The SABRE South Experiment at the Stawell Underground Physics Laboratory

European Physical Society for High Energy Physics

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Dark Matter Annual Modulation

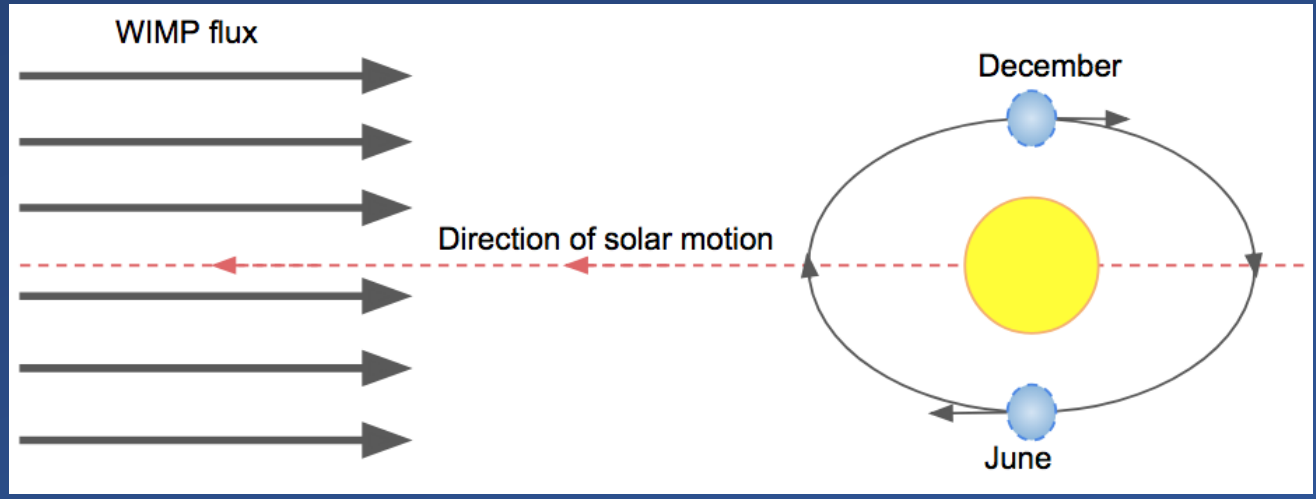
Given the Standard Halo Model hypothesis, the scattering rate of dm with terrestrial detectors will modulate with a maximum on June 2nd, minimum on December 2nd, and period of 1 year.

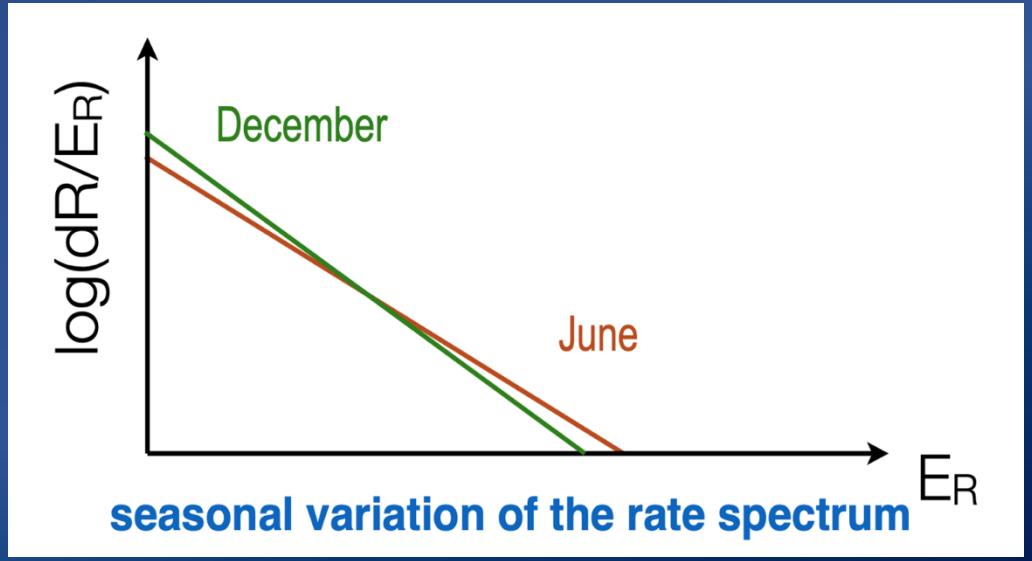
$$R_{\Delta E}(t) \approx R_{0,\Delta E} + R_{m,\Delta E}\cos\left(\omega(t - t_0)\right)$$

Non-modulating component

modulating component

$S_m \approx 0.01 * S_0$





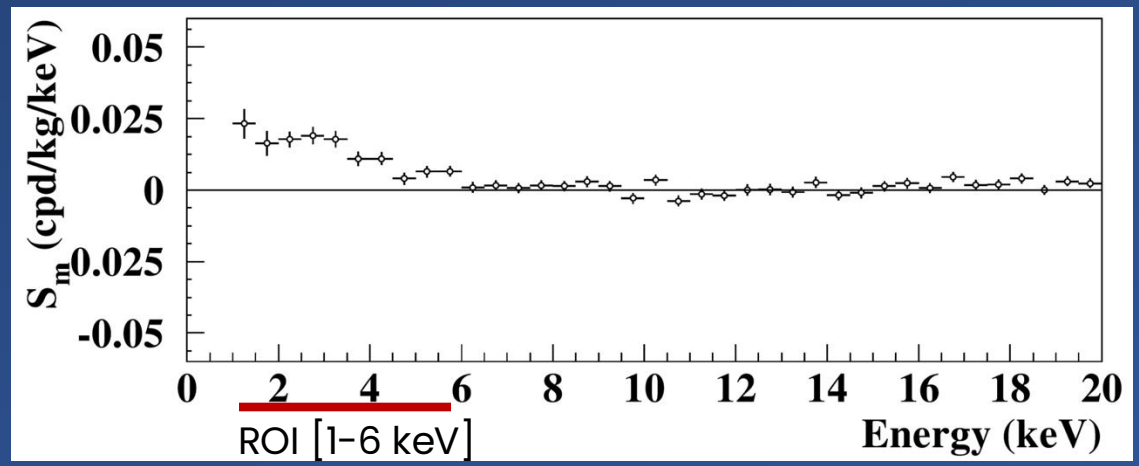
Annual Modulation:

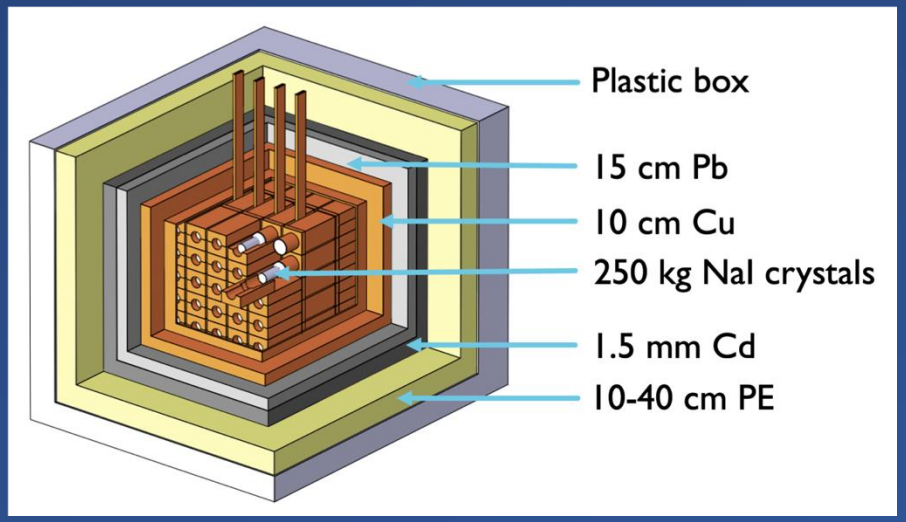
- Model Independent signature of DM
- Require strict control over modulating backgrounds

