SABRE: Sodium-iodide with Active Background Rejection

WHAT

An experiment based on NaI(Tl) scintillating crystals and focused on the achievement of an ultra-low background

WHERE

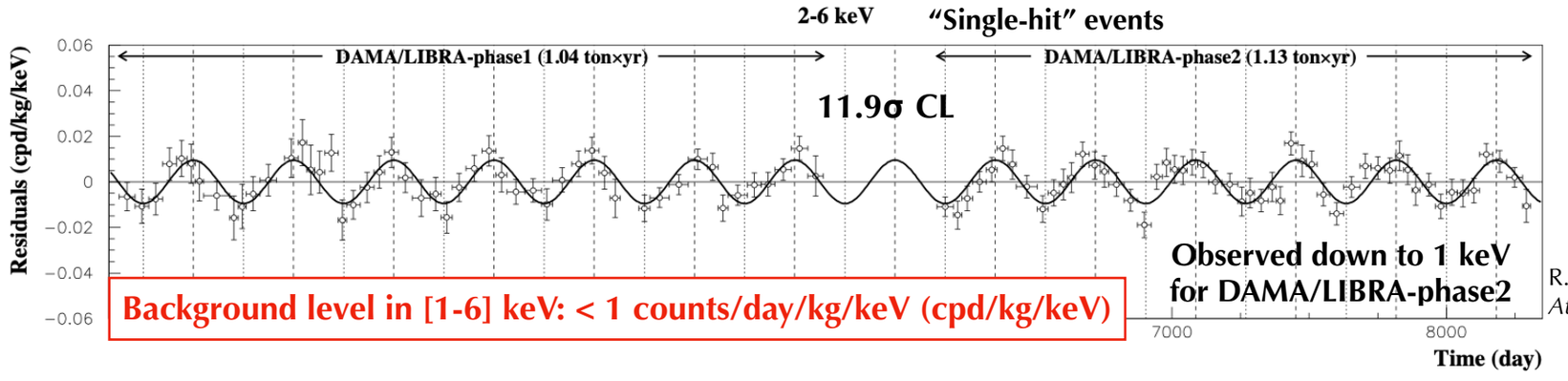
At the Gran Sasso National Laboratory (LNGS, Italy) and Stawell Underground Physics Laboratory (SUPL, Australia)

WHY

Search for galactic dark matter (DM) through the annual modulation effect and model-independent test of the long-standing DAMA result

An annually modulated signal compatible with the DM hypothesis has been observed by the DAMA/LIBRA experiment at LNGS, in Italy.

250 kg of high purity NaI(Tl) crystals + passive shielding



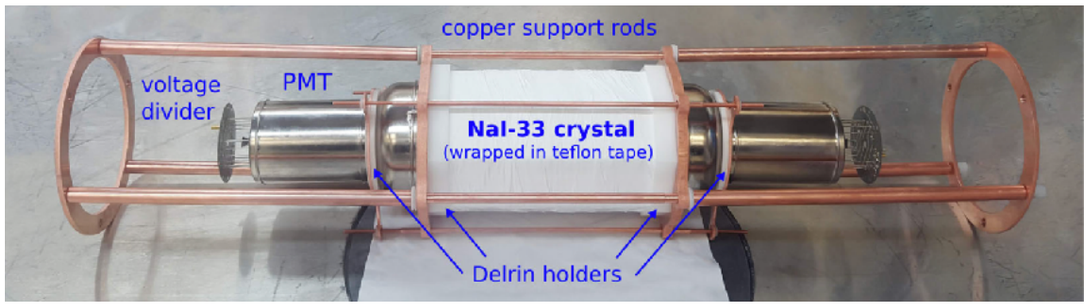
R. Bernabei et al., *Nuclear Physics and Atomic Energy*, 19(4):307–325, 2018.

- Experiments using different target materials seem to exclude the interpretation of DAMA signal as due to spin-independent DM scattering off nuclei in the standard WIMP galactic halo hypothesis.
- Currently running experiments using the same target (ANAIS-112 and COSINE-100), have not yet reached the ultra-low background and sensitivity achieved by DAMA → **A new high sensitivity and low background measurement with NaI(Tl) crystals is needed.**

The SABRE Proof-of-Principle (PoP)

Goals:

- Assess the radio-purity of SABRE NaI(Tl) crystals;
- Test the veto performance.



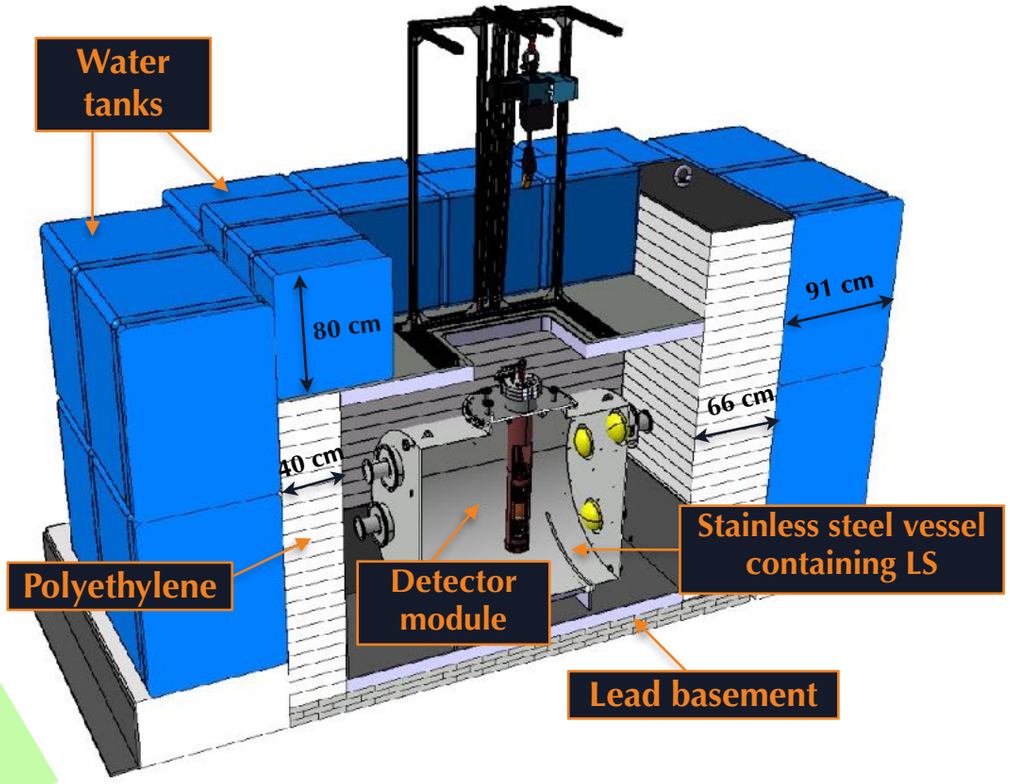
Setup:

- **One SABRE detector module** at a time;
  - high-purity copper enclosure containing the crystal wrapped with PTFE reflector and directly coupled to two high quantum efficiency and low radioactivity 3″ Hamamatsu R11065-20 PMTs;
- **Stainless steel vessel** containing ~2 tons of **liquid scintillator (LS)** and equipped with ten 8″ PMTs;
- External passive shielding made of **lead, polyethylene** and **water**.

