The SABRE South Experiment at the Stawell Underground Physics Laboratory

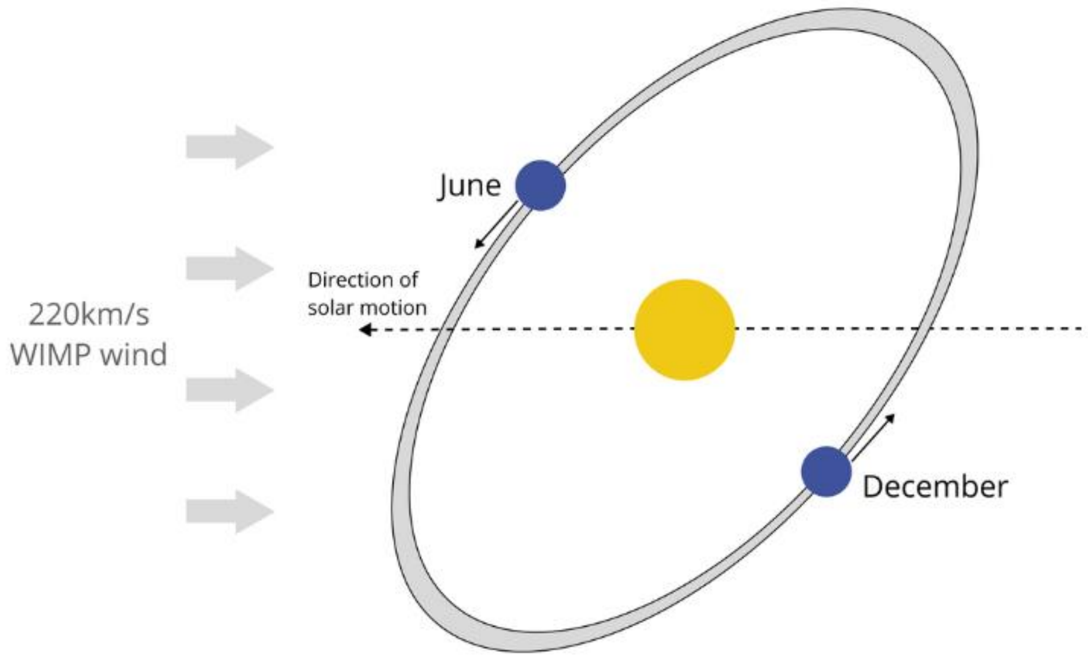
Lachlan Milligan, on behalf of SABRE South

SABRE

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
$(t_0 = 152.5\ days)$

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

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

Events are rare and low energy

- Small WIMP-nucleon cross section ~ 10^{-48} – 10^{-40}
- keV scale (1-100 keV) energies for WIMP of mass 10-1000 GeV/c^2

Requires tight control of modulating backgrounds

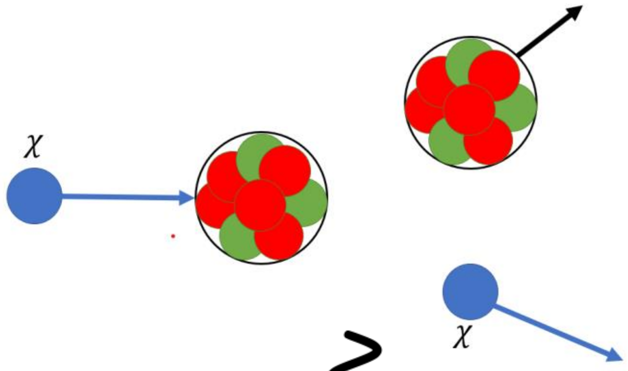
Interaction Mechanism

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

Properties of dark matter imply low energy (keV) scatters

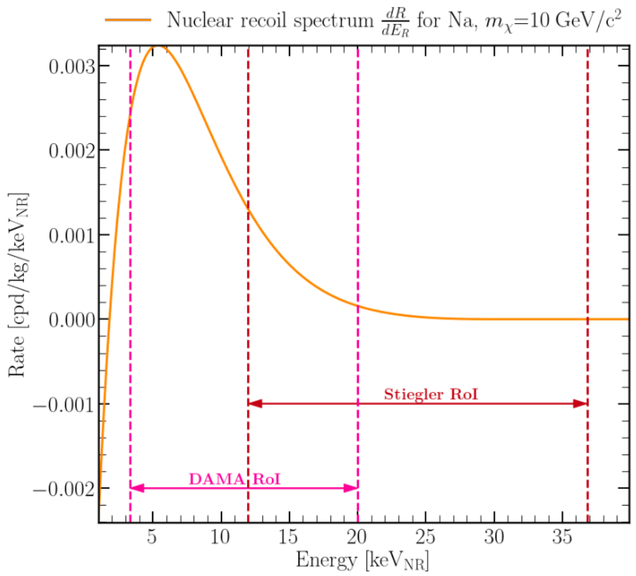
Observable: scintillation light in crystal

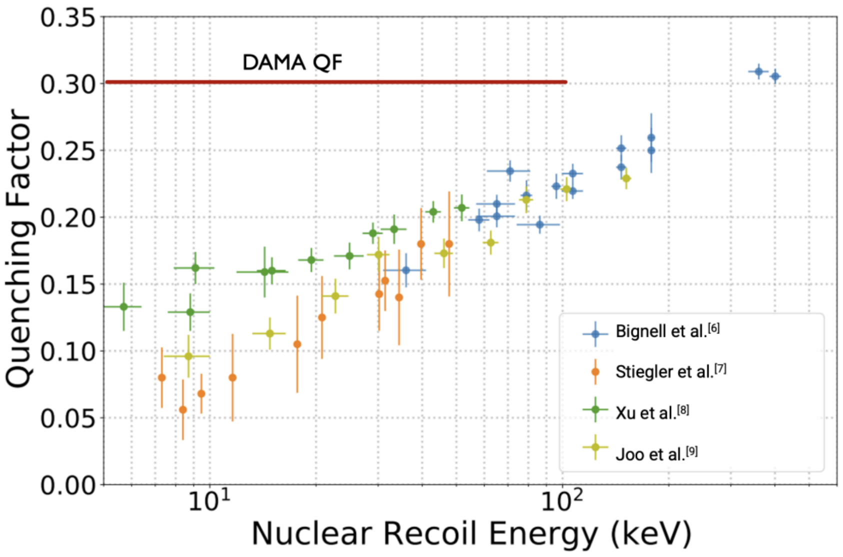
Reconstruction of recoil energy -> understanding of quenching factor

