ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

ANNUAL REPORT 2022

acknowledgments

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 **AV Graphic Design** for design services provided for the production of this Annual Report.

Cover photo: CDM and EQUS Centre members participating on the National Quantum and Dark Matter Road Trip. Image courtesy of Kristen Hartley.

advisory board chair message

The ARC Centre of Excellence for Dark Matter Particle Physics has enjoyed a year of collaboration and engagement in 2022. This year has provided opportunities for Centre members to meet in person, travel overseas, strengthen their relationships and seed new collaborations.

A highlight for me was the Centre's first in-person annual workshop in Geelong in November, aptly titled "Forging and Strengthening Collaboration". I was fortunate to be able to attend part of it in person and walking into the workshop dinner the energy in the room was evident. Speaking with Centre members emphasised the importance of interacting in person rather than virtually. The Advisory Board also had the opportunity to hold our first face-to-face meeting, with five Advisory Board members in attendance at the workshop.

It was another big year for outreach and education, with a strong focus on developing long-term relationships with regional and remote schools. Building on a successful road trip in 2021, the National Quantum and Dark Matter Road Trip, run in collaboration with the ARC Centre of Excellence for Engineered Quantum Systems, saw Centre researchers share their passion for physics with high school students across the country and through numerous public events.

The Centre also featured heavily in the media during 2022, with the road trip and other activities, but the key impact came from the official celebration of the completion of Stage 1 of the construction of the Stawell Underground Physics Laboratory. The Centre received wide national and international press coverage featuring broad representation of researchers.

Steady progress has been made on the existing research of the Centre, with ongoing projects and new research activities both in theory and experiments.

The SABRE South researchers and institutions recognise the critical importance of SABRE and have been working to coordinate the activities required to complete and install the experiment in SUPL. SABRE will lay essential groundwork and capabilities here in Australia for a new generation of novel underground experiments as well as a rich training environment for future research leaders.

The ORGAN experiment also completed its first comprehensive search for axion dark matter. Results ruling out dark matter in a specific mass range, but improvements to the detectors will achieve greater sensitivity and wider future searches.

The Centre's theorists and experimentalists have worked together to build on our understanding of dark matter. New avenues and ideas to look for dark matter have been developed. The annual workshop featured sessions on theoretical and experimental convergence as well as theory discussion sessions that provided opportunities for new cross node research collaborations.

There is a real sense of excitement for the future of the Centre, and 2023 is already looking to be a year of world class research, increased collaboration and many opportunities for mentoring and training.

Aidan Byrne

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

Centre: ARC Centre of Excellence for Dark Matter Particle Physics

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

RHD: Research Higher Degree

SABRE: Sodium Iodide with Active Background Rejection Experiment

SUPL: Stawell Underground Physics Laboratory

contents

director's message

The ARC Centre of Excellence for Dark Matter Particle Physics entered an exciting period in 2022 as opportunities to meet in person and travel increased. I particularly enjoyed seeing the interaction between the nodes and meeting Centre researchers and international guests at the annual workshop. These interactions have helped us to build a stronger, more supportive and engaged Centre, and to experience our values – collaboration, trust and passion – in action.

A strong sense of collaboration across the Centre is crucial to our success. Working together with people from different institutions, with different skills and perspectives, enables us to share knowledge and resources. In a truly collaborative enterprise we can be more cost effective, productive, creative, and competitive.

In 2022, we were also able to welcome many new members including overseas postdoctoral researchers and we welcomed the Centre's first ongoing appointment in Sydney, Dr Theresa Fruth.

As a Centre, we have ambitious targets for female researchers. While the ratios have not shifted as much as we would have liked, we have made some positive steps to recruit more women to the Centre and will be focusing on supporting women and other under-represented groups going forward.

There has been a lot of international travel in 2022, and many of us were able to once again attend international conferences in person and collaborate with our international colleagues. I was at the International Conference for High Energy Physics (ICHEP) in Bologna where over 1000 particle physicists gathered. From the large number of talks on dark matter and neutrinos, and from discussions with other scientists, lab directors and funding agencies, it transpired that a sizeable number of high energy physicists are moving to direct detection or neutrino physics. I found myself sharing ideas on direct detection techniques with colleagues with whom I used to share techniques on improvements to Higgs coupling measurements.

The field is accelerating efforts on proposals for new detectors as well as vibrant R&D programs, which include new quantum technologies. Current R&D on new techniques will improve established detector performance and new methods to mitigate background and extend the physics reach. Dark matter detection is becoming a very dynamic field and the coming decade will be an exciting time for dark matter searches. Soon we may reach the point where axion searches will have sensitivity to the QCD axion across a vast mass range. The UWA group published the first ORGAN result that was also shown during the ICHEP22 plenary.

The field is developing new technologies to detect very low-energy recoils and we are moving towards a broad and multi-scale experimental program to test many different hypotheses, cross-check possible signals, and triangulate the properties of dark matter if detected. Theory and the study of systematics, backgrounds, and calibration are essential to understand the reach of these experiments.

We had a very positive ISAC review of the Centre research program. They congratulated the Centre for the impressive work done during the pandemic. They reminded us that SABRE will be the first large scale direct detection experiment built in Australia, by Australians. Its successful completion will be a key milestone for the Centre's success and for science in Australia. They were impressed by the progress of axion research and related R&D and acknowledged that the theory effort at the ARC Centre is vibrant, and it was clear to the ISAC that the interactions between the Centre's theorists and experimentalists enriched the intellectual and scientific culture of this institution.

We also saw a number of achievements across the Centre's research areas which you can read about in the research section of this report. These included the new collaboration CYGNUS-Oz, Centre members joining the XLZD consortium, characterisation of materials used in dark matter detectors through our metrology research program and Centre members again being able to work at the LHC with the ATLAS experiment recording data in 2022.

Centre researchers have been celebrated internationally as significant contributors in the field. You can see the full list in the Awards and Honours section, and highlights include: PhD student Grace Lawrence (SUT) was awarded the Young Scientist Award at the Identification of Dark Matter conference to recognise scientific achievements by young scientists presenting their work at the conference – an important dark matter focused event; Postdoc Michaela Froehlich (ANU) was awarded best presentation in the Instruments & Method Development Session at the South Pacific Environmental Radioactivity Association conference; CI Celine Boehm (UoS) was awarded the Women in Leadership Medal by the Australian Institute of Physics, and CI Michael Tobar (UWA) gave numerous talks across Australia and internationally in 2022 as part of his IEEE UFFC Distinguished Lecture Series.

We also recognised the achievements of our Centre members with awards at our annual workshop.

National Science Week was a highlight of the year and I am immensely proud of the achievements of our professional staff and early career researchers in putting together a successful National Quantum and Dark Matter Road Trip, in partnership with EQUS. Participants travelled from Brisbane to Perth and this event reached over 2000 people including 1400 high school students from regional and remote Australia.

You can read more about the Centre's progress and achievements in 2022 across our research themes and other portfolios in this report. We have built strong momentum in 2022 and it bodes very well for the breadth of Centre activities in 2023.

All the best for 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 2023:

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

- Undertake research to advance the Centre's theoretical and experimental goals (see Research Program sections and Research Activity Plan for 2023)

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
- Building international collaborations in Outreach through IPPOG and overseas connections
- National Quantum and Dark Matter Road Trip during National Science Week
- Dark Matters exhibition at Science Gallery Melbourne and associated activities
- Focus on outreach and education activities that promote diversity and inclusion

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

- Launch of the first round of Special Initiatives funding for students and ECRs
- Funding to support collaborations between nodes and with Partner Organisations through the Mentoring and Career Development portfolio with a focus on ECRs
- Provide diverse training opportunities to Centre members
- Implement Mentoring 2.0 with the establishment of the Mentorloop platform

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

- Provide the legacy of a world-class underground physics facility that takes full advantage of Australia's southern hemisphere location
- Continue installation and commisioning of SABRE South in SUPL
- 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
- Vigourous R&D and prototyping for future dark matter experiments based in Australia and overseas including liquid Xenon detectors, gas detectors for directional detection, Axion detectors, superfluid, optomechanics and quantum technologies (see Research Program sections and Research Activity Plan for 2023)

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

- Innovation Laboratory activities including sponsoring Centre members to participate in CERN's Innovation Lab "IdeaSquare" in Geneva
- Training in innovative thinking to help translate discoveries into social and economic benefits
- Open the first round of applications for Centre members to apply for DST Group funding

6. Cohesive national and international environment with a strong EDI program

- Implementation of the Equity, Diversity and Inclusion action plan (see EDI report)
- Continuation of the Artist in Residence program with the Science Gallery Melbourne
- Continue to initiate conversations and develop relationships with First Nations Peoples in areas where research is being undertaken by the Centre

timeline

2019

28 August 2019
Centre awarded

2020

14 August 2020
Centre commenced

2021

22 September 2021
Centre launch

2022

2023

March 2023
Current day

Q4 2023-Q1 2024 (tba)
ARC Mid-term review

2024

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 substantial 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) – Alan Duffy on parental leave
- Andrew Stuchbery (Node leader, ANU)
- Michael Tobar (Node leader, UWA)
- Raymond Volkas (Node leader, UoM)
- Anita Vecchies (COO)
- Irene Bolognino (ECR representative UoA)

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 Directors 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)
- Ben McAllister (ECR representative, postdoc)
- Markus Mosbech (ECR representative, PhD student)

*correct as at 31 December 2022

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 Barrell AO (former Chief Scientist at the Bureau of Meteorology; SUPL Ltd Chair)
- Tamara Davis (ARC Laureate Fellow, University of Queensland)
- Campbell Olsen (CEO of Arete Capital Partners; major shareholder of Stawell Gold Mine)
- Robyn Owens (DVCR, University of Western Australia)
- 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 members are:

- Chair – Janet Conrad (MIT, USA; Spokesperson of Isodar; former Spokesperson of MiniBoone)
- Deputy 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, USA; Spokesperson of SuperCDMS-SNOLAB)
- Carlos Frenk (Durham University, UK; Fellow of the Royal Society)
- Dan Hooper (University of Chicago, USA)
- 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 KPIs of the Centre

The Equity, Diversity and Inclusion Committee is comprised of:

- Co-chair - Cedric Simenel (ANU)
- Co-chair, Phillip Urquijo (UoM)
- Emily Filmer (UoA)
- Michaela Froehlich (ANU)
- Teresa Fruth (UoS)
- Markus Mosbech (UoS)
- Harish Potti (UoA)
- Zuzana Slavkovska (ANU)
- Christine Thong (SUT)
- Michael Tobar (UWA)
- Yi Yi Zhong (ANU)
- Madeleine Zurowski (UoM)

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:

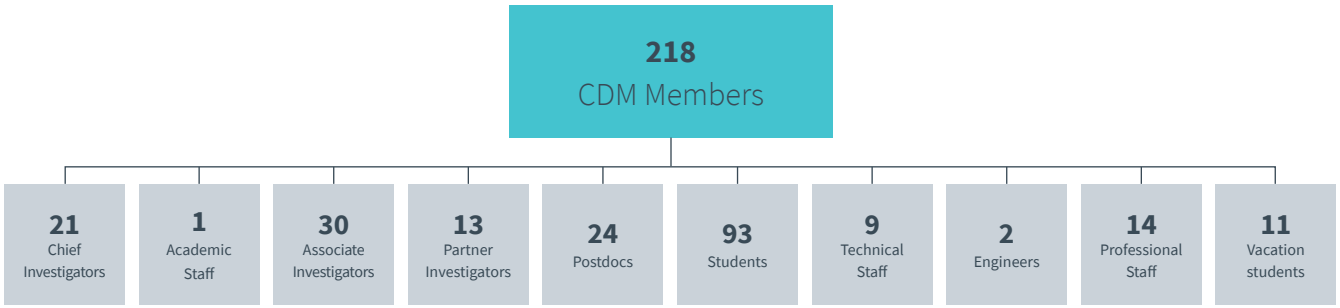
- Chair – Anthony Thomas (UoA)
- Michaela Froehlich (ANU)

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 2022 the members were:

- Irene Bolognino (UoA)
- Ben McAllister (SUT/UWA)
- Markus Mosbech (UoS)

centre membership snapshot



These numbers include people were Centre members during 2022. 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 2022. 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

Theresa Fruth (UoS)

Associate Investigators

Paul Altin (ANU)
Geoffrey Brooks (SUT)
Frank Calaprice (Princeton)
Zhenwei Cao (SUT)
Peter Cox (UoM)
Darren Croton (SUT)
Sara Diglio (CNRS France)
Zengwei Ge (SICCAS)
Eugene Ivanov (UWA)
Dominik Koll (ANU and HZDR)
Shanti Krishnan (SUT)
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)
Marurizio Toscano (UoM)
Jan Van Driel (UoM)
Christian Weiser (Ufreib)
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)
Innes Bigaran (UoM)
Lindsey Bignell (ANU)
Irene Bolognino (UoA)
Jeremy Bourhill (UWA)
Giorgio Busoni (ANU)
Graeme Flower (UWA)
Michaela Froehlich (ANU)
Matthew Gerathy (UoM)
Ben McAllister (UWA/SUT)
Peter McNamara (ANU)
Robert Mostoghiu Paun (SUT)
Jayden Newstead (UoM)
Francesco Nuti (UoM)
Harish Potti (UoA)
Dipan Sengupta (UoA)
Ellen Sirks (UoS)
Zuzana Slavkovska (ANU)
Xuan-Gong Wang (UoA)

Postdoctoral Researchers (Affiliated)

Rebecca Allen (SUT)
Adam Batten (SUT)
Chris Flynn (SUT)
Federico Scutti (SUT)
James Webb (UoM)

Students

PhD

Raghda Abdel Khaleq (ANU)
Joseph Allingham (UoS)
Ramtin Amintaheri (UoS)
William Campbell (UWA)
Isabel Carr (UoM)
Dylan Dance (SUT)
Ferdos Dastgiri (ANU)
Mitchell Dixon (SUT)
Matthew Fewell (UoA)
Emily Filmer (UoA)
Graeme Flower (UWA)
Gangyong Fu (UoM)
Kenn Goh (UoA)
Charles Grant (UoA)
Minh Tan Ha (UoA)
Elrina Hartman (UWA)
Fredrick Hiskens (UoM)
Liam Hockley (UoA)
Tyler Hughes (SUT)
Nicholas Hunt-Smith (UoA)
Wasif Husain (UoA)
Renee Key (SUT)
Albert Kong (UoA)
Navneet Krishnan (ANU)
Judith Kull (UoA)
Grace Lawrence (SUT)
Kyle Leaver (UoA)
Nicholas Leerdam (UoA)
Adam Leinweber (UoA)
Jesper Leong (UoA)
Ben Li (UoS)
Bill Loizos (UoA)
Ibtihal Mahmood (UoM)
Emily McDonald (UoM)
Lachlan McKie (ANU)
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)
Zachary Picker (UoS)
Aaron Quiskamp (UWA)
Alex Ritter (UoM)
Tristan Ruggeri (UoA)
Alexander (Alexei) Sopov (UoM)
Nathan Spinks (ANU)
Owen Stanley (UoM)
Catriona Thomson (UWA)
Edmund Ting (UoA)
Adam Ussing (SUT)
Peter Verwayen (UoS)
Michael Virgato (UoM)
James Webb (UoM)
Scott Williams (UoM)
Joshua Wood (UoM)
Wanli Xing (UoA)
Yiyi Zhong (ANU)
Madeleine Zurowski (UoM)

MPhil

Nathanael Botten (UoA)
Meera Deshpande (UoA)
Joshua Gill (UoA)
Sam Thompson (ANU)
Alexander Woodcock (UoA)

Masters by Coursework

Fatimah Alharthi (UoM)
Max Amerl (UoA)
Victoria Bashu (ANU)
Sen Sam Chhun (UoM)
Ishaan Goel (UWA)
Maaz Hayat (UoM)
Jack Irving-Dinsdale (UoM)
Carol Isaac (UoM)
Robert Limina (UWA)
Campbell Millar (UWA)
Jeongoh Park (UoM)
Deepali Rajawat (UWA)
Bryn Roughan (UWA)
Kieran Rule (UoM)
Nimrod Shapir (UoM)
Iman Shaukat Ali (UoM)
Owen Stanley (UoM)
Tony Tran (UoM)
Joshua Wood (UoM)

Honours

James Gallagher (UoA)
Matthew Green (UoA)
Cameron Harris (UoA)
Emma Paterson (UWA)
Matthew Rumley (UoA)
Steven Samuels (UWA)
Thomas Venville (SUT)

Technical Staff

Scott Collins (SUT)

Chris Kafer (ANU)

Padric McGee (UoA)

Steve Osborne (UWA)

Daniel Tempra (ANU)

Raffaele Timpano (SUT)

Ben Tranter (ANU)

Tom Tunningley (ANU)

Craig Webster (SUT)

Engineers (Affiliated)

Tiziano Baroncelli (UoM)

Giulia Milana (SUT)

Professional Staff

Jackie Bondell (Education and Outreach Officer)

Linda Barbour (UWA Administration)

Sharon Johnson (UoA Administration)

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)

Silvana Santucci (UoA Administration)

Anita Vecchies (Chief Operating Officer)

Martina Velandi (Administration Officer)

Michelle Abbott (Administration Officer)

Jade McKenzie (Database Administrator)

Vacation students funded by the Centre

Camron Alley (SUT)

Josh Green (UWA)

Aryan Gupta (UWA)

Michael Hatzon (UWA)

Ashley Johnson (UWA)

Bill Loizos (UoA)

Kyle Leaver (UoA)

Duncan McClay (UoA)

Dylan O'Donohue (UWA)

Emma Paterson (UWA)

Daniel Tobar (UWA)

case study 1

Student collaboration across nodes and physics sub-disciplines

A collaboration that unites astrophysics with particle physics has offered valuable opportunities for two Centre members to gain new skills and knowledge.

Completing PhD students, Grace Lawrence (SUT) and Madeleine Zurowski (UoM), are working together to explore corrections and uncertainties in the calculation of dark matter direct detection rates.

The two aim to take the detailed simulated velocity distributions at various points in the galaxy that Grace has generated, and combine them with detector effects, and more complex models for dark matter interactions than are typically assumed.

The two decided to collaborate after Maddy heard Grace's talk about her work on velocity distributions, and comparing them to the standard assumptions (called the Standard Halo Model).

The talk sparked Maddy's interest.

> *"One of the things that I think is cool about Grace's simulations is that they revealed a lot of substructure at various velocities. Even though this didn't create significant deviations from the results you get with the simple spin independent, elastic dark matter model, I have studied other dark matter models that can vary a lot more with small changes in velocity, and so was interested in how assuming Grace's velocity distributions would change the results."*

Grace brings a specialised understanding of astrophysics to the partnership, while Madeleine's background is in particle physics and detectors.

"Combining our respective specialities, we investigated the expected annual modulation signal for our Milky Way using the realistic velocity distribution functions from my work, and the particle physics rate calculations from Maddy," said Grace.

"Additionally, we have plans to explore the unique 'turnover mechanism', which sees the complete reversal of the annual modulation phase, from both the astrophysics and particle physics perspectives."

The two plan to produce research papers resulting from their work, and have discussed combining the code for computing direct detection rates under different assumptions that they created independently.

> *"People talk about the interaction/observation rate as having an astrophysics and a particle physics component, and I think our expertise matches pretty well with that."*

The collaboration has provided Grace with new skills and knowledge in an area in which she was less familiar.

"Originating from an Astronomy background, working with Maddy has given me a new understanding of the complex detector effects than come into play for differential rate calculations, in particular for the SABRE South experiment, as well as a broadened insight into how important the combination of astrophysics and particle physics is for the future of dark matter science."

Similarly, the collaboration has offered Madeleine a better understanding of what the velocity distribution physically corresponds to, as well as providing a different focus to her usual work.

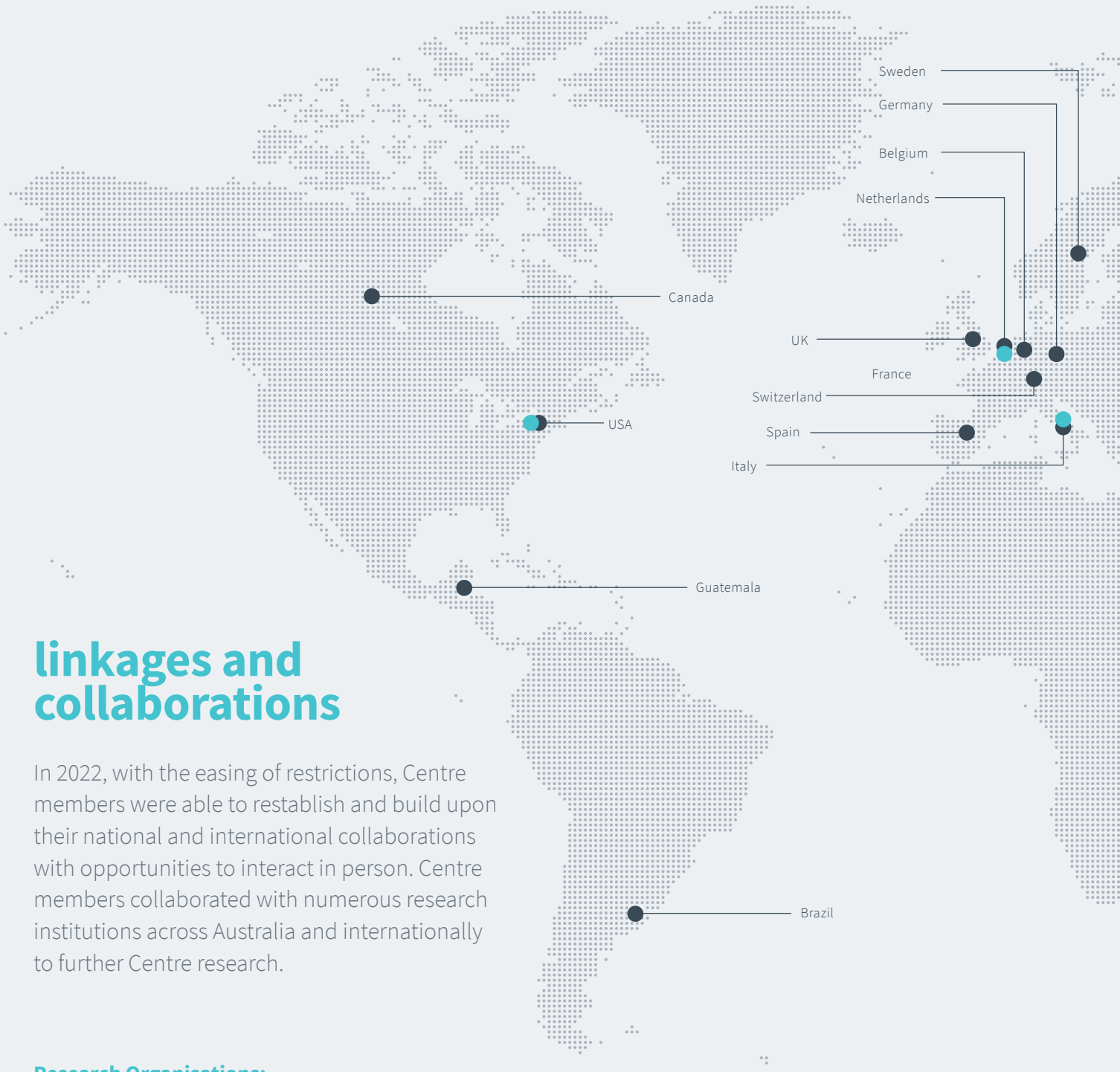
> *"It's been very enjoyable working on something a bit more abstract than dealing with all the details of designing and assessing a single detector!"*

Along with gaining new knowledge, the two have gained enjoyment from the experience of working together, across nodes and areas of specialism.

