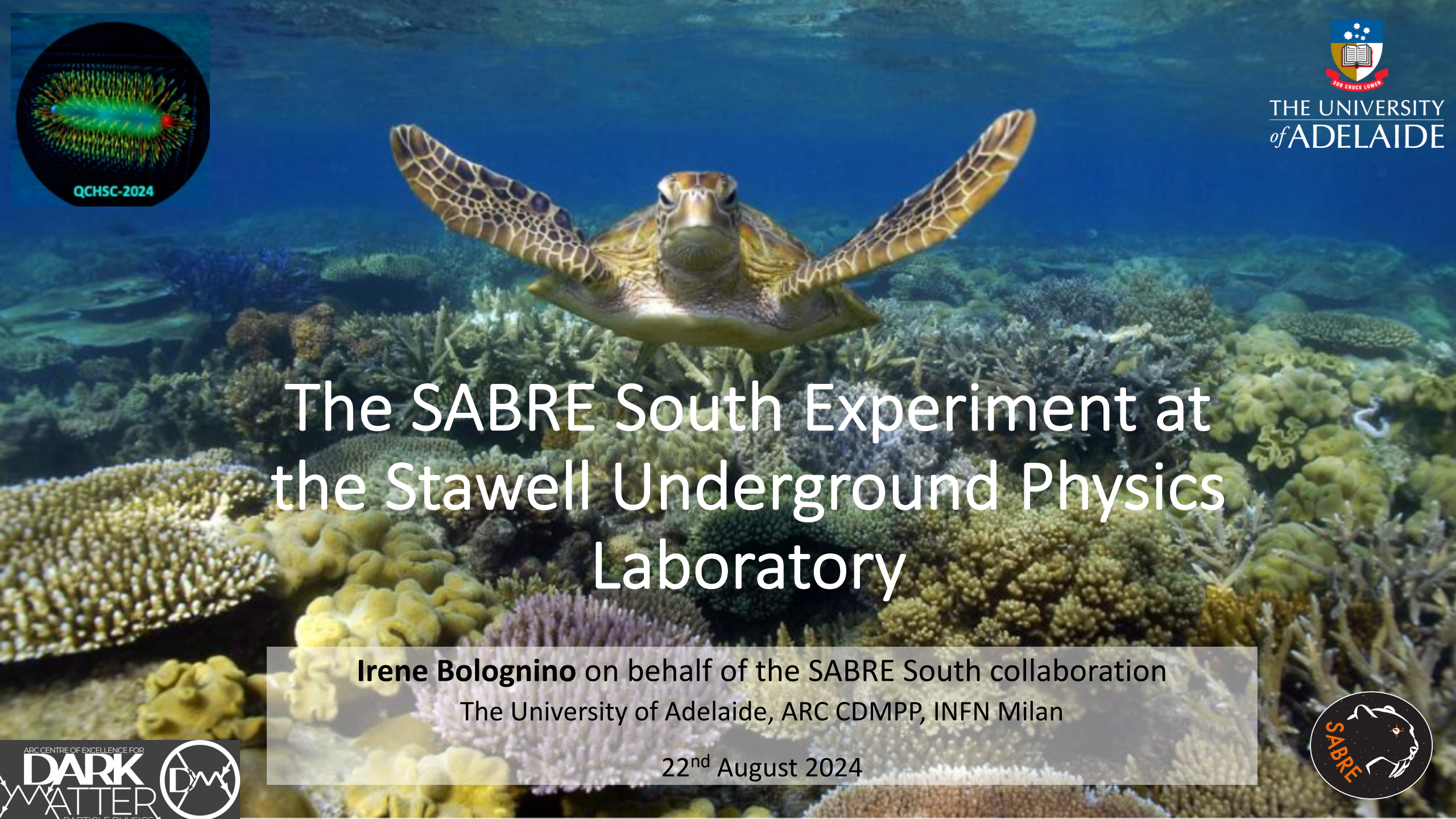


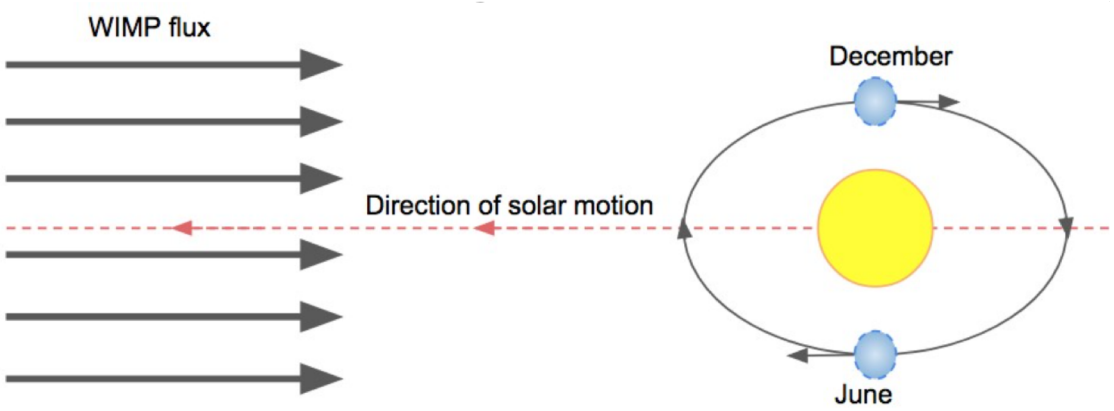
The SABRE South Experiment at the Stawell Underground Physics Laboratory

Irene Bolognino on behalf of the SABRE South collaboration

The University of Adelaide, ARC CDMPP, INFN Milan

22nd August 2024

SABRE Motivation – Annual Modulation

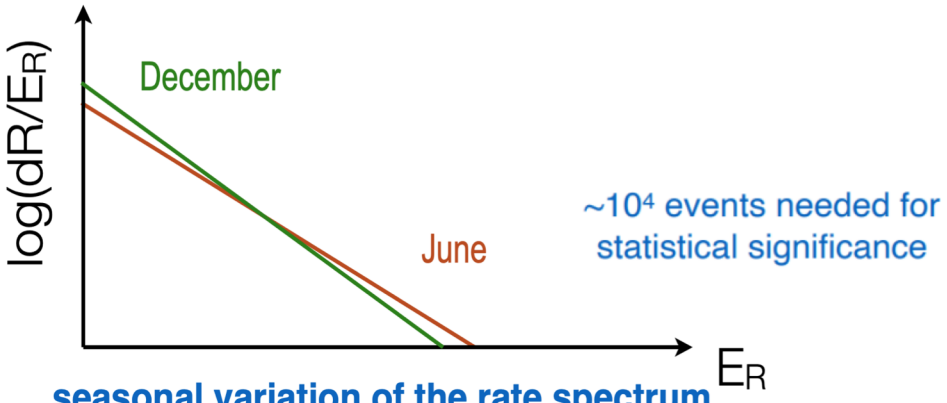


- Standard halo model hypothesis: spherical halo of cold, dark matter (WIMP particles) permeating the galaxy

Annual modulation: maximum and minimum expected on June 2nd and on 2nd December

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

Modulating component ~ 2-10% of R(t)

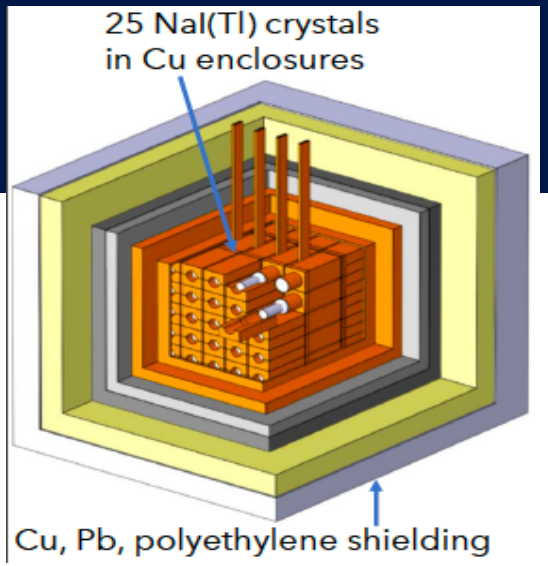


Rare and low energy events:

- very low expected rate ~0.01 cpd/kg/keV (few% of which modulates)
- expected recoil energy is 1-100 keV for a WIMP of mass 10-1000 GeV/c^2

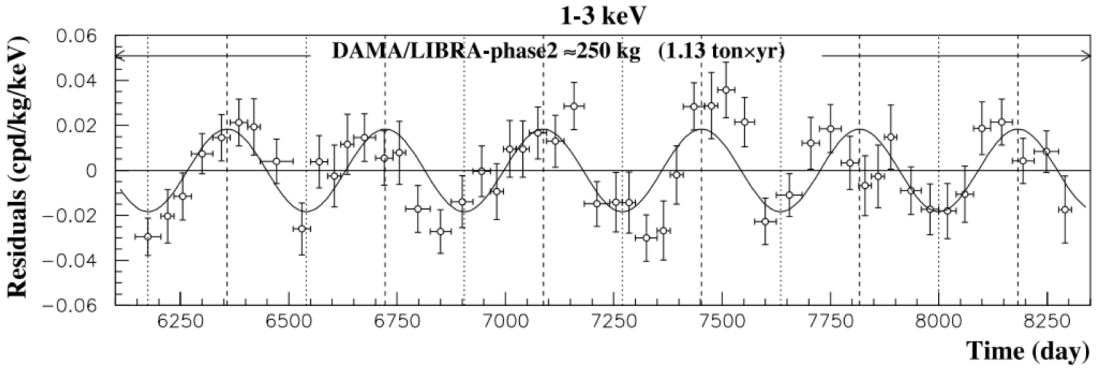
Annual modulation is a <u>model independent</u> signature of Dark Matter interaction, but control of modulating background is key

SABRE Motivation – DAMA/LIBRA results

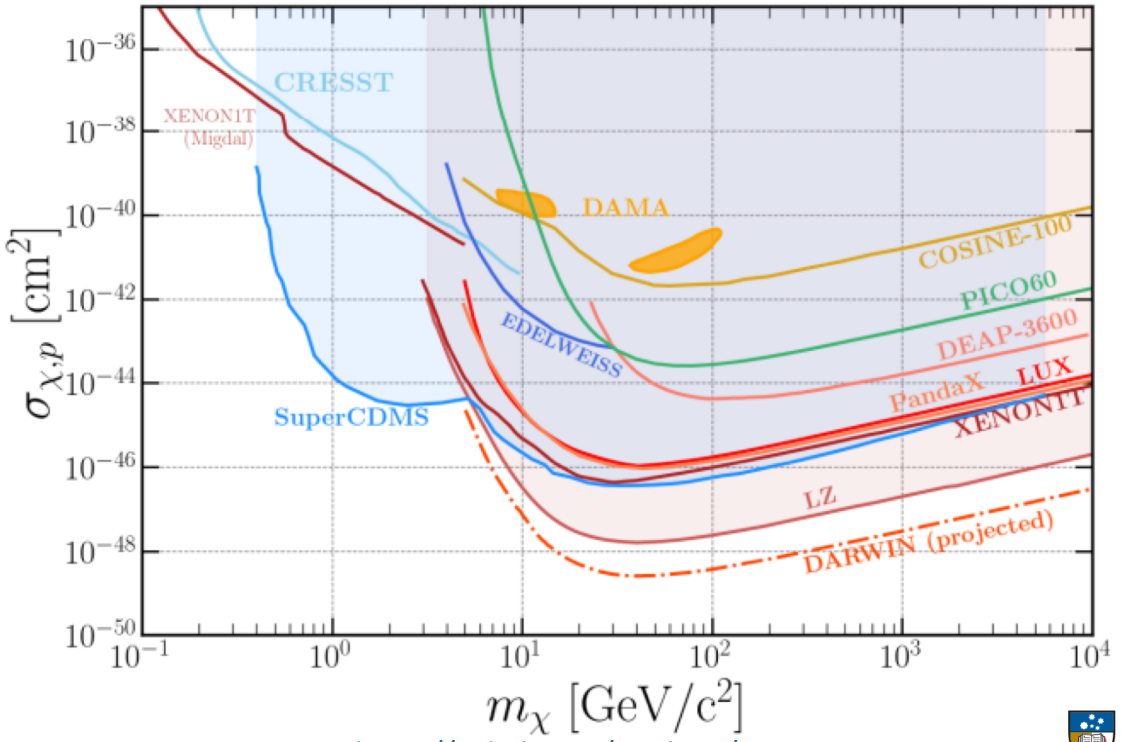


The **DAMA/LIBRA** experiment has observed a modulation for about 2 decades:

- located at Laboratori Nazionali del Gran Sasso, Italy.
- 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.



