Exploring the Dark Side of the Universe
EDSU–Tools 2024

The SABRE South Experiment at the Stawell Underground Physics Laboratory

Owen Stanley on behalf of the SABRE South collaboration

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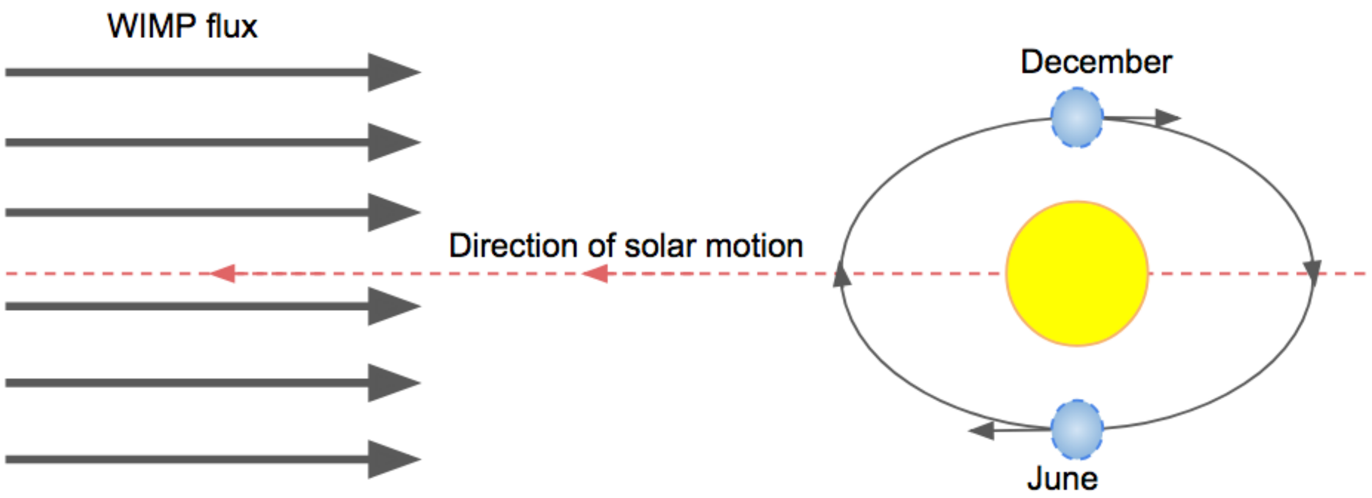
Annual Modulation



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

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

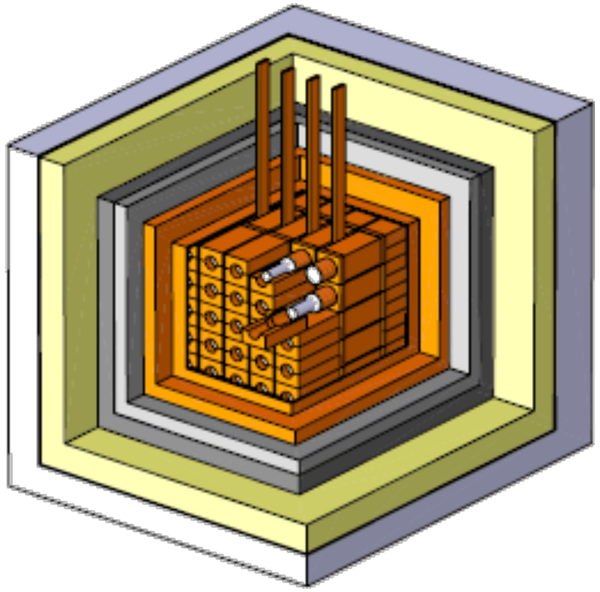
Non-Modulating DM rate

Modulating DM rate

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

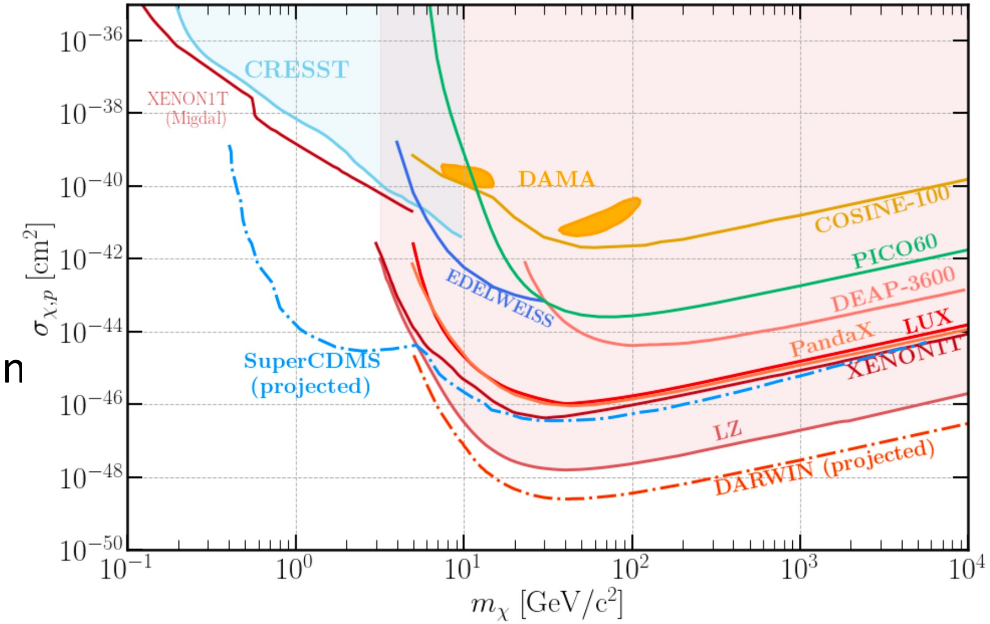
Annual Modulation:
- **Model Independent signature of DM**
- **Require strict control over modulating backgrounds**

Motivation- DAMA/LIBRA Results

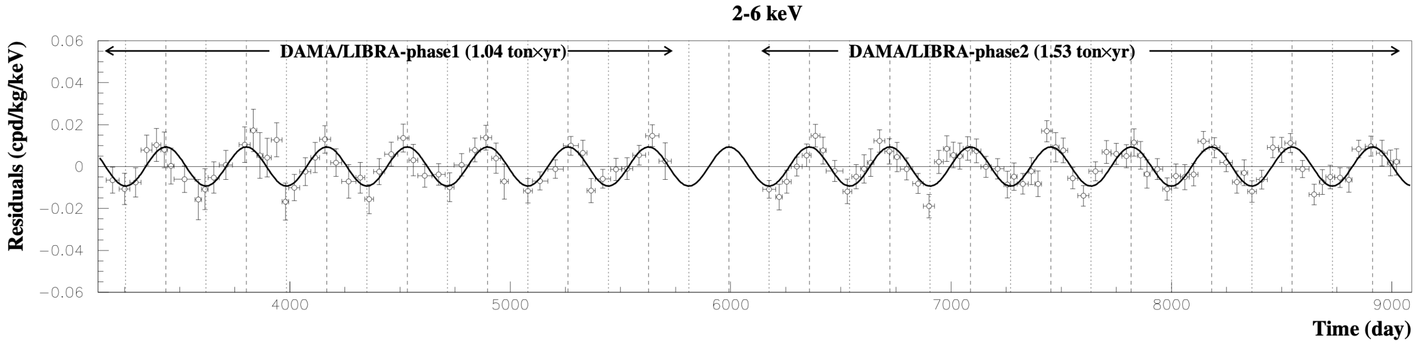


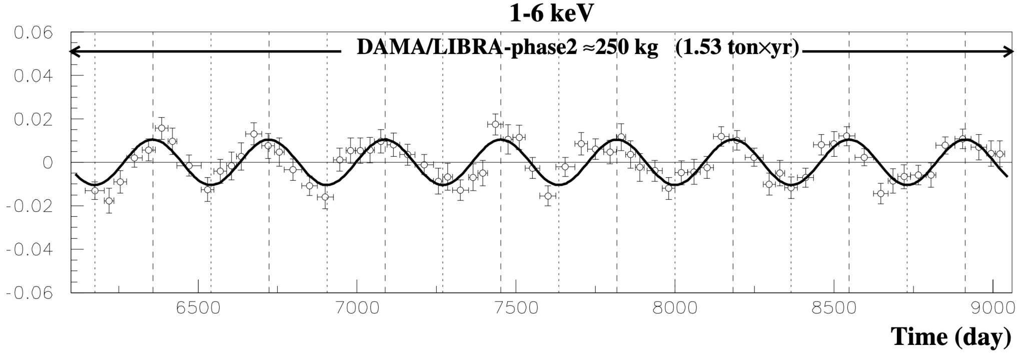
The DAMA/LIBRA Experiment has been running for 20+ years

