Deep Underground Physics

The SABRE South Experiment at the Stawell Underground Physics Laboratory

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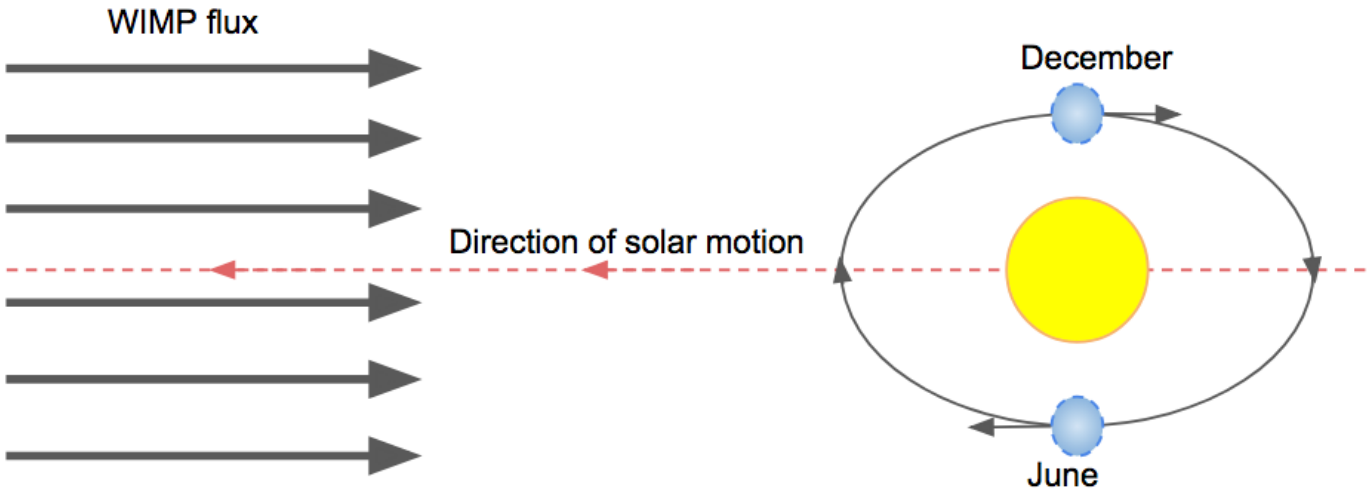
Annual Modulation

Standard Halo model hypothesis:
spherical halo of cold, dark matter permeating the galaxy



Results in Annual modulation with maximum (June 2nd) and minimum (December 2nd)

DM Rate

$$R(E) = R_0(E) + R_m(E)\cos(\omega(t - t_0))$$

Non-Modulating DM rate

Modulating DM rate

Annual Modulation:

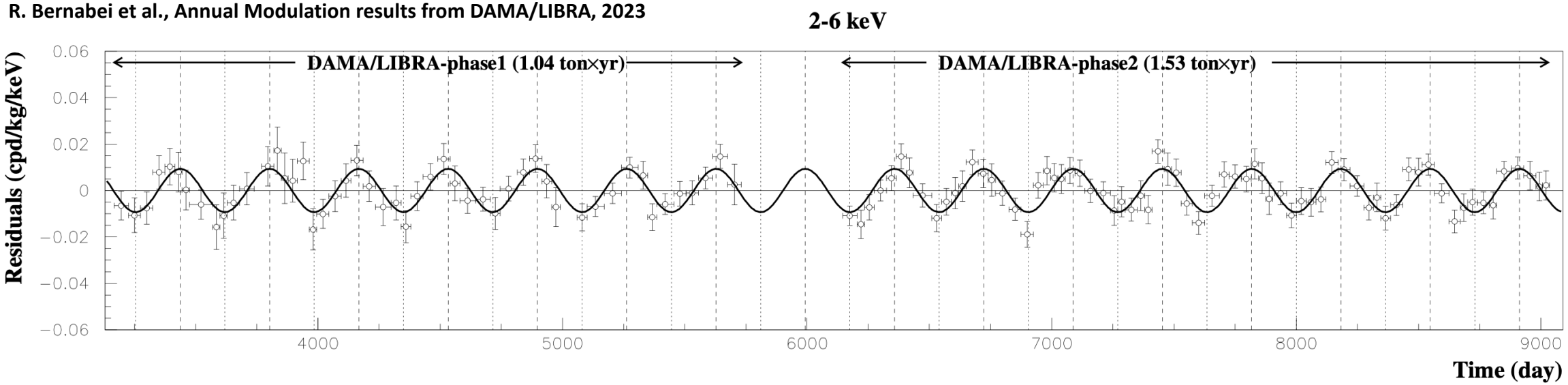
- **Model Independent signature of DM**
- **Require strict control over modulating backgrounds**

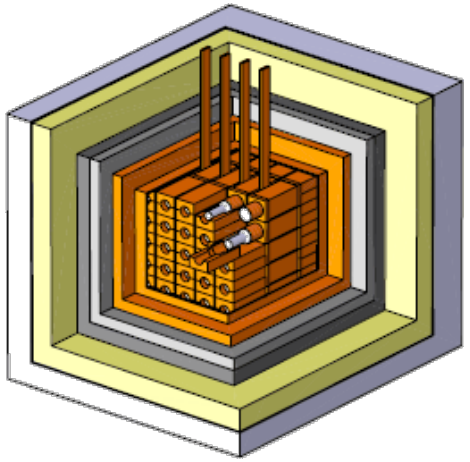
Rare and Low energy events:

- **Very low expected rate** < 1 counts/day/kg (few % modulates)
- Expected recoil energy **1-100 keV** for **WIMP** of mass 10 – 1000 GeV/c^2

DAMA/LIBRA Results

R. Bernabei et al., Annual Modulation results from DAMA/LIBRA, 2023





The DAMA/LIBRA Experiment has been running for 20+ years

- Located at **LNGS**
- Total mass **250 kg of NaI(Tl)**
- Observed **~0.01 cpd/kg/keV** modulation in the 1-6 keV (second phase) energy range
- **12.9 σ** significance

The DAMA/LIBRA signal: explanations ?

- Artefact of the analysis procedure ?
  - Unlikely and a decaying background can not lead to these modulations [https://arxiv.org/abs/2408.08697]

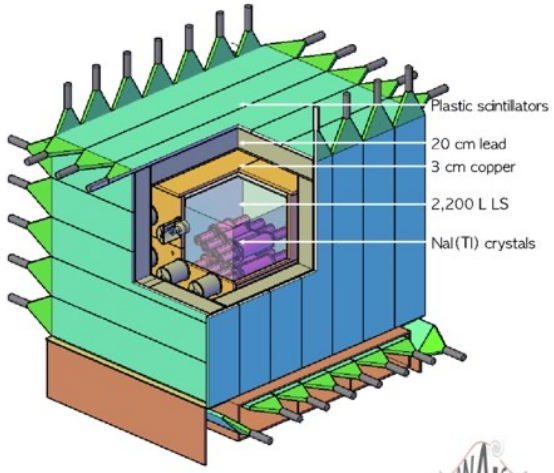
- Seasonal background or systematic effect (muon-induced neutrons? …)
  - Requires an experiment that can monitor/VETO for seasonal backgrounds

- Dark matter signal with a more complex interaction mechanism (to explain lack of detection)

From APPEC (Astroparticle physics European consortium) :

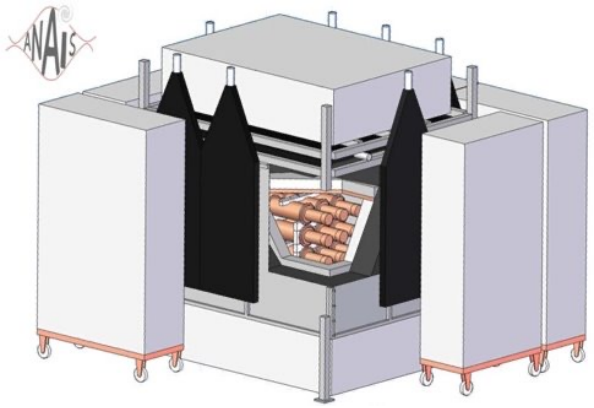
"The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material"

