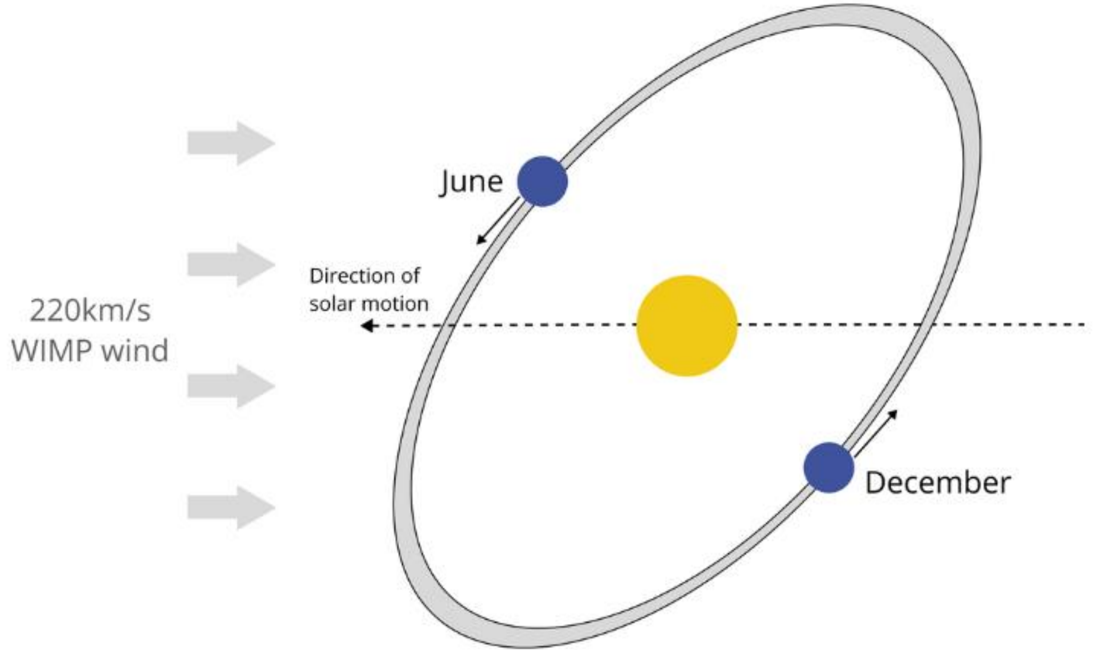
The SABRE South Experiment at the Stawell Underground Physics Laboratory

Lachlan Milligan, on behalf of SABRE South

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

Annual Modulation of DM

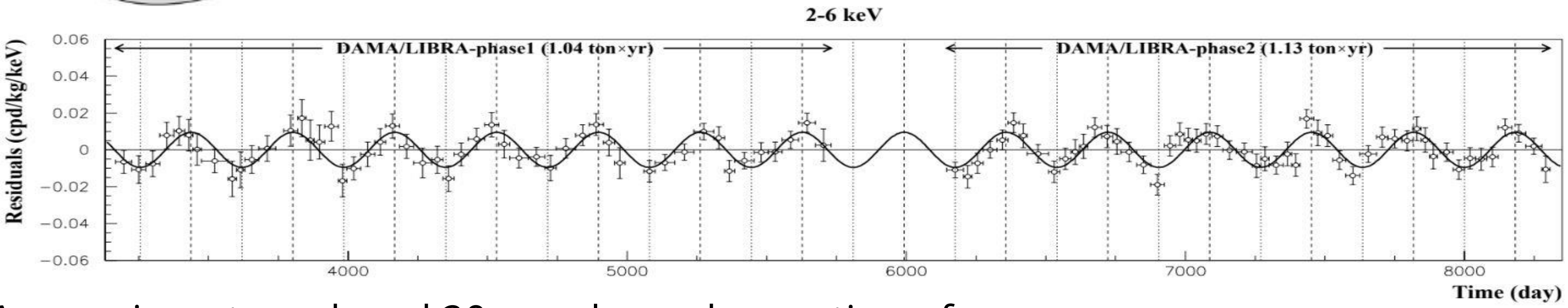


A model independent signal for dark matter due to relative motion of earth through DM halo

Period of 1 year, peaking June 2nd
$(\boldsymbol{t_0 = 152.5}$ **days**$)$

Expect very low modulation amplitude ~0.01 cpd/kg/keV

$$\frac{dR}{dE_R}dt = S_0(E_R) + S_m(E_R)\cos\omega(t - t_0)$$



DAMA/LIBRA, *Nucl.Phys.Atom.Energy* 19 (2018) 4, 307-325

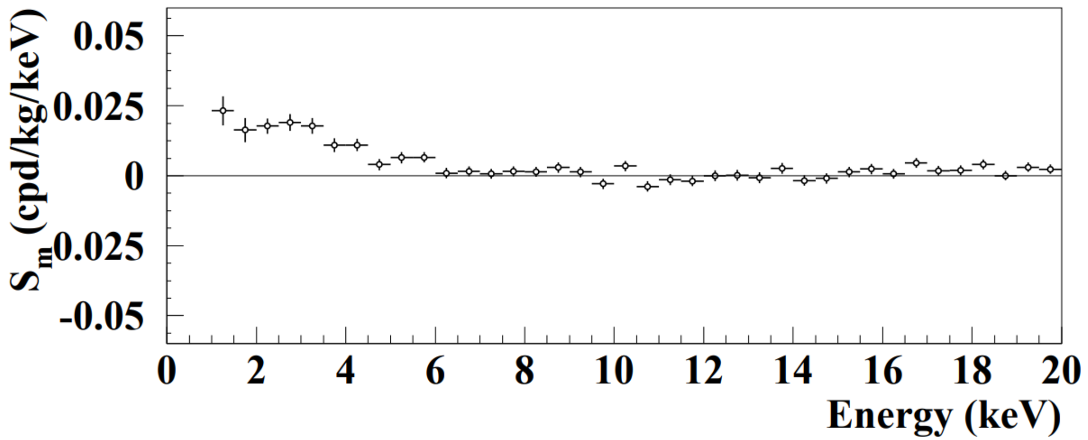
The DAMA/LIBRA experiment produced 20 year long observation of annual modulation

- 1-6 keV nuclear recoils at a significance of 12.9 σ
- **Is currently unresolved**

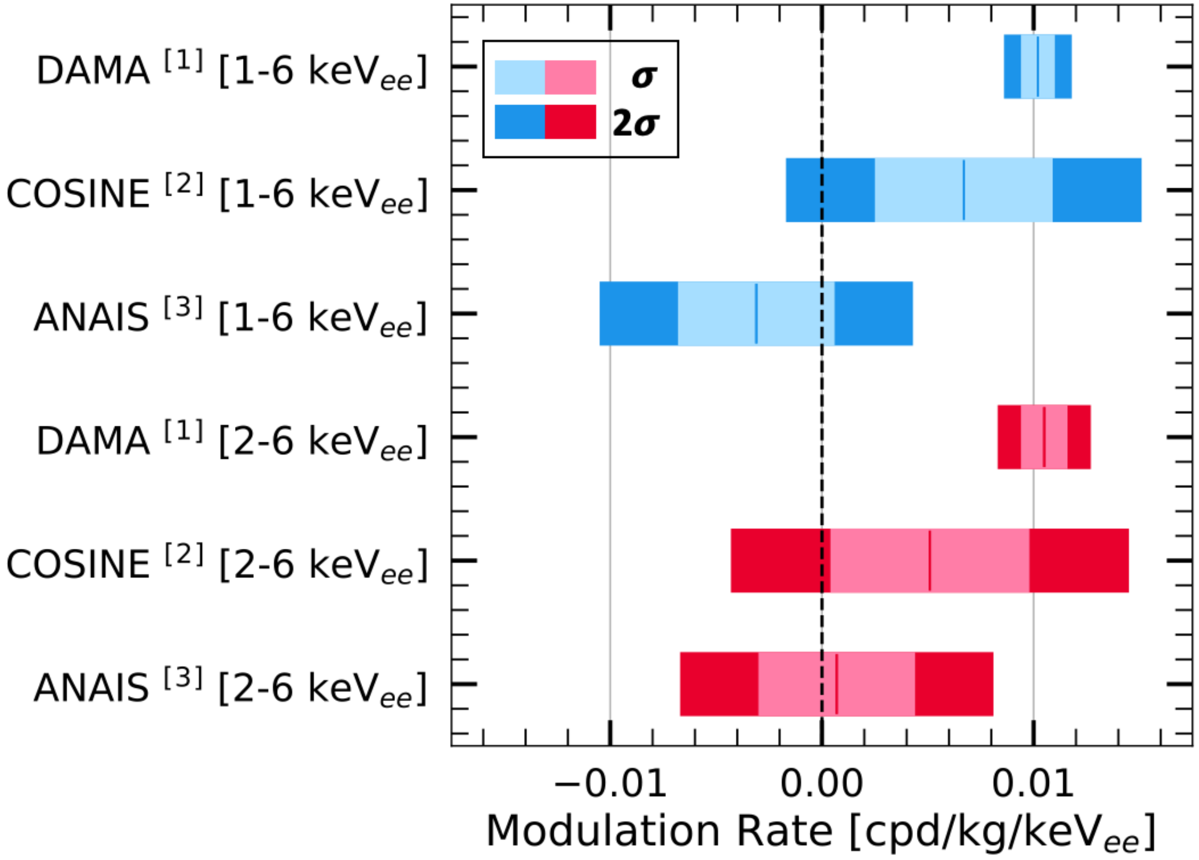
The DAMA/LIBRA Anomaly

Anomaly best tested by similar, but improved, detectors:
- ANAIS – Canfranc underground lab, Spain
- COSINE100 – Yangyang lab, South Korea
- Cosinus – LNGS, Italy (NaI, cryogenic, no Tl)
- **SABRE – SUPL, Australia and LNGS, Italy**

Current tests of DAMA/LIBRA results are inconclusive



DAMA/LIBRA, *Nucl.Phys.Atom.Energy* 19 (2018) 4, 307-325



[1] DAMA, *Prog.Part.Nucl.Phys.* 114 (2020) 103810
[2] COSINE100, *Phys.Rev.D* 106 (2022) 5, 052005
[3] ANAIS-112, *arXiv:2404.17348*, (2024)

A. Ianni IDM talk find higher than expected correlation between 1-6 and 2-6 keV for ANAIS (0.42 vs. 0.2 background only) – unaccounted for noise/background

