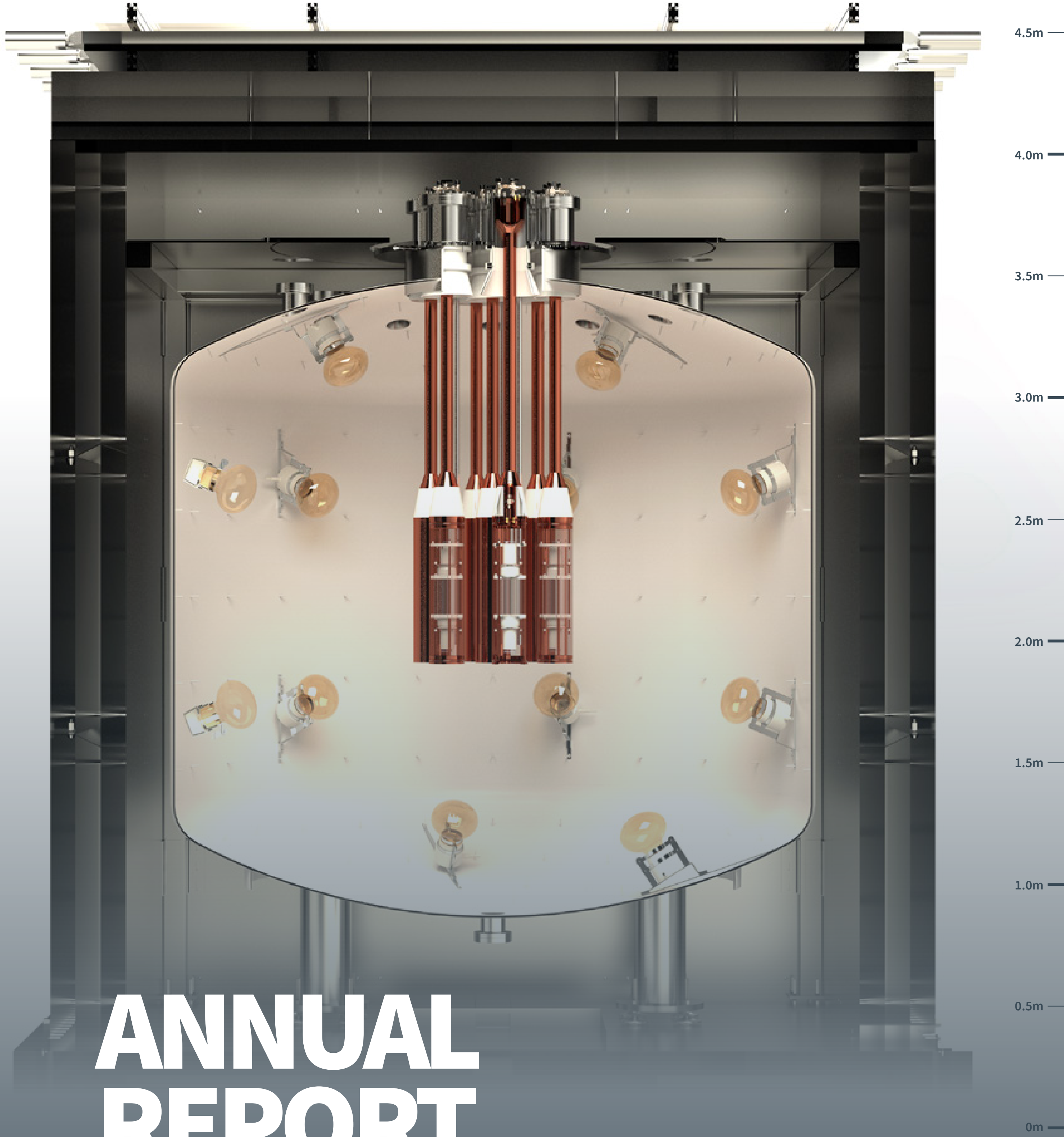
ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS



ANNUAL REPORT 2021

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 The University of Melbourne for design services provided for the production of this annual report.

Cover photo: Cross-sectional 3D render of the SABRE South vessel in its shielding with muon chamber above. Veto PMTs are visible on the interior of the vessel wall as well as the copper tubing containing the NaI crystals. Image courtesy Phillip Urquijo and SABRE South collaboration.

advisory board chair message

I have been heartened by the determination of the leaders of the Centre of Excellence for Dark Matter Particle Physics and the enthusiasm and engagement of its members, particularly its early career researchers and students, enabling the smooth establishment of the Centre during 2021, another challenging year.

2021 also saw the University of Sydney officially join as a collaborating university and the Centre's official launch, an important milestone after 12 months of operation, showcasing the passion of its researchers who are searching for the elusive substance that is dark matter.

Whilst it has been difficult to establish a Centre due to the lockdowns and travel restrictions, I have been reassured by the efforts that have been made to implement key initiatives in the Centre's portfolios such as training in equity, diversity and inclusion, one-on-one mentoring and building culture around the Centre's values of collaboration, passion and trust.

Positive impacts have also been made in terms of outreach in schools and the public, a highlight being the road trip during National Science Week. Dark matter researchers have also generated much excitement about their research in the media both nationally (including in regional Australia) and internationally.

This Centre provides a real drive for the discipline in Australia to harness talent and make a global contribution to the area of physics. I am excited by the technologies of the Centre and also to see its experiments develop, particularly SABRE and real progress in the construction of SUPL which will create a competitive advantage in the southern hemisphere. Using the Centre to further integrate theoretical and experimental physics, building a critical mass to create an enduring legacy.

I sense a collective optimism and sense of purpose of the Centre's researchers whose challenge is to create a unified vision for the future direction of the Centre's research. The next year will provide more opportunities to bring people together to collaborate and grow.

Aidan Byrne

www. centredarkmatter.org

@ARC_DMPP

@CDMPP.org

ARC Centre of Excellence for Dark Matter Particle Physics

@arc_cdmpp

acronyms and abbreviations

Institutions:

ANSTO:	Australian Nuclear Science and Technology Organisation
ANU:	Australian National University
Caltech:	California Institute of Technology
DSTG:	Defence Science and Technology Group
HZDR:	Helmholtz-Zentrum Dresden-Rossendorf
INFN:	Istituto Nazionale di Fisica Nucleare (Italian National Institute for Nuclear Physics)
LNGS:	Laboratori Nazionali del Gran Sasso
MIT:	Massachusetts Institute of Technology
SUT:	Swinburne University of Technology
Stockholm:	University of Stockholm
UoA:	University of Adelaide
UAmst:	University of Amsterdam
UFreib:	University of Freiburg
UoM:	University of Melbourne
UoS:	University of Sydney
USheff:	University of Sheffield
UWA:	University of Western Australia
UWash:	University of Washington

General:

AI:	Associate Investigator
CDM:	Centre for Dark Matter (abbrev for ARC Centre of Excellence for Dark Matter Particle Physics)
Centre:	ARC Centre of Excellence for Dark Matter Particle Physics
CI:	Chief Investigator
COO:	Chief Operating Officer
ECR:	Early Career Researcher
KPIs:	Key Performance Indicators
ORGAN:	Oscillating Resonant Group AxioN Experiment
PI:	Partner Investigator
PPB:	Parts Per Billion
PPM:	Parts Per Million
Postdoc:	Postdoctoral Researcher or Postdoctoral Research Associate
SABRE:	Sodium Iodide with Active Background Rejection Experiment
SUPL:	Stawell Underground Physics Laboratory

contents

director's message

Welcome to the second Annual Report of the ARC Centre of Excellence for Dark Matter Particle Physics. It summarises key research activities at the Centre in 2021 and highlights our achievements and impacts across the Centre's portfolios.

I would like to commend our researchers and the administrative team on their significant achievements during another year that was challenged by the global pandemic, including making impressive progress across our science themes, increasing momentum, and inspiring the public and engaging students in STEM through our education and outreach efforts.

On September 22, we held the Centre Launch with members across Australia and national and international partners. The Centre was officially launched by ARC CEO Professor Sue Thomas and like so many events in 2021 the launch was held virtually. We were fortunate to also have as a guest speaker Her Excellency Francesca Tardioli, Ambassador of Italy to Australia, who reiterated the strong links between the Centre and the Istituto Nazionale di Fisica Nucleare in Italy. To make the day even more memorable, a magnitude 5.9 earthquake happened in Victoria just prior to the commencement of proceedings!

In this report, you will read about the progress of our many research projects. A project that is a source of great excitement within the Centre and beyond is the Stawell Underground Physics Laboratory (SUPL). In 2021 the excavation of a section of the Stawell Gold Mine was completed, and the laboratory construction started. SUPL is an essential facility for the Centre, as it will host the Centre's SABRE South experiment. In April 2021, Victorian Regional Development Minister Mary-Anne Thomas visited SUPL to mark the award of the construction contract to H. Troon.

I would like to highlight our two major dark matter experiments, based in Australia. The SABRE experiment at SUPL will be the first large scale direct detection experiment built in Australia by Australians, and the UWA based dark matter detection experiment, ORGAN, that started to take data in 2021. Their successful completion will be a key milestone for the Centre and for Australia. Theorists have been engaged in a wide range of research activities collaborating across nodes and sub-disciplines. An example of this cross pollination is the study on how uncertainties in the galactic dark matter spatial and velocity distributions impact our interpretation of signals in direct detection experiments.

We thank the International Science Advisory Committee (ISAC) for their advice and guidance. In their review of the Centre's research program, they produced a written report where they stated, "The ISAC grades the Centre's progress as outstanding. We find that the topics of study are well-chosen and cohesive, the members have demonstrated great expertise, and the Centre is well-organized. Throughout the review, we noted that many of the speakers were early-career faculty, and that the Centre is already contributing to the future leadership of astroparticle and dark matter physics in Australia. The ISAC notes that it is very difficult to start up such a centre in the midst of a global pandemic and so we find the progress especially impressive."

One of the Centre's primary aims is to nurture the scientific talent of the future, and it was clear from presentations at the recent ECR workshop that there will be many opportunities to challenge and support these researchers. Our early career researchers are already thriving, with Ciaran O'Hare awarded an ARC DECRA grant to connect particle and astrophysics for the discovery of dark matter particles, Ben McAllister winning first prize in the UWA Rising Stars Awards 2021 and awarded the Forrest Prospect Fellowship by the Forrest Foundation, and Michael Baker nominated European Physical Journal distinguished referee. Other researchers in the Centre received important recognitions: Nicole Bell was named the Particles and Fields representative for Australia in the International Union of Pure and Applied Physics (IUPAP), Alan Duffy was appointed the inaugural Director of the new Space Technology and Industry Institute at Swinburne University of Technology, and Michael Tobar was awarded the international IEEE Distinguished Lectureship for Frequency Control, and as part of this, is travelling around the world to present his research achievements.

We also had events that brought the Centre together and provided the opportunity to celebrate our successes with each other and the wider community. In February there was a two-day ECR workshop on Zoom. In late October, representatives from each node offered their time to take part in Dark Matter Day, and in December, our Annual Workshop brought together researchers from across the country to share their research and were presented the inaugural Centre awards, recognising four students and ECRs for their achievements and commitment to Centre values. It was wonderful to showcase all the diverse talent we have within the Centre, and to look towards the exciting research that is planned for the coming years.

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 2022:

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

- Undertake research to advance the Centre's theoretical and experimental goals (see Research Program Overview)

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

- Education program with special emphasis on regional schools and affirmative action plan
- National Road Trip during National Science Week
- Focus on outreach and education activities that promote diversity and inclusion

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

- Funding to support collaborations between nodes and with Partner Organisations through the Mentoring and Career Development portfolio with a focus on Early Career Researchers
- Provide diverse training opportunities to Centre members

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
- SUPL completed in May 2022 and SABRE installed by the end of 2022
- Extend the dark matter discovery potential of ORGAN and continue taking data
- Expand R&D on superfluids

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

- Innovation Laboratory activities, including training in innovative thinking, to help translate discoveries into social and economic benefits
- Strengthen the collaboration with the DST Group and continue student internship program

6. Cohesive national and international environment with a strong equity, diversity and inclusion program

- Implementation of the Equity, Diversity and Inclusion action plan (see EDI report)
- Launch of the Artist in Residence with the Science Gallery Melbourne
- Initiate conversations 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 — March 2022
Current day

2023

2024

2025

2026

2027 — 13 August 2027
Centre end date

governance

The Centre is administered by The University of Melbourne. 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, 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 Leader, 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 interaction and cooperation of the nodes, Centre resources and oversees the activities of the various portfolios of the Centre.

Led by the Centre Director, the Centre Executive Committee comprises Node Leaders and the COO. One postdoctoral researcher from the Early Career Researcher Committee also attends the Executive Committee meetings 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)
- Alan Duffy (Node leader, SUT)
- Andrew Stuchbery (Node leader, ANU)
- Michael Tobar (Node leader, UWA)
- Raymond Volkas (Node leader, UoM)
- Anita Vecchies (COO)
- Zuzana Slavkovska (ECR representative, ANU)

Research Committee

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

The Research Committee is comprised of:

- Chair - Elisabetta Barberio (Director)
- Cedric Simenel (Deputy Director)
- Anthony Williams (Deputy Director)
- Greg Lane and Michael Tobar (Direct Detection leaders)
- Steve Tims (Precision Metrology leader)
- Nicole Bell (Theory leader)
- Geoffrey Taylor (LHC leader)
- Lindsey Bignell (ECR representative, postdoc)
- William Melbourne (ECR representative, PhD student)

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 (former Chief Scientist at the Bureau of Meteorology)
- 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 advise the Director, the Executive Committee and the Research 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; spokesperson of SuperCDMS-SNOLAB)
- Carlos Frenk (Durham University, UK; Fellow of the Royal Society)
- 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)
- Michaela Froehlich (ANU)
- Zuzana Slavkovska (ANU)
- Christine Thong (SUT)
- Yi Yi Zhong (ANU)
- Madeleine Zurowski (UoM)

Early Career Researcher Committee

Established 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, help coordinate activities targeted to ECRs, 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 2021 the members were:

- Lindsey Bignell (ANU)
- William Melbourne (UoM)
- Zuzana Slavkovska (ANU)

centre membership snapshot

180
CDM Members

20 Chief Investigators	**25** Associate Investigators	**13** Partner Investigators	**19** Postdocs	**82** Students	**7** Technical Staff	**2** Engineers	**13** Professional Staff

These numbers include people who were Centre members during 2021. Members will be counted who in multiple categories if their role in the Centre changed during the year.

centre members

The following people were Centre members during 2021. 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)
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)

Associate Investigators

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)
Shanti Krishnan (SUT)
Justin Leontini (SUT)
Ian McArthur (UWA)
Victoria Millar (UoM)
Francesco Nuti (UoM)
Ciaran O'Hare (UoS)
Peter Quinn (UWA)
Pat Rajeev (SUT)
Marc Schumann (Ufreib)
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)

Partner Investigators

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

Postdoctoral Researchers (Funded)

Michael Baker (UoM)
Lindsey Bignell (ANU)
Jeremy Bourhill (UWA)
Michaela Froehlich (ANU)
Matthew Gerathy (UoM)
Ben McAllister (UWA/SUT)
Jayden Newstead (UoM)
Harish Potti (UoA)
Sandra Robles Portilla (UoM)
Federico Scutti (UoM/SUT)
Zuzana Slavkovska (ANU)
Wei Su (UoA)
Xuan-Gong Wang (UoA)

Postdoctoral Researchers (Affiliated)

Rebecca Allen (SUT)
Chris Flynn (SUT)
Jason Oliver (UoA)
Abhishek Sharma (UoA)
Andre Scaffidi (UoA)
Federico Scutti (UoM)

Students

PhD

Raghda Abdel Khaleq (ANU)
Joseph Allingham (UoS)
Ramtin Amintaheri (UoS)
William Campbell (UWA)
Ferdos Dastgiri (ANU)
Mitchell Dixon (SUT)
Emily Filmer (UoA)
Graeme Flower (UWA)
Leon Friedrich (UoM)
Gangyong Fu (UoM)
Charles Grant (UoA)
Elrina Hartman (UWA)
Fredrick Hiskens (UoM)
Liam Hockley (UoA)
Nicholas Hunt-Smith (UoA)
Wasif Husain (UoA)
Renee Key (SUT)
Albert Kong (UoA)
Navneet Krishnan (ANU)
Shanti Krishnan (SUT)
Jo-Frederik Krohn (UoM)
Grace Lawrence (SUT)
Nicholas Leerdam (UoA)
Adam Leinweber (UoA)
Ben Li (UoS)
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)
Theo Motta (UoA)
Riley Patrick (UoA)
Zachary Picker (UoS)
Aaron Quiskamp (UWA)
Shahinur Rahman (ANU)
Alex Ritter (UoM)
Tristan Ruggeri (UoA)
Isaac Sanderson (UoM)
Nathan Spinks (ANU)
Minh Tan Ha (UoA)

Centre members at the University of Sydney

Pierre (Thor) Taylor (UoM)
Catriona Thomson (UWA)
Edmund Ting (UoA)
Adam Ussing (SUT)
Peter Verwayen (UoS)
Michael Virgato (UoM)
James Webb (UoM)
Scott Williams (UoM)
Yiyi Zhong (ANU)
Madeleine Zurowski (UoM)

MPhil
Isabel Carr (UoM)
Meera Deshpande (UoA)
Anna Mullin (UoA)
Sam Thompson (ANU)
Alexander Woodcock (UoA)

Masters by Coursework
Fatimah Alharthi (UoM)
Max Amerl (UoA)
Victoria Bashu (ANU)
Carol Isaac (UoM)
Goel Ishaan (UWA)
Robert Limina (UWA)
Tim Martonhelyi (UoM)
Will McDonald (UoM)
Jay Mummery (UWA)
Katerina Patsis (UoM)
Bryn Roughan (UWA)
Iman Shaukat Ali (UoM)
Alexander Sopov (UoM)
Owen Stanley (UoM)
Joshua Wood (UoM)

Honours
Kenn Goh (UoA)
Judith Kull (UoA)
Kyle Leaver (UoA)
Jesper Leong (UoA)
Bill Loizos (UoA)
Hitarthi Pandya (UoA)
Thomas Venville (SUT)
Harry Wyatt (ANU)

Technical Staff

Scott Collins (SUT)
Chris Kafer (ANU)
Padric McGee (UoA)
Steve Osborne (UWA)
Daniel Tempra (ANU)
Ben Tranter (ANU)
Tom Tunningley (ANU)