Current NaI(Tl) experiments



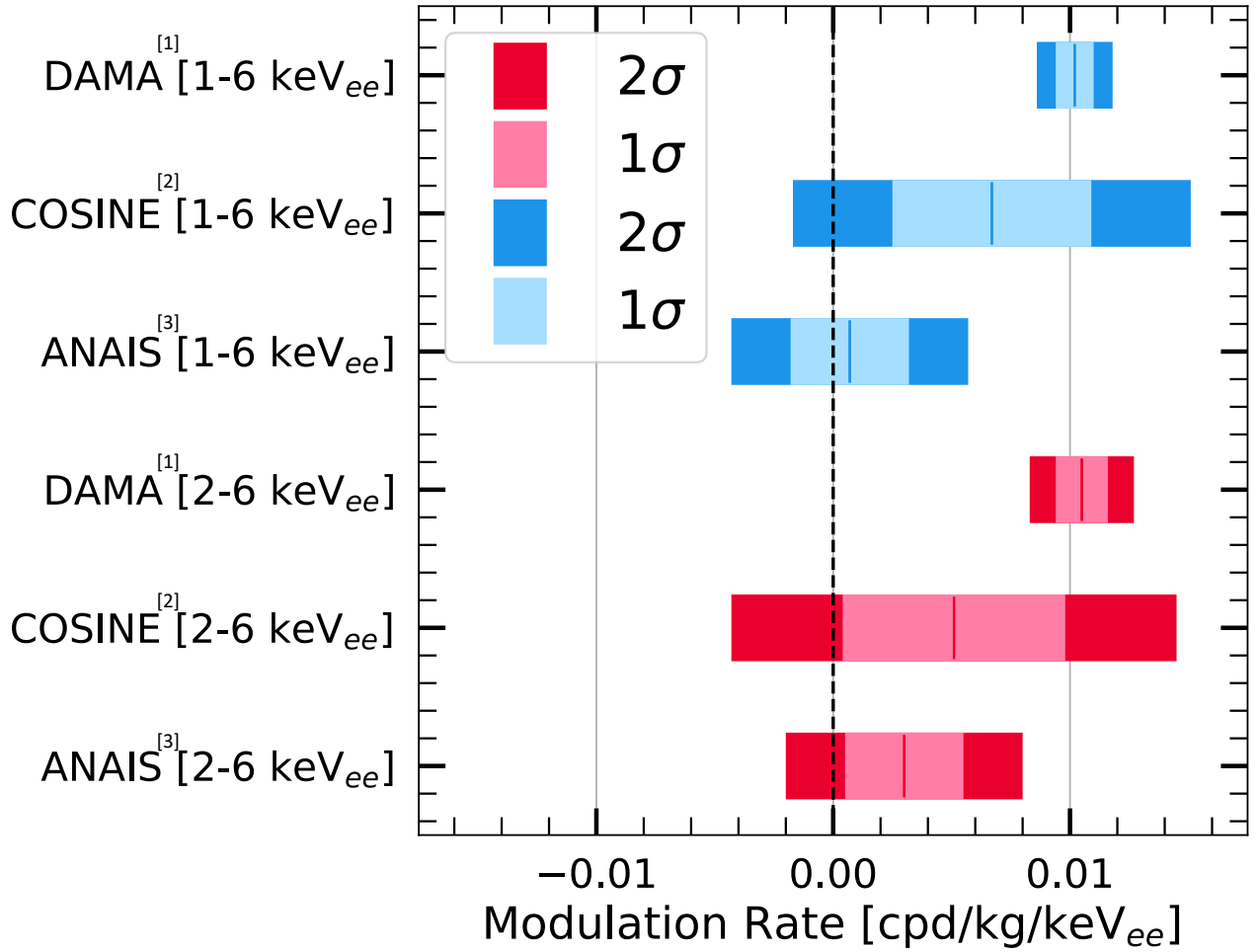
COSINE-100

100 kg NaI(Tl)
Yang Yang National Laboratory, South Korea



ANAIS-112

112 kg NaI(Tl)
Canfranc national laboratory, Spain



[1] R. Bernabei et al., Annual Modulation results from DAMA/LIBRA, 2023

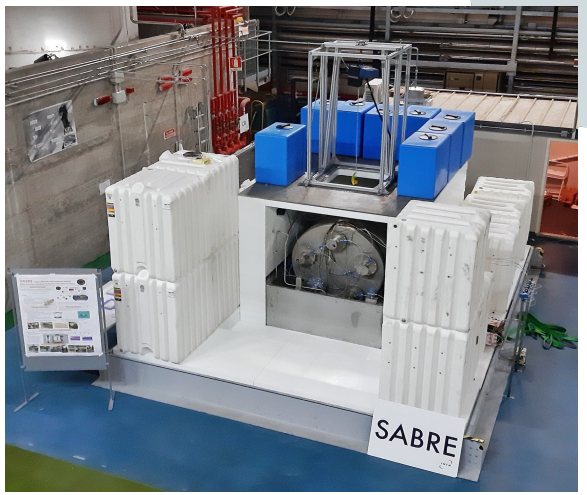
[2] G. Adhikari et al., Three-year annual modulation search with COSINE-100, 2021.

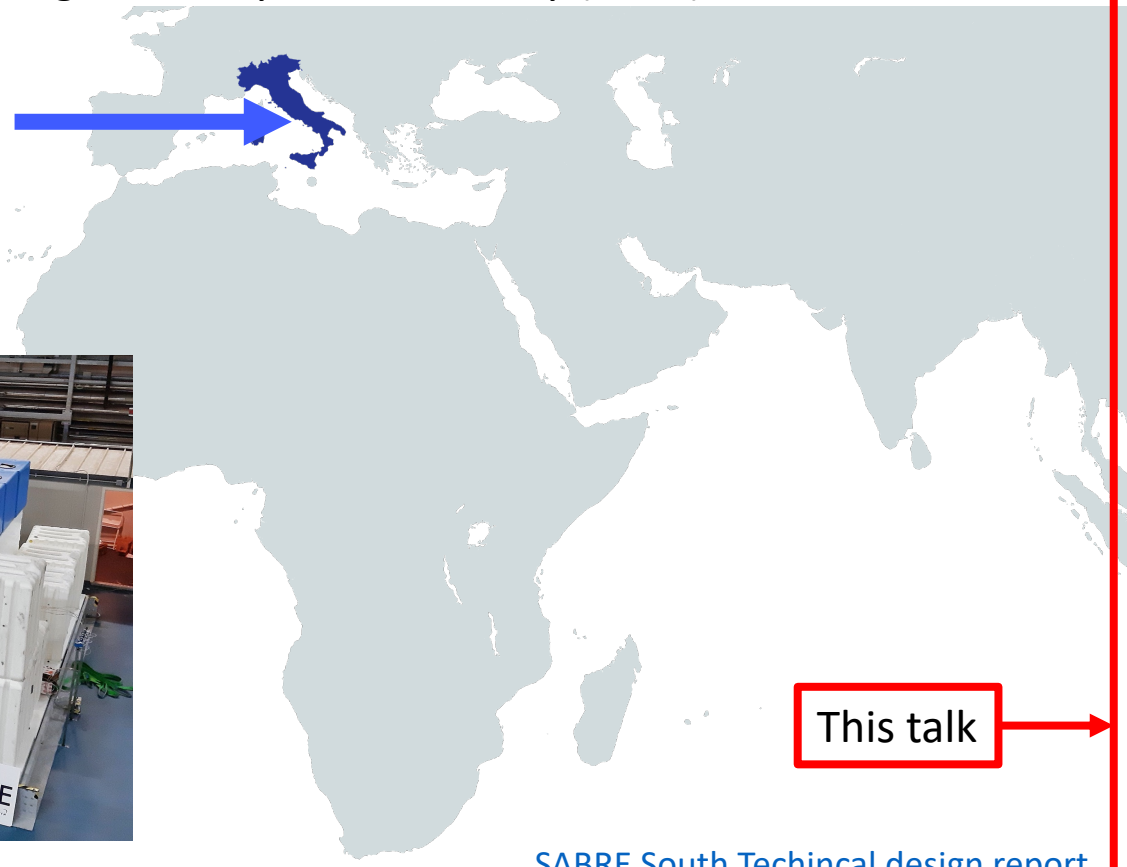
[3] ANAIS Collaboration, I. Coarasa Casas, ANAIS-112: the most sensitive experiment to test the DAMA/LIBRA signal in a model independent way, in 15th International Workshop on the Identification of Dark Matter, L'Aquila Italy, 2024

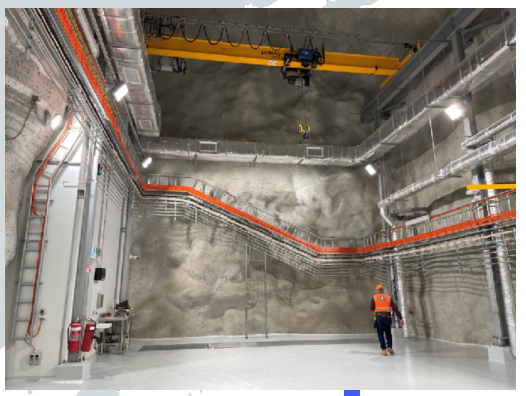
SABRE: a dual site experiment

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







[SABRE South Techincal design report]

The SABRE Collaboration

SABRE **North and South** detectors have **common core features**:

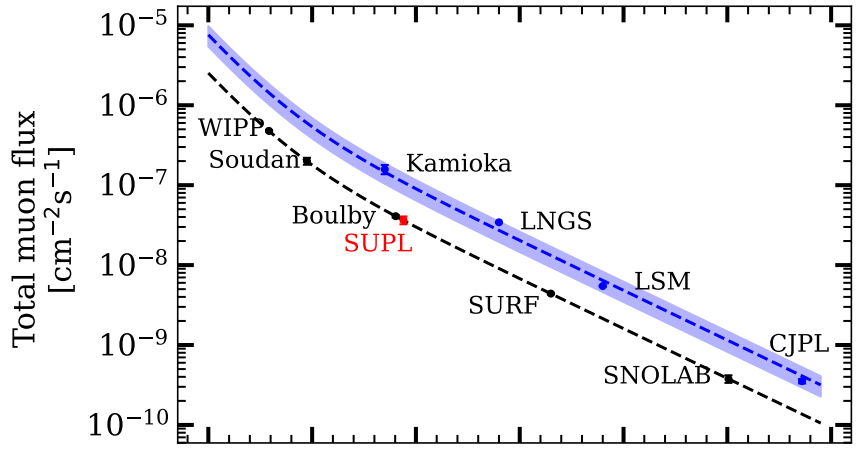
- Will use the same crystal growth powder and crystal PMTs (HPK R11065)
- Will share simulation, DAQ and software frameworks
- Exchange of engineering knowledge: collaborative agreements between INFN and ARC Centre of Excellence for Dark Matter Particle Physics