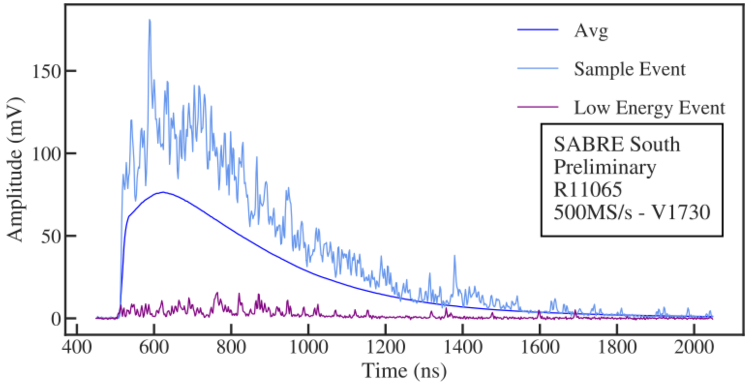


$$E_{ee} = Q(E_{NR})E_{NR}.$$

M. J. Zurowski, arXiv: 2211.15861



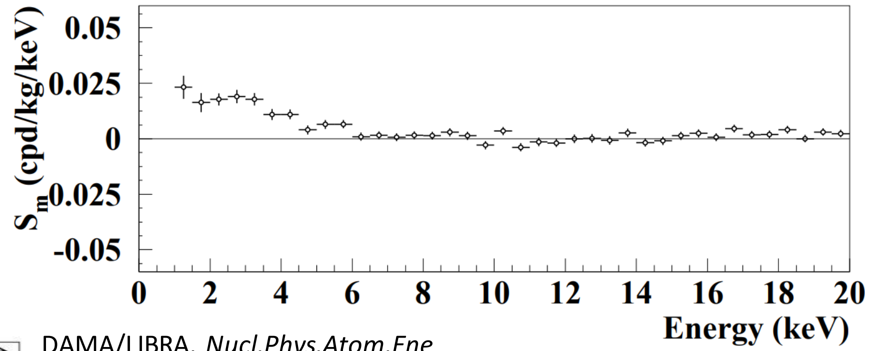




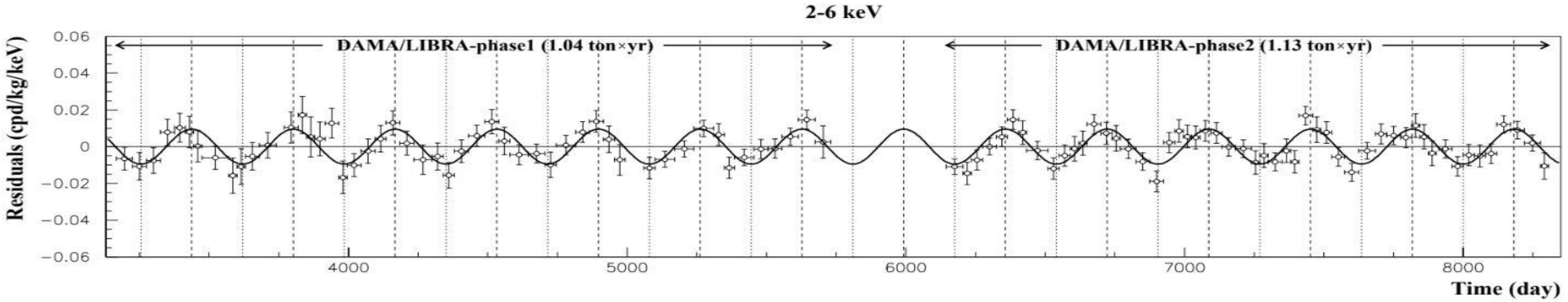
The DAMA/LIBRA Anomaly

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

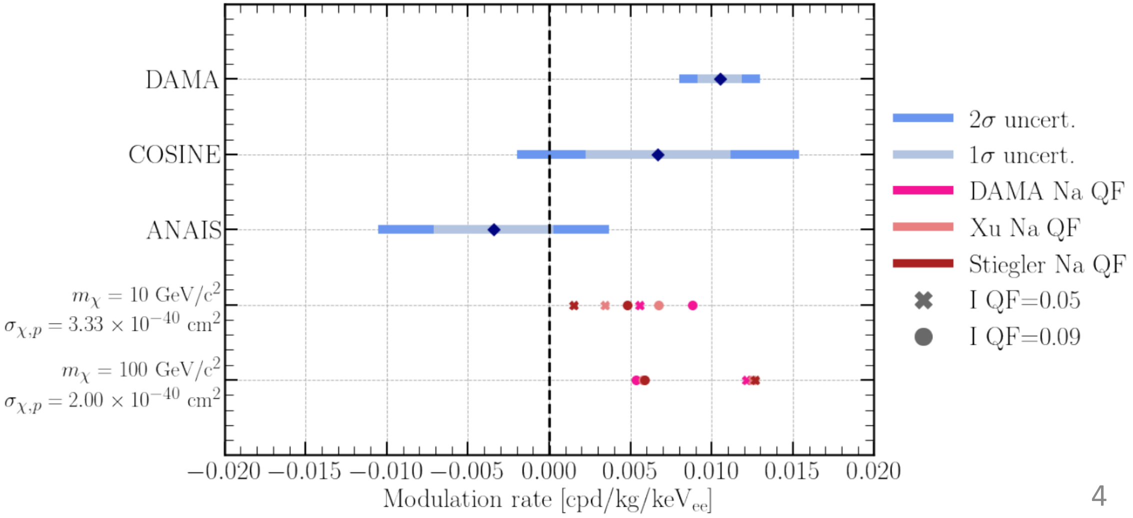
- 1-6 keV nuclear recoils at a significance of 12.9 σ
- **Is currently unresolved**



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



M. J. Zurowski, arXiv: 2211.15861



Anomalies best tested by similar, but improved, detectors:

- ANAIS – Canfranc underground lab, Spain
- Cosine100 – Yangyang lab, South Korea
- Cosinus – LNGS, Italy
- **SABRE – Stawell, Australia and LNGS, Italy**

Current tests of DAMA/LIBRA results are inconclusive

The SABRE Collaboration

Detectors in two locations:

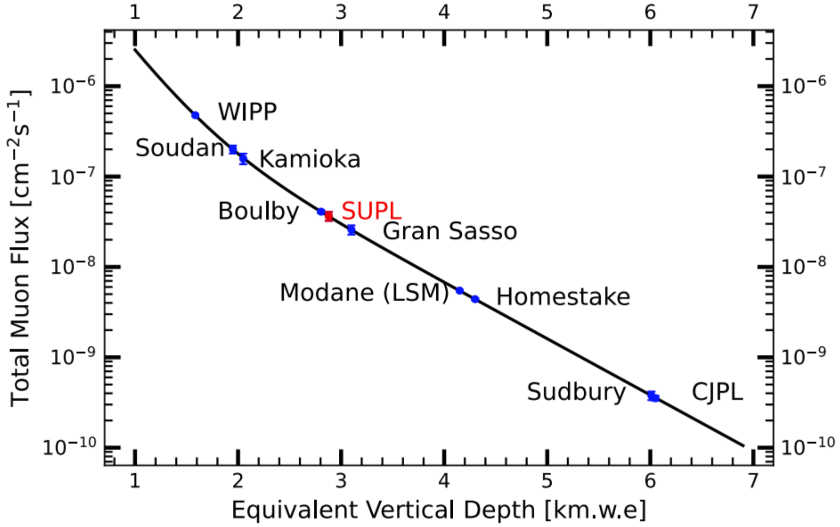
- SABRE North: Laboratori Nazionali del Gran Sasso (LNGS), Italy
- *SABRE South: Stawell Underground Physics Laboratory (SUPL), Australia*

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

SABRE South is a first for Australia:

- **First deep underground laboratory at 1025 m**
- **First underground dark matter experiment**