Accomplishments:

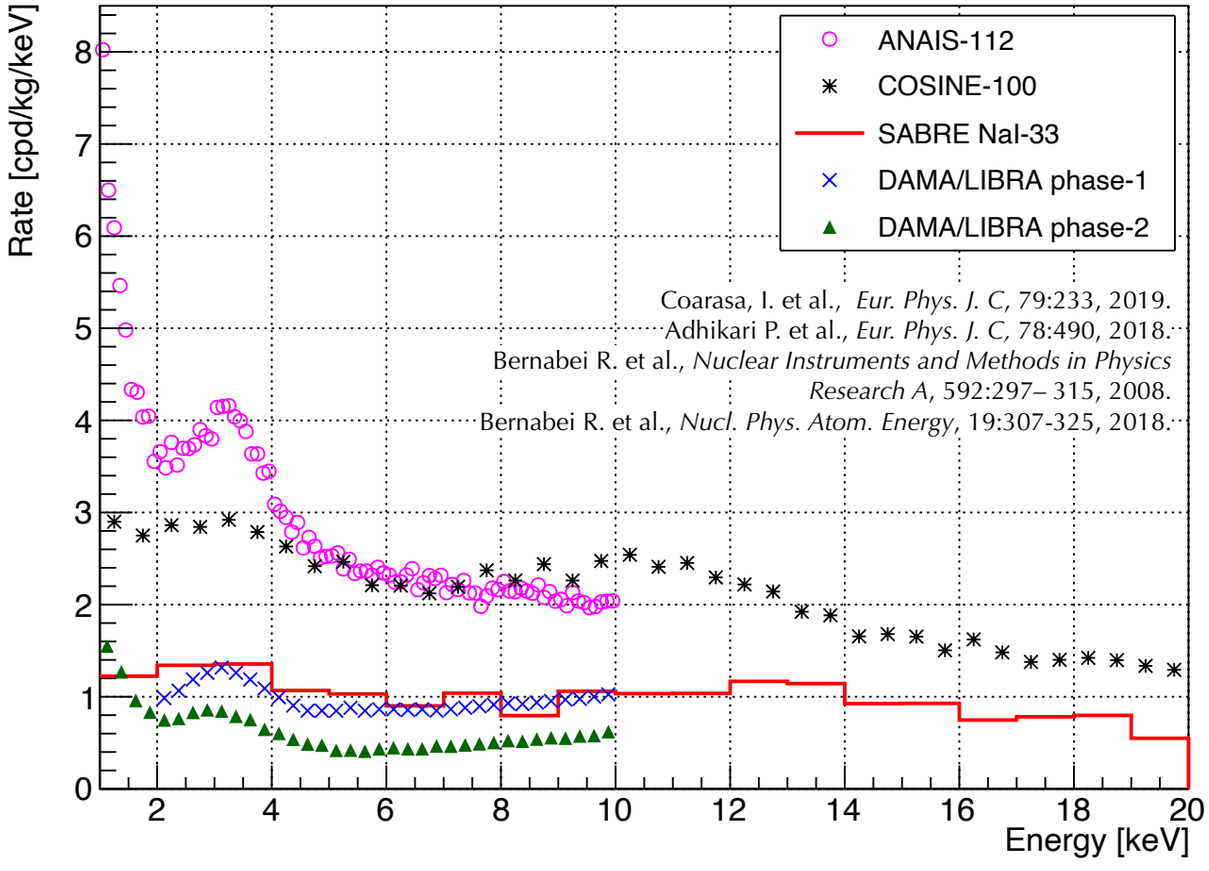
- Measurement of the **potassium content** with direct counting;
- **Low energy analysis** using a cut-based approach to select scintillation events;
- **Background model** for **NaI-33** crystal.

CONCLUDED



Summary of the results from SABRE PoP

	NaI-31	NaI-33	DAMA/LIBRA crystals	ANAIS crystals	COSINE crystals
LY [phe/keV]	9.1 ± 0.1	12.1 ± 0.2	6-10	15	15
FWHM/E @59.5 keV	14.1%	13.5%	15.8%	11.2%	11.8%
^{40}K activity [mBq/kg] (direct counting)	0.49 ± 0.10	< 0.15	< 0.62	0.70-1.33	0.58-2.5
^{238}U content [ppt] (Bi-Po-214 direct counting)	-	< 0.5	0.7-10	0.2-0.8	< 0.02-0.12
^{232}Th content [ppt] (Bi-Po-212 direct counting)	-	< 0.5	0.5-7.5	0.1-1	0.3-2.4
Alpha rate [mBq/kg] (PSD analysis)	1.02 ± 0.07	0.54 ± 0.01	0.08-0.12	-	0.74-3.20
^{210}Pb activity [mBq/kg] (^{210}Po build-up)	-	0.51 ± 0.02	0.005-0.03	0.7-3.15	-
Exposure	60 kg·days	90 kg·days	2.17 ton·yr	313.95 kg·yr	97.7 kg·yr
Average rate in [1-6] keV [cpd/kg/keV]	-	1.20 ± 0.05	< 1	3.605 ± 0.003	2.73 ± 0.14



PoP setup sensitive to a ppb-level ^{nat}K contamination in the crystal:

^{nat}K < 4.7 ppb at 90% CL in NaI-33

NaI-33, in terms of radio-purity, is the best crystal ever produced after DAMA/LIBRA.
Average count rate in [1-6] keV ROI:
1.20 ± 0.05 cpd/kg/keV

M. Antonello et al., *Eur. Phys. J. C*, 81(4):299, 2021.
F. Calaprice et al., *Phys. Rev. D*, 104 (2), L021302, 2021.

The SABRE PoP-dry setup

- At the beginning of 2021 the SABRE PoP setup was modified to restart crystals characterization **<u>without</u> the LS veto.**
- Removed the LS vessel, the detector modules were placed directly inside the PoP passive shielding.
- To compensate for the missing shielding power of the LS, were added (from inside to outside):
  - **Low radioactivity copper** (10 cm on all sides and top, 15 cm below);
  - **Polyethylene slabs on sides.**

