ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

ANNUAL REPORT 2020

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

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF WESTERN AUSTRALIA

Australian National University

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ANSTO Science. Ingenuity. Sustainability.

INTERNATIONAL PARTNERS

INFN

California Institute of Technology

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The University Of Sheffield.

University of Washington

UNI FREIBURG

UvA Universiteit van Amsterdam

THE UNIVERSITY OF MELBOURNE

The Dark Matter Centre wishes to acknowledge the University of Melbourne for design services provided for the production of this Annual Report.

advisory board chair message

The year was a tumultuous one for many of us and a particularly challenging one in which to launch a new Centre of Excellence.

Yet, despite the complications of establishing a Centre during a pandemic, what has been clear to me has been the excitement and purposefulness of those who are participating in the search for dark matter at the ARC Centre of Excellence for Dark Matter Particle Physics.

At the Centre, the work of our researchers aims to open a new frontier of knowledge about the particle nature of dark matter, which constitutes so much of the universe's matter.

We are pleased that researchers from across Australia and internationally are joining us in this research, not only for the combined knowledge and skills they offer, but also for the benefits implicit in building a strong and collaborative community of particle physicists that will play an important role in Australia's scientific landscape.

At the Centre we hope to inspire the future generation of scientists through our research and outreach work and our communications activities. We plan to work with schools across Australia, starting with Stawell Secondary College, to introduce students to the thrill of scientific exploration. In this way, we aim to create a more diverse scientific community, and in particular, attract women to the field of particle physics. In the media, we would like to show women and other traditionally under-represented groups the potential to thrive in an exciting and fulfilling career.

I see great potential in the research that will occur at the Stawell Underground Physics Lab, which along with the data coming from its counterpart in Italy, will expand our knowledge of dark matter, as will our participation in the ORGAN and SABRE experiments. In synergy with these researchers, the Centre's theorists will incorporate the results from direct detection and large hadron collider searches into a new fundamental theory of nature.

Underpinning all of this work is the collaboration between researchers, across nations and different areas of study, in order to strengthen our knowledge and build on our capacity to further explore the great questions of the universe.

I look forward to seeing this Centre, established at a time of uncertainty, play an important role in helping solve one of the world's great unknowns, and I feel privileged to be part of this fascinating journey.

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

SIT: Swinburne Institute of Technology

Stockholm: University of Stockholm

SUPL: Stawell Underground Physics Laboratory

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

ECR: Early Career Researcher

KPIs: Key Performance Indicators

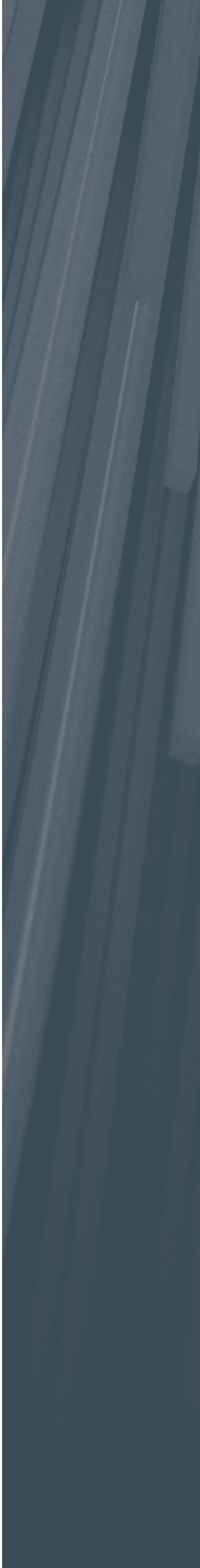
RA: Research Associate

SABRE: Sodium Iodide with Active Background Rejection Experiment

SUPL: Stawell Underground Physics Laboratory

PI: Partner Investigator

Cover photo: Dr Francesca C Ungaro



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director's message

I am pleased to present the Annual Report of the ARC Centre of Excellence for Dark Matter Particle Physics. Since the beginning of the Centre in August 2020, it has been a time of excitement and positivity, despite the challenges of establishing a Centre of Excellence during a pandemic.

Through many Zoom meetings and several lockdowns, our researchers and administrative staff have maintained their focus and commitment to ensuring the Centre can fulfil its potential to explore the nature of 84 per cent of the universe's matter, known as dark matter.

One of the Centre's priorities has been to bring together physicists from across Australia to create a truly collaborative environment. In this report you will see many examples of cross node and cross sub-discipline collaborations.

You will read about the progress of our SABRE project. This unique experiment brings the direct detection of dark matter to Australia. We are well on track to take data by 2022.

Dark matter terrestrial experiments have produced contradictory results so far. The DAMA/LIBRA experiment report of the measurement of an annual modulation consistent with a dark matter signal remains intriguing, whilst other experiments do not observe any positive dark matter signal. The SABRE experiment aims to resolve this debate by detecting annual modulation using the same type of target employed by DAMA/LIBRA and by placing identical twin detectors in the Northern and Southern Hemispheres. The Northern Hemisphere detector will be in the same location as the DAMA/LIBRA experiment at the Grand Sasso National Laboratory in Italy, and the other at the Stawell in Victoria, Australia. The SABRE South experiment is the first of its kind in the Southern Hemisphere: it will look for dark matter 1 km below ground in the Stawell Gold Mine.

The Stawell Underground Physics Laboratory (SUPL) is a source of great excitement within the Centre and beyond. Excavation of a section of the Stawell Gold Mine has been completed, and construction is set to begin in coming months. SUPL is an essential facility for the Centre, as it will host the Centre's SABRE South experiment from the end of 2021. In addition, SUPL, in collaboration with ANSTO, will provide facilities to screen materials for low-background experiments.

The Centre, in collaboration with ANSTO, is developing new and innovative Accelerator Mass Spectrometry (AMS) techniques to provide several orders of magnitude with better sensitivity than current techniques to estimate the level of radioactive impurities in the detector materials. Centre researchers at the ANU node have demonstrated a 100-fold improvement in AMS sensitivity for ^{210}Pb detection (an important contaminant in the SABRE detectors) compared to existing AMS literature.

The UWA node is exploring the wide-ranging implications for how dark matter technologies can be applied in the future, including developing even better low noise oscillators with more secure communication capabilities.

Theoretical collaborations across nodes and sub-disciplines (particle and nuclear physics) have resulted in a new avenue to look for dark matter, using neutron stars. The Cygnus project has also seen a closer collaboration between theorists and experimentalists.

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 Early Career Researcher Workshop that there will be many opportunities to challenge and support these researchers. Two of our early career researchers are already achieving impressive results, with Dr Peter Cox receiving a DECRA to investigate new models of dark matter and Ben McAllister awarded a fellowship by the Forrest Research Foundation to look for axion-like dark matter particles.

In our first months, one of our priorities has been to produce a code of conduct, that includes our values and establish the basis of respectful and inclusive culture, where diversity is embraced.

In the first six months of the Centre, we developed our communication and outreach strategic plan led by Prof Alan Duffy. In the coming years, we aim to inspire the scientists of the future through our outreach program, with a particular eye to regional Australia. We have already formed a partnership with Stawell Secondary College that will give regional students access to the latest dark matter research.

Researchers in the Centre have received important recognition, with Prof Nicole Bell being elected Vice President of the Australian Institute of Physics. I am sure she will successfully guide the direction of the institute and inspire a new generation of women in her new role.

In December, our Annual Workshop brought together members from across the country to share their research. 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 coming years.

All the best for the year ahead,

Elisabetta Barberio

strategy

The Centre 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.

1. Discover the particle nature of dark matter using state-of-the-art experiments based in Australia and create new theories of Nature that contain dark matter particles

- Research to advance the Centre's theoretical and experimental goals
- Deployment of the SABRE south experiment

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

- Continue Cygnus R&D, as well as R&D on phonon and photon detection technologies
- SUPL will be a world-class underground physics facility that takes full advantage of Australia's Southern Hemisphere location

3. Foster and develop the scientific leaders of the future

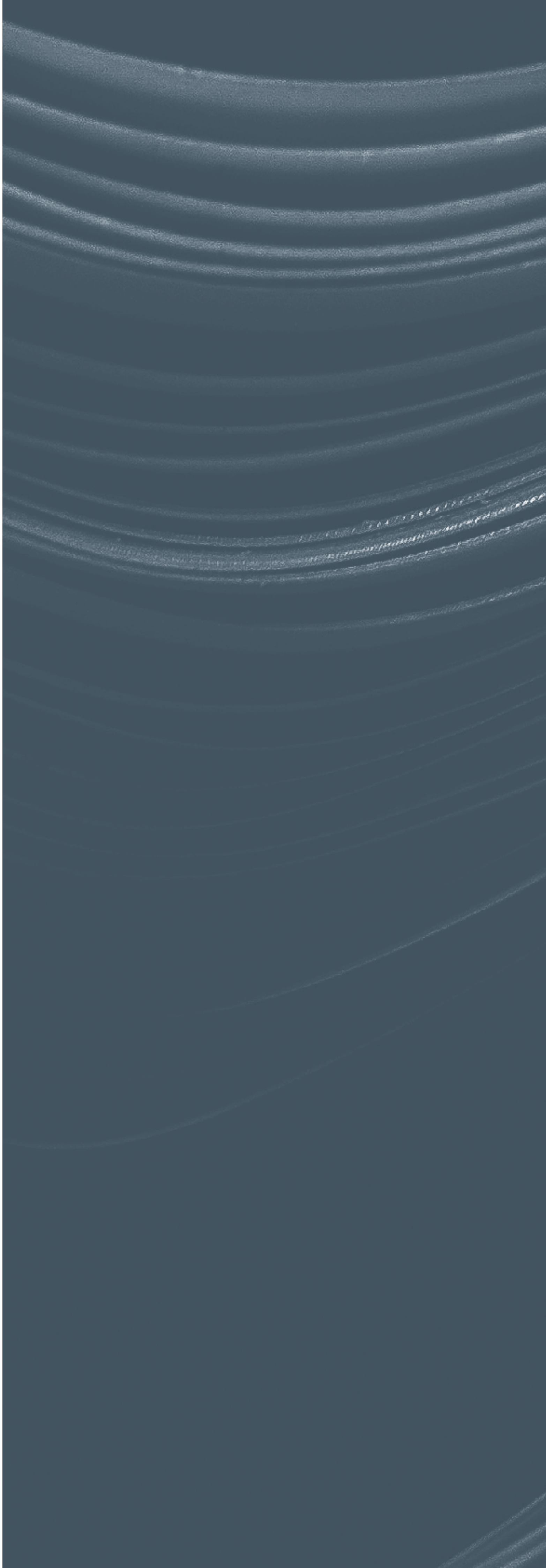
- Deployment of the internode mentoring program for Early Career Researchers
- Collaboration with DST Group for internships on the StarShot program
- Funding to support collaborations between CDM nodes and partner investigators for our ERCs

4. Translate the new technologies to industry, defence and the public through a dedicated Innovation Laboratory

- Increase our collaboration with DST Group on new technology for directional detector and launch of the Innovation Laboratory
- Training in innovative thinking in collaboration with Design Factory Swinburne to help translate discoveries into social and economic benefits

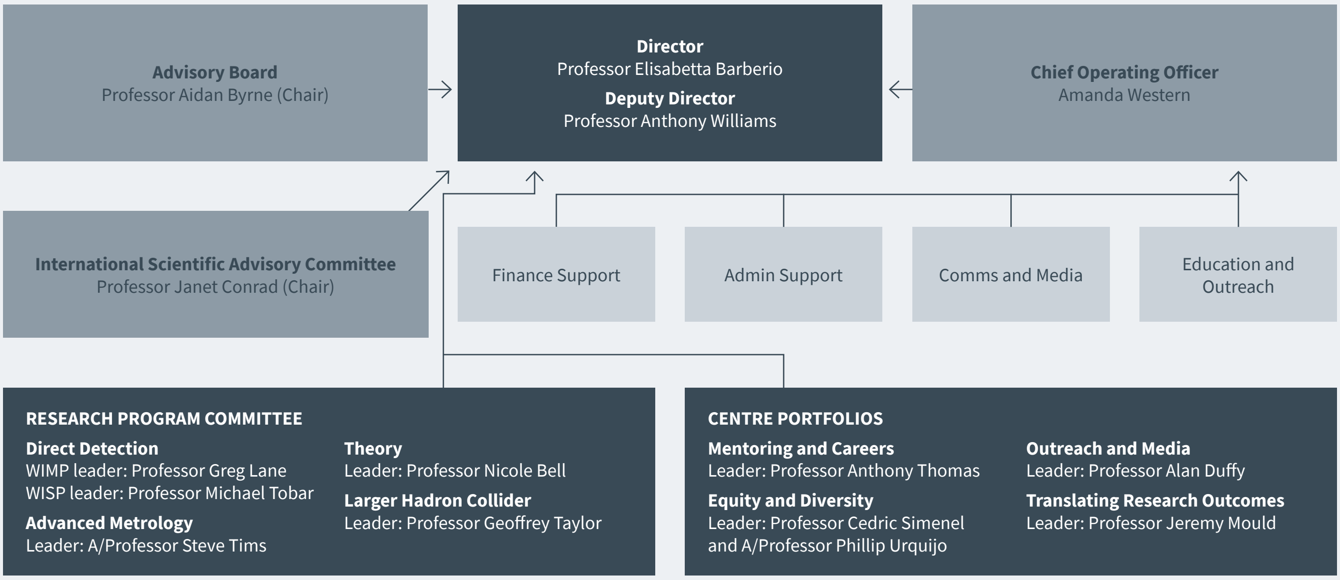
5. Cohesive national environment with a strong equity and diversity program

- Diversity and inclusion training for all Centre students and researchers
- Deployment of women only positions
- Strong emphasis on outreach and public education
- Inspire a new generation of physicists and engineers through activities including our pilot education program at Stawell Secondary College
- Collaboration with the UoM School of Education to provide curriculum-aligned content on Dark Matter at various school levels
- Training in communication and collaboration to help translate discoveries into social and economic benefits.



governance

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



Executive: Elisabetta Barberio (Director), Anthony Williams (UoA), Nicole Bell (UoM Node), Celine Boehm (UoS), Alan Duffy (SIT), Andrew Stuchbery (ANU), Michael Tobar (UWA), Amanda Western (COO).

Operation and Management

The Centre Director and Chief Investigator, Prof 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), Amanda Western, who oversees the day-to-day operational matters of the Centre and also provides strategic advice to the Director. The COO and her Central Operations Team of professional staff members are responsible for the Centre's financial management, human resources, outreach and education programs, event management, communications and preparation of annual reports and budget documents. Internal communications include fortnightly meetings and an enewsletter.

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

Executive Committee

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

Led by the Centre Director, the Centre Executive Committee comprises the Node Managers and the COO. There is provision for one Research Associate to become a member of the Executive Committee. The process for this RA nomination is under consideration by the Centre's cohort of Early Career Researchers and will be enacted in 2021.

Research Committee

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

The role of the Research Committee is to oversee research at the Centre.

Advisory Board

The Centre's Advisory Board assists the Centre Director by contributing to the development of strategies and the 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 – Prof Aidan Byrne** (University of Queensland Provost, Past CEO of the Australian Research Council)
- **Mr Campbell Olsen** (CEO of Arete Capital Partners; major shareholder of Stawell Gold Mine)
- **Prof Justin Zobel** (Pro Vice-Chancellor, Graduate & International Research, Chancellery (Research and Enterprise), the University of Melbourne)
- **Prof Robyn Owens** (DVCR, University of Western Australia)
- **Robyn Williams** (ABC science journalist and presenter)
- **Len Sciacca** (Enterprise Professor, Defence Science & Technology, University of Melbourne)
- **Dr Sue Barrel** (former Chief Scientist at the Bureau of Meteorology).

International Scientific Advisory Committee

The role of the International Scientific Advisory Committee is to mentor 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 directions in the field of the Centre and on the highest priorities for the allocation of Special Initiatives funds each year.