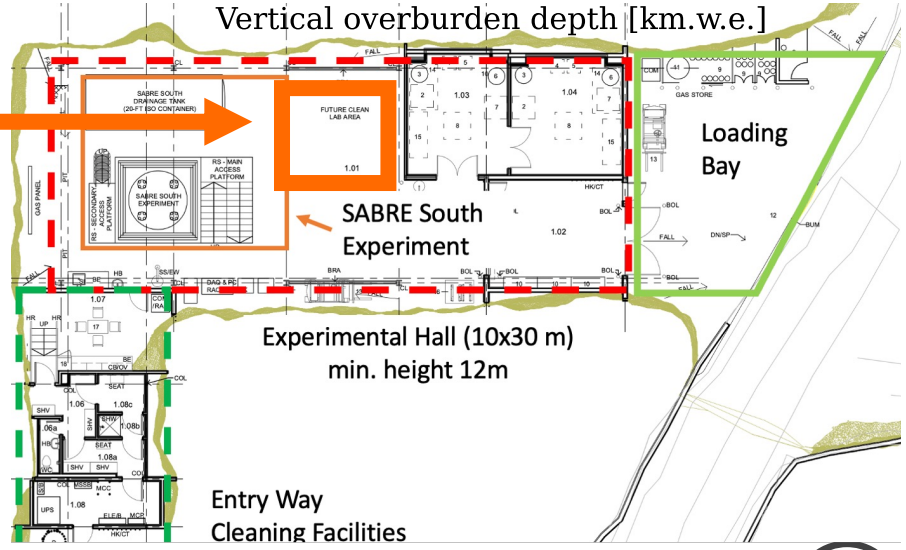
SABRE North and South detectors **have** different **shielding designs:**

- Phase-out of organic scintillators at LNGS → SABRE North will use fully passive shielding. Will achieve required low background levels through zone refining process
- SABRE South will use LAB liquid scintillator for active background rejection → less stringent requirements on crystal background levels

Stawell Underground Physics Laboratory

- **SUPL** is the first deep underground lab in the Southern Hemisphere **(37º 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.
- Helical drive access.
- Commissioning started in **November 2023**





SABRE South Detector

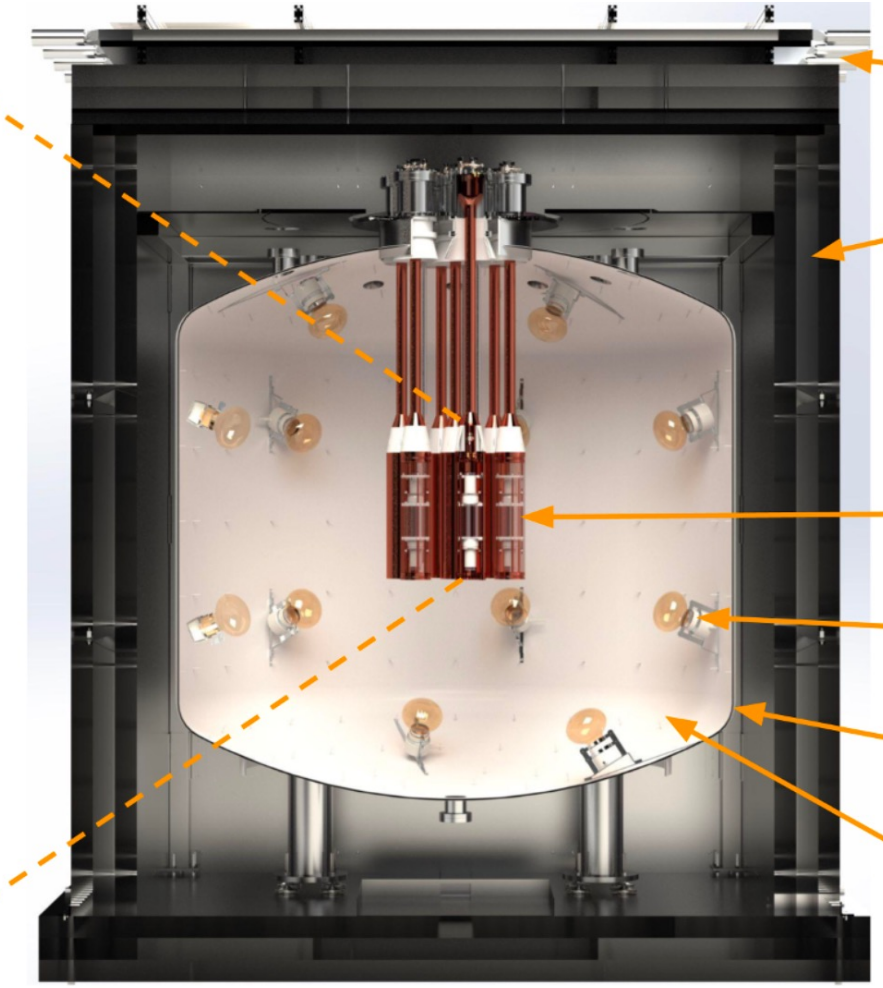
Feedthrough plate

OFHC Cu enclosure

Teflon internal structure

7.6 cm R11065 Hamamatsu PMTs

NaI(Tl) crystal



9.6 m^2 EJ200 scintillators for muon detection and rejection

Shielding to reduce external background:
- 8 cm of steel
- 10 cm of PE
- 8 cm of steel

NaI(Tl) crystals in Cu enclosures (coupled to two low radioactivity PMTs)

Eighteen R5912 PMTs for veto system

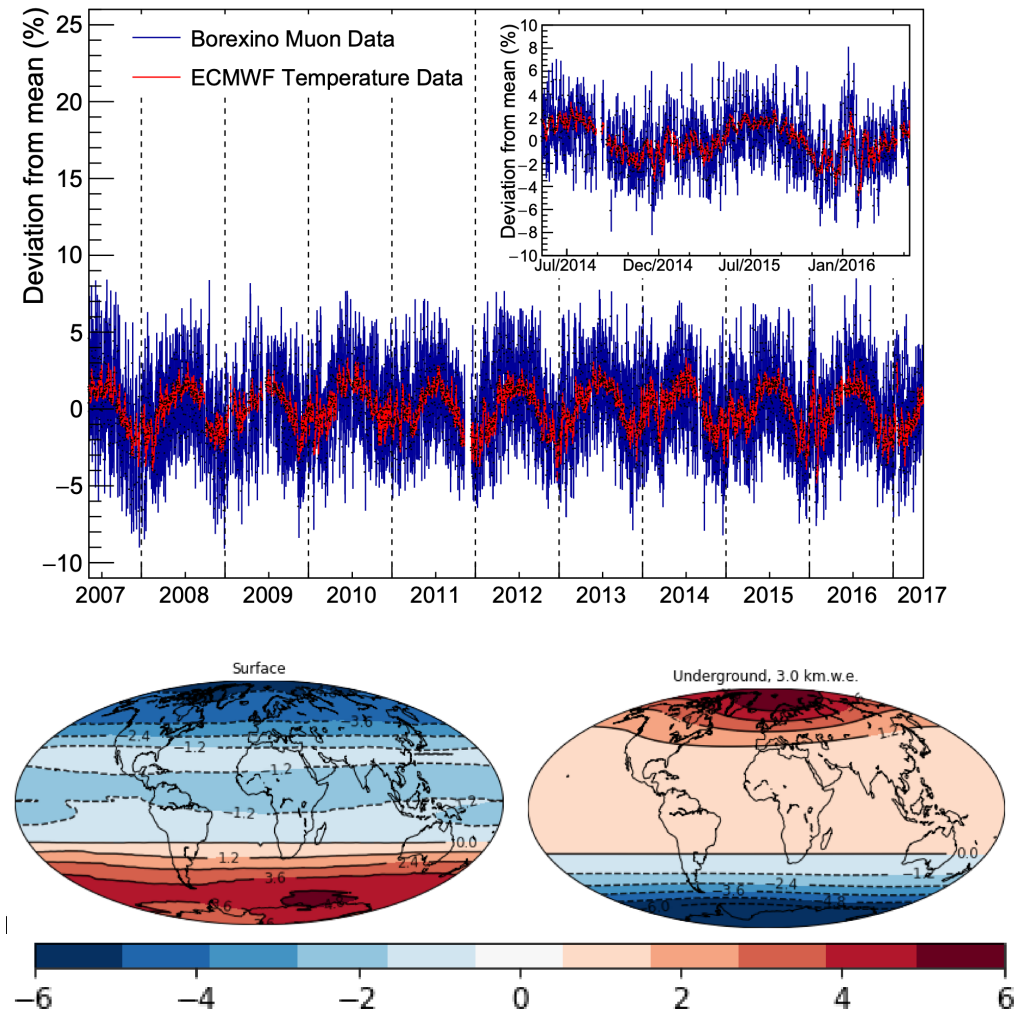
Steel veto vessel filled with 12 kL of LAB doped with PPO (3.5 g/L) and Bis-MSB (15 mg/L)

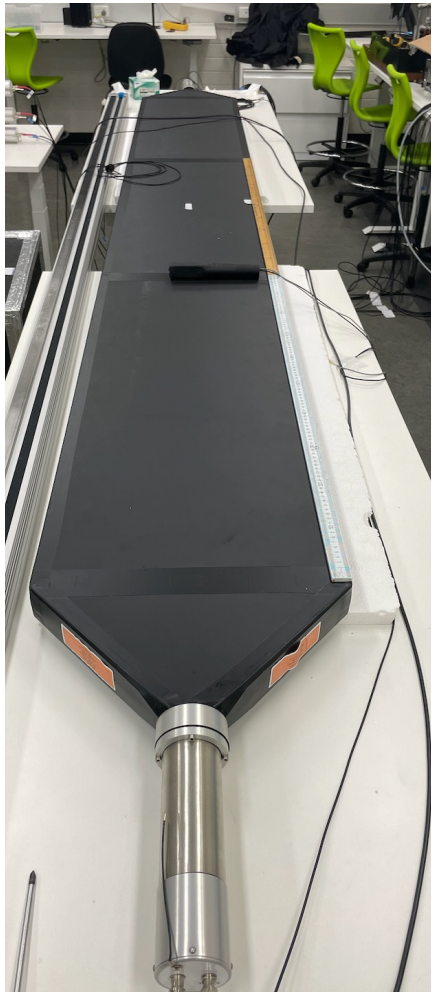
Reflective Lumirror coating

[SABRE South Techincal design report]

Muon veto system

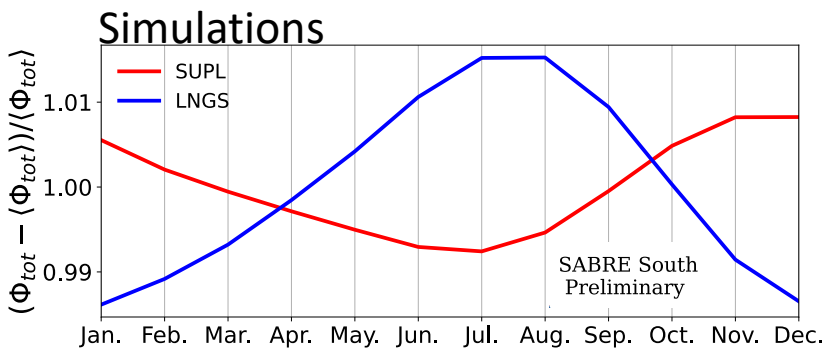
- Underground cosmic ray muon flux annualy modulates annually.
- Muon interactions in the rock walls can produce neutrons via spallation. With the potential to modulate seasonally
- The muon systems consists of 8x panels, providing a 9.6 m2 coverage above the SABRE Vessel.
  - Each panel consists of EJ200 plastic scintillators with 2xPMTs,
  - Acting as a veto against muons for the crystal modules.

