ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

The SABRE South Experiment at the Stawell Underground Physics Laboratory

Theresa Fruth (University of Sydney)

Lepton-Photon 2025

Australian Government
Australian Research Council

THE UNIVERSITY of ADELAIDE

Australian National University

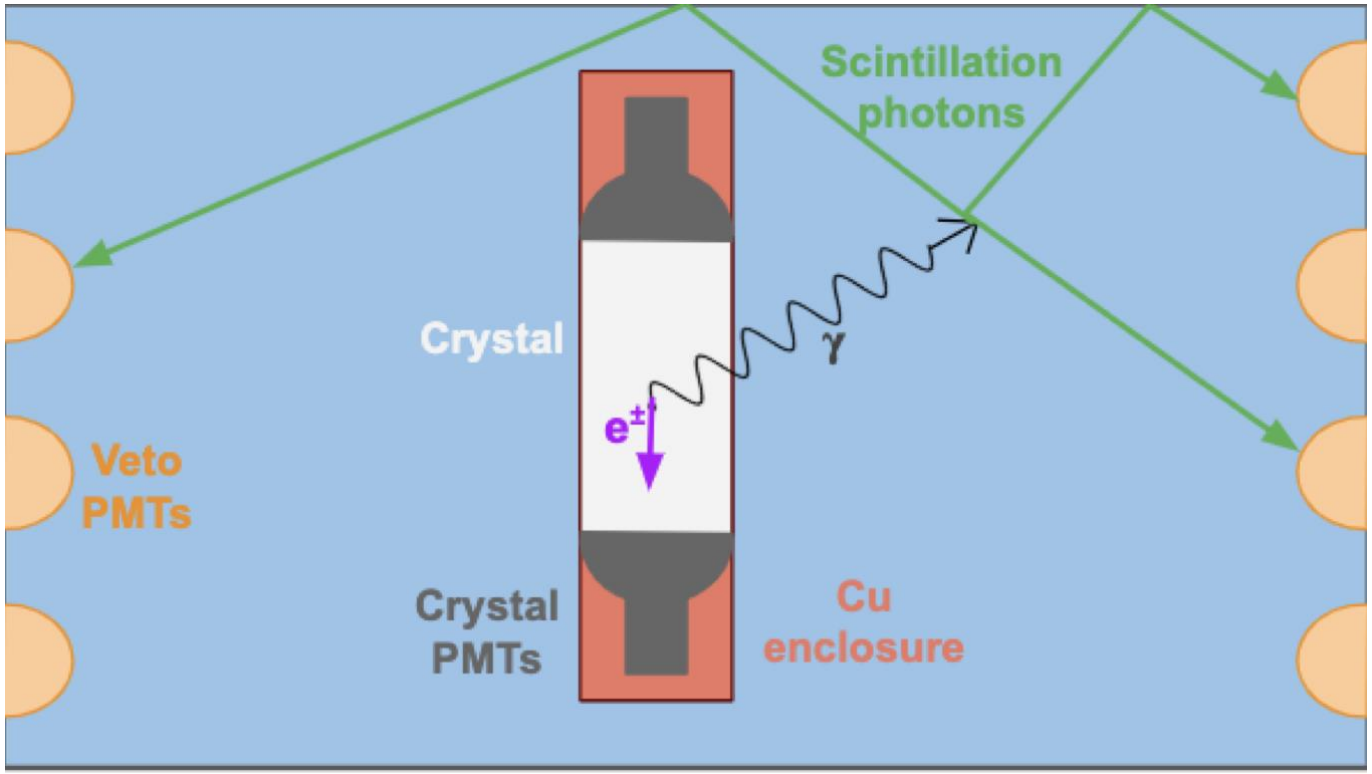
THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF SYDNEY

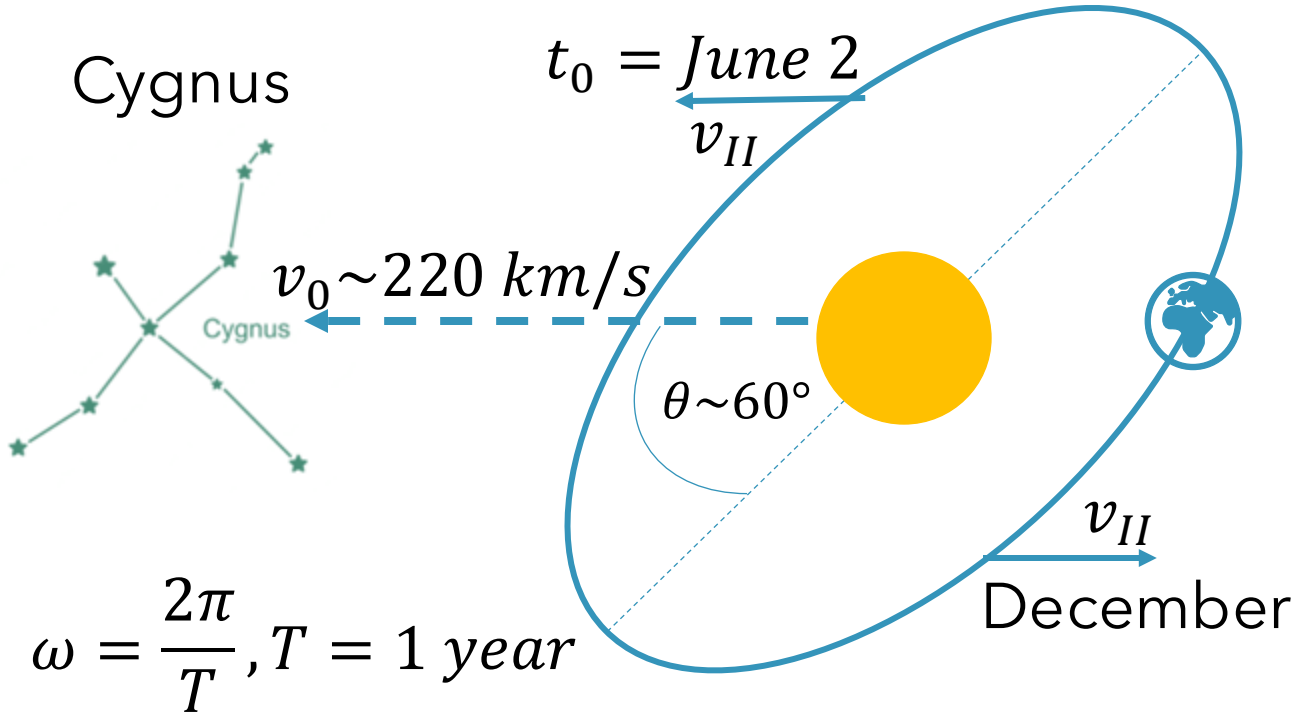
THE UNIVERSITY OF WESTERN AUSTRALIA

NaI Scintillating Crystal Detector



- NaI crystal with Tl doping
- Scintillation light detected by PMTs coupled to crystal
- Ultra-pure crystals for low backgrounds
- Active veto can help reduce backgrounds
- Annual modulation signature

Background Discrimination



$$\omega = \frac{2\pi}{T}, T = 1\ year$$

$$v_{earth} = v_0 + v_{II} \cos\theta \cos[\omega(t - t_0)]$$

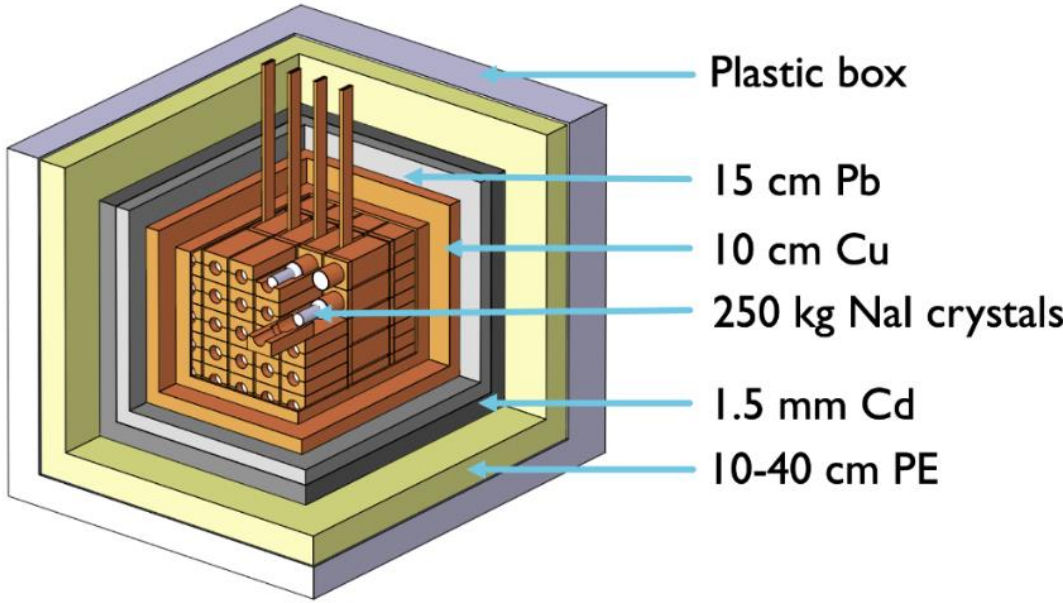
$$S(t) = B(t) + S_0 + \boxed{S_m \cos[\omega(t - t_0)]}$$

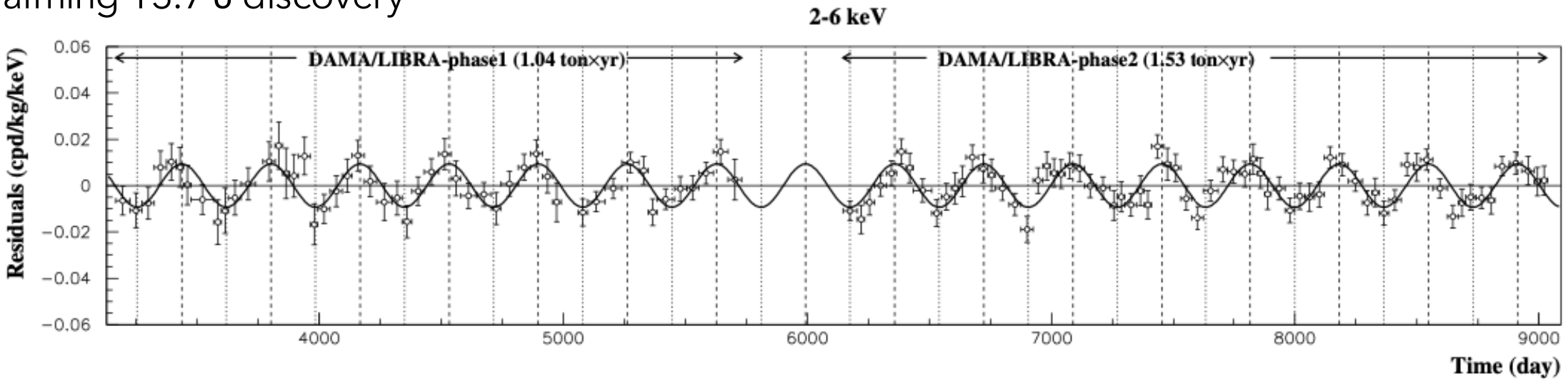
$$\mathcal{O}(v_0/v_{II}) \sim 5\%$$

DAMA/LIBRA

R. Bernabei, et al. Nucl. Phys. At. Energy 2021, volume 22, issue 4, pages 329-342.

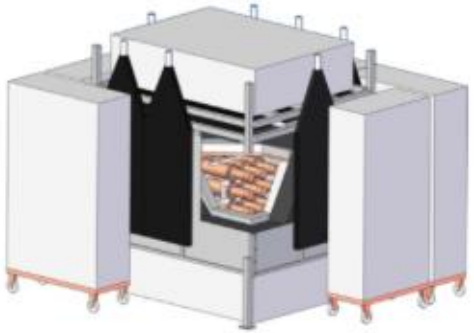
- Phase 2 setup (2011-2025):
  - 250 kg high-purity NaI(Tl) crystals
  - R6233MOD PMTs
  - No veto detectors
- Single hit scintillation events in 2-6keV energy window
- Total exposure: 2.86 ton x yr over 22 annual cycles
- Claiming 13.7 σ discovery



