Ben McAllister
Swinburne University of Technology

CELLAR

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Cryogenic Experimental Laboratory for Low-background Australian Research

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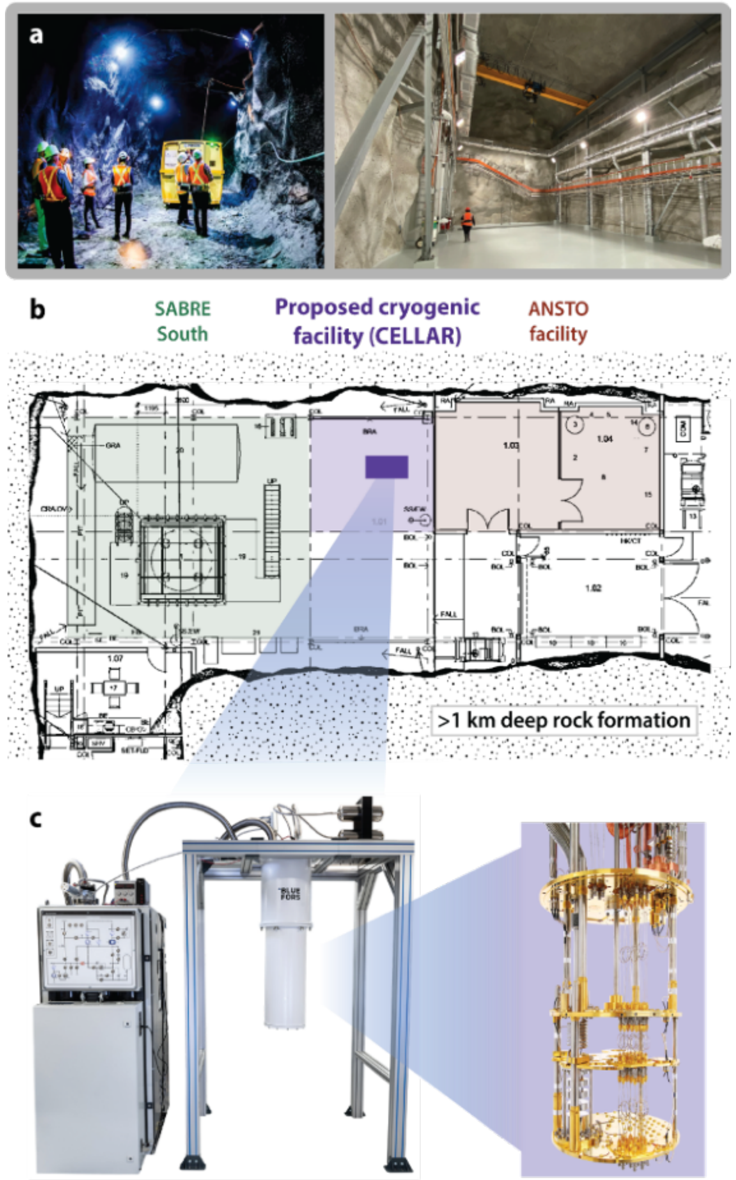
CELLAR Summary

- Dilution refrigerator (10 mK base) in SUPL (Stawell Underground Physics Laboratory)
- Another at Swinburne University of Technology (also 10 mK base)
- Research areas: quantum technology, gravitational waves, dark matter, clocks and oscillators, etc
- Open to collaboration - time is available for people with cool ideas



SUPL - Stawell Underground Physics Laboratory

- SUPL is the only deep underground laboratory in the Southern Hemisphere
- Located in Stawell in regional Victoria - a few hours drive from Melbourne

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- Stawell Gold Mine is an operational gold mine
- Disused shaft has been effectively donated for use as SUPL

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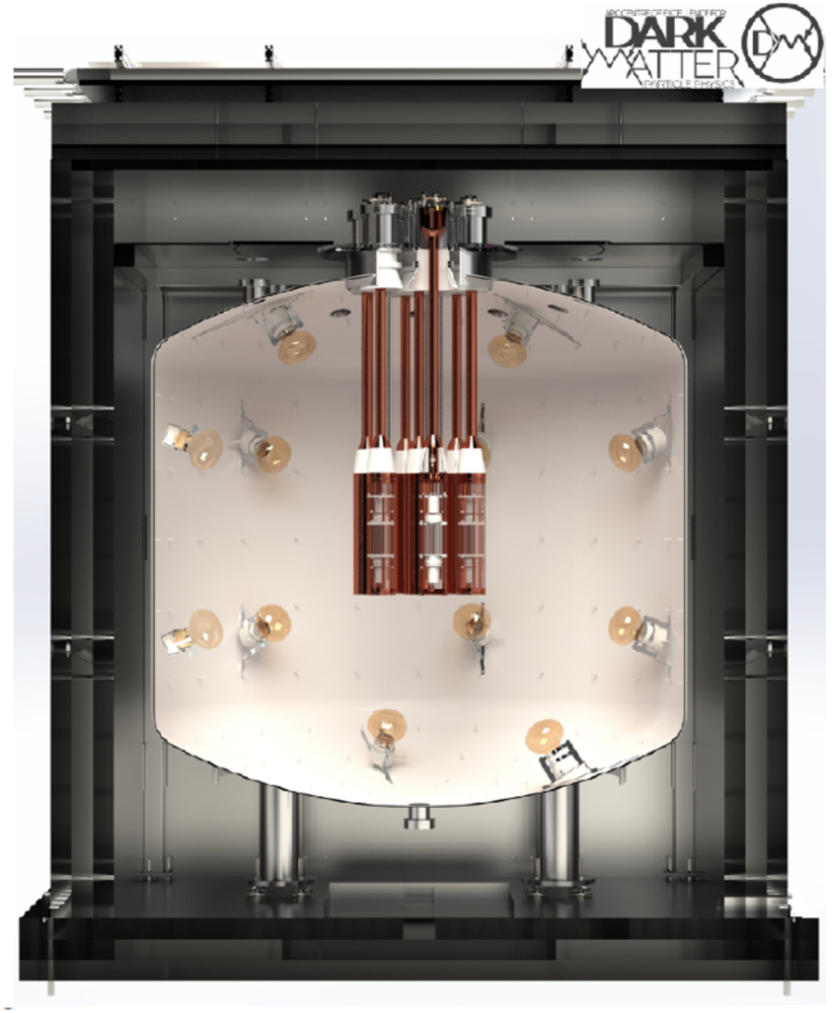
- SUPL was built primarily to host the SABRE South experiment (dark matter)



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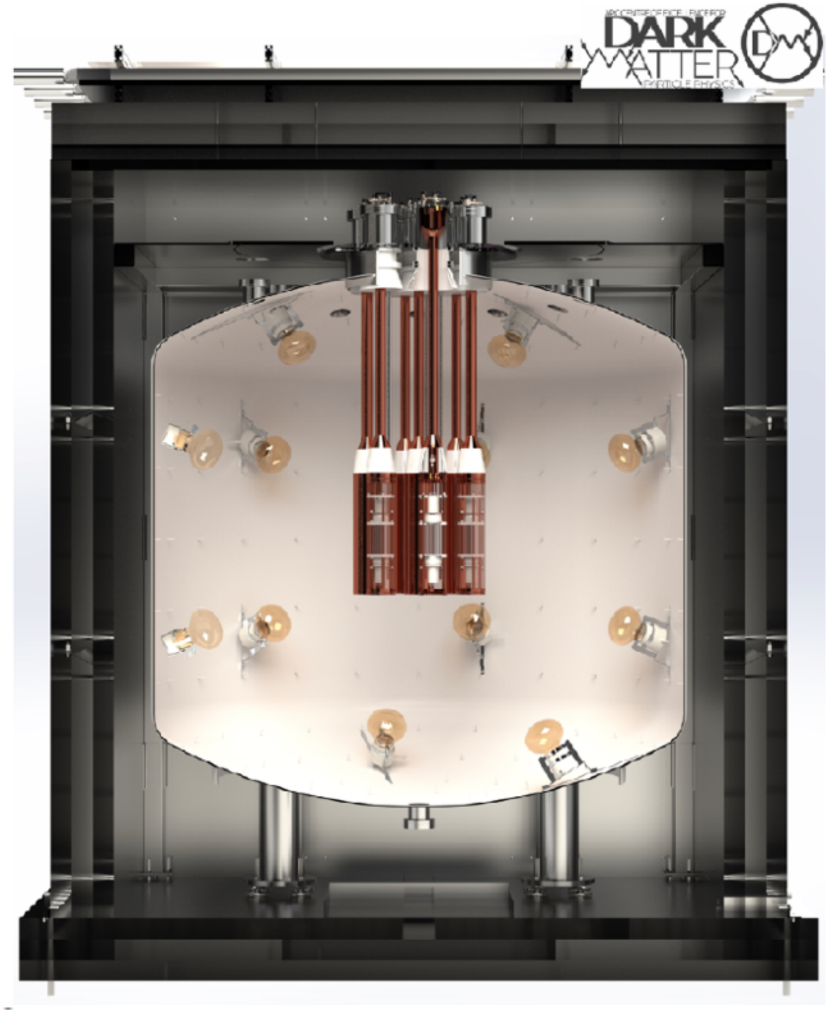
- Lab 'opened' in late 2022
- First experiments deployed in 2024



