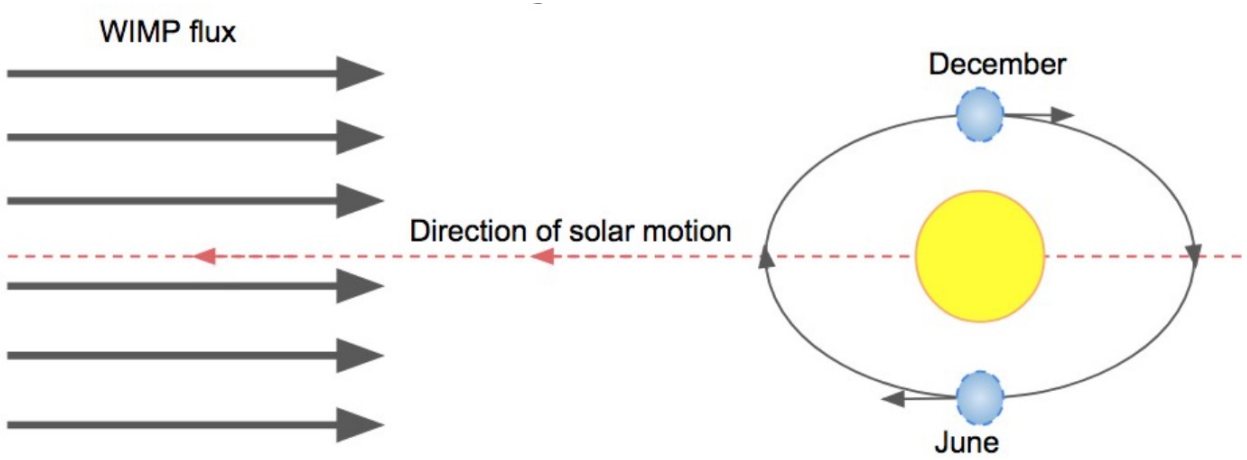
The SABRE South Experiment at the Stawell Underground Physics Laboratory

Irene Bolognino on behalf of the SABRE South collaboration

The University of Adelaide

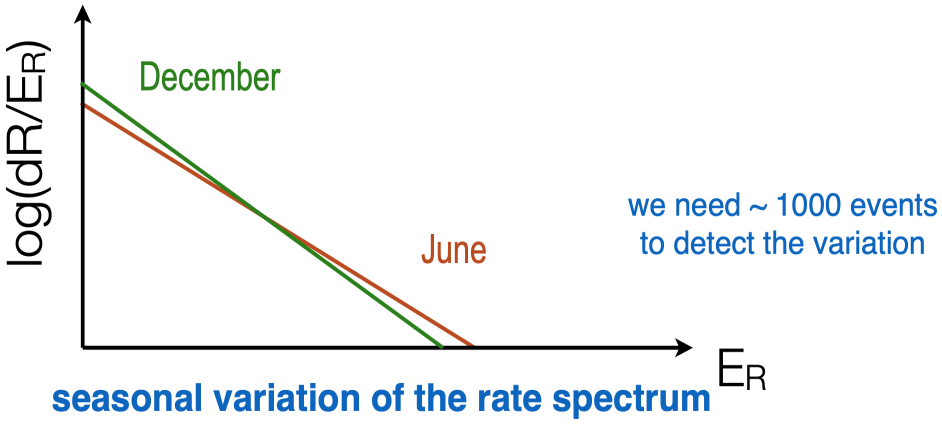
SABRE Motivation – Annual Modulation



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

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

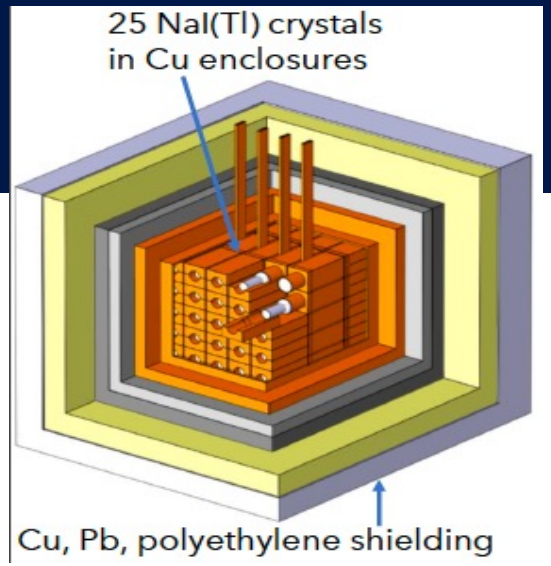
Annual modulation: maximum and minimum expected on June 2nd and on 2nd December



Rare and low energy events:
- very low expected rate < 1 count/day/kg (few% of which modulates)
- expected recoil energy is 1-100 keV for a WIMP of mass 10-1000 GeV/c²

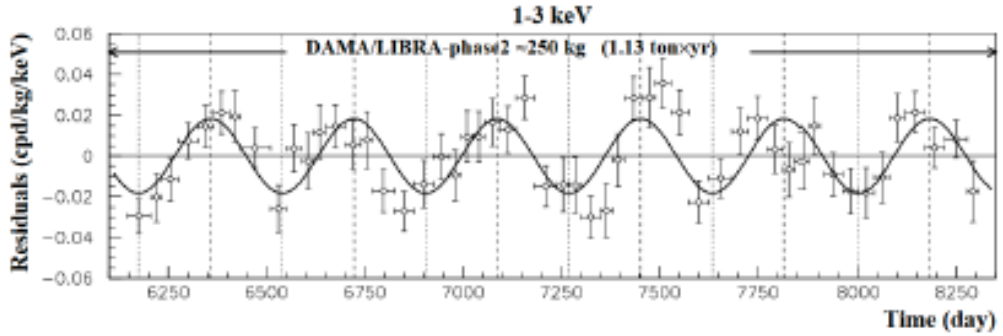
Annual modulation is a <u>model independent</u> signature of Dark Matter interaction, but control of modulating background is key

SABRE Motivation – DAMA results

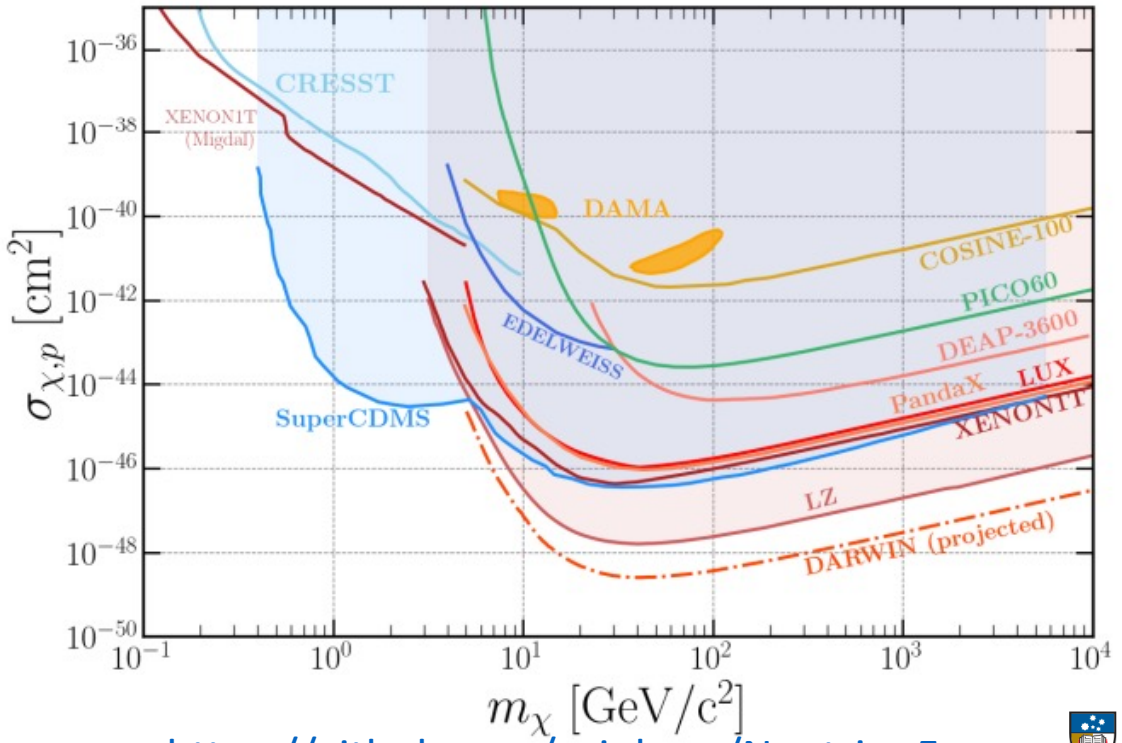


The **DAMA/LIBRA** experiment has observed a modulation for about 2 decades:

- 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



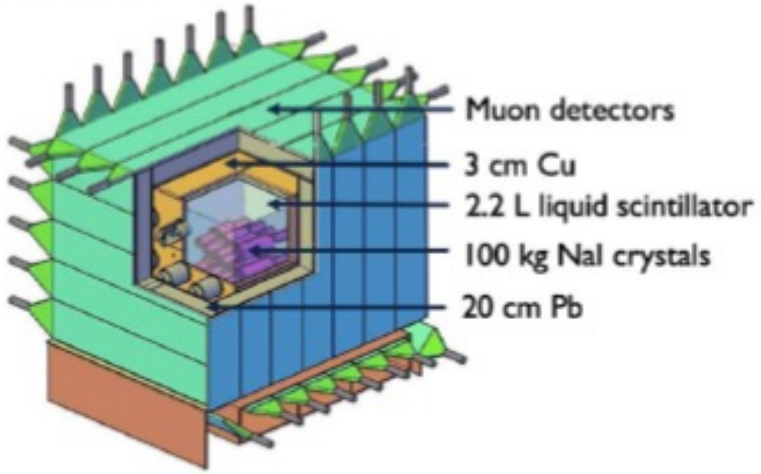
Bernabei et al. PPNP114 103810 (2020)