- 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



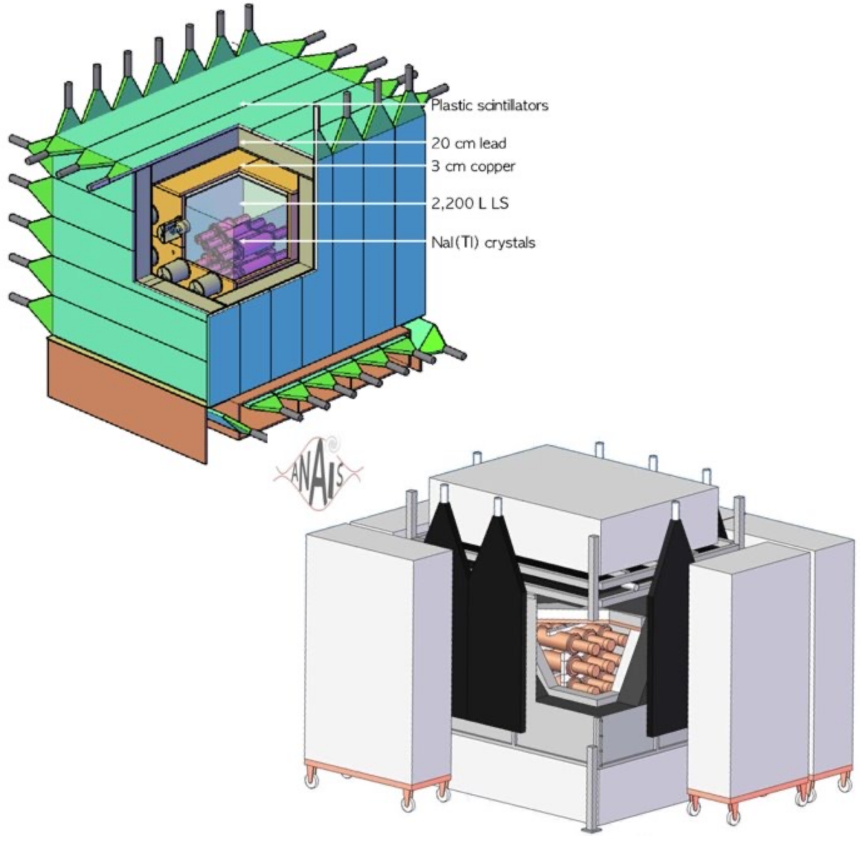
https://github.com/cajohare/NeutrinoFog

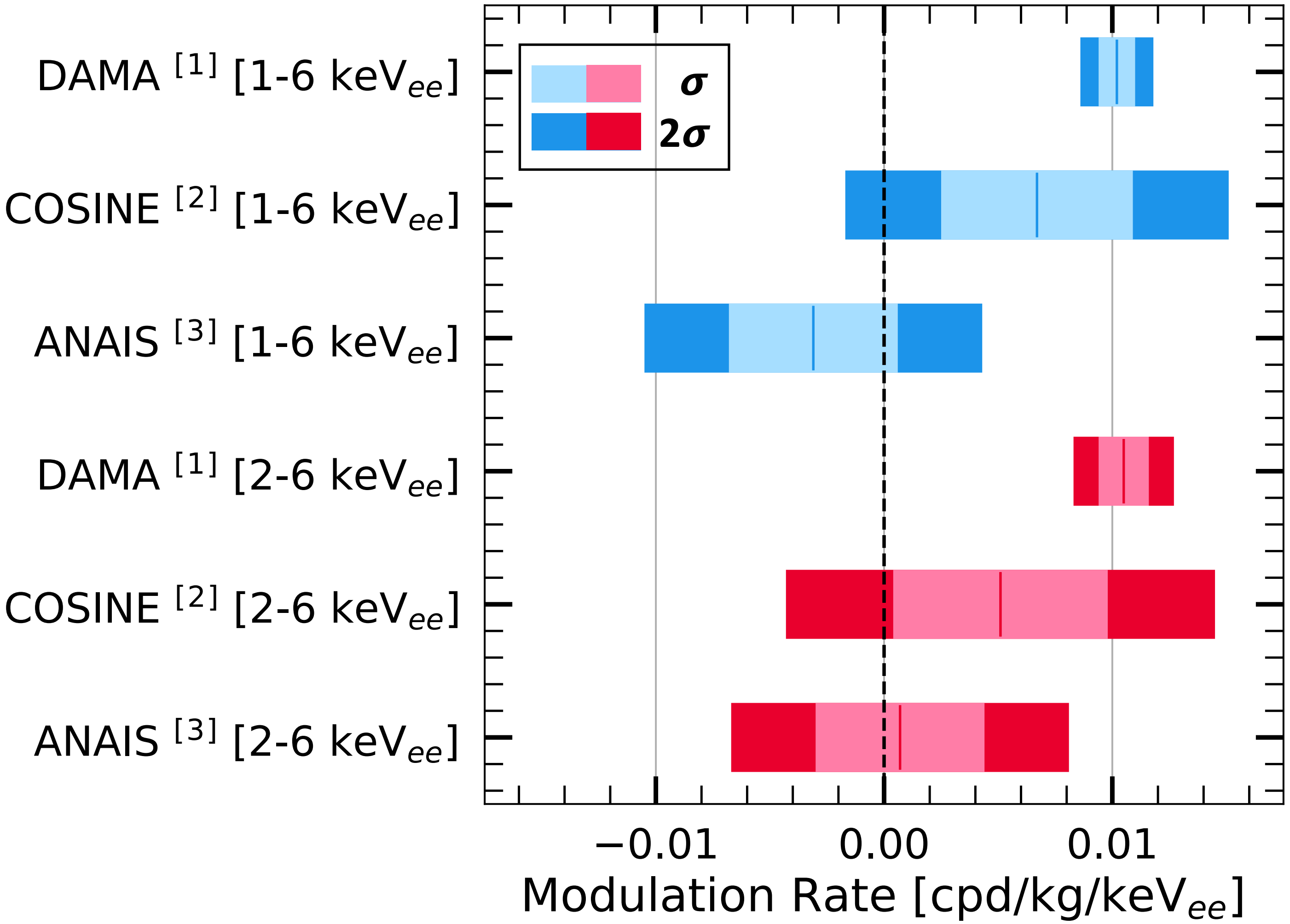




R. Bernabei et al., Annual Modulation results from DAMA/LIBRA, 2023

Current running NaI(Tl) detectors



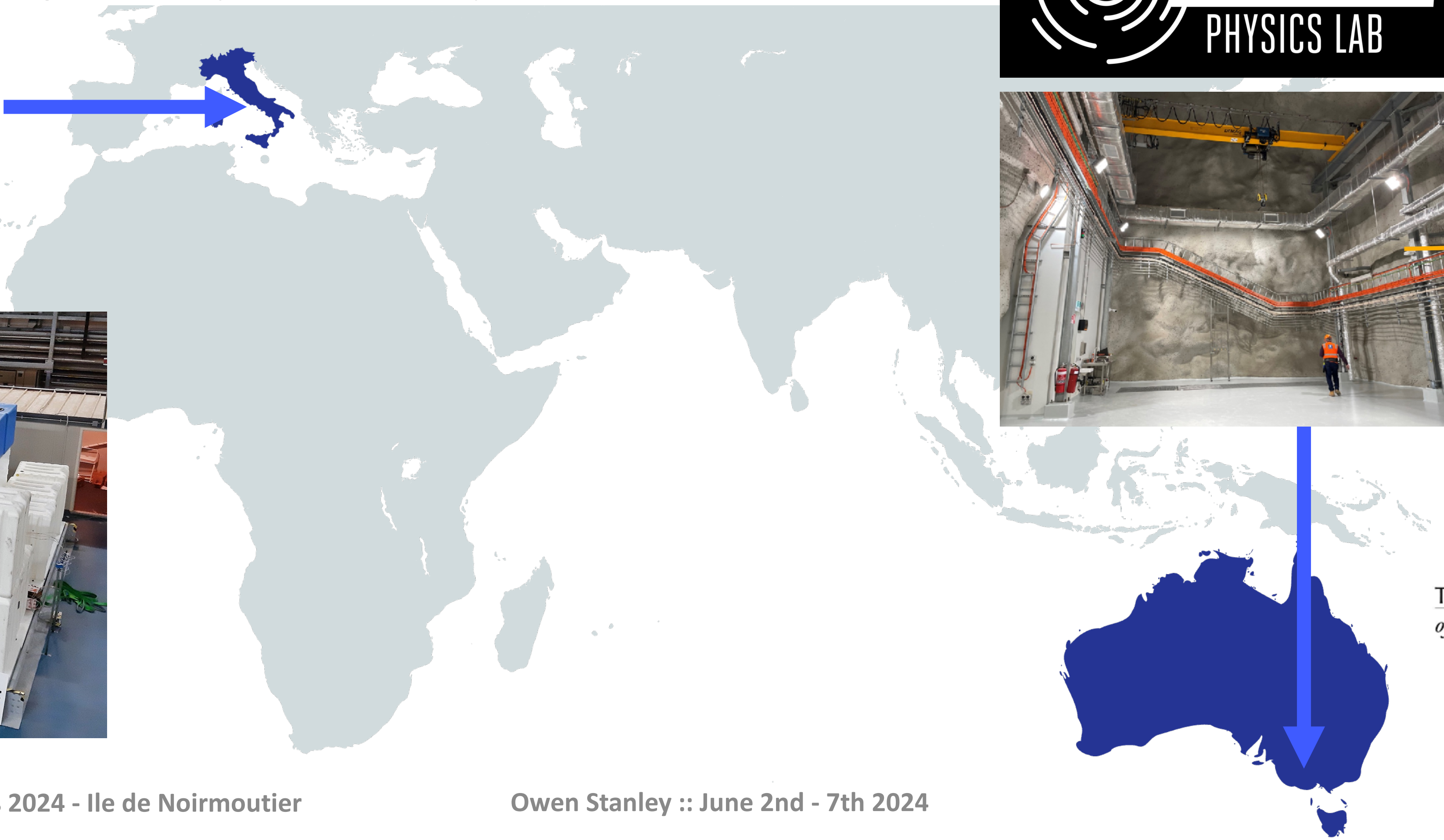


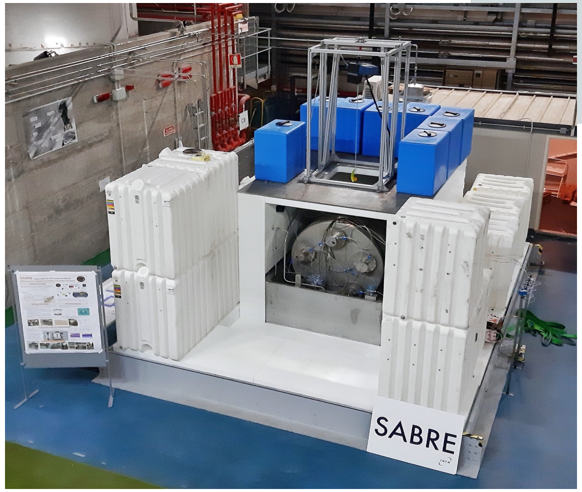
[1] R. Bernabei et al., Annual Modulation results from DAMA/LIBRA, 2023
[2] G. Adhikari et al., Three-year annual modulation search with COSINE-100, 2021.
[3] I.Coarosa et al., ANAIS-112 three years data: a sensitive model independent neg the DAMA/LIBRA dark matter signal.

SABRE: a dual site experiment

The ambitious program of SABRE foresees two detectors in two underground locations:

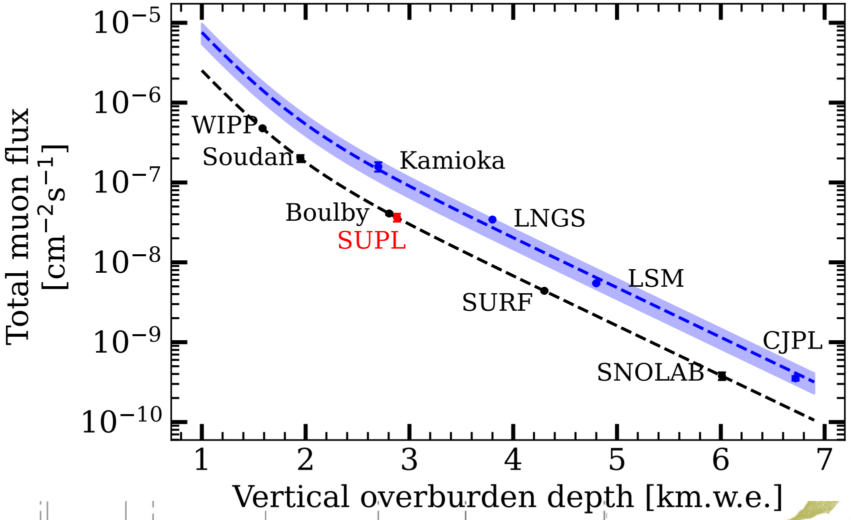
- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