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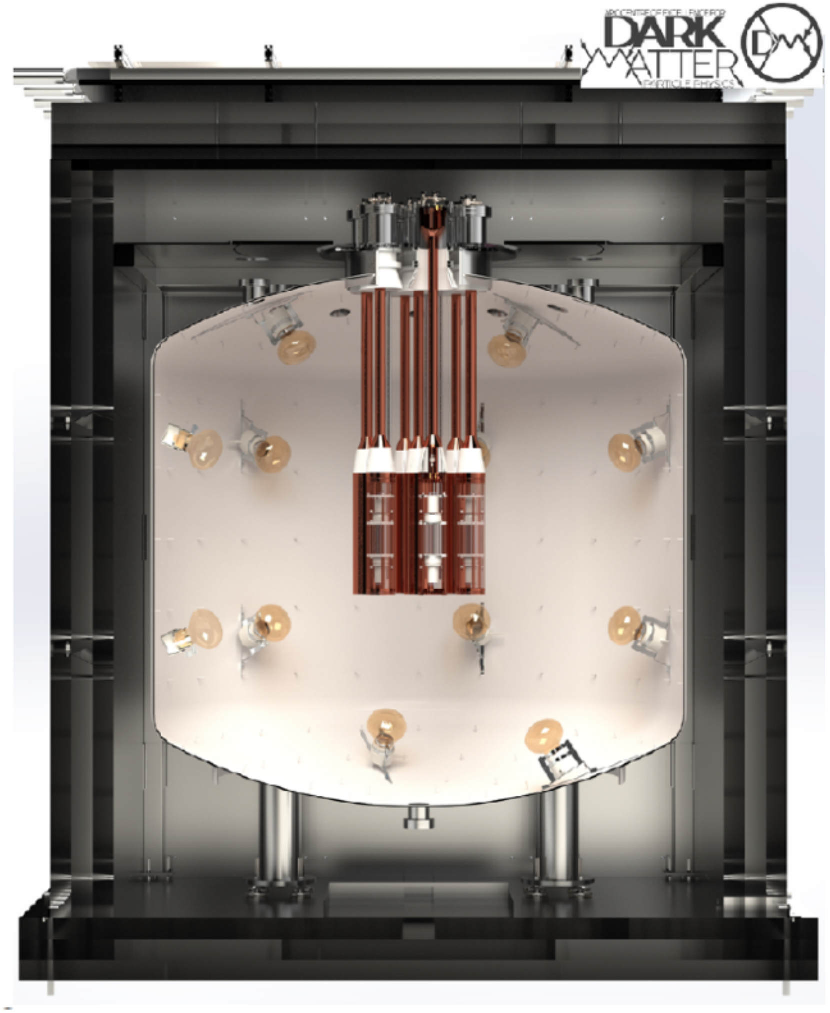

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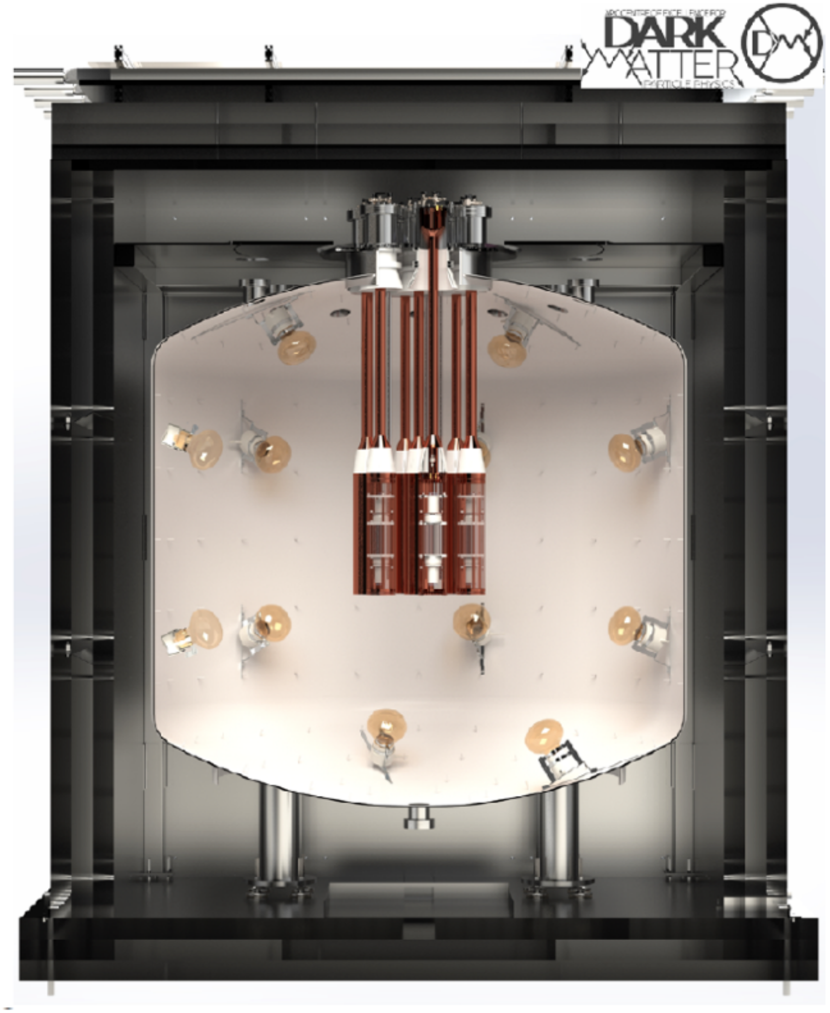
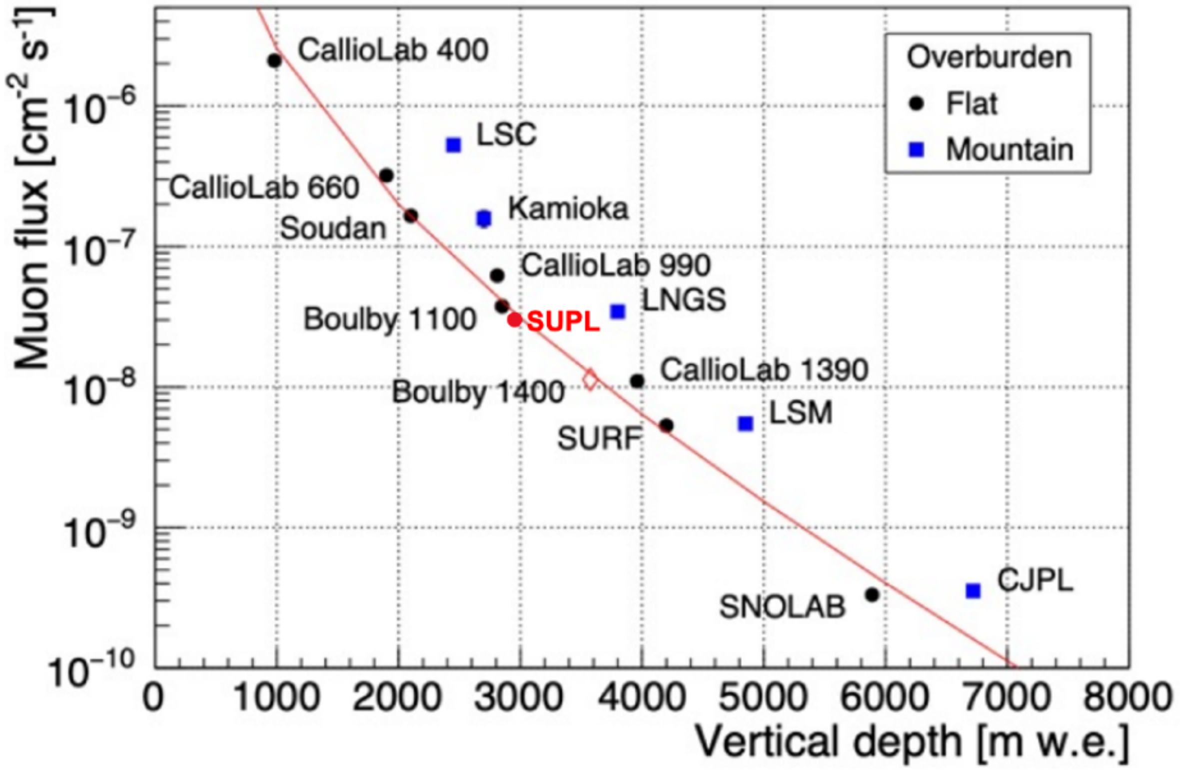
- As a decline (ramp) mine cars and trucks can be driven directly to the laboratory site
- CELLAR will occupy a closed, isolated 'clean' room within the lab