They will continue with the collaboration from their new roles, Madeleine as a postdoctoral researcher at the University of Toronto, with a continued involvement as a Centre Associate Investigator with the SABRE South experiment, and Grace has recently submitted her PhD thesis, which is currently under examination. She hopes to undertake a dark matter post-doctoral research position.

In the future they plan to seek further opportunities to collaborate together and with members from other nodes.

L-R Madeleine and Grace

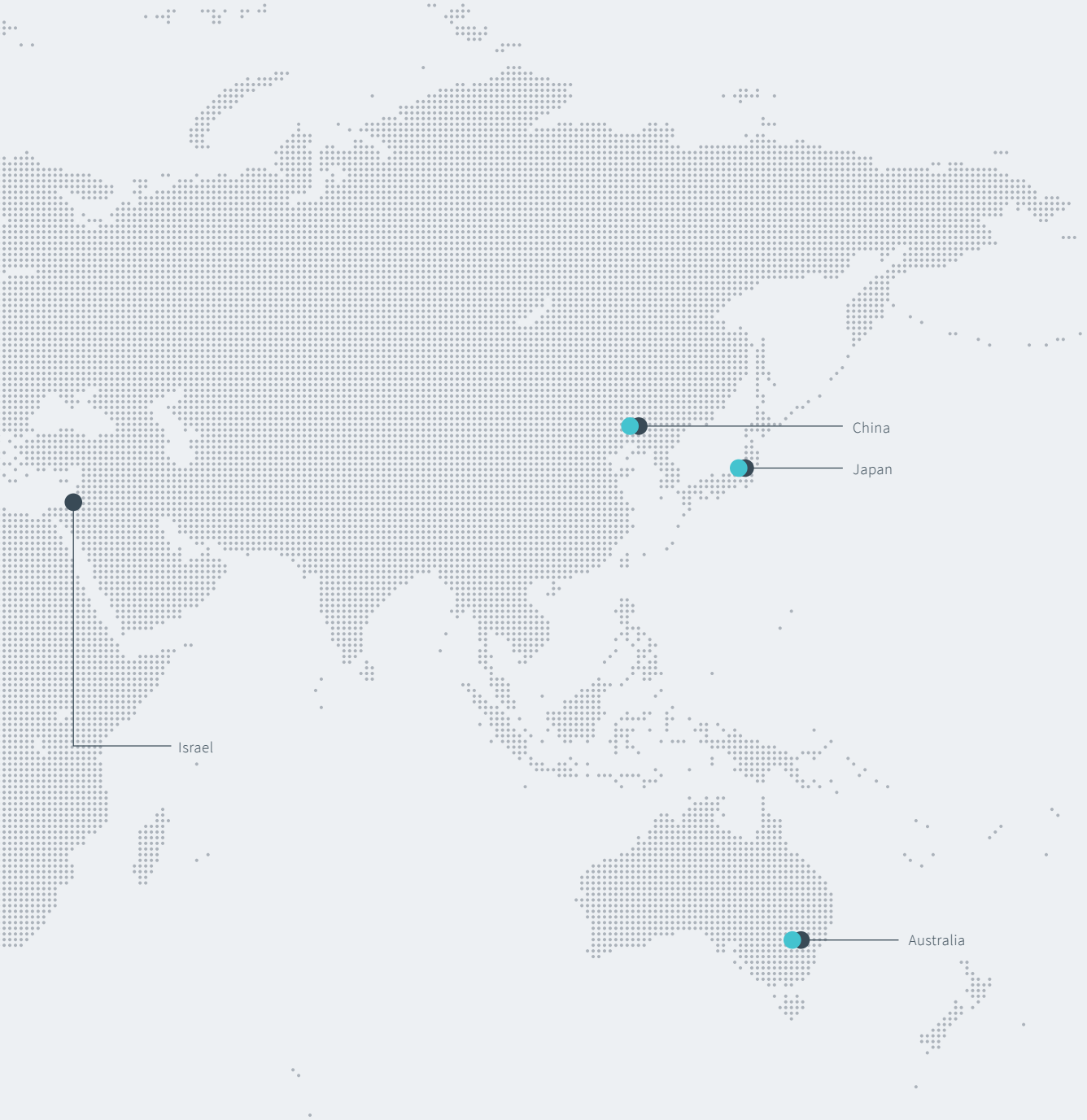


linkages and collaborations

In 2022, with the easing of restrictions, Centre members were able to restablish and build upon their national and international collaborations with 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*
Cruzeiro do Sul, Brazil
Defence Science and Technology Group (DSTG), Australia
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 for Theoretical Physics IFT (UAM-CSIC), Spain
Istituto Nazionale di Fisica Nucleare (INFN) Roma, Italy
Japanese High-Energy Accelerator Research Organization (KEK), Japan*
Kings College London, UK*
Kobe University, Japan
KTH Stockholm, Sweden
LANL, New Mexico, USA
Lawrence Livermore National Laboratory, USA
Los Alamos National Laboratory, USA
Lund University, Sweden
Mainz University, Germany
Massachusetts Institute of Technology (MIT), USA
Oxford University, UK
Pacific Northwest National Lab (PNNL), USA
Princeton University, USA
Purdue University, USA*
SACLAY, IRFU, France
Sam Houstan State University, USA
Sapienza Universita di Roma, Italy
Stockholm University, Sweden
SYRTE - Paris Observatory, France
TD Lee Institute, Shanghai Jiao Tong University, China
Texas A&M University, USA
The Technion – Israel Institute of Technology, Israel
Thomas Jefferson Lab (JLab), USA
TRIUMF, Canada
UC Berkeley, USA
UCAS, China



UNESP, Brazil
Universita degli Studi di Milano, Italy
University of Amsterdam, Netherlands
University of Bern, Switzerland
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 Chicago, USA
University of Florida, USA
University of Freiburg, Germany
University of Geneva, Switzerland
University of Glasgow, UK
University of Göttingen, Germany
University of Hawaii, USA
University of Hawaii, Manoa, USA
University of Illinois Urbana-Champaign, USA
University of Massachusetts Amherst, 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 Tokyo, Japan*
University of Toronto, Canada*
University of Washington, USA
University of Zaragoza, Spain*
UNSW, Australia
Virginia Tech, USA
Washington University in St. Louis, USA
Yale University, USA
Zurich University, Switzerland

* New in 2022

Industry collaborations:

The Centre also engaged with industry in 2022 to develop technologies and equipment to further our scientific work.

Airbus, Netherlands
Hamamatsu Photonics, Japan
Palazzi SRL, Italy
RMD A Dynasil Company, USA
Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS), China
Stawell Gold Mines, Australia
Swagelok, USA
WT Partnership, Australia

Research Organisations
Industry Organisations

case study 2

Scavenger hunt: Searching for the optimal target material for low-level ^{210}Pb accelerator mass spectrometry

Centre postdocs Michaela Froehlich and Zuzana Slavkovska, PhD student Ferdos Dastgiri and Chief Investigator Steve Tims (all from ANU) have been collaborating with Associate Investigator Dominic Koll (HZDR) and Partner Investigators Michael Hotchkis (ANSTO) and Anton Wallner (HZDR) with the aim of measuring ^{210}Pb in 1 kg of NaI via accelerator mass spectrometry (AMS) for the SABRE South experiment.

Radionuclides including ^{238}U, ^{232}Th, ^{210}Pb and ^{40}K, which are intrinsically present in the detector materials or arise because of surface contamination, will provide a fundamental limit to the sensitivity of the SABRE experiment. Therefore, the characterisation of these radioimpurities is essential for the identification of any additional signal above this background. They focused on ^{210}Pb, since radiation associated with its beta decay overlaps with the low-energy region in which the dark matter signal is expected. Lead-210 measurements are usually performed by decay counting or Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) depending on the sample size, matrix and concentration. However, the past ~20 years have seen significant developments in heavy-ion detection by accelerator mass spectrometry (AMS). Studies were performed at the 1 MV VEGA accelerator at ANSTO to test the abundance sensitivity and measurement background of ^{210}Pb-AMS with a state-of-the-art facility specifically designed for heavy-ion detection. However, most ion source output tests for different sample compositions were performed at the ANU.

The first step is to find the optimal target material (chemical compound and binder) to produce the highest and most stable negative ion output. The group initially studied the outputs from Pb3O4, PbO and PbF2 mixed 1:2 with Ag. The 208PbO2− and 208PbF3− currents were 0.5–1.2 µA with the procedural PbF2 compound performing slightly better. Based on these results, they explored the performance of PbF2 mixed with fluorinating agents such as AgF, AgF2 and SbF3 at different ratios. The 1:1 mixture was the best for all additives.

The results were published in *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 529 (2022) **https://doi.org/10.1016/j.nimb.2022.08.015**

Associate Professor Steve Tims said the collaboration had expanded to include groups at the universities of Vienna, Austria, and Ottawa, Canada, and offered a range of benefits to the researchers involved.

"The collaboration has provided frank, open and highly fruitful discussions on how to achieve the required sensitivity for the ^{210}Pb measurements, and given me personal insight into the capabilities of the specialised infrastructure unique to the associated facilities.

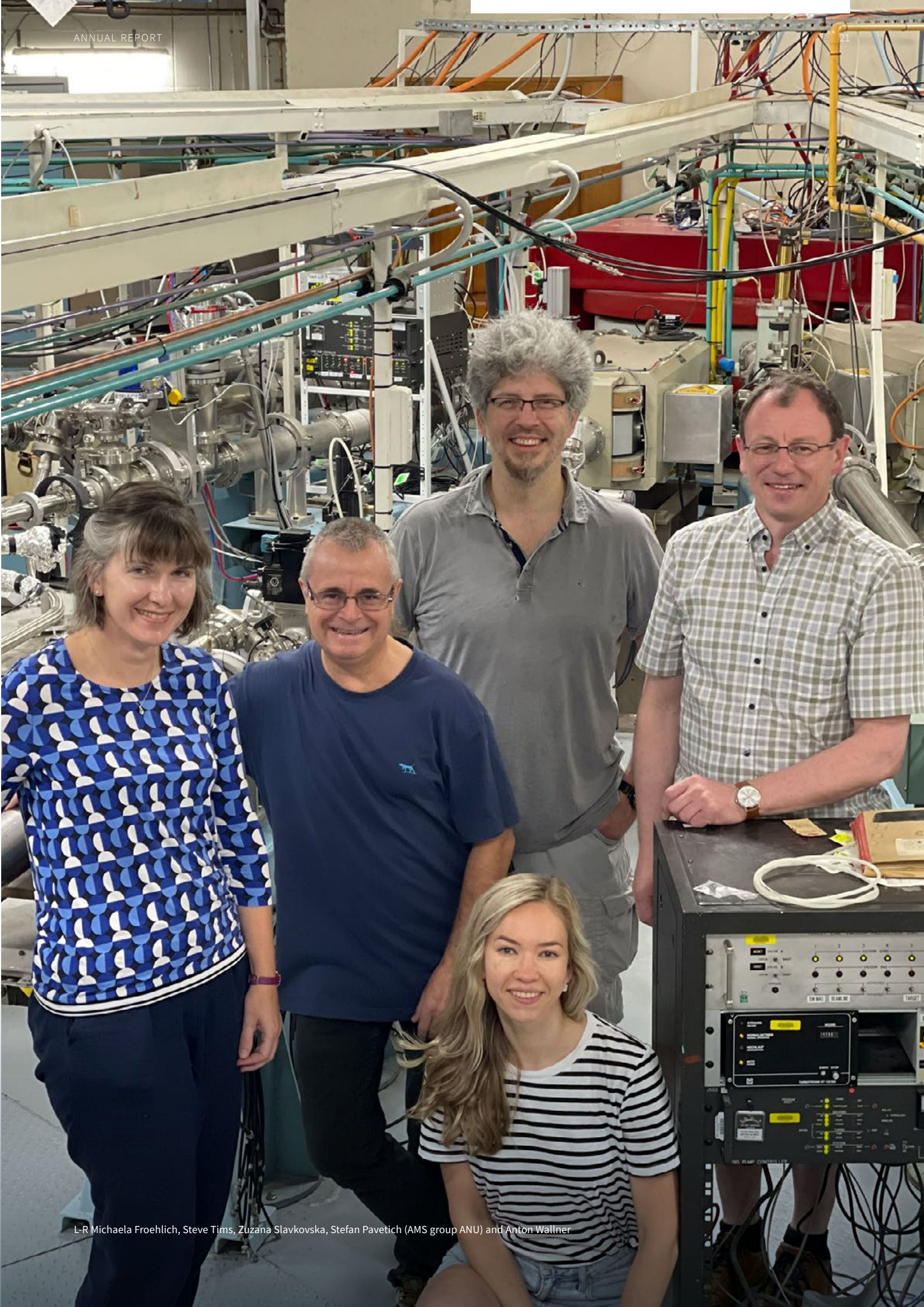
"It has strengthened the relationships between the research groups involved and is having a positive impact on other collaborative projects with these groups that are outside of the scope of Centre activities. A highlight of the activities has been the desire and enthusiasm shown by younger members in the collaboration to engage in the discussions and participate in development of the cross-disciplinary techniques being developed."

Dr Froehlich said she was proud of the achievements of the collaboration, along with the opportunity to work with local and international researchers.

"A highlight of our collaborations is certainly our diversity: it has brought together scientists from across the globe with different backgrounds of expertise and various levels of experience (from PhD students to senior scientists)."

Dr Slavkovska said the opportunity to collaborate had provided her with new knowledge and experience.

"I am a physicist involved not only in the physics but also with chemistry for this project and the learning curve was huge for me. I learned several chemical procedures. Furthermore, I had the opportunity to chat to experienced international chemists and collaborate with them. The highlight of this project for me was to run the AMS machine VEGA at ANSTO when measuring ^{210}Pb samples together with our Partner Investigator Mike Hotchkis."



L-R Michaela Froehlich, Steve Tims, Zuzana Slavkovska, Stefan Pavetich (AMS group ANU) and Anton Wallner

case study 3

New relationship with the CNRS

Scientists from France and Australia will collaborate on two multinational projects using xenon to search for dark matter particles.

Centre research on direct detection was showcased during a visit from France's scientific governing body Centre National de la Recherche Scientifique (CNRS) to the Dark Matter Centre headquarters. The president of the CNRS visited the Centre as part of his visit to Australia to inaugurate CNRS in Oceania. We had presentations and represenations from UWA, UoS, SUT and UoM. We agreed to strengthen our ties with the CNRS to capitalise on the cotutelles, and collaborative research that is ongoing in the Centre.

The Melbourne CNRS Network in May also announced the successful recipients of the second call for proposals to establish joint PhD projects between the UoM and CNRS. One of the successful recipients was Elisabetta Barberio, with the project 'Luminous Dark Matter searchers with XENONnT and DARWIN experiments'.

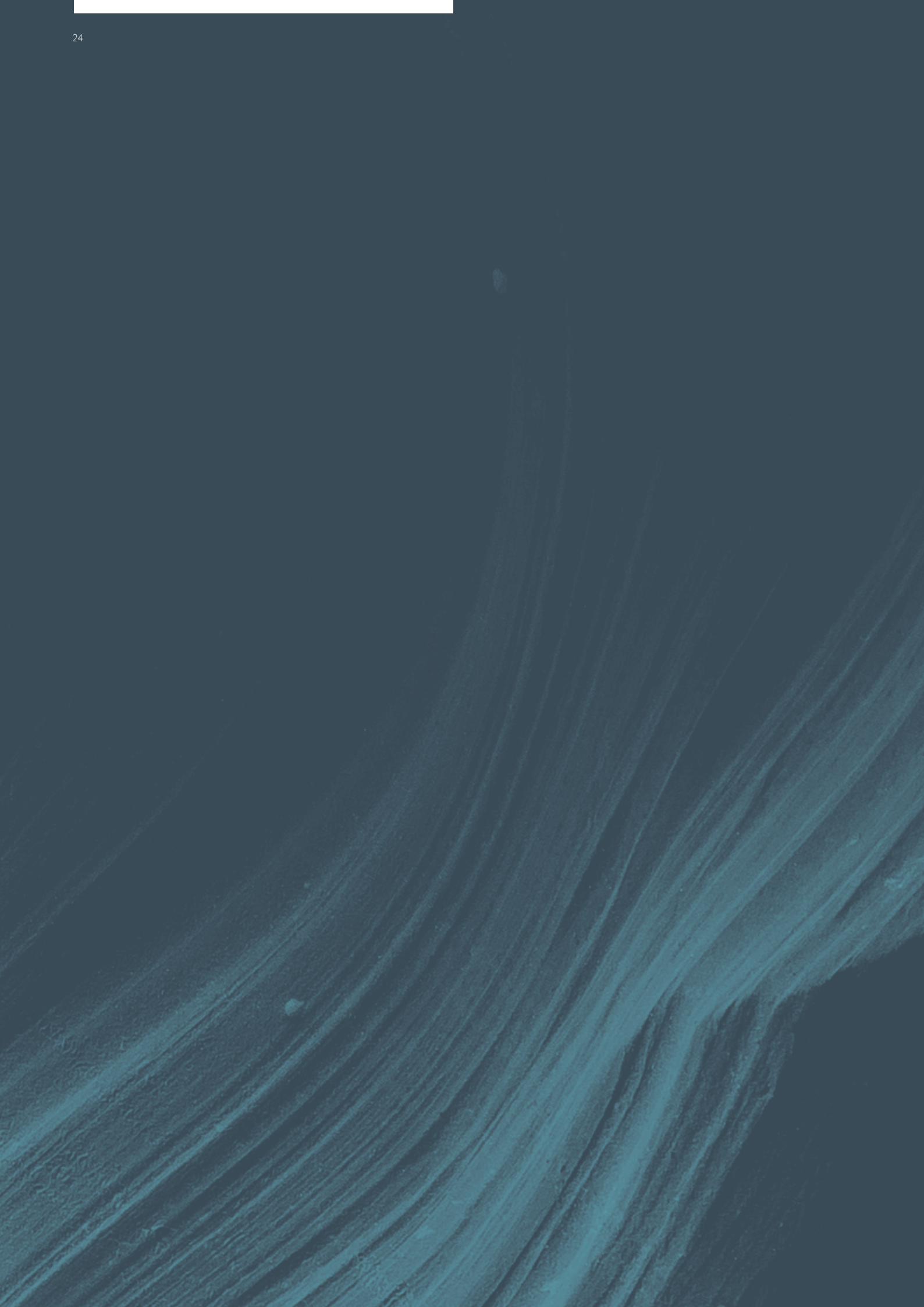
Professor Barberio will collaborate with Centre postdoc Jayden Newstead and Associate Investigator Sara Diglio from the Laboratoire de physique subatomique et des technologies associées (SUBATECH). Sara attended the CDM annual workshop and gave a keynote titled Prospects on Noble gas experiments (Xe and Ar).

The joint project was one example of the international collaboration happening at the Centre.

Centre postdoc Jeremy Bourhill will also be working with French scientists, using 3D printing to produce previously off-limit devices for quantum information processing, generating unique states of light, and dark matter detection.

"This research aims to provide technologies that will fundamentally alter the scope of problems we can solve computationally, the types of properties and scale of objects we can sense, and answer questions about the fundamental nature of the universe," he said.

Associate Investigator Sara Diglio and Elisabetta Barberio



research program overview

Since we have no information on their particle nature or mass of dark matter, the Centre's program covers a wide mass range. CDM research is organised in four integrated Research Program areas:

Program 1: Direct Detection (6 nodes, 35 researchers, 28 RHD 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 producing data and the SABRE South experiment (SUPL) is in the construction phase. The Centre is producing new direct detection technologies to extend our dark matter searches via our robust R&D program.

Program 2: Precision Metrology (2 nodes, 8 researchers, 9 RHD students)

Selecting ultra-pure materials for the underground experiments requires the development of excellent ultra-low background radioactivity measurements. The Centre is exploiting 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, 14 RHD 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, 18 researchers, 37 RHD students)

The Centre's theoretical 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, UoA, UoM, SUT, UoS

Chief Investigators: E. Barberio, C. Boehm, A. Duffy, G. Hill, G. Lane, J. Mould, A. Stuchbery, G. Taylor, P. Urquijo, A. Williams

Academic Staff: T. Früth

Postdocs: L. Bignell, I. Bolognino, M. Froelich, M. Gerathy, P. McNamara, F. Nuti, F. Scutti, Z. Slavkovska

Engineers: T. Baroncelli, G. Milana

RHD students: F. Alharthi, S. S. Chhun, F. Dastgiri, G-Y. Fu, J. Irving-Dinsdale, C. Isaac, K. Leaver, I. Mahmood, W. Melbourne*, M. Mews, L. McKie, P. McNamara*, L. Milligan, K. Rule, N. Spinks*, O. Stanley, M. Tan Ha, Y-Y. Zhong*, M. Zurowski*

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

Professional and Technical Staff: J. McKenzie, R. Timpano

*Graduated or submitted thesis for examination

Introduction

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

The experiment is made up of three sub-detector systems: (i) the NaI(Tl) crystal detector system, (ii) the linear alkyl benzene 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 2026/2027. SABRE South will be installed at SUPL over the coming year. A large number of off-site activities have been underway over the past year described in more detail below.

The SABRE South organisation chart is shown below. The working groups report to the executive management, while the committees manage broad collaboration-wide topics such as safety, SUPL-SABRE interface, conferences, publications and outreach. Working groups are typically convened by early career postdoctoral researchers and engineers.

Management

Spokesperson	Elisabetta Barberio (UoM)
Technical Coordinator	Phillip Urquijo (UoM)

Working groups (convenors)

Physics Analysis	Francesco Nuti (UoM)
Software and Computing	Federico Scutti (SUT)
DAQ and Slow Control	Matthew Gerathy (UoM)
Veto System	Lindsey Bignell (ANU)
NaI(TI)Detector	Zuzana Slavkovska (ANU)
PMTs	Theresa Fruth (UoS)

Technical Groups (chairs)

SUPL Liason	Geoffrey Taylor (UoM)
Project Management	Leo Fincher-Johnson (UoM)
Safety	Geoffrey Brooks (SUT)
Engineering	Giulia Milana (SUT)

Committees (chairs)

Speakers	Irene Bolognino (UoA)
	Peter McNamara (ANU)
Publications	Gary Hill (UoA)
Outreach & Inclusion	Padric McGee (UoA)

NaI(Tl) detector

Nominally seven NaI(Tl) crystals will be grown from Sigma Aldrich (Merck) Nal astrograde powder, which has an ultra low potassium content, and placed within 570mm long oxygen free copper enclosures. Each crystal has a length of around 150-200mm, and diameter of around 100mm giving a mass of about 7kg. The total crystal mass will therefore be around 50kg. Each crystal is instrumented with two ultra radio pure, low noise 76mm Hamamatsu R11065 photomultiplier tubes (PMTs) to detect dark matter.

Crystal production
Crystal production is the most critical item for the success of SABRE South, as it is the 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 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 2022 a zone refining oven was setup for the RMD production line by collaborators at Princeton and INFN. We expect to commence production with this process in 2023.

The second production line involves centre AIs from SICCAS who will use a modified Bridgman method with a double-walled platinum crucible technique. This method has been demonstrated to work in earlier prototypes. An MoU between UoM and SICCAS was signed in 2022 for this work.

