# The SABRE South Experiment
## at the Stawell Underground Physics Laboratory

**Irene Bolognino** on behalf of the SABRE South collaboration

The University of Adelaide

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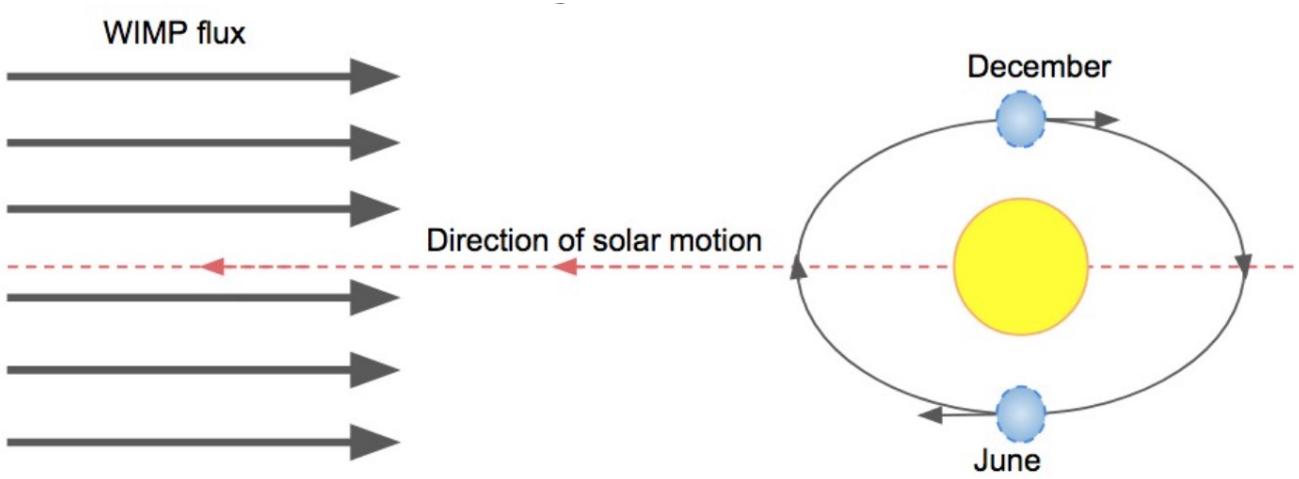
# SABRE Motivation – Annual Modulation



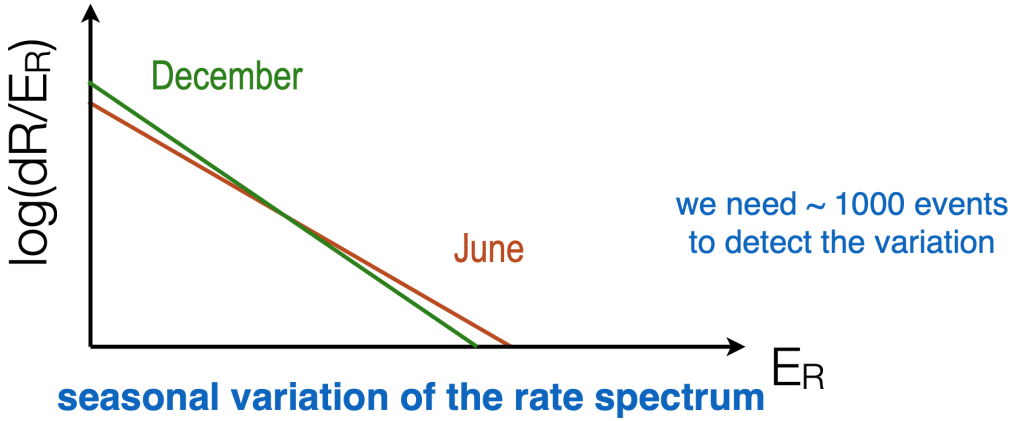

WIMP Rate $\frac{dR}{dE_R}(t) = S_0(E_R) + S_m(E_R)\cos\omega(t - t_0)$

Rare and low energy events:

- expected WIMP-nucleon $\sigma \sim 10^{-48}$ - $10^{-40}$ cm$^2$
- 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/c$^2$

- Standard halo model hypothesis: spherical halo of cold, dark matter (WIMP particles) permeating the galaxy
- local energy density $\rho_{WIMP} \sim 0.3$ GeV/cm$^3$
- Maxwell velocity distribution

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

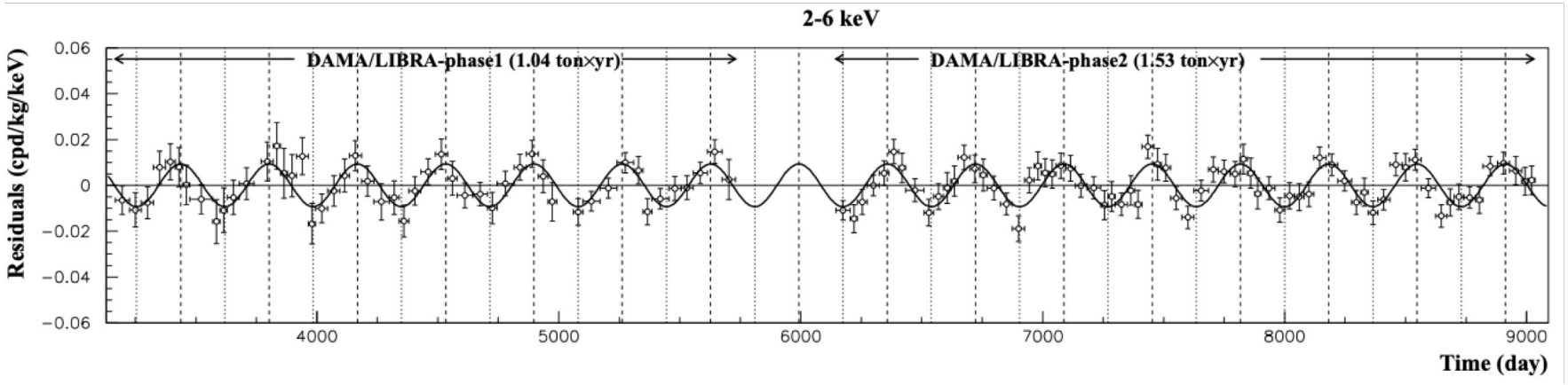


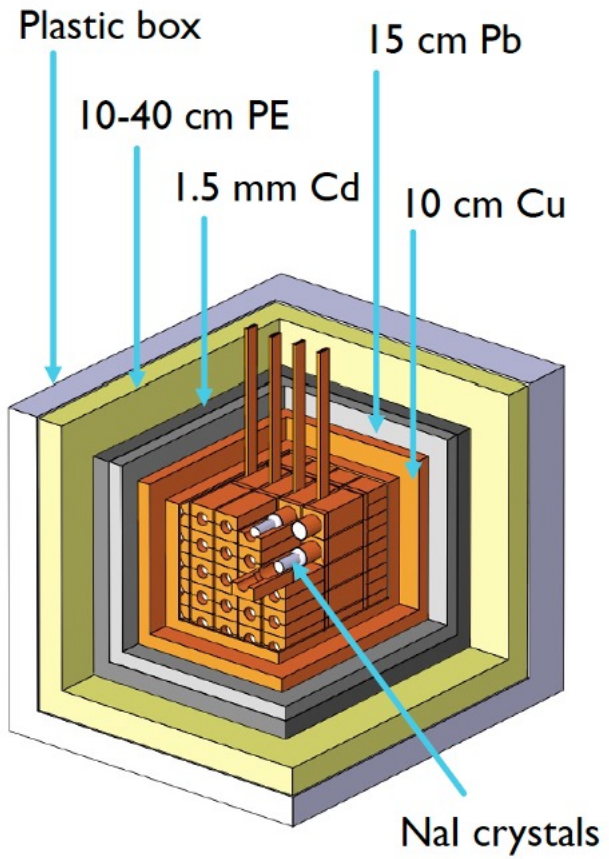

**Annual modulation is a <u>model independent</u> signature of Dark Matter interaction, but control of modulating background is key**

# 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




If interpreted as WIMPs undergoing a spin-independent nuclear scattering:

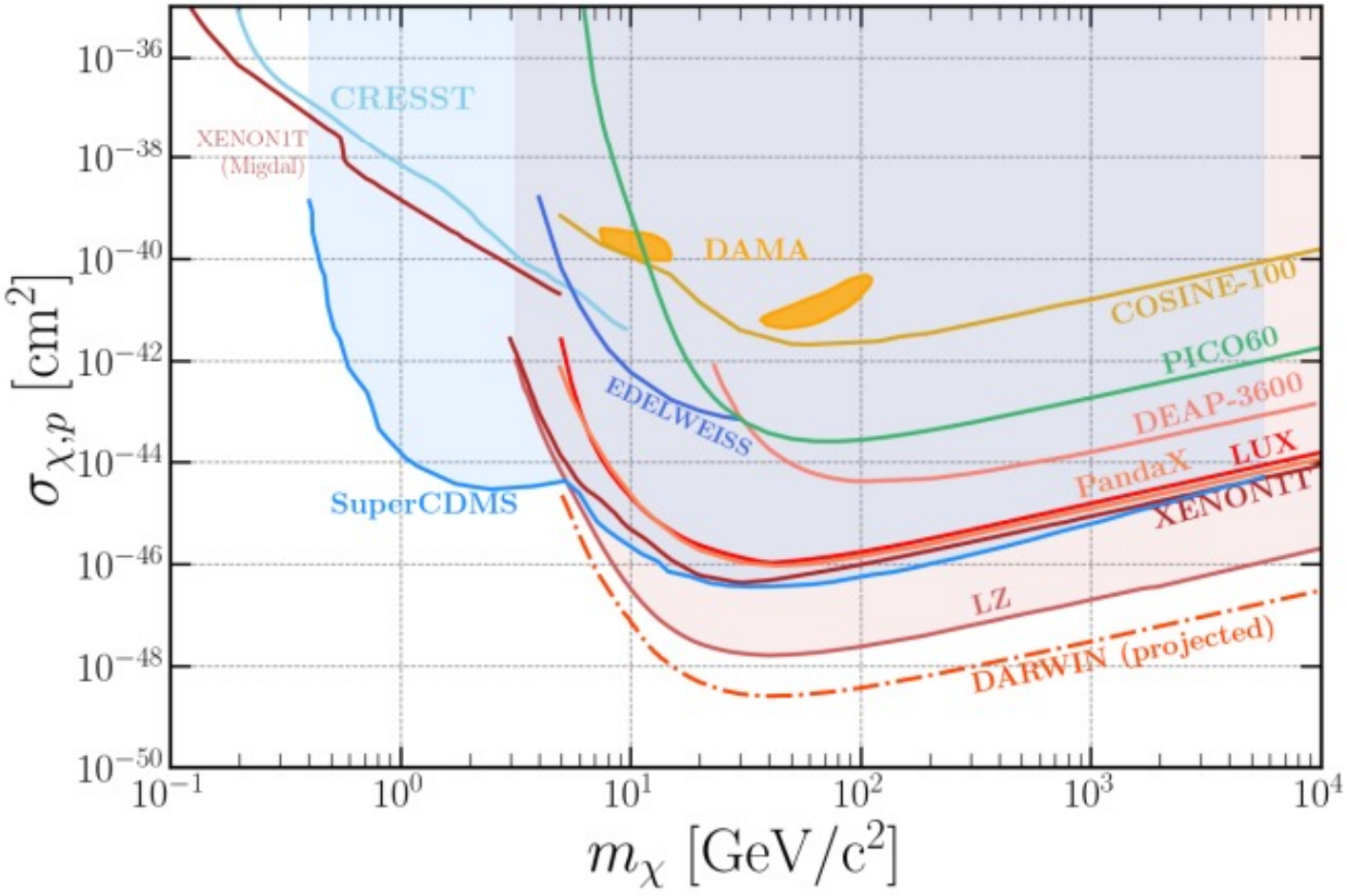
- Na nuclei $M_{WIMP} \sim 10$ GeV, $\sigma \sim 10^{-40}$ cm$^2$
- I nuclei $M_{WIMP} \sim 80$ GeV, $\sigma \sim 10^{-41}$ cm$^2$

R. Bernabei, et al., Nuclear Physics and Atomic Energy 19(4), 307 (2018). DOI 10.15407/jnpae2018.04.307

# SABRE Motivation – Experimental tension

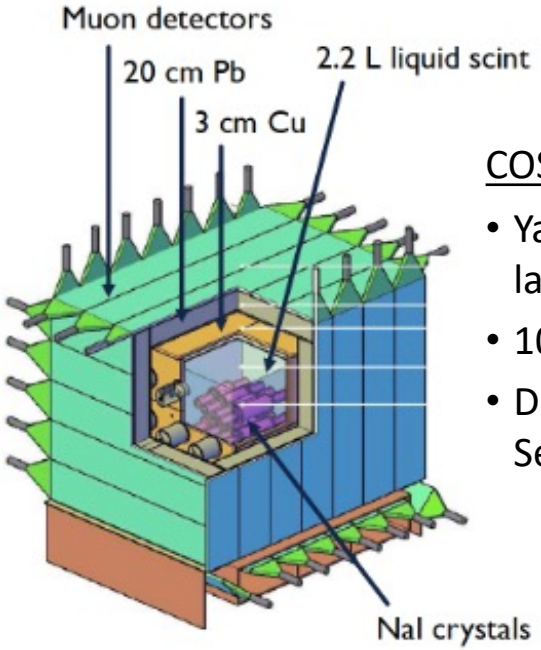
Interpretation as DM is strongly constrained by null results from different targets.

| Target | Experiment/s |
|---|---|
| O, CaW | CRESST |
| F | PICO, PICASSO |
| Ne | NEW-G |
| NaI(Tl) | DAMA |
| Si | DAMIC |
| Ar | DEAP, DarkSide |
| Ge | CDMS, EDELWEISS |
| Xe | Xenon, LUX, PandaX, LZ |




https://github.com/cajohare/NeutrinoFog

# Current running NaI(Tl) detectors

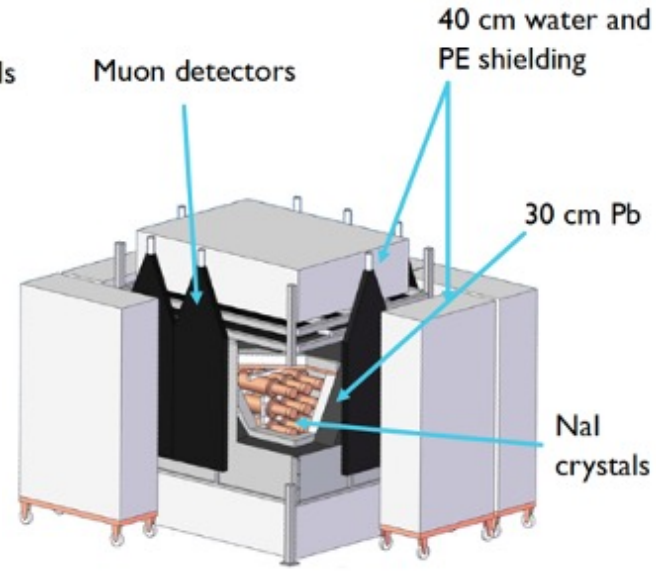



COSINE:

- Yangyang underground laboratory, South Korea.
- 106 kg of NaI(Tl).
- Data taking from September 2016.