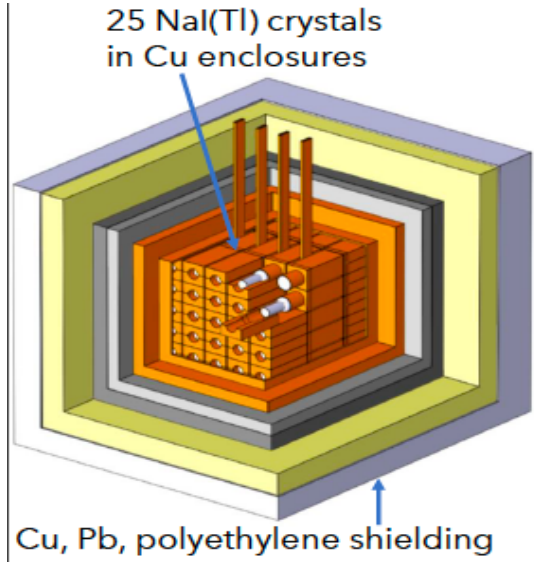
Bernabei et al. PPNP114 103810 (2020)



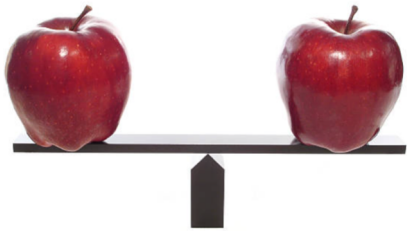
https://github.com/cajohare/NeutrinoFog

DAMA/LIBRA signal: possible explanations

- Seasonal background or systematic effect: e.g. muon-induced neutrons → alternative tests that can discriminate against this.
- Dark matter signal with complex interaction mechanism: explain lack of detection elsewhere → alternative tests utilising the same target material.



From APPEC: *The long-standing claim from DAMA/LIBRA [...] needs to be independently verified using the same target material.*

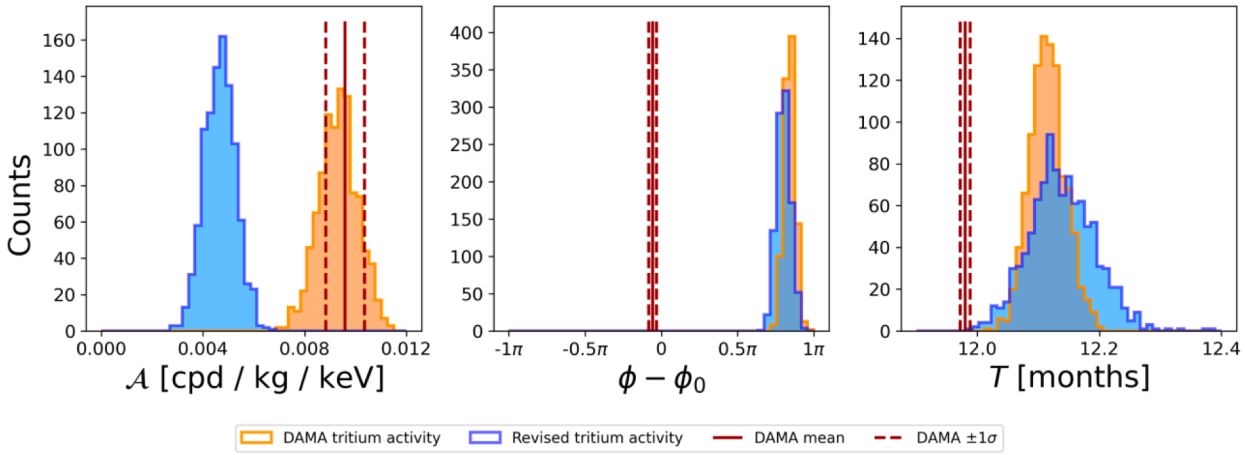


Induced Modulation

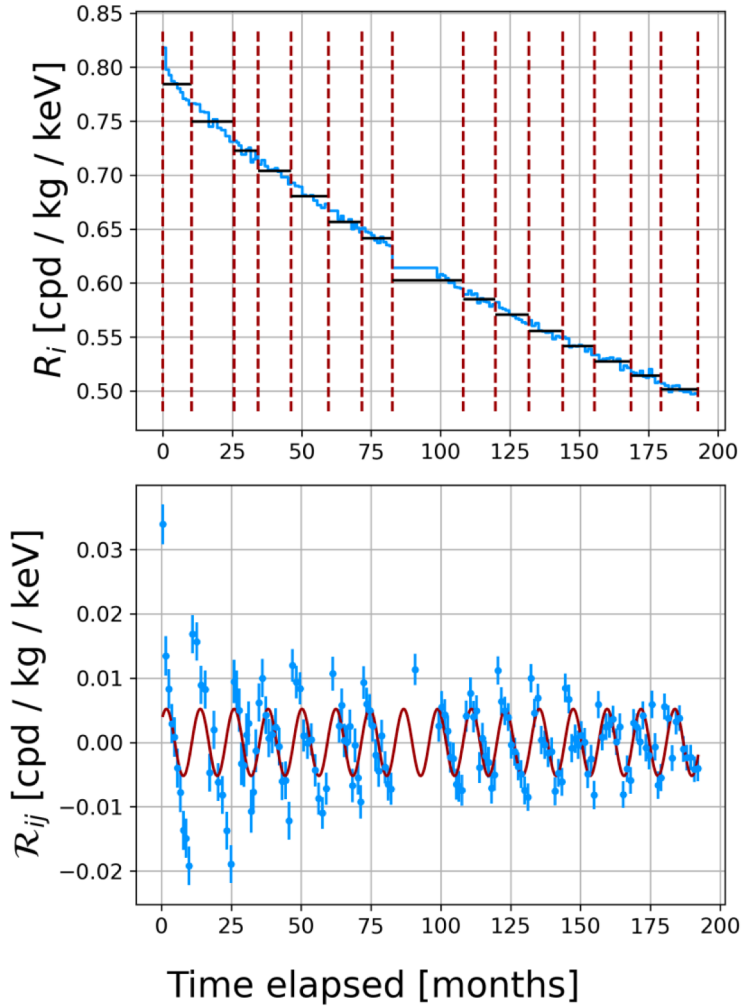
https://arxiv.org/abs/2408.08697

- DAMA analysis relied on subtracting average rate over ~ annual cycles.
- This procedure can induce a modulation effect consistent with their signal in the presence of a decaying background rate.
- DAMA tritium activity likely over-estimated.
  - Revised tritium activity found by using SABRE South crystal simulation;
  - ^{210}Pb taken from DAMA data.

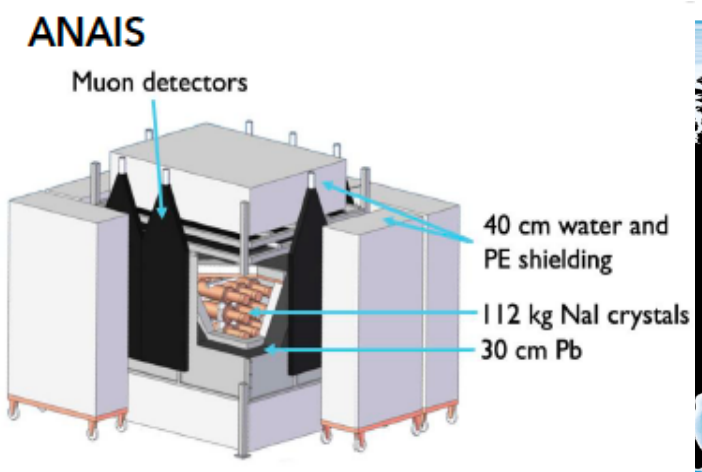
No sizeable induced modulation was observed with DAMA background subtraction → **DAMA background is low enough that shape of background/subtraction method doesn't matter, there is no induced modulation.**



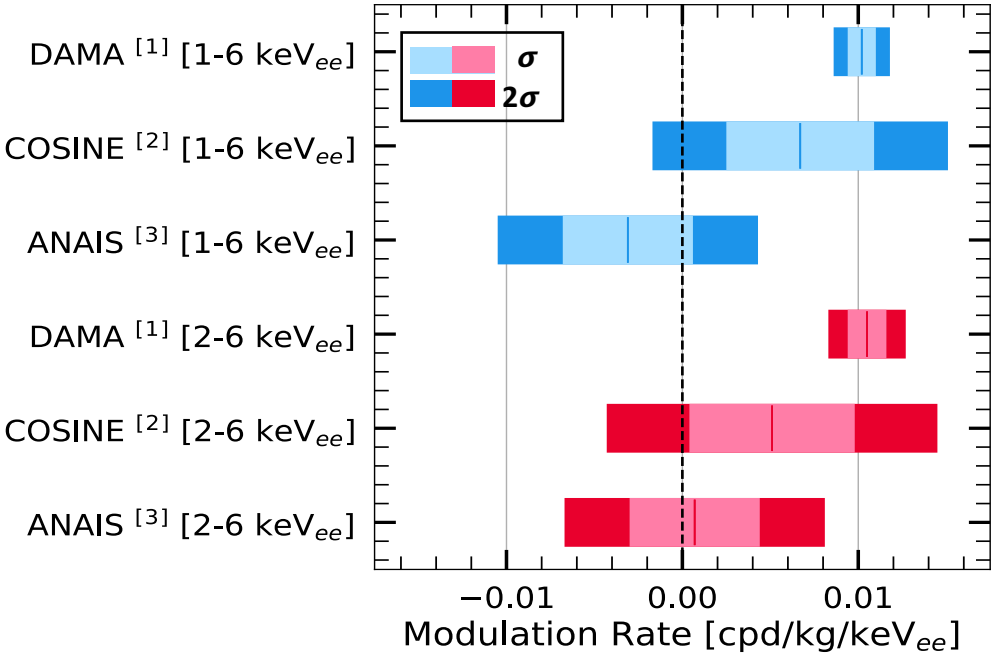
A: Amplitude
Φ: Phase
T: Period

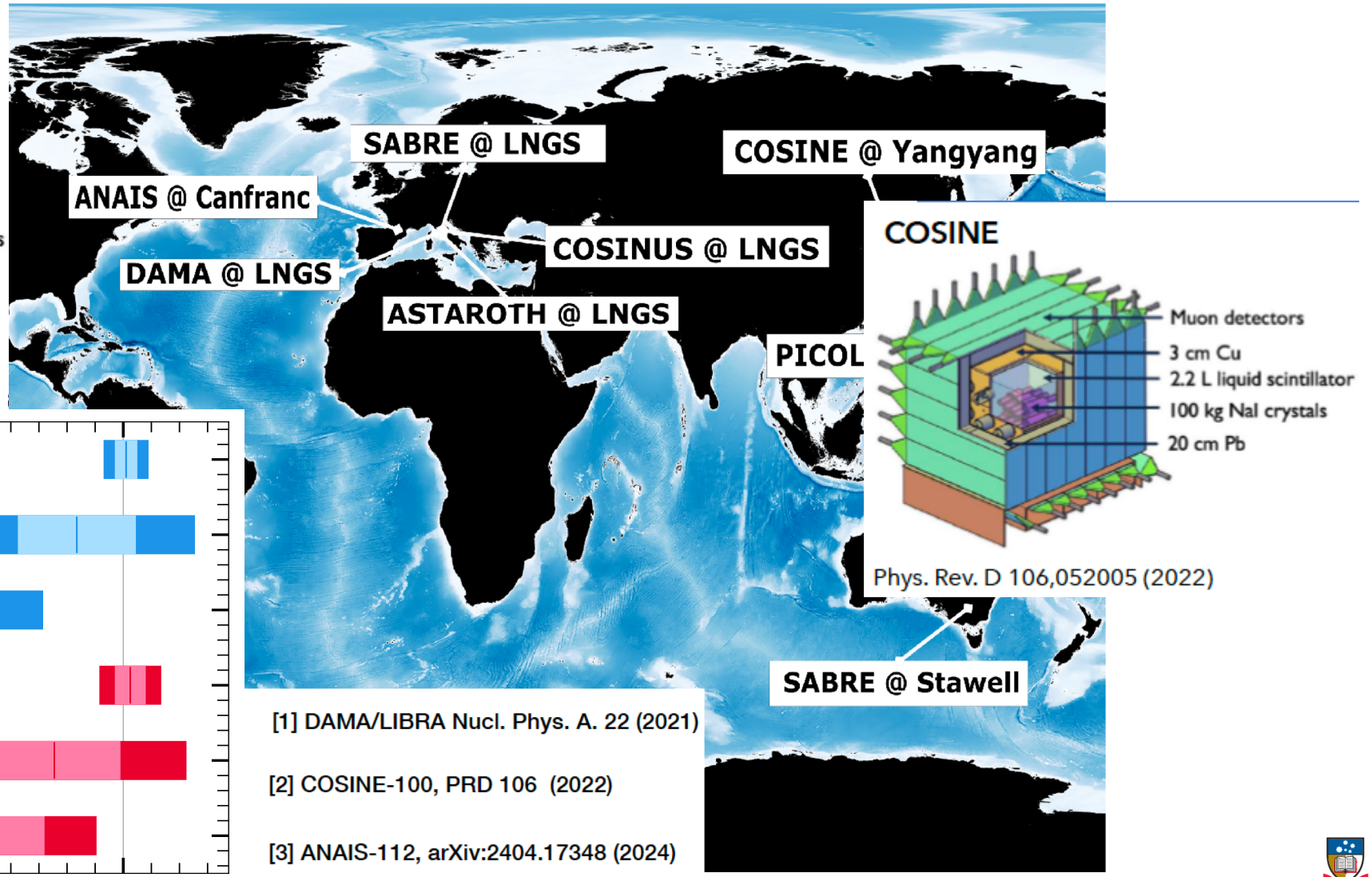


NaI detectors: a worldwide effort



Phys.Rev.D 103 (2021) 10,102005





Phys. Rev. D 106,052005 (2022)

[1] DAMA/LIBRA Nucl. Phys. A. 22 (2021)

[2] COSINE-100, PRD 106 (2022)

[3] ANAIS-112, arXiv:2404.17348 (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

The SABRE South Collaboration

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

- Same crystal production and R&D.
- Same detector module concept (ultra-pure crystals and HPK R11065 PMTs).
- Common simulation, DAQ and data processing frameworks.
- Exchange of engineering know-how with official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN.

