrod Shapir (UoM)

MPhil:

Meera Deshpande (UoA)
Sam Thompson (ANU)

PhD:

Ramtin Amintaheri (UoS)
Wasif Husain (UoA)
Grace Lawrence (SUT)
Peter McNamara (UoM)
William Melbourne (UoM)
Markus Mosbech (UoS)
Madeleine Zurowski (UoM)

2022 student completions that were not recorded in previous annual report:

Honours:

James Gallagher (UoA)
Matthew Green (UoA)
Cameron Harris (UoA)

Masters:

Fatima Alharthi (UoM)
Victoria Bashu (ANU)
Maaz Hayat (UoM)

MPhil:

Alexander Woodcock (UoA)

key performance indicators

Performance Measure	Target 2023	Actual 2023
1 Number of research outputs		
• Journal articles	60	64
2 Quality of research outputs		
• % of publications in peer reviewed, international journals	80%	100%
3 Number of workshops/conferences held/offered by the Centre		
Topical workshops with national or international speakers	3	3
International conferences	1	0
4 Number of training courses held/offered by the Centre		
Professional training/development courses offered by the Centre	4	7
Number of Centre attendees at all professional training/development courses offered by the Centre	>150	195
Culture Building/Be Your Best Training	1	1
Innovative Thinking training (Innovation Lab)	1	1
5 Number of additional researchers working on Centre research		
• Postdoctoral researchers	9	2
• Honours students	8	3
• PhD students	10	12
• Masters by research students	1	2
• Masters by coursework students	10	10
• Associate Investigators	7	7
6 Number of postgraduate completions		
PhD	5	7
Honours/MSc/MPhil Completions	15	9
7 Number of mentoring programs offered by the Centre		
Mentoring programs	5	5
Industry/ External internships for PhDs	5	4
8 Number of presentations/briefings		
• To the public	30	26
• To government (parliamentarians and department/agencies at both State and Federal level)	5	5
• To industry/business/end users	7	8
• To non-government organisations	5	4
• To professional organisations and bodies	5	8
News stories	15	45
Press releases	9	9
9 Number of new organisations collaborating with, or involved in, the Centre		
International	3	2
National	1	1
10 Number of female research personnel		
Female	>30%	25.4%
11 Centre-specific KPIs		
Number new of Continuing/Tenure Track Positions in Centre nodes seeded by the Centre	0	0
Number of new female-only Continuing/Tenure Track Positions in Centre nodes, seeded by the Centre (50% of the total number Continuing/Tenure Track Positions)	0	0
School visits or webcasts	35	40
Number of invited talks/papers/keynote lectures given at major international meetings (including those held in Australia)	20	37
Centre's Dark Matter Prize for high school students (# entries)	25	42

publications

Publication co-authorship in 2022 of Centre members across the six nodes.

V. Ananyev, C. Balázs, A. Beniwal, L. L. Braseth, A. Buckley, J. Butterworth, C. Chang, M. Danninger, A. Fowlie, T. E. Gonzalo, A. Kvellestad, F. Mahmoudi, G. D. Martinez, M. T. Prim, T. Procter, A. Raklev, P. Scott, P. Stöcker, J. Van den Abeele, M. White and Y. Zhang, Collider constraints on electroweakinos in the presence of a light gravitino, *The European Physical Journal C*, 83, 493 (2023) https://doi.org/10.1140/epjc/s10052-023-11574-z

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ATLAS Collaboration

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financial report

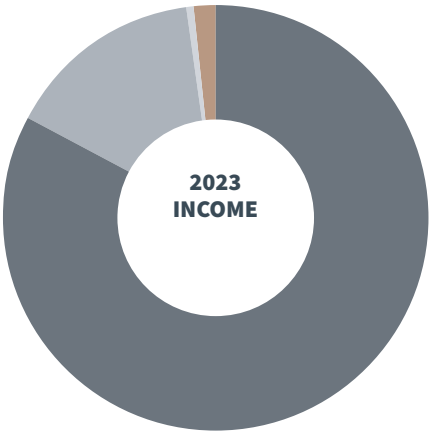
Statement of Income and Expenditure for Year ended 31 December 2023, preceding years and estimated budget for 2024