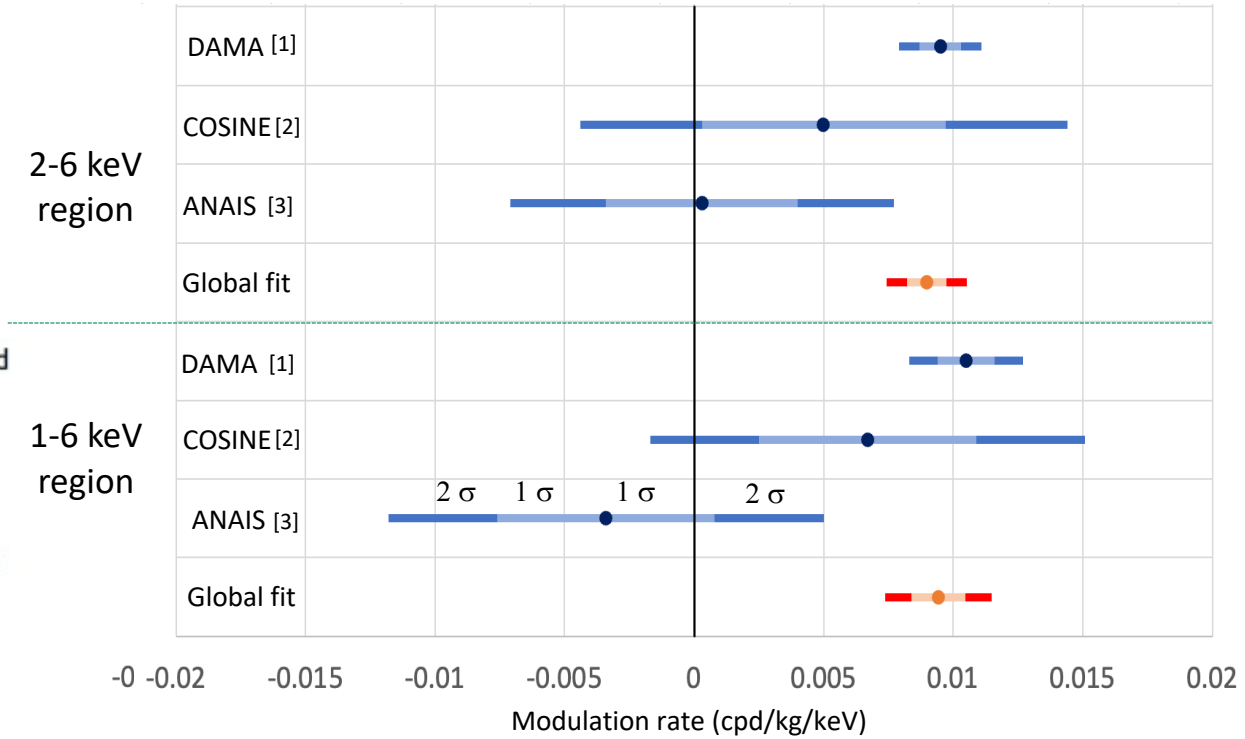
ANAIS:

- Canfranc underground laboratory, Spain.
- 112.5 kg of NaI(Tl).
- Data taking from August 2017.




Global fit shows tension(<3σ) between DAMA and ANAIS. Neither ANAIS nor COSINE have significant discovery or exclusion of DAMA.

M. Zurowski, arXiv: 2211.15861




Global fit= weighted average assuming no correlation


[1] Bernabei et al. PPNP114 103810 (2020)
[2] Amare et al. PRD 103, 102005 (2021)
[3] Adhikari et al. Phys. Rev. D, 106 (2022)

# The SABRE Collaboration

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

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

STAWELL UNDERGROUND PHYSICS LAB

# 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 of background rejection and particle identification.

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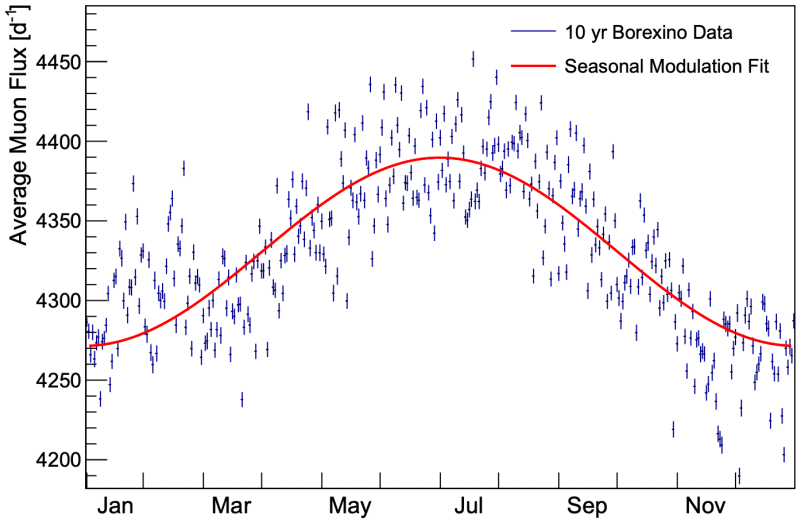
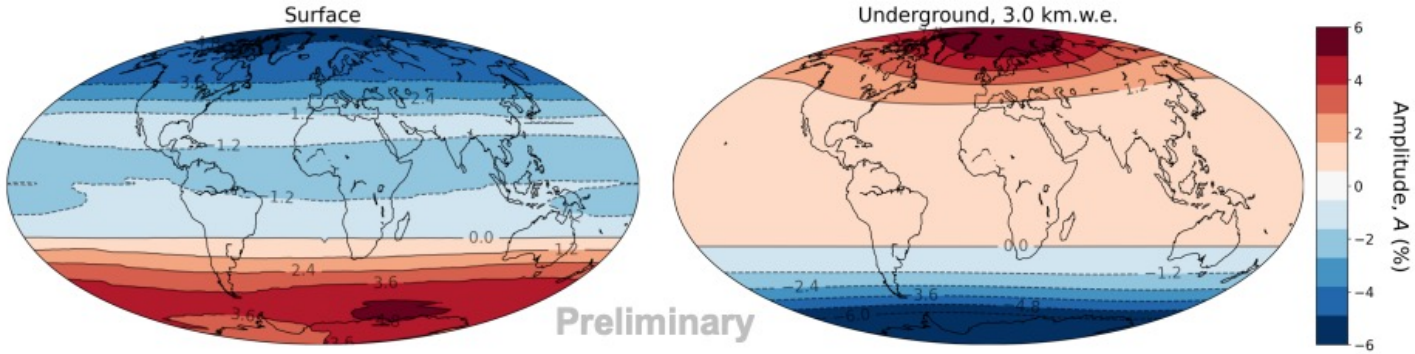
# Exclusion of seasonal effects

- 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.

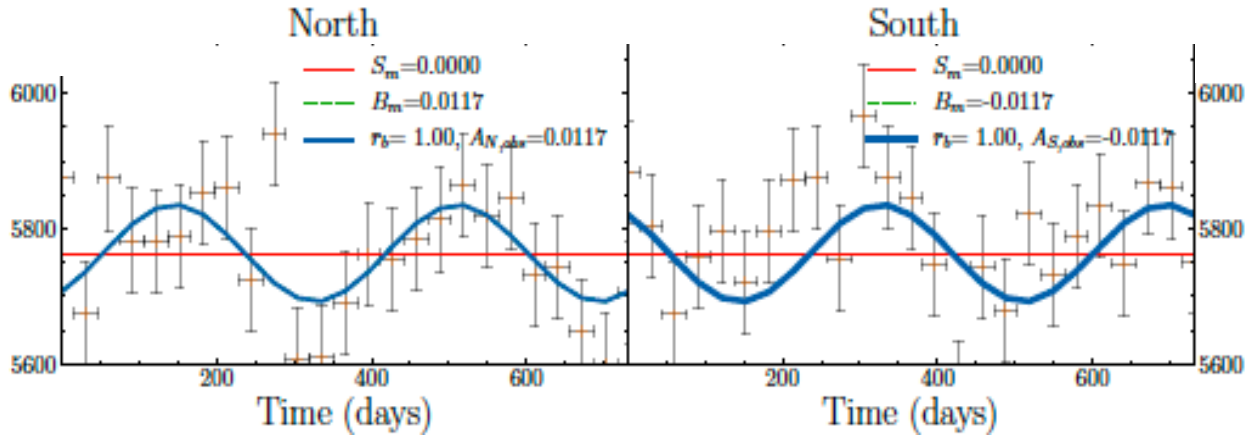



Average muon rate at Borexino over 10 yrs [1]