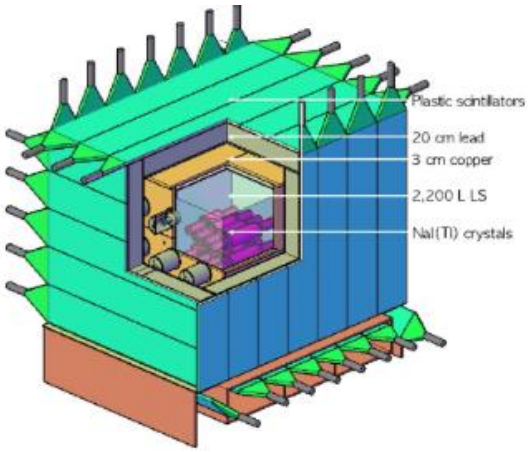


Other NaI experiments

N. Carlin et al. 2025
arXiv:/2503.19559

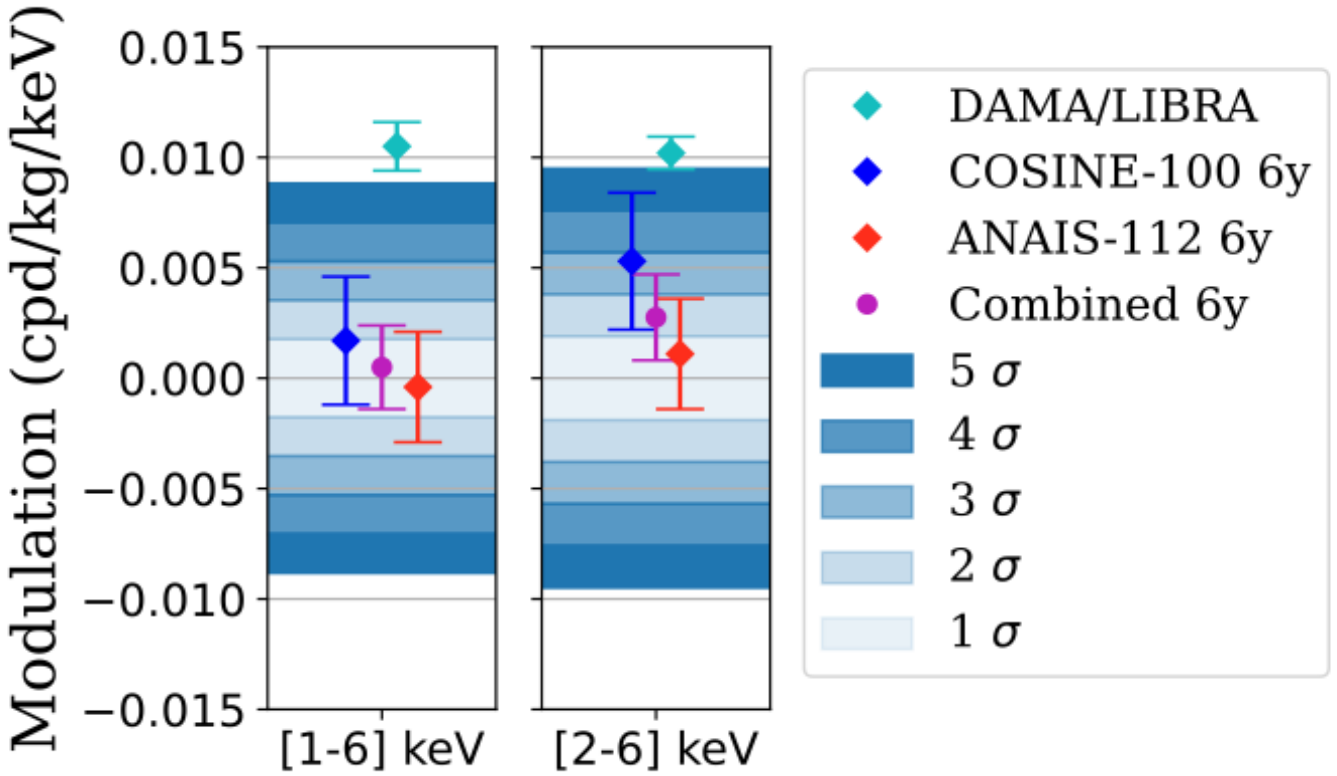


ANAIS0-112 (Canfranc)
ANAIS-112, Commun.Phys. 7 (2024) 1, 345



COSINE-100 (South Korea)
COSINE-100, PRD 106 (2022)

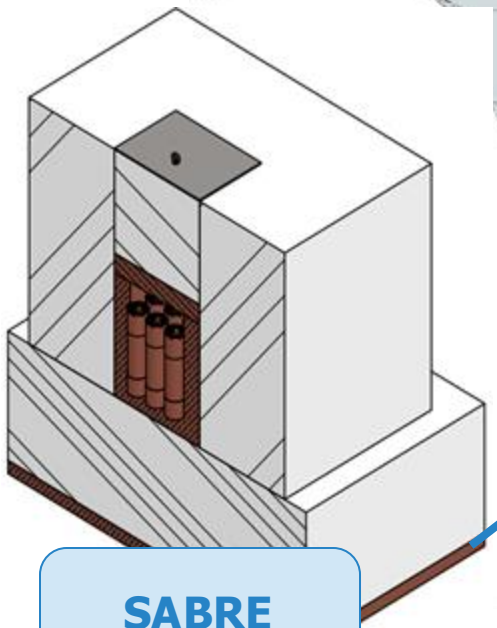
Combination results:



SABRE North and South

SABRE North and South

LNGS, Italy



SABRE North

SABRE South

SUPL, Australia

SABRE Collaboration

South

Australian Government
Australian Research Council

KEK-JAPAN

SWINBURNE

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY of ADELAIDE

Australian National University

North

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

SAPIENZA

PRINCETON UNIVERSITY

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

UNIVERSITÀ DEL SALENTO

Crystals

RMD
A Dynasil Company

SICCAS Since 1928

Screening

Australian Government
ANSTO

UKRI Science and Technology Facilities Council
Boulby Underground Laboratory

UCL

Veto LS & PMTs

Institute of High Energy Physics
Chinese Academy of Sciences

SABRE North and South

Common core features:

- Same crystal production and R&D.
- Same detector module concept (Ultra-pure crystals and HPK R11065 PMTs)
- Common simulation, DAQ and data processing frameworks
- Exchange of engineering know-how with official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN

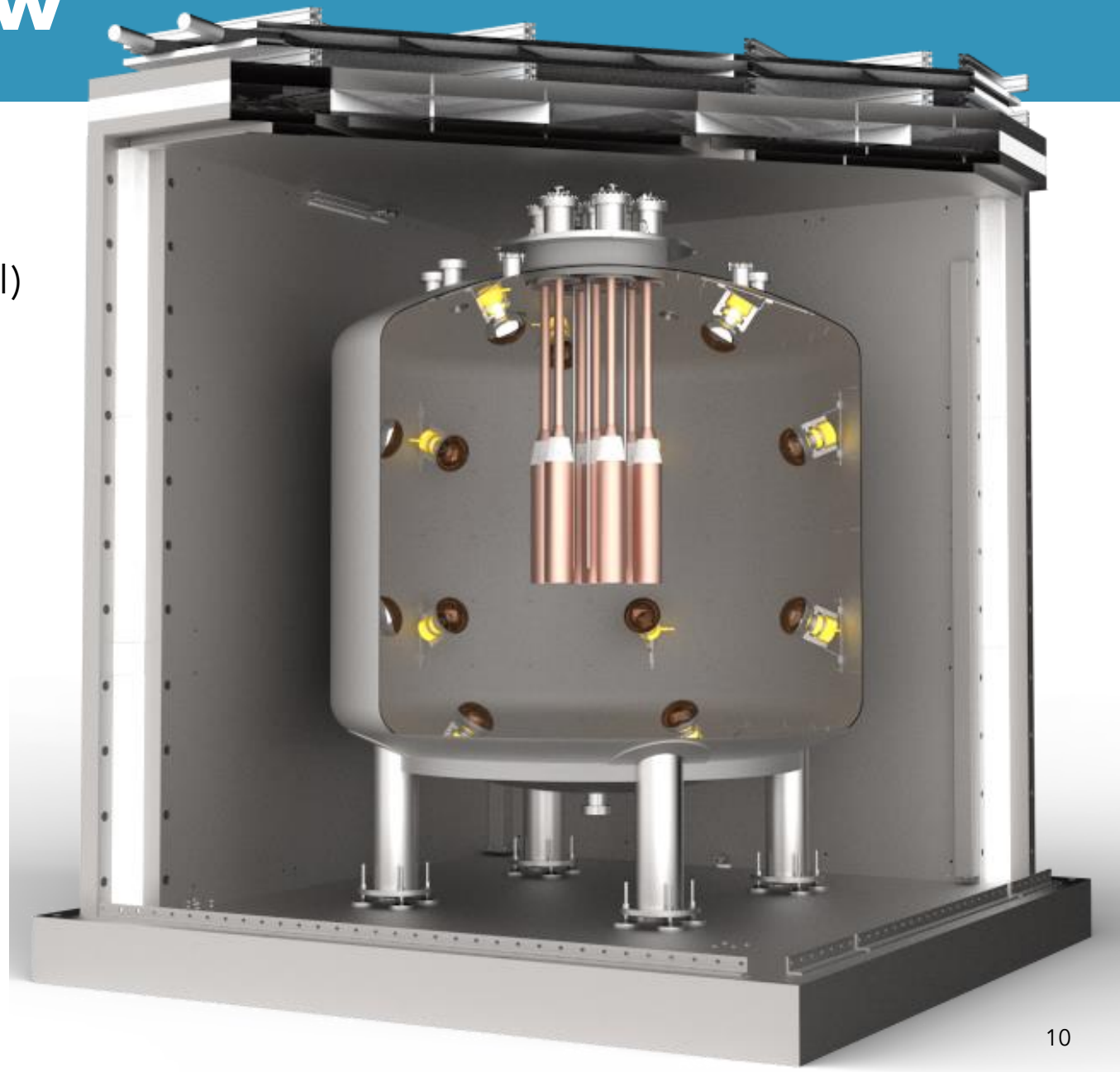
Different shielding designs:

- SABRE North has opted for a fully passive shielding due to the phase out of organic scintillators at LNGS. Direct counting and simulations demonstrate that this is compliant with the background goal of SABRE North at LNGS.
- SABRE South will be the first experiment in SUPL. The liquid scintillator will be used for in-situ evaluation and validation of the background, in addition to background rejection and particle identification.

SABRE South Overview

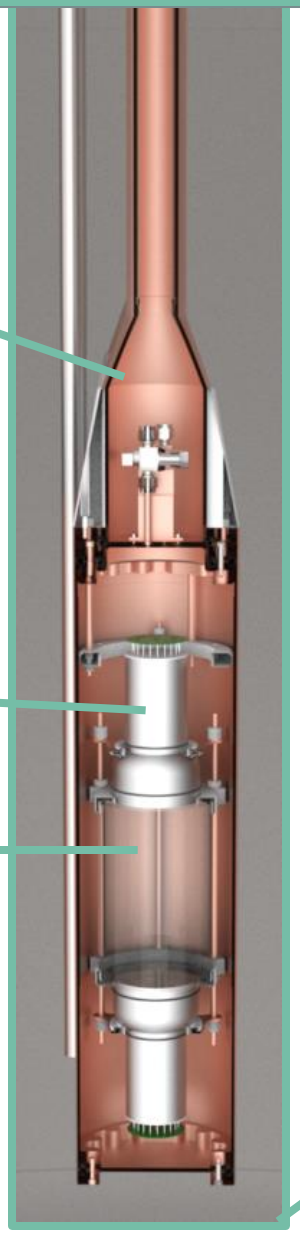
E. Barberio *et al* 2025 *JINST* **20** T04001

- **DM Target Detector:**
  - 50 kg of NaI(Tl) Crystals in 7 modules
  - 14 x R11065 low radioactivity PMT
  - 1 keV energy threshold for 1-6 keV ROI in NaI(Tl)
- **Liquid Scintillator Veto System:**
  - 12kL Linear Alkyl Benzene + PPO & Bis-MSB
    Stainless steel, non-thoriated welds
  - Lumirror lining
  - Oil-proof base R5912 PMT x 18(32)
- **Muon System:**
  - 9.6 m^2 x 5 cm EJ200
  - R13089 PMT
- **Passive shielding**
  - Steel & HDPE
- **Laser and radioactive source calibration systems**



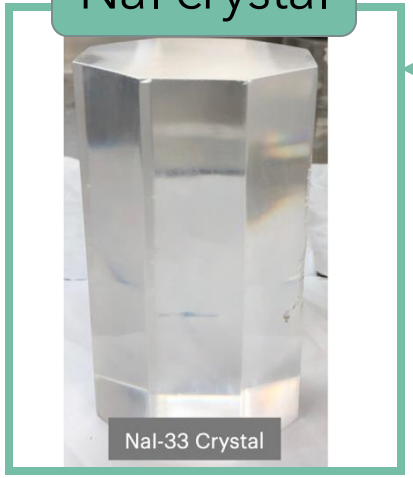
Oxygen-free Copper enclosure

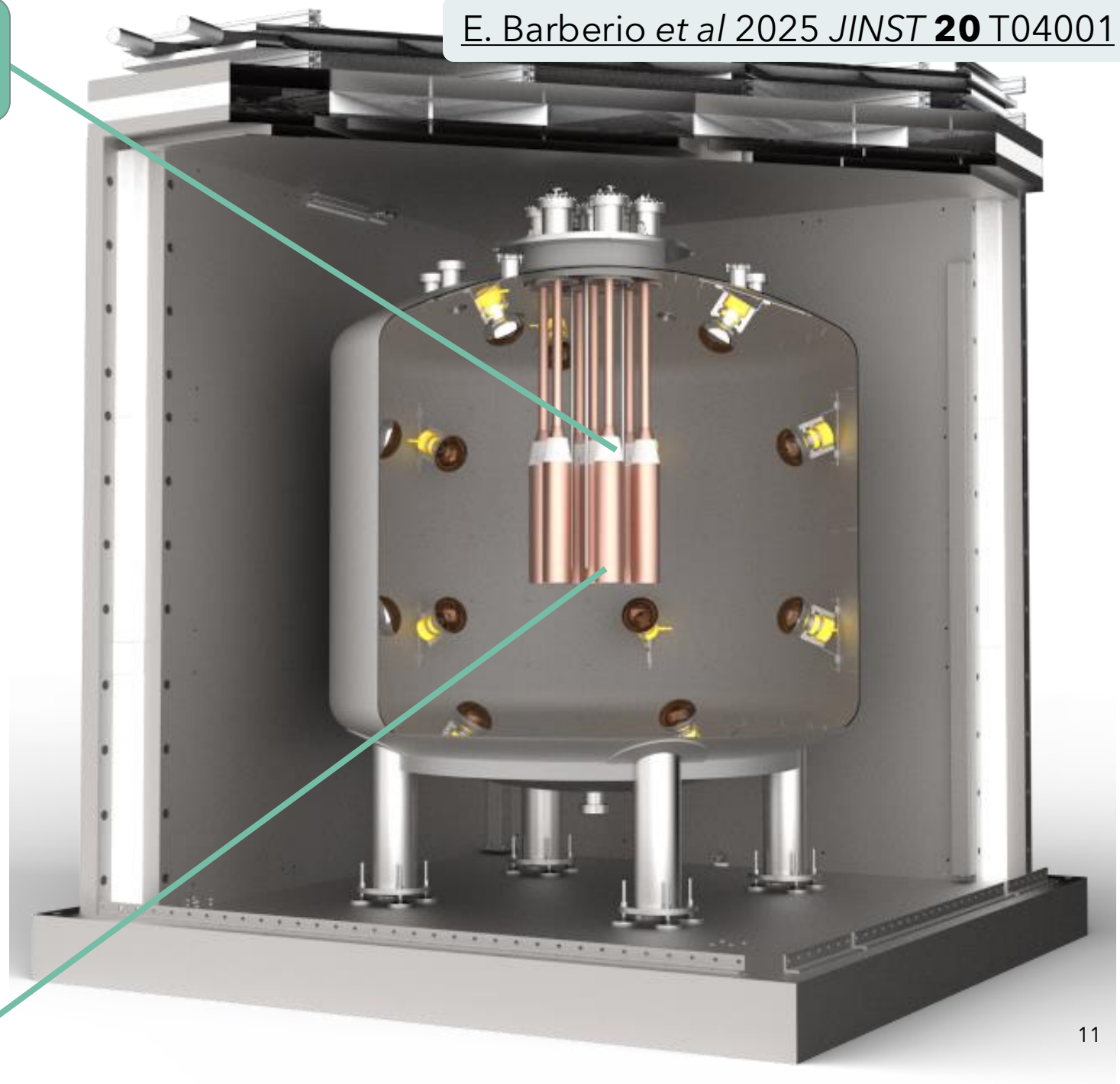
Crystal Detector Module



R11065 PMTs

NaI crystal





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NaI Crystal Production

- NaI(Tl) Crystals grown from Astrograde powder
- **RMD & Mellen:**
  - Modified Bridgeman method with Zone Refining (ZR) to reduce intrinsic backgrounds (Phys. Rev. Applied 16, 014060 (2021))
  - Standard method (non ZR) are also usable for SABRE South (due to veto) - but slightly higher typical background
  - 3.5-5kg typical mass
- **SICCAS:**
  - Seedless Bridgman method for a longer crystal
  - Achieved 10kg of crystal with standard powder (6.9 kg after cutting)
  - Preproduction: 2x 0.5kg Astrograde crystals with powder grown and studies for surface treatment optimisation to minimise ^{210}Pb contamination
  - UCL & Boulby assisting with ICPMS for ^{40}K, SUPL in-situ studies for ^{210}Pb
  - Full production awaiting performance/background characterisation.

