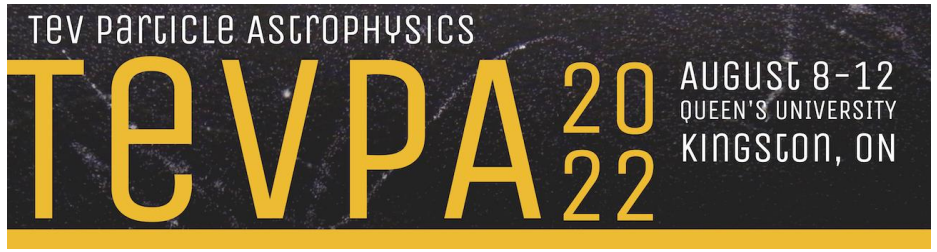
The SABRE South Experiment

at the Stawell Underground Physics Laboratory

William Melbourne on behalf of SABRE South



SABRE – a dual site experiment

SABRE (Sodium iodide with Active Background REjection) is an independent replication of DAMA/LIBRA with dual detectors in both hemispheres.

SABRE South - at the Stawell Underground Physics Laboratory (SUPL)

SABRE North - at the Gran Sasso National Laboratory (LNGS)

SABRE Proof of Principle in Hall C, LNGS

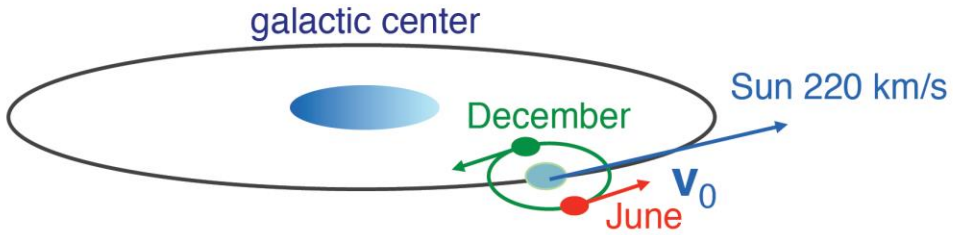
Experiments share:

- Same NaI(Tl) detector module with Ultra-pure crystals
- Common simulation, DAQ and analysis framework
- Extensive joint engineering efforts between INFN and CDMPP

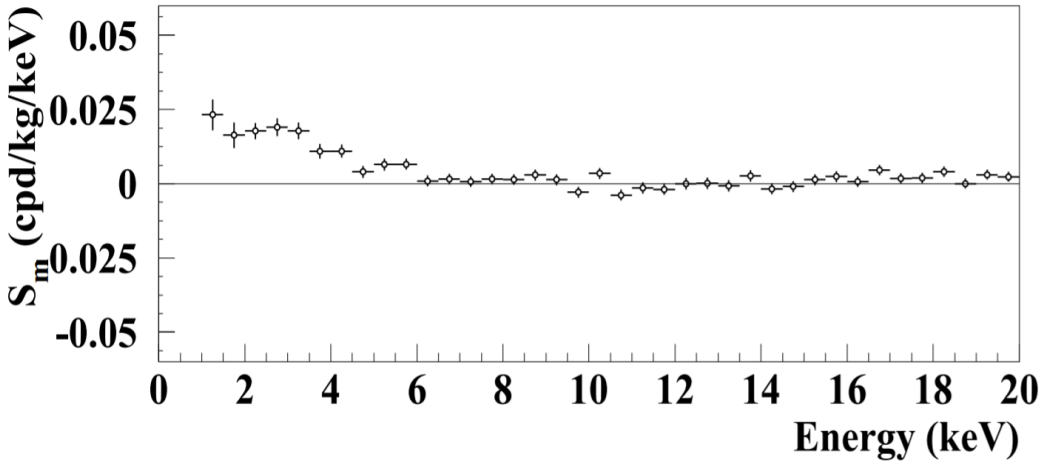
Divergence on veto/shielding designs due to restriction of liquid organic scintillators at LNGS

Annual Modulation & DAMA/LIBRA

Unique model independent signal for dark matter caused by relative motion of the earth through galactic halo



$$R = R_0 + S_m \cdot \cos\left(\frac{2\pi(t - t_p)}{1\ yr}\right)$$

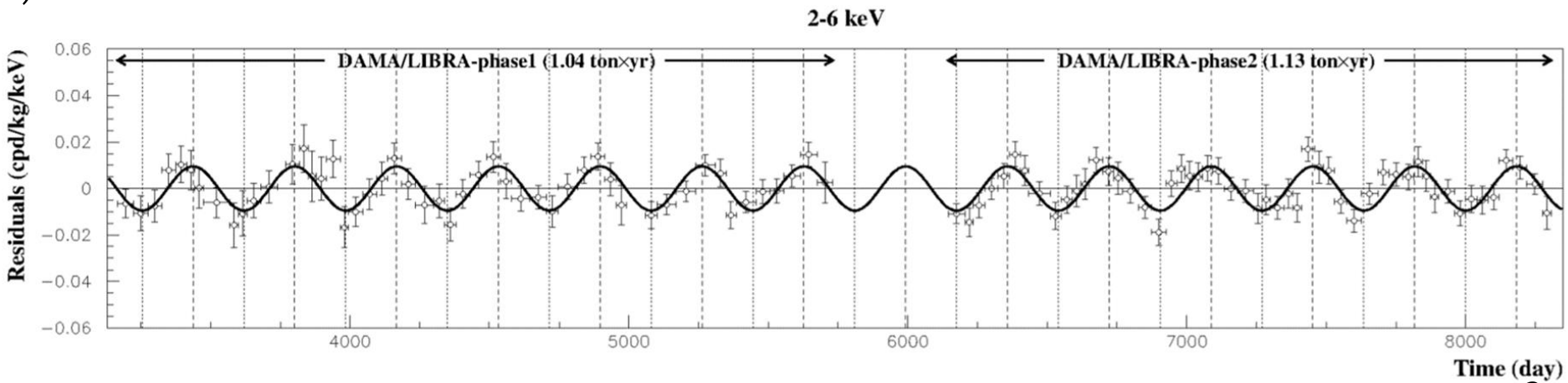


DAMA has a 20-year record of the modulation in the 2-6 keV energy range with combined significance of 12.9 σ

R. Bernabei, et al. "First model independent results from DAMA/LIBRA–phase2." *Universe* 4.11 (2018): 116.

Modulating Signal signatures:

- Period of one year
- Peaks on June 2nd ($t_p = 152.5\ days$)
- $S_m/R_0 \approx 0.01 - 0.03$

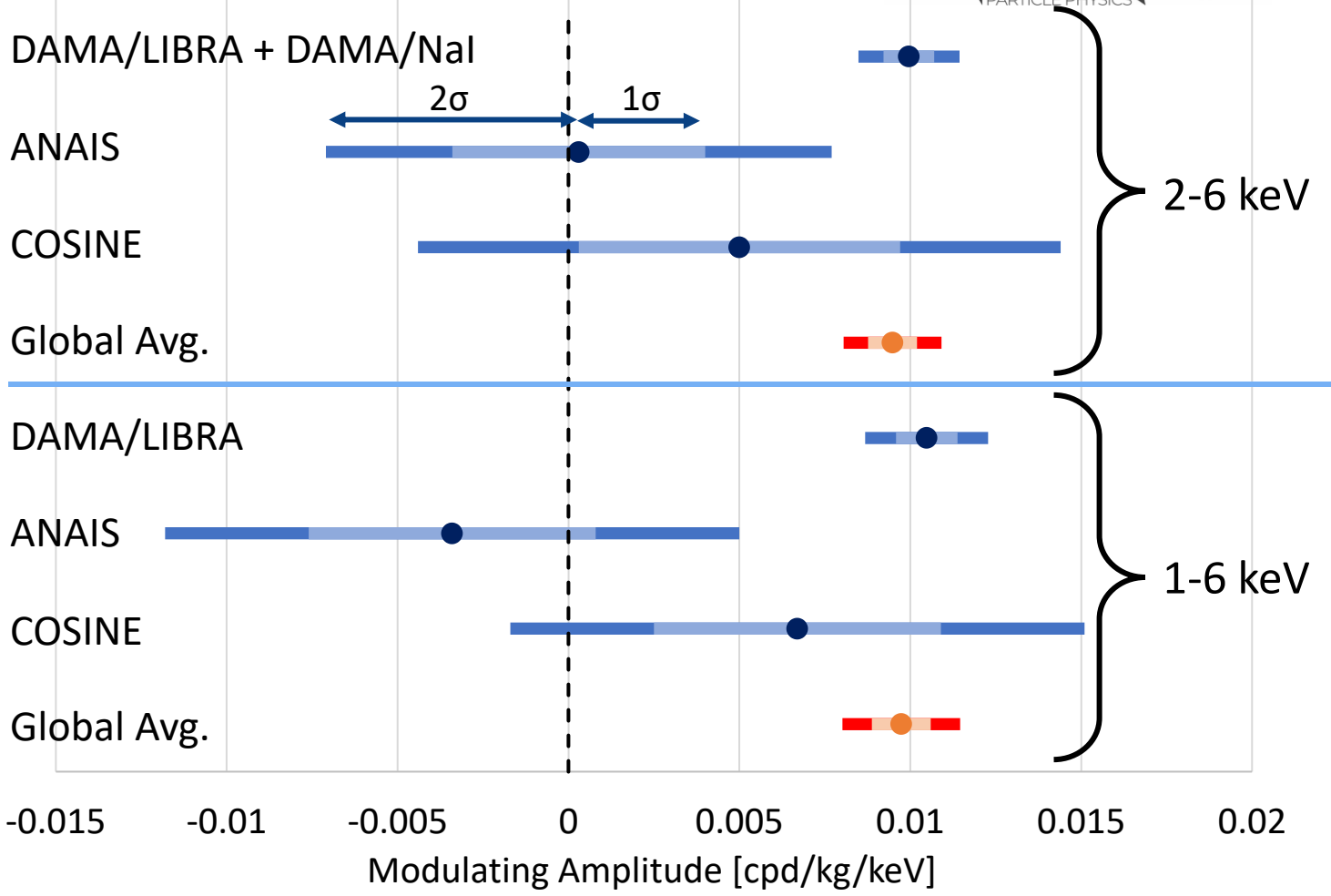


Recent result & Global Average

ANAIS: 110 kg of NaI(Tl) with muon veto at Canfranc underground laboratory (Spain).
Background: ~3-4 dru,
Exposure: 314 kg x yr.
Phys.Rev.D 103 (2021) 10, 102005

COSINE100: 100 kg of NaI(Tl) with veto system at Yang Yang underground lab (Korea).
Background: ~3 dru,
Exposure: 173 kg x yr.
Arxiv:2111.08863

2-6 keV Global Avg.	R_{mod}	0.0095 ± 0.0007
	χ^2/n_{dof}	7.6/2
	p	2.2%
1-6 keV Global Avg.	R_{mod}	0.0097 ± 0.0009
	χ^2/n_{dof}	11.0/2
	p	0.4%