[1] Borexino collab. JCAP02(2019)046



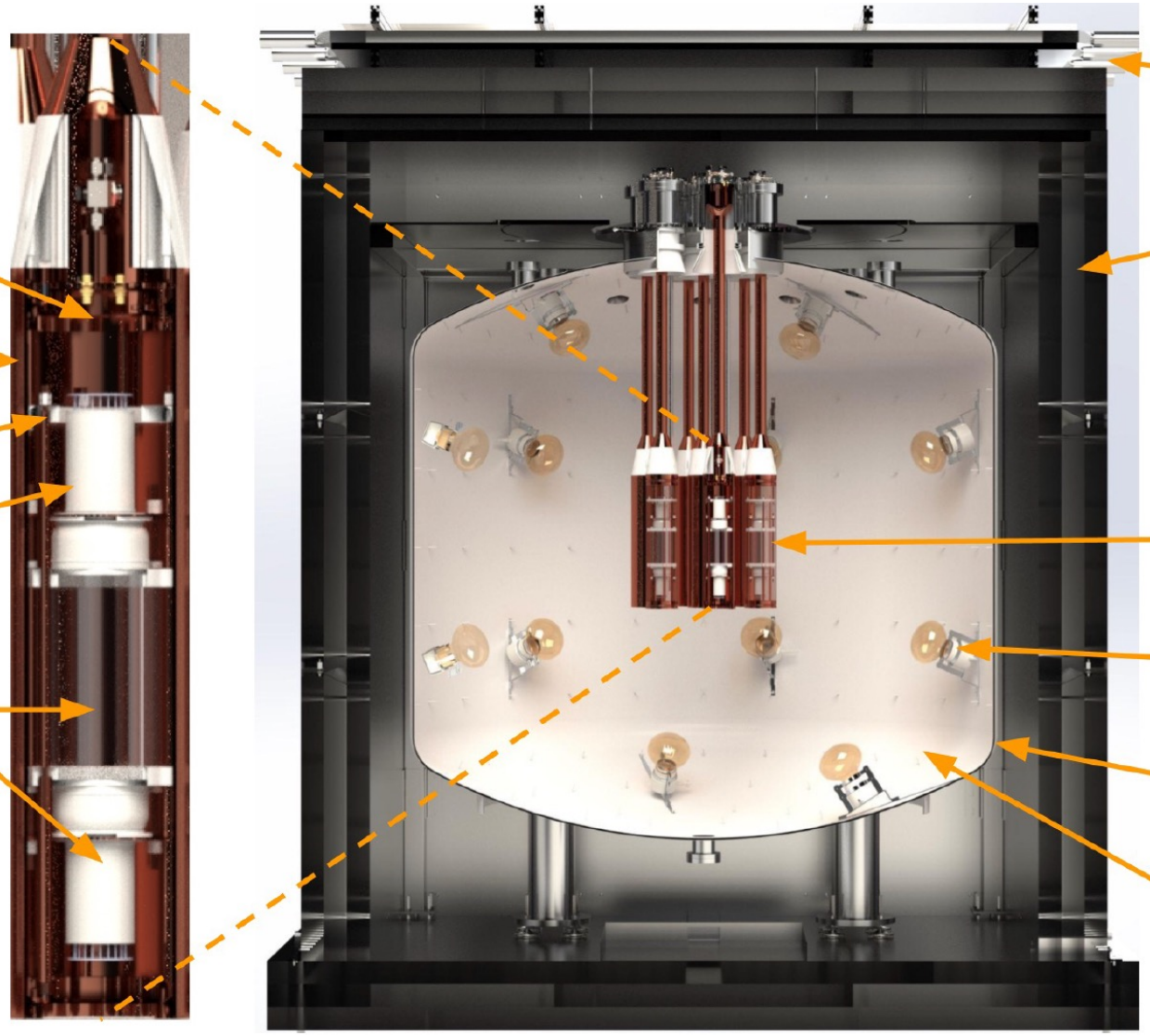

Kyle Leaver's talk, Tuesday 13 December, 3 pm




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

# 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)

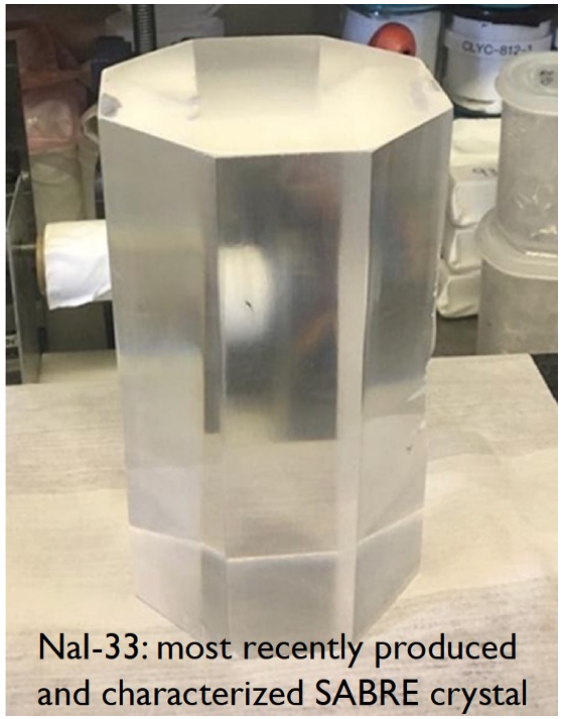
Reflective lumirror coating

# High-purity NaI(Tl) crystals

Two R&Ds:

- Radiation Monitoring Devices (RMD).
- Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS).

| | NaI-33 | DAMA/LIBRA crystals | ANAIS crystals | COSINE crystals |
|---|---|---|---|---|
| LY [phe/keV] | 12.1 ± 0.2 | 6-10 | 15 | 15 |
| FWHM/E @59.5 keV | 13% | 16% | 11% | 12% |
| $^{238}$U [ppt] | < 0.5 | 0.7-10 | 0.2-0.8 | < 0.02-0.12 |
| $^{232}$Th [ppt] | < 0.5 | 0.5-7.5 | 0.1-1 | 0.3-2.4 |
| Alpha rate [mBq/kg] | 0.54 ± 0.01 | 0.08-0.12 | 0.7-3.15 | 0.74-3.20 |
| $^{nat}$K [ppb] (from ICP-MS) | 4.6 ± 0.2 | < 20 | 17-43 | 17-82 |



Nal-33: most recently produced and characterized SABRE crystal

M. Antonello et al. EPJC 81 299 (2021)

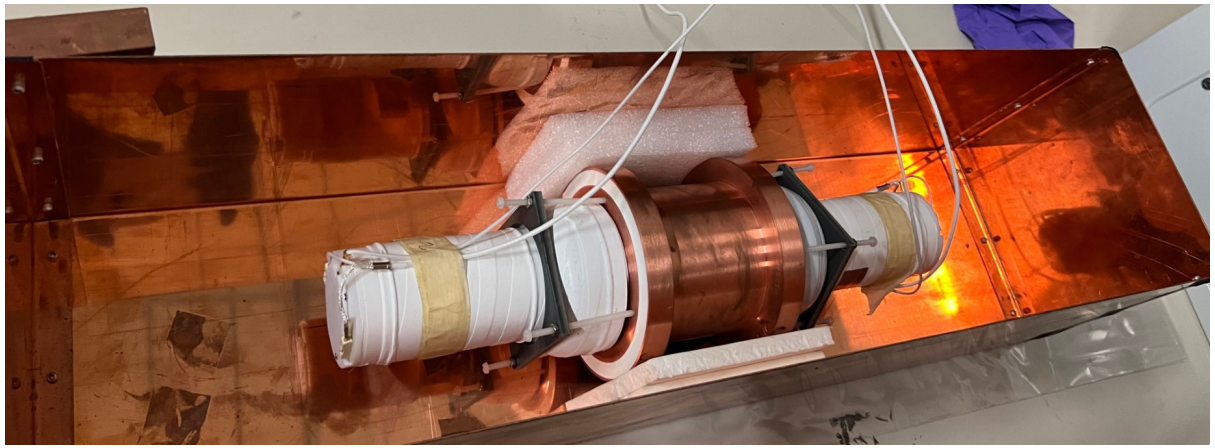
SABRE crystal mass = 3.4 kg


[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

- RMD recently grew a NaI(Tl) crystal (NaI-35) of final mass = 3.3 kg.
- SABRE South crystal is currently being characterized at LNGS (as of last May). Approx. light yield of 11.6 Photoelectrons/keV.

Ferdos Dastgiri's talk: Thursday 3:15pm, Room E3.
Nathan Spinks's talk: Thursday 5pm, Room E3.



# Active Background Rejection

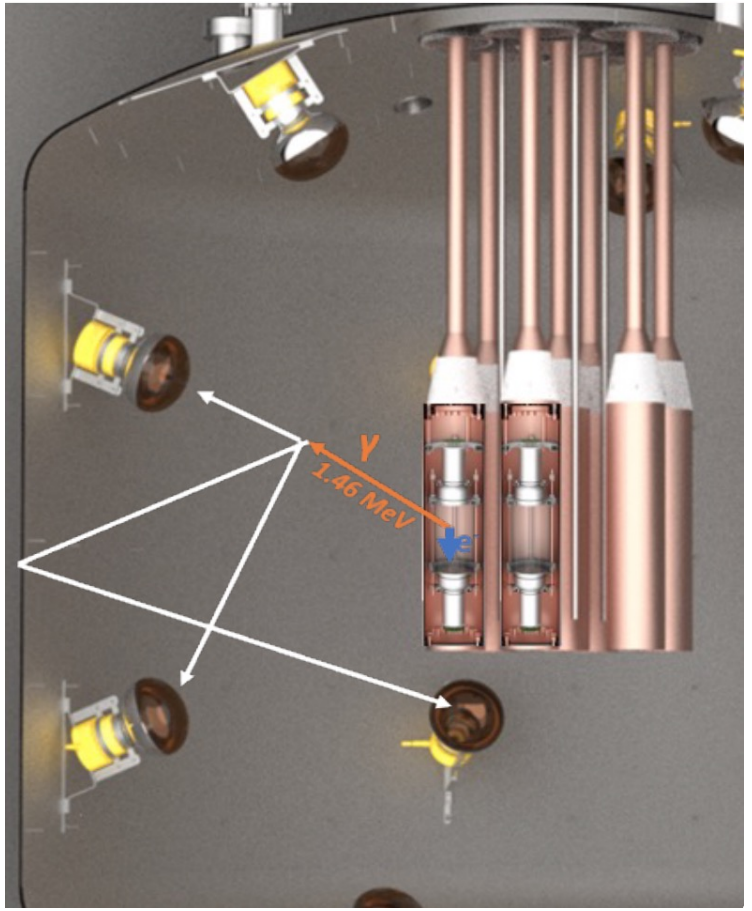
SABRE South also uses an external tagging system to remove high energy decay products observable in the liquid scintillator.

System has $4\pi$ 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 ~0.17 PE/keV, though strong position dependence.

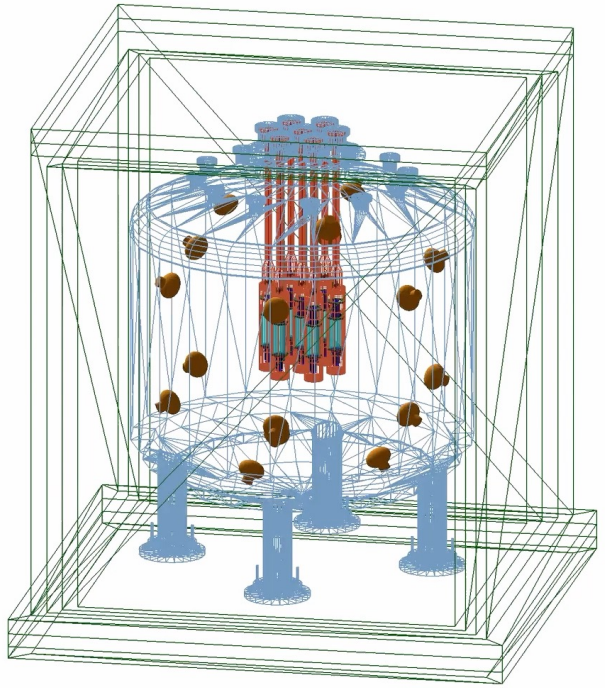
Energy threshold of 50 keV which is able to reduce the background by 25%, giving a total background of <1cpd/kg/keV.



# Active Background Rejection

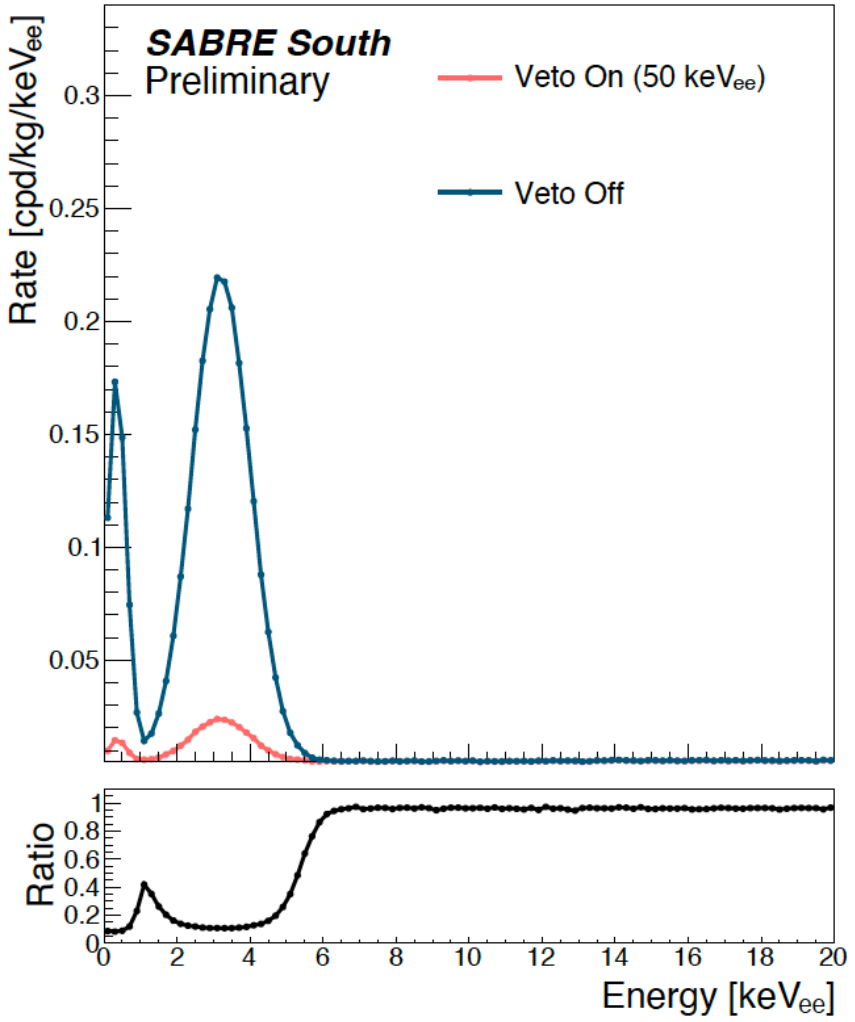
Any radioactive decay with gamma >100 keV can be vetoed.