SUPL - Stawell Underground Physics Laboratory

- Depth of 1025 m gives ~2900 m.w.e
- Flat rock overburden
- Muon flux similar to LNGS, Boulby



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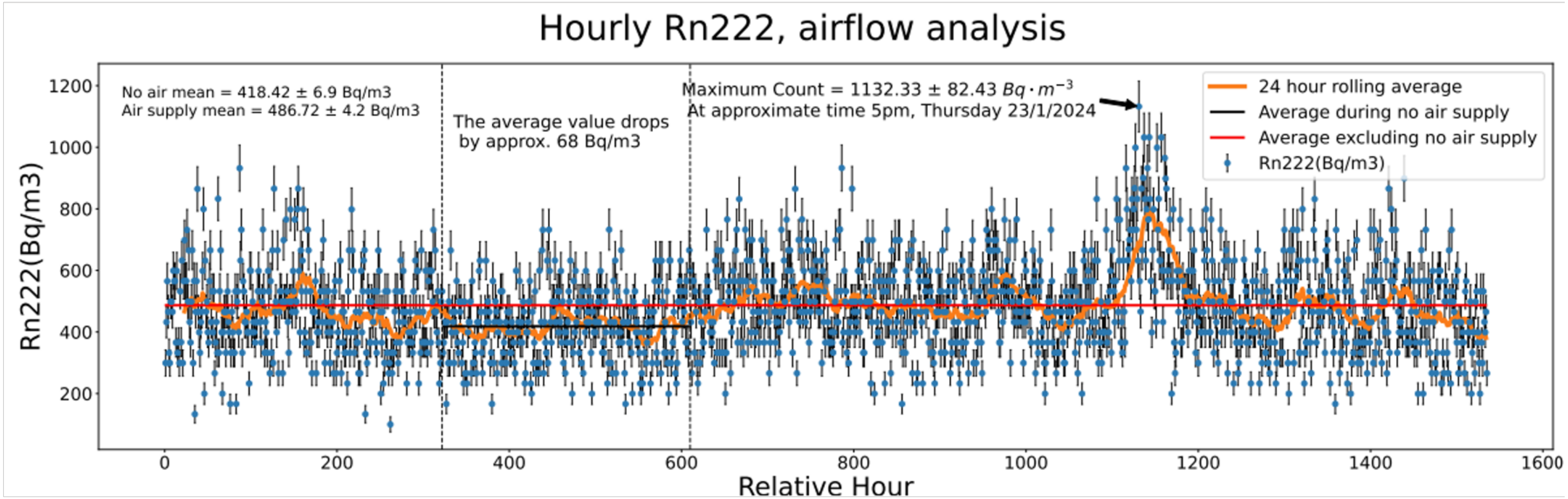
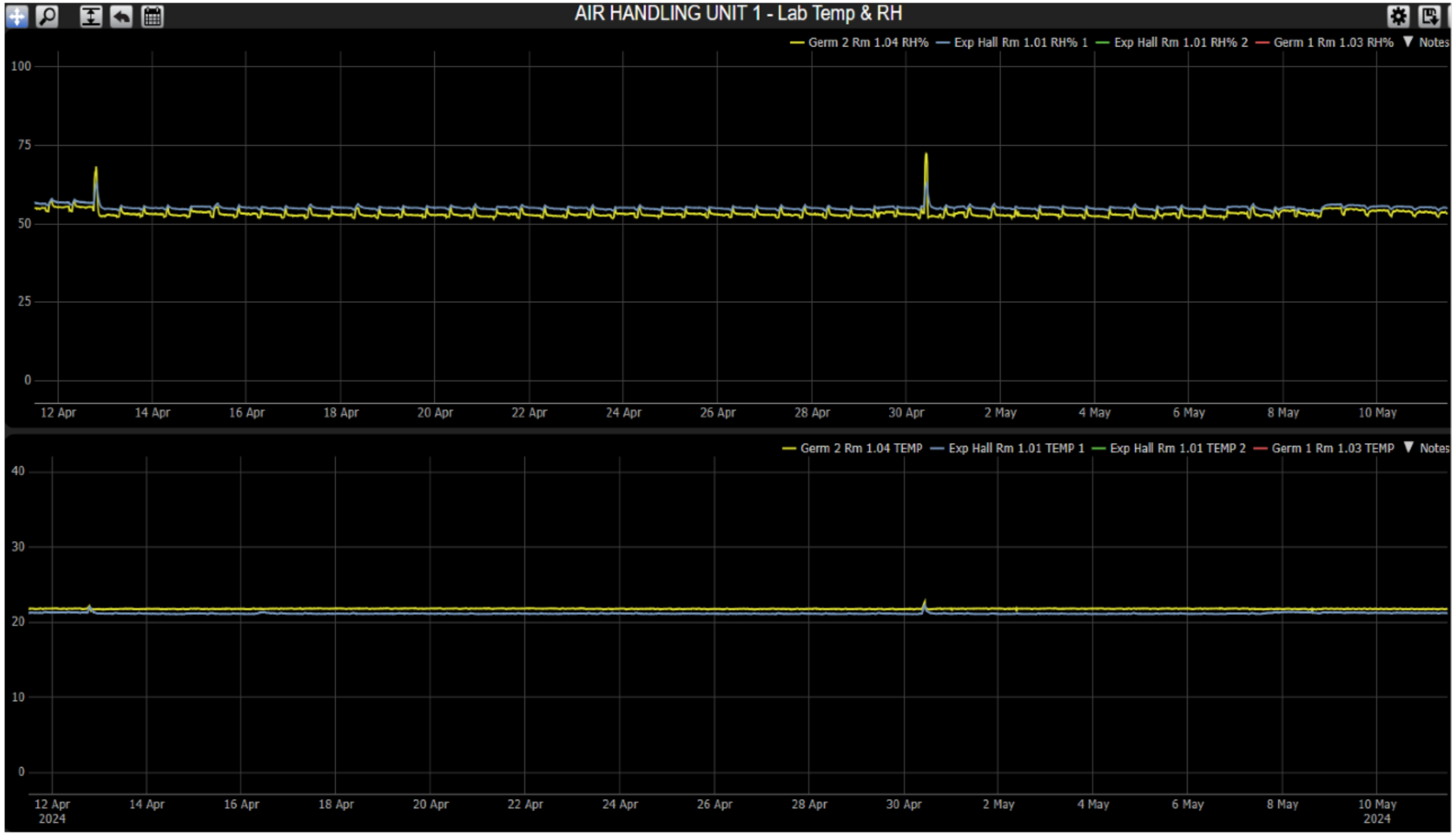


SUPL are currently scoping a compressed air line from the surface to provide radon-reduced air to experiments (~40Bq/m3).