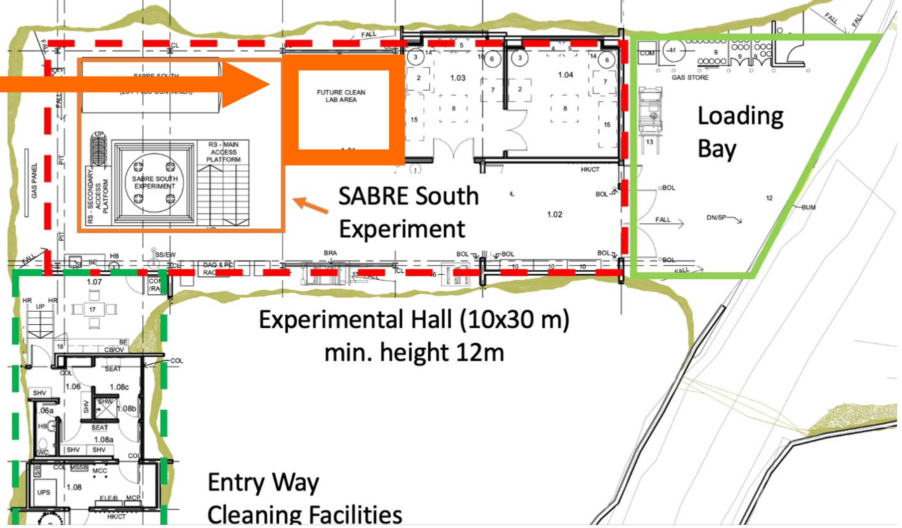




Stawell Underground Physics Laboratory

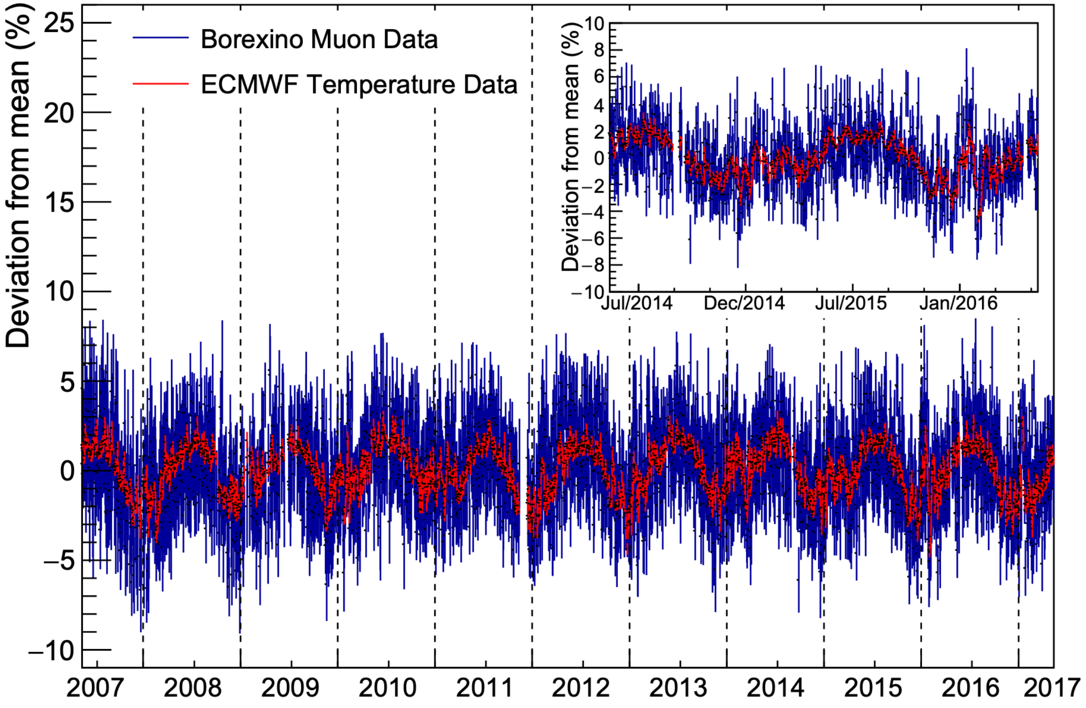
- **SUPL** is the first deep underground lab in the Southern Hemisphere **(37º South)** located 240 km west of Melbourne
- Lab is 1025 m (approx. **2900 m w.e.**) underground with a **flat** over burden inside of the Stawell Gold Mine.
- Helical drive access.
- Commissioning started in **November 2023**



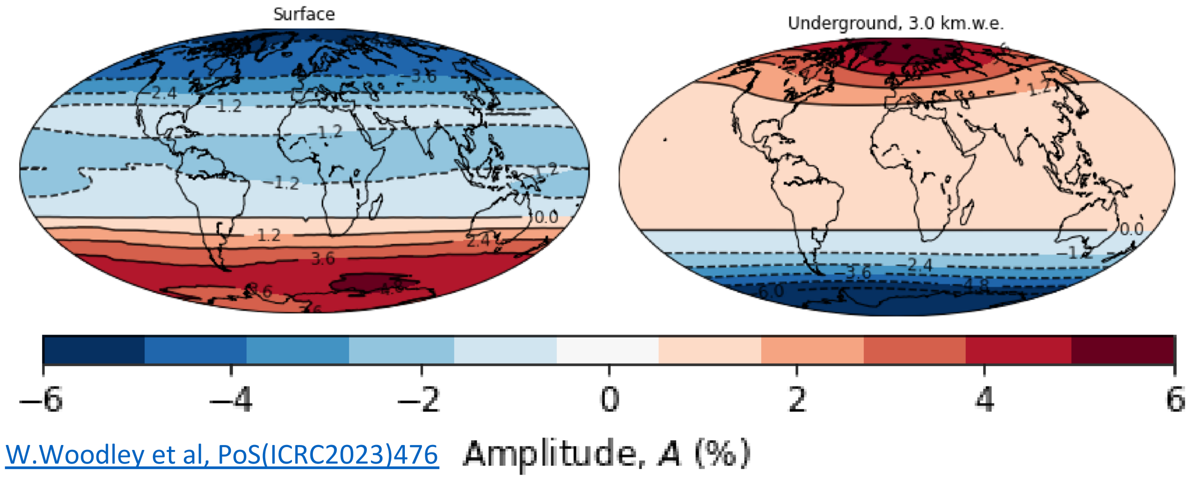


Exclusion of seasonal effects

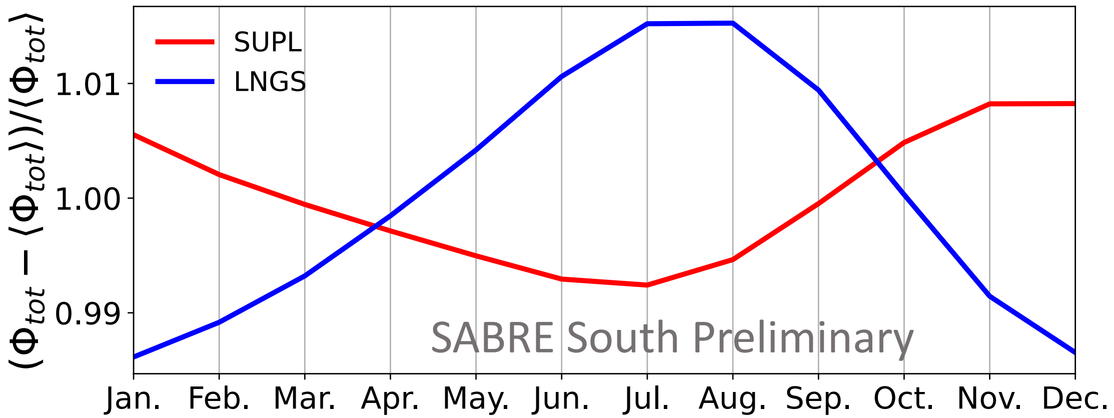
- The site in the northern and southern hemisphere is important to exclude seasonal effects.
- Muons are particular issues for the DM modulation search as they have similar seasonal phase due to seasonal dependance.



Borexino collab. JCAP02(2019)046



W.Woodley et al, PoS(ICRC2023)476



The SABRE Collaboration

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

- **Same detector** module concept (**Ultra-pure** crystals and HPK R11065 PMTs)
- **Common** simulation, DAQ and software 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 to background rejection and particle identification.

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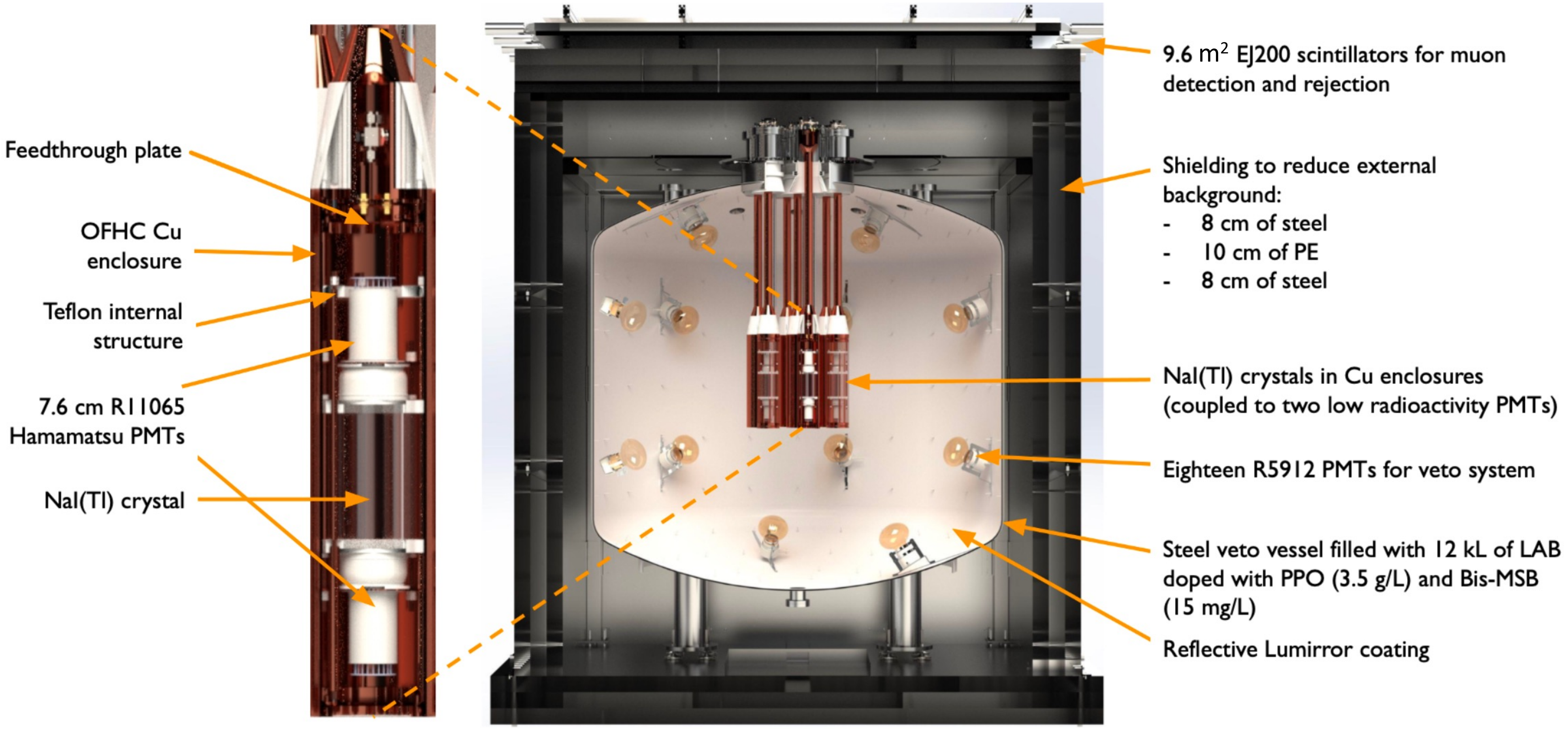
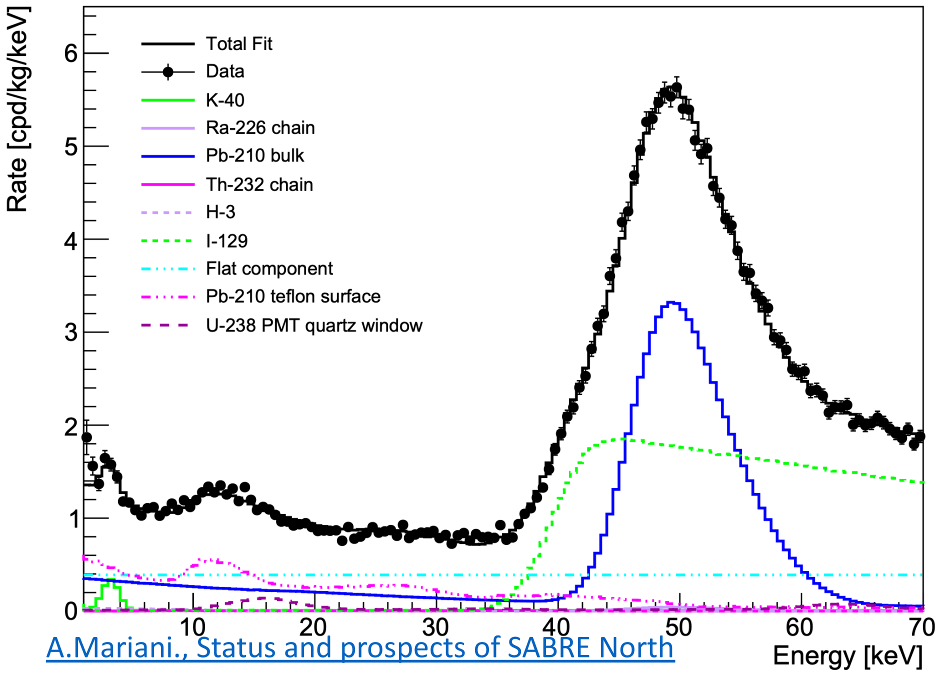
SABRE South Detector