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



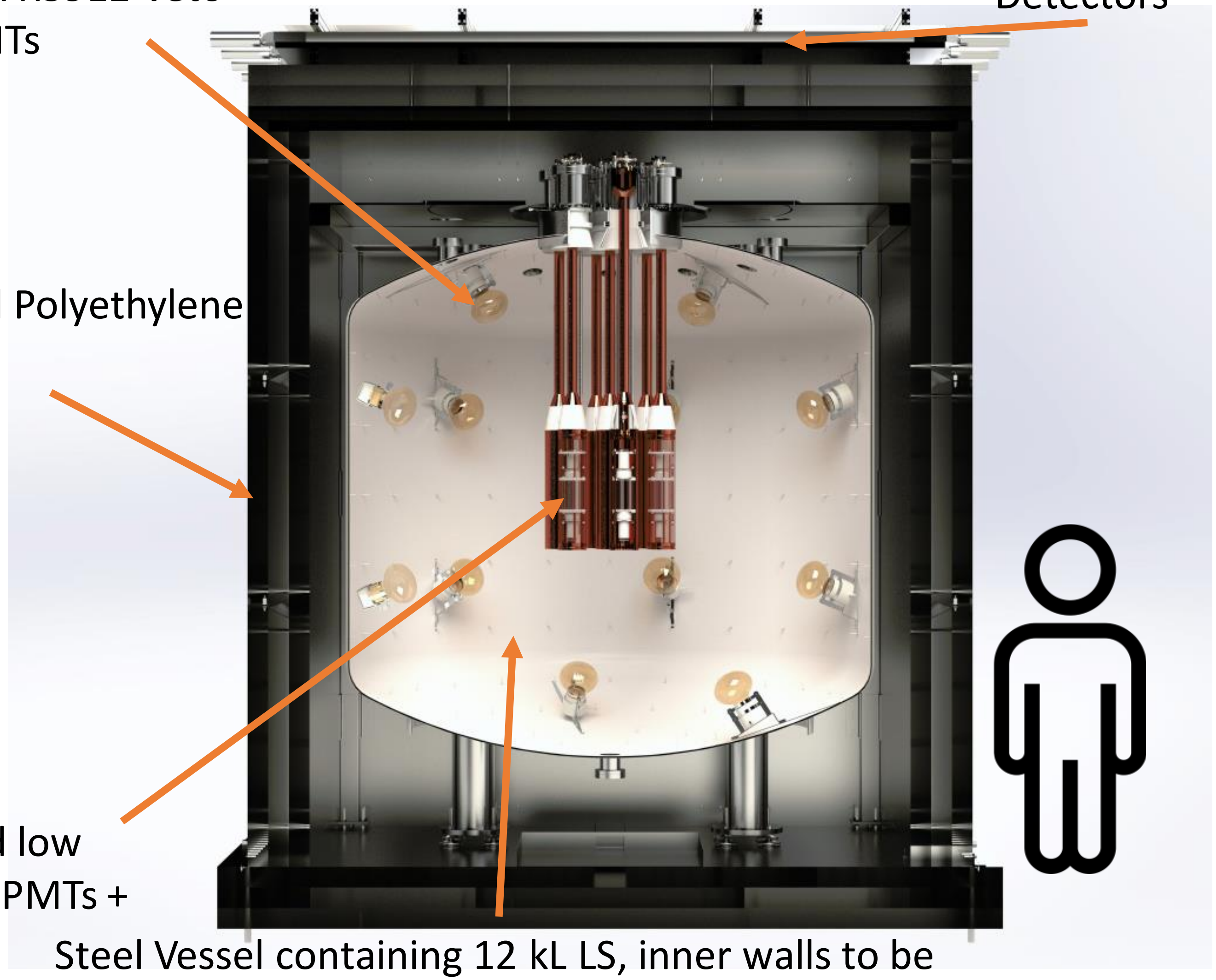
The SABRE South Detector

To test the DAMA/LIBRA annual modulation result
- Same target material of NaI(Tl) crystals

Improvement on similar detectors:
- Higher purity, low background crystals
- **Southern hemisphere location**
- **Active background veto**
- Particle ID, basic position reconstruction capabilities

1 keV energy threshold for 1-6 keV ROI

In-situ optical and radioactive calibration possible



Background Simulations

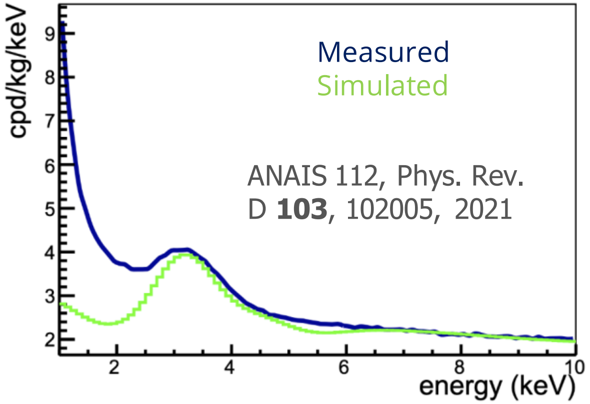
SABRE South arXiv: 2205.13849

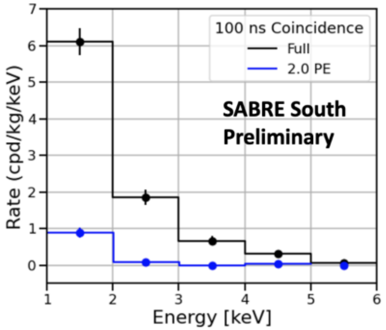
Total experimental background for SABRE South simulated, expecting overall background of **0.72 cpd/kg/keVee**

Dominated by both radiogenic and cosmogenic NaI impurities, despite ^{40}K suppression - < 10% of background external to crystals

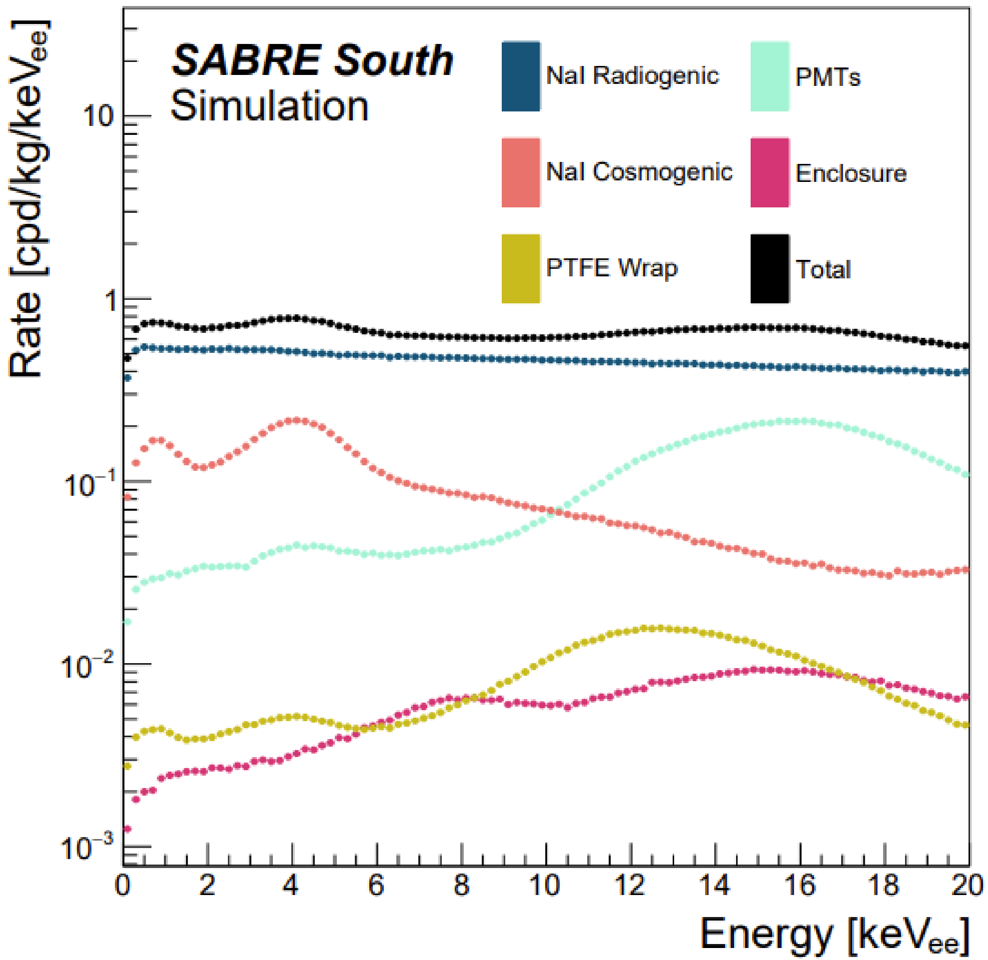
Component	Rate (cpd/kg/keV)	Veto efficiency (%)
Crystal intrinsic	$<5.2 \times 10^{-1}$	13
Crystal cosmogenic	1.6×10^{-1}	45
Crystal PMTs	3.8×10^{-2}	57
Crystal wrap	4.5×10^{-3}	11
Enclosures	3.2×10^{-3}	85
Conduits	1.9×10^{-5}	96
Steel vessel	1.4×10^{-5}	>99
Veto PMTs	1.9×10^{-5}	>99
Shielding	3.9×10^{-6}	>99
Liquid scintillator	4.9×10^{-8}	>99
External	5.0×10^{-4}	>93
Total	**0.72**	**27**