| 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% |



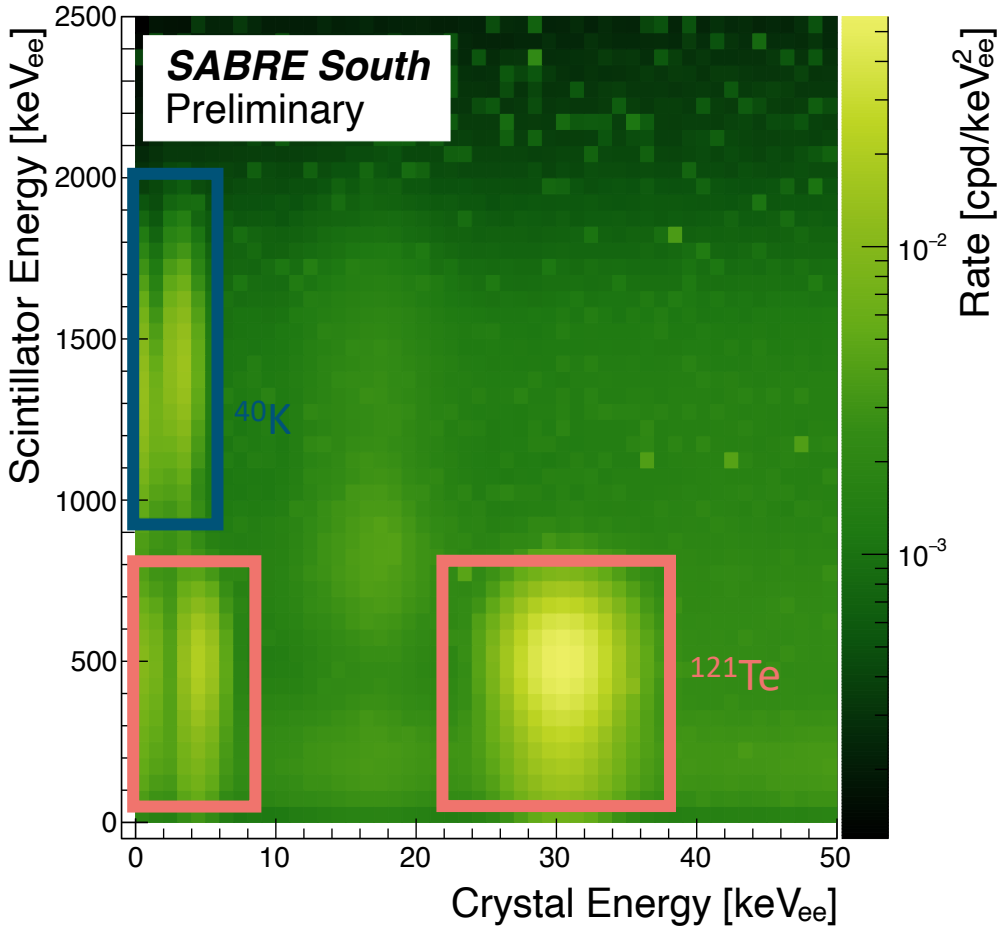
Collaboration paper submitted to EPJC about full background characterisation by using GEANT4 Monte Carlo simulations.
http://arxiv.org/abs/2205.13849

Background spectrum of $^{40}$K decays in the crystal with and without the veto requirement



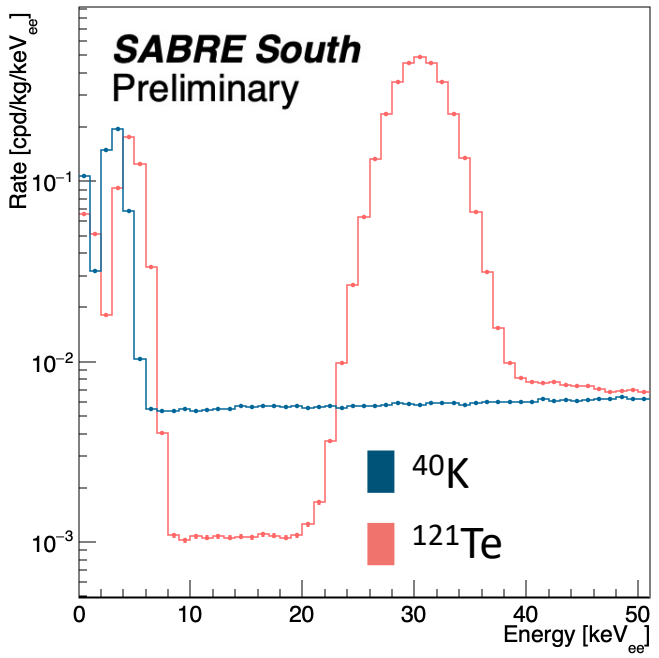
# Total Background Model

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

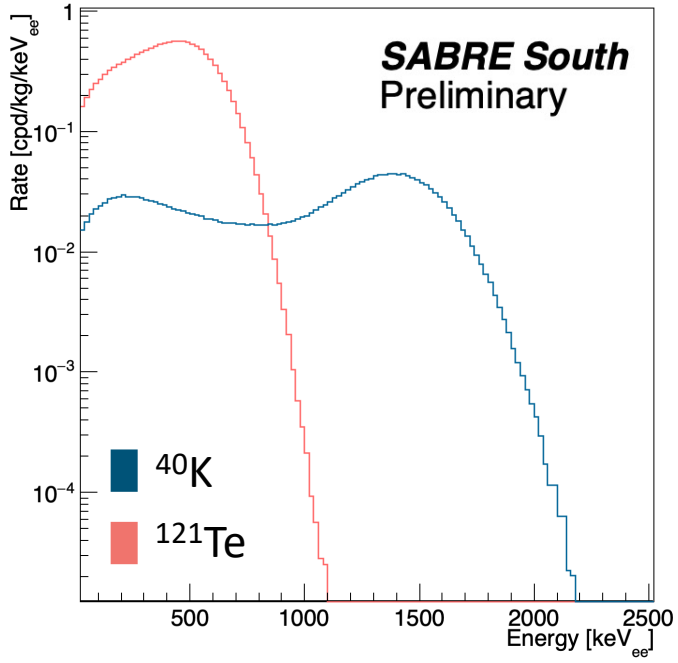



E.g., $^{40}$K and $^{121}$Te both have distinct islands in crystal-scintillator energy plane

Rate in crystals

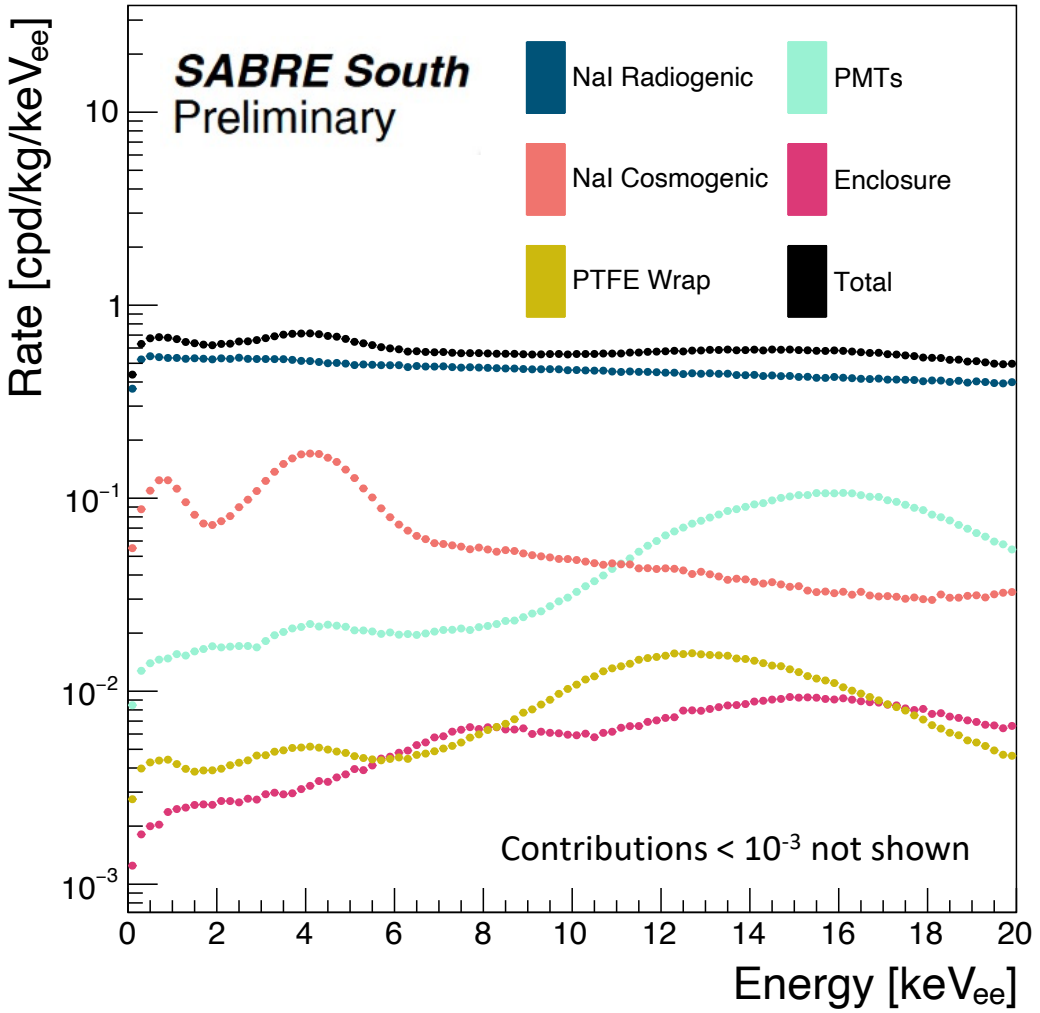



Rate in liquid scintillator




SABRE South Collab. arxiv:2205.13849

# Total Background Model




SABRE South Collab. arxiv:2205.13849

| 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** |

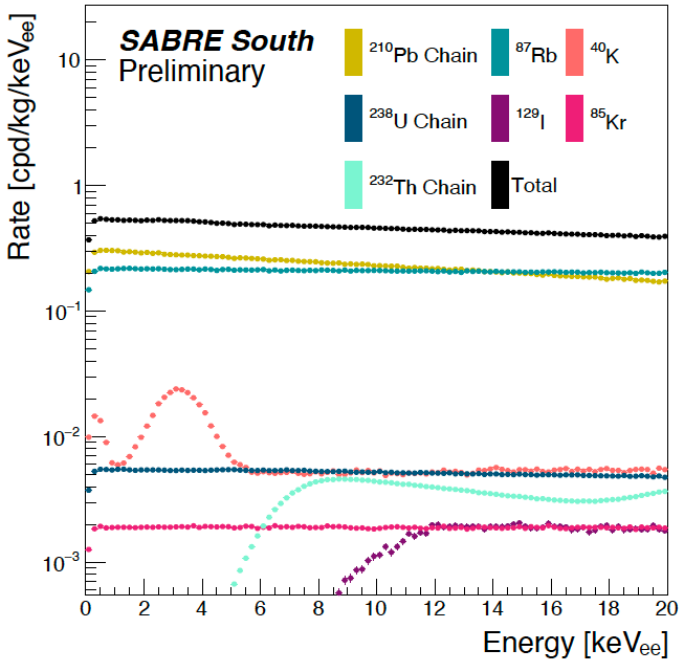
< 10% of background from non-crystal sources.

# NaI(Tl) Background Simulations

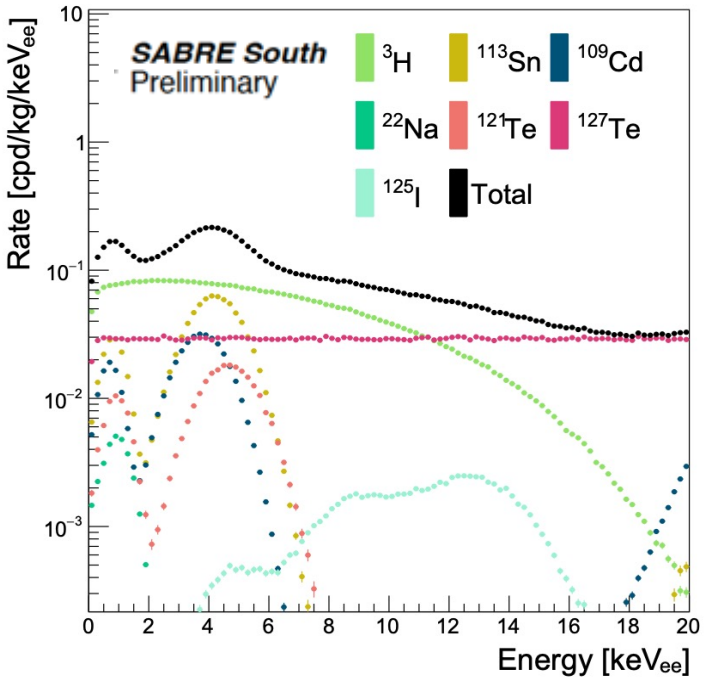
- Background of SABRE South crystal have been both simulated and directly measured (on NaI-33) with Inductively coupled plasma mass spectrometry (ICP-MS).
- Main radiogenic background represented by $^{210}$Pb, $^{87}$Rb (very conservative upper limit). No $^{87}$Rb was found with the ICP-MS measurement,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

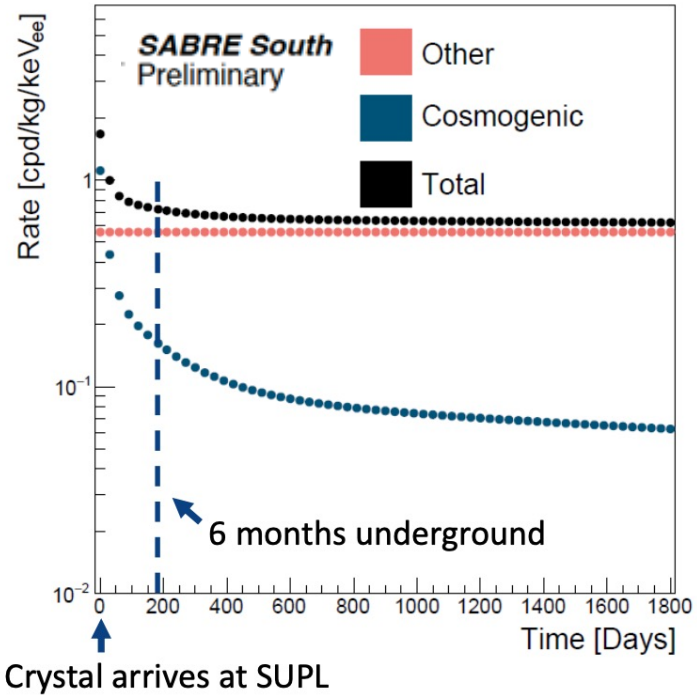
Radiogenic Background




Cosmogenic Background
(6 months underground)