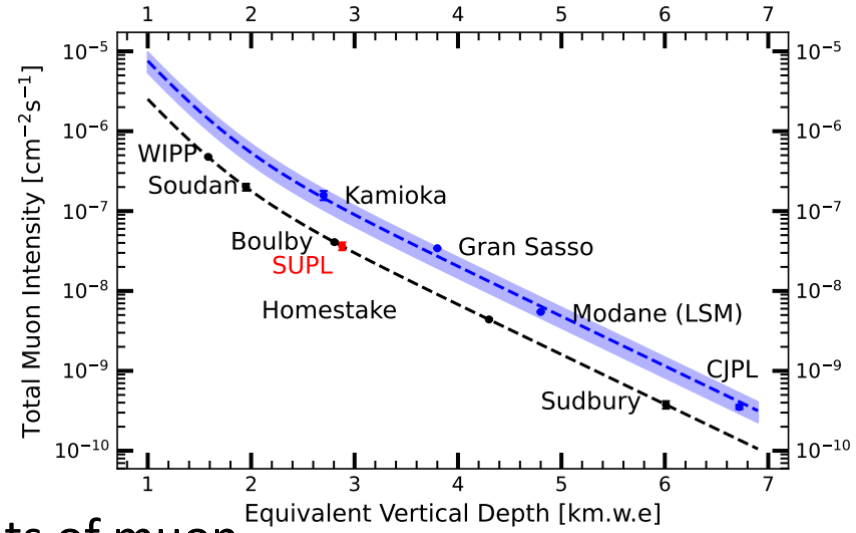


Global fit shows tension(<3σ) between DAMA and ANAIS.
Neither ANAIS or COSINE have significant discovery or exclusion of DAMA.
Motivates additional low-background search in Southern Hemisphere

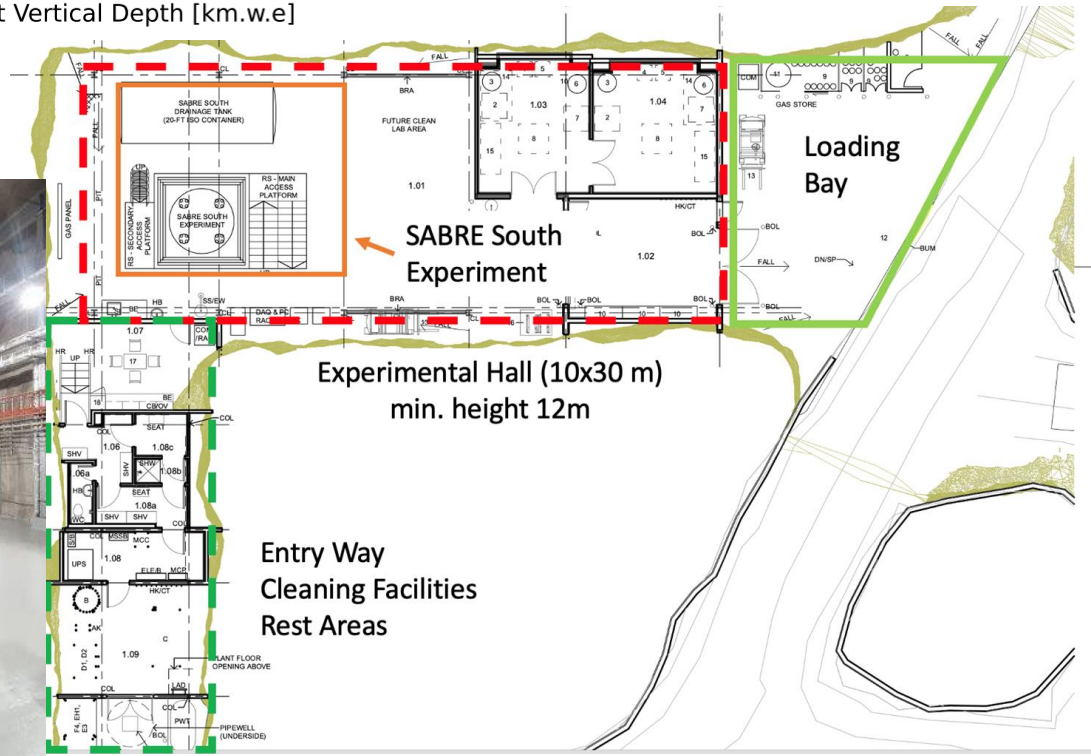
Stawell Underground Physics Lab

SUPL is the first deep underground lab in Southern Hemisphere (37° South).
1025 m below the surface with flat overburden (2900 mwe).

Lab construction finished and lab handed over to managing company.



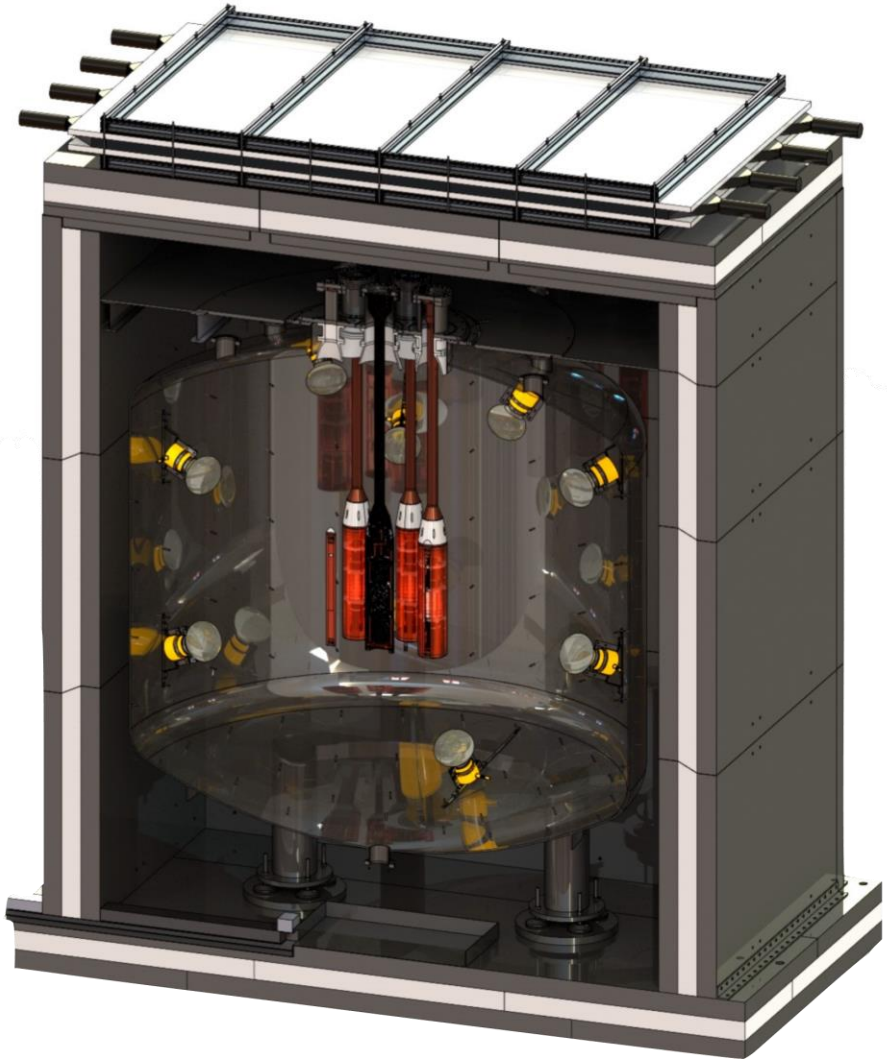
SABRE South will make detailed measurements of muon, neutron, and gamma backgrounds later this year



SABRE South

Key features of SABRE South:

- Southern hemisphere location
- Ultra-low background crystals
- Active veto system
- 1 keV energy threshold (1-6 keV R.o.I.)
- Particle ID, Localisation, & Directionality capability for backgrounds

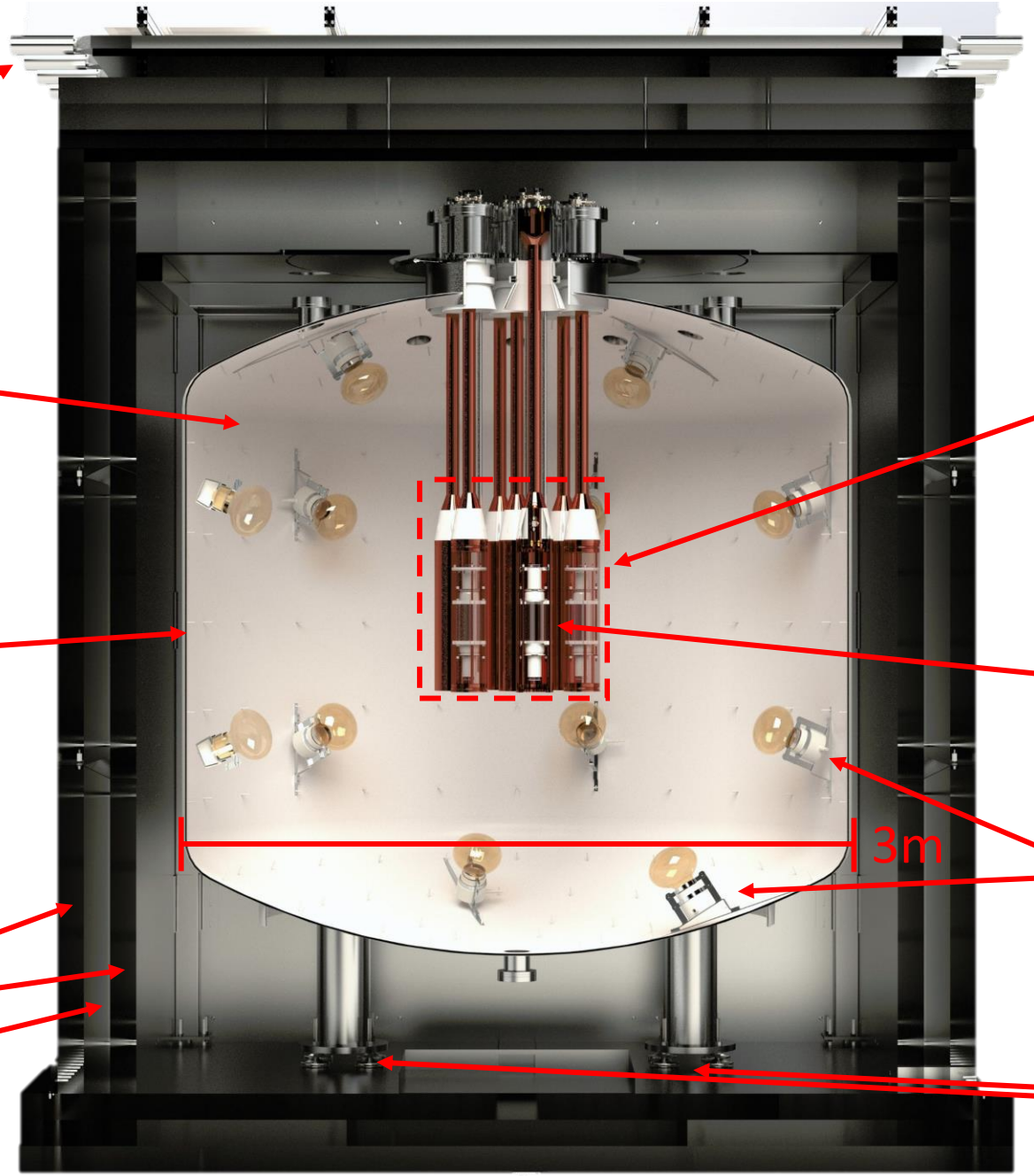


Muon Veto
(9.6 m² array)

12,000 L
LAB with
PPO & Bis-MSB

Veto Vessel
Stainless-Steel
Lumirror coating

External Shielding
Steel
Polyethylene



Crystal Array:
- NaI(Tl) crystal
- 2x 76mm R11065 Hamamatsu PMTs

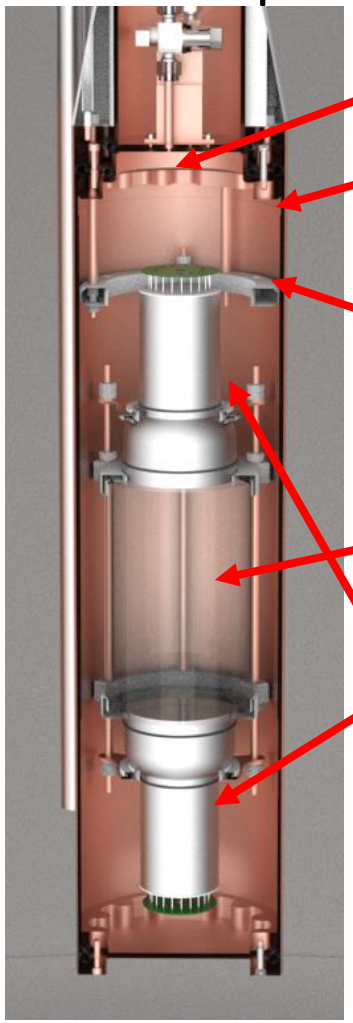
Calibration Sources

Veto PMTs
18xHamamatsu R5912

Passive Damping System

NaI(Tl) Detectors

Array of 7 NaI(Tl) detectors immersed in the liquid veto, Minimal material between crystal and liquid scintillator. NaI(Tl) purged with high purity dry N_2.