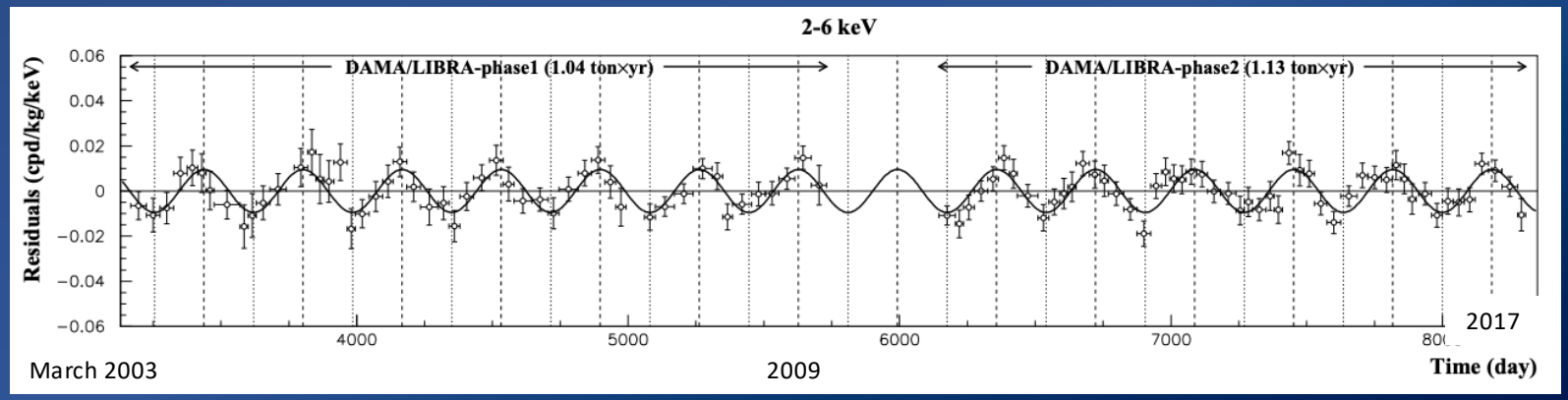
The DAMA/LIBRA signal

The DAMA/LIBRA experiment has measured an annual modulation in the residual distribution of nuclear recoils in their NaI(Tl) scintillators

- Over 20 years of operation
- Period 1 year
- Peak on June 2nd
- Modulation of ~0.01 cpd/kg/keV observed in residual distribution over 2-6 keV energy region (combined Phase I and Phase II) @ 12.6 σ significance; 1-6 keV (phase II) @ 11.8 σ significance



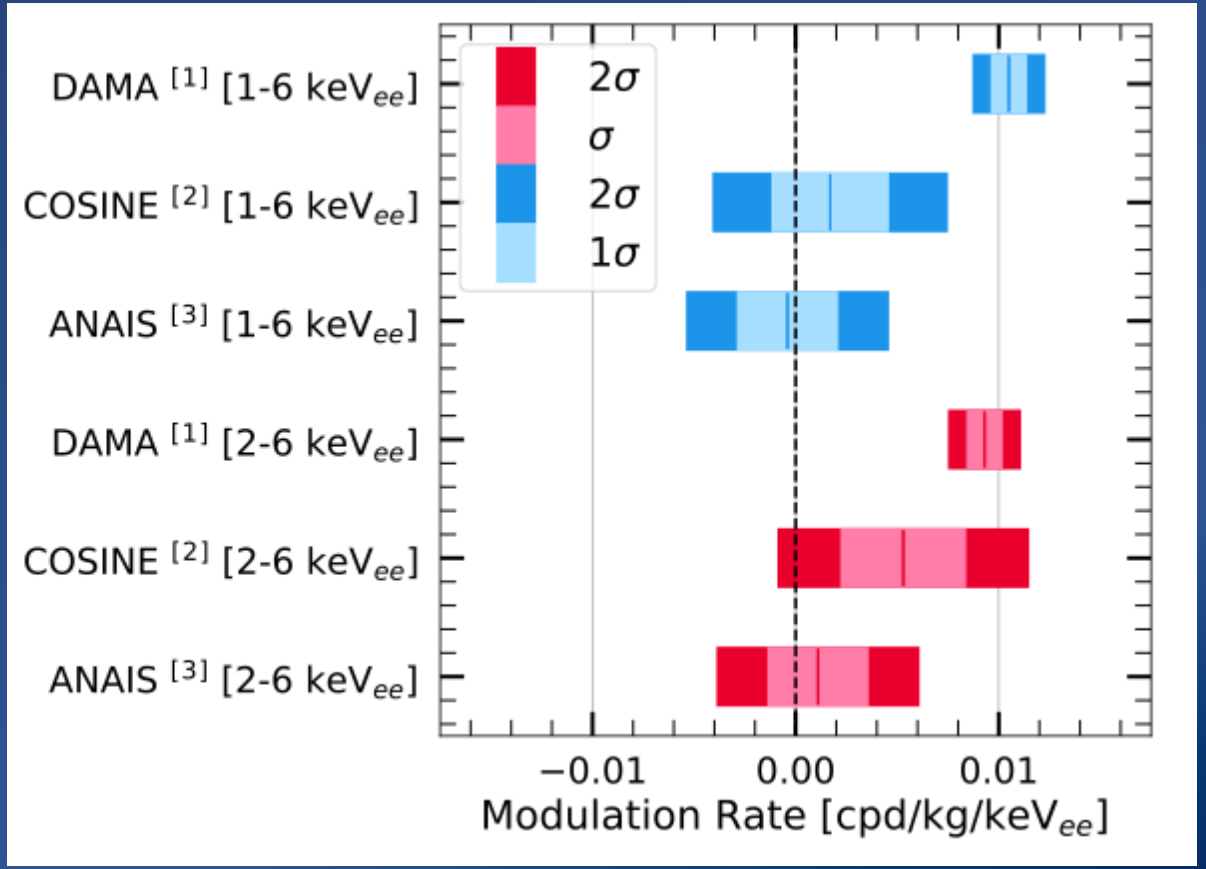




R. Bernabei et al, Progress in Particle and Nuclear Physics, vol. 114, 2020, 103810

Testing DAMA/LIBRA

- This signal is best tested by similar but improved detectors
- Current model independent tests of DAMA/LIBRA are inclusive
- Uncertainties regarding quenching factors makes comparison between NaI experiments difficult (M. J. Zurowski arXiv:2211.15861)
- From APPEC (Astroparticle physics European consortium): "The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material"



[1] R. Bernabei et al., Annual Modulation results from DAMA/LIBRA, 2023
[2] G. Adhikari et al., Three-year annual modulation search with COSINE-100, 2021.
[3] ANAIS Collaboration, I. Coarasa Casas, ANAIS-112: the most sensitive experiment to test the DAMA/LIBRA signal in a model independent way, in 15th International Workshop on the Identification of Dark Matter, L'Aquila Italy, 2024

The DAMA/LIBRA signal: Induced Modulation?

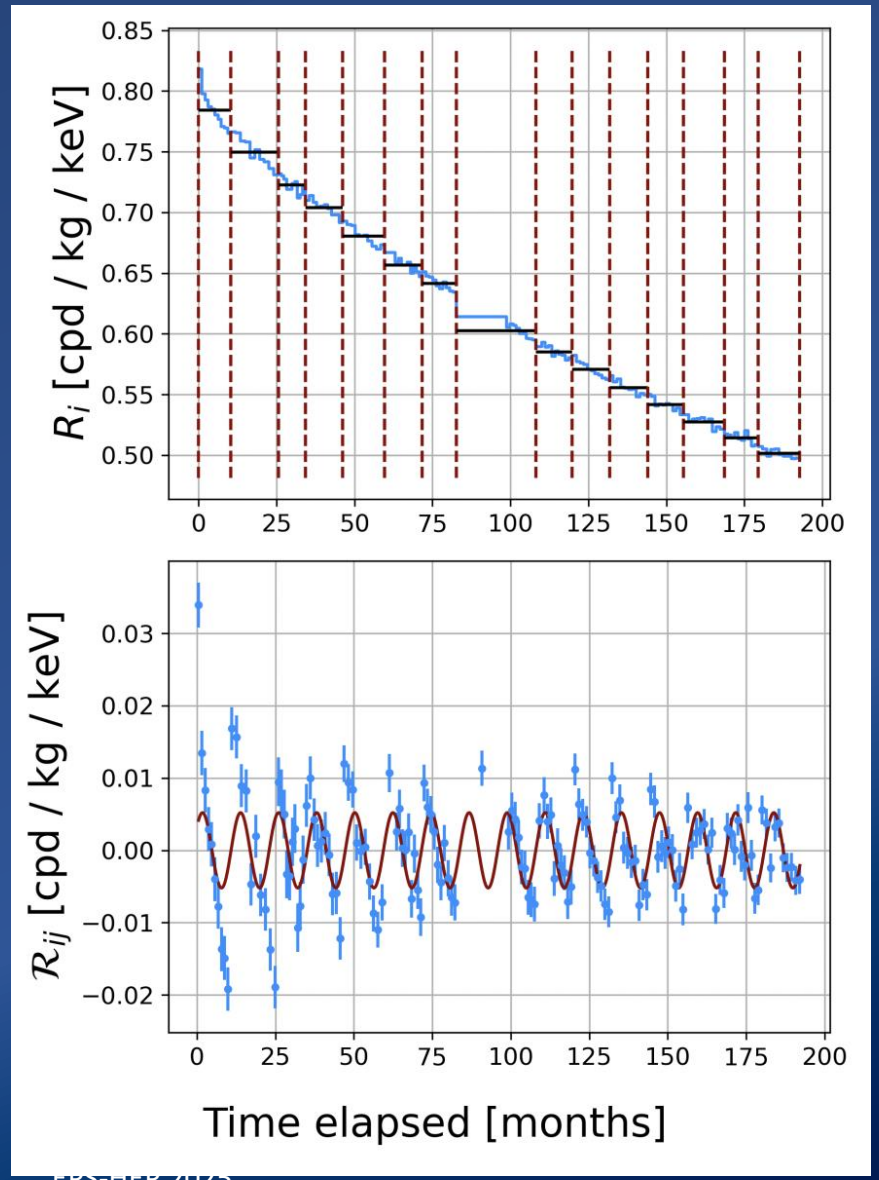
Claims that DAMA/LIBRA's analysis method could induce a modulation consistent with their signal