https://github.com/cajohare/NeutrinoFog

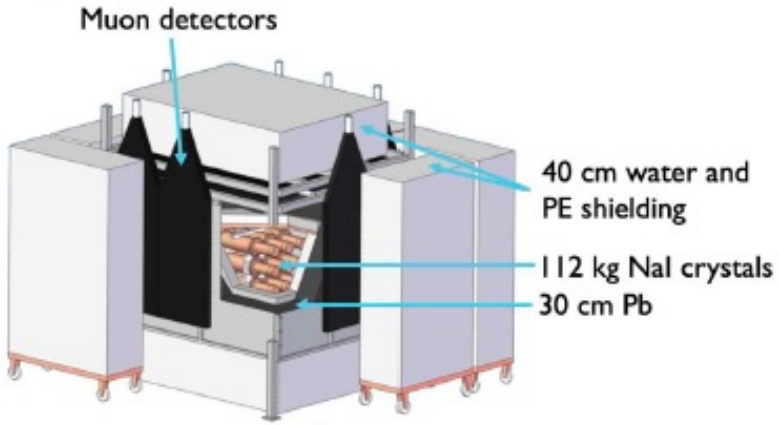
Current running NaI(Tl) detectors

COSINE

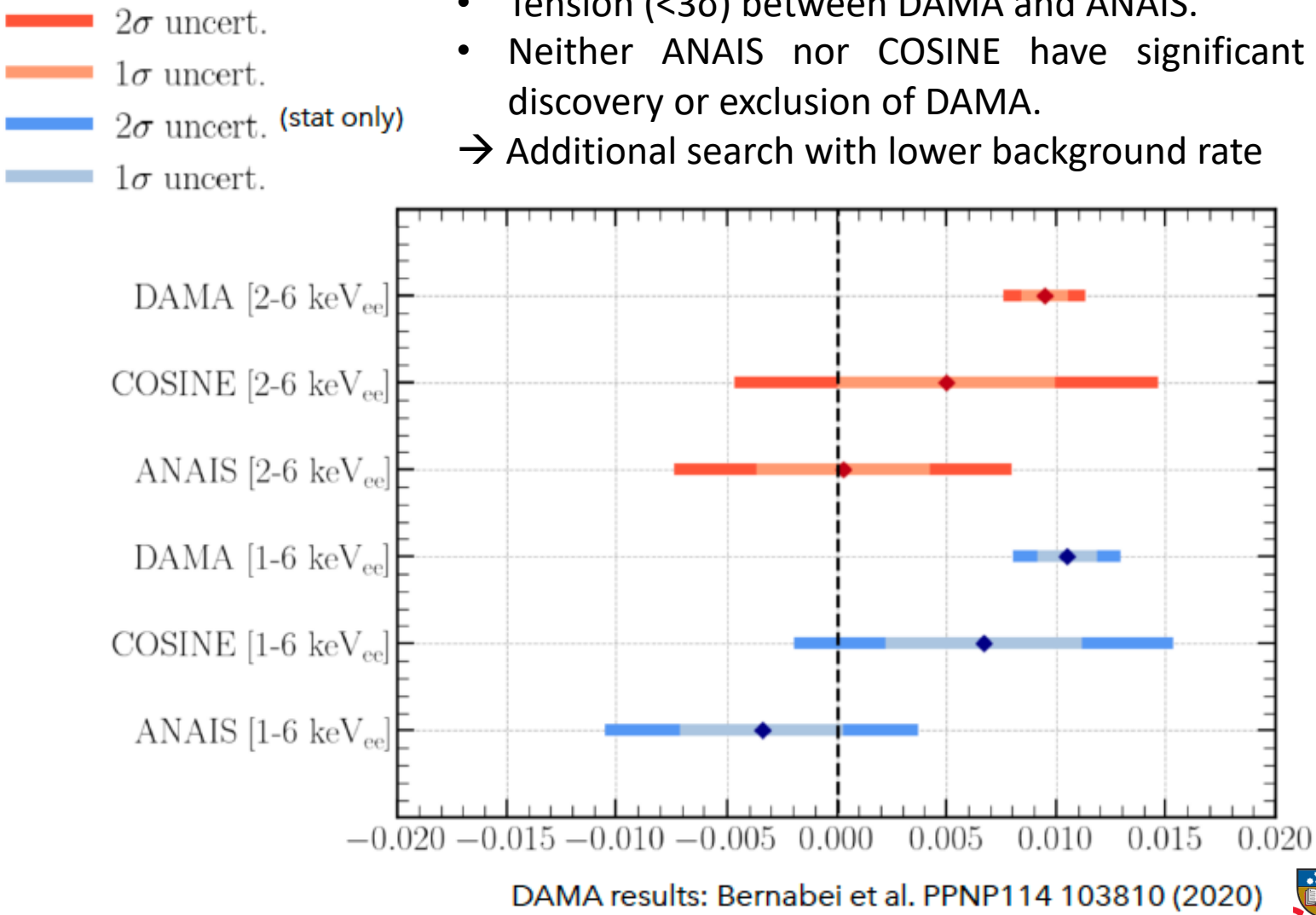


Phys. Rev. D 106,052005 (2022)

ANAIS



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



DAMA results: Bernabei et al. PPNP114 103810 (2020)

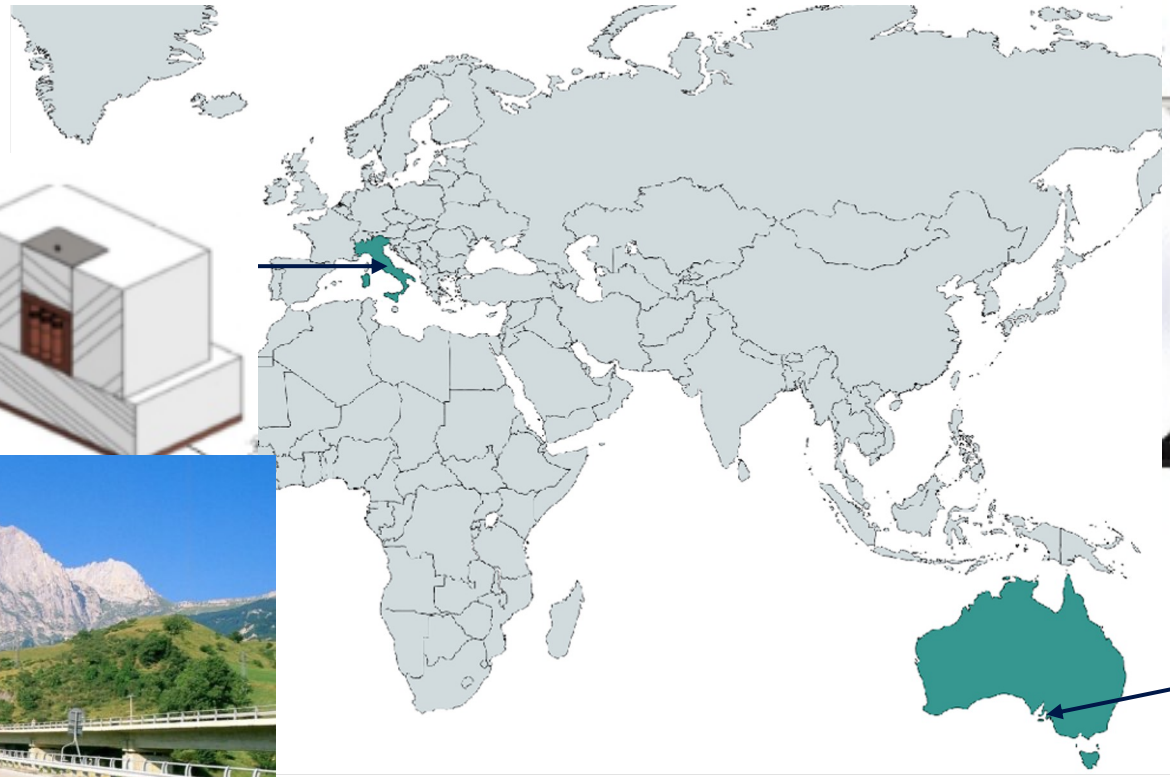
- Tension (<3σ) between DAMA and ANAIS.
- Neither ANAIS nor COSINE have significant discovery or exclusion of DAMA.

→ Additional search with lower background rate

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 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.

A MoU for the full SABRE experiment has been drafted and will be signed in the following months.

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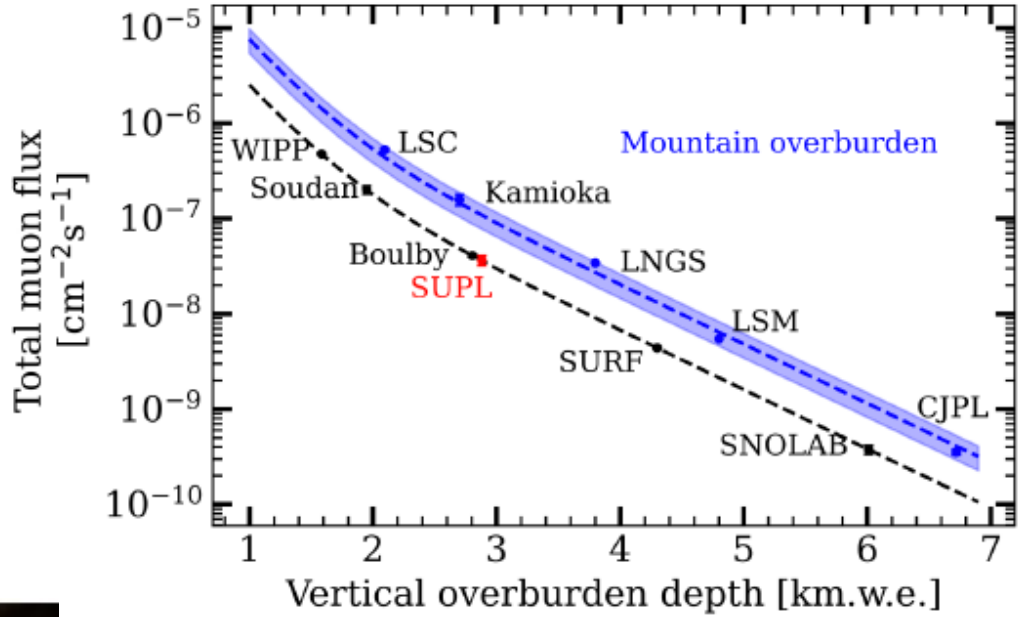
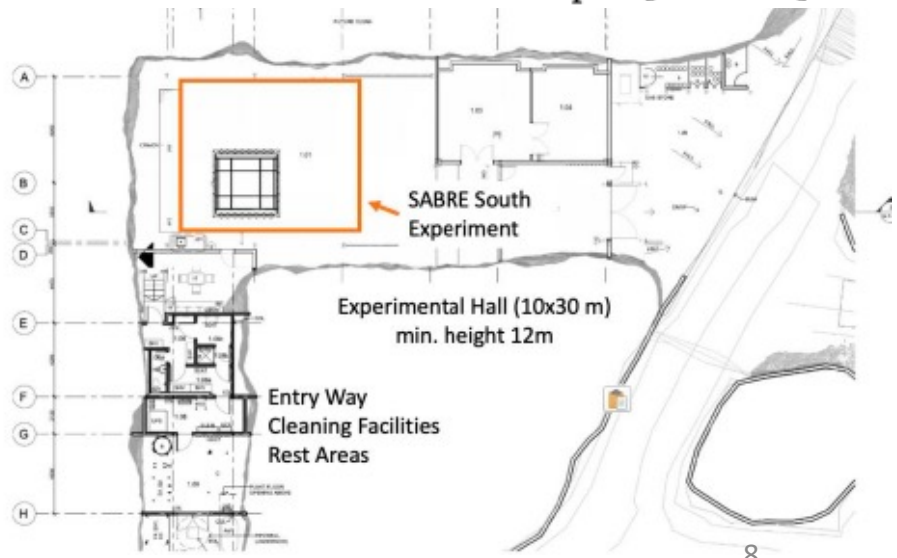
Stawell Underground Physics Lab