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

- SABRE North has opted for a fully passive shielding due to the phase out of organic scintillators at LNGS. Direct counting and simulations demonstrate that this is compliant with the background goal of SABRE North at LNGS.
- SABRE South will be the first experiment in SUPL, the liquid scintillator will be used for in-situ evaluation and validation of the background in addition of background rejection and particle identification.

The SABRE South Collaboration

KEK-JAPAN

SWINBURNE

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY OF SYDNEY

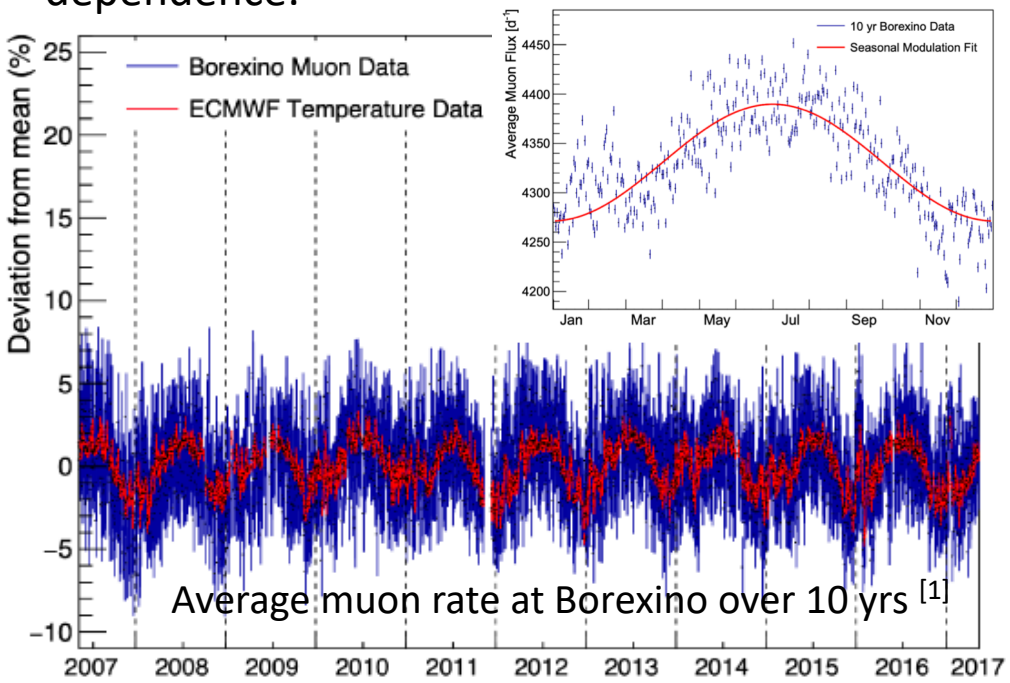
THE UNIVERSITY of ADELAIDE

Australian National University

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Exclusion of seasonal effects

- The site in the Southern hemisphere is important to exclude seasonal effects.
- Muons are a particular issue for dark matter modulation searches as they have a similar phase due to seasonal dependence.



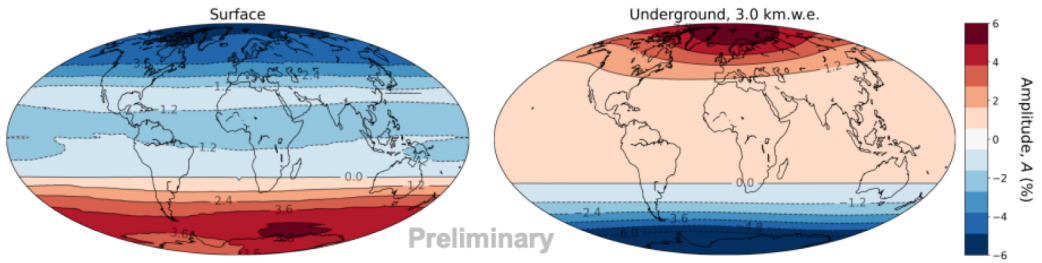
Average muon rate at Borexino over 10 yrs [1]

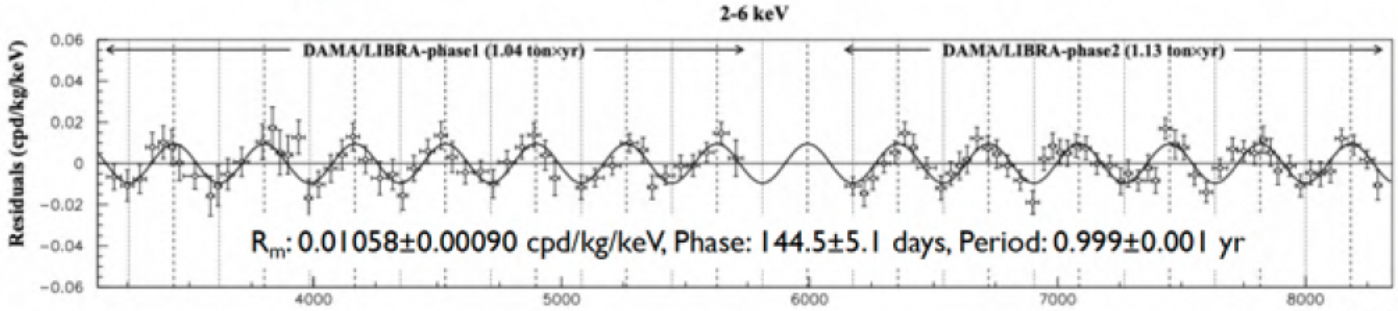
[1] Borexino collab. JCAP02(2019)046

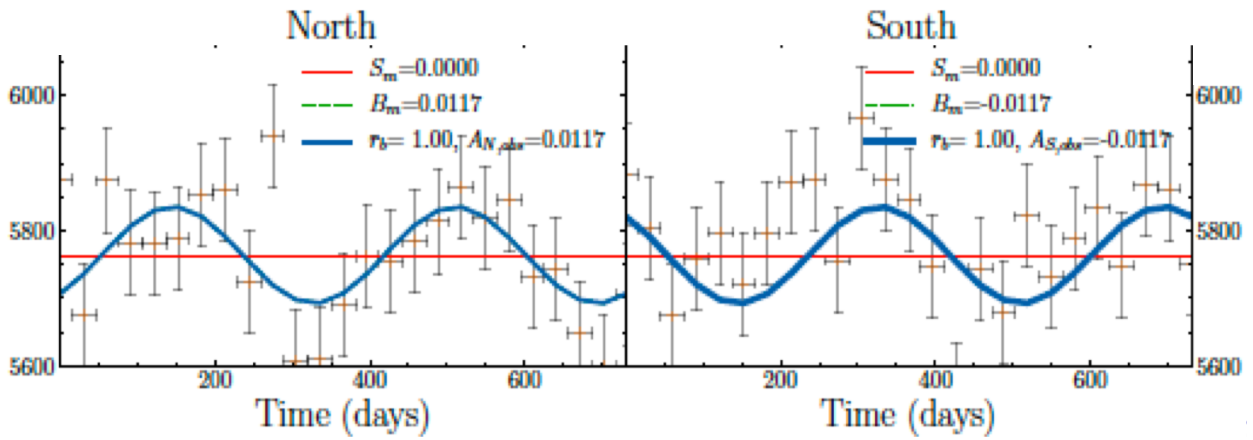
Modulations of the cosmic muon signal in ten years of Borexino data

M. Agostini[1], K. Altenmüller[1], S. Appel[1], V. Atroshchenko[2], Z. Bagdasarian[3], D. Basilico[4], G. Bellini[4], J. Benziger[5], D. Bick[6], I. Bolognino[4] + Show full author list

MUTE Astrophys.J. 928 (2022)







SABRE (Sodium iodide with Active Background REjection) South

Feedthrough plate

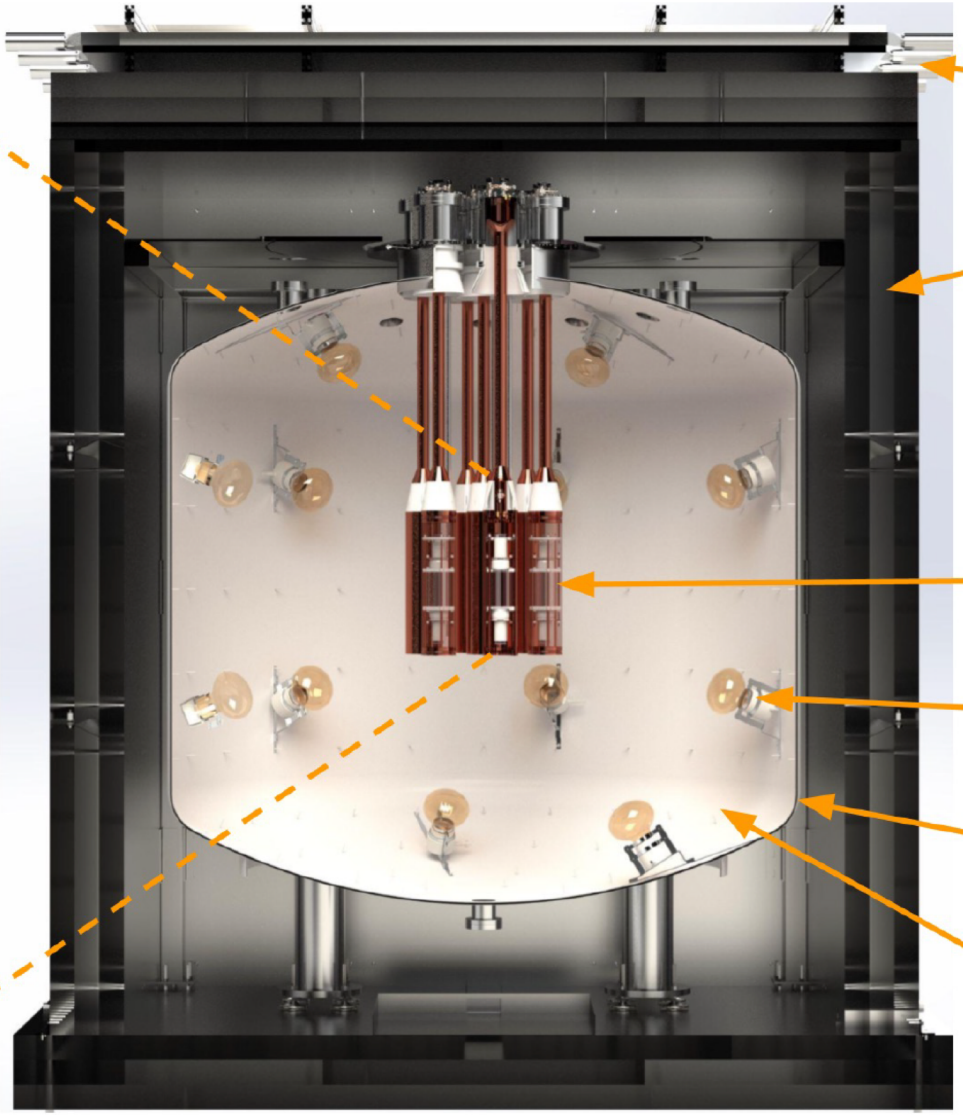
OFHC Cu enclosure

Teflon internal structure

7.6 cm R11065 Hamamatsu PMTs

NaI(Tl) crystal

Crystal procurement ongoing with SICCAS and RMD



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

7 NaI(Tl) crystals in Cu enclosures (each with 2 low radioactivity PMTs)

18 R5912 PMTs for veto

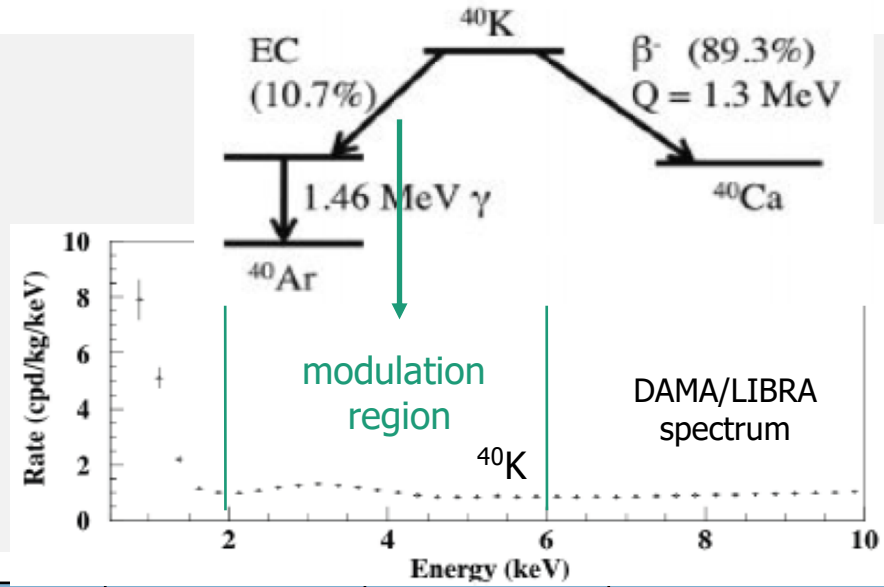
Veto vessel filled with 10T of LAB from JUNO doped with PPO (3.5 g/L) and Bis-MSB (15 mg/L)

Reflective lumirror coating

NaI(Tl) crystals production

Two providers: SABRE South crystals to be provided by SICCAS and/or RMD.

