

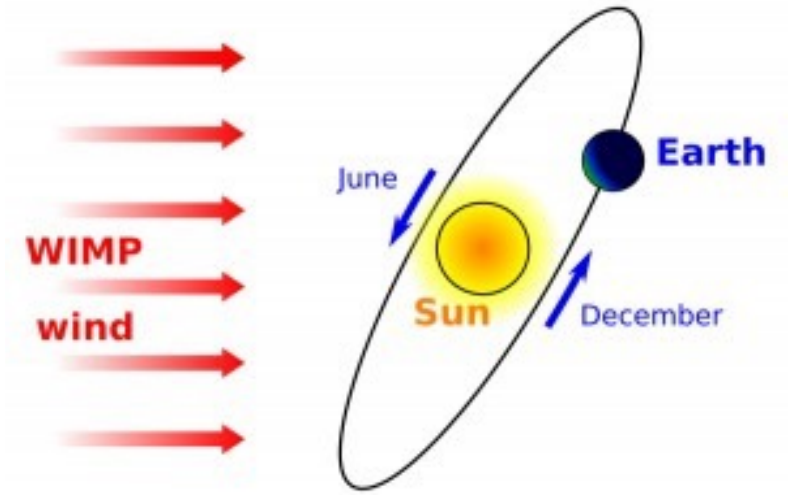
Anthony G. Williams

Adelaide University

ARC Centre of Excellence for Dark Matter Particle Physics

The SABRE South Experiment at the Stawell Underground Physics Laboratory

WIMP Wind– Annual Modulation Signal



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

Modulating component ~ few % of R(t)

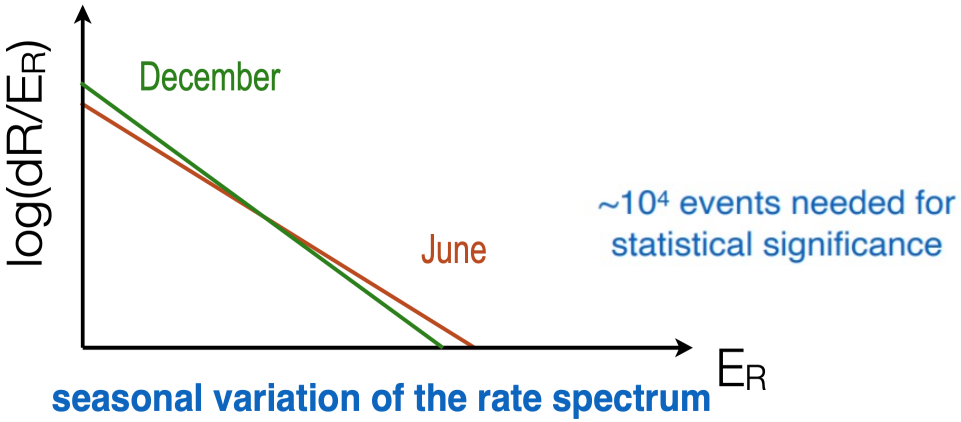
- Rare and low energy events.
- Low expected rate S_0 < 1 cpd/kg/keV
  (only a few % of which modulates, S_m).

➡️ **Expect very low modulation amplitude**
< ~ 0.01 **cpd/kg/keV.**

Standard halo model hypothesis:

- spherical halo of cold, dark matter (WIMP particles) permeating the galaxy
- approximately static DM halo
- local energy density $\rho_{WIMP} \sim 0.3$ GeV/cm^3
- Maxwell speed distribution

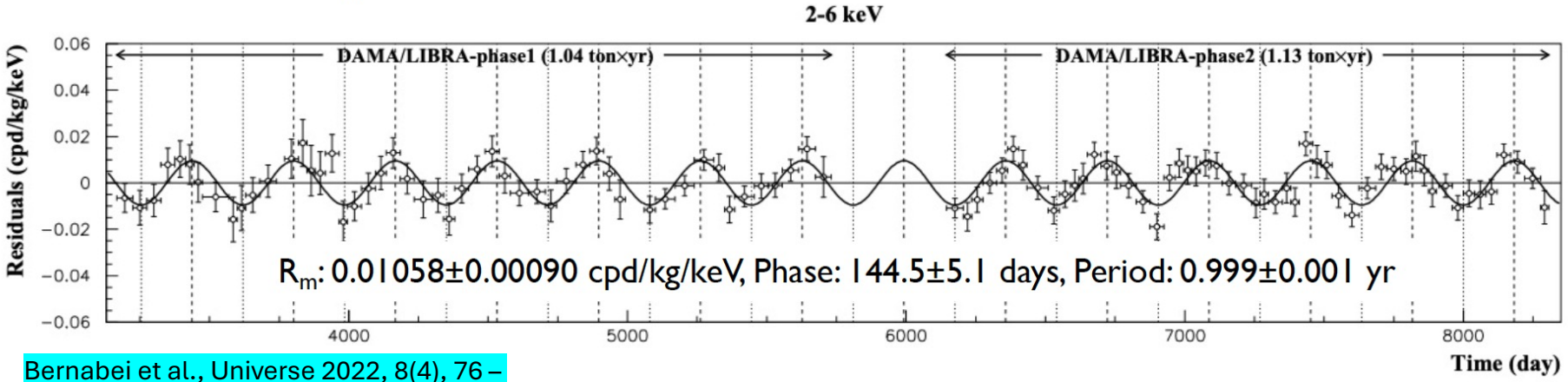
Annual modulation: maximum and minimum expected on June 2nd and on 2nd December



seasonal variation of the rate spectrum

The control of any modulating background is key

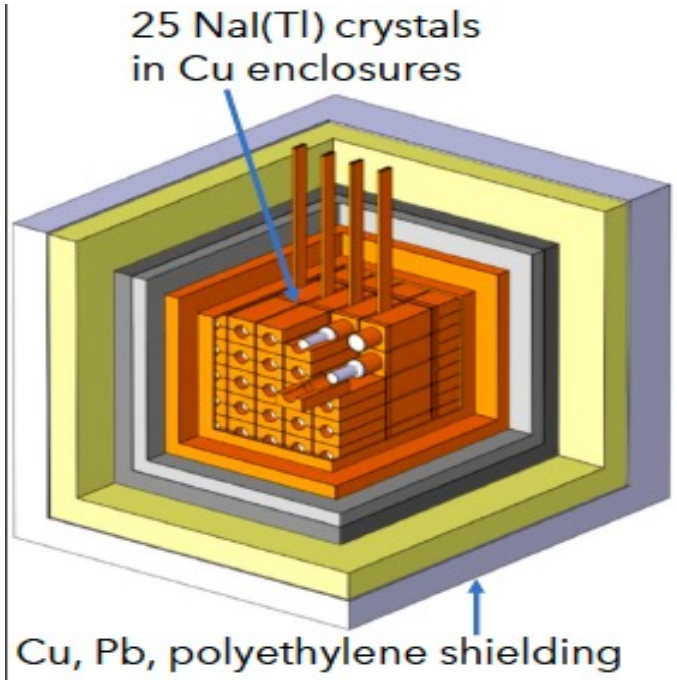
DAMA/LIBRA results



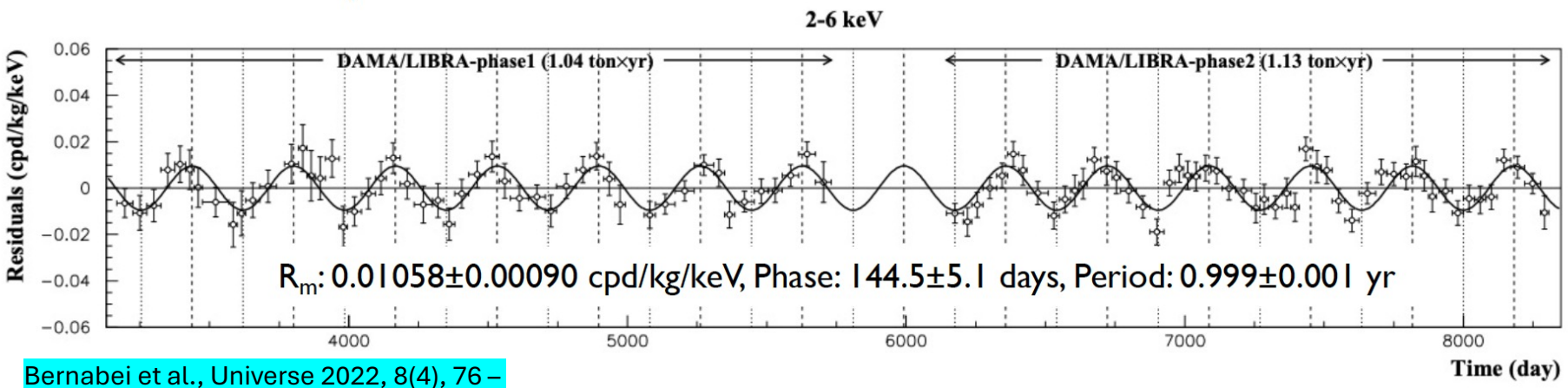
Bernabei et al., Universe 2022, 8(4), 76 – DOI: 10.3390/universe8040076