The International Scientific Advisory Committee is comprised of:

- **Chair – Prof Janet Conrad** (MIT, USA; Spokesperson of Isodar; former Spokesperson of MiniBoone)
- **Deputy Chair – Prof Nigel Smith** (Director, SNOLAB)
- **Prof Tom Browder** (University of Hawaii, former USA Spokesperson of Belle II)
- **Prof Aaron Chou** (Leader of axion dark matter group at Fermilab, USA)
- **Prof Priscilla Cushman** (University of Minnesota; Spokesperson of SuperCDMS-SNOLAB)
- **Prof Carlos Frenk** (Durham University, UK; Fellow of the Royal Society)
- **Prof Ian Shipsey** (Head of Particle Physics at Oxford University, UK)
- **Prof Stephen Buckman** (Australian National University)

centre membership snapshot

131 CDM Members

19	19	12	10	51	6	2	12
Chief Investigators	Associate Investigators	Partner Investigators	Postdocs	Students	Technical Staff	Engineers	Professional Staff

Student number inclusive of summer students

National Partners

THE UNIVERSITY of ADELAIDE

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF WESTERN AUSTRALIA

Australian National University

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International Partners

INFN

California Institute of Technology 1891

MIT

Stockholm University

The University Of Sheffield.

University of Washington 1861

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centre members

Director

Elisabetta Barberio (UoM)

Chief Investigators

Prof Elisabetta Barberio (UoM)
Prof Nicole Bell (UoM)
A/Prof Matthew Dolan (UoM)
Prof Alan Duffy (SIT)
Dr Maxim Goryachev (UWA)
A/Prof Gary Hill (UoA)
Prof Paul Jackson (UoA)
Prof Gregory Lane (ANU)
Prof Jeremy Mould FAA (SIT)
Prof Cedric Simenel (ANU)
Prof Andrew Stuchbery (ANU)
Prof Geoffrey Taylor FAA (UoM)
Prof Anthony Thomas AC FAA (UoA)
A/Prof Steve Tims (ANU)
Prof Michael Tobar FAA (UWA)
A/Prof Phillip Urquijo (UoM)
Prof Raymond Volkas FAA (UoM)
A/Prof Martin White (UoA)
Prof Anthony Williams (UoA)

Associate Investigators

Dr Rebecca Allen (SIT)
Prof Celine Boehm (UoS)
Prof Geoffrey Brooks (SIT)
Prof Frank Calaprice (Princeton)
Prof Zhenwei Cao (SIT)
Dr Peter Cox (UoM)
Prof Darren Croton (SIT)
Prof Eugene Ivanov (UWA)
Prof Ian McArthur (UWA)
Dr Francesco Nuti (UoM)
Dr Ciaran O'Hare (UoS)
Dr Jason Oliver (UoA)
Prof Peter Quinn (UWA)
Dr Andre Scaffidi (UoA)
Dr Jafar Shojaii (UoM)
Dr Abhishek Sharma (UoA)
Dr Andrea Than (UoM)
Prof Christine Thong (SIT)
Prof Anton Wallner (HZDR)

Partner Investigators

Dr Richard Garrett (ANSTO)
Dr Michael Hotchkis (ANSTO)
Dr Damian Marinaro (DSTG)
Prof Gianfranco Bertone (UAmst)
Prof Marcello Diemoz (INFN)
Prof Philip Hopkins (Caltech)
Prof Aldo Ianni (INFN)
Prof Karl Jakobs (UFreib)
Prof Gray Rybka (UWash)
Prof Tracy Slayter (MIT)
Prof Neil Spooner (USheff)
Prof Frank Wilczek (Stockholm)

UWA node members at the 2020 CDM Annual Workshop

Postdoctorate Researchers

Dr Michael Baker (UoM)
Dr Lindsey Bignell (ANU)
Dr Michaela Froehlich (ANU)
Dr Ben McAllister (UWA)
Dr Jayden Newstead (UoM)
Dr Sandra Robles Portilla (UoM)
Dr Federico Scutti (UoM)
Dr Zuzana Slavkovska (ANU)
Dr Wei Su (UoA)
Dr Xuang-Gong Wang (UoA)

Students

PhD

Mr William Campbell (UWA)
Mr William Dix (UoM)
Ms Emily Filmer (UoA)
Mr Graeme Flower (UWA)
Mr Leon Friedrich (UoM)
Mr Frederick (Fred) Hiskens (UoM)
Mr Wasif Husain (UoA)
Mr Albert Kong (UoA)
Ms Shanti Krishnan (SIT)
Ms Grace Lawrence (SIT)
Mr Nicholas Leerdam (UoA)
Mr Adam Leinweber (UoA)
Mr Peter McNamara (UoM)
Mr Ibtihal Mahmood (UoM)
Mr Michael Mews (UoM)
Mr Theo Motta (UoA)
Mr Aaron Quiskamp (UWA)
Mr Riley Patrick (UoA)
Mr Gregory Peiris (UoM)
Mr Shahinur Rahman (ANU)
Mr Alex Ritter (UoM)
Mr Tristan Ruggeri (UoA)
Mr Isaac Sanderson (UoM)
Mr Nathan Spinks (ANU)
Mr Minh Tan Ha (UoA)
Mr Edmund Ting (UoA)
Mr Michael Virgato (UoM)
Ms Yiyi Zhong (ANU)
Ms Madeleine Zurowski (UoM)

MPhil

Ms Meera Deshpande (UoA)
Mr Lachlan McKie (ANU)
Ms Anna Mullin (UoA)
Ms Catriona Thomson (UWA)
Mr Alexander Woodcock (UoA)

MSci by Coursework

Ms Fatimah Saad H Alharthi (UoM)
Ms Elrina Hartman (UWA)
Mr William McDonald (UoM)
Mr Lachlan Milligan (UoM)
Mr Jay Mummery (UWA)
Ms Katerina Patsis (UoM)
Mr Owen Stanley (UoM)
Mr Alexei Sopov (UoM)

Honours

Mr Mitchell Bonham (SIT)
Mr Charles Grant (UoA)
Ms Renee Key (SIT)
Mr Shiryo Owa (UoA)
Mr Navneet Krishnan (ANU)
Mr Zachary Searle (UoA)

Summer Students

Mr Robert Crew (UWA)
Ms Jade McKenzie (UoM)
Mr Kieran Rule (UoM)

Technical Staff

Mr Stephen Battisson (ANU)
Dr Padric McGee (UoA)
Mr Steve Osborne (UWA)
Mr Daniel Tempra (ANU)
Mr Ben Tranter (ANU)
Mr Thomas Tunningley (ANU)

Engineers (Affiliated)

Mr Tiziano Baroncelli (UoM)
Ms Giulia Milana (UoM)

Professional Staff

Dr Jackie Bondell
(Education and Outreach Officer)

Linda Barbour
(UWA Administration)

Sharon Johnson
(UoA Administration)

Fleur Morrison
(Communications and Media Officer)

Mary Odlum
(Finance Manager)

Petra Rickman
(ANU Administration)

Kathryn Ryan
(UoM Administration)

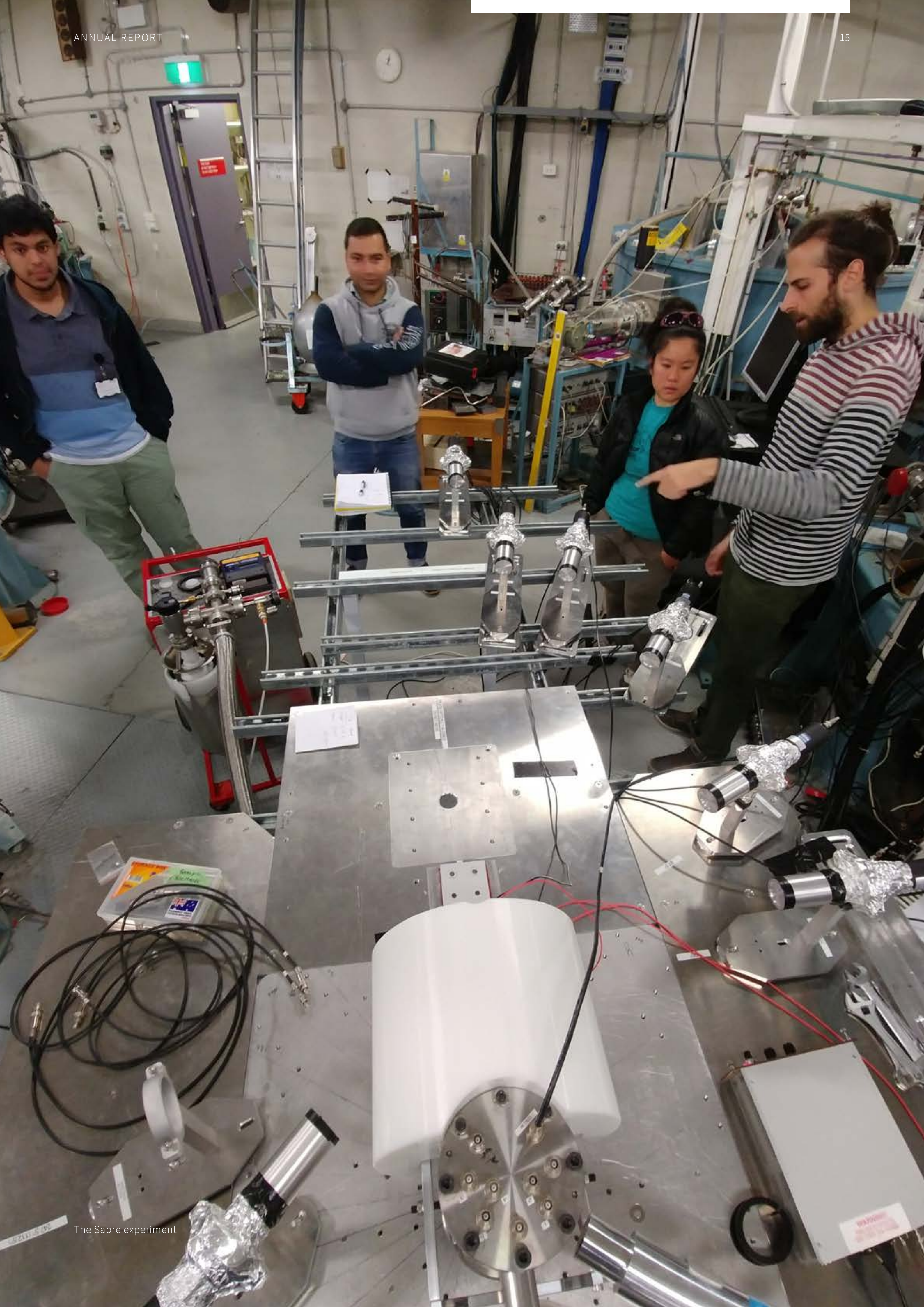
Darvy Sam
(Finance and Technical Officer)

Silvana Santucci
(UoA Administration)

Luana Spadafora
(SIT Administration)

Martina Velandi
(Administration Officer)

Amanda Western
(Chief Operating Officer)



The Sabre experiment

linkages and collaborations

In the Centre's first few months of operation in 2020, we were already busy establishing and building collaborations across the globe.

Research Organisations:

CP3, Louvain University, Belgium
Universidade Estadual Paulista-Unesp (UNESP), Brazil
Universidade Cruzeiro do Sul, Brazil
Snolab, Canada
TRIUMF, Canada
Langzhou University, China
Shanghai Jiao Tong University, China
Tsung-Dao Lee Institute, China
CEA, Saclay, France
University of Freiburg, Germany
University of Göttingen, Germany
Helmholtz-Zentrum Dresden-Rossendorf, Germany
Universita degli Studi di Milano, Italy
Sapienza Universita di Roma, Italy
University of Amsterdam, Netherlands
Radbound University, Netherlands
University of Cambridge, UK
UCAS, UK
The University of Sheffield, UK
University of Oxford, UK
Amherst Center for Fundamental Interactions, USA
Argonne National Lab, USA
UC Berkeley,Washington , USA
California Institute of Technology (Caltech), USA
University of California, USA
University of Chicago, USA
Fermi National Laboratory, USA
University of Florida, USA
University of Hawaii, USA
Illinois Institute of Technology, USA
University of Illinois Urbana-Champaign, USA
Lawrence Livermore National Lab (LLNL), USA
Los Alamos National Laboratory, USA
Massachusetts Institute of Technology (MIT), USA
Pacific Northwest National Lab (PNNL), USA
Princeton University, USA
Sam Houston State University, USA
INFN Laboratori Nazionali del Gran Sasso (LNGS), Italy
University in St. Louis, USA
Texas A&M University, USA
Thomas Jefferson Lab (JLab), USA
University of Washington, USA
University of Valencia, Spain
Lund University, Sweden
KTH Stockholm, Sweden
Stockholm University, Sweden
University of Bern, Switzerland
University of Geneva, Switzerland

Companies:

ATA Steel
Australian Surface Treatments
Bluescope Australia
Eureka Concrete
Eljay Engineering
FE Consultants
Hamamatsu Photonics
Ipromo Srl
Palazzi Srl
Plastifab
Stawell Goldmines
RMD Dynasil
Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS)
Tasweld Pty Ltd
WSP Engineering

industry collaborations

The Centre has been active in building collaborations with industry. In 2020, our growing list of collaborators includes:

SABRE

- FE Consultants (Bowen Hills, QLD, Australia) - Mechanical design of SABRE veto vessel, certifications.
- Tasweld Engineering (Warrnambool, VIC, Australia) - Manufacturing of SABRE veto vessel. Mechanical and leak testing of SABRE vessel.
- Eljay Engineering (Bayswater, VIC, Australia) - Manufacturing and assembly of aluminum frame for SABRE Crystal Insertion System, including motor/drive system for travelling bridge.
- Plastifab - MB Plastics (Cheltenham, VIC, Australia) - Manufacturing of PMMA chamber for veto PMTs characterization and testing.
- Australian Surface Treatments (Campbellfield, VIC, Australia) - Analysis of possible solutions for SABRE vessel internal coating, supply of samples for radioactivity testing on paints/blasting materials.
- ATA Steel (Hope Valley, WA, Australia) - Supply of steel samples from Hyundai Steel for radioactivity testing (steel as possible candidate for SABRE shielding).
- Bluescope Australia (offices all around Australia) - Collaboration on steel procurement for SABRE shielding.
- WSP Engineering - Final structural design and certification of SABRE Shielding (not yet finalised).
- Eureka Concrete, Ballarat (concrete strength testing for concrete floor design for under SABRE).

International companies:

- Palazzi Srl (Pomezia, Rome, Italy) - Manufacturing of PMMA glove box for the SABRE Crystal Insertion System.
- Ipromo Srl (Milan, Italy) - Supply of prototypes for PVC bellow for SABRE crystal insertion system.
- Hamamatsu Photonics (electron tube division) (Japan), R&D on low radioactivity photomultipliers.
- RMD Dynasil.
- Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS), R & D for crystals.

research program overview

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

Program 1: Direct Detection (5 nodes, 14 researchers, 16 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 Centre plans to produce new detection technologies to extend our dark matter searches via a robust R&D program.