NaI(Tl) crystals production



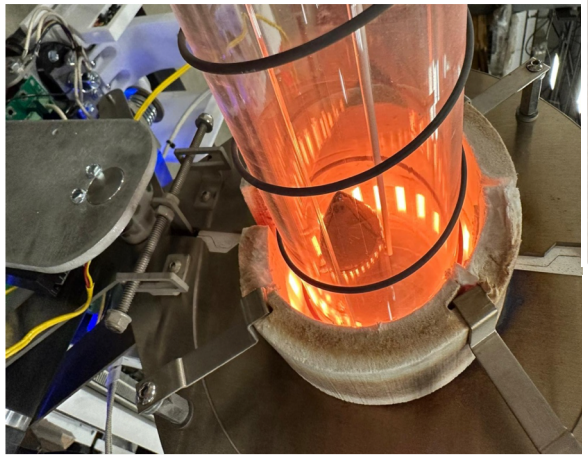
SABRE crystal mass = 3.4 kg

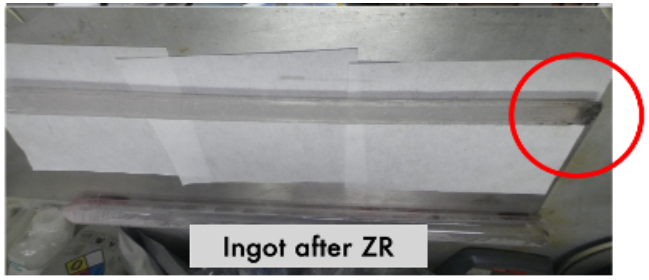
	^{nat}K [ppb]	^{238}U [ppt]	^{232}Th [ppt]	^{210}Pb [mBq / kg]	Mass [kg]
SABRE NaI-33 [1]	4.3 ± 0.8	0.4 ± 0.05	0.20 ± 0.07	0.46 ± 0.01	3.4
DAMA [2]	13	0.3 - 2	0.5 - 7.5	(5 - 30) x 10^{-3}	10.0
COSINE-100 [3]	35.1	<0.12	0.4 - 2.4	0.7 - 3	13.3
ANAIS [4]	31	<0.81	0.1 - 1.0	0.7 – 3.2	12.5

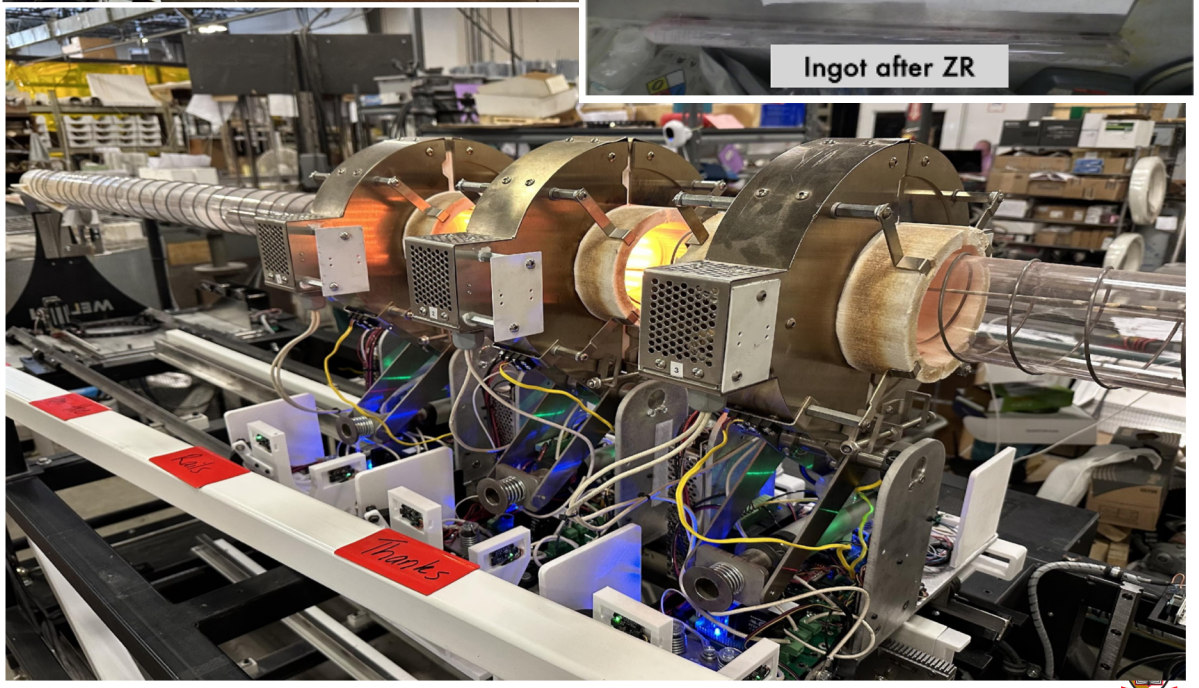
[1] B. Suerfu et al., Phys. Rev. Research 2, 013223 (2020)
[2] R. Bernabei et al., NIMA 592(3) (2008)
[3] P. Adhikari et al., Phys. Rev. Lett. 123, 031302 (2019)
[4] J. Amare et al., EPJC 79 412(2019)

Zone Refining Technique

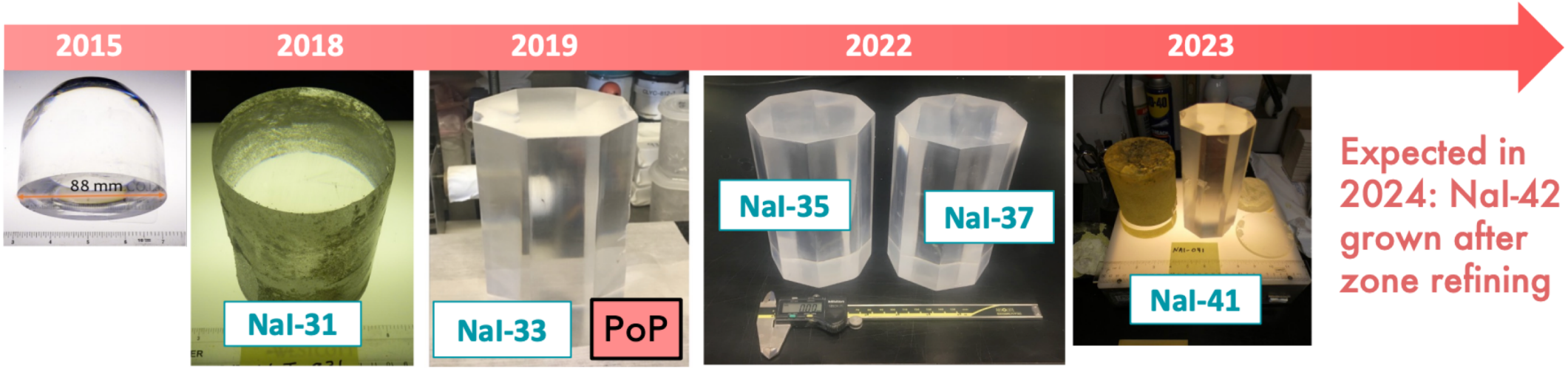
- Technique successfully used in semiconductor industry.
- Zone refining 100 kg of crystal powder prior to crystal growth has been built in collaboration with MELLEN, NH, USA.
- Four runs with 900 gr of AstroGrade NaI powder have been performed so far.
- Impurities are segregated to one side of the ingot by the moving ovens and then removed.
- Zone refining could reduce to about 1/3 the Pb content, almost 1 order of magnitude K and possibly other internal contaminants like Rb.





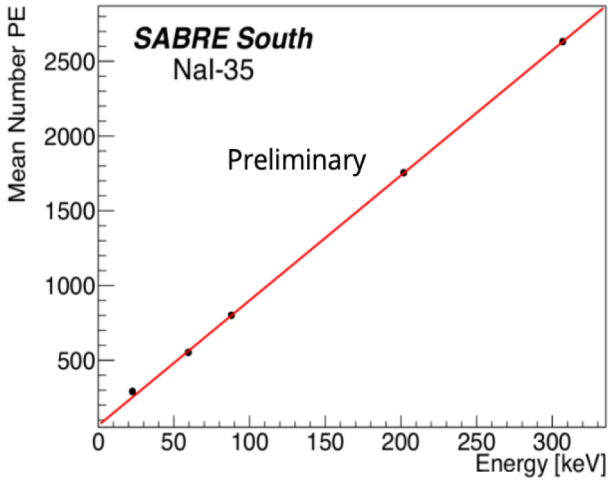


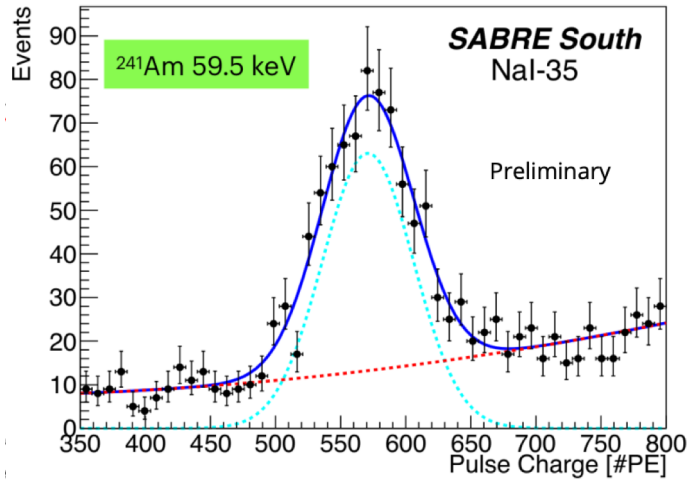
NaI(Tl) crystals production timeline



NaI-35, SABRE South test crystal, grown to 3.7kg by RMD 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.



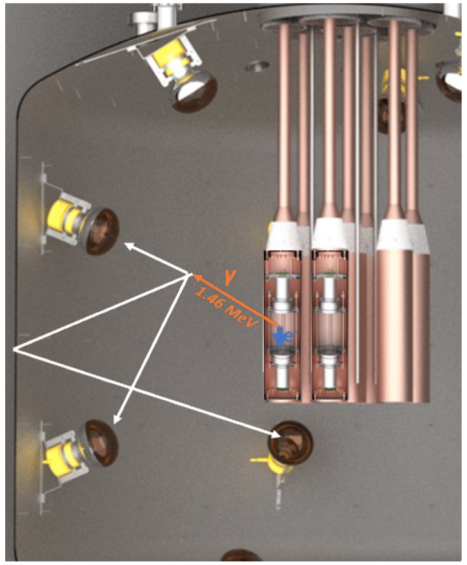


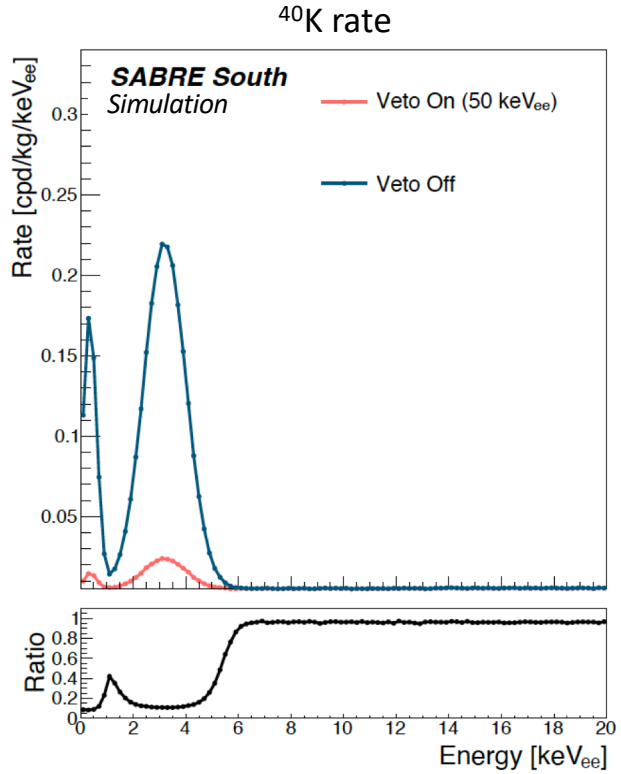
SABRE South TDR, DOI: https://doi.org/10.26188/14618172.v3

Active Background Rejection

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

- 12 kL (10 tons) linear alkyl benzene (LAB) sourced from JUNO doped with PPO and Bis-MSB.
- 18 Hamamatsu 20.4 cm R5912 PMTs sampled at 500 MS/s.
- Average light yield of ~0.17 PE/keV, though strong position dependence.
- Energy threshold of 50 keV (~10 PE) - ~ 0.20 PE/keV detectable by single PMT.
- Overall background reduction ~25%.