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

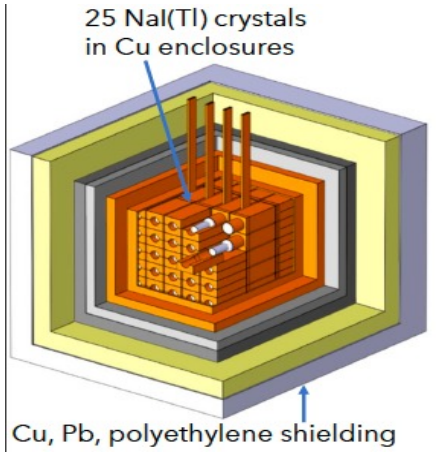
- located at Laboratori Nazionali del Gran Sasso (LNGN), Italy.
- total mass: 250 kg of NaI (Tl).
- observed **~0.01 cpd/kg/keV** modulation in the 1-6 keV (second phase) energy range.
- 13.7 σ significance.



DAMA/LIBRA results

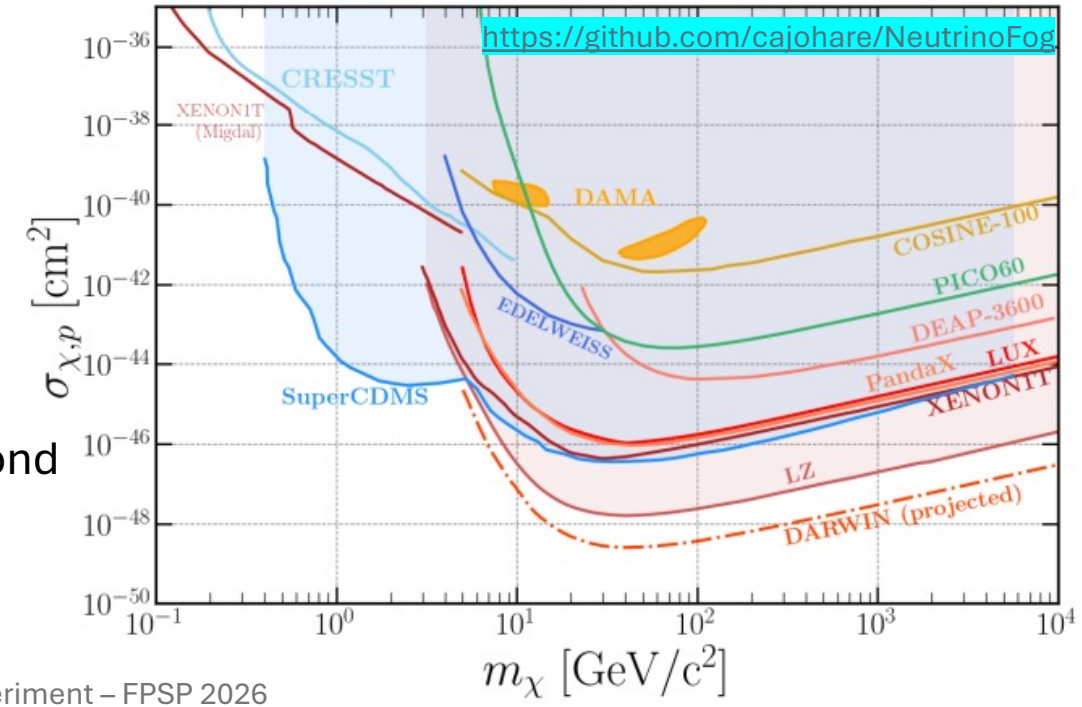


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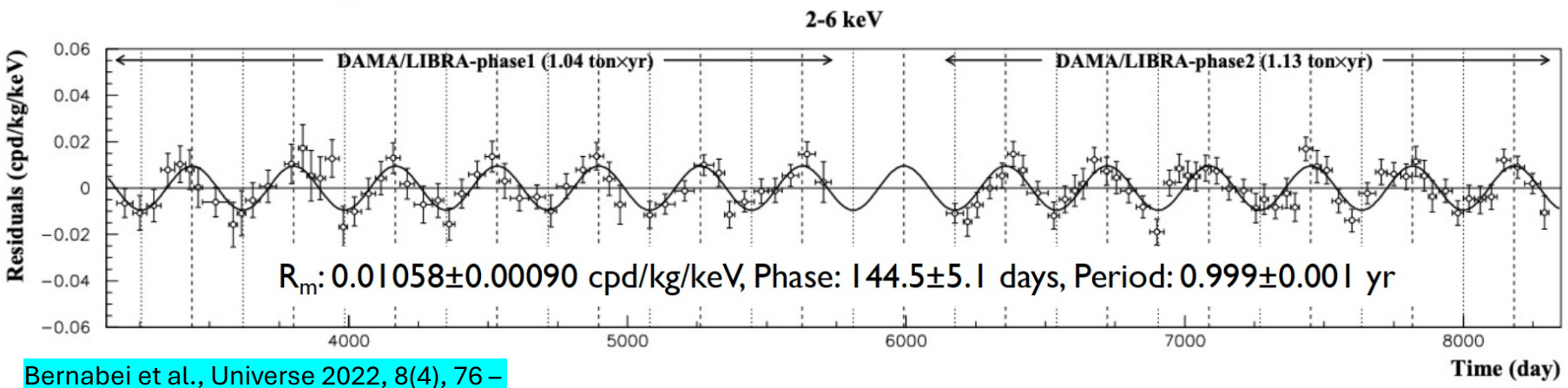


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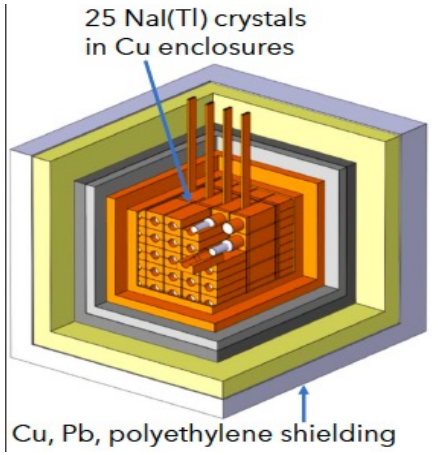
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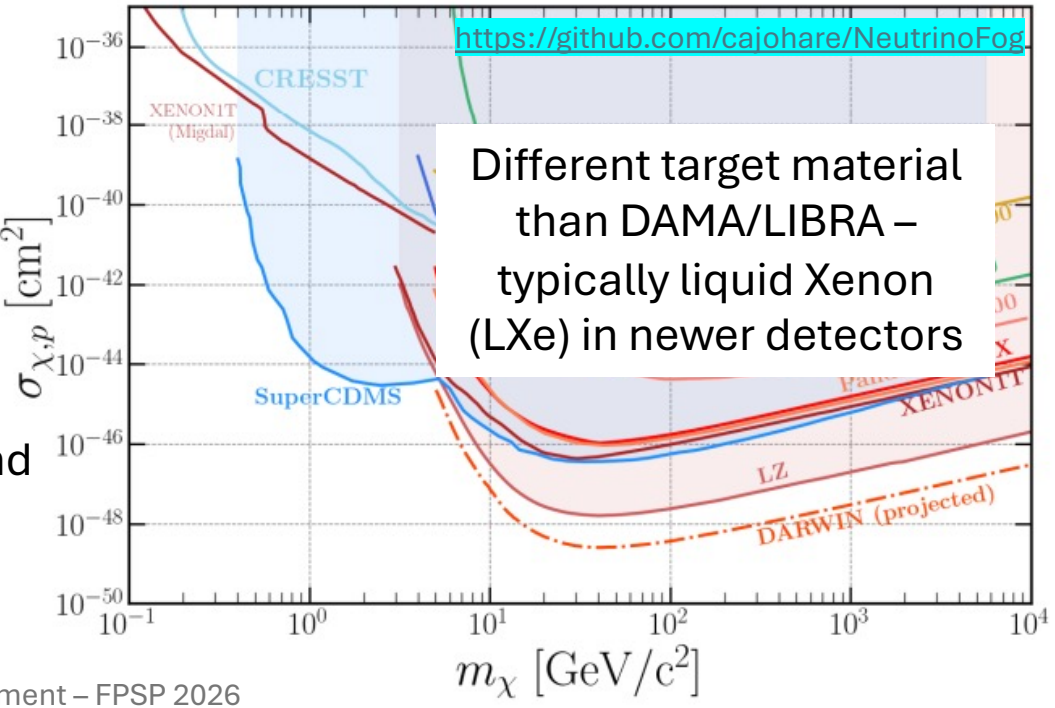