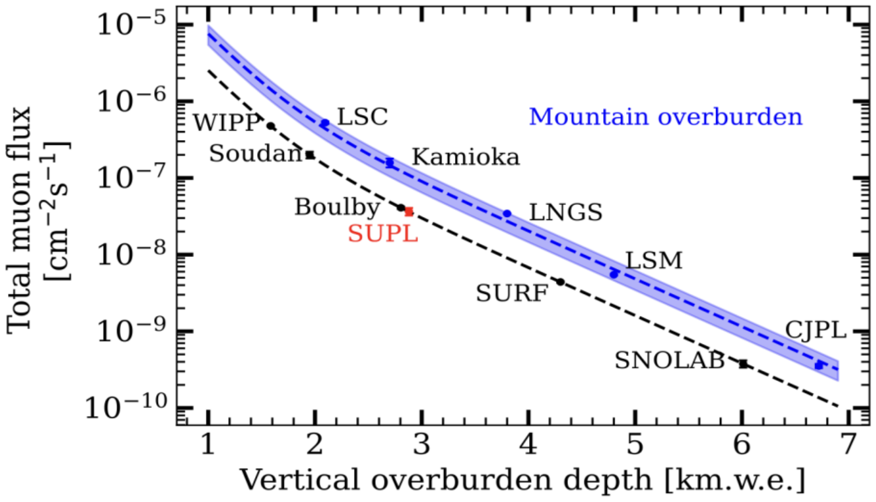
The SABRE Collaboration

Detectors in two locations:
- SABRE North: Laboratori Nazionali del Gran Sasso (LNGS), Italy
- *SABRE South: Stawell Underground Physics Laboratory (SUPL), Australia*

Dual hemisphere – seasonal backgrounds opposite phase i.e. Muon induced

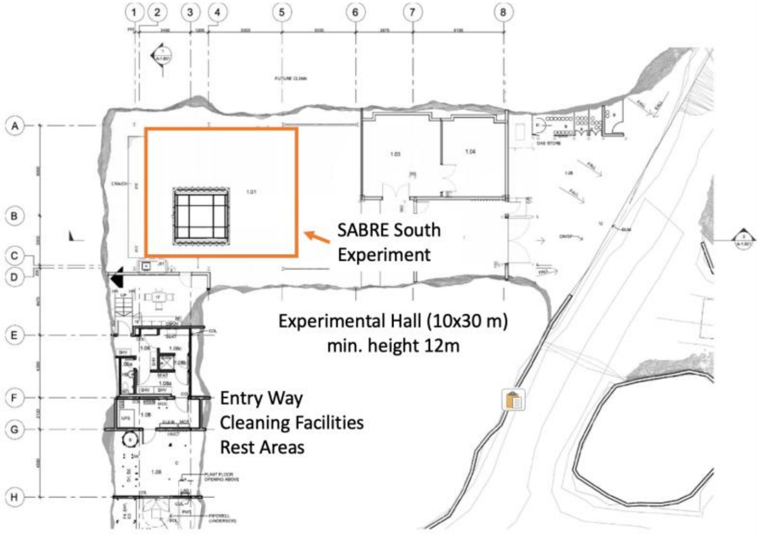
SABRE South is a first for Australia:
- **First deep underground laboratory at 1025 m in southern hemisphere**
- **First underground dark matter experiment**

Lab completed in 2022/2023, SABRE South to be assembled **2024-2025**



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

STAWELL UNDERGROUND PHYSICS LAB

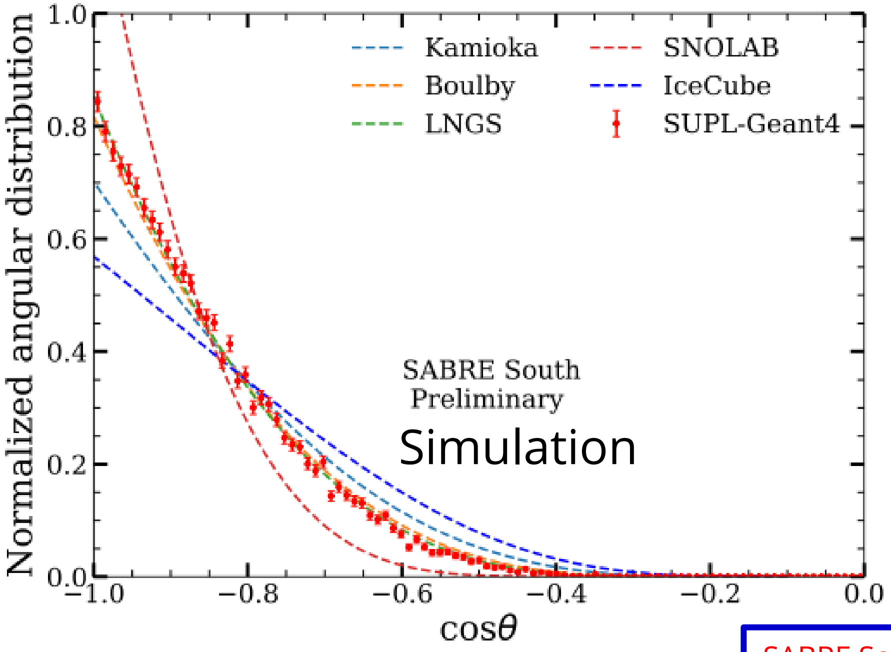


The Stawell Underground Physics Laboratory

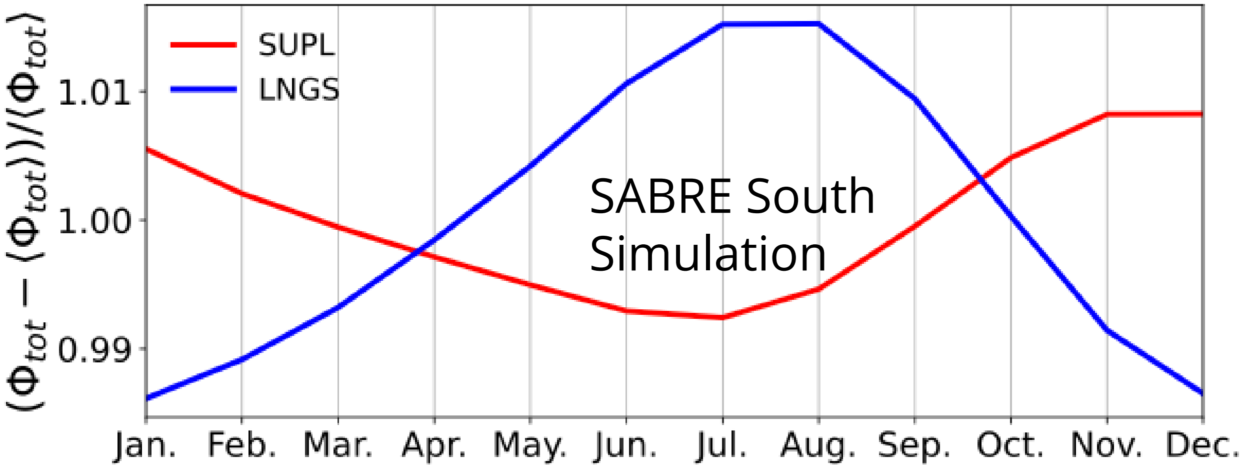
Stawell Underground Physics Laboratory (SUPL) has been completed, and **first detectors commissioned early 2024**

- SABRE South **muon veto assembled in "telescope mode"** for measurement of muon flux and angular spectrum
- Currently collecting data and analysis is underway

Also providing the first test of the remote data acquisition system (DAQ) and processing pipelines



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



SABRE South TDR, DOI: https://doi.org/10.26188/14618172.v3

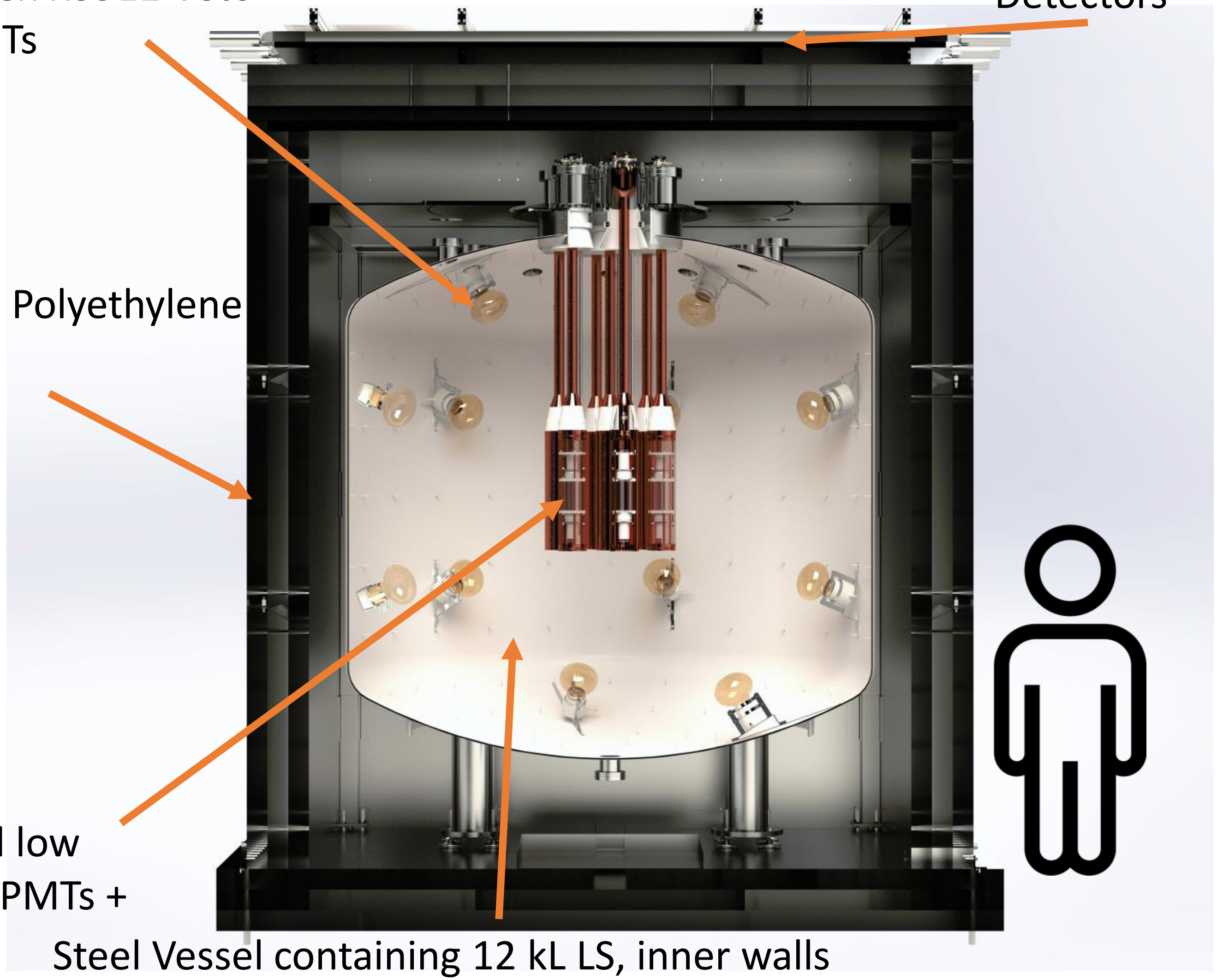
The SABRE South Detector

Improvement on similar detectors:

- Higher purity, low background crystals
- **Southern hemisphere location**
- **Active background veto**
- Particle ID, some position reconstruction capabilities

1 keV energy threshold for 1-6 keV ROI in NaI(Tl)

In-situ optical (in LS) and radioactive calibration possible



Background Simulations

Total experimental background for SABRE South simulated, expecting overall background (after application of veto) of **0.72 cpd/kg/keVee**

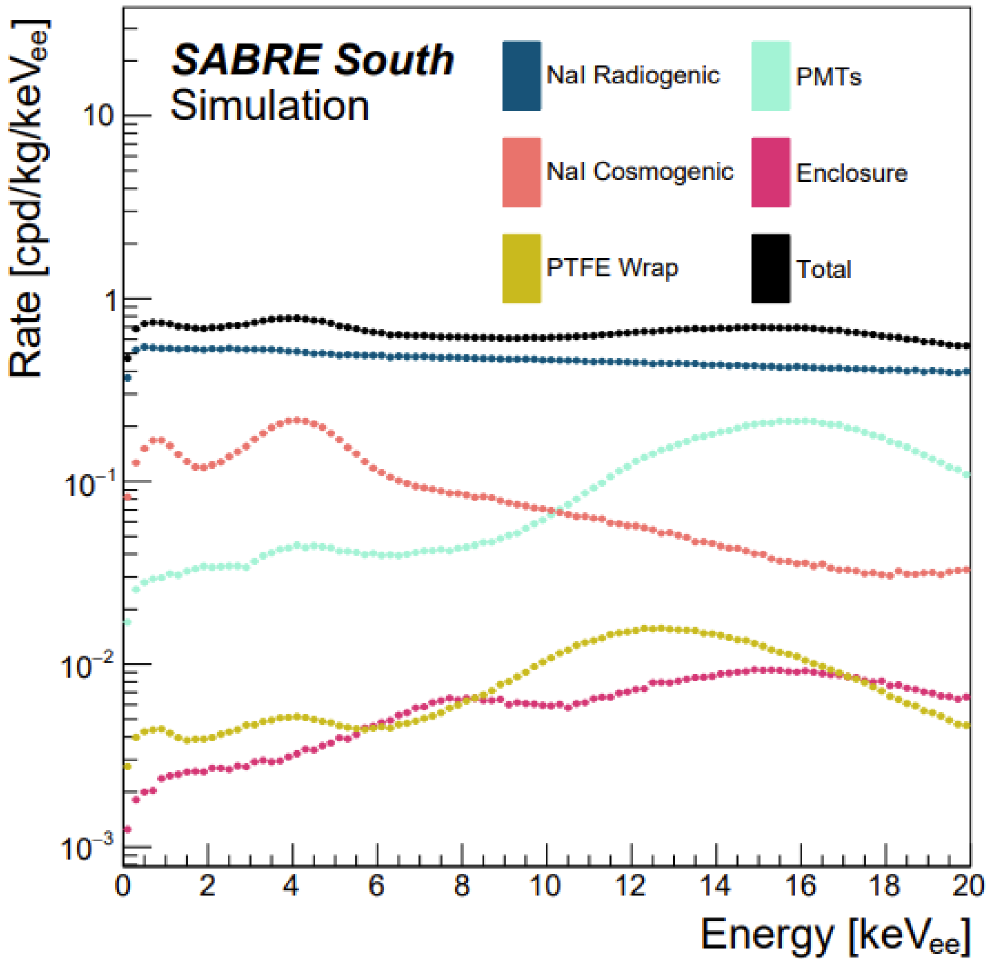
Dominated by both radiogenic and cosmogenic NaI impurities, despite ^{40}K suppression

< 10% of background external to crystals by design

Veto efficiency: percentage of background vetoed by LS veto detector

Component	Rate (cpd/kg/keV$_{ee}$)	Veto efficiency (%)
Crystal radiogenic	$5.2 \cdot 10^{-1}$	13
Crystal cosmogenic	$1.6 \cdot 10^{-1}$	40
Crystal PMTs	$3.8 \cdot 10^{-2}$	60
PTFE wrap	$4.5 \cdot 10^{-3}$	13
Enclosures	$3.2 \cdot 10^{-3}$	85
Conduits	$1.9 \cdot 10^{-5}$	96
Liquid scintillator	$4.9 \cdot 10^{-8}$	> 99
Steel vessel	$1.4 \cdot 10^{-5}$	> 99
Veto PMTs	$1.9 \cdot 10^{-5}$	> 99
Shielding	$3.9 \cdot 10^{-6}$	> 99
External	$O(10^{-4})$	> 99
Total	$7.2 \cdot 10^{-1}$	27

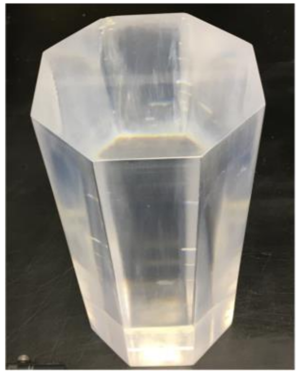
EPJC, Vol 83, 878 (2023)
https://doi.org/10.1140/epjc/s10052-023-11817-z



NaI(Tl) Crystal Production

Very low background NaI(Tl) crystals have been grown by the SABRE Collaboration [1]

	^{nat}K [ppb]	^{238}U [ppt]	^{232}Th [ppt]
SABRE NaI-33 [1]	4.7 ± 1.4	<1	<1
DAMA [2]	13	<10	<10
COSINE-100 [3]	17.8	<20	0.6



* Not to be encapsulated for final detector

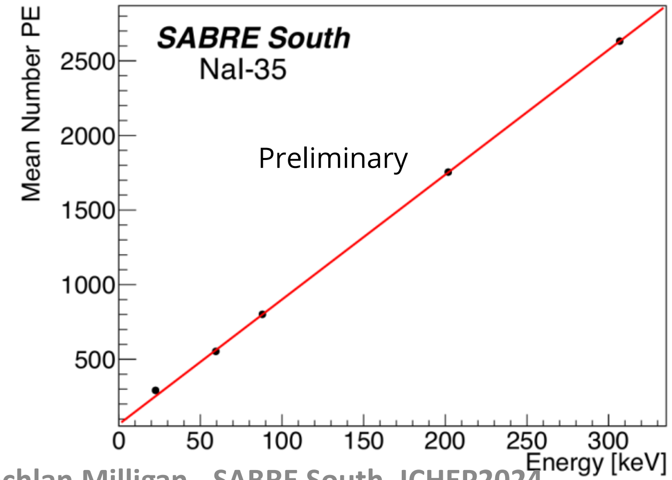
NaI-35*, SABRE South test crystal, grown to **3.7kg** by RMD Boston undergoing tests since 2022

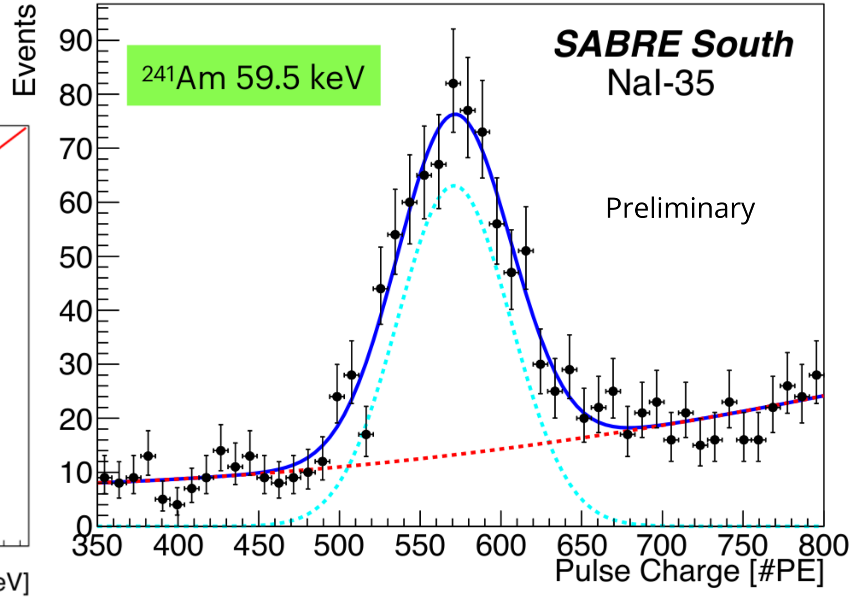
- Preliminary light yield of **9.29 ± 0.03 ± 0.11 PE/keV at 59.5 keV**
- Ongoing work to characterise background rates

SABRE South TDR, DOI: https://doi.org/10.26188/14618172.v3

SABRE South crystals to be provided by SICCAS and/or RMD

Also see Gabriella's talk from SABRE North next!