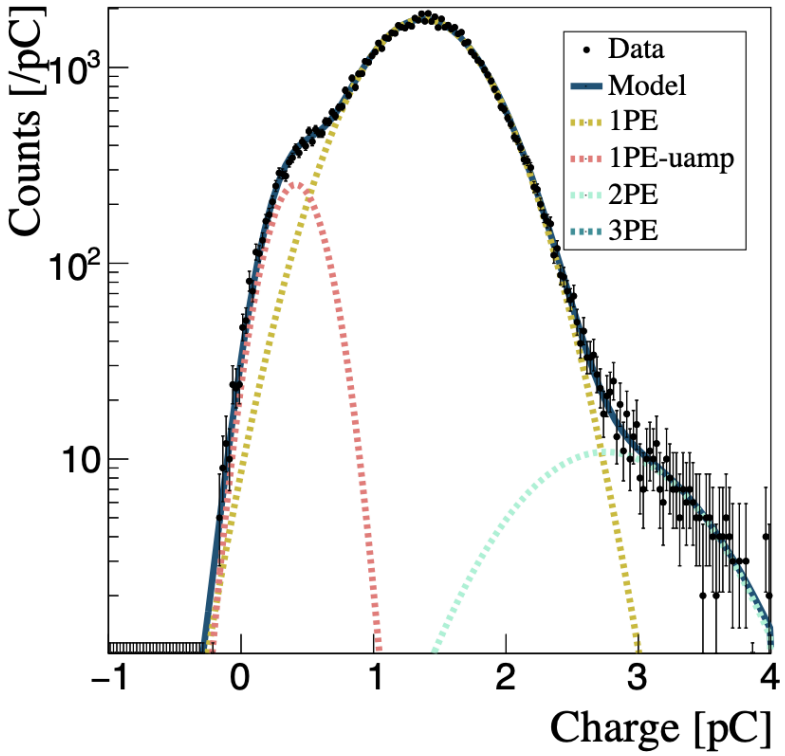
Zone Refining at Mellen

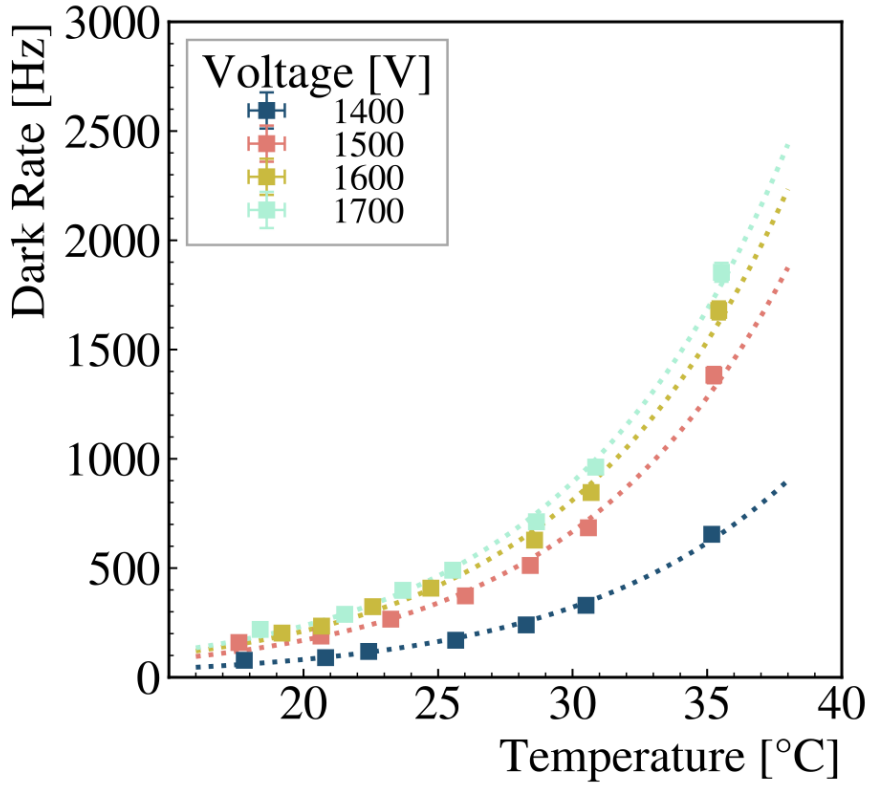
SICCAS

R11065 Hamamatsu PMTs

O. Stanley et al 2025 JINST 20 P07052

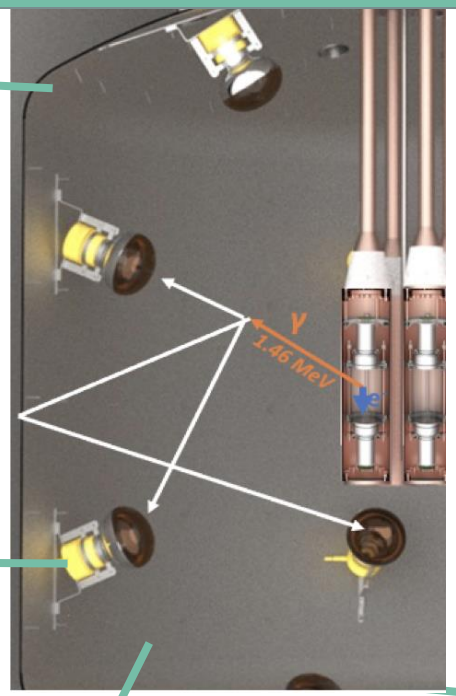
- Pre-calibration of PMTs at Uni Melbourne
- Single photoelectron modelling, understanding gain and dark rate including dependence on voltage and temperature
- Determined that dark counts from thermionic emission can be used for in situ PMT calibration





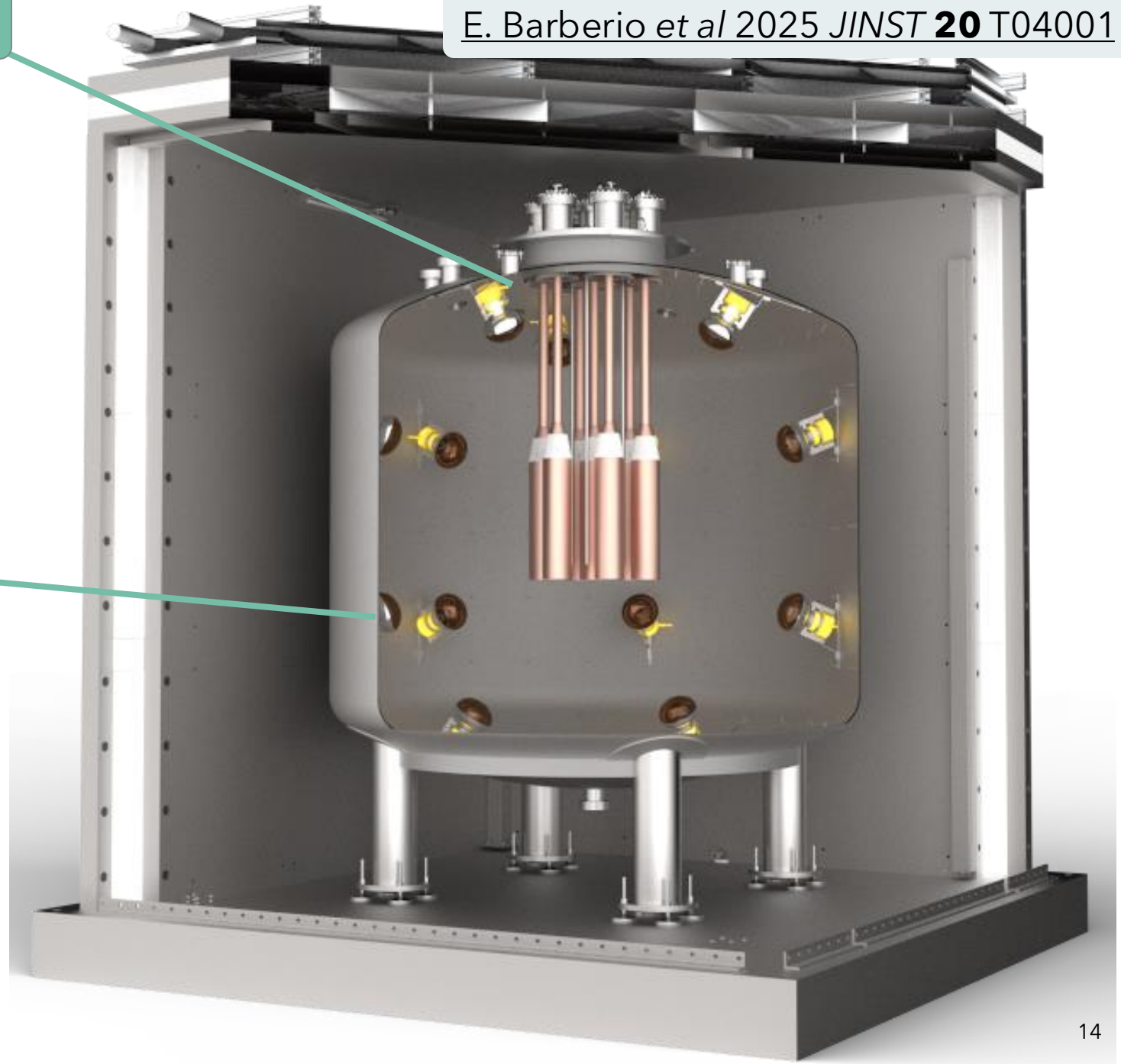
Veto Vessel

Active Veto



R5912 PMTs

Liquid Scintillator



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SABRE South Veto

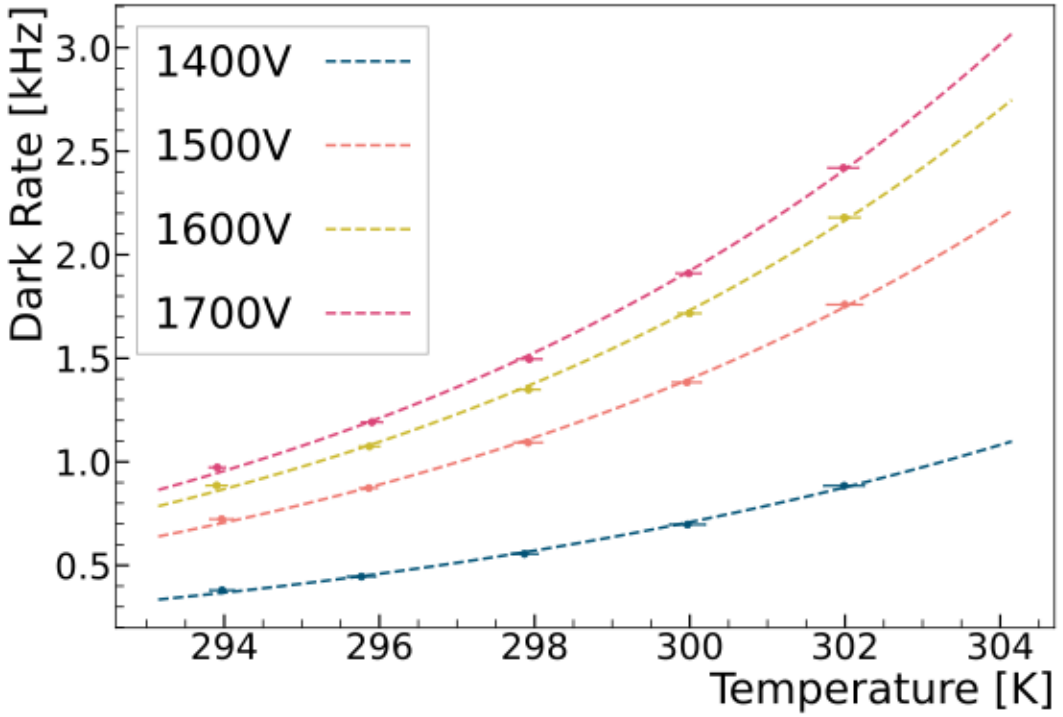
L.J. Milligan *et al* 2025 *JINST* 20 P07049