Applying this analysis method to a best-faith replication of DAMA/LIBRA's background results in a small modulation with a phase opposite to that of DAMA/LIBRA's signal

DAMA/LIBRA's crystal background alone couldn't replicate the energy spectrum of the modulation (arxiv.org/pdf/2408.08697)

$$\mathcal{R}_{ij} = R_i - \langle R_i \rangle_j$$

The ijth residual is calculated by subtracting the average rate of the ith bin of the the jth data taking cycle from the rate of the ith bin



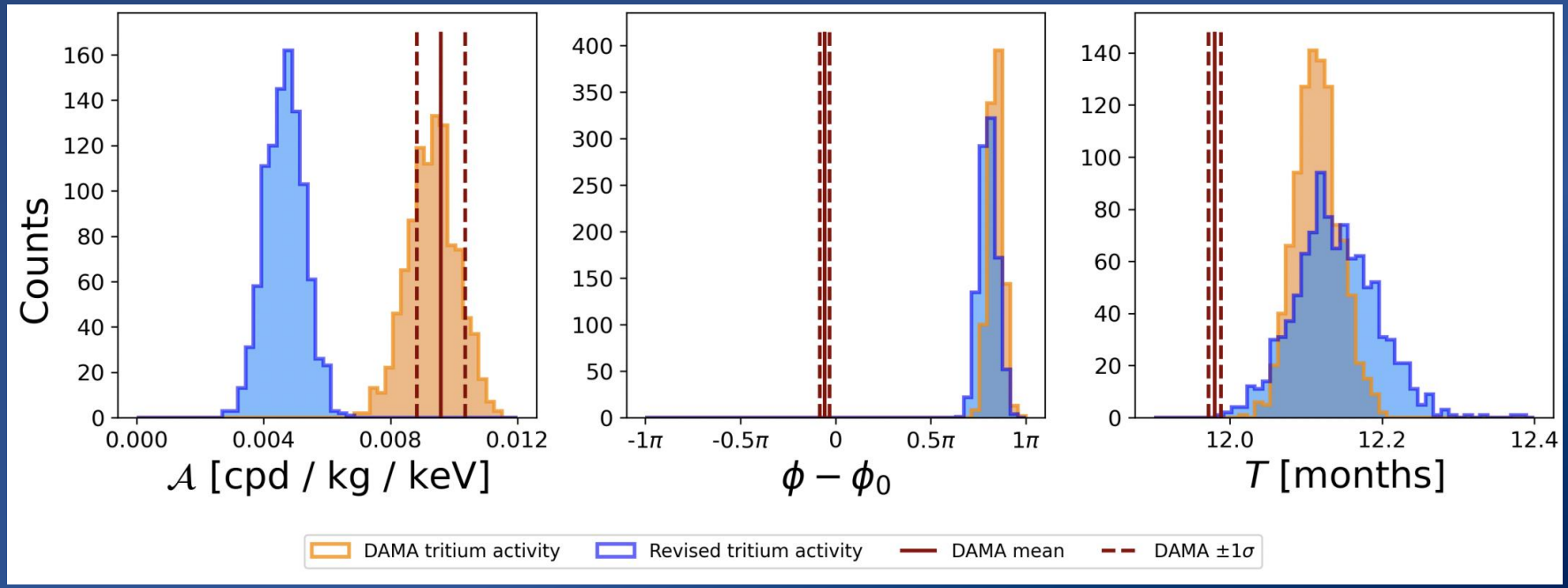
The DAMA/LIBRA signal: Induced Modulation?

Applying this analysis method to a best-faith replication of DAMA/LIBRA's background results in a small modulation with a phase opposite to that of DAMA/LIBRA's signal

DAMA/LIBRA's crystal background alone couldn't replicate the annual modulation nor energy spectrum of the modulation (arxiv.org/pdf/2408.08697)

DAMA tritium activity = 0.09 mBq/kg and is based on total event rate
(R. Bernabei et al., The DAMA/LIBRA apparatus, Nuclear Instruments and Methods in Physics Research Section A 592, 297–315 (2008))

Revised tritium activity = 0.031 mBq/kg calculated based on most up-to-date model of cosmogenic activation of tritium

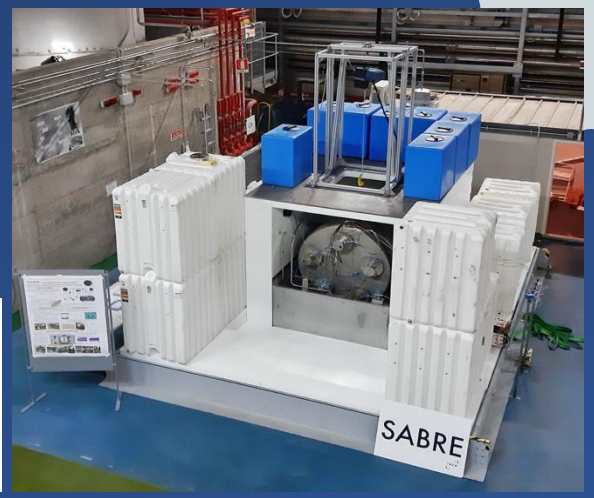


SABRE: a dual site experiment

The ambitious program of SABRE foresees two detectors in two underground locations:

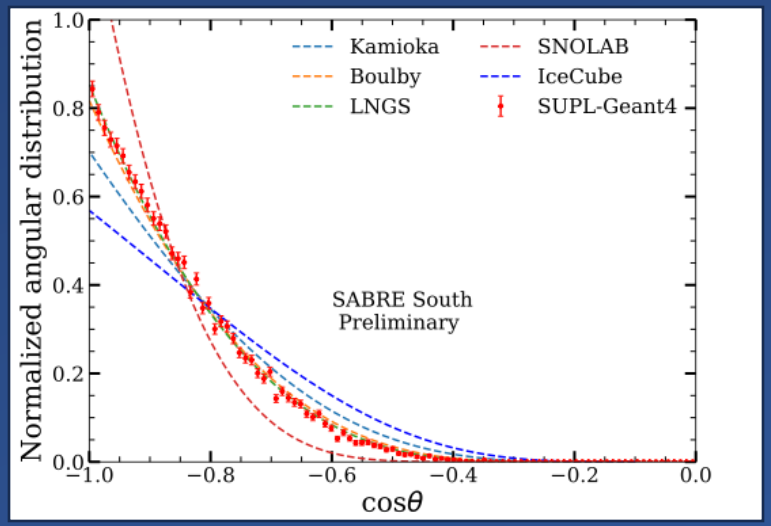
- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