[1] – SABRE, *Eur. Phys. J. C* 81, 299 (2021)

[2] – DAMA/LIBRA Nucl. Instrum. Methods Phys. Res. A: 592.3 (2008): 297-315

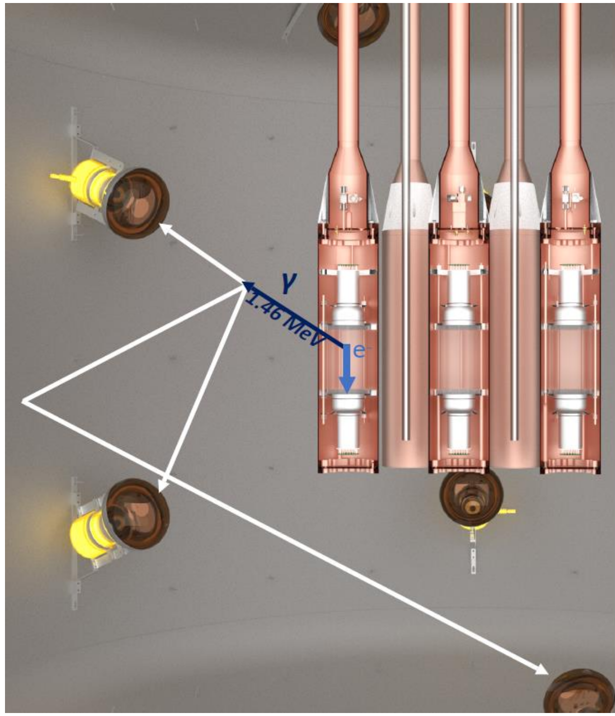
[3] - COSINE-100 Eur. Phys. J. C 78.2, 1-19 (2018)

Active Veto System

Key requirements:
- **Reduce ^{40}K background by factor of 10**

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

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



^{40}K Rate

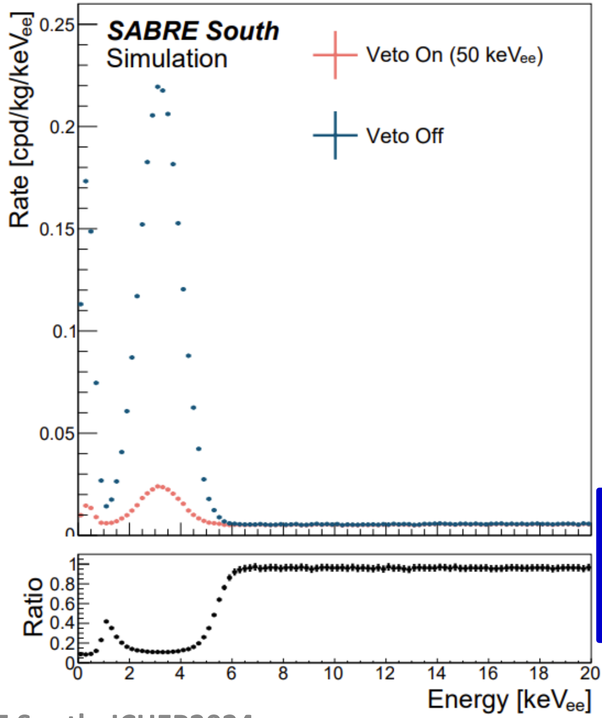
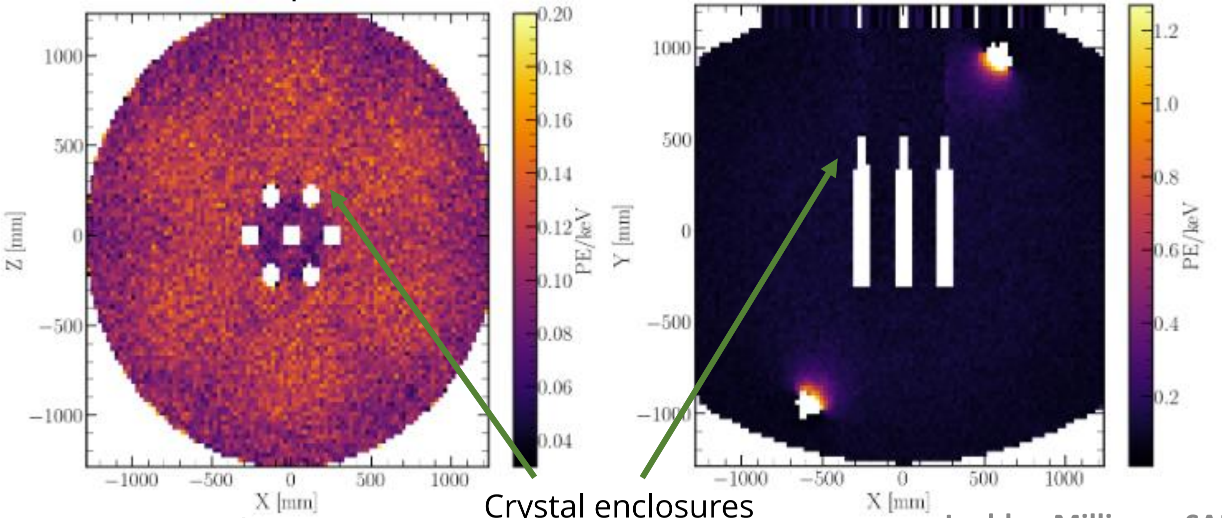


Photo-electron detection probabilities in veto vessel

Vessel top-down

Vessel vertical slice



Crystal enclosures

SABRE South Preliminary

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

PMT Pre-calibration

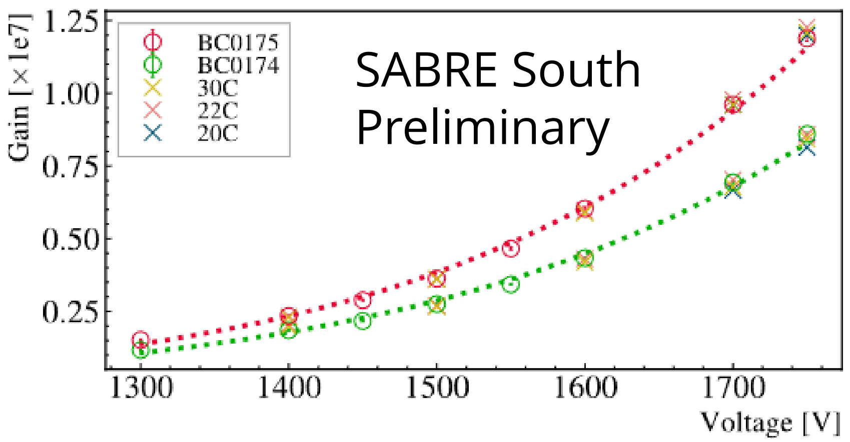
PMT response needs to be understood to optimise PE detection efficiency and noise rejection via thresholds defined by number of SPEs detected, i.e. **Pre-calibration** of all PMTs:

1. **Single photoelectron response (SPE) and gain**
2. **Dark rate, and temperature dependent dark rate**

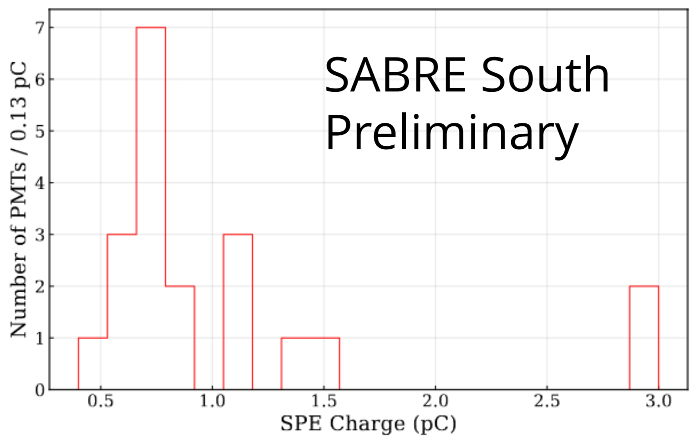
Other measurements: relative quantum efficiency, **linearity of response – i.e. for reconstructing high energy crystal deposits**

Datasets can be used for noise classifiers

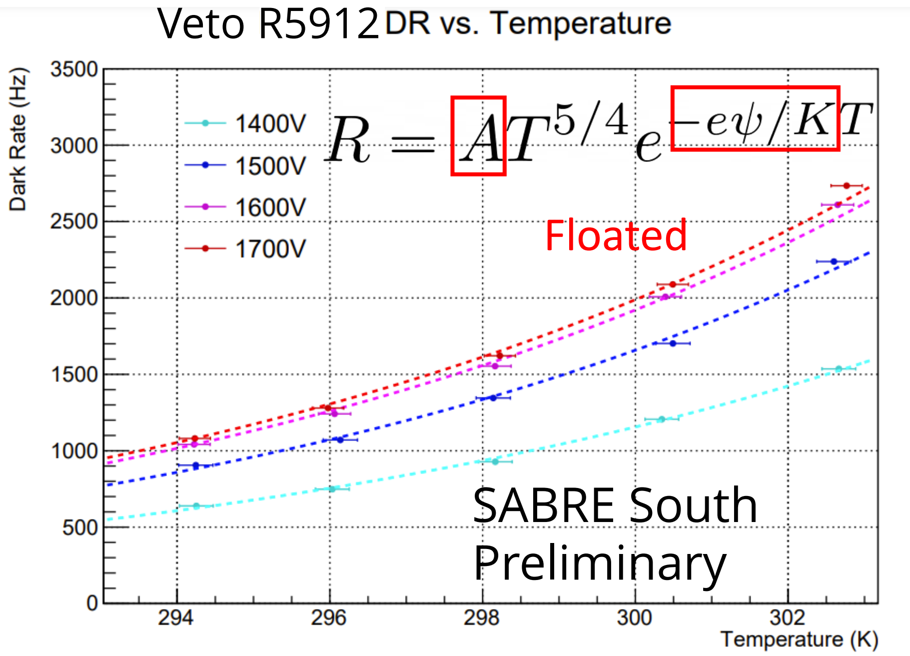
Crystal PMT



Veto PMT



Veto R5912



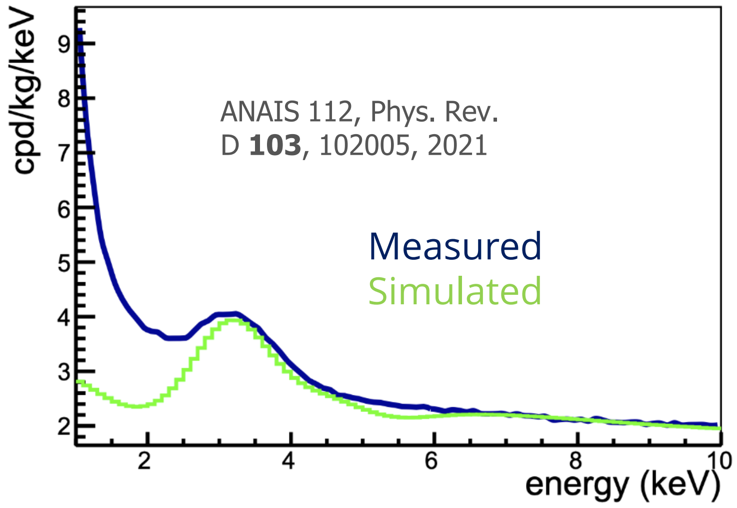
DR can vary on scale of ~500 Hz over few degrees – noise source that can very over time – needs to be controlled/accounted for