Enclosure, glove box and insertion system engineering
Within the copper enclosure, the crystals are directly mounted to the PMTs using high purity copper and PTFE (teflon) parts. The design of the enclosure is complete, and prototypes of the end-cap plates in copper have been tested to ensure good seals for handling high purity nitrogen and to ensure no leakage from the liquid scintillator. The nitrogen flushed glove box for assembly of these detectors has been designed and refined based on experience from the INFN-LNGS system, which was commissioned in 2022. 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. The tests for the crystal PMTs have been focused on the single photo-electron response, quantum efficiencies, gain and stability over time, as well as dark rate and its temperature dependence. Datasets collected are being used to develop machine learners to mitigate noise. Furthermore PMT base electronics studies have been undertaken to optimise for dynamic range for calibration of intrinsic crystal background.

Crystal characterisation and analysis
In 2022 two new crystals were delivered from RMD to LNGS for characterisation and development of the crystal detector assembly process. Several members of SABRE South 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 ^{210}Pb 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. The former is particularly important to achieve low energy thresholds, particularly below 2 keV and depends on temperature. The latter is a broad spectrum contribution across energy levels that may also modulate if induced by cosmic rays. In both cases, machine learning algorithms were developed and trained on data from the PMT test bench, NaI35 run at LNGS, and the Heavy Ion Accelerator Facility at ANU.

Bill Melbourne, Zuzana Slavkovska and Ferdos Dastgiri with a crystal enclosure during their visit to LNGS.

Veto detectors, calibration systems and shielding

Liquid scintillator veto

The liquid scintillator vessel is made of stainless steel and lined with lumirror reflector foil. 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 top torispherical section has 12 flanges for cabling, gas flow, and systems. The liquid scintillator is a mixture of linear alkyl benzene (LAB) and fluorophores PPO and Bis-MSB. The vessel is instrumented with 18 204mm Hamamatsu R5912 PMTs with oil-proof electronics bases to detect veto signals with very low energy thresholds.

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

With the vessel already built, the current effort is focused on LAB transport, PMT and lumirror mounting, cleaning, and fluid handling. 17kL of LAB, procured from Nanjing via the IHEP JUNO group, 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.

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 liquid scintillator handling. A design has been developed in collaboration with INFN Rome, and is with the project management team.

Shielding

The vessel is surrounded by a shielding system made of a 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 the steel and neutrons with the 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.

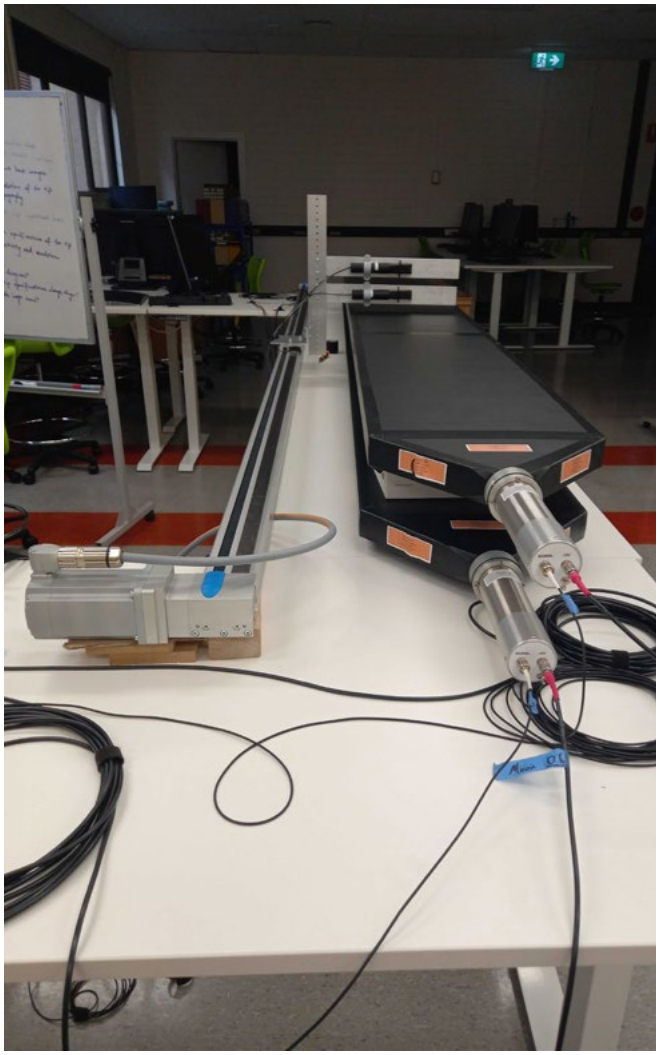
The shielding design is final, with the project now being managed by a UoM project management team who will work with an external company for fabrication and assembly.

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, (ii) a pulsed optical system to test the LS system, and (iii) a radioactive source based system for the muon detectors. 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 2023 until its integration with the full SABRE detector in 2024. In 2022 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.



Two of the muon detectors being tested with a calibration stage at UoM.

Data acquisition, monitoring and control systems

DAQ infrastructure

The data acquisition (DAQ) system of SABRE South is primarily comprised 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 across sub-detector 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 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. In 2022 we integrated this system with the slow control and environmental monitoring system developed by SUT.

Online computing infrastructure

The local SUPL computing infrastructure for SABRE South was procured using UoM funding. 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 full system is backed up by a smart UPS. Stress testing of the system with the DAQ and monitoring software is underway.

Software and offline computing

There are three main projects under development for SABRE South.

- The GEANT4 based full simulation of the experiment was developed and a publication on this work was submitted in 2022. The next major step is to introduce detector digitisation and resolution effects to fully mimic waveform data acquired by the readout system. This will be used to develop more advanced analysis algorithms in all subsystems.
- The python based data processing and analysis framework (Pyrate) processes data from either the DAQ system or from the GEANT4 simulations. The second major release of this package was finalised in January, and supports a wide range of ongoing calibration and machine learning based pulse shape analysis studies.
- The conditions database is crucial for managing calibration data, and to correlate environmental conditions into data analysis.

The offline storage for SABRE South 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 transfer of data and remote control of detector systems.

R&D CYGNUS

Nodes involved: ANU, UoA, UoM, UoS

Chief Investigators: N. Bell, C. Boehm, G. Lane, A. Williams

Postdocs: L. Bignell, J. Newstead, Z. Slavkovska

RHD students: V. Bashu, F. Dastgiri, L. McKie, P. McNamara

Associate Investigators: C. O'Hare

2022 saw the Australian CYGNUS R&D efforts coalesce into a new collaboration, CYGNUS-Oz. The collaboration has 20 current members, all affiliated with the Centre and drawn from 4 institutions: ANU, UoA, UoM and UoS. The institutional board includes Greg Lane (ANU, spokesperson), Paul Jackson (UoA), Nicole Bell (UoM), and Ciaran O'Hare (UoS). Members are a mix of theorists and experimentalists, with a shared interest in directional detection of particles using gaseous Time Projection Chambers (TPCs). While the potential uses of such detectors may be quite diverse, the current focus of the research effort is aimed primarily at dark matter detection, with additional potential for neutrino detection and industrial applications. CYGNUS-Oz expects to contribute towards the global community of scientists operating under the international umbrella of the CYGNUS proto-collaboration. Our goal is the development of the underlying science, leading towards operation of detectors in Australia as well as participation in international CYGNUS detectors and coordinated analysis. The local Australian detectors are anticipated to include technology development systems at individual Australian institutions, a proposed 1 m3-scale demonstrator detector in the Stawell Underground Physics Laboratory and eventual operation of a large-scale directional dark matter detector that will be a part of the international network of directional dark matter detectors that is envisaged to be operated in coordination with other detectors that form part of the international CYGNUS project.

Research activities for CYGNUS-Oz have continued with the characterisation and development of the CYGNUS-1 gas TPC prototype. The detector has measured particle events from a variety of sources with the existing charge readout onto wires and optical readout using a photomultiplier. These measurements have been supported by efforts towards modelling the TPC, including the development of custom software for emulating carrier diffusion and readout that will aid future studies of larger detector designs. Detailed electric field modelling of the prototype, several avalanche gain structures, and induction fields towards the charge readout, have also been performed, and this modelling will be used to refine the signal emulation software predictions. Preliminary results from these studies have been presented by CYGNUS-Oz students during 2022 at the AIP Congress and the Dark Side of the Universe conference.

CYGNUS-Oz collaborators from the ANU, UoA, UoM, and UoS together with international CYGNUS spokesperson and PI Neil Spooner at the 2022 CDM Annual Workshop.

Current and Next Generation Liquid Xenon TPC

Nodes involved: UoM, UoS

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

Academic staff: T. Früth

Postdocs: J. Newstead

RHD students: O. Stanley

Associate Investigators: S. Diglio, C. O'Hare

In 2022, the Centre's dark matter direct detection stream gained a new experimental effort as researchers from the University of Sydney and the University of Melbourne joined LUX-ZEPLIN (LZ) and DARWIN, a current and a next-generation liquid xenon detector. 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. The technology profits from xenon's high atomic mass and density, low intrinsic backgrounds, and the ability to scale up the detector size.

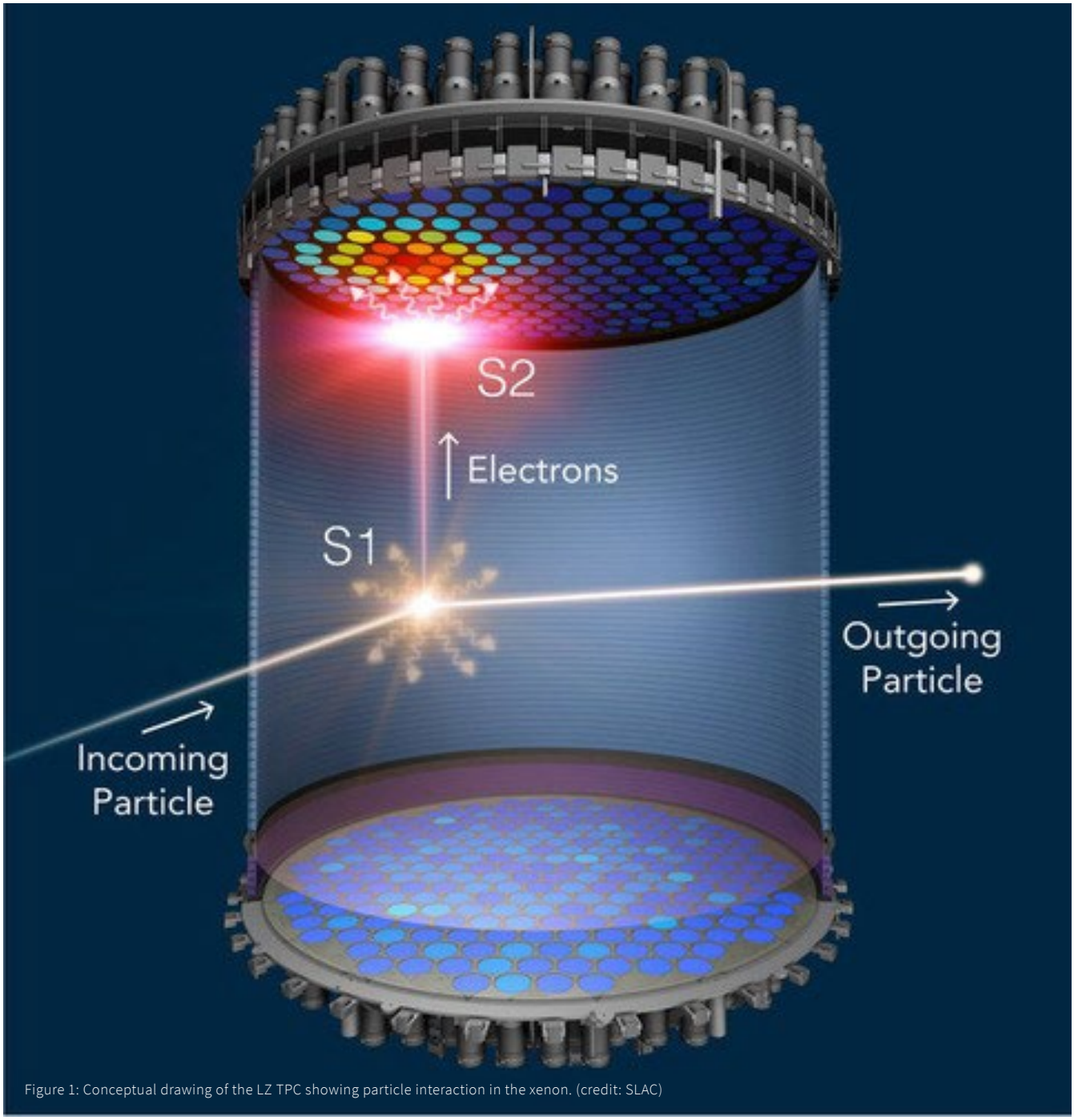


Figure 1: Conceptual drawing of the LZ TPC showing particle interaction in the xenon. (credit: SLAC)

Figure 2: XLZD collaborators from the UoM, the UoS and Subatech at the Centre's Annual Meeting in Geelong

The LZ collaboration currently operates a detector with 7 tonnes of xenon as active mass at the Sanford Underground Research Facility in South Dakota (USA). The experiment announced results from its initial engineering run in July 2022, setting new world-leading limits for WIMP-like dark matter for masses above 9 GeV/c^2 [arXiv:2207.03764]. The University of Sydney joined this effort in November 2022. As LZ continues its 1000-day dark matter search, the UoS LZ group has already contributed expertise in simulations and detector monitoring sensors.

DARWIN, a continuation of the successful xenon experiment's legacy, is currently conducting R&D towards a next-generation observatory for rare-event searches. Researchers from the Centre (UoM and UoS) are now part of this collaboration's experimental and theoretical efforts. The XENONnT, LZ, and DARWIN have formed the XLZD consortium to design and build the ultimate liquid xenon dark matter detector together. Its scientific reach is outlined in a white paper to be published in early 2023 [arXiv: 2203.02309]. Beyond probing dark matter down to the neutrino fog, the envisioned detector would be multi-purpose with sensitivity to neutrinoless double-beta decay, solar and astrophysical neutrinos, and other beyond the standard model topics. Researchers from the Centre are already involved in design and sensitivity studies. This includes three 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

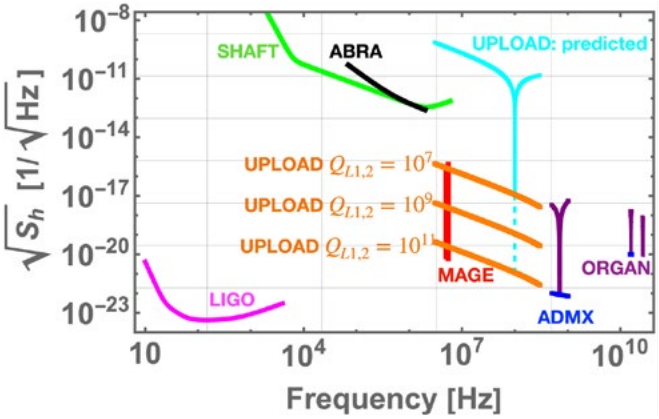
Postdocs: B. McAllister, J. Bourhill, G. Flower

RHD Students: W. Campbell, I. Goel, E. Hartman, R. Limina, A. Quiskamp, D. Rajawat, B. Roughan, C. Thomson

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

Partner Investigators: G. Rybka

At the start of the Centre, this program was only concentrated at UWA, now significant contributions are coming from three other Centre nodes, expanding the program across the Centre. The program is focused on searching for what the community now calls "wave-like" dark matter, also known traditionally as Weakly Interacting Sub-eV Particles (WISPs). This is because these types of experiments require precision measurements, where the output of the detector is akin to detecting an extremely weak classical wave. This has been highlighted by the SNOWMASS process, which is a particle physics community planning exercise sponsored by the American Physical Society. During this process, scientists develop a collective vision for the next seven to ten years for particle physics research in the USA. Sub-eV dark matter is categorised as "Cosmic Frontier" CF2 Dark Matter: Wave-like, as opposed to CF1 Dark Matter: Particle-like. Centre members were involved in two Wave-like SNOWMASS community white papers, on Axion Dark Matter and on New Horizons: Scalar and Vector Ultralight Dark Matter (see publications at the end of the annual report for details). During 2022 the Centre has made some significant advances in both these directions.



Spectral sensitivity, for LIGO, 10Hz-4kHz, compared to MAGE and some well-known axion detectors.

Many dark matter experiments are also sensitive to high-frequency gravitational waves. For example, resonant acoustic experiments that are sensitive to scalar dark matter (like the dilaton) can also operate as resonant-mass gravitational wave detectors, we have developed the Multi-mode Acoustic Gravitational wave Experiment (MAGE), which is sensitive to scalar dark matter and gravitational waves above 5 MHz. Furthermore, all axion detectors have been shown to be sensitive to high frequency gravitation waves through the inverse Gertsenshtein effect. This means all Centre WISP dark matter experiments can be used to search for high frequency gravitational waves. This fact inspired the UWA group to calculate the spectral sensitivity of their experiments, ORGAN, UPLOAD, MAGE etc., which also allowed comparison of dissimilar axion haloscopes, [Symmetry, 14, 10, 2165 (2022)]. Thus, we introduced to the community a way to compare the sensitivity of instruments independent of the dark matter signal, in the same way the gravity wave community compare noise in their instruments, through spectral sensitivity.

ORGAN

The flagship axion program of the Centre is the ORGAN experiment, targeting the 15-50 GHz or 60-200 micro eV in mass, where serious theoretical prediction suggests the axion exists. The first short, targeted scan, Phase 1a, has finished and successfully excluded Axion Like Particle Cogenesis models between 15.3–16.2 GHz (63-67 micro eV). Results were published in 2022 [Science Advances, 8, 27 (2022)]. During 2022 preparations have been underway for Phase 1b, a targeted run to search for Axion Like Particle Cogenesis models between 26-27 GHz. The experiment is nearly ready to run, most of the year consisted of designing a new haloscope cavity suitable for this phase, and the run will occur in 2023. In 2022 researchers began developing an off-shoot experiment, ORGAN-Q, which will look to implement quantum technologies and novel resonant designs in the lower frequency (~6 GHz) range. This experiment will also commence in 2023. R&D on quantum technologies and cavity resonators for Phase 2 continues. In parallel researchers are investigating dielectrically loaded cavities with novel tuning and single photon detectors in our frequency range. Graeme Flower finished his PhD thesis, where a part of it looked at characterising Josephson junctions as a single photon counter for ORGAN. This work is ongoing.

It has been shown that axion haloscopes are sensitive to other kinds of dark matter, such as dark photons, scalar field dark matter, and axion-electromagnetic couplings motivated by quantum electromagnetodynamics. A new collaboration between UWA, SUT, UoS and ANU, computed the sensitive of various resonant haloscopes to these dark matter candidates, and then computed the exclusion limits on the other candidates from ORGAN 1a, and the project sensitivity for some future ORGAN phases [arXiv:2212.01971]. Of note was that the dark photon limits are the most sensitive to date in some regions of the parameter space.

case study 4

ORGAN experiment

We may still be in the dark about what dark matter IS, but we have a better idea about what it ISN'T.

Hosted at UWA, the ORGAN experiment is Australia's first major contribution to dark matter detection. After four years of research and development it is now fully online and searching for axions, and is a major player in the quest to solve the mystery of the nature of dark matter.

There are lots of experiments around the world testing different hypotheses and searching for different mass ranges predicted by the theory. It is a process of elimination to figure out which one is correct.

PhD student Aaron Quiskamp said the first results from ORGAN rule out a popular theory about the nature of dark matter, narrowing the possibilities for what it could be.

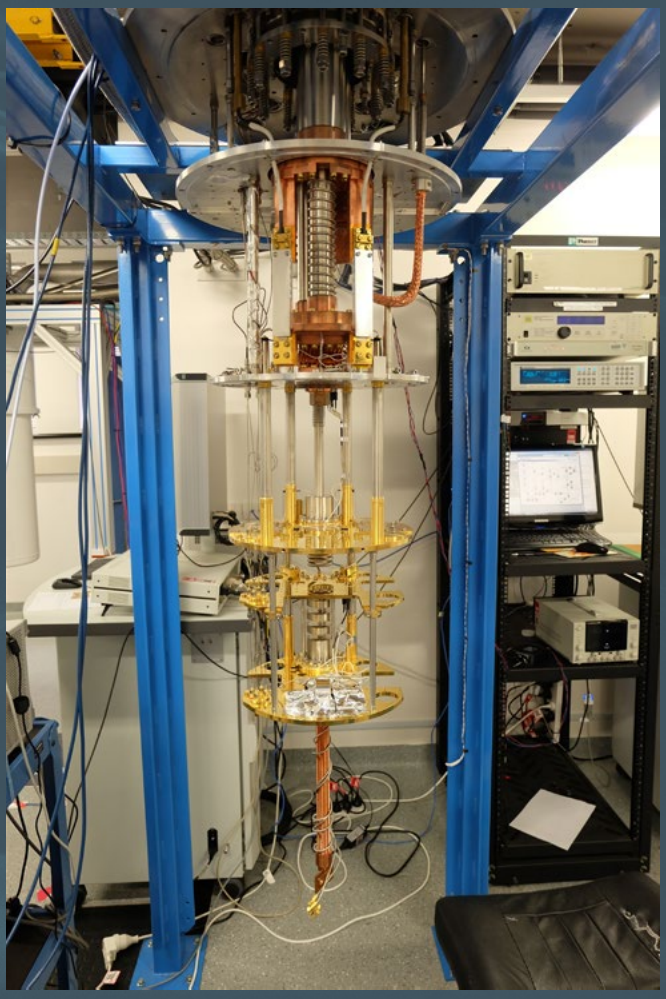
"We performed the most sensitive search so far for axion dark matter in a theoretically well-motivated mass range," he said.

> *"Although we didn't find any, it's very exciting because it's Australia's first large-scale, long-term direct dark-matter detection experiment. It's also given us useful information about what axion dark matter isn't, which tells future axion searches across the globe where not to look."*

Postdoc Ben McAllister says "We've shown that high-mass axion searches are possible, but a lot of work is needed to search in other relevant mass ranges. We're currently making technical improvements to our detector to achieve greater sensitivity and enable wider-ranging searches."

The first results from ORGAN are a big step for Australian research in this space.

Results were published in *Science Advances.*



The dilution refrigerator used to cool ORGAN down to cryogenic temperatures

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

Rather than a DC background magnetic field, which ADMX and ORGAN use, this experiment uses an AC background field as an excited high-Q mode in a microwave cavity resonator. Then another high-Q readout mode is read out to search for frequency or power perturbations and looks for axions at the difference frequency between the two modes, so searches for lower mass axions compared to the DC haloscope. For this to work the readout mode and the background mode must have a non-zero overlap between them. Our work in 2022 analysed the mode pairs with non-zero overlap, working out general analytical equations for a cylindrical cavity resonator. Then the second room temperature prototype experiment was completed in 2022, with a preprint available [arXiv:2301.06778]. The experiment was configured in two ways. The first was with state-of-the-art frequency stabilisation, and it was found that the circuit was quite complicated and hard to run. Thus, we configured it to measure power of the thermally excited readout mode. In principle both techniques have similar sensitivity, however the simplicity of this technique allowed faster scanning with lower noise, which improved our previous results by three orders of magnitude and searched for axions in the 1.1 – 1.2 micro eV range. To improve this further a full cryogenic experiment is required.