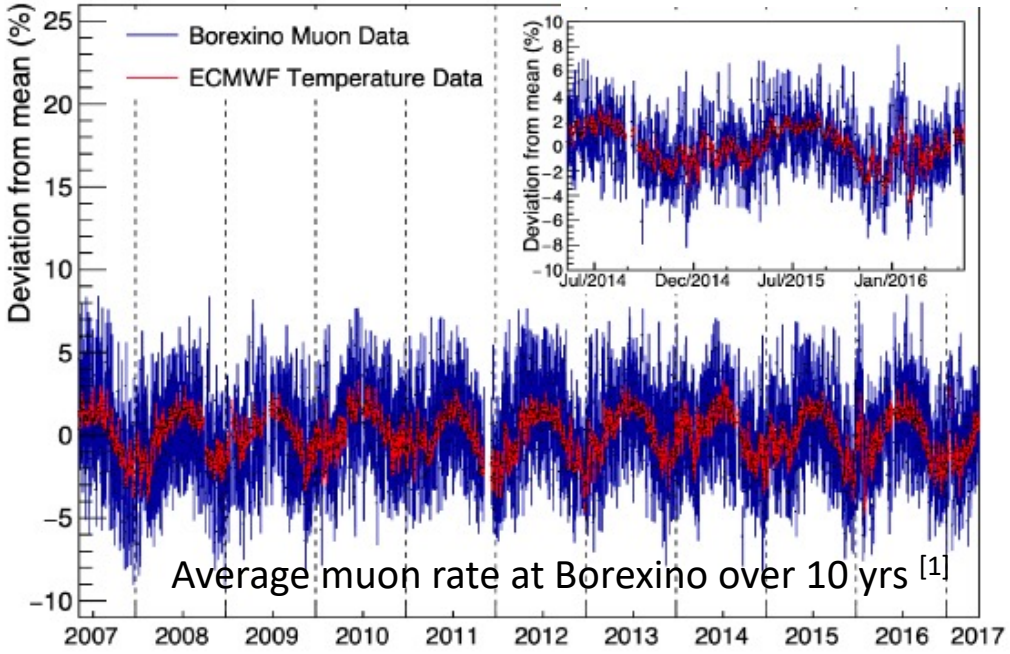
- SUPL is the first deep underground lab in Southern Hemisphere (37°South) located in western Victoria 240 km from Melbourne.
- Lab is 1025 m (~2900 m water equivalent) below ground with flat over burden within the Stawell Gold Mine.
- Helical drive access
- Lab completed in 2022/2023. SABRE South assembled 2023-24.





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.

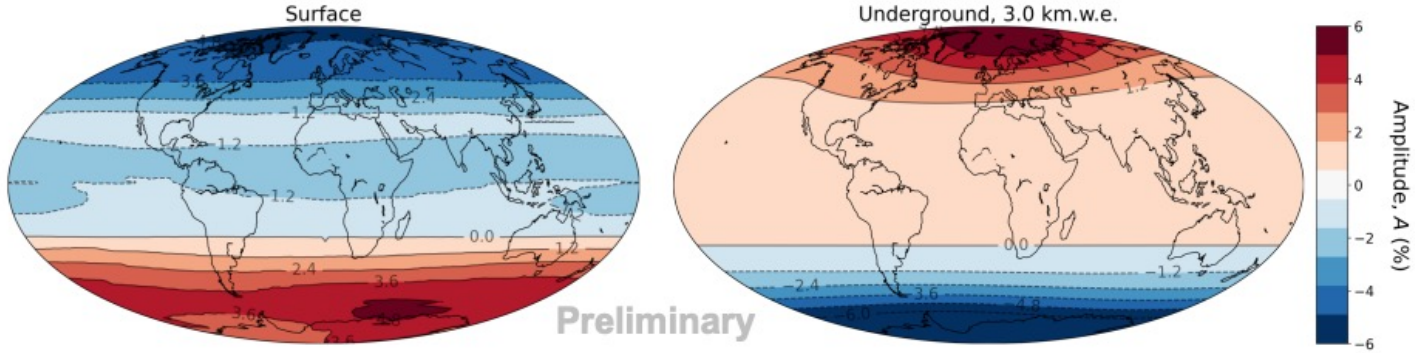


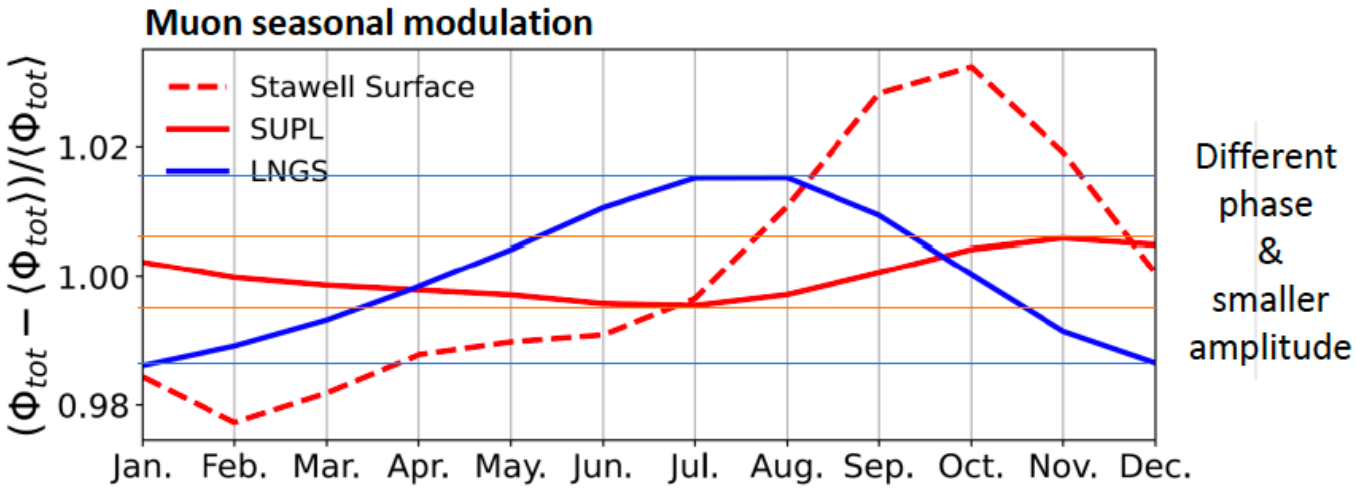
Average muon rate at Borexino over 10 yrs [1]

[1] Borexino collab. JCAP02(2019)046

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

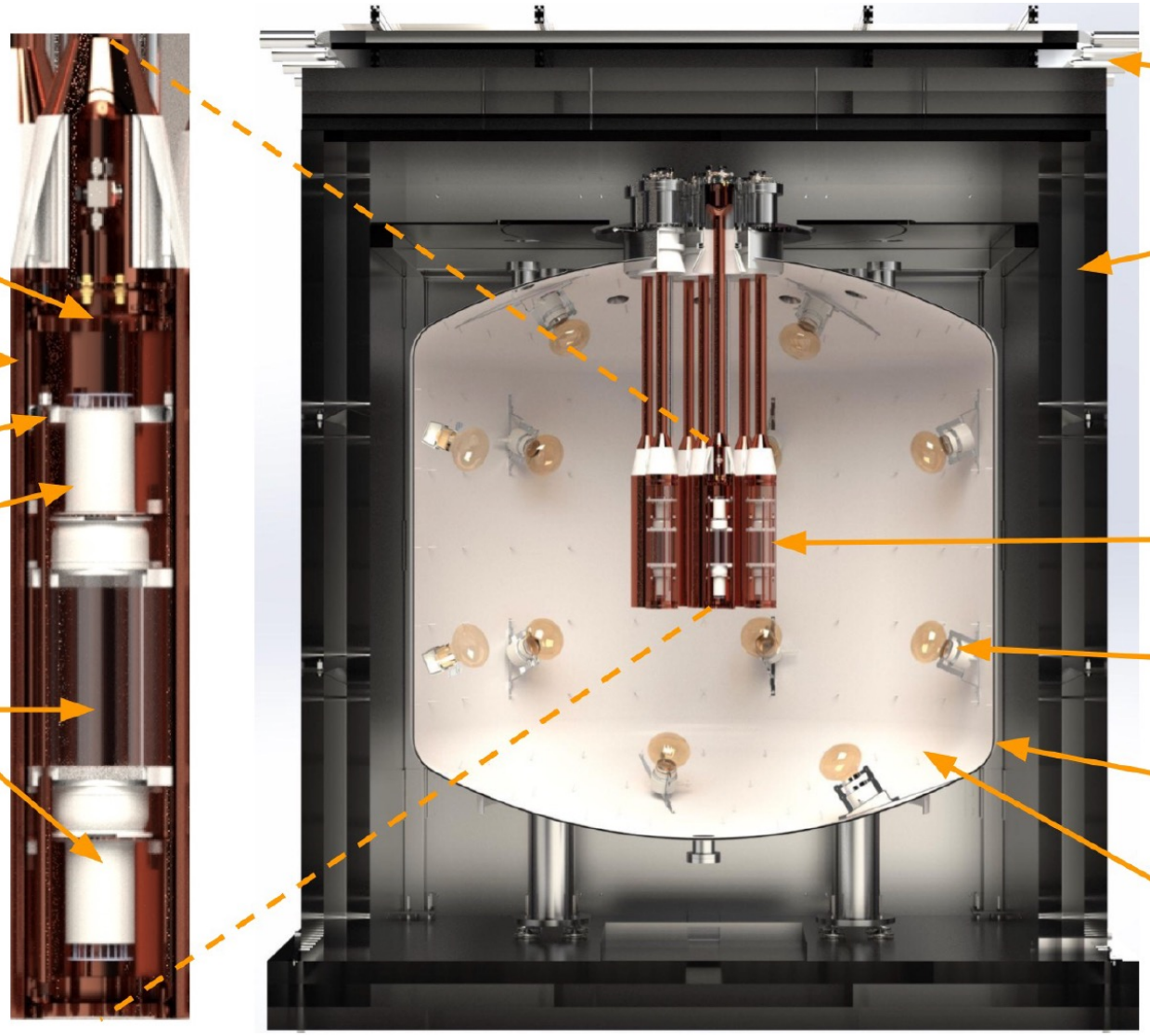
M. Agostini[1], K. Altenmüller[1], S. Appel[1], V. Atroshchenko[2], Z. Bagdasarian[3], D. Basilico[4], G. Bellini[4], J. Benziger[5], D. Bick[6], I. Bolognino[4] + Show full author list





Different phase & smaller amplitude

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)

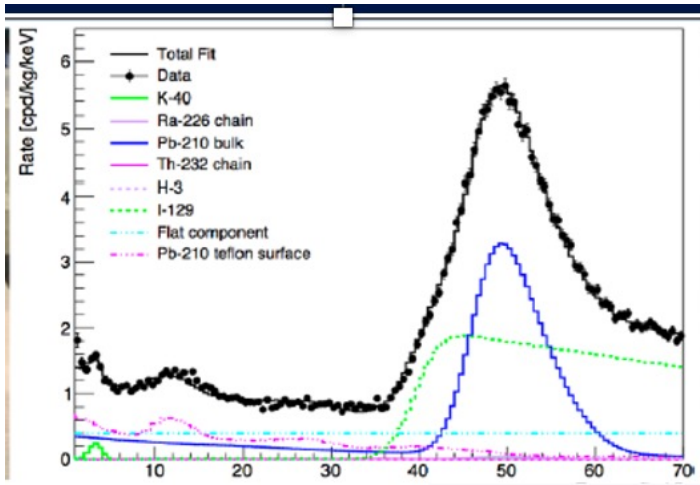
18 R5912 PMTs for veto

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

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.
- Four crystals have been tested at LNGS.
- Light yield 9-12 phe/keV.
- Two more crystals are arriving in the next months to complete the testing phase.