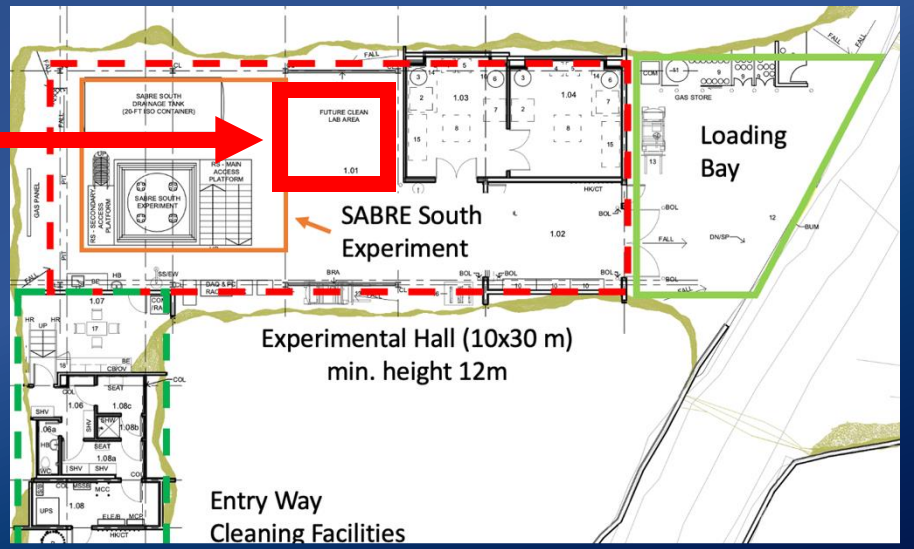
The dual hemisphere design allows for better discrimination of seasonal backgrounds



Stawell Underground Physics Laboratory

- SUPL is the first deep underground lab in the Southern Hemisphere (37° South) located 240 km west of Melbourne
- Lab is 1025 m (approx. 2900 m w.e.) underground with a flat over burden inside of the Stawell Gold Mine
- Muon veto assembled in early 2024 and data collection and analysis is completed with a paper in preparation
- Crystal castle delivered in preparation for crystal testing





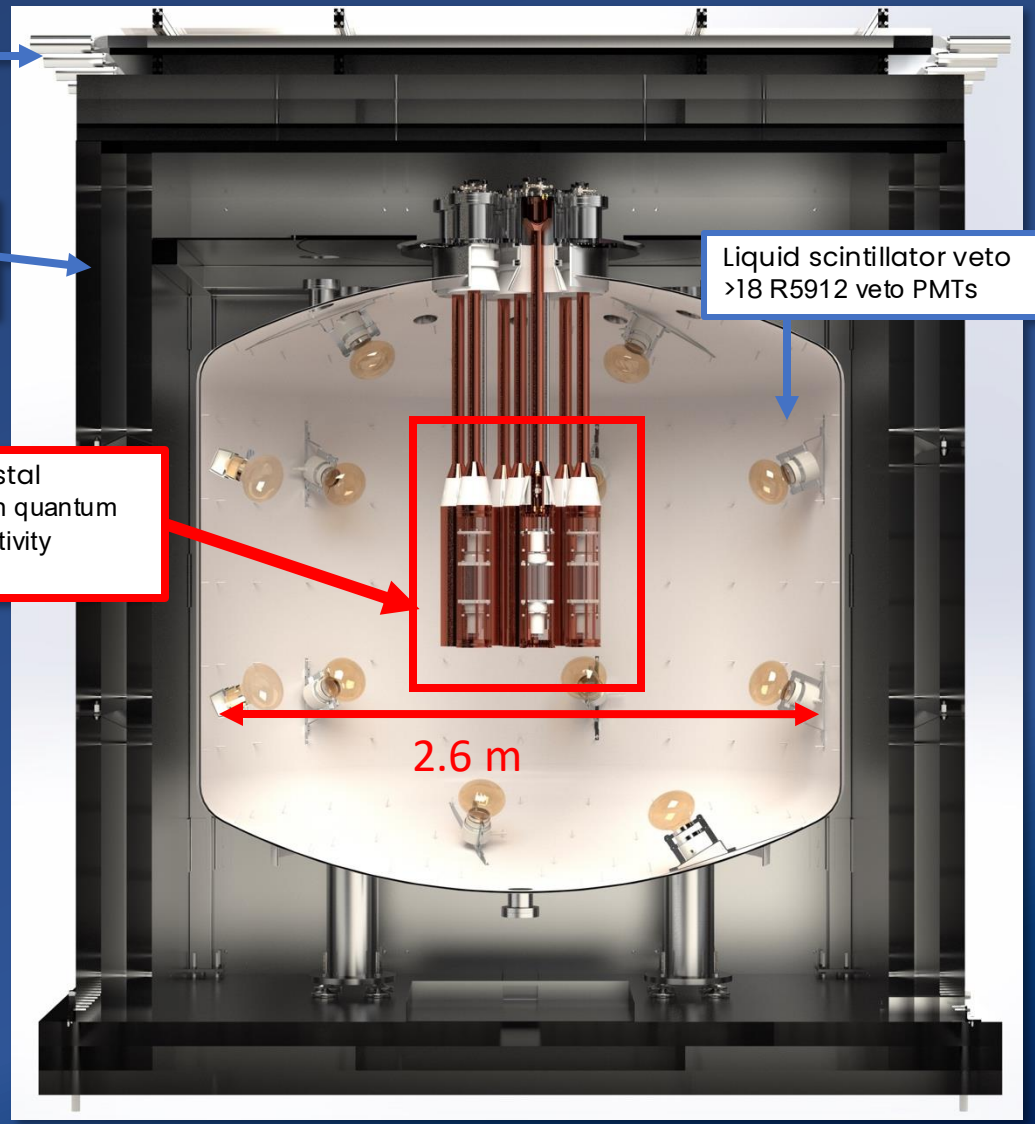
A. Fedynitch, W. Woodley, M.C. Piro (MUTE Collab.) Published in: Astrophys.J. 928 (2022) 1, 27

The SABRE South Detector

Features of SABRE South:

- Southern hemisphere location
- Active veto system
- 2.9 km water equivalent flat overburden
- 1 keV energy threshold
- Ultra high purity NaI(Tl) crystal
- 0.72 cpd/kg/keV simulated background

Improved crystal growth techniques have allowed SABRE South to develop lowest background NaI(Tl) detector.



E. Barberio et al, European Physical Journal C 83, 13849 (2023)

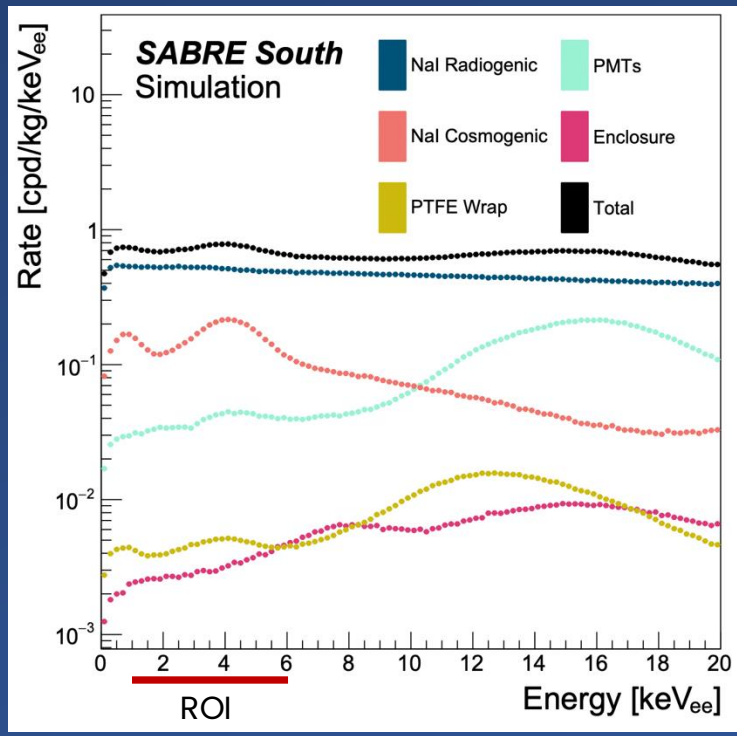
SABRE South Background Simulation

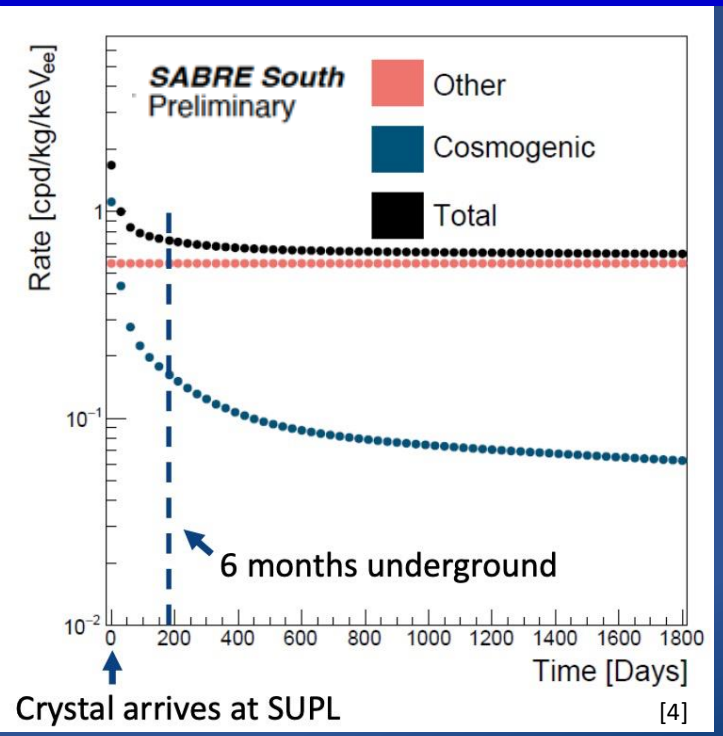
EPJC, Vol 83, 878 (2023)
https://doi.org/10.1140/epjc/s10052-023-11817-z

SABRE South background characterized through
- spectral analysis
- alpha counting
- inductively coupled plasma mass spectrometry (ICPMS)
- measurements on crystal off-cuts
- GEANT4 simulations

Lowest NaI(Tl) detector background of 0.72 cpd/kg/keV.