High-purity NaI(Tl) crystals

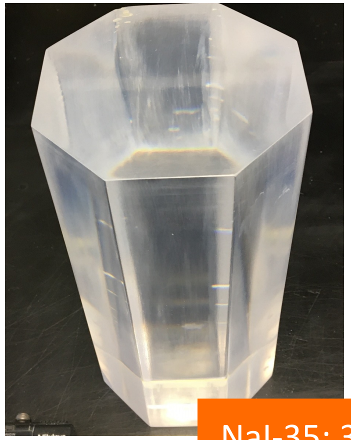
- Ultra-pure Astrograde NaI powder from R&D with Merck.
- High-purity, low background crystals are being grown in collaboration with Princeton and RMD and SICCAS.
- Four crystals have been tested at LNGS.
- Light yield 9-12 phe/keV.



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	$(5\text{-}30)\times10^{-3}$	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	-	$<5.7\times10^{-3}$	-	~20 (goal)

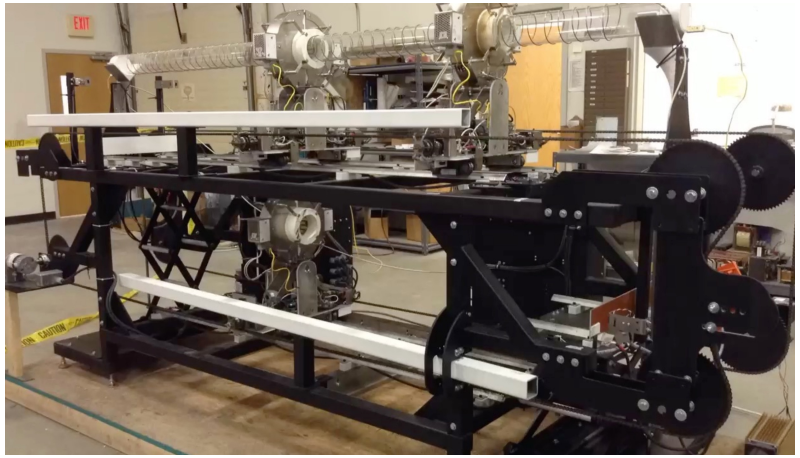
NaI-33: 3.40 kg



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)

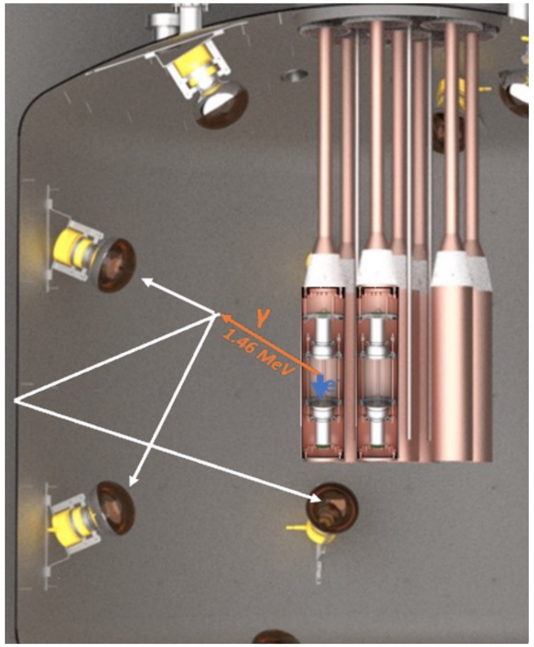
High-purity NaI(Tl) – Zone Refining



- 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

Active background rejection



2 main systems:

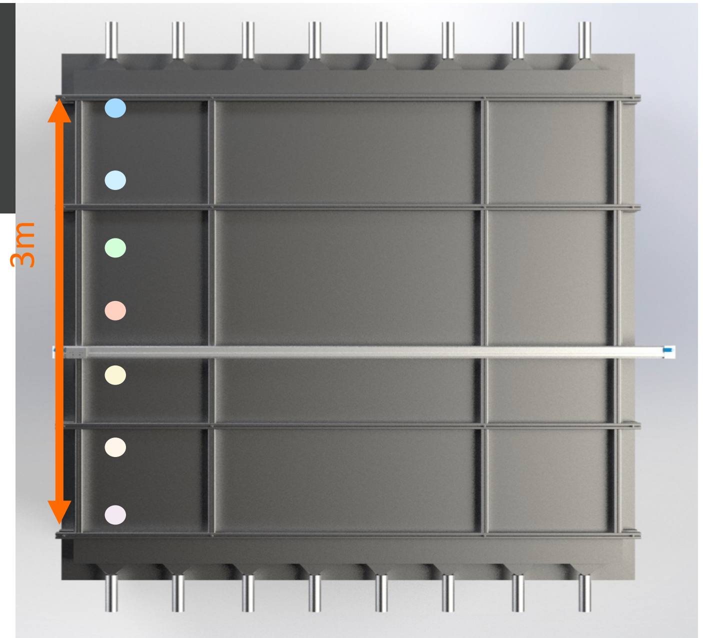
Linear Alkyl Benzene (LAB)

- 18x R5912 PMTs
- 12 kL (sourced from JUNO)
- PPO and Bis-MSB doped

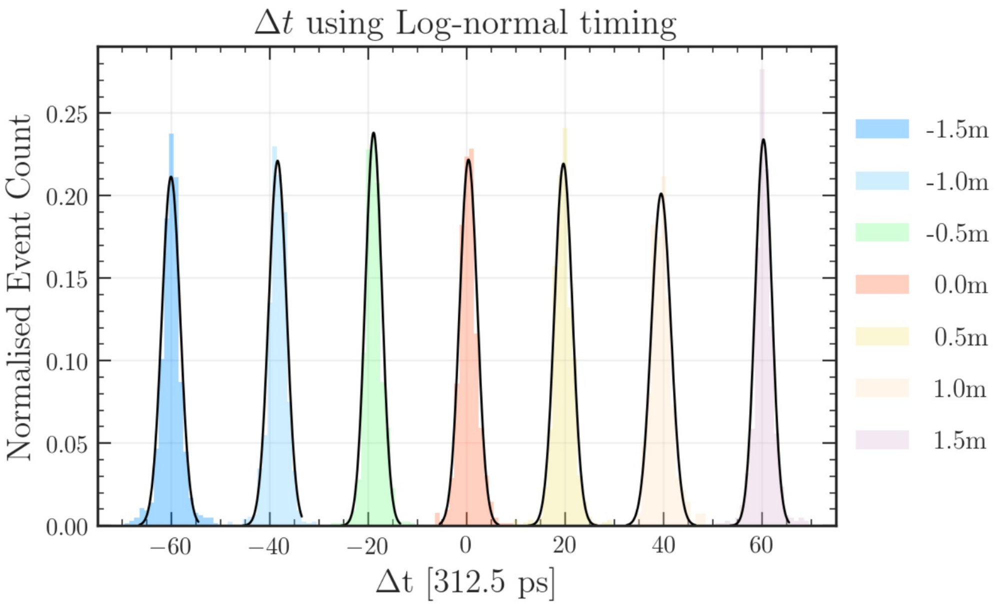
Provide **tagging** of high energy radiogenic decay.

Muon detector:

- Cover **9.6 m²** above the detector
- Measure cosmic ray muon
- Provides **improved** particle ID and localization in the LAB