Data taking on March 2021 -> June 2022

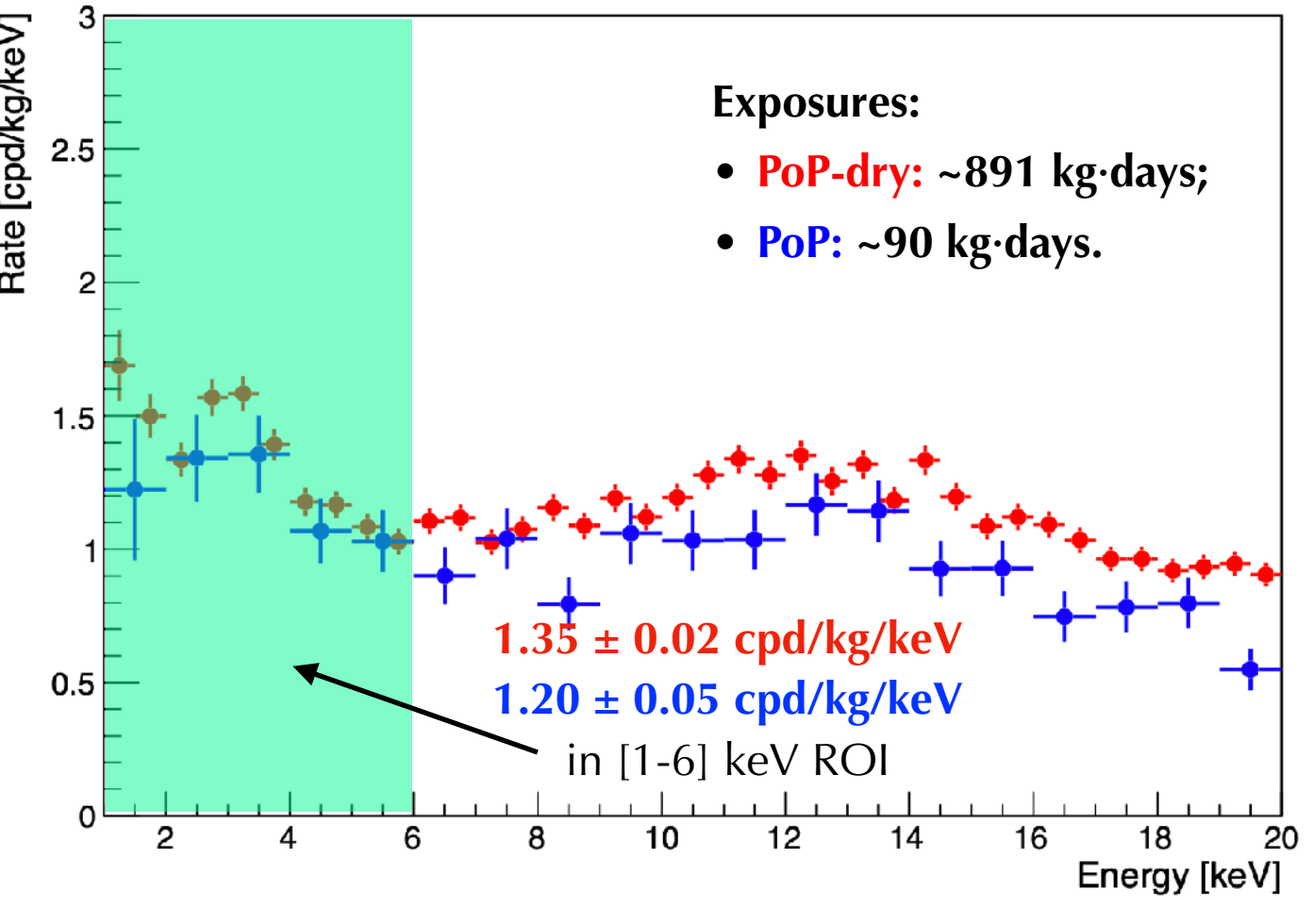
arXiv:2205.13876

NaI-33 background model

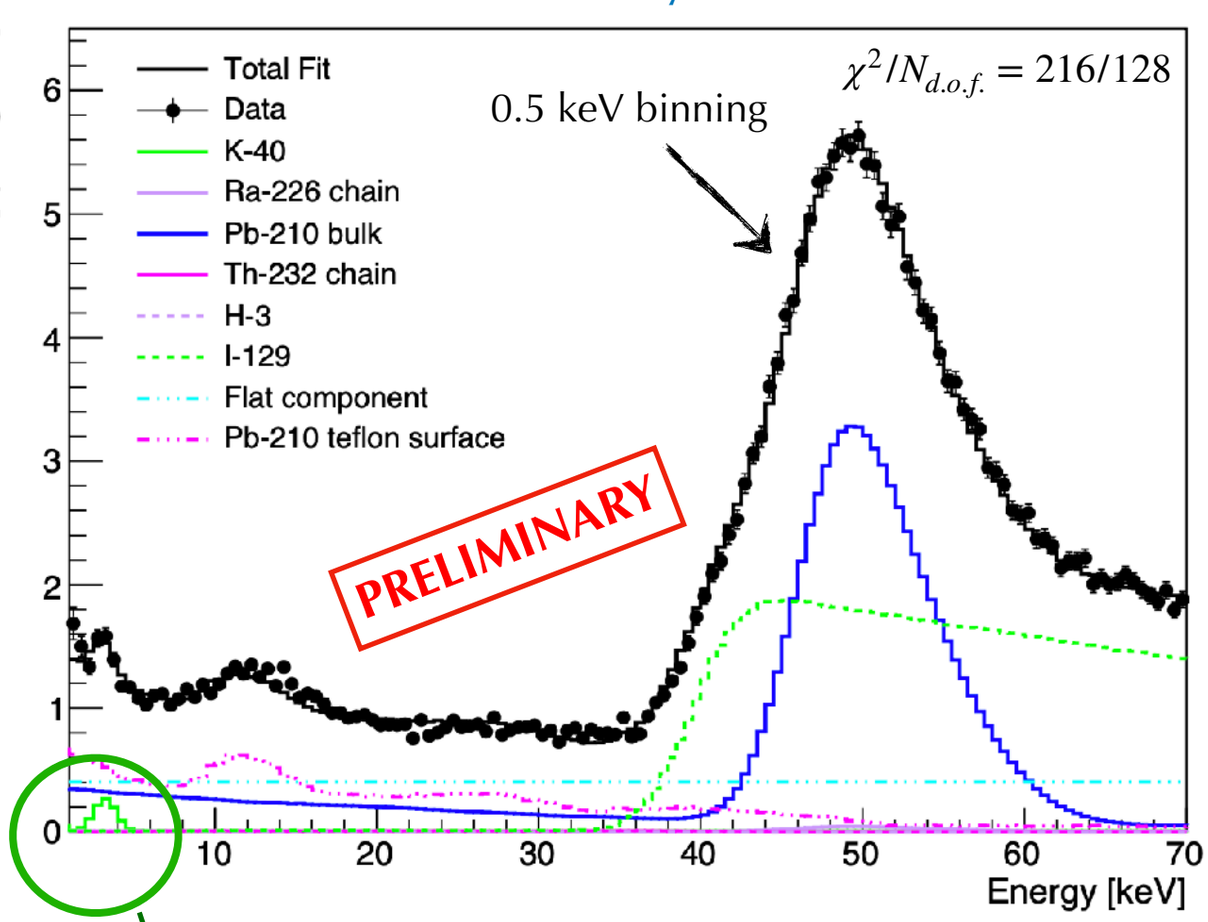
Fit with Monte Carlo spectral shapes to build the background model

Exposures:

- **PoP-dry:** ~891 kg·days;
- **PoP:** ~90 kg·days.



PoP-dry data



The low K content in NaI-33 produces a contribution to the background rate in ROI sub-dominant with respect to that of other components.