Pre-calibration papers to be submitted to journal/arxiv July 2024

PMT Noise Rejection

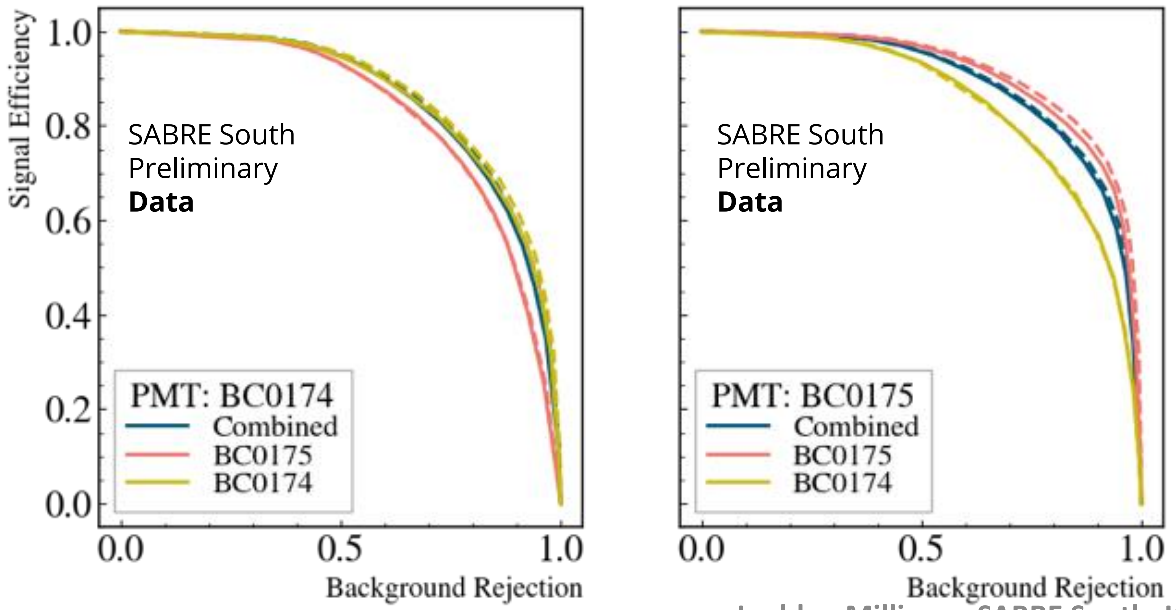
Experimental studies with R11065 PMTs and commercial NaI(Tl) crystal **to develop low energy noise rejection in crystal detectors**

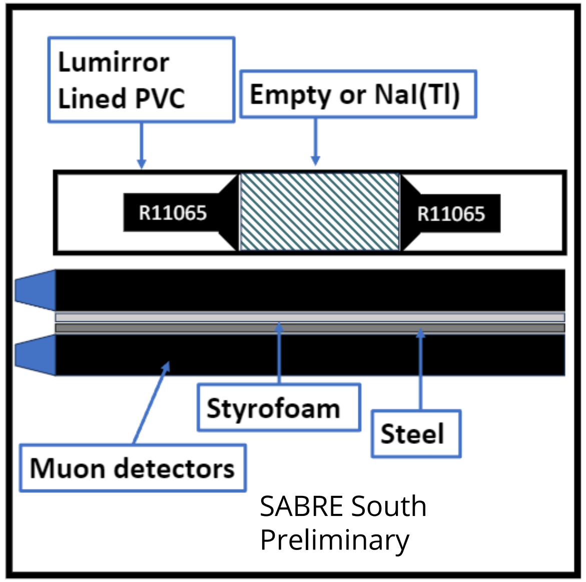
- Use of multivariate BDT classifiers should offer improvement of cuts on single variables (i.e. DAMAs X1 and X2)
- Aiming for improved noise rejection in low energy region, to bring SABRE South energy threshold to ~1 keV_{ee}



Potential PMT noise contribution at low energies

5 – 30 PE Region





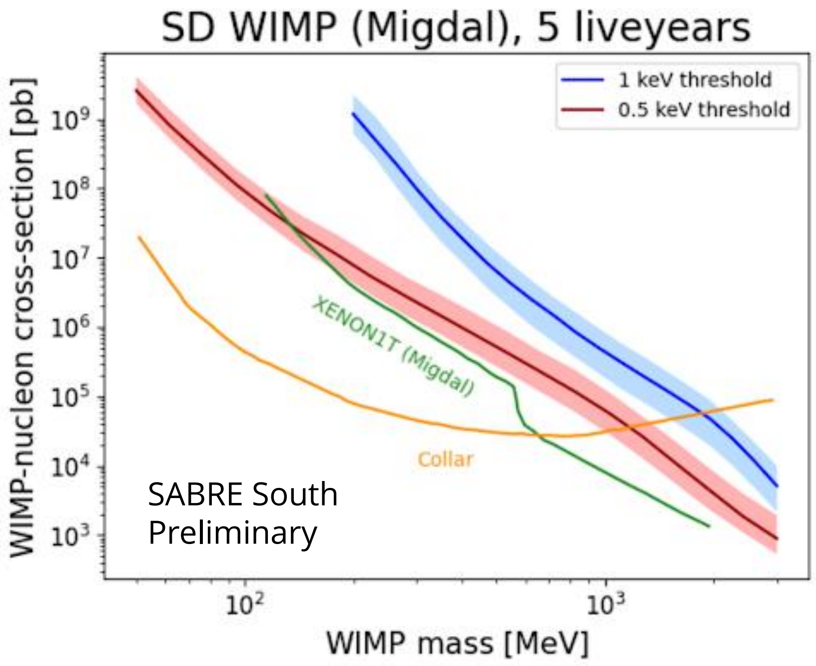
Physics Program

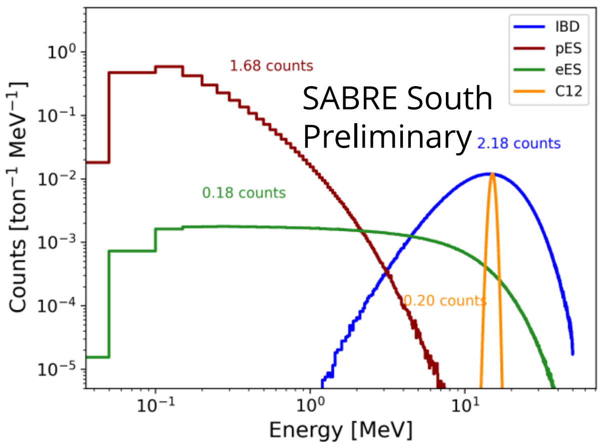
SABRE South has been exploring different types of physics detector can exploit

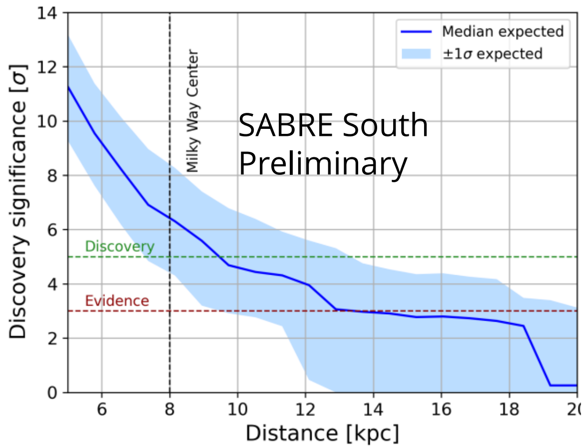
- Both crystal detectors and veto detector

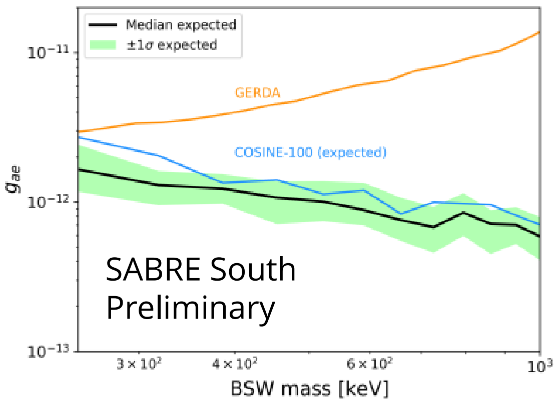
Preliminary sensitivity studies performed on

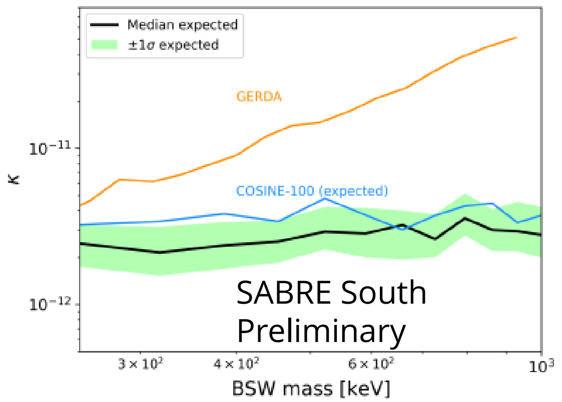
- Migdal effect
- Bosonic super-WIMPs
- Sensitivity to supernova neutrinos – yielding the possibility of SABRE South could join a Supernova Early Warning System (SNEWS)











SABRE South TDR, DOI: https://doi.org/10.26188/14618172.v3

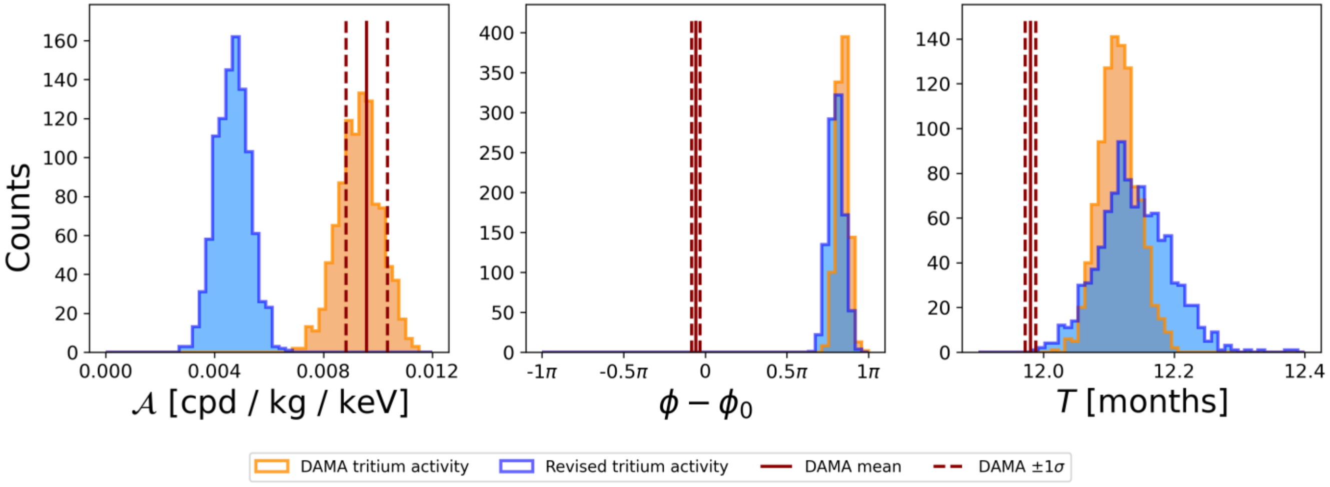
Induced Modulation

Study potential of induced modulation from DAMA/LIBRA's background subtraction technique **using best faith reproduction of their backgrounds**