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Different target material than DAMA/LIBRA – typically liquid Xenon (LXe) in newer detectors

Observation rates and detector dependence

Rate *(R)* of nuclear recoils as a function of nuclear recoil energy *(E_R)* :

Zurowski, SciPost Phys.Proc. 12 (2023) 027

Lawrence, Duffy, Mon.Not.Roy.Astron.Soc. 524 (2023) 2, 2606-2623

DECONSTRUCTING THE WIMP DIRECT DETECTION DIFFERENTIAL RATE EQUATION

$$\frac{dR}{dE_R} = N_T \frac{\rho \sigma_0 m_T}{m_\chi 2\mu_N^2} \sum_{i,j} \sum_{a,b=0,1} \hat{c}_i^{(a)} \hat{c}_j^{(b)} \left(F_{ij}^{(ab),1}(q) \int \frac{f_{\text{lab}}(\vec{v})}{v} d^3v + F_{ij}^{(ab),2}(q) \int v f_{\text{lab}}(\vec{v}) d^3v \right)$$

DM & TARGET PROPERTIES

- $\frac{dR}{dE_R}$: Differential scattering rate (counts/keV/kg/day)
- N_T : Number of target nuclei in detector
- ρ : Local DM halo density
- σ_0 : Benchmark DM-nucleon cross-section
- m_T : Mass of target nucleus
- m_χ : Mass of the WIMP DM particle
- μ_N : DM-nucleon reduced mass $(\frac{m_\chi m_n}{m_\chi + m_n})$

EFT INTERACTION & COUPLINGS

- $\sum_{i,j}$: Sum over all 15 EFT operators (e.g., $\mathcal{O}_1, \mathcal{O}_4 \ldots$)
- $\sum_{a,b}$: Sum over isospin states
- $a, b \in \{0, 1\}$: Isospin indices: 0=Isoscalar $(c^p + c^n)$, 1=Isovector $(c^p - c^n)$
- $\hat{c}_i^{(a)}$: Wilson coupling constants (effective field theory parameters)

NUCLEAR RESPONSE (Form Factors)

- q : Momentum transfer $(\sqrt{2 m_T E_R})$
- $F_{ij}^{(ab),1}(q)$: Velocity-INDEPENDENT response function (maps to $\int \frac{f}{v}$)
- $F_{ij}^{(ab),2}(q)$: Velocity-DEPENDENT response function (maps to $\int v f$)



DM ASTROPHYSICS & VELOCITY

- $\int \frac{f_{\text{lab}}(\vec{v})}{v} d^3v$: Velocity integral, standard term ($\propto v^{-1}$ flux)
- $\int v f_{\text{lab}}(\vec{v}) d^3v$: Velocity integral, higher-order term ($\propto v^1$ flux)
- $f_{\text{lab}}(\vec{v})$: DM velocity distribution relative to the Earth/detector
- $\vec{v}$: WIMP velocity vector

Observation rates and detector dependence

Number of events observed as a function of *measured event energy*, *E'*. , *(note: E_{ee} = electron equivalent energy).*

$$\frac{dR}{dE'} = \epsilon(E') \frac{1}{(2\pi)^{1/2}} \int_0^\infty \frac{dR}{dE_R} \frac{dE_R}{dE_{ee}} \frac{1}{\Delta E_{ee}} \exp\left[\frac{-(E' - E_{ee})^2}{2(\Delta E_{ee})^2}\right] dE_{ee}$$

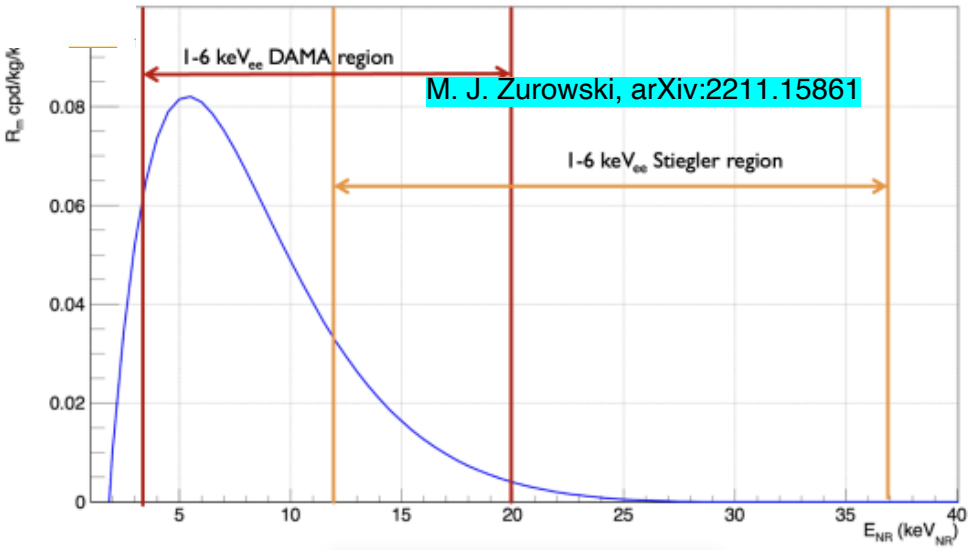
Efficiency/threshold
Imperfect/realistic detector setup

Interaction rate
As per last slide

Quenching factor
Transformation from nuclear recoil energy to observable energy

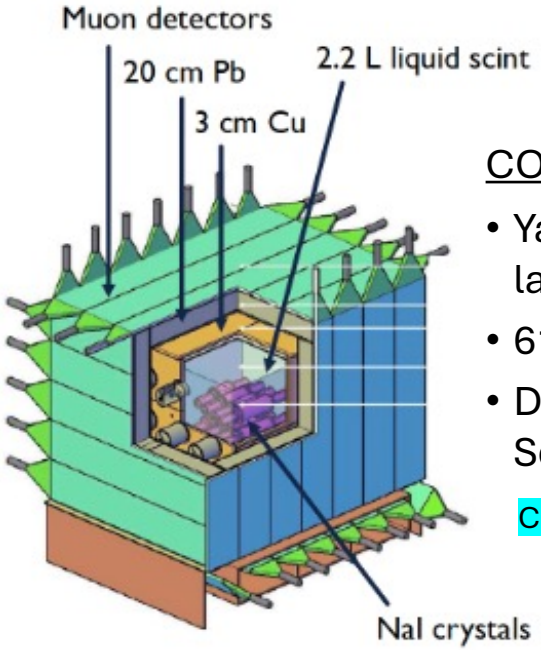
Resolution
Ability to resolve fine details in energy spectrum

Energy resolution, ΔE_{ee}, of the detectors and quenching factors, $Q \equiv dE_R/dE_{ee}$, for the crystals must be understood so that dR/dE_R can be estimated from dR/dE'.



- Quenching factors *(Q)* may vary significantly between crystals, particularly those grown with different techniques as they strongly depend on the optical properties of the crystal.
- Changing relationship between nuclear recoil and observed energy means the 1-6 keVee observable region of interest is "accessing" different parts of the nuclear recoil energy spectrum.
- Optical transport effects that may vary between crystals are also under investigation Brown et al. arXiv:2403.02668v2 .