Veto efficiency: percentage of background vetoed by LS veto detector





Potential PMT noise contribution at low energies



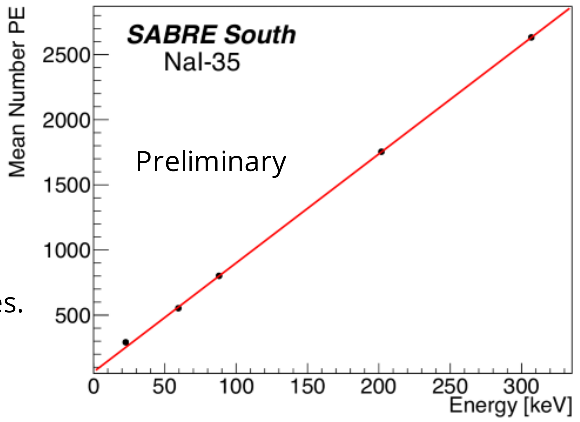
NaI(Tl) Crystal Production

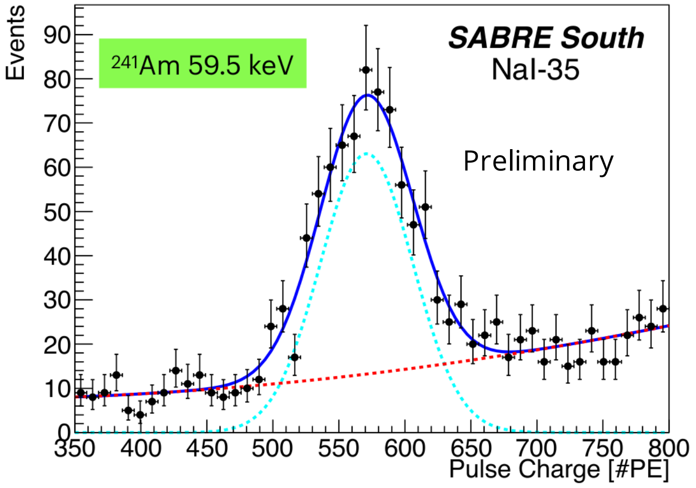
Very low background NaI(Tl) crystals have been grown by the SABRE Collaboration [1]

	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

NaI-35*, first 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



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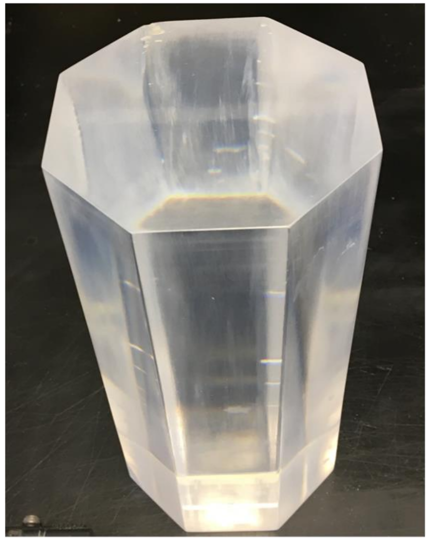


* Not to be encapsulated for final detector

[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

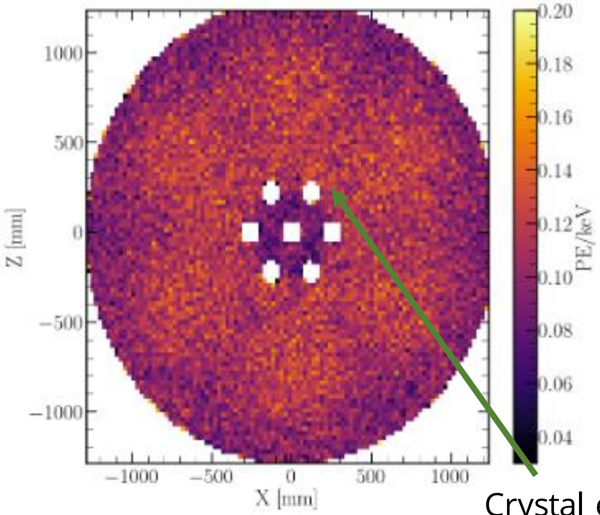
Key requirements:
- **Reduce ^{40}K background by factor of 10**

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

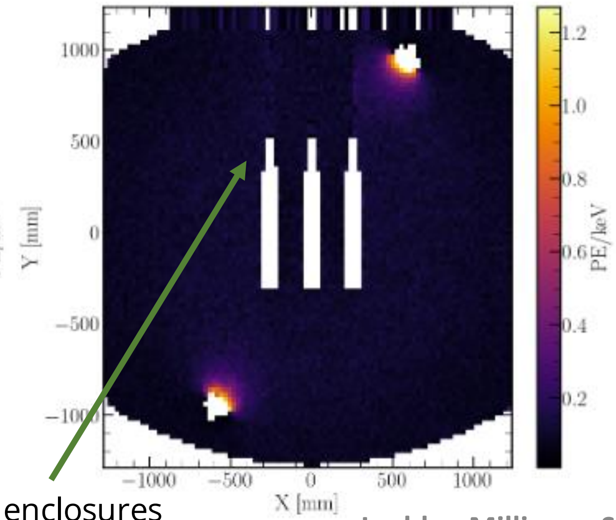
Approx threshold of 50 keV (~10 PE) – expect low amounts of detectable photons at keV energies - **~ 0.20 PE/keV detectable by single PMT**
- **Understanding of PMT response/noise imperative**