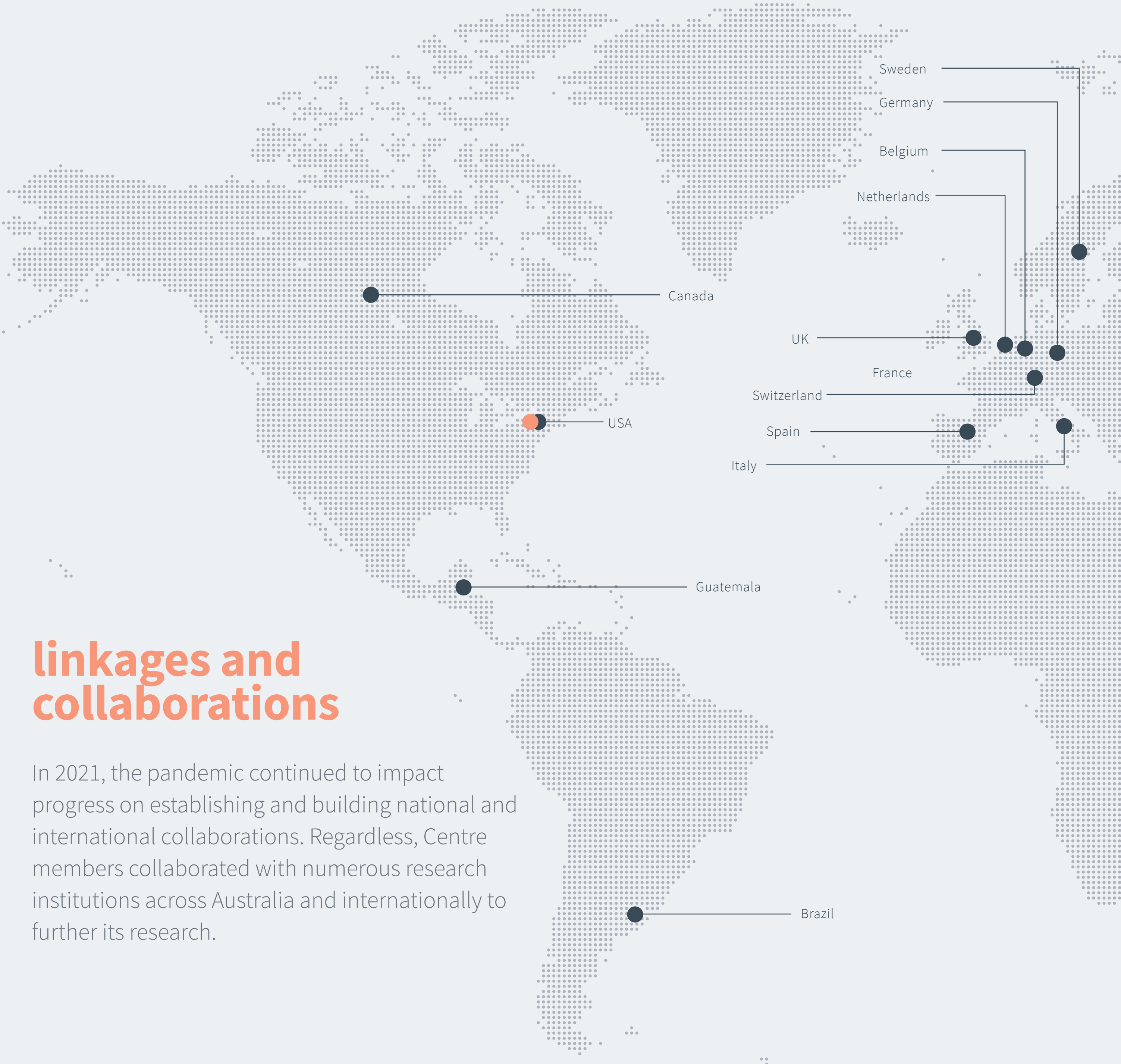
Engineers (Affiliated)

Tiziano Baroncelli (UoM)
Giulia Milana (UoM)

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)

Students inspecting the SABRE vessel

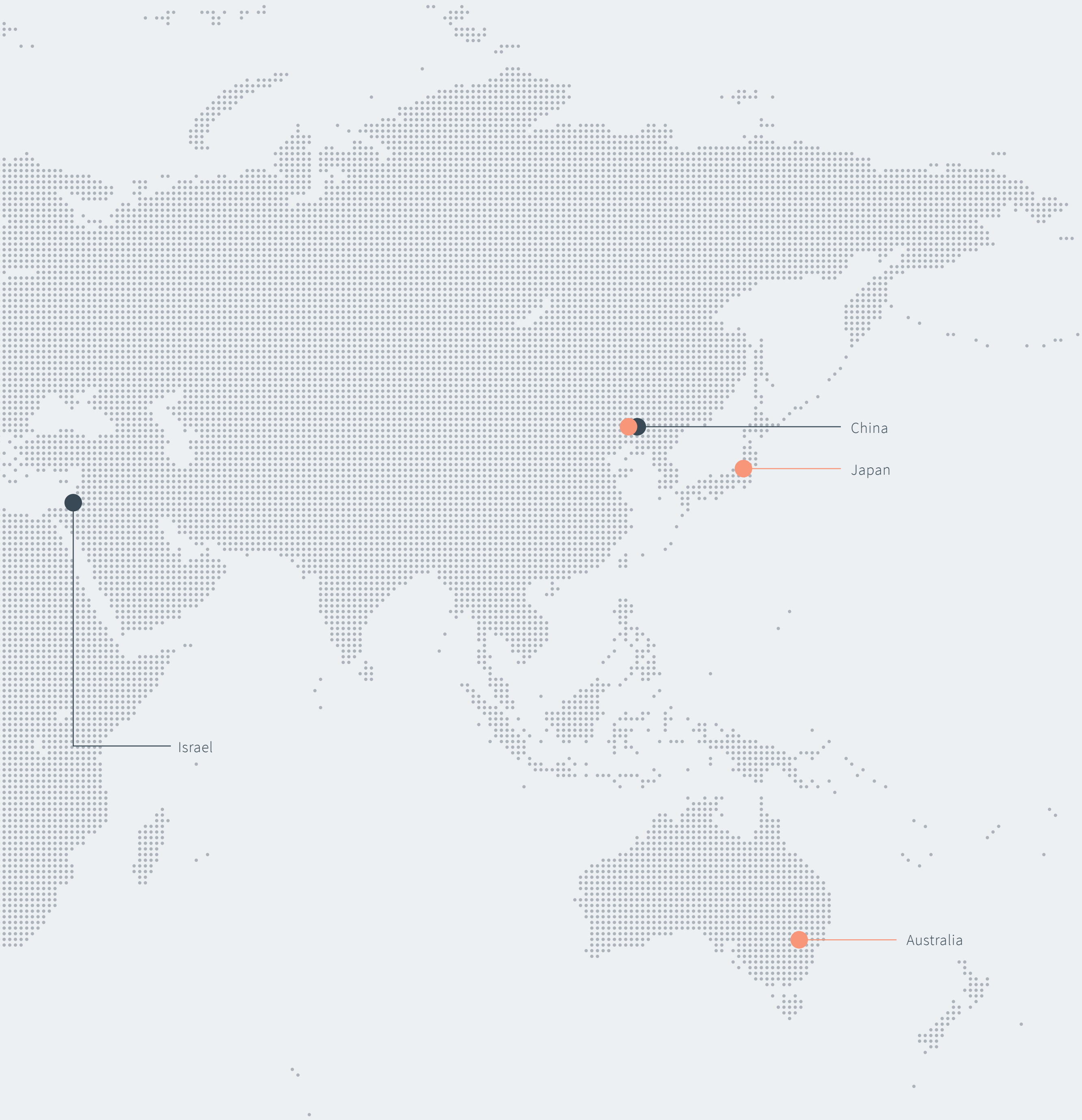


linkages and collaborations

In 2021, the pandemic continued to impact progress on establishing and building national and international collaborations. Regardless, Centre members collaborated with numerous research institutions across Australia and internationally to further its research.

Research Organisations:

Argonne National Lab, USA
Australian Nuclear Science and Technology Organisation (ANSTO), Australia
Berkeley University, USA
California Institute of Technology (Caltech), USA
Cambridge University, UK
CEA, Saclay, France
Cruzeiro do Sul, Brazil
DSTG (Defence Science and Technology Group), Australia
Durham University, UK
FEMTO-ST Institute, France
FermiLab National Accelerator Laboratory, USA
Grand Sasso Science Institute, Italy
Helmholtz-Zentrum Dresden Rossendorf, 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
Kobe University, Japan
KTH Stockholm, Sweden
LANL, New Mexico, USA
Lawrence Livermore National Laboratory, USA
Los Alamos National Laboratory, USA
Louvain University, Belgium
Lund University, Sweden
Mainz University, Germany
Massachusetts Institute of Technology (MIT), USA
Max Planck Institute for Physics, Germany
Oxford University, UK
Pacific Northwest National Lab (PNNL), USA
Princeton University, USA
Radbound University, Netherlands
SACLAY, IRFU, France
Sam Houstan State University, USA
San Carlos de Guatemala University, Guatemala
Sapienza Universita di Roma, Italy
Shanghai Jiao Tong University, China
Stockholm University, Sweden



SYRTE - Paris Observatory, France
TD Lee Institute, China
Texas A&M University, USA
The Technion – Israel Institute of Technology, Israel
The University of Massachusetts Amherst, USA
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 Autonoma, Spain
University of Bern, Switzerland
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, Honolulu, USA
University of Hawaii, Manoa, USA
University of Illinois Urbana-Champaign, USA
University of Massachusetts Amherst, USA
University of New Mexico, USA
University of Notre Dame, USA
University of Queensland, Australia
University of Sheffield, UK
University of Valencia, Spain
University of Washington, USA
University of New South Wales, Australia
Virginia Tech, USA
Washington University in St. Louis, USA
Yale University, USA
Zurich University, Switzerland

New research collaborations

The Centre has partnered with the Melbourne Graduate School of Education's (MGSE) science education team who have a focus on innovation and inclusive ways to communicate modern science. With a focus on the SUPL outreach program, this multi-year partnership incorporates an investment in science outreach with the Stawell community and schools as well as the Science Gallery Melbourne, giving rise to a remarkable opportunity to undertake science education research in a setting that is rare in scale, education investment and provision of access to cutting edge physics research.

Leveraging the development of scientific infrastructure, particularly in regional areas, to influence a young person's scientific identity, MGSE is funding two PhD scholarships on STEMM uptake in schools.

The first will focus on how modern areas of physics, like how dark matter research, can be incorporated into a traditional secondary school physics curriculum, how teachers can be supported in introducing contemporary physics ideas and how they are perceived by young people.

Considering the historical decline in participation in science, the second project will investigate the influence of science outreach on science aspirations and identity, with a focus on underrepresented groups.

Elisabetta Barberio initiated a long-term collaboration with new Associate Investigator Sara Diglio at IMT Atlantique Nantes to work on the international DARWIN project. The DARWIN project aims to design and construct a multi-ton target of liquid xenon for the direct detection of particle dark matter in a sensitive time projection chamber to be located most probably in Europe. The starting point is a cotutelle agreement with UoM, and the first PhD student in the cotutelle has started her PhD in Nante. The French collaborators have expertise in constructing and operating large Xenon dark matter detectors and UoM collaborators have expertise in detector simulation and data interpretation. This collaboration will be extended to the UoS and the UoM theory group to include theoretical modelling.

Industry engagement

The Centre also engaged with industry in 2021 to develop technologies and equipment to further its scientific work. This included:

AIRBUS

ALS Environmental Sydney, Australia

Hamamatsu Photonics, Japan

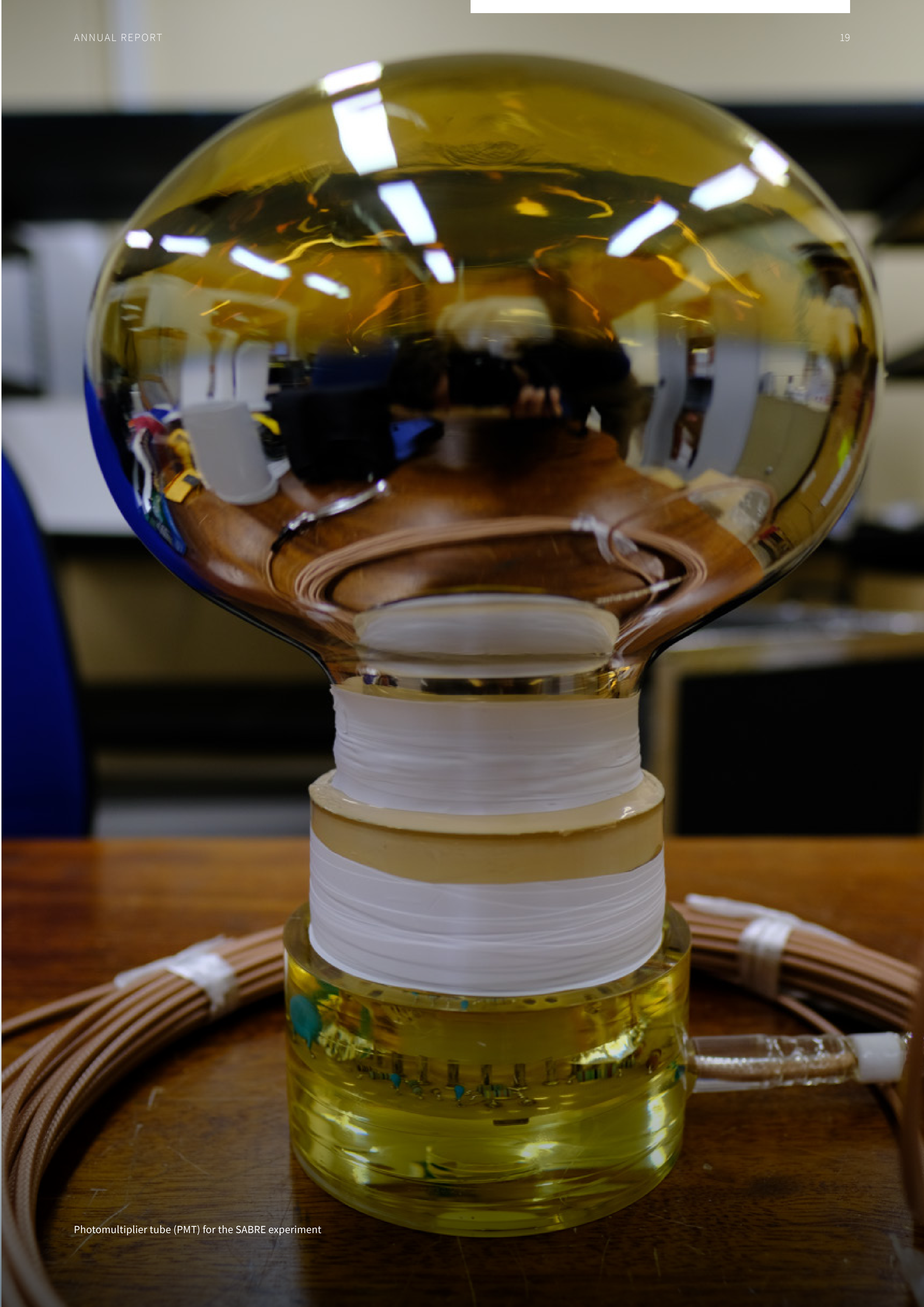
RMD A Dynasil Company, USA

Stawell Gold Mine, Australia

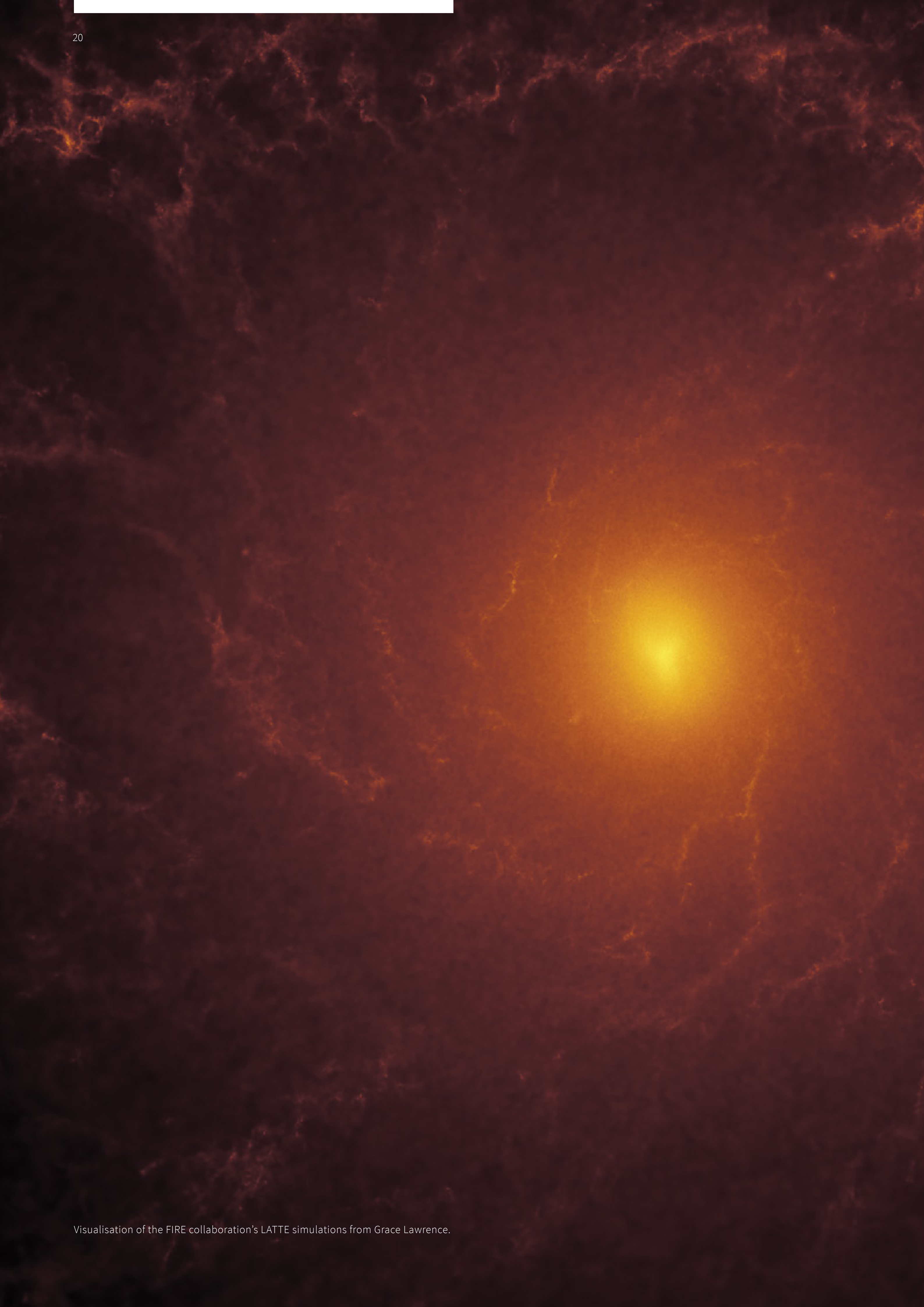
Shanghai Institute of Ceramics,
Chinese Academy of Science (SICCAS), China

Improving the sensitivity of techniques to measure radioactivity in Australia

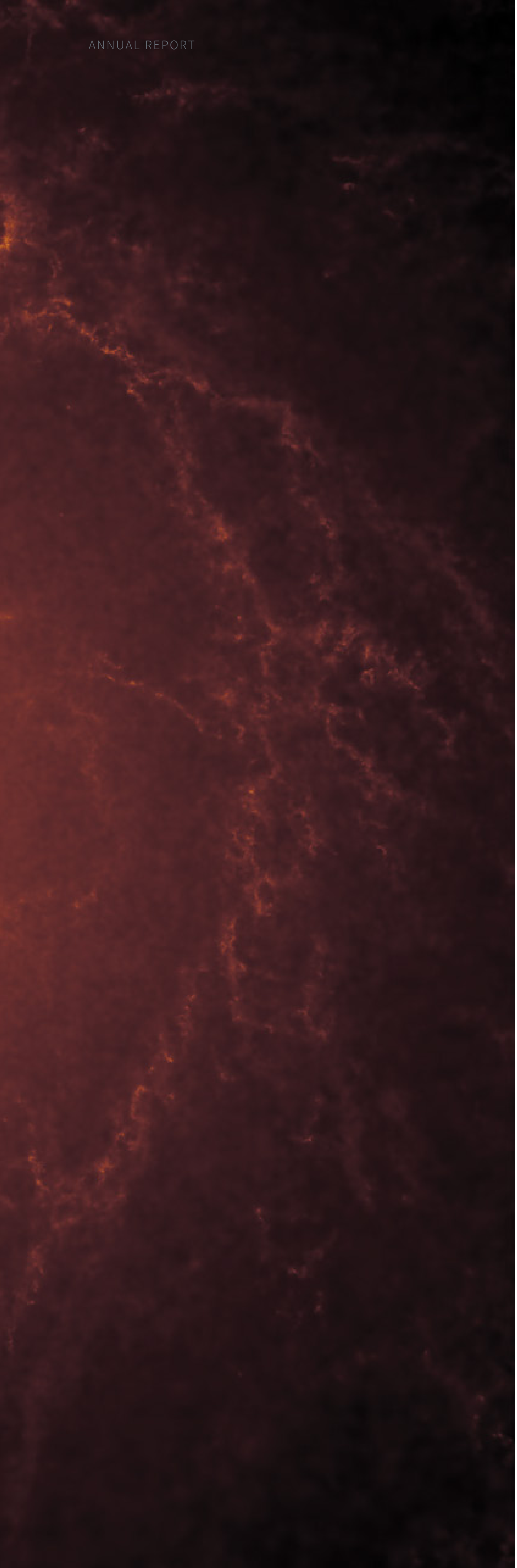
In order for the SABRE South experiment to operate at the sensitivity levels required to detect dark matter and be the most sensitive NaI(Tl) detector in the world, it's critical that every potential source of radioactivity is measured, monitored and minimised. Some of these measurements are undertaken using Inductively Coupled Plasma - Mass Spectrometry (ICP-MS). Measurements of the concentrations of trace elements like ^{40}K are required at the ppm-ppb level, however there was no facility in Australia that could measure trace elements such as ^{40}K or Rubidium at the ppb level. Samples are usually sent overseas. ANU postdoc Zuzana Slavkovska and PhD student Ferdos Dastgiri have been collaborating with ALS Environmental Sydney and have developed techniques to prepare the test samples that has improved the sensitivity of their equipment. Reaching the ppb level will improve ICP-MS in Australia and improve the capability and utilisation of these facilities for isotopic tracing for a number of diverse applications. These may include tracking food provenance, tracking groundwater, studying paleo-climate or meteorite compositions.