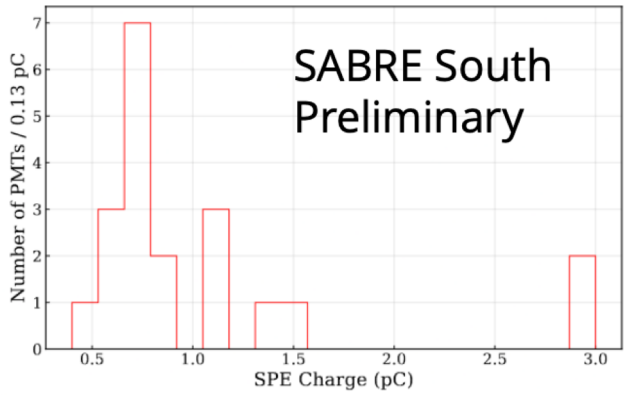
cpd/kg/keV per mBq/kg	^{238}U	^{232}Th	^{210}Pb	^{85}Kr	^{87}Rb	^{40}K
1-6 keV no veto	0.963	0.250	0.681	0.191	0.695	0.650
1-6 keV with veto	0.921	0.216	0.681	0.191	0.695	0.095
Veto efficiency	4.3%	13.3%	0.0%	0.0%	0.0%	85.4%

PMT Characterisation

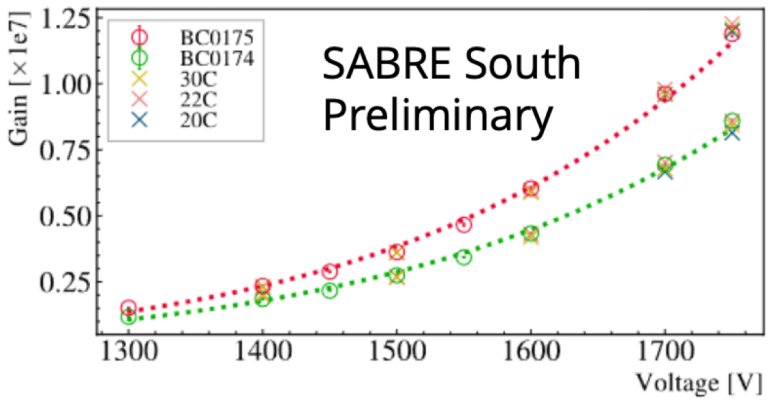
- Single photoelectron response, gain, dark rate and temperature dependent dark rate.
- Relative quantum efficiency, linearity of response – i.e. for reconstructing high energy crystal deposits.
- Detailed waveform simulation framework also developed → machine learning algorithms: quantify trigger selection efficiencies and reject PMT noise events.

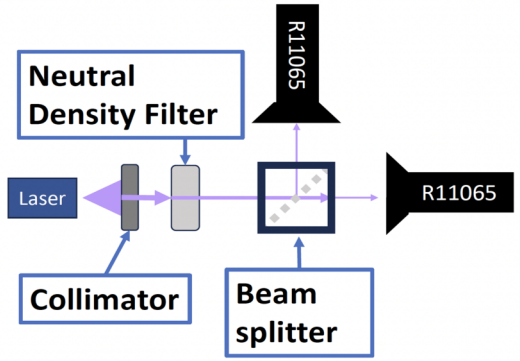
Pre-calibration papers to be submitted to journal/arxiv September 2024

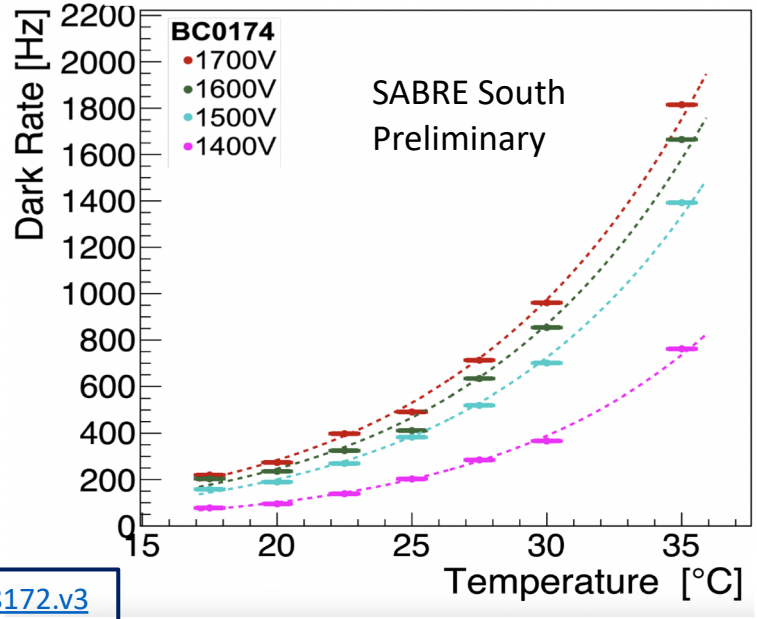
Veto PMT



Crystal PMT





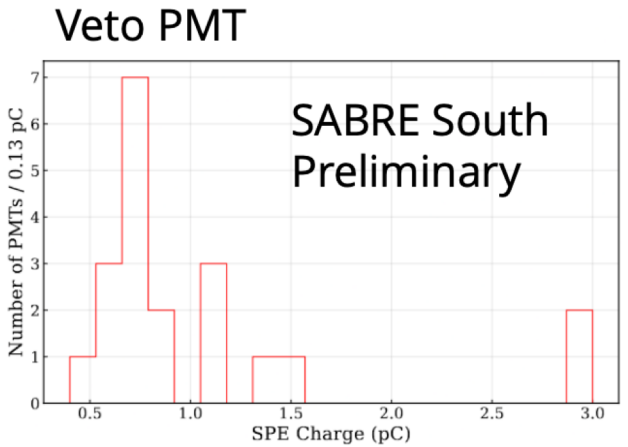


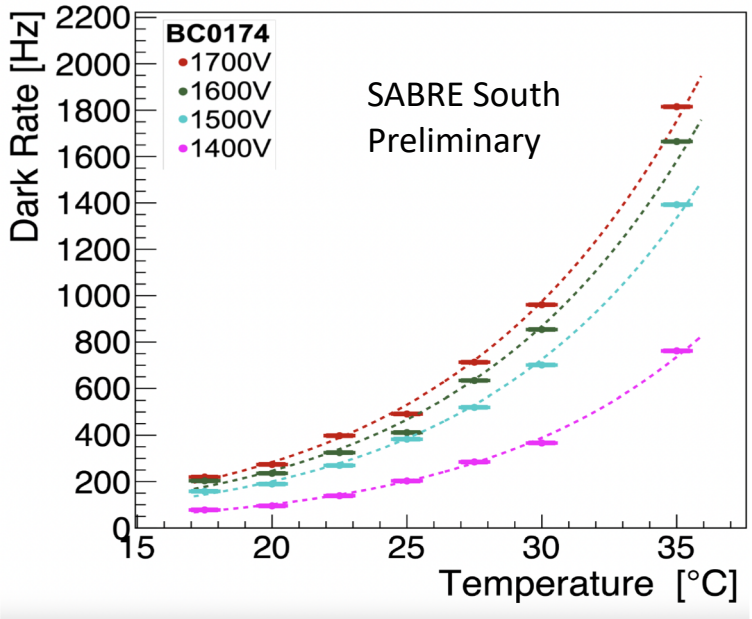
SABRE South TDR, DOI: https://doi.org/10.26188/14618172.v3

PMT Characterisation

- Single photoelectron response, gain, dark rate, and temperature dependent dark rate.
- Relative quantum efficiency, linearity of response – i.e. for reconstructing high energy crystal deposits.
- Detailed [illegible] developed → machine learning to identify trigger selection efficiencies and reject PMT noise events.

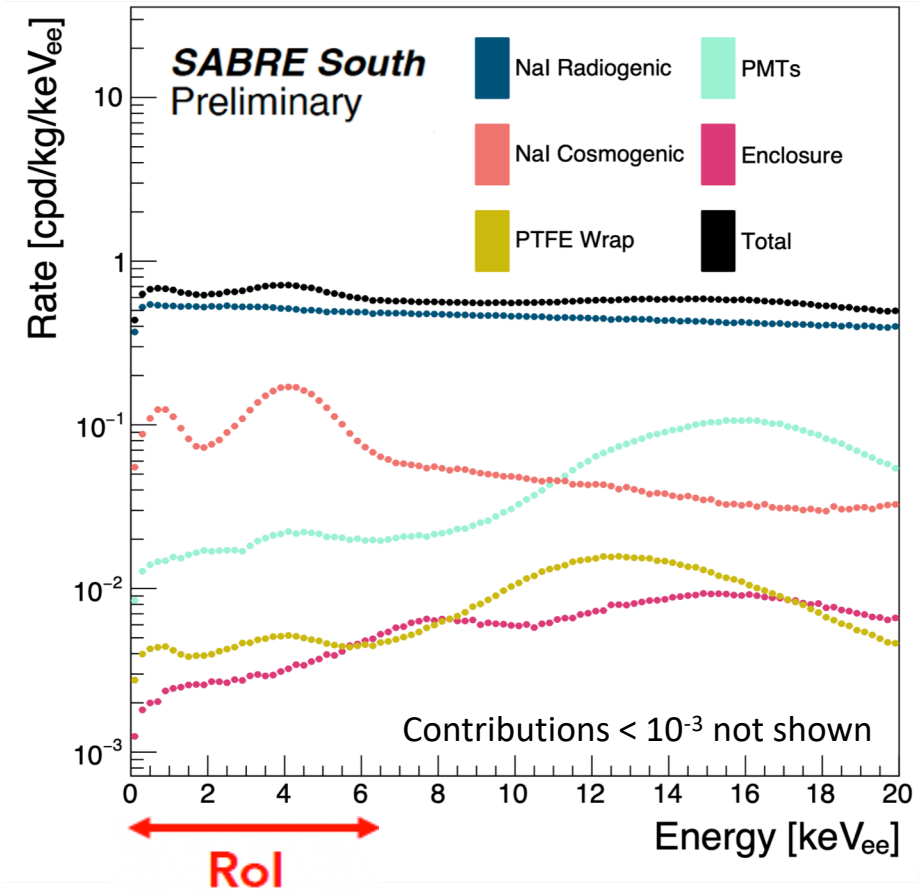
Kamiel's talk "**Optical calibration of SABRE-South veto photomultiplier tubes**" – session G – Tuesday 20th August, at 16:40.





Total Background Model

Using background from NaI-33, with 50 kg of NaI, expect 0.72 cpd/kg/keV in RoI.



[SABRE South Collab. Eur. Phys. J. C (2023) 83: 878]

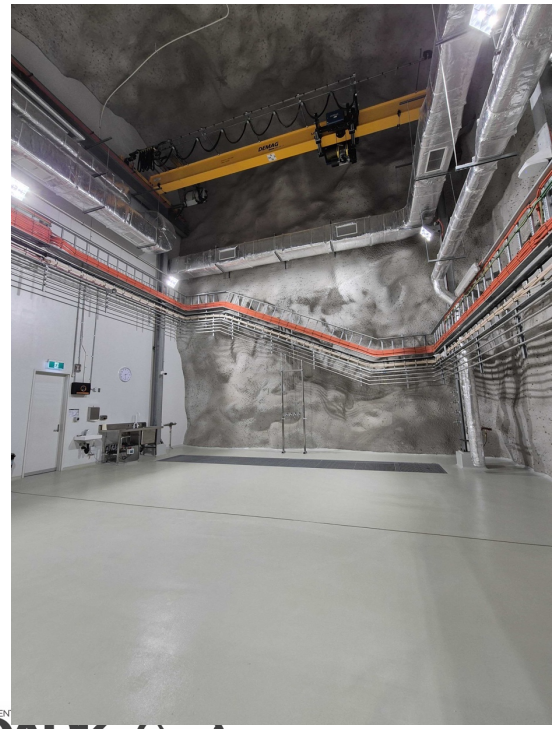
Zone refining ~0.5 cpd/kg/keV_{ee}

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

< 10% of background from non-crystal sources.

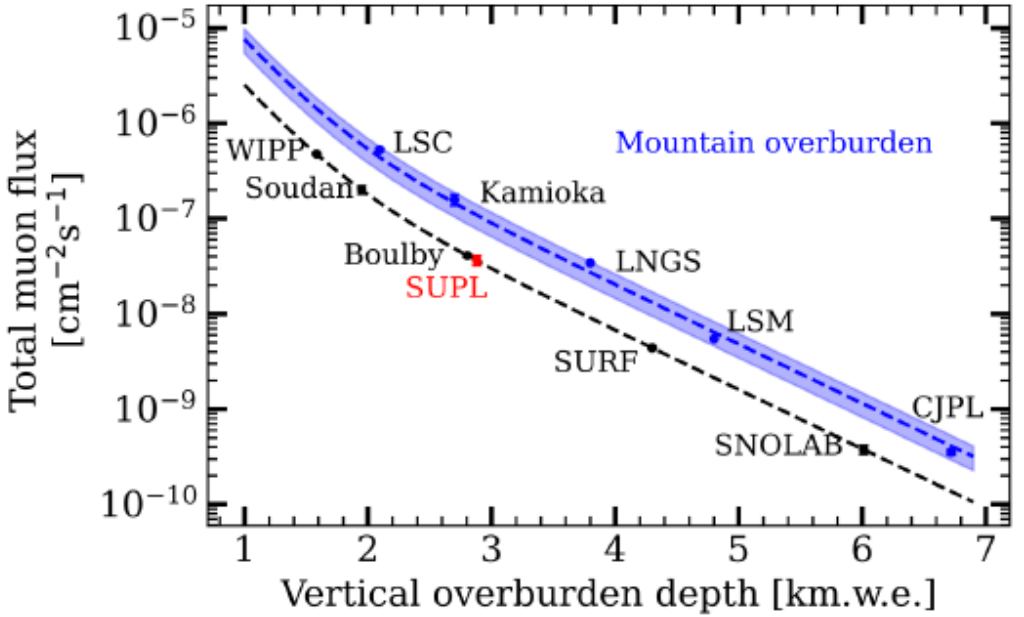
The Stawell Underground Physics Laboratory

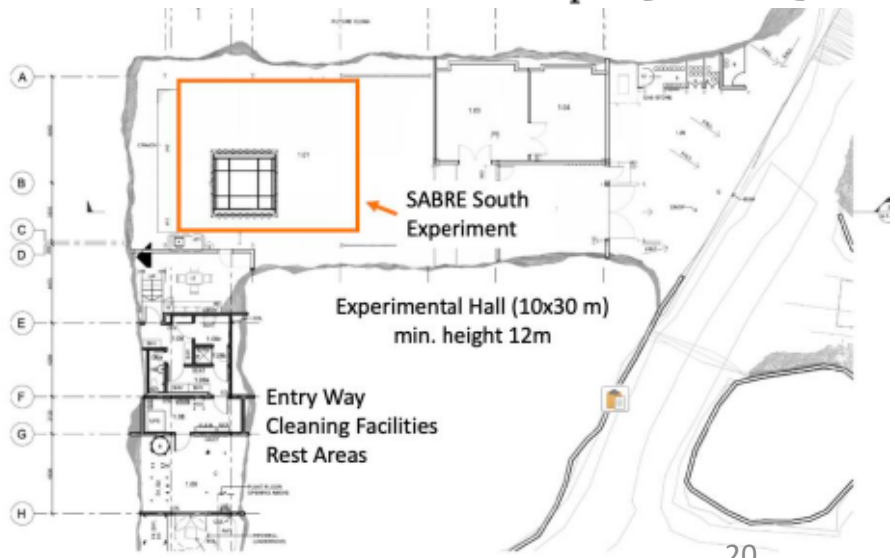
- SUPL is the first deep underground lab in Southern Hemisphere (37°South) located in western Victoria 240 km from Melbourne.
- Lab is 1025 m (~2900 m water equivalent) below ground with flat over burden within the Stawell Gold Mine.
- Helical drive access
- Lab completed in 2022/2023.