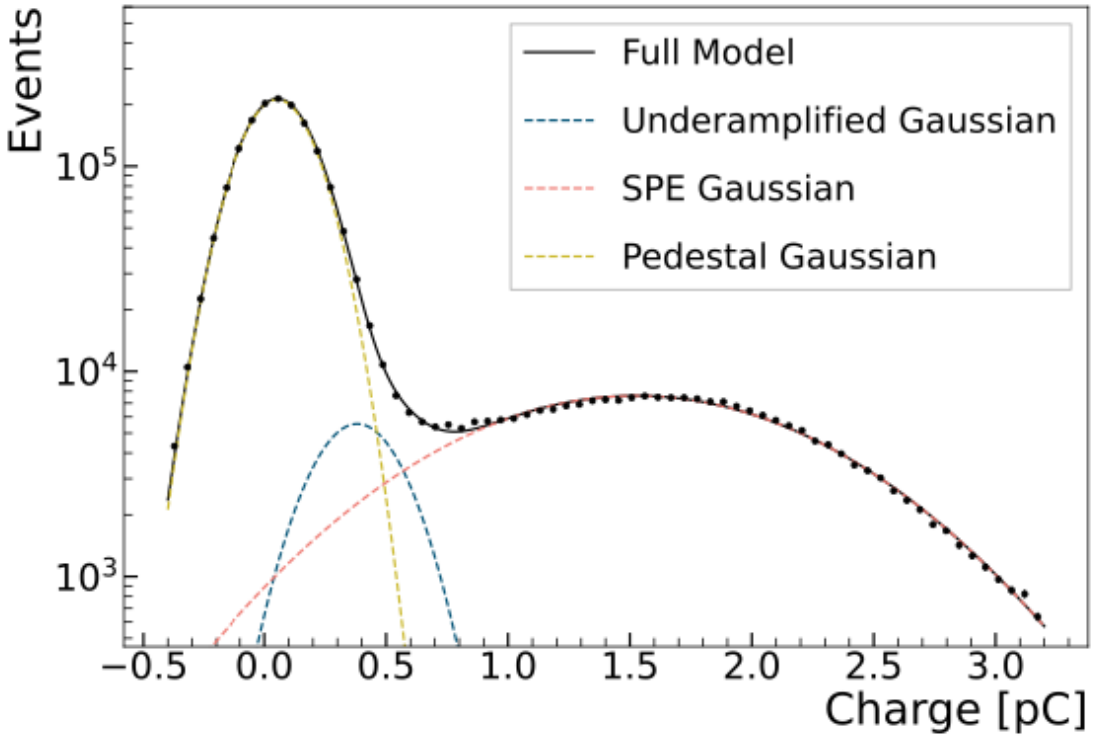
- 12kL of linear alkyl benzene (LAB) procured from JUNO production line, doped with PPO and bisMSB
- Assembly tests of Lumirror, PMT and cable installation above ground
- Test of particle identification in LAB

R5912 Hamamatsu PMTs

L.J. Milligan *et al* 2025 *JINST* 20 P07049

- All PMTs pre-calibrated with ps laser (gain, QE, timing) and thermal systems for background benchmarks (time-dependent noise, afterpulsing rate, potted base emissions).





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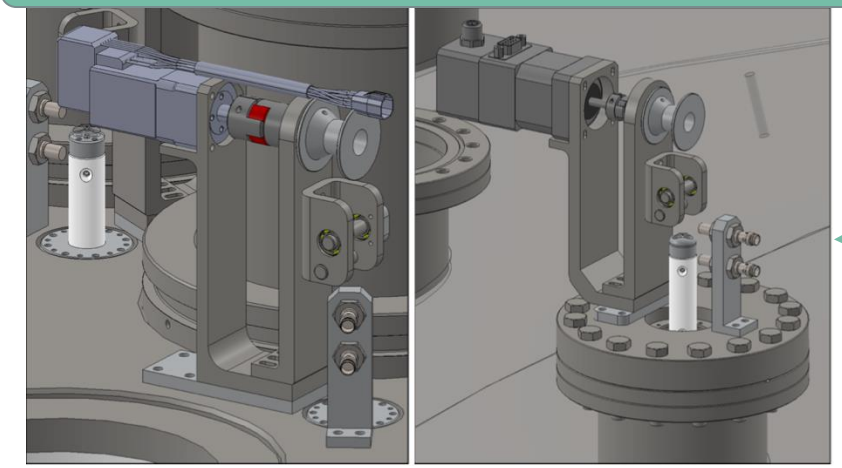
Radioactive Calibration System

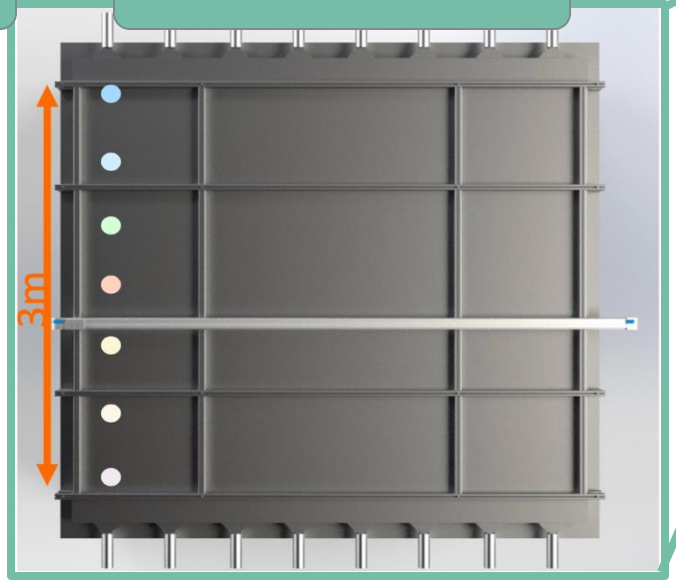


Optical Calibration System

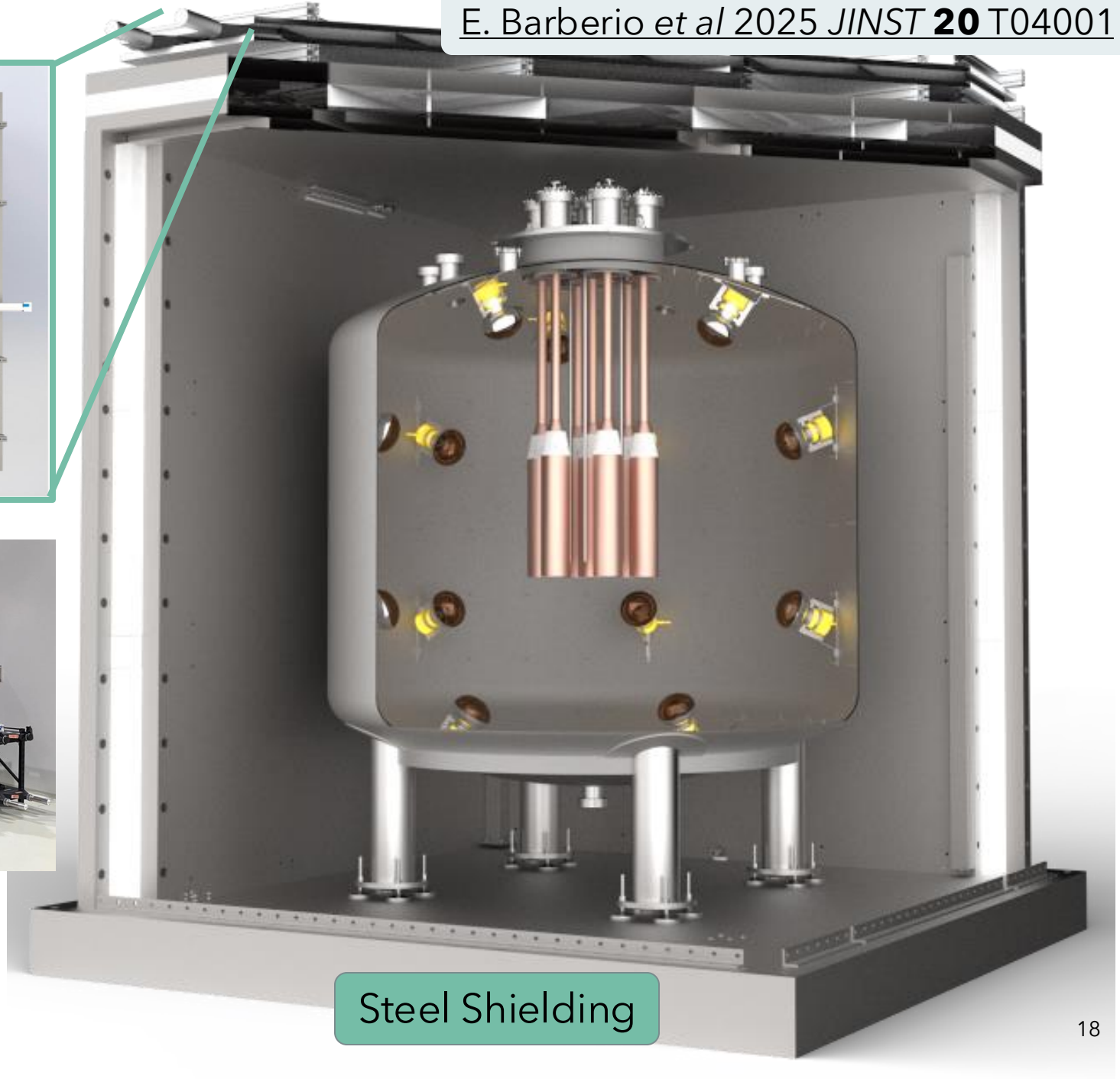
- Design with Teflon laser ball to ensure efficient single photon calibration of veto PMTs

Muon module

Muon veto



Underground



Steel Shielding

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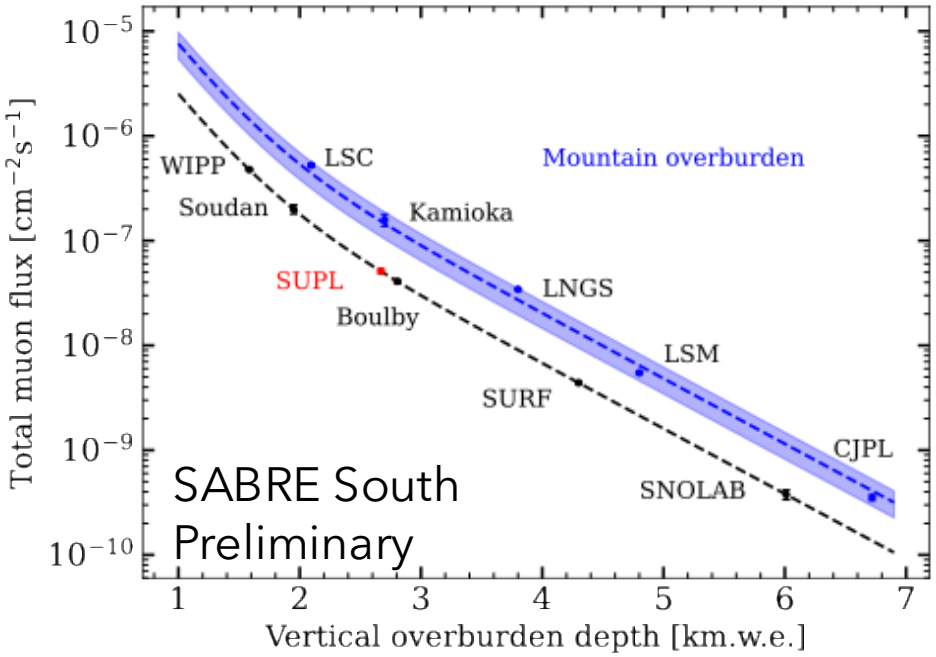
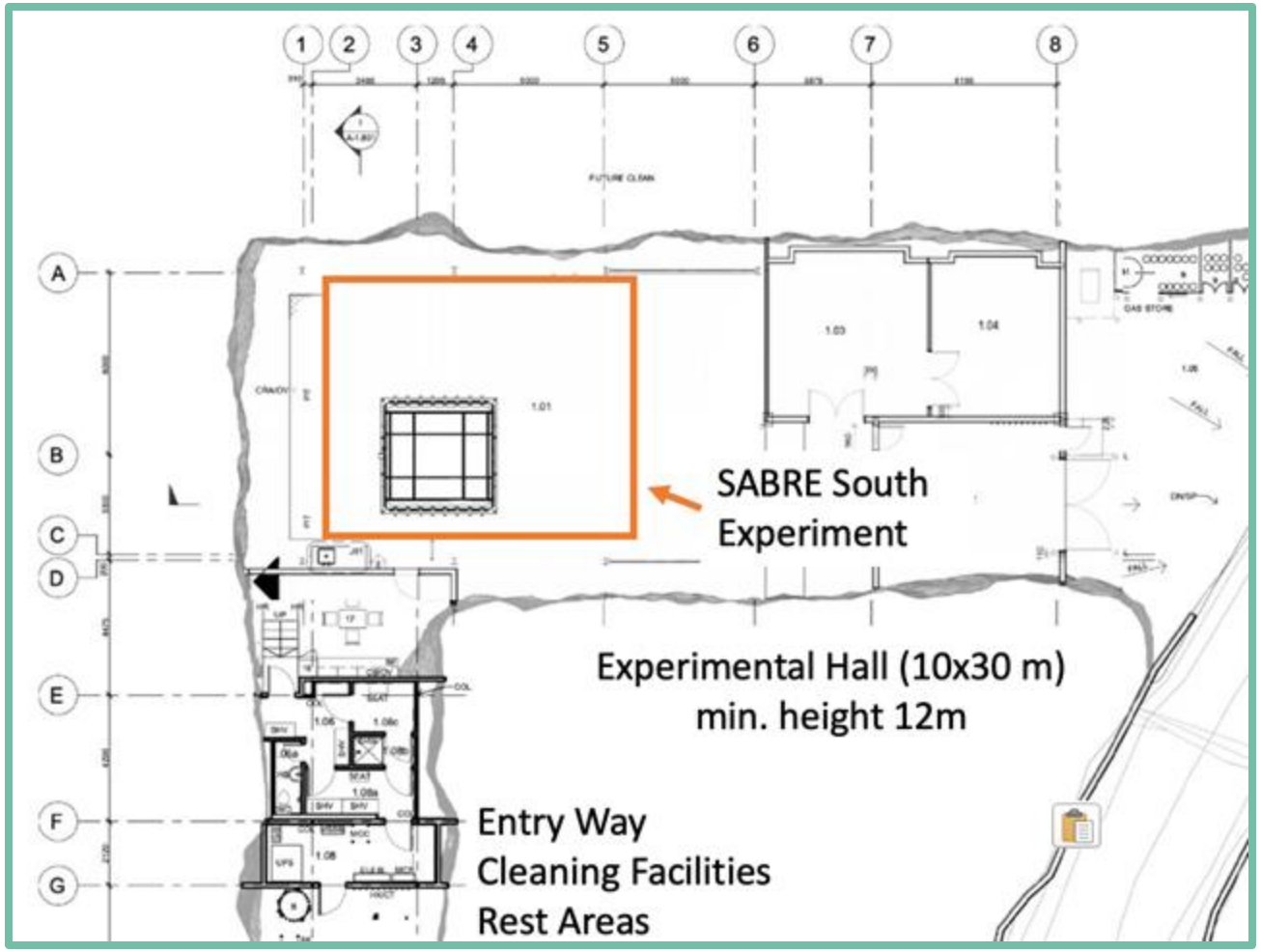
Stawell Underground Physics Lab (SUPL)