Reporting Period	2020	2021	2022	2023	2024 forecast
INCOME					
ARC Grant	$5,089,998	5,181,620	5,228,255	5,411,246	5,833,324
University Contributions ^	$1,218,397	1,254,589	1,950,090	988,469	1,074,537
Partner Contributions	$20,000	70,000	20,000	20,000	20,000
Other Income*		250,000	21,250	100,000	
TOTAL INCOME	**$6,328,396**	**6,756,209**	**7,219,596**	**6,519,715**	**6,927,861**
EXPENDITURE					
Salaries	$1,008,666	2,421,777	3,028,290	3,394,740	4,697,136
Equipment	$134,593	281,025	369,066	1,465,857	1,316,999
Travel, Visitor Support & Conferences	$3,481	44,234	552,053	729,961	1,289,396
Research Computing, Lab Maintenance & Consumables	$58,129	87,093	109,028	150,076	253,271
Management and Administration	$18,797	60,413	99,008	95,316	320,615
Outreach, Communications & Mentoring	$41,490	47,730	49,478	87,547	259,375
Scholarships	$12,467	192,599	171,625	252,863	552,633
Other expenditure*		250,000	21,250	20,000	80,000
TOTAL EXPENDITURE	**$1,277,624**	**3,384,871**	**4,399,800**	**6,196,361**	**8,769,423**
TOTAL CARRY FORWARD TO NEXT YEAR #	**$5,050,772**	**8,422,110**	**11,241,906**	**11,565,260**	**9,723,698**

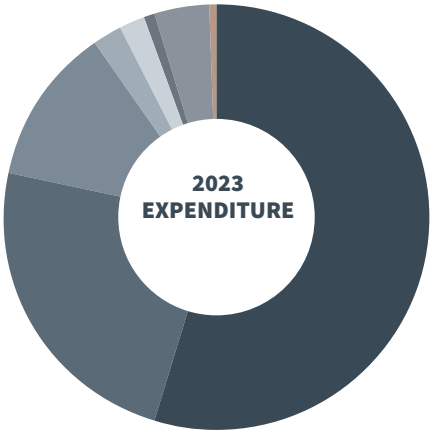
* 2021 University of Melbourne support for SABRE. 2022 $20,000 National Science Week Grant (UoM_CDM Road Trip), $1,250 National Science Week Grant (ANU_Dark Matter in the Pub). 2023 $20,000 National Science Week Grant (UOM_CDM Road Trip) $80,000 University of Melbourne DVCR support for SABRE for expenditure in 2024.

^ ANU given $629,596 towards University contributions in 2022 for 2023-2026

Carry forward includes $2,500,000 of ARC Grant to fund the first six months of 2027 due to Centre starting in August 2020 .



- ARC Grant (83%)
- University Contributors (15%)
- Partner Contributors (0.31%)
- Other income* (1.5%)



- Salaries (55%)
- Equipment (24%)
- Travel, Visitor Support & Conferences (13%)
- Research Computing, Lab Maintenance & Consumables (2%)
- Management and Administration (2%)
- Outreach, Communications & Mentoring (1%)
- Scholarships (4%)
- Other Expenditure* (0.3%)

In Kind Contributions

Contributor	2023 Reporting Period
The University of Melbourne	2,170,896
The Australian National University	760,048
The University of Adelaide	576,540
Swinburne University of Technology	323,020
The University of Sydney	188,970
The University of Western Australia	384,112
ANSTO	142,000
DST Group	45,372
The University of Sheffield*	-
INFN Gran Sasso National Laboratory (LNGS)	4,354,428
University of Amsterdam	11,093
California Institute of Technology (Caltech)	12,970
University of Freiburg	23,000
The University of Washington	11,093
Massachusetts Institute of Technology (MIT)	11,093
Stockholm University	12,970
Helmholtz-Zentrum Dresden-Rossendorf (HZDR)	25,000
Total	**9,052,605**

* PI Neil Spooner is an Honorary and his in kind time cannot be included in the contributions.

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