Photomultiplier tube (PMT) for the SABRE experiment



Visualisation of the FIRE collaboration's LATTE simulations from Grace Lawrence.



research program overview

Since we have no information on their particle nature or their mass, 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, 29 researchers, 21 students)

The Centre's program covers a wide range of putative dark matter particle masses with Australian based experiments using above-ground precision quantum techniques at UWA and deep underground experiments in SUPL. The ORGAN experiment (UWA) is already producing data and the SABRE experiment (SUPL) will start taking data by the end of 2022. The Centre is producing new detection technologies to extend our dark matter searches via our robust R&D program.

Program 2: Precision Metrology (2 nodes, 7 researchers, 5 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 Pb210[2021]. UWA will develop ultra-precise measurement frequencies needed for sub eV dark matter searches that are described in the Axion searches section.

Program 3: Large Hadron Collider Searches (2 nodes, 7 researchers, 11 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 are less sensitive.

Program 4: Dark Matter Theory (5 nodes, 17 researchers, 25 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.

research program action plan

Program		2022	2023	2024	2025	2026	2027
WIMP Direct Detention	SABRE South						
	DARWIN						
WISP Direct Detention	ORGAN						
	ADMX						
	ADMX Upgrade, 8-16 μeV						
	UPLOAD						
LHC (Run 3)	ATLAS						

Shut down/no experiment

Data taking

Full design phase/upgrade

Construction and commissioning

SABRE South vessel delivered at SUT (Wantirna site)

direct detection research program

WIMP direct detection

SABRE South

Nodes involved: ANU, UoA, UoM, UoS

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

Postdocs: L. Bignell, M. Froelich, M. Gerathy, F. Scutti, Z. Slavkovska

Engineers: G. Milana, T. Baroncelli

Students: F. Alharthi, F. Dastgiri, G-Y. Fu, C. Isaac, I. Mahmood, W. Melbourne, M. Mews, L. McKie, P. McNamara, L. Milligan, N. Spinks, O. Stanley, M. Tan Ha, Y-Y. Zhong, M. Zurowski

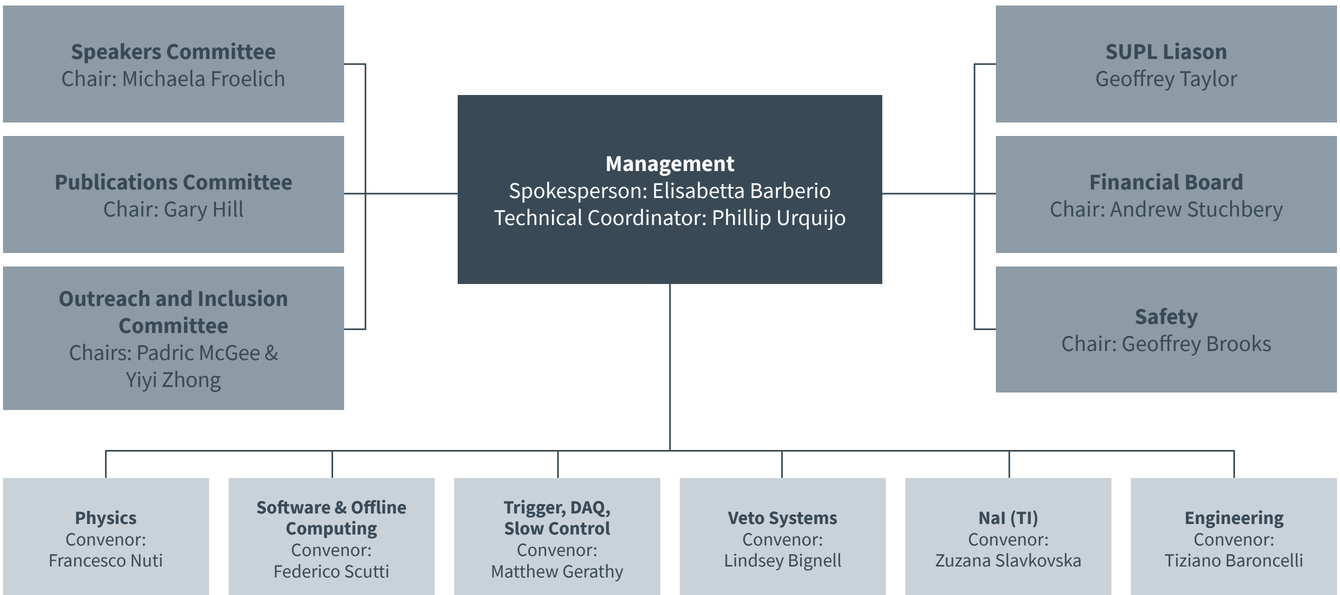
Associate Investigators: G. Brooks, F. Nuti

Introduction

The SABRE South experiment is designed to detect dark matter with a sodium iodide target with active background rejection in the Stawell Underground Physics Laboratory. A cross sectional view of the SABRE South detector is shown on the front cover of this annual report. The experiment is made up of three sub-detector systems: (i) the NaI(Tl) crystal detector, (ii) the linear alkyl benzene liquid scintillator system, and (iii) the EJ200 plastic muon paddle 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, and is expected to overtake its nearest competitors within two years of operation. Combined with the Southern Hemisphere perspective SABRE South should confirm or refute the DAMA/LIBRA excess by around 2025/2026. 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.

To undertake such a complex project, the SABRE South collaboration has put together a working group and committee structure as shown in the figure. 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.



NaI(Tl) detector

Nominally seven NaI(Tl) crystals will be grown from Sigma Aldrich NaI 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 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. 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 ICPMS and found to satisfy the crystal requirements for the final experiment except for mass. These requirements include 39K, 210Pb, 129I contamination level limits, as well as light yield and resolution. To scale up to 7kg crystal production, Centre AIs from SICCAS will use a modified Bridgman method with a double-walled platinum crucible technique. This method has been demonstrated to work in earlier prototypes.

PMT characterisation testbench

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. After a significant laboratory renovation, the Melbourne group built a new dark room facility for PMT characterisation. The hardware in this new facility includes multiple dark boxes on an optical table, picosecond pulsed laser source, picoammeter, thermal chamber, and CAEN readout.

The tests for the crystal PMTs are focused on the single photo-electron thresholds, quantum efficiencies, gain and stability over time, as well as dark rate and its temperature dependence. Furthermore PMT base electronics studies have been undertaken to optimise for dynamic range and noise minimisation.

Enclosure 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 almost complete, however, a final prototype of the end-cap plates in copper is being tested to ensure good seals for handling high purity nitrogen. The nitrogen fluxed glove box for assembly of these detectors has been designed.

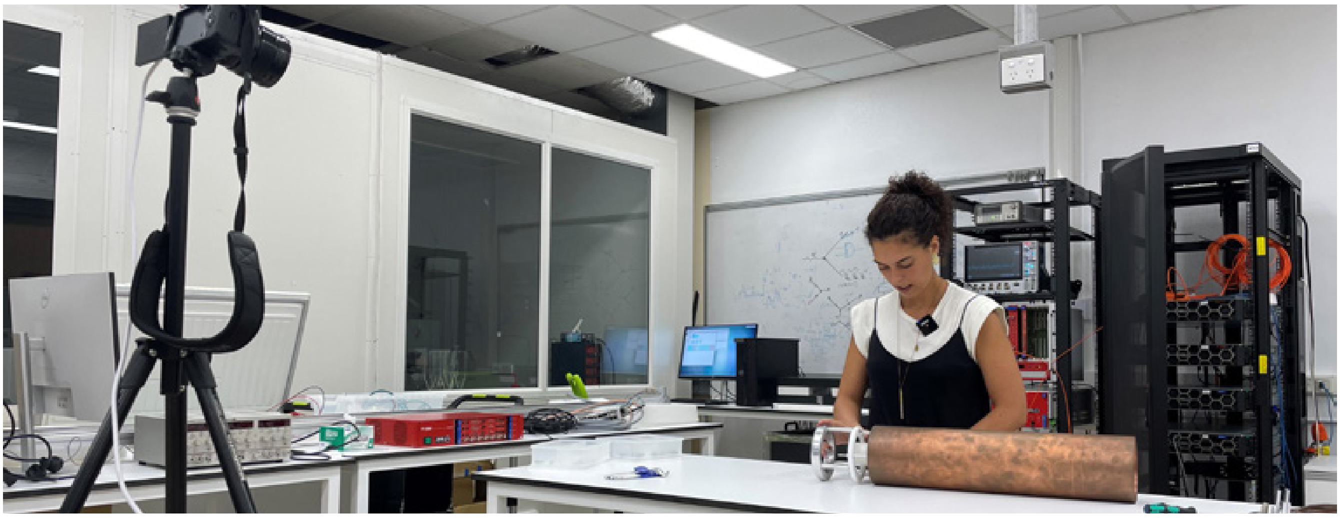
The crystal insertion system has been designed and manufactured.

Low energy studies and crystal properties

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 2keV 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 are being developed. Low energy PMT background is being studied at the Melbourne PMT testbench.

At ANU, the 14 UD pulsed beam accelerator at HIAF has been utilised for measurements of the nuclear recoil energy scale, or quenching factor, in NaI(Tl). Such measurements are crucial to interpret the mass scale and the compatibility of results across similar detectors. The measurement method has been published, and the procedure repeated for offcuts on the most recent RMD crystals.



Giulia Milana assembling the crystal detector enclosure at UoM dark matter laboratory

Liquid scintillator veto detector

The liquid scintillator vessel is made of stainless steel and lined with lumirror reflector foil. It is approximately 3.3m tall with a 2.6m diameter and designed to hold 10kL 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 electron, gas and calibration 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. A similar set of PMT characterisation tests to that of the crystal PMTs is well underway with a strong focus on particle ID and suppression of background mimicking low energy signatures.

Engineering

With the vessel already built, the current effort is focused on LAB procurement, PMT and lumirror mounting, cleaning, feedthroughs, and fluid handling.

In 2021 17kL of LAB was procured from Nanjing via the IHEP JUNO group. It was developed to meet the tighter requirements of JUNO, with excellent photon attenuation and radioactive contamination properties. The storage tank was processed for long term storage at SUPL and has been hosted by the Australian Synchrotron until the completion of SUPL. The fluorophores have also been procured. The mixing procedure is being developed by ANU.

To work within the vessel, SABRE members enrolled in industrial on-site training at the Swinburne Wantirna campus for working at heights and in confined spaces.

Calibration and prototypes

Two types of calibration systems will be deployed: (i) a radiation source based system based on small sources inserted in the aluminium calibration pipes, and (ii) optical systems based on light pulsed through optical fibres into the vessel. Simulations of the calibration system have been developed, informing the final design to be built in 2022. A small prototype named SABRINA, with a single PMT and 32 litres of scintillator has been used to cross-check the simulations and to develop particle identification techniques.

Shielding and Fluid handling

The vessel is surrounded by a shielding system made of an 80mm layer of polyethylene sandwiched between two 80mm 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, and to inform cost based decisions. The total mass of steel is over 150 tonnes.

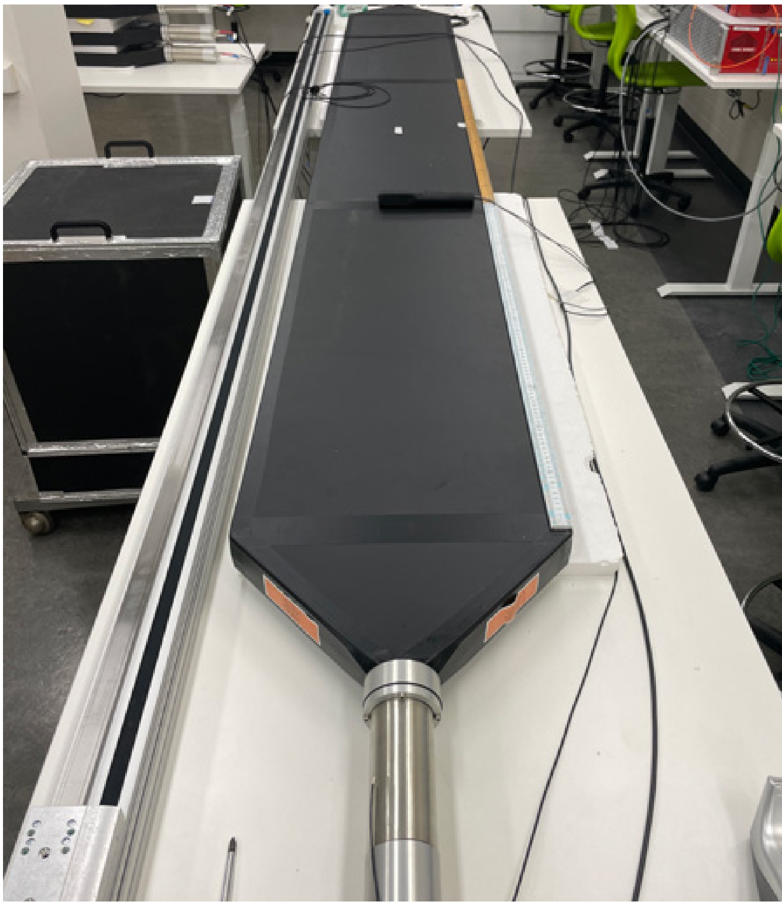
The shielding design is close to final, with the project now being managed by a UoM project management team who will work with an external company for fabrication and assembly.

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 and internally reviewed and is also with the project management team.

Muon detector

On top of the vessel is the EJ200 muon detector, made up of eight 3.0m x 0.4m x 5cm paddles. 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. Although it was envisioned that this system would be deployed in 2021 in the mine, Covid-19 restrictions did not allow it. We expect to use the system to perform angle dependent flux and flux modulation measurements in 2022 until the commencement of SABRE operations.

The performance of the muon detectors has been 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. A 3m long calibration stage has been procured by the UoM for source based calibration underground, where the muon flux is not sufficient for precision studies.



Muon detector paddle at UoM dark matter laboratory

Data acquisition and slow control

DAQ infrastructure

The data acquisition (DAQ) system of SABRE 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 and CSS (Control Systems Studio) system has been developed in the past year for DAQ run control, 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. The ongoing effort now is to integrate this system with the slow control and environmental monitoring system developed by SUT.

Online computing infrastructure

The local SUPL computing infrastructure for SABRE 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.

- The GEANT4. The full simulation of the experiment has been developed and a publication on this work will be submitted by mid 2022.
- The python based data processing and analysis framework (Pyrate) that processes data from either the DAQ system or from the GEANT4 simulation. The first major release of this package was finalised in January, and supports a wide range of ongoing calibration and testbench studies. Next major releases in 2022 will incorporate full event reconstruction.
- The conditions database is crucial for managing calibration data, and to correlate environmental conditions into data analysis.

The offline storage for SABRE is provided by UoM. It is currently 50 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.

Discussing the SABRE software framework.

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

Students: V. Bashu, F. Dastgiri, L. McKie, P. McNamara

Associate Investigators: C. O'Hare

The experimental CYGNUS R&D has focused its efforts on the development of the CYGNUS-1 prototype in 2021. The prototype was designed and manufactured in-house at the ANU Node (figure 1). The gas TPC is a 1.5L volume, with 20cm drift length and a gas electron multiplier (GEM) gain stage. The TPC design uses a ceramic accelerator tube repurposed from the ANU's 14UD, which has excellent field uniformity and low outgassing properties. The high voltage is distributed along the outside of the vacuum region, and users are protected using an interlocked ground shield. CYGNUS-1 is capable of a charge readout (multi-wire proportional counter) and will soon have an optical (PMT, mid-2022) readout and an intensified camera readout (late-2022). The gas system is capable of arbitrary mixtures of up to three gases, currently limited to atmospheric pressures but with an upgrade to below-atmospheric pressure operation slated for the near future (mid-2022). The run control is centrally achieved using a customised version of the BlueTongue software originally written for SABRE. The prototype will be a key R&D platform to support gas TPC studies for CYGNUS in Australia over the near-term. In 2022 we will commence science measurements, studying the optical and charge yields of various gases as we continue to upgrade CYGNUS-1.

The experimental infrastructure required for operating the CYGNUS-1 detector was also put in place in 2021. The necessary safety approvals were granted, and we have recommissioned a disused clean room to permit the direct handling of the detector internals without risk of damaging the GEMs. A residual gas analyser is being repurposed to use in outgassing studies with CYGNUS-1. We are also putting in place the necessary analysis infrastructure to permit detector modeling studies; developing tools for track-to-reconstruction event simulation. Further optimisation and integration of these tools will occur over 2022. An early result from this effort was the investigation of backgrounds for Migdal effect measurements in a prototype similar to CYGNUS-1, with 7Li(p,n) neutrons – this study found that pulsing the beam to mitigate the prompt gamma rays was insufficient to exclude the dominant gamma ray background and careful shielding design is needed.

Collaborative activities within the Centre continue to deepen, with an emphasis on ensuring close relationships between the theory and the experimental researchers. Within the international collaboration, O'Hare, Bignell and McNamara have contributed to the Snowmass process by co-writing the Recoil Imaging White Paper document led by CYGNUS collaborator S. Vahsen. Ciaran O'Hare, together with Sven Vahsen and Dinesh Loomba, surveyed techniques for directionally detecting nuclear and electron recoils in Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224. They highlight that direct recoil imaging using high-definition micro-pattern gas detectors seems to be one of the only viable strategies for achieving excellent directionality at large scale. Future R&D in this direction will be essential if we wish to go below the neutrino floor.

The CYGNUS-1 TPC prototype with most of the experimental team at ANU.

R&D new directions (superfluids)

Nodes involved: UoM, UWA

Chief Investigators: E. Barberio, M. Dolan, M. Goryachev, M. Tobar

Associate Investigators: P. Cox

Exploring the full range of possibilities for dark matter will necessarily require a diverse range of experiments. The next frontier for WIMP dark matter is the low-mass regime (keV - 100 MeV), which has to date remained largely unexplored. The detection of such light dark matter will require new types of detectors and has become an important focus of R&D. Members of the Centre's theory and experimental programs are working in close collaboration to identify the technology that will form the basis of a next-generation dark matter experiment targeting low mass WIMPs.

The primary focus of this project is superfluid detection. Superfluids have several properties that make them advantageous as detectors, namely their excellent energy resolution, range of detectable signals, and exceptional radiopurity. We are exploring the potential of an optical or microwave cavity to detect excitations in bulk superfluid produced by the scattering of WIMPs. At UWA, we have successfully demonstrated confinement of a few milli-litres of superfluid in a re-entrant cavity. The cavity demonstrated a rich spectrum of low frequency fluctuations when excited on resonance. In addition, fast events have been observed.