Axion Dark Matter eXperiment (ADMX) Generation 1 and 2

The ADMX collaboration has finished run 1c, the new cavities for ADMX run 1D have been made and will be shipped to Seattle soon and should begin in 2023. Also, the ADMX collaboration, in particular with UWA and Swinburne, have shown a growing interest in the lower-mass axion regime – below 1 micro eV. Various detector designs are being considered for implementation in future ADMX searches.

The UWA group is involved in characterising the ferroelectric materials, with permittivity that may be altered at low temperatures using a DC field. Such materials include single crystal STO and KTO and could be useful for electrically tuning axion haloscope cavities. A paper on characterising such materials has been published [IEEE Trans on UFFC, 69, 1 (2022)], and research continues on these materials for Axion detectors.

Low mass detectors for axions with LCR circuits

This project investigates experiments to search for axions below 1 μeV in mass using lumped mass LCR circuits. We applied Poynting theorem to axion modified electrodynamics and created a systematic way to calculate the sensitivity of an axion haloscope. The work identified two possible Poynting vectors, one which is like the Abraham Poynting vector in electrodynamics and the other like the Minkowski Poynting vector. We showed that Minkowski Poynting theorem picks up extra nonconservative terms, due to an ignored surface term, while the Abraham does not (consistent with a zero total derivative, assuming no surface terms).

The nonconservative terms may be categorized more generally as “curl forces,” which in classical physics are nonconservative, non-dissipative and localized in space, not describable by a scalar potential and exist outside the global conservative equations of motion. To understand the energy conversion and power flow in the detection systems, we apply the two Poynting theorems to both the resonant cavity haloscope and the broadband low-mass haloscope. Our calculations show that both theorems give the same sensitivity for a resonant cavity axion haloscope, but predict markedly different sensitivity for the low-mass broadband haloscope [Phys. Rev. D, 105, 045009 (2022) Erratum Phys. Rev. D, 106, 109903 (2022)]. Like the Abraham-Minkowski controversy in classical electrodynamics we, postulate the only way to solve this controversy is through experiment.

At low masses, extracting photon power from dark matter using an electric circuit is very similar to extracting and producing voltages from an electric generator. We have furthered this research to active Electric Dipole Energy Sources and shown that two-potential theory must be used to explain the voltages, due to effectively a “curl force” related to an extra surface term, in a similar way to axion electrodynamics [Sensors, 22, 18 (2022)]. This work was recently used by others to explain the charge distribution in a triboelectric energy source verifying the theory.

Scalar dark matter

With a new collaboration with UNSW, we established new experiments to search for dark matter based on a model of a light scalar field with a dilaton-like coupling to the electromagnetic field, which is strongly motivated by superstring theory [Phys. Rev. D, 105, 055037 (2022)]. We estimated the power of the photon signal in the process of a nonresonant scalar-photon transition experiment such as CAST, and in a cavity resonator permeated by electric and magnetic fields. We showed that existing cavity resonators employed in experiments like ADMX have a low but nonvanishing sensitivity to the scalar-photon coupling. As a result, by repurposing the results of the ADMX and CAST experiments, we found new limits on the scalar-photon coupling in various scalar field mass ranges. We also proposed a broadband experiment for scalar field dark matter searches based on a high-voltage capacitor.

Research highlights

- Devised new experiments to search for scalar field dark matter
- Devised a way to compare dissimilar axion haloscopes independent of the type of dark matter signal
- Developed a systematic way to calculate axion haloscope sensitivity using Poynting theorem

precision metrology research program

Nodes involved: ANU, UWA

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

Postdocs: M. Froehlich, Z. Slavkovska

RHD Students: W. Campbell, F. Dastgiri, G. Flower, I. Goel, R. Limina, C. Millar, A. Quiskamp, B. Roughan, C. Thomson

Associate Investigators: E.Ivanov

Partner Investigators: A. Wallner, M. Hotchkis

Characterisation of the materials used in dark matter detectors is proceeding at the ANU node. This is to ensure the intrinsic radioactive background present in the detector components is minimised, particularly where it would contribute to the energy region of interest for dark matter detection. Significant progress has been made towards improving detection sensitivity for a number of the uranium decay series radionuclides at ANU, and for ^{210}Pb at ANSTO.

The UWA node continues the development of low phase noise oscillators as detectors in the sub-eV range, and their potential for improving bolometers to detect axions as described in the AXION section.

Nuclear metrology

AMS capability

During 2022 we have been developing new AMS techniques and chemical separation and purification methods to improve AMS sensitivity for the important isotope ^{210}Pb. A major focus this year has been towards identifying a suitable lead carrier material to quantify the fraction of Pb atoms chemically extracted from materials where they will only be present at trace levels. It is imperative that the carrier has a ^{210}Pb content that is low enough that it will not interfere with the ^{210}Pb measurements of the material to be measured.

The relative abundance of ^{210}Pb to the other Pb isotopes in the carrier material needs to be orders of magnitude lower that what is normally present in most cases. Consequently, chemical processing alone cannot produce suitable carrier material and, the proportion of ^{210}Pb in the carrier needs to be close to, or below, the current detection limits achievable with AMS.

In parallel with the search for a suitable carrier material, and, in collaboration with our PIs from ANSTO and HZDR, we have been progressing the development of new AMS techniques to improve ^{210}Pb measurement sensitivity. The VEGA accelerator at ANSTO was specifically designed to measure isotopes of similar mass to ^{210}Pb, and potentially could have the required sensitivity. In 2021 we identified PbF_2 as the optimal sample material for extraction of lead from the accelerator ion source (as PbF_3 negative ions) and subsequent AMS measurement of Pb atoms. Significant progress was made in 2022, with substantial improvements in the yield, stability and intensity of lead tri-fluoride beams (see Figure below). Extracted beam currents are up to a factor of ~30 larger than reported at other AMS facilities [Nucl. Instrum. Methods Phys. Res. B 529 (2022) 18], which should translate to a similar improvement in sensitivity. The experimental endeavour to improve the sensitivity will continue in 2023. In parallel with this, there is an effort to understand the effect of trace-level contaminants in materials.

Modifications to the time-of-flight detector have improved the noise levels and detector resolution, and allowed first tests of integration of the detector equipment with the fast-isotope switching system. These initial tests were very successful and led to subsequent preliminary tests of automated measurements of ^{236}U with the time-of-flight detector equipment. Preliminary results from these recent tests indicate a range of uranium decay series isotopes could be measured with the greater precision.

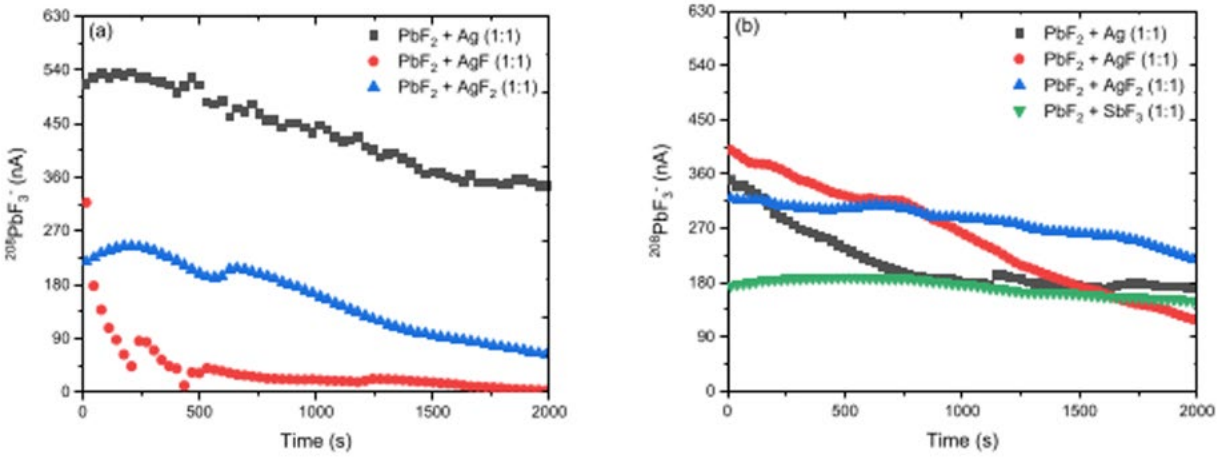


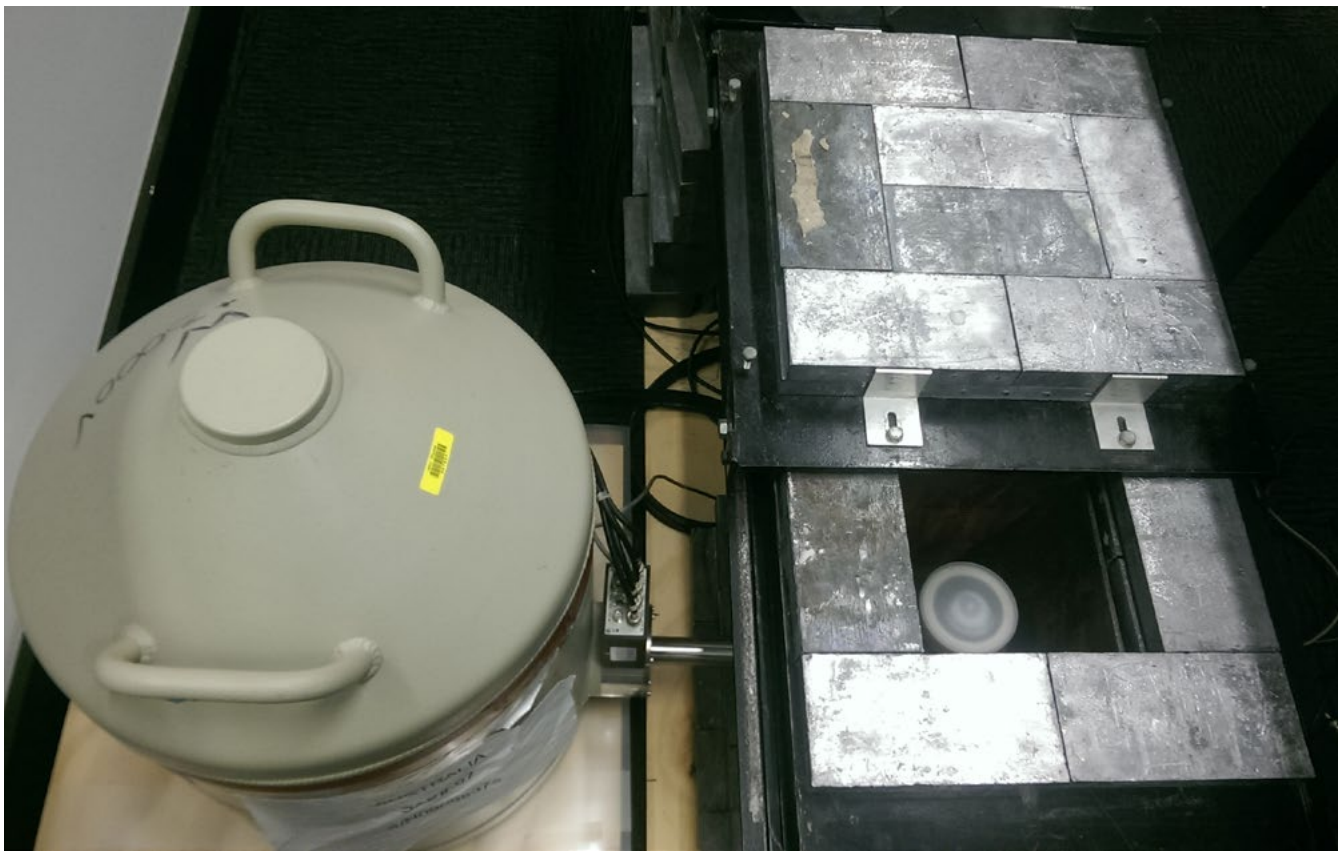
Figure: Time evolution of PbF_2 mixed 1:1 with different additives at (a) ion source Cs temperature of 93℃ and (b) 86℃.

ICP-MS

Tests with dilutions of certified reference materials at the ANU ICP-MS facility appear to have improved the quality of the results reported for ^{40}K analysis. The sensitivity is now close to what is needed, however there still appears to be an issue with accuracy. Further discussions and measurement tests are in progress. The ANU facility and a local commercial ICP-MS laboratory both seem capable of making satisfactory measurements to ^{40}K levels of ~10 ppb, but this remains at least an order of magnitude above what is desired.

New low background Ge detector

A third low background germanium detector has been installed in newly constructed lead castle at ANU. The new detector is currently being commissioned and will initially be used to, assess the internal radioactivity in sapphire crystal oscillators used by the UWA node.



Newly installed germanium detector at ANU.

LHC research program

Nodes involved: UoA, UoM

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

Postdocs: H. Potti, J. Webb

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

Partner Investigator: K. Jakobs

Collider Searches for dark matter: Large Hadron Collider - ATLAS experiment

The Centre for dark matter Particle Physics provides an opportunity to search for dark matter direct production at a unique facility 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. Throughout 2022, 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 2023.

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 combined various production and decay mechanisms to increase the sensitivity to invisible decays of the Higgs boson.

DM searches with ATLAS data are underpinned by performance work and require a thorough understanding the objects that manifest in the 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.

Beyond performance and physics analysis 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.

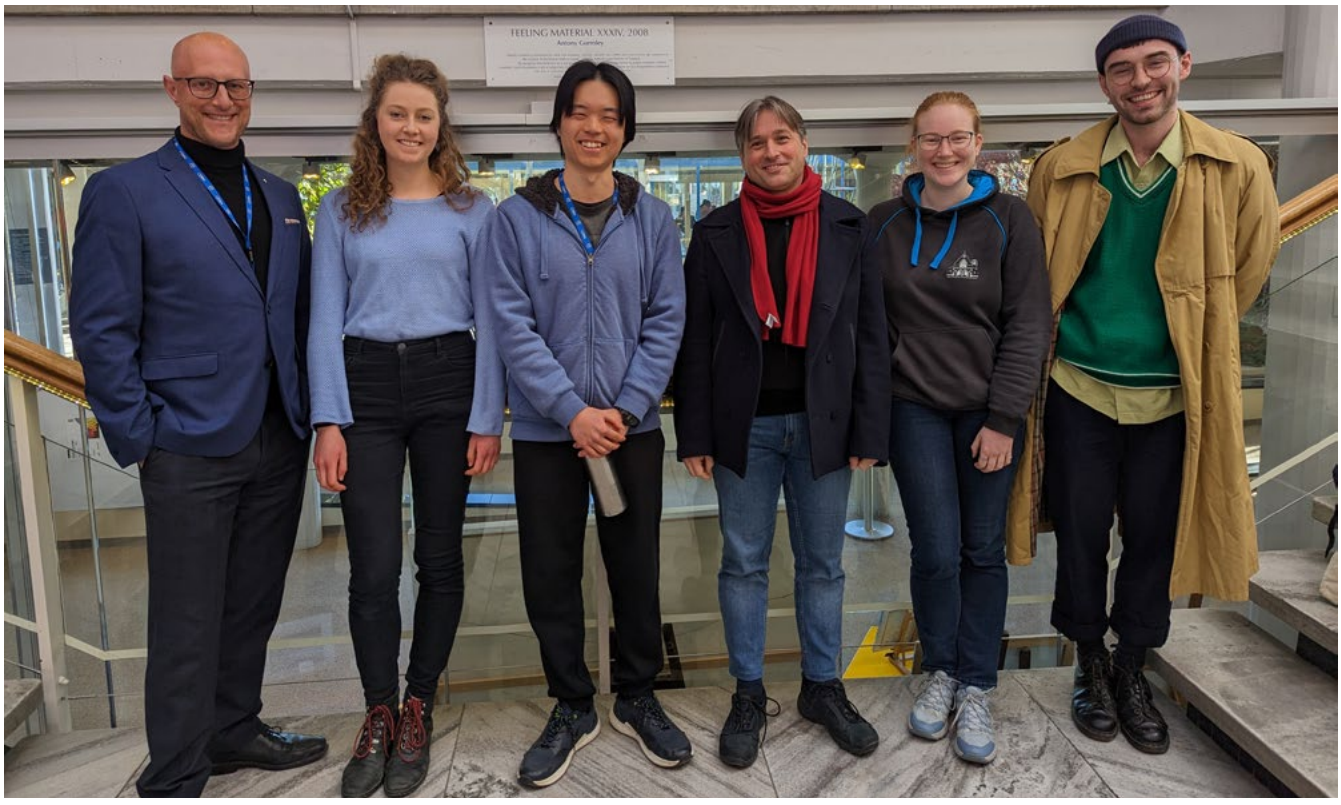
Dark matter searches in the context of pair produced objects and using initial-state-radiation signatures have benefitted from the application of Recursive Jigsaw Reconstruction which Centre researchers pioneered. Within the Centre we continue to lead all aspects of deploying this method within the ATLAS experiment.

In models where the Higgs boson decays to dark matter, we would be sensitive to inferring its presence by studying invisible decays of the Higgs boson. Combining various production and decay mechanisms increases the sensitivity to this and within the Centre we are heavily involved in these combinations to extract the greatest sensitivity to invisible decays of the Higgs boson.

All these searches, and others like them, are undergirded by performance work in understanding the objects that manifest in the detector environments. Most prominently for dark matter searches this involves hadronic jets and missing momentum. 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.

Beyond performance and physics analysis, the long-term health and productivity of the detector is important. In the upcoming High-Luminosity LHC era this will require new subdetectors as ATLAS is completely revamped. Centre researchers are focused on the construction, testing and deployment of modules for the inner tracker upgrade, known as ITK. In the Centre we leverage the symbiotic relationship between the Adelaide and Melbourne groups to drive this work forward. We anticipate first modules to be produced in Melbourne in the coming year and then sent to Adelaide for testing and quality assurance steps.

P. Jackson (UoA) and J. Pham (UoM) visiting the ATLAS experiment.



Current and former Centre members gathering at CERN: (l-r) P. Jackson (UoA), A. Mullin (now University of Cambridge), A. Kong (UoA), F. Deliot (IJClab Saclay), E. Filmer (UoA) and C. Grant (UoA).

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

RHD Students: R. Abdel Khaleq, J. Allingham, R. Amintaheri, N. Botten, D. Dance, M. Deshpande, M. Dixon, J. Gill, K. Goh, M. Hayat, F. Hiskens, L. Hockley, T. Hughes, N. Hunt-Smith, W. Husain, R. Key, N. Krishnan, G. Lawrence, N. Leerdam, J. Leong, B. Li, B. Loizos, M. Mosbech, S. Owa, J. Park, Z. Picker, A. Ritter, N. Shapir, I. Shaukat Ali, A. Sopov, S. Thompson, A. Ussing, P. Verwayan, M. Virgato, J. Wood, A. Woodcock, W. Xing

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

Partner Investigators: P. Hopkins

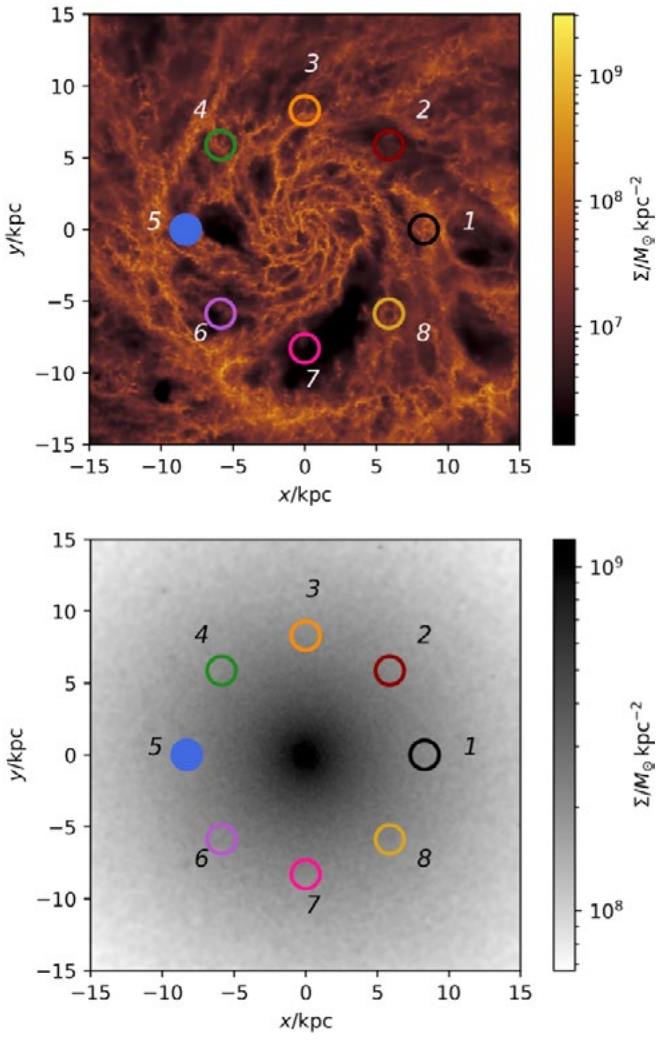
Centre theorists have continued to pursue a wide-ranging research program in 2022, including the exploration of novel experimental and astrophysical probes of dark matter, and the construction of dark matter models. Some highlights of theory research undertaken in 2022 are described below.

Gusts in the Headwind: Uncertainties in direct dark matter detection

Using high-resolution galaxy formation simulations Grace Lawrence, Alan Duffy and Philip Hopkins investigated the inherent variation of dark matter distributions within the Sun's orbit around the Milky Way, and its impact on direct dark matter detection. These simulations show there are significant changes to the dark matter's spatial and velocity distributions beyond what is traditionally assumed. These are experienced as 'gusts' of dark matter wind around the Solar Circle, potentially complicating interpretations of direct detection experiments on Earth. They found that these velocity substructures, or gusts, contribute additional astrophysical uncertainty to the interpretation of event rates. However, their impact on summary statistics, such as the peak day of annual modulation, is generally low [Mon. Not. Roy. Astron. Soc. stac2447 (2022)].

Inelastic nuclear scattering from neutrinos and dark matter

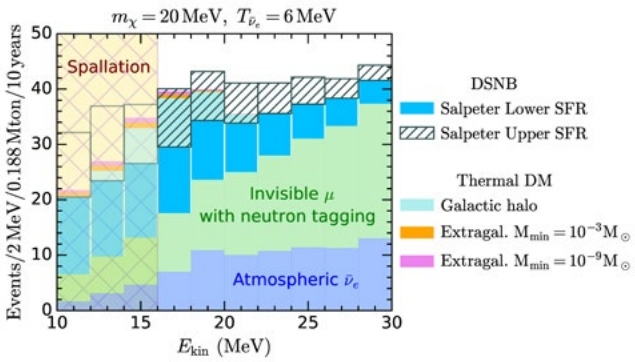
Neutrino sources with energy of O(10 MeV) are an invaluable tool for studying neutrino interactions with nuclei, previously enabling the first measurement of coherent elastic scattering. They can also potentially produce a large flux of light dark matter. Neutrinos and dark matter in this energy range will also excite nuclei, giving us another physics channel to study. Jayden Newstead and collaborators considered the inelastic nuclear scattering of neutrinos and dark matter from a variety of targets of interest. To calculate the relevant cross sections, large scale nuclear shell model calculations were performed using BIGSTICK. They found that some potentially interesting signals could be observed by future experiments and novel DM search strategies are now possible [Phys. Rev. D 106, 113006 (2022)].