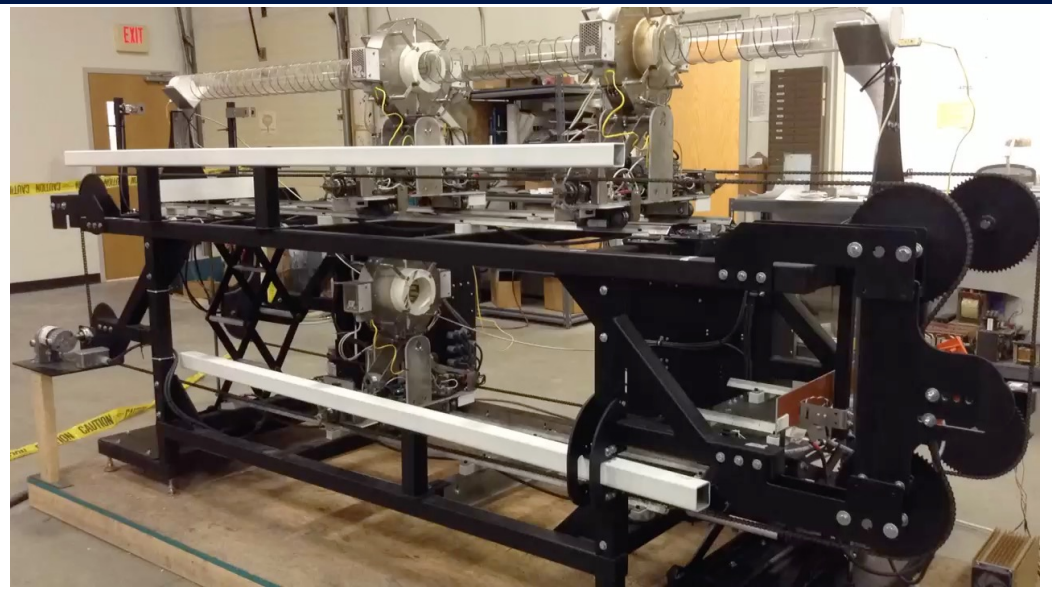
Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)	Active mass (kg)
DAMA [1]	13	0.7-10	(5-30)x10^{-3}	0.5-7.5	250
ANAIS [2]	31	<0.81	1.5	0.36	112
COSINE [3]	35.1	<0.12	1-1.7	<2.4	~60
SABRE [4]	4.3	0.4	0.49	0.2	~35+40=75 (total goal)
PICOLON [5]	<20	-	<5.7x10^{-3}	-	~20 (goal)

SABRE crystal mass = 3.4 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, 031302 (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) crystals - Zone Refining

- Strategic and unique to the SABRE project is the idea to zone refine the 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
- Being used at RMD to prepare a final test crystal.



Impurity concentration (ppb)

Isotope	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

B. Suerfu, Phys. Rev. Applied 16, 014060 (2021)

Active Background Rejection

SABRE South also uses an external tagging system to remove high energy decay products observable in the liquid scintillator.

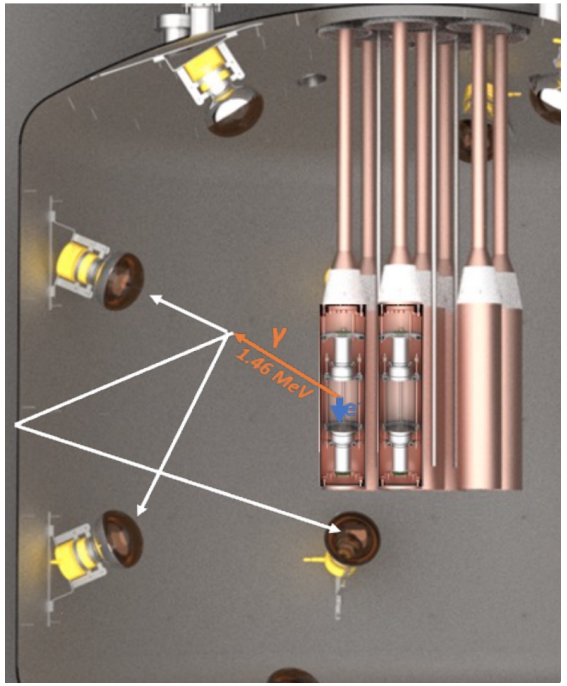
System has 4π coverage made up of:

- 12 kL (10 tons) linear alkyl benzene (LAB) doped with PPO and Bis-MSB.
- LAB is sourced from JUNO.
- 18 Hamamatsu 20.4 cm R5912 PMTs sampled at 500 MS/s.

Average light yield of ~0.12 PE/keV, though strong position dependence.

Energy threshold of 50 keV which is able to reduce the background by 25%.

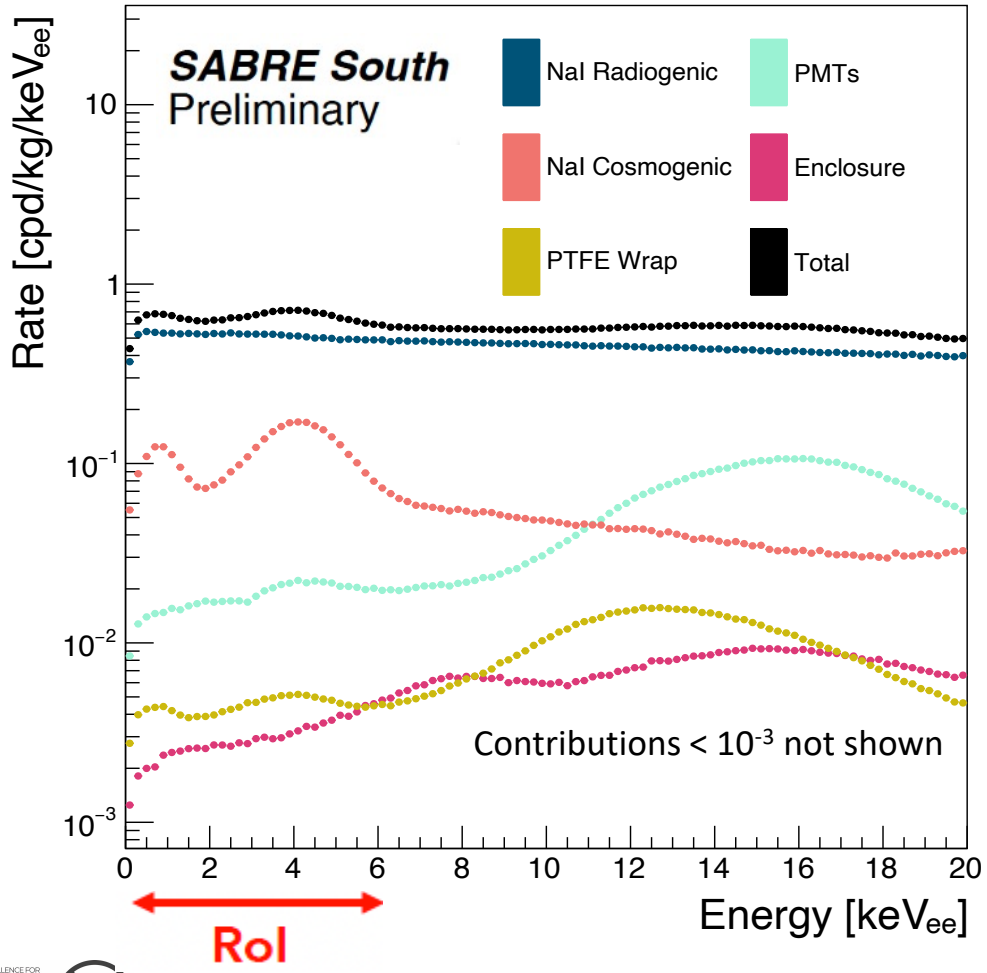
Small scale prototype used to study the properties.



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%

Total Background Model

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



SABRE South Collab. arxiv:2205.13849 (accepted to EPJC)