Several other unconventional methods of particle detection have been considered at the UWA node in collaboration with ARC Centre of Excellence for Engineered Quantum Systems (EQUS). In particular, we have considered superconducting nanowire detectors, phase transitions in sapphire masers at milli-Kelvin temperatures, superconducting granule detectors, and acoustic systems operating at cryogenic temperatures. All these platforms, previously used for other purposes, are being characterised as precise calorimeters.

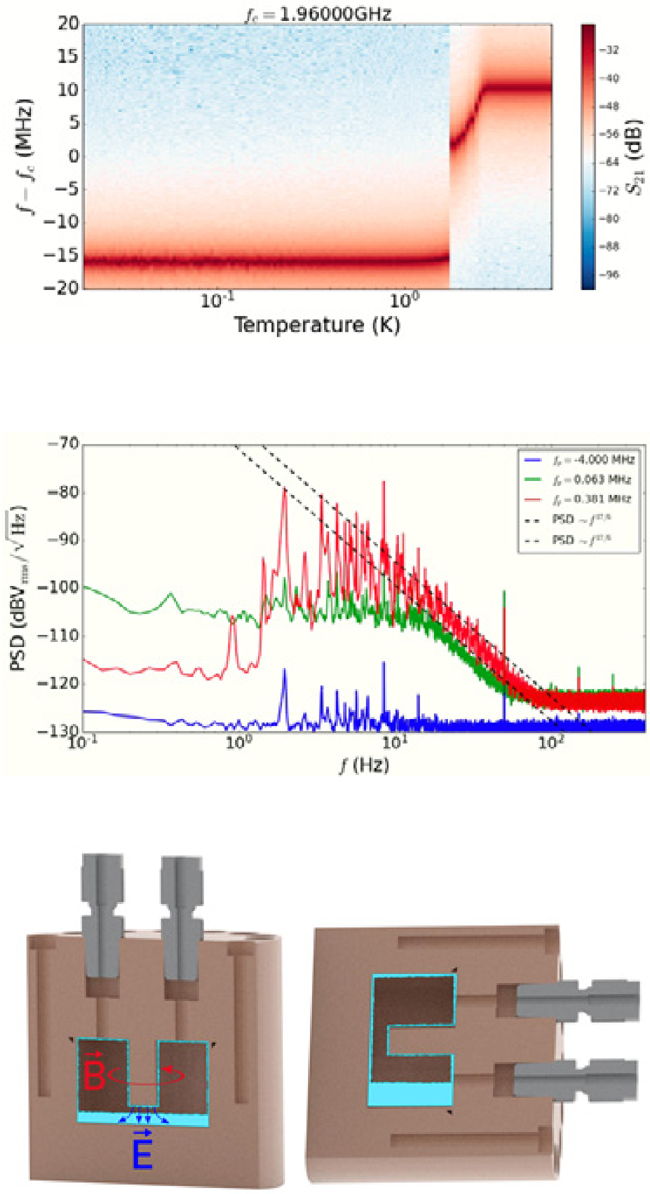


Figure 1: (A) Superfluid phase transition of Helium in a microwave cavity as observed by its resonance frequency. (B) Spectra of low frequency fluctuations in the cavity observed through modulation of the carrier excitation. (C) Metallic microwave re-entrant cavity filled with superfluid Helium.

Axion and WISP direct detection

Nodes involved: SUT, UWA

Chief Investigators: M. Tobar, M. Goryachev

Postdocs: J. Bourhill, B. McAllister

Students: A. Quiskamp, G. Flower, C. Thomson, W. Campbell, E. Hartman

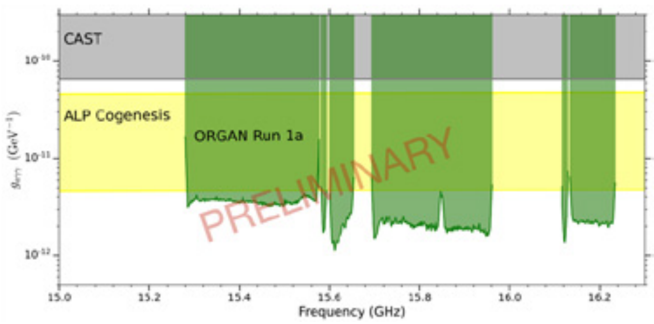
Associate Investigators: E. Ivanov, C.Zhao

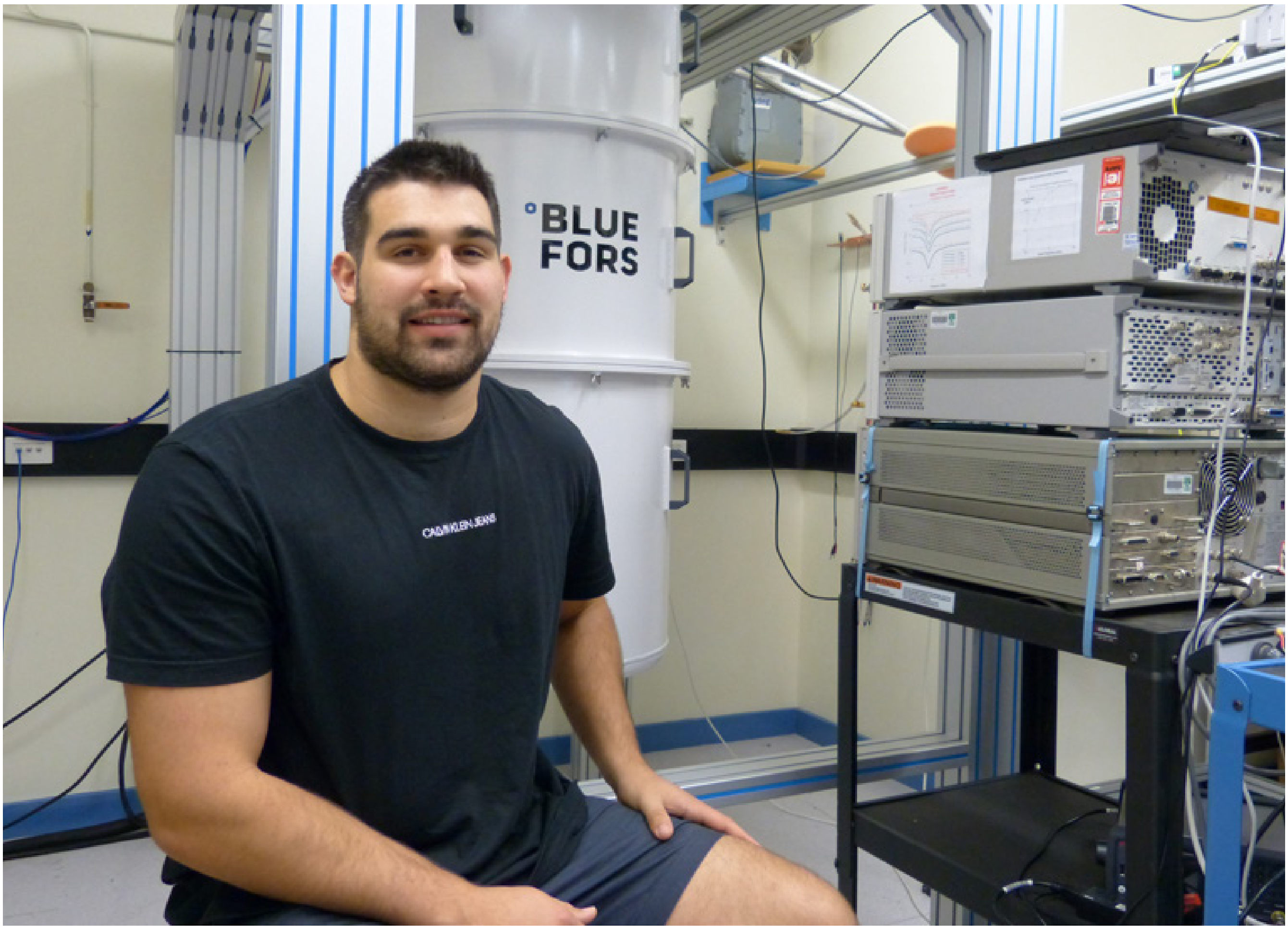
Partner Investigators: G. Rybka

Oscillating Resonant Group AxioN (ORGAN) experiment

ORGAN is the centre's flagship high mass axion haloscope, targeting the 15-50 GHz or 60-200 meV in mass, in a range where serious theoretical prediction suggests the axion exists. In 2017 our pathfinding run placed the first limits on axions from a haloscope above 15 GHz, beating CAST at 26.6 GHz. After this, ORGAN entered a planning and commissioning stage for long term operations (Phase 1 and 2), which commenced in 2021. Phases 1a and 1b are short, targeted scans of around the 15-16 GHz and 26-27 GHz ranges respectively, using equipment on hand (HEMT amplifiers and established resonator designs).

Phase 2 encompasses the entire 15-50 GHz region, broken down into 5 GHz sub-phases, which will re-scan the regions in Phase 1 with enhanced sensitivity, using single photon counters (SPCs), or quantum limited amplification. In collaboration with UQ and the EQUS centre of excellence we are investigating SPCs, and with efficient GHz SPCs ORGAN aims to reach the QCD axion limits. Phase 2 is expected to commence in 2023. Phase 1a, successfully excluded Axion Like Particle Cogenesis models between 15.3–16.2 GHz (63-67 meV), with a paper under preparation. Phase 1b is in commissioning, expected to commence in 2022, using HEMT amplification, and newly designed sapphire loaded cavity resonators with dielectric-boosted sensitivity. The figure below shows our preliminary limits.





Aaron Quiskamp with the ORGAN detector at UWA.

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

Operation of the first room temperature prototype experiment was published in 2021 placing limits in the mass range 7.44–19.38 neV [Phys. Rev. Lett. 126, 081803 (2021) Erratum: Phys. Rev. Lett. 127, 019901 (2021)]. Now we have built the second version, which uses state-of-the art frequency stabilisation at room temperature. This offers some orders of magnitude improvement over the initial prototype and approaches the level of sensitivity of the CERN Axion Solar Telescope (CAST) experiment. Data taking and sensitivity improvements are currently underway. Recently it was found by Pierre Sikivie that adiabatic fluctuations produced in the primordial plasma by cosmological inflation resonantly excite the axion field during the QCD phase transition, suggesting enhanced signals above a meV (240 MHz), and for this reason we will target our next search between 240 to 500 MHz, which is currently unexplored.

A cryogenic version of this experiment is proposed for the future, and we are using this room temperature version to understand what the best way will be to do this in the future.

Low mass detectors for axions with LCR circuits

This project will see us undertake experiments to search for axions below 1 μeV in mass using lumped mass LCR circuits. We have determined that extracting photon power from dark matter using an electric circuit is very similar to extracting and producing voltages from an electric generator. From this understanding we investigated the electrodynamics of electric energy generation [Phys. Rev. Applied 15, 014007 (2021)]. We determined that Faraday's law is effectively modified in the process. This highlights that in principle dark matter is a clean energy source. Meanwhile, we are designing lumped element circuit to search for axion dark matter.

We have also joined a working group with ADMX to search for axions in the 240-500 MHz regime, called ADMX Low Frequency. Ben McAllister is leading this working group and Elrina Hartman is looking at 3D lumped resonators to implement in her PhD project. A first prototype experiment has been built at the University of Florida.

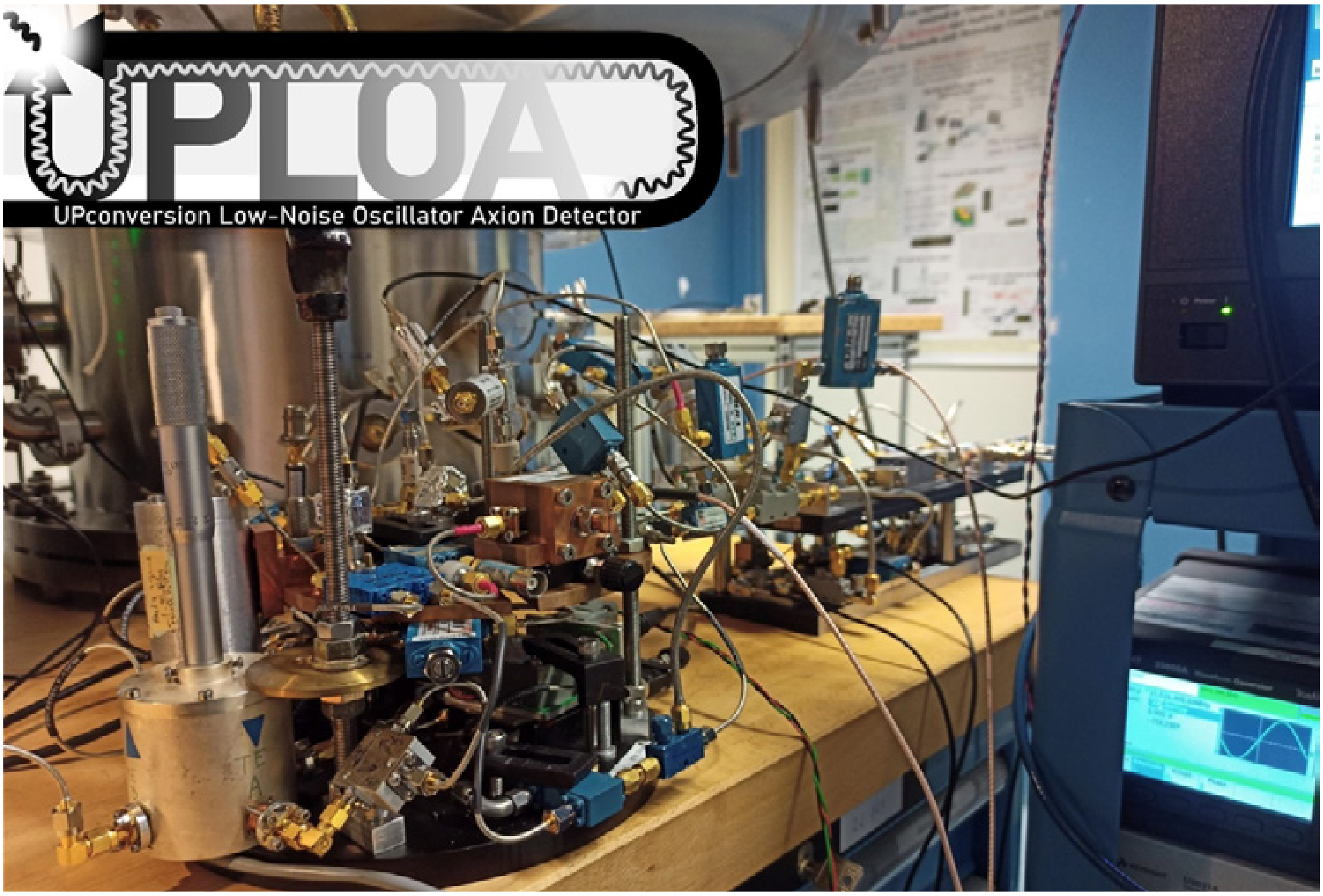
Axion Dark Matter eXperiment (ADMX) Generation 1 and 2

ADMX recently published results of their Generation 1b [Phys. Rev. D. 103, 032002 (2021)] and 1c [Phys. Rev. Lett. 127, 261803 (2021)] experimental runs situated in Seattle at Washington University. In particular, the UWA node has contributed by simulating the form factor of the microwave cavity as it tunes and understanding the limits on its performance. The node is involved with the high-resolution analysis of possible dark matter axion cold flows from the centre of the galaxy. As ADMX gen1 continues to search for axions, we will continue to add our expertise to the collaboration to enable this search. It is likely our students will travel to Seattle and be involved with these experiments as the borders open.

The next generation experiment, ADMX G2 is already funded, and is one of the US Department of Energy's flagship dark matter searches, and the only one looking for axions. The experiment consists of a large magnet, a microwave cavity, and ultra-sensitive low-noise quantum electronics and will be situated at Fermi Lab. Currently we are involved in helping design the cavities and topology of this experiment.

Searches for scalar dark matter

We successfully put first limits on scalar wave-like dark matter, by searching for oscillations in fundamental constants [Phys. Rev. Lett. 126, 071301 (2021)]. This was achieved by comparing state of the art photonic, atomic, and mechanical oscillators. We have a program to improve acoustic BAW oscillators at cryogenic temperatures, for use in scalar dark matter, quantum gravity and gravitational wave detection experiments [Phys. Rev. Lett. 127, 071102 (2021)]. We are looking at coupling them to superconducting quantum technologies, have written our own simulation software and will be doing experiments soon to test our ideas. We have also improved the performance of our sapphire oscillators [IEEE Microwave and Wireless Components Letters. 31, no.4, pp. 405-408 (2021)] and we are looking at buying a new H-maser. We calculate that if in the future we can make our quartz oscillators make use of the 10^{10} cavity Q at low temperatures, we will see several orders of magnitude improvement in sensitivity. Meanwhile variations of this technology were used to search for gravitational waves [Phys. Rev. Lett. 127, 071102 (2021)], which could also be sensitive to WIMP-like dark matter.



Centre member Catriona Thomson at UWA.

precision metrology research program

Nodes invovled: ANU, UWA

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

Postdocs: M. Froehlich, Z. Slavkovska

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

Associate Investigators: E.Ivanov

Partner Investigators: A. Wallner

At the ANU node the advanced metrology program aims to characterise the materials used in dark matter detectors to ensure the intrinsic radioactive background present in the detector components is minimised. It is particularly important that, in the energy region of interest for dark matter detection, the contribution to the signal that arises from background radioactivity is as low as possible.

The UWA node is focussed on the development of low phase noise oscillators as detectors in the sub-eV range, and their potential for improving bolometers to detect WIMP dark matter as described in the AXION section.

Nuclear metrology

Characterisation of detector materials

The next generation of direct detection dark matter experiments will require state-of-the-art radio purity. Accelerator Mass Spectrometry (AMS) is a single atom counting technique that can measure ultra-trace levels of rare radioactive isotopes. During 2021 the Centre, in collaboration with ANSTO, has been developing new AMS techniques and chemical separation and purification methods, to improve sensitivity. A major focus this year has been towards developing the capability to use AMS to quantify ^{210}Pb in the NaI(Tl), as ^{210}Pb is a dangerous background for the SABRE in the dark matter signal region. At present, the only way to measure this radioisotope is to measure the flux of alpha particles in a fully grown NaI(Tl). The proposed techniques will need to be improved to reach the required sensitivity. The VEGA accelerator at ANSTO was specifically designed to measure isotopes of similar mass, and can be used to obtain the required sensitivity. The experimental endeavour to improve the sensitivity will continue in 2022. In parallel with this, there is an effort to understand the effect of trace-level contaminants in materials.

To increase the efficiency of extracting ^{210}Pb from sample materials. This is a collaborative effort between ANU and PI institutions, HZDR and ANSTO. Preliminary results indicate that extracting a beam of PbF_3- from a mixture of PbF_2 and Ag gives the most intense, stable output for injection into the AMS system. New AMS techniques have been established to reduce these interferences to manageable levels. The Covid-19 pandemic has severely impacted progress due to long delays in securing essential materials and through extended periods of laboratory closure or restricted access.