Environmental measurements:
muons, radioactivity, neutrons.

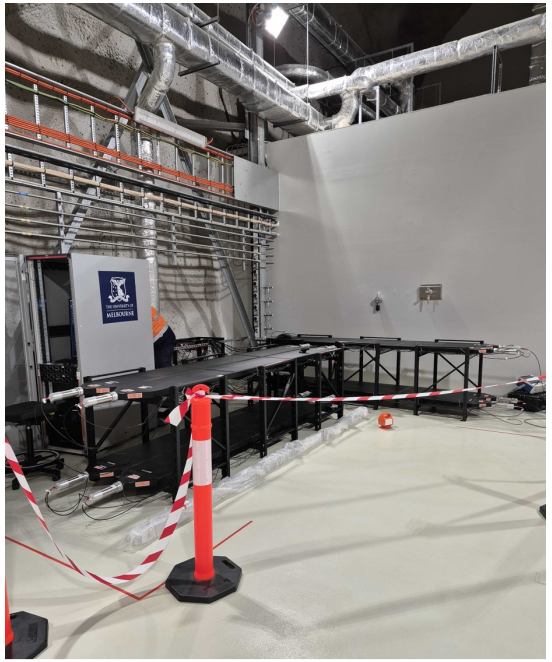
Kyle Leaver's talk – "Neutron Monitoring System at the Stawell Underground Physics Laboratory", session F - Monday 19th August, at 16:40.

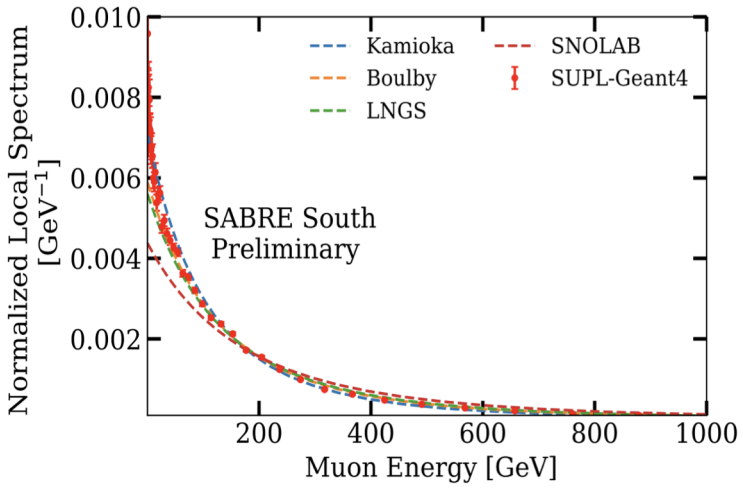


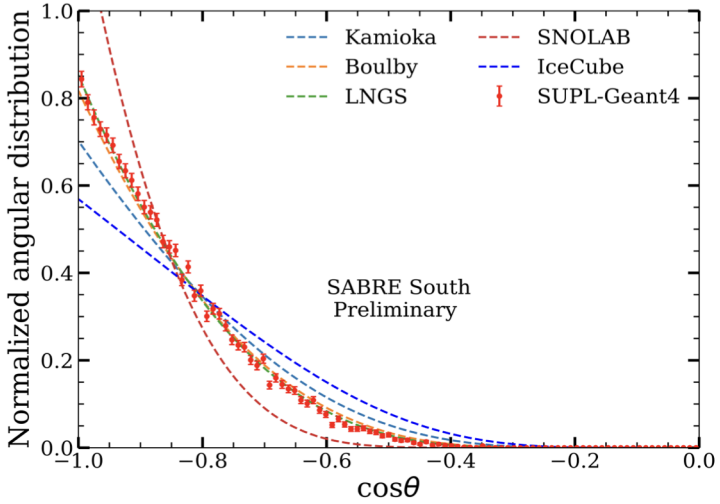


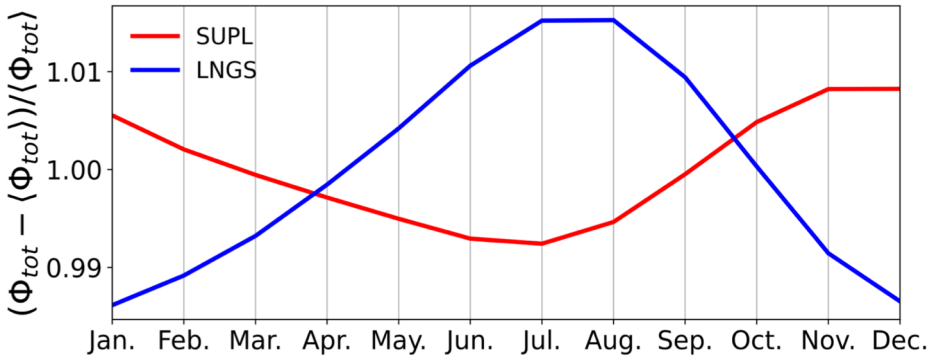
Muon Detector System

- First detectors commissioned early 2024 in SUPL.
- 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.









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

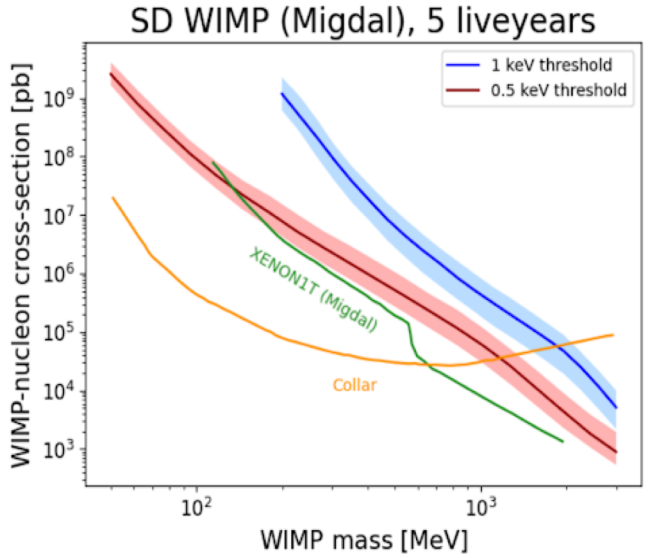
Physics Program

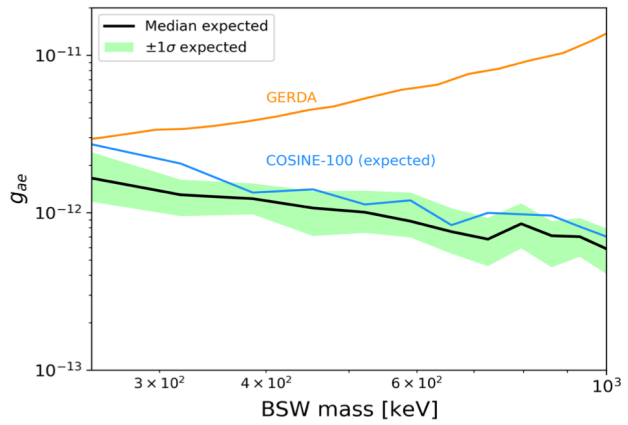
SABRE South has been exploring different types of physics detector can exploit

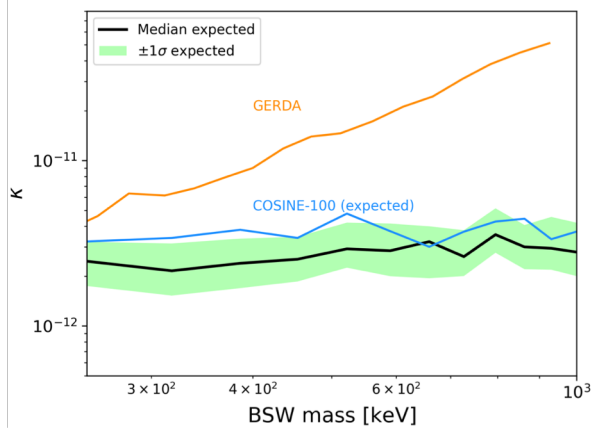
- Both crystal detectors and veto detector.

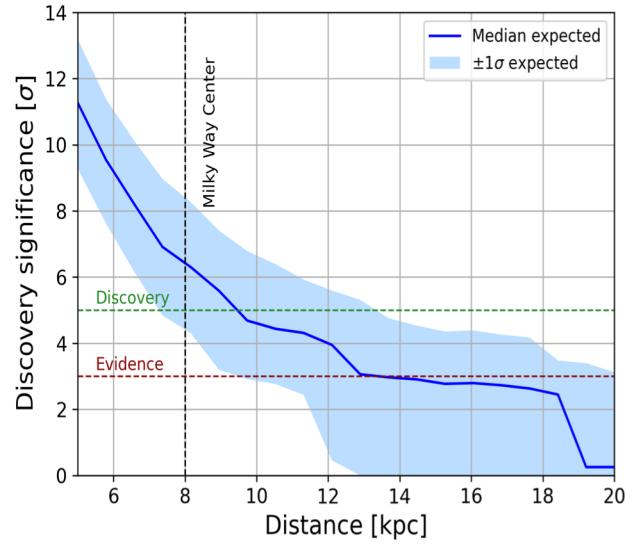
Preliminary sensitivity studies performed on:

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







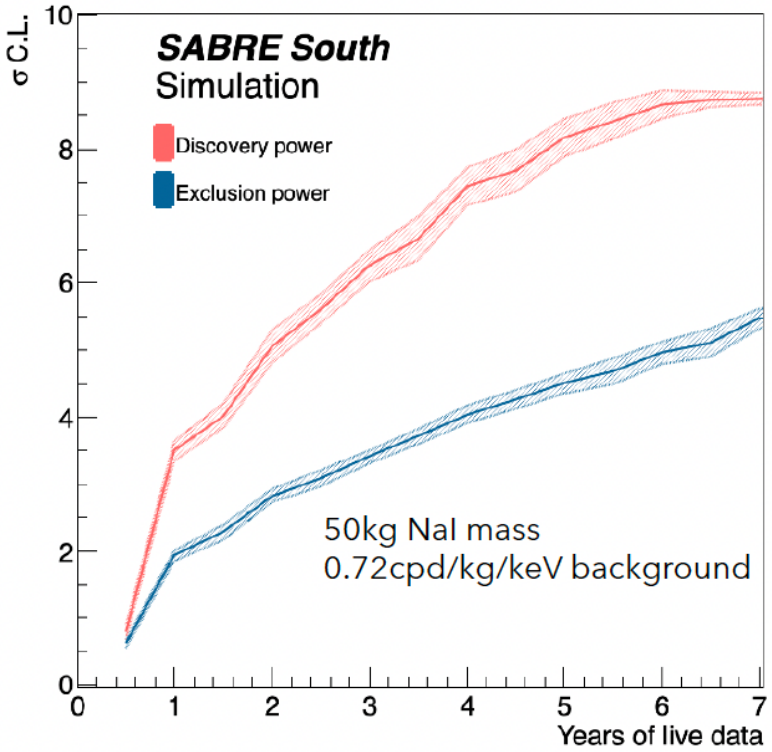


SABRE South TDR, DOI: https://doi.org/10.26188/14618172.v3

Status/Summary

https://www.sabre-experiment.org.au

- SABRE aims to focus on ultra-high purity NaI(Tl) detectors: crystal production is commencing this year.
- Access to SUPL commenced: muon detectors in SUPL since February.
- Pre-calibration of PMTs for veto system complete, publication to come in September 2024.
- Gas handling system and insertion system ready to be deployed. Continued progress on Software/DAQ/Computing/Database.
- Total projected background - 0.72 cpd/kg/keV$_{ee}$.
- Expect discovery or exclusion results with 2 years data (with a single site).
- NaI(Tl) experiments (ANAIS, COSINE, SABRE South and North) signed an agreement to collaborate and exchange knowledge.
- Rich physics program – SABRE South potential inclusion in SNEWS.
- Induced modulation studies: modulation not induced by background subtraction method https://arxiv.org/abs/2408.08697