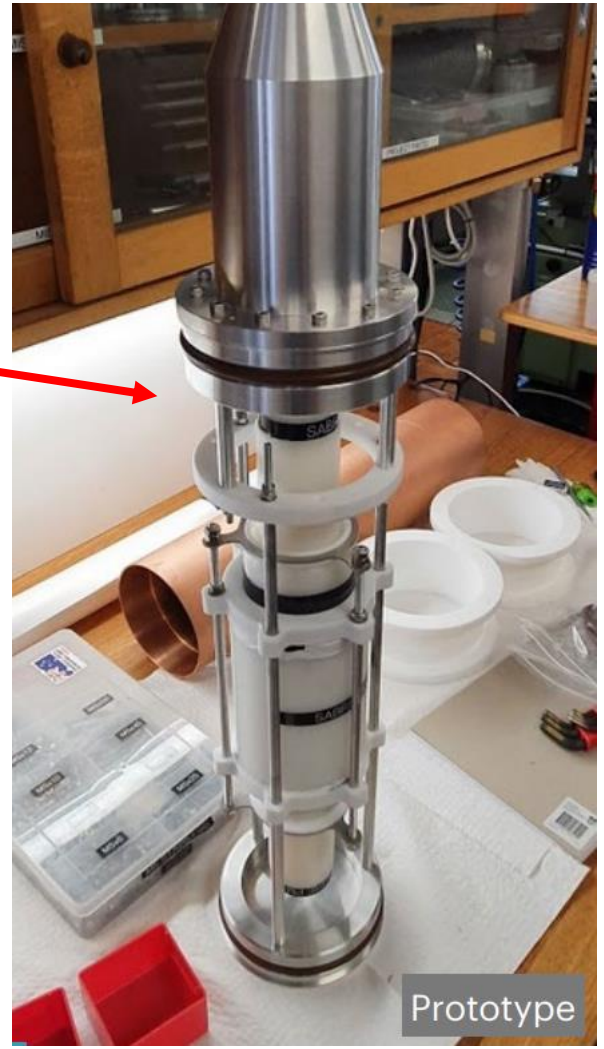
Feedthrough Plate

OFHC Copper Enclosure
3 mm wall thickness
Internal Teflon structure

~**7** kg NaI(Tl) Crystal
L.Y. ~ 12 PE/keV

76mm Hamamatsu R11065 PMT:
-Low background metal body
-QE >30% at 420 nm
-Readout at 500 MS/s with CAEN V1730
-Threshold ~0.3 SPE peak

Prototype enclosure machined from Al for testing



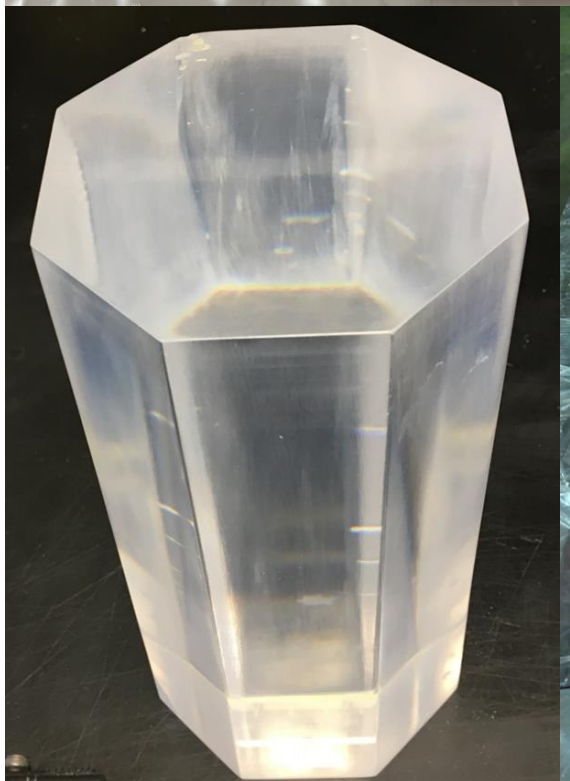
Low Background NaI(Tl) Production

The SABRE Collaboration has successfully grown very low background NaI(Tl) crystals [1].

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

SABRE South test crystal "NaI-35" – 3.7 kg grown by RMD using Bridgman-Stockbarger process developed with SABRE. ICPMS measured K: tip 5 ppb, bulk <10 ppb.

Currently being characterised at LNGS, preliminary results are comparable with NaI-33 for key backgrounds and light yield. Approx. light yield of 11.6 Photoelectrons/keV



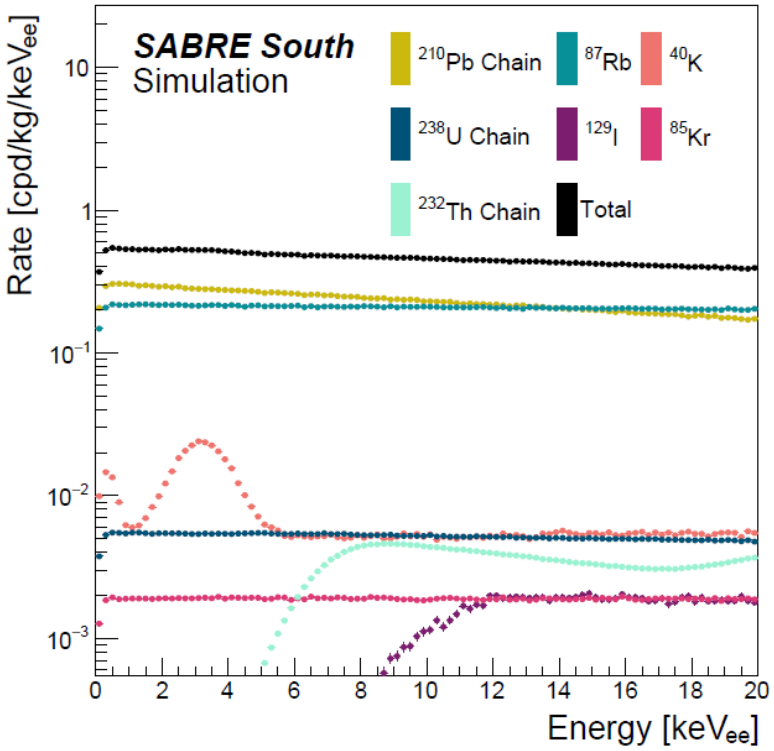
[1] – M. Antonello, et al.," Characterization of SABRE crystal NaI-33 with direct underground counting." *Eur. Phys. J. C* 81, 299 (2021)
[2] – R. Bernabei, et al. "The DAMA/LIBRA apparatus." Nucl. Instrum. Methods Phys. Res. A: 592.3 (2008): 297-315.
[3] – G. Adhikari, et al. "Initial performance of the COSINE-100 experiment." The European Physical Journal C 78.2 (2018): 1-19.

NaI(Tl) Background Simulation

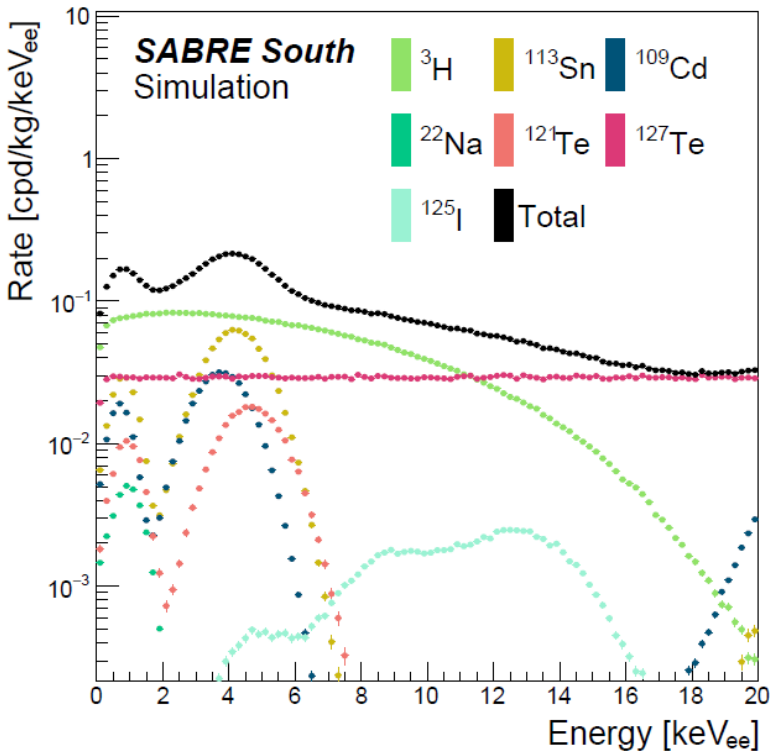
Using direct counting of NaI-33 and ICP-MS, have simulated background of SABRE South crystals.