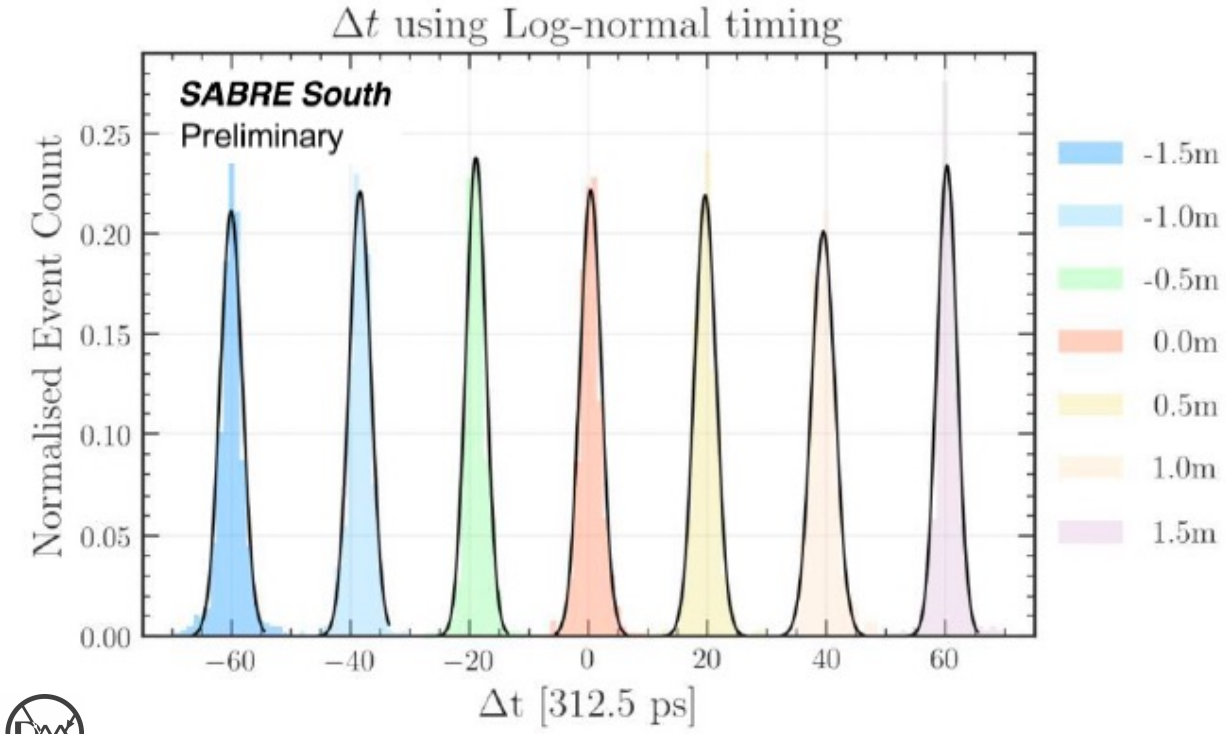
Zone refining ~0.3 cpd/kg/keV$_{ee}$

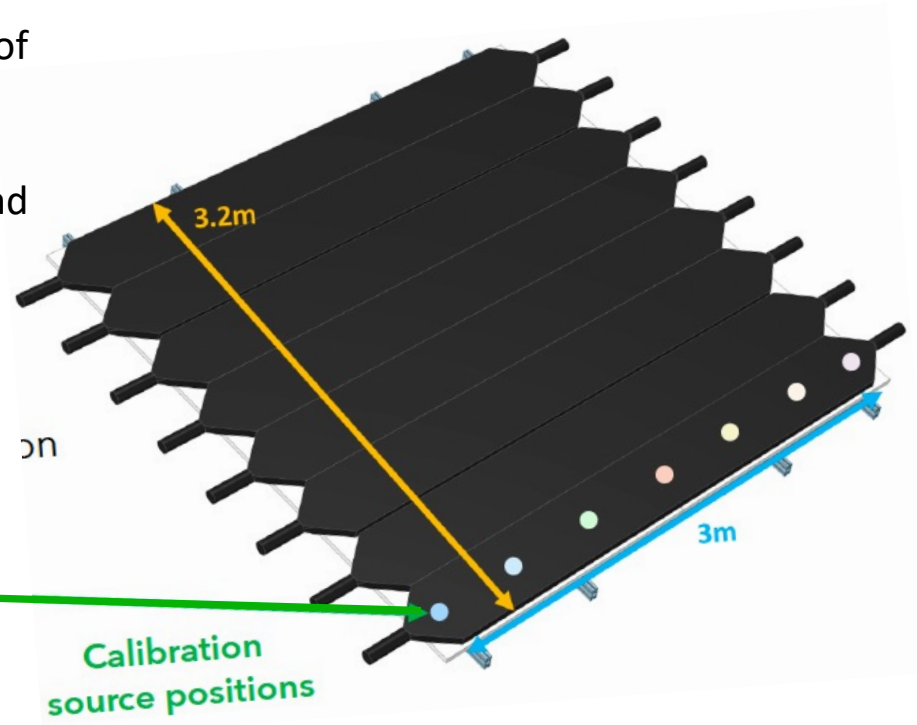
Component	Rate (cpd/kg/keV$_{ee}$)	Veto efficiency (%)
Crystal intrinsic	$<5.2 \times 10^{-1}$	13
Crystal cosmogenic	1.6×10^{-1}	45
Crystal PMTs	3.8×10^{-2}	57
Crystal wrap	4.5×10^{-3}	11
Enclosures	3.2×10^{-3}	85
Conduits	1.9×10^{-5}	96
Steel vessel	1.4×10^{-5}	>99
Veto PMTs	1.9×10^{-5}	>99
Shielding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

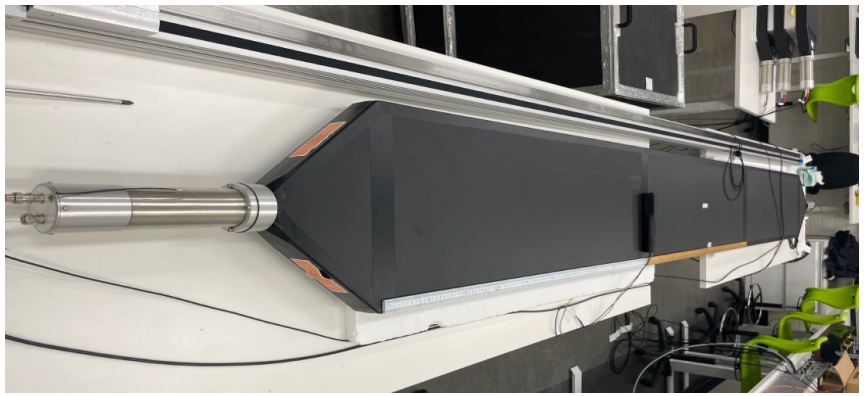
< 10% of background from non-crystal sources.

Muon Detector System

- Provides additional tagging of cosmic muons, and long-term measurements of muon modulation at SUPL.
- Will be used to improve particle ID and localisation in LS Veto.
- 8 x EJ200 organic scintillator panels (3x0.4x0.05 m) with PMTs at opposite ends and sampled at 3.2 GS/s.
- Longitudinal position resolution of 3.2 cm using CFD trigger.
- Total coverage 9.6 m^2 above main vessel.
- Each panel is being characterised for timing and efficiency on surface.





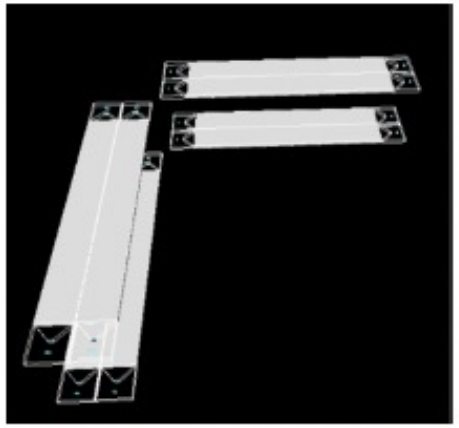


Underground Muon Measurements

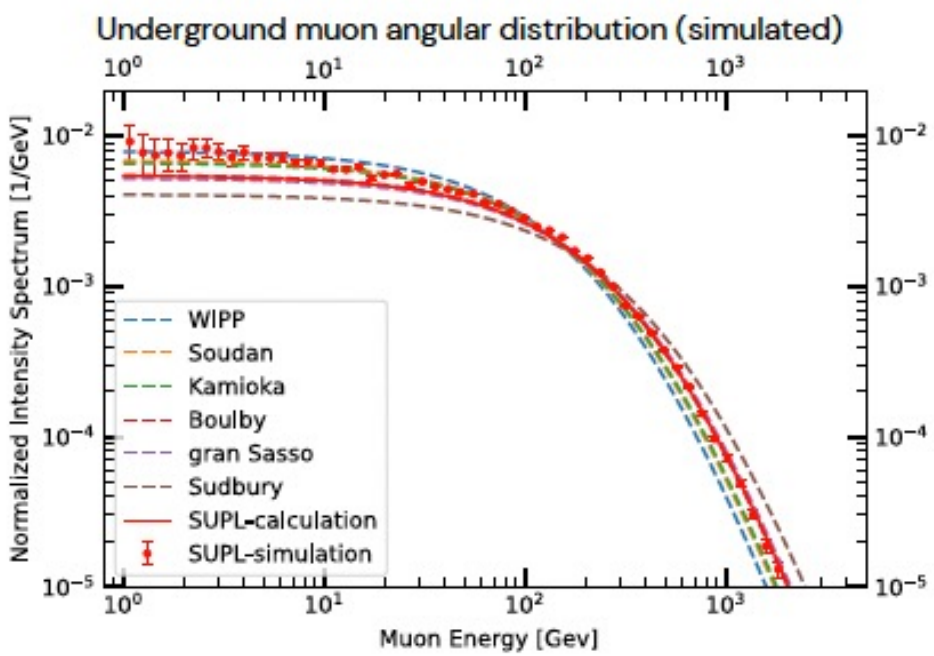
Muon detectors ready to be installed in SUPL in the coming months.

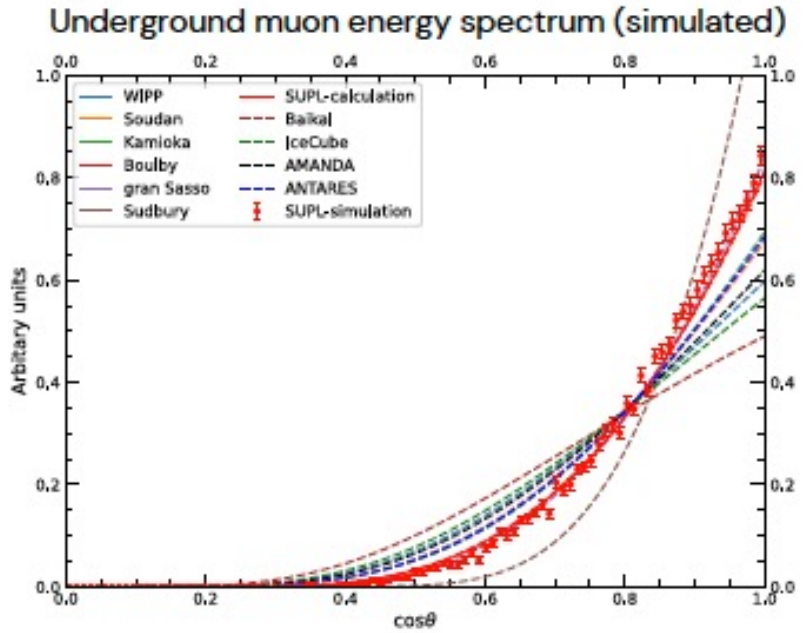
As the first detector in SUPL, this system will:

- measure the muon flux and its angular distribution;
- provide the first test of the remote data acquisition and processing pipeline.