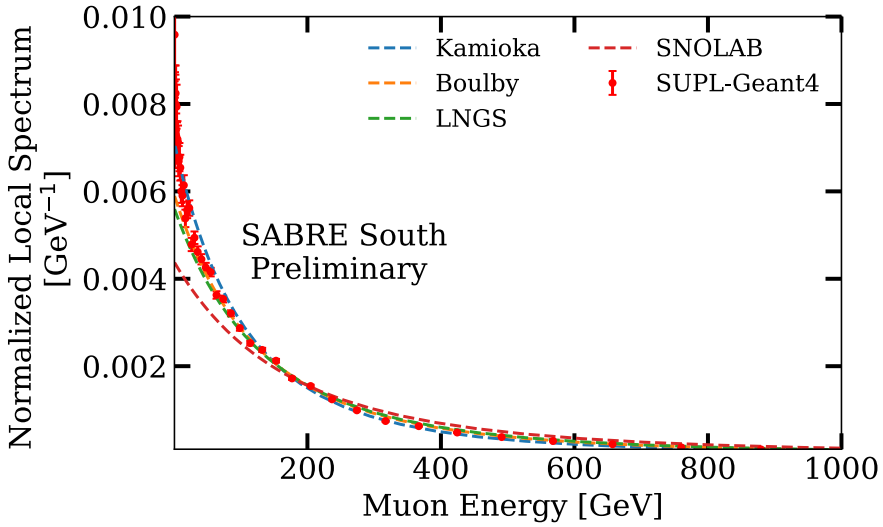


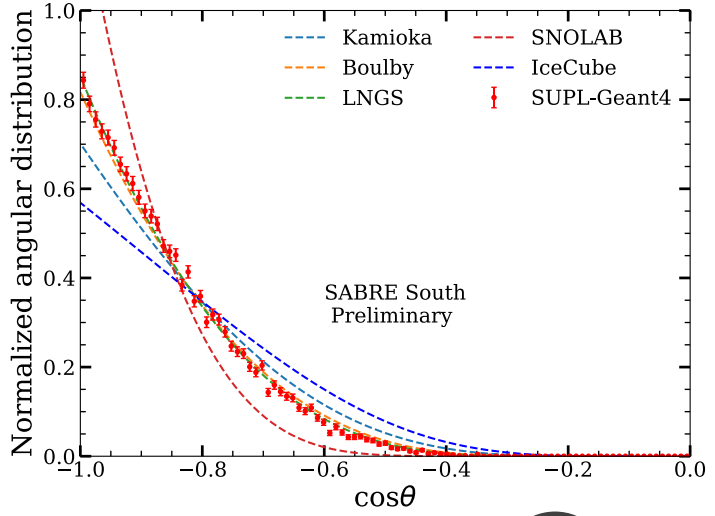


Towards muon flux measurement

- The system is operating in 2 layers and planned to map the angular distribution
  - Map the overburden
- Current goal: Measurement of the angular distribution
- Long term also measure the modulation, and better understand the muon induced neutrino background



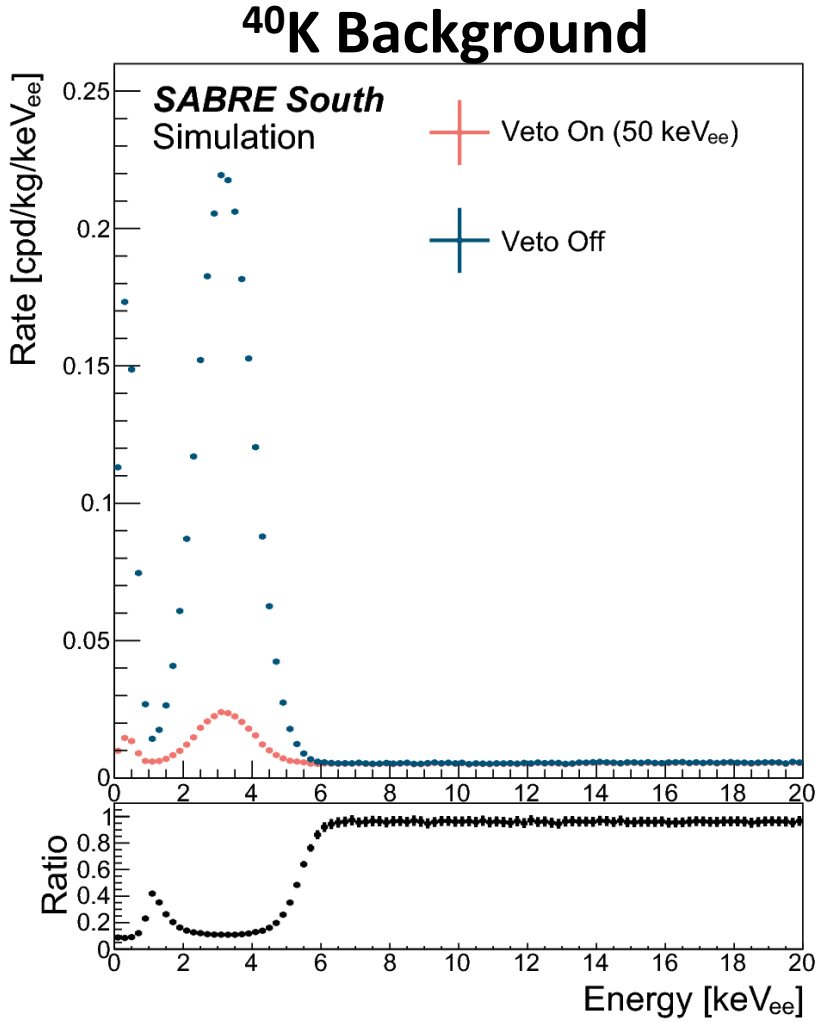


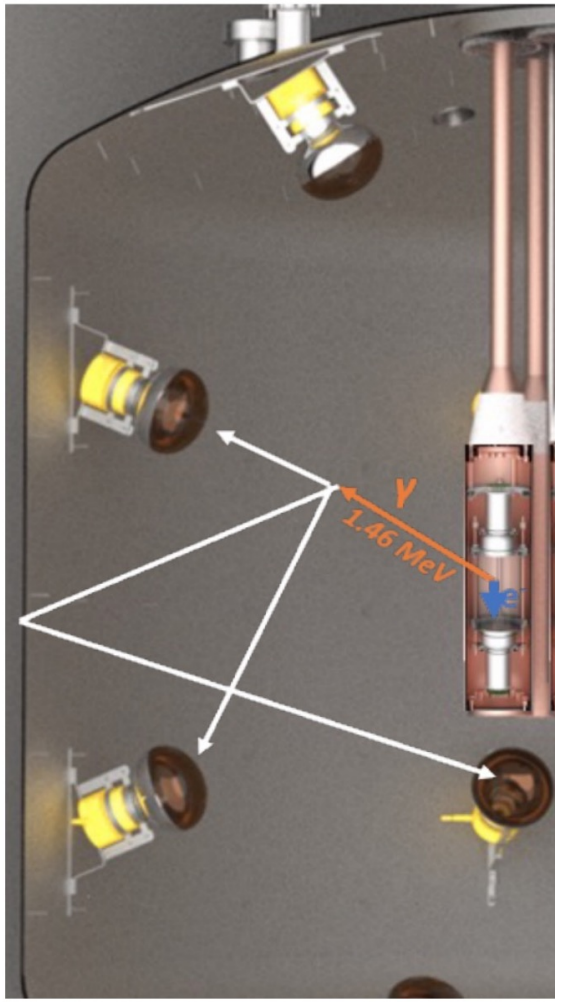


Liquid Scintillator veto

- 12 kL of linear alkyl benzene (LAB) sourced from JUNO experiment.
  - Doped with Bis-MSB and PPO
- Instrumented with 18x (nominally) R5912 PMTs providing 4π coverage.
  - Additional PMTs sourced from Daya Bay are being tested and may be used in the final set-up.

Effective LY [phe/keV]	Background Reduction [%]	
	40K	Total
~0.12	~85	~25

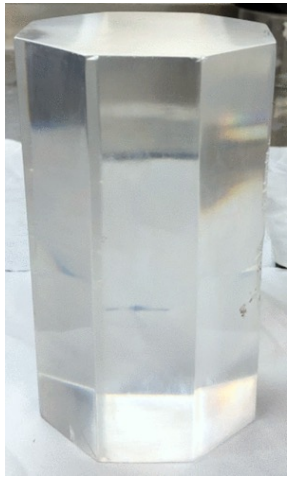




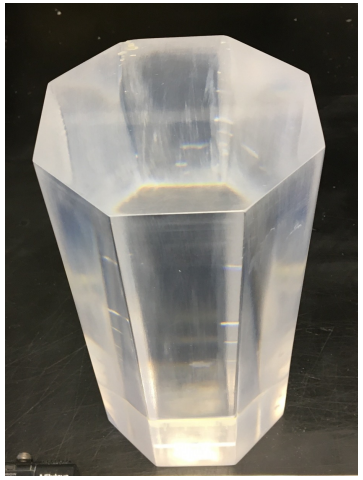
SABRE South crystal production

- Ultra-pure “Astrograde” powder procured from MERCK used for NaI(Tl) crystal growth.