A simulated Milky-Way analogue face-on, showing gas (left) and dark matter (right) distributions, along with eight regions for which the impact of 'gusts' in the dark matter headwind was determined for event rates in Earth-based detectors.E. Filmer (UoA) and C. Grant (UoA).

Dark matter pollution in the Diffuse Supernova Neutrino Background

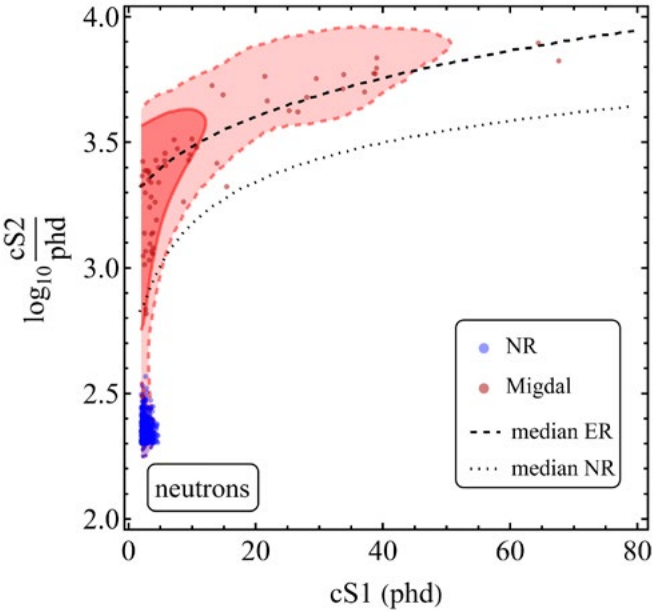
The Hyper-Kamiokande (HyperK) experiment is expected to precisely measure the Diffuse Supernova Neutrino Background (DSNB). This requires that the backgrounds in the relevant energy range are well understood. One possible background that has not been considered thus far is the annihilation of low-mass dark matter to neutrinos. Nicole Bell, Matthew Dolan and former Centre postdoc Sandra Robles simulated the DSNB signal and backgrounds in HyperK, to quantify the extent to which dark matter annihilation products can pollute the DSNB signal. They found that dark matter could impact the correct determination of stellar parameters, such as the effective neutrino temperatures and the star formation rate. While it may be possible to simultaneously characterise the DNSB and identify dark matter via an indirect detection signal, they found that disentangling the dark matter and DSNB signals would be challenging, due to the inherent lack of angular discrimination in low energy neutrino signals [JCAP 11, 060 (2022)].



Event rate at Hyper-Kamiokande due to the diffuse supernova neutrino flux (DSNB), dark matter (DM) annihilation to neutrinos, and the atmospheric neutrino flux, including invisible muon events.

Observing the Migdal effect with nuclear recoils of neutral particles with liquid xenon and argon detectors

Dark photons kinetically mixed with the Standard Model photon can be searched for with many of the same techniques as axions. However dark photon dark matter possesses a fundamental property that axion dark matter does not— a polarisation. Ciaran O'Hare, in collaboration with Caputo, Millar and Vitagliano, presented a thorough analysis of the inherent directionality in searches for the dark photon that arise due to this polarisation. These effects are crucial to understand, not just for repurposing axion searches, but also for optimising dedicated searches for dark photons in the future. They obtained robust limits on low-mass dark photons, exploiting past data from searches for the axion, and make recommendations for run strategies and orientation adjustments that future searches should adopt in order to maximise their sensitivity [Phys. Rev. D 104, (2021) 095029].



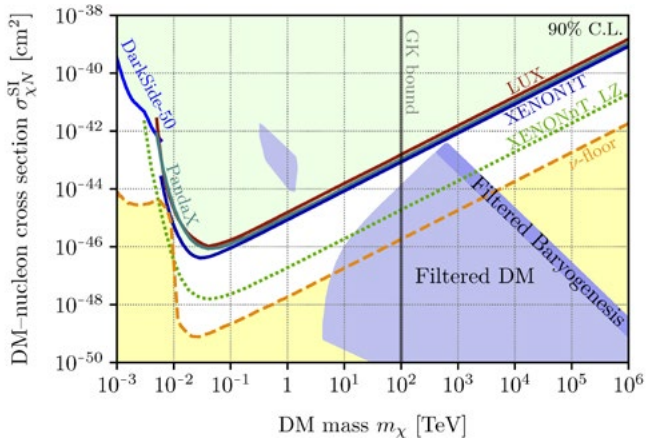
Regions for elastic (nuclear recoil) and Migdal events in the S1-S2 plane due to neutron scattering. The dots show events from a representative exposure of 1 kg-day.

Indirect detection of low mass dark matter in direct detection experiments with inelastic scattering

Jayden Newstead, Nicole Bell and collaborators revisited the detection of luminous dark matter (LDM) in direct detection experiments. In this scenario, dark matter scatters endothermically to produce an excited state, which decays to produce a photon. They explored ways to differentiate the electron recoil signal from the decay photon from other electron recoil signals with a narrow spectral shape. They found that large volume/exposure xenon detectors will be unable to differentiate the signal origin without improvements in detector energy resolution of around an order of magnitude. Motivated by the advancements in energy resolution with solid-state detectors, they found that sub-eV resolution would enable the discovery of LDM in the presence of background levels that would otherwise make observation impossible. Sub-eV resolution could also be used to determine the shape of the LDM decay spectrum and thus constrain the dark matter mass and velocity distribution [Phys. Rev. D 106, 103016 (2022)].

Filtered Baryogenesis

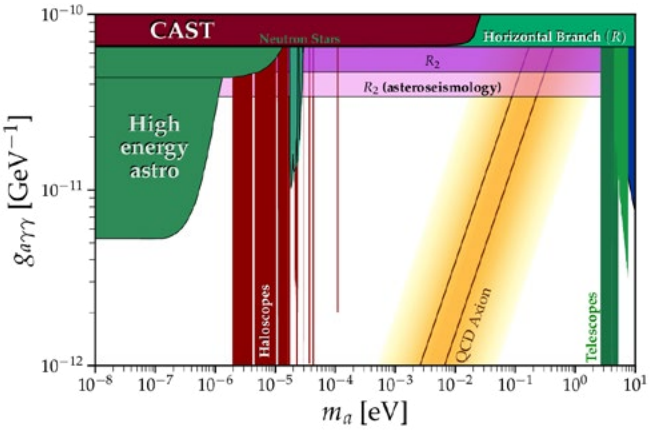
Michael Baker and collaborators built on their earlier work on Filtered Dark Matter to show that the observed dark matter abundance and the baryon asymmetry of the Universe can be simultaneously explained. In the original mechanism, dark matter particles acquire a large mass during a first-order phase transition, which implies that only a small fraction of them are energetic enough to enter the advancing bubbles and survive until today, while the rest are reflected and annihilate away quickly. Supplementing this scenario with a CP violating interaction creates a chiral asymmetry in the population of dark matter particles. A portal interaction quickly converts the dark sector chiral asymmetry into a Standard Model lepton asymmetry, which is then partially converted to a baryon asymmetry by standard electroweak sphaleron processes [JHEP 08, 010 (2022)].



The viable parameter space for Filtered Dark Matter (blue) on the dark matter direct detection cross-section vs dark matter mass parameter space. Filtered Baryogenesis can successfully occur in the dark blue band.

Advancing globular cluster constraints on the axion-photon coupling

Axions are very light and very weakly interacting spin-zero bosons that are motivated by a famous problem in the theory of the strong interactions called the “Strong-CP Problem”. In general, the well-established theory of quantum chromodynamics (QCD) requires quarks and antiquarks to exhibit different microscopic behaviours, but this disagrees with high-precision measurements. The QCD axion is a by-product of the favoured solution to the problem, and amazingly it is also a viable dark matter candidate. However, axions, and cousins known as “axion-like particles (ALPs)”, contribute to energy loss from stars, thereby altering their evolution. Constraints can be placed on their coupling strength to photons of light by requiring that this non-standard energy loss rate is sufficiently low so as not to spoil agreement between astronomical observations and the successful theory of stellar evolution. Matthew Dolan, Fred Hiskens and Raymond Volkas, showed for the first time that the measured relative populations of “horizontal branch” and “asymptotic giant branch” stars in globular clusters place a world-leading upper bound on the axion-photon coupling strength for a large range of axion and ALP masses. This result has contributed substantially to our knowledge of observationally allowed axion/ALP properties [JCAP 10, 096 (2022)].



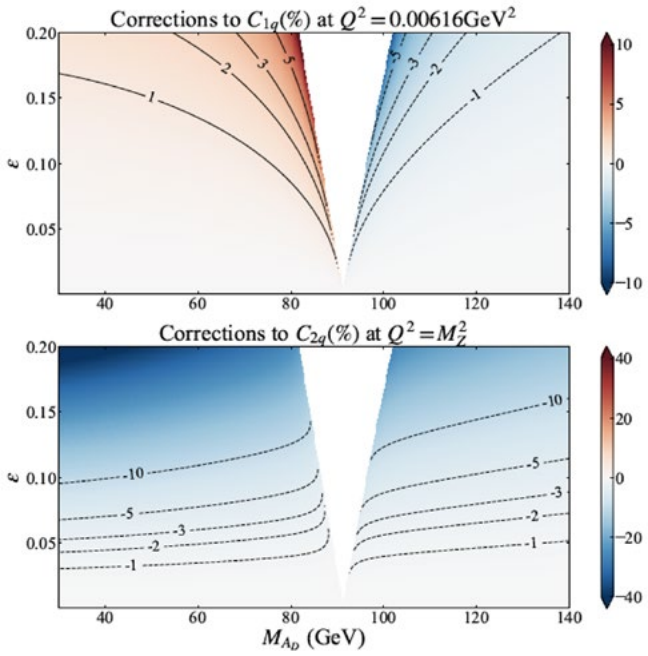
The axion-photon coupling strength vs the axion mass. The excluded region is shown by the purple shaded regions R2.

A new tool to search for the dark photon

The dark photon as a portal connecting dark matter and ordinary particles has been attracting considerable attention. Exploring new powerful tools to test its existence and place constraints on its parameters is of great interest.

Anthony Thomas, Xuan-Gong Wang, and Anthony Williams proposed that the parity-violating electron scattering (PVES) is such a new tool, which has the potential to discover the dark photon. They calculated the dark photon contributions to PVES asymmetries in both elastic and deep inelastic scatterings. These contributions can be characterised by corrections to the Standard Model weak couplings C_{1q}, C_{2q}, and C_{3q}, which could be measured very precisely by the upcoming experiments at SoLID, P2, and EIC. They found that the inclusion of dark photon could lead to corrections as large as 5% for C_{1q}, which may reconcile a surprising discrepancy between the ^{208}Pb neutron skin thickness inferred from the PREX experiment at Jefferson Lab and the nuclear model predictions. The corrections to C_{2q} at DIS scale are as large as 10%, which may significantly affect the valence quark distributions extracted from data taken at HERA in Germany [Phys. Rev. Lett. 129, 011807 (2022)].

In a follow-up publication, Anthony Thomas and Xuan-Gong Wang extracted the favoured region of the dark photon parameters by fitting the currently available parity violation data and the latest W-mass anomaly, both favouring a heavy dark photon with mass above MZ [Phys. Rev. D 106, 056017 (2022)].



Corrections to the Standard Model weak couplings C_{1q} and C_{2q} as a function of the dark photon mass.

Dark matter and the neutron lifetime puzzle

The lifetime of the neutron has been a puzzle since its discovery. Neutrons show a different lifetime when measured using different methods, namely the “beam” method (counting protons resulting from neutron decay) and the “bottle” method (counting neutrons remaining in an ultracold trap). The lifetime of neutron should be the same, regardless of the method of the measurement, unless there is new physics involved. Wasif Husain and Anthony Thomas tested and explored the consequences of neutron decay into dark matter.

One of the hypotheses to solve the neutron lifetime puzzle is that 1% of the time neutrons decay into dark matter and the dark matter remains uncounted in the beam method because there the number of protons is counted, while in the bottle method the dark matter effect is unconsciously included when they count the number of neutrons left after the decay. Therefore, if we include the effect of proposed decay channel, the puzzle seems to be solved. To investigate this hypothesis, Wasif Husain and Anthony Thomas applied it to neutron stars, which are very compact stars present in the universe and made predominantly of neutrons. So, if neutrons decay into dark matter, then they must decay inside the neutron star also, and that could give us a signal. Therefore, if we could detect a signal, it would not only solve neutron’s lifetime problem but also the dark matter problem.

Wasif Husain and Anthony Thomas applied two hypotheses regarding the neutron decay into dark matter particles. In the first, they assumed that neutrons decay into dark matter and a massless boson (which leaves the neutron star immediately). Second, following Strumia, they assumed that the neutron decays into 3 identical dark matter particles. Both hypotheses led to a potentially observable signal. Specifically, they showed that for both hypotheses, the neutron stars must spin up in the range 5%-15% and must glow with the temperature ranging 2-6 MeV. If the suggested signal is able to be observed, then it would provide support for the idea that the neutrons decay into dark matter and open a new door in dark matter particle physics [JCAP 10, 028 (2022)].

Determination of uncertainties in parton densities

Anthony Thomas, Nicholas Hunt-Smith, Martin White and collaborators rigorously examined methods of uncertainty quantification on parton distribution functions, finding that a popular neural network approach has the potential to inflate uncertainties. This is relevant for dark matter searches at the Large Hadron Collider, but also applies to attempts to find evidence for dark photon interactions in analyses of proton structure (where the dark photon might be our first observed portal to a dark sector) [Phys. Rev. D 106, 3, 036003 (2022)].

Simple and statistically sound recommendations for analysing physical theories

Martin White contributed to a community report that provides a set of recommendations for performing statistical tests of beyond-Standard Model theories. It summarises insights gained during studies of dark matter models by the GAMBIT Community, in addition to other major global fit teams [Rept. Prog. Phys. 85, 5, 052201 (2022)].

The Dark Machines anomaly score challenge: Benchmark data and model independent event classification for the Large Hadron Collider

This project, carried out within the DarkMachines collaboration, including Martin White and Nicholas Hunt-Smith, applied a series of anomaly detection algorithms to simulated Large Hadron Collider data in order to rank their performance. Such techniques have the potential to remove model-dependence from LHC searches for dark matter, by allowing analysts to highlight events that are "non-SM-like" rather than specifying particular model assumptions. The key insights that will be essential in developing a machine-learning-based anomaly detection programme during Run 3 of the LHC were summarised [SciPost Phys. 12, 1, 043 (2022)].

Sommerfeld enhancement and bound state formation in t-channel simplified dark matter models

Dipan Sengupta and collaborators analysed the impact of Sommerfeld enhancement and bound state formation in simplified t-channel dark matter models. They demonstrated that these non-perturbative corrections significantly impact the calculation of dark matter relic abundance and open up a wider range of available parameter space for LHC, cosmology and future probes [JHEP 08, 145 (2022)].

Leptoquark manouevres in the dark : A simultaneous solution of the dark matter problem and RD anomalies

There is a long-standing anomaly in the branching ratio of B Mesons into leptonic final states measured by LHCB, Belle and Babar experiments. A solution to resolving these anomalies is the existence of leptoquarks. Dipan Sengupta and collaborators demonstrated that a leptoquark portal between the Standard Model and the dark sector can serve as a solution to these anomalies. They analysed the LHC, direct detection constraints and relic abundance estimates to delineate the viable region of parameter space [JHEP 02, 042 (2022)].

Multilepton signatures from dark matter at the LHC

Dipan Sengupta and collaborators studied well motivated dark matter models that produce multilepton signatures at the LHC. In specific models, they extended the constraints on the parameter space from relic abundance, direct and indirect searches as well as LHC. In addition, they projected the discovery capabilities and future constraints for the upcoming high luminosity LHC run [JHEP 09, 173 (2022)].

The Forward Physics Facility: Sites, experiments and physics potential

The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era. Located along the beam collision axis and shielded from the interaction point by at least 100 m of concrete and rock, the FPF will house experiments that will detect particles outside the acceptance of the existing large LHC experiments and will observe rare and exotic processes in an extremely low-background environment. In a community report, authored by a large international team including Dipan Sengupta, the current status of FPF plans were summarised. The report reviewed the many Standard Model and new physics topics that will be advanced by the FPF, including searches for long-lived particles, probes of dark matter and dark sectors, high-statistics studies of TeV neutrinos of all three flavors, aspects of perturbative and non-perturbative QCD, and high-energy astroparticle physics [Phys. Rep. 968, 1-50 (2022)].

Particle detection and tracking with DNA

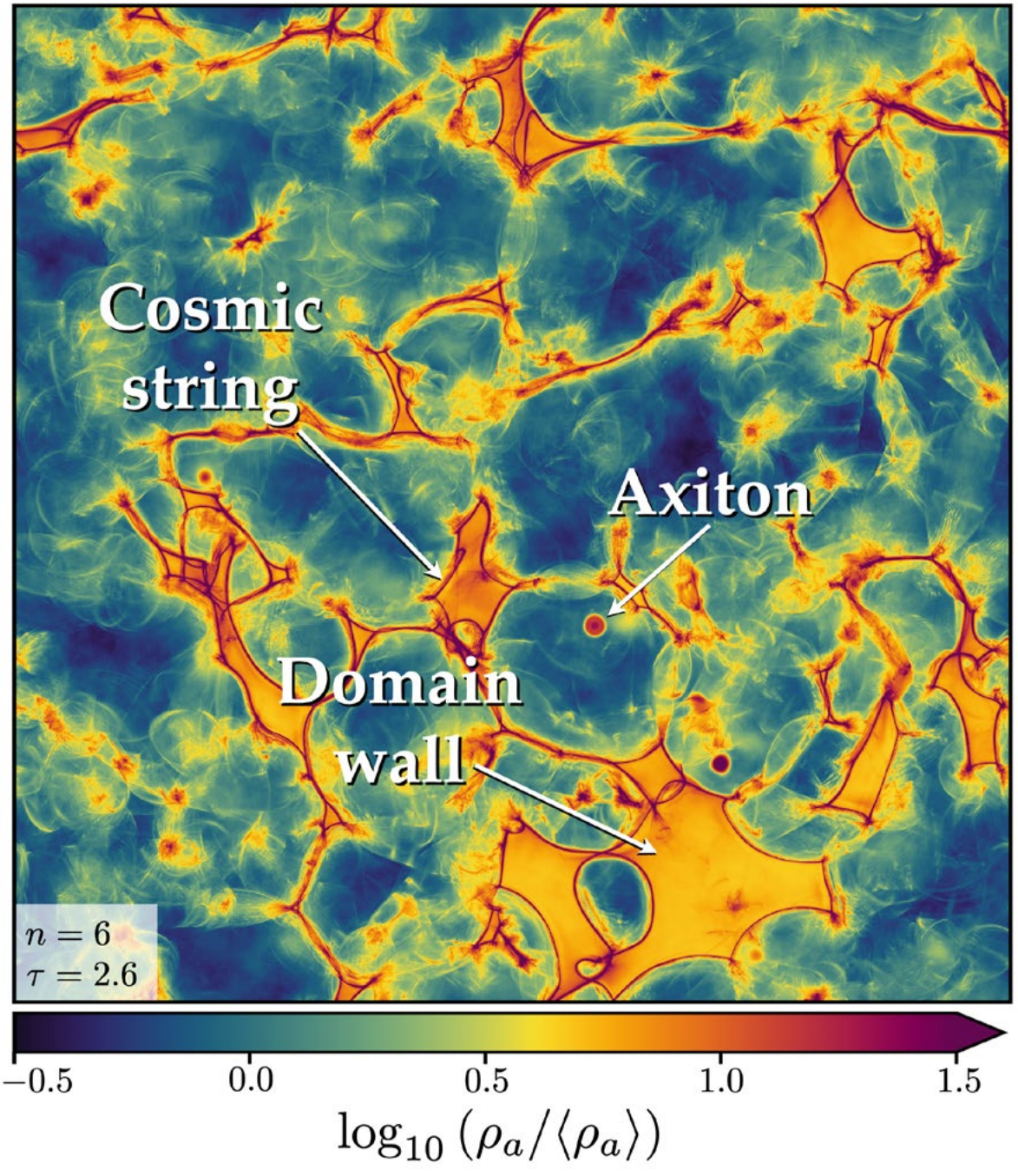
Ciaran O'Hare, Celine Boehm, and collaborators from USyd and internationally, performed the first simulations of a highly radical particle detector concept based on strands of DNA. The idea would involve arranging a large network of DNA strands with precisely known sequences of base pairs. When a particle enters the network of strands it would damage the bases in a particular pattern depending on its energy and direction. This damage pattern can then be amplified and reconstructed thanks to modern advances in biotechnology, PCR, and DNA sequencing. These new simulations provided a proof-of-concept for the idea, showing that it could in principle be used to measure directions of low-energy recoils from cosmic rays and perhaps one day dark matter [Euro. Phys. J. C, 82, 306 (2022)].

Phenomenology of the companion-axion model: photon couplings

The axion is a particle designed to solve the Strong CP problem—the unexplained absence of CP violation in the strong interactions. However, it can be shown that this famous solution is jeopardised if there is any additional and independent CP violation coming from physics at very high energies, e.g. gravity. Ciaran O'Hare and Zachary Picker studied the phenomenology of one of the solutions to this "new" Strong CP problem—namely, adding a second, companion axion. They predict that future haloscope experiments should find the existence of one or more axions making up the dark matter if the problem is solved in this way [Eur. Phys. J. C, 82, 940 (2022)].

Simulations of axion-like particles in a post-inflationary production scenario

Ciaran O'Hare and collaborators performed simulations of the production of axion dark matter in the early universe. They focus on the so-called post-inflationary scenario, which leads to a universe full of very small-scale clumps of dark matter called "axion miniclusters". These miniclusters are important substructures to understand for present-day efforts to detect the axion—they have the possibility to generate new indirect astrophysical signatures, but may also hinder direct detection experiments on Earth [Phys. Rev. D 105, 055025 (2022)].



A projection of the axion energy density around the time the string-wall network is almost fully collapsed.

case study 5

Student project with Defence Science and Technology Group

PhD student Lachlan Milligan (UoM) has been working on a project chiefly involving the development of a GEANT4 simulation modelling a new neutron spectrometer purchased by DSTG – a Nested Neutron Spectrometer (NNS) – which can be used to measure and characterise specific radioactive sources emitting neutrons.

The creation of this simulation was not only useful in the sense that it is a tool for DSTG to validate their experimental measurements, but also in the sense that it allowed for a transfer of expertise relating to the modelling of low energy hadronic/neutron interactions in a detector – something that the SABRE South experiment has familiarity with through the detail simulation of our own detector.

In simulating the response of this NNS, we were able to produce a detector response that differed from the one described by the manufacturer in current publications. The cross-checking of this response against experimental data indicated that the GEANT4 simulation produced in this project is a more faithful/improved simulation of the detector (as opposed to the manufacturer's simulation), due to improved reconstruction of lower energy neutrons from a specific radioactive source. Some results from this project were presented at the CDM annual workshop in the form of a poster, which was attended by Daniel De Oliveira Damas from DSTG.