Layout of muon detectors in simulation and proposed SUPL configuration

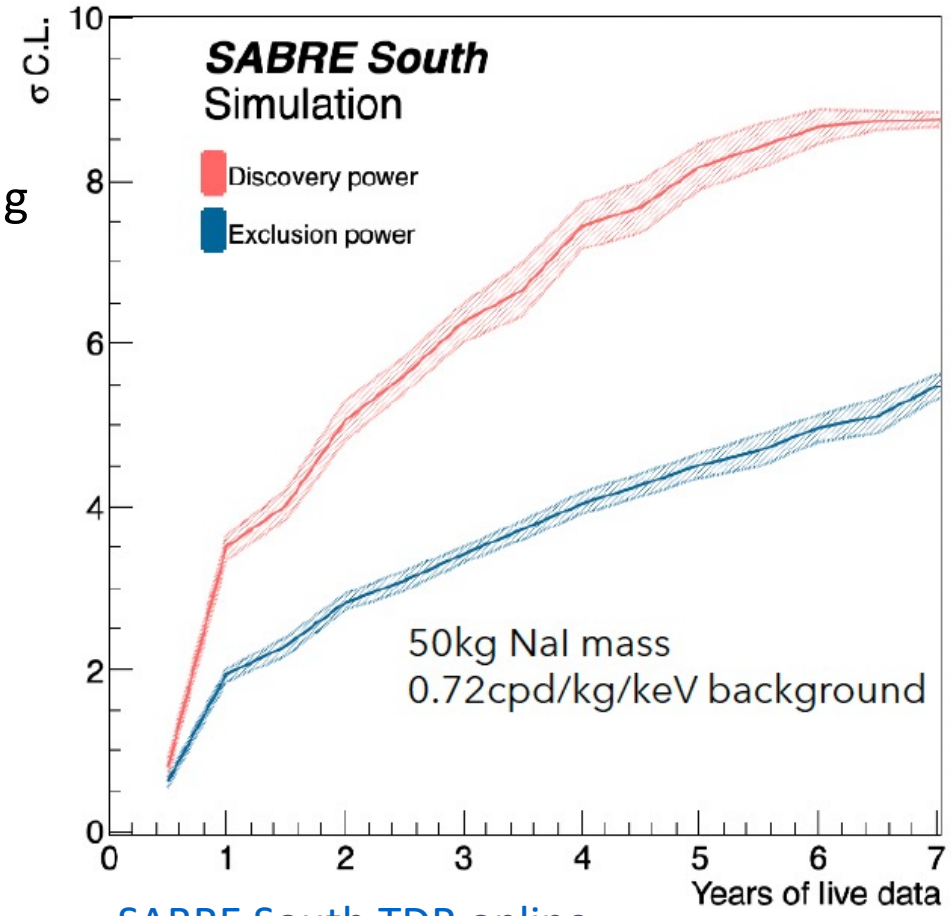




Summary

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

- The main goal of SABRE is to deploy two nearly identical detectors in the both Hemispheres.
- SABRE aims to focus on ultra-high purity NaI(Tl) detectors:
  - four crystals tested at LNGS now;
  - two more arriving in the next months to complete the testing phase.
- SABRE South is the first dark matter direct-detection experiment in the Southern Hemisphere and will be located inside the new SUPL underground laboratory.
- SABRE South construction/commissioning to start towards the end of this year, completing in 2024. Vessel, LAB, PMTs, muon detectors, DAQ, crystal insertion system all ready.
- Expect discovery or exclusion results after about 2.5 years of continuous operation (with a single site).



SABRE South TDR online

Background paper (accepted to EPJC)

Acknowledgements

SABRE South

Australian Government

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY of ADELAIDE

Australian National University

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY OF SYDNEY

SWINBURNE UNIVERSITY OF TECHNOLOGY

KEK

SABRE North

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

UNIVERSITÀ DEGLI STUDI DI MILANO

UNIVERSITÀ DEL SALENTO

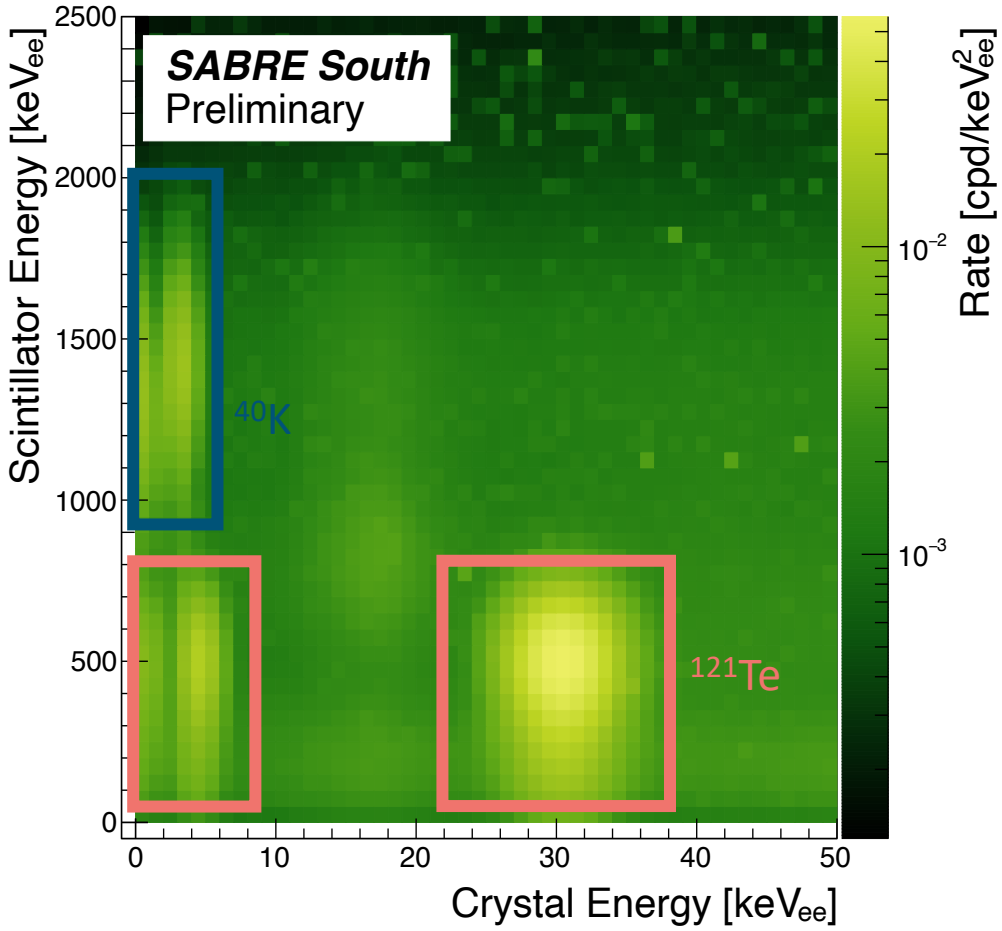
INFN
Istituto Nazionale di Fisica Nucleare

SAPIENZA
UNIVERSITÀ DI ROMA

PRINCETON UNIVERSITY

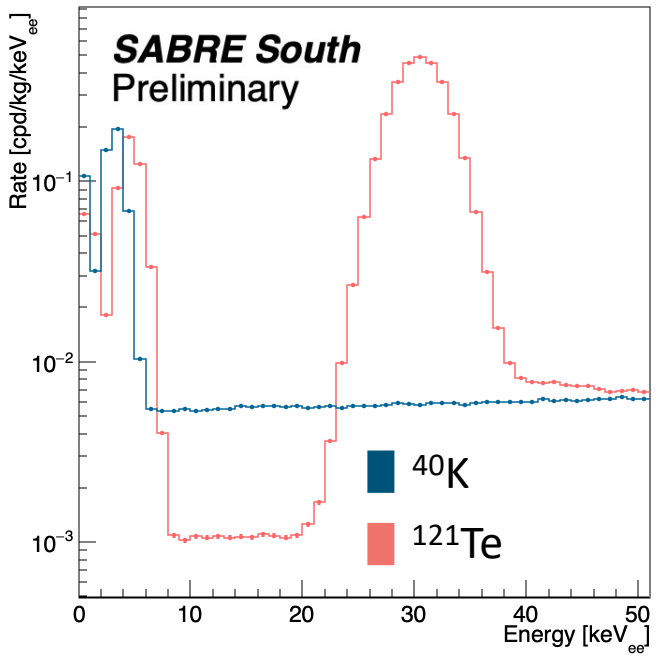
Total Background Model

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

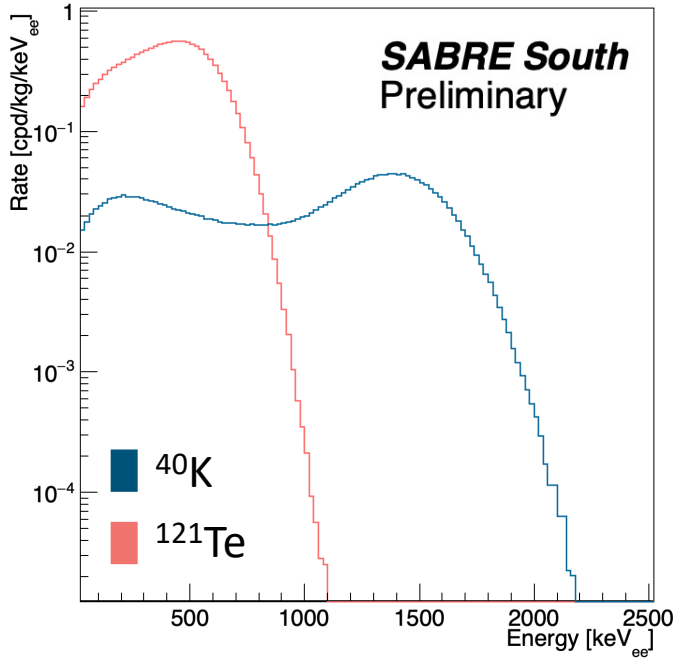


E.g., ^{40}K and ^{121}Te both have distinct islands in crystal-scintillator energy plane

Rate in crystals



Rate in liquid scintillator



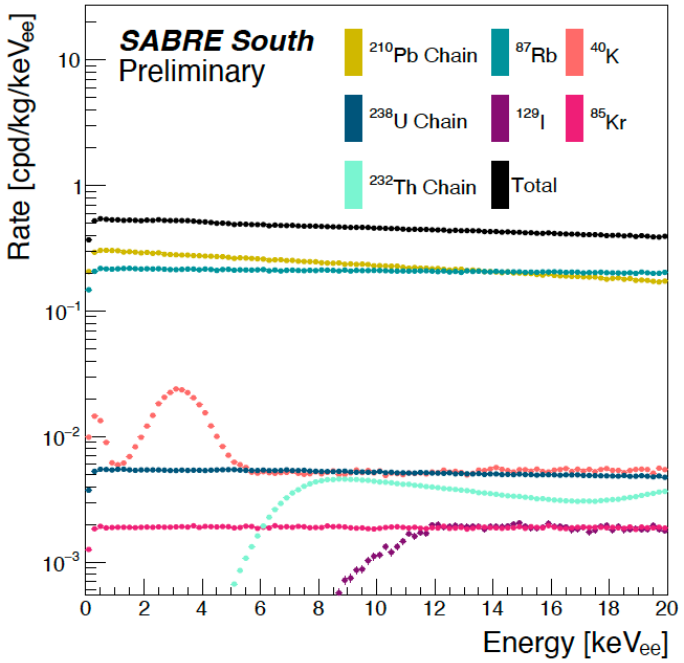
SABRE South Collab. arxiv:2205.13849

NaI(Tl) Background Simulations

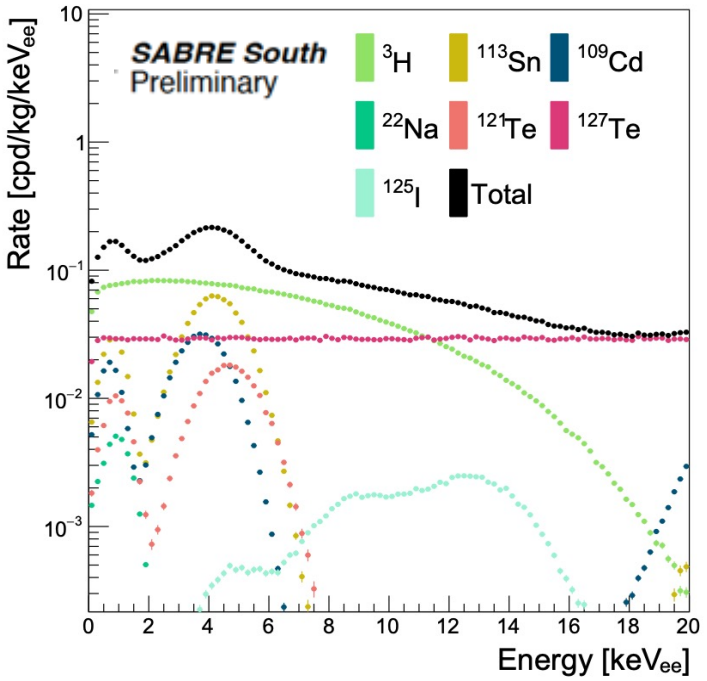
- Background of SABRE South crystal have been both simulated and directly measured (on NaI-33) with Inductively coupled plasma mass spectrometry (ICP-MS).
- Main radiogenic background represented by ^{210}Pb, ^{87}Rb (very conservative upper limit). No ^{87}Rb was found with the ICP-MS measurement, and 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

