Australian National University

# The SABRE South Experiment at the Stawell Underground Physics Laboratory

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Australian National University

DSU 2024
13th September, Corfu

**On behalf of the SABRE South collaboration**

# Talk Content

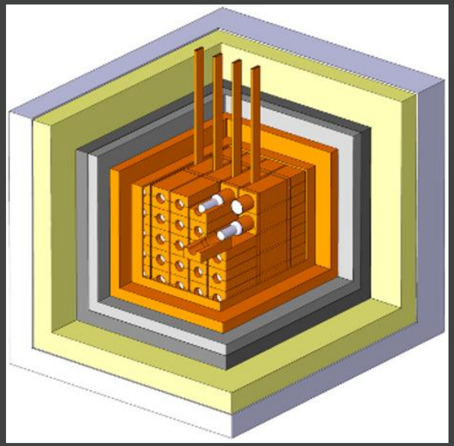
## SABRE South dark matter experiment


## SUPL underground lab in an active gold mine

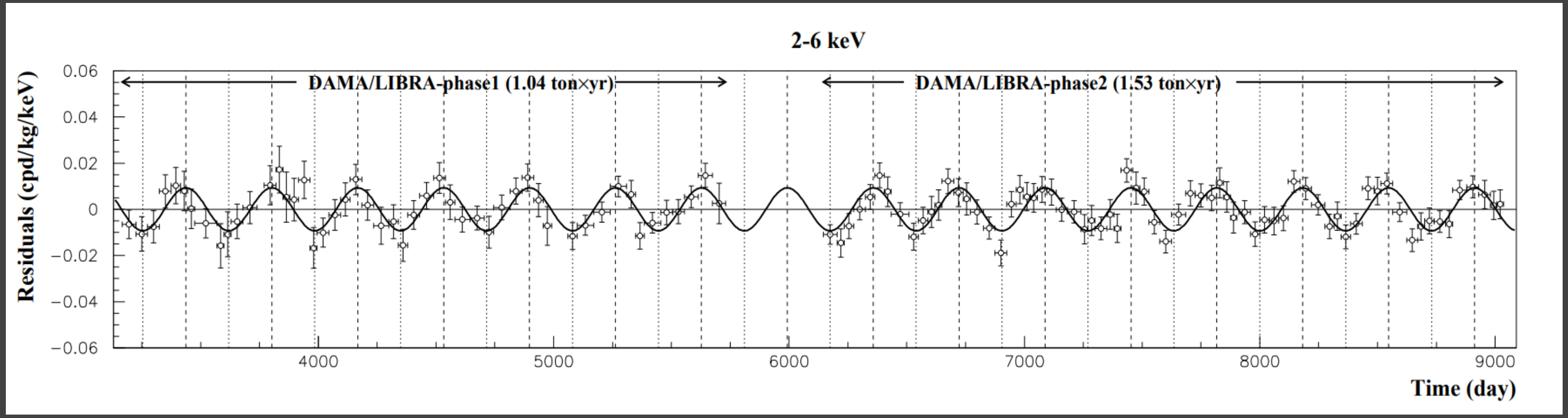
## First deep underground lab in the Southern Hemisphere

# SABRE Motivation

- **DAMA/LIBRA** at **L**aboratori **N**azionali der **G**ran **S**asso (**LNGS**) in Italy
  250 kg pure NaI(Tl) crystals



~20 years of observation, **signal modulation period of exactly 1 year**
- Observed **~0.01 cpd/kg/keV modulation** in the 1-6 keV energy range
- Other experiments could not confirm DAMA/LIBRA results

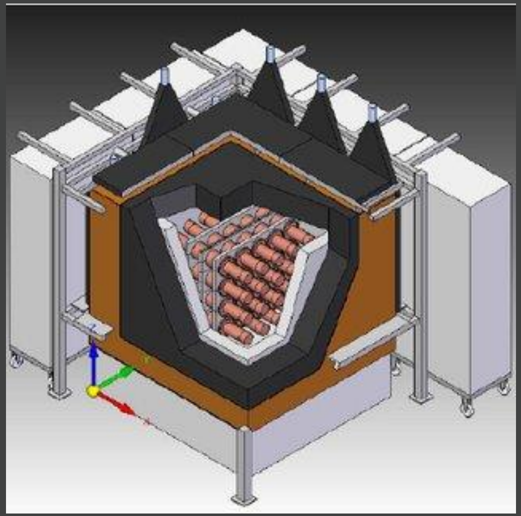



Bernabei et al. 2021

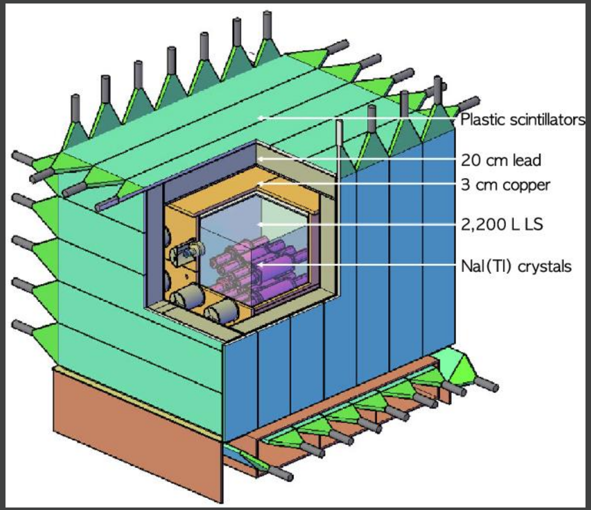
**Is it dark matter?** Other NaI(Tl) experiments could not confirm the modulation.

# Other NaI(Tl) Experiments

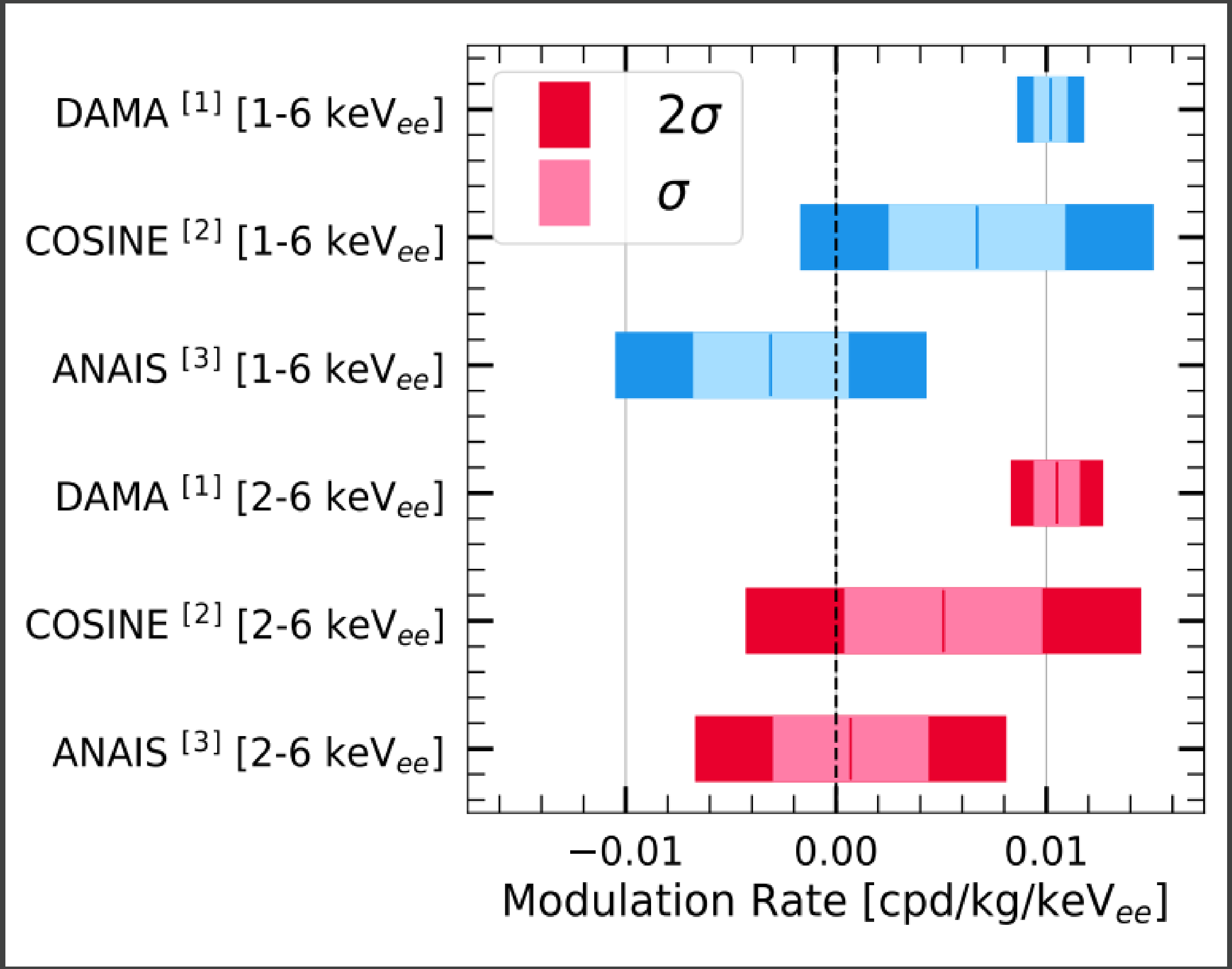
- **Anomaly tested by similar improved detectors:** DAMA has the smallest uncertainty and best sensitivity)
- **ANAIS -** at Canfranc underground lab, Spain
- **COSINE** at Yangyang lab, South Korea



**ANAIS**




**COSINE**





[1] Bernabei et al. Annual modulation results from DAMA/LIBRA, 2023.
[2] Adhikari et al, Three-year annual modulation search with COSINE-100, 2021.
[3] Coarasa et al., ANAIS-112 three years data: a sensitive model independent negative test of the DAMA/LIBRA dark matter signal, 2024.


ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# SABRE: A Dual Site Experiment

The scientific 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

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEL SALENTO

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI MILANO

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

MELLEN

RMD A Dynasil Company

STAWELL UNDERGROUND PHYSICS LAB

Australian National University

THE UNIVERSITY OF SYDNEY

KEK High Energy Accelerator Research Organization

SWINBURNE

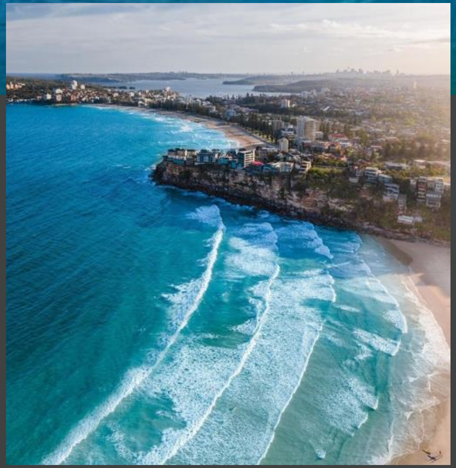
THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY of ADELAIDE

# SABRE: A Dual Site Experiment

# Stawell vs. Sydney





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# The SABRE Collaboration

## SABRE North and South 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 framework.
- Exchange of engineering know-how with collaboration agreements between the ARC Centre of Excellence for Dark Matter Particle Physics and INFN.

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- Same detector module concept (ultra-pure crystals and HPK R11065 PMTs).
- Common simulation, DAQ and data processing framework.
- Exchange of engineering know-how with collaboration agreements between the ARC Centre of Excellence for Dark Matter Particle Physics and INFN.

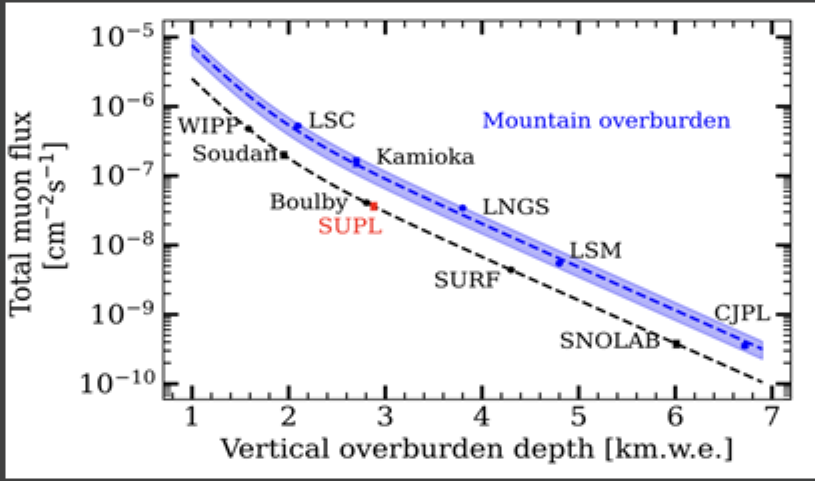
## SABRE North and South have different shielding designs:

- **SABRE North** has a fully passive shielding
- **SABRE South** uses liquid scintillator: it will be used for in-situ evaluation and validation of the background in addition to background rejection and particle identification.

# SUPL

**SUPL (S**tawell **U**nderground **P**hysics **L**aboratory)

- In an **active gold mine** in Stawell, Victoria, Australia.
- **1,025 m** underground (2900 m water equivalent).
- Decline mine with a single portal.
- 30-minute drive to the laboratory.
- 40ºC (104 F) .
- First underground lab in the **Southern Hemisphere .**

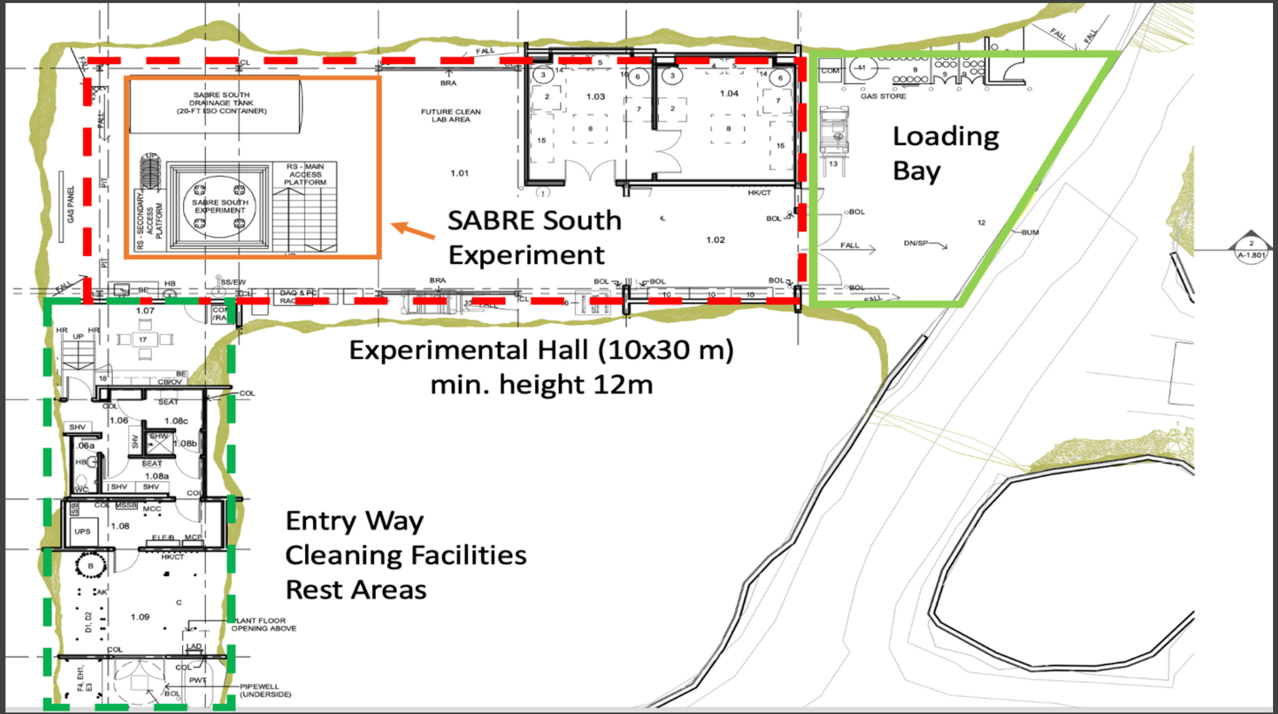




# SUPL

Construction complete and installation of SABRE South experiment started in 2023.

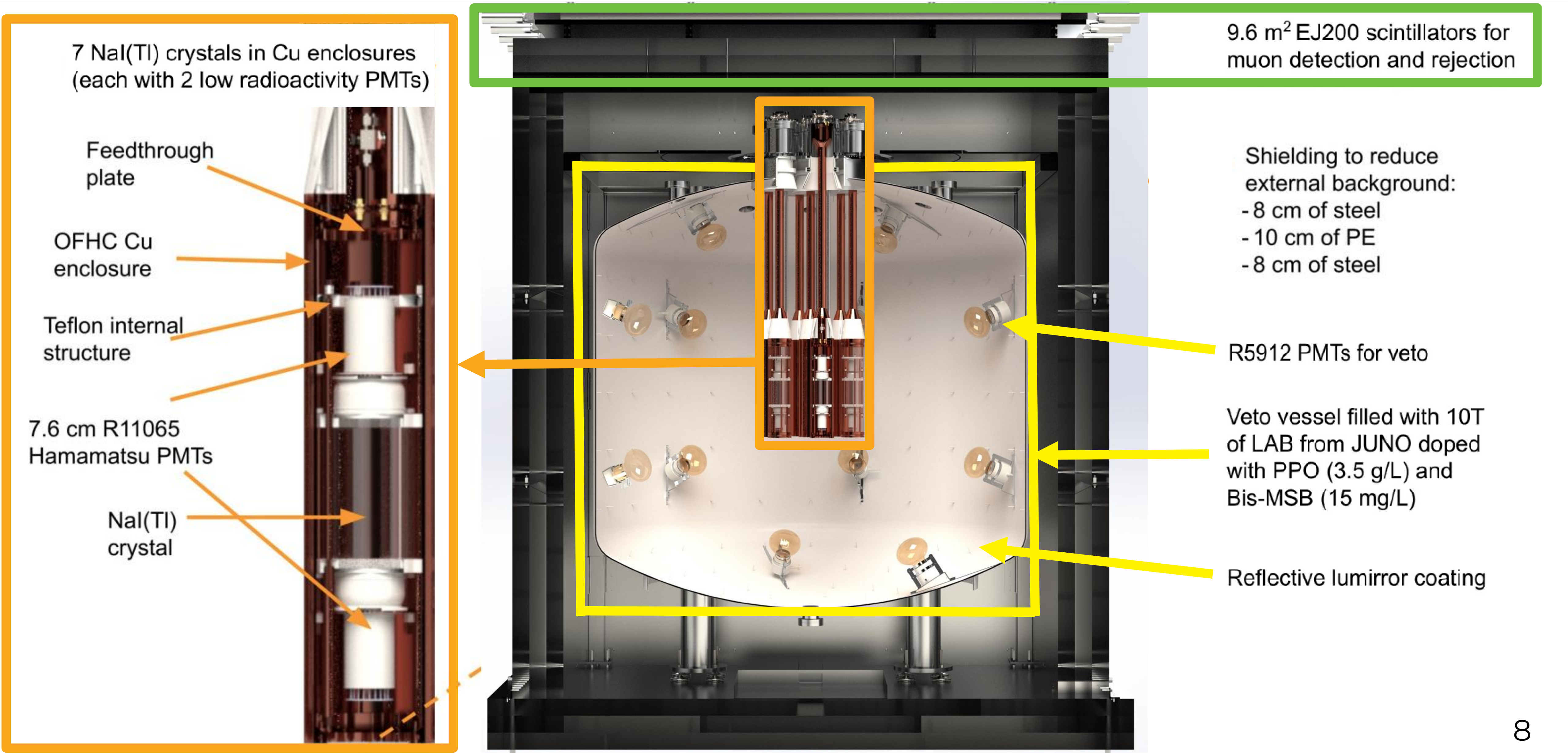
First detectors commissioned in early 2024, collecting data.