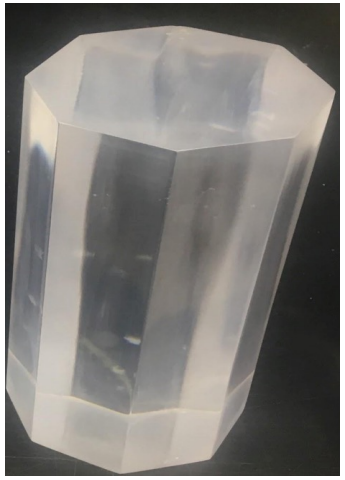
- SABRE South will utilise 7 crystal modules.
  - Encapsulated in Copper & PTFE enclosures
  - Direct coupling between 2xHamamatsu R11065-20 PMTs with the crystal
  - Assembly process being finalized.



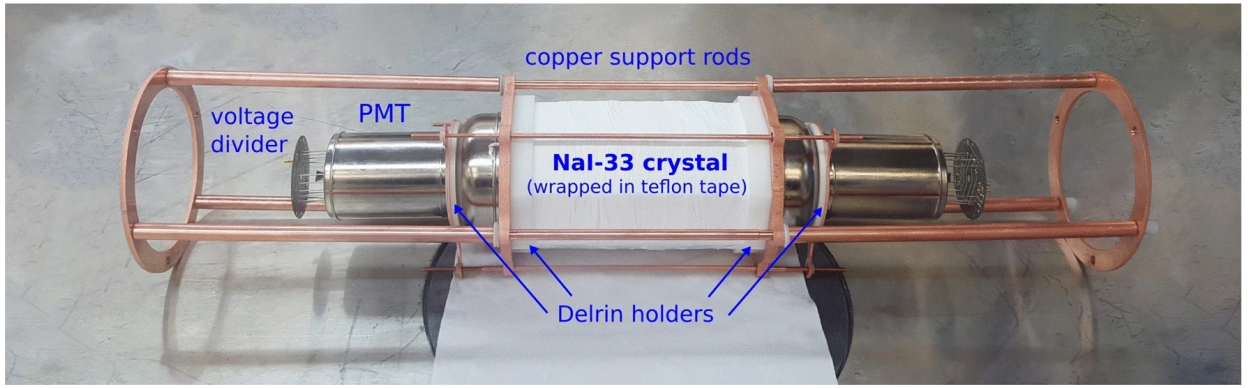
NaI-33



NaI-35



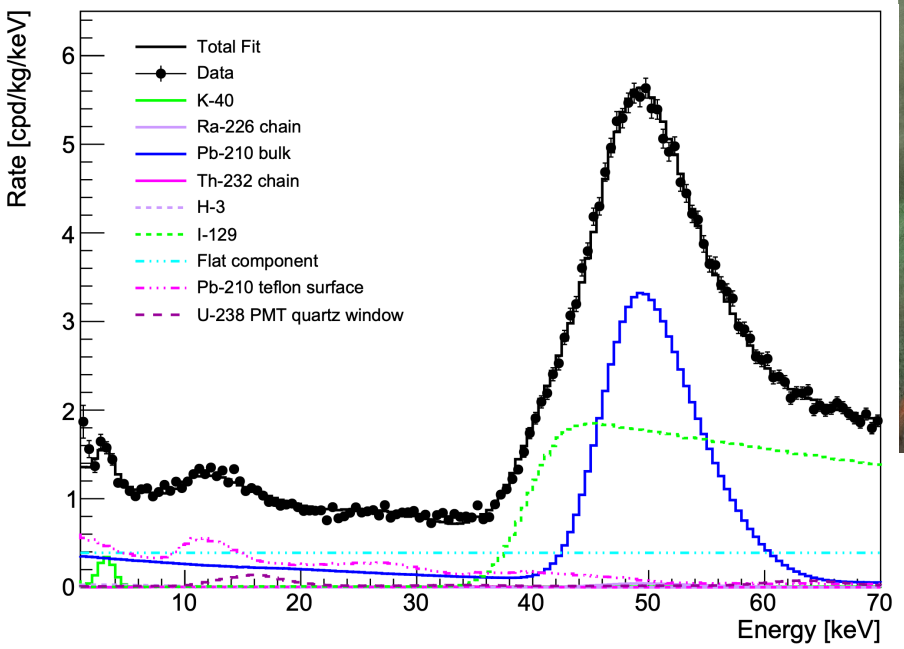
NaI-37



SABRE South Crystal characterisation

- 5x~3.5 kg test crystals have been grown by RMD (and measured by SABRE North)
- Radioactive contaminant levels used to inform the first SABRE South background model

- Target: 50 kg
  - Effective light yield > 10 phe/keV to allow for 1 keV energy threshold
  - Additional characterisations are planned in a steel castle at SUPL

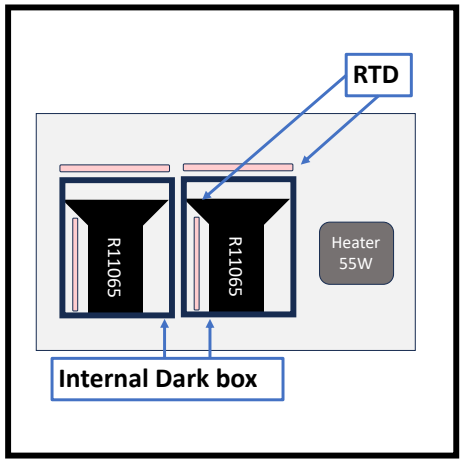


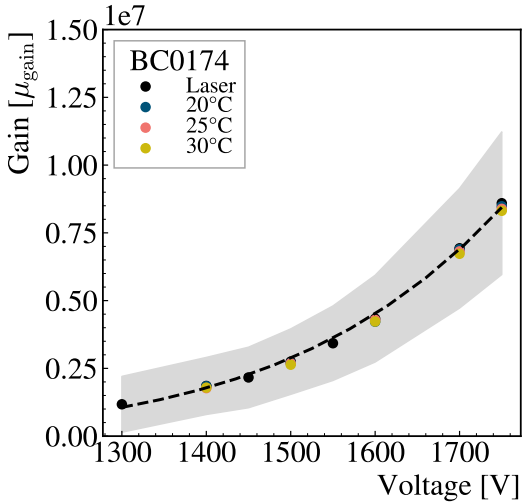
https://arxiv.org/abs/2012.02610

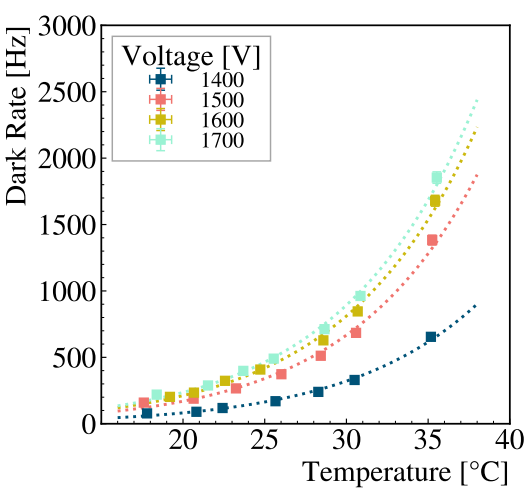
^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)	Active Mass (kg)
4.3 ± 0.8	0.47 ± 0.05	0.40 ± 0.07	0.46 ± 0.01	3.40

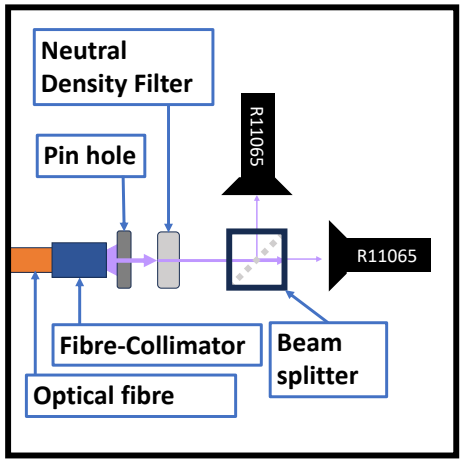
SABRE South PMT Calibration

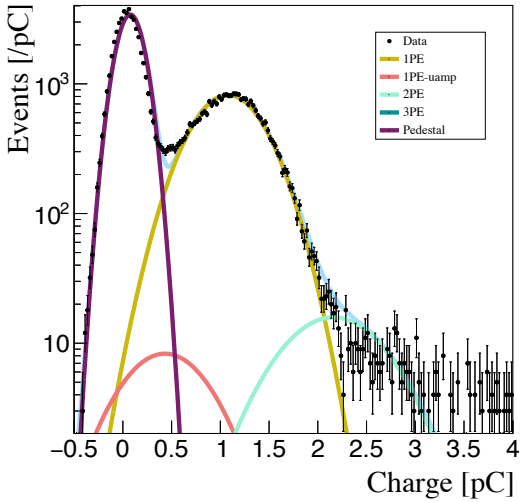
- PMT Characterisation are being conducted, measuring the gain, transit time, dark rate …
  - Needed to accurately model the detector response near the ROI
- Methods explored and verified for in-situ gain tracking.
- Machine learning model being developed to reject PMT noise.
- Detailed waveform simulation being developed to further drive the machine learning development and trigger selection efficiencies.