To test DAMA/LIBRA we require:
- Crystal background > 90% of total background
- Total background < 1 cpd



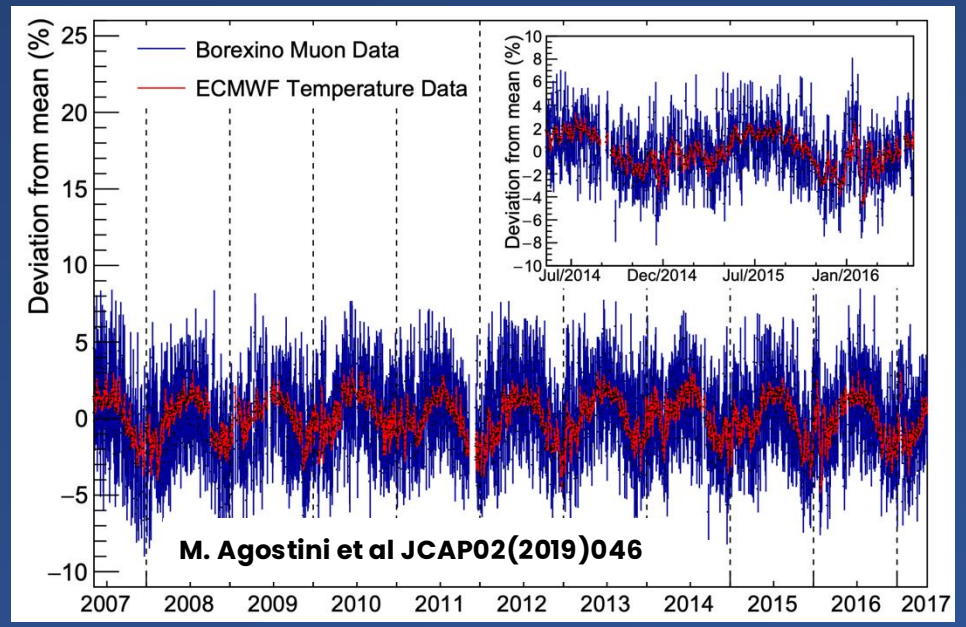


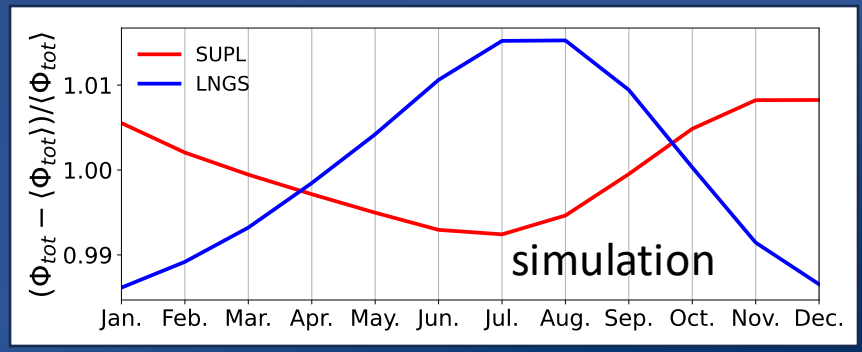
	Mass (kg)	Background (cpd/kg/keV)
DAMA/LIBRA Phase 1 [1]	250	0.8
COSINE [2]	61.3	2.7
ANAIS [3]	112.5	3.2
SABRE South [4]	50	0.72

[1] R. Bernabei et al, Progress in Particle and Nuclear Physics, vol. 114, 2020, 103810
[2] G. Adhikari et al, Phys. Rev. D 106, 052005 (2022)
[3] J.Amare et al, Phys. Rev. D 103, 102005 (2021)
[4] E. Barberio et al, European Physical Journal C 83, 13849 (2023)

Muon Veto System

- There is an annual modulation in the rate of underground muon flux
- Muon interactions with matter produce neutrons via spallation
- 8 EJ200 plastic scintillators with 2xPMTs, provide a 9.6 m2 coverage above the SABRE Vessel. Acting as a veto against muons for the crystal modules
- The first measurement of the SUPL muon flux is soon to be published



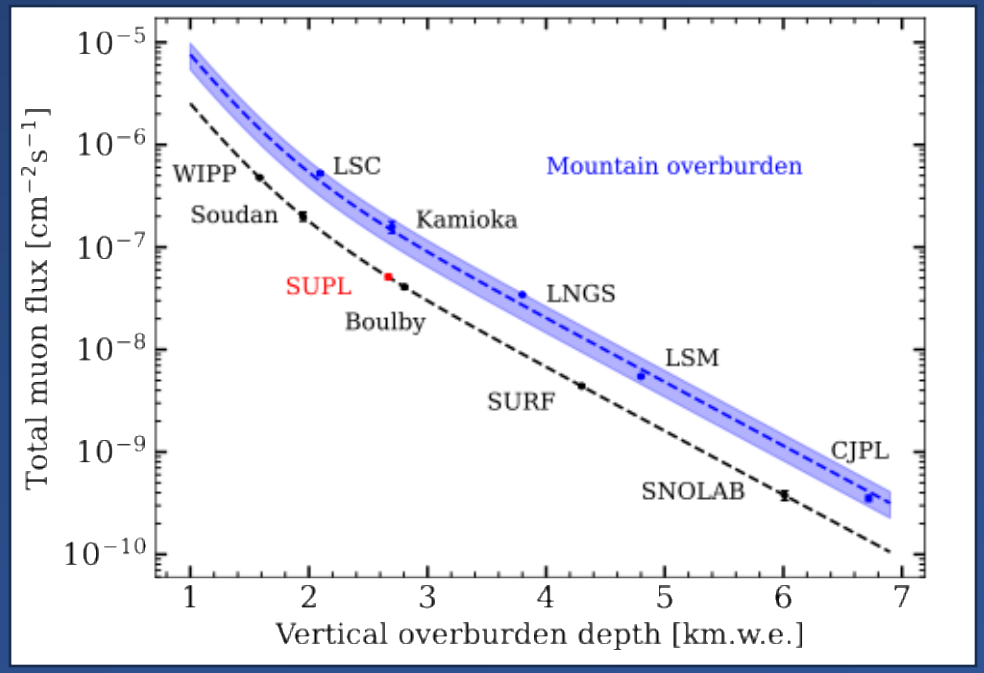


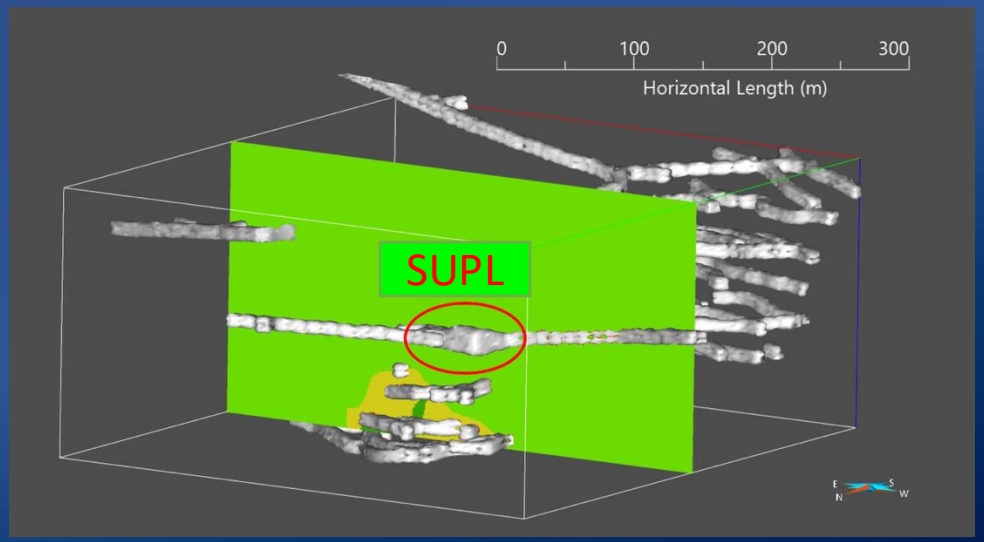
First Muon Flux Measurements

- 236 days of data from the muon veto system in a telescopic configuration gives a total flux of

$$\left(5.127 \pm 0.029_{stat} \pm 0.250_{sys}\right) \times 10^{-8}[s^{-1} \times cm^{-2}]$$