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%

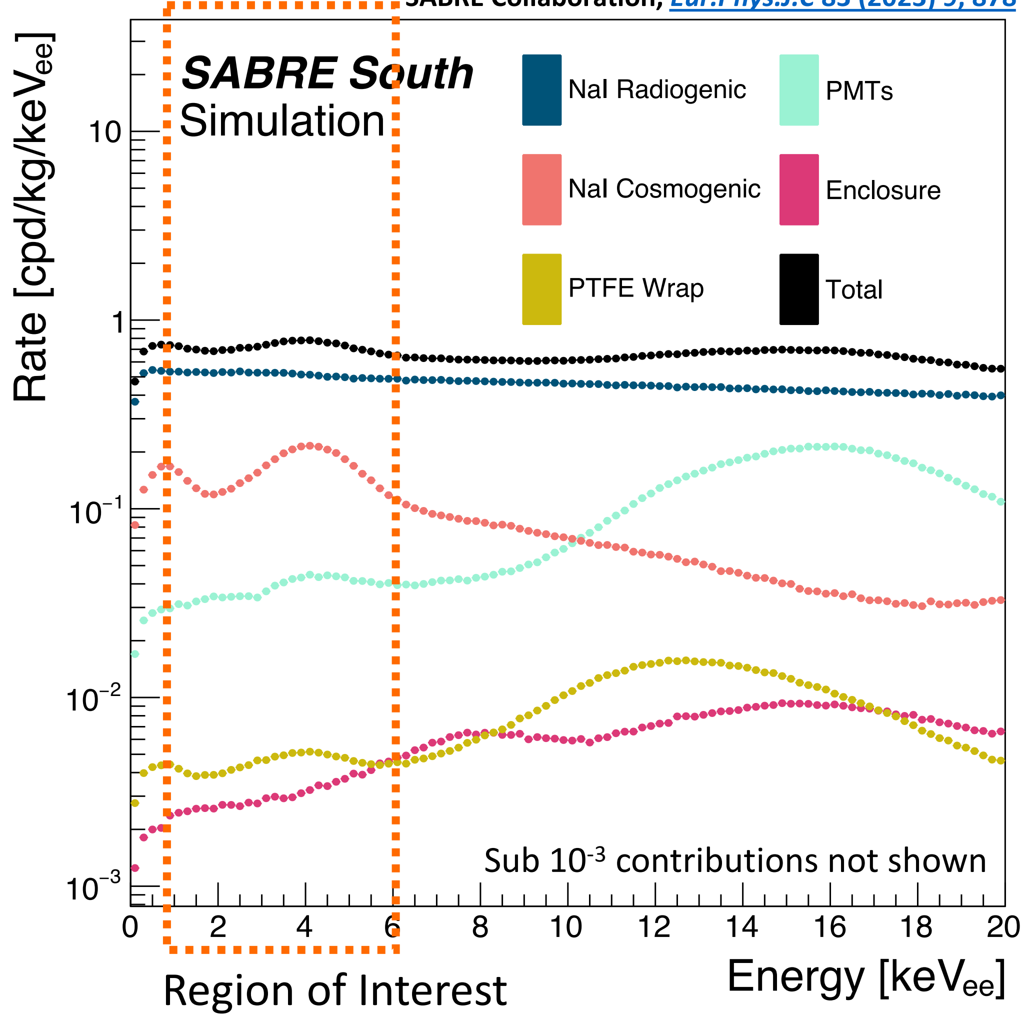


Total Background Model – VETO

< 10 % background from non-crystal sources

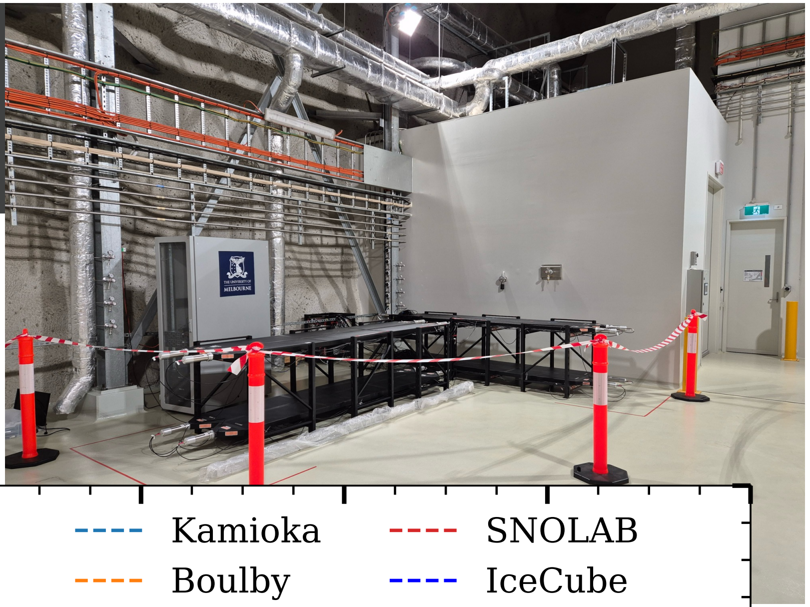
With Zone refining $3x10^{-1}$

SABRE Collaboration, *Eur.Phys.J.C* 83 (2023) 9, 878



Component	Rate (cpd/kg/keV)	Veto efficiency (%)
Crystal Intrinsic	< 5.2×10^{-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

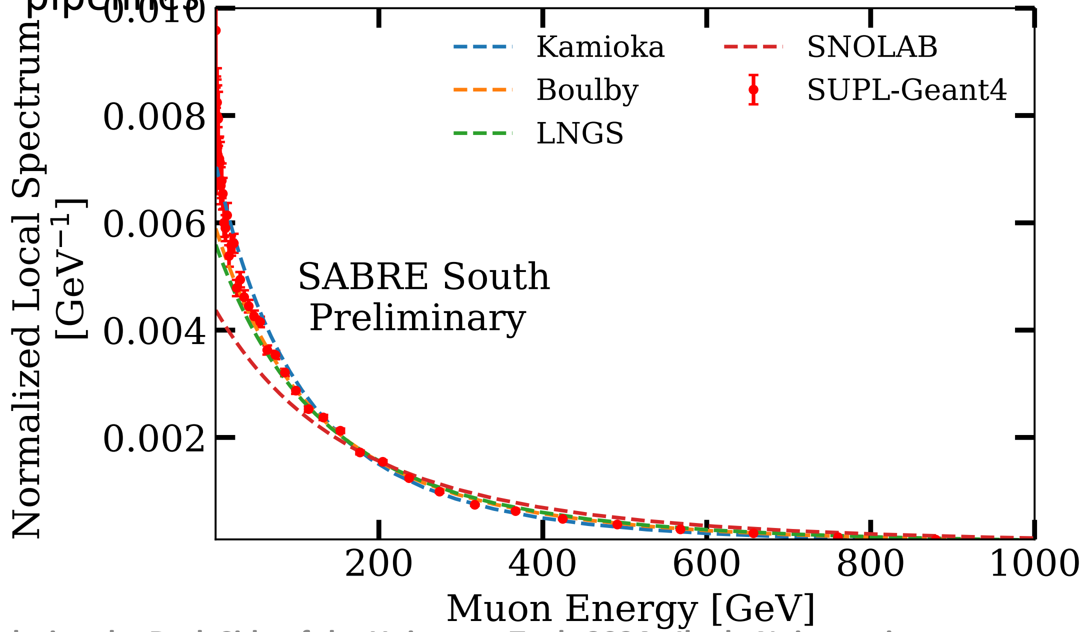
Towards muon flux measurements

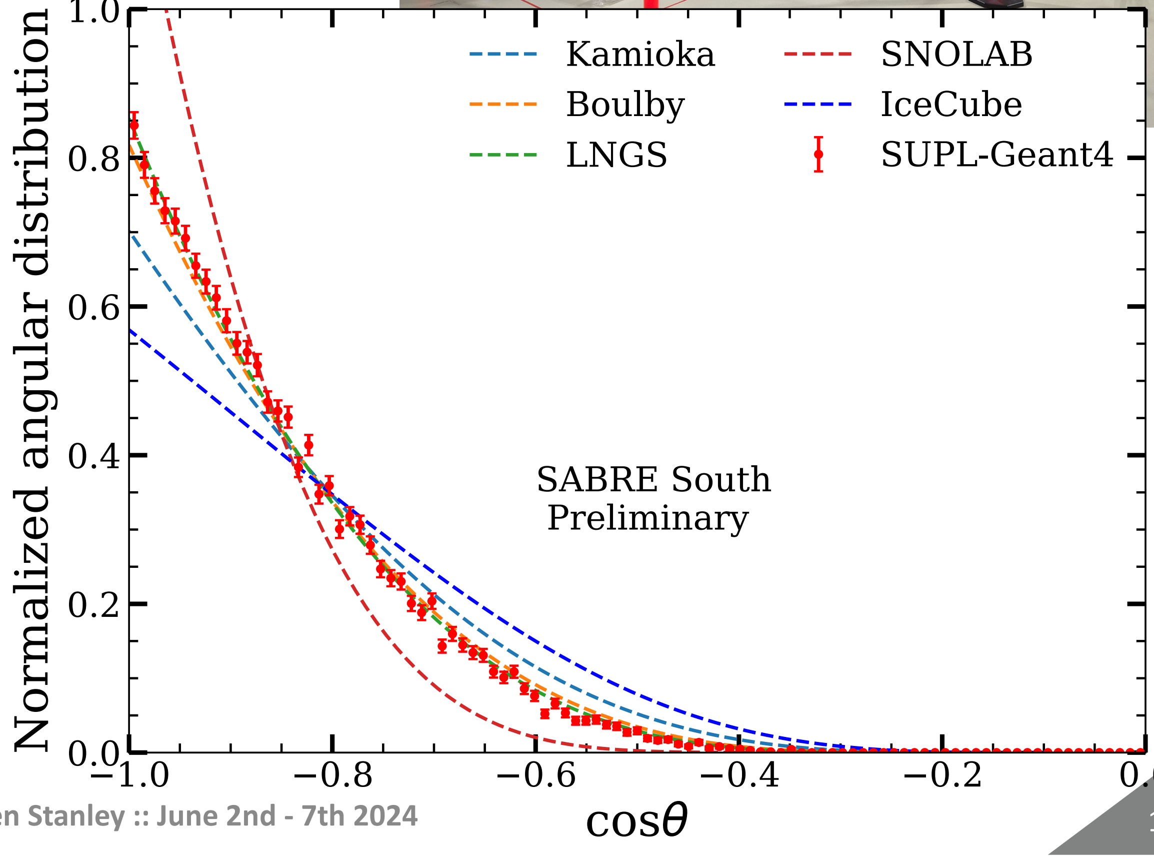


Muon detectors have been **installed** for muon flux measurements at SUPL and currently collecting data.

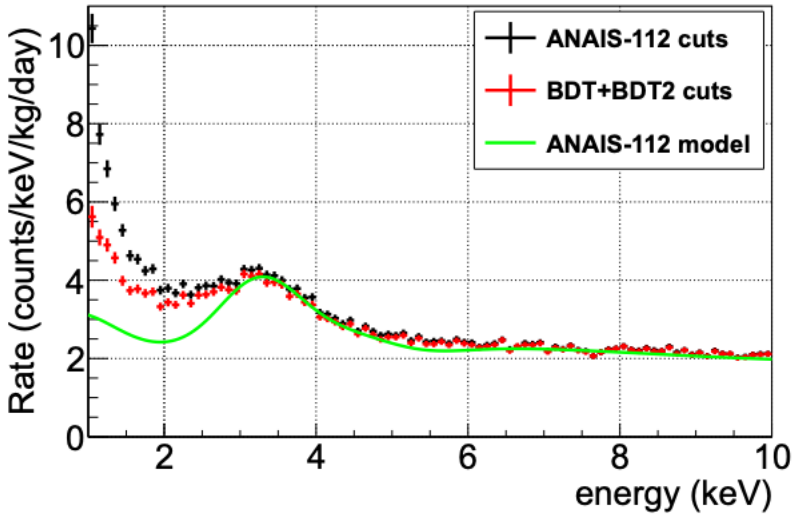
The first detectors set-up at SUPL:

- Measure of muon flux and angular distributions
- Provides the first test of the remote data acquisition system (DAQ) and processing pipelines





PMT Characterisation



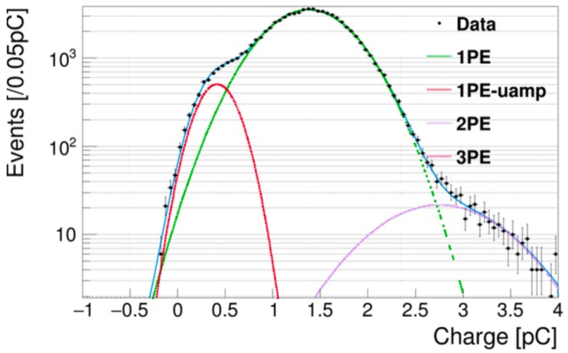
Machine-learning techniques applied to three-year exposure of ANAIS–112. ANAIS-112 Collaboration

Characterise:

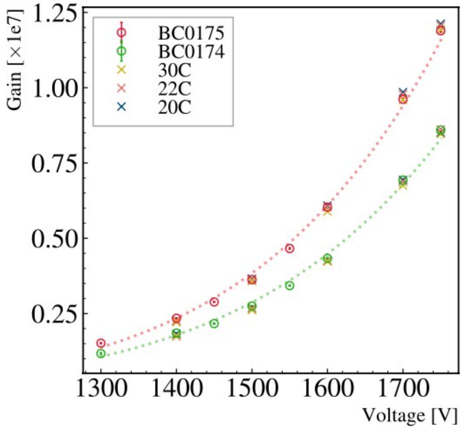
- Dark Rate
- Gain
- After-pulsing
- Quantum Efficiency
- Linearity
- Transit Time

Develop discriminator models to remove noise.