NaI(Tl) detectors: experiments results



COSINE-100:

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

COSINE-100, PRD 106 (2022)

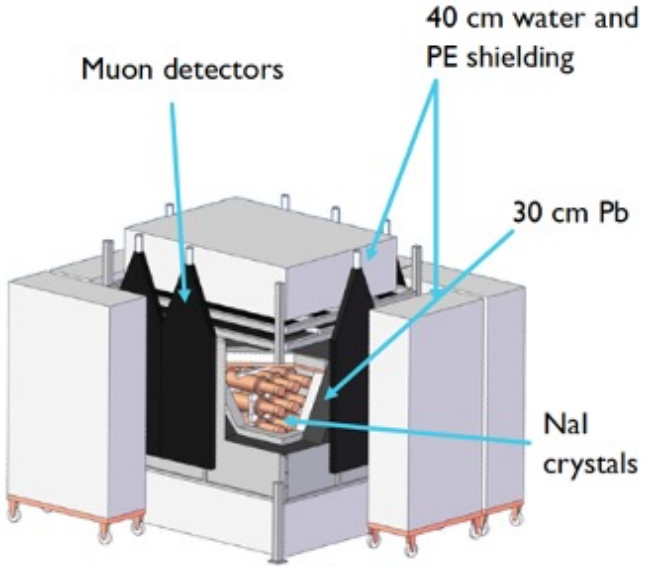
Note: 1 dru = 1 cpd/kg/keV

Setup	Mass (kg)	Bkg. (dru)	S_m (1–6 keV) (dru)	S_m (2–6 keV) (dru)
DAMA/LIBRA-phase2	250	0.8	0.0105 ± 0.0009	0.0093 ± 0.0009
COSINE	61.3	2.7	0.0017 ± 0.0029	0.0051 ± 0.0047
ANAIS	112.5	3.2	0.0007 ± 0.0025	0.0030 ± 0.0025

ANAIS:

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

ANAIS-112, Commun.Phys. 7 (2024) 1, 345

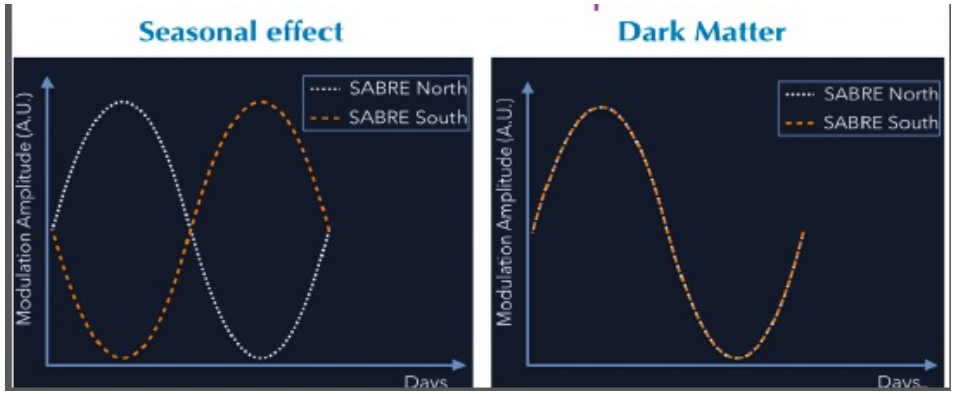


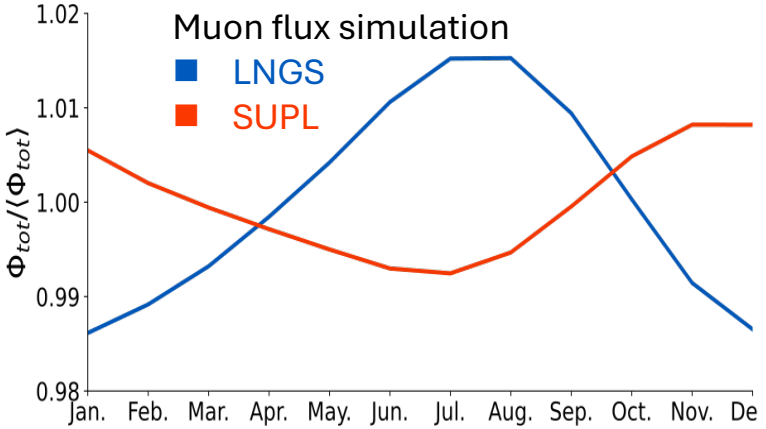
- Beginning to reach good sensitivity.
- Compatible with DAMA within 1 σ (COSINE) and ~3-4 σ (ANAIS).
- Both compatible with null hypothesis.
- Higher background levels.

SABRE: a dual site experiment

- Similar experiments; **SABRE North in LNGS** has *passive shielding*, while **SABRE South in SUPL** has an *active veto* with liquid scintillator.
- Dual-site experiment allows for better discrimination of seasonal backgrounds







SABRE: a dual site experiment

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 to background rejection and particle identification.

SABRE South: a brief history

- A SABRE South experiment and the need for a deep underground site was **first considered in 2014**.
- **First funding** for development was provided **in 2015** (from Federal Government and State of Victoria).
- **Construction of** the Stawell Underground Physics Laboratory (**SUPL**) **began in 2016** in the Stawell Gold Mine (SGM), but then the mine was closed by the owners.
- SGM reopened by new highly supportive owners in 2017. **SUPL construction restarted in 2019** and was completed in August 2022.
- Funding for SUPL: $6.75m from Federal Government, $6.75m from the State Government of Victoria, $2m from the U of Melbourne, and very generous in-kind contributions from Stawell Gold Mine and North Grampians Shire Council. **Total funding for SUPL approx. $15.5 million**.
- SUPL was founded by its partners who also fund its operations: U Melbourne, ANSTO, Adelaide U, ANU, Swinburne U. In 2025 U Sydney was added.
- **SABRE South experiment** development and construction **funded by a series of ARC grants**: LP150100705, LE160100080, LE170100162, LE190100196, LE250100018. *(A tough way to manage a 15 to 20-year project)*.
- **Also supported by CDMPP** (ARC CoE for Dark Matter Particle Physics) (CE200100008) - funded in 2020 for 7 years.

SUPL - Stawell Underground Physics Laboratory

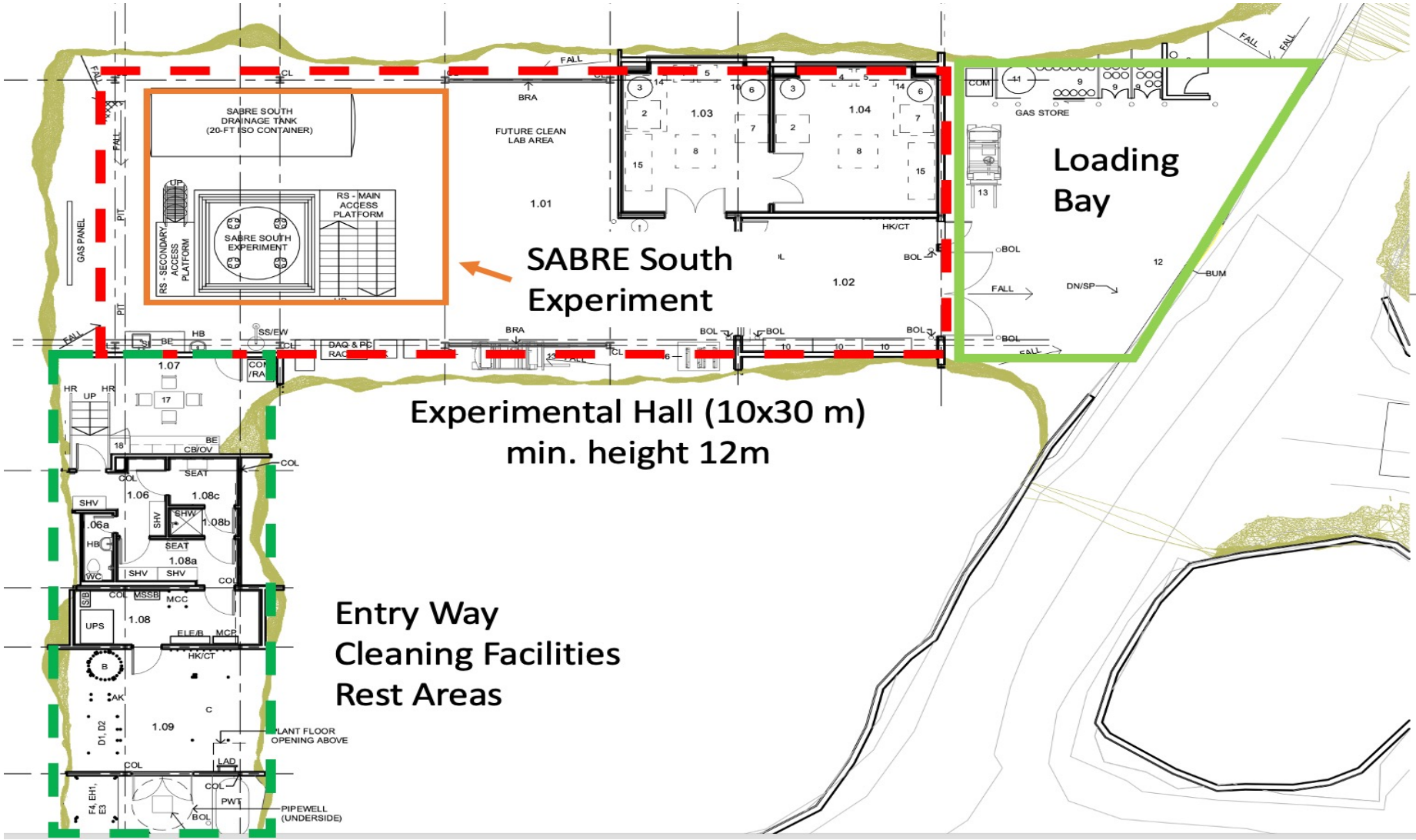
- First deep underground laboratory in the Southern Hemisphere, completed August 2022. First access in Feb 2024.
- 1025 m deep with flat overburden (2900 m water equivalent)
- Located in Stawell Gold Mine, 240 km west of Melbourne
- Helical drive access in an operating gold mine
- SABRE South is SUPL's flagship experiment
- Virtual tour can be found here: Virtual Tour - Stawell Underground Physics Lab