Program 2: Metrology (2 nodes, 6 researchers, 4 students)

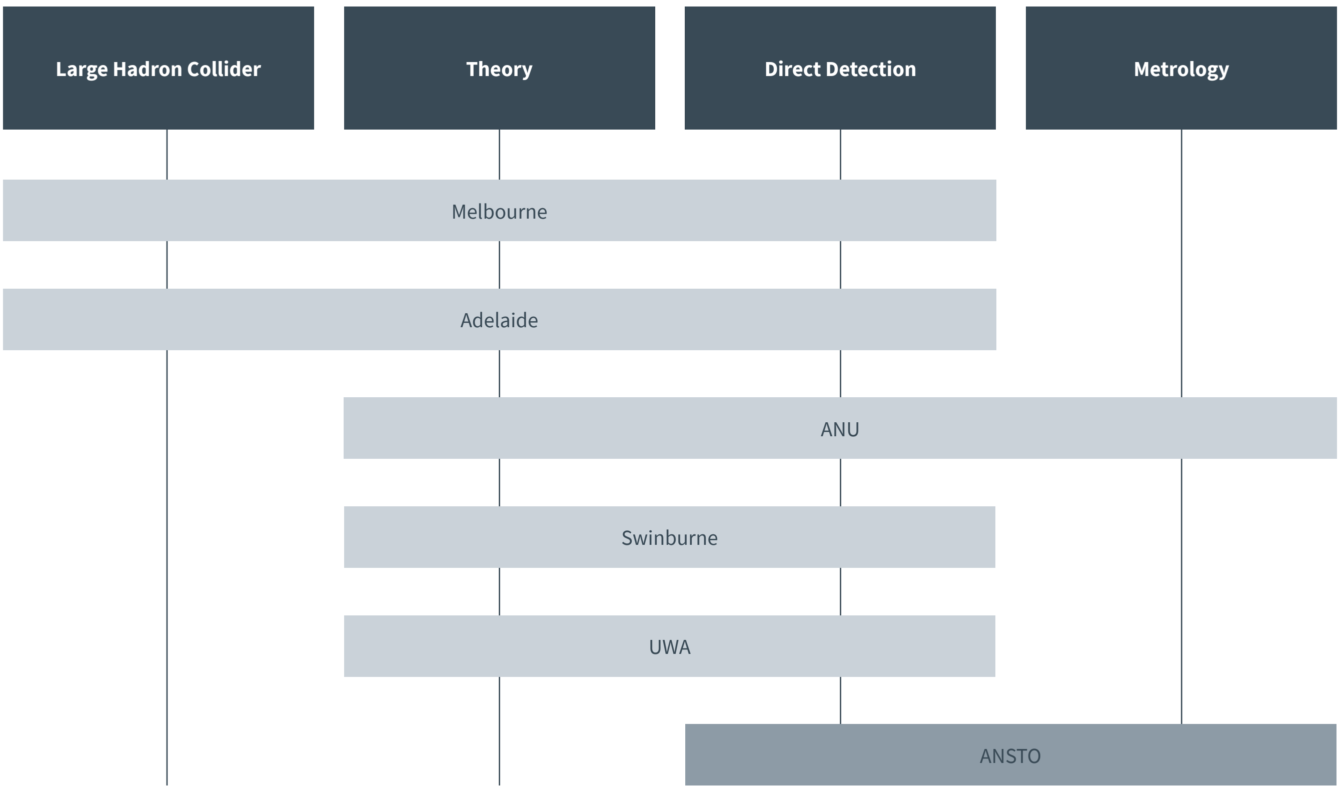
Selecting ultra-pure materials for the underground experiments requires the development of excellent ultra-low background radioactivity measurements. The Centre aim to exploit ANU and ANSTO Accelerator Mass Spectrometry (AMS) and precision gamma-ray spectroscopy expertise to develop ultra-sensitive radioactivity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

Program 3: Large Hadron Collider Searches (2 nodes, 4 researchers, 4 students)

Dark matter searches with the ATLAS experiment at the Large Hadron Collider at CERN (Switzerland) will extend the Centre's experimental reach to dark matter masses and interactions in regions where the direct detection experiments have less sensitivity.

Program 4: Dark Matter Theory (5 nodes, 13 researchers, 13 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 will inform and help interpret the Centre's experimental results, drive future searches and foster strong particle-astrophysics links.



research program action plan

Program		2020	2021	2022	2023	2024	2025	2026	2027
WIMP Direct Detention	SABRE proof-of-principle (Italy)								
	SABRE South								
	Cryogenic Detector								
	CYGNUS small prototype								
	CYGNUS 1m^3 prototype								
WISP Direct Detention	ADMX Run 1b and Run 1c								
	ADMX Upgrade, 8–16 µeV								
	ORGAN								
	ORGAN Upgrade								
R&D for WIMP & WISP Searches (including Precision Metrology)	Room temp. NaI and veto systems								
	Cryogenic bolometer/phonon sensors								
	TPC large scale								
	Precision frequncy schemes								
Nuclear Metrology	ICPMS – Develop native capability								
	HPGe – Rationalise native capability								
	AMS Improve ToF system								
	AMS Improve resolution of iron chamber								
	AMS Intergrate electrostatic analyzer								

R&D and new experiments

Detector operation

Construction and commissioning

direct detection research program

Nodes: UWA, ANU, Swinburne, Adelaide, UoM

Sub-program 1a) WIMP direct detection underground experiments

Most direct detection experiments attempt to reduce background to an absolute minimum and interpret any excess counts as a dark matter signal. A comprehensive program to reduce background noise using a combination of material screening, radio-pure shielding and active veto detectors, has resulted in projected background levels of below 1 event/kg of target mass/year. In the first year of the Centre, the WIMP direct detection activities focused on the construction of the SABRE experiment and R&D for the CYGNUS experiment.

Cygnus Highlights

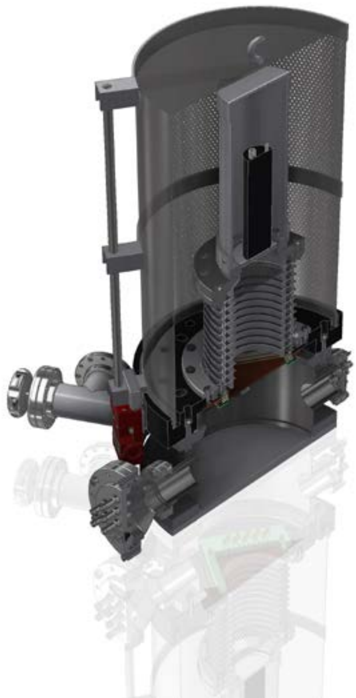
CIs: E. Barberio, G. Lane, A. Stuchbery, P. Urquijo
Postdocs: L. Bignell
Students: L. McKie, P. McNamara

The directional detector concept is a compelling option for WIMP-like dark matter searches to permit searches below the neutrino floor and, post-discovery, for WIMP astronomy. Directional detection will require development of new detector technologies, such as a low-pressure gas *Time Projection Chamber* (TPC) as part of the CYGNUS effort led by PI Spooner. Our research strategy is to develop a prototype gas TPC that can address the remaining detector technology challenges faced by Cygnus.

Once fully operational, the prototype will have a finely segmented readout capable of sensing both the charge and optical signals from the particle events, with arbitrary gas mixtures and pressures. This will be hosted at the ANU node, to leverage the existing detector R&D infrastructure including the 14 UD accelerator.

We are developing the prototype using a staged approach. The first stage, Cygnus-Lite, was completed in November 2020. We constructed a small-scale atmospheric pressure gas TPC which acquired benchmark data for validating simulation code developed primarily at the Melbourne node. These early results also included the first measurements of track inclination, a 1-dimensional directionality result.

Plans have been developed for an enhanced prototype, Cygnus-1, with a larger TPC volume to permit larger tracks and longer drift distances to allow studies of track diffusion and negative ion gases. The readout system will also be upgraded to include optical measurements of the avalanche light. At the time of writing, the ANU workshop was fabricating parts for Cygnus-1, and the high voltage safety interlock and gas recovery systems were being finalised.



First directional measurements have been made with the Cygnus-lite prototype (left). The larger Cygnus-1 prototype (right) will commence measurements in 2021 with an enhanced readout.

SABRE ORGANISATION

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Institutions: Univeristy Adelaide, Australian National University, Gran Sasso National Laboratory, INFN–Roma, University of Melbourne, University of Milan, Princeton University, PNNL, University of Rome and Swinburne University of Technology.

SABRE Highlights

CIs: E. Barberio, A. Duffy, G. Hill, G. Lane, A. Stuchbery, G. Taylor, P. Urquijo, A. Williams
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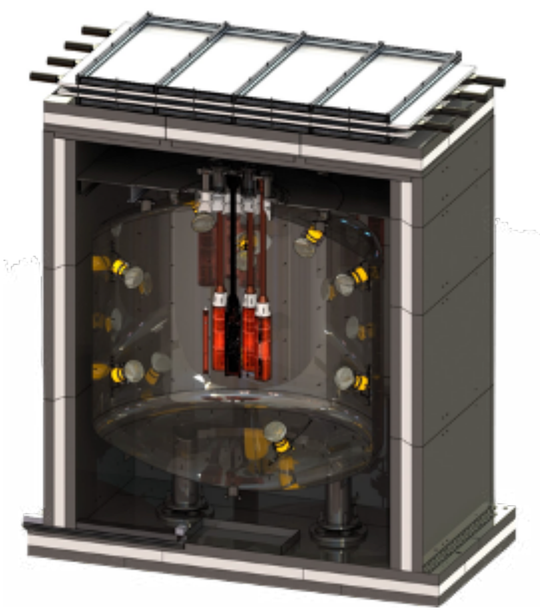
The SABRE experiment is designed to detect WIMP dark matter using a sodium iodide target with active background rejection in the Stawell Underground Physics Laboratory. It is the first deep underground dark matter experiment in the Southern Hemisphere. SABRE is expected to provide a definitive test of the DAMA/LIBRA result in the first four years of the Centre. The organization of the sabre experiment is described in the above diagram.

The fundamental model-independent signature for dark matter particles interacting in the detector is the annual modulation of the expected interaction rate. In Australia the experimental effort comprises teams from the Adelaide, ANU, Melbourne and Swinburne nodes. Significant progress has been made since the commencement of the centre on simulation, software, physics and prototyping of the complex SABRE experiment. The experiment is on track to commence commissioning soon after the completion of SUPL in latter 2021. Recent developments on each subsystem are described in turn below.



3-dimensional engineering render of the SABRE experiment.

Crystal and crystal enclosure

Thallium doped sodium-iodide (NaI(Tl)) crystals are the core elements of the SABRE experiment. The interaction of dark matter with atoms of its crystalline structure causes the production of scintillation light. The higher the energy of the interaction, the larger is the number of emitted scintillation photons. This light is measurable and is collected with low radiation, high quantum efficiency photomultiplier tubes (PMTs). A SABRE detector unit comprises a naI(Tl) crystal wrapped in a reflective Teflon layer and coupled to two metal-body Hamamatsu R11065 PMTs A total of 7 of these units will make up the core detection component of SABRE. Recent progress has been made on underground characterisation studies of prototypes, beam tests and quenching factors, and on engineering.

- *Prototype studies at Gran Sasso National Laboratory (LNGS).* The SABRE NaI(Tl) crystals are custom made by the SABRE collaboration as they require extremely low levels of radioactive contamination and excellent scintillation properties. The properties of a recently produced high quality 3.4 kg crystal by the University of Princeton were measured underground at LNGS, Italy [1]. The potassium-40 contamination was measured to be 4.3±0.2 ppb, the lowest contamination ever achieved in an NaI(Tl) crystal, and half of that achieved by DAMA/LIBRA. The study also demonstrated the ability to suppress electronic noise in the lower part of the energy spectrum.

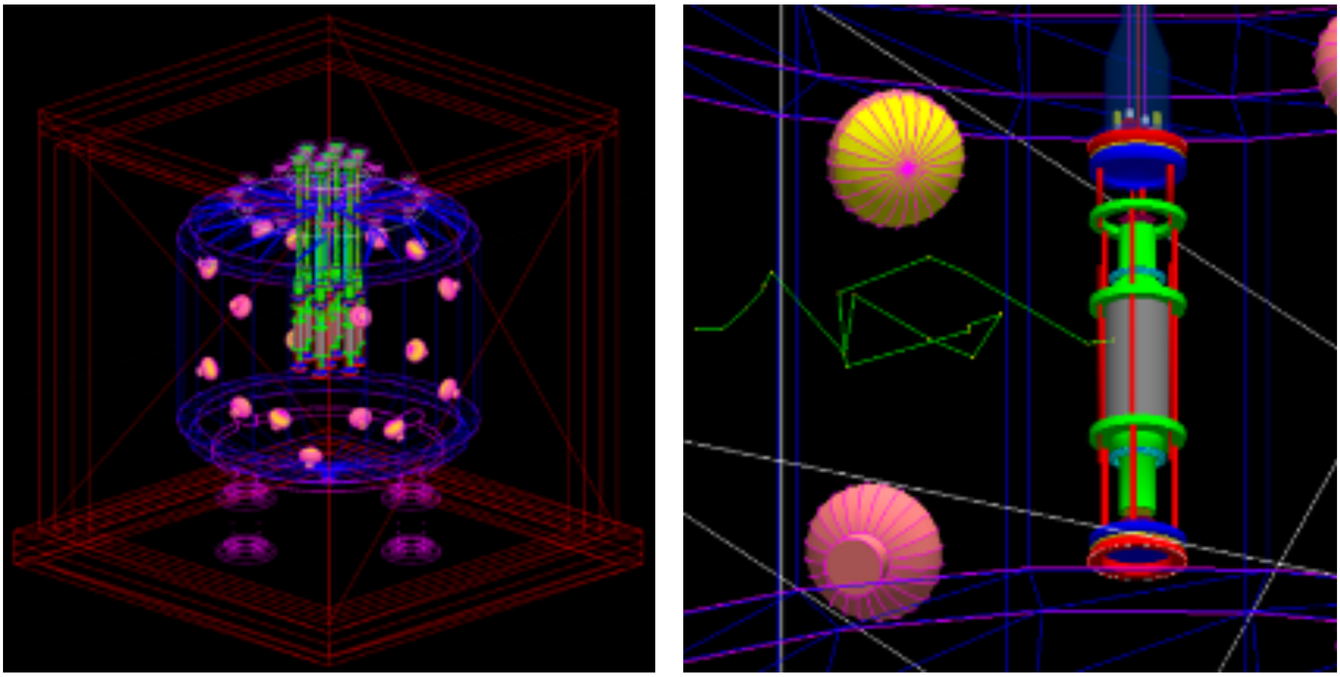

The NaI-33 crystal prior to Teflon wrapping.

- *Beam tests.* The SABRE background will be dominated by radioactive decay events from the trace amount of naturally occurring radioactivity present in the detector. These background events generate electron recoils in the NaI(Tl), while many WIMP-like dark matter models expect a nuclear recoil signal. Studies are underway to develop particle identification algorithms to separate out electron recoil-like background, using waveforms of the photon signal from the scintillator. Datasets of nuclear and electron recoils have been produced utilising beams from ANU's 14 UD accelerator for the development of machine learning algorithms. Early results indicate promising performance for multivariate likelihood-based approaches that provide much better separation than common cut-based approaches.
- *Quenching factor measurements.* The ANU 14 UD pulsed beam has also been utilised to perform accurate measurements of the nuclear recoil energy scale (or quenching factor) in NaI(Tl), which is difficult to obtain by other means. Such measurements are critical for interpreting the mass scale of WIMPs to which SABRE will be sensitive. A study reporting a new analysis methodology for such measurements has recently been submitted for publication [2].
- *Enclosure engineering*. The crystal enclosure consists of an internal structure made of copper and Teflon that holds the crystal and the PMTs together, and an external encapsulation made of copper. It is designed to house cylindrical NaI(Tl) crystals of 10 cm diameter and a height in the range of 12 cm – 25 cm. The total height of the enclosure excluding the gas and electrical connectors is approximately 60 cm. The design of the enclosure has been finalised, and ANU will produce the first mock-up assembly.

Veto vessel and PMTs

The SABRE veto vessel is a stainless steel pressure vessel filled with 12 tonnes of liquid scintillator based on an organic solvent, Linear Alkyl-benzene (LAB), mixed with fluorophores Bis-MSB and PPO. The vessel has an outer diameter of 2.6 m and height of 3.1m, and engineered to AS1210:2010 standards. The internal surface will be lined with Lumirror reflective foil, and 18 Hamamatsu R5912 (20 cm) Veto PMTs mounted on the walls of the vessel. The R5912 PMTs have an oilproof base that encapsulates the electrical connections at the back of the bulb, allowing for direct submersion in the LAB. The main vessel top-flange has 7 smaller flanges for the insertion of the crystal enclosures in the detector. The top torispherical section of the vessel has 12 flanges for electrical and gas connections, and for the calibration systems of the Veto PMTs. Recent progress has been made on PMT characterisation, LAB studies and vessel engineering.