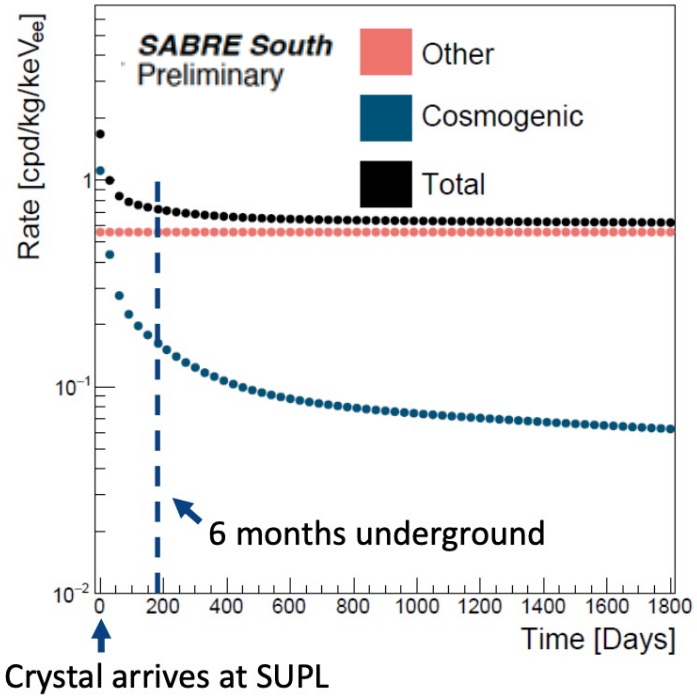
Radiogenic Background



Cosmogenic Background
(6 months underground)



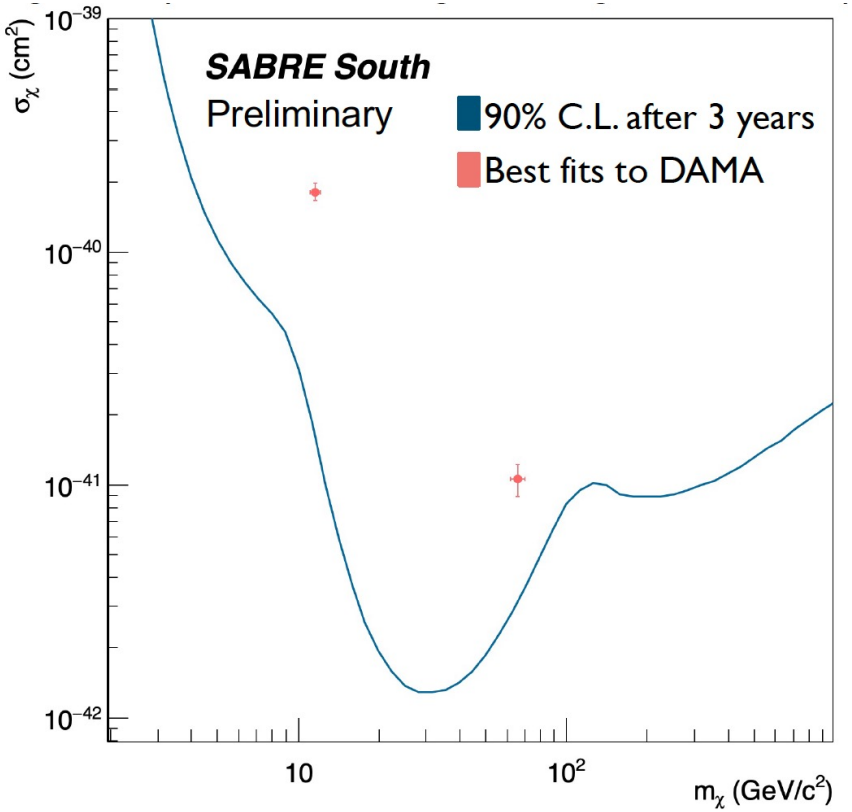
Time Dependence of Background



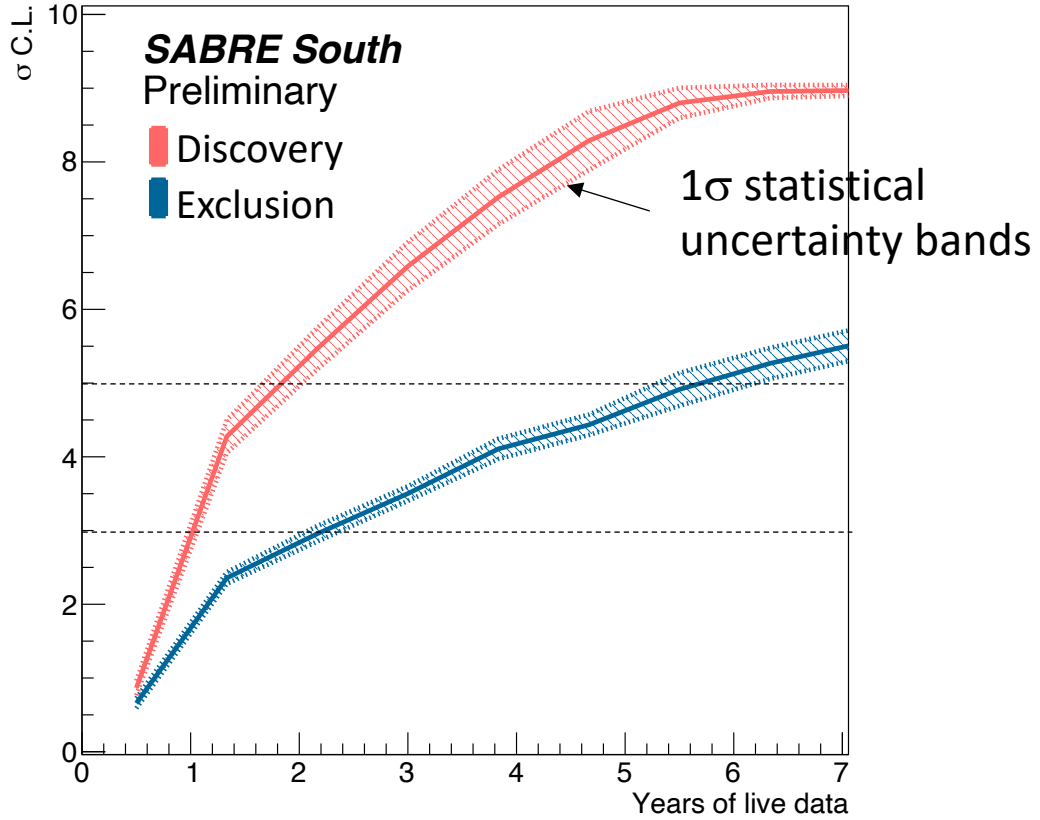
Sensitivity

Assuming total crystal mass of 50 kg and background of 0.72 cpd/kg/keV$_{ee}$ from simulated radioactivity.

90% exclusion curve for the SABRE South experiment after 3 years of data taking .



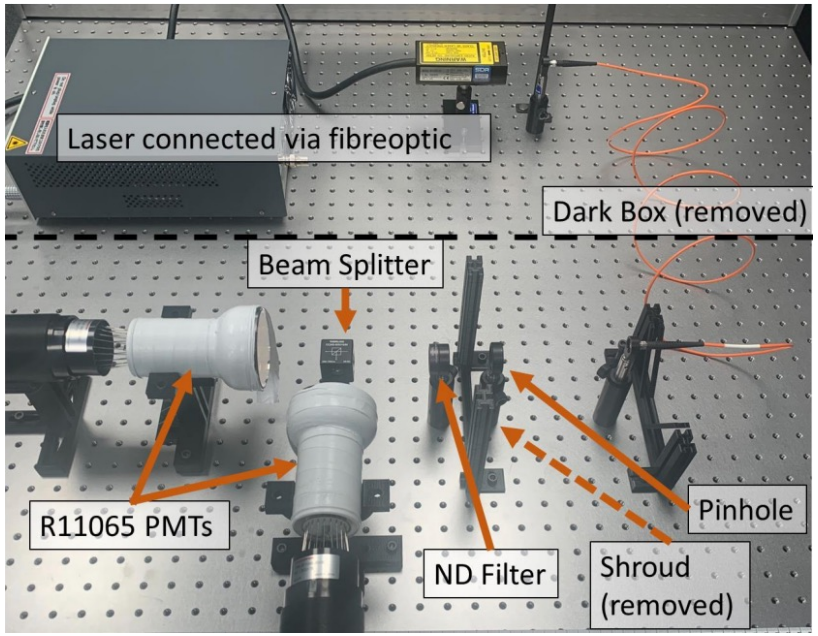
Evolution of discovery/exclusion power as a function of live time.