STAWELL UNDERGROUND PHYSICS LAB



SUPL - Stawell Underground Physics Laboratory





Anthony G. Williams - SABRE South Experiment – FPSP 2026

SABRE (Sodium iodide with Active Background REjection) South

The SABRE South technical design report executive summary, E. Barberio et al [2025 JINST 20 T04001]



Feedthrough plate

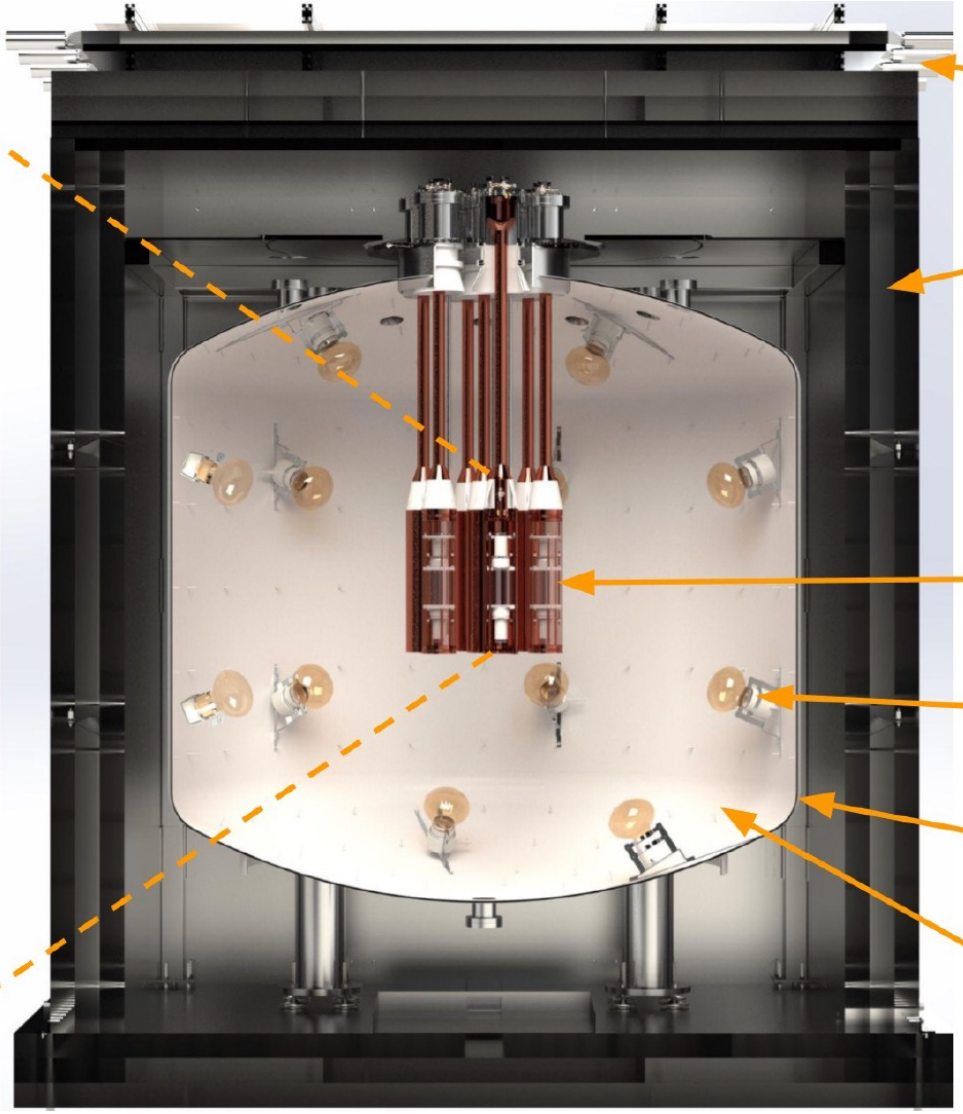
OFHC Cu enclosure

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 → Increased to 32

Veto vessel filled with 10T of LAB from JUNO doped with PPO (3.5 g/L) and Bis-MSB (15 mg/L)