Photo-electron detection probabilities in veto vessel

Vessel top-down



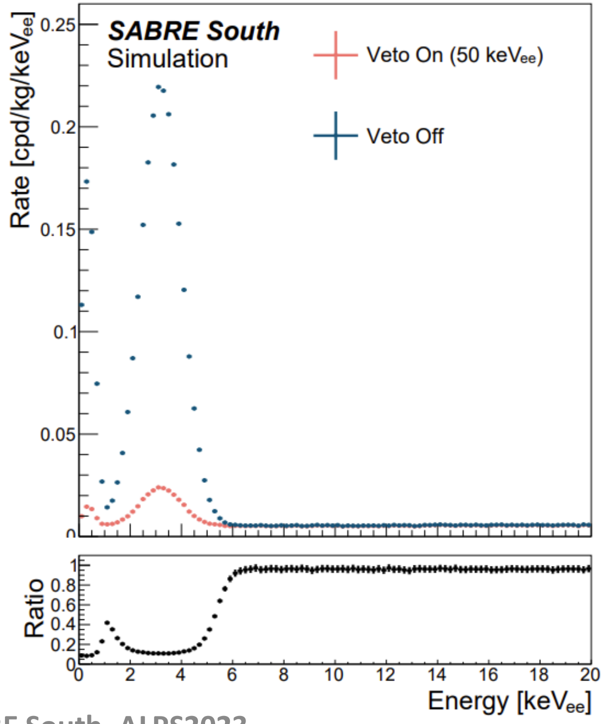
Vessel vertical slice

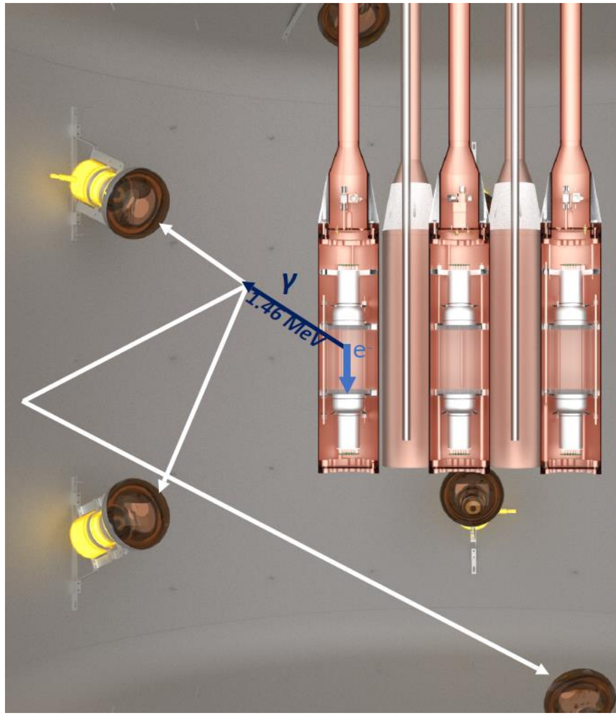


Crystal enclosures

SABRE South Preliminary

^{40}K Rate





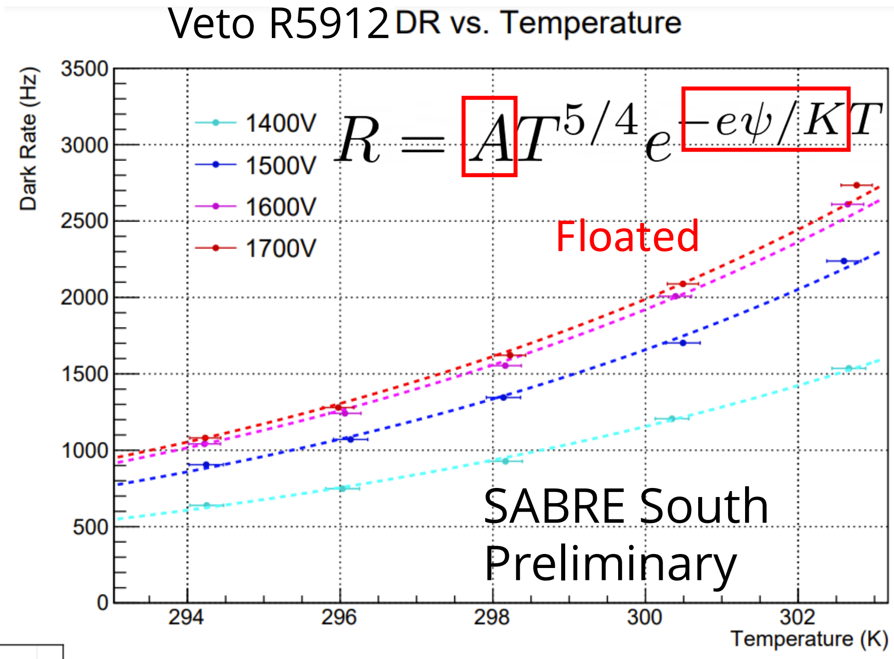
PMT Pre-calibration

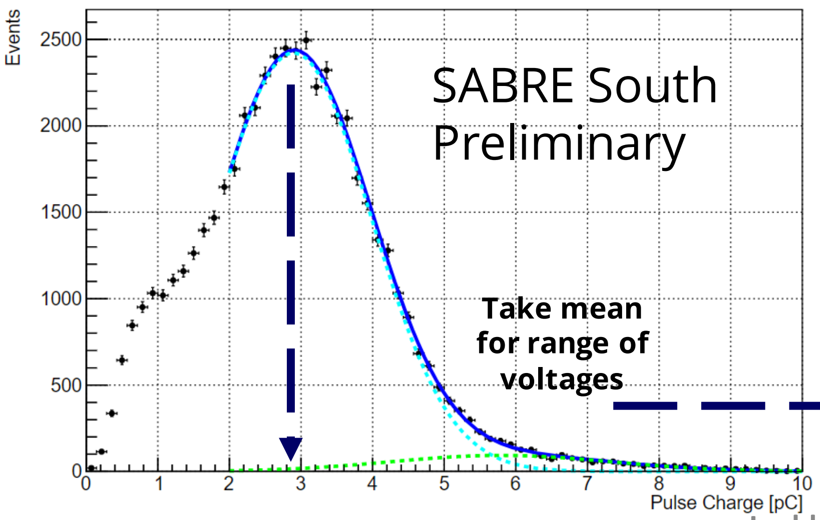
PMT response needs to be understood to optimise PE detection efficiency and noise rejection via thresholds defined by number of SPEs detected i.e. **Pre-calibration** of all PMTs:

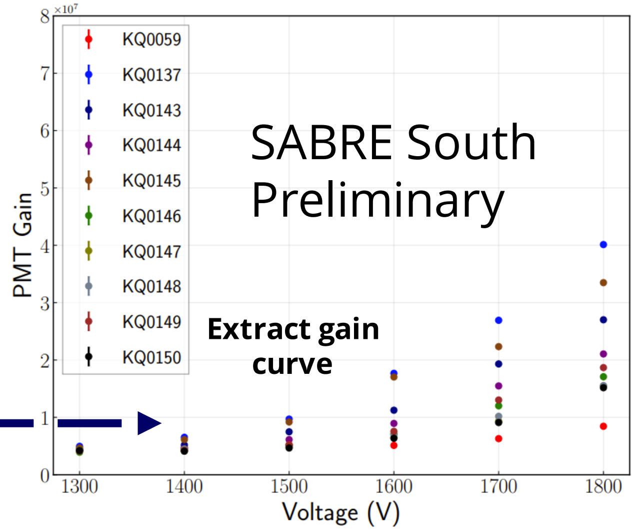
1. **Single photoelectron response (SPE) and gain**
2. **Dark rate, and temperature dependent dark rate**

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

Datasets can be used for noise classifiers







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

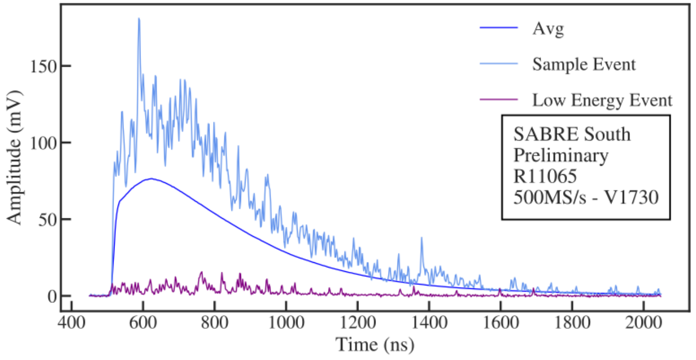
Pre-calibration papers to submit mid 2023

Event Reconstruction

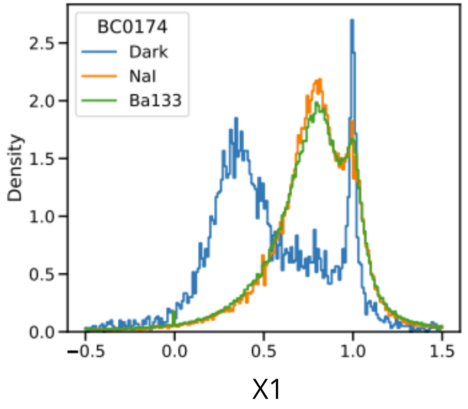
F. Scutti, https://iopscience.iop.org/article/10.1088/1742-6596/2438/1/012061/pdf

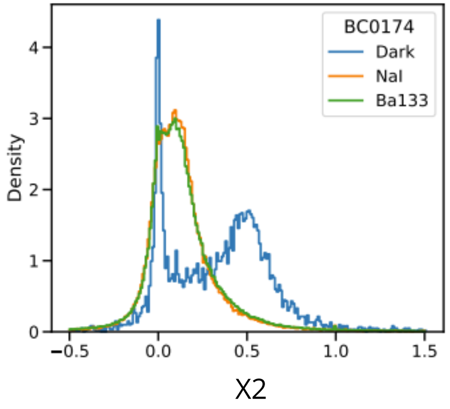
Pyrate – Flexible python-based software frame work for analysis and reconstruction

Process waveforms



Produce variables for reconstruction





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

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

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

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

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

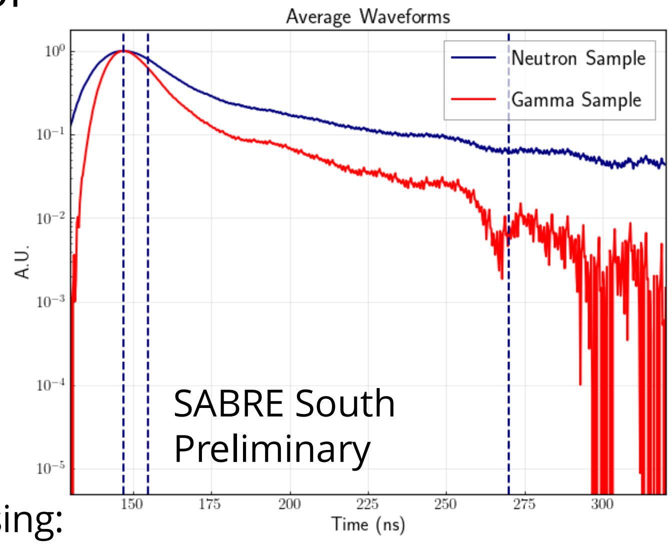
Particle ID Development

Multivariate reconstruction/event selection methods in development for both crystal detectors and veto detector

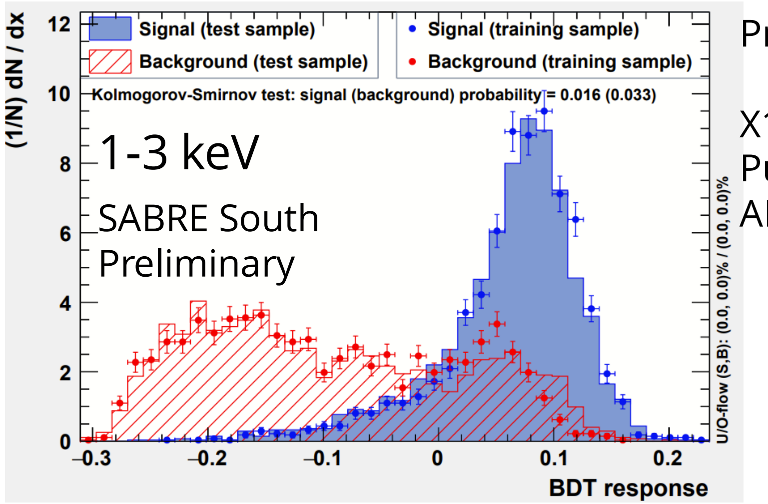
To improve:

- Crystal detector NR/noise classification
- Veto detector background reconstruction – e.g. to disentangle backgrounds interacting in detector

Exploit pulse shape discrimination



Crystal



Prototype with one PMT, using:

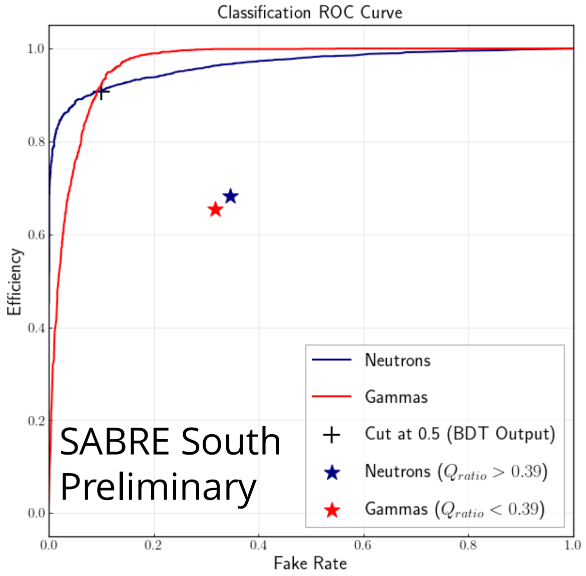
X1, X2
Pulse mean time
ANAIS CAP(x) (100-600)

Veto

$$Q_{ratio} = \frac{Q_{delayed}}{Q_{prompt}}$$

Neutron/gamma discrimination w/ scaled down LS prototype detector (1 PMT)

Multivariate approach indicating improvement discrimination



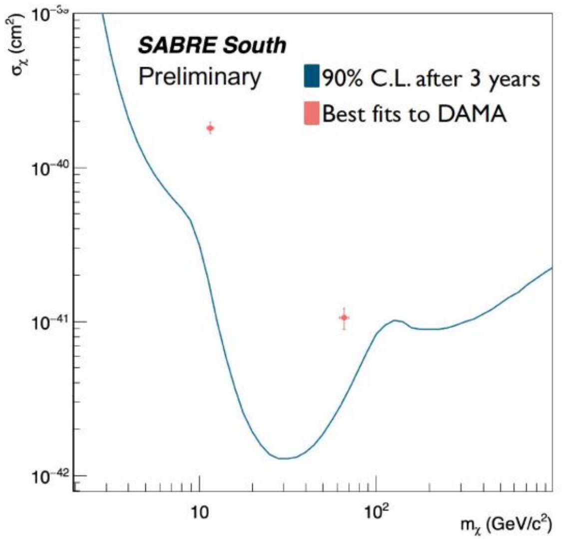
See also N. Spinks et al. NIM A (2022) 167773 - ER vs. NR discrimination

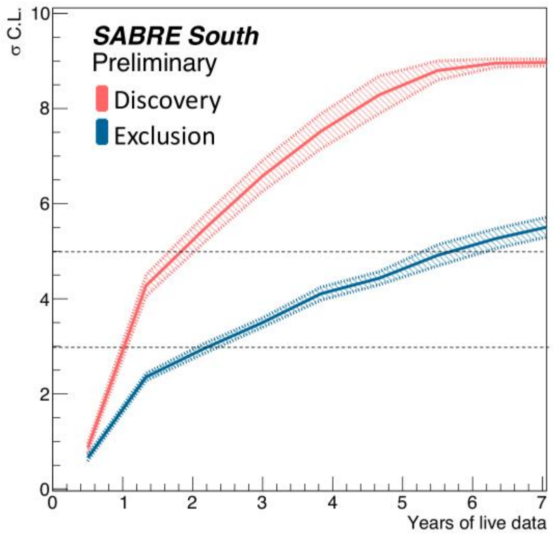
Status/Summary

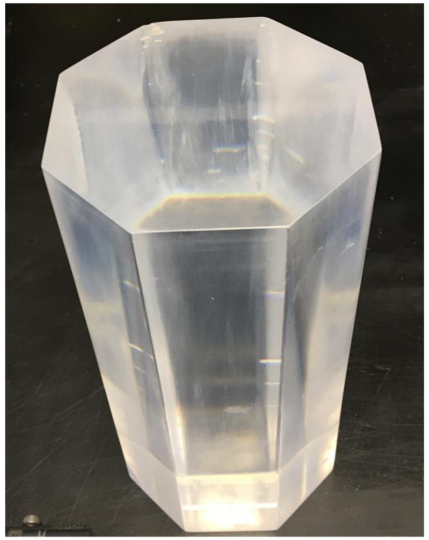
SUPL is built and ready for use. Detector assembly to start in 2023, aiming for completion in 2024

- **Pre-calibration of all PMTs begun – key for optimal detector response and noise reduction**
- First SABRE South test crystal (NaI-35) being characterised at LNGS
- Ongoing crystal R&D, **production beginning later this year**
- Veto vessel fit-out testing to begin March-April 2023, 17 kL of LAB scintillator in Melbourne **– underground late 2023 early 2024**
- Underground **muon measurements with SABRE South muon veto to begin this year** – background muon flux characterisation
- Total projected background – **0.72 cpd/kg/keV$_{ee}$**

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







Acknowledgements

SABRE South

Australian Government

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY of ADELAIDE

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Australian National University