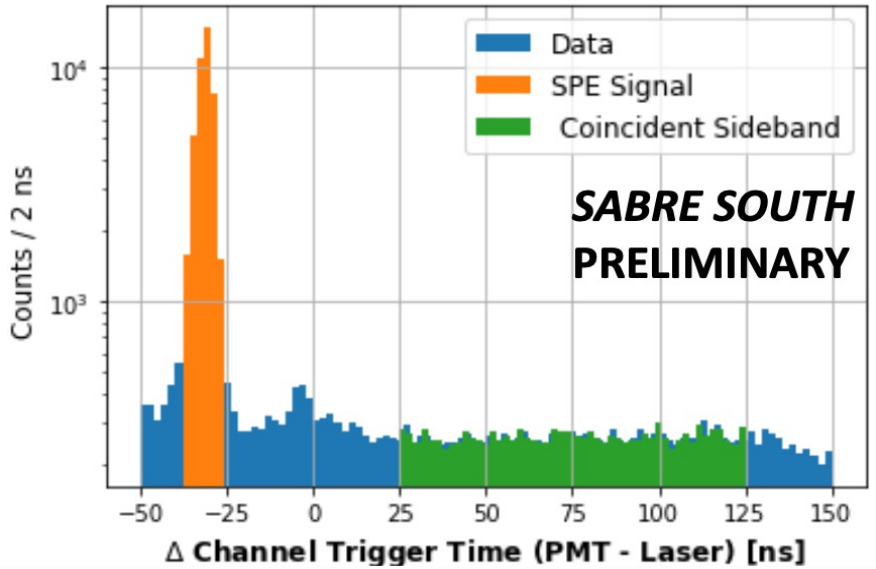


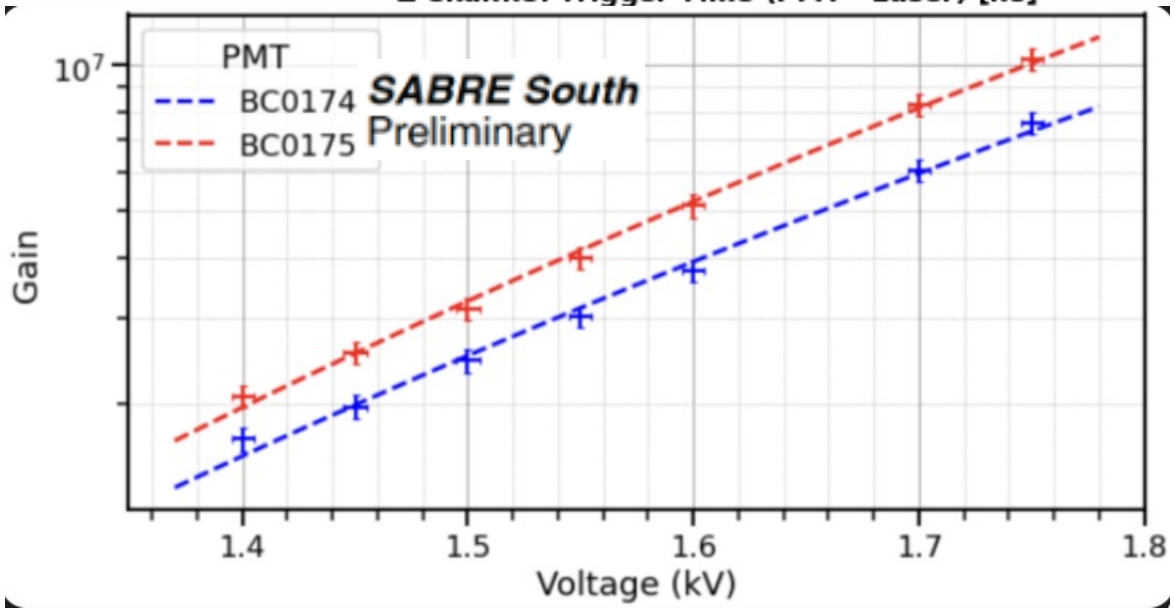
SABRE South Collab. arxiv:2205.13849

PMT Characterisation

- 14 crystal and 18 veto PMTs (+ spares) are being characterised.
- Setup consists in a single photon test bench 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.
- Veto PMTs will be calibrated on site through radioactive sources and laser.

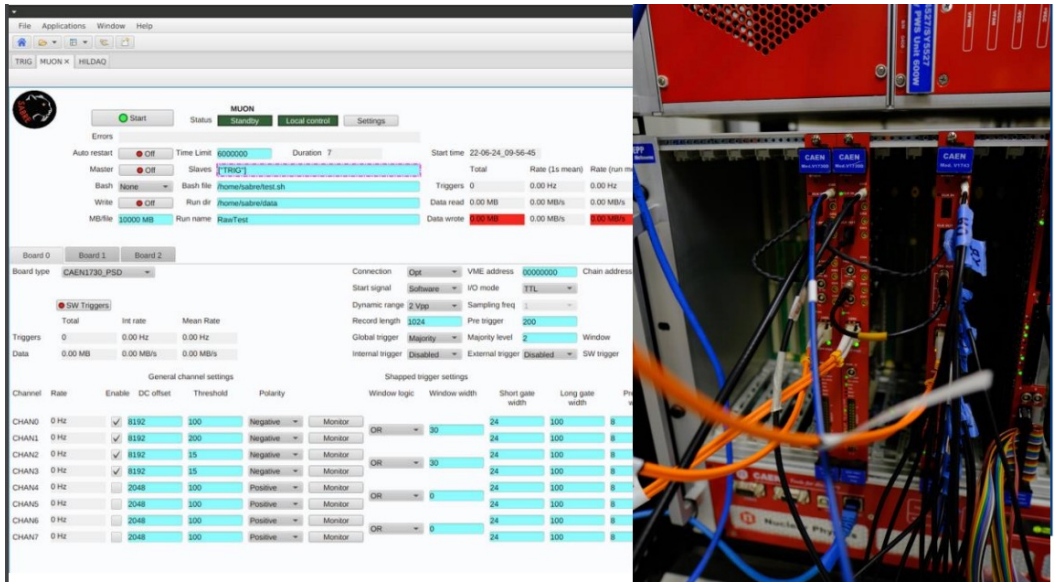


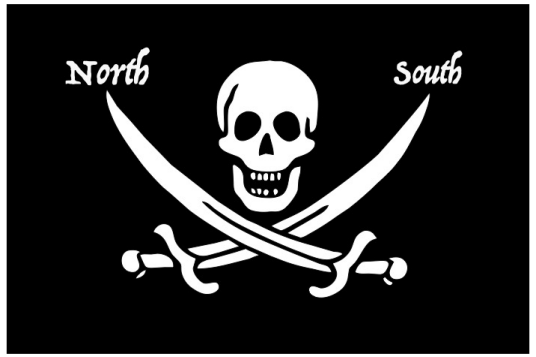




DAQ & Software

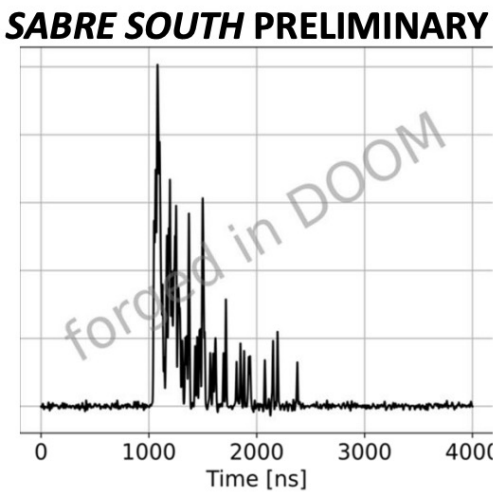
- SABRE South has developed DAQ for the SABRE collaboration: independent EPICS based instances for each subdetector (crystal, veto, & muon).
- Global trigger managed by CAEN V2495 FPGA with custom firmware.
- Prototype currently running NaI test at LNGS.





- SABRE South has developed a flexible python-based tool for data processing and analysis code called Pyrate.
- This reconstruction code will be used by the whole SABRE collaboration.
- Designed to process many digitised channels, currently in use for PMT and NaI characterisation. DOI:10.5281/zenodo.6257646

Mike Mews's talk: Monday 12 December 12:00 pm.



SABRE North status

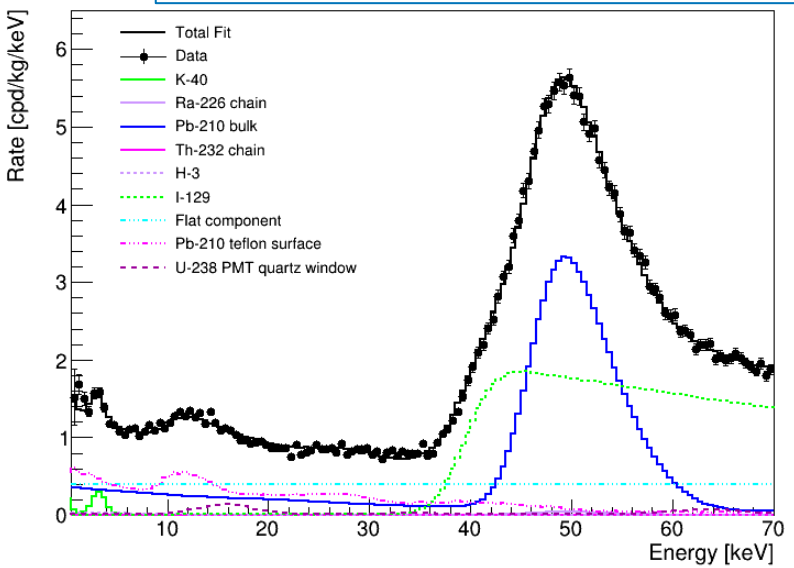
Proof-of-Principle phase (1 crystal + active veto) concluded

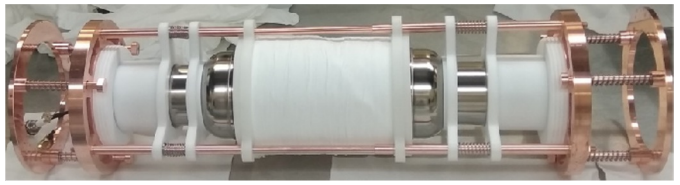
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, **lowest since DAMA/LIBRA**.

Goals for near future:

- Test reproducibility of crystal radiopurity
- Demonstrate lower background with zone refining of NaI powder

Full Monte-Carlo simulation model of crystal NaI-33 to identify background components



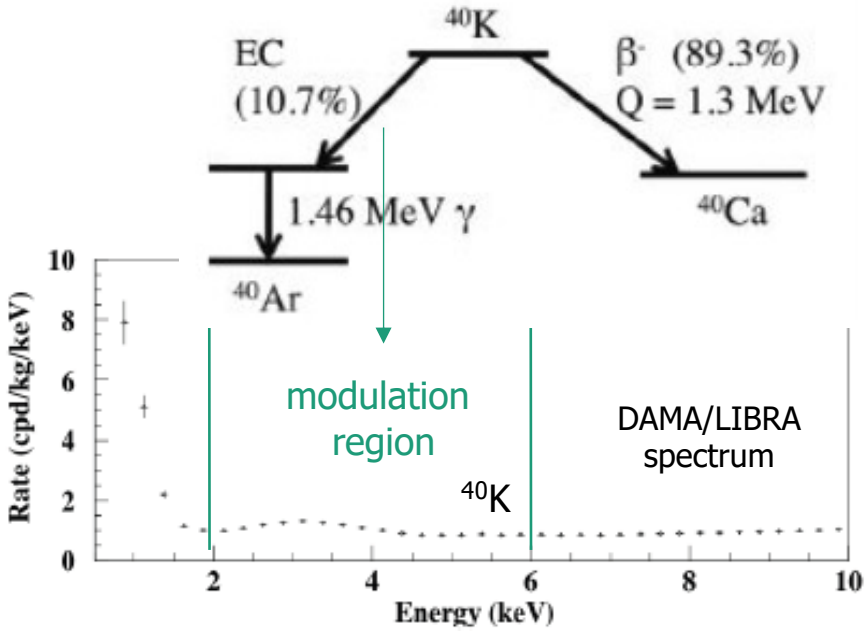


Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding

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.



Other Physics

New physics	Potential observable/s
Pauli exclusion principle	Proton emission above 10 MeV
Solar axions	Axion to photon conversion, electron scattering
MIMPs (heavy DM, boosted DM)	Excess events in crystal or LS
Charge non conserving decays in Na or I	Electron disappearance, gamma excess
Sub GeV DM	Particle ID fro ER-DM events, Migdal effect
Supernova neutrinos	Scattering in crystal or LS