10 m x 16.4 m x 12 m **experimental hall**, two small **gamma spectroscopy rooms** + **clean tent.**




# The SABRE South Experiment

Three detector systems: **Crystal, Liquid Scintillator** and **Muon** detectors.

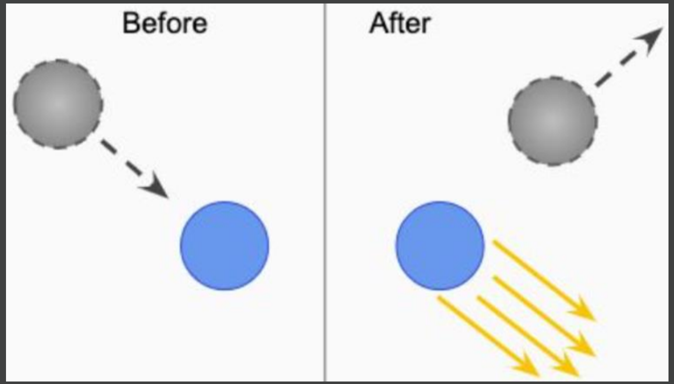


# SABRE Principle

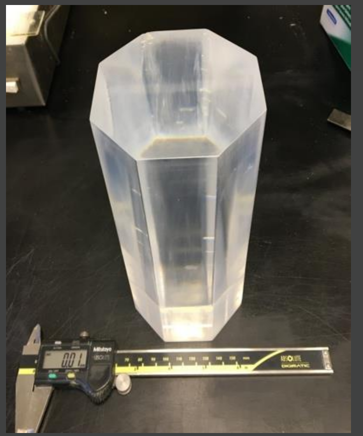
SABRE aims to observe WIMP's through **scattering off target nuclei.**


When this happens, the particle the dark matter scatters off will recoil with an energy related to **the dark matter properties.**

We use **ultra-pure NaI(Tl) crystals** as target.

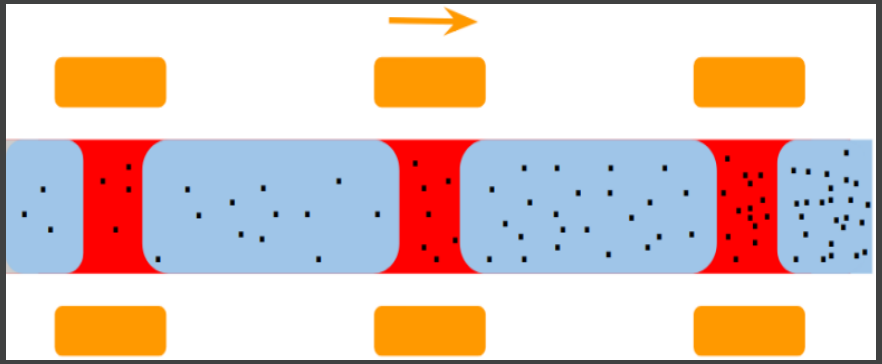


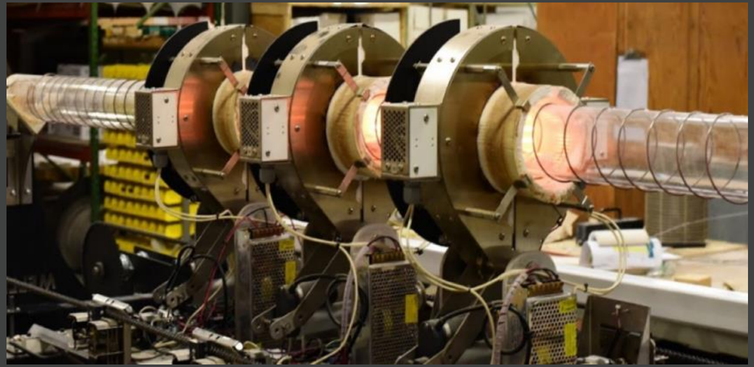
# SABRE Crystals



- **SABRE** (**S**odium Iodide with **A**ctive **B**ackground **RE**jection)
- **Ultra-pure astro-grade quality** NaI powder from Merck.
- **Seven ultra-pure NaI(Tl)** crystals for (35 kg – 50 kg total mass).
- Test crystals have been grown at RMD (US) and SICCAS (China).
- **Light yield** 9-12 phe/keV.
- 1 keV **energy threshold** for 1-6 keV RoI in NaI(Tl).
- Handled in a **glove box.**


- **Zone refining**: Impurities are segregated to the end of the crystal.





# SABRE Crystals

- **Crystal intrinsic background** – naturally occurring isotopes in the NaI(Tl) powder (94% of the total).

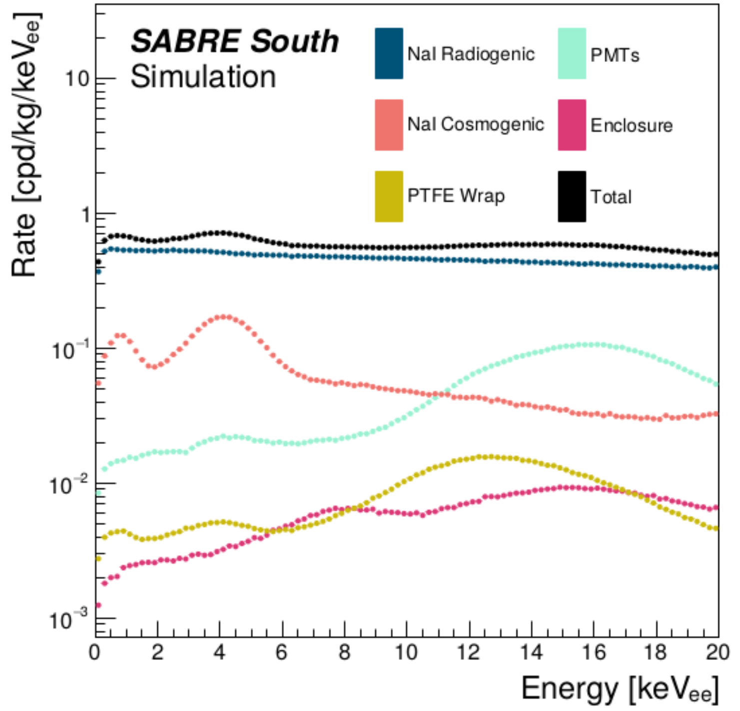
- **Cosmogenic background** – through exposure to cosmic rays at sea-level.
- Cool-down period of 6 months to decrease activities.

- **Background from material radioactivity** – various components (PMTs, PTFE wrap, crystal enclosure,...).