- *PMT characterisation system.* A single photon characterisation system has been developed at Melbourne for the measurement of quantum efficiencies (the proportion of single photons arriving at the photocathode that produce a measurable electronic pulse), gain, dark rate and dark current as a function of temperature, and timing characteristics of all PMTs in SABRE (Veto, Crystal and Muon systems). This provides critical information for the calibration and analysis of data from the experiment. The first PMTs to be used in the SABRE vessel have been tested to confirm that they meet the requirements of the experiment.
- *Prototypes and LAB Studies.* A small prototype system was constructed at Melbourne consisting of 32 L of liquid scintillator in an acrylic chamber coupled to an R5912 PMT. It has been used for the development of particle identification in the SABRE veto. The performance of time of flight (measured in conjunction with the muon detectors) and pulse shape discrimination techniques were demonstrated to be effective in discriminating cosmic muons, gamma rays and neutrons, and will be used to disentangle background contributions in SABRE. At ANU studies of the scintillator light yield and optical attenuation have been used to determine the most suitable fluorophore concentrations, and critical compatibility tests were conducted to ensure any materials used in the construction of SABRE that are immersed in LAB do not react and affect the light attenuation of the liquid over the duration of the experiment's lifetime.
- *Engineering.* The SABRE veto vessel was manufactured and certified by Tasweld Engineering in 2019. Since then modifications to the mechanical design of the top flange were implemented to allow for mechanical testing of the Crystal Insertion System (CIS). The SABRE vessel is now sitting at Swinburne's Wantirna campus for installation tests of the Lumirror reflective foil and the Veto PMT mounts.



GEANT4 renders of SABRE. Left: the NaI(Tl) and LAB veto systems. Right: a background Potassium-40 decay producing scintillation light in the veto system.

Muon system and background measurements

One of the most notable sources of a modulating background for the SABRE experiment is from cosmic muons. The rate of cosmic muons varies seasonally throughout the year with a higher flux in summer compared to winter. Cosmic muons will not only pass through the experiment, but also will eject spallation neutrons which can mimic a dark matter signal in SABRE's crystals. At the depth of 1025m, this flux is reduced by a factor 106 compared to the surface flux, but still presents challenges. To address this, the SABRE experiment is instrumented with a muon veto detector, purpose built to detect cosmic muons for modulation studies, and to remove their contribution from the signal analysis.

- *Engineering.* The muon detection system, comprised of 8 muon detector panels, will be mounted onto the shielding roof. The muon detector modules are each comprised of an EJ200 scintillator panel 3.0 m by 0.4 m by 0.05 m, coupled to light guides and two Hamamatsu R13089 PMTs (one at each end). The muon detection system will be mounted on an aluminium frame that locks the individual detectors into position and allows for manoeuvring operations in SUPL. All modules are built and currently situated in Melbourne.
- *Performance studies.* With a total area of approximately 10 m^2, the muon veto detector will allow for precise measurements of the cosmic ray flux in the SUPL site, and potentially other background radiation, including neutrons in addition to its role as a veto system. The detector is undergoing testing and calibrations to characterise its performance capabilities. The R13089 PMTs have been chosen for their excellent (~200 ps) timing resolution, providing 5 cm position resolution along the length of the panels, and time of flight (ToF) when used in multi-layer operation. Prior to installation in SABRE the sub-detector panels have been arranged vertically for measurements of the muon flux as a function of angle, modulation at the surface, and particle identification studies. The ToF performance is excellent, clearly separating muons and gamma rays from the slower moving neutrons. Muons and gamma rays can be further separated using the charge collected in the PMT. The setup is intended to be used in the SABRE experiment in conjunction with the liquid veto vessel to classify the background. Supporting this work has been the development of a new SABRE specific data acquisition system that will be adopted for the full experiment.

Shielding

The SABRE Veto vessel is surrounded by a 124 tonne, 300 mm-thick radiation shielding structure with outer dimensions of 3.5 m (width) by 3.5 m (depth) by 4.2 m (height). The shielding sits on a 30 cm-thick floor with a footprint of 3.8 m by 3.8 m. All shielding panels are composed of three 10 cm-thick layers of steel, high-density polyethylene, and steel respectively. Over the past year all materials have been screened for radiation levels at Melbourne with an ANSTO gamma-ray spectrometer. A preliminary design of the SABRE shielding and its internal frame has been prepared, based on static and dynamic analyses. It is currently being reviewed by the engineering consultancy firm WSP.

Software, simulation and physics

Dark matter detection involves searches for signals on the order of 1 count per day, per kg of target material, and so we require very low background experiments to observe these signals. This will depend on both the construction and background of the experiment, and the interaction we are trying to observe. SABRE takes advantage of the fact that the signal should be modulating, and primarily measures the modulation rather than the total rate. However, the sensitivity of the experiment is driven by the contribution of residual radioactive contamination in the surrounding rock or detector structures. The collaboration is constantly improving the accuracy of the background model, and has studied various signal interaction types, to estimate the experiment's reach in cross section and mass parameter space. Major steps forward have been taken on simulation, software for analysis, and physics sensitivity studies.

- *GEANT4 simulation.* The full SABRE detector has been implemented into GEANT4 simulation, from the crystal enclosures through to the muon detectors and shielding. It has provided critical information to inform the overall design of the detector layout, choices of materials and the leading background to the experiment.
- *Software for future analyses.* A large amount of data is expected to be collected and simulated by the SABRE experiment, of order 100 TB of raw data per year. It will largely contain background from radioactive background processes and low-energy thermionic emission of electrons in the PMTs. Ultimately, this vast dataset needs to be reconstructed, filtered, and analysed to extract physics information. To achieve this, the SABRE offline software framework is integrated with cutting-edge machine learning and data-analytics tools. It contains algorithms to transform data from the raw data-acquisition level through to formats with full-detector event structure for analysis. It also includes with algorithms to calibrate and clean the signals from each of the PMT channels.
- *Physics*. Preliminary studies have found that if the DAMA signal is due to dark matter interactions, SABRE's ultra-low background (seen in NaI-33) would allow for a 5-sigma discovery within 2 years of commencing operation with 50 kg of NaI(Tl). Furthermore it would take only 3 years to exclude the DAMA result at 3-sigma. SABRE is expected to be significantly more sensitive than competing northern-hemisphere experiments with lower (worse) crystal radiopurity, even if it does not have the largest target mass. This is particularly relevant for the discovery power, which is more strongly dependent on the background level than the exclusion power (see Ref [4] for a description of the analysis methodology).

Sub-program 1b) Axion and Wave Like Dark Matter Detection

A comprehensive exploration of the nature of dark matter requires multiple experiments with complementary sensitivity. This is perhaps most obvious for the case of Wave Like Dark Matter, where different experimental techniques cover different dark matter mass ranges. Through many different probes we will explore the sub eV dark matter mass ranges.

Project: Oscillating Resonant Group AxioN experiment (ORGAN)

CIs: M. Goryachev

Postdocs: B. McAllister, C. Zhao

PhD Students: G. Flower, A. Quiskamp

The ORGAN Experiment is the first Australian axion dark matter experiment, and is situated at UWA. The experiment will run for 7 years, from 2021-27, continuing the work of the original pathfinding experiment. ORGAN searches for axions at higher mass range when compared to other axion haloscopes (60-200 μeV), corresponding to 15-50 GHz in photon frequency. To overcome the significant technical challenges four main avenues of research are being pursued.

1. Design of novel resonators based on higher order modes in resonant cavities and dielectric materials, to increase form factors and volumes at high frequency[1].
2. Novel schemes for combining multiple resonators, such as cross-correlation, to increase effective detector volume.
3. Consideration of high critical field superconducting coatings to increase quality factors of resonators.
4. Single photon counting technologies, and/or sub-quantum limited linear amplification.

The experiment will consist of 2 phases, each broken down into stages. Phase 1 will consist of two targeted scans at 15-16 GHz and 26.1-27.1 GHz. Phase 2 will consist of the entire 15-50 GHz region, broken down into 5 GHz stages, and will test Axion Cogenesis in 2021.

Project: Search for Light Scalar Wave Like Dark Matter

CIs: M. Goryachev, M. Tobar

Postdocs: B. McAllister

PhD Students: W. Campbell

This project searches for possible scalar wave like dark matter, such as the Dilaton. Such dark matter is predicted to cause oscillations in fundamental constants, and at UWA we will pursue two types of experiments sensitive to these interactions.

1. Search for detectable signals through clock comparisons between acoustic, atomic and photonic oscillators. arXiv:2010.08107 [hep-ex]
2. Search for excitation of acoustic resonant-mass systems, which are also sensitive to incident gravitational waves. arXiv:2102.05859 [gr-qc]

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

CIs: M. Tobar, M. Goryachev

AIs: P. Altin

Postdocs: B. McAllister

PhD Students: C. Thomson

Special configurations of dual-mode resonator-oscillators have been shown to be sensitive to low mass axions through the principle of upconversion and precision frequency metrology. The signal sensitivity is derived from the two-photon axion process, which does not destroy the axion, but causes frequency modulation of the photon frequencies inside the resonator. At UWA a first simple table-top experiment has been achieved (arXiv:1912.07751), placing exclusion limits. In the future, a frequency-stabilized cryogenic version of this technique will achieve best limits in an axion mass range of less than 1μeV. This group of projects will continue in concurrent stages:

1) Development of frequency stabilized oscillators based on an invar silver plated microwave cavity operating in vacuum. This will start operation by 2021, with the ability to test ALP Cogenesis in the mass range less than 10neV:

2) A cryogenic version of the experiment based on high-Q superconducting Tesla cavities designed by Fermilab, with a proof of principle experiment to begin in 2021-2. This will be followed up with a properly designed system able to test QCD axions below 10−11eV and conventional alignment mechanisms below 10−8eV, tentatively scheduled to begin in 2023 after the necessary R&D.

Project: Low mass detectors for axions with LCR Circuits

CIs: M. Goryachev, M. Tobar

AIs: P. Altin

Postdocs: B. McAllister

This project will see us undertake experiments to search for axions below 1 meV in mass using lumped mass LCR circuits. There will be two approaches:

1. We will contribute to a collaboration with ADMX researchers on the ADMX-SLIC (Superconducting Lc-circuit Investigating Cold axions) experiment. This is led by researchers from the University of Florida (Pierre Sikivie and David Tanner). A large reentrant resonator haloscope will be built for the ADMX site at the University of Washington and operated there, after the next version of ADMX gets upgraded allowing use of the current equipment. The current ADMX magnet has a dilution refrigerator and a zero-field region, allowing operation of SQUID amplifiers. The detector should have quantum-limited sensitivity and reach the DFSZ limit at the upper limit of the search range.
2. Broadband Electrical Action Sensing Technique (BEAST), this experiment is proposed by UWA and uses lumped elements to undertake sensitive experiments below 1 meV in axion mass range[2].

Project: Axion Dark Matter eXperiment (ADMX)

CIs: M. Goryachev, M. Tobar

AIs: P. Altin

Postdocs: Ben McAllister

PhD Student: A. Quiskamp, C. Thomson

ADMX uses a resonant microwave cavity within a large superconducting magnet to search for cold dark matter axions in the local galactic dark matter halo. This collaboration is run by Fermilab, with the experiment situated in Seattle at Washington University. The collaboration consists of ten institutes in the USA, two in Europe and one in Australia (UWA). UWA have officially been a member of the collaboration since January 2019 (arXiv:2010.06183 [astro-ph.CO]). They are currently contributing to the Haloscope microwave cavity design and the high-resolution analysis to search for narrow axion dark matter signals.

Project: Searches for axions through coupling with electron spins via magnon spin waves

CIs: M. Goryachev, M. Tobar

AIs: P. Altin

Postdocs: B. McAllister

PhD Students: G. Flower

The UWA node is one of the leading research groups in designing hybrid Magnon-Cavity polaritons for Quantum Electrodynamics experiments and metrology applications[3]. This technology can be used to search for axion interactions with spins. This experiment is on hold until the axion is discovered. This experiment can distinguish between separate axion models when combined with experiments that search for axion photon coupling.

1 AP Quiskamp, BT McAllister, G Rybka, ME Tobar, "Dielectric-boosted sensitivity to cylindrical azimuthally varying transverse-magnetic resonant modes in an axion Haloscope," Phys. Rev. Applied vol. 14, 044051, 2020.

2 ME Tobar, BT McAllister, M Goryachev, "Broadband electrical action sensing techniques with conducting wires for low-mass dark matter axion detection", Physics of the Dark Universe, vol. 30, 100624, 2020.

3 G Flower, BT McAllister, M Goryachev, ME Tobar, Determination of Niobium Cavity Magnetic Field Screening via a Dispersively Hybridized Magnonic Sensor, Appl. Phys. Lett., vol. 117, 162401, 2020.

Axion / Wave like Dark Matter Research Highlights

Sub-program 1b) Axion and Wave Like Dark Matter Detection (Case study)

Axions are a popular dark matter candidate that are often searched for in experiments known as "haloscopes", which exploit a putative axion-photon coupling. These experiments typically rely on transverse-magnetic (TM) modes in resonant cavities to capture and detect photons generated via axion conversion. PhD student Aaron Quiskamp from the UWA node presented a study of a resonant-cavity design for application in haloscope searches, which was a collaboration with PI Rybka, which was published in Phys. Rev. Applied[1].

In particular, the new axion haloscope design allows a better sensitivity in the push to higher-mass axion searches (above approximately 60μeV). Aaron on the UWA team took advantage of azimuthally varying TMm,1,0 modes that, while typically insensitive to axions due to field nonuniformity, can be made axion sensitive (and frequency tunable) through the strategic placement of dielectric wedges, becoming a type of resonator known as a dielectric-boosted axion-sensitivity (DBAS) resonator. Results from finite-element modelling were presented and compared with a simple proof-of-concept experiment. The results show a significant increase in axion sensitivity for these DBAS resonators, if made from a low-loss dielectric such as sapphire, over their empty-cavity counterparts and high potential for application in high-mass axion searches when benchmarked against simpler more traditional designs that rely on fundamental TM modes.

While the sapphire DBAS resonator is being built and characterised for use in ORGAN run1b, the run1a search will be underway, incorporating a TM0,1,0 based tuning-rod haloscope to test the ALP co-genesis model in the 15-17GHz region of the axion-photon coupling parameter space. This initial phase of ORGAN will operate at 4K in a 12 T magnetic field, and uses readily available low noise HEMT-based amplifiers to place the strongest limits to date in the high-mass region

Aaron Quiskamp, holding a sapphire resonator and standing in front of a mK BlueFors dilution fridge, undergoing low temperature measurement of microwave cavities under large magnetic fields. His new DBAS resonator will be manufactured from sapphire and will sit inside a 14 T magnetic field to search for axions with the ORGAN dark matter detector.

1 AP Quiskamp, BT McAllister, G Rybka, ME Tobar, "Dielectric-boosted sensitivity to cylindrical azimuthally varying transverse-magnetic resonant modes in an axion Haloscope," Phys. Rev. Applied vol. 14, 044051, 2020.

advanced metrology

CIs: M. Goryachev, S. Tims, M. Tobar

Postdocs: M. Froehlich, B. McAllister, Z. Slavkovska

PhDs: W Campbell, G Flower, A. Quiskamp, C Thomson

Characterisation of dark mater detector materials

Nuclear recoils induced by dark matter interactions typically have energies in a region heavily affected by environmental radioactivity and cosmic background radiation. Materials used in the experiment need to be chosen for their ultra-low radioactivity, and therefore require careful screening for any possible contamination. Similarly, care must be taken during manufacturing of the components. The next generation of direct-detection dark-matter experiments will require even more stringent radiopurity. AMS is a single-atom counting technique that measures extraordinarily low concentrations of rare radioactive isotopes. AMS setups at the HIAF and ANSTO, coupled with experienced personnel in innovative developments in AMS, are key sites globally for radionuclide detection. Dark-matter experiments have used in-situ data to estimate the level of radioactive impurities in the detector materials. Recent developments in mass spectrometry produced a paradigm shift, allowing for testing and improvement of detector components before building a detector prototype. The Centre, in collaboration with ANSTO, will develop new and innovative AMS techniques and technologies, such as ultra-clean ion sources and new chemical separation and purification methods, to provide several orders of magnitude better sensitivity than all current techniques. AMS has been successfully applied at HIAF to quantify the amount of 129I in the NaI material for the SABRE detectors. In collaboration with ANSTO, a 100-fold improvement in AMS sensitivity for 210Pb detection (an important contaminant in the SABRE detectors) has been demonstrated compared to existing AMS literature. Further increases in sensitivity through optimization of the AMS techniques also appear possible. The measurement of Pb at these low levels requires a 210Pb-free 'carrier' material to be added to the samples to provide enough lead atoms for AMS measurement. Potential materials with which to prepare such a carrier have been identified, protocols and reagents to chemically purify the material are being developed and produced and measurements of the 210Pb content in the candidate carrier materials are scheduled for measurement with the ANSTO VEGA accelerator early next year.