SABRE South Technical Design Report
DOI: https://doi.org/10.26188/14618172.v3

Acknowledgements

South

Australian Government
Australian Research Council

KEK-JAPAN

SWINBURNE

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY of ADELAIDE

Australian National University

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

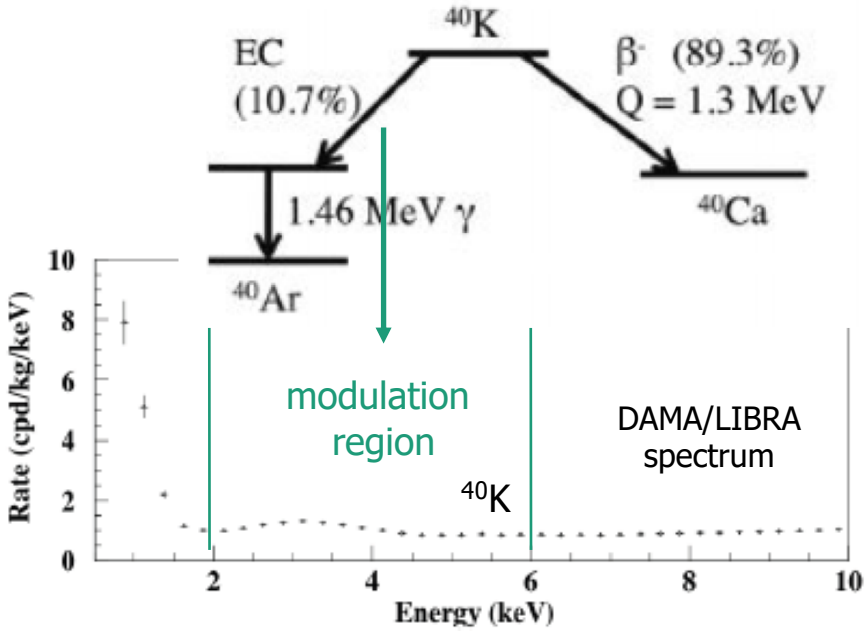
PRINCETON UNIVERSITY

UNIVERSITÀ DEL SALENTO

Background from ^{40}K

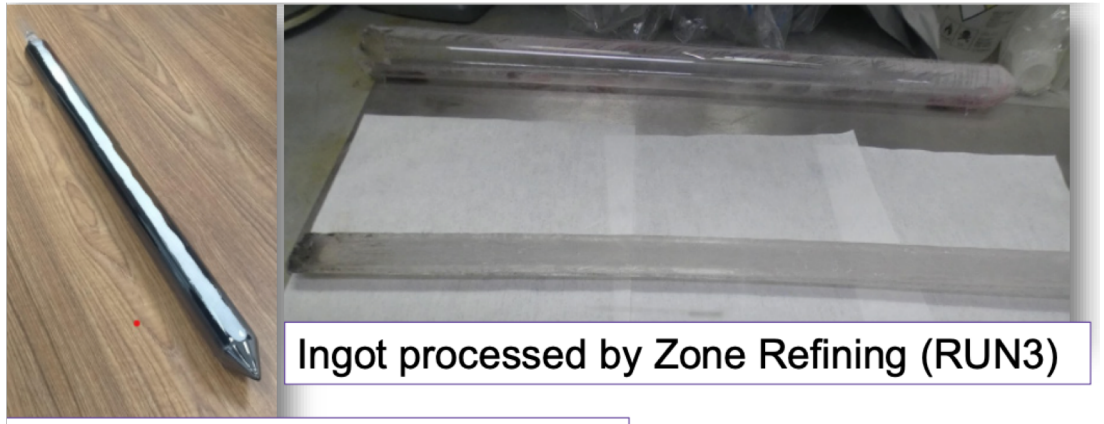
Most dangerous long-lived background in the Region of Interest:

- **^{40}K** decays by e^- capture (BR~11%).
- excited state of ^{40}Ar emitting a 1461 keV gamma.
- Auger e^- or X-ray followed by a cascade with a total energy of 3.2 keV.



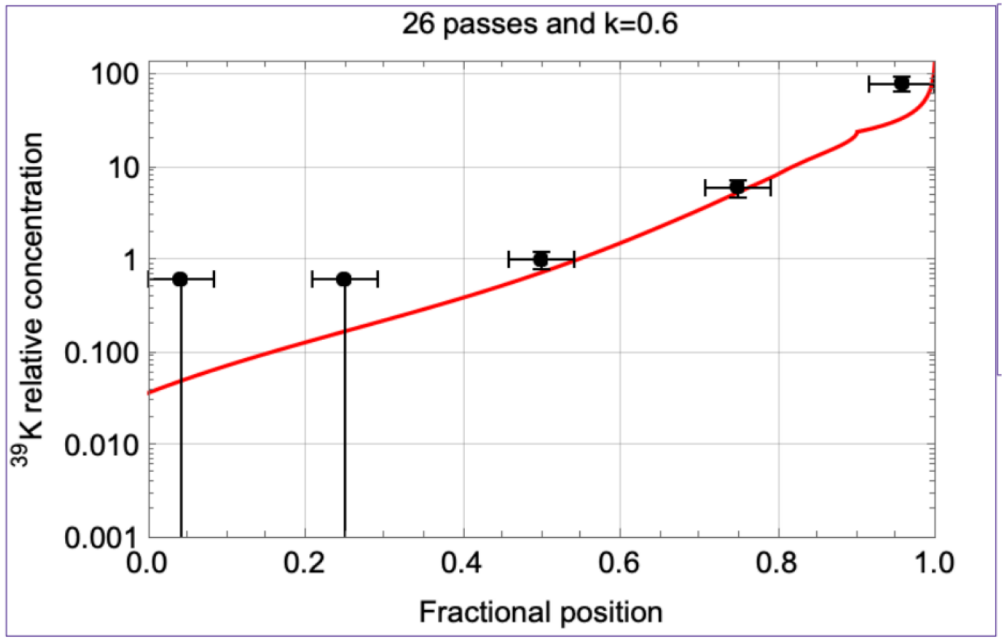
Zone Refining Technique

- RUN1: Carbon coated ampoule
- RUN2: Carbon coated ampoule with increased number of passes
- RUN3: No coating + use of SiCl4 to avoid sticking
- RUN4: No coating + use of SiCl4
  Ampoule sealed without gas inside



Ingot processed by Zone Refining (RUN3)

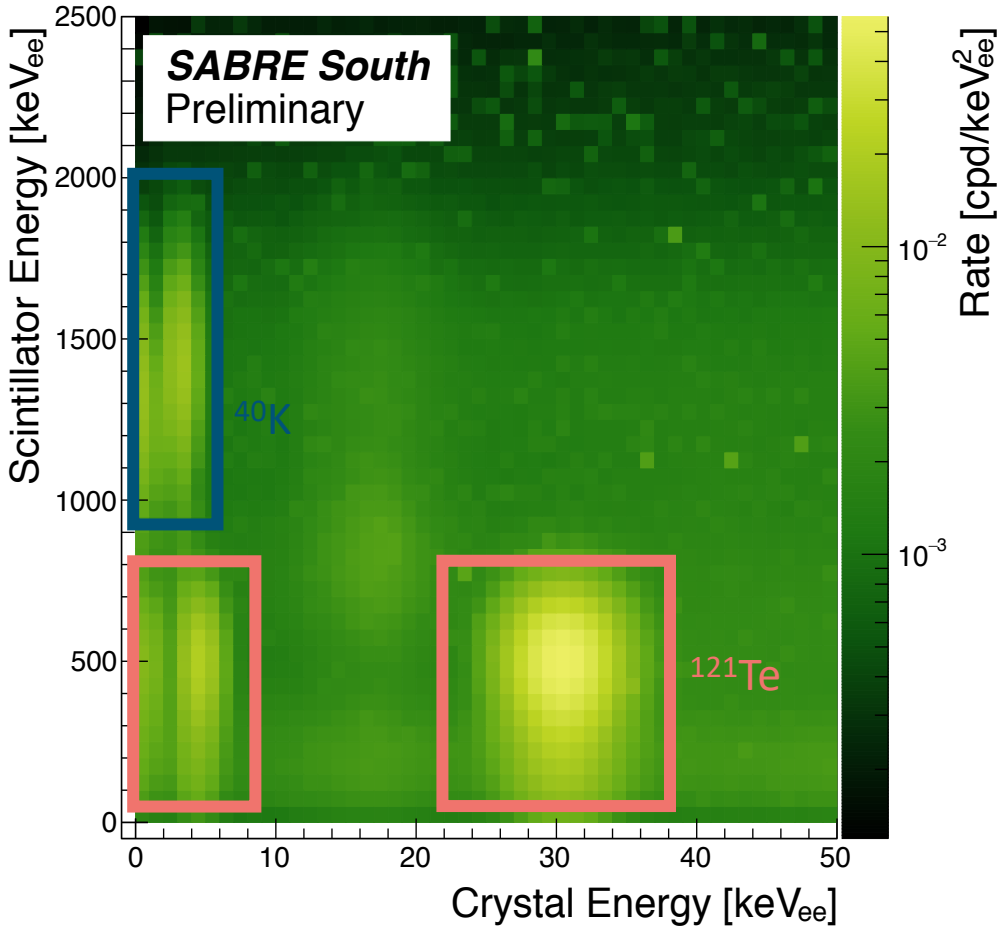
Carbon coated ampoule (RUN1)



For each run taken 5 samples from ingot of length equal to 60 cm taken and shipped to Canfranc Laboratory and Seastar for ICPMS measurements.

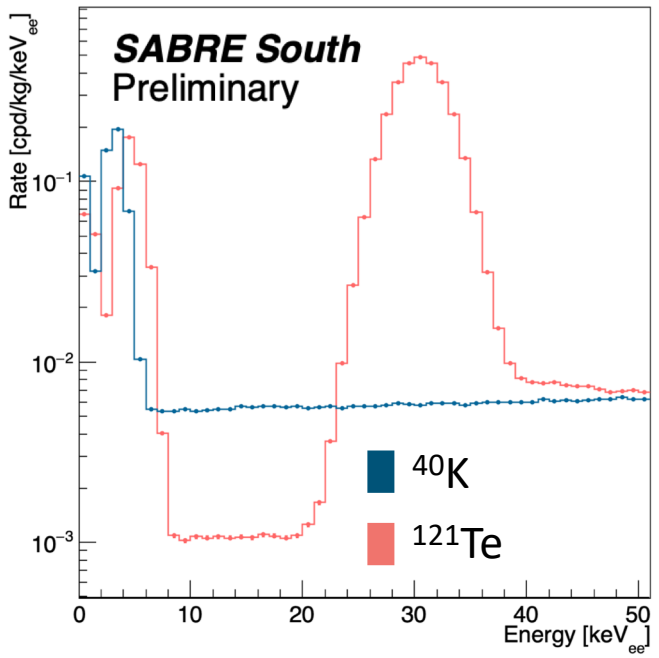
Total Background Model

Veto system not only reduces background but also allows for in situ measurements and particle ID.

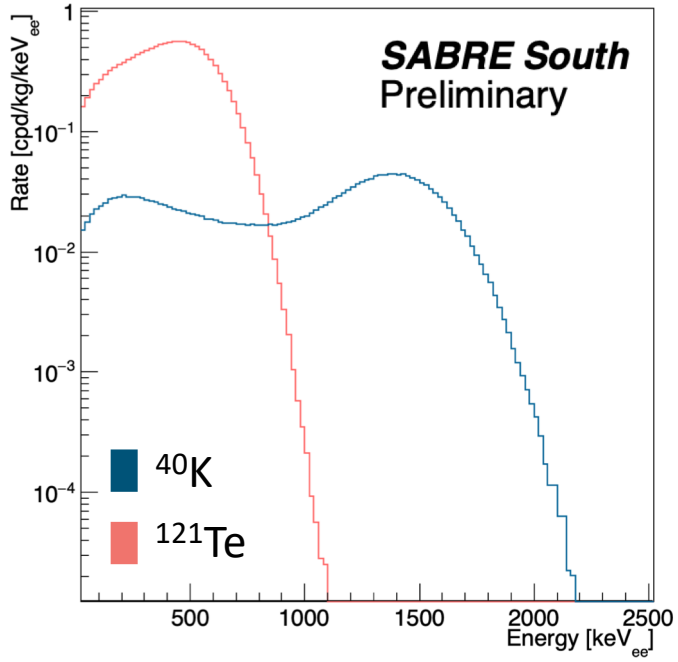


E.g., ^{40}K and ^{121}Te both have distinct islands in crystal-scintillator energy plane