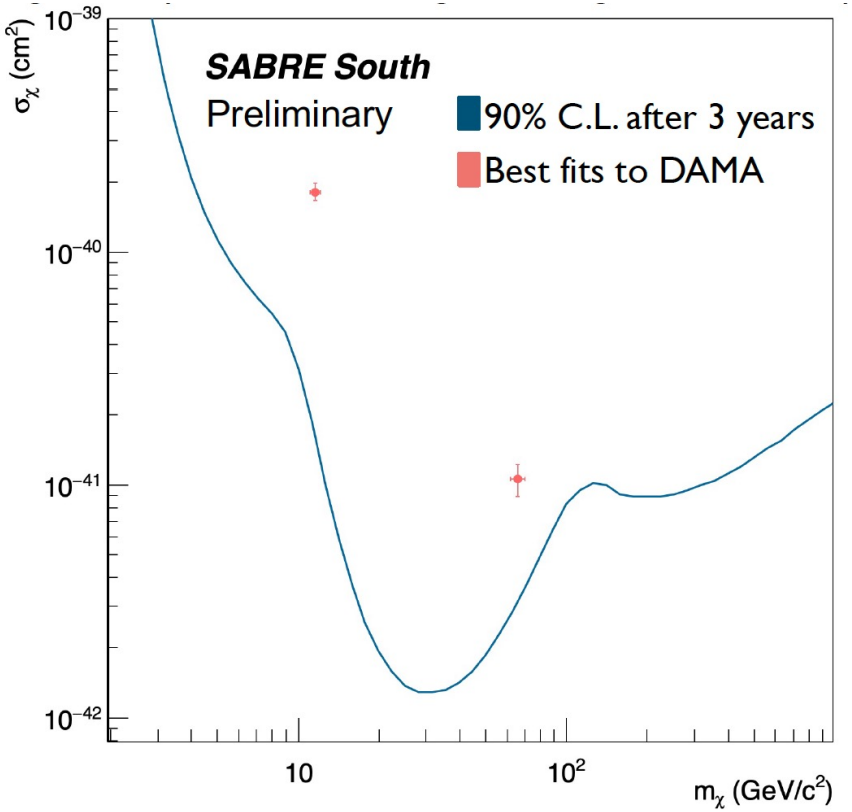

Time Dependence of Background



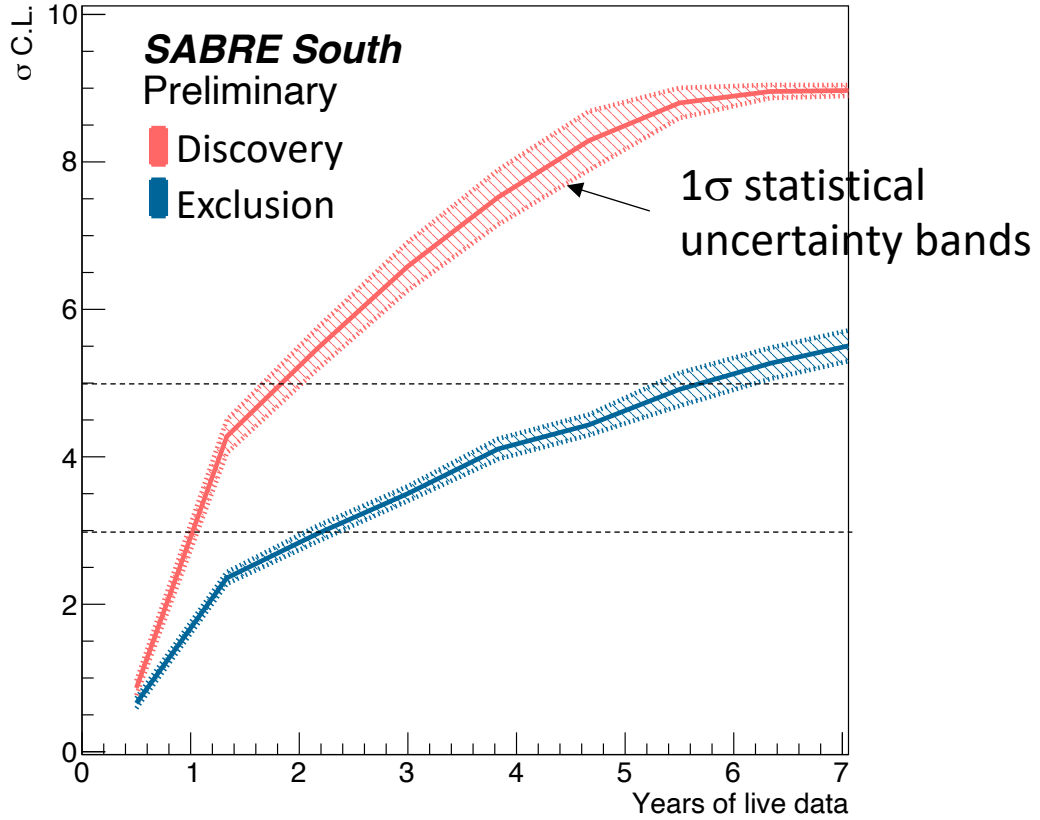
# Sensitivity

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 .



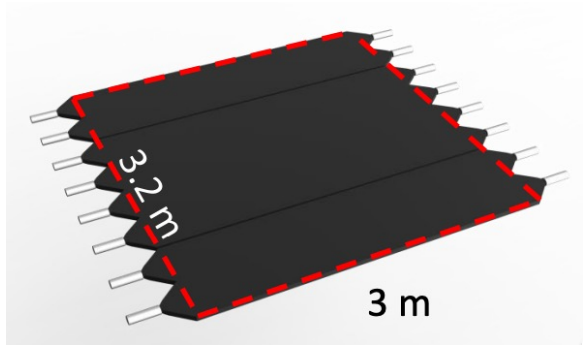

Evolution of discovery/exclusion power as a function of live time.