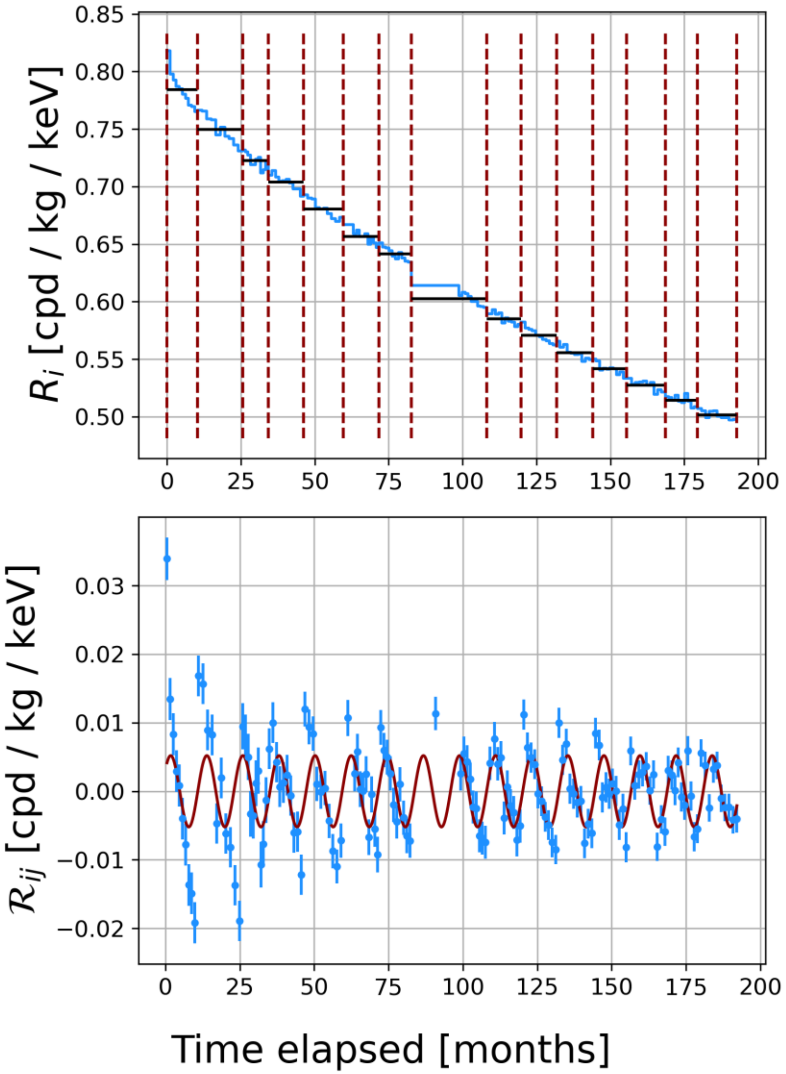
DAMA tritium activity likely over-estimated

- Revised activity found by using SABRE South simulated tritium activity and revised calculation of exposure
- Induced modulation is lower amplitude, out of phase

Key takeaway: DAMA/LIBRA background is low enough that shape of background/subtraction method doesn't matter, there is no induced modulation



A: Amplitude
Φ: Phase
T: Period

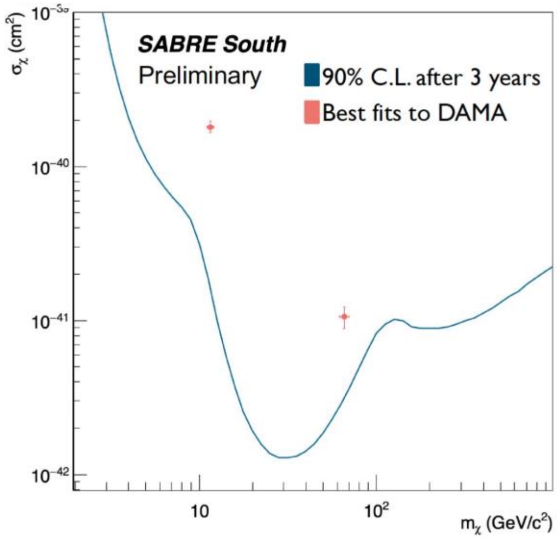


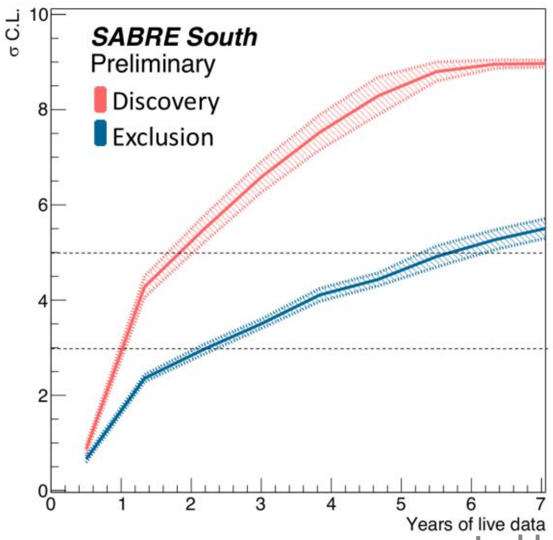
Status/Summary

SUPL is built and in use. Detector assembly to start in 2024, aiming for completion in 2025

- SABRE South Technical Design Report is public (https://doi.org/10.26188/14618172.v3)
- **Pre-calibration of PMTs for veto system complete, publication to come in July 2024**
- Crystal production commencing this year
- Veto vessel fit-out testing undertaken in 2023, 17 kL of LAB scintillator in Melbourne **– underground late in 2024**
- Underground **muon measurements with SABRE South muon veto have begun** – background muon flux characterisation underway, and testing of remote DAQ system
- Total projected background – **0.72 cpd/kg/keV$_{ee}$**
- **Rich physics program –** SABRE South potential inclusion in SNEWS
- Induced modulation studies to be public in July 2024 – modulation not induced by background subtraction method

5σ discovery (3σ exclusion) power to a DAMA-like signal with 2 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

Australian Government
Australian Research Council

KEK-JAPAN

SWIN BUR NE

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY of ADELAIDE

Australian National University

North

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BACKUPS

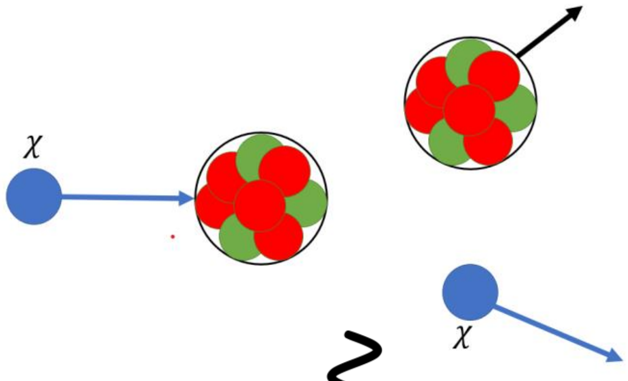
Interaction Mechanism

Search for nuclear recoils of WIMP off of Na/I nuclei

Properties of dark matter imply low energy (keV) scatters

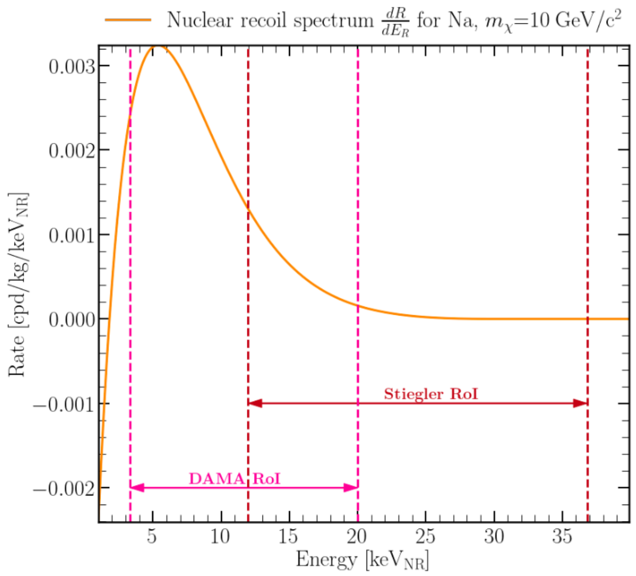
Observable: scintillation light in crystal

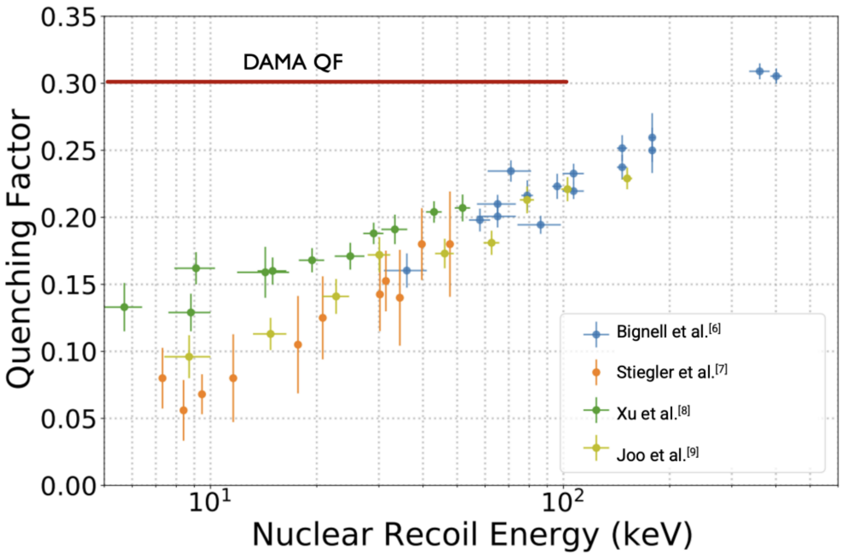
Reconstruction of recoil energy -> understanding of quenching factor