SUPL - Stawell Underground Physics Laboratory



Relative humidity
55%

Temperature
21°C

CELLAR Background

- Various CDM and EQUS researchers began discussion for installing a DR in SUPL and another on the surface in late 2022
- Had discussions with SUPL management
- Applied for LIEF funding in 2023 - project named ‘CELLAR’
- University of Queensland, University of Western Australia, Swinburne University of Technology, and University of Melbourne partners on the LIEF

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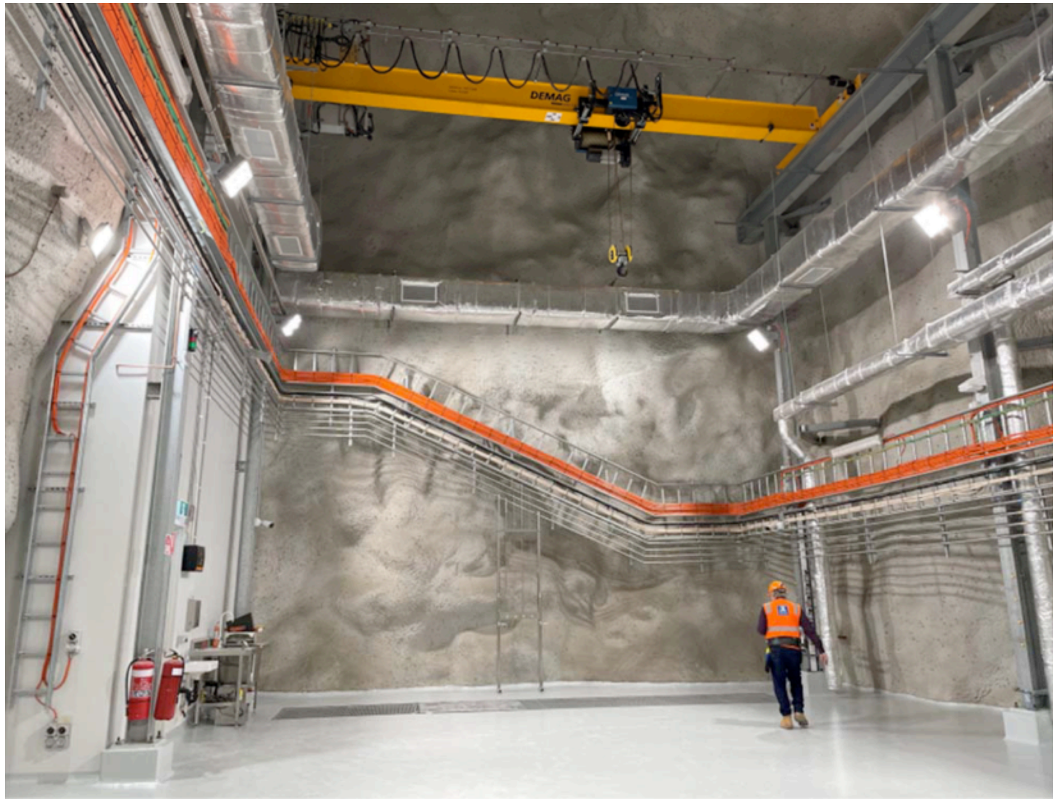
- **Successful! Funding announced October 2023**
- **CELLAR will become a reality!**

EQUS

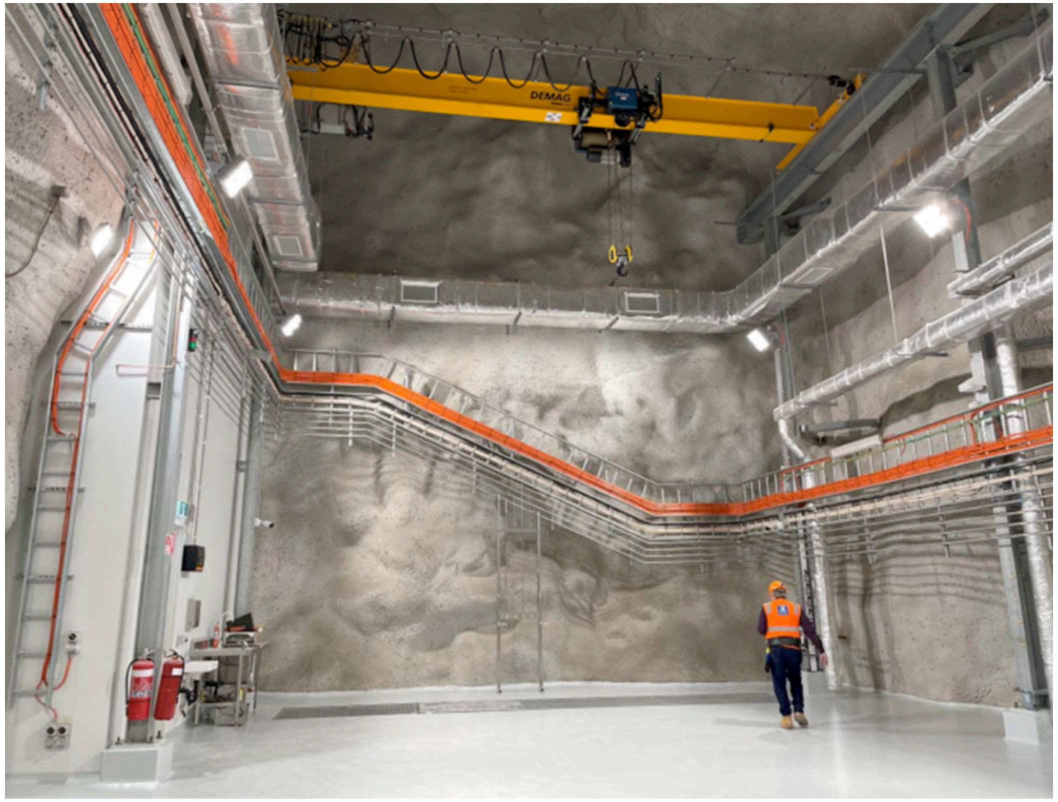
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Acquisition & Installation



Acquisition & Installation

- Sought quotes for two fridges from various suppliers



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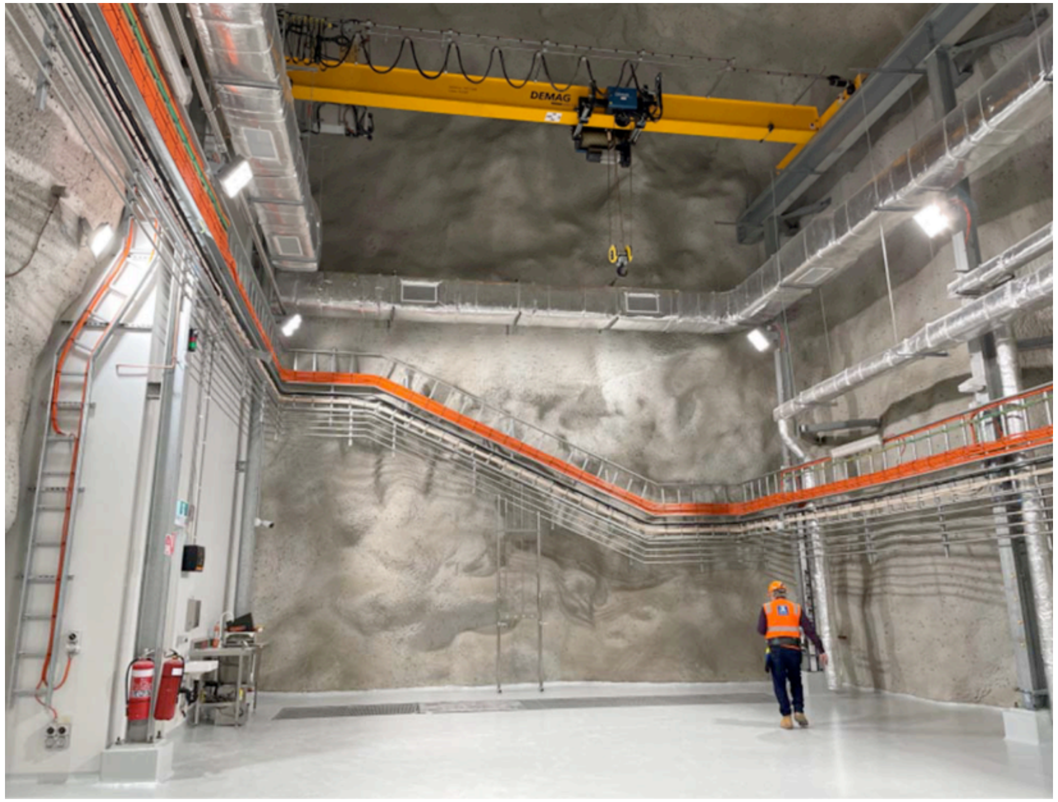
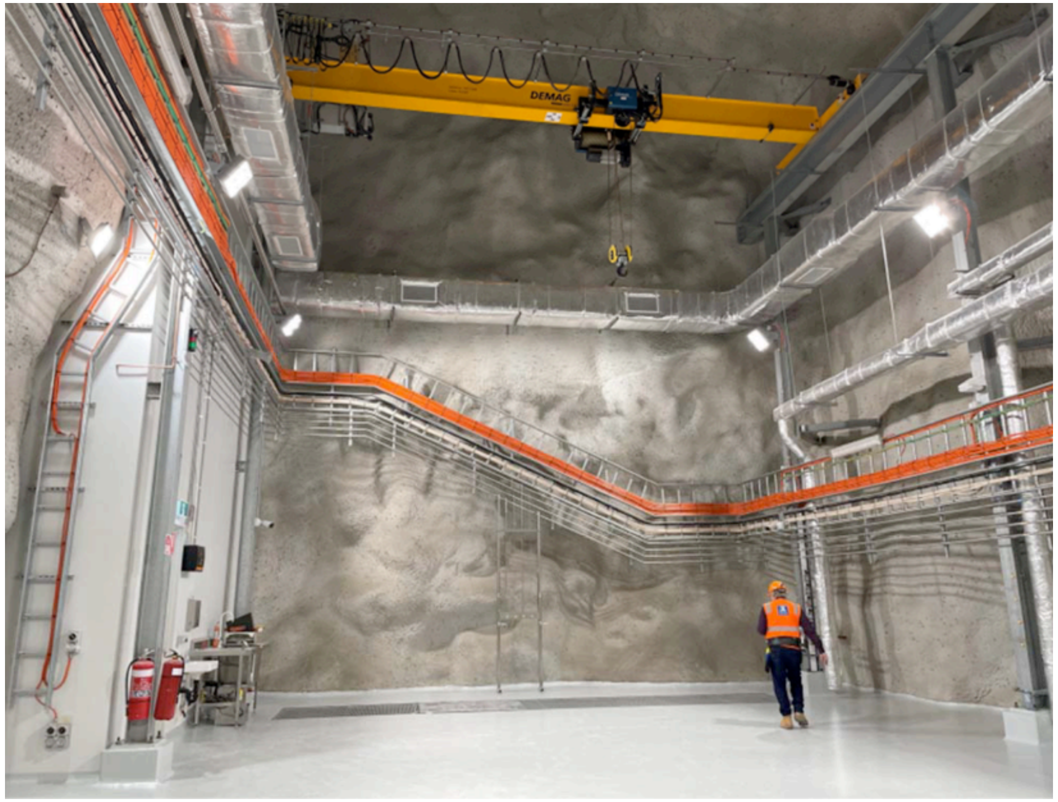