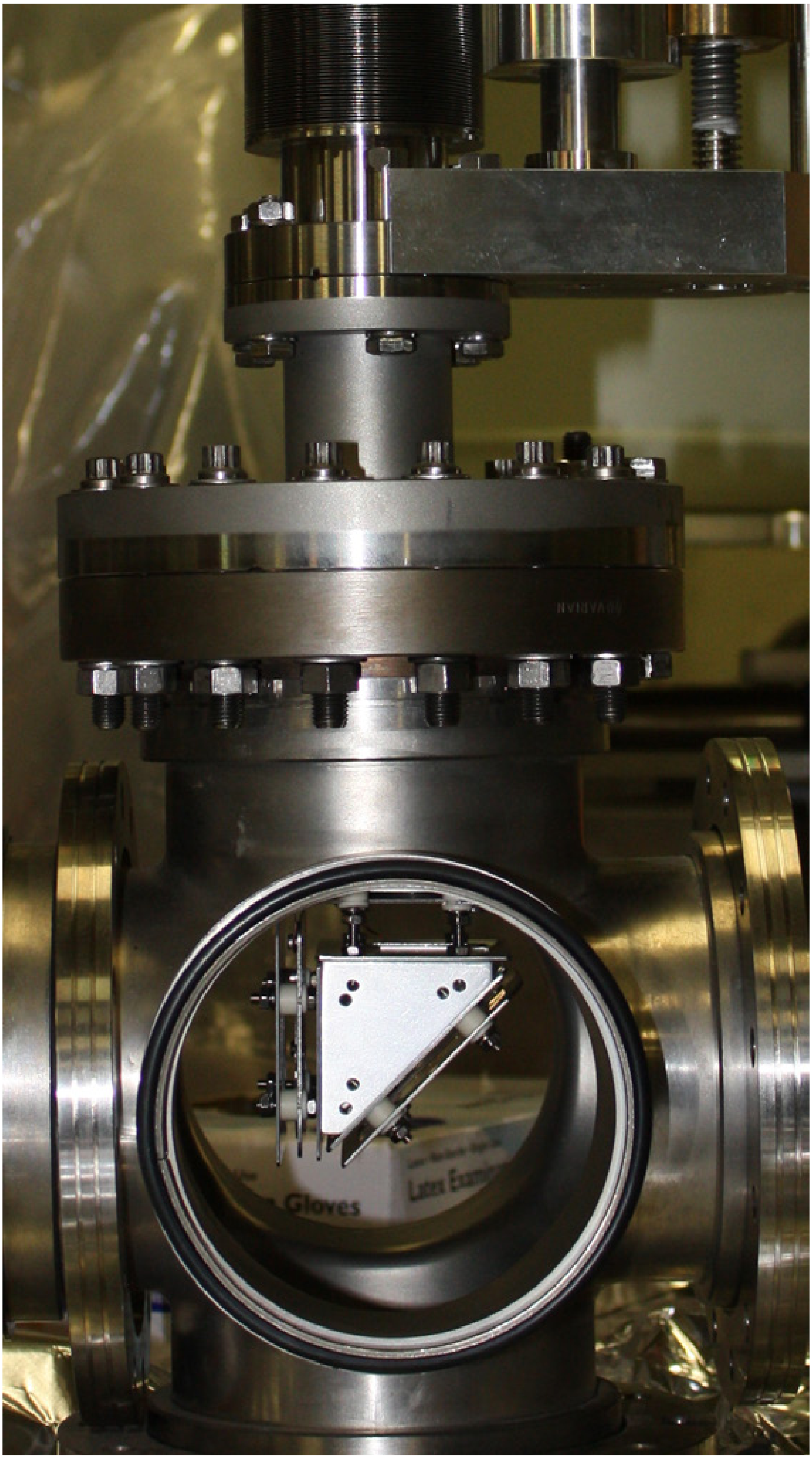
ICP-MS

Progress with ICP-MS is being driven by Slavkovska and Dastgeri. They have been collaborating with a local commercial laboratory ALS Environmental Sydney to set up measurement of ^{40}K at ppb level. Preliminary results show a sensitivity in the ppm-ppb range. More testing is underway to reach the required sensitivity.

Preliminary ICP-MS measurements of the rubidium, thorium and uranium content in the NaI astropowder have also started with results expected in 2022.

AMS capability improvements

To improve the AMS sensitivity, a number of modifications to the time-of-flight detector system were made to reduce the noise in the system. These resulted in a small improvement in resolution, however it has allowed identification of other issues that hamper achieving the ultimate resolution of the ANU AMS setup. Not all issues were resolved due to Covid-19 access restrictions and an electrical safety upgrade at HIAF. However, the capability to automate the fast-switching system at HIAF was implemented for the first time. A series of manual and automated measurements using plutonium isotopes show much longer counting periods allowed by this automation significantly improved the statistical precision in the data, and hence the sensitivity of the system.



Part of the time-of-flight detector at ANU during removal to allow modifications to reduce signal noise.

LHC research program

Nodes invovled: UoA, UoM

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

Postdocs: H. Potti, J. Oliver, A. Sharma

Students: M. Amerl, I. Carr, E. Filmer, C. Grant, A. Kong, J. Kull, H. Pandya, T. Ruggeri, E. Ting, J. Webb, S. Williams

The Centre provides an opportunity to search for dark matter direct production at a unique facility in the world, namely the experimental environment provided by the 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. Centre researchers focus their attention on several aspects of the search for dark matter with ATLAS, aiming to find evidence of Standard Model particles produced in conjunction with a signature of missing energy, which it is postulated would be carried away by the dark matter candidate(s).

Centre researchers have focused on analyses searching for evidence of hadronic jets produced in association with a significant amount of missing transverse momentum with a particular focus on jets that have been tagged as originating from charm-quarks. These analyses, referred to colloquially as tcMET and ccMET, are sensitive to models of Supersymmetry or other beyond Standard Model theories that pair produce 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 converging, with leadership from Centre researchers and we await the results.

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 it is important that we keep a keen eye on the long-term health and productivity of the detector. 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 testing and quality assurance steps.

ITK module construction at the UoM silicone clean room.

theory research program

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

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

Postdocs: M. Baker, J. Newstead, S. Robles, W. Su, X-G. Wang

Students: R. Abdel Khaleq, J. Allingham, R. Amintaheri, M. Deshpande, L. Friedrich, F. Hiskens, L. Hockley, N. Hunt-Smith, W. Husain, N. Krishnan, G. Lawrence, N. Leerdam, A. Leinweber, B. Li, W. McDonald, M. Mosbech, T. Motta, R. Patrick, Z. Picker, A. Ritter, I. Sanderson, A. Sopov, P. Verwayen, M. Virgato, J. Wood, A. Woodcock

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

Partner Investigators: P. Hopkins

In 2021, Centre theorists have been engaged in a wide range of research activities. This includes the construction of dark matter models, the evaluation of constraints on dark matter interactions arising from existing and future experiments, complementary constraints on dark matter interactions arising from astrophysics, improved calculations of dark matter scattering rates in direct detection experiments, and an evaluation of astrophysical uncertainties in dark matter direct detection rates. Some highlights of theory research undertaken in 2021 are described below.

Constraining dark matter with solar gamma rays

Nicole Bell and Isaac Sanderson, in collaboration with James Dent, considered the indirect detection of dark matter that is captured in the Sun and subsequently annihilates to long-lived dark mediators. If these mediators escape the Sun before decaying, they can produce striking gamma ray signals, either via the decay of the mediators directly to photons or via bremsstrahlung and hadronization of the mediator decay products. Using recent measurements from the HAWC Observatory, they determined model-independent limits on heavy dark matter that are orders of magnitude more powerful than direct detection experiments, for both spin-dependent and spin-independent scattering. They applied this technique to the well-motivated scenario in which fermionic dark matter annihilates to dark photons, enabling a previously unconstrained region of dark photon parameter space to be excluded.

Dark photons in deep inelastic scattering

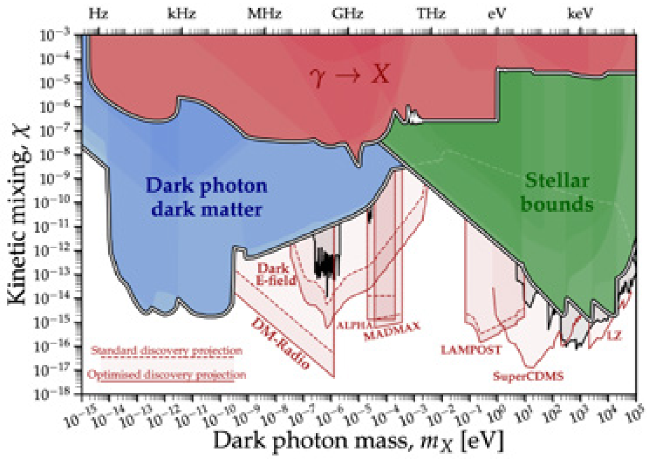
While the direct detection of weakly interacting massive particles is an area of very active investigation, the stringent limits from null experiments have motivated a number of alternative hypotheses for the nature of dark matter. In recent years, the dark photon has been receiving considerable attention, as a portal of interactions between dark matter and Standard Model particles.

The dark photon contribution to the proton structure function leads to non-Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (non-DGLAP) scaling violations, which were proposed as a smoking gun relevant for future experiments [G. D. Kribs, D. McKeen, and N. Raj, Phys. Rev. Lett. 126,011801 (2021)]. However, the parton distribution functions (PDFs) used in that work were from the best-fit results of the HERA analysis without consideration of the possibility of a dark photon. When examining the consequences of the addition of a dark photon, it is desirable to extract the PDFs from the data taking into account the changes which result from including the dark photon contribution to the scattering.

Anthony Thomas, Xuan-Gong Wang and Anthony Williams carried out an exploratory investigation of the dark photon parameter space constraints that arise from studies of deep inelastic scattering. A two-component model was applied to the proton structure function that incorporated vector-meson dominance (VMD) to reproduce the correct photo-production limit, in addition to including the dark photon. They found that the inclusion of the VMD contribution significantly improved the fit before the addition of the dark photon. Including the dark photon, and allowing variations in the goodness of fits to the extracted parton distribution functions, they derived constraints on the dark photon kinetic mixing parameter, as a function of dark matter mass, which are comparable to electroweak precisions limits [Phys. Rev. D 105, L031901 (2022)].

Dark photon limits: a handbook

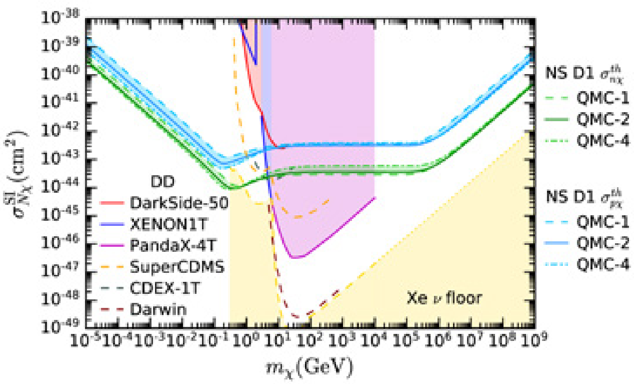
Dark photons kinetically mixed with the Standard Model photon can be searched for with many of the same techniques as axions. However dark photon dark matter possesses a fundamental property that axion dark matter does not— a polarisation. Ciaran O'Hare, in collaboration with Caputo, Millar and Vitagliano, 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].



The capture of dark matter in neutron stars

The scattering of dark matter particles with a neutron star can lead to the capture of dark matter in the star, and associated heating. The observation of cold neutron stars would therefore provide a way to set highly sensitive constraints of the strength of dark matter interactions with ordinary matter. A Melbourne-Adelaide collaboration of Nicole Bell, Giorgio Busoni, Theo Motta, Sandra Robles, Anthony Thomas and Michael Virgato made important improvements to the calculation of the dark matter capture rates, incorporating critical effects that were missing from all previous calculations. Specifically, they accounted for nucleon interactions and momentum dependent form factors, which were found to suppress the capture rate by up to three orders of magnitude [Phys. Rev. Lett. 127, 11803 (2021)]

In a follow-up publication, this work was extended to derive sensitivity projections for the dark matter scattering cross section. They found that the projected sensitivity for dark matter scattering on neutrons or protons greatly exceeds that of nuclear recoil experiments, for a wide dark matter mass range, for both spin-independent and spin-dependent scattering [JCAP 11 (2021) 11, 056].

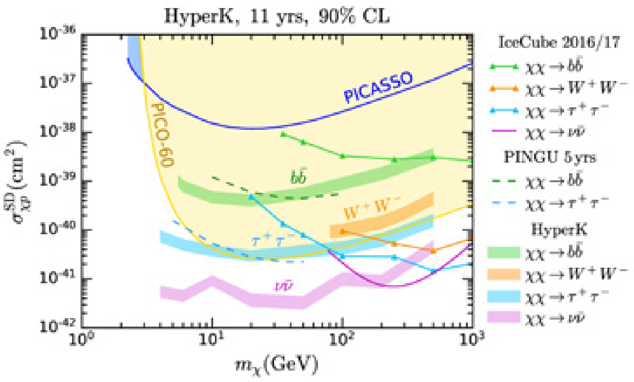


Dark matter effects on neutron stars

As neutron stars are expected to capture substantial amounts of dark matter, the study of the effects such matter might have on their properties is a potentially rich source of information on dark matter itself. Anthony Thomas and Wasif Husain explored the effects on the mass, radius and tidal deformability of a neutron star of both bosonic and fermionic dark matter. It is especially interesting that fermionic dark matter tends to form a halo around a star extending to many times the normal radius [JCAP 10 (2021) 086].

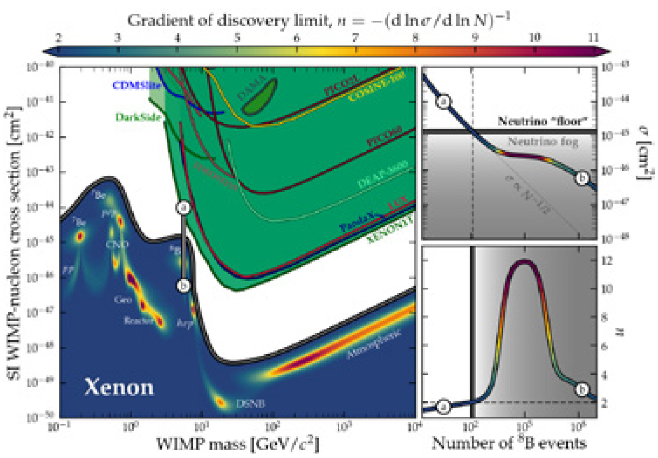
Searching for dark matter in the Sun using Hyper-Kamiokande

Nicole Bell, Matthew Dolan and Sandra Robles studied the ability of the Hyper-Kamiokande (HyperK) experiment, currently under construction in Japan, to constrain a neutrino signal produced via the annihilation of dark matter captured in the Sun. They simulated relevant neutrino event classes at HyperK, using Super-Kamiokande (SuperK) atmospheric neutrino results for validation. They found that HyperK will improve upon current SuperK limits on the dark matter spin-dependent scattering cross-section by a factor of 2–3, with a further improvement in sensitivity possible if systematic errors can be decreased relative to SuperK [JCAP 11 (2021) 004].



Venturing into the neutrino fog

The neutrino floor is the supposed ultimate sensitivity limit of direct searches for WIMPs, beyond which the unshieldable background of solar and atmospheric neutrinos will start to inhibit their ability to identify a signal, even if it were present. In recent years the language surrounding the neutrino floor has softened somewhat because it was realised that neutrinos do not completely prohibit dark matter discovery in this regime, only make it much more challenging. In other words rather than a neutrino floor, it is more accurate to refer to a neutrino 'fog'. Ciaran O'Hare proposed a new definition for the neutrino floor, that situates it at the 'edge' of this fog. The new limit is therefore placed on a more robust statistical basis than earlier definitions—one that reflects the true role that neutrinos will play in the upcoming generation of direct dark matter search [Phys. Rev. Lett. 127, (2021) 251802.]



Astrophysics uncertainties in dark matter direct detection

Uncertainties in the galactic dark matter spatial and velocity distributions may impact our interpretation of signals in direct detection experiments. Grace Lawrence and Alan Duffy investigated this topic, in collaboration with Chris Blake and Centre PI Philip Hopkins. Their paper, *Gusts in the Headwind: Uncertainties in Direct Dark Matter Detection* [submitted to MNRAS, Nov 2021], studies how the inherent fluctuations of dark matter around the Solar Circle of a simulated Milky Way analogue impacts predictions for terrestrial dark matter detectors, like SABRE. Across certain scales dark matter is not smoothly distributed, meaning that some variation in the dark matter environment around the Solar Circle is expected. Phase-coherent structures like stellar streams or debris flows have potential to cause strong impacts on the flux of dark matter through the Earth. This change in flux, and the consequent impact on rates of detection in direct detectors, was explored in this work using hydrodynamic simulations. It finds that high velocity substructure in the velocity distributions does not persist into the annual modulation predictions. The impact of the non-Maxwellian velocity distribution on annual modulation summary statistics, such as the peak day of annual modulation, is minimal, indicating that, to the precision of our measurements, the Standard Halo Model is an appropriate approximation.

Asymmetric dark matter

A clue to the particle nature of dark matter may lie in the observed relation $\Omega_{dark} \approx 5\Omega_{baryon}$ between the dark and ordinary matter mass densities, which in the cosmological context is a near equality. This is either a coincidence or a consequence of a common origin for both types of matter. The baryon mass density is the product of the baryon number density, which has its origin in baryogenesis (the matter-antimatter asymmetry), and the proton mass. A common origin would arise if the dark matter was distinct from dark antimatter and two other conditions held: there is a dark asymmetry related to the baryon asymmetry, and the dark matter particle mass is related to the proton mass. The latter requirement has had scant attention in the literature, and is the focus of ongoing work by Raymond Volkas and Alex Ritter. In 2021, they pursued the idea that there is a 'dark QCD' related to ordinary QCD by an interchange symmetry, with the dark matter particle being a stable 'dark neutron' that necessarily has a similar mass to the proton [Phys. Rev. D104 (2021) 3, 035032].

Eliminating the LIGO bounds on primordial black hole dark matter

Primordial black holes (PBHs) are usually modelled with the standard Schwarzschild metric—a spacetime that approaches flat Minkowski space at large distances. However in the early universe, if PBHs existed, they would have been influenced by the rapidly expanding background of space around them. Celine Boehm, Ciaran O'Hare, and collaborators, proposed the use of the so-called Thakurta metric for a proper evaluation of this scenario, since it stands out among its alternatives as the only option free of pathological issues. They discovered that 30-100 solar-mass primordial black holes modelled with the Thakurta metric generate far fewer observable merger events than previously thought. This means that the stringent LIGO bounds set under the assumption of a specific rate of early-universe merger events no longer apply—opening up the possibility that a sizeable fraction of the DM could be in the form of LIGO-mass black holes [JCAP 03 (2021) 078].

Dark matter and black holes from cosmological phase transitions

Following the non-discovery of supersymmetry at the TeV scale at colliders and of supersymmetric dark matter at direct and indirect detection experiments, theorists are now considering a much wider variety of possible dark matter candidates and production mechanisms than the canonical WIMP. Filtered dark matter, proposed by Michael Baker and collaborators, is a new mechanism where dark matter is produced during a first-order cosmological phase transition. This mechanism can give a viable dark matter candidate up to much higher masses than the standard freeze-out picture, motivating experiments to more seriously consider these high-mass regions. In 2021, Michael and collaborators showed that this new dark matter production mechanism can also be tweaked to give a new production mechanism of primordial black holes [arXiv:2110.00005; arXiv:2105.07481]. Future work will extend these calculations to predict the PBH mass distribution, and explore observational tests in collaboration with Alan Duffy at Swinburne.

Inelastic dark matter

Inelastic dark matter is a well-motivated scenario in which the dark-sector particle spectrum includes two states of almost degenerate mass. The characteristic feature of these models is that the scattering of dark matter off baryonic matter is possible only via inelastic scattering to the higher (or lower) mass state. Depending on the cosmological context, the relic dark matter that makes up the galactic halo may be in the lighter state, or a mixture of the lighter and heavier state. Nicole Bell, Jayden Newstead, and collaborators, extended the formalism of two low-mass dark matter search strategies to include inelastic scattering: the Migdal effect and cosmic-ray dark matter. In both cases, they found that significant parameter space is accessible and can be excluded by current experiments.