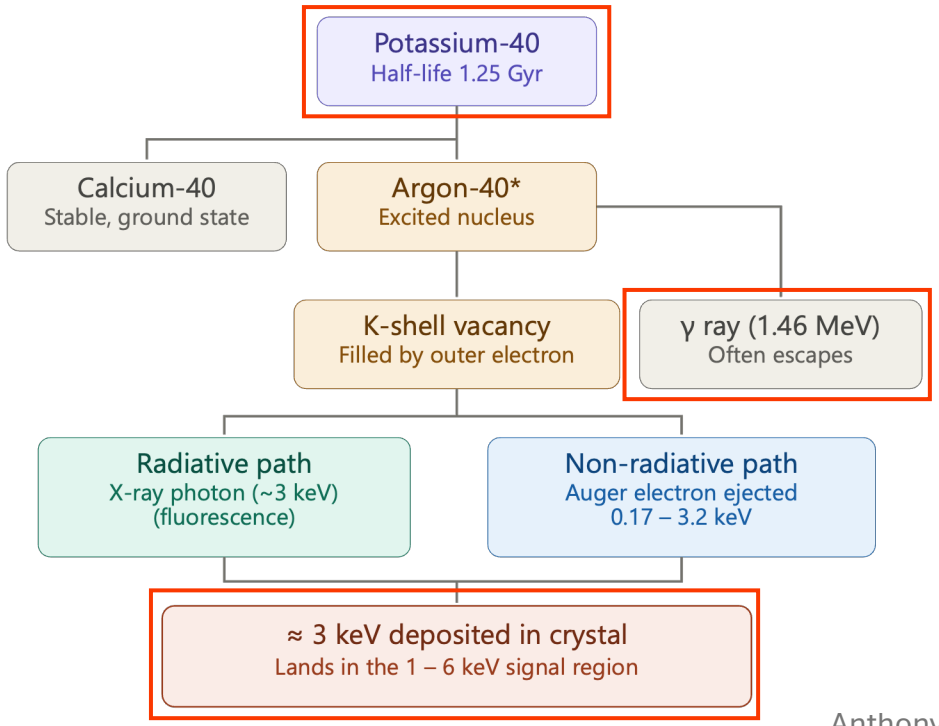
Reflective lumirror coating

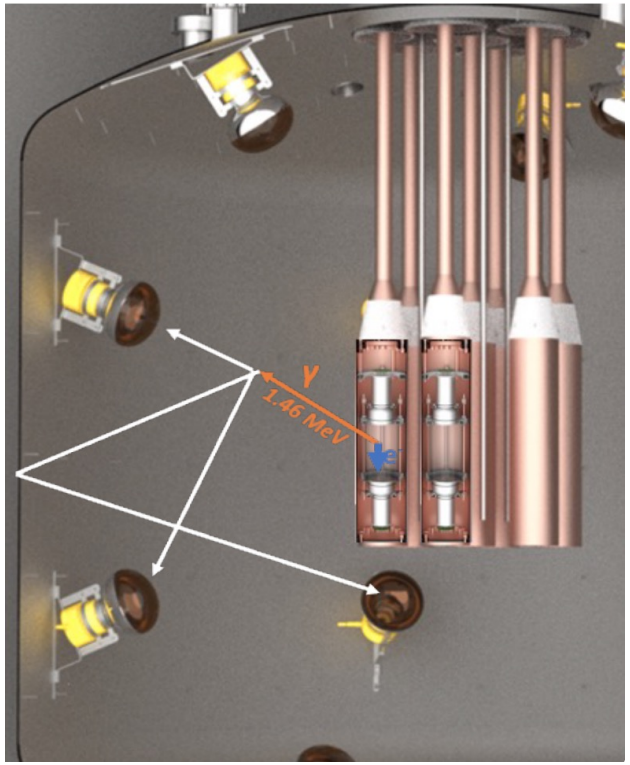
Active Liquid Scintillator Veto

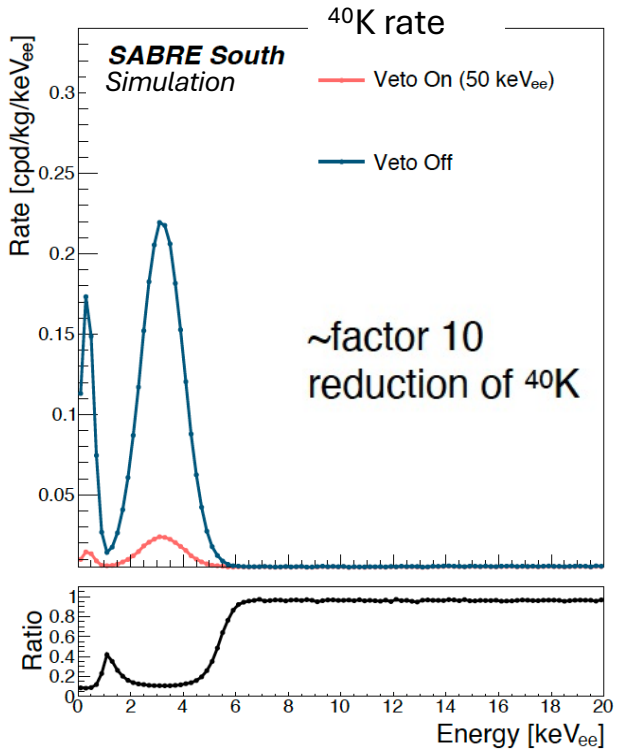
- 12 kL of linear alkyl benzene (LAB), procured from JUNO, doped with PPO and bisMSB (reduces light absorption & shifts UV to visible to maximize light yield).
- Average number of observed photoelectrons (PE) in LAB is ~0.75/keV, photon attenuation > 20m.
- 18 (+14 from Daya Bay) R5912 oil-proof PMTs sampled at 500 MS/s to resolve pulse shape.
- Efficient tagging of secondary particles created in the decay process in- and outside the crystal modules.

JINST 20 T04001 (2025)

Eur. Phys. J. C (2023) 83:878





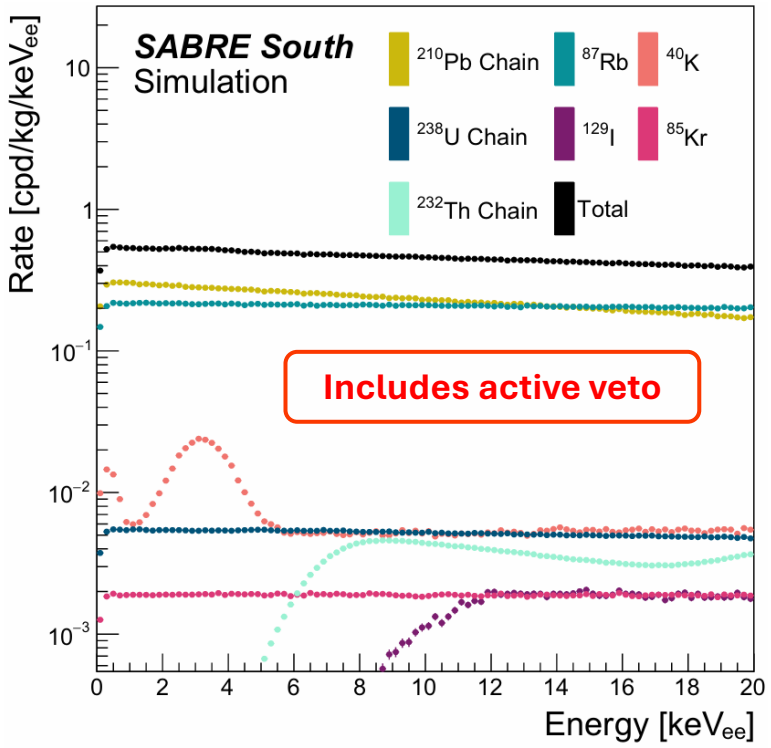


Expected Background

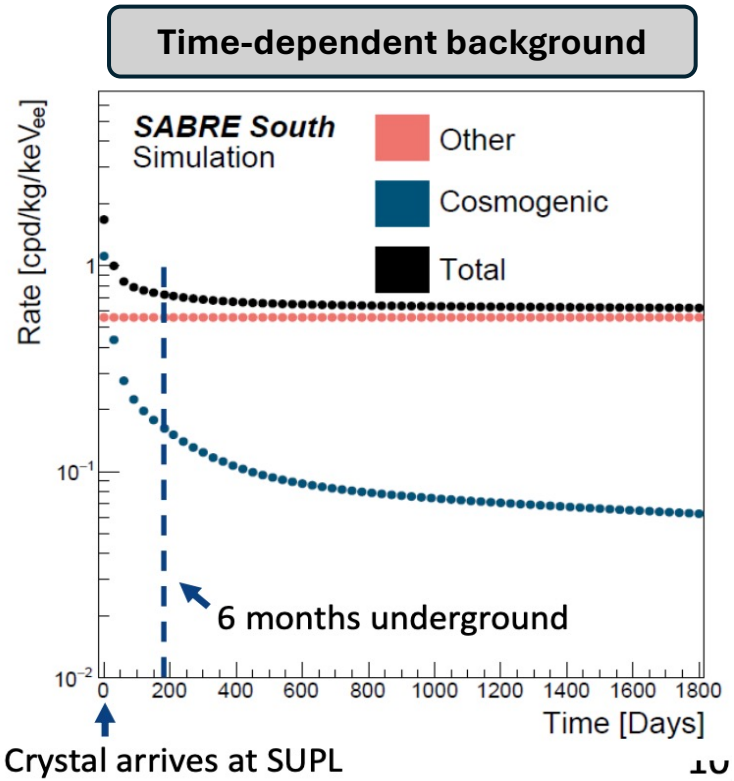
Eur. Phys. J. C (2023) 83:878

- Assuming a 6-month cooldown for cosmogenic backgrounds, the expected SABRE South background is **0.72 cpd/kg/keVee** in the 1-6 keV region.
- 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).