^{40}K effectively suppressed by veto, main radiogenic background are ^{210}Pb, ^{87}Rb (very conservative upper limit)
Cosmogenic background after 180 days mainly ^{3}H (12.4 yrs) and ^{113}Sn (115 days)

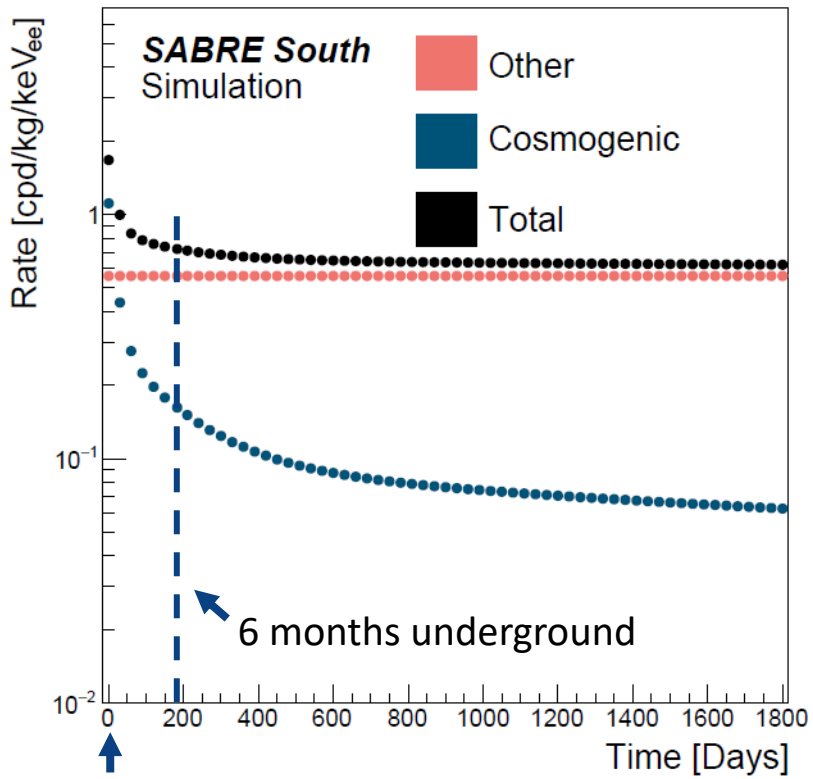
Radiogenic Background



Cosmogenic Background
(6 months underground)



Time Dependence of Background

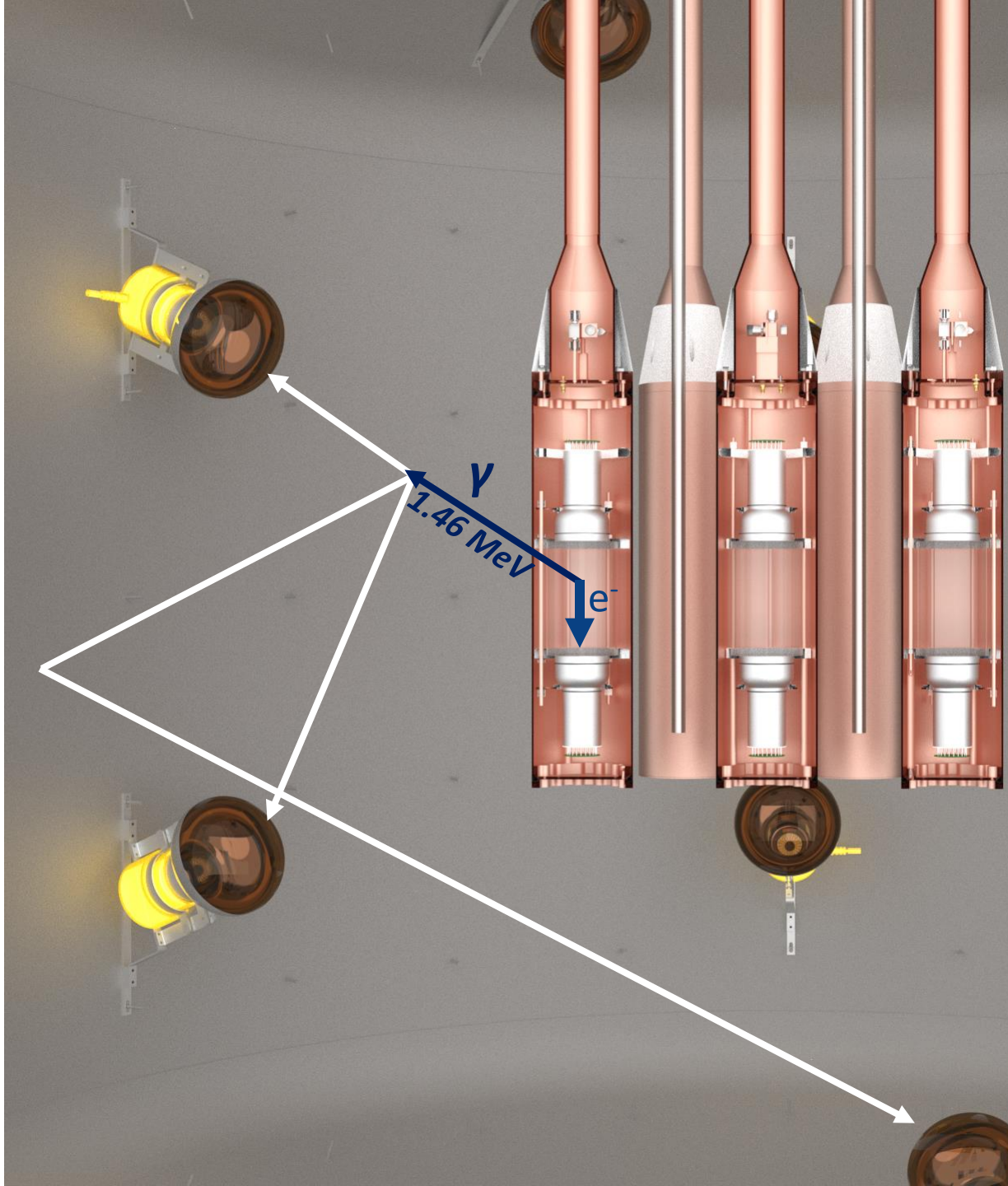


Active Veto System

Veto system provides 4π coverage of NaI(Tl) detectors. Primary purpose is ^{40}K veto

Liquid scintillator veto:

- 12,000 L of Linear Alkyl-Benzene (LAB) doped with PPO and Bis-MSB.
  From JUNO supplier
- 18 Hamamatsu R5912 PMTs with oil-proof base. Readout at 500 MS/s (CAEN V1730)
- Expected Light yield 17 PE/100 keV



Active Veto System

The active veto is designed to:

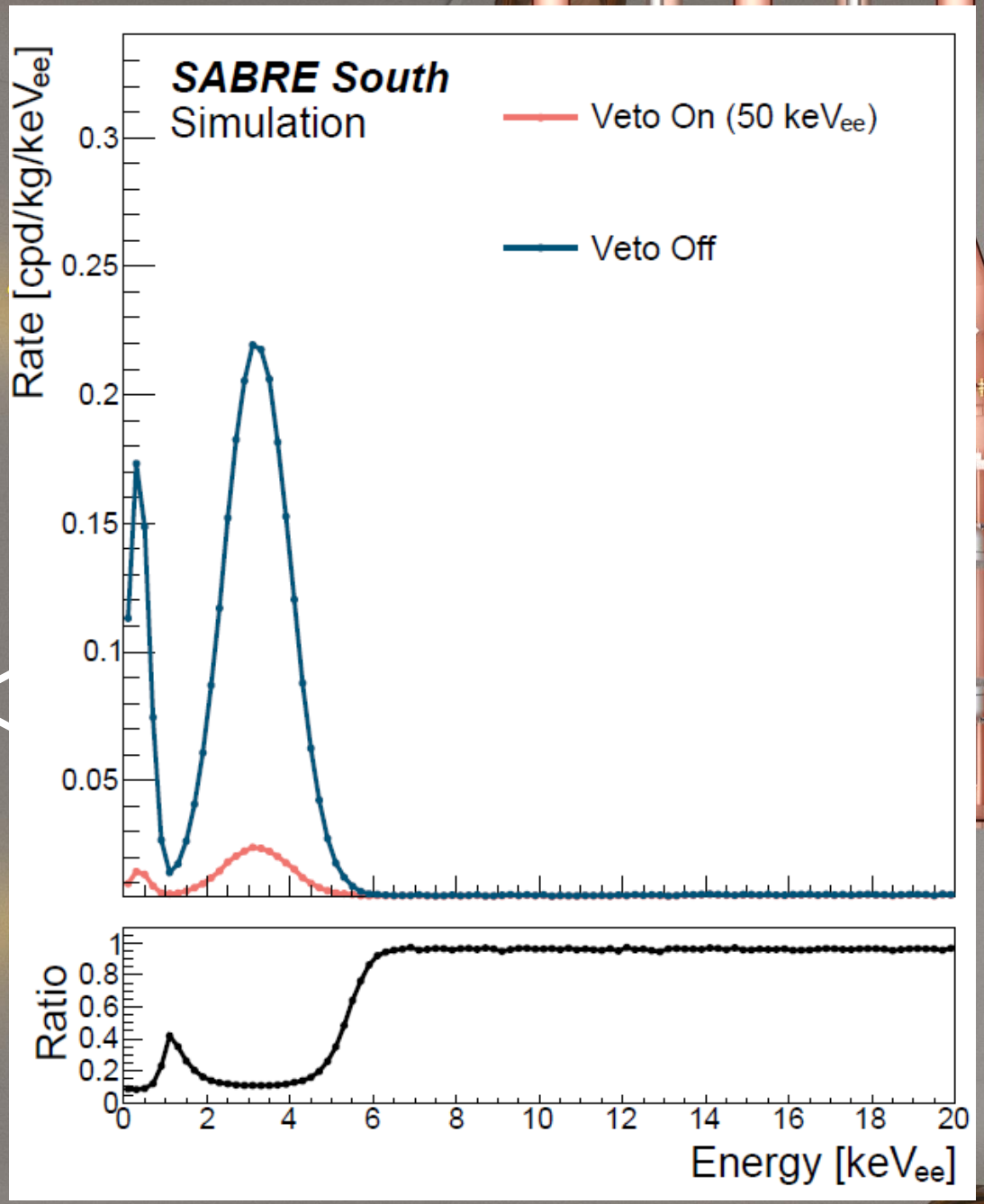
- Veto ^{40}K decays in NaI(Tl) with >85% efficiency.
- Be sensitive to >50 keV energy deposition

This reduces some key backgrounds by factor 10, including some cosmogenics.

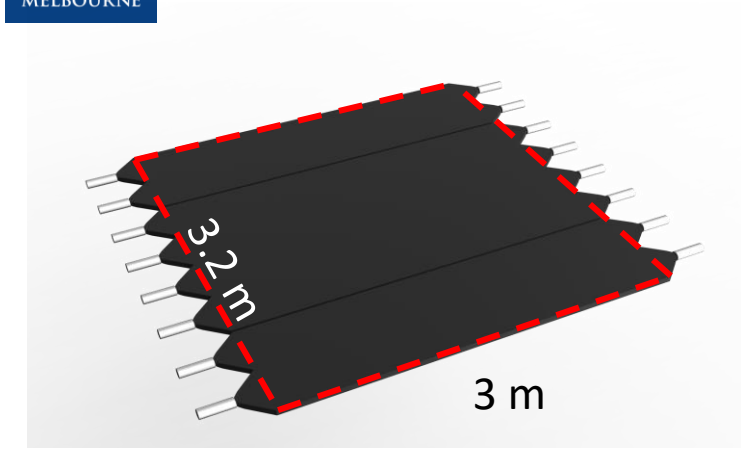
Veto trigger on coincident single photons in 2+ PMTS so actual threshold likely to be lower.

Veto performance position dependent.

Makes exact threshold complex, requires simulation digitisation to study precisely.