"This project allowed me to gain experience in using/simulating a detector I would not have otherwise gained with my current PhD projects, and let me improve my GEANT4 knowledge/ skills by being able to develop a full detector simulation" - Lachlan

research activity plan for 2023

WIMP Direct Detection:

SABRE South:

- Construction and assembly of SABRE South in SUPL
- Phase 1 Commissioning of the experiment
- Technical design report and white paper theory experiments

R&D Cygnus:

- Augmentation of CYGNUS-1 prototype with intensified camera readout
- Indentification of translation applications and focus on fast neutron detection
- Development of CYGNUS-Oz underground directional detection program
- 8th CYGNUS workshop on Directional Recoil Detection to be hosted by UoS

Current and next generation liquid xenon TPCs:

- Contributions to simulations and detector monitoring sensors
- XLZD design and sensitivity studies

Axion and WISP Direct Detection:

- ORGAN Phase 1b and ORGAN-Q operations and data analysis
- R&D on novel quantum technologies and to produce cavity resonators for ORGAN Phase 2
- Investigate cryogenic implementation of UPLOAD
- Increase the range of axion masses covered by the ADMX and ORGAN experiments
- ADMX sensitivity studies for future dark matter high and low mass extensions
- Improve the sensitivity of Scalar DM detection experiments to extend their scope to search for WIMPs and gravitational waves

Precision metrology (nuclear):

- Continued development of an AMS capacity to measure ^{210}Pb at ANSTO accelerator
- Commissioning of the integrated fast isotope switching / time-of-flight detection systems
- Commissioning a new low background germanium detector at the ANU
- Progress ICP-MS measurement sensitivity and capability for ^{40}K and other relevant naturally occurring radionuclides

LHC:

- Complete searches for invisible Higgs decays and final states with jets and missing transverse momentum
- Extend analyses techniques for further novel searches for Dark Matter
- Production and QC of the silicon detectors for the ATLAS inner tracker upgrade for High luminosity LHC

Theory:

- Project the sensitivity of Migdal-effect constraints on light dark matter in new experimental configurations
- Study the thermalisation of dark matter in neutron stars
- Determine the effect of a dark photon on high energy scattering data
- Better understand and quantify the impact of nuclear structure on dark matter direct detection rates
- 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.

dark matter mural

In early 2022, a 20m long mural was commissioned in the hallway leading to the dark matter laboratory at the University of Melbourne. The following is a summary of each different element of the mural and the brief snippets of inspiration behind the imagery and artistic representation of part of the dark matter story.

Introduction

What is the universe made of? Elements and what we can see and understand.

Approximately is 20% observable 'ordinary' matter, the rest is invisible and unknown. Inferred only by the gravitational interaction.

A special thanks to Apparition Media for translating the story into the final design and installing the mural.

What we know

Vera Rubin, an American astronomer who established the presence of dark matter in spiral galaxies in the 1970s. The modulation of the earth around the sun and the flux of dark matter around the earth.

DAMA signal - the only observed dark matter signal is consistent with this phenomenon represented as the modulation graphic.

Different ideas of what dark matter might be, including different theories and ways of interacting.

Different experiments across the globe all using different approaches to find evidence of dark matter and confirm the theory.

The experiment

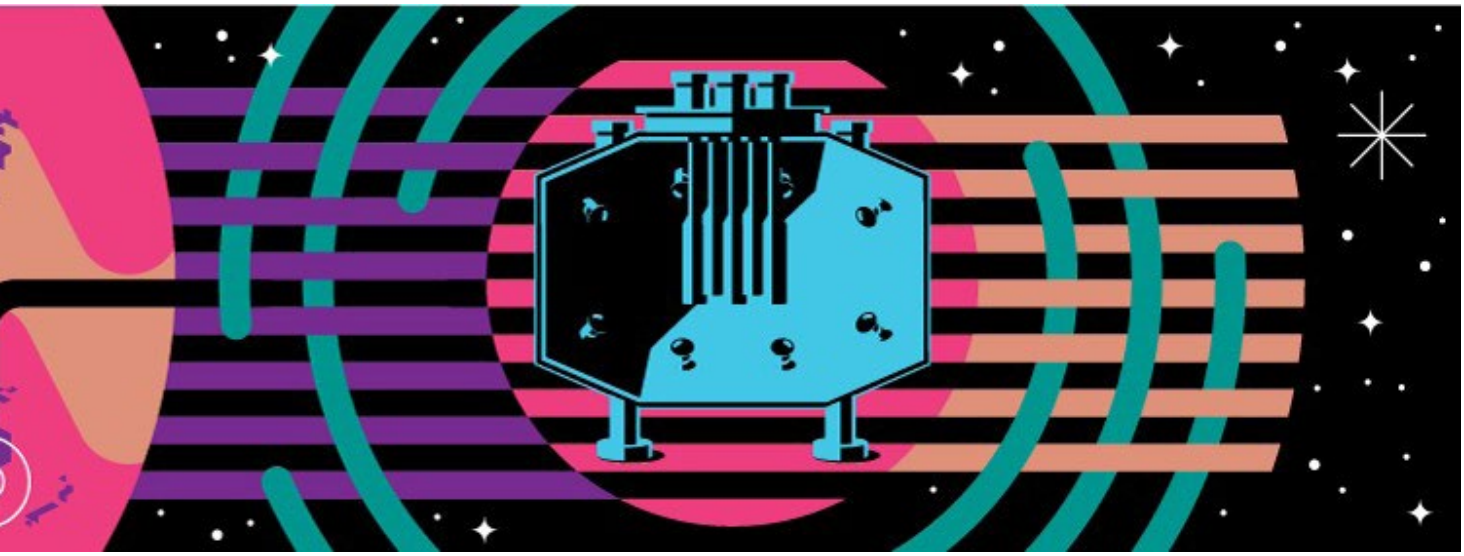
SABRE North (Gran Sasso, Italy) and SABRE South (Stawell, Victoria, Australia), both 1km underground.

The SABRE South vessel which will be housed in the Stawell Underground Physics Laboratory.

The possibilities…

Practical applications of the research, where to next?

We are taking part in a scientific revolution that will transform our understanding of the universe.



SUPL update

The Stawell Underground Physics Laboratory (SUPL) was officially unveiled in August 2022 and completion of the construction of Stage 1 was celebrated with a visit to the laboratory and an aboveground celebration in Stawell.

Attendees included representatives from the Northern Grampians Shire Council, Regional Development Victoria, Stawell Gold Mines, SUPL Ltd, the University of Melbourne, the University of Adelaide, Swinburne University of Technology, ANSTO, the Australian National University, Stawell Secondary College, H Troon and Neboro Consulting as well as Victoria's Chief Scientist Dr Amanda Caples and local Member for Mallee Dr Anne Webster.

Elisabetta Barberio said with the upcoming installation of the SABRE South experiment, the laboratory would provide the opportunity to understand a substance that has long eluded scientists.

"With the Stawell Underground Physics Laboratory, we have the tools and location to detect this dark matter. Proving the existence of dark matter will help us understand its nature and forever change how we see the universe."

SABRE South will run in conjunction with the complementary SABRE experiment taking place in Laboratori Nazionali del Gran Sasso, Italy. For details on the progress of SABRE South, see the Research Themes section.

Deputy Vice Chancellor (Research) at the University of Melbourne Professor James McCluskey said universities are places of deep discovery supported by global partnerships in advancing the frontiers of knowledge.

"Research which is needed to address the great unanswered questions – such as 'what is dark matter?' – is nearly always done in collaboration," Professor McCluskey said.

> *"Working with our partners and sharing our collective knowledge and expertise, the Stawell Underground Physics Laboratory will facilitate experiments which are critical in the global search for dark matter."*

The Australian and Victorian governments each contributed $5 million in funding for the building of SUPL, boosted by funding from the University of Melbourne.

The laboratory was constructed by Ballarat based H. Troon, using many local contractors throughout the build.

The Stawell laboratory will be managed by SUPL Ltd., which is co-owned by the University of Melbourne, ANSTO, the Australian National University, Swinburne University of Technology and the University of Adelaide.

SUPL Ltd. Chair Dr Sue Barrell AO said the eyes of the world would soon turn to the historic Victorian town of Stawell.

"Stawell sits at a junction between the SUPL partner organisations in Sydney, Canberra, Melbourne and Adelaide. And now with the establishment of this laboratory, SUPL sits at the centre of dark matter research globally."

There was a flurry of media activity surrounding the event, for details see the Media section.

SUPL main experimental hall and overhead gantry crane (credit: Sue Barrell)

dark matter, duct tape and designing fast trains

Understanding the visible and invisible dimensions of Innovation.

Broadly, innovation can be defined as “the introduction of new things, ideas or ways of doing something” (**Oxford Learners Dictionary, 2023**) which may be applied to all sorts of industries, contexts and at small or large scales. It may be disruptive, breakthrough, sustaining (or incremental) in nature, or be the very effort of conducting basic research itself (**Satell, 2017**). Dark Matter research is no exception and when asking members from the Centre to describe innovation at the 2022 annual workshop, the notion of new ideas and doing things differently was evident (see Fig 1). The methods for doing innovation also emerged, where creativity was identified as a key ingredient.

Fig. 1. Word cloud of CDM Members response to “how would you describe innovation” using no more than 3 words.

There were also many examples of innovation practice shared, showing Centre researchers have good understanding of applying innovation practices. When asked, 31 examples of innovation were shared in about 60 seconds, ranging from people who are innovators (e.g. MacGyver), to new day to day processes (e.g. preparing coffee - using pods), physical objects (e.g. hot water bottle) to tech-enabled (e.g. teleconferencing) and varied industries including pharmaceuticals (e.g. vaccines) and intersections of agriculture and energy (e.g. sheep keeping grass short in solar research facilities). These are visible examples of innovation, but what goes on behind the scenes that enables such visible outcomes of innovation practices?

Let’s come back to the headline, and consider what does Dark Matter, Duct Tape and Designing Fast Trains have to do with visible and invisible dimensions of innovation? Dark Matter science applies innovation in many ways including the less visible thinking to propose new theories and the more visible conception of new experiment and equipment design (at all kinds of scales) to understand the nature of Dark Matter. Duct tape is a visible tool of innovation, whether it is being applied as a short-term improvisation to problem solve fixing experimental equipment, or used as part of a quick prototype of an idea for a new health screening that can facilitate early feedback from potential end-users. However without the less visible creative thinking behind it – would not be a useful tool of innovation practice. Designing Fast Trains applies innovative thinking to conceive and integrate use of new technologies and production capabilities that enables extremely high speeds to be safely achieved by trains, and the outcomes of applying innovation practices are quite evident in the train and support infrastructure itself, that many people around the world use to travel across cities and countries.

All three examples would not have meaningful outcomes of innovation if it wasn’t for the less visible components. While specific skills to materialise innovation outcomes are important, such outcomes are not possible if individuals, team or organisations are not open to new ideas and ways of doing things. A culture and mindset that supports innovation is critical in the practices of innovation, and harder to measure, articulate and cultivate.

And at CDM, we can see our researchers across the nodes building understanding of innovation attitude. In the many professional examples of innovation shared relating to CDM, we could see examples describing different thinking (e.g. problem solving in experiments like ORGAN), adaptive use of equipment beyond the originally intended function (e.g. “misuse” of a telescope for better images) to adapting functional knowledge for cost-effective solutions across industry applications (e.g. appropriating catering trolleys to effectively store lab equipment).

For the Centre, fostering a culture that supports innovation, is about opening doors to apply innovation mindset and processes in different ways. This maximises opportunities to transform knowledge; from advancing scientific endeavour in Dark Matter research fields to conceiving new products and services that we use in day to day life based on technology or science derivative from Dark Matter experimentation. Providing opportunities to build innovation skills, mindset and experience applied to United Nation Sustainable Development Goals, CDM is showing researchers they can harness their innate curiosity and expertise as a scientist to be applied broadly, to broaden career pathways across different types or organisation and industry sectors, and create positive change in society.

equity, diversity and inclusion

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

The EDI committee includes representatives from each node and has been very active in 2022, meeting on a bi-monthly basis. EDI training and awareness activities initiated in 2021 have been pursued in 2022, while new actions targeting Women in Physics were initiated in 2022. In particular, the Centre sponsored three of its female ECRs to undertake the intensive Leading Edge program offered by Women Leadership Australia (see details under Training and Development below).

The SBS Inclusion program has been our primary support for EDI training in 2022. Beyond skills and knowledge, this program is designed to improve the workplace by maximising the benefit of diversity and inclusion. In addition to the core inclusion module, another one focusing on gender issues (which is particularly relevant in Physics) was selected. A majority of Centre members belonging to all categories (from students to professional staff, as well as academics) have fully completed the modules. A survey on the SBS training has been done at the annual workshop that will indicate further needs and aspirations in terms of EDI training topics such as culture, Indigenous, LGBTIQ+, age and disability.

As part of the registration process for the Centre's annual workshop, the Centre offers support to members who have caring responsibilities so that they can attend in person. Conference organisers work with individuals to assess their needs and discuss the best options for support. The Centre and EDI committee will review other ways that we support our members in 2023.

Associate Investigator Christine Thong led the EDI session of the annual meeting which showcased Virginia Kilborn, Chief Scientist at Swinburne University of Technology, who gave an inspiring presentation on gender diversity in science. Prof Kilborn was then joined by postdoc Zuzana Slavkovska (scholar of the Leading Edge program) and Chief Investigator Nicole Bell (incoming AIP President) for a Q&A session.

The Centre continues to seed new tenure and tenure track positions within its nodes with a particular emphasis on hiring women ECRs, in line with its commitments outlined in the proposal. The University of Sydney has now hired Theresa Fruth, who, despite being at an early stage of her career, has already established her international leadership in dark matter direct detection within the LZ experiment. The University of Adelaide has advertised a new female only continuing position and the selection process is ongoing. The impact of COVID on the ANU Research School of Physics budget has unfortunately delayed ANU's female only continuing position. ANU CIs are strongly engaged in the process to secure a recruitment in 2023.

media and communications

The Centre aims to develop and celebrate our members, highlight our research, promote diversity and inspire a future generation of researchers through its media engagement activities.

In 2022, the Centre's work attracted considerable media attention.

Veritasium reaches more than 6 million viewers

One major opportunity to reach a wide, international audience was through an episode of Veritasium – a YouTube channel with more than 13 million subscribers – about dark matter which featured the Centre.

The Veritasium team visited the Stawell Underground Physics Laboratory and Swinburne University of Technology, where the SABRE vessel is located. Centre members Madeleine Zurowski, Phillip Urquijo and Alan Duffy featured in the episode, which was viewed more than six million times.

SUPL launch attracts mainstream media attention

Another significant media event for the Centre was the announcement of the completion of Stage 1 construction works at SUPL.

The University of Melbourne led the coordination of the launch event, including a two-day media visit to the underground laboratory.

The launch appeared in the media 400 times, including Channel 9 news, ABC tv, radio and online, SBS tv, The Guardian, The Australian, and The Age, as well as regional newspapers and radio stations. It also featured in international news items.

The mainstream media coverage showed how engaging science can be, and that our researchers are at the forefront of scientific exploration.

The coverage featured representatives from each node, and included both men and women at different levels in their careers. In this way, the Centre showcased the diversity of our researchers, portraying science as a potential career for all.

National road trip takes physics across Australia

Another campaign that brought science to a mainstream audience was the National Quantum & Dark Matter Road Trip with EQUS during National Science Week.

The road trip generated more than 140 media pieces, including a segment on WIN TV Toowoomba (syndicated across Queensland), an AAP article syndicated across the country and interviews on ABC, 2GB and 3AW radio. It also appeared in numerous regional newspapers and radio stations.

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 event provided the opportunity for Early Career Researchers across nodes to gain valuable media experience. Throughout the road trip, nine students and researchers were interviewed, many for the first time.

The interviews with regional and rural media provided a less intimidating forum for our young members to gain valuable media experience.

Madeleine Zurowski being filmed by Veritasium


THE AUSTRALIAN

All sections HOME THE NATION WORLD BUSINESS COMMENTARY SPORT ARTS

Physics lab in a mine races to confirm existence of dark matter

By EMILIE LAUER

A new underground physics lab in regional Victoria is setting Australian universities up in the race to unveil the secrets of dark matter, and potentially make the

Becoming thought leaders to inspire and challenge stereotypes

Through our media engagement activities, we have been working to position the Centre as a thought leader, in the process challenging community attitudes about science, and physics.

On International Day of Women and Girls in Science last year, we secured a place for Elisabetta Barberio to be interviewed by Virginia Trioli on her ABC Mornings program, one of Melbourne's most listened to radio shows. We set the agenda by highlighting women in science, and female scientists rang in to talk about their careers and why they loved working in science.

On the same day, Zuzana Slavkovska spoke on ABC Canberra about her journey towards a career in physics and her passion for science.

A couple of months later we again shone a spotlight on women in science when Madeleine Zurowski spoke to Jacinta Parsons on ABC Afternoons about her work. The segment was an opportunity to promote a young woman in science and challenge stereotypes about physics careers. The interview reached an estimated audience of more than 75,000 through its broadcast and online presence.

By making our female members visible in the media, we show girls that they belong in an industry where women continue to be vastly under-represented.

Highlighting the value of fundamental research

Another way we led the conversation last year was during Dark Matter Day. We decided to highlight the day by writing an opinion piece explaining why fundamental research, like the search for dark matter, is so important. This idea stemmed from questions we received about why we were bothering to search for dark matter.

Ben McAllister wrote the piece and it was picked up by ABC online, via ABC Religion & Ethics, attracting over 30,000 readers on the ABC website alone and the chance to share the piece on our own channels.

In this way we set out the value of fundamental science, thereby highlighting the importance of our work.

Renee Key (SUT) on WIN News Toowoomba

Social media

The Centre has Twitter, Facebook, LinkedIn and Instagram accounts, 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, promoted diversity and inspired future generations.

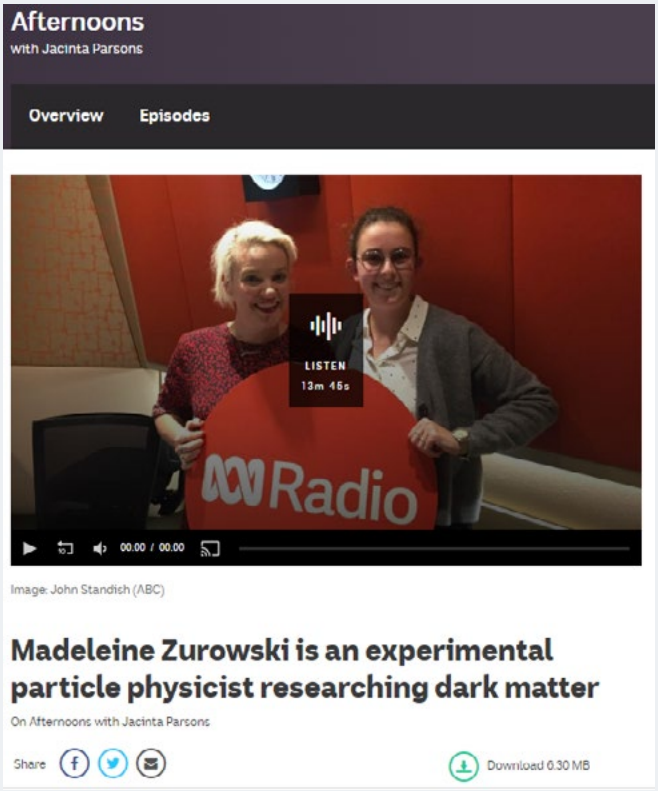
These channels also provide the opportunity to highlight our events and be involved in dialogue with the national and international academic and scientific communities.

Internal communications

The Dark Matters newsletter is distributed to Centre members every two months via email and includes information about Centre events, research and members' successes.

It also helps to build a sense of belonging within the Centre and cohesion between members by familiarizing them with the activities of the Centre and their peers.

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, and store and share documents and technical information.



media highlights

Videos

Tik Tok featuring Madeleine Zurowski

350,000 views (plus 33,800 likes)

go.unimelb.edu.au/45is

Veritasium

6.4 million views (plus 231,000 likes)

go.unimelb.edu.au/t5is

ABC SUPL launch

23,000 views

go.unimelb.edu.au/d5is

Pursuit video produced by University of Melbourne

4,900 views

go.unimelb.edu.au/v5is

SUPL launch

More than 400 media pieces, including Channel 9 news, ABC tv, radio and online, SBS tv, The Guardian, The Australian, and The Age, as well as regional newspapers and radio stations. It also featured in international news items.

471	4	21
Print/online articles	Television segments*	Radio interviews


Physics lab in a mine races to confirm existence of dark matter

By EMILIE LAUER

9:32PM SEPTEMBER 6, 2022

7 COMMENTS

National Quantum & Dark Matter Road Trip

More than 140 media pieces, including a segment on WIN TV, an AAP article syndicated across the country and interviews on ABC, 2GB and 3AW radio. It also appeared in numerous regional newspapers and radio stations.


Quantum physics and dark matter explored by Eastern Goldfields College Year 12 students

Madeleine Clark | Kalgoorlie Miner

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Madeleine Clark

PHYSICS LAB

NATIONAL ROAD TRIP

* WIN Tv (syndicated across Queensland), SBS News, ABC News, Channel 9 News

social media highlights

Accounts

Twitter - CDM

Impressions: 2021 - 164,570, 2022 – 205,666

Followers: 343 (Dec 2021) 725 (Dec 2022)

Twitter – Road trip account

Impressions: 36,048 over a two-month period

LinkedIn

Impressions: 2021 - 1,349, 2022 – 10,518

Followers: Dec 2021 – 139, Dec 2022 - 503

Campaigns

International Day of Women and Girls in Science campaign

More than 32,000 impressions on Twitter

SUPL launch campaign

More than 70,000 Twitter impressions

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 2022, there were many opportunities for in person outreach and education activities and the resuming of in person activities meant that Centre members were able to interact with over 60 schools, visit and participate in conferences and participate in over 20 public events.

Partnership with the Melbourne Graduate School of Education (MGSE)

The partnership with MGSE's science education team who have a focus on innovation and inclusive ways to communicate modern science continued in 2022. The outreach project team wrote a systematic literature review on science outreach bringing together the current research that has been undertaken on science outreach aimed at young people revealing the need for a more in depth longitudinal study of the influence of science outreach on how young people perceive science. They also reviewed policy that incentivises science outreach across three international regions. This review article is expected to reveal an increasing emphasis on science research organisations being incentivised to undertake science outreach. They have also commenced interviews with scientists who participate in outreach programs to explore the reasons they become involved and will undertake an ARC Discovery Project to research the influence of science outreach on young people.

School partnerships

After the success of the CDM Partner Schools Pilot program in 2021, the Centre expanded its partner schools program to two additional regional schools across Western Victoria. These schools will have long-term partnerships with the centre with lessons delivered across the entire school population over the course of multiple years. Ideally this long-term engagement will highlight interest of and pathways in science for students from regional locations. Additionally, these partnerships have fostered opportunities for regional students to engage with Centre researchers at the University of Melbourne. In 2023, CDM will look to create partner schools in additional node states.

Teacher engagement

One of the most effective ways to reach many students is through engaging with teachers. If teachers feel prepared and empowered to introduce topics related to the search for dark matter to their students, then they can inspire more students than the Centre can directly engage. In 2022, the centre engaged with teachers through professional development workshops at the local (Science Teachers Association of Victoria VCE Physics Conference), the national (Australian Science Teachers Association CONASTA 69), and the international (International Baccalaureate Global Conference) levels. In 2023, we will continue to network with various teacher networks to provide professional development workshops to teachers to offer them the opportunity to implement curriculum-aligned activities for their classrooms.