https://www.supl.org.au

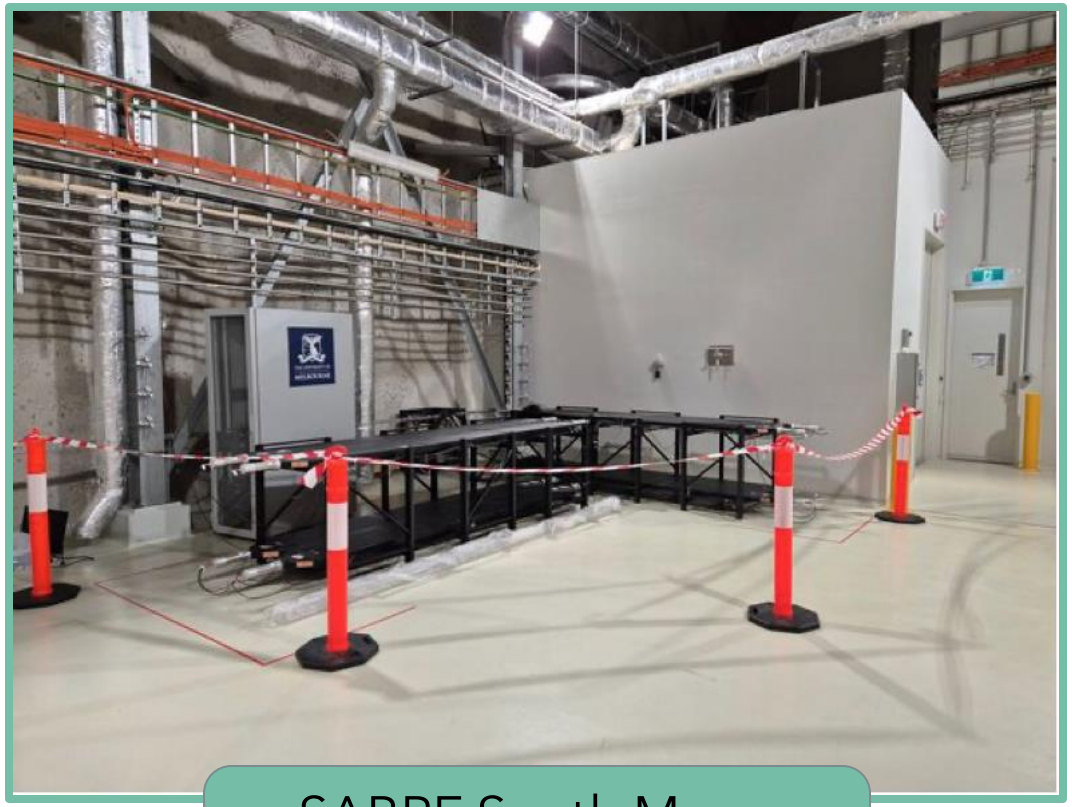
- First deep underground laboratory in the Southern Hemisphere, completed in 2023
- 1025 m deep (2900 m water equivalent) with flat overburden, helical drive access.
- Located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia.



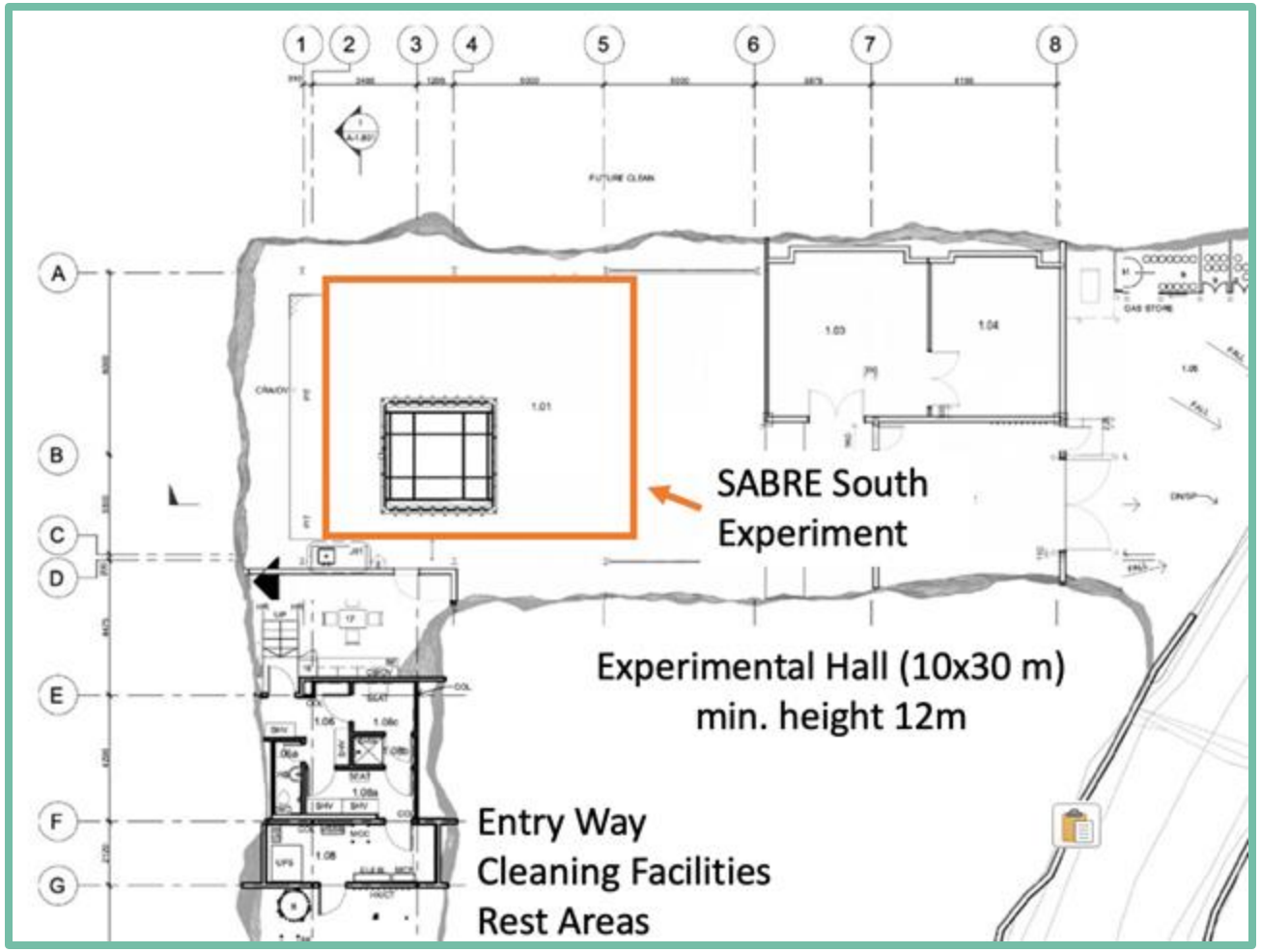


Stawell Underground Physics Lab (SUPL)

https://www.supl.org.au



SABRE South Muon detectors at SUPL



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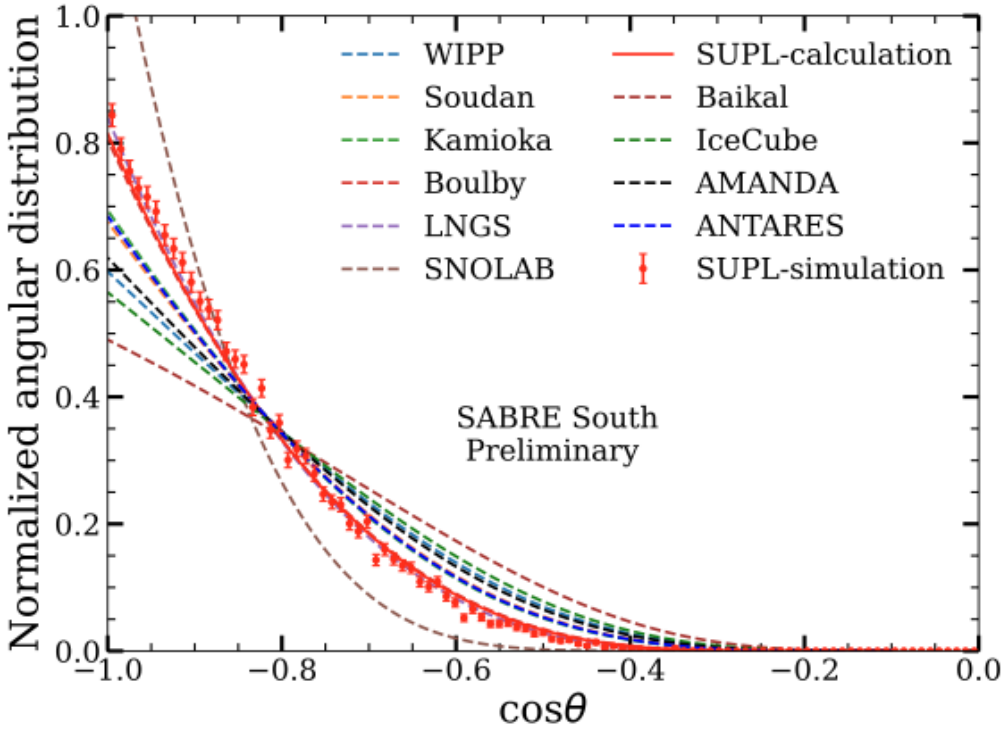
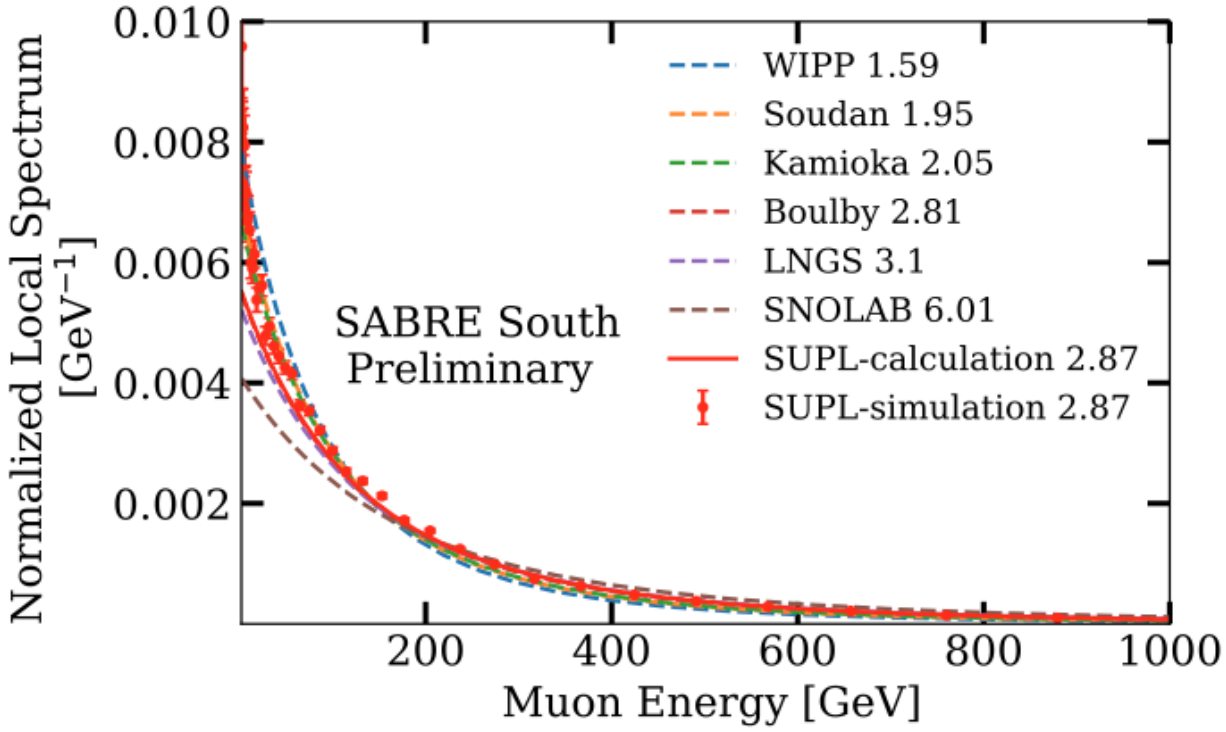
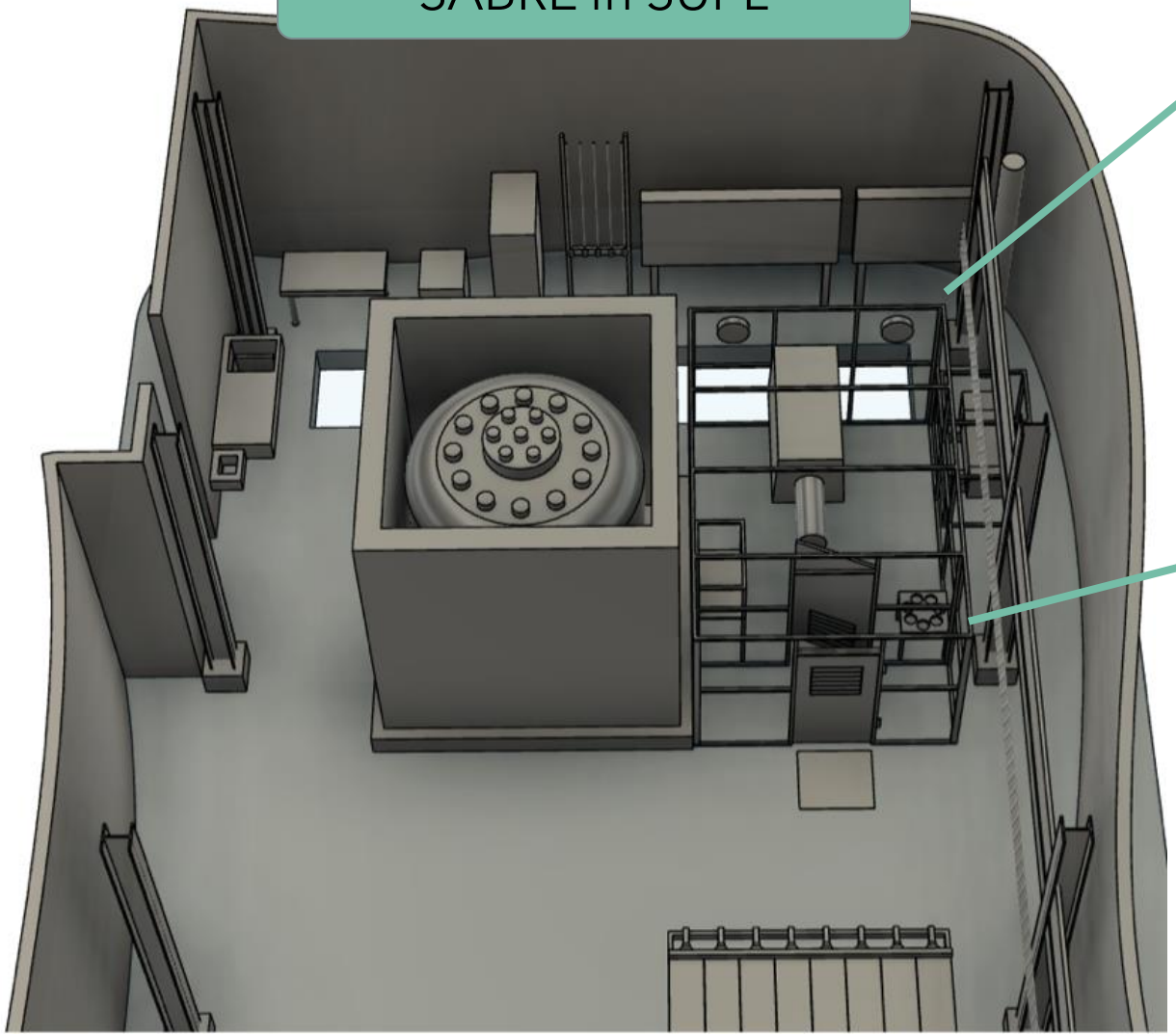
SUPL Muon Measurements