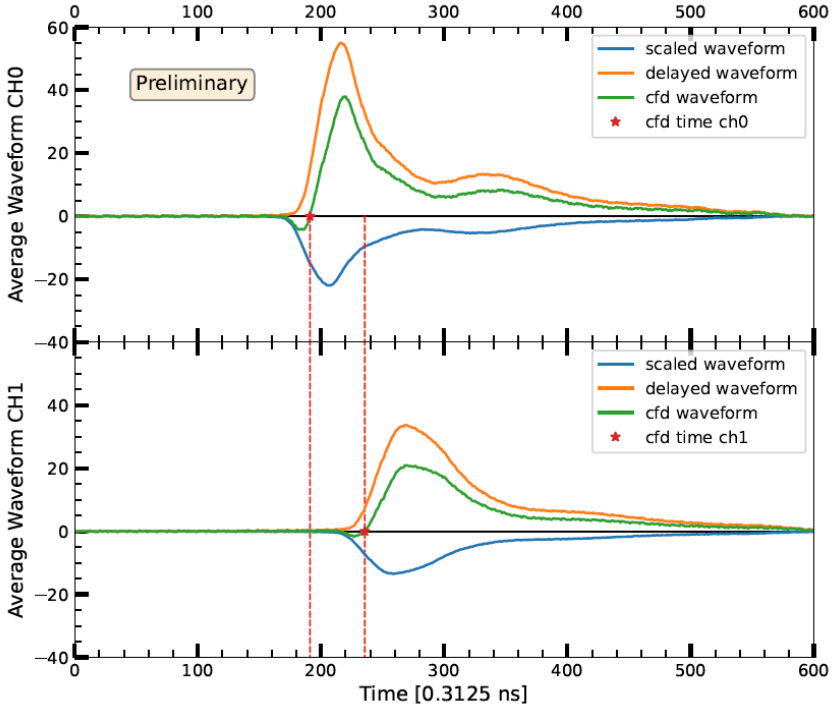
Muon Veto System

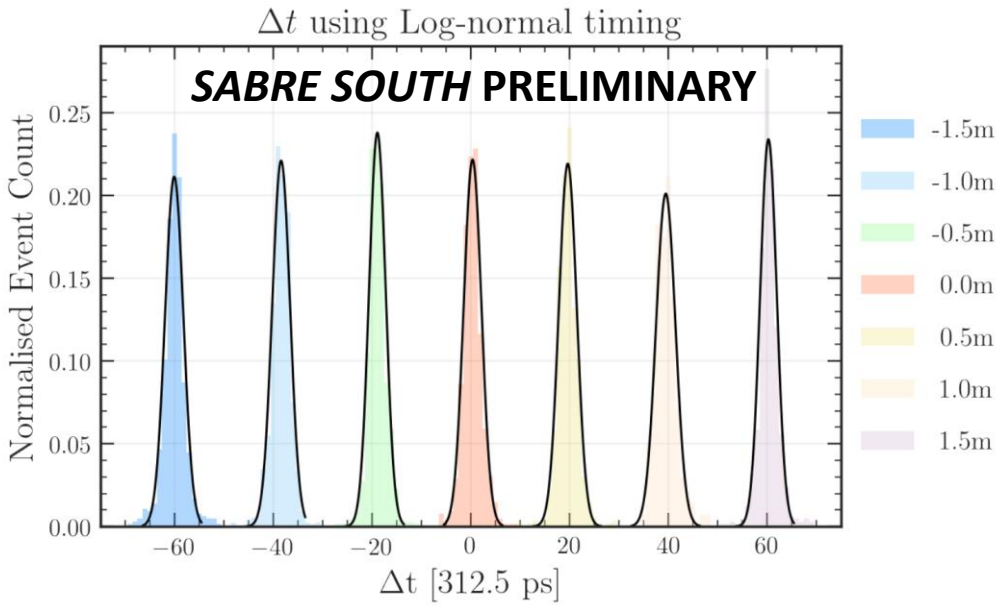


Provides additional tagging of cosmic muons, and measurements of muon modulation at SUPL (with LS veto)

8 x EJ200 organic scintillator panels (3x0.4x0.05 m) with PMTs at opposite ends. Readout at 3.2 GS/s which gives longitudinal position resolution of 3.2 cm using CFD trigger.

Will be used to improve particle ID and localisation in LS Veto





Each panel is being characterised for timing and efficiency on surface

Background Simulation

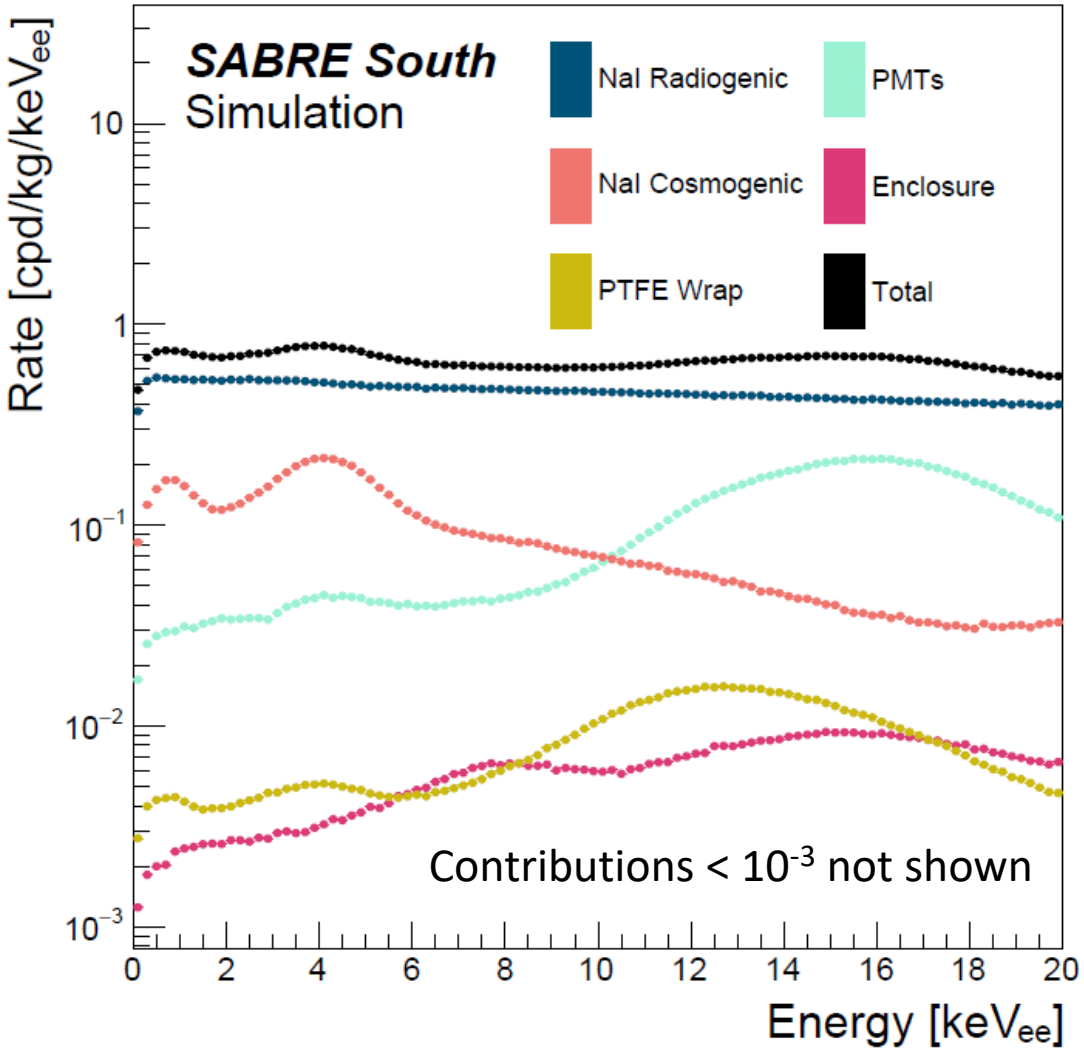
Total experimental radioactive background has been simulated (arXiV:2205.13849).

We expect an overall background of **0.72 cpd/kg/keV$_{ee}$**

Dominated by NaI background (radiogenic and cosmogenic) with ^{40}K effectively suppressed.

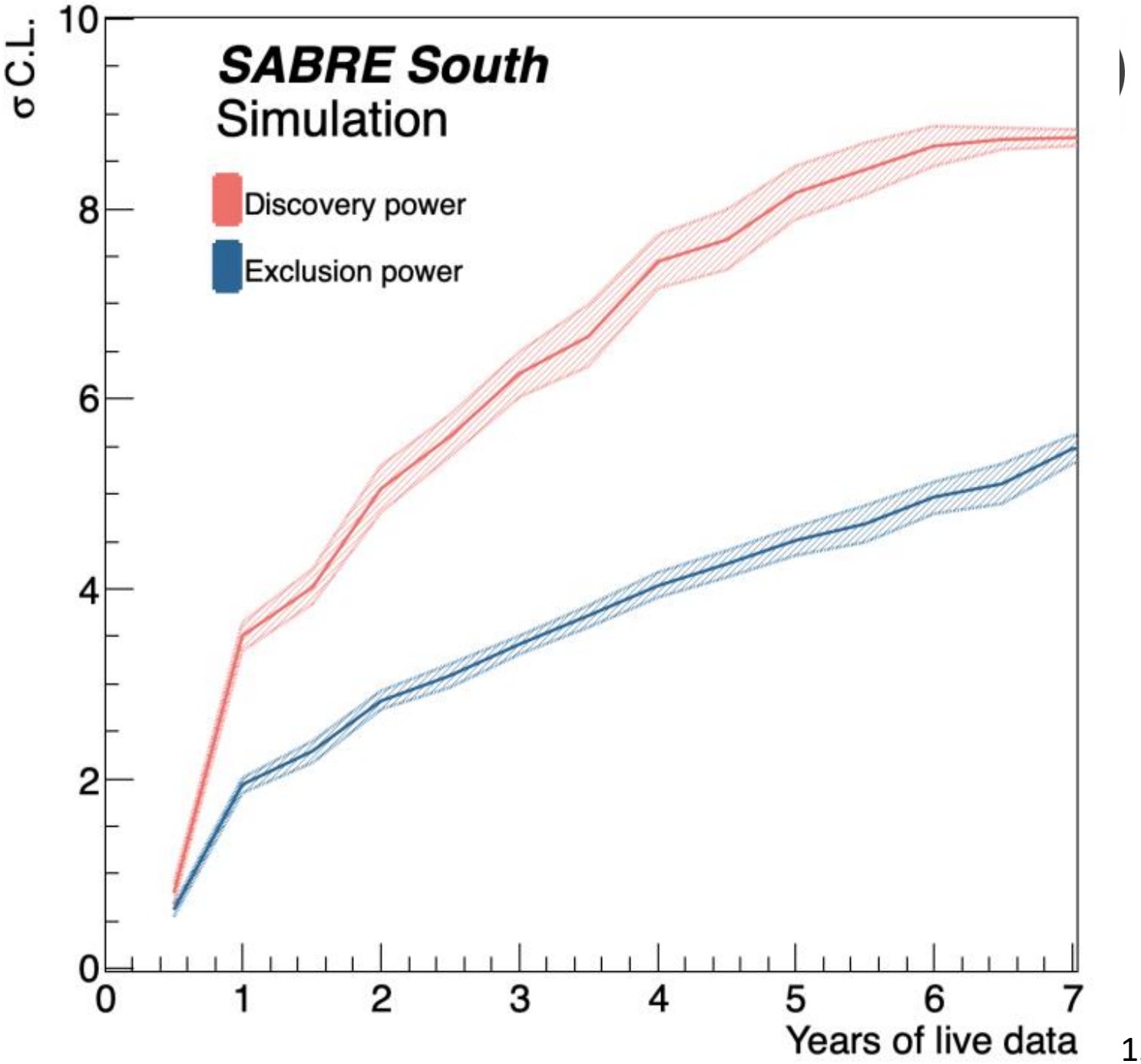
Satisfy SABRE South goal of <10% of background from non-crystal sources.