NaI-33 background model results

	PoP-dry Exposure: ~891 kg·days	
Source	**Activity**	**Rate in ROI [cpd/kg/keV]**
^{40}K	(0.12 ± 0.02) mBq/kg	0.096 ± 0.014
^{210}Pb (bulk)	(0.46 ± 0.01) mBq/kg	0.32 ± 0.01
^{226}Ra	(5.9 ± 0.6) µBq/kg	0.0049 ± 0.0005
^{232}Th	(1.6 ± 0.3) µBq/kg	
^{3}H	≤ 3 µBq/kg	≤ 0.004
^{129}I	(1.31 ± 0.01) mBq/kg	
^{210}Pb (PTFE)	(0.93 ± 0.04) mBq	0.51 ± 0.02
Flat component (external)		0.40 ± 0.02
Total		1.34 ± 0.03

Dominant background contributions

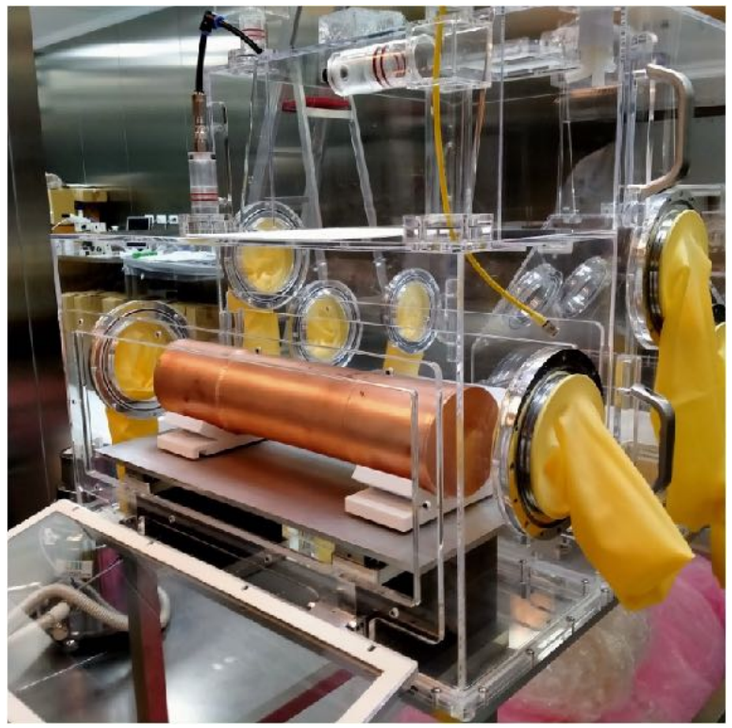
flat component: passive shielding is not yet optimized

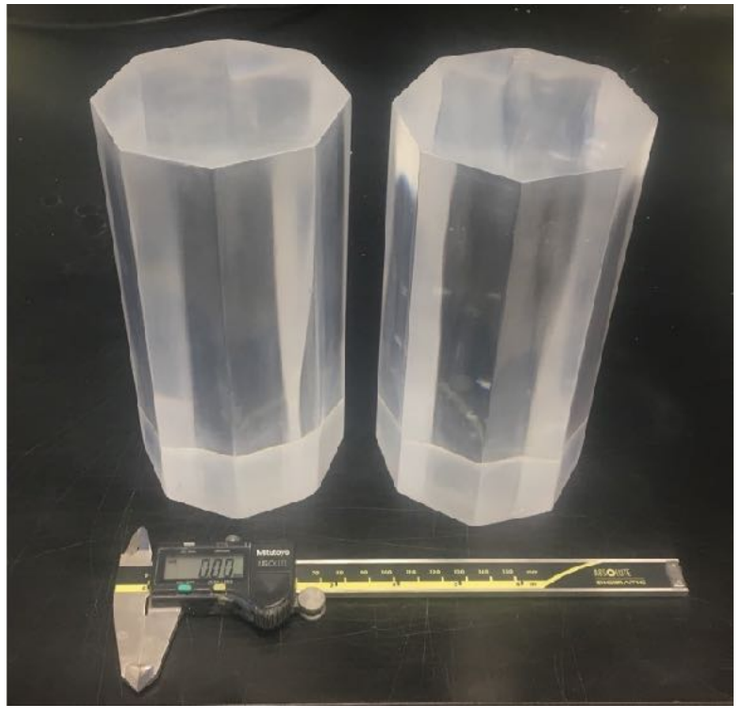
Take-home messages:

1. **Dominant contributions are <u>not</u> affected by the presence of the veto**
2. **Upcoming design with <u>passive</u> shielding for the physics phase of SABRE North**
3. **Projected background rate: 0.5 cpd/kg/keV**

Upcoming activities

1. Replace the **PTFE** reflector on NaI-33
   - **radio-clean** material already procured and tested
   - glove-box for detector module assembly under commissioning
   - new data taking in summer
2. Received **new crystal NaI-37 from RMD** (~ 4.5 kg)
   - grown out of Astrograde powder
   - Goal: **verify reproducibility of the method**
     - crucible preparation, cut&polishing by the company
   - radio-purity essay by ICP-MS at LNGS soon
   - complete characterization in PoP-dry in autumn
3. Received new crystal NaI-35 from RMD
   - purchased by SABRE-South copper case with fused silica window
   - started measurement at LNGS Hall B setup in April





CSNII funding scheme for SABRE

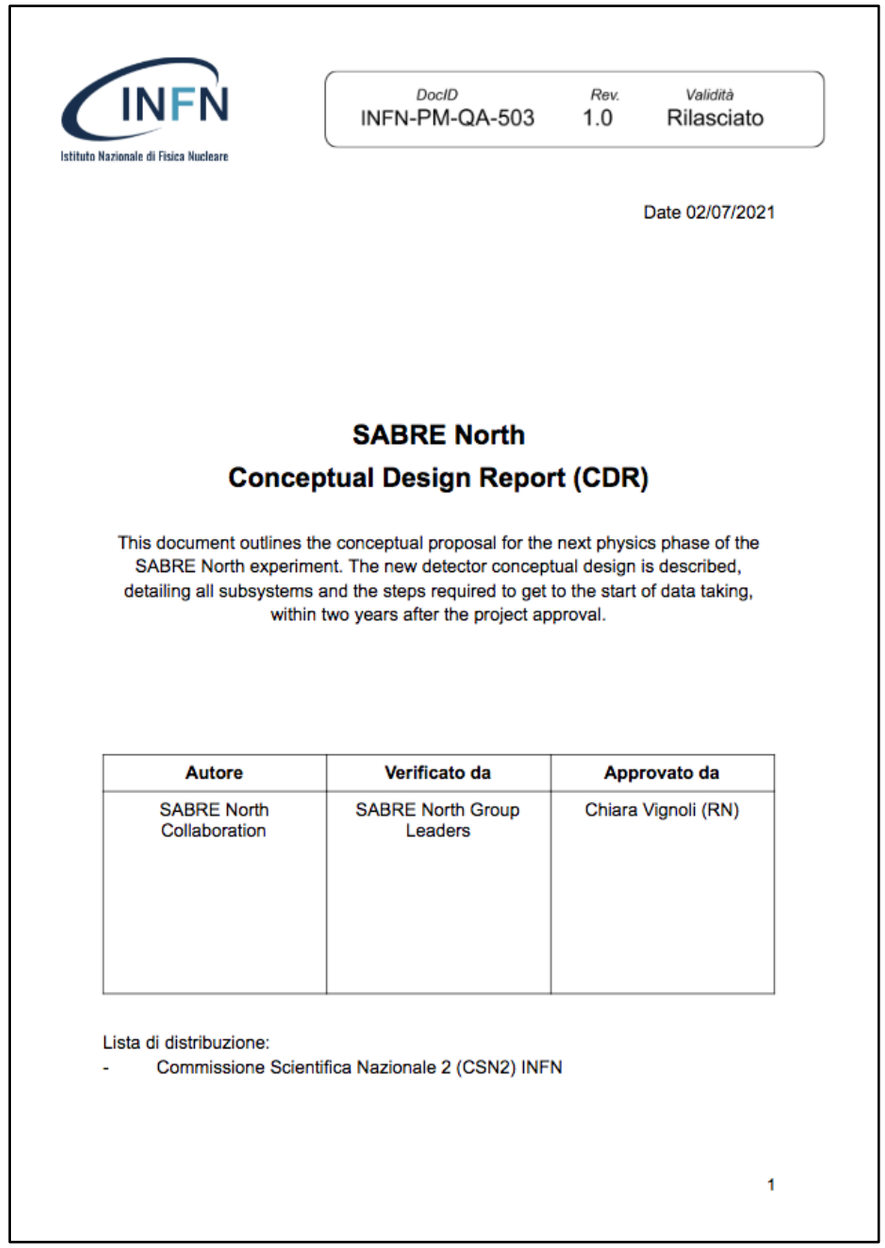
2016-2021 Proof-of-Principle Phase: concluded