**We expect 0.72 cpd/kg/keV in RoI,** based on a background from the test crystal NaI-33.

Antonello et al., Eur. Phys. J .C 81, 299 (2021)

| | Rate [ cpd/kg/keV] | Veto Efficiency [%] |
|---|---|---|
| Crystal radiogenic | $5.2 \cdot 10^{-1}$ | 13 |
| Crystal cosmogenic | $1.6 \cdot 10^{-1}$ | 40 |
| Crystal PMTs | $3.8 \cdot 10^{-2}$ | 60 |
| PTFE wrap | $4.5 \cdot 10^{-3}$ | 13 |
| Enclosures | $3.2 \cdot 10^{-3}$ | 85 |
| Conduits | $1.9 \cdot 10^{-5}$ | 96 |
| Liquid scintillator | $4.9 \cdot 10^{-8}$ | > 99 |
| Steel vessel | $1.4 \cdot 10^{-5}$ | > 99 |
| Veto PMTs | $1.9 \cdot 10^{-5}$ | > 99 |
| Shielding | $3.9 \cdot 10^{-6}$ | > 99 |
| External | $O(10^{-4})$ | > 99 |
| Total | $7.2 \cdot 10^{-1}$ | 27 |

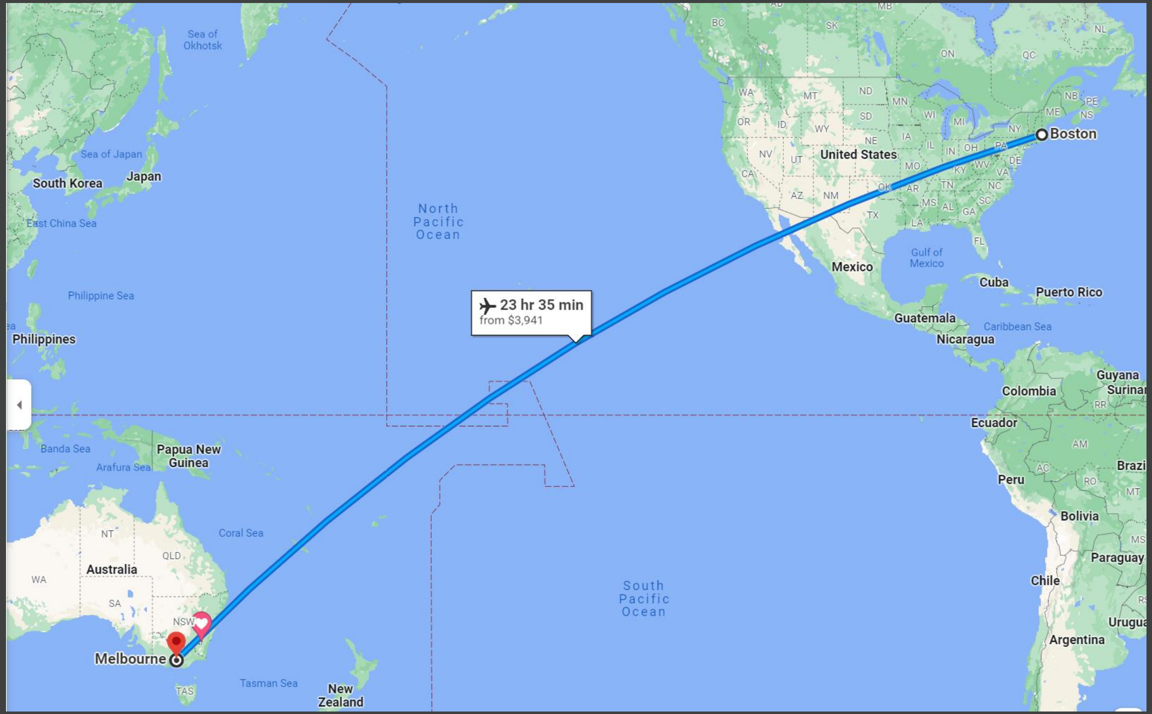


# Potential crystal providers

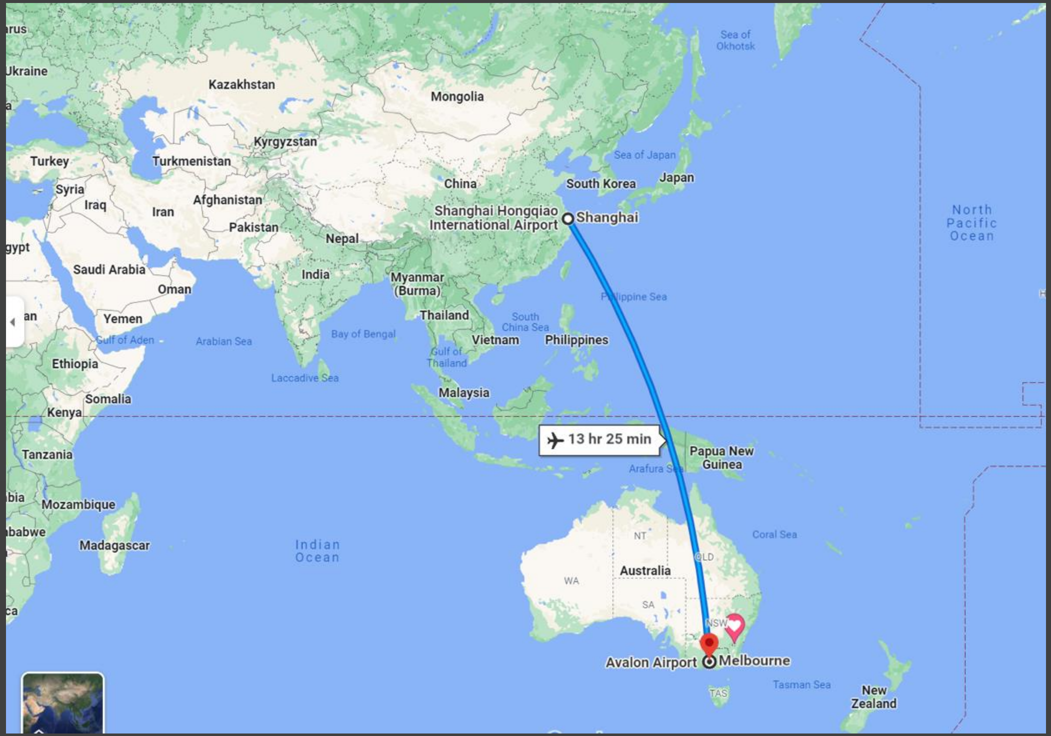
**RMD (R**adiation **M**onitoring **D**evices, Boston, MA, US)

**SICCAS** (**S**hanghai **I**nstitute or **C**eramics, **C**hinese **A**cademy of **S**ciences)

- Activation during **manufacturing, storage, transport** taken into account
- Cosmogenic flux influenced by **altitude, geomagnetic activity and solar activity**




Boston to Stawell




Shanghai to Stawell

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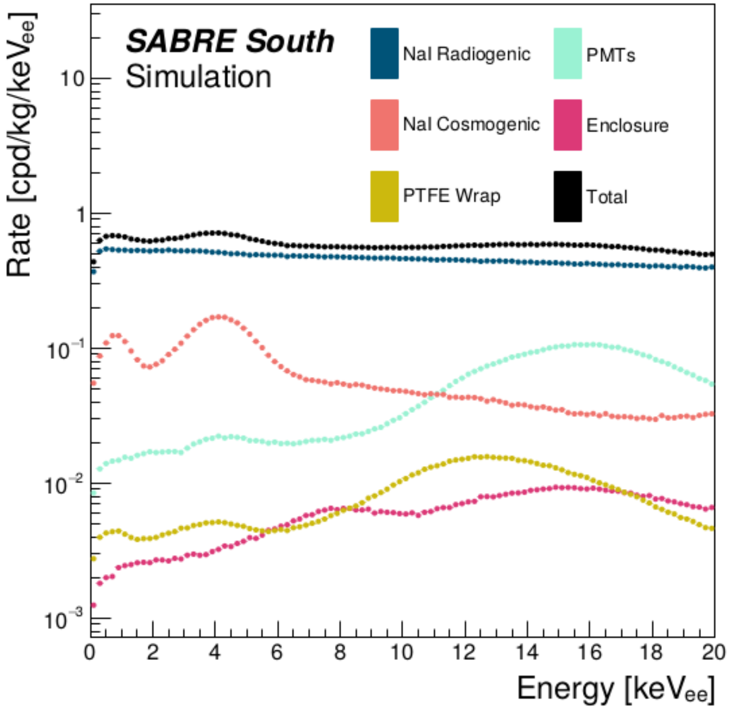


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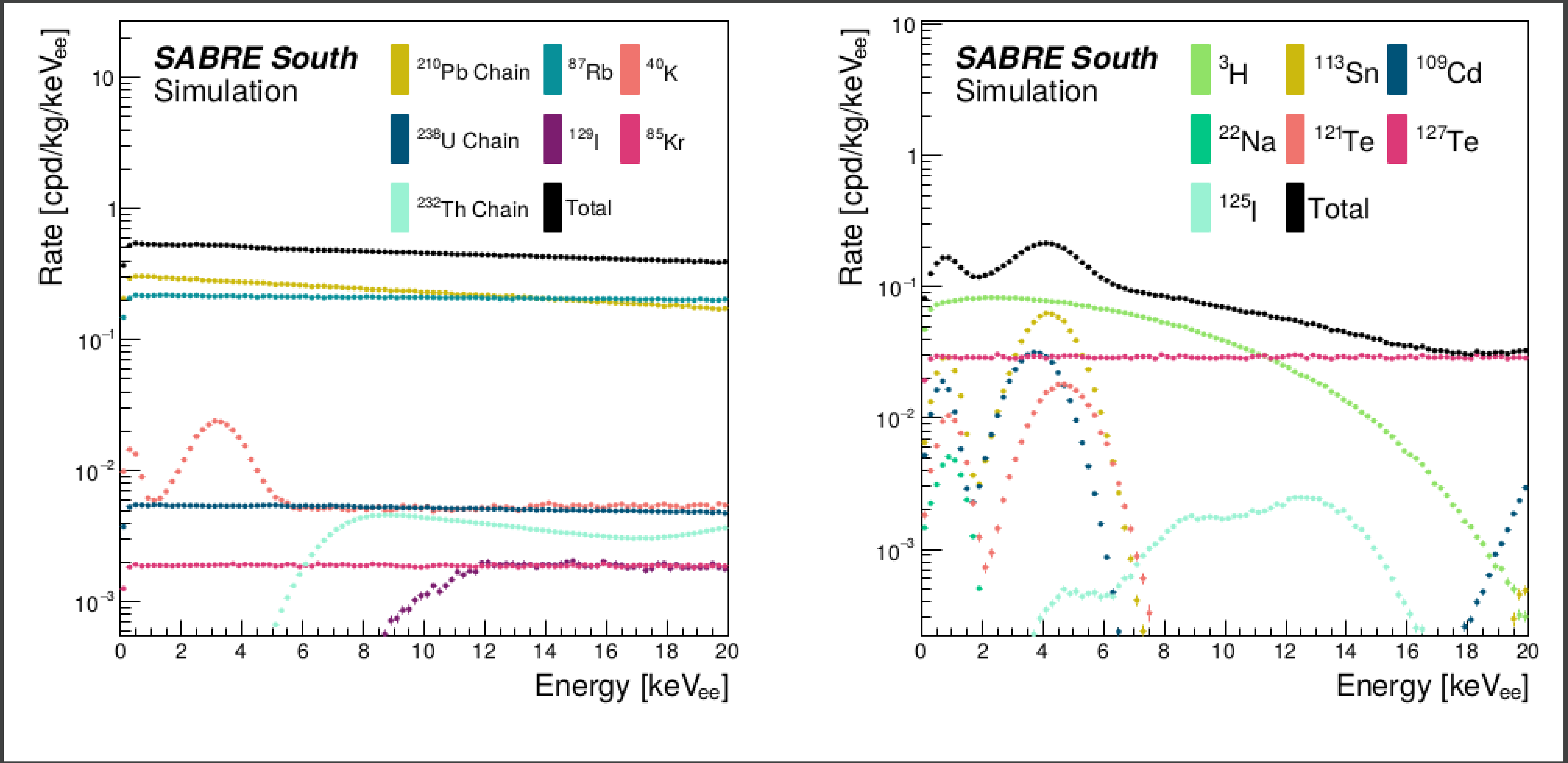
# SABRE Crystals