ICP-MS development

Measurements in collaboration with the ANU Research School of Earth Sciences ICP-MS research facility to characterise capabilities for determination of 40K concentrations in detector materials have begun, with first measurements of high purity Sodium Iodide indicating significant improvement is required to reach the desired levels. Further testing is in planning, in parallel with discussions with RSES to identify where appropriate improvements can be made to the ICP-MS equipment to achieve the requisite sensitivity.

AMS capability improvements

New approaches to measure uranium isotopes and the associated naturally occurring radioactive decay progeny are being trialed at ANU. The first stage of a project to assess if an extremely thin self-supporting foil can be incorporated into the existing time of flight detector to improve detector resolution has been completed, but unfortunately indicates the anticipated improvement in timing resolution will not be achieved. A possible alternative is to replace the foil with a silicon nitride window and this will be explored in the near future. There are however a number of other independent modifications to the time of flight system yet to be implemented as part of this project, and the results of this first trial have no bearing on the potential improvements to be gained across other parts of the detector.

Characterisation research highlights

One of the most significant sources of environmental radioactivity with potential to impact detector sensitivity arises from uranium and thorium and their respective decay progeny. The VEGA accelerator at ANSTO was specifically designed to measure isotopes in the populated mass range, and already has a sensitivity close to that needed to measure some of the isotopes that will impact dark matter detectors. The sensitivity required to measure 210Pb, for example, is within an order of magnitude of that already attainable with the VEGA system. Experiments to optimize the 210Pb yields extracted from the samples during AMS analysis are proceeding and already indicate up to 50% more yield can be obtained from the VEGA ion source.

AMS measurements of several of the radioisotope species that arise in the radioactive decay chains, however, still require significant improvement to achieve the sensitivities desired for the dark matter detector. The unique 6m time of flight detection system at the ANU, designed for actinide discrimination, complements the VEGA system in that it has superior sensitivity for some radioisotope species where higher accelerator voltages are needed to remove interference.

The first proof-of-concept actinide trial measurements using the fast isotope switching system, recently implemented at the ANU for 36Cl determination, were successfully carried out in December, and have already yielded a small improvement in sensitivity. The trial measurements, made using plutonium isotopes, indicate that extension of the technique to several of the naturally occurring uranium, thorium and actinium decay series members should be possible. Fast-switching measurements of other decay-chain species is now planned for next year. These first trials of the fast-switching system pave the way, and are also essential, for automation of actinide measurements in the longer term. Automated measurements are expected to significantly improve the statistical precision of the data (and hence sensitivity) by allowing for much longer counting periods. The first automated accelerator runs at ANU are also planned for next year.

New Technology for direct detection

Precision and quantum metrology techniques developed at the UWA are some of the world's best and are directly suited to the sub eV low mass program; in particular the lowest phase noise oscillators ever achieved will be developed. However, these techniques can also be investigated for application to the WIMP dark matter program, in an effort to make better bolometers to sense changes of temperature due to WIMP dark matter. These new techniques form an exciting new area of metrology development.

Low phase noise oscillators will be improved through the use of low temperatures in combination with interferometric noise cancellation; they are expected to be two orders of magnitude better than current state of the art. Quantum and precision frequency bolometer techniques will be investigated to improve cryogenic WIMP detectors.

LHC research program

CIs: E. Barberio, Paul Jackson, Geoffrey Taylor, Martin White

Students: I. Carr, E. Filmer, A. Kong, T. Ruggeri

The interaction that allows WIMPs to scatter off nuclei in a direct detection experiment also allows the production of WIMPs in proton-proton collisions at the Large Hadron Collider (LHC). These experimental searches are complementary to direct detection in terms of the mass of the dark matter particles and their interactions. In addition, the LHC experiments provide limits on the mass and cross sections of WIMP particles in regions of parameter space that complement or overlap with direct detection experiments.

WIMPs will not be directly seen at the LHC, but their presence can be inferred when produced in association with visible particles. In fact, in many new physics theories containing dark matter, there are additional new particles that can be produced at the LHC.

CDM plays an active role in dark matter particles searches in ATLAS, motivated by theories like Supersymmetry. Supersymmetry is a very popular extension of the Standard Model of Particle physics that include WIMPs. The analyses were done using data collected between 2015 and 2018 (Run 2) by the ATLAS detector at the LHC, at a centre-of-mass energy of 13 TeV.

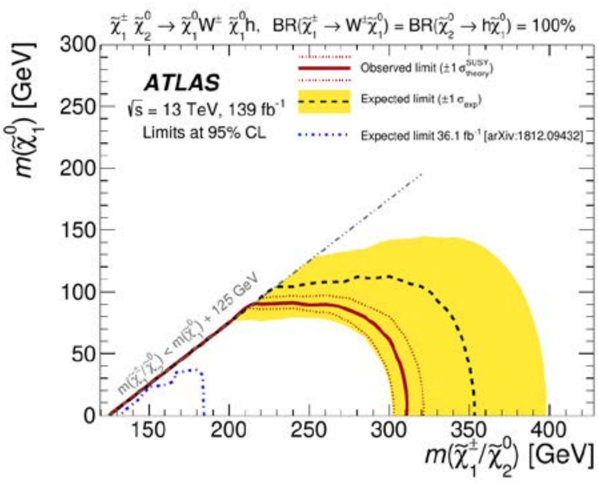
We searched for new physics with narrow resonances using a machine-learning anomaly detection procedure that does not rely on signal simulations for developing the analysis selection. Weakly supervised learning was used to train classifiers directly on data to enhance potential signals. Specific dijet event topologies and the mass of the two jets were used in the machine learning algorithm. There is no significant evidence of a localized excess in the dijet invariant mass spectrum between 1.8 and 8.2 TeV. For some masses range we were able to set limits up to 10 times more sensitive than those obtained by previous searches.

We performed a search for direct top squark pair production in events with missing transverse momentum plus either a pair of jets consistent with Standard Model Higgs boson decay into *b*-quarks or a same-flavour opposite-sign dilepton pair with an invariant mass consistent with a *Z* boson. No excess is observed in the data above the Standard Model predictions. The results are interpreted in simplified models featuring direct production of pairs of either the lighter top squark or the heavier top squark , excluding at 95% confidence level $\tilde{t}_1$ and $\tilde{t}_2$ masses up to about 1220 and 875 GeV, respectively.

The observed (solid line) and expected (dashed lines) exclusion limit contours at 95% CL for the $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0})$ production. in the $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0})$ plane. The dotted lines represent the $\pm 1\sigma$ theoretical uncertainty for the observed limit. The $\pm 1\sigma$ expected exclusion limit contour is shown as the shaded band.

Lastly, we have contributed to a search for a chargino–neutralino pair decaying via the 125 GeV Higgs boson into photons. No significant excess over the expected background is observed.

Collaborative work has commenced between the Universities of Melbourne and Adelaide on the future of the ATLAS Collider Program – Australian contribution to the replacement Inner Detector, with the all-silicon Inner Tracker, ITk. These Centre groups will produce high-technology silicon detector modules for the end-cap of ITk. Students from both groups are participating in this effort both in the laboratory and with computer simulation of the performance of the upgraded ATLAS detector and its improved capacity to detect the effects of potential Dark Matter particles.



The receiver-operator characteristic of nuclear recoil identification in NaI(Tl).
Our new particle identification approach outperforms more commonly used methods.

theory program

Nodes involved: Adelaide, ANU, Melbourne and Swinburne
Chief Investigators: N. Bell, M. Dolan, A. Duffy, C. Simenel, A. Thomas, R. Volkas, M. White, A. Williams

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

PhD Students: L. Friedrich, F. Hiskens, W. Husain, N. Krishnan G. Lawrence, N. Leerdam, A. Leinweber, R. Patrick, A. Ritter, I. Sanderson, M. Virgato, E. Ting, T. Motta

MSci by Coursework: A. Sopov

The overarching aims of the theory program are to determine how a dark matter candidate can be placed into the broader elementary particle physics framework and to provide support for the Centre's experimental programs. Centre theorists will develop theoretical models to describe dark matter particles and their interactions, drawing together the results from experimental programs, together with complementary data from astrophysics and cosmology.

The Centre Theory Program has a large team of researchers, spanning five nodes, with a diverse skill set that incorporates strong expertise in particle, nuclear and astrophysics aspects of dark matter theory. These complementary skill sets will enable us to develop a comprehensive range of dark matter theories and fully explore their observational signatures in a systematic way. To successfully achieve these outcomes, the Centre's theory and experimental programs will be strongly interwoven.

Key aspects of the Theory Program:

- Centre theorists will construct and analyse new high-energy theories that incorporate viable dark matter sectors, guided by experimental results. Phenomenological constraints on these models will be determined using supercomputer simulations and all available experimental data, to powerfully discriminate between different underlying theories (Adelaide, Melbourne).
- The sensitivity of direct detection experiments to particular dark matter candidates will be examined, and ideas for novel experimental signatures will be developed (Adelaide, ANU, Melbourne).
- Cross section calculations for DM-nucleon scattering interactions will be refined, in order to accurately interpret the results of nuclear recoil direct detection experiments (Adelaide, ANU).
- Particle astrophysics techniques will be used as complementary probes of dark matter candidates and their interactions, e.g., indirect detection of dark matter annihilation or decay in regions of high dark matter density; the capture of WIMP-type dark matter in neutron stars; astrophysics constraints on axion-type dark matter (Adelaide, Melbourne).
- Galaxy simulations will be developed to distinguish between different classes of dark matter candidates, such as self-interacting or warm dark matter. Local dark matter density and velocity profiles will impact expected event rates for direct detection experiments and dark matter annihilation signals (Swinburne).

The areas of particular focus for the Theory Program all span multiple Centre nodes. Some key cross-node discussions and collaborations have been initiated and will be expanded in 2021. Highlights of theory research undertaken in 2020 are described below.

Theory Research Case Studies

Explaining Xenon1T with luminous dark matter

In June 2020, the XENON1T direct detection experiment reported an excess of electronic recoil events that could not be attributed to background. Nicole Bell, Jayden Newstead and collaborators explored the possibility of explaining the excess with luminous dark matter [Phys. Rev. Lett. 125 161803, (2020)]. This scenario involves dark matter (excited by a nuclear recoil) decaying within the detector, to produce a photon with energy of approximately 3 keV. They determined that this was a viable explanation for the measured excess for a range of dark matter masses from 1-15 GeV. This work was highlighted as an editor's suggestion in Physical Review Letters, and Newstead was interviewed for a Physics World podcast.

The best fit line signal for a luminous dark matter model with (green) and without (blue) the inclusion of a tritium component, compared with the background only event rate (red) and the background plus tritium event rate (orange). The data points are the Xenon1T measurements. [Figure taken from Bell, Dent, Dutta, Ghost, Kumar and Newstead, Phys. Rev. Lett. 125 161803, (2020).]

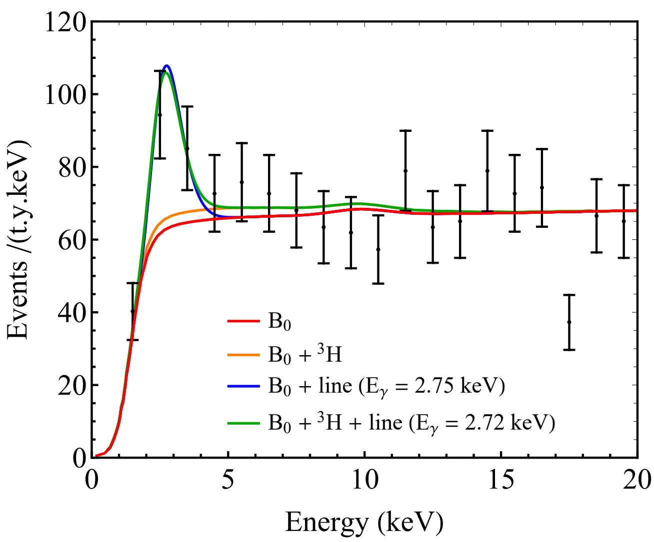
Dark matter annihilation at the Galactic Centre

Nicole Bell, Matthew Dolan and Sandra Robles studied prospects for the indirect detection of dark matter via its annihilation to neutrinos in the Galactic halo, focusing on dark matter of mass below 1 GeV [JCAP 09, 019 (2020)]. They undertook a dedicated simulation of the forthcoming HyperKamiokande neutrino detector, which was benchmarked against the existing SuperKamiokande experiment. They found that HyperKamiokande is sensitive to thermal annihilation cross-sections for dark matter with mass of order 20 MeV.

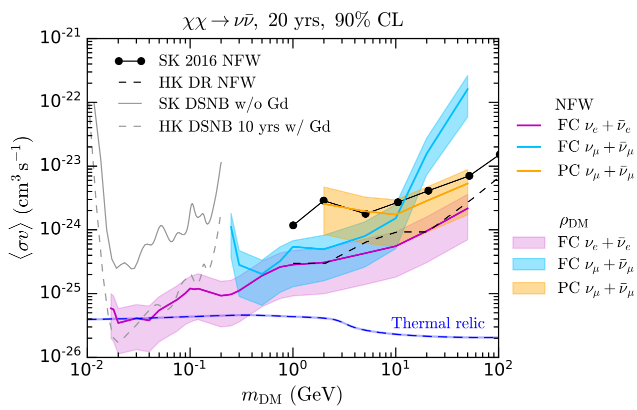
Projected limits for the annihilation of dark matter to neutrinos, , using the fully contained (FC) and partially contained (PC) event classes at the HyperKamiokande experiment. [Figure taken from Bell, Dolan and Robles, JCAP 09, 019 (2020).]

Detecting neutrinos in dark matter experiments

Jayden Newstead and collaborators characterised the sensitivity of the future DARWIN liquid xenon dark matter direct detection experiment to solar neutrinos interacting via elastic electron scattering [Eur.Phys.J.C 80 (2020)]. They found that measurement of 5 of the major flux components is possible within 10 years. This measurement could provide valuable insight to the solar model and the electron-neutrino survival probability at low energies.



The best fit line signal for a luminous dark matter model with (green) and without (blue) the inclusion of a tritium component, compared with the background only event rate (red) and the background plus tritium event rate (orange). The data points are the Xenon1T measurements. [Figure taken from Bell, Dent, Dutta, Ghost, Kumar and Newstead, Phys. Rev. Lett. 125 161803, (2020).]



Projected limits for the annihilation of dark matter to neutrinos, χχ→v¯v , using the fully contained (FC) and partially contained (PC) event classes at the HyperKamiokande experiment. [Figure taken from Bell, Dolan and Robles, JCAP 09, 019 (2020).]

Dark matter capture in neutron stars

Nicole Bell, Giorgio Busoni, Sandra Robles and Michael Virgato examined the capture of dark matter in neutron stars [JCAP 09, 028 (2020)]. This process is controlled by the same scattering cross section that is probed in terrestrial dark matter direct detection experiments and, for many interaction types, can be orders of magnitude more sensitive. They developed an improved treatment of dark matter capture that goes beyond the simplifying approximations commonly used, and which correctly incorporates relevant physical effects such as gravitational focusing, a fully relativistic scattering treatment, Pauli blocking, neutron star opacity and multi-scattering effects.