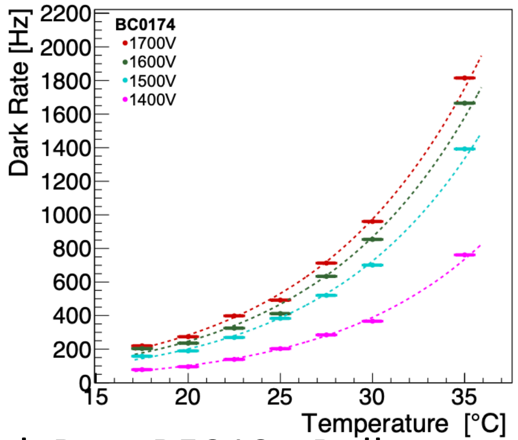
R11065 – BC0174 @ 1700V SPE Fitting



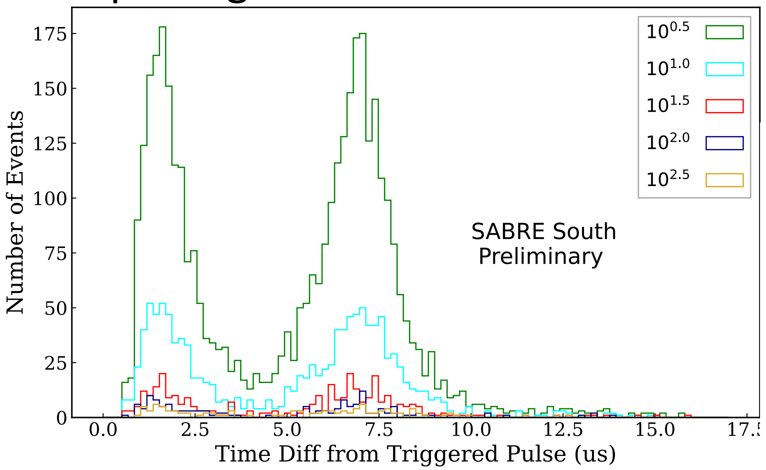
Gain Callibration



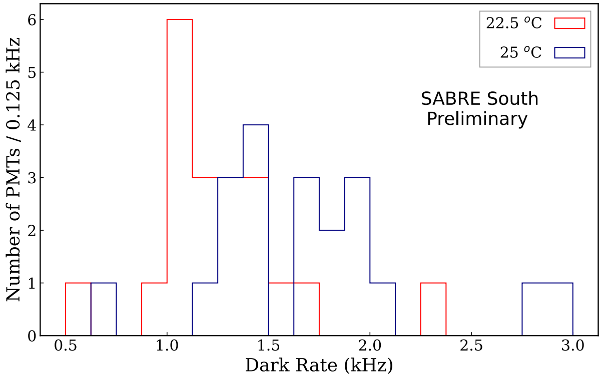
Dark Rate

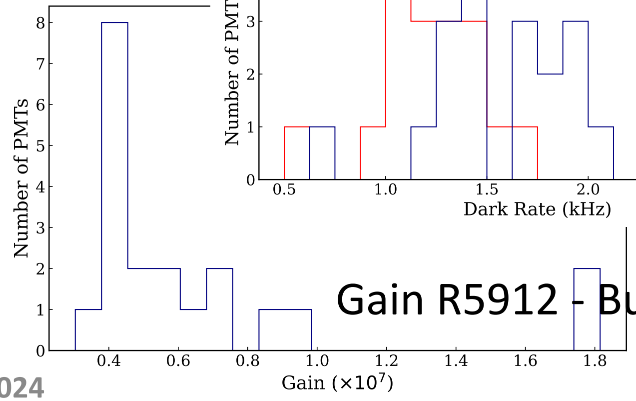


Afterpulsing R5912



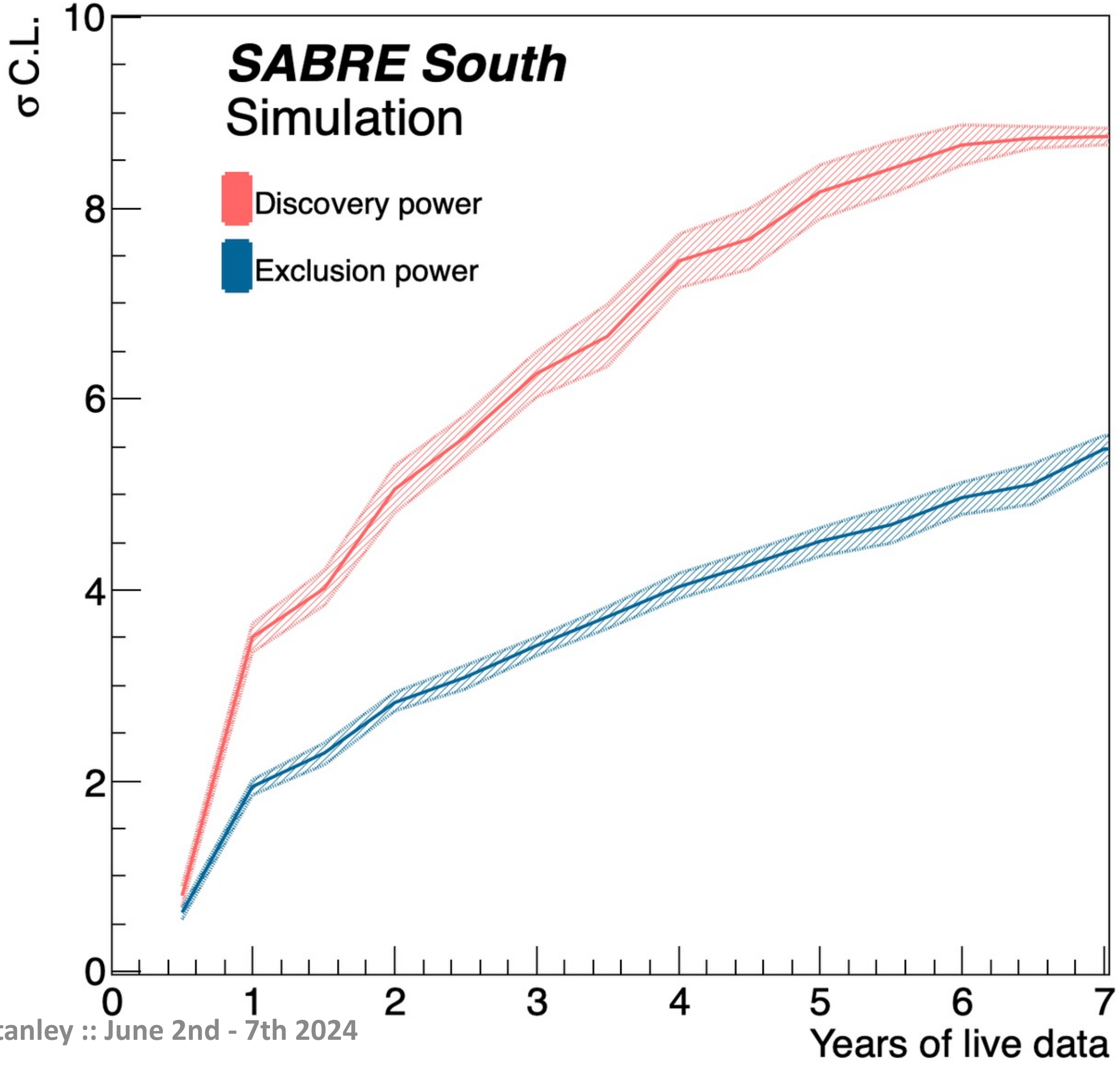
Dark Rate R5912 - Bulk





Summary

- The main goal of SABRE South is to deploy a detector in the Southern Hemisphere. Providing an independent test of DAMA/LIBRA.
- SABRE aims to focus on ultra-high purity NaI(Tl) detectors:
  - 4x crystals tested at LNGS now;
  - Two more expected to arrive in the next months.
- 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.
- Expect discovery/exclusion results after about 2.5 years of continuous operation (with a single site).



Acknowledgements

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

SABRE

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

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

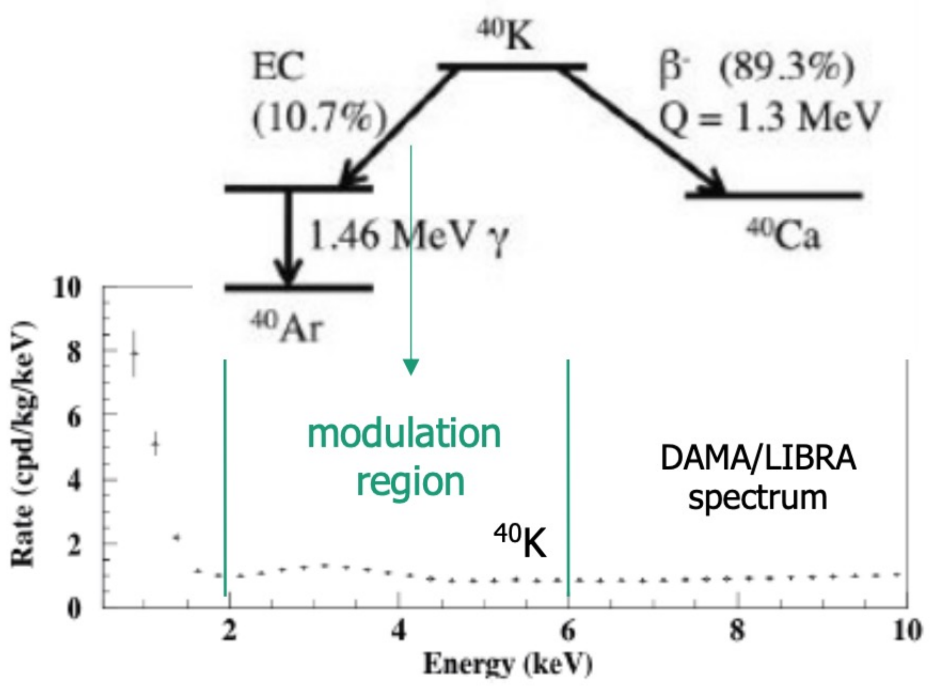
PRINCETON UNIVERSITY

UNIVERSITÀ DEL SALENTO

Effects of backgrounds (^{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.



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.

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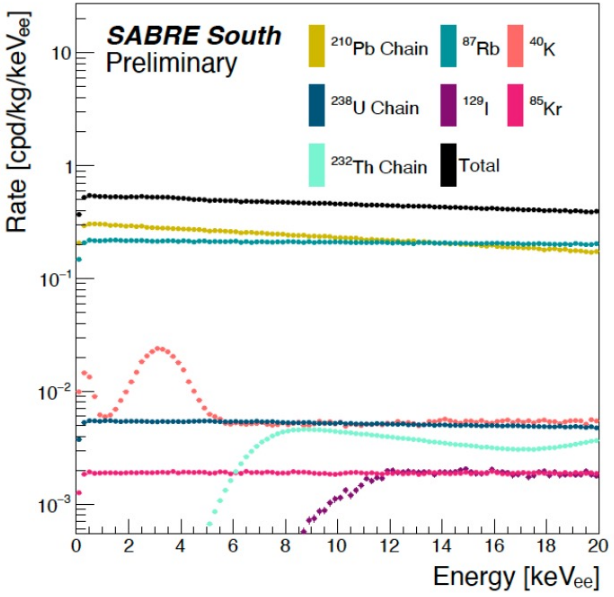
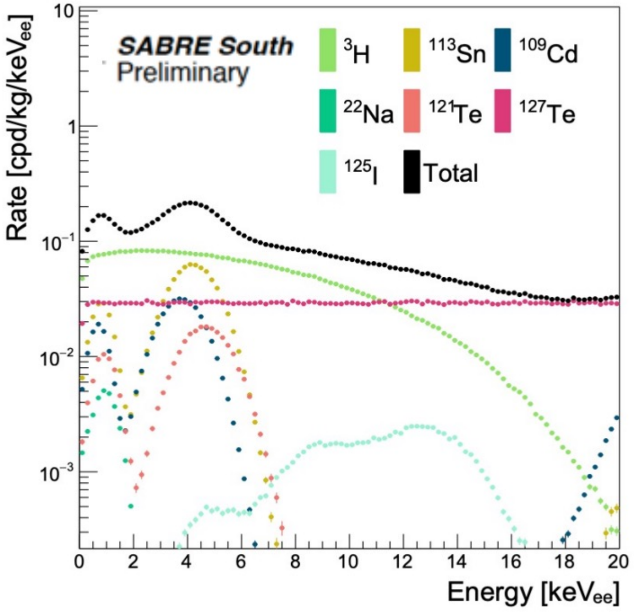
- Cosmogenic background after 180 days underground mainly due to ^{3}H (12.4 yrs) and ^{113}Sn (115 days).