Migdal effect

Bell and Newstead found that using the Migdal effect, searches for the inelastic scattering of low-mass dark matter at direct detection experiments have degeneracies between the dark matter mass and the mass splitting that are difficult to break. Using XENON1T, data they set bounds on a previously unexplored region of the inelastic dark matter parameter space. For the case of exothermic scattering, they found that the Migdal effect allows xenon-based detectors to have sensitivity to dark matter with O(meV) mass far beyond what can be obtained with nuclear recoils alone [Phys. Rev. D. 104, 076013 (2021)].

Cosmic ray boosted dark matter

Cosmic rays can upscatter halo dark matter to significant energies, giving direct detection experiments access to previously unreachable regions of parameter-space at very low dark matter mass. Conventional direct detection of non-relativistic halo dark matter is limited to mass splittings below about 10 keV and is highly mass dependent. Bell and Newstead found that including the effect of cosmic ray upscattering can extend the reach to mass splittings of order 100 MeV, and maintain that reach at much lower dark matter mass [Phys. Rev. D. 104, 076020 (2021)].

research activity plan for 2022

WIMP Direct Detection:

SABRE South:

- Construction and assembly of SABRE
- Commissioning of the experiment
- SUPL environmental long-term background measurements
- Finalisation of the technical design report and white paper theory experiments

R&D Cygnus:

- Further develop the CYGNUS-1 prototype readout and low pressure capabilities
- Measurements of the light/charge yield of various candidate TPC gas mixtures, including with negative ion gas SF_6
- Develop event reconstruction capability with a focus on particle ID
- Migdal effect background studies

R&D new directions:

- Investigate the potential of a superfluid dark matter detector based on recent progress in superfluid optomechanics
- Improve the sensitivity of a microwave cavity to probe excitations in bulk superfluid
- Design and construct a superfluid-filled microwave crystal Whispering Gallery Mode cavity
- Construct and run a superconducting granule-based detector and characterise its sensitivity to cosmic rays

Axion and WISP Direct Detection:

- ORGAN Phase 1b implementation and R&D on quantum technologies and cavity resonators for ORGAN Phase 2
- Complete second UPLOAD data run and R&D towards future cryogenic implementations
- Investigate low-mass axion detection experiments to increase the range of axion masses covered
- Continue with ADMX sensitivity calculations, data analysis and simulations and modeling for future high and low mass extensions
- Improve existing Scalar DM detection experiments and extend their scope to search for WIMPs and gravitational waves

Precision metrology (nuclear):

- Investigate integration of fast isotope switching system for the time-of-flight detection equipment
- Install and test new low background germanium detector system at SUPL
- Progress ICP-MS measurement sensitivity

LHC:

- Probe dark matter sensitive final states with novel new approaches
- Develop techniques and tools to improve the performance of object reconstruction throughout LHC Run 3 (2022-2025)
- Continue work on the construction, testing, and deployment of modules for the inner track upgrade

Theory:

- Theorists and experimentalists across the Centre are currently collaborating on a SABRE white paper, which will identify dark matter scenarios that can be tested at SABRE and provide an assessment of the expected sensitivity reach. For example, the impact of uncertainties in the dark matter halo model will be examined. We will also consider applications of the SABRE detector to probe other novel physics questions, such as tests of fundamental quantum mechanics
- Continue calculations to demonstrate the feasibility of a Xenon-based Migdal calibration experiment and working on refining Migdal calculations
- Continue efforts to better understand and quantify the impact of nuclear structure on direct detection
- Continue theory experiment collaboration for future dark matter direct detection experiments

SUPL update

The Stawell Underground Physics Laboratory (SUPL) construction made significant progress in 2021 despite lockdowns and construction restrictions, with Ballarat's H Troon Pty Ltd appointed the head contractor responsible for the construction of the laboratory.

The crushed rock sub-base and concrete slab were the first major works to be completed early and involved significant material testing to ensure that materials did not exceed the radiation levels required for the SABRE experiment. Tekflex, a spray on liner was then applied to the walls and ceiling of the main cavern. Structural steel and partitions, plumbing and electrical services were also installed. The 9m high gantry crane at the top of experimental hall, pictured spanning the width of the cavern, will be used to lift key components of the SABRE experiment and has a weight limit of 10 tonnes.

Final fit out and commissioning of the laboratory will occur in early 2022 and SABRE construction will begin shortly after.

In September, SUPL announced the appointment of Dr Sue Barrell as incoming chair of the SUPL Board. Sue is an accomplished executive and leader committed to delivering valued outcomes for society and the environment through science, technology and data.

SUPL Ltd, the company that will be responsible for SUPL operations, was officially registered in November. The founding members of the company are also the collaborators that are part of the SABRE experiment; Australian National University, The University of Adelaide, Swinburne University of Technology, The University of Melbourne and ANSTO.

"We are looking forward to taking our equipment down into the laboratory and starting to collect data that we hope will help us understand the nature of dark matter. It is incredible to think that what was once a cavern will be a fully functioning physics laboratory."

Elisabetta Barberio

"SUPL will also enable Australian scientists to expand the horizons of fundamental physics knowledge through the development and use of ultra-sensitive detectors and experimental techniques, which will offer new and innovative opportunities to Australian industry. And SUPL, located deep within the Stawell Gold Mine, is also the perfect vehicle for teaching the next generation about how exciting and seriously cool science can be!"

Sue Barrell
SUPL Ltd Chair

Alan Duffy and Phillip Urquijo filming with The Project in the SUPL experimental hall.

translation – focus on innovation

The Innovation Lab is part of CDM's translation portfolio, using design methods and innovation mindset to explore new ways that fundamental science from the Centre can positively impact society.

Bringing a culture of innovation and creative problem solving, the Innovation Lab identifies and develops opportunities to demonstrate the commercial and/or societal potential of fundamental science, while building capability in the future workforce with skills to innovate with deep technology. Activities commenced in 2021, offering members the opportunity to participate in workshops and mentor teams of innovation, with students working on projects that explore deep technology solving United Nation Sustainable Development Goals (UN SDG).

The first workshop powered by the Innovation Lab offered members insight into the value that design innovation can offer fundamental science, by translating technologies from experimentation into everyday products, services and systems. However, this becomes challenging if disciplines that practice design innovation can't sufficiently appreciate the capability offered by a technology due to technical jargon. The workshop ran an exercise using a template to guide CDM members to break down and chose words to explain their area of expertise to someone new (e.g. how would you explain your knowledge in one or two sentences to an elite sports person, 10-year-old, nurse, etc.). Outcomes from the exercise are useful not only to support design innovation, but build capacity in science communication and outreach.

The second workshop powered by the Innovation Lab was in conjunction with the Equity, Inclusivity and Diversity team, to support engagement around the recently launched training modules available to CDM members. A task was devised to facilitate discussion around exclusion, assumptions and unconscious bias – considering consequence and ways of avoiding specific scenarios. CDM members from all nodes participated, discussing their examples as part of the Centre's Annual Meeting.

The 2021-2022 edition of the international student program, Challenge Based Innovation (CBI) A3, integrated CDM capabilities into the collaboration mix along with CERN and ANSTO, enriching the ecosystem of deep technology related expertise. In this CBI A3 edition, three teams of students in Australia and Germany have identified challenges associated with UN SDG 15 Life on Land to tackle, such as urban food production, fertilization-based pollution and naturalisation of soil. CDM researchers, such as Phillip Urquijo, are providing mentorship to these interdisciplinary teams of students, sharing expertise that helps identify appropriate ways to use imaging, detecting, AI or data computing related deep technologies in their design work.

Halo Hero 4-3" - a student project at CBI A3

equity, diversity and inclusion

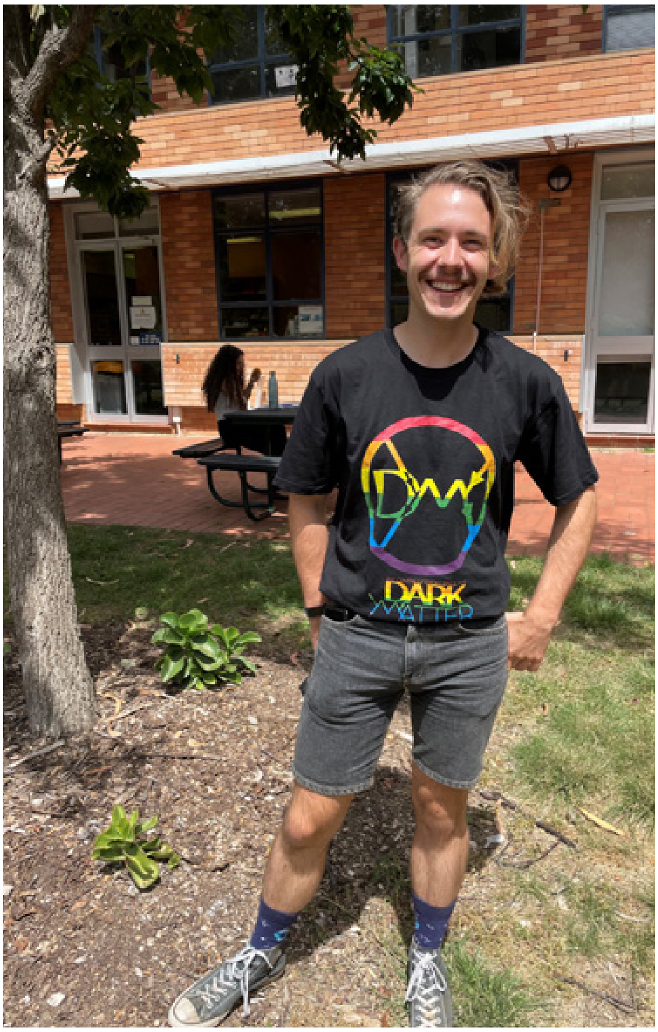
The objectives of the Equity, Diversity and Inclusion (EDI) portfolio are to improve gender balance in STEM, support families and carers, inspire a new, more diverse generation towards STEM and build a culture of respect and inclusion. Although these missions span the lifetime of the Centre, concrete actions were kicked off in 2021 (the first full year of the Centre) with a focus on raising awareness and training of Centre members on EDI issues.

The SBS Inclusion program has been selected as one of our primary supports for EDI training. 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 focussing on gender issues (which is particularly relevant in physics) was selected. The online training is open to all members of the Centre from Honours students to professional staff and CIs. A total of 124 members registered to undertake these modules in 2021. Following feedback on these modules, others addressing issues on culture, indigenous, LGBTIQ+, age and disability will be provided in 2022.

Centre members were able to consolidate some of the concepts from the training and exchange and brainstorm ideas around inclusion at a dedicated workshop. Associate Investigator Christine Thong led the session which commenced with the introductory video to the SBS program. Case studies about the impact of exclusion, assumptions and unconscious bias were put forward and participants were encouraged to individually reflect upon each case. they then discussed them in groups, and brainstormed ideas that could be implemented at the level of the Centre.

With an EDI committee in full momentum, several projects have matured in 2021, such as EDI academic papers discussed at local journal clubs as well as a CDM logo with the pride rainbow (see photo). Ambitious new projects will also keep Centre members busy in 2022, including a fellowship to support early career female leaders, diversity summer scholarships to students, and interviews of academic leaders with diverse backgrounds on our website.

As outlined in the proposal, the Centre has committed to through its node universities at ANU and the University of Sydney, two female only continuing academic appointments. As with many new positions, COVID has delayed the recruitment process, however the easing of restrictions meant that the position at Sydney was adverstised in late 2021 and recruitment is pending. The position at ANU has been approved and will be advertised in 2022. In addition, the University of Adelaide has also created a new female only continuing postion that will be advertised in 2022.



Lachlan McKie wearing the Centre's rainbow logo tshirt.

media and communications

The Centre's communications activities are built around the key communications objectives that aim to support the Centre mission. They are:

- To generate excitement about Australia's role in the search for dark matter
- To inspire and nurture the scientists of the future
- To promote diversity in science, especially gender diversity
- To build the profile of Centre researchers
- To develop a strong and effective research community within the Centre

In a focused effort in 2021 to target high profile media with broad audiences, the Centre attracted significant media coverage via some of Australia's most popular programs and outlets, raising the profile of the Centre and its members.

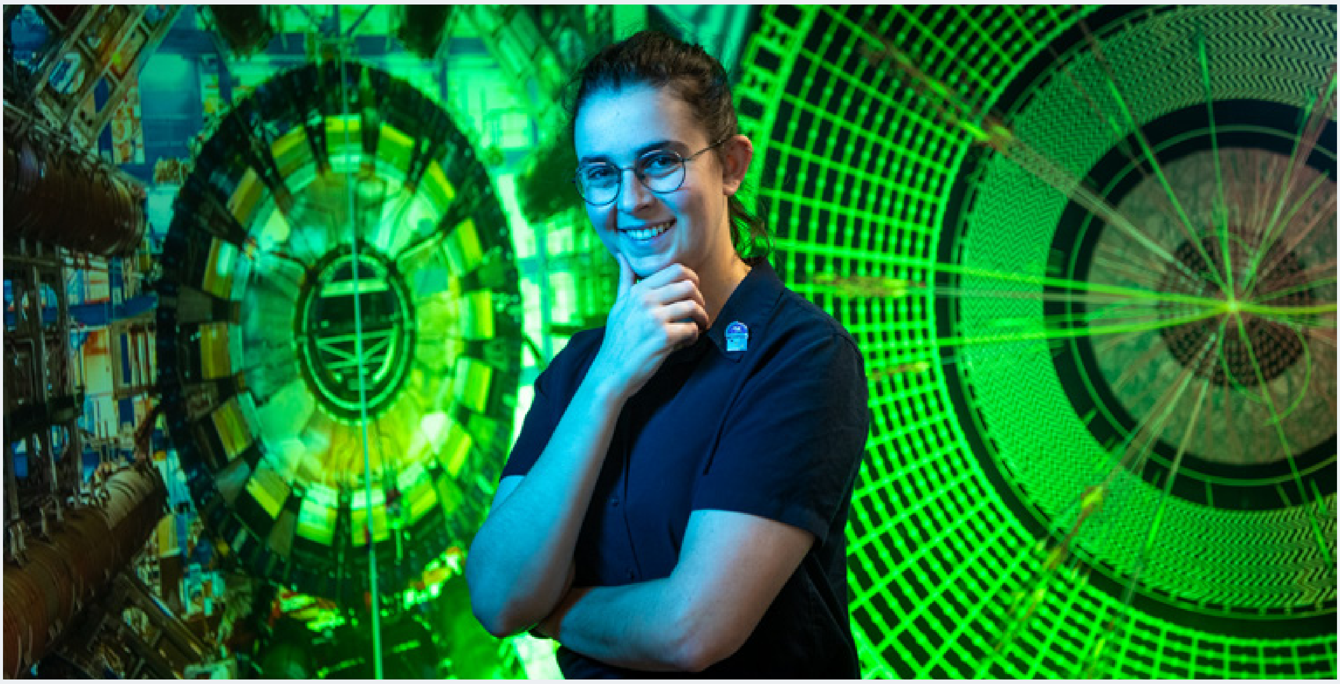
Channel 10's The Project introduced hundreds of thousands of viewers to the SABRE South experiment and Stawell Underground Physics Laboratory and was presented by Chief Investigator Alan Duffy, who interviewed fellow Chief Investigator Phillip Urquijo (see opposite page). SABRE South also appeared in a feature in The Age and The Sydney Morning Herald, and international readers were introduced to the project in The Guardian and NPR's Shortwave podcast. Centre events also attracted media attention, with Dark Matter Day, the Centre Launch, National Science Week activities all featuring interviews with Centre members on ABC Radio.

The Centre also provided students and ECRs with the opportunity to gain media exposure and experience throughout the year. In addition to connecting researchers with media opportunities, Communications and Media Officer, Fleur Morrison also assists in their preparation for interviews. PhD student Madeleine Zurowski (pictured below) was featured in a print and online article talking about her research in the MyCareer section of The Age and The Sydney Morning Herald. She also appeared with fellow PhD student William Melbourne on ABC Wimmera to promote their National Science Week presentation.

Alongside these mainstream channels, the Centre's research reached the scientific community through appearances in scientific publications including Cosmos Magazine, New Atlas and Space Australia.

In addition, Centre members conducted numerous radio interviews with over half on regional programs across Australia.

These media opportunities introduced new audiences to Australia's role in the global search for dark matter, encouraged young people to consider a career in science, introduced audiences to the diverse faces of physics, and provided Centre members with opportunities to build their public profile and gain media experience.



Social media

The Centre has Twitter, Facebook, LinkedIn and Instagram accounts. Twitter mainly reaches an academic audience, LinkedIn appeals to a professional audience and Facebook and Instagram reach a mainstream audience.

These channels aim to celebrate the successes of Centre members, promote research at the Centre, inspire the scientists of the future and generate excitement about Australia's role in the search for dark matter. There is also a strong focus on diversity and inclusion, for example we celebrated International Day of Women and Girls in Science with a series of social media posts featuring remarkable women who study or work in the CDM.

Audiences and engagement on each of the channels are steadily increasing since the beginning of the Centre in 2020 and this growth has been consolidated in 2021.

Internal communications

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

It also aims to build cohesion between Centre members through the use of headshots and profiles about members at different stages of their career.

Researchers communicate informally across the nodes via SLACK, using different channels for research, outreach and ECR activities.

The Centre uses the Atlassian collaboration software Confluence to coordinate meeting agendas, store and share documents and technical information.

media highlights

News

The Project, December 2021

"Aussie mission to crack dark matter mystery"

The Guardian, 10 October 2021

"Waiting for a ghost"

"To study the stuff of the universe, you have to block it out, and that is exactly what a bold project in regional Victoria is trying to do"

The Age/Sydney Morning Herald, 14 August 2021 – 40,000 distribution

"Painted white and bathed in floodlights, it has the quality of an underground cathedral."

Cosmos Magazine, 20 August, 2021

"Genius lair: Australia's dark matter experiment underfoot"

SMH/The Age, October 15, 2021

"Burying vital physics study can only shed light"

Genius lair: Australia's dark matter experiment underfoot

By Jacinta Bowler / 13 August 2021

Credit: The ARC Centre of Excellence for Dark Matter Particle Physics.

social media highlights

Twitter

164,570 Impressions

Most popular tweet

Today we celebrate the launch of the Centre. We're thrilled to join the world-wide search for #darkmatter and thank the national and international partners who are sharing this journey with us. @ANSTO @Sydney_Uni @ UniofAdelaide @uwanews @ANUmedia @UniMelb @Swinburne @arc_gov_au

8,371 impressions, 155 engagements

13X Follower increase from January – December (+343)

Support the Guardian
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The Guardian

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Australia news

This article is more than 6 months old

'Waiting for a ghost': the search for dark matter 1km under an Australian town

To study the stuff of the universe, you have to block it out, and that is exactly what a bold project in regional Victoria is trying to do

Tory Shepherd

Facebook

52,109 Reach

Instagram

37,595 Reach

Most popular post
It was wonderful to visit the site of the Stawell Underground Physics Lab with @SciMelb Dean Moira O'Bryan. We were dwarfed by the space where our research into dark matter will happen. Thanks for the tour and your hospitality Stawell Gold Mines.

2,149 impressions, 198 reactions

LinkedIn most popular post
Our search for #darkmatter is capturing international attention. It's wonderful to see others getting as excited as we are about the groundbreaking research happening in regional Victoria.

1,349 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 2021, in-person activites were still limited but there were plenty of opportunities to engage with school students, teachers and the general public.

Pilot of Schools Program: Using Dark Matter Inspired Science to Engage Rural and Regional Students

A core component of the Centre's education program is the development of long-term engagements with regional schools across our node states. The goal is to meet with students at all year levels over multiple years at select regional and rural schools with the goal of increasing diversity in science by creating more pathways for student engagement. It also provides the opportunity to bring the Centre's ECRs into the classroom to meet with large groups of students. In 2021, the Centre developed the interactive lessons and piloted the curriculum-aligned education activities at Stawell Secondary College in Stawell, Victoria, home of SUPL. This program was piloted in collaboration with the science teachers at Stawell Secondary, who provided valuable feedback related to student understanding of and engagement with the dark matter-inspired lessons. Using this feedback, the Centre will edit and enhance these lessons and expand to more partner schools in 2022. Additionally, the Centre entered a collaboration with the Melbourne Graduate School of Education to study the impact of these contemporary physics lessons on students' science identity.