International collaborations in education

CDM is part of a greater international community focused on contemporary physics outreach and education. In 2023, Jackie Bondell, Education and Outreach Coordinator for CDM, will take over from Paul Jackson (CDM - University of Adelaide) the role of Australian Representative to the International Particle Physics Outreach Group (IPPOG). Jackie is also collaborating with Science Education Researchers in the US to develop an interactive augmented reality (AR) app to help students understand modern physics concepts. In 2023, the centre will continue to engage in these projects to not only implement ideas from international partners into CDM's education and outreach programs, but also to share what is developed here with a geographically diverse network of education practitioners.

Holiday programs

CDM recognises that students engage in learning programs outside of the traditional school setting. Non-traditional programs provide additional opportunities to connect with students in less formal settings. These programs include holiday programs, university campus visits, and STEM workshops. In 2022, these programs included events in regional areas of Queensland and Tasmania as well as the virtual National Youth Science Forum with students from across Australia. In 2023, the Centre has been invited to be part of these programs again.

Public lectures

In addition to public lectures that formed part of broader events during National Science Week (detailed below), Centre members also gave a number of public lectures across the country.

Public lecture in Stawell

Elisabetta Barberio (pictured top left) gave a public lecture on SABRE South and hosted a Q&A session at Stawell Town Hall during a visit of the SABRE South collaboration for a workshop on the experiment. The event was attended by members of the local community, Stawell Gold Mines, the Northern Grampians Shire Mayor and other councillors. The community asked many questions of the SABRE South collaboration about SUPL, SABRE South and the search for dark matter. It provided a valuable opportunity to meet with the Stawell community, which has been a great supporter of the project.

Dark Matter Day at the University of Sydney

Hosted by Veritasium's Petr Lebedev, the University of Sydney hosted an international Dark Matter Day public lecture with the Centre's Ciaran O'Hare (pictured top right) and Theresa Fruth as guest speakers. They spoke about the evidence for the existence of dark matter, theories of what it might be and how scientists are searching for it as well as some great questions from the public.

World Science Festival

Nicole Bell and Lindsey Bignell explored the big question of the nature of dark matter at the World Science Festival in Brisbane. The two appeared in a panel discussion titled "The Elusive Darkness of the Universe" exploring how we know dark matter and dark energy exist, whether we can find evidence for them through the Centre's research on WIMPs, axions, underground experiments, SABRE South, the neutrino floor and dark matter directional detection. The YouTube recording of the discussion has been watched over 20,000 times.

dark matter art

High School Art Competition

High school 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. Entries were submitted by Dark Matter Day and competition winners (see below) had their work displayed on the Centre's website. Each received a certificate and gift voucher from the Centre.

Y7-9 category - joint winner - Tabitha

Universe Glue - If theories are correct and axions are related to dark matter, then when dark matter (the glue that holds the universe together) exists at temperatures that are only just above absolute zero (so that no other objects can emit light/heat), it will emit a very faint light.

Universe Glue by Tabitha

Y7-9 category - joint winner - Bethan

Noninteractive - My interpretation of dark matter is based on the premise that it is not immediately visible but encompasses a lot of the universe.

Noninteractive by Bethan

Y10-12 category – winner – Yifei

(un)detectable - The artwork is inspired by the nature of dark matter; how it is essentially undetectable and how it doesn't interact with normal matter. The artwork shows mysterious objects and hands overlapping Vera Rubin (one of the leading scientists in dark matter). In normal light, everything can be seen. In blue light, only Vera and traces of dark matter are visible, and in red light, only clear, yet mysterious representations of dark matter are visible. This reflects how dark matter interacts with normal matter and the mystery around it.

(un)detectable by Yifei

Science Gallery Melbourne partnership

The Centre has strengthened its relationship with the Science Gallery Melbourne in 2022. The 'Art x Science' residency program supports a First Nations artist or collective to research and develop a new work between Arts House and Science Gallery Melbourne. The Centre is also a project partner on the residency. The residency provides these artists the opportunity to deep dive into their ideas, with financial support, mentoring, resources and networking with academics. It is non-outcome based, with the option to consider programming their projects as a part of Dark Matters public programs if it is desirable.

The residency is underway with the two selected artists, Jackie Sheppard and Tyler Willay, completing the first phases of their residencies at Science Gallery Melbourne. This has included excursions and coming into Science Gallery Melbourne to spend time with the team and developing their project concepts further and identifying researchers they want to consult with during the residency. Jackie is exploring somatic movement and unforeseen knowledge that remains in the landscape. Tyler is exploring the ethics of acquiring knowledge. The artists will return in stage two in early 2023 to creatively develop their projects further and they will be connecting to Centre scientists during this time.

Their residencies will result in a project presentation of their work-in-development to Science Gallery and Arts House in mid-2023.

In July, the Science Gallery Melbourne held an open call for projects which will be shortlisted and included in their 2023 exhibition DARK MATTERS which will run between August and December 2023. In its most successful open call to date, over 300 applicants proposed projects, tools, scenarios, and relational experiences that enable a deeper exploration of this extraordinary experience we call life and nature and all the dark matter that flows under it, runs through it and collides with it. A selection of projects will be included in the DARK MATTERS exhibition, curated in collaboration with Mónica Bello, Head of Arts at CERN and a curatorial panel of young people. The exhibition will be developed in collaboration with Arts at CERN and the Centre with the support of an expert panel. High school students will also participate in coordinated excursions to the Science Gallery and associated hands on activities.

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 2022. These included a Dark Matter at the Pub event in Canberra and a national road trip partnering with the ARC Centre of Excellence for Engineered Quantum Systems (EQUS). Centre researchers at all of these events engaged with schools and the community to educate, inspire and to spread the word about dark matter.

Dark Matter in the Pub

Is Sponge Bob a good dark matter detector? How can we hide from radioactive monsters like Godzilla? Why is dark matter a miracle? Why is a detector like a dog park?

These questions and much more were answered at "Dark Matter in the Pub", which took place at Canberra's Smith's Alternative as part of National Science Week, organised by Centre members Lindsey Bignell and Zuzana Slavkovska.

Sponsored by a National Science Week grant from Inspiring the ACT, the Australian Institute of Physics and the Centre, the event featured talks from Lindsey and Zuzana as well as other Centre members Yiyi Zhong, Lachlan McKie, and Elisabetta Barberio. About 130 enthusiastic participants learned about the mysterious dark matter that composes 85% of the mass in the universe.

It was an evening full of fun, including a demonstration of the Doppler effect using a phone in a sock, dark matter songs, radioactive banana giveaways, and physicists attempting jokes. After such success, this event will be back again next year.

You can view the event here:
https://www.youtube.com/watch?v=sr_t7qCzPL0

National Quantum and Dark Matter Road Trip

CDM and EQUS worked together to plan, organise, promote and undertake the 2022 National Quantum & Dark Matter Road Trip which saw 24 members of the Centres drive on various legs from Brisbane to Perth over National Science Week, 8–26 August. The team visited 25 regional and remote schools across six states and territories and delivered 14 public events during the trip, engaging members of the public at schools, pubs and community venues in all things quantum and dark matter.

NATIONAL
Quantum & Dark Matter
ROAD TRIP

Funded by both Centres and a National Science Week grant, the road trip was successful in its aims to bring quantum physics, dark matter and creative expression to regional and remote areas of Australia. We transported enthusiastic and passionate research scientists to communities across Australia to share their excitement about physics and engage members of the public that would not normally have access to these types of activities. They described their research and highlighted the importance of fundamental research and the role it plays in the development of future technologies. The scientists came from eight universities across the different states and territories that the road trip passed through and they also had diverse backgrounds in terms of gender, ethnicity and research interests. They included theorists, experimentalists, physicists and engineers, most of whom are starting out in their scientific careers.

Road trip stats

24	scientists and science communicators
13	CDM members across the nodes
22	days of road-tripping activities
12,372	kilometres on the odometer
25	school visits
14	public events
40+	cities & towns
3,000+	items of merch
2,000+	people engaged
1,400	school students
120	pub goers
165	public talk or lecture attendees
315	attendees at other public events

Participants at the Adelaide public event with their handmade dark matter badges (credit: Emily Filmer).

The CDM members who joined the trip were: Renee Key, Ben McAllister, Jackie Bondell, Matthew Gerathy, Emily Filmer, Harish Potti, Raghda Abdel Khaleq, Giorgio Busoni, Will Campbell, Elrina Hartman, Graeme Flower and Jeremy Bourhill.

Whilst the road trip itself provided an opportunity to acknowledge and celebrate the contributions of our scientists, an additional benefit was that it generated a great deal of media interest. Our early career researchers were provided with opportunities to be interviewed across digital and print media as well as radio and television and were able to practice their science communication.

Some of the hands-on demonstration activities had already been developed to be used in school outreach but the road trip participants also developed new presentations and activities to test and become part of our future outreach portfolio. They were developed to have broad appeal and be accessible to people of all ages.

Overall, the road trip was a huge success. The feedback so far has been really positive, especially from students, teachers and attendees at the public events, but also from the road-trippers. Many of the teachers commented that their students don't have opportunities to learn about contemporary science in the ways that students living in metro centres do, meeting a need of communities that have traditionally been underserved with respect to access to STEM opportunities. They expressed their appreciation that the presenters included so many females and that was a bonus highlight for their students.

Promoted via a dedicated website and social media as well as the National Science Week website, the team engaged around 2,000 people at schools, pubs and community centres in quantum technologies and dark matter, including around 1,400 high-school students.

Renee Key (SUT) "It was a really wonderful time - especially to be on the road visiting new places for me post-covid!

"One of the best parts of the trip was the feedback we got from teachers and students. Often programs offered to regional schools require a minimum number of students to attend, cost a considerable fee, or require the students to travel several hours to a nearby city. Being able to be part of the roadtrip was so brilliant, because we were able to talk to anyone who was willing to attend our presentations!

"It felt so rewarding to see the students ask incredible questions and engage with our demonstrations, but also very eye-opening to hear the teachers' stories about regional science education and the challenges that underfunding to schools bring."

Harish Potti (UoA): "The Quantum & Dark Matter Road Trip is a really great initiative and I completely loved it. The experience of meeting & presenting my research to future Australian scientists is a really great one. I hope I was able to convince at least a few school students to pursue a career in science.

"Based on the enthusiastic questions from the students about gravity, I can definitely say that Gravitational force is the Gen Alpha favorite out of the four fundamental forces :-). An additional bonus for me from this trip was that I was able to visit many beautiful places in rural Victoria and South Australia."

Will Campbell (UWA): "The Quantum and Dark Matter road trip was a fantastic opportunity to finally meet some fellow researchers from the other nodes, while of course participating in some great outreach.

"The school visits were particularly engaging where we met some great kids that showed genuine curiosity and interest. It was a great experience and I have to give a huge thanks to all of the organisers for making such a crazy project happen."

Emily Filmer (UoA): "I took part in the Road Trip from Kalgoorlie to Perth, speaking at eight schools across five days, as well as speaking about Dark Matter on the radio to ABC Great Southern.

"At every school, we were met by enthusiastic students and teachers, who asked lots of questions about our presentations, and particularly enjoyed drawing their own interpretations of Dark Matter and having them made into badges! I had a great time getting to share my knowledge and love of science with the students, as well as spending time with other CDM members and discussing the different projects we work on."

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 2022 the ECR Committee consisted of Ben McAllister, Markus Mosbech (Research Committee) and Irene Bolognino (Executive Committee).

With border closures and restrictions easing for the first time in the Centre's history, 2022 was a year to get ECRs talking, and kick-start the Centre's inter-node collaborations.

The first goal of the Committee in 2022 was the orchestration of a survey, to capture the opinions and demographics of ECRs. The results were shared with the Research and Executive Committees. Unsurprisingly, given the largely remote nature of the Centre thus far, many ECRs reported feeling somewhat disconnected from other nodes, unsure of their place in the Centre, and not yet actively engaging in collaboration.

With this information in hand, the Committee set about organizing the first in-person ECR workshop, factoring in ECR feedback on what they would like to see at such an event, and a desire from the Centre executive to increase collaboration and a feeling of belonging.

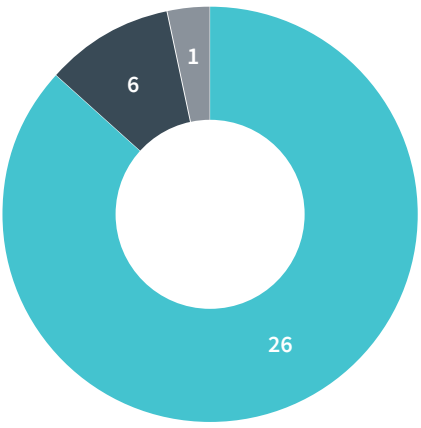
The workshop was a major milestone for Centre ECRs, allowing many to meet members from other nodes in person for the first time. This was held at the Novotel Geelong in November, in conjunction with the Centre annual workshop.

An inter-node collaboration activity at the ECR workshop.

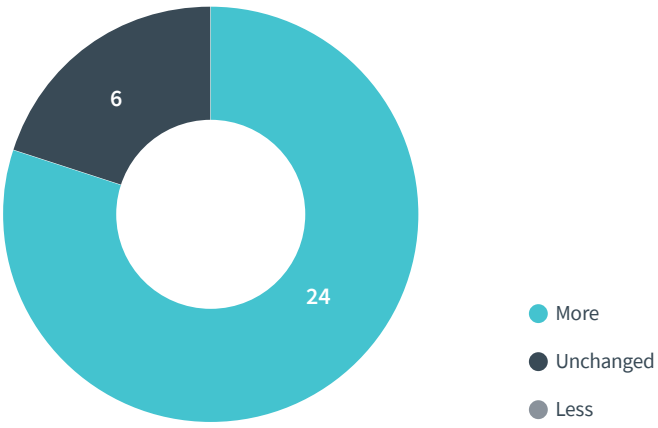
The schedule included science lectures, research presentations from ECRs, a communication workshop, and social and networking events. The workshop was a great success, with positive feedback from participants, and more than 85% of respondents in the post-workshop survey reporting feeling more a part of the Centre than previously, and more likely to collaborate across nodes.

This year also saw the implementation of initiatives to support ECRs, including an onboarding package to help people new to the Centre understand the structure, and the launch of a Strategic Initiative Grant Program to fund ideas and new collaborations from ECRs, which will have its first round in 2023.

Do you feel more part of the centre after the workshop?



Do you feel more likely to start new collaborations within the centre after the workshop?



mentoring

As part of her participation in the Leading Edge program of Women & Leadership Australia, mentoring committee member Michaela Froehlich undertook a project that focused on mentoring. She conducted a survey, with additional help from Markus Mosbech, reaching out to each mentee and mentor individually to gain a better understanding of both needs.

Through the ECR committee, she received feedback about what ECRs would like in terms of information sessions and workshops. Michaela consulted with the ANU NECTAR Mentoring Program facilitator, Ozgecan Ozyildirim about how to run a successful mentoring program and investigated a number of mentoring platforms.

Following feedback, the ECR's top preference for an information session was "preparing for interviews". At the annual workshop, the committee ran a session where guest presenter Hrayr Matevosyan from the University of Adelaide gave a presentation on the career path from particle physics to data science with tips on preparing for interviews and Sue Barrell (AO) from SUPL Ltd and the Advisory Board shared tips on how to approach applying for jobs. This was followed by a broader Q&A session involving other Centre members.

The committee also launched the Centre's Mentoring Program 2.0 where they summarised the survey feedback, outlined the benefits and expectations of a mentoring program and the responsibilities of participants. The Centre has signed up to Mentorloop Pro which will be launched in early 2023 and open to all Centre members including professional staff.

Other mentoring activities in the Centre included the ECR Committee sitting on the Executive and Research Committee meetings, aiding their development as future leaders, as well as more informal mentoring activities like the participants on the National Quantum and Dark Matter Road Trip. Road trippers that had not engaged with the media previously, received media talking points from the Centre's Media and Communications Officer as well as support from more experienced members on the road trip for radio, print and television interviews. In addition, the participants also gave presentations at schools and public events and afterwards they discussed them with fellow road trippers and identified ways to refine and improve them at subsequent events.

member profiles

"It has always been my philosophy that you need to do what you are passionate about, because that is what you will be best at"

Michaela Froehlich

Michaela Froehlich, ANU

As a mother-of-two and chemist, Michaela Froehlich is a trailblazer in her field. She is part of the metrology team at ANU and her research spans environmental chemistry, nuclear physics and astrophysics. She is on the editorial board of the Journal of Environmental Radioactivity and was awarded best presentation at the South Pacific Environmental Radioactivity Association (SPERA) 2022 conference (Instruments & Method Development session).

When she welcomed her first child, she was the only woman in a team of male researchers. On her return from maternity leave from ANU, she had to challenge her own expectations and those of her colleagues.

"I certainly had expectations of my return to work and myself – I thought nothing at work would change but actually a lot changed." she said. "It took some time for my colleagues and also myself to understand that I couldn't work the same hours and wasn't as flexible as I was before having children."

She believes a greater presence of women in academia would ensure new mothers did not have to break down barriers in the same way. To that end, she volunteers her time in the Curious Minds STEM program which pairs a female academic with a Year 9 and 10 girl who are interested in a STEM career.

Despite the challenges of academia, Michaela can't imagine doing anything else. It is a message she would like to pass on to her mentee.

member profiles

"I have been part of the ATLAS collaboration for the past 8 years. As a PhD student at the University of Texas at Austin, I worked on several precision measurements of the Higgs boson and the top quark. I was one of the lead analyzers and an analysis coordinator for the recent ATLAS paper on the first observation of single top quark + photon production. My current work is focused on the searches for long-lived particles in proton-proton collisions, upgrades for the Inner Tracking for HL-LHC, and run-3 ATLAS operations."

Harish Potti

Harish Potti, University of Adelaide

In the ATLAS collaboration, early career members make up more than 50% of the collaboration (>3000 out of ~ 5900 people). The Early Career Scientist Board (ECSB) is created to represent the best interests of the young scientists in the ATLAS collaboration.

It is also a direct advisory group to the ATLAS collaboration board and the ATLAS management. The ECSB consists of seven scientists at three career levels: doctoral students; post-doctoral scientists; junior academics and research staff. Centre postdoc Harish Potti is one of the seven scientists on this board.

Harish's role on the ECSB is to represent the views and needs of the young scientists to the ATLAS collaboration board and the management and help to organise various social events, software tutorials, and soft skills workshops.

Harish is also an active member of the Centre's EDI Committee. He is promoting a culture of respect and inclusion across the Centre in this position. He has harnessed these skills and uses his experiences including those on the ECSB to mentor masters and PhD students in the Centre.

training and development

CDM is committed to the development of all of its members. In 2022, the Centre offered a range of formal and informal training activities, many with a strong focus onEDI. These included:

- Pyrate users tutorial
- Saltwater Media Solutions – media interview training
- Phil up on Science - Science Communication workshop
- En Masse - Optimising collaboration into 2023 – Chief Investigator training at CDM Annual Workshop
- SBS Inclusion Program – continuation of online Gender and Core Inclusion modules
- How to prepare for an interview
- Virginia Kilborn – Chief Scientist at SUT – Gender diversity in science at CDM Annual Workshop
- Leading Edge program – Women in Leadership Australia
- Applied Innovation Laboratory workshop

Leading Edge program – Women & Leadership Australia

The Centre sponsored three female postdoctoral researchers to participate in the Leading Edge program of Women & Leadership Australia. Delivered part-time over four months, the program is designed to turn early career females into confident, capable and motivated leaders. The program involves virtual workshops, self-assessments, interactive webinars, self-directed learning modules, peer coaching and a workplace application project.

Irene Bolognino (UoA), Michaela Froehlich (ANU) and Zuzana Slavkovska (ANU) all participated in the program in 2022. This support was an initiative of the EDI committee and aligned with its mission to improve gender balance in STEM through engaging with external programs offering targeted, outstanding leadership training.

“Participating was a privilege! The training was fantastic, well-structured and gave me the opportunity to meet many people, with whom I still keep in touch. I learnt different leadership approaches and techniques and was also able to consolidate my skills. The most important thing I have gotten out? The ability to find solutions on my own, through self-analysis and with targeted questions, thanks to the several coaching sessions!” - Irene

“I worked in a team with a woman that has worked as a firefighter for years. Working with her on assignments was very enjoyable and gave me an insight into a world very different from academia. However, with the same leadership challenges. We shared our leadership experiences and struggles and gave each other support and feedback during the whole course. I gained a lot from this experience and I would highly recommend this course to all females that would like to learn about successful leadership”. - Zuzana

“What stood out for me was the structure of this program, it was pretty clever as we are in the “Zoom era” to have a self-paced component. Although we never met in person, it felt like that we did this course as a group and not on our own. Participants were from across Australia, all walks of life with inspiring stories to share and the motivation to improve professionally and personally. Each module had something to offer where I was able to improve myself and grow. The most significant personal insight was to understand and re-align with my personal and professional values and to accept that not everyone has the same. My communications skills have improved and feel better equipped when it comes to difficult conversations or even conflict management. Although the program was time-consuming, I would recommend it as it was a wonderful and rewarding experience.” - Michaela

Media training

In response to feedback about the needs of Centre members, a range of media and communications training activities were provided in 2022. The Centre’s Fleur Morrison provided one-on-one sessions to Centre members in the lead up to media interviews to discuss interview techniques, answer practice questions and gain an understanding of the Centre’s messaging. These sessions aimed to provide members, especially ECRs, with an understanding of the media and the confidence to undertake media interviews. Saltwater Solutions ran a 2-hour virtual training session on preparing for media interviews for 21 Centre members across all nodes and levels of seniority which aimed to build Centre members’ skills and confidence in sharing their research with the wider public through the media. This was followed by a Q&A session run by Alan Duffy. Feedback from the training was overwhelmingly positive, with responses including:

“Really useful and enjoyable - engaging and gave great strategies.”

“It was informative, well rounded and focused.”

Participants expressed an interest in a hands-on media training session in the future.

In addition to the media training session, Phil Dooley from Phil up on Science ran a half day workshop for students and ECRs at the ECR annual workshop in Geelong.

events

Centre events offer 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. For the most part in 2022, events were held in person with some opportunities for people to join remotely.

The Centre's ECR and Annual Workshop were the first 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.

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 International Day of Women and Girls in Science, National Science Week and Dark Matter Day, profiled in other sections of this report.

SABRE South Workshop – reflections from ANU postdoc Zuzana Slavkovska

After a successful year for SABRE South with many project-related breakthroughs and a lot of media attention. In November, 32 members of the SABRE South collaboration came together in a yearly meeting. There was no better place to organise this meeting than Stawell, the home of SUPL. This way the collaboration members could experience the atmosphere of the town and practice the travel to a place where they will work in future.

Two days of talks and discussions started with the overall SABRE status and group reports. Several further topics including SUPL installation, safety and cleanliness followed. After almost two years of Zoom meetings, many of us met in person for the first time. It was exciting for me to see my colleagues' faces not on a screen but with my own eyes. The discussions did not stop by pressing the "leave meeting" button but kept going on during breaks and during the relaxed conference dinner. This meeting brought the collaboration closer together by introducing the personal factor.

SABRE South collaboration meeting in Stawell

Advances in Subatomic Physics

A joint Workshop on "Advances in Subatomic Physics" was held in Cairns between Adelaide Centre members and the Centre for the Subatomic Structure of Matter. There were also several attendees from other nodes (UoM and ANU) and from overseas.

Over 20 Centre members (academic staff, ECRs and students) gave presentations. There were many highlights to the week's talks including, searching for dark matter with Hyper-Kamiokanda, recent developments in dark photon searches, nuclear parton distributions, finite-volume effective field theory for nuclei and a rapid-fire "Three minute thesis" session for students.