- Muon detectors currently collecting data at SUPL
- Measure muon flux and angular distributions
- Provides the first test of the remote data acquisition system (DAQ) and processing pipelines



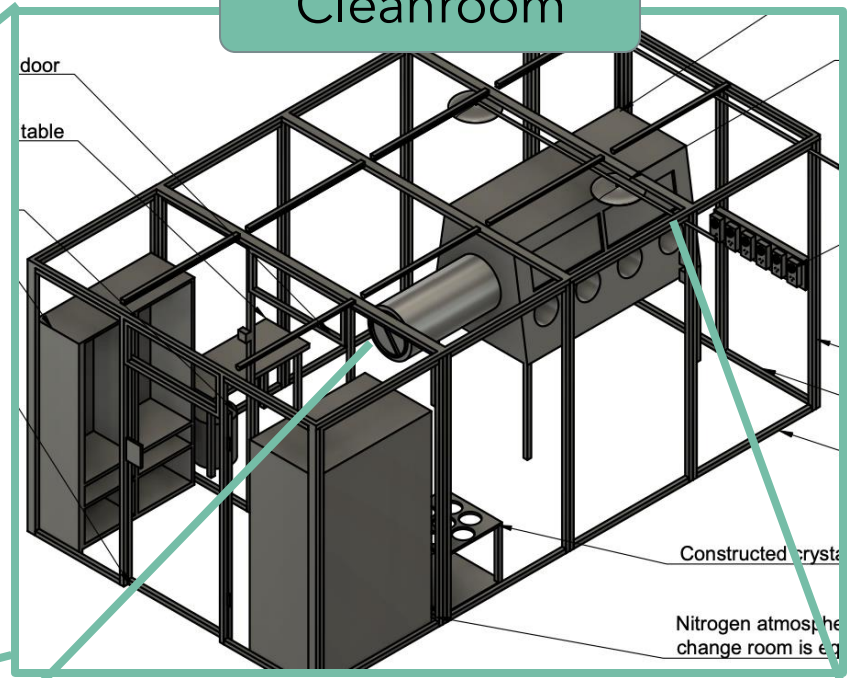


SABRE in SUPL

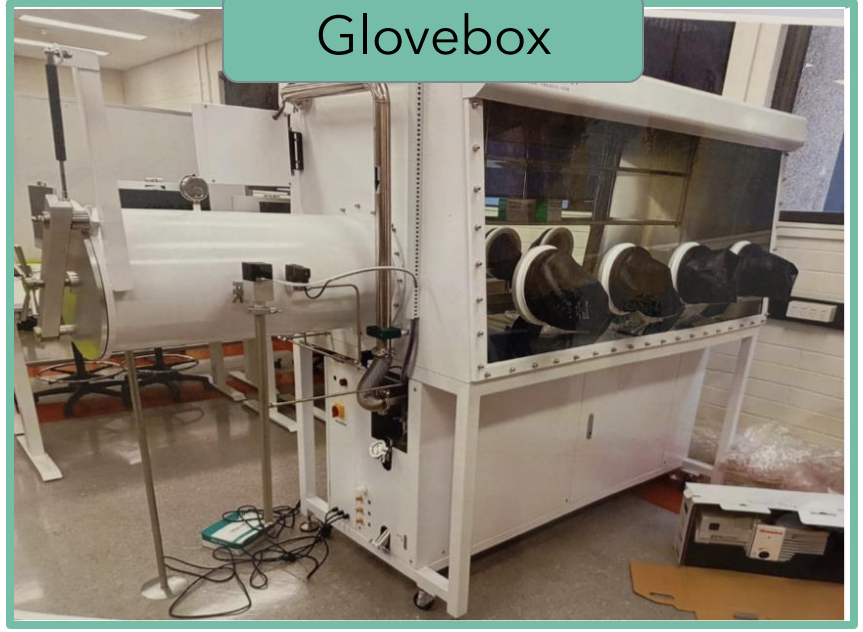


Credit: Adam Sarbutt

Cleanroom



Glovebox

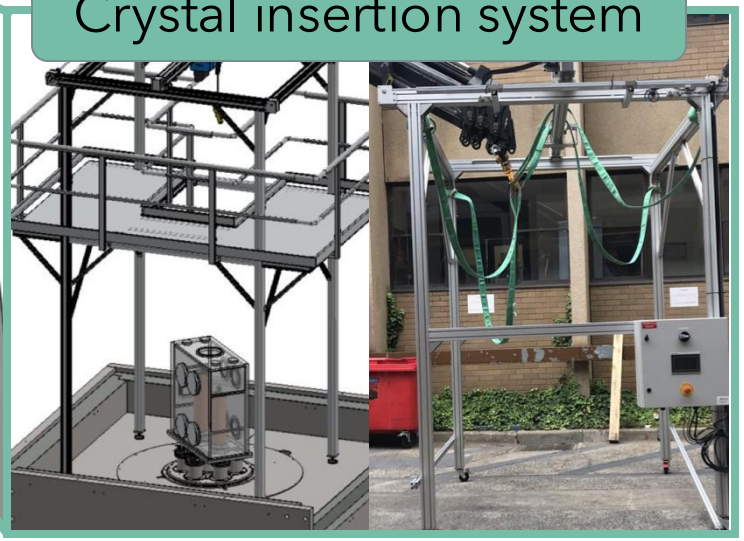


SABRE in SUPL

DAQ & Server

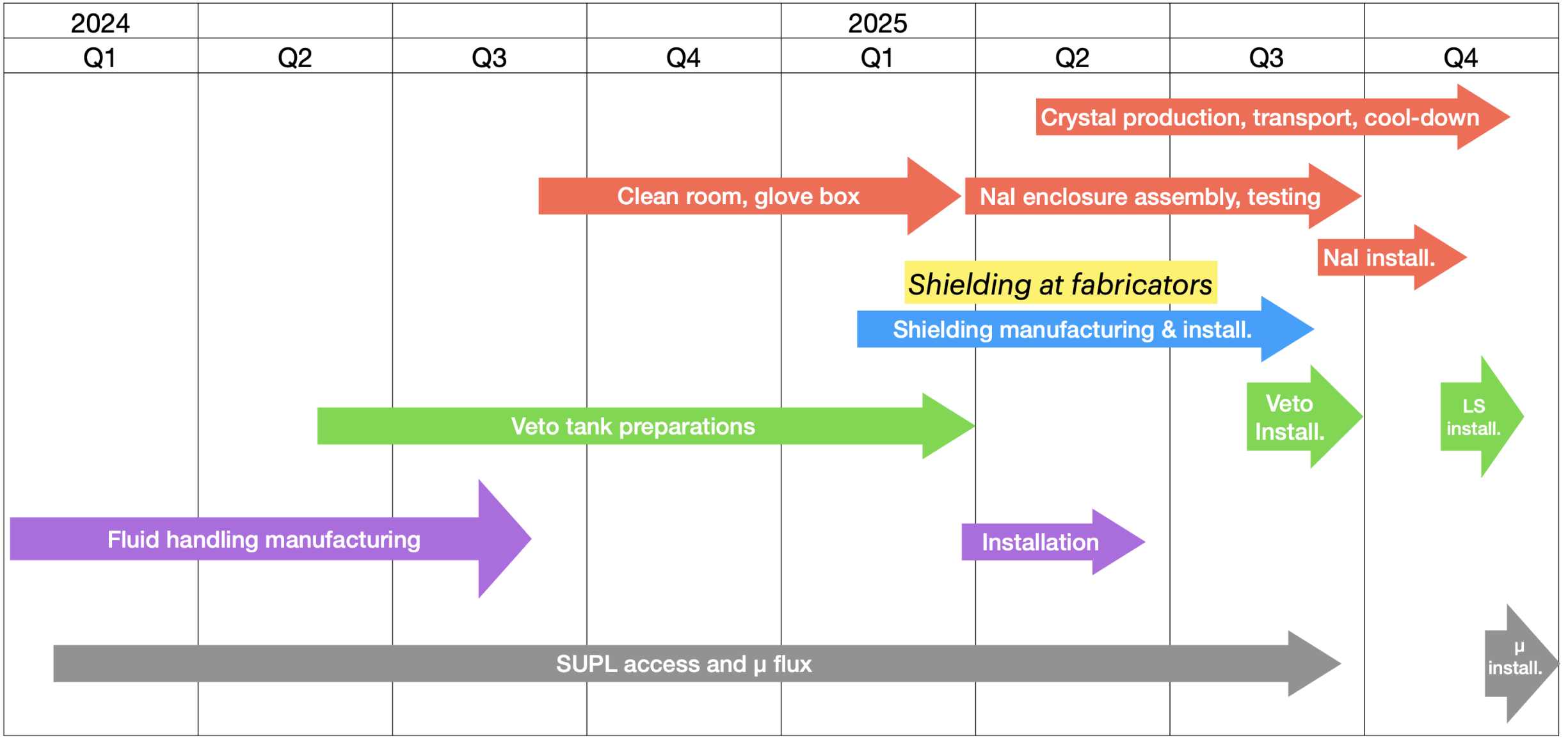
Gas handling system

Crystal insertion system



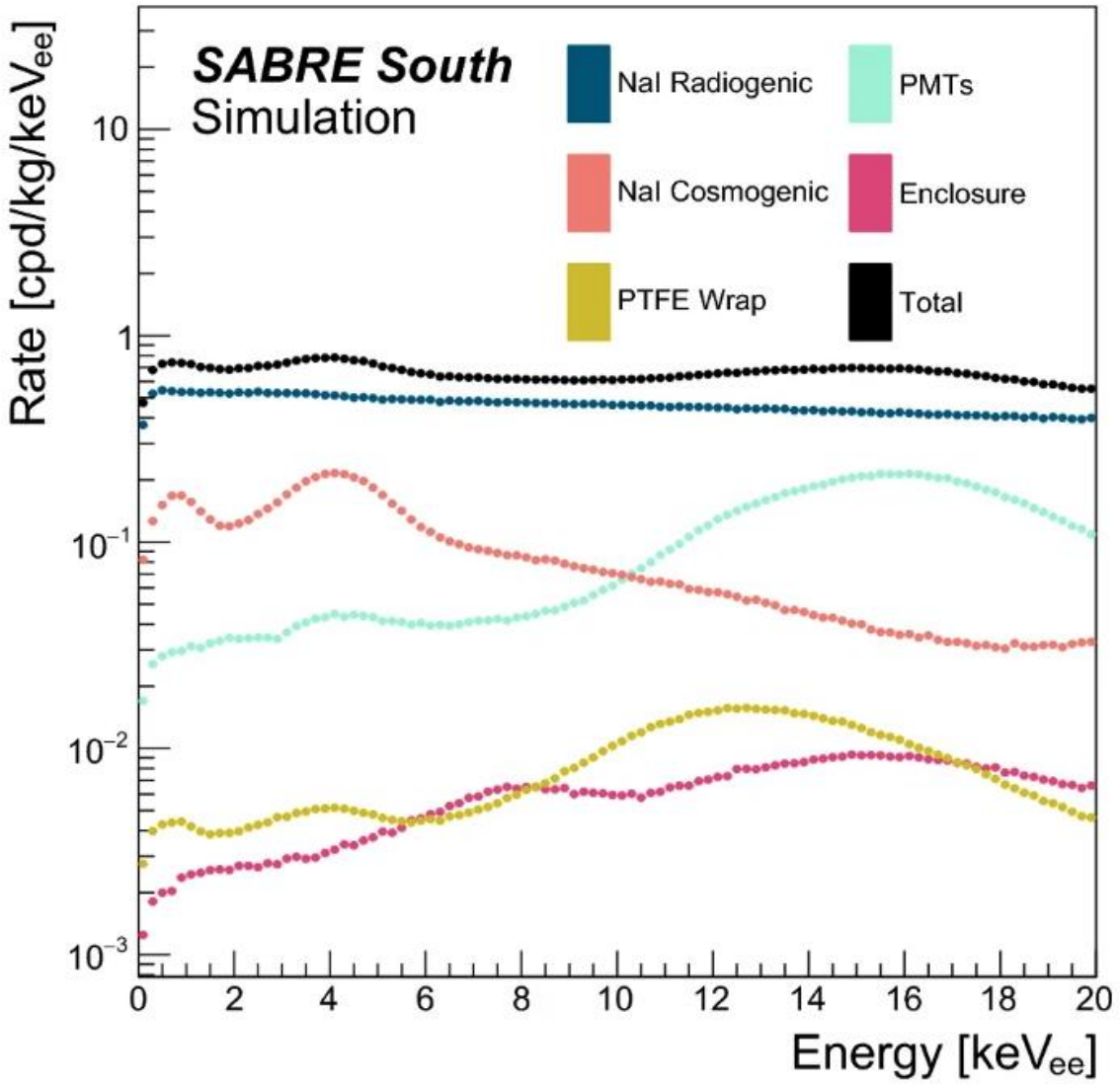
Credit: Adam Sarbutt

SABRE South Timeline



Expected Background

Barberio, E. *et al.* *Eur. Phys. J. C* **83**, 878 (2023).

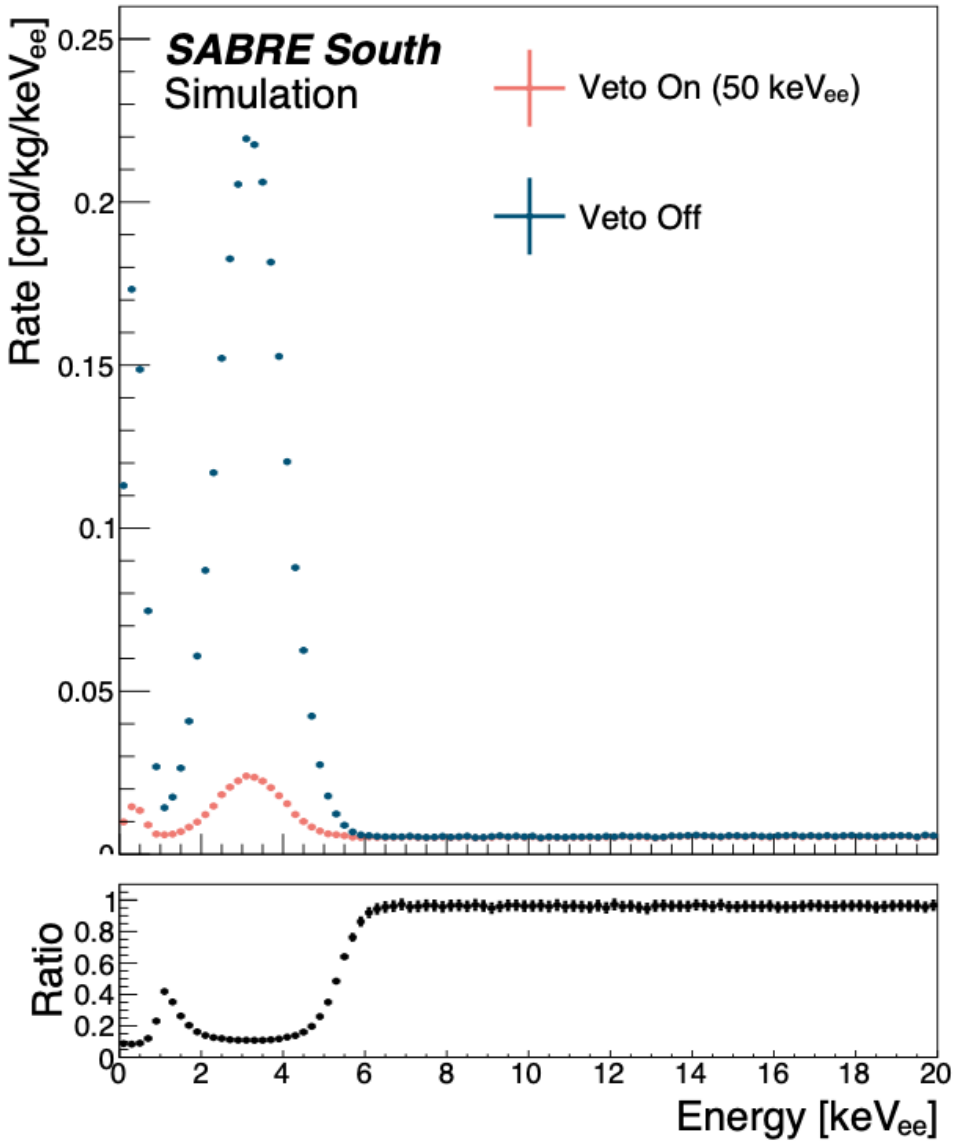


- Expected SABRE South radiogenic backgrounds after a 6-month "cooldown", i.e. time under ground.
- 0.72 cpd/kg/keV$_{ee}$ (with Veto background rej.)
- Dominated by ^{210}Pb

Parameter	Value
Crystal light yield	11.1 ± 0.2 PE/keV [34]