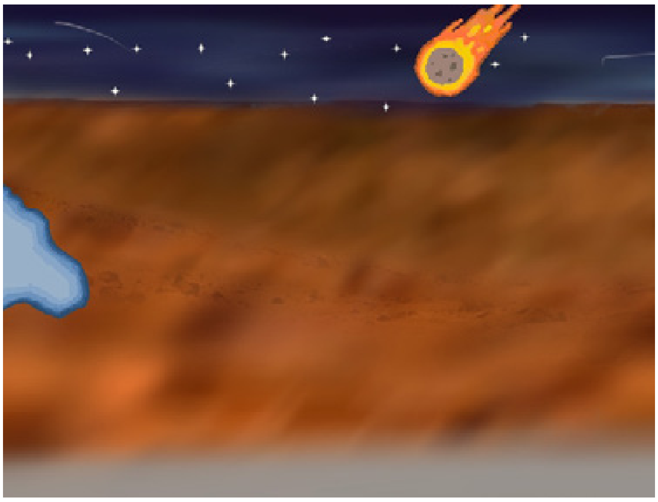
Train the Trainer: Bringing Dark Matter Science to Secondary Teachers

In 2021, the Centre hosted workshops related to using dark matter-inspired science in their classrooms. Taking advantage of virtual formats, the Centre's Education and Outreach Office Jackie Bondell hosted workshops for the State Science Teachers of Victoria's Annual Conference, the AIP-sponsored Physics Teachers Workshop in Hobart, and the Polar Star Educators program led from Athens, Greece. In December, Jackie and the principal of Stawell Secondary, Carlos Lopez, presented an in-person workshop as part of the Quantum Victoria STEM Education Workshop. In all, these programs introduced over 100 teachers worldwide to the Centre's science and education programs.

Harnessing Creativity with Science-Art programs

Creativity is one of the most important qualities for scientists at the leading edge of innovation. The Centre harnesses this idea in a variety of programs and collaborations that use science concepts to inspire the arts. PhD student Raghda Abdel Khaleq incorporated her love of art and science to design a lesson, with both written and video instructions for teachers, that encourages students to use light to create projected artworks. The lockdown thwarted the centre's planned in-person delivery of this activity to students and teachers, but it is part of the 2022 plans. The Centre also hosted its first student art competition in November. For the 'Mystery Matter!' competition, students in year levels Prep-9 submitted works reflecting on the hunt for dark matter with the prompt 'what do you wish existed and why?' The three student age group winners came from three separate states and won gift cards for themselves and their teachers!

Spencer (Vic) - Prep-2 winner's portal to a multiverse that has a planet called "Mass-ive" in it. It is made up of heavy masses that accounts for the unidentified dark matter. On the planet mass-ive there lives lots of happy aliens.



Deema (NSW) - Year 6-8 winner's game that she built with digital drawings that allows the user to move around a tiny fragment of a parallel universe.

The Learning Doesn't Stop During School Holidays!

The Centre recognises that the school holidays present unique opportunities to engage with enthusiastic youth interested in learning more about science. In 2021, the Centre hosted school holiday activities as part of both local and Australia-wide initiatives for students of all ages. In the January holidays, the Centre hosted a session for up to 100 students for the National Youth Science Forum Year 12 program related to dark matter and Australia's role in the search for it. In the April and October school holidays, we hosted multiple sessions for campers at the YMCA Canberra's Space Squad Program. Finally, in July, we presented a series of hands-on activities for 'Dark Science Day' at Casey Tech School in Berwick, Victoria.

Erine (ACT) - Year 3-5 winner

dark matter art

Art and science might seem to be odd bedfellows, but that is not the case for PhD student Raghda Abdel Khaleq. Describing herself as an artistic physicist, Raghda combines her creativity with her scientific knowledge to produce science-inspired art.

In Raghda's Painting with Light photography series (see opposite), she has created beautiful, vivid pieces using her knowledge and understanding of physics to take pictures of the effects of refracted light projected onto a dark wall. She has also shared this passion for art and physics with secondary school students who have had the opportunity to try their hands at creating their own science-inspired artworks through the Centre's Outreach program.

Raghda's own interest in art was ignited as a child, while it was only later that she developed a passion for physics. "My mother loved to paint and draw and my sisters and I also liked to draw. In high school, I had a teacher that was really encouraging and allowed me to stay inside at lunchtime and recess to work on my art. Then in years 9 and 10 we had a physics unit and I really started enjoying science. I was a bit of a late bloomer, but again, I remember having a really supportive teacher who answered all my questions."

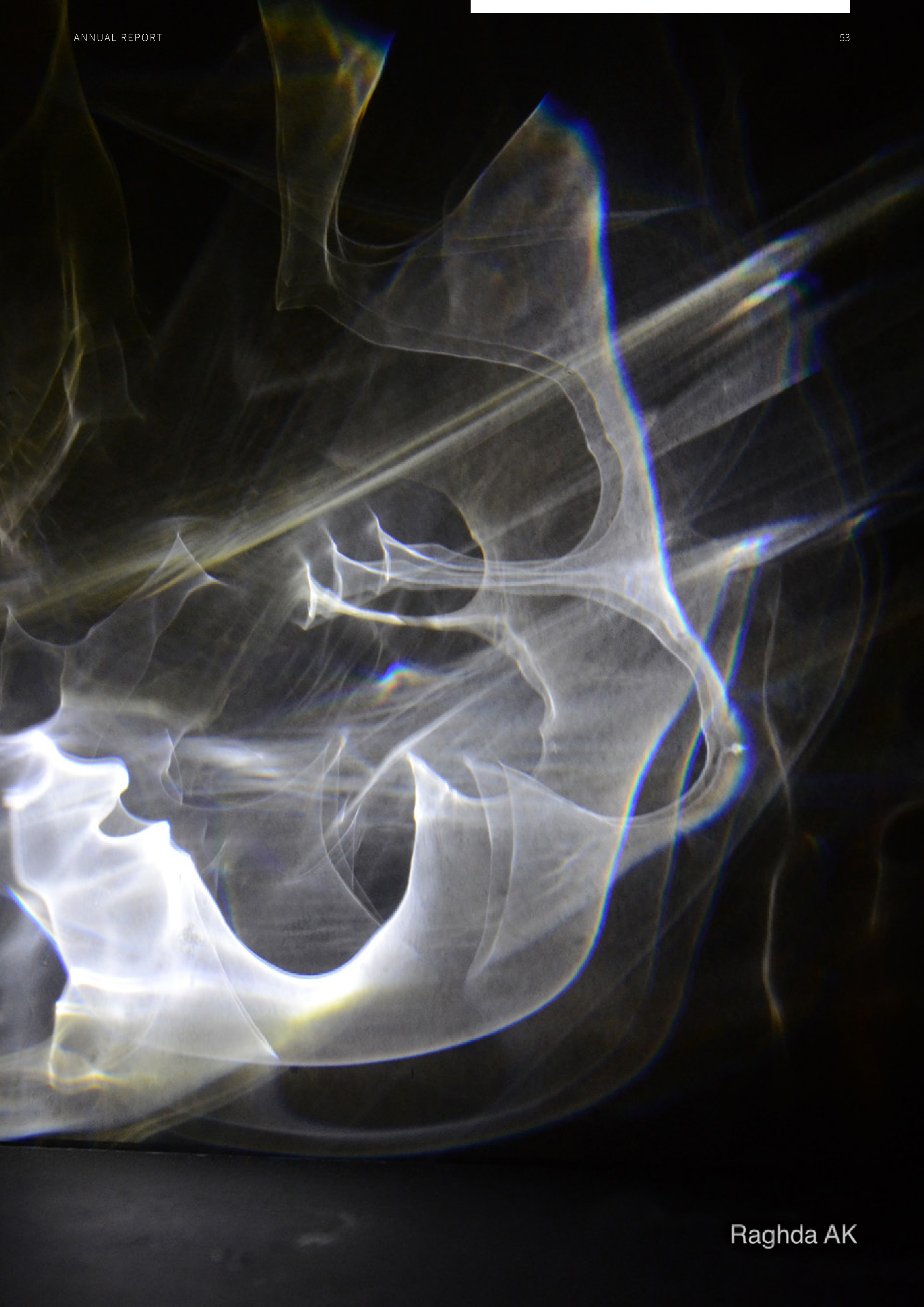
She says it is important for school students to see the interdisciplinary practices at play, and she is looking forward to sharing her passions with the artists and scientists of the future.

"These activities bring creativity and experimentation to science education and I hope that my art will stimulate their curiosity and lead to discussions about the science that inspired it. If I can also encourage women – or any students – to consider careers in STEM, that would also be a good thing."

Science Gallery Melbourne

Exploring the collision of art and science, Science Gallery Melbourne is part of the acclaimed Global Science Gallery Network bringing a Southern Hemisphere flair to its innovative models of engaging 15-25 year-olds with science. The Centre has forged a partnership with Science Gallery Melbourne which kicked off in 2021 with the first interdisciplinary research and creative development residency round open for applications. In partnership with Arts House, this is an opportunity for a First Nations artist or collective to work across Arts House, Science Gallery Melbourne and the Centre in a six-week residency to be undertaken in the second half of 2022.

Over six weeks, selected artists will be supported in the residency to develop their own research directions. The selected project will receive a project fee contribution and the residency will run for two weeks at Arts House and up to four weeks at Science Gallery, including opportunities to meet with leading academics and scientists of the Centre. The plan is to provide this opportunity annually during the life of the Centre.



Raghda AK

national science week

Centre members participated in a range of activities to promote science to students and the wider community during National Science Week 2021 in August. These included a mid-afternoon masterclass, a Dean's lecture and a road trip in Western Australia where a team of researchers visited schools and the community to spread the word about dark matter.

The National Science Week events attracted media attention across Australia, with postdoc Ben McAllister interviewed on ABC Great Southern and Bunbury Community Radio and PhD student Madeleine Zurowski interviewed on Geelong's The Pulse radio stations and with William Melbourne on ABC Wimmera.

Masterclass introduces students and community to dark matter

Students across Victoria learnt about the work of the CDM during a National Science Week masterclass.

Centre students Madeleine Zurowski and William Melbourne talked about SUPL's role in exploring dark matter in a Mid-Afternoon Masterclass titled Lighting the Dark Universe. The webinar and live Q&A session was one of the week's showcase events during The University of Melbourne's Festival of Science held as part of National Science Week.

The event was broadcast to schools, and attracted members of the wider community interested in science. It was one of the most popular masterclasses held during the festival, second only to one which addressed COVID-19.

Road Trip spreads the word about quantum systems and dark matter

A team of researchers took to the road during National Science Week to introduce residents in the southwest of Western Australia to all matters quantum systems and dark matter.

The Centre researchers joined their counterparts from the ARC Centre of Excellence for Engineered Quantum Systems (EQUS) in the Quantum and Dark Matter Road Trip on their tour of schools and communities.

With funding from National Science Week Small Grants, EQUS and CDM, high school students and interested members of the public had the opportunity to be informed and entertained.

The team travelled to country towns in a 12-seater bus from UWA and spoke to students ranging from Year 7 to Year 12 over the five-day trip, as well as at a Community Fair at Newton Moore Senior High School in Bunbury.

"It's important that students understand what fundamental research looks like in practice so that they know that they can be part of this exciting area of study in the future. It is also beneficial for members of the community to gain an insight into the research that their public institutions are funding, so that they can understand its implications and potential."

William Melbourne

"The road trip was an awesome experience - getting out into regional and rural communities to spread the excitement and wonder of science was so rewarding."

"We were really pleased with the student response – everywhere we went the kids were engaged, and always had the kind of insightful questions that remind you how intelligent a switched on 14-year-old can be."

Ben McAllister

dark matter day

The 2021 Dark Matter Day built on the work carried out the previous year to celebrate the Centre's research and introduce more Australians to its search for dark matter.

Due to COVID-19 restrictions the event was again held online using the Gather.town platform.

This enabled members of the public to register their interest in attending and log in on the day to virtually explore talks by Centre researchers, tour the Centre's laboratories, including the Stawell Underground Physics Laboratory and attend a science/art workshop.

Centre researchers and students volunteered their time to host Q&A sessions, offer tours, present a workshop and record presentations for the day.

The event attracted 95 registrations and attendees included a range of ages who interacted online with Centre staff and each other. Some of the primary school aged children who attended were engaged and asking questions right up until the end of the session.

The event also attracted significant media attention, with event organisers, postdocs Michael Baker and Ben McAllister, interviewed on ABC Radio National with Patricia Karvalas, ABC Melbourne with Libbi Gorr, ABC Perth and ABC Western Australia, and articles appearing in The Stawell Times and The Canberra Weekly.

Dark Matter Centre Retweeted

Harish Potti @HarishPotti4 · Oct 31, 2021

I am bored of celebrating Halloween with regular pumpkins. Wouldn't it be cool if we have pumpkins made out of Dark Matter particles😲? That's one of my motivations to search for dark matter at the LHC with the @ATLASexperiment as part of @ARC_DMPP team.

Happy #DarkMatterDay

"It's incredibly exciting to be part of the search for dark matter. We know that there is something out there, and it is up to us to figure out what it is. The ARC Centre of Excellence for Dark Matter Particle Physics is a fantastic venture involving top scientists from around the country, and we can't wait to tell you about our work this Dark Matter Day."

Michael Baker

mentoring

The mentor scheme for students within the Centre is based on the realisation that our students are a precious asset. We aim to encourage each of them to develop to their fullest potential not only in their scientific research but also in important ‘soft skills’, including training in leadership, management, selling their ideas and themselves, intellectual property and commercialisation.

The program began in 2021 with more than 50 students assigned a mentor at a different node. All Centre Chief Investigators agreed to take part, with each taking responsibility for at least three students. While there wasn’t an opportunity to travel and meet in person with mentees, each mentor made contact with their assigned students and arranged meetings via Zoom.

Initial reactions have been overwhelmingly positive. We look forward to further feedback during 2022 and to the opportunity for in-person meetings. There are also plans for some mentoring seminars and workshops to coincide with Centre meetings.

Members of the Centre’s ECR Committee have been elected by their peers and are recognised for their leadership potential. In addition to representing their peers, and coordinating ECR focused activities, members of the ECR committee sit in on Executive and Research Committee meetings. This provides them with an opportunity to present updates to the relevant committees and to observe the way that the committees operate which aids in their development as future leaders.

Node members at the University of Adelaide.

training and development

The CDM is committed to the development of all of its members. In 2021, the Centre offered a range of training activities, many with a strong focus on equity, diversity and inclusion. These included:

- Confined spaces and working at heights training, specifically for work with the SABRE vessel
- Dark Matter lecture series (details below)
- Code of Conduct deployment (for all Centre members) and workshops in individual nodes
- SBS Inclusion Program (Gender and Core Inclusion modules)
- Understanding and building emotional intelligence – an interactive, mobile accessible module linked to the Centre's code of conduct and core values of Passion, Trust and Collaboration
- Education and Outreach activity at CDM Annual Meeting for all Centre members
- Exclusion, assumptions and unconscious bias activity at CDM Annual Meeting
- Innovation Lab - Research Impact preparation activity at CDM Annual Meeting
- Training on SABRE software framework

Dark Matter Lecture Series

Some of the Centre's ECRs initiated a fortnightly lecture series comprising lectures on dark matter theory and detection. These lectures provide a very pedagogical introduction to all aspects of dark matter physics covered by the Centre research themes and are primarily aimed at PhD students, newcomers to the field, or researchers working in disciplines that are the most distant from the topic being covered. The lectures are mostly provided in a whiteboard style, are recorded and a pdf copy of the notes are available afterwards to further share knowledge between Centre members. This series has provided speaking opportunities for Centre members and encouraged inter-node and inter-disciplinary collaboration between the Centre's ECRs. This has been particularly valuable in the establishment of the Centre during lockdown.

The Dark Chatter podcast on YouTube has also promoted the work of several Centre students. Dark Chatter is a series of informal chats between young scientists working on dark matter and other topics from astroparticle physics to cosmology. In recognition of his contributions to these activities, particularly in their initiation and promotion, Associate Investigator Ciaran O'Hare was nominated for and awarded the Centre's Collaboration and Centre Values award at the Centre's Annual Meeting.

Confined spaces and working at heights training

There weren't any white lab coats among the scientists taking part in confined spaces training that will enable them to work with, and in, the SABRE vessel that is to be installed in SUPL. Instead, the researchers wore harnesses to learn how to safely work on, in and around with the vessel.

SABRE stands at a height of more than two metres and the researchers' work may call for them to climb on top of or into the vessel to make adjustments to the detectors, place the reflective lining or alter the wiring.

Six students and researchers from the Centre have undertaken the training which centred on safety issues involved with working in small spaces as well as from a height.

"We were taught about different safety and procedural aspects, such as the proper use of harnesses and pulleys as well as procedures to eliminate (manage) hazards and risks, while working on top of (and inside of) SABRE," said Owen Stanley, one of the Centre's Masters students.

"It's really exciting to be part of this research, building something that could potentially change the way we see the universe. This training is the next step towards working on that research."



events

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

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

Events continued to be offered virtually due to the pandemic and where restrictions allowed, there were oportunities at some nodes for in-person attendance.

In February, a two day ECR workshop featured over 40 participants presenting their research to their peers and the Chief Investigators. There was also an opportunity for them to contribute to a discussion about their priorities as ECRs and also how they would best like to be represented in the Centre.

The Centre's official launch and Annual Meeting brought people together and are both profiled on the next pages.

Centre members also made a significant contribution to the 2021 Australian Institute of Physics Summer Meeting held as a hybrid event. As a part of its scientific program, there were a number of Focused Sessions consisting of invited talks by eminent speakers on cutting-edge research themes. The Focused Sessions were selected through a competitive process with Dark Matter Particle Physics being one of the selected session coordinated and chaired by Cedric Simenel, and Elisabetta Barberio gave the introductory talk. In total, 28 Centre members from all nodes gave presentations. Keynote and invited speakers from the Centre included Nicole Bell, Andrea Thamm, Mike Tobar and Raymond Volkas.

Sponsored by the Centre, CKM2021 was the 11th International Workshop on the CKM Unitarity Triangle, held in an online format hosted by the UoM. The CKM series is a well-established international meeting in the field of quark-flavour physics that brings together experimentalists and theorists to a common platform. It included searches for new phenomena in rare decay transitions involving dark sector particles that may feebly interact with ordinary matter. Centre members (led by Phillip Urquijo) assisted with assembling the program committee, finding speakers for plenary sessions and convenors for the working groups and managing the online aspects of the conference and proceedings. In total, there were 257 online participants and 150 presentations spread over 30 sessions.

There were many Centre researchers who gave invited talks, keynotes and plenary presentations at conferences and workshops throughout the year. Some highlights are:

The Snowmass process is a particle physics community planning exercise organised by the Division of Particles and Fields of the American Physical Society. It consists of a series of meetings and workshops which brings the entire particle physics community together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Scientists were invited to submit letters of interest about what they hoped the next decade of particle physics research would bring - over 1500 letters were submitted. Centre members Mike Tobar and Ben McAllister gave talks in the Wave-Like Dark Matter community meetings as part of the Cosmic Frontier (one of ten identified frontiers). Mike also provided input into two of the white papers written by the community as a result of Snowmass.

Hosted by Yongsei University, South Korea, the Asia-Pacific Workshop on Particle Physics and Cosmology 2021 took place online and brought together nearly 200 researchers working in the fields of theoretical particle physics and cosmology. The workshop featured several invited pedagogical review talks including from Celine Boehm on Dark Matter Cosmology. There were also many contributed presentations from students and early-career researchers, including four from the Centre, on a range of topics including dark matter.