Acquisition & Installation

- Sought quotes for two fridges from various suppliers
- Working with SUPL on requirements in lab:
  - Paperwork
  - Chilled water
  - Three phase power
  - Compressed air
  - Liquid nitrogen
  - Radon reduction
  - Dust mitigation/control



Acquisition & Installation

- Sought quotes for two fridges from various suppliers **(Oxford Instruments)**
- Working with SUPL on requirements in lab:
  - Paperwork
  - Chilled water
  - Three phase power
  - Compressed air
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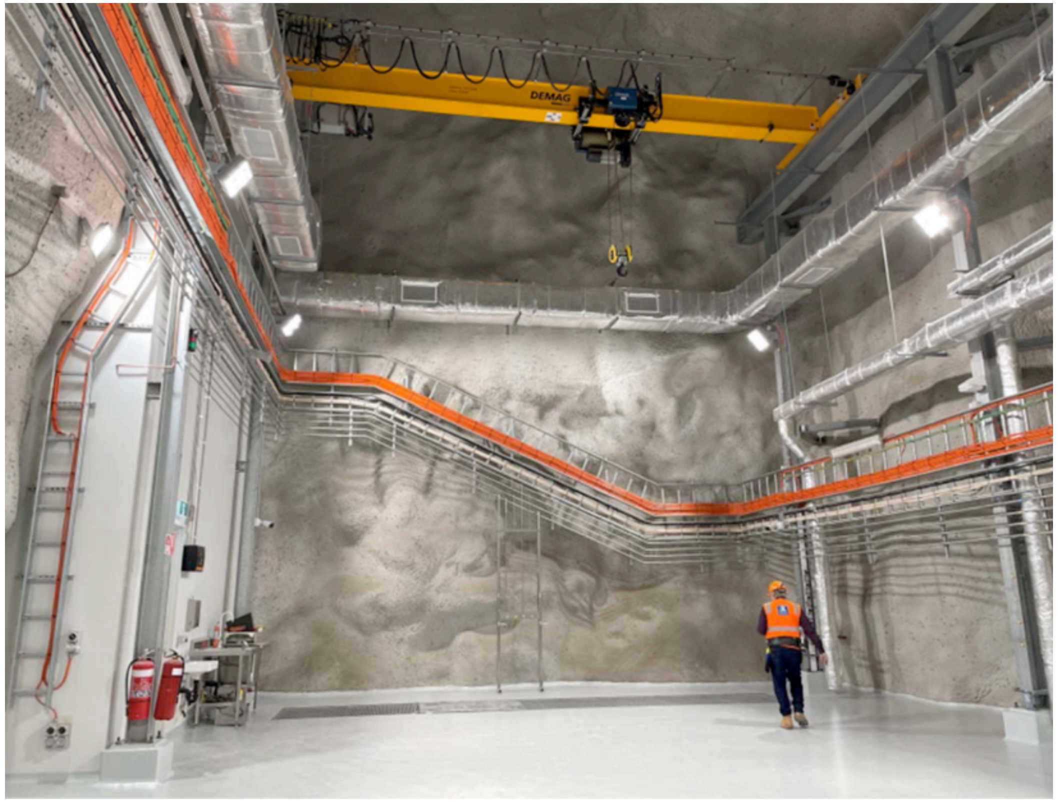
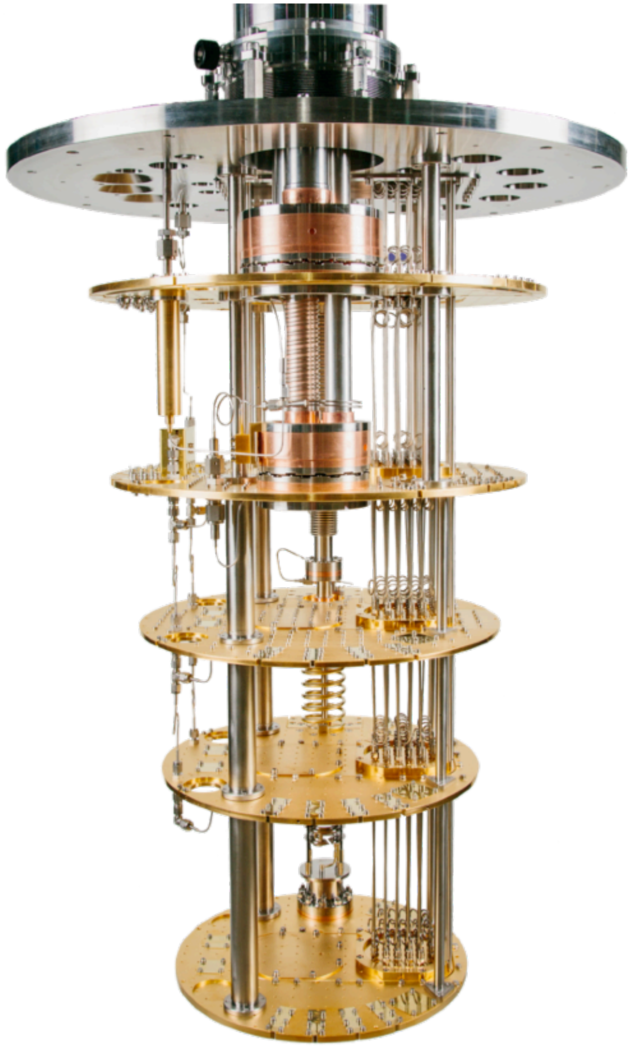
  - Radon reduction
  - Dust mitigation/control
- **Expect installation of both fridges in Q4 2024**