Crystal background rate expected from intrinsic (left) and cosmogenic (right) contamination

# SABRE Crystals

- One of the biggest challenges: **Purity**
- **Radioactive and cosmic contaminants**
➔ might mimic dark matter signals

- **Identify**
- **Quantify**
- **Reduce**

| Isotope | Activity [mBq/kg] |
|---|---|
| $^{40}$K | $1.4 \cdot 10^{-1}$ |
| $^{238}$U | $< 5.9 \cdot 10^{-3}$ |
| $^{232}$Th | $< 1.6 \cdot 10^{-3}$ |
| $^{87}$Rb | $< 3.1 \cdot 10^{-1}$ |
| $^{210}$Pb | $4.1 \cdot 10^{-1}$ |
| $^{85}$Kr | $< 1.0 \cdot 10^{-2}$ |
| $^{129}$I | 1.3 |

Activity of **radiogenic isotopes** in SABRE crystals

$t_{1/2}$ ($^{40}$K) = 1.25 Ga, primordial origin

**Inductively Coupled Plasma – Mass Spectrometry**

SEASTAR CHEMICALS


$t_{1/2}$ ($^{210}$Pb) = 22.2 a, omnipresent

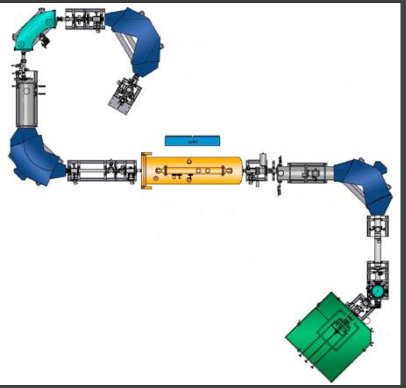
**α-counting + development of Accelerator Mass Spectrometry**

Ratio of $^{210}$Pb/$^{208}$Pb

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms
Volume 529, 15 October 2022, Pages 18-23

Scavenger hunt: Searching for the optimal target material for low-level $^{210}$Pb accelerator mass spectrometry

M.B. Froehlich [a, b], Z. Slavkovská [a, b], D. Koll [a, 1], S. Pavetich [a], F. Dastgiri [a, b], L.K. Fifield [a], M.A.C Hotchkis [c], S. Merchel [a, d, 2], S.G. Tims [a], A. Wallner [a, 1]



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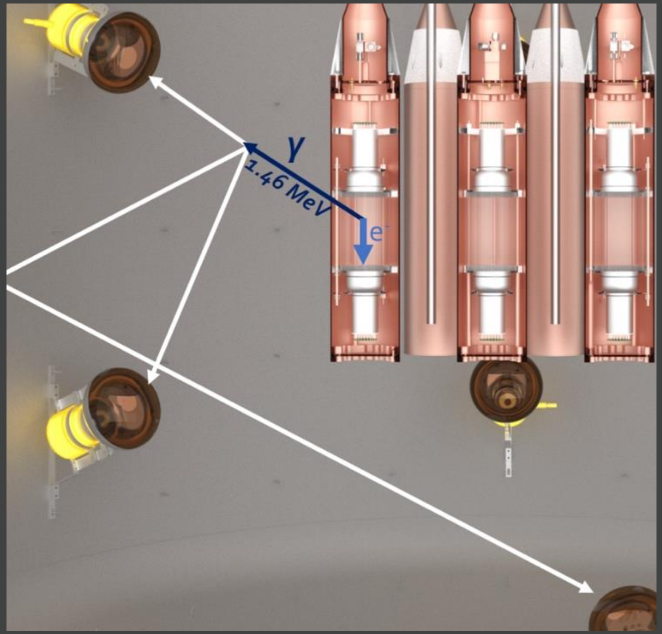
# SABRE Veto

- Crystals embedded in a **veto system** for active background rejection
  -> tag and remove high energy background decay products with 4π coverage.

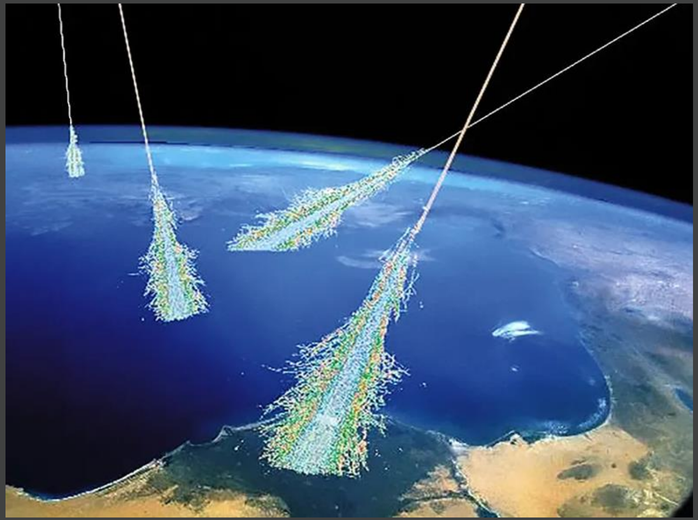
**Veto PMT**

- **Submerged in 12,000 litres LAB** (Linear Alkyl Benzene) Scintillator.
- Key requirement: Reduction of $^{40}K$ by a factor of 10 (down to $1.3 * 10^{-2}$ cpd/kg/keV$_{ee}$).



# SABRE Muon Detectors

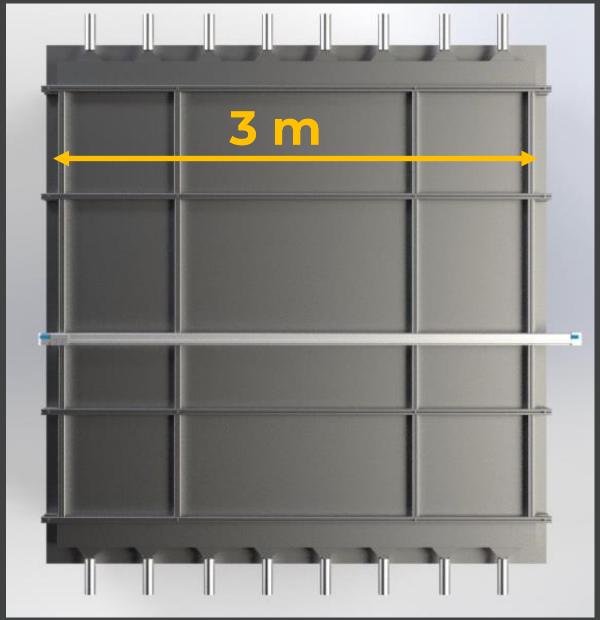
- Tagging of **cosmic rays by muon flux measurements.**
- **Plastic scintillator** 300 cm x 40 cm x 5 cm.
- **8 muon panels** covering 9.6 $m^2$.
- **Information combined** with liquid veto to reconstruct tracks.



- Muon detectors **installed in SUPL and are collecting data:**

1) Measuring muon flux and angular distribution.

2) First test of remote DAQ and processing pipelines.