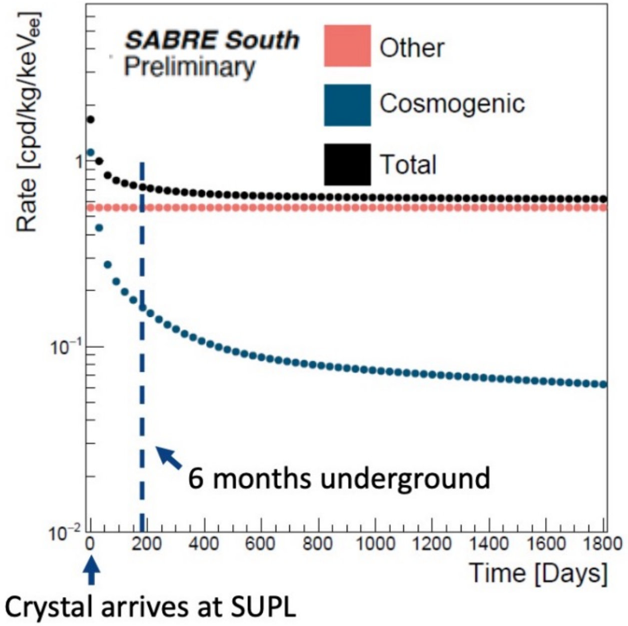
Radiogenic Background



Cosmogenic Background
(6 months underground)

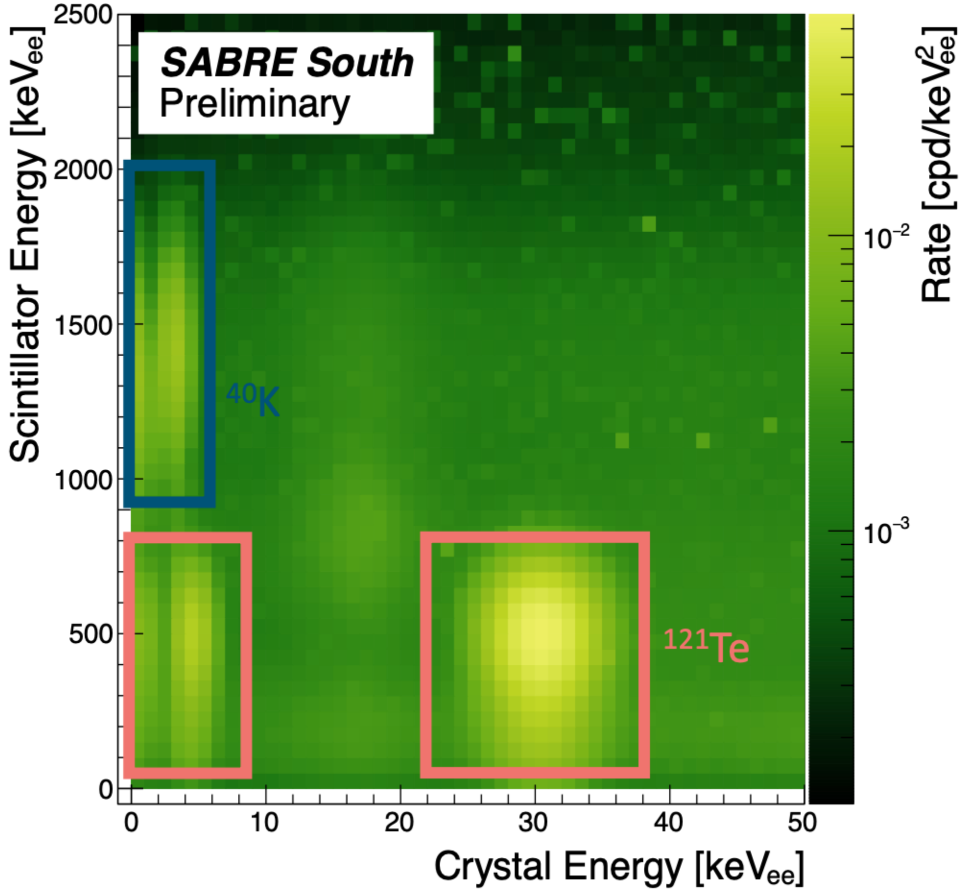


Time Dependence of Background



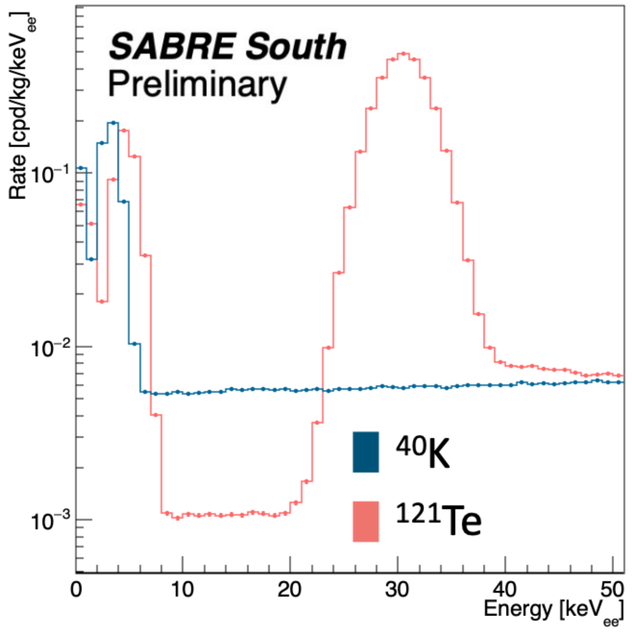
Total Background Simulation

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

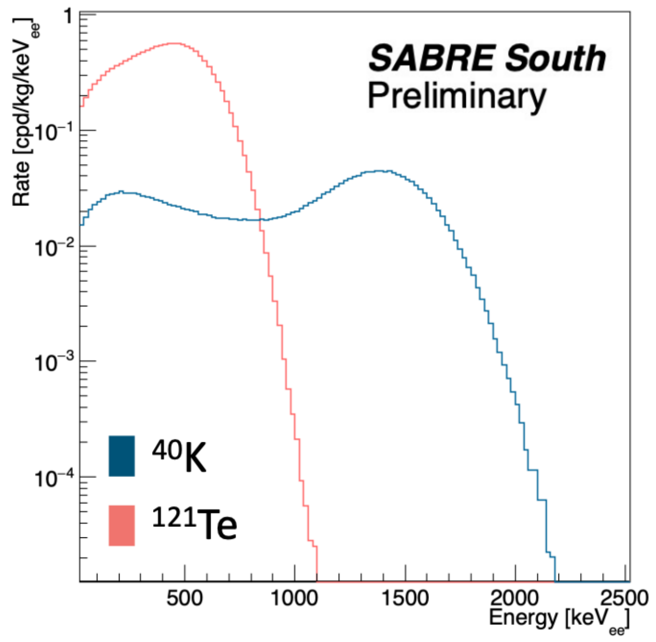


E.g., ^{40}K and ^{121}Te both have distinct islands in crystal-scintillator energy plane