External backgrounds, shielding, LS bulk, and veto PMTs contribute less than 10^{-3} cpd/kg/keV



Sensitivity

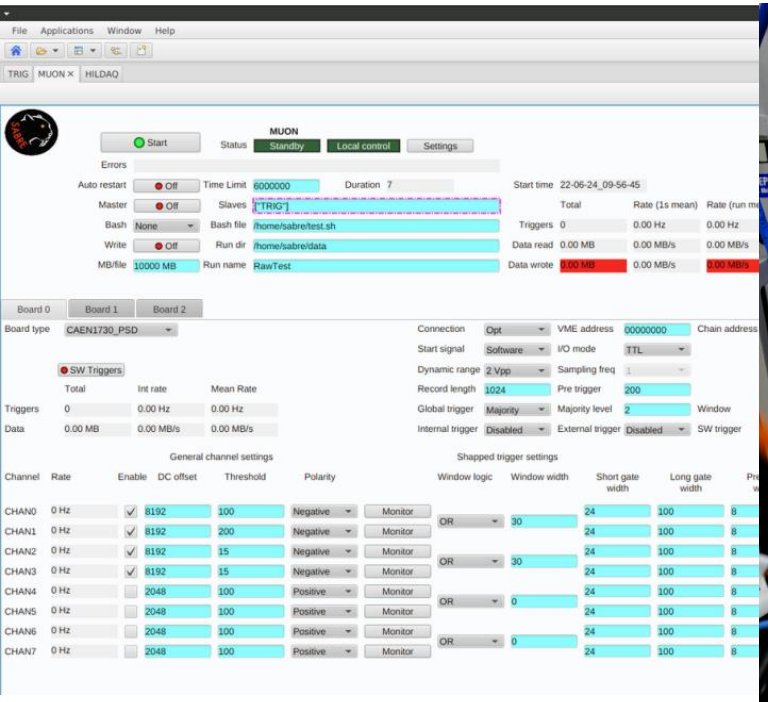
SABRE South will have 5σ discovery (3σ exclusion) power to a DAMA-like signal with 2 years of data taking.

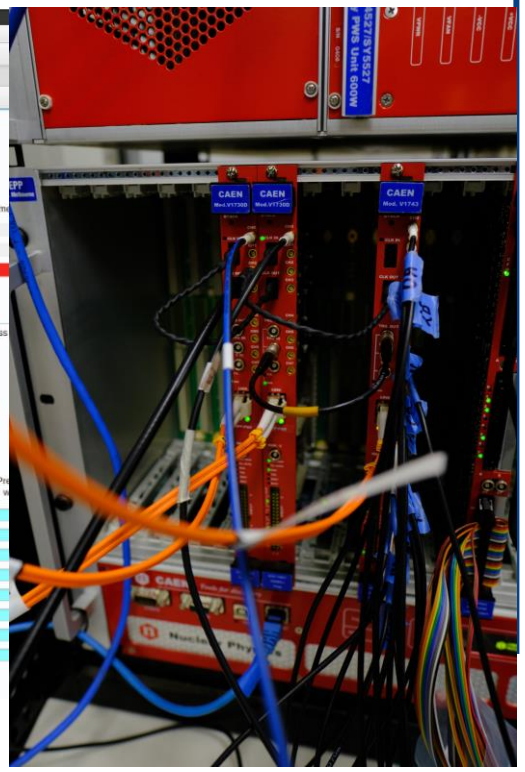


Software and DAQ

SABRE South has developed DAQ for SABRE: Independent EPICS based instances for each sub-detector (crystal, veto, & muon)

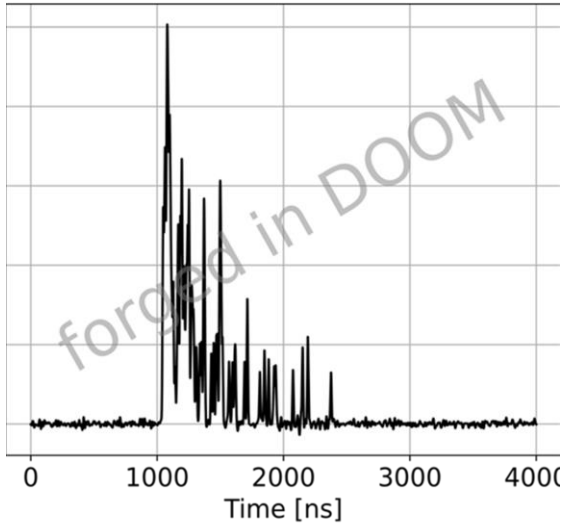
Global trigger managed by CAEN V2495 FPGA with custom firmware.
Prototype currently running NaI test at LNGS





Have developed a flexible python based tool for data processing and analysis code – pyrate. Designed to process many digitised channels, currently in use for PMT characterisation and NaI characterisation. **DOI:10.5281/zenodo.6257646**

***SABRE SOUTH* PRELIMINARY**

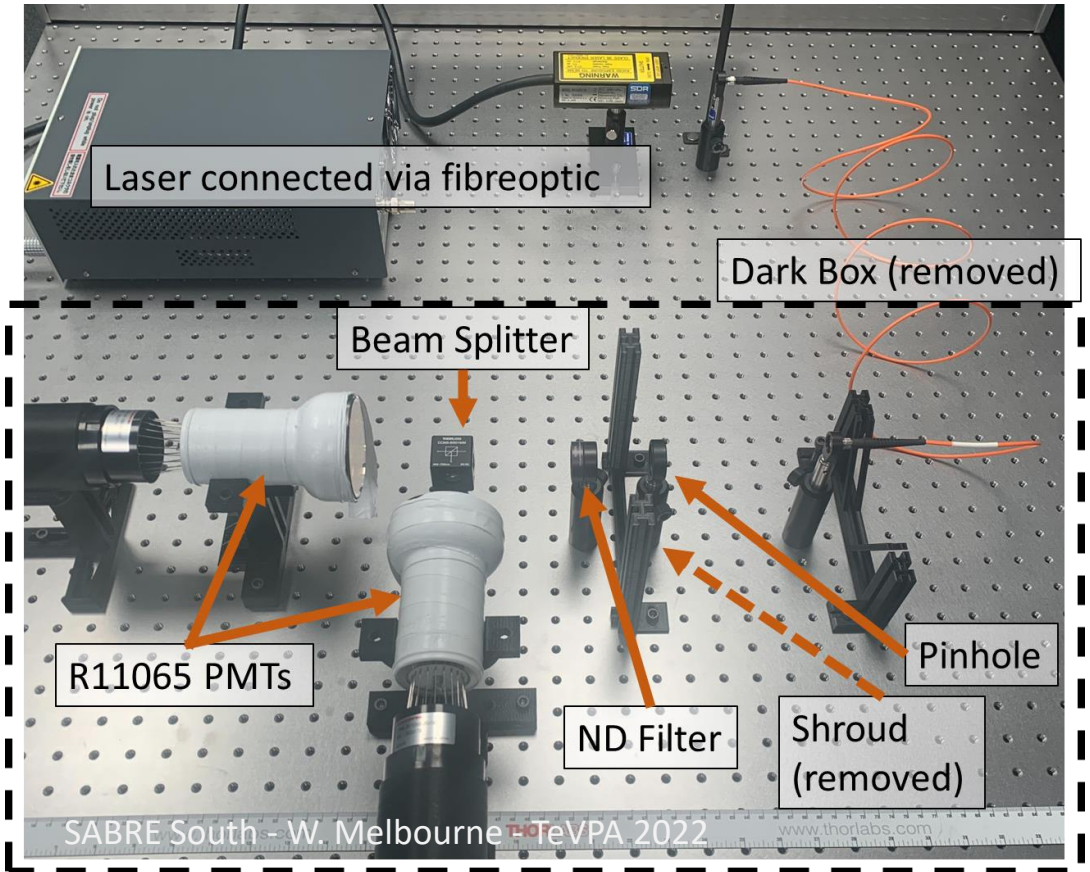


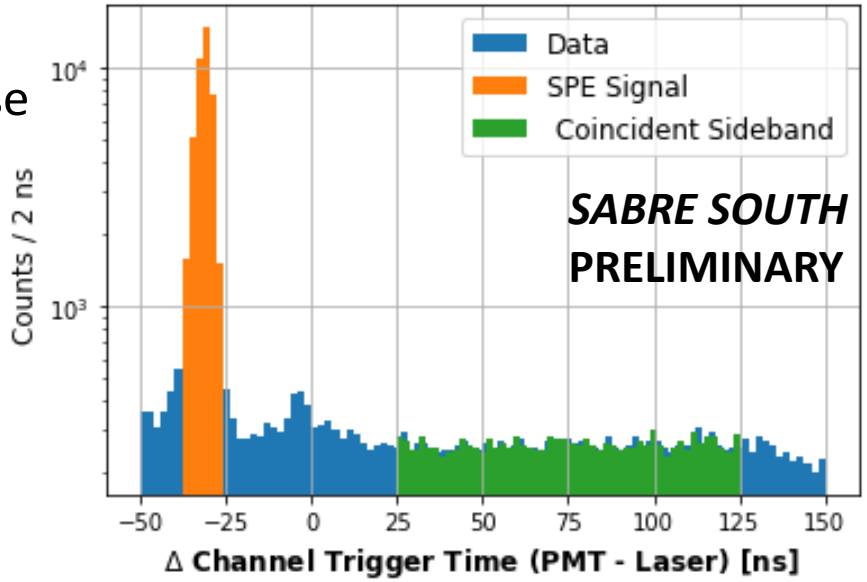
Also developing a detector emulation and digitisation tool – DOOM (Digitisation Of Optical Monte carlo). Used to develop data sets from SABREMC to test reconstruction tools

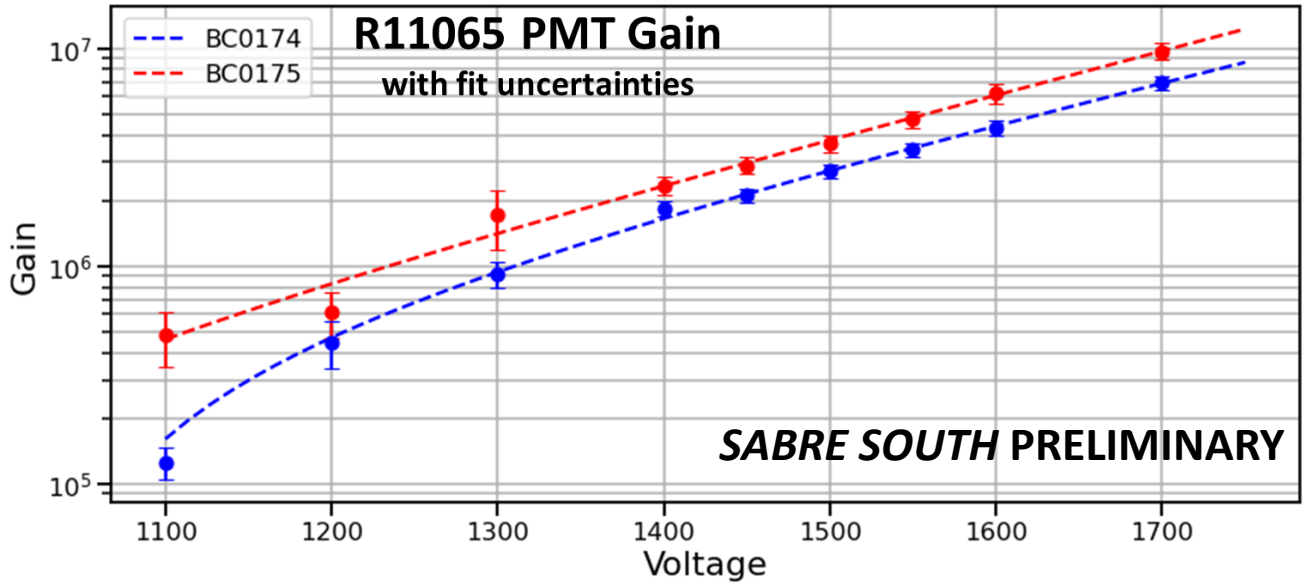
PMT Characterisation

Setup a single photon test bench at Melbourne University with ps pulsed laser with filters to have mean occupancy of 0.05 photons/pulse