- This result takes into account experimental effects such as the muon detection efficiency and telescope acceptance
- Measurement of the telescope geometric acceptance was conducted using lithological data and material density provided by the Stawell Gold Mine
- Long term also measure the modulation, and better understand the muon induced neutron background






Muon veto system in the telescopic configuration

Liquid Scintillator Veto System

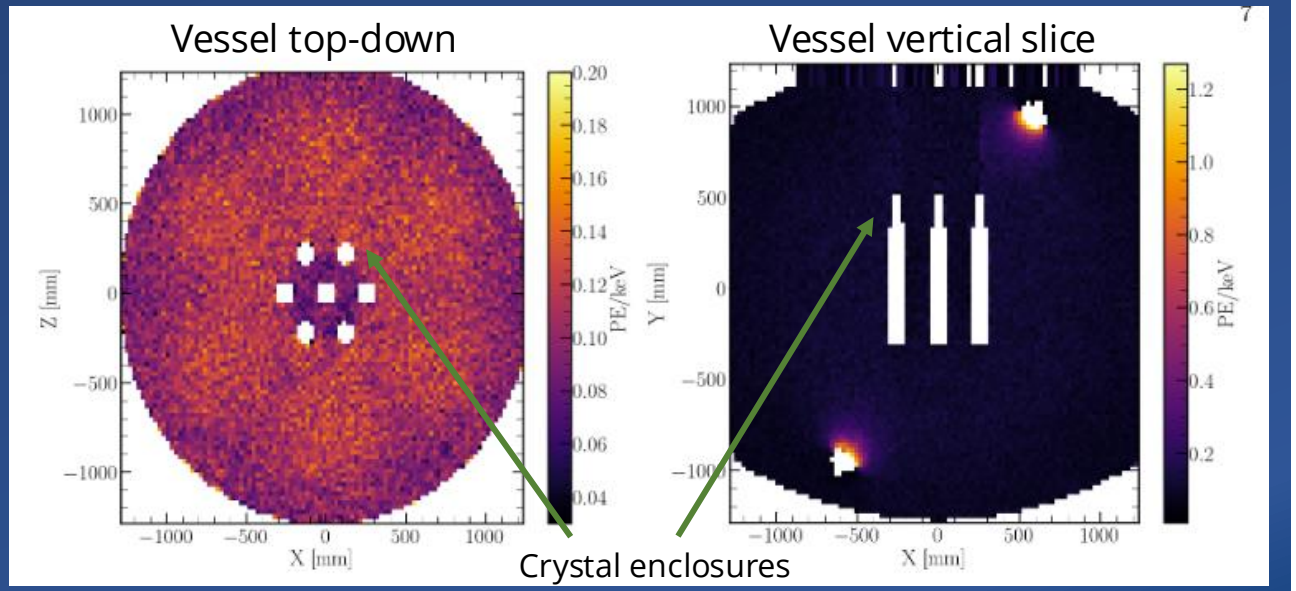
Consists of 12 kL of linear alkyl benzene (LAB) procured via JUNO experiment production line, doped with PPO and bisMSB with a light yield of ~0.17 photons/keV

LAB is coupled with >18 high quantum efficiency and low radioactivity R11065 PMTs

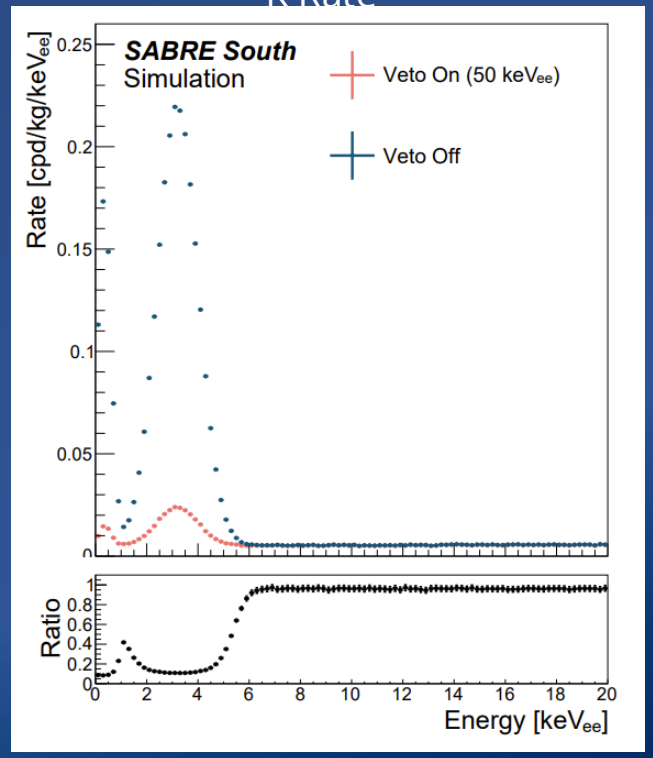
The liquid scintillator veto's main purpose is reducing the 40K background

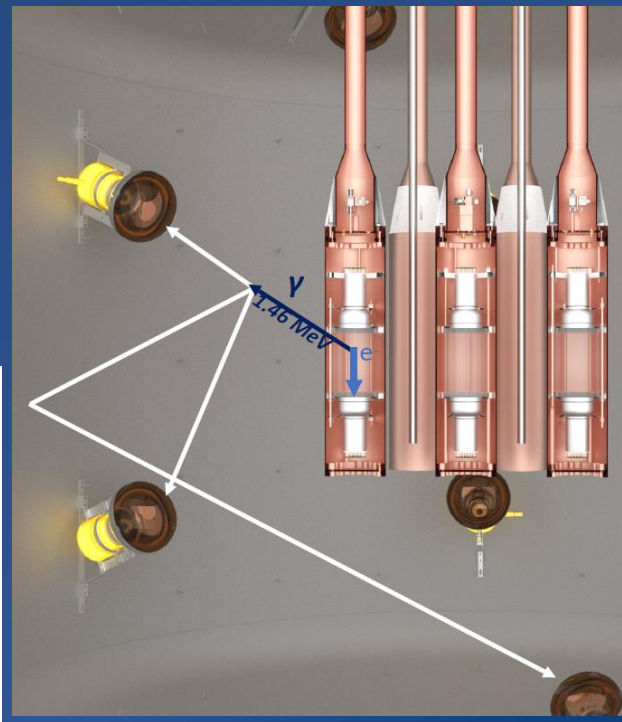
Approx threshold of 50 keV (~10 PE) – expect low amounts of detectable photons at keV energies - ~ < 0.20 PE/keV detectable by single PMT

Photo-electron detection probabilities in veto vessel



^{40}K Rate



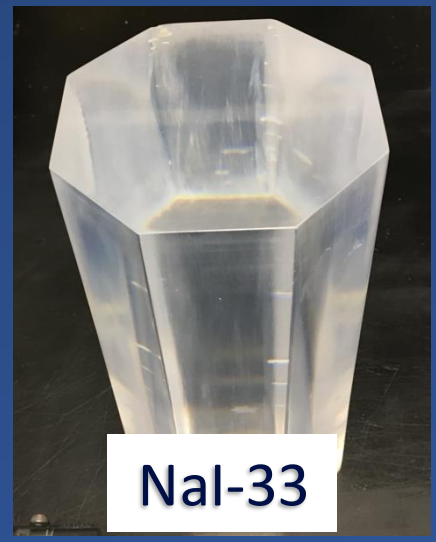


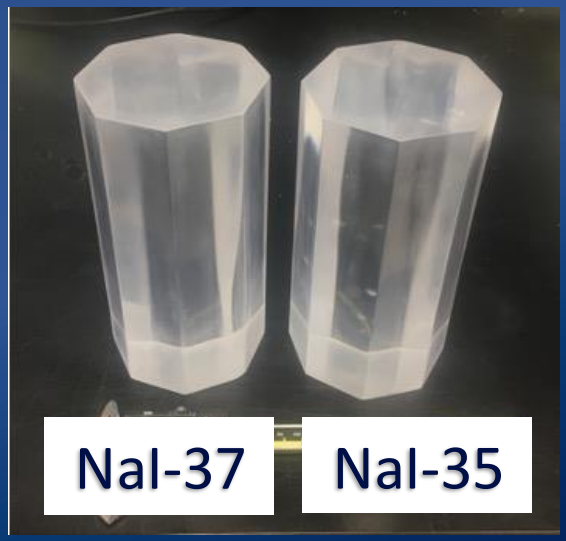
EPJC, Vol 83, 878 (2023)
https://doi.org/10.1140/epjc/s10052-023-11817-z