The Embassy of Italy, the Italian Cultural Institute in Sydney and the Australian Academy of Science held 'An Italian Night with Five Southern Stars' in Canberra at the Shine Dome. Elisabetta Barberio was among five scientists invited to speak to the public at this event. Ambassador of Italy to Australia H.E. Francesca Tardioli opened the event.

centre launch

On 22 September 2021, the Centre was officially launched by ARC CEO Professor Sue Thomas. Like so many events in 2021, what was originally to be held as an in-person event was postponed several times and eventually held virtually. And to make the day even more memorable, a magnitude 5.9 earthquake happened in Victoria just prior to the commencement of proceedings!

CDM deputy director Cedric Simenel MC'd the event and the Centre was fortunate to also have guest speakers Professor Mark Hargreaves, Pro Vice-Chancellor (Research Partnerships & Infrastructure) on behalf of The University of Melbourne and Her Excellency Francesca Tardioli, Ambassador of Italy to Australia. The Embassy of Italy has been involved and supported the SUPL project since its beginning, and Her Excellency described it as, "a very successful story that shows the important role of science diplomacy in strengthening the links between countries".

In a short video screened at the launch, students and researchers of the Centre talked about why they are inspired by the search for dark matter, and what it would mean to them to be part of the discovery of this mysterious substance.

Sue Thomas said that, "the Centre is putting Australia into a leading position in the global quest to understand the fundamental question of "what is the universe really made of?" and that the Centre had "assembled a strong and diverse team of physicists from particle, nuclear and quantum physics as well as particle astrophysics".

Guests at the launch included members of the Centre's Advisory Board, collaborators from DSTG and ANSTO, representatives and collaborators from the Stawell Gold Mine, collaborators from Science Gallery Melbourne, Victoria's Lead Scientist, dignitaries from collaborating universities, colleagues from other Centres of Excellence and staff and students of the Centre.

annual workshop

With COVID-19 still limiting interstate travel, the Centre held its Annual Meeting in a hybrid format over three days at the end of November. The third morning was held jointly with the ARC Centre of Excellence for Engineered Quantum Systems.

The Melbourne and Swinburne nodes were able to meet at The University of Melbourne, while the Adelaide, Western Australia, Sydney and ANU nodes gathered in person in their respective states under COVID-safe conditions and joined virtually via Zoom.

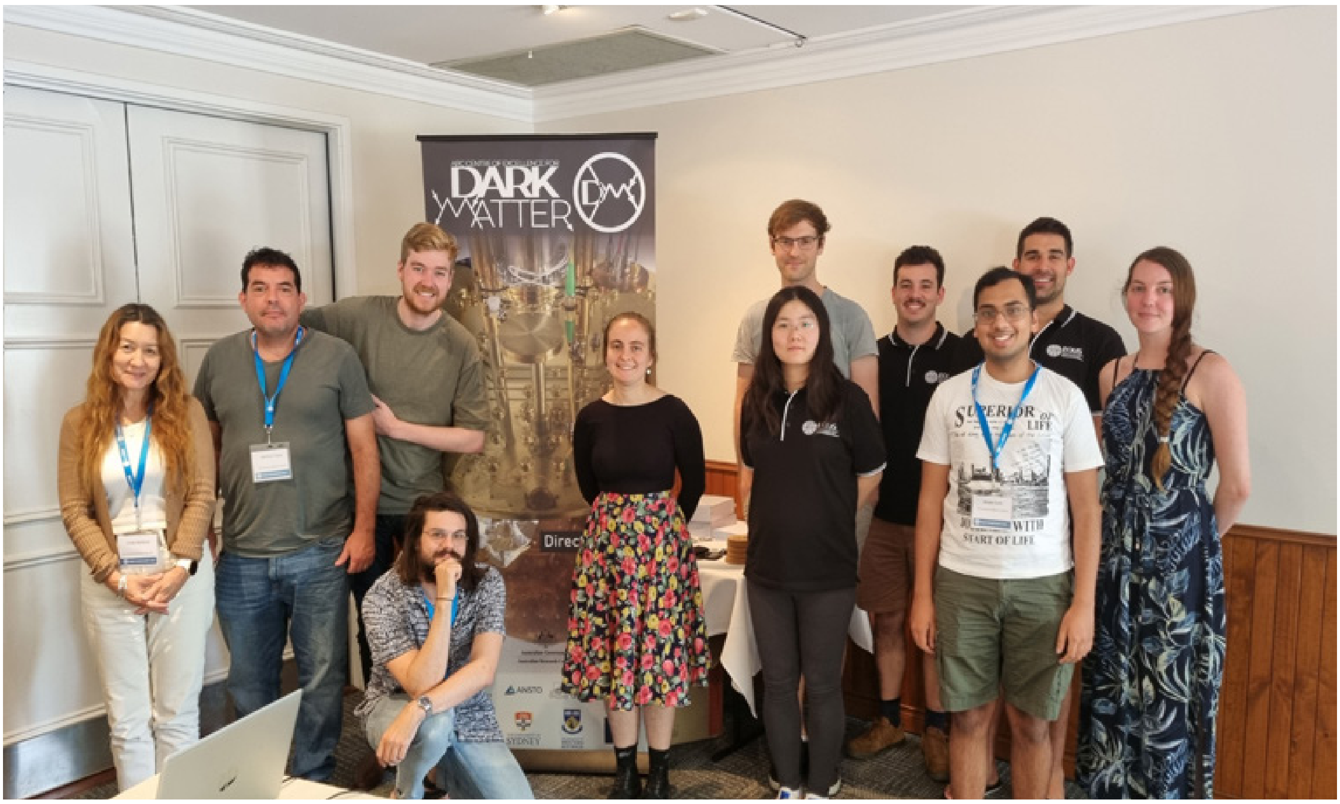
Opening with an introductory welcome from the Centre Director, Elisabetta Barberio, the three days included a selection of research talks spanning the Centre's research themes with an emphasis on Early Career Researcher presenters where possible.

Highlights included keynote presentations on low-mass dark matter detection from Noah Kurinsky from the SLAC National Accelerator Laboratory which generated discussion around the future directions of the search for dark matter, and Chelsea Bartram from the University of Washington with a presentation on wave-like dark matter in the ADMX Run 1C dataset.

There was a virtual poster session on the platform Gather where students and ECRs from across the Centre and research themes presented their research and interacted with other Centre members.

Associate Investigator Christine Thong, the head of the Innovation Lab at Swinburne University of Technology, guided members through an activity on increasing the impact of science.

Other sessions included a scientific activity that had been developed for school outreach, a talk on media and communications and a presentation on equity, diversity and inclusion with an introduction to the SBS training modules (Gender and Core Inclusion) made available to Centre members to complete. Attendees broke into groups to complete a worksheet focusing on the themes of exclusion, assumptions and unconscious bias. It provided an opportunity to address important discussions across the nodes and connect to some of the values outlined in the Centre's Code of Conduct. CEO of En Masse, Mark Dean, officially deployed the Code of Conduct and launched a module on Emotional Intelligence. The Early Career Researcher committee provided an ECR update including plans for 2022.



Some of the UWA node members

Advisory Board member Justin Zobel presented the inaugural Centre Awards, recognising four students and ECRs who had shown leadership, actively engaged in key Centre activities and exhibited the values that the Centre is striving to ensure become part of its way of operating.

Chair of the Advisory Board, Aidan Byrne, spoke about the establishment of the Centre and recognised the impact that the Centre will make on physics in Australia by building capacity and undertaking research of global importance.

Advisory Board member and SUPL Ltd Chair, Sue Barrell, gave a short presentation on making SUPL operational and how the Centre can work in collaboration with the company to advance physics research and achieve impact in outreach and other activities.

Centre Director Elisabetta Barberio shared her vision for the future of the Centre, well wishes for the end of the year and gratitude for all those involved. Although being able to come together in person is always preferable, the hybrid format was an overall success and provided many opportunities for Centre members to learn, share and interact with one another. Feedback from Centre members indicated that they were excited about the year ahead and hopeful of finally meeting in person.

CDM Collaboration and Centre Values Award

Ciaran O'Hare (UoS)

Madeleine Zurowski (UoM)

CDM Outreach and Impact Award

Raghda Abdel Khaleq (ANU)

Michael Baker (UoM)

Best Poster Award (panel vote)

Graeme Flower for the poster titled: *Choosing Dissipative Models for Josephson Junction based Single Photon Counters*

Best Poster Award (Centre member vote)

Madeleine Zurowski for the poster titled: *Influence of NaI background and mass on model independent tests of DAMA's modulation*

Some of the SUT and UoM node members

awards and prizes

Max Amerl (UoA)
Silver Bragg Medal (for best undergraduate GPA)
awarded by the University of Adelaide

Michael Baker (UoM)
European Physical Journal Distinguished Referee
awarded by the European Physics Journal

Elisabetta Barberio (UoM)
Fellow of the Australian Institute of Physics
elected by the Australian Institute of Physics

Elisabetta Barberio (UoM)
Thomas H Laby Professor of Physics
awarded by The University of Melbourne

Navneet Krishnan (ANU)
John Carver Physics Prize
awarded by the Research School of Physics,
Australian National University

Ben McAllister (UWA)
Forrest Prospect Fellowship
awarded by the Forrest Research Foundation

Ben McAllister (UWA)
Rising Stars 2021 Award
awarded by The University of Western Australia

Theo Motta (UoA)
Alexander von Humbolt Fellowship
awarded by the Humbolt Foundation

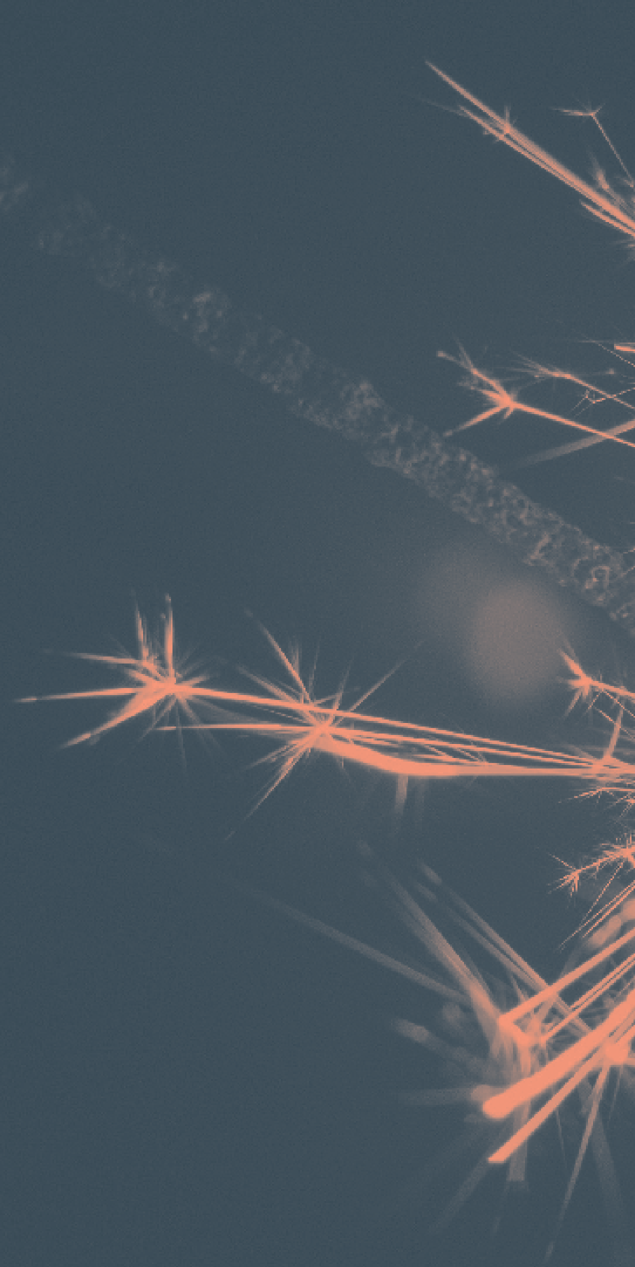
Anna Mullin (UoA)
Gates Cambridge Scholarship
awarded by Gates Cambridge

Catriona Thomson (UWA)
2021 Best Student Paper Award for the paper titled:
Using Precision Frequency Metrology for Dark Matter Searches
awarded by the EEFT-IFCS

Michael Tobar (UWA)
Distinguished Lecturer for Frequency Control
awarded by the IEEE Ultrasonics,
Ferroelectrics and Frequency Control Society (UFFC)

Madeleine Zurowski (UoM)
Dr Jean Laby Women in Physics Travel Award
awarded by the Laby Foundation

Ciaran O'Hare (UoS)
ARC DECRA project that aims to connect the particle and astrophysics of dark matter, to accelerate us towards its first detection in the lab.
awarded by the Australian Research Council



student completions

Honours:

Kenn Goh (UoA)

Kyle Leaver (UoA)

Jesper Leong (UoA)

Bill Loizos (UoA)

Hitarthi Pandya (UoA)

Harry Wyatt (UWA)

Masters by Coursework:

Will McDonald (UoM)

Jay Mummery (UWA)

Katerina Patsis (UoM)

Alexander Sopov (UoM)

Joshua Wood (UoM)

MPhil

Anna Mullin (UoA)

PhD:

Leon Friedrich (UoM)

Shanti Krishnan (SUT)

Theo Motta (UoA)

Riley Patrick (UoA)

Shahinur Rahman (ANU)

Isaac Sanderson (UoM)

key performance indicators

Performance Measure	Target 2021	Actual 2021
1 Number of research outputs		
• Journal articles	30	91
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	2	1
International conferences	1	1
4 Number of training courses held/offered by the Centre		
Professional training/development courses offered by the Centre	3	3
Number of Centre attendees at all professional training/development courses offered by the Centre	15	27
Culture Building/Be Your Best Training	2	4
Innovative Thinking training (Innovation Lab)	1	2
5 Number of additional researchers working on Centre research		
• Postdoctoral researchers	10	4
• Honours students	8	8
• PhD students	10	16
• Masters by research students	1	1
• Masters by coursework students	10	6
• Associate Investigators	7	7
6 Number of postgraduate completions		
PhD	0	6
Honours/MSc/MPhil Completions	10	12
7 Number of mentoring programs offered by the Centre		
Mentoring programs	3	1
Industry/ External internships for PhDs	3	2**
8 Number of presentations/briefings		
• To the public	15	18
• To government (parliamentarians and department/agencies at both State and Federal level)	5	10
• To industry/business/end users	5	9
• To non-government organisations	n/a	n/a
• To professional organisations and bodies	5	6
News stories	10	47
Press releases	8	7
9 Number of new organisations collaborating with, or involved in, the Centre		
International	2	2
National	1	1
10 Number of female research personnel		
Female	>25%	24%
11 Centre-specific KPIs		
Number new of Continuing/Tenure Track Positions in Centre nodes seeded by the Centre	3	3*
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)	2	2*
School visits or webcasts	30	32
Number of invited talks/papers/keynote lectures given at major international meetings (including those held in Australia	20	39
Centre's Dark Matter Prize for high school students (# entries)	25	10

*One position advertised in 2021 at UoS, two positions approved at UoA and UoM that will be advertised and appointed in 2022. The UoA and UoS postions are female only.

**Two PhD students have commenced projects with DSTG.

publications

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ATLAS Collaboration

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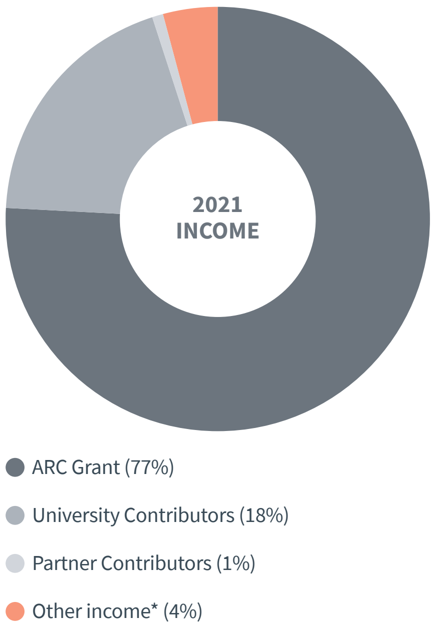
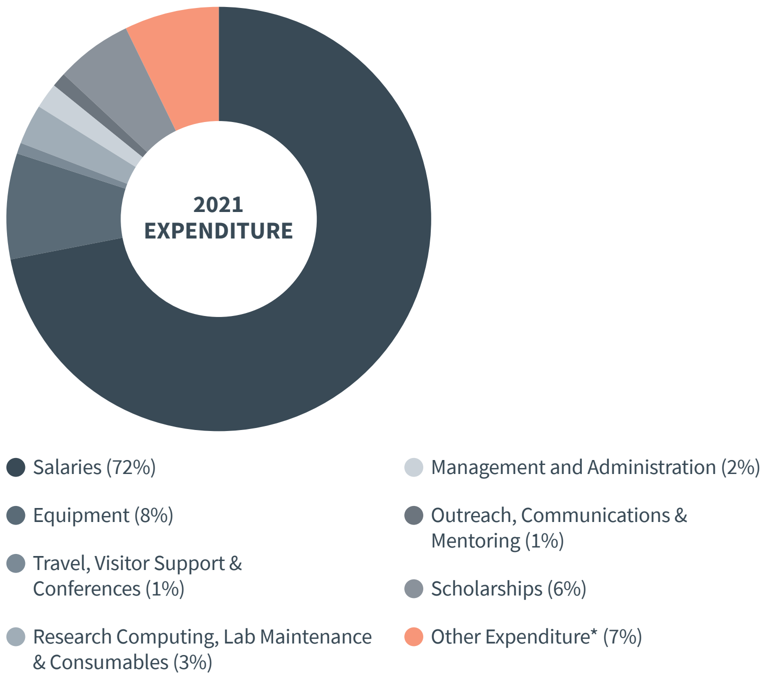
financial report

Statement of Income and Expenditure for Year ended 31 December 2021, preceding calendar year and estimated budget for 2022

Reporting Period	2020	2021	2022 forecast
INCOME			
ARC Grant	$5,089,998	5,181,620	5,228,255
University Contributions	$1,218,397	1,254,589	1,223,558
Partner Contributions	$20,000	70,000	20,000
Other Income*		250,000	
TOTAL INCOME	**$6,328,396**	**6,756,209**	**6,471,813**
EXPENDITURE			
Salaries	$1,008,666	2,421,777	3,986,703
Equipment	$134,593	281,025	1,032,804
Travel, Visitor Support & Conferences	$3,481	44,234	859,200
Research Computing, Lab Maintenance & Consumables	$58,129	87,093	214,100
Management and Administration	$18,797	60,413	287,310
Outreach, Communications & Mentoring	$41,490	47,730	159,625
Scholarships	$12,467	192,599	461,392
Other expenditure*		250,000	
TOTAL EXPENDITURE	**$1,277,624**	**3,384,871**	**7,001,134**
TOTAL CARRYFORWARD TO NEXT YEAR #	**$5,050,772**	**8,422,110**	**7,892,789**

* University of Melbourne support for SABRE
# Carryforward includes $2,500,000 of ARC Grant to fund the first six months of 2027 due to Centre starting in August 2020.





In Kind Contributions

Contributor	2021 Reporting Period*
The University of Melbourne	2,776,763
The Australian National University	1,136,238
The University of Adelaide	533,147
Swinburne University of Technology	301,623
The University of Sydney#	81,879
The University of Western Australia	384,112
ANSTO	130,900
DST Group	45,372
The University of Sheffield	28,576
INFN Gran Sasso National Laboratory	2,530,026
University of Amsterdam	11,093
California Institute of Technology	12,970
University of Freiburg	23,000
The University of Washington	11,093
Massachusetts Institute of Technology	11,093
Stockholm University	12,970
Helmholtz-Zentrum Dresden-Rossendorf#	12,500
Total	**8,043,355**

*The in kind contributions are reduced, impacted again by COVID-19 restricting access to facilities and equipment.
#In kind contribution based on six-months due to joining the Centre mid-year 2021.

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