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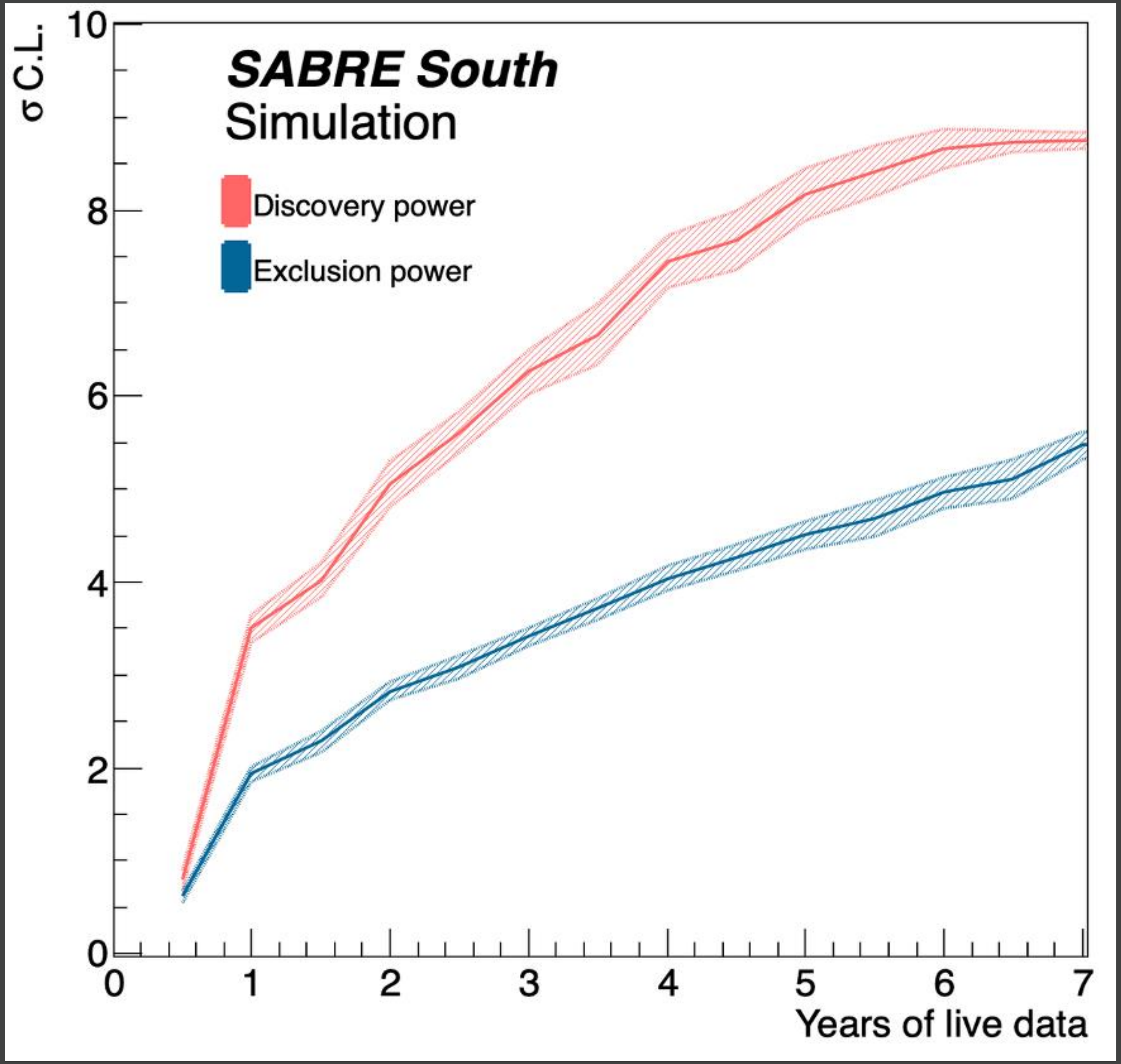
# SABRE Sensitivity

SABRE South will have a **5σ discovery (3σ exclusion) power** to a DAMA-like signal within 2.5 years of data taking.

(The shaded regions indicate 1 sigma statistical uncertainty bands).



# SABRE Summary

- **SABRE is a dual site experiment** with two similar detectors:
  **- SABRE South** at SUPL in Australia and
  **- SABRE North** at LNGS in Italy.

- SABRE uses **ultra-high purity NaI(Tl) crystals.**
- Key design focus is the **low background.**

- **Data taking has begun in early 2024.**

- With the expected backgrounds, we expect a **discovery or exclusion after about 2.5 years** of continuous operation.

# SABRE South Collaboration

THE UNIVERSITY of ADELAIDE

Australian National University

THE UNIVERSITY OF MELBOURNE

SWIN BUR NE

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Australian Government
Australian Research Council

THE UNIVERSITY of ADELAIDE

Australian National University

THE UNIVERSITY OF MELBOURNE

SWIN BUR NE

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

ANSTO

DST GROUP

## INTERNATIONAL PARTNER ORGANISATIONS:

California Institute of Technology

INFN LNGS

Massachusetts Institute of Technology

Stockholms Universitet

Uni Freiburg

Universiteit van Amsterdam

The University Of Sheffield.

University of Washington

# Backup Slides

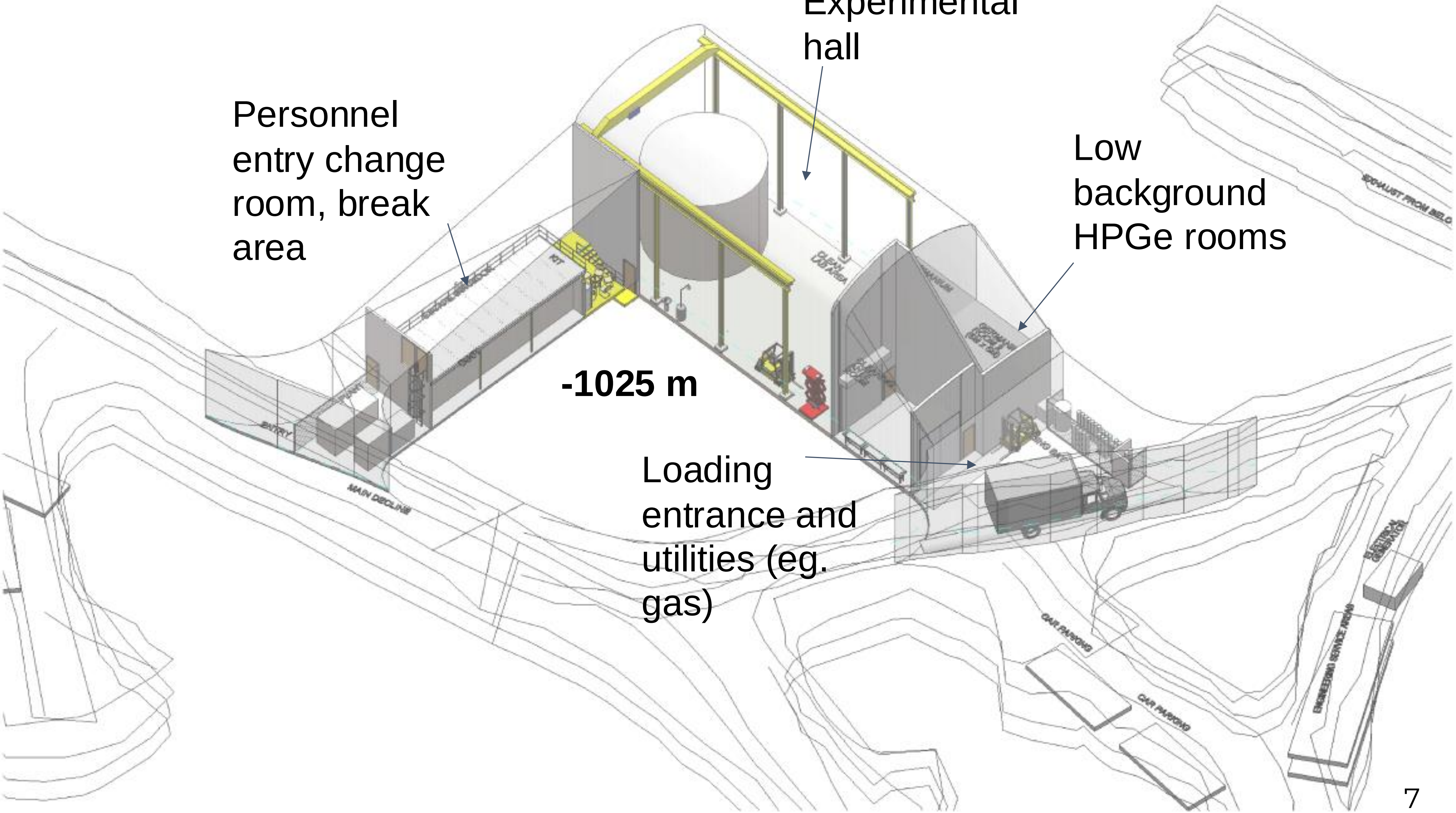
# SABRE South Sensitivity

### 4.2 Projected sensitivity of the SABRE South experiment

The sensitivity of SABRE South to a typical WIMP has also been computed. These calculations are performed assuming the spin-independent effective field theory operator $\mathcal{O}1$ from Ref. [41], Standard Halo Model velocity distribution, an efficiency equivalent to that of COSINE [42], and the DAMA/LIBRA quenching factor values for both Na and I. Figure 8 shows the 90% confidence level (CL)

**Table 15** Expected event rate and sample purity in the $^{121}$Te and $^{40}$K measurement regions

| Region | Total rate (cpd) | Sample purity |
|---|---|---|
| $^{40}$K measurement region A | 13 | 90% |
| $^{40}$K measurement region B | 0.32 | > 99% |
| $^{121}$Te measurement region A | 130 | 90% |
| $^{121}$Te measurement region B | 3.2 | > 99% |


Experimental hall
Personnel entry change room, break area
Low background HPGe rooms
-1025 m
Loading entrance and utilities (eg. gas)