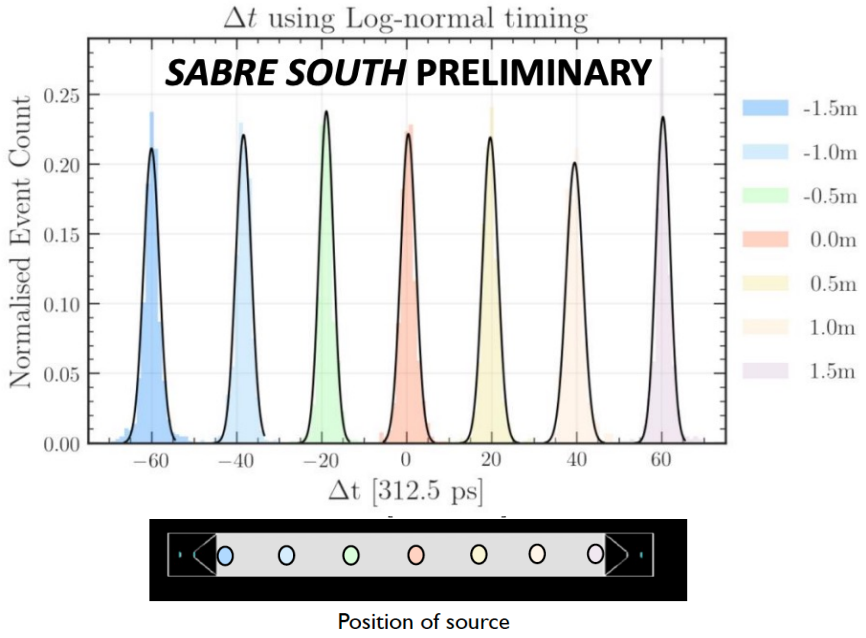


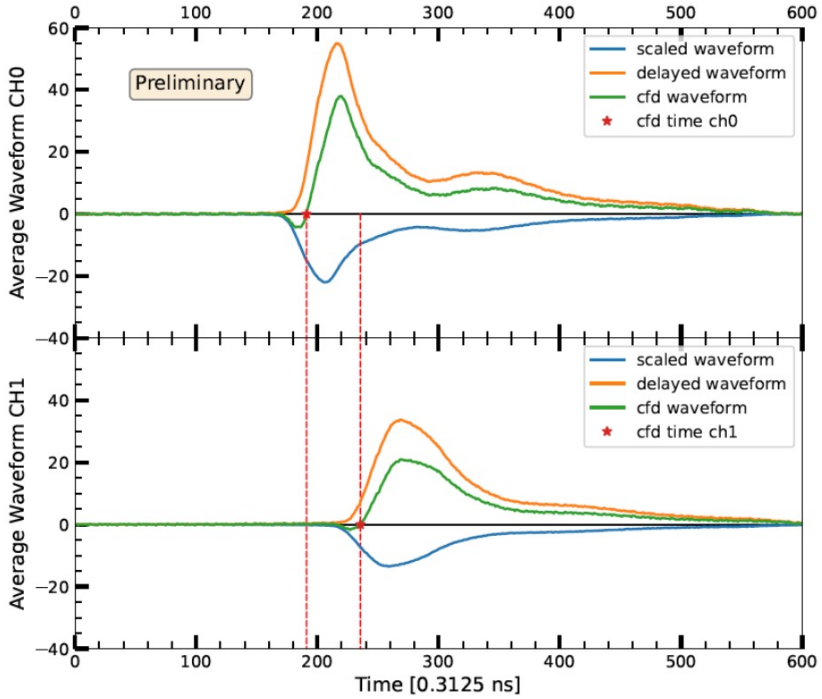

SABRE South Collab. arxiv:2205.13849

# 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.

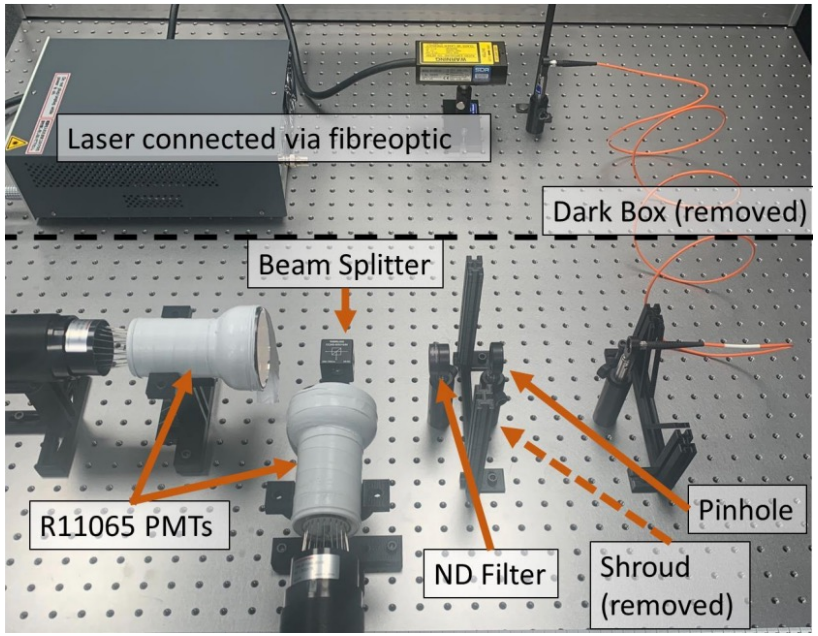


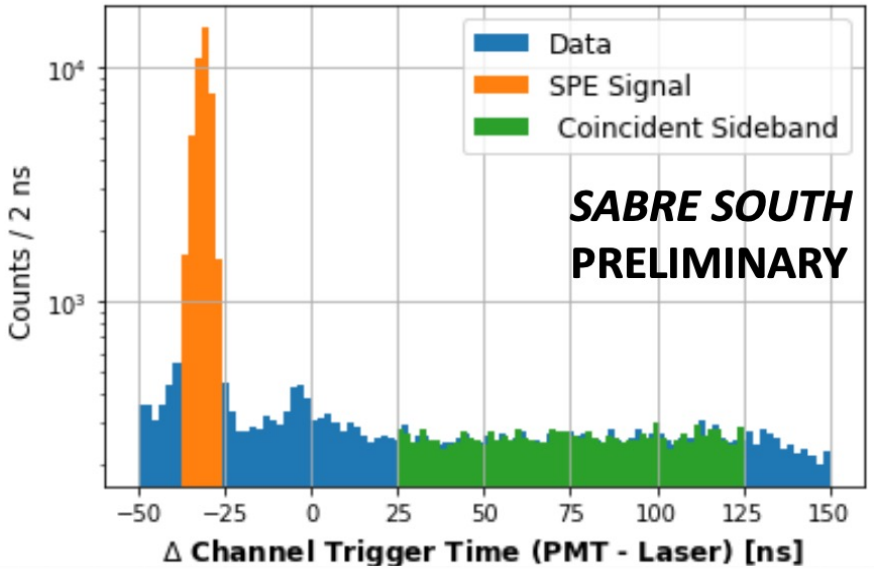



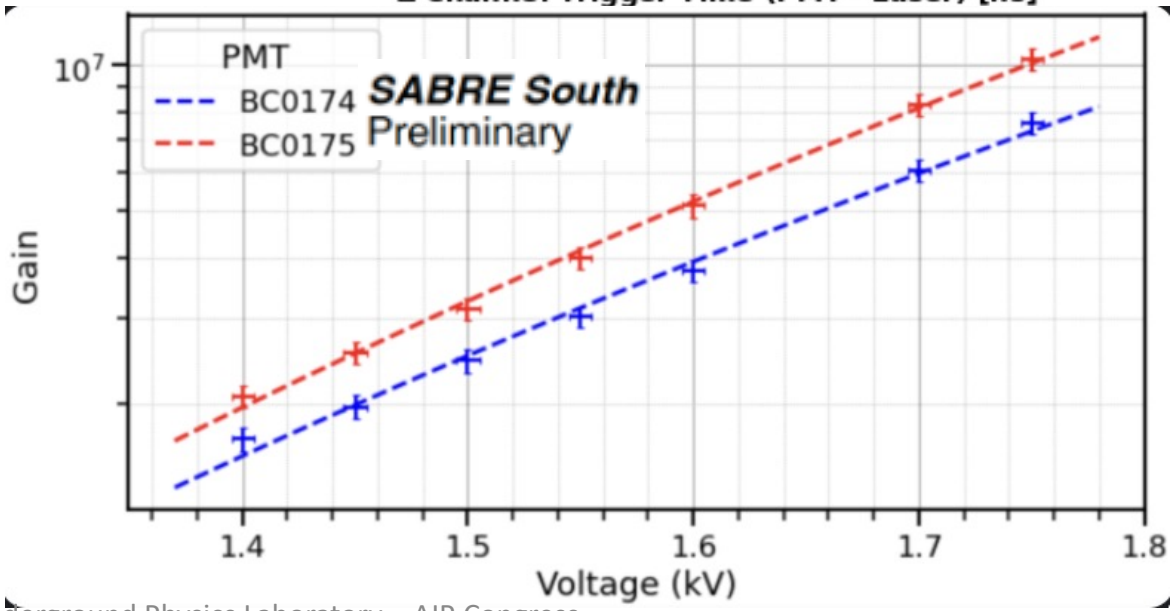



# PMT Characterisation

- 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.



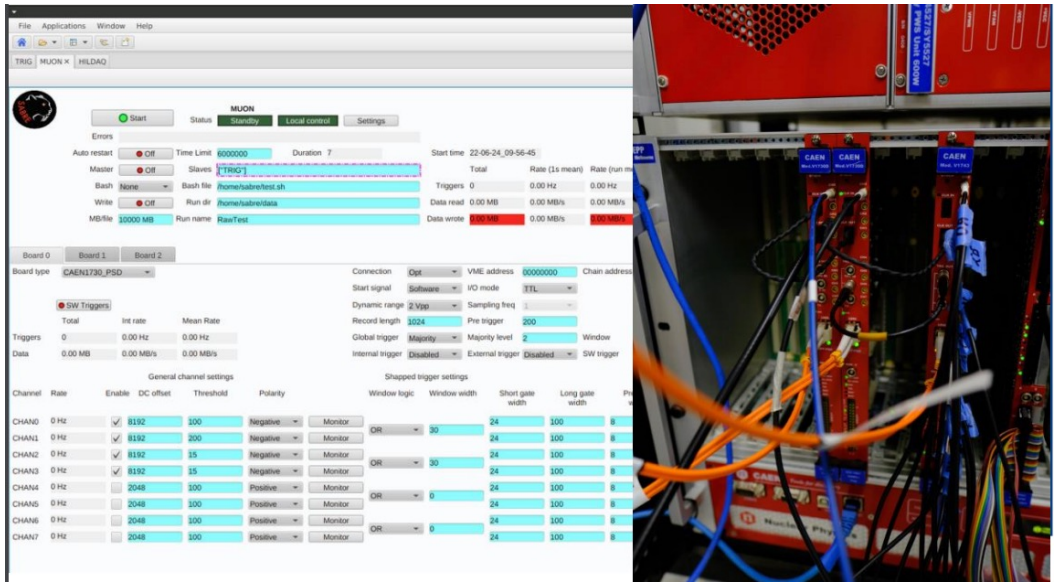



# DAQ & Software

- 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.



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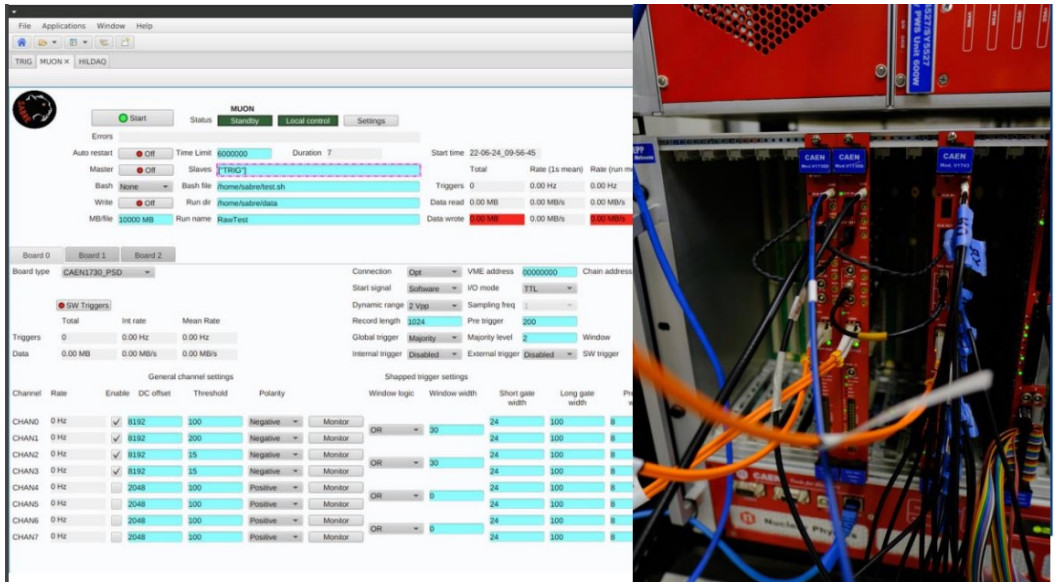
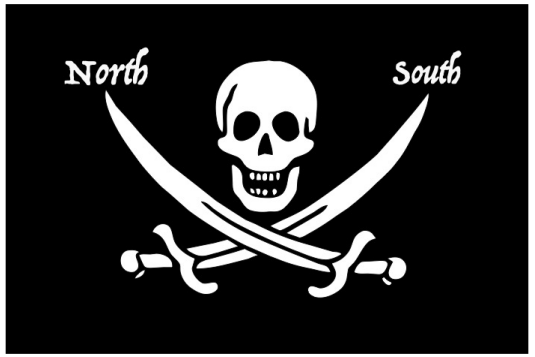
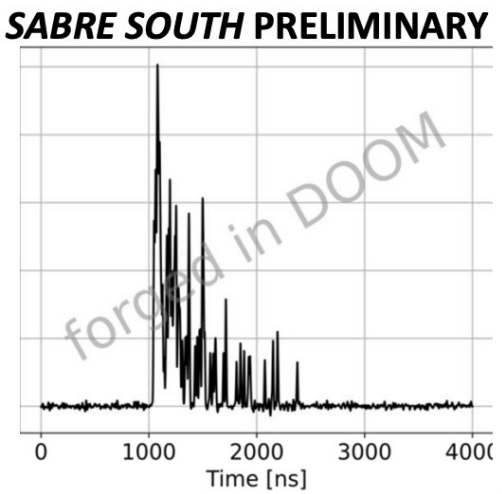
- Prototype currently running NaI test at LNGS.





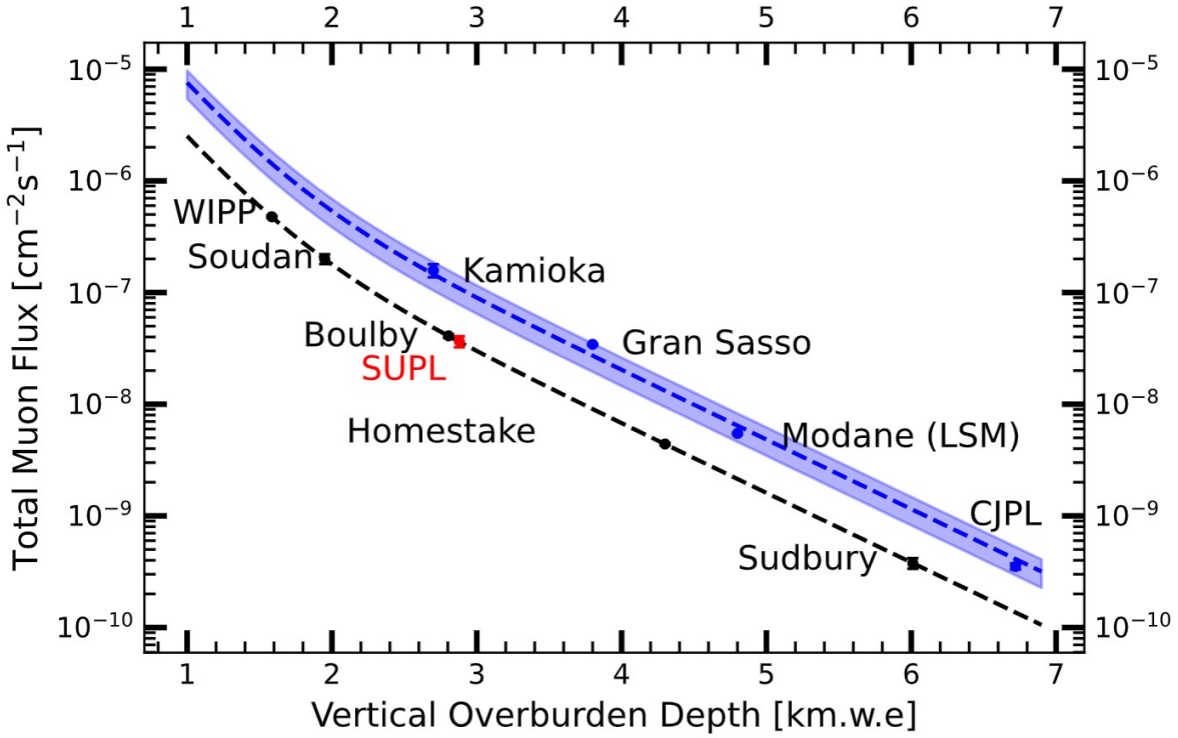

- SABRE South has developed a flexible python-based tool for data processing and analysis code called Pyrate.
- This reconstruction code will be used by the whole SABRE collaboration.
- Designed to process many digitised channels, currently in use for PMT and NaI characterisation. DOI:10.5281/zenodo.6257646

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



# Stawell Underground Physics Lab

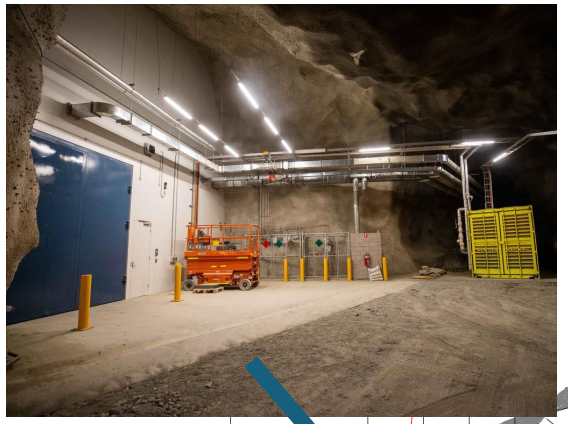
- SUPL is the first deep underground lab in Southern Hemisphere (37°South) located in western Victoria 240 km from Melbourne.
- Lab is 1025 m (~2900 m water equivalent) below ground with flat over burden within the Stawell Gold Mine.
- Lab construction finished on mid June 2022 and lab handed over to managing company.
- Strong support of the local community and of media.