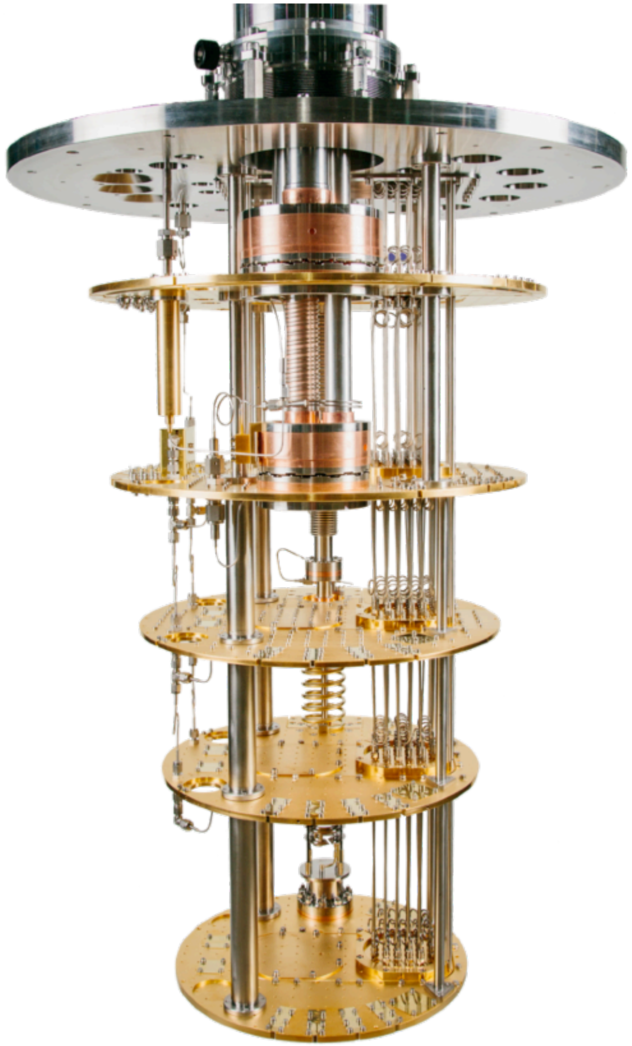
Acquisition & Installation

- Proteox MX system underground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines, optical fibre



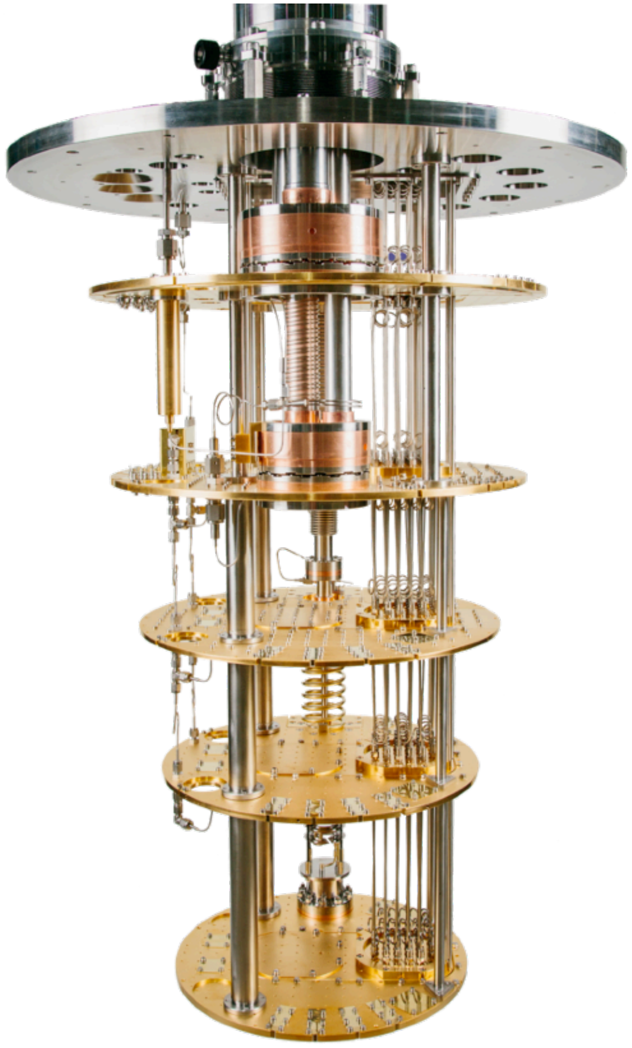
Acquisition & Installation

- Proteox MX system underground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines, optical fibre
- Proteox S system above ground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines



Acquisition & Installation

- Proteox MX system underground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines, optical fibre
- Proteox S system above ground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines
- Working on lead shielding for both systems at the moment



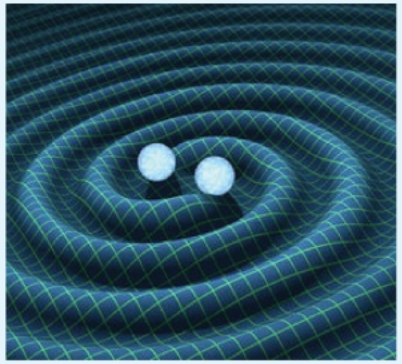
CELLAR Research

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

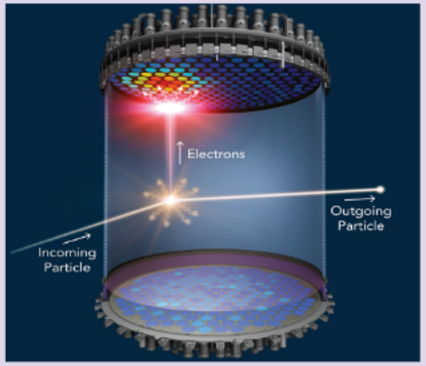
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

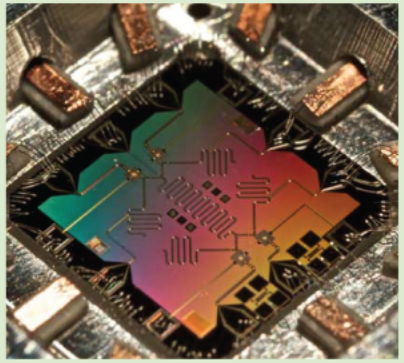
Gravitational wave



Dark Matter



Quantum Tech.



THE UNIVERSITY OF WESTERN AUSTRALIA

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Research Plan Baseline

	LIEF: 2024			2025	2026	2027
SUPL	*Tender Process*	*Laboratory space preparation*	*Delivery & installation of cryostat*	Quantum Tech	Dark Matter	HFGW
Swinburne				Dark matter	HFGW	*Open for proposals*
	Procurement and Installation			Proposed research plan		

Quantum Technology Research

Quantum Technology Research

Article | Published: 26 August 2020

Impact of ionizing radiation on superconducting qubit coherence

Antti P. Vepsäläinen ✉, Amir H. Karamlou, John L. Orrell ✉, Akshunna S. Dogra, Ben Loer, Francisca Vasconcelos, David K. Kim, Alexander J. Melville, Bethany M. Niedzielski, Jonilyn L. Yoder, Simon Gustavsson, Joseph A. Formaggio, Brent A. VanDevender & William D. Oliver

Nature **584**, 551–556 (2020) | Cite this article

Quantum Technology Research

Direct evidence for cosmic-ray-induced correlated errors in superconducting qubit array

Xue-Gang Li, Jun-Hua Wang, Yao-Yao Jiang, Guang-Ming Xue, Xiao-Xia Cai, Jun Zhou, Ming Gong, Zhao-Feng Liu, Shuang-Yu Zheng, Deng-Ke Ma, Mo Chen, Wei-Jie Sun, Shuang Yang, Fei Yan, Yi-Rong Jin, Xue-Feng Ding, Hai-Feng Yu

Correlated errors can significantly impact the quantum error correction, which challenges the assumption that errors occur in different qubits independently in both space and time. Superconducting qubits have been found to suffer correlated errors across multiple qubits, which could be attributable to ionizing radiations and cosmic rays. Nevertheless, the direct evidence and a quantitative understanding of this relationship are currently lacking. In this work, we propose to continuously monitor multi-qubit simultaneous charge-parity jumps to detect correlated errors and find that occur more frequently than multi-qubit simultaneous bit flips. Then, we propose to position two cosmic-ray muon detectors directly beneath the sample box in a dilution refrigerator and successfully observe the correlated errors in a superconducting qubit array triggered by muons. By introducing a lead shielding layer on the refrigerator, we also reveal that the majority of other correlated errors are primarily induced by gamma rays. Furthermore, we find the superconducting film with a higher recombination rate of quasiparticles used in the qubits is helpful in reducing the duration of correlated errors. Our results provide experimental evidence of the impact of gamma rays and muons on superconducting quantum computation and offer practical insights into mitigation strategies for quantum error correction. In addition, we observe the average occurrence rate of muon-induced correlated errors in our processor is approximately 0.40 $min^{-1}cm^{-2}$, which is comparable to the muon event rate detected by the muon detector with 0.506 $min^{-1}cm^{-2}$. This demonstrates the potential applications of superconducting qubit arrays as low-energy threshold sensors in the field of high-energy physics.