Rate in crystals



Rate in liquid scintillator



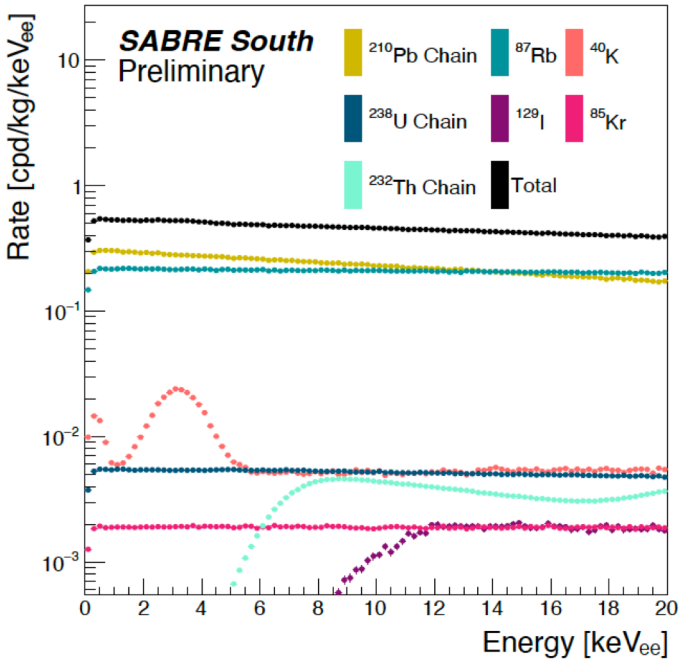
SABRE South Collab. arxiv:2205.13849

NaI(Tl) Background Simulations

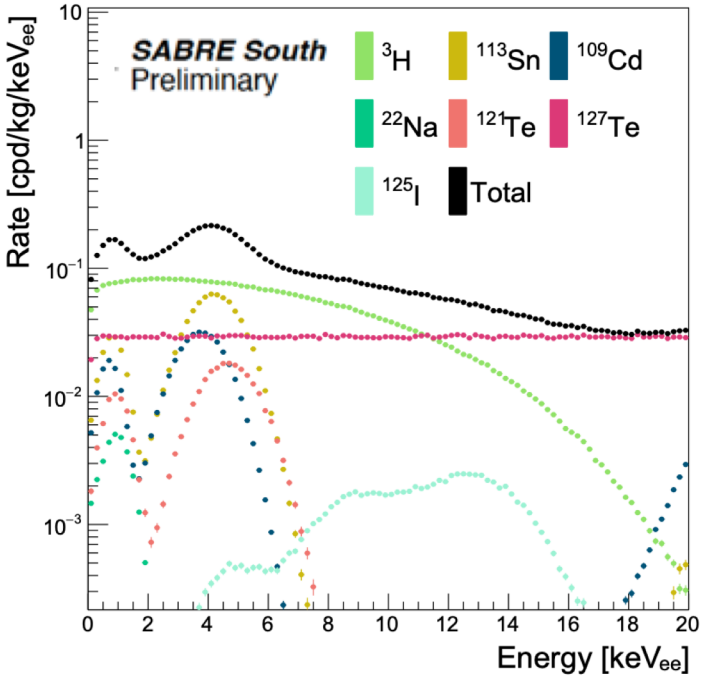
- Background of SABRE South crystal have been both simulated and directly measured (on NaI-33) with Inductively coupled plasma mass spectrometry (ICP-MS).
- Main radiogenic background represented by ^{210}Pb, ^{87}Rb (very conservative upper limit). No ^{87}Rb was found with the ICP-MS measurement, and the order of magnitude of this contamination is currently unknown.
- Cosmogenic background after 180 days underground mainly due to ^{3}H (12.4 yrs) and ^{113}Sn (115 days).

SABRE South Collab. arxiv:2205.13849

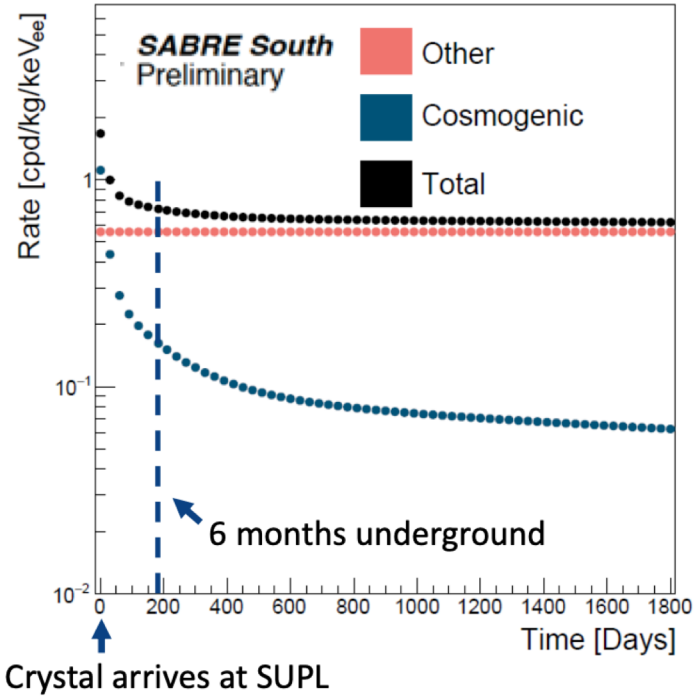
Radiogenic Background



Cosmogenic Background
(6 months underground)

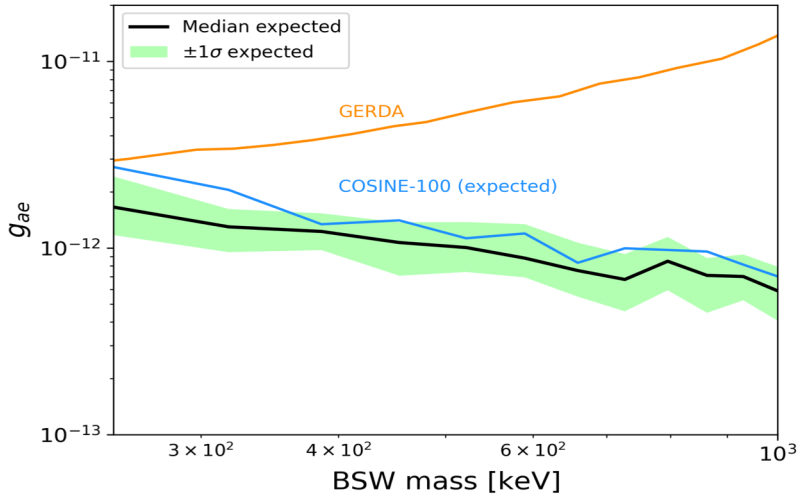


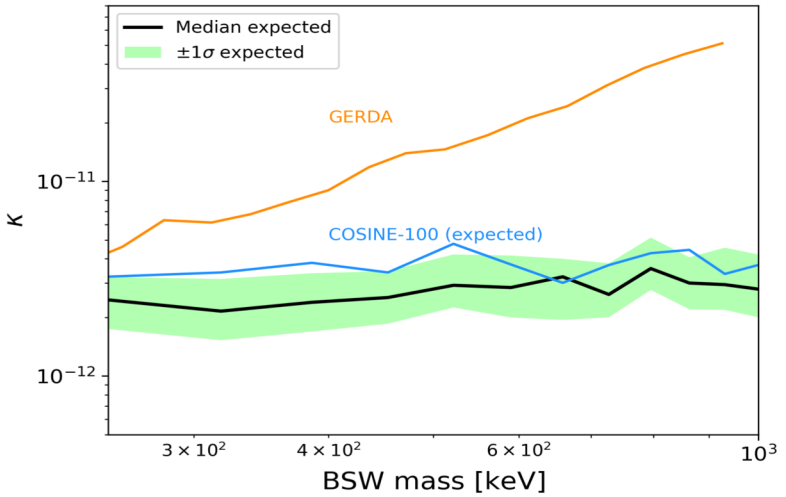
Time Dependence of Background



Sensitivity to bosonic super-WIMPs

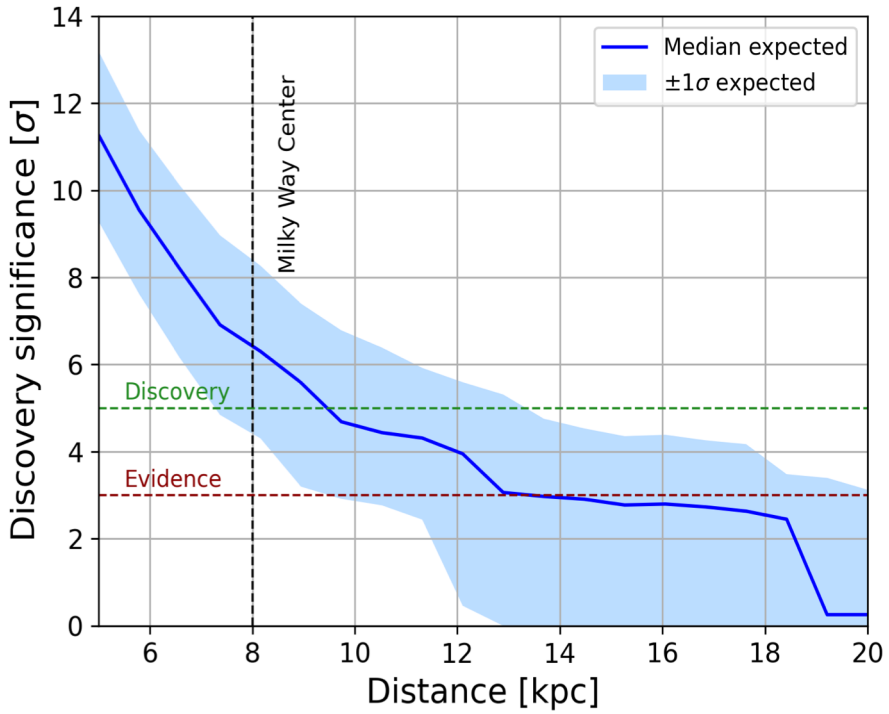
- Viable keV-scale pseudoscalar and vector bosonic dark matter candidates can be proposed in EFT extensions of the Standard Model. In a bosonic scenario, couplings consistent with astrophysical bounds are accessible to direct detection experiments.
- Interactions in NaI(Tl) experiments can take place via either absorption (considered here) or Compton-like scattering (deferred to future work).
- For ~100 kg year exposure SABRE South could set world-leading constraints on these channels (current world-leading constraints from COSINE-100 [1]).





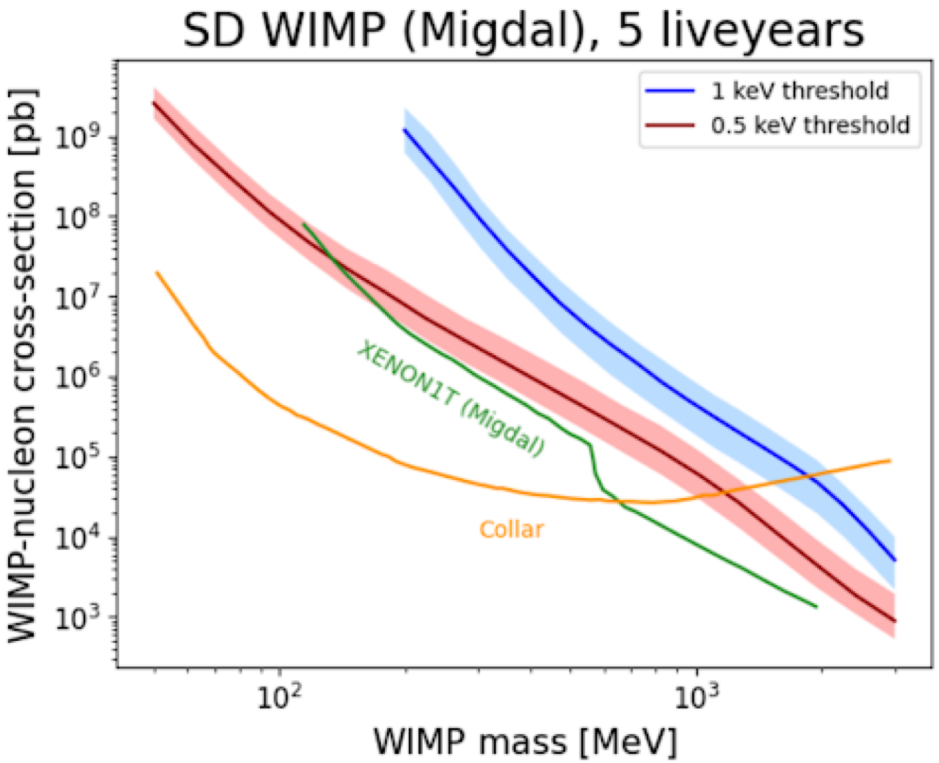
Supernova neutrino detection

- LAB liquid scintillator veto system could be used as a detector for supernova neutrino scattering.
- Core-collapse supernova explosion produces an intense flux of neutrinos over ~10 s.
- Projected sensitivity of the SABRE South veto system to a typical (27 solar masses) core-collapse supernova explosion at different distances: currently assuming nominal number of PMTs.
- Potential for SABRE South to become part of the supernova early warning system (SNEWS).



Sensitivity to spin-dependent WIMPs

- Odd number of protons in both sodium and iodine: NaI target is particularly sensitive to spin-dependent WIMP scattering
- So-called Migdal effect predicts enables a lower threshold: portion of the nuclear recoil energy is deposited in the electron recoil channel (not quenched)
- Here, we project the 90% C.L. expected upper limit over 5 live years with 50 kg crystal mass for the nominal 1 keV threshold as well as a 0.5 keV threshold that may be within reach with advanced PMT noise rejection techniques



SABRE North status

3 x 3 matrix of crystals of ~5 kg mass each

Fully passive **shielding** design: **15 - 25 cm copper + 40-60 cm PE**
→ enough shielding power and negligible contribution to the total background

- Expected background **0.5 cpd/kg/keV (with ZR)** or 1 **cpd/kg/keV (w/o ZR)**

CDR presented in July 2021 **TDR due in summer 2024**

- **if approved, begin installation in 2025**
- **crystal production and detectors deployment 2025-2027**

Two story's building:
Ground floor (PT): set-up SABRE NORTH
First floor (P1). DAQ & counting room

New SABRE experimental area at LNGS.