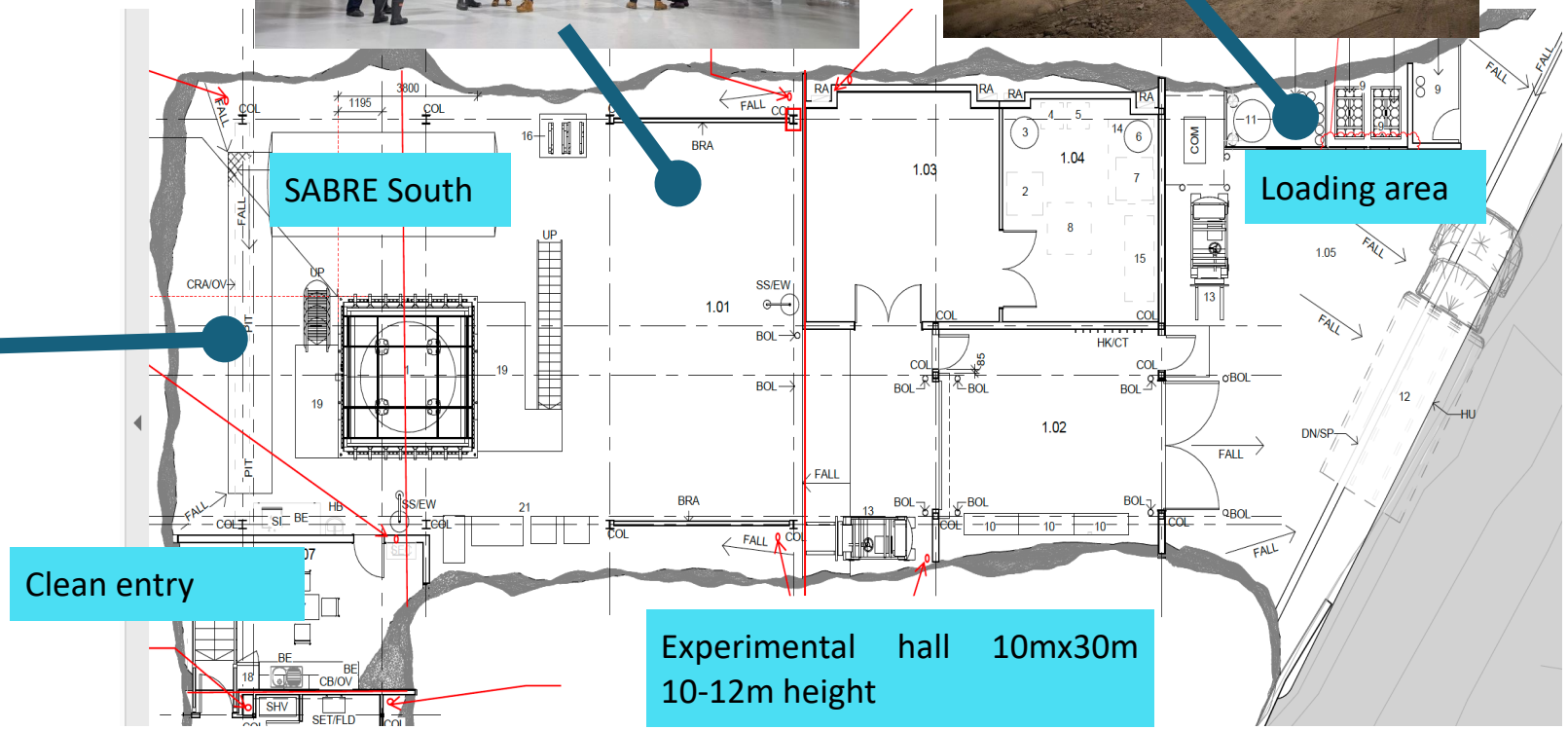



# Stawell Underground Physics Lab

- Walls pinned with steel, sprayed with low radioactivity shotcrete and coated with Tekflex.
- Environmental background measurements.

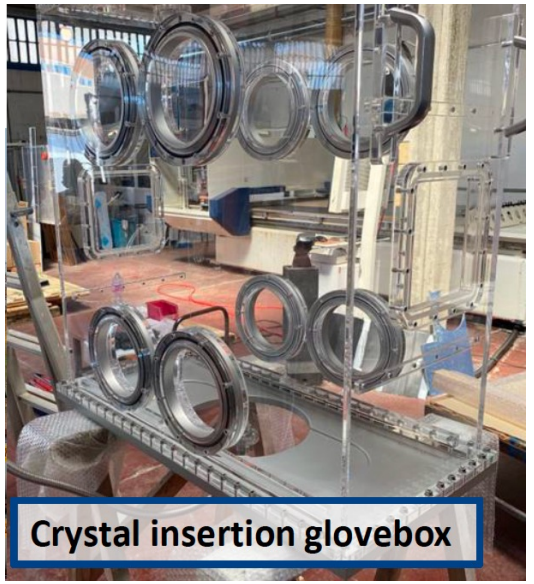
Geoff Taylor's talk: Thursday 2:00 pm, room E3.





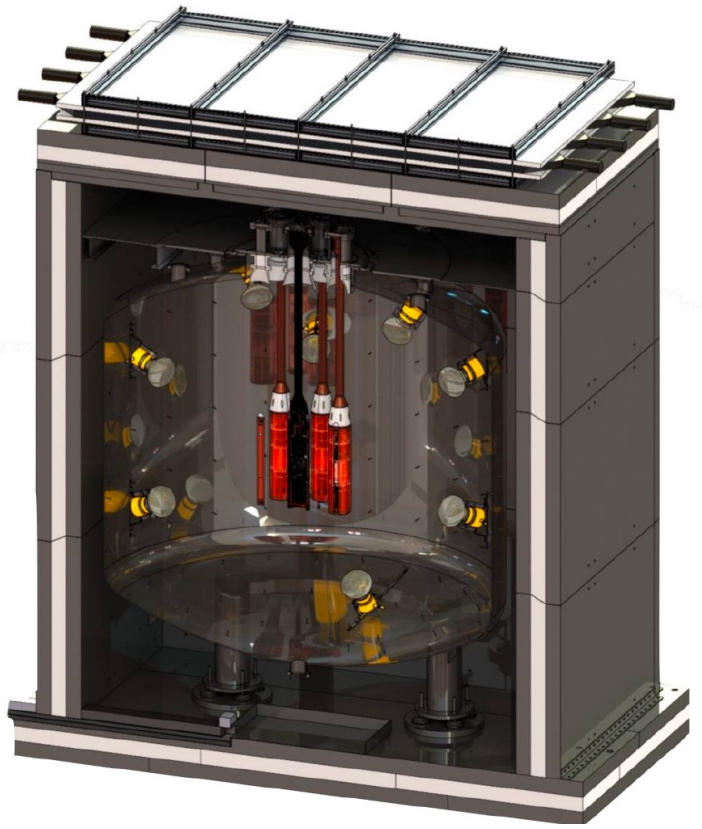
# SABRE South timeline

- SABRE commissioning will start mid 2023.
- Vessel + LAB, PMTs, muon detector, DAQ electronics, slow control, Crystal insertion system ... all ready.
- Muon veto will be the first assembled detector underground (next weeks).
- Crystal procurement is on-going. Crystal insertion operations are planned in Q3/Q4 2023.
- Veto vessel will be completed (including PMT installation) in the second half of 2023 and the LAB will be introduced right after.


# Summary

- SABRE South is part of the SABRE Collaboration designed to test DAMA modulation.
- 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 will use 50 kg of ultra-low background NaI(Tl).
- High purity crystals and large active veto give ultra-low background of 0.72 cpd/kg/$keV_{ee}$.
- SABRE South will have 5σ discovery (3σ exclusion) power to a DAMA-like signal with 2 years of data taking.
- SABRE commissioning expected mid-2023.



# Acknowledgements


**SABRE South**







**SABRE North**






# Possible outcomes from SABRE

1. SABRE doesn't observed any signal $\Longrightarrow$ DAMA/LIBRA detects some false signal introduced somehow;

2. SABRE North and South detect modulation out of phase $\Longrightarrow$ strong evidence that some seasonal background exists and needs to be understood;

3. SABRE North and South detect annual modulation in phase $\Longrightarrow$ some non-seasonal source that is somehow not seen in any other Dark Matter experiments.

All outcomes are interesting.

# Back up

# SABRE North status

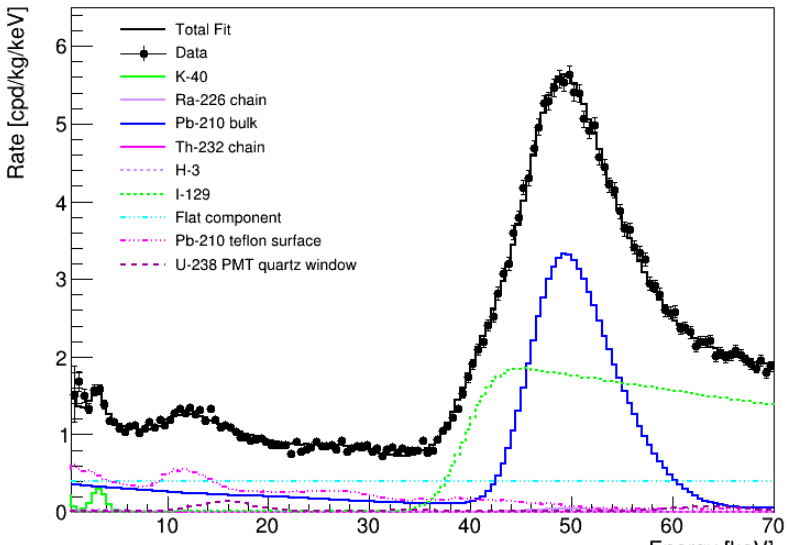
Two low background NaI(Tl) crystals (NaI-31 and NaI-33) tested and characterised.
Proof-of-principle phase (1 crystal + active veto) concluded.

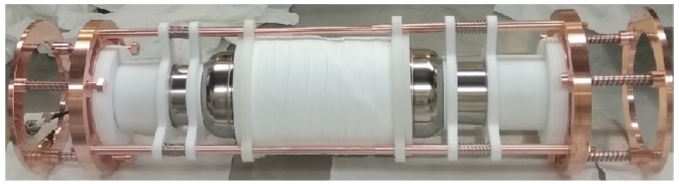
Results:

- Full Monte-Carlo simulation model to identify background components
- 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 the same crystal (NaI-33) with a lower radioactivity reflector
- Test reproducibility of crystal radiopurity
- Assembly of detector modules at LNGS with a new custom glove box.



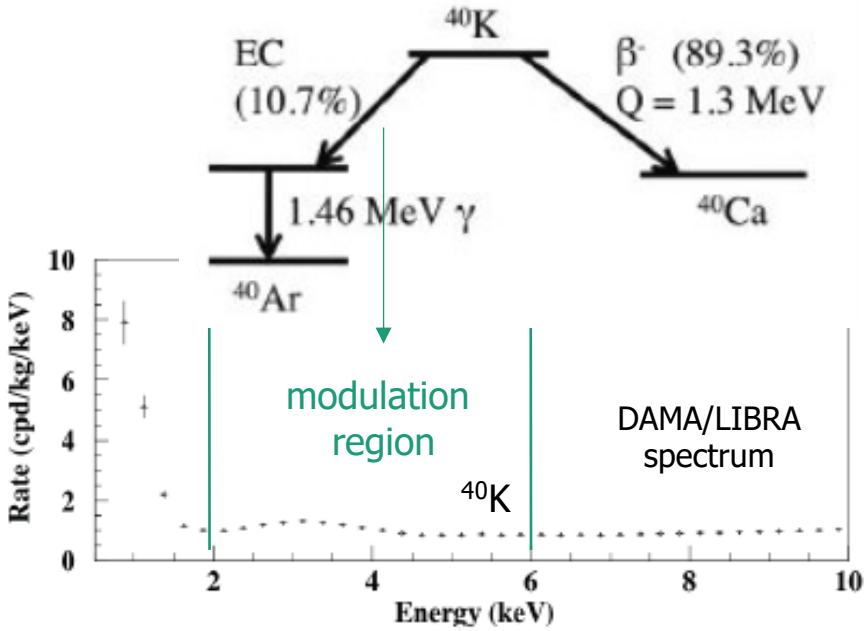
Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding



# Background from $^{40}$K

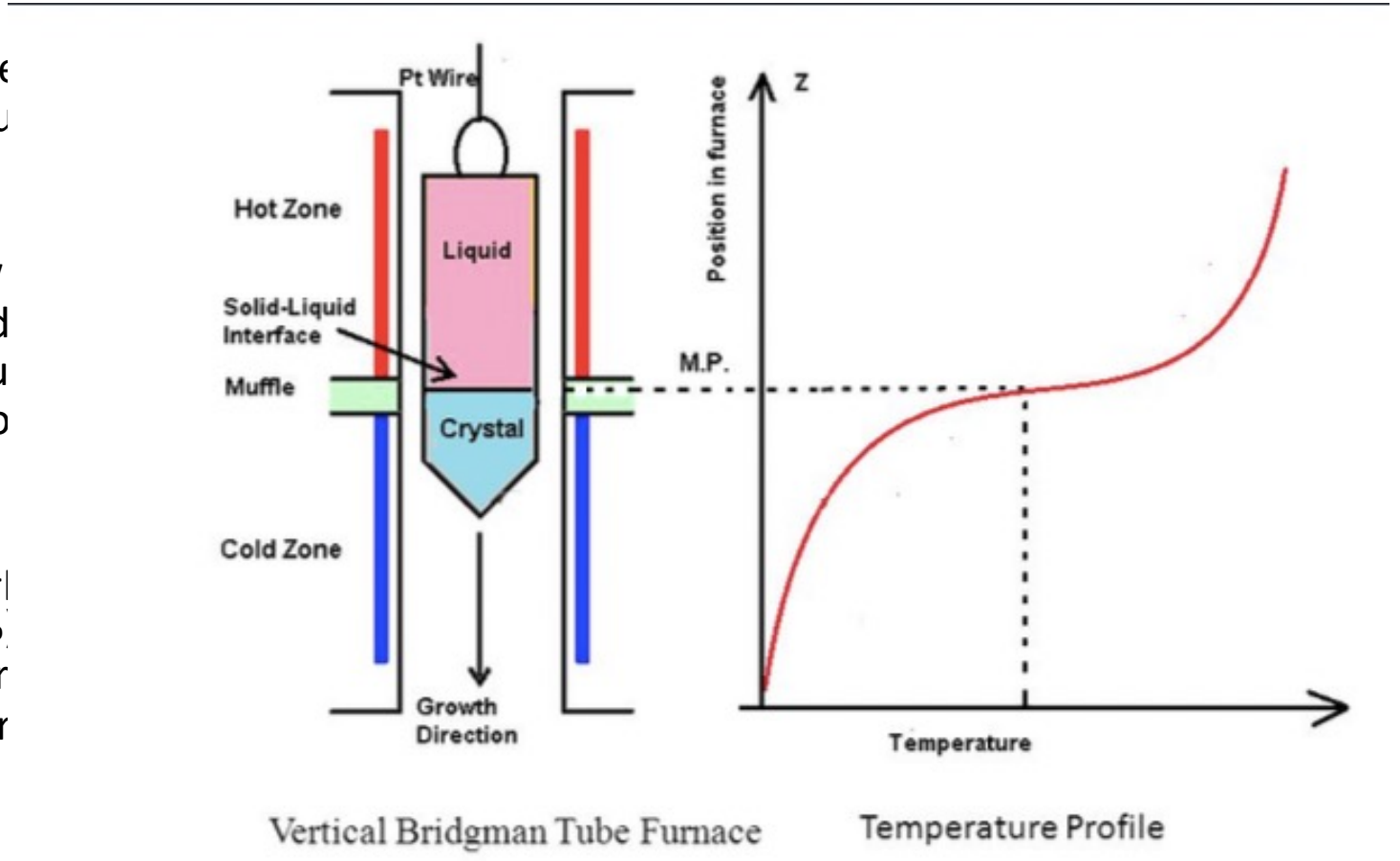
Most dangerous long-lived background in the Region of Interest:

- **$^{40}$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.