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Synchronous Detection of Cosmic Rays and Correlated Errors in Superconducting Qubit Arrays

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Quantum information processing at scale will require sufficiently stable and long-lived qubits, likely enabled by error-correction codes. Several recent superconducting-qubit experiments, however, reported observing intermittent spatiotemporally correlated errors that would be problematic for conventional codes, with ionizing radiation being a likely cause. Here, we directly measured the cosmic-ray contribution to spatiotemporally correlated qubit errors. We accomplished this by synchronously monitoring cosmic-ray detectors and qubit energy-relaxation dynamics of 10 transmon qubits distributed across a 5x5x0.35 mm^3 silicon chip. Cosmic rays caused correlated errors at a rate of 1/(10 min), accounting for 17±1% of all such events. Our qubits responded to essentially all of the cosmic rays and their secondary particles incident on the chip, consistent with the independently measured arrival flux. Moreover, we observed that the landscape of the superconducting gap in proximity to the Josephson junctions dramatically impacts the qubit response to cosmic rays. Given the practical difficulties associated with shielding cosmic rays, our results indicate the importance of radiation hardening -- for example, superconducting gap engineering -- to the realization of robust quantum error correction.

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First Measurement of Correlated Charge Noise in Superconducting Qubits at an Underground Facility

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We measure space- and time-correlated charge jumps on a four-qubit device, operating 107 meters below the Earth's surface in a low-radiation, cryogenic facility designed for the characterization of low-threshold particle detectors. The rock overburden of this facility reduces the cosmic ray muon flux by over 99% compared to laboratories at sea level. Combined with 4π coverage of a movable lead shield, this facility enables quantifiable control over the flux of ionizing radiation on the qubit device. Long-time-series charge tomography measurements on these weakly charge-sensitive qubits capture discontinuous jumps in the induced charge on the qubit islands, corresponding to the interaction of ionizing radiation with the qubit substrate. The rate of these charge jumps scales with the flux of ionizing radiation on the qubit package, as characterized by a series of independent measurements on another energy-resolving detector operating simultaneously in the same cryostat with the qubits. Using lead shielding, we achieve a minimum charge jump rate of $0.19^{+0.04}_{-0.03}$ mHz, almost an order of magnitude lower than that measured in surface tests, but a factor of roughly eight higher than expected based on reduction of ambient gammas alone. We operate four qubits for over 22 consecutive hours with zero correlated charge jumps at length scales above three millimeters.

Quantum Technology Research

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Short term plans to do various qubit measurements both above ground and underground to continue to try and understand cosmic ray influences

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Also interest from collaborators (companies, universities) for work in other kinds of quantum circuits, systems and devices where QP/cosmic ray influence is suspected

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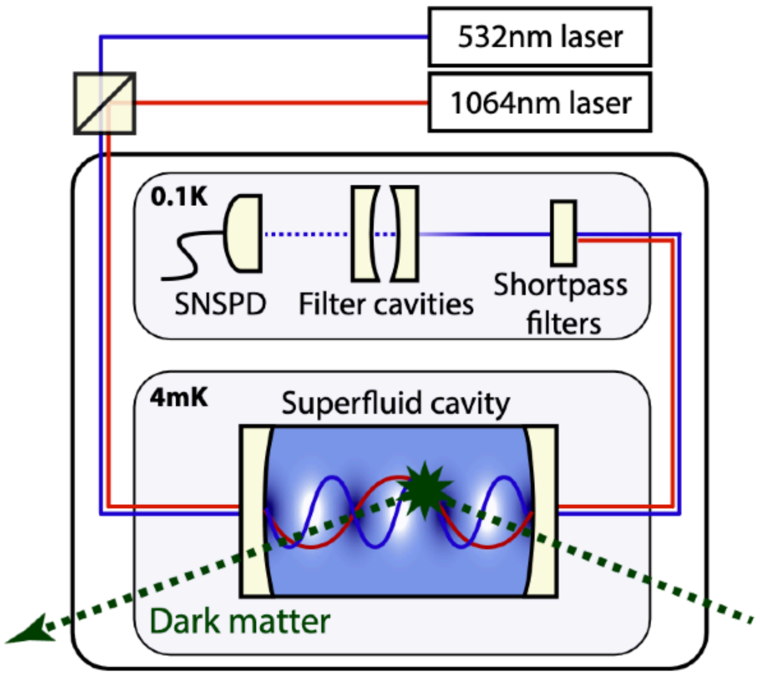

FIG. 1. Schematic diagram of the Optomechanical Dark-matter INstrument (ODIN). Dark matter scatters off a highly populated phonon mode (*scattering mode*), which is optically pumped by a 1064 nm laser. The scattered phonon is converted to an anti-Stokes photon through the optomechanical interaction with a 564 nm laser. The presence of that photon is registered by a single photon detector after passing through a series of optical filters.

https://doi.org/10.48550/arXiv.2306.09726

Dark Matter Research

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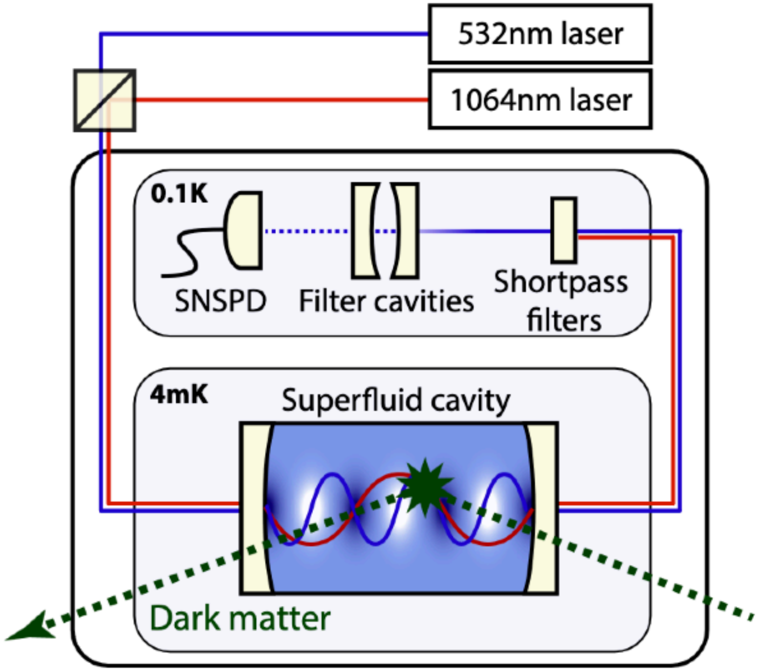
- Superfluid-based detectors have been identified as a promising platform for dark matter searches in this mass range
- Cannot currently be realised in many underground laboratories owing to the lack of cryogenic facilities
- We plan to demonstrate an underground superfluid-based dark matter detector and probe an interesting region of parameter space



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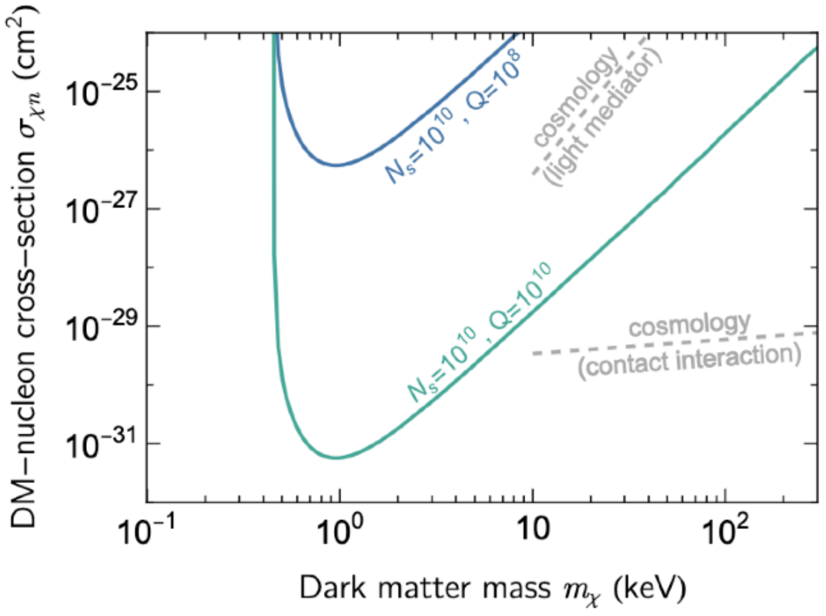

FIG. 4. Projected 90% C.L. upper limits on the dark matter–nucleon cross-section at ODIN, $\sigma_{\chi n}$, assuming a run time of 100 days.