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:

Ciaran O'Hare, Grace Lawrence, Madeleine Zurowski and Raghda Abdel Khaleq at IDM 2022

Australian Institute of Physics (AIP) congress

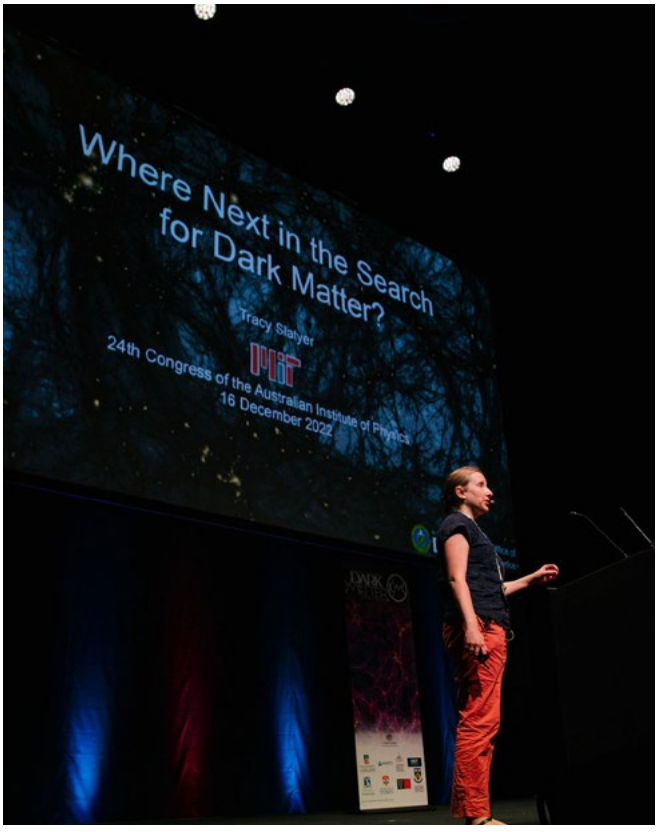
Centre members made a significant contribution to the 24th Congress of the AIP in Adelaide in 2022. With over 1000 Australian and international attendees, the congress spanned a diverse range of physics disciplines. CI Nicole Bell was on the organising committee and Anthony Thomas was part of the Scientific Program Committee, with Adelaide node administrators Sharon Johnson and Silvana Santucci playing a significant role in supporting the organisation of the event.

The Centre sponsored PI Tracy Slatyer as one of the plenary speakers who's talk titled "Where Next in the Search for Dark Matter" was the final of the conference.

CI Celine Boehm was presented with the AIP Women in Leadership Medal (see Awards and Honours below).

In total, 23 Centre members, including students, postdocs and Chief Investigators, gave presentations and nine presented posters. Adelaide postdoc Irene Bolognino gave an invited talk titled "The Sabre South Experiment at the Stawell Underground Physics Laboratory" and UWA CI Michael Tobar gave an invited talk titled "Precision Metrology with Photons, Phonons and Spins: Answering Major Unsolved Problems in Physics and Advancing Translational Science".

Centre Outreach and Education Coordinator Jackie Bondell attended the South Australian Science Teachers Association Education Day and engaged with other Secondary Physics educators.



PI Tracy Slatyer giving a plenary at the AIP Congress (credit: Laura Vanags Photography)

International Conference on Identification of Dark Matter (IDM)

The aim of IDM, which was held in Vienna, Austria, is to draw a complete picture of the current knowledge of dark matter from cosmological scale down to particle physics, from accelerator searches to recent results in indirect and direct detection and to give a glance at future prospects and technological advancements on the endeavour to identify dark matter.

Centre members gave talks and presented posters over the four days. UoS AI Ciaran O'Hare gave the concluding summary talk of the conference and SUT PhD student Grace Lawrence was one of the three recipients of the Young Scientist Award for her talk "Gusts in the Headwind: Uncertainties in Direct Dark Matter Detection". Selected from the 90 talks given by young scientists.

Dark Side of the Universe (DSU2022)

AI Ciaran O'Hare and CI Celine Boehm were part of the local organising committee of DSU 2022 held in Sydney in December. DSU brings together a wide range of theorists and experimentalists to discuss current ideas on models of the dark sector of the Universe and to relate them to ongoing and future experiments.

Of the plenaries presented at the conference, Centre director Elisabetta Barberio gave a plenary titled "Dark matter searches in the southern hemisphere", CI Ray Volkas gave a plenary titled "Brief review of neutrino mass models" and UoS Centre member Theresa Fruth's plenary was titled "Status and prospects for dark matter direct detection searches". In total, 17 Centre members gave presentations over the five days.

ACAMAR Meeting on Astroparticle Physics

Held online due to travel restrictions, the Australia-China Consortium for Astrophysical Research looked at the nature of dark matter, other 'cosmic relics' and studies of high-energy particles and their origins. All relevant activities were encouraged to contribute, from astronomy, particle physics, particle cosmology, experiment to theory, radio waves to gamma rays, cosmic rays, neutrinos and gravitational waves. Six Centre members gave presentations during the conference.

IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society – Distinguished Lecturer series

As part of his appointment as a IEEE UFFC Distinguished Lecturer, UWA CI Michael Tobar presented numerous talks in 2022 across Australia and internationally (including France, Germany, UK and Singapore). His talk was titled "Precision Metrology with Photons, Phonons and Spins: Answering Major Unsolved Problems in Physics and Advancing Translational Science". Distinguished Lecturers are selected not only because of personal stature and contribution to a field, but also because of broad knowledge of the field and give 20-40 lectures over an 18-month period.

A selection of other plenary talks from Centre members in 2022 included:

- 11th Australasian Conference on General Relativity and Gravitation (ACGRG) – Ben McAllister, Plenary titled "The Axion Dark Matter Experiment"
- International Conference on Neutrinos and Dark Matter (NuDM-2022) – Nicole Bell, Plenary titled "Dark Matter Signals in Hyper-Kamiokande" and Raymond Volkas, Plenary titled "VISHnu: flavour-variant DFSZ axion model for inflation, neutrino masses, dark matter and baryogenesis"
- International Symposium on Cosmology and Particle Astrophysics in 2022 (CosPA 2022) – Nicole Bell, Plenary titled "The Capture of Dark Matter in Stars" and Irene Bolognino, Plenary titled "The SABRE South Experiment at the Stawell Underground Physics Laboratory"
- KEK Theory Meeting on Particle Physics Phenomenology (KEK-¬PH2022) and the International Joint Workshop on the Standard Model and beyond – Jayden Newstead, Plenary titled "Inelastic nuclear scattering from neutrinos and dark matter" and Anthony Thomas, Plenary titled "Tests and Consequences of the Existence of a Dark Photon"

annual workshop

Centre members and international partners from across Australia and internationally attended the CDM's first in-person Annual Workshop over three days in Geelong in November.

A range of talks and events were held to provide members with the opportunity to meet, share ideas, and plan for the year ahead. Highlights of the event included:

- Research talks from Centre members and discussions across the Centre's research themes as well as keynote presentations from AI Sara Diglio (CNRS France), PI Neil Spooner (University of Sheffield), Pippa Cole (University of Amsterdam), AI Darren Croton (SUT) and AI Ciaran O'Hare (UoS)
- A poster session with 34 posters presented by Centre students and ECRs (poster prize details below)
- The workshop dinner where Centre awards were presented by Advisory Board Chair Aidan Byrne (details below)
- A report on the National Quantum and Dark Matter Road Trip, which informed members on the National Science Week event and its impact on communities in regional and rural areas of Australia and featured some highlights from road trip participants
- An innovation activity led by AI Christine Thong (SUT)
- The launch of the Centre's Mentoring Program 2.0 and guest speakers Hrayr Matevosyan (UoA) and Sue Barrell (Advisory Board member and chair of SUPL Ltd)
- The Equity, Diversity and Inclusion committee's diversity breakfast and session with guest speaker Virginia Kilborn (Swinburne Chief Scientist) who also participated on a panel with Centre members Nicole Bell (UoM) and Zuzana Slavkovska (ANU)
- The Centre's Advisory Board's first in-person meeting during the workshop
- Final wrap up talks featuring Centre Director Elisabetta Barberio, CI Geoff Taylor, and Advisory Board members Aidan Byrne, Campbell Olsen and Sue Barrell
- The diversity of speakers, with women giving 40% of presentations during the event

Finally, the clear highlight of the workshop was the opportunity to meet in person and talk with members from different nodes and learn about the breadth of dark matter research happening across the Centre. Responses collected in a post workshop survey were very positive, when asked "What did you like about the annual workshop?" a majority of respondents mentioned meeting people from other nodes in person as well as:

> *"Finally being together in person... finally felt like a centre!"*
>
> *"The collaboration and opportunity to meet other centres for the first time"*
>
> *"Meeting many people for the first time face to face, meeting new people, the chance to build relationships"*

CDM Collaboration and Centre Values Award recipients

Irene Bolognino (UoA)

Irene, an experimental physicist, joined the Centre in 2022 as a postdoctoral researcher at the University of Adelaide. She has become a highly visible and a well-respected collaborator throughout the Centre and has taken positive action to build collaborations on direct detection experiments across multiple nodes within the centre. She listens and is open to the opinions of others and generates a level of trust which is aligned directly with the Centre values. As speakers committee chair for the SABRE South collaboration she put effort into helping ECRs securing opportunities at conferences. As ECR representative, she has continued to work hard on behalf of ECRs and helped to organise the ECR workshop with her fellow committee members. Despite her being temporarily unable to travel, she has been engaged and present at Centre talks and activities.

Markus Mosbech (UoS)

Markus is a theoretical physicist and PhD student at the University of Sydney. He proactively supports inclusiveness across the centre as an engaged member of both the ECR and EDI committees. He was an active organiser of the ECR workshop and in all aspects of his engagement with the Centre, provides constructive and well informed ideas on improvements and initiates and participates in discussion. He has a passion about equity and diversity and works hard to make the Centre a more inclusive place. His behaviour is directly in line with the Centre values.

CDM Outreach and Impact Award recipient
Ben McAllister (SUT/UWA)

Ben is an experimental physicist and postdoctoral researcher with a joint appointment at UWA and SUT. He is an enthusiastic ambassador for the Centre, and dark matter research in general. He raises the profile of the Centre in the public eye, and devotes a significant amount of time and effort to outreach activities. He works on various channels of public engagement, both to generate enthusiasm for our research, and to enhance outcomes for school students in STEM. Ben was one of the members of the organising committee and participants on the National Quantum and Dark Matter Road Trip. He showed leadership and also trained and mentored the more junior road trip participants. He generated a lot of media and always delivers the key messages about the centre and its research in his interviews. He is a positive role model to the students and ECRs in the centre.

Best Poster Award (panel vote)
Renee Key (SUT)
For poster titled *"AMPM: Asteroid-Mass Primordial Black Hole Microlensing"*

Best Poster Award (Centre member vote)
Wasif Husain (UoA)
For poster titled *"Consequence of Neutron Decay Inside Neutron Stars"*

awards and honours

Raghda Abdel Khaleq (ANU)
John Carver Seminar Series – Dean's Prize & People's Choice Awards
awarded by the Research School of Physics, the Australian National University for proactively seeking out opportunities to fuse expertise in arts and science to create and engage into various arts/science events

Raghda Abdel Khaleq (ANU)
Physics Director's School Service Award – Individual Award
awarded by the Research School of Physics, the Australian National University for talk titled: "Sensitivity of Dark Matter-Nucleus Interactions To Nuclear Structure"

Michael Baker (UoM)
Early Career Researcher Global Collaborations Award
travel grant awarded by The University of Melbourne

Michael Baker (UoM)
Royal Society International Exchanges Travel Grant
awarded by The Royal Society

Sue Barrell AO (CDM Advisory Board and chair of SUPL Ltd)
Officer of the Order of Australia in the Australia Day Honours List
former Chief Scientist at the Bureau of Meteorology (BoM), Sue received the award for 'distinguished service to earth science through meteorology and research organisations'.

Lindsey Bignell (ANU)
National Science Week ACT Grant
awarded by the ACT Government

Celine Boehm (UoS)
Women in Leadership Medal
awarded by the Australian Institute of Physics for her excellence in academic research and leadership of large international collaborations, for her distinguished role in shaping astroparticle physics research in Australia, exemplary academic mentorship and her outstanding performance as a Head of School, which resulted in an inclusive, supportive and transparent workplace environment in the School of Physics at the University of Sydney and, notably, a significant increase in the number of female academics and professional staff and mid and early career researchers in leadership roles.

Michaela Froehlich (ANU)
Best presentation SPERA 2022 Instruments & Method Development session
awarded by the South Pacific Environmental Radioactivity Association for talk titled "Investigating the lead-210 background in lead materials and chemical reagents"

Guangyong Fu (UoM)
N.D. Goldsworthy Scholarship for Physics (PhD)
awarded by The University of Melbourne

Grace Lawrence (SUT)
Young Scientists Prize
awarded by the 14th International Conference on Identification of Dark Matter for talk titled "Gusts in the Headwind: Uncertainties in Direct Dark Matter Detection", selected from 90 talks given at the conference, it is recognition that her research is an important new direction which bridges particle and astrophysics.

Ben McAllister (SUT/UWA)
UWA Aspire Award
awarded by the University of Western Australia

Robert Mostoghiu Paun (SUT)
Honorific Thesis Mention
awarded by the Universidad Autónoma de Madrid, Spain

Hitarthi Pandya (UoA)
Poster and Peoples choice award
awarded by the University of Adelaide for the best poster at the APSS Symposium

Quantum and Dark Matter Road Trip National Science Week Grants 2022 grant
awarded by the Department of Industry, Science, Energy and Resources

Quantum Technologies and Dark Matter Research Laboratory, QDM Lab - Michael Tobar, Jeremy Bourhill, Evgeny Ivanov - (UWA)
School Award for Research Impact and Innovation
awarded by the School of Physics, Mathematics and Computing, University of Western Australia

Alexei Sopov (UoM)
McKellar Prize in Theoretical Physics
awarded by the University of Melbourne

Phillip Urquijo (UoM)
promoted to Professor by the University of Melbourne recognising his leadership in the field of physics and the impact he has made in shaping the physics program of Belle II and as the technical coordinator of SABRE South.

student completions

Honours:

Steven Samuels (UWA)

Masters:

Max Amerl (UoA)
Ishaan Goel (UWA)
Carol Isaac (UoM)
Robert Limina (UWA)
Campbell Millar (UWA)
Deepali Rajawat (UWA)
Bryn Roughan (UWA)
Iman Shaukat Ali (UoM)
Owen Stanley (UoM)
Joshua Wood (UoM)

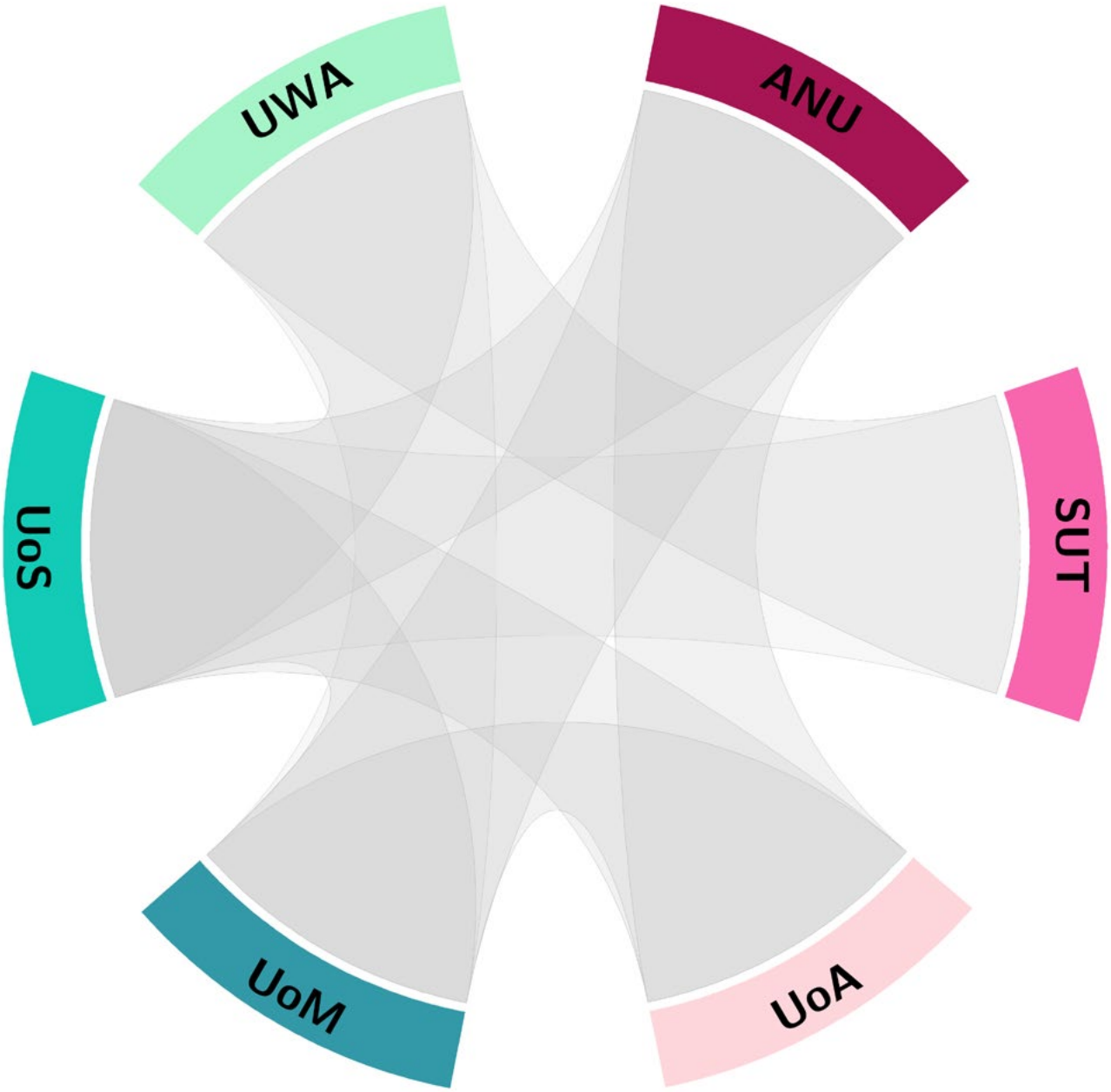
PhD:

Joseph Allingham (UoS)
Graeme Flower (UWA)
Adam Leinweber (UoA)
Ibtihal Mahmood (UoM)
Zachary Picker (UoS)
James Webb (UoM)

key performance indicators

Performance Measure	Target 2022	Actual 2022
1 Number of research outputs		
• Journal articles	60	56
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	0	0
4 Number of training courses held/offered by the Centre		
Professional training/development courses offered by the Centre	4	5
Number of Centre attendees at all professional training/development courses offered by the Centre	20	80
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	2	8
• Honours students	8	7
• PhD students	10	14
• Masters by research students	1	2
• Masters by coursework students	10	6
• Associate Investigators	7	5
6 Number of postgraduate completions		
PhD	0	6
Honours/MSc/MPhil Completions	15	11
7 Number of mentoring programs offered by the Centre		
Mentoring programs	5	4
Industry/ External internships for PhDs	4	1
8 Number of presentations/briefings		
• To the public	25	29
• To government (parliamentarians and department/agencies at both State and Federal level)	5	10
• To industry/business/end users	5	6
• To non-government organisations	n/a	n/a
• To professional organisations and bodies	5	9
News stories	10	82
Press releases	8	9
9 Number of new organisations collaborating with, or involved in, the Centre		
International	3	4
National	1	0
10 Number of female research personnel		
Female	>30%	23%
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	63
Number of invited talks/papers/keynote lectures given at major international meetings (including those held in Australia	20	41
Centre's Dark Matter Prize for high school students (# entries)	25	35

publications



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ATLAS Collaboration

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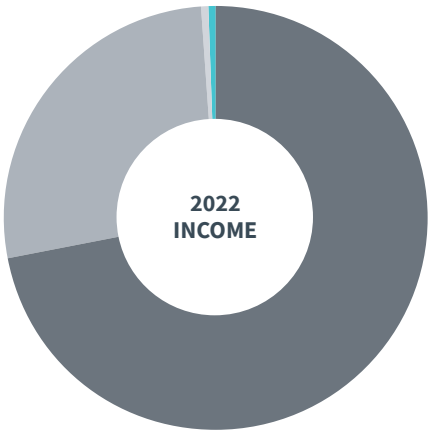
financial report

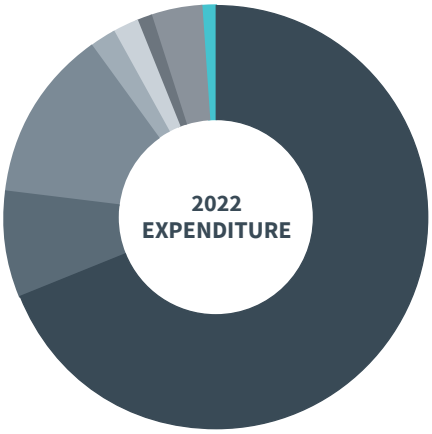
Statement of Income and Expenditure for Year ended 31 December 2022, preceding years and estimated budget for 2023

Reporting Period	2020	2021	2022	2023 forecast
INCOME				
ARC Grant	$5,089,998	5,181,620	5,228,255	5,411,246
University Contributions ^	$1,218,397	1,254,589	1,950,090	1,020,359
Partner Contributions	$20,000	70,000	20,000	20,000
Other Income*		250,000	21,250	-
TOTAL INCOME	**$6,328,396**	**6,756,209**	**7,219,596**	**6,451,605**
EXPENDITURE				
Salaries	$1,008,666	2,421,777	3,028,290	4,621,516
Equipment	$134,593	281,025	369,066	1,822,247
Travel, Visitor Support & Conferences	$3,481	44,234	552,053	1,065,168
Research Computing, Lab Maintenance & Consumables	$58,129	87,093	109,028	187,250
Management and Administration	$18,797	60,413	99,008	189,999
Outreach, Communications & Mentoring	$41,490	47,730	49,478	974,808
Scholarships	$12,467	192,599	171,625	380,662
Other expenditure*		250,000	21,250	-
TOTAL EXPENDITURE	**$1,277,624**	**3,384,871**	**4,399,800**	**9,241,650**
TOTAL CARRY FORWARD TO NEXT YEAR #	**$5,050,772**	**8,422,110**	**11,241,906**	**8,451,861**

* 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)
^ 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 (72%)
- University Contributors (27%)
- Partner Contributors (>1%)
- Other income* (>1%)



- Salaries (69%)
- Equipment (8%)
- Travel, Visitor Support & Conferences (13%)
- Research Computing, Lab Maintenance & Consumables (2%)
- Management and Administration (2%)
- Outreach, Communications & Mentoring (1%)
- Scholarships (4%)
- Other Expenditure* (1%)

In Kind Contributions

Contributor	2022 Reporting Period
The University of Melbourne	2,053,934
The Australian National University	973,139
The University of Adelaide	533,147
Swinburne University of Technology	206,285
The University of Sydney	182,944
The University of Western Australia	384,112
ANSTO	142,000
DST Group	45,372
The University of Sheffield	28,576
INFN Gran Sasso National Laboratory (LNGS)	3,843,374
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	**8,500,102**

* The In Kind contributions are reduced impacted again by Covid 19 restricting access to facilities equipment.

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