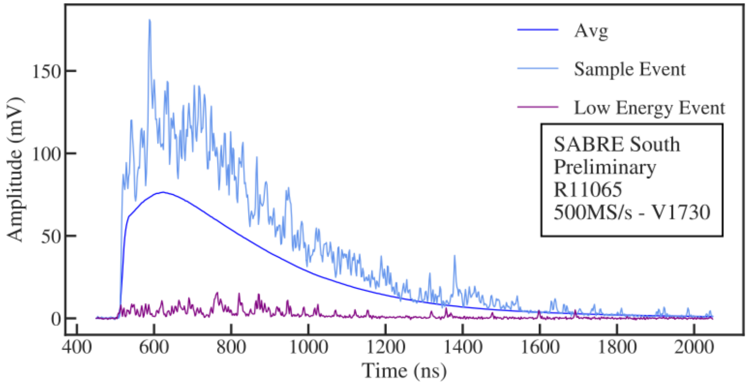


$$E_{ee} = Q(E_{NR})E_{NR}.$$

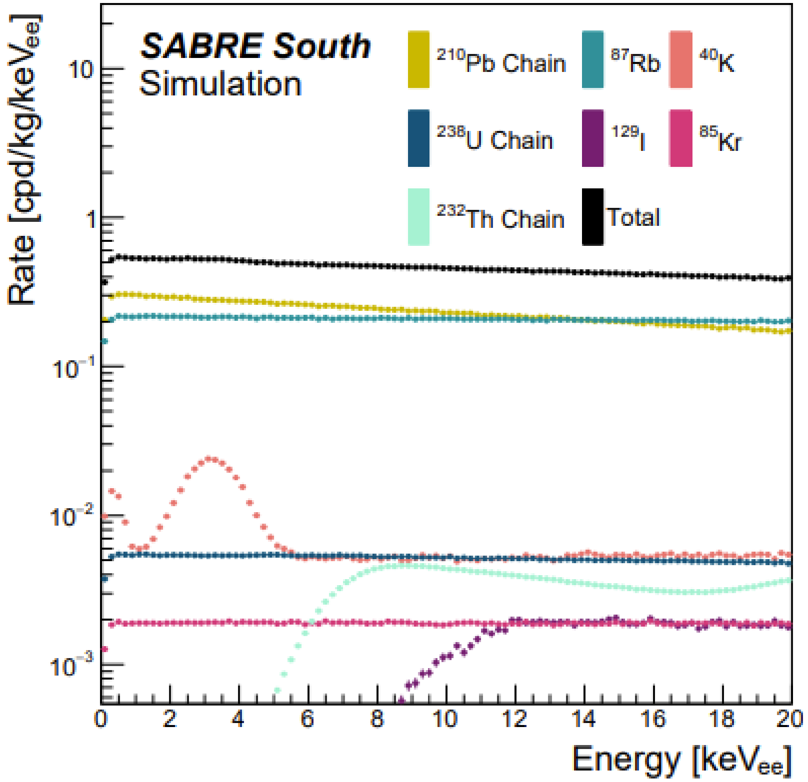
M. J. Zurowski, arXiv: 2211.15861

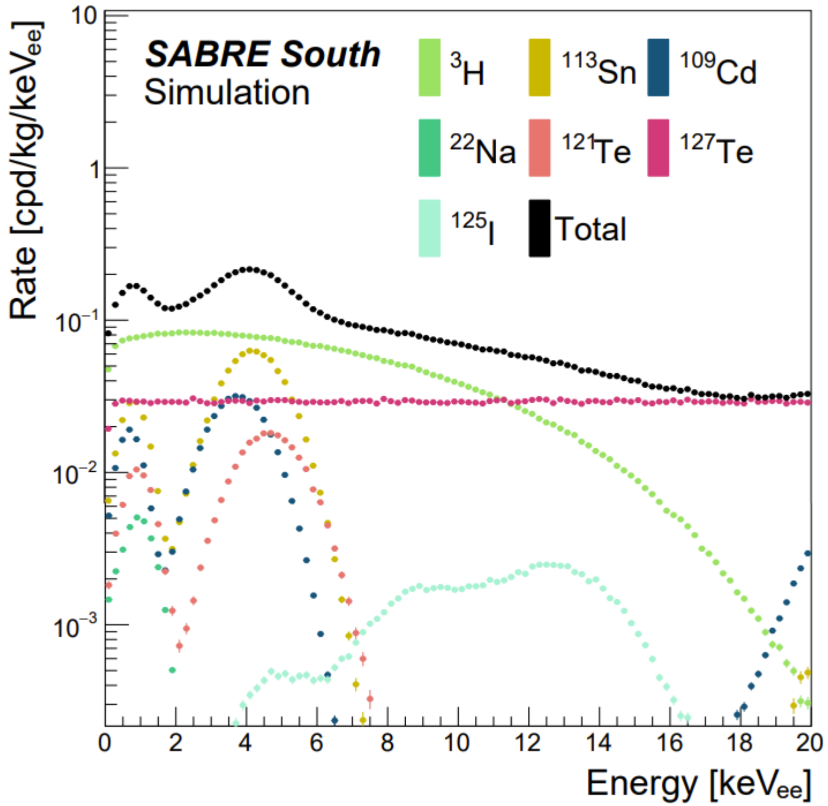


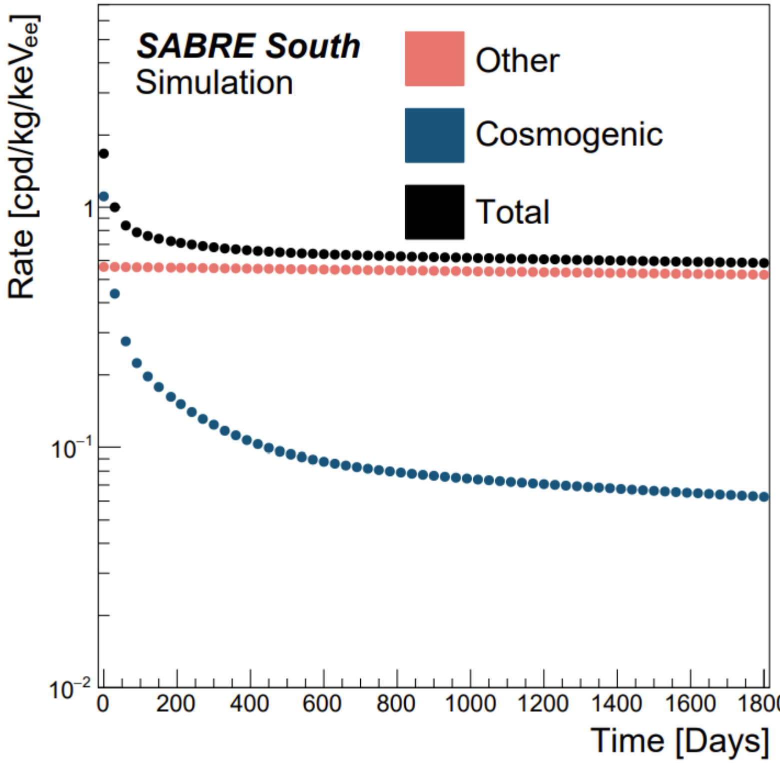




Key Backgrounds



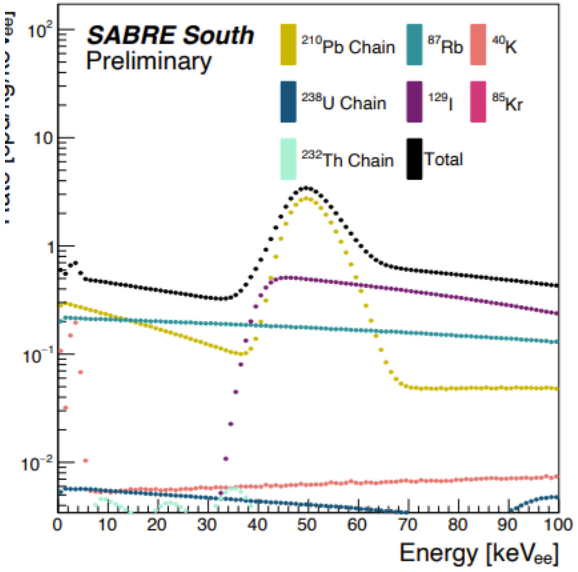




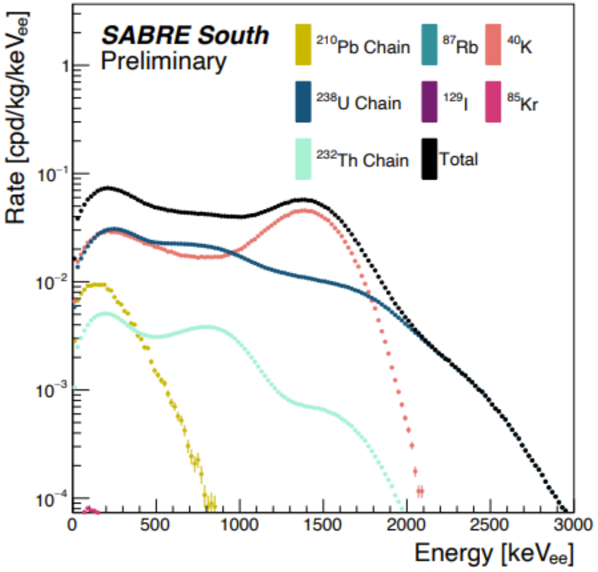
Key Backgrounds

Contamination from intrinsic radiation of crystals

Deposition in crystal

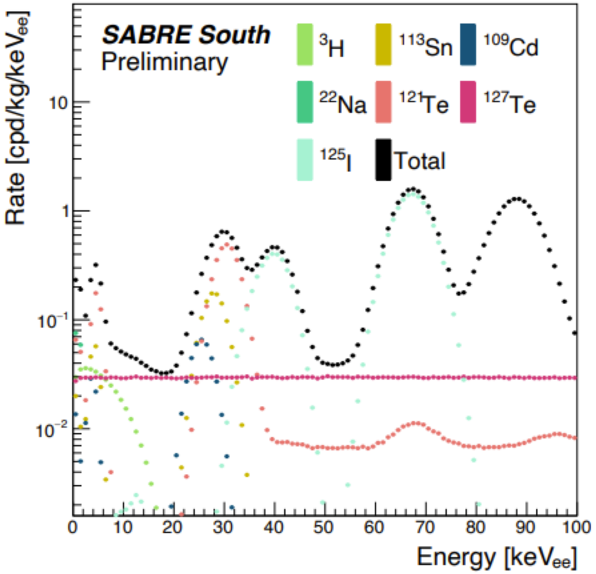


Deposition in veto

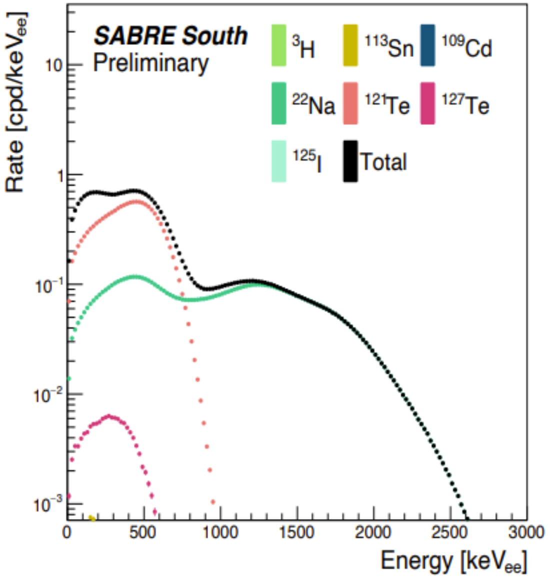


Contamination from cosmogenic activation of crystals

Deposition in crystal



Deposition in veto



Induced Modulation

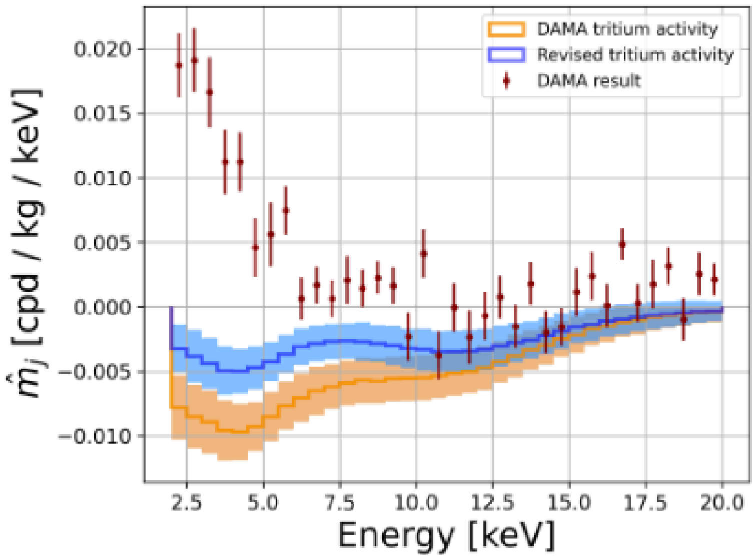


FIG. 3. Results of 1000 MC realisations of the maximum likelihood fit described in the text, performed over energy bins. For each energy bin, the mean and $\pm 1\sigma$ values of the fitted parameter $\hat{m}_j$ are shown. The same two scenarios for the initial activity of ^{3}H as in Fig. 2 are explored. We compare the results of these toy fits to the result of the same fit as reported by DAMA [1].

$$\mu_{ij} = \left[c_j + m_j \cos\left(\frac{2\pi}{T}(t_i - t_0)\right)\right] \mathcal{E}_i \Delta E_j \epsilon_j .$$

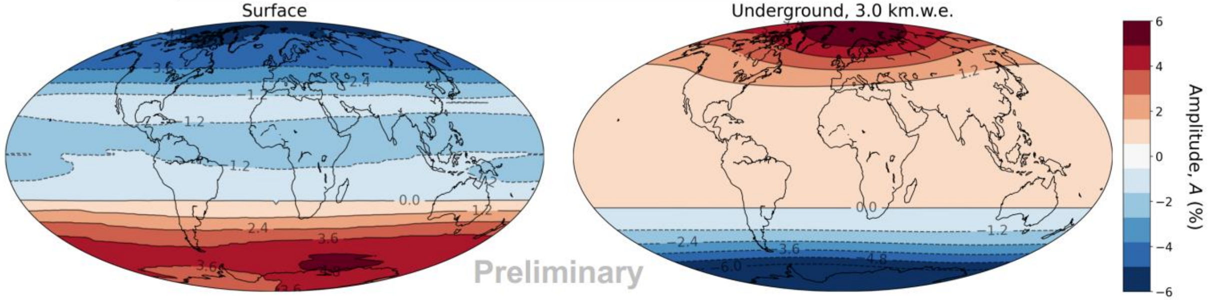
Muon Flux

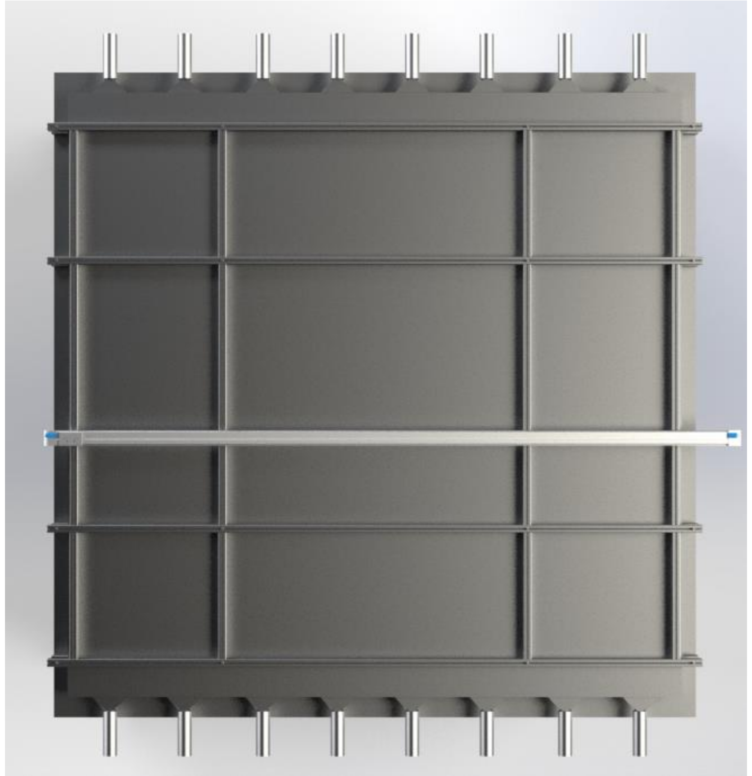
First major muon flux/muon modulation measurement to occur in SUPL very soon