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Gravitational Wave Research

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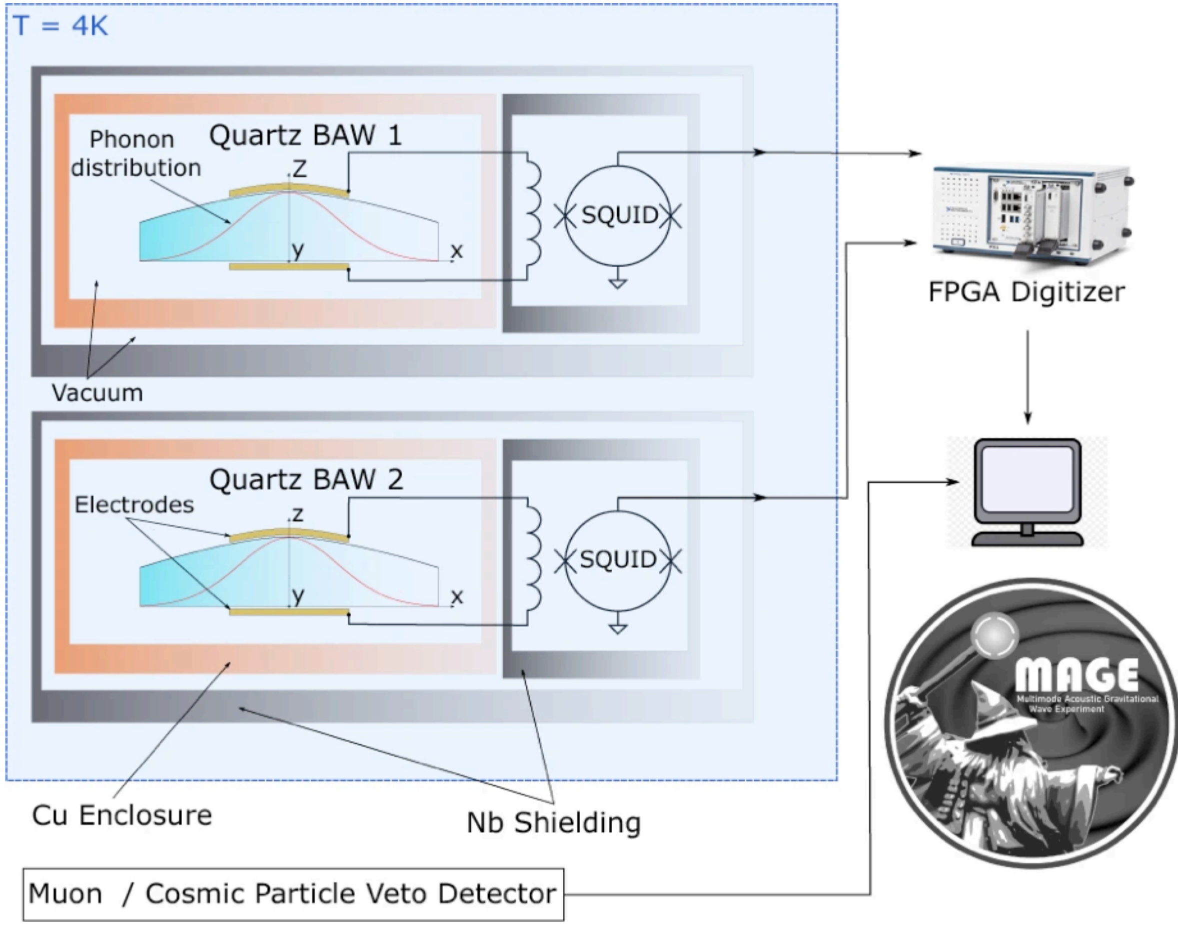
- HFGW detector based on mechanical resonators has been implemented in a cryogenic system
- Beyond HFGWs, this experiment is sensitive to various other new physics candidates, such as some kinds of dark matter, Lorentz Invariance violations, etc



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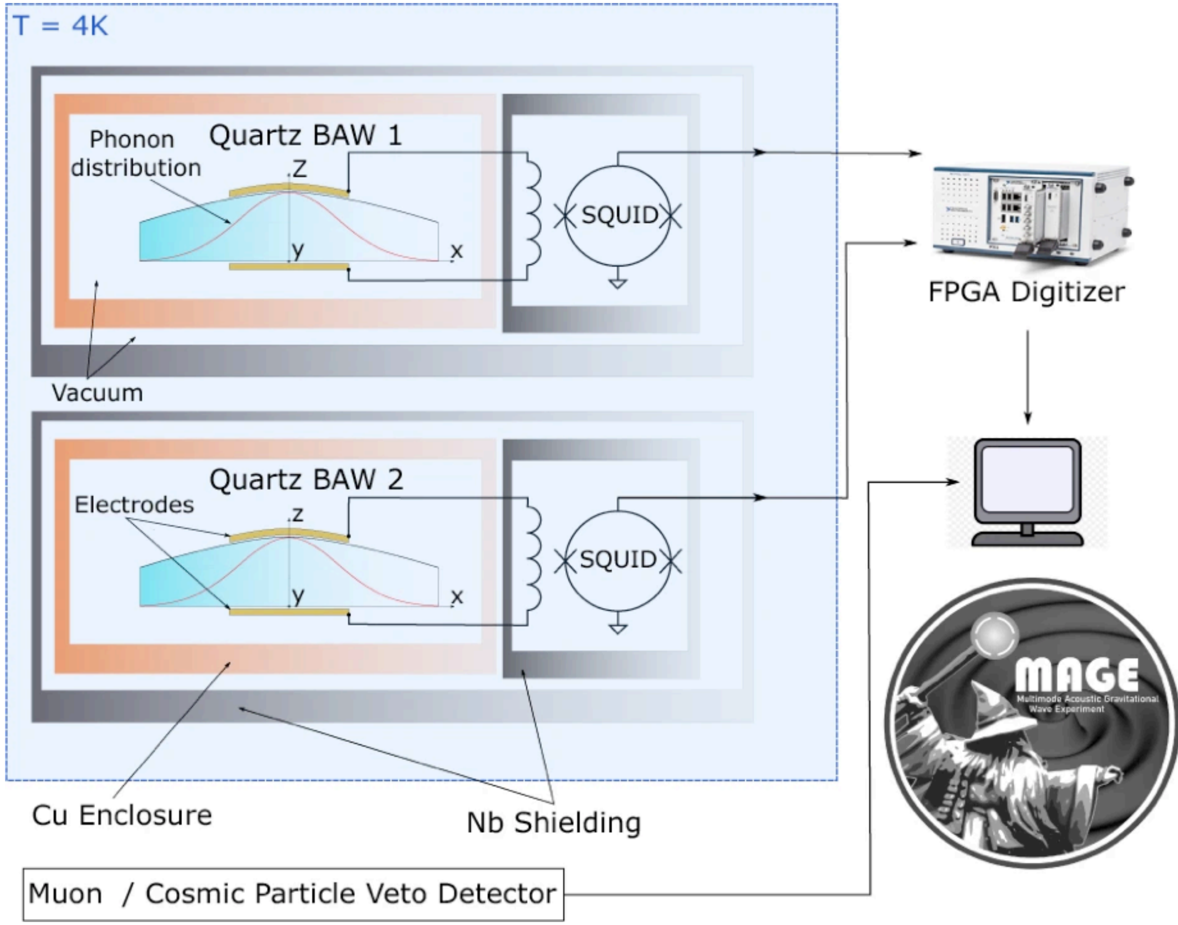
- High frequency gravitational waves (HFGWs) are interesting to probe for new physics
- HFGW detector based on mechanical resonators has been implemented in a cryogenic system
- Beyond HFGWs, this experiment is sensitive to various other new physics candidates, such as some kinds of dark matter, Lorentz Invariance violations, etc
- On the surface of the Earth this experiment is partially limited by cosmic rays
- CELLAR will enable a search like this in a suitably low-background environment



https://doi.org/10.1038/s41598-023-35670-y

‘Open Access’ Facility

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- **Please get in touch if you’d like to collaborate**

Conclusions

- CELLAR will open in late 2024
- Hosted in SUPL (Victoria, Australia), ~2900 m.w.e
- Plans for research in quantum technology, dark matter, other new physics such as HFGWs
- Two dilution refrigerators, one at Swinburne and one in SUPL
- Collaborate with us!