# Radio-impurities in SABRE South

**Focus on radioactive isotopes** -> in detector materials

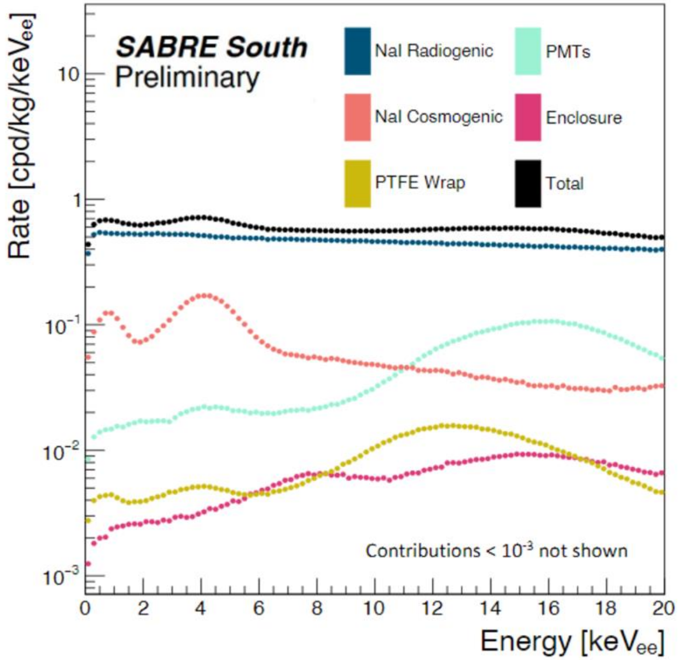
-> around the detector material (+ environment)

$^{40}K$, $^{129}I$, $^{210}Pb$, $^{232}Th$, $^{238}U$

in particular Radon

(radioactive chains from Th and U, decays in $^{210}Pb$)

<10% from outside the crystal




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

# Radio-impurities in SABRE South

## Crystal growing

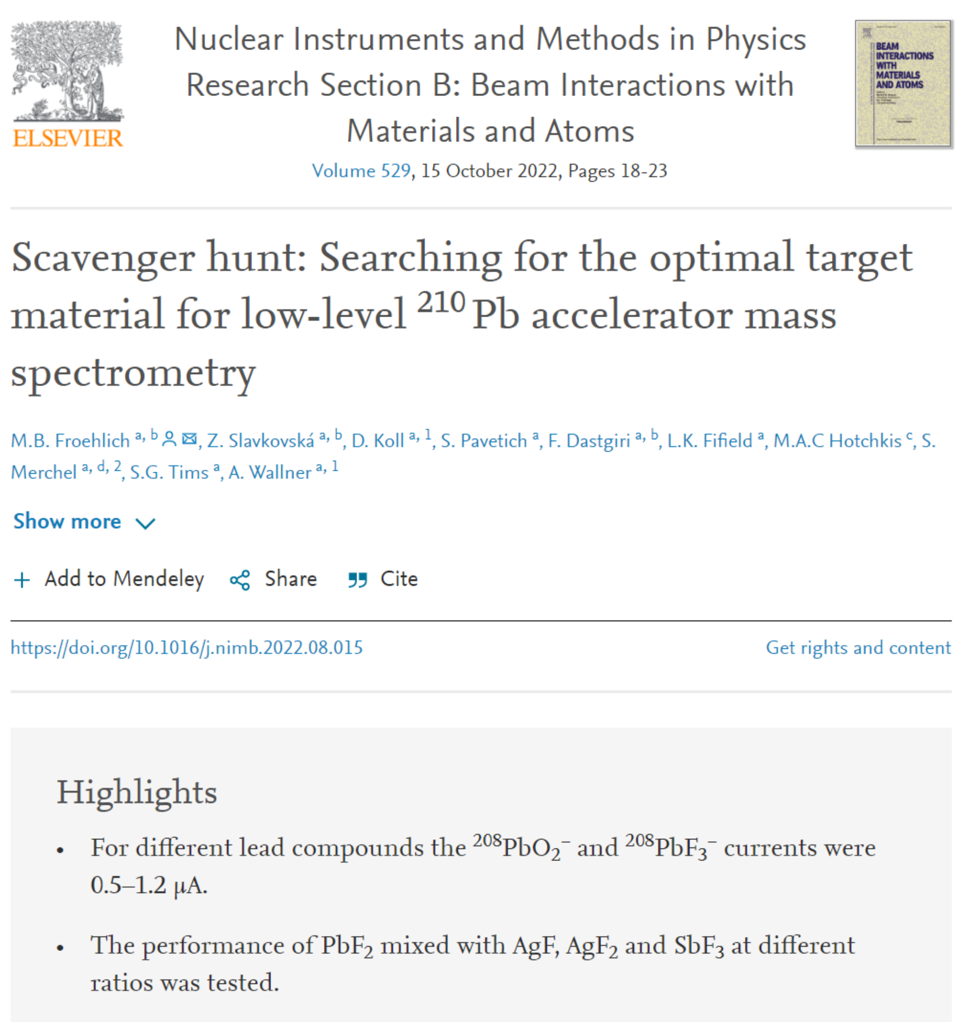
Cut into an octagonal shape using a diamond saw

Polished with semiconductor grade ethanol/isopropyl alcohol to remove any surface contamination

**Purification techniques developed to reduce $^{40}K$ and $^{210}Pb$ in the crystal**

B. Suerfu et al., Phys. Rev. Research 2, 013223 (2020)

Crystal NaI-33



ELSEVIER

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms

Volume 529, 15 October 2022, Pages 18-23

Scavenger hunt: Searching for the optimal target material for low-level $^{210}Pb$ accelerator mass spectrometry

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Highlights

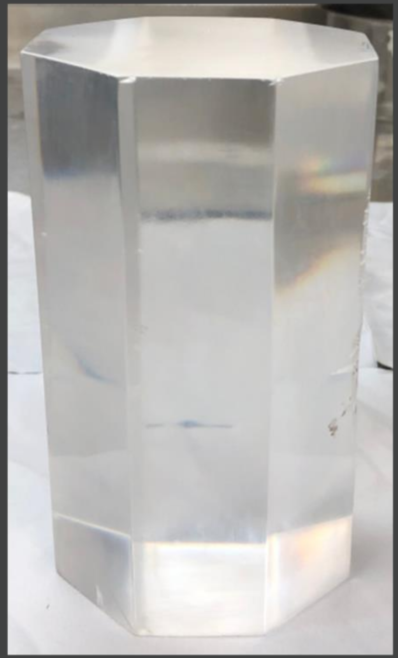
- For different lead compounds the $^{208}PbO_2^-$ and $^{208}PbF_3^-$ currents were 0.5–1.2 μA.
- The performance of $PbF_2$ mixed with AgF, $AgF_2$ and $SbF_3$ at different ratios was tested.

# Radio-impurities in SABRE South

## Crystal growing

- **Requirements** based on simulations and DAMA/LIBRA purity
- Desired **total intrinsic radiogenic crystal background** < 0.4 cpd/kg/keV
- **$^{210}$Pb and $^{40}$K** levels of critical importance

| Background | Limit mBq/kg |
|---|---|
| Pb-210 | < 0.3 |
| K-39 | < 0.3 (10 ppb) |
| Rb-87 | < 0.31 |
| U-238 | < 0.05 |
| Kr-85 | < 0.01 |
| Th-232 | < 0.035 |



Crystal NaI-33

Desired light yield > 10 pe/keV corresponding to ~ 30 photons/keV

# Radio-impurities in SABRE South

- Most problematic radio-impurity is $^{210}Pb$

| Isotope | Rate, veto ON [ cpd/kg/keV$_{ee}$ ] |
|---|---|
| $^{210}Pb$ | $2.8 \cdot 10^{-1}$ |
| $^{87}Rb$ | $< 2.2 \cdot 10^{-1}$ |
| $^{40}K$ | $1.3 \cdot 10^{-2}$ |
| $^{238}U$ | $< 5.4 \cdot 10^{-3}$ |
| $^{85}Kr$ | $< 1.9 \cdot 10^{-3}$ |
| $^{232}Th$ | $< 3.4 \cdot 10^{-4}$ |
| $^{129}I$ | $9.2 \cdot 10^{-5}$ |
| Total | $< 5.2 \cdot 10^{-1}$ |

$t_{1/2}$ ($^{210}Pb$) = 22.2 a

$^{210}Pb$ produces spectrum in the low energy region that cannot be vetoed

Present in environment due to naturally occurring $^{238}U$ and $^{226}Rn$, also in dust

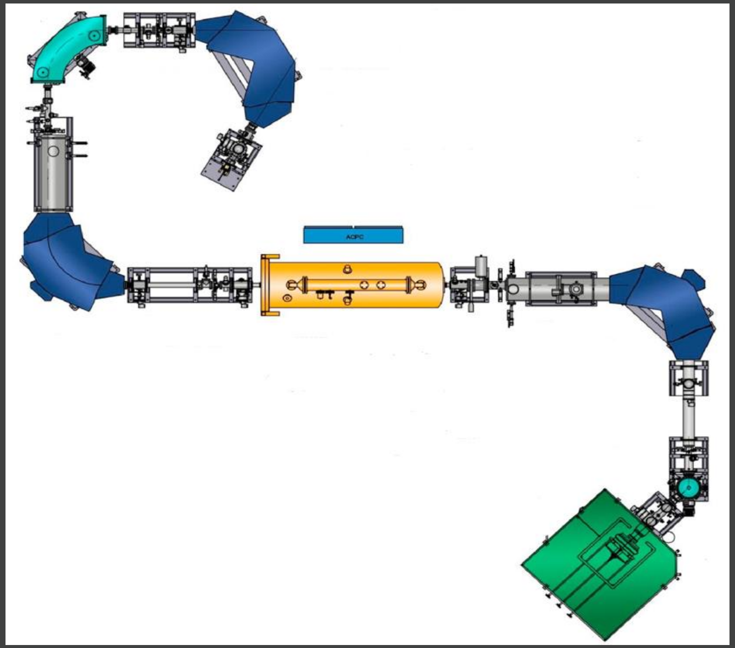
Need to develop a measurement technique for material screening