- CDR for Physics phase presented in Jul 2021
- Approved in a 2+3 scheme

2022-2023 Validation Phase: ongoing

- Prove clean PTFE removes surface 210Pb backer.
- Prove RMD company can reproduce the NaI-33 result
- opt.: Prove Zone Refining purification of a full scale crystal
- TDR for physics phase expected Jul 2023

2024 -202? Physics Phase



INFN
Istituto Nazionale di Fisica Nucleare

DocID	Rev.	Validità
INFN-PM-QA-503	1.0	Rilasciato

Date 02/07/2021

SABRE North

Conceptual Design Report (CDR)

This document outlines the conceptual proposal for the next physics phase of the SABRE North experiment. The new detector conceptual design is described, detailing all subsystems and the steps required to get to the start of data taking, within two years after the project approval.

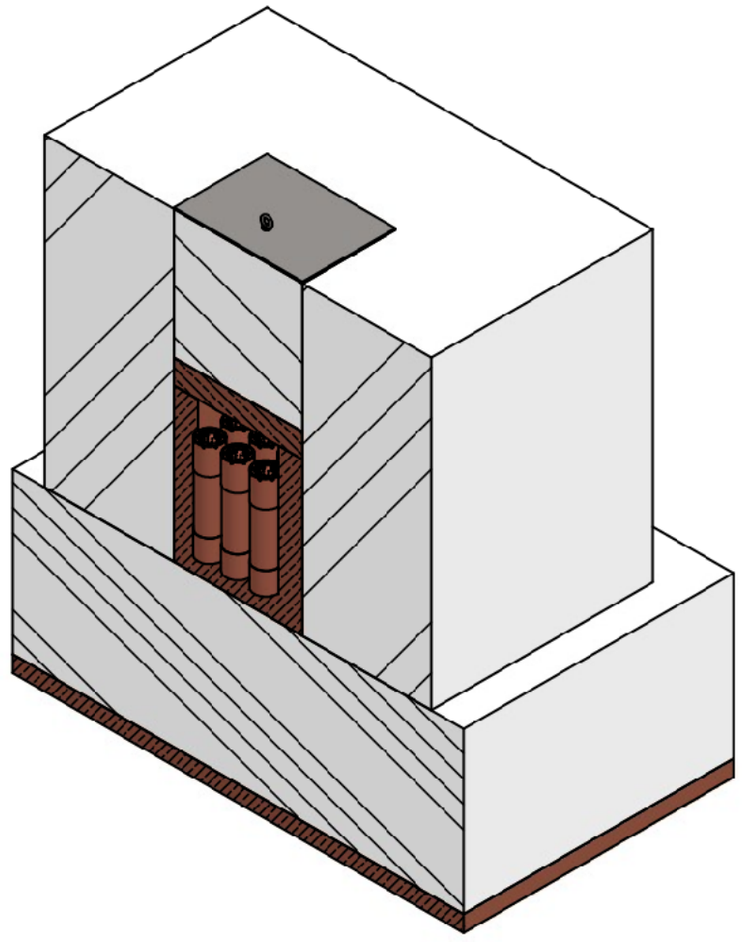
Autore	Verificato da	Approvato da
SABRE North Collaboration	SABRE North Group Leaders	Chiara Vignoli (RN)

Lista di distribuzione:
- Commissione Scientifica Nazionale 2 (CSN2) INFN

1

Design for Physics Phase

- No liquid scintillator is necessary thanks to the high purity of the crystals -> <u>environmental compliant with LNGS restrictions</u>
- 3 x 3 matrix of 5 kg NaI detectors
- Inside 5 mm thick Cu box
- 15 cm Cu and 80 cm PTFE shielding structure
- Vertical crystals deployment
- Optimized re-use of existing material from PoP
- Simulations ongoing
- Finalisation of the design **<u>by Jul 2023 (TDR due)</u>**



Anagrafica, Richieste e Task Milano

Milano	FTE
Davide D'Angelo (resp. loc.)	0.5
Andrea Zani	(0.5)
Maddalena Antonello	0.5
Totale Milano	(1.5) 1.0

(invariata) a meno di A. Zani che deve mettere 100% su Fellini, comunque sinergico. Da settembre 2022 prende servizio come tecnologo

TASK 2023

Supporto attività LNGS (presenza due laureandi): montaggio rivelatori e operatività setup sala B.

Misura di rumore indotto da parti dell'enclosure (PTFE, rame) in assenza di cristallo.

Richieste 2023

- Missioni: 10k + 3k SJ
- Consumo: 2k elettronica (PCB, montaggio, cavi, connettoristica, etc.)
- Inventario: 7.5k digitizer (CAEN v1730, 8ch)