In follow up work, a Melbourne-Adelaide collaboration of Bell, Busoni, Robles and Virgato with Anthony Thomas and Theo Motta outlined two further important effects that are missing from all existing evaluations of the dark matter capture rate in neutron stars. The use of (i) momentum dependent form factors in the scattering matrix elements and (ii) effective masses to account for nucleon interactions was found to suppress the capture rate by up to 3 orders of magnitude. This work will be finalized for publication in 2021.

Axion dark matter

Jayden Newstead and collaborators showed that XENON1T and future liquid xenon direct detection experiments are sensitive to axions through the standard axion-photon coupling due to inverse-Primakoff scattering [Phys.Rev.Lett. 125, 131805, (2020)]. This previously neglected channel significantly improves the sensitivity to the axion-photon coupling, with a reach extending to for axion masses up to a keV, thereby extending into the region of heavier QCD axion models.

Ciaran O'Hare, together with collaborators at Partner Organisation Stockholm University, looked at the flux from a previously ignored source of axions in the Sun [Phys. Rev. D 102, 043019 (2020)]. This emission involves the resonant conversion of longitudinal modes in Sun's magnetised plasma. Accounting for this flux can lead to improved bounds on axions, and will improve the ability to use helioscopes to measure axion properties.

Projected photon spectra in the International Axion Observatory, for a range of pressures in the buffer gas mode. The solid lines show the contribution to the signal from the Primakoff flux alone, and the dashed lines indicate the upper bound of the contribution from the longitudinal plasmon flux. [Figure from O'Hare, Caputo, Millar and Vitagliano, Phys. Rev. D 102, 043019 (2020).]

Model building

Wei Su, Martin White and Anthony Williams explored two-Higgs-doublet models (2HDMs) at the LHC [arXiv:1909.09035]. Many dark matter models feature extra Higgs fields, which can be probed through searches for the extra Higgs bosons or measurements of the Standard Model (SM)-like Higgs boson. They demonstrated that the sensitivity of current interpretations of the LHC results can be significantly improved by including next-to-leading order effects. This work will be published in early 2021.

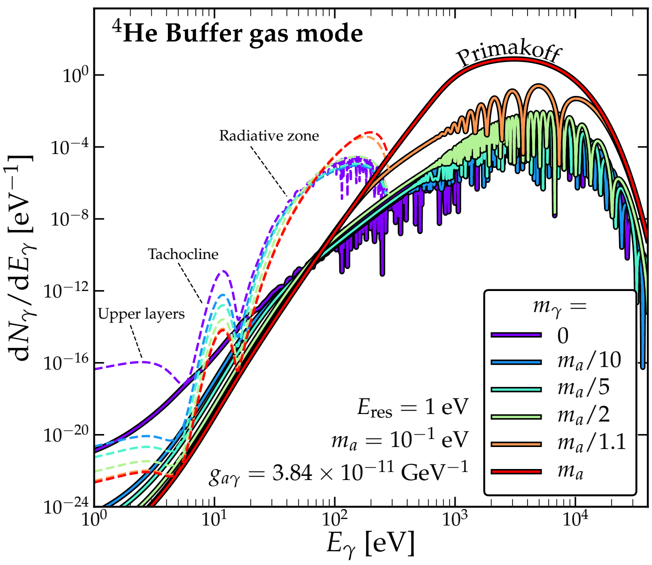
Alex Ritter and Ray Volkas developed an asymmetric dark matter model based on the spontaneously-broken mirror matter concept in order to address the mystery of why the present-day mass densities of ordinary and dark matter are so similar. They showed that a cosmological asymmetry between dark matter and dark antimatter can be generated in the dark sector and then reprocessed into the ordinary sector. Importantly, this was achieved in a context where the dark matter is identified with the dark baryon and naturally has a mass similar to the proton mass, thus explaining the similarity of mass densities. This work will be published in 2021.

CosmoBit

Martin White and collaborators developed CosmoBit, which is a new module for the Global and Modular beyond-Standard Model Inference Tool (GAMBIT) – a general purpose software tool for interrogating models of new physics with a broad spectrum of particle astrophysics data [arXiv:2009.03286]. CosmoBIT will provide a flexible framework for studying beyond standard model physics, including dark matter models. This work will be published in early 2021.

Dark matter-nucleon scattering

Xuan-Gong Wang and Anthony Thomas worked on the effective field theory (EFT) of DM-nucleus scattering [arXiv:2012.10144]. They derived the corrections to the nonrelativistic effective DM-nucleon operators by taking into account nuclear dynamics, notably the relativistic mean-field. Certain interactions receive non-negligible corrections, which may significantly enhance the sensitivity of the scattering cross section. This work will be published in early 2021.



Projected photon spectra in the International Axion Observatory, for a range of pressures in the buffer gas mode. The solid lines show the contribution to the signal from the Primakoff flux alone, and the dashed lines indicate the upper bound of the contribution from the longitudinal plasmon flux. [Figure from O'Hare, Caputo, Millar and Vitagliano, Phys. Rev. D 102, 043019 (2020).]

SUPL update

The Stawell Underground Physics Laboratory (SUPL) is on track to become the first underground physics laboratory in the Southern Hemisphere. The University of Melbourne is project managing the construction of the laboratory with funding from Regional Development Victoria ($5m) and the Australian Government's Department of Education, Skills and Employment ($5m).

The early works package was completed in August 2020 and the photo on page 37 of the excavated and prepared cavern is demonstrative of the size of the Main Experimental Hall where the SABRE will be housed. This hall is 33m in length, 12m high and 10m wide.

SUPL is at a depth of 1,025m underground within the existing operational Stawell Goldmines (SGM). To access the laboratory, scientists are currently driven by SGM staff through 7km of underground road network, an approximate 35 minute journey. Once construction is completed, several laboratory technicians/ scientists will be trained and accredited to drive in this unique underground operational goldmine.

SUPL is adjacent to the Stawell township in central western Victoria. The SUPL location was selected as the preferred laboratory site as it has the required geology, depth and underground conditions needed for the operation of ultra-precise research equipment (such as SABRE). The Stawell location also has the benefits of providing a good level of local accommodation and services and being reasonably accessible to the important Australian research, education and population centres of Melbourne, Adelaide and Canberra.

The tender for construction of SUPL was issued in December 2020. The award of the contract and commencement of the SUPL fit out is anticipated to commence in April 2021, with the laboratory programmed for completion by the end of 2021.

High precision hypersensitive measurements, such as the search for dark matter, require an ultra-low background environment of an underground laboratory. Currently Australian scientists must travel overseas to one of several international underground research laboratories, all of which are located within the Northern Hemisphere. A key issue with the research undertaken to date has been the potential impact of seasonality on research outcomes. As a result, there has long been a need for the development of an underground research facility in the Southern Hemisphere, in order to account for, or discount, observed seasonal fluctuations in experiments hosted in the Northern Hemisphere. A Southern Hemisphere laboratory also supports local scientific research and increases the opportunity for Australians to participate in, and lead, international research collaborations.

To manage the operation of the SUPL facility a new organisation, the Stawell Underground Physics Laboratory Company (SUPLC), will be established in 2021. SUPLC will undertake the operation of the SUPL facility and is a collaboration between the SUPL Research Partners. The inaugural members of the SUPL partnership are as follows:

- University of Melbourne
- Swinburne University of Technology
- University of Adelaide
- Australian National University
- Australian Nuclear Science and Technology Organisation (ANSTO).

University of Melbourne Dean of Science, Prof Moira O'Bryan examines the prepared excavation for the SUPL Experimental Hall with Prof Elisabetta Barberio, Amanda Western and SGM Safety Adviser, Tony Silk.

translation – focus on innovation

The Innovation Lab is aimed at exploring new opportunities for Dark Matter science to positively impact society and/or translate related technology to commercial application. It will use design innovation methods to imagine and demonstrate new possibilities for using sensing and detecting technologies needed by Dark Matter experimentation.

The goal is to create an innovation culture, foster collaboration across science, design + business, and use experimental design processes that may increase the number of breakthrough technologies developed like MRI and touchscreens, and work with student groups to equip next generation of innovators with skills and mindsets to leverage the potential of Australia's research expertise in science and deep technology.

In Australia, we are positioned very well to create economic growth through better translating and investing in deep technology. We have the technical knowledge, but often fail to convert it to commercial application. A recent study undertaken for Cicada Innovations (an Australia incubator for deep technology, established 20 years) highlights that every $1 generated by a deep tech company, $3 of value is received back to other parties such as the general public and start-ups. *"While deep tech's long timeframes can be daunting, they yield the technologies that can help us hear, cure cancer, connect us across oceans and feed us"* .[1]

The Innovation Lab complements work of traditional technology transfer and translation portfolios, by using design demonstrate new possibilities for deep technologies that may otherwise appear obscure to most professions. It works with early stage innovation process to imagine applications that connect science with commercial and societal needs, assisting technologies to cross 'the valley of death'.[2]

A range of innovation activities will be available to Centre members, stakeholders and communities. We will host innovation workshops, seed fund the development of good ideas that increase the Centre's impact on society and develop a range of challenge based innovation programs aimed at exploring new products and commercial applications using Dark Matter technologies. This will include research and development of Kreativity Kits, to create empowering learning opportunities at the intersection of science and design innovation for secondary schools students, particularly in remote locations.

1 https://www.innovationaus.com/deep-tech-is-an-unprecedented-opportunity/
2 The valley of death refers to the point where scientific knowledge fails to translate from the lab to a commercial application

equity, diversity and inclusion

The physics skilled workforce in Australia is largely dominated by men and three times more male students choose physics subjects in high school. Only 15% of Research Fellows in physics are women, and they have less chance of securing a continuing position than men[1]. Improving gender balance in physics is a priority and must be done at a much faster pace than is currently happening.

Equity is not limited to gender balance. Major inequalities persist around the world, as illustrated by the recent Black Lives Matter movement. In Australia, part of the problem of racial inequality is rooted into the reduced educational opportunities for Aboriginal and Torres Strait Island people that would equip them with skills such as those required in academia.

The Equity, Diversity and Inclusion (EDI) is one of the key portfolios of the Centre. Its mission is to develop innovative initiatives to significantly improve gender balance in STEM, to reach towards indigenous communities, and to ensure that the Centre offers an inclusive and respectful workplace to all its members and associates.

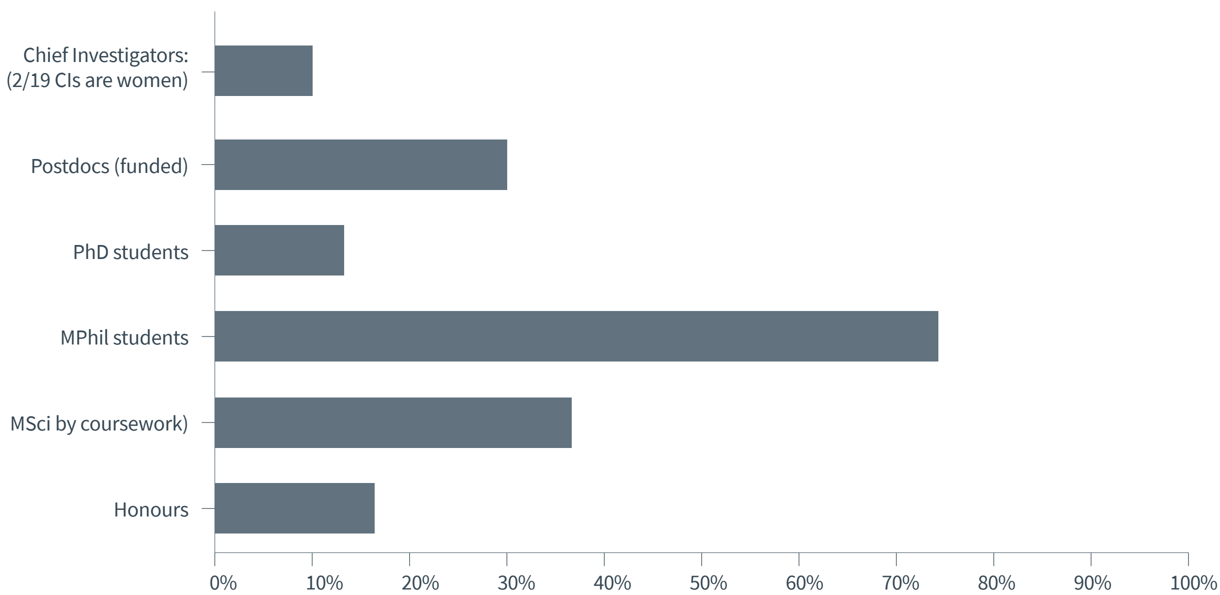
During four months of activities in 2020, the focus of the EDI committee has been in the elaboration and adoption of the strategic plan that details our equity, diversity and inclusion objectives and strategies for the lifetime of the Centre. Our vision is to, "Lead by example towards equity and diversity through inclusion, flexibility, and inspiring new generations".

Our mission is to:

1. Improve gender balance in STEM through ambitious policies
2. Support families and carers
3. Inspire a new, more diverse generation toward STEM
4. Build a culture of respect and inclusion

To achieve this mission, we have identified many objectives, from hiring policies to carer support, fellowships, and training. Our code of conduct is central to ensure the best working environment for all members. Our mentoring program is tailored for women. Meetings and Centre events take place at family friendly hours and child care will be available at in person workshops. Already we have secured five academic positions, seeded by the Centre, which will all be continuing positions at the end of the Centre, and at least four of these positions will be occupied by women.

Percentage of women



1 2012 Australian Physics Decadal Plan

Equity and Diversity Case Study: PURL and Code of Conduct

Physics has moved from individual or small group works to large international collaborative endeavour progressively over the 20th Century. The purpose of a Centre of Excellence is to support such collaborations. It is composed of people who aspire to achieve more together than what they would be capable of as a collection of individuals.

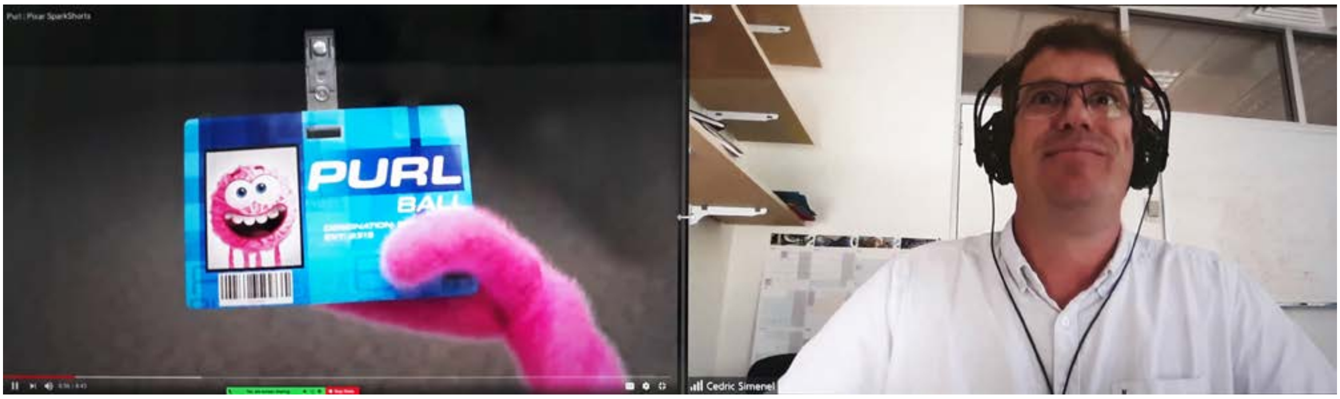
To progress and achieve its goals, a Centre requires communication, supervision, exchange of ideas and even debates between its members in an inclusive and respectful way. It can be beneficial for a framework to be put in place to outline a common culture as well as the rules under which these interactions are expected to take place.

Since its official start, the Centre has been developing, implementing and communicating about its Code of Conduct. The Code of Conduct specifies the Centre's values, its policy, as well as the expected behaviour of its members, including their use of social media. It also provides guidance on how to deal with difficult situations and potential grievances.