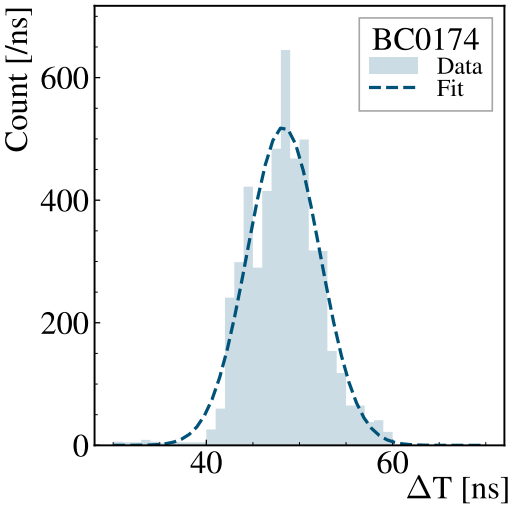




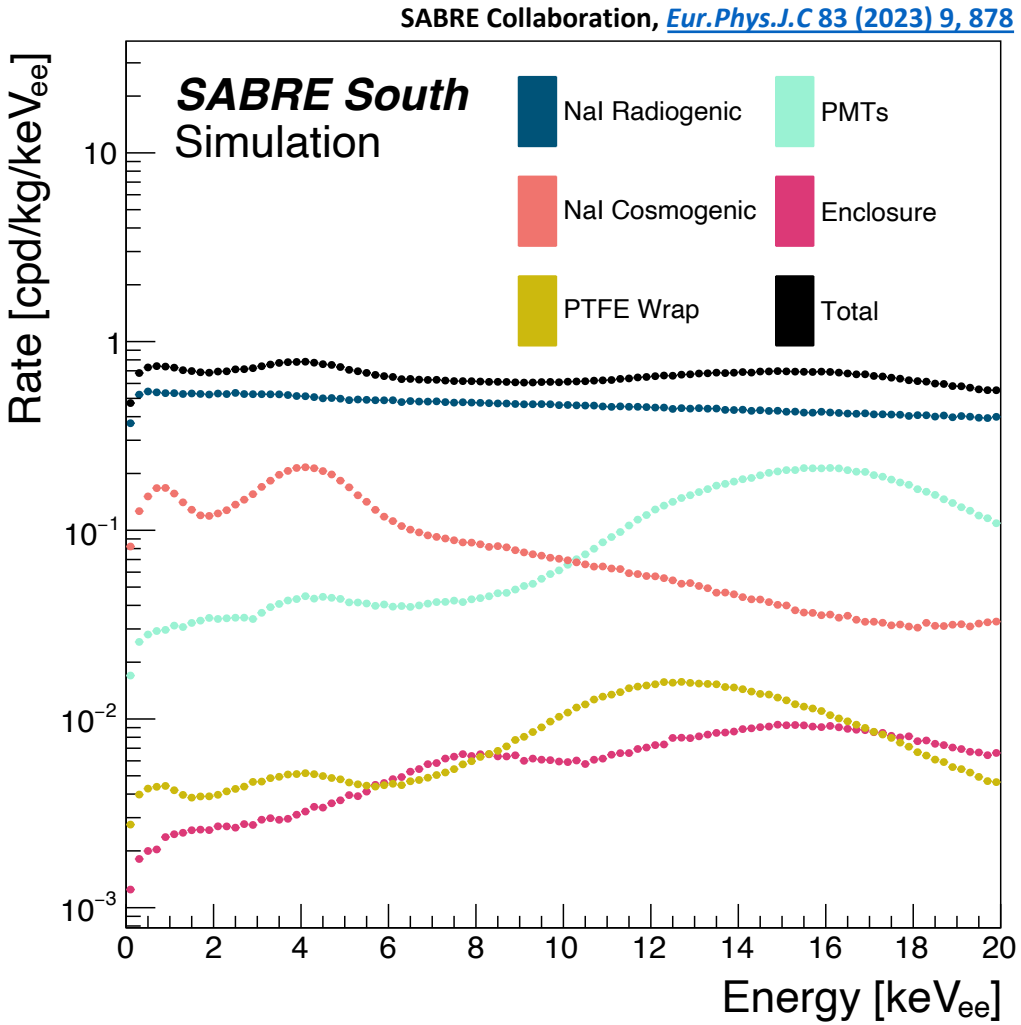








Background Model



- The backgrounds of the experiment was simulated via GEANT4
  - Taking inputs from the characterisation of the NaI-33 crystal
- Cosmogenic background will be reduced by minimizing activation during transport and requiring a 6 month cooldown.
- Background rate: 0.72 cpd/kg/keV
  - 0.52 cpd/kg/keV comes from intrinsic crystal background (Radiogenic)
  - Dominated by 210Pb, 87Rb.
  - 40K contribution tagged by VETO system.
- Development on going for a more detailed simulation framework; detailed detector response, systematic uncertainties and modelling of calibration sources

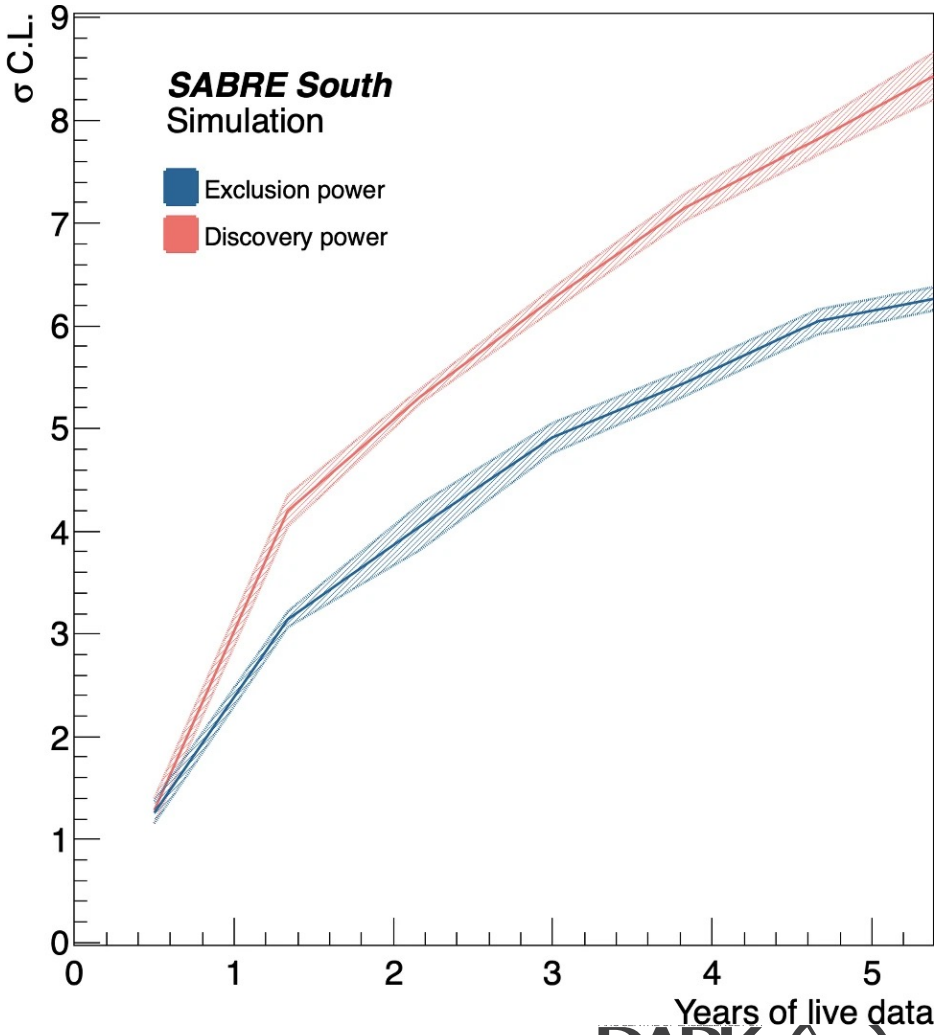
Crystal performance comparison

Crystal	Light yield [PE/keV]	Resolution [σ/E]	Intrinsic Background [cpd/kg/keV]
DAMA	7.6±1.5	6.7% @ 59.9 keV	<0.8
COSINE-100	12.4±1.3	5% @ 59.9 keV	3.5±1.2
ANAIS	14.5±0.1	4.8% @ 59.9 keV	3.6

Projected Sensitivity – Annual Modulations

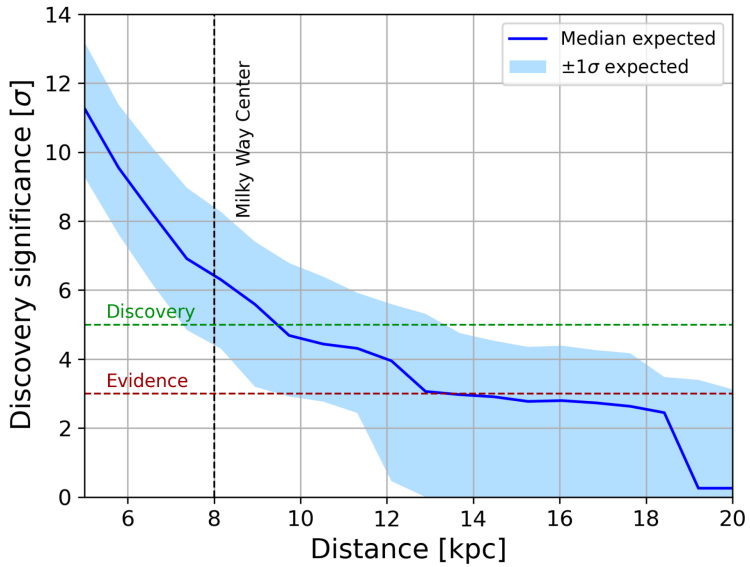
- The SABRE South by itself will be able to provide a 5σ exclusion of DAMA/LIBRA modulation ~2.5 years after data taking begins (~2 years for observation) for a 50kg crystal based on our background model.