SABRE North

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

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

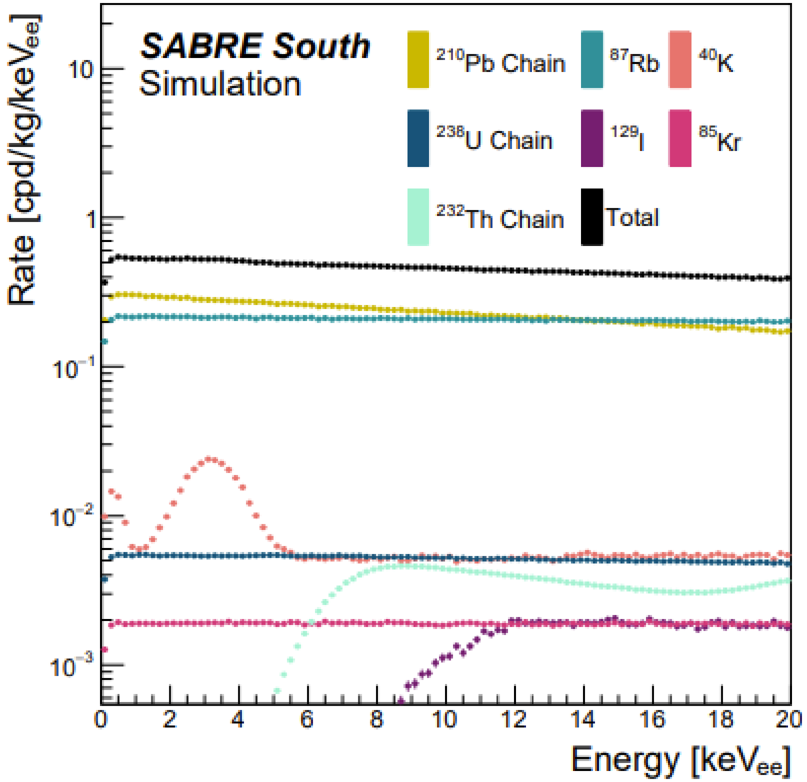
SAPIENZA UNIVERSITÀ DI ROMA

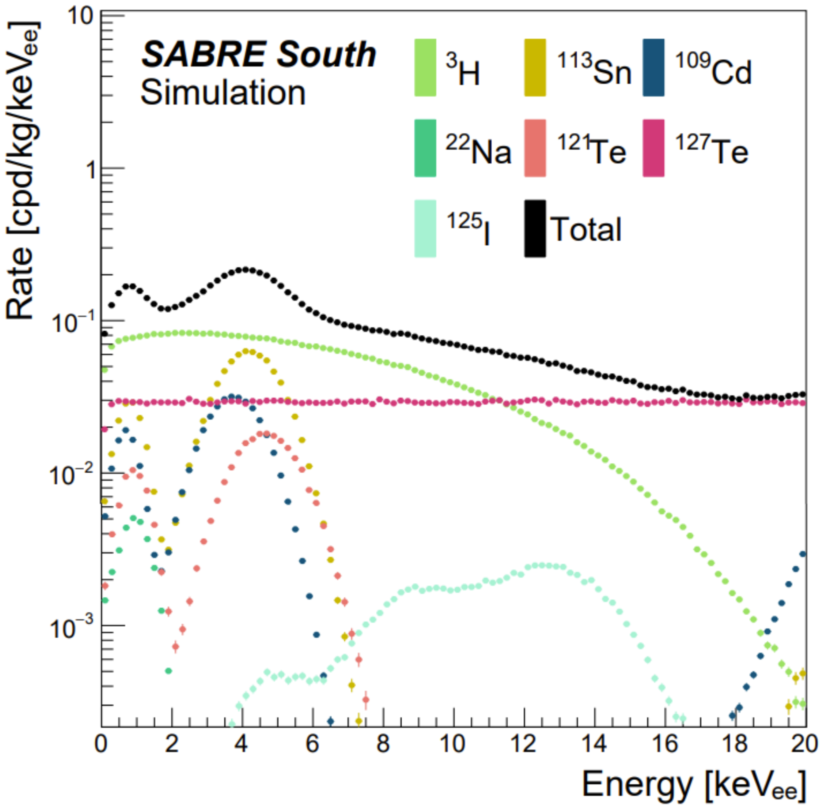
Pacific Northwest NATIONAL LABORATORY

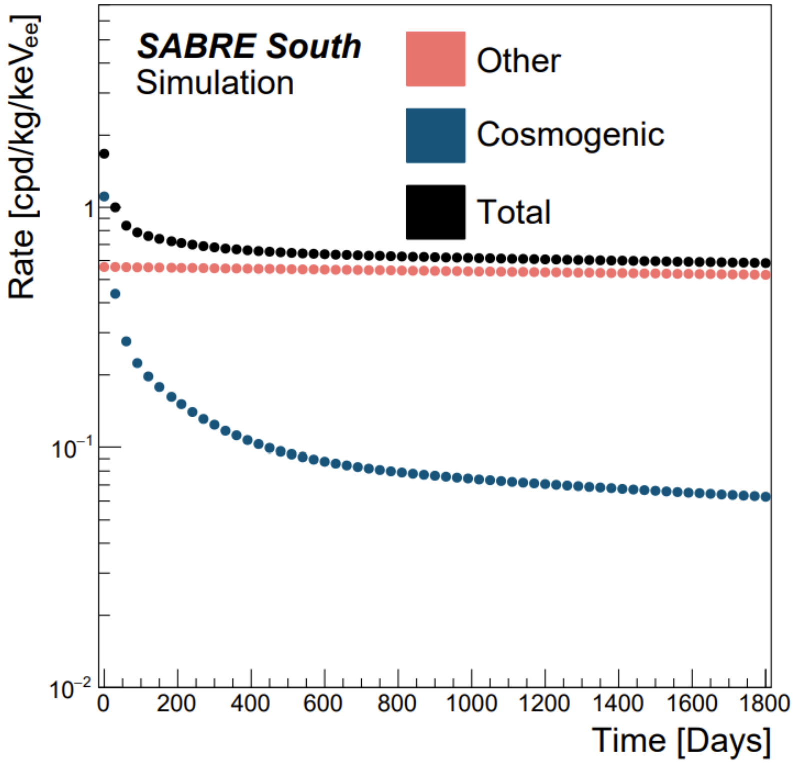
PRINCETON UNIVERSITY

BACKUPS

Key Backgrounds



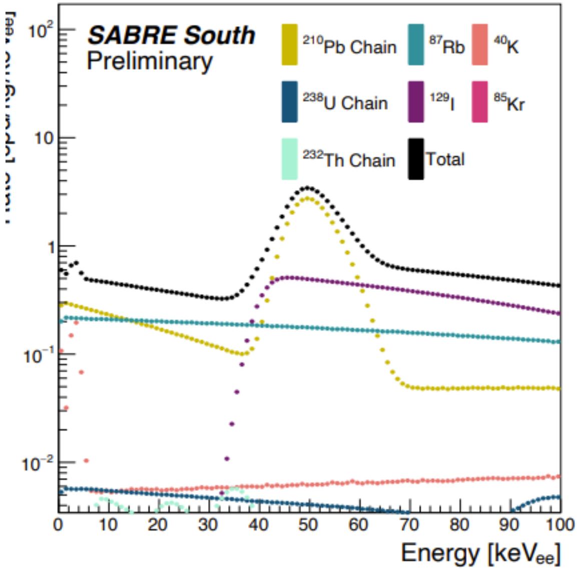




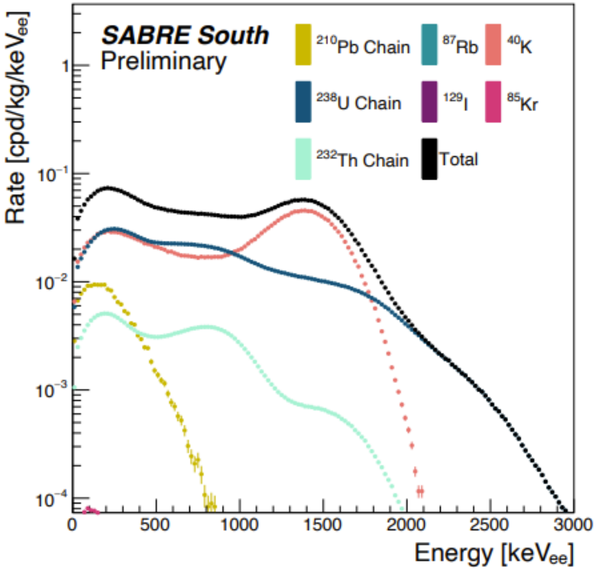
Key Backgrounds

Contamination from intrinsic radiation of crystals

Deposition in crystal

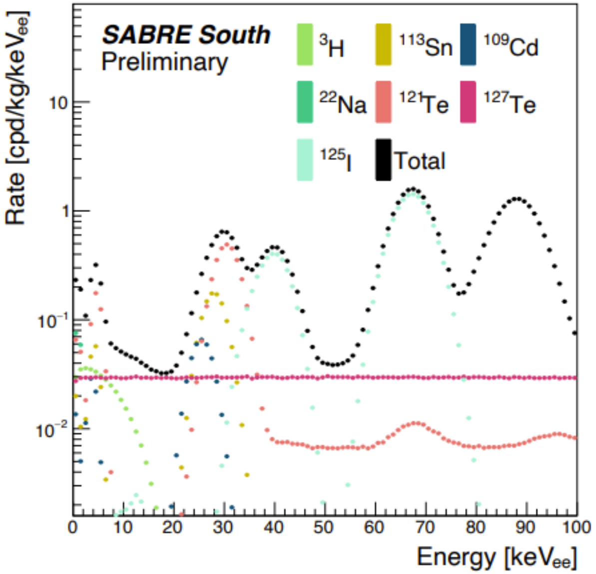


Deposition in veto

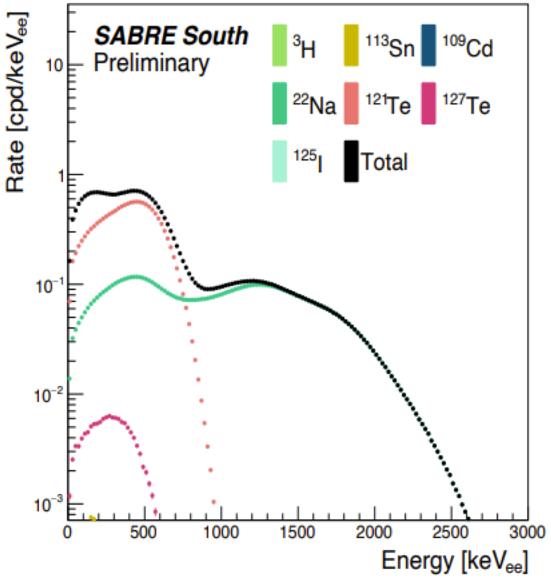


Contamination from cosmogenic activation of crystals

Deposition in crystal



Deposition in veto



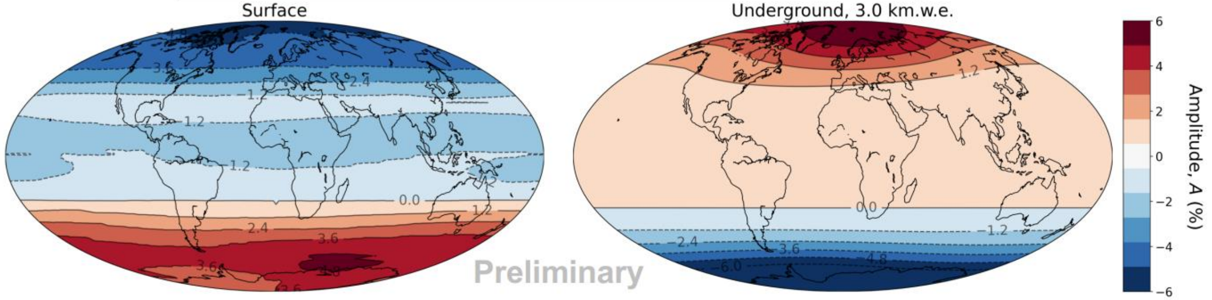
Muon Flux

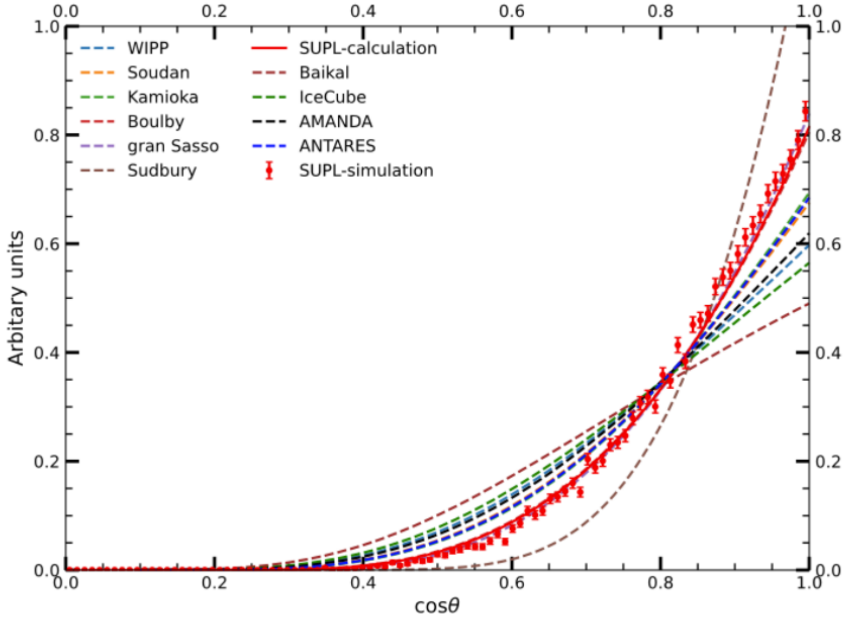