Crystal energy resolution	13.2% (FWHM/E) at 59.5 keV [34]
Crystal energy threshold	1 keV
Veto energy threshold	50 keV
Total active mass	50 kg
Background rate (South)	0.72 cpd/kg/keV [11]

Background Rejection

Barberio, E. *et al.* *Eur. Phys. J. C* **83**, 878 (2023).

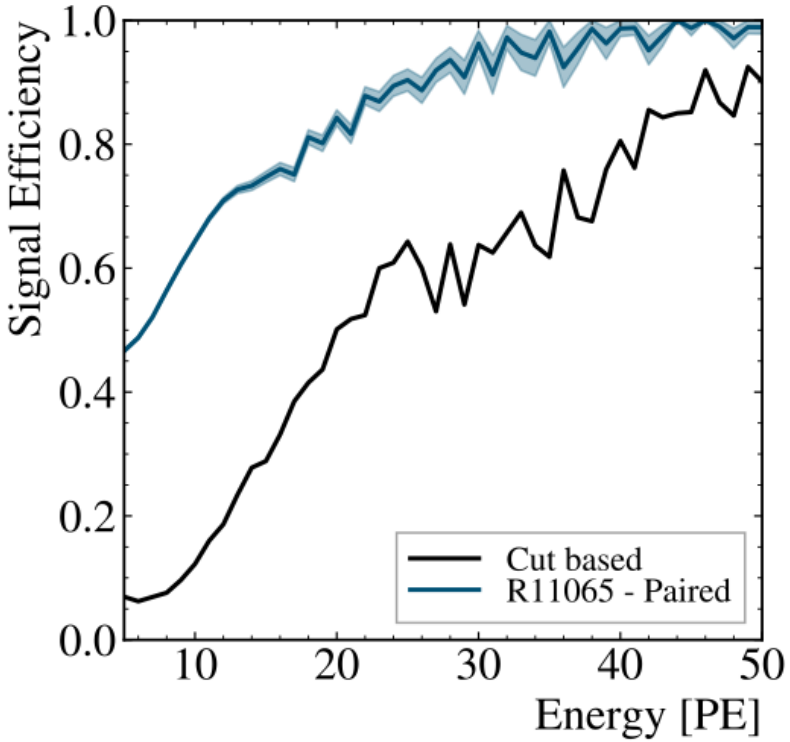


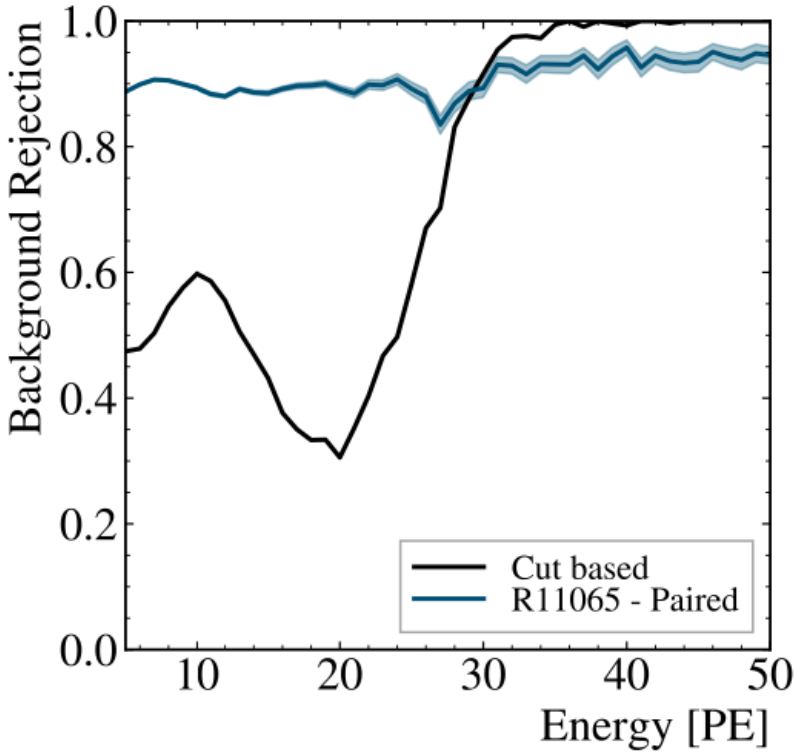
- The liquid scintillator veto provide PID for different backgrounds
- From simulations expect photon-detection efficiency of 0.75 PE/keV/PMT.
- Provides 85% ^{40}K background reduction at 50 keV energy cut

Background Rejection

O. Stanley et al 2025 JINST 20 P07052

Paired PMT BDT:

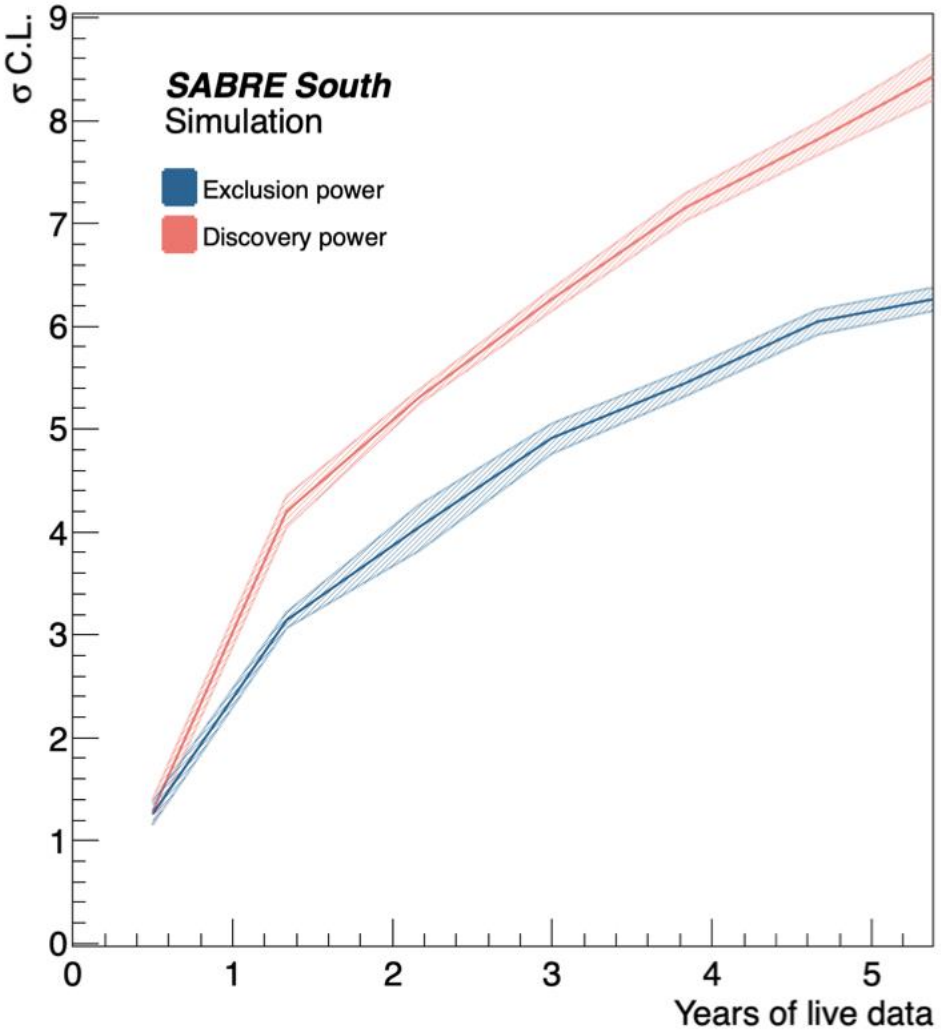




- Low energy signal (1-3keV), PMT noise is an important consideration
- Machine learning methods are being explored to reduce the PMT noise
  - Pulse shape
  - Charge asymmetry
  - Timing

Barberio, E. *et al.* *Eur. Phys. J. C* **83**, 878 (2023).