Crystal Production

- Several crystals have been grown by Radiation Monitoring Devices (RMD) and SICCAS.
  - The crystals are grown from Merck Astrograde NaI powder, with potassium contamination < 10 ppb
  - Bridgman-Stockbarger method is used to prevent additional contamination introduced during the growth process
  - Impurities measured with inductively coupled plasma mass spectroscopy (ICP-MS)

- SICCAS have shown the ability to produce high-purity crystals
- Pb210 plating rates of polishing methods by SICCAS will soon be measured using two test crystals
- SUPL clean room facility currently being prepared for these measurements





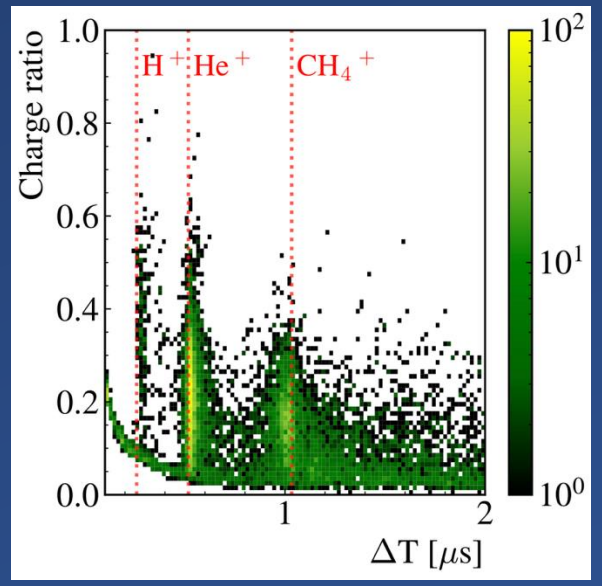
Crystals	Mass [kg]	LY [pe/keV]	^{39}K [ppb]	^{238}U [ppb]	^{232}Th [ppb]	Rate (1-6 keV) [cpd/kg/keV]	Exposure [kg day]
NaI - 31	3.00	9.1±0.1	16.5±1.1	-	-	2.74±0.03	786
NaI - 33 [a]	3.40	11.1±0.2	4.3±0.8	0.47±0.05	0.40±0.07	0.95±0.05	95.2
NaI - 35	4.36	8.7±0.1	8.3±0.6	0.18±0.03	-	1.26±0.35 [b]	35.6
NaI - 37	4.35	7.8±0.2	8.0±0.6	0.61±0.05	0.27±0.06	2.71±0.05 [b]	243.6

a: SABRE PoPI-dry in new shielding
b: Preliminary rate in [2,6] keV ROI

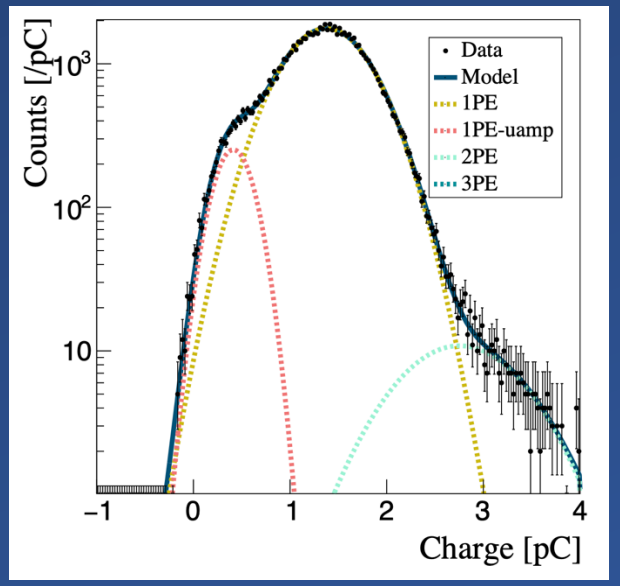
B. Suerfu PhD thesis, Department of Physics, Princeton University, 2018.

PMT Characterisation

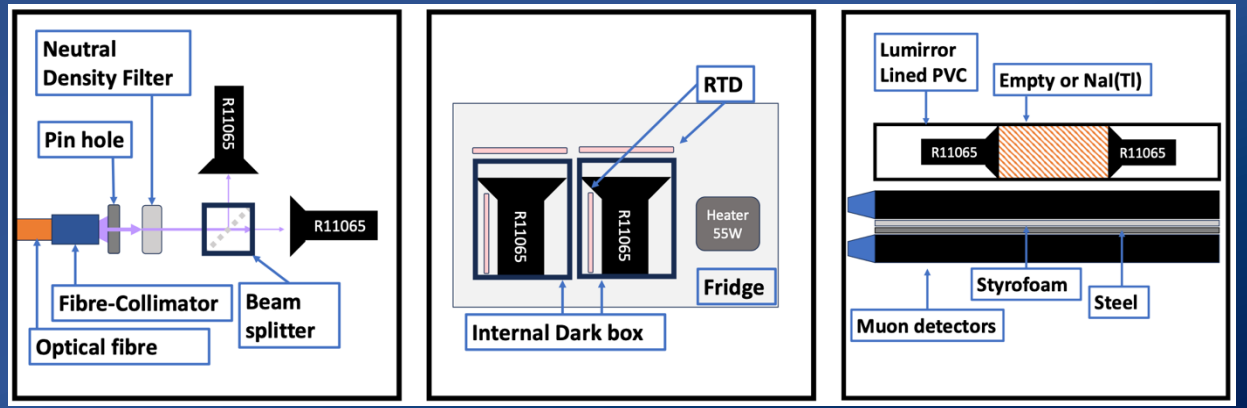
- Detector sensitivity and energy threshold (aiming for sub keV) is currently limited by PMT noise
- Methodology for characterisation and calibration of the veto PMTs and NaI(Tl) detector PMTs is in pre-print (arXiv:2505.10353, arXiv:2504.17209)
- Study PMT specific backgrounds such as afterpulsing and provide input for waveform simulation
- Machine learning methods for PMT noise rejection have been outlined in the pre-prints



Charge ratio of the initial pulse with after-pulse against the time difference between the main and after-pulse peak in crystal PMTs