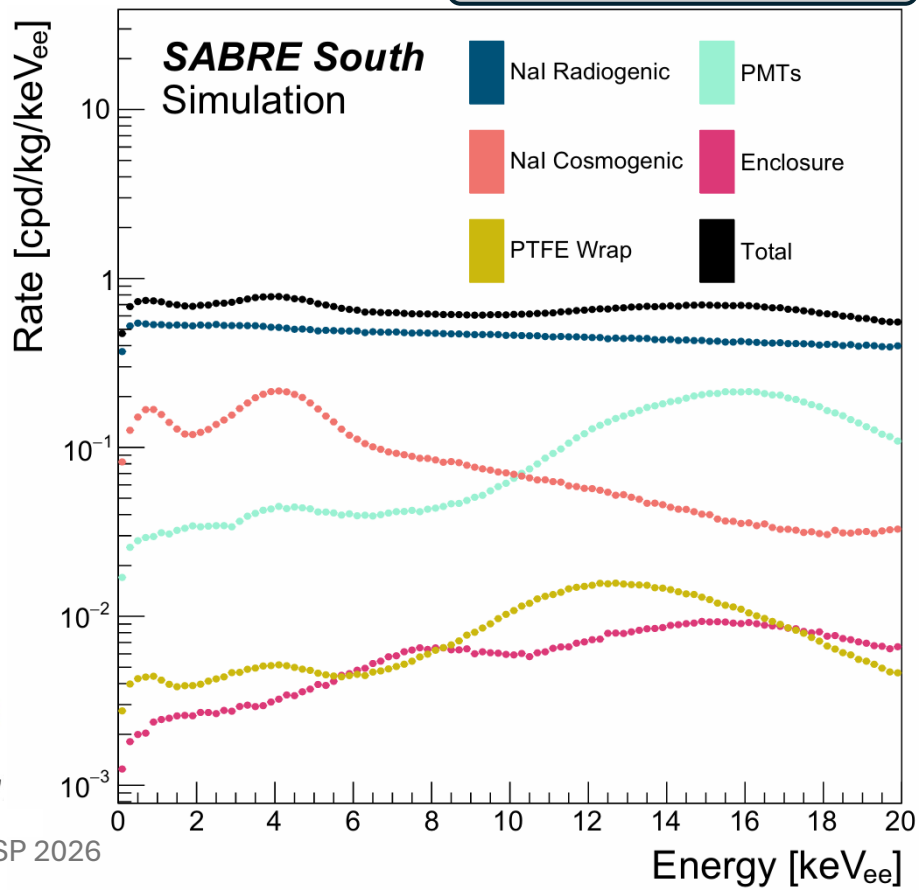
Intrinsic crystal background



Time-dependent background

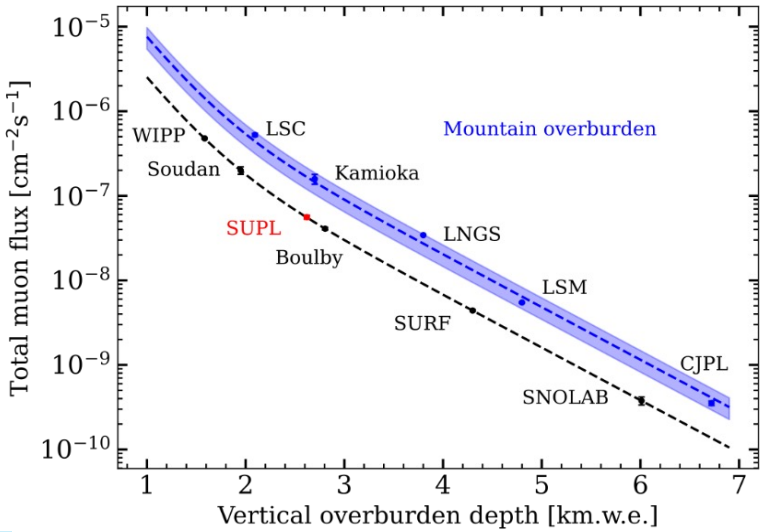


Total background



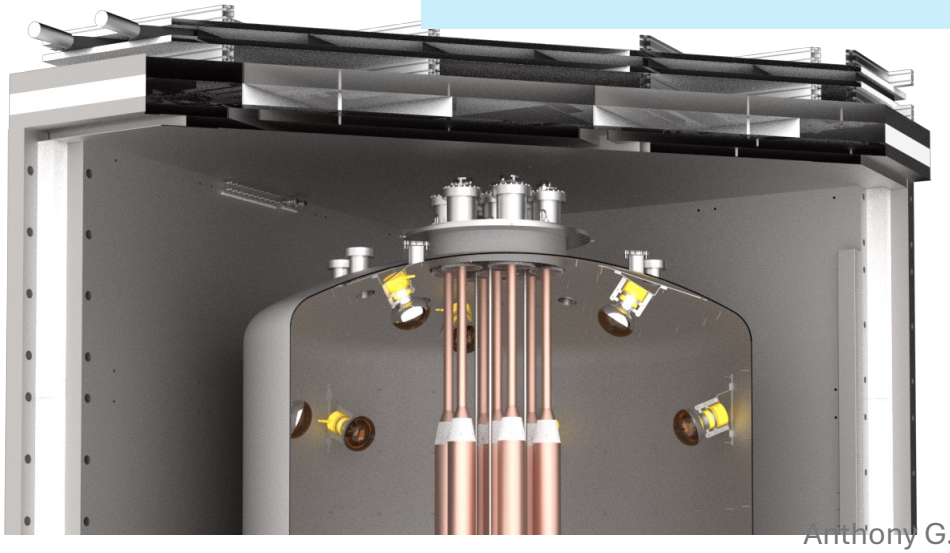
Muon Detector System

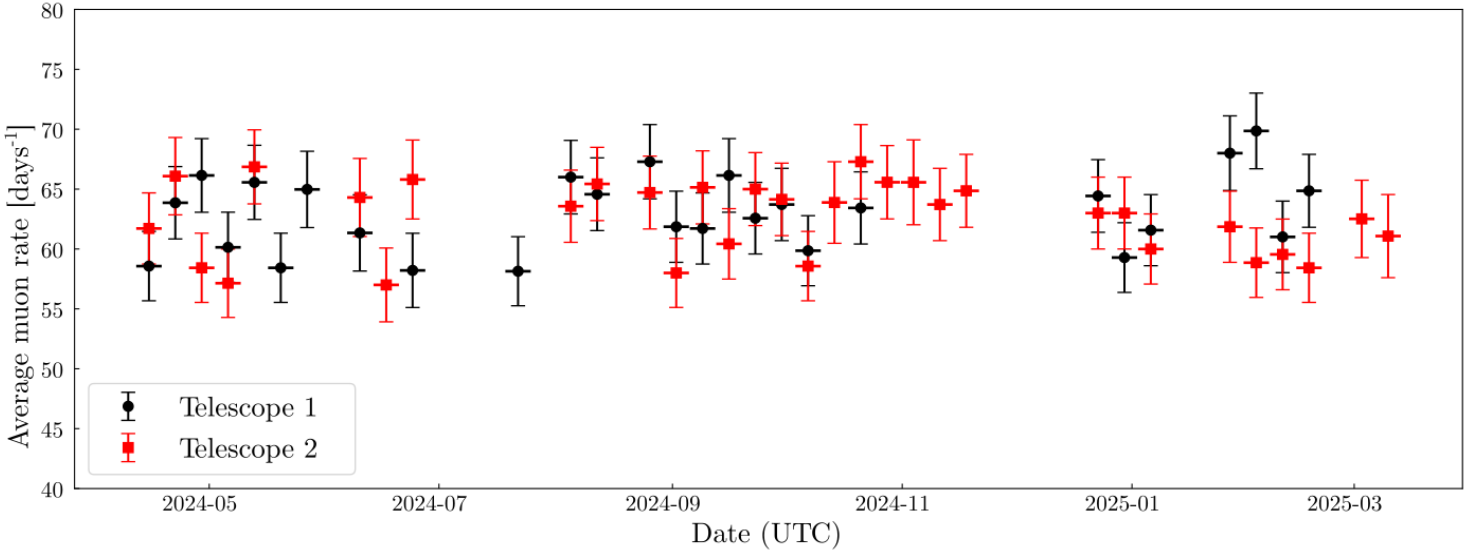
- Tags muon-induced events
- 8 x 1.2m^2 x 5cm EJ200 plastic scintillator panels
- 16 R13089 PMTs (two per panel)
- First physics result from SUPL:
  Measurement of the cosmic muon flux using the SABRE South muon veto system