Totale nazionale (LNGS + Milano + Roma1+Lecce): 6.5 FTE

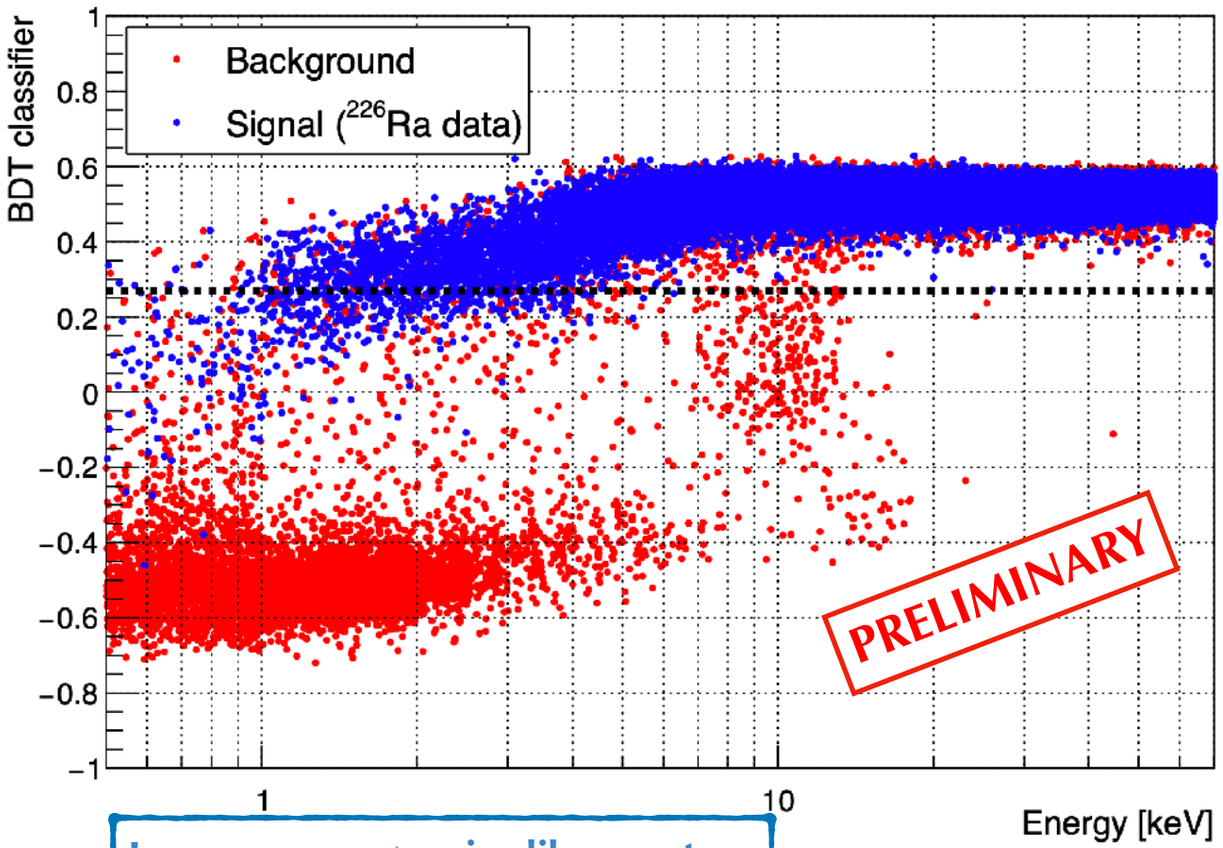
resp. naz. Aldo Ianni (LNGS)

New entry!

Backup

SABRE PoP-dry NaI-33 low energy data analysis

A more innovative **Boosted Decision Trees (BDT)** approach used to maximize the acceptance of scintillation events at very low energies while efficiently rejecting noise.

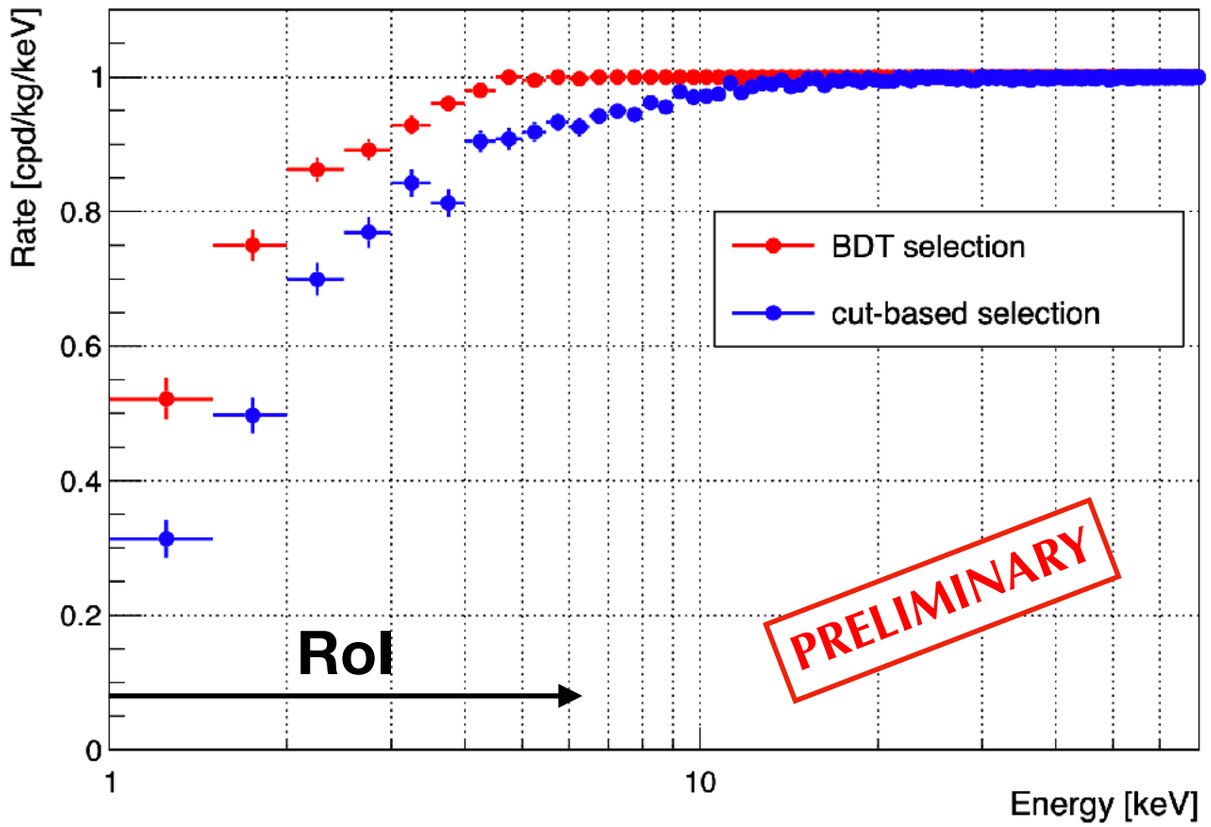


Lower scores → noise-like events.

Higher scores → signal-like events.

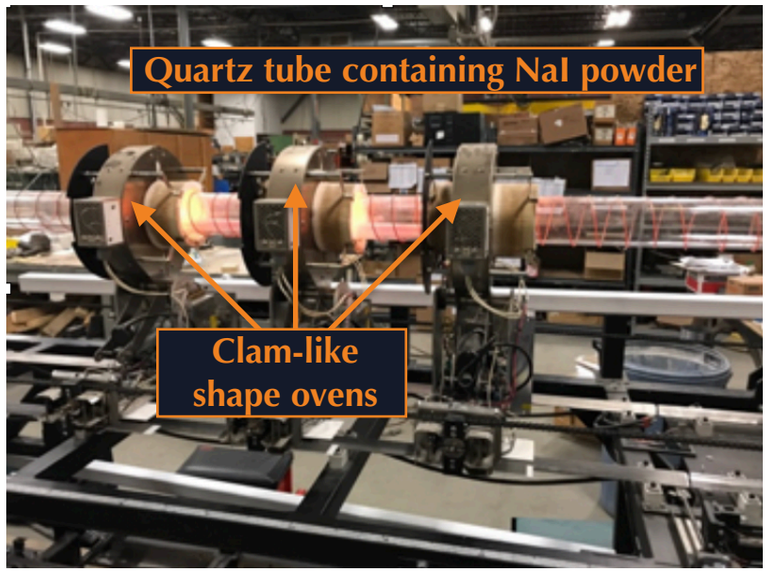
Training samples:

- **Signal:** ^{226}Ra source data acquired by triggering only on coincidences between the two crystals, selecting events in the 0.5-10 keV energy region;
- **Noise:** background runs selecting events in the 0.5-4 keV energy region (dominated by noise).