Using a timing cut can obtain >99% pure single photoelectron sample.
Ready for bulk characterisation of 14 crystal and
18 veto PMTS (+spares)



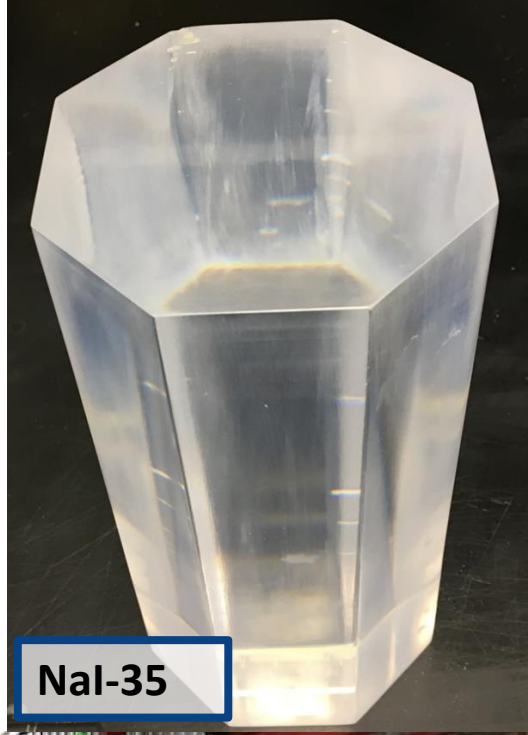




SABRE South Status & Timeline

Assembly in SUPL will start in September 2022 and commissioning will start mid/late 2023.

- 1 low background crystal (NaI-35) currently being characterised at LNGS. procurement of full compliment being finalised
- All PMTs currently at U. Melb. Bulk characterisation in late 2022.
- Veto vessel and 17,000L LAB scintillator in Melbourne
- Muon veto assembled underground this year, to begin background measurements


NaI-35

17,000L of LAB in transit


Crystal insertion glovebox


Completion of Veto Vessel

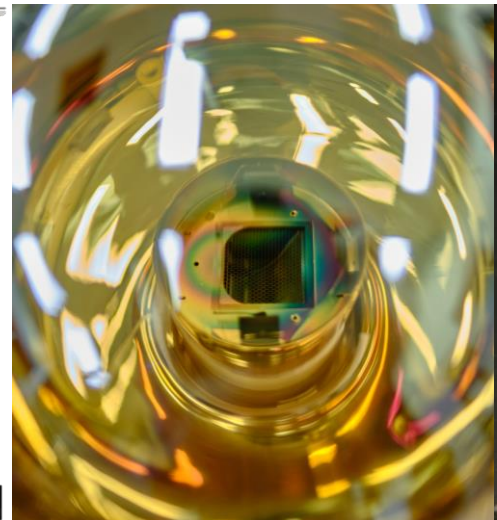
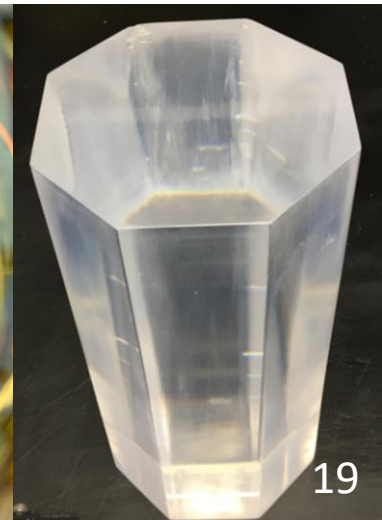
Summary

SABRE South is a low background model-independent replication of DAMA and the first dark matter direct-detection experiment in the Southern Hemisphere. Using 50kg of ultra-low background NaI(Tl) with a projected background of 0.72 cpd/kg/keV$_{ee}$

Construction will begin later this year with commissioning expected mid-2023.

SABRE South will have 5σ discovery (3σ exclusion) power to a DAMA-like signal with 2 years of data taking



Acknowledgements

SABRE South

Australian Government

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY of ADELAIDE

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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

Backup Slides

SABRE North status

Two low background NaI(Tl) crystals (NaI-31 and NaI-33) tested and characterised.
Proof-of-principle phase (1 crystal + active veto) concluded.

Results:

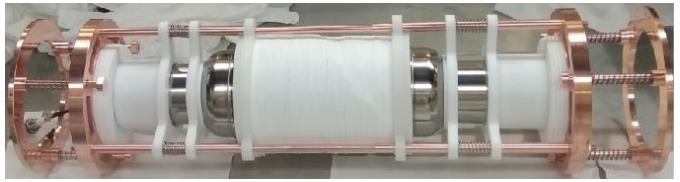
- Full Monte-Carlo simulation model to identify background components
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, lowest since DAMA/LIBRA.

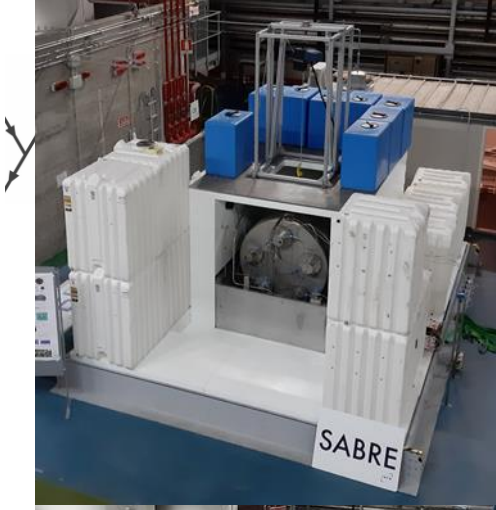
Goals for near future:

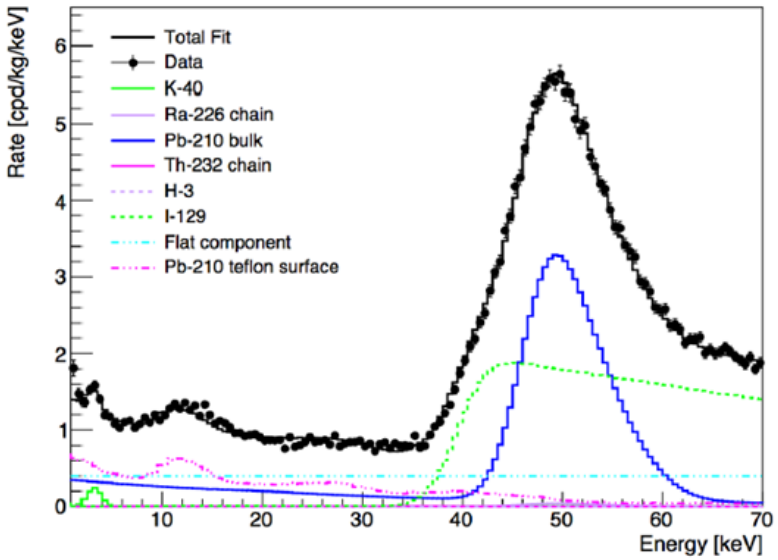
Test the same crystal (NaI-33) with a lower radioactivity reflector

- Test reproducibility of crystal radiopurity
- Assembly of detector modules at LNGS with a new custom glove box.

Demonstrated feasibility of full scale experiment without active veto







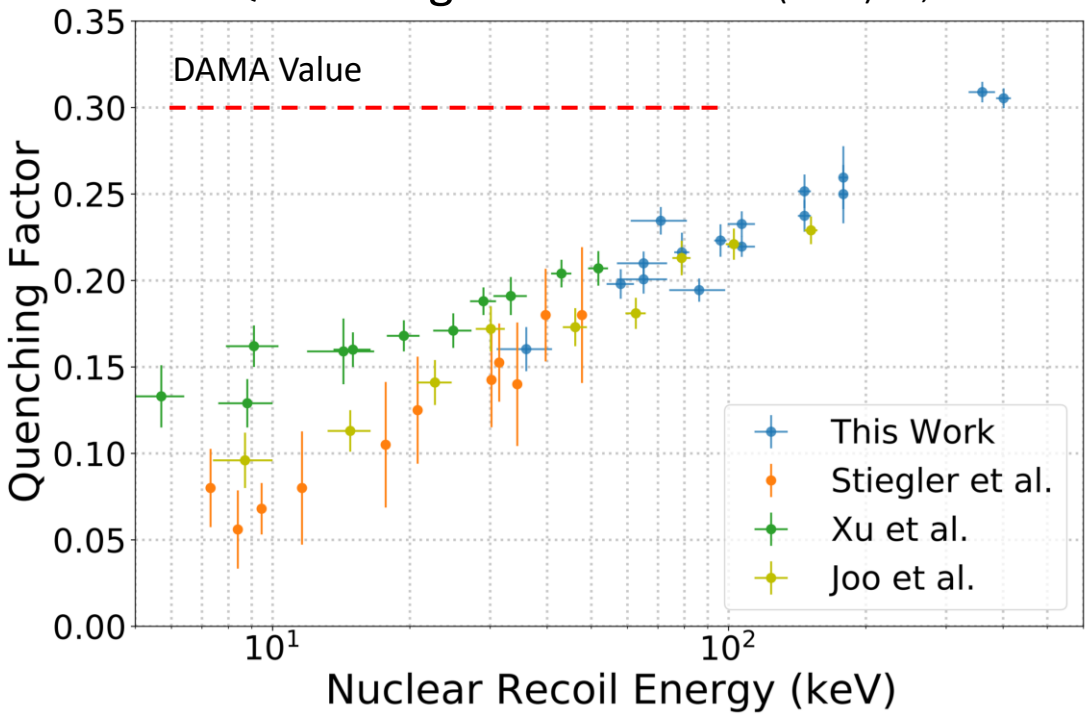
Effect of Quenching Factor

$$E_{ee} = QF \times E_{NR}$$

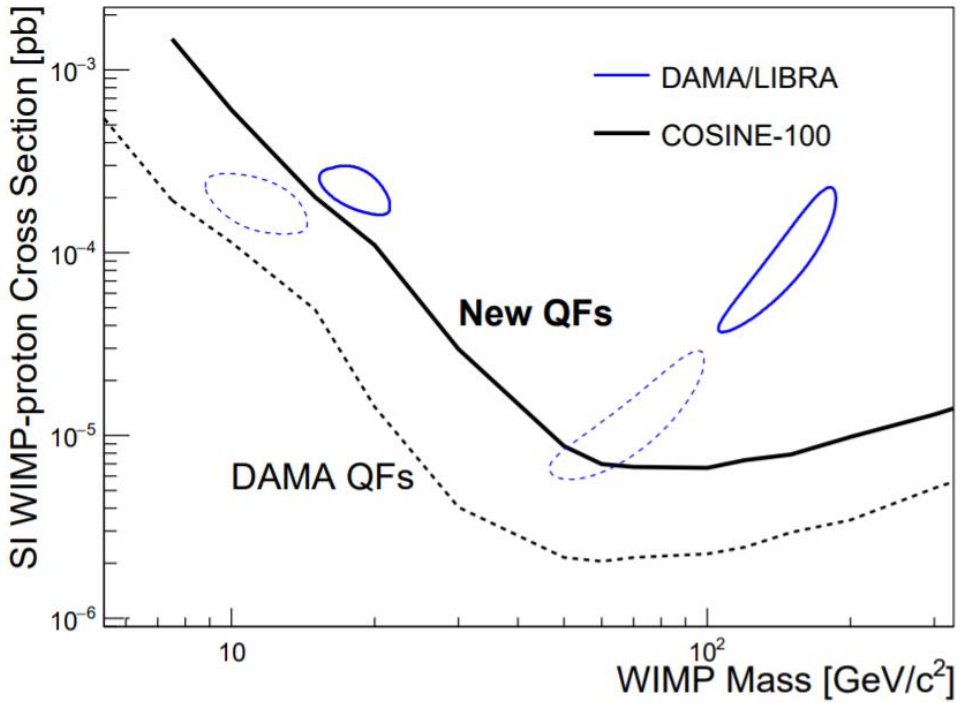
Detectors calibrated with electron recoils & WIMP recoils are nuclear recoils