Fitted charge spectra for crystal PMT at 1750 V

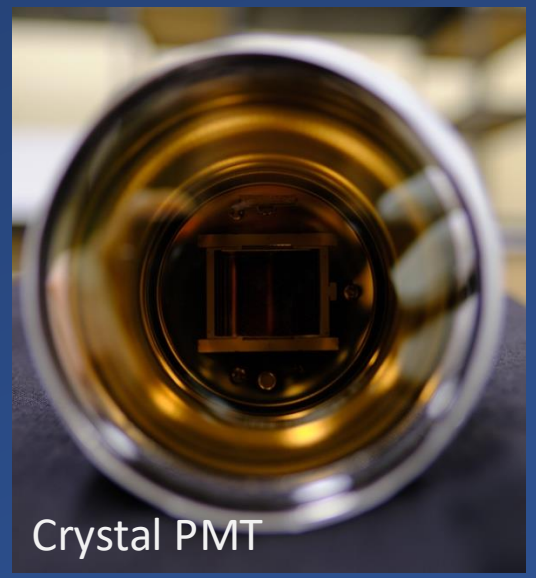


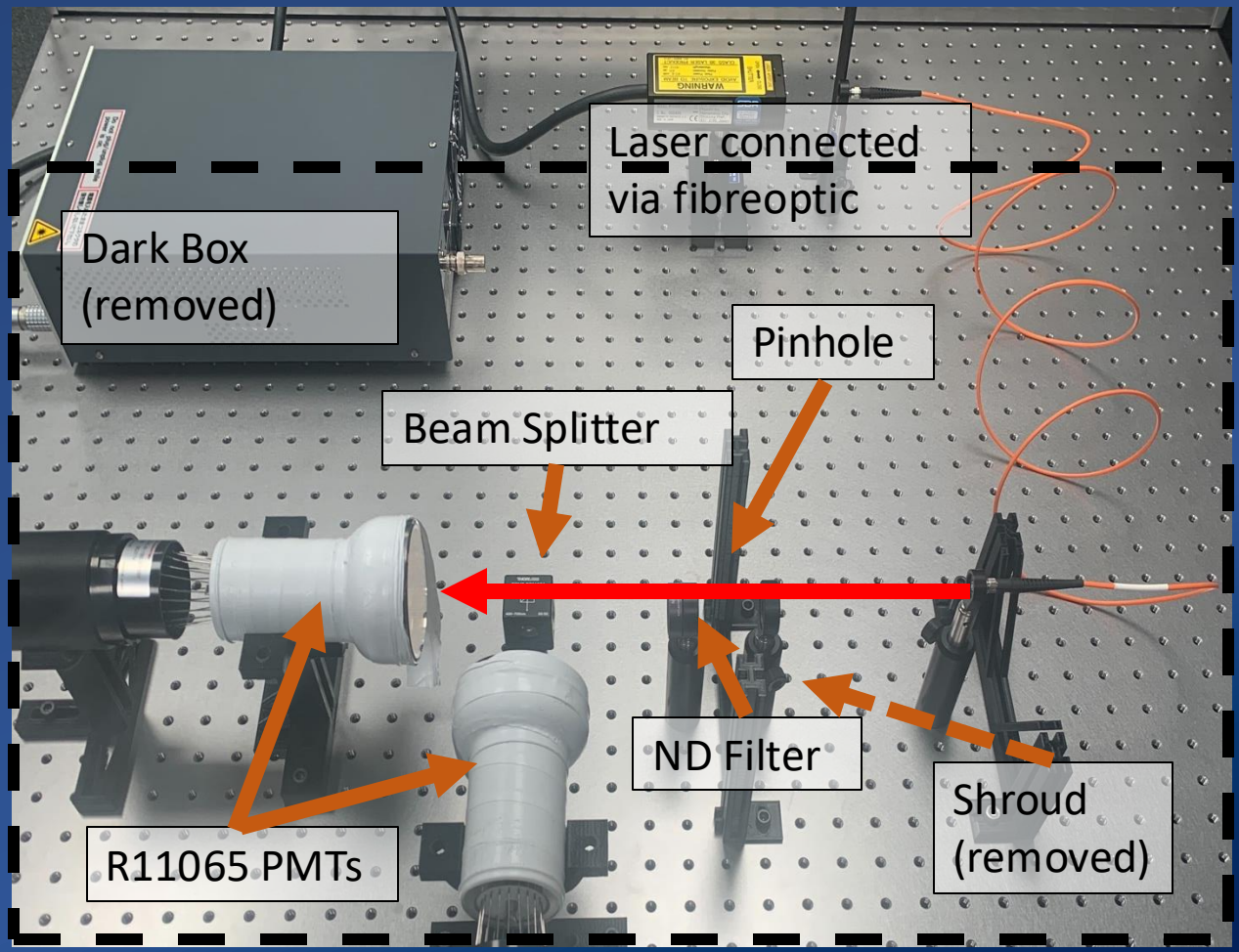
Experimental setups for (left) pico second pulsed laser system, (middle) thermal testing chamber, (right) SABRE detector mockup

PMT Characterisation

Crystal PMTs are being characterized at the University of Melbourne to understand the response and noise characteristics:

- Dark rate as a function of temperature
- Single photoelectron response (SPE) & gain
- Quantum Efficiency (QE)
- Transit time and spread
- Linearity
- After pulsing

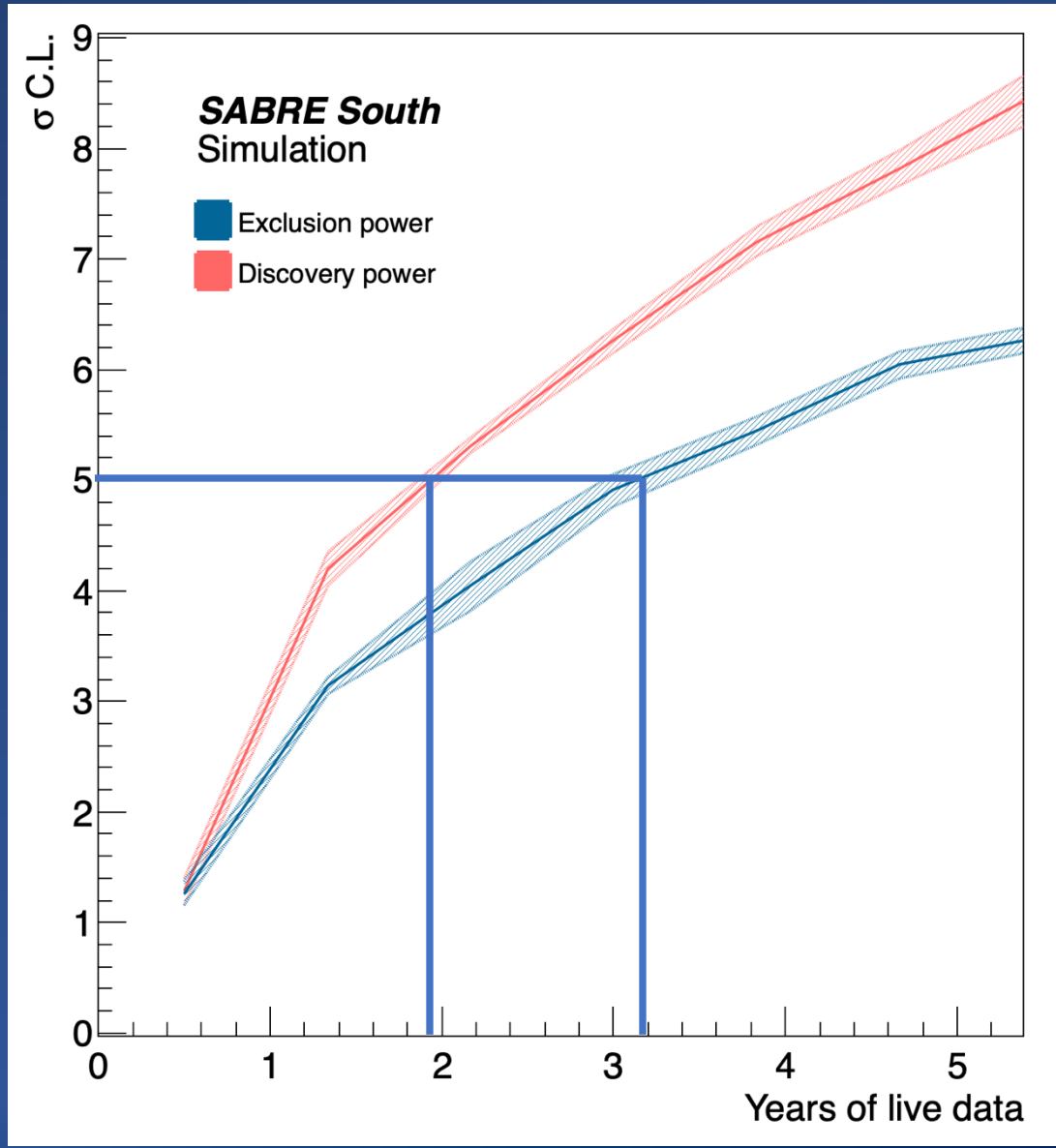




SABRE South Background Simulation

SABRE South will have the power to confirm (exclude) a DAMA/LIBRA-like signal to 5σ significance in ~2(3) years of data taking, respectively.

SABRE South will utilise a detailed background model and a frequentist inference methodology to properly account for systematic uncertainties as nuisance parameters



Summary & Outlook

- SUPL is operational and the first measurements using SABRE South's muon veto system is complete with publication on its way.
- SABRE South currently undergoing commissioning at the Stawell Underground Physics Laboratory in VIC, Australia. Full deployment expected by end of 2025
- SABRE South Technical Design Report is public (doi.org/10.26188/14618172.v3)
- Pre-calibration of PMTs for veto system and NaI(Tl) detectors complete with pre-prints available (arXiv:2505.10353, arXiv:2504.17209)
- Crystal production has commenced
- 5σ discovery (exclusion) power to a DAMA-like signal with ~2(3) years data
- NaI(Tl) experiments (ANAIS, COSINE, SABRE South and North) recently signed an agreement to collaborate and exchange knowledge to solve the mystery posed by DAMA/LIBRA

Acknowledgements

South

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KEK-JAPAN

SWINBURNE

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY of ADELAIDE

Australian National University

North

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

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