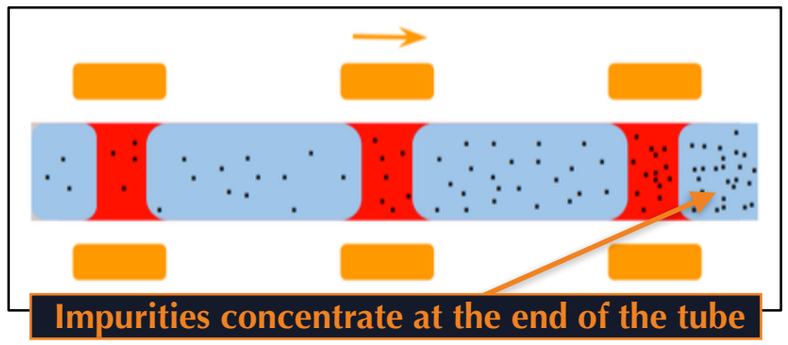


BDT cut threshold (black dashed line) chosen based on data acquired with the ^{226}Ra source to have an average event acceptance in the RoI > 90%.

Zone Refining



Zone refining system developed in collaboration with the Mellen Company.



B. Suerfu, *PhD thesis,* Princeton University, 2018.

Further improvements on crystals radio-purity are under investigation: Zone Refining (ZR) purification tests on NaI powder

- ZR is a purification process in which impurities in the powder are moved, together with the molten material, in the same direction as the ovens move.
- Test operation made in 2019: samples taken from five successive sectors along the tube to perform ICP-MS measurements and estimate the purification factors.

Ovens motion direction →

Isotope	Powder [ppm]	S_1 [ppm]	S_2 [ppm]	S_3 [ppm]	S_4 [ppm]	S_5 [ppm]
^{39}K	0.0085	< 0.0008	< 0.0008	0.001	0.016	0.46
^{208}Pb	0.0012	0.0004	0.0004	0.0004	0.0005	0.0005
^{85}Rb	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	0.0007

B. Suerfu et al., *Phys. Rev. Applied* 16, 014060, 2021.

ZR reduces ^{40}K and ^{87}Rb (from ^{39}K and ^{85}Rb measurements) to negligible levels, and ^{208}Pb by at least a factor of 2.5

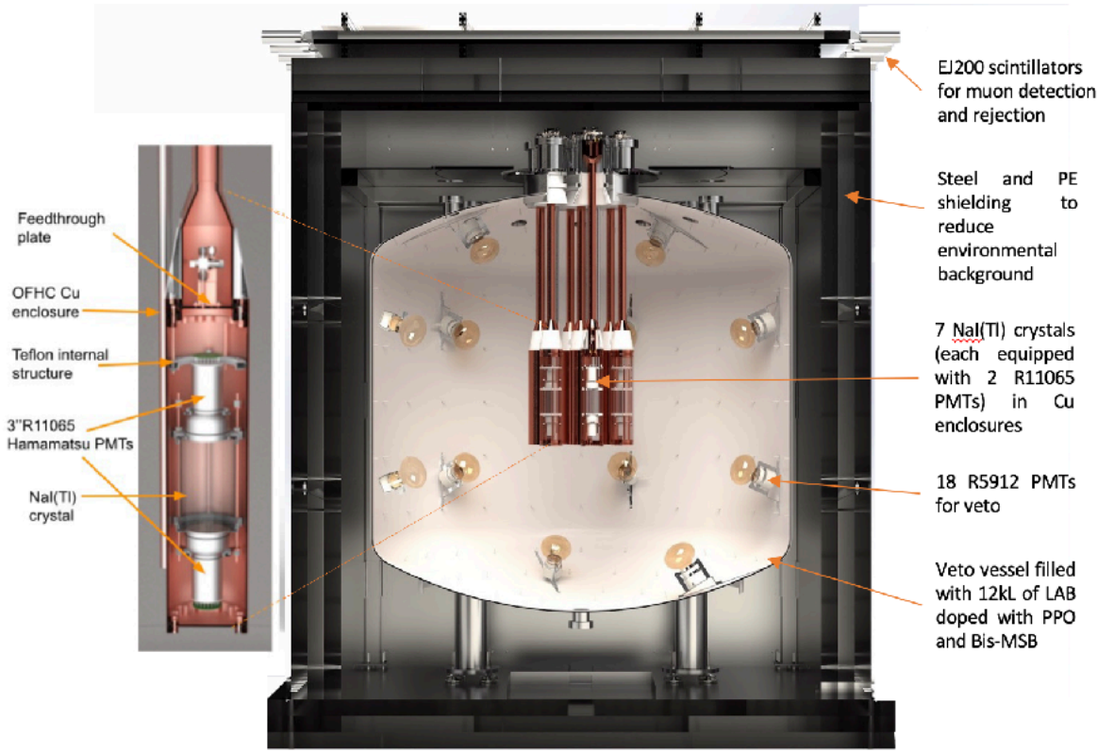
Assuming NaI-33 contamination after scaling for the reduction factors observed in ZR tests and using a clean PTFE reflector:

SABRE crystals would reach a background level in the ROI ≤ 0.3 cpd/kg/keV

↓

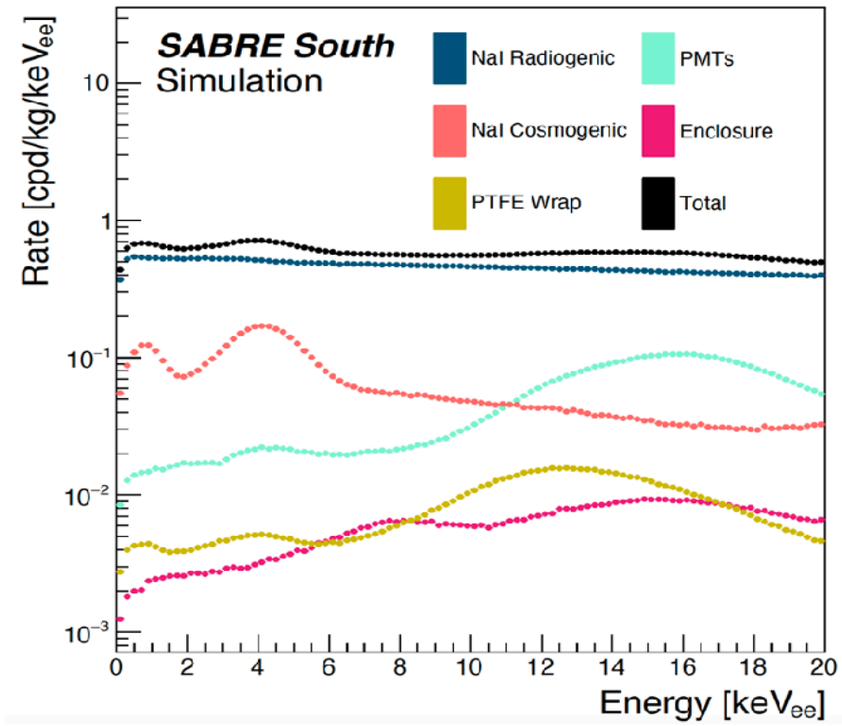
Mostly due to ^{210}Pb contamination in the crystal

SABRE South



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

- Vessel + LAB, PMTs, muon detector, DAQ electronics, slow control, Crystal insertion system … all ready
- Crystal procurement is on-going
- One low background NaI(Tl) crystal **in** testing phase at LNGS.