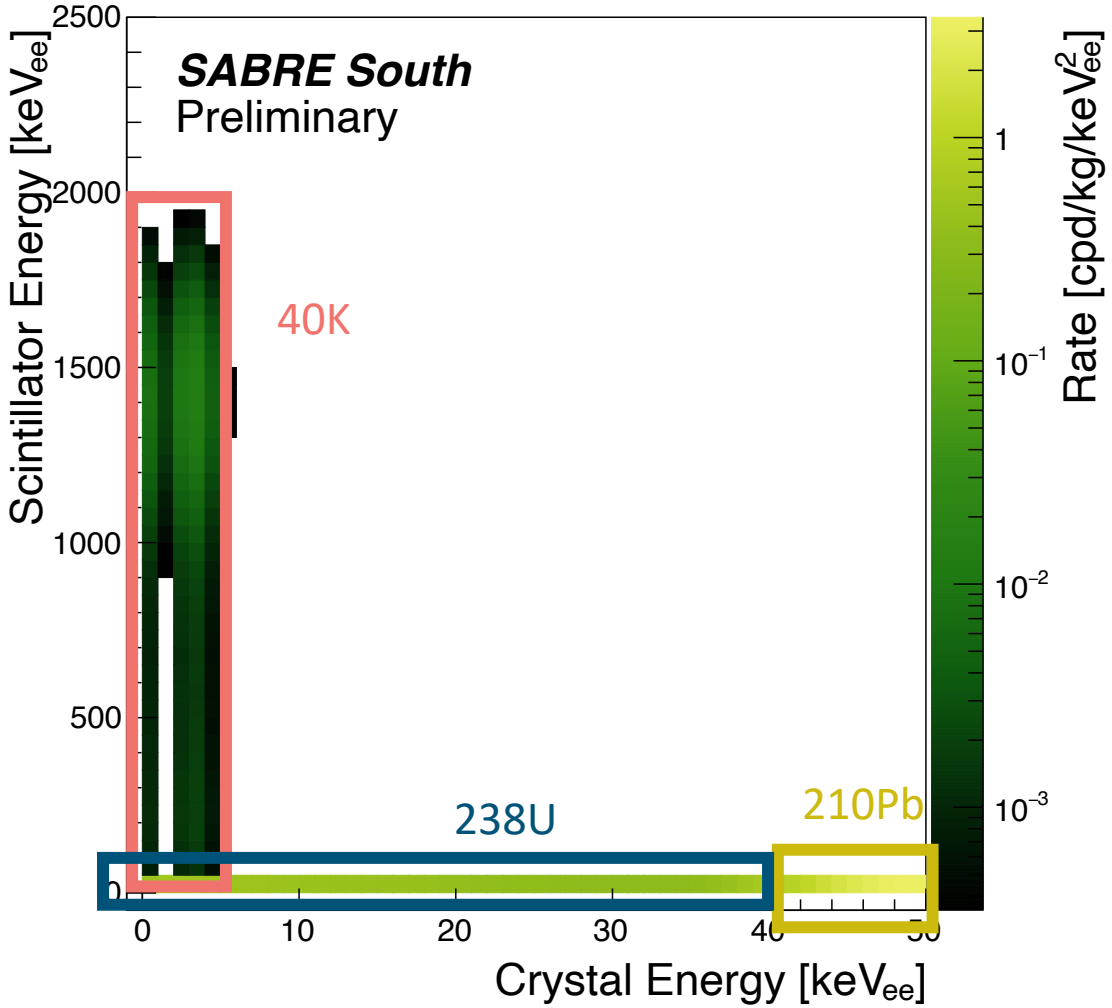


# Crystal growth

- Crystals are grown in a precision-cle carbon coated synthetic fused quartz cru using the vertical Bridgman method.
- Furnace is headed to 750 °C over a few then crucible is slowly lowered into cold (500 °C) at a rate of 7-10 mm/day. The fu is then cooled to room temperature o week before crystal is removed.
- The dry NaI powder is mixed with high-| thallium iodide (TlI) powder (99.999%| sealed inside a high-purity crucible. To pr contamination, the crucible is car cleaned with high-purity acids.

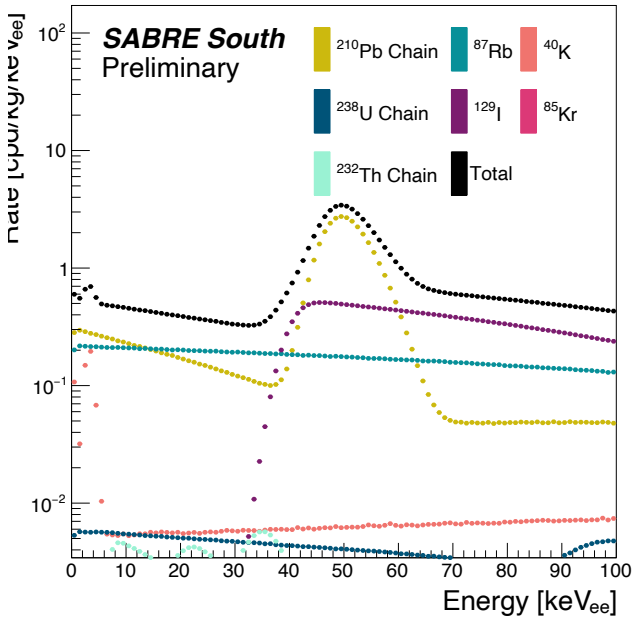


# Total Background Model

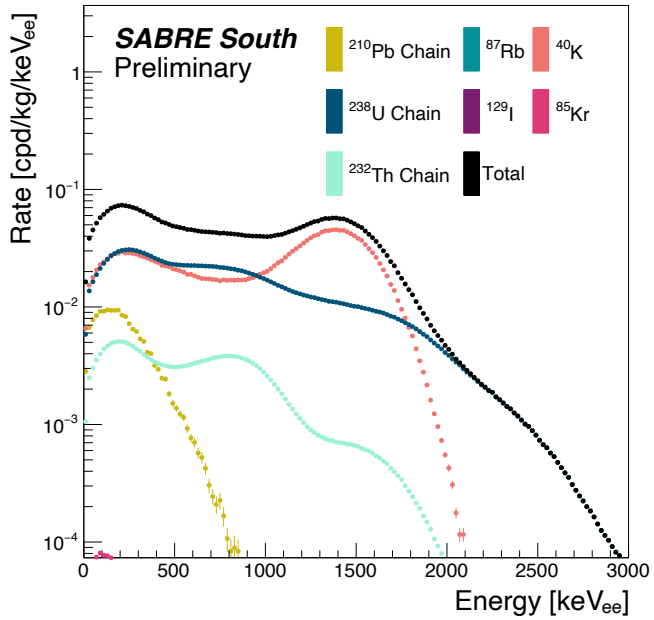



Contamination from intrinsic radiation of crystals

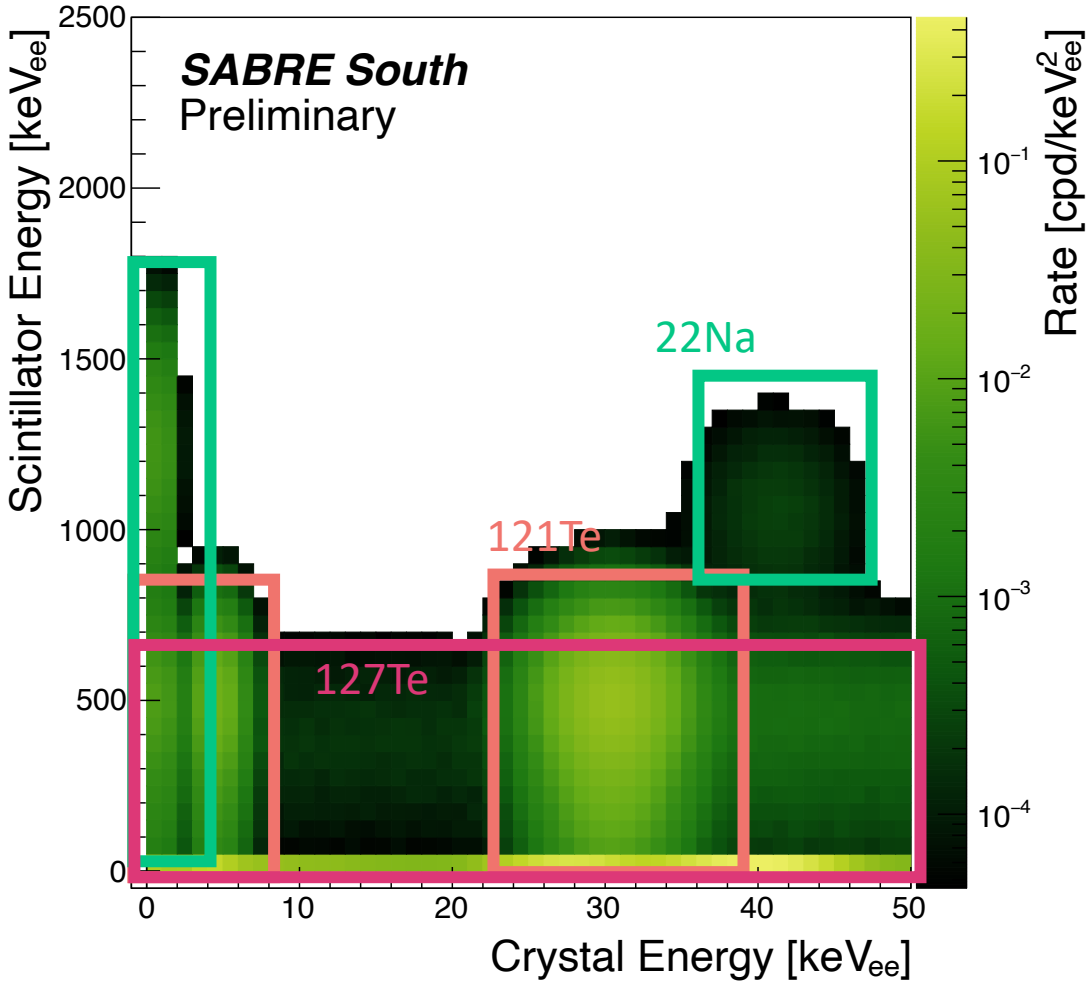
Deposition in crystal




Deposition in veto

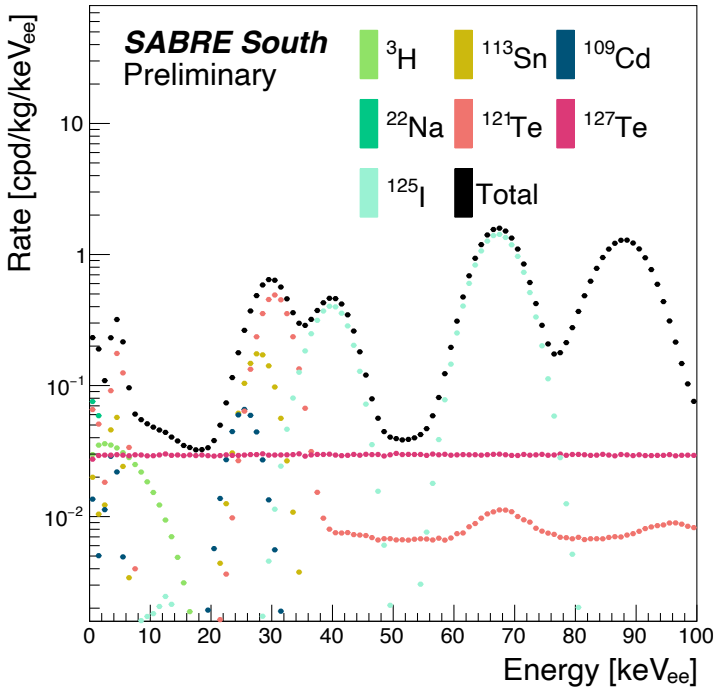


# Total Background Model




Contamination from cosmogenic activation of crystals

Deposition in crystal




Deposition in veto