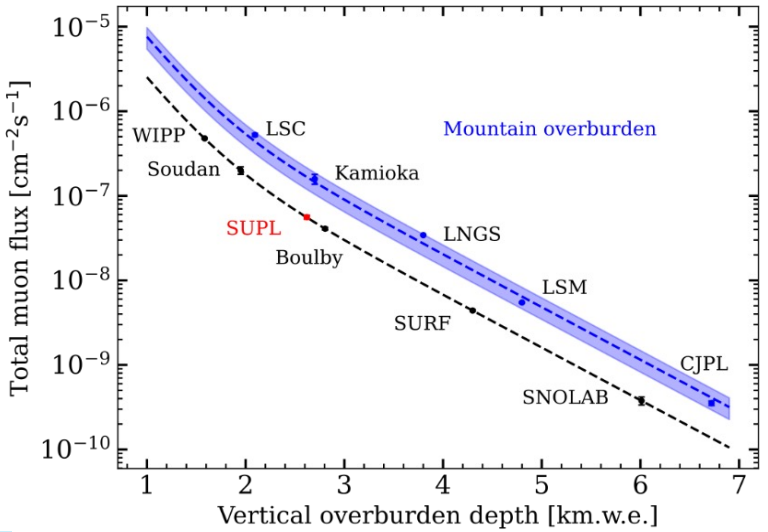
J. Astropart. Phys 2026.103240





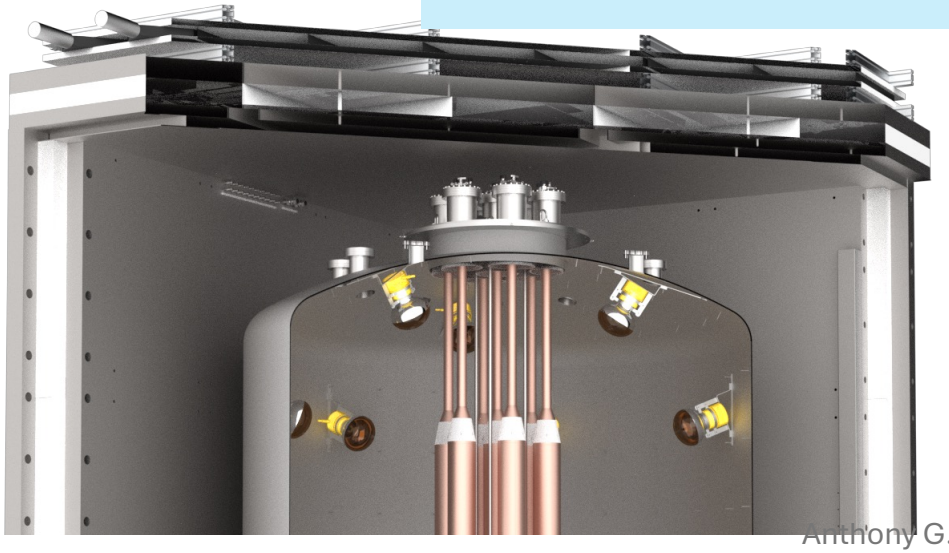
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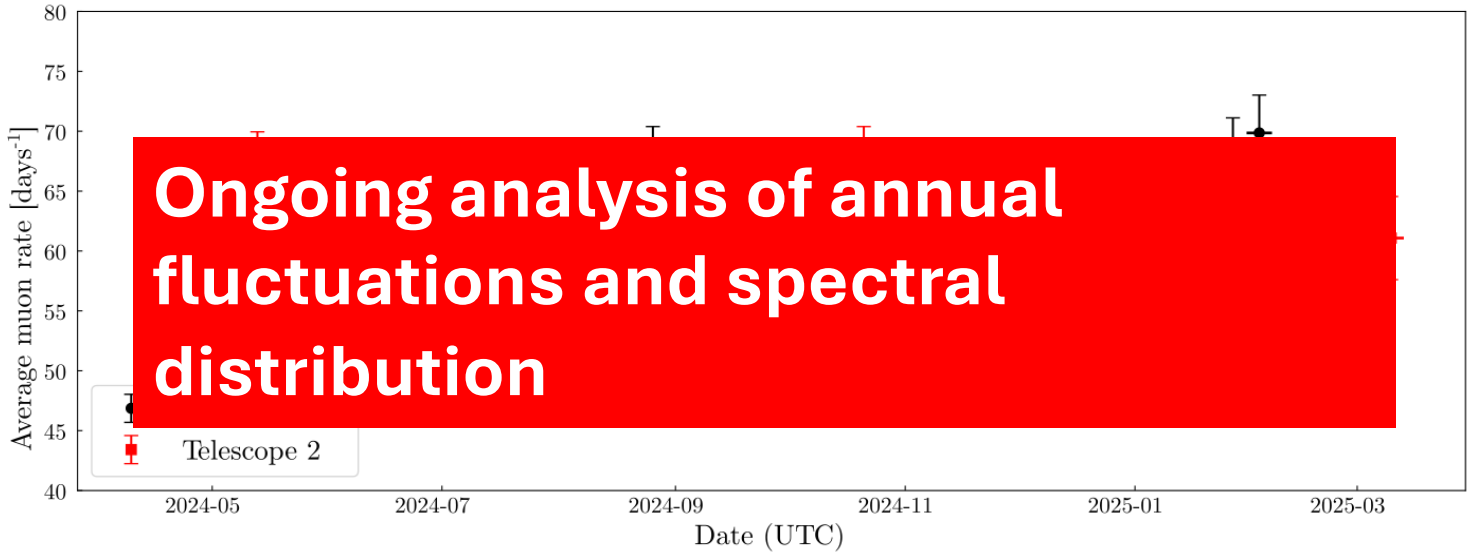
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J. Astropart. Phys 2026.103240





Ongoing analysis of annual fluctuations and spectral distribution

PMTs & Crystals

Crystal PMTs

- *Low energy region at 1-3 keVee affected by **PMT noise** (potentially time-dependent background)*
- *Developed **Boosted Decision Tree based (BDT) noise rejection (using measured pulse shape)** to discriminate thermionic noise from genuine low-energy crystal events**

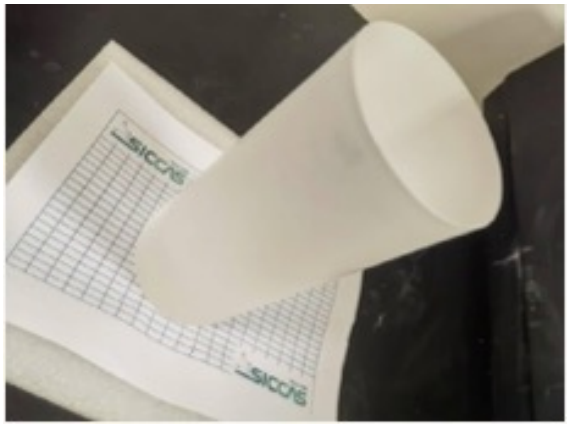


Veto PMTs

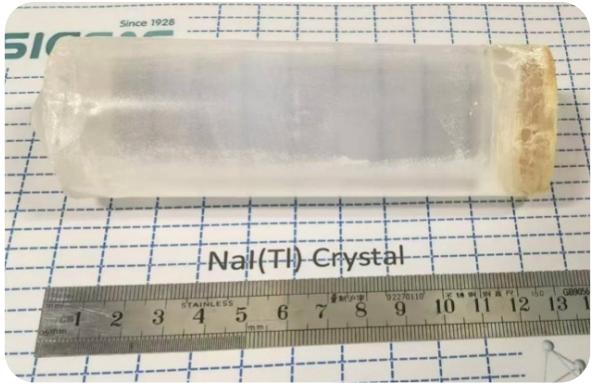
- ***50 keVee veto threshold** demonstrated for background discrimination with LAB veto***



Full characterisation
**JINST 20 P07052 (2025)*
***JINST 20 T04001 (2025)*



Mech. test crystal
*6.68 kg NaI(Tl) **crystal (SICCAS)** to be brought underground for **enclosure assembly tests and** cleaning procedure validation*

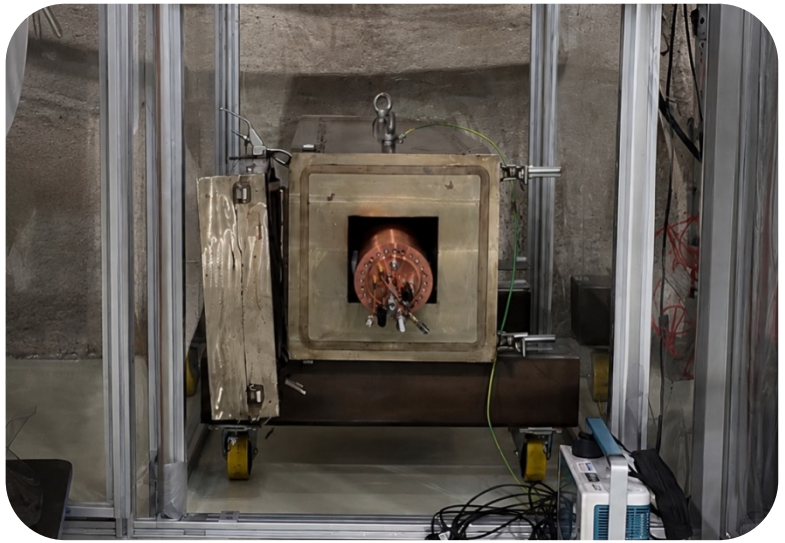