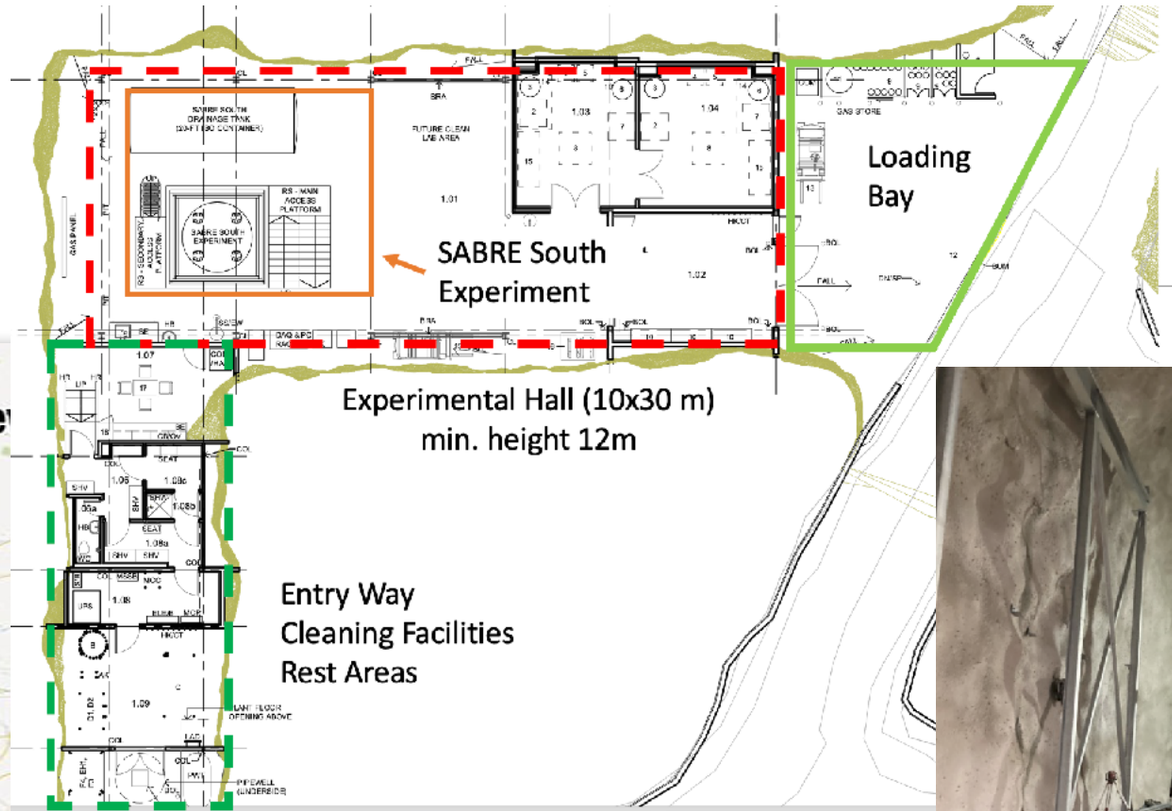


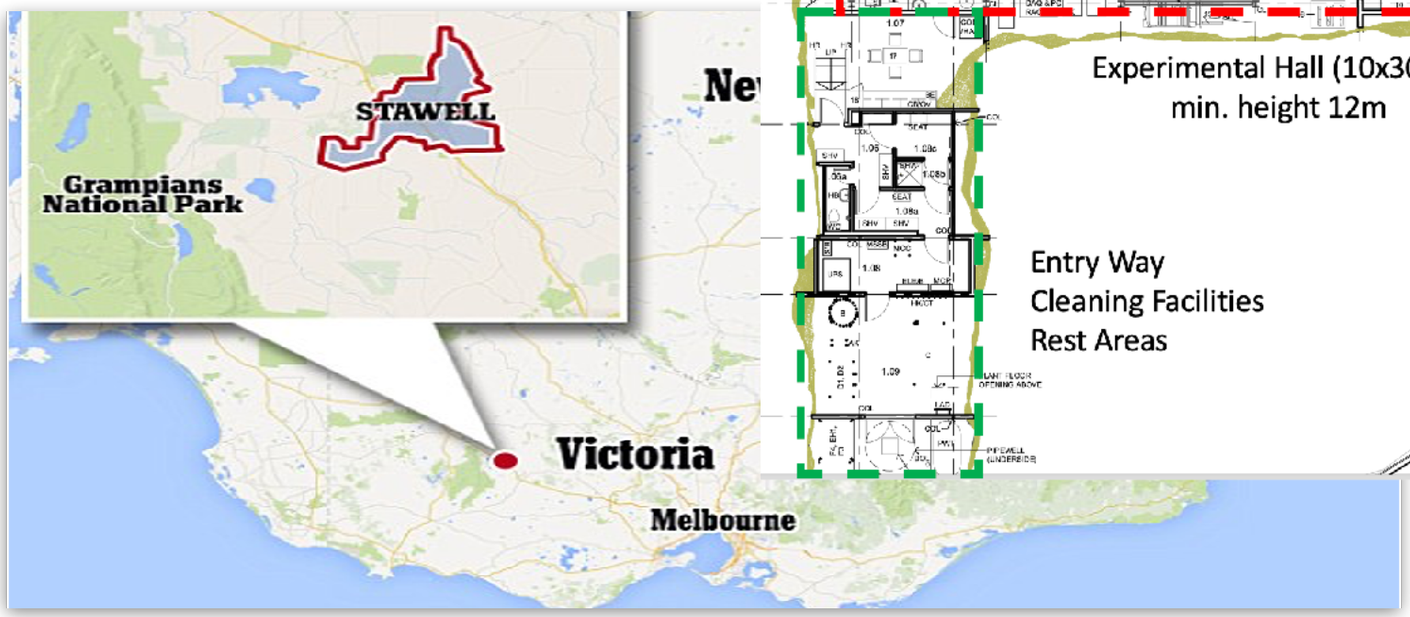
Highest purity crystals and largest active veto: 0.7 cpd/kg/keV

http://arxiv.org/abs/2205.13849.

Stawall Undeground Physics Lab (SUPL)

- First deep underground laboratory in the Southern Hemisphere
  - 1025 m deep (2900 m water equivalent) with flat over burden
- Construction complete and operations will start in August 2022
- Located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia
  - Helical drive access





SABRE North and South Synergy

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 LS will be used for in-situ evaluation and validation of the background in addition of background rejection and particle identification.