# Radio-impurities in SABRE South

- Technique used: **Accelerator Mass Spectrometry (AMS)**
- Precise atom counting technique utilising accelerator technology


~3 mg

- Sample material sputtered
- Mass analysed
- Electrons stripped off, molecular breakup
- Selection in analysing magnet
- Counting nuclei
  (ratio of radioactive to stable isotope): $^{210}Pb/^{208}Pb$



Schematic image VEGA, 1MV ANSTO, Sydney

# Radio-impurities in SABRE South

## Material screening, cleaning and selection

- Focus on $^{210}$**Pb**
- **Accelerator Mass Spectrometry used:** Not enough Pb to produce AMS sample after NaI extraction
- **Optimal carrier,** as low $^{210}$Pb content as possible
- 18th century roof, detector shielding, Roman lead, Hampton Court Palace roof


- Chemical processing


+ Accelerator Mass Spectrometry

# Crystal Glove Box

## Crystal handling

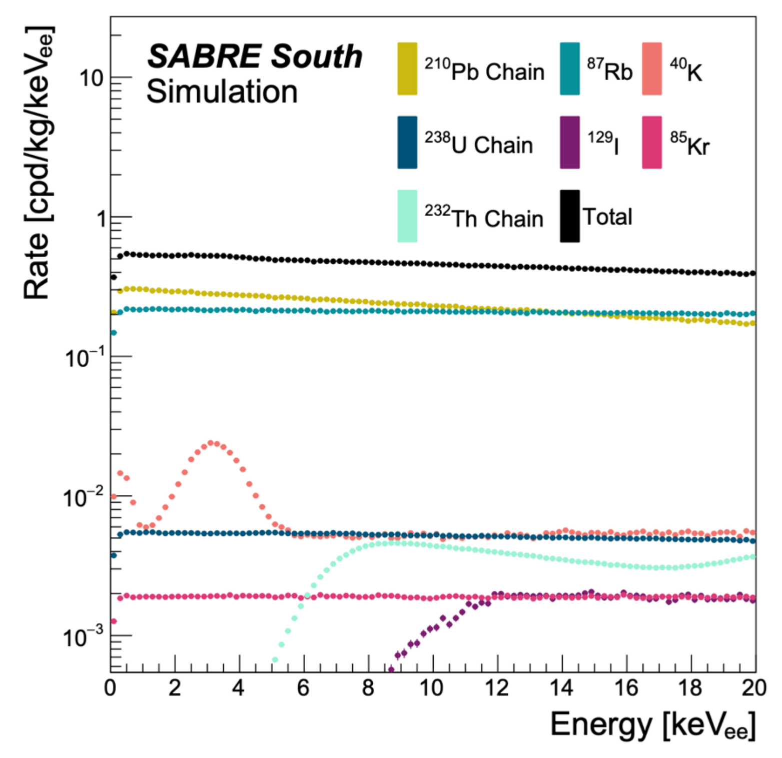
Glove box at LNGS

Mock-up glove box testing

Procedure testing inside the glove box

# Radio-impurities in SABRE South

**Material screening, cleaning and selection:** intrinsic + cosmogenic crystal radiation > 90% total background

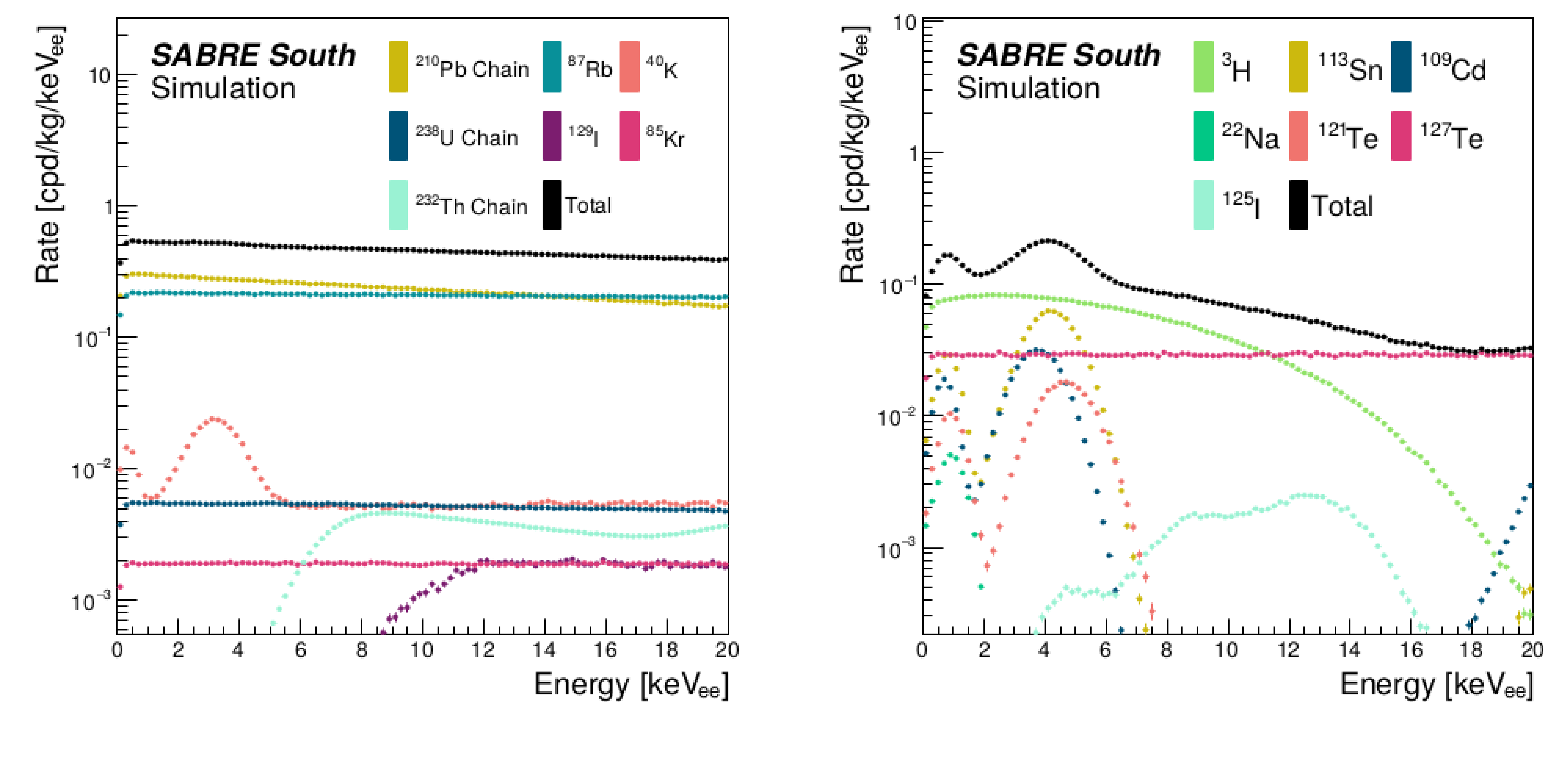



| | Rate [ cpd/kg/keV$_{ee}$ ] |
|---|---|
| Crystal radiogenic | $5.2 \cdot 10^{-1}$ |
| Crystal cosmogenic | $1.6 \cdot 10^{-1}$ |
| Crystal PMTs | $3.8 \cdot 10^{-2}$ |
| PTFE wrap | $4.5 \cdot 10^{-3}$ |
| Enclosures | $3.2 \cdot 10^{-3}$ |
| Conduits | $1.9 \cdot 10^{-5}$ |
| Liquid scintillator | $4.9 \cdot 10^{-8}$ |
| Steel vessel | $1.4 \cdot 10^{-5}$ |
| Veto PMTs | $1.9 \cdot 10^{-5}$ |
| Shielding | $3.9 \cdot 10^{-6}$ |
| External | $O(10^{-4})$ |
| Total | $7.2 \cdot 10^{-1}$ |

| Isotope | Rate, veto ON [ cpd/kg/keV$_{ee}$ ] |
|---|---|
| $^{210}$Pb | $2.8 \cdot 10^{-1}$ |
| $^{87}$Rb | $< 2.2 \cdot 10^{-1}$ |
| $^{40}$K | $1.3 \cdot 10^{-2}$ |
| $^{238}$U | $< 5.4 \cdot 10^{-3}$ |
| $^{85}$Kr | $< 1.9 \cdot 10^{-3}$ |
| $^{232}$Th | $< 3.4 \cdot 10^{-4}$ |
| $^{129}$I | $9.2 \cdot 10^{-5}$ |
| Total | $< 5.2 \cdot 10^{-1}$ |

Careful cleaning in **clean room environment**

# Radio-impurities




Crystal background rate expected from intrinsic (left) and cosmogenic (right) contamination