The Code of Conduct is not the only tool at our disposal to ensure respect, equality and inclusion in the workplace. Several initiatives of the Equity, Diversity and Inclusion committee, including training and awareness, have the same goals.

One creative and effective example of the ways the Centre has communicated the importance of respect, equality and inclusion has been through the projection of the Pixar video "Purl" at the 2020 annual meeting. The video shows the difficulties encountered by a new member of a company, and how she triggers changes in the workplace that make it more diverse and inclusive.

Poorly chosen jokes can be harmful, but a good sense of humour is a great way of communicating powerful ideas! Responses to a survey asking for feedback after the event highlighted the impact of the video in both entertaining Centre members and conveying an effective and impactful message about the value of inclusion.



Messages about Equity and Diversity were communicated by Prof Cedric Simenel through the Code of Conduct and the more informal introduction of PURL at the Annual Workshop

engagement and media portfolio

One of the core roles portfolios at the new Centre is ensuring its engagement program lives up to the aspirations created in the Centre's successful ARC bid.

Over the course of several lengthy workshops in the second half of 2020, a team of 15 volunteers from across the Centre, Science Gallery Melbourne, ANSTO and beyond outlined the Engagement Strategic Plan to ensure the Centre makes a real difference to the community in Australia.

At its heart the Centre wants to share the excitement and benefits of Australia's hunt for dark matter to inspire and train a new generation of innovative thinkers. From deploying real experiments to schools to developing Kreative Kits that teach design thinking, the technology and techniques that come from this 'hunt' will find new uses in society and underpin that this fundamental science is both inspirational but also impactful.

The Centre has a particular focus on regional Australia, so often missed from Centre of Excellence initiatives because it is harder to reach, but for the Dark Matter Centre it's where some of the key experiments are located, allowing us to change that dynamic. Unlike other Centres we won't spread out engagement efforts but rather we will focus them on key school partnerships, investing in them, their teachers and students, over many years.

The Centre does this to demonstrate how targeted projects can increase STEM enrolments, particularly of girls, and offer that as a study for others to emulate.

The Centre has also been introducing a broader audience to the concept of dark matter through its partnership with the National Gallery of Victoria. The gallery's Triennial exhibition featured art by Alicja Kwade exploring the mystery of dark matter and the Centre Director supplied an article titled, "Exploring the most unknown universe", which appeared in the NGV Triennial 2020 publication. The Centre will pursue further collaboration between the art and scientific worlds in coming years.

The Centre media strategy is similar, aiming to make an impact not just hit 'appearance targets' with number of press releases produced. Having dynamic and distributed the Centre research teams front and centre of major news items is the key to developing a new generation of media stars. Investing in training and powerful visualisations that help to better tell our story will further support this younger cohort.

Based on the excitement and enthusiasm the Centre has already experienced it will be exciting to see how far we share our Centre's work and the significance of the impact it will make on Australia and beyond.

The Triennial 2020 exhibition at the National Gallery of Victoria featured works by Alicja Kwade exploring the mystery of dark matter.

media highlights

The Centre has featured across broadcast, online and print media for mainstream and science publications. The Stawell Underground Physics Laboratory appeared in many of the articles, at the site.

Other news covered the search for dark matter, the Centre's annual workshop and its partnership with Stawell Secondary College.

- **31 August 2020 – Channel 9 News**

  "Australia's top scientists will begin experiments on the historic mining town of Stawell to detect dark matter as part of the plan to replicate findings made in Italy's Gran Sasso National Laboratory.."

- **28 August 2020 – ABC Australia-wide**

  "Most physicists say dark matter holds the universe together, but it's never actually been detected. Australia is now joining the search for dark matter."

- **30 October 2020 – 3AW**

  "Scientist are searching for dark matter which is a remnant of the Big Bang in an underground gold mine in Stawell. An underground laboratory is being built."

- **31 October – Herald Sun**

  "Stawell gold mine's high tech lab aims to unlock a mystery of the universe."

- **22 November 2020 – Science Friction, ABC Radio National**

  "How do you solve a problem like Dark Matter?"
  With poet Alicia Sometimes

- **12 December 2020 - It's Just Not Cricket, ABC**

  "Out there under here. How do you examine the mysteries of the universe by digging a big hole?"

- **17 December 2020 - The Stawell Times**

  "An exciting new partnership will see Stawell students granted front-row access to world-leading research."

case study: education program

The Centre's Education Program aims to build long-term and high-impact relationships with regional schools.

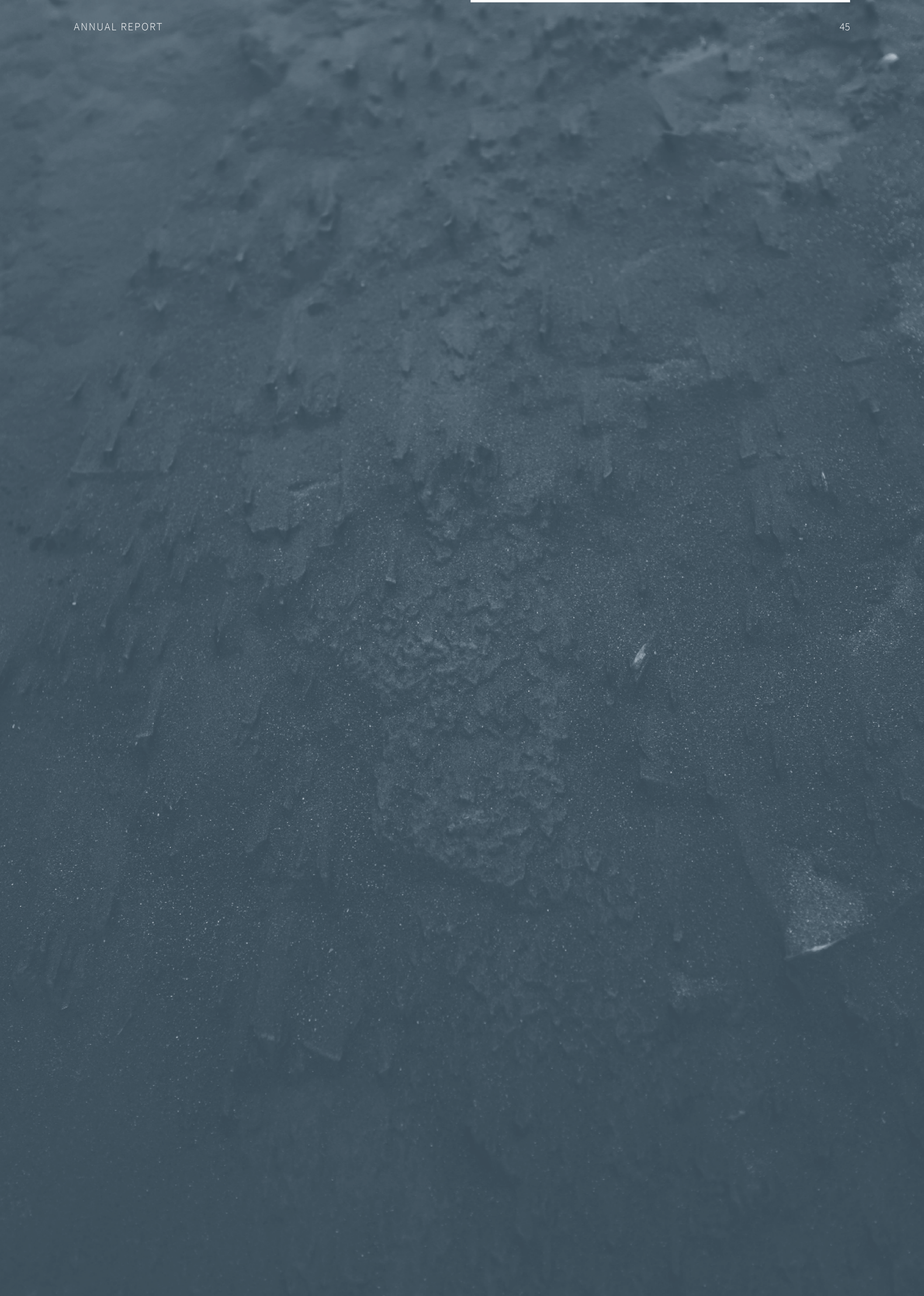
The goal is to leverage partnerships between the Centre, regional communities and schools to design and incorporate unique education experiences for students and professional development opportunities for teachers. By working with regional schools, the Centre aims to highlight STEM opportunities, including tertiary pathways, with special focus on increasing the participation of women in STEM.

Components of the education program will be: using and, where applicable, collecting, real data in science engagements; incorporating innovative design experiences in conjunction with the Melbourne Design Factory; and offering artist-in-residence workshops to highlight creativity in science. These elements will be incorporated across all year levels of secondary instruction and will be developed in collaboration with teachers at the partner schools. They will include input for the Centre's partners such as node universities, SUPL, and CSIRO.

These lessons and activities, while scaled appropriately for year levels, will be united by common themes. Students will participate in activities across subsequent years and across disciplines while investigating how to model that which cannot be seen. They will incorporate a special sense of place and time relating to the schools' regional and rural locations, the local knowledge, and the temporal logic embedded in dark matter detection. Furthermore, all lessons and activities will be curriculum-aligned to be embedded within the curriculum goals of the schools.

This education will be piloted at Stawell Secondary College in 2021 with scaled arts, science, and innovation activities developed with the teachers and delivered in conjunction with the Centre's ECRs. After the pilot year, the Centre will collaborate with regional schools across node states. Additionally, all materials developed for this education program will be made available to educators across Australia through Centre-delivered professional development workshops.

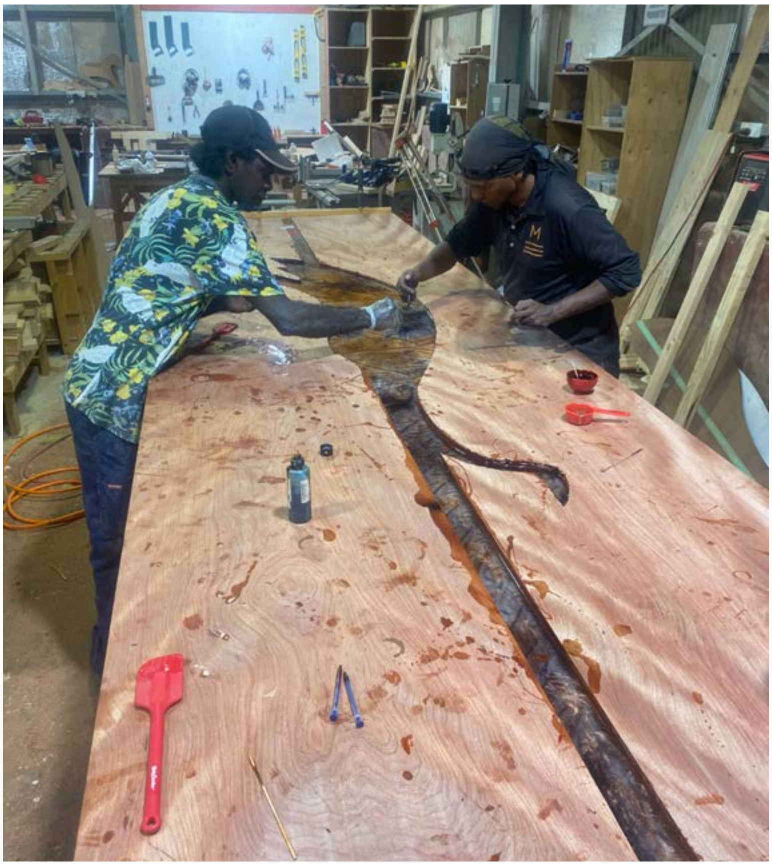
Stawell Secondary College principal Carlos Lopez and Dark Matter Centre Chief Operating Officer Amanda Western are thrilled to join forces for the STEM pilot program. Picture: Ben Fraser



centre headquarters

The Centre's new boardroom table was designed and constructed by the Yolgnu people in East Arnhem Land.

Students Katerina Patsis and Michael Mews at the Centre entrance.



Josiah Baker and Dawson Garrawurra pouring one of the seven layers of epoxy used to create the Kallaia Galaxy.

Manapan table onsite

events

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

The Centre 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.

While the Centre launched during the COVID-19 pandemic, forcing events to be held online via Zoom, in the case of some nodes where restrictions were not as tight, members were able to attend in person.

On Dark Matter Day, the Centre carried out a range of promotional activities to inform the scientific, academic and wider communities of the significance of the search for dark matter.

This included a webinar and media and social media promotion of both the event and the excitement of the Centre's exploration into the nature of dark matter.

The Annual Workshop in December brought together students, researchers and professional staff from across the Centre's nodes to introduce and stimulate discussion about current projects.

It also offered Portolio leaders, including Alan Duffy in Outreach and Media, Anthony Thomas in Mentoring and Cedric Simenel in Equity, Diversity and Inclusion, with the chance to share their ideas and plans for the year ahead.

The day offered a valuable opportunity to share knowledge and experience between members and across projects, and led to media opportunities with the ABC, including interviews with Elisabetta Barberio and Greg Lane, discussing the aims of the Centre, with a focus on the construction of SUPL.

Student, Grace Lawrence has provided her thoughts on her experience of the workshop in later pages.

annual workshop: a student's perspective

The cross-pollination of research ideology became the focus of the two-day Annual Workshop, which distilled the knowledge and expertise of scientists from nuclear, quantum, particle and astronomy backgrounds with the common goal of understanding the nature of dark matter.

The Centre aims to explore, both theoretically and experimentally, the dark matter candidates within the mass range of a micro-electron volt, where dark matter starts to behave like waves instead of particles, all the way up to the micro-Earth mass.

Starting from the top of this mass range, a team of astronomers is searching for asteroid-mass primordial black holes as dark matter by hunting for microlensing events near the Large Magellanic Cloud.

Collider physics is searching for high mass candidates, including the WIMP (Weakly Interacting Massive Particle), using the LHC. The search is for the missing transverse momentum that would indicate that smashing two proton beams together, at close to the speed of light, generates dark matter.

Direct detection took centre stage with the SABRE south experiment, a direct response to the DAMA/LIBRA detection claim of annual modulation due to dark matter. Hosted in the Stawell Underground Physics Laboratory, the experiment is half of a dual-hemisphere effort using radio-pure crystals to search for the nuclear recoil signature left when a dark matter particle collides with the nucleus of a sodium iodide detector. Its active scintillating veto and dual-hemisphere aspect make SABRE, and its directional processor Cygnus, a cutting-edge opportunity for dark matter direct detection.

Centre members working on advanced metrology are developing methods to measure contamination which may be present in these detector materials.

The theory chapter, while underpinning all work, is also exploring some novel signals. For example, the capture of dark matter in neutron stars whereby the kinetic energy of captured dark matter could heat neutron stars to above expected ranges. This would allow an exclusion region of parameter space for dark matter mass and cross-section to be determined.

The Centre forges collaborations at the interface of many fields, providing the opportunity for high-yield, multidisciplinary science that will define dark matter research over the next seven years and continue to inform and shape the discipline for many years afterward.

Grace Lawrence

dark matter day

To celebrate Dark Matter Day on 31 October 2020, the Centre held a webinar that was open to members and the wider community.