Default assumption has been to assume that it is consistent for all experiments. However experiments report different values.

Na Quenching Factor - *JINST* 16 (2021) 07, P07034

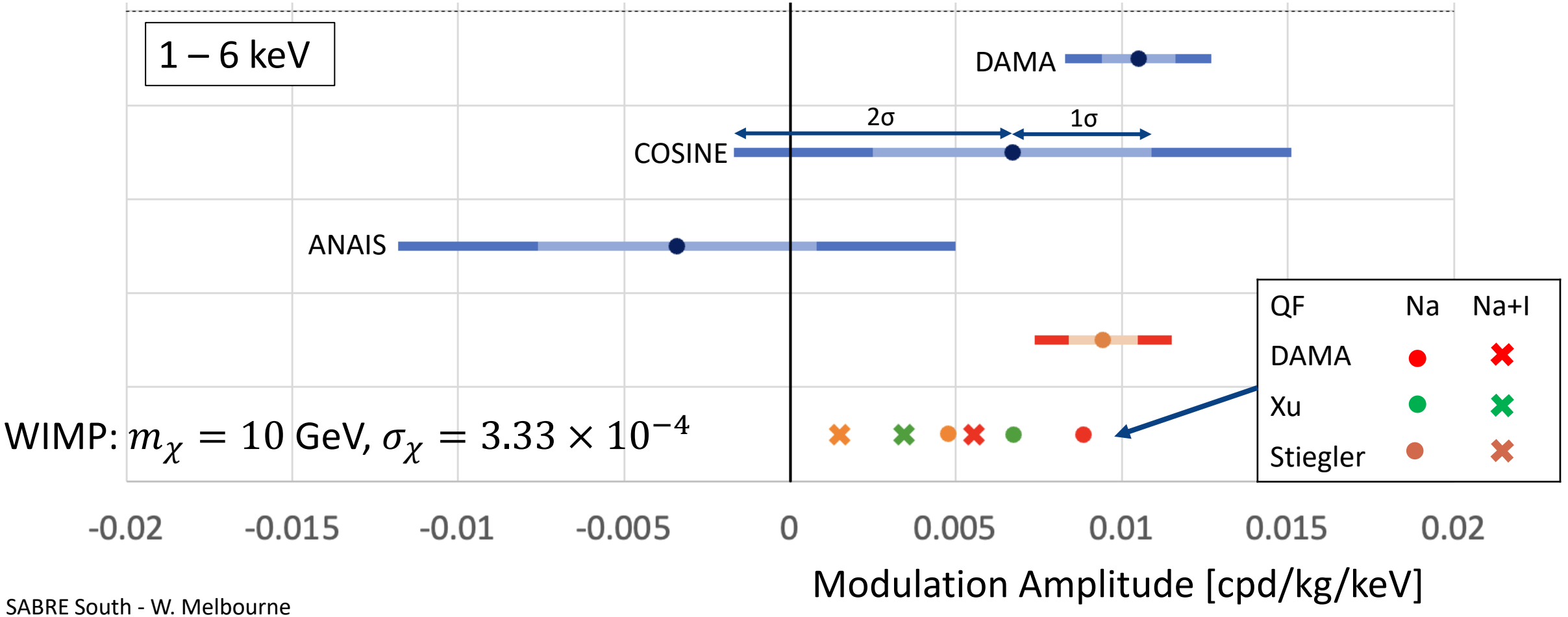


Journal of Cosmology and Astroparticle Physics 2019.11 (2019): 008.



Effect of Quenching Factor

If QF is different, the DAMA modulation will appear differently in other experiments

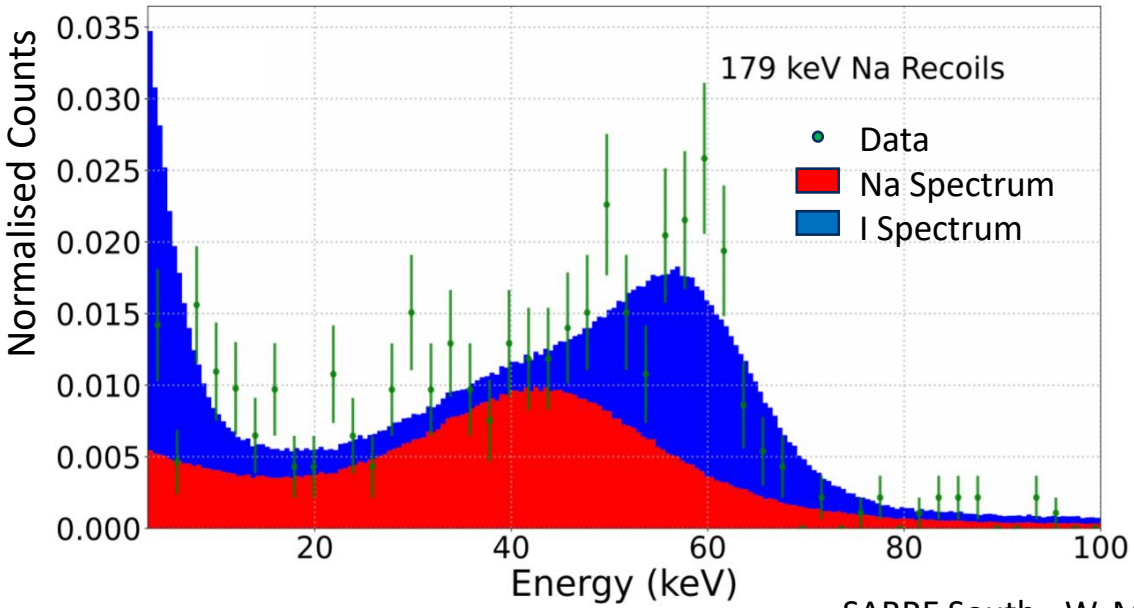


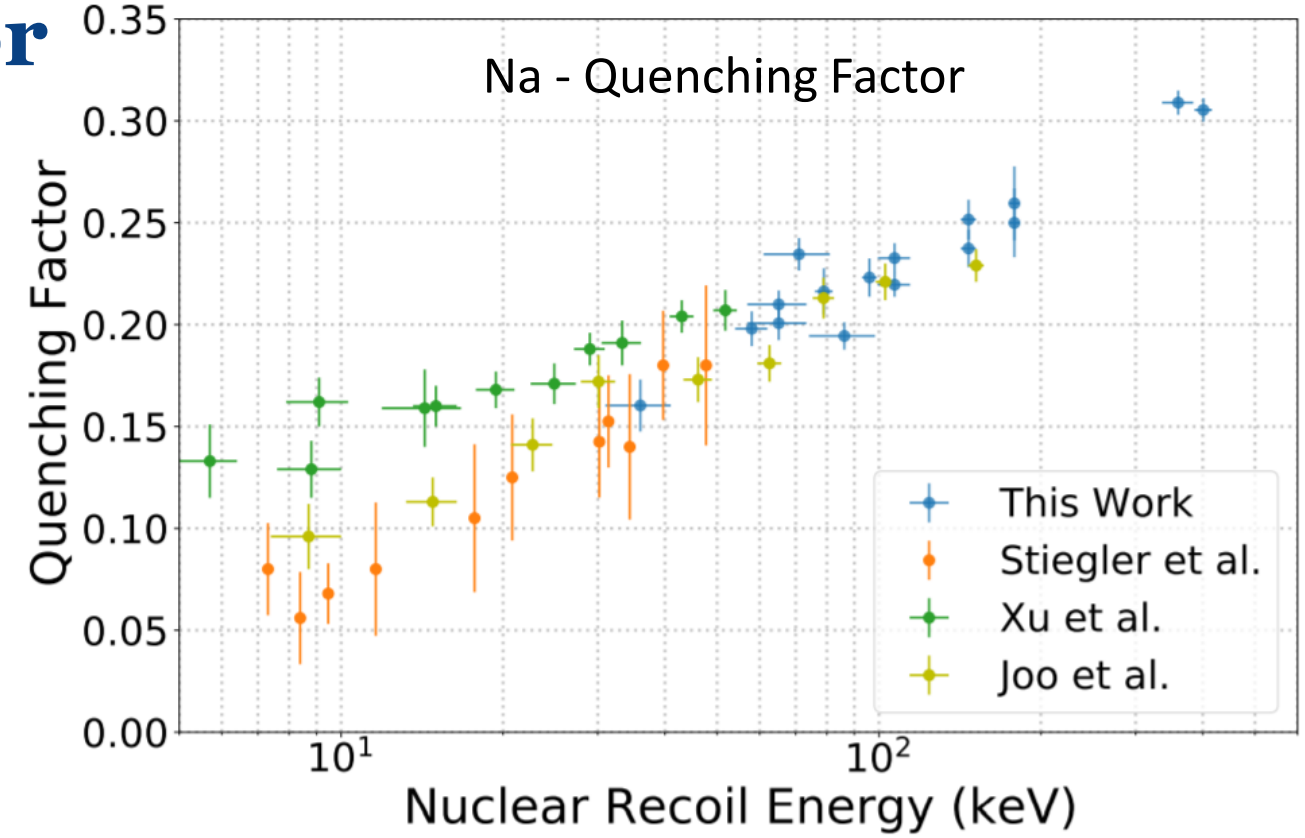
Na Quenching Factor

Measured Na QF in NaI(Tl) with spectrum fitting for 30-300 keV neutron recoils.

Used Heavy Ion Accelerator Facility (HIAF) at ANU to generate pulsed neutron beam

Recoil spectrum determined using Markov chain Monte Carlo. Then fit to data floating the





New measurements underway with Astro-grade offcuts from SABRE South test crystal

L. J. Bignell, et al. "Quenching factor measurements of sodium nuclear recoils in NaI: Tl determined by spectrum fitting." *Journal of Instrumentation* 16.07 (2021): P07034.