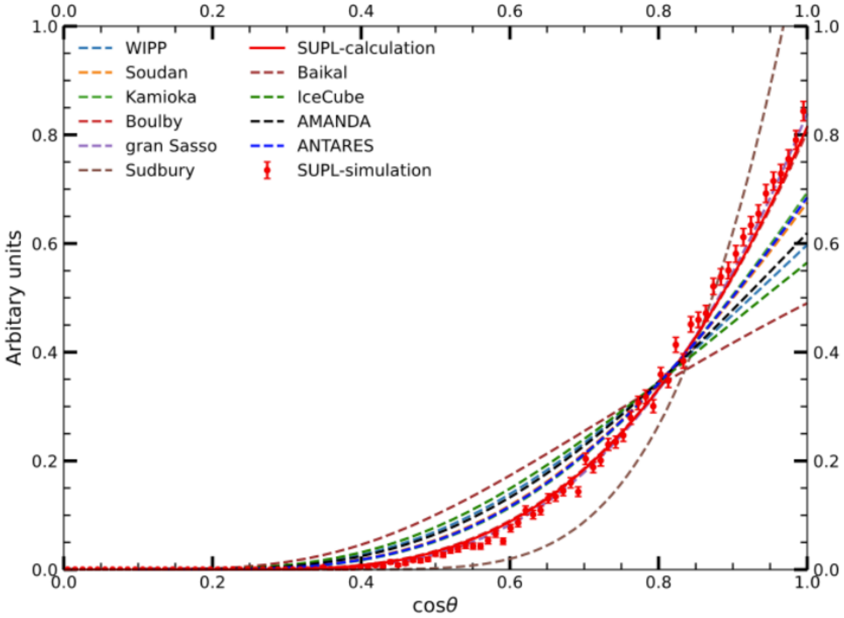
To measure flux and angular resolution, with ~4cm spatial resolution along two sided panels

In the summer, the atmosphere is taller, meaning muons travel longer distances and decay more often ⇒ the muon flux is **lower** at the surface in summer.

However, there are also more higher-energy muons in the summer, which reach deeper underground ⇒ the muon flux is **higher** underground in summer.





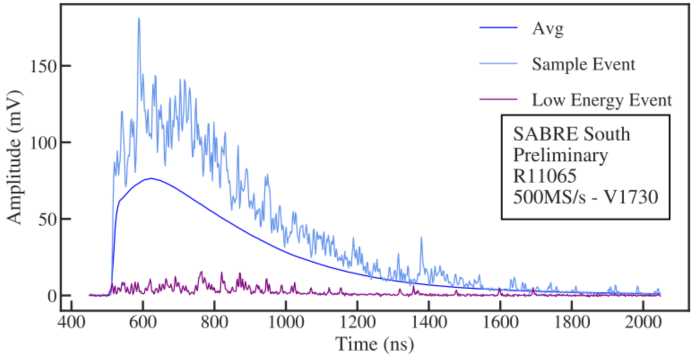


Event Reconstruction

F. Scutti, https://iopscience.iop.org/article/10.1088/1742-6596/2438/1/012061/pdf

Pyrate – Flexible python-based software frame work for analysis and reconstruction

Process waveforms



Collection of mixed charge/time domain pulse shape variables for event classification/reconstruction e.g.

Pulse mean time

$$\langle t \rangle = \frac{\sum_i A_i t_i}{\sum_i A_i}.$$

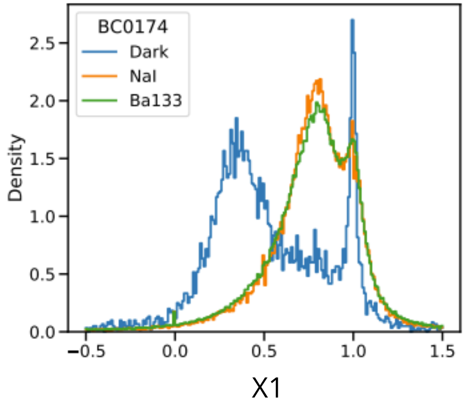
Charge ratio variables

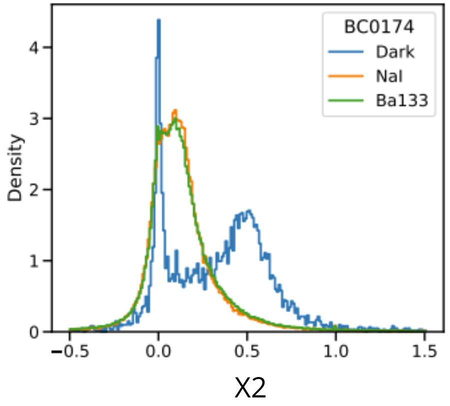
$$X_1 = \frac{\Sigma_{t=100ns}^{600ns} A(t)}{\Sigma_{t=0ns}^{600ns} A(t)}$$

$$X_2 = \frac{\Sigma_{t=0ns}^{50ns} A(t)}{\Sigma_{t=0ns}^{600ns} A(t)}$$

$$CAP_x = \frac{\Sigma_{t=0ns}^{xns} A(t)}{\Sigma_{t=0ns}^{t_{max}} A(t)}$$

Produce variables for reconstruction





e.g. signal/noise discrimination for a PMT crystal system – allow for reduction of PMT noise component in background