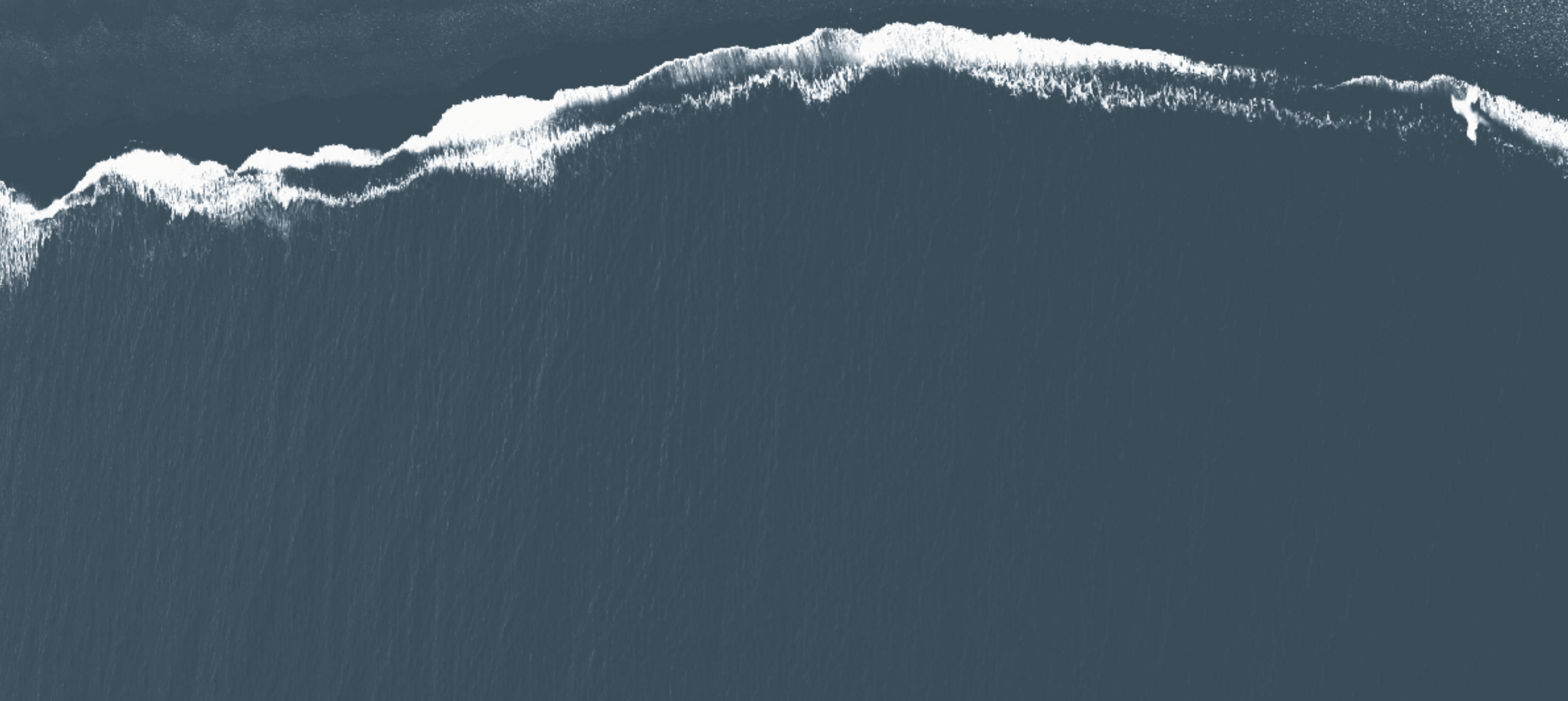
Researchers from across the country took part in the event. Dr Ciaran O'Hare (University of Sydney) spoke about the Evidence for Dark Matter, Dr Michael Baker (University of Melbourne) covered the Theory of Dark Matter, Dr Ben McAllister (University of Western Australia) spoke about Direct Detection and offered a guided 3D virtual tour of the ORGAN experiment at UWA and Cate MacQueen (University of Melbourne) spoke about Collider Searches.

Question and answer sessions offered participants the opportunity to become involved in the discussion.

The event provided an opportunity for researchers to collaborate and share the research happening at the Centre with a wider audience, promoting the search for dark matter.

The Centre's celebration of Dark Matter Day generated media attention, with an article appearing in the Herald Sun titled *"Stawell gold mine's high tech lab aims to unlock a mystery of the universe."* In the article, Centre member and event organiser Dr Michael Baker was interviewed about the search for dark matter and the role of SUPL in the search.

The Centre aims to mark future Dark Matter Days with similar events, with the aim of educating the public about the significance of dark matter, celebrate the exciting search for dark matter, and provide researchers with the chance to collaborate with and present to their colleagues and audiences outside the Centre.



awards and prizes

Dr Michael Baker
Dyason Fellowship 2020
awarded by the University of Melbourne

Prof Nicole Bell
2020 Nancy Millis Medal
awarded by the Australian Academy of Science

Dr Matthew Dolan
Dean's Award for Excellence in Research
awarded by the University of Melbourne

Navneet Krishnan
John Carver Physics Prize
awarded by the Australian National University

Prof Anthony William Thomas
Companion of the Order of Australia
awarded by the Governor General of Australia

Professor Christine Thong
2020 Vice Chancellor's Engagement Award for Industry Engagement (team)
awarded by Swinburne University of Technology

student completions

Honours:

Charles Grant (UoA)

Zachary Searle (UoA)

Shiryo Owa (UoA)

Navneet Krishnan (ANU)

Masters:

Elrina Hartman (UWA)

Lachlan McKie (ANU)

Lachlan Milligan (UoM)

key performance indicators

Performance Measure	Target 2020	Actual 2020
1 Number of research outputs		
• Journal articles	10	25
2 Quality of research outputs		
• % of publications in peer reviewed, international journals	80%	89%
3 Number of workshops/conferences held/offered by the Centre		
Topical workshops with national or international speakers	n/a	n/a
International conferences	n/a	n/a
4 Number of training courses held/offered by the Centre		
Professional training/development courses offered by the Centre	n/a	n/a
Number of Centre attendees at all professional training/development courses offered by the Centre	n/a	n/a
Culture Building/Be Your Best Training	1	1
Innovative Thinking training (Innovation Lab)	n/a	n/a
5 Number of additional researchers working on Centre research		
• Postdoctoral researchers	9	10
• Honours students	5	6
• PhD students	5	29
• Masters by research students	0	5
• Masters by coursework students	5	8
• Associate Investigators	5	19
6 Number of postgraduate completions		
PhD	n/a	n/a
Honours/MSc/MPhil Completions	2	7
7 Number of mentoring programs offered by the Centre		
Mentoring programs	n/a	n/a
Industry/ External internships for PhDs	n/a	n/a
8 Number of presentations/briefings		
• To the public	2	15
• To government (parliamentarians and department/agencies at both State and Federal level)	n/a	4
• To industry/business/end users	n/a	9
• To non-government organisations	n/a	n/a
• To professional organisations and bodies	5	6
News stories	2	37
Press releases	3	3
9 Number of new organisations collaborating with, or involved in, the Centre		
International	0	0
National	n/a	n/a
10 Number of female research personnel		
Female	>20%	22%
11 Centre-specific KPIs		
Number new of Continuing/Tenure Track Positions in Centre nodes seeded by the Centre	1	1
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)	1	1
School visits or webcasts	1	10
Number of invited talks/papers/keynote lectures given at major international meetings (including those held in Australia	5	15
Centre's Dark Matter Prize for high school students (# entries)	n/a	n/a

publications

A.P. Quiskamp, B.T. McAllister and M.E. Tobar, “Dielectric-Boosted Sensitivity to Cylindrical Azimuthally Varying Transverse-Magnetic Resonant Modes in an Axion Haloscope”, *Phys. Rev. Applied* 14 – (2020)

E. Barberio, “Exploring the most unknown universe”, *Contribution to the NGV Triennial,* ISBN 9781925432848 *(2020)*

E.N .Taylor, M.E. Cluver, A.R. Duffy, P. Gurri, H. Hoekstra, A. Sonnenfeld, M.N. Bremer, M.M. Brouwer, N.E. Chisari, A. Dvornik, T. Erben, H. Hildebrandt, A.M. Hopkins, L.S. Kelvin, S. Phillipps, A.S.G Robotham, C. Sifón, M. Vakili, A.H. Wright, “GAMA + KiDS: empirical correlations between halo mass and other galaxy properties near the knee of the stellar-to-halo mass relation”, *Monthly Notices of the Royal Astronomical Society*, 499, 2 (2020)

F. Froborg, A.R. Duffy, “Annual modulation in direct dark matter searches”, *Journal of Physics G: Nuclear and Particle Physics*, 47 (2020)

J.B. Dent, B. Dutta, J.L. Newstead, A. Thompson, “Inverse Primakoff Scattering as a Probe of Solar Axions at Liquid Xenon Direct Detection Experiments”, *Phys. Rev. Lett.* 125 (2020)

K.A. Cheminant, D. Góra, D.E. Alvarez Castillo, A. Ćwikła, N. Dhital, A.R. Duffy, P. Homola, K. Kopański, M. Kasztelan, P. Kovacs, M. Marek, A. Mozgova, V. Nazari, M. Niedzźwiecki, D. Ostrogórski, K. Smolek, J. Stasielak, O. Sushchov, J. Zamora-Saa "Search for ultra-high energy photons through preshower effect with gamma-ray telescopes: Study of CTA-North efficiency”, *Astroparticle Physics*, 123, 102489 (2020)

L. J. Bignell, E. Barberio, M. B. Froehlich, G. J. Lane, O. Lennon, I. Mahmood, M. S. Rahman, C. Simenel, N. J. Spinks, A. E. Stuchbery, H. Timmers, L. Wang, J. Wu, Y. Y. Zhong, “SABRE and the Stawell Underground Physics Laboratory Dark Matter Research at the Australian National University “, *EPJ Web of Conferences* 232 (2020)

Md.S. Rahman, W.D. Hutchison, L.J. Bignell, G.J. Lane, H. Timmers, “ Investigation of Viton O-Ring Performance for the SABRE Dark Matter Experiment”, *JMEP* 29 (2020)

M. Antonello (INFN, Milan) et al., “Characterization of SABRE crystal NaI-33 with direct underground counting”, Dec 4, 2020. 10 pp.

M.E.Tobar, B.T.McAllister, M. Goryachev, “Broadband electrical action sensing techniques with conducting wires for low-mass dark matter axion detection”, *Physics of the Dark Universe* 30 (2020)

M.J. Zurowski, E. Barberio (Melbourne U.), G. Busoni (Heidelberg, Max Planck Inst.), “Inelastic Dark Matter and the SABRE experiment“, *JCAP* 2012 (2020)

N.F. Bell, J.B. Dent, B. Dutta, S. Ghosh, J. Kumar, J.L. Newstead, “Explaining the XENON1T Excess with Luminous Dark Matter”, *Phys. Rev. Lett.* 125 (2020)

N.F. Bell, G. Busoni, S. Robles and M. Virgato, “Improved treatment of dark matter capture in neutron stars”, *Journal of Cosmology and Astroparticle Physics*, 2020, (2020)

N.F. Bell, M.J. Dolan, S. Robles, “Searching for Sub-GeV dark matter in the galactic centre using Hyper-Kamiokande", *Journal of Cosmology and Astroparticle Physics*, 2020, (2020)

The ATLAS collaboration

ATLAS authors from the ARC Centre of Excellence for Dark Mater Particle Physics are Elisabetta Barberio, Isabel Carr, Paul Jackson, Albert Kong, Peter McNamara, Tristan Ruggeri, Scott Williams, Federico Scutti, Geoffrey Taylor, Tony Tran, Phillip Urquijo, Martin White.

“Performance of the missing transverse momentum triggers for the ATLAS detector during Run-2 data taking”, *JHEP* 2020 (2020)

“Search for top squarks in events with a Higgs or Z boson using 139 fb−1 of *pp* collision data at s√=13 TeV with the ATLAS detector”, *The European Physical Journal C* 80 (2020)

“Performance of the upgraded PreProcessor of the ATLAS Level-1 Calorimeter Trigger”, *Journal of Instrumentation*, Volume 15

“Dijet Resonance Search with Weak Supervision Using √s=13 TeV pp Collisions in the ATLAS Detector”, *Phys. Rev.* Lett. 125 (2020)

“Search for Heavy Resonances Decaying into a Photon and a Hadronically Decaying Higgs Boson in pp Collisions at √s=13 TeV with the ATLAS Detector”, *Phys. Rev Lett* . 125, 251802 (2020)

“Search for direct production of electroweakinos in final states with missing transverse momentum and a Higgs boson decaying into photons in pp collisions at s√*s* = 13 TeV with the ATLAS detector”, *JHEP* 2020, 5 (2020)

“Search for new non-resonant phenomena in high-mass dilepton final states with the ATLAS detector”, *JHEP* 2020, 5 (2020)

“Operation of the ATLAS trigger system in Run 2”, *JINST* 15 (2020)

Cosmic-Ray Extremely Distributed Observatory (CREDO) Collaboration

CREDO author from CDM is Alan Duffy. “Cosmic-Ray Extremely Distributed Observatory”, *Symmetry* 12(11), 1835 (2020)

“Towards A Global Cosmic Ray Sensor Network: CREDO Detector as the First Open-Source Mobile Application Enabling Detection of Penetrating Radiation”, *Symmetry*, 12(11), 1802 (2020)

“The first CREDO registration of extensive air shower”, *Physics Education*, 55, 5 (2020)

Darwin Collaboration

DARWIN collaboration author from CDM is Jayden Newstead.

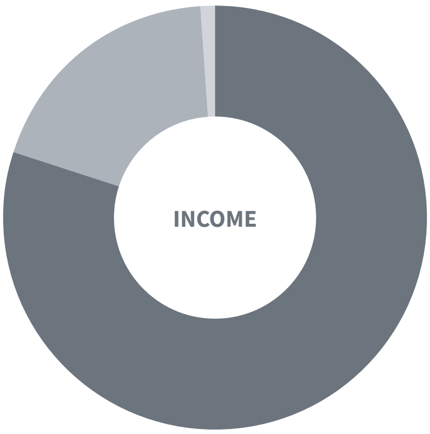
“Solar neutrino detection sensitivity in DARWIN via electron scattering“, *The European Physical Journal C* 80, 1133 (2020)

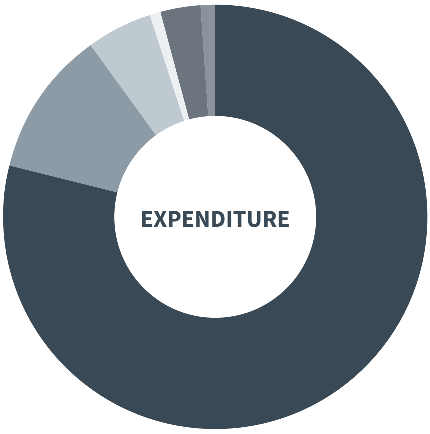
financial report

Statement of Income and Expenditure for year ended 31 December 2020

Reporting Period	2020
INCOME	
ARC Grant	$5,089,998
University Contributions	$1,218,397
Partner Contributions	$20,000
TOTAL INCOME	$6,328,396
EXPENDITURE	
Salaries	$1,008,666
Equipment	$134,593
Travel, Visitor Support & Conferences	$3,481
Research Computing, Lab Maintenance & Consumables	$58,129
Management and Administration	$18,797
Outreach, Communications & Mentoring	$41,490
Scholarships	$12,467
TOTAL EXPENDITURE	**$1,277,624**
TOTAL CARRYFORWARD TO NEXT YEAR #	**$5,050,772**

Carryforward includes $2,500,000 of ARC Grant to fund the first six months of 2027 due to Centre starting in August 2020.
Travel, Visitor Support & Conferences not included as less than 0.5%.





- ARC Grant (80%)
- University Contributers (19%)
- Partner Contributors (1%)

- Salaries (79%)
- Equipment (11%)
- Research Computing, Lab Maintenance & Consumables (5%)
- Management and Administration (1%)
- Outreach, Communications & Mentoring (3%)
- Scholarships (1%)

In Kind Contributions

Contributor	2020 Reporting Period*
The University of Melbourne	1,720,350
The Australian National University	340,287
The University of Adelaide	271,207
Swinburne University of Technology	82,728
The University of Western Australia	192,056
ANSTO	20,646
DST Group	7,686
The University of Sheffield	14,288
INFN Laboratori Nazionali del Gran Sasso (LNGS)	1,260,000
University of Amsterdam	5,547
California Institute of Technology (Caltech)	6,485
University of Freiburg	11,500
The University of Washington	5,547
Massachusetts Institute of Technology (MIT)	5,547
Stockholm University	6,485
Total	**3,950,356**

*The in kind support is based on six months in 2020 due to the late start of the Centre and is reduced due to Covid 19 restricting access to facilities, equipment and the LNGS and Boulby underground laboratories.

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