Annual Modulation Sensitivity



- SABRE South expects:
  - 3σ exclusion in 2 years
  - 5σ confirmation in 3 years

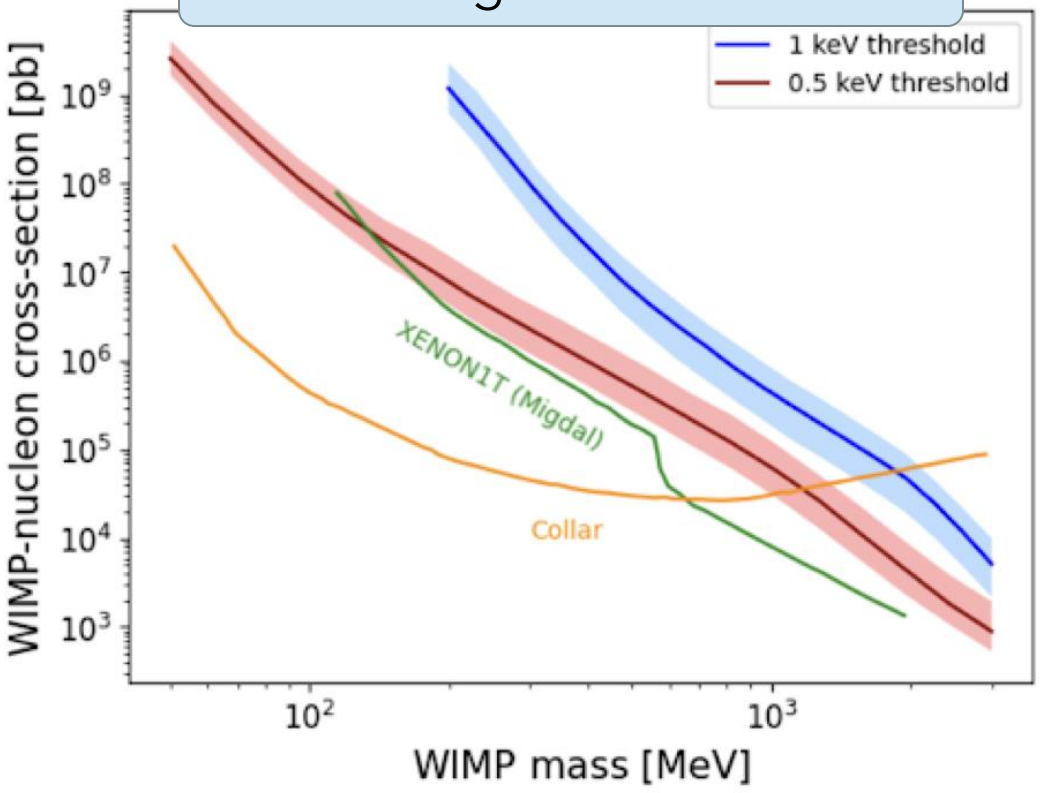
of data collection for a DAMA/LIBRA-like modulation signal.

Extended physics program

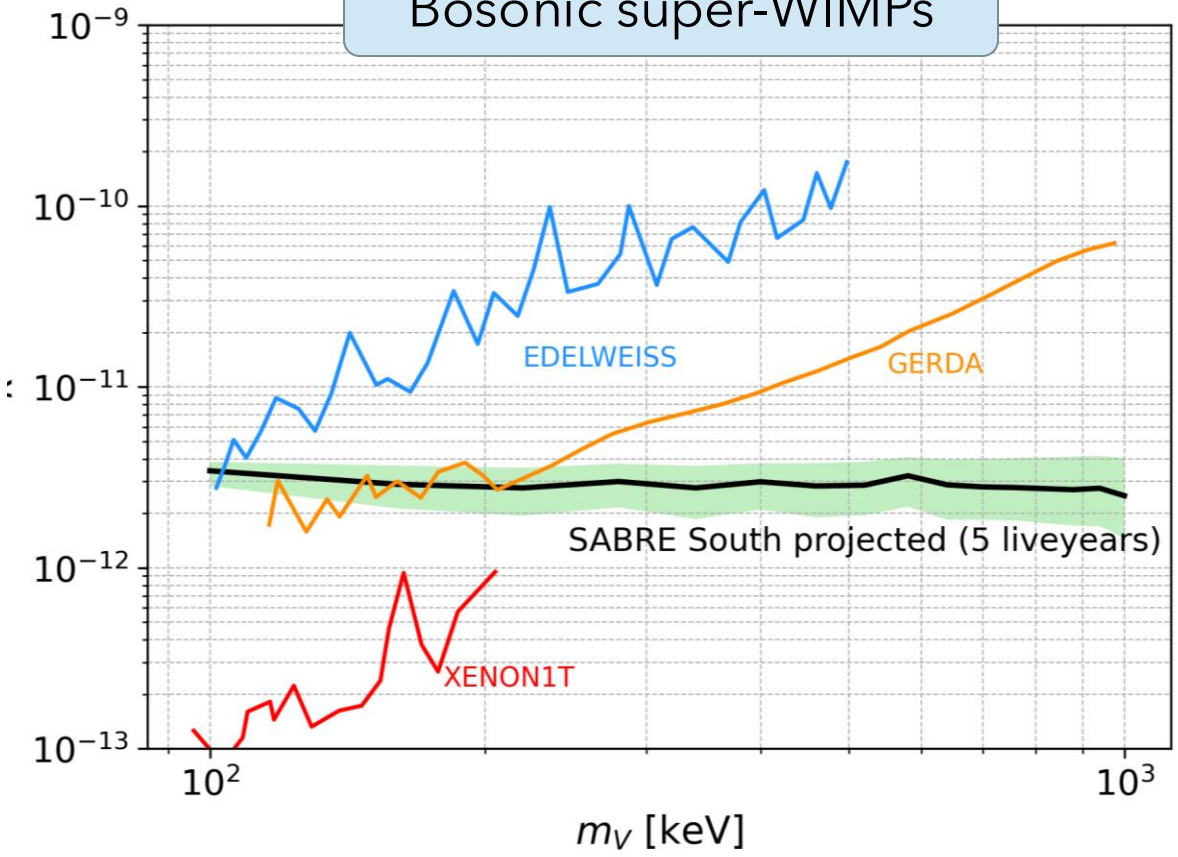
SABRE South TDR (full), DOI: 10.26188/14618172.v3

Preliminary sensitivity studies:

Migdal effect



Bosonic super-WIMPs



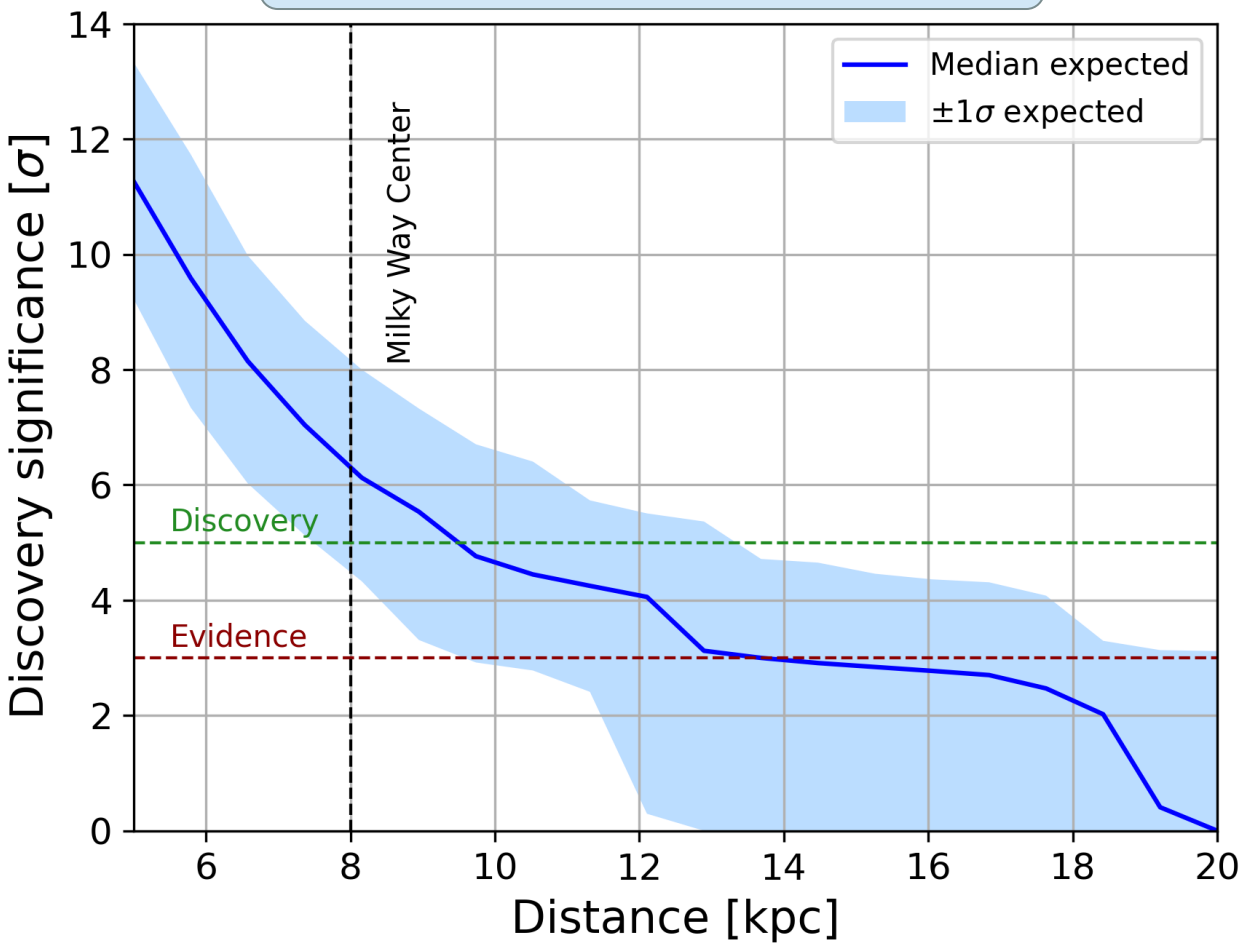
- SD WIMP scattering via the Migdal effect
- 97.7 kg years exposure

- Vector BSW

Beyond dark matter

SABRE South TDR (full), DOI: 10.26188/14618172.v3

Supernova neutrinos



- Veto (LAB): Sensitivity to supernova neutrinos – possibility to join SNEWS
- Interaction channels:
  - Inverse beta decay
  - Proton elastic scattering
  - Electron elastic scattering
  - ^{12}C nuclear excitation

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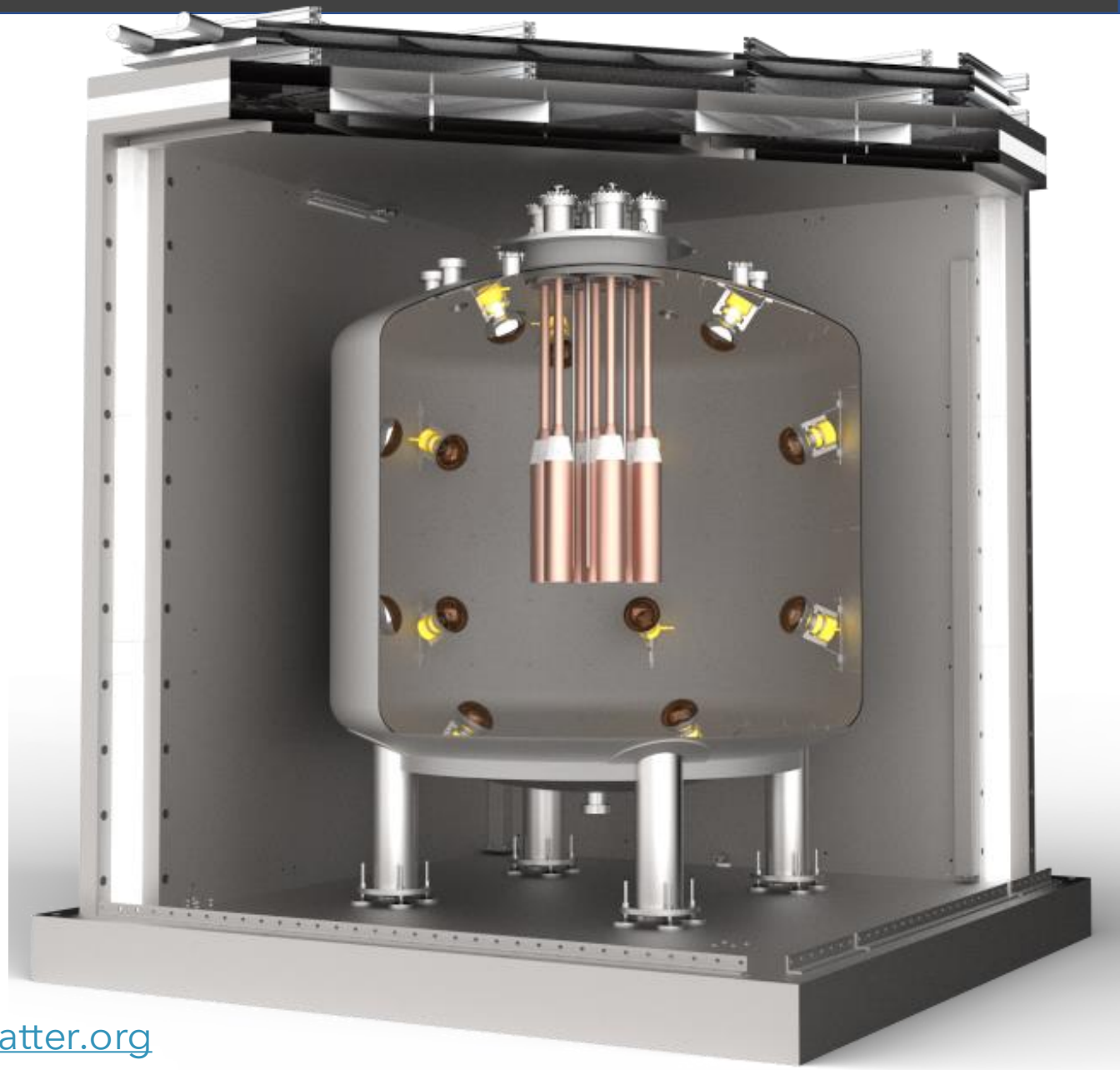
Thank you!



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

https://www.centredarkmatter.org