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



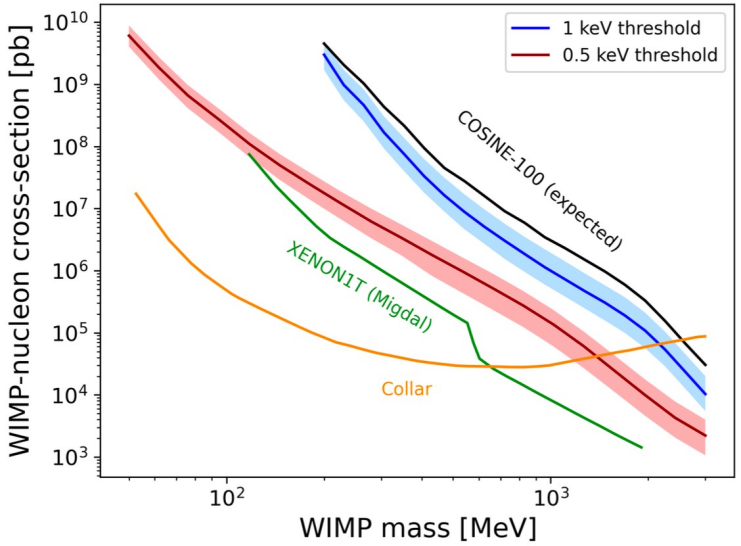
Projected Sensitivity – Non-annual modulations

Super**n**ova **E**arly **w**arning **s**ystems (SNEWS)



- Exploring potential to detect super-nova events, and contribute to the SNEWS network
- Providing 5 $\boldsymbol{\sigma}$ confirmation at up to 10 kpc and 3 $\boldsymbol{\sigma}$ at up to 15 kpc

DM with **Migdal** effect



- Exploring limits from Migdal induced dark matter interactions
- Heavily dependent on sensitivity threshold
- Comparible to COSINE-100

Additional physics programs

From talk by R.James @ Pascos 2024

Further expanding the physics programme

Model	Comments
Boosted DM (inelastic and elastic)	MeV-scale signal: multiple-scatter in the inelastic case. Certain parameter values would enable exploration of unprobed dark photon parameter space
Solar axions	Bragg-Primakoff photoconversion in crystal lattice
Pauli Exclusion Principle violation	Search for exotic nuclear transitions that would only be allowed given a small level of PEP violation. Direct muon hits dominant background, muon veto will aid this search
Upscattered MIDM	Currently has no direct experimental constraints – signal from upscattering of MIDM in the Earth's crust, then a decay into a photon in the detector volume. Scales with volume not mass, so promising channel via the LS veto

SABRE South Techincal design report

Summary

- **The main goal:**
  - Deploy a detector to independently test the observed DAMA/LIBRA signal, taking advantage of the opposite phase in seasonal backgrounds.
  - Focus on ultra-high purity NaI(Tl) detector:
    - Crystal background comparable to DAMA?LIBRA and ~3x smaller than current experiments

- SABRE South is the first dark matter direct-detection experiment in the southern hemisphere and is located inside the new SUPL underground laboratory.
- SABRE South commissioning has started, with measurements of the muon flux.
- Expect observation/exclusion results after about 2/2.5 years of continuous operation (with a single site).

The SABRE South Collaboration : Thank you!

Papers
SABRE South Technical Design Report
SABRE South TDR Summary [ETA: End of Oct]
SABRE South background simulation
The DAMA/LIBRA signal ? An Induced modulation effect
The Calibration of the SABRE South Hamamatsu R11065-20 PMTs [ETA: End of Oct]
The SABRE South VETO R5912 PMT bulk calibration

2023 CM @ University of Adelaide

KEK-JAPAN

SWINBURNE

THE UNIVERSITY OF MELBOURNE

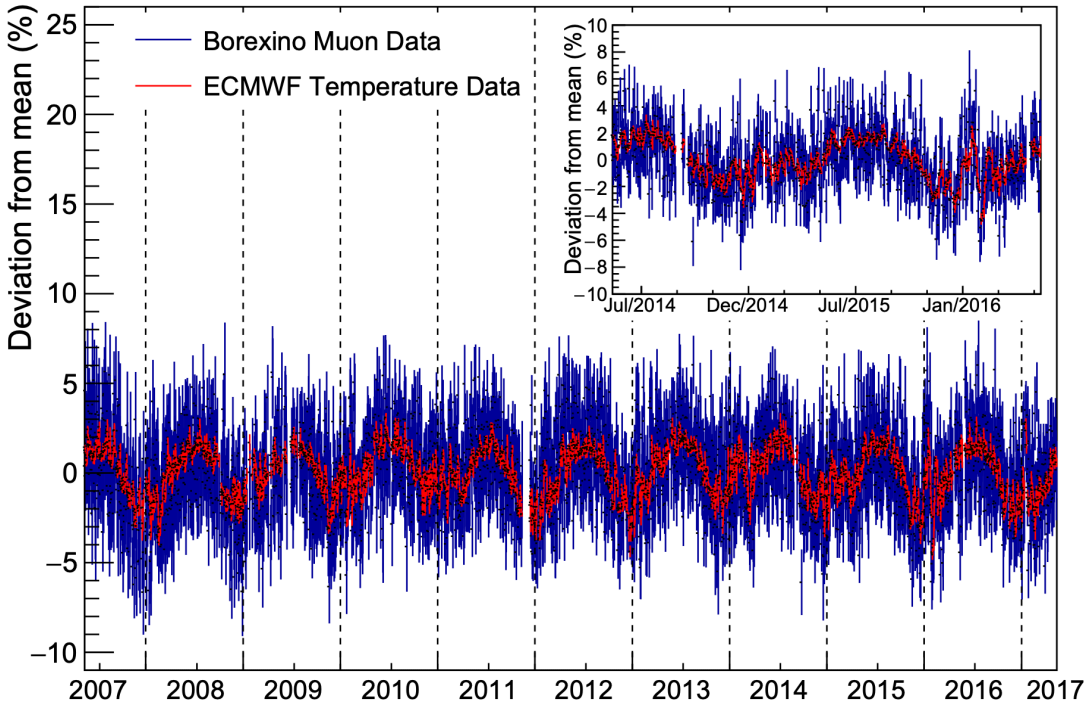
THE UNIVERSITY OF SYDNEY

THE UNIVERSITY of ADELAIDE

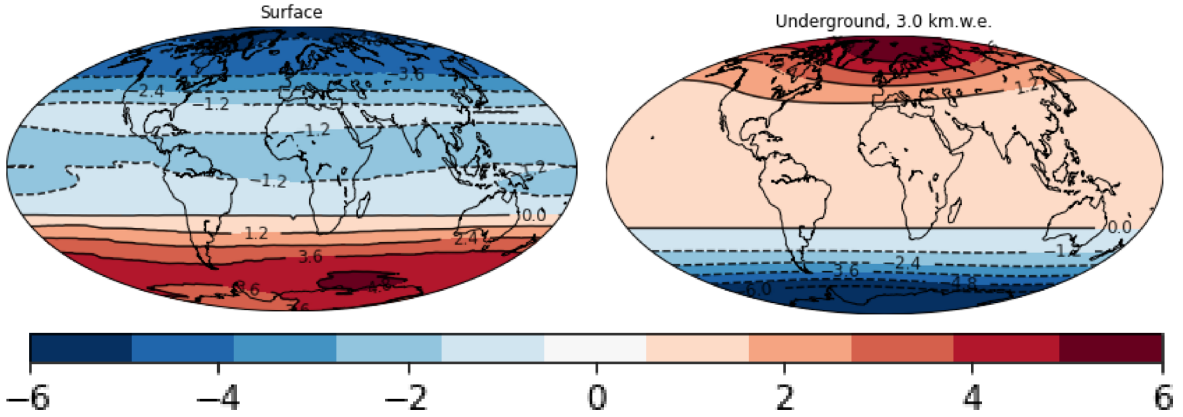
Australian National University

Exclusion of seasonal effects

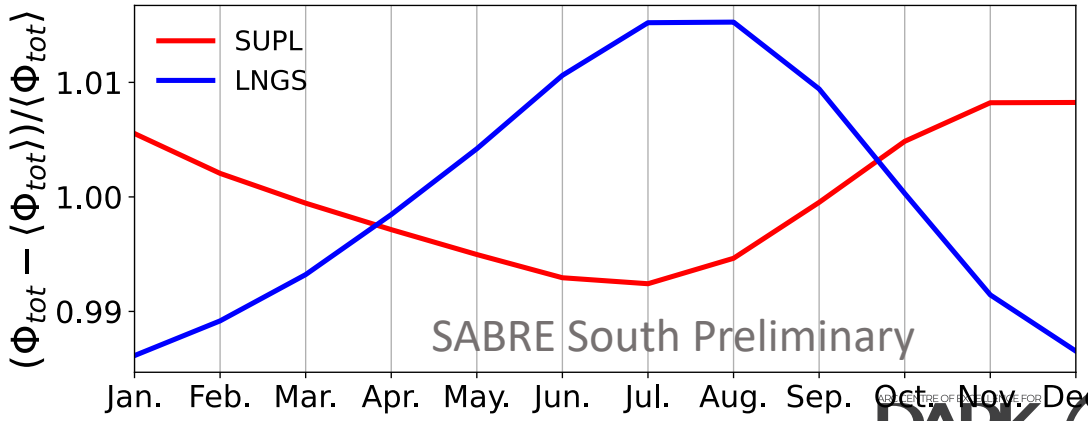
- The site in the northern and southern hemisphere is important to exclude seasonal effects.
- Muons are particular issues for the DM modulation search as they have similar seasonal phase due to seasonal dependance.