First major muon flux/muon modulation measurement to occur in SUPL very soon

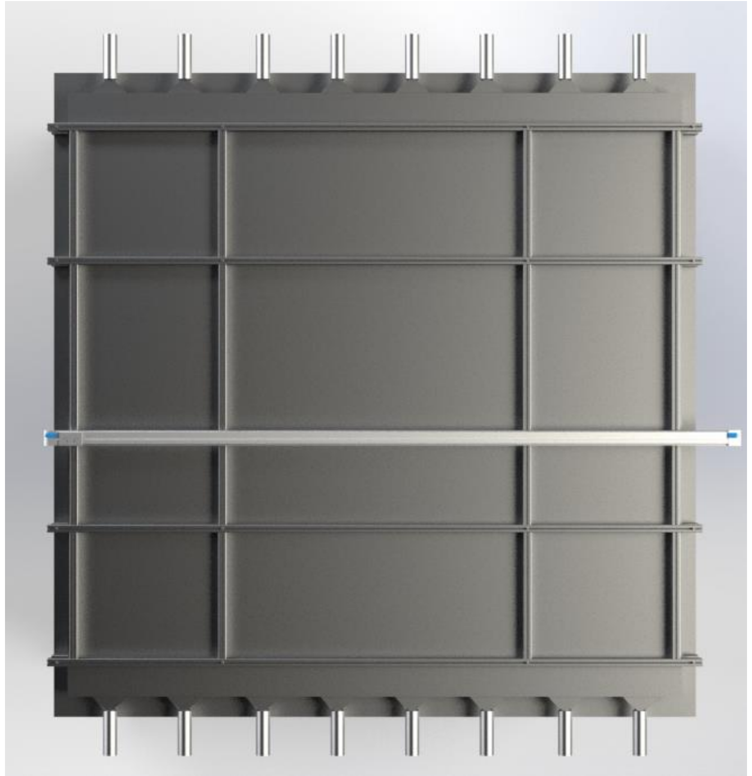
To measure flux and angular resolution, with ~4cm spatial resolution along two sided panels

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.







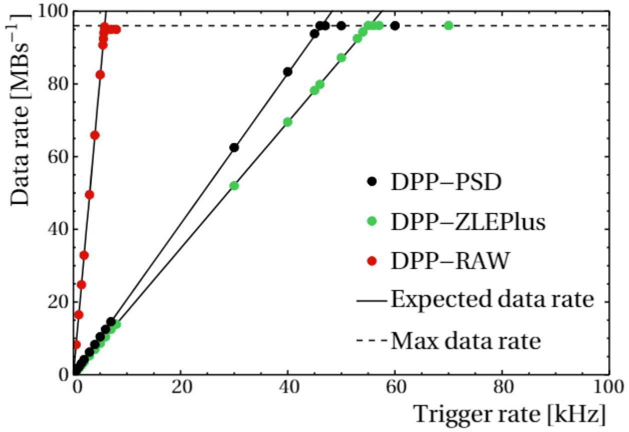
Software and DAQ

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

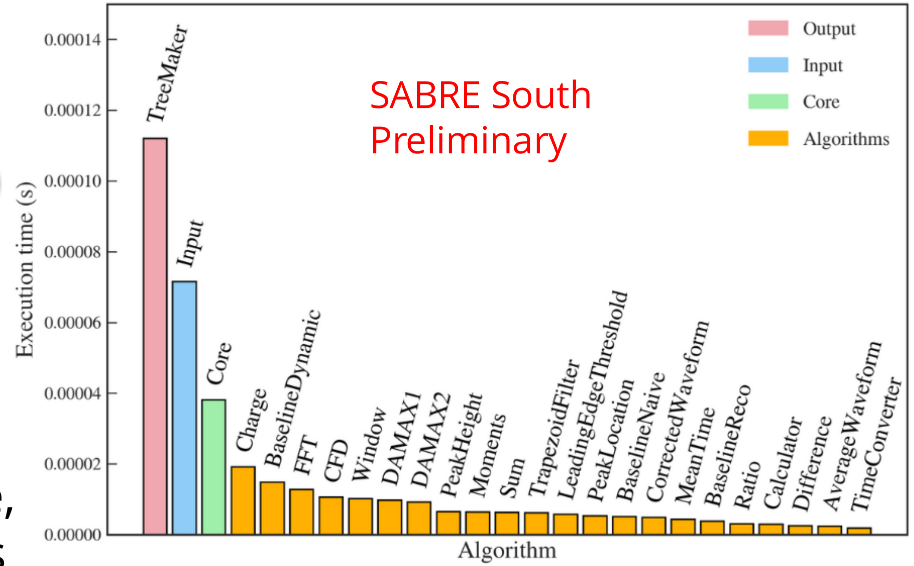
Simplified SABRE South data flow:

Data acquisition via SABRE South designed EPICS-based control system
6 CAEN digitisers for 48 signal channels

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



Expected max PMT trigger rate ~40-50 kHz per instance, for max data rate < 100MB/s



Expect SABRE to run multiple pyrate instances for live processing – rate and threshold dependent