Rate in crystals



Rate in liquid scintillator



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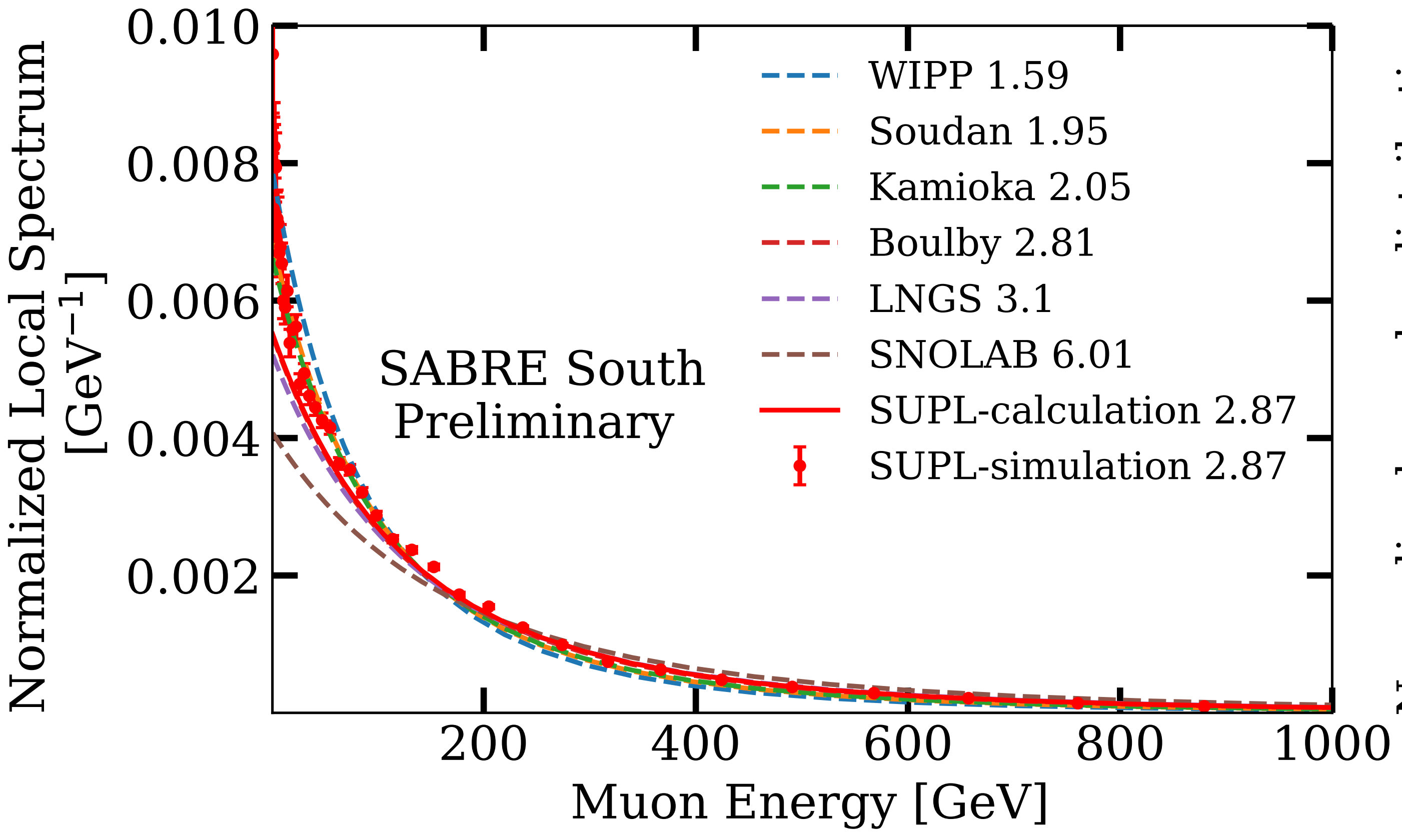
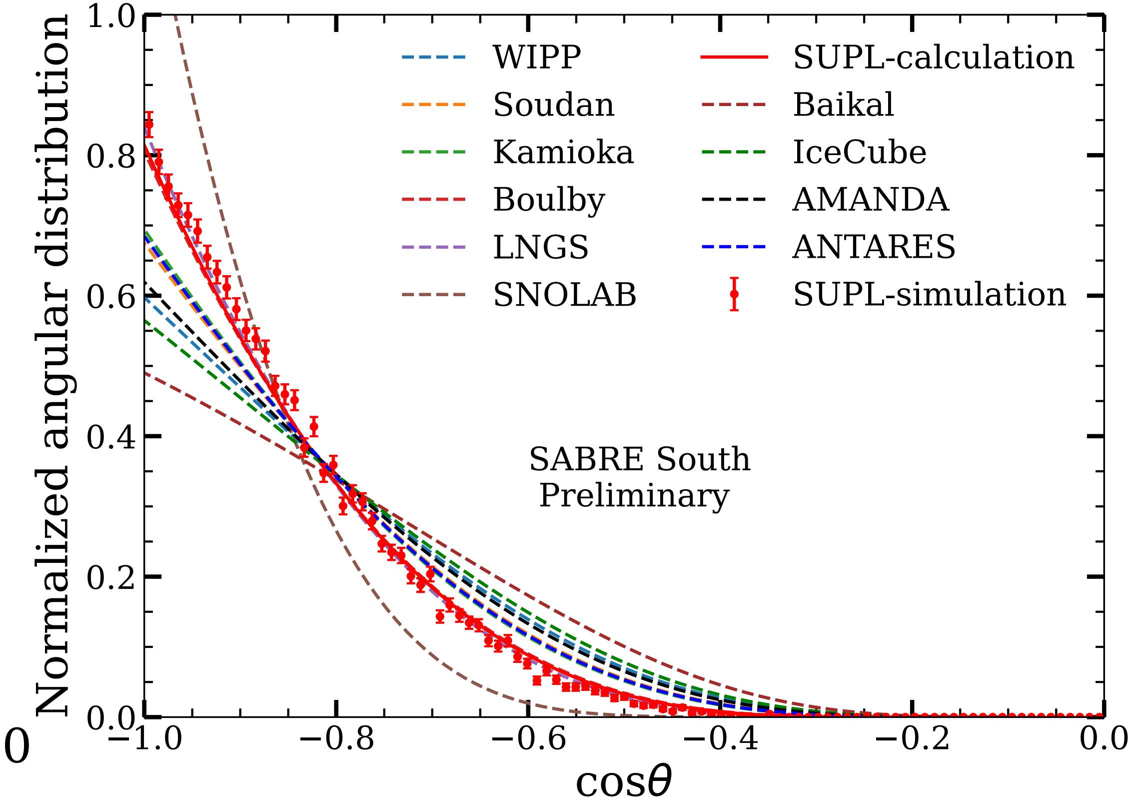
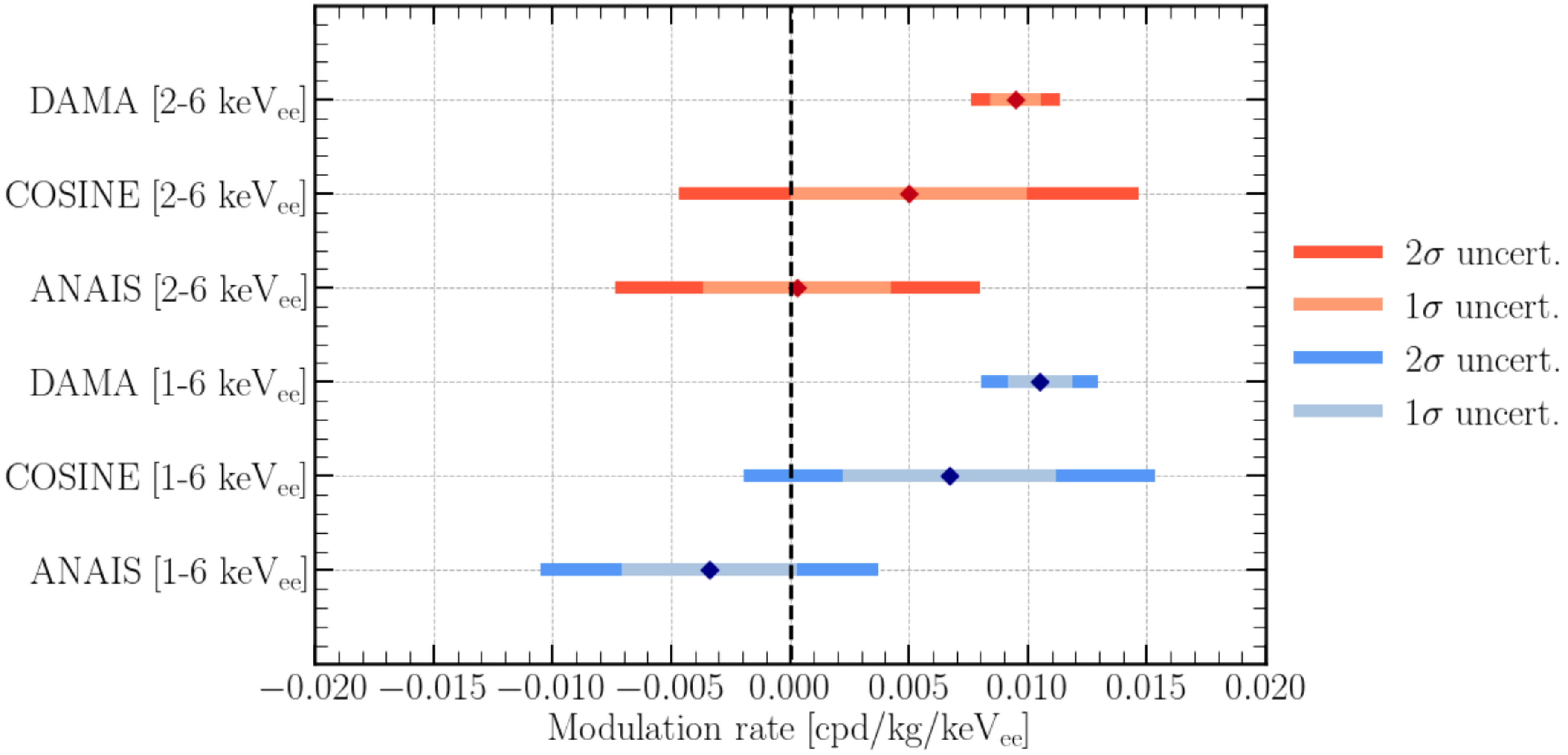
Full Muon sim-comparison



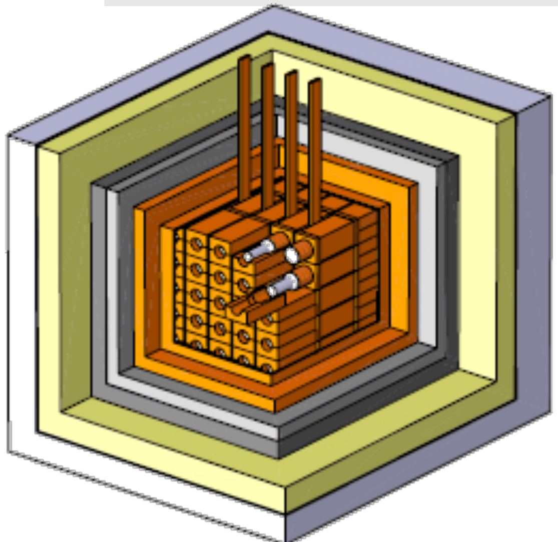


OLD

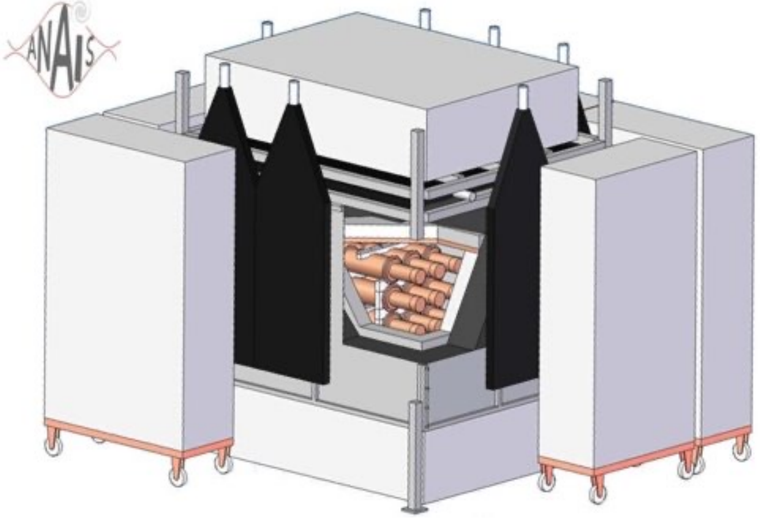

DAMA [2-6 keV$_{ee}$]
COSINE [2-6 keV$_{ee}$]
ANAIS [2-6 keV$_{ee}$]
DAMA [1-6 keV$_{ee}$]
COSINE [1-6 keV$_{ee}$]
ANAIS [1-6 keV$_{ee}$]
−0.020 −0.015 −0.010 −0.005 0.000 0.005 0.010 0.015 0.020
Modulation rate [cpd/kg/keV$_{ee}$]
2σ uncert.
1σ uncert.
2σ uncert.
1σ uncert.

Radiogenic Background Rate Comparison

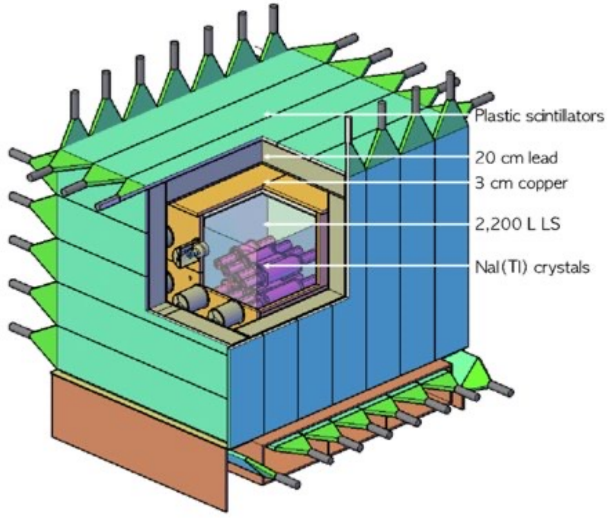
Experiment	Mass (kg)	Background (cpd/kg/keV)	Uncertainty (cpd/kg/keV)
DAMA [1]	250	<0.8	0.0011
ANAIS [2]	112.5	3.2	0.0042
COSINE [3]	61.3	2.7	0.0042
SABRE South*	50	0.72	-



[1] R. Bernabei et al., The dark matter: DAMA/LIBRA and its perspectives, 2021



[2] J. Amaré et al., Annual modulation results from three-year exposure of ANAIS-112, Phys. Rev. D 103 (May, 2021) 102005.



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