Borexino collab. JCAP02(2019)046

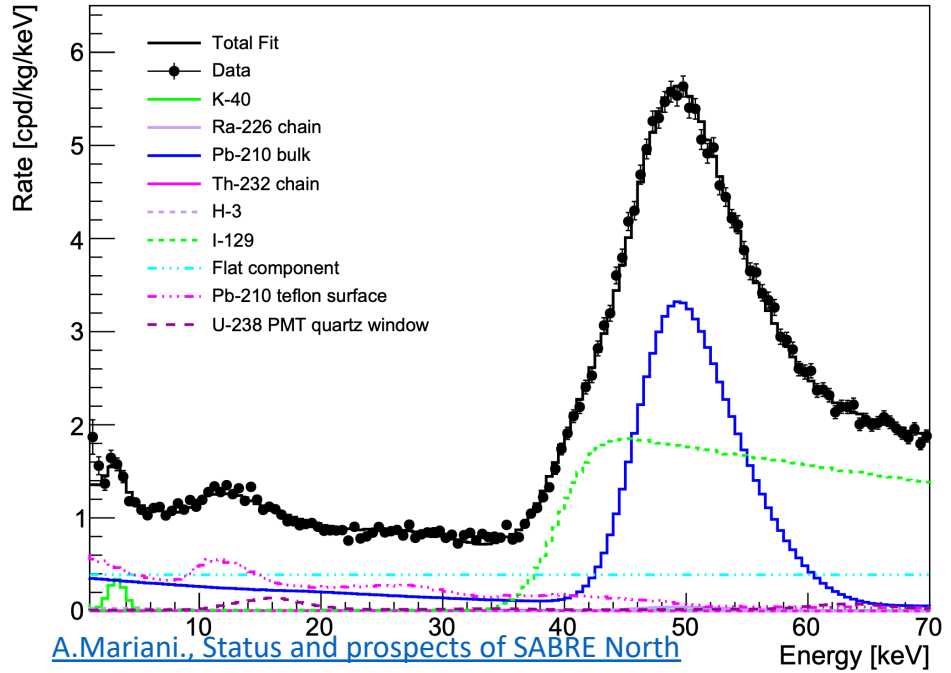


W.Woodley et al, PoS(ICRC2023)476



High-purity NaI(Tl) crystals

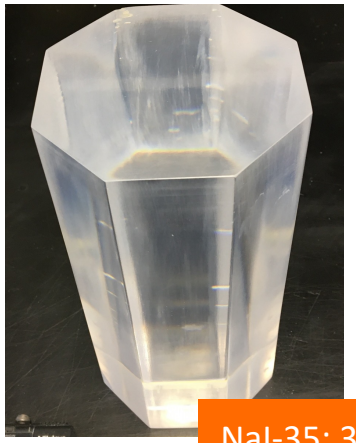
- Ultra-pure Astrograde NaI powder from R&D with Merck.
- High-purity, low background crystals are being grown in collaboration with Princeton and RMD and SICCAS.
- Four crystals have been tested at LNGS.
- Light yield 9-12 phe/keV.



A.Mariani., Status and prospects of SABRE North

Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)	Active Mass (kg)
DAMA [1]	13	0.7-1.0	(5-30)x10^{-3}	0.5-7.5	250
ANAIS [2]	31	<0.81	1.5	0.36	112
COSINE [3]	35.1	<0.12	1-1.7	<2.4	~60
SABRE [4]	4.3	0.4	0.49	0.2	~35+40=75 (total goal)
PICOLON [5]	<20	-	<5.7x10^{-3}	-	~20 (goal)

NaI-33: 3.40 kg

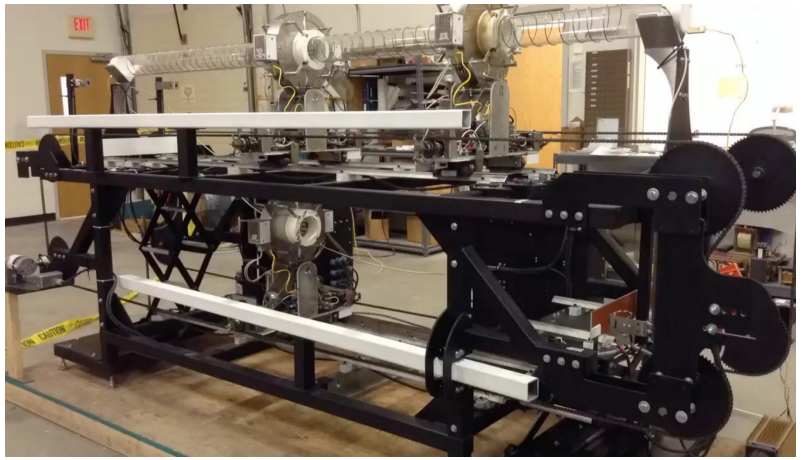


NaI-35: 3.72 kg

[1] R. Bernabei et al., NIMA 592(3) (2008)
[2] J. Amare et al., EPJC 79 412(2019)
[3] P. Adhikari et al., Phys. Rev. Lett. 123, 0.31302 (2019)
[4] B. Suerfu et al., Phys. Rev. Research 2, 013223 (2020)
[5] K. Fushimi et al., PTEP 4 043F01 (2021)

High-purity NaI(Tl) – Zone Refining

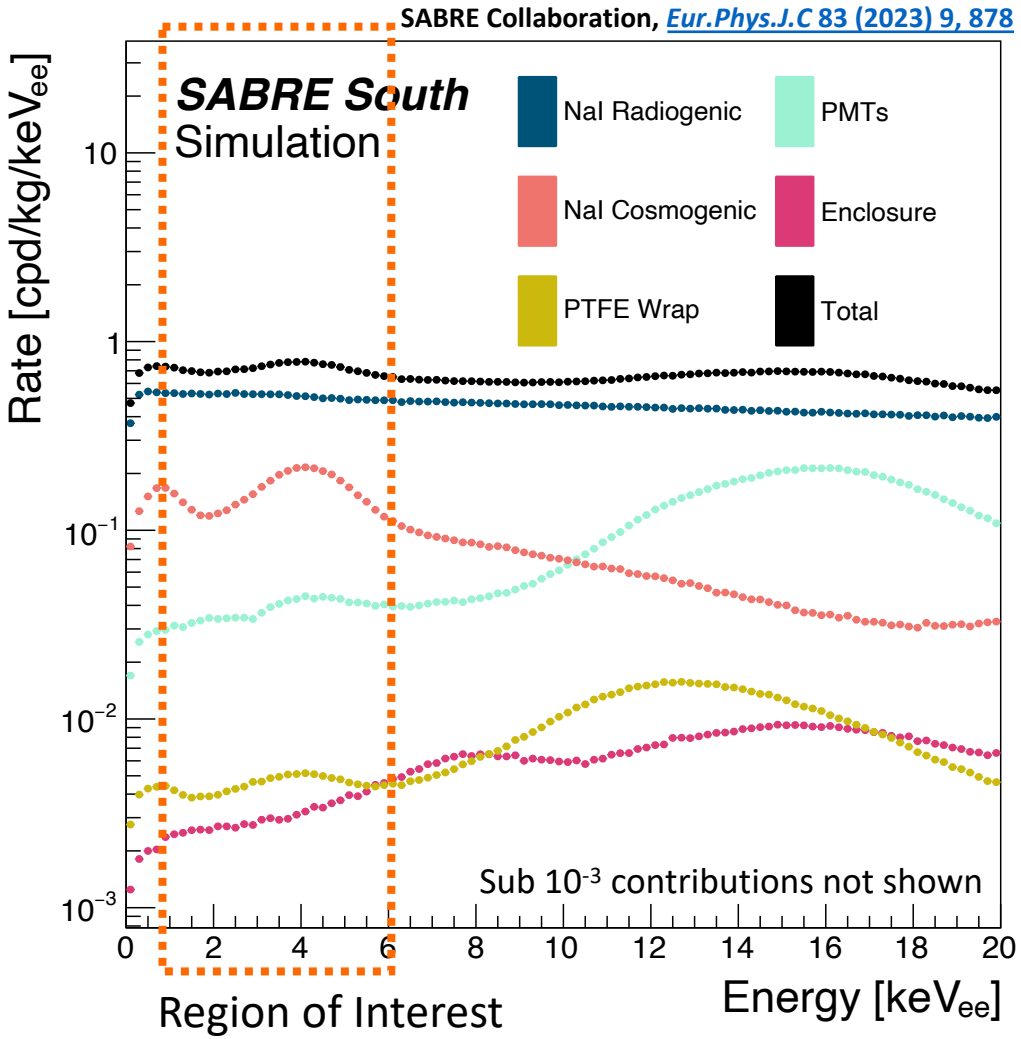
- Strategic and unique to the SABRE project is the zone refinement of the crystal powder prior to growth.
- Zone refining 100 kg of crystal powder prior to crystal growth has been built in collaboration with MELLEN.



- Impurities are pushed to the end of the refining tube and are then removed. Reduction factors of:
  - ^{40}K: 10 – 100
  - ^{87}Rb: 10 - 100
  - ^{210}Pb: 2
- Used at RMD to prepare a final test crystal

Isotope	Impurity concentration (ppb)					
	Powder	Sample Location (mm)				
		7±7	325±9	492±10	635±20	783±30
^{39}K	7.5	< 0.8	< 0.8	1	16	460
^{85}Rb	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.7
^{208}Pb	1.0	0.4	0.4	< 0.4	0.5	0.5
^{65}Cu	7	< 2	< 2	< 2	2	620
^{133}Cs	44	0.3	0.2	0.5	23.3	760
^{138}Ba	9	0.1	0.2	1.4	19	330

Total Background Model – VETO



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 Performance

cpd/kg/keV per mBq/kg	^{40}K	^{85}Kr	^{87}Rb	^{210}Pb	^{232}Th	^{238}U
1-6 keV no veto	65.0%	19.1%	69.5%	68.1%	25.0%	96.3%
1-6 keV with veto	9.5%	19.1%	69.5%	68.1%	21.6%	92.1%
Veto efficiency	85.4%	0.0%	0.0%	0.0%	13.3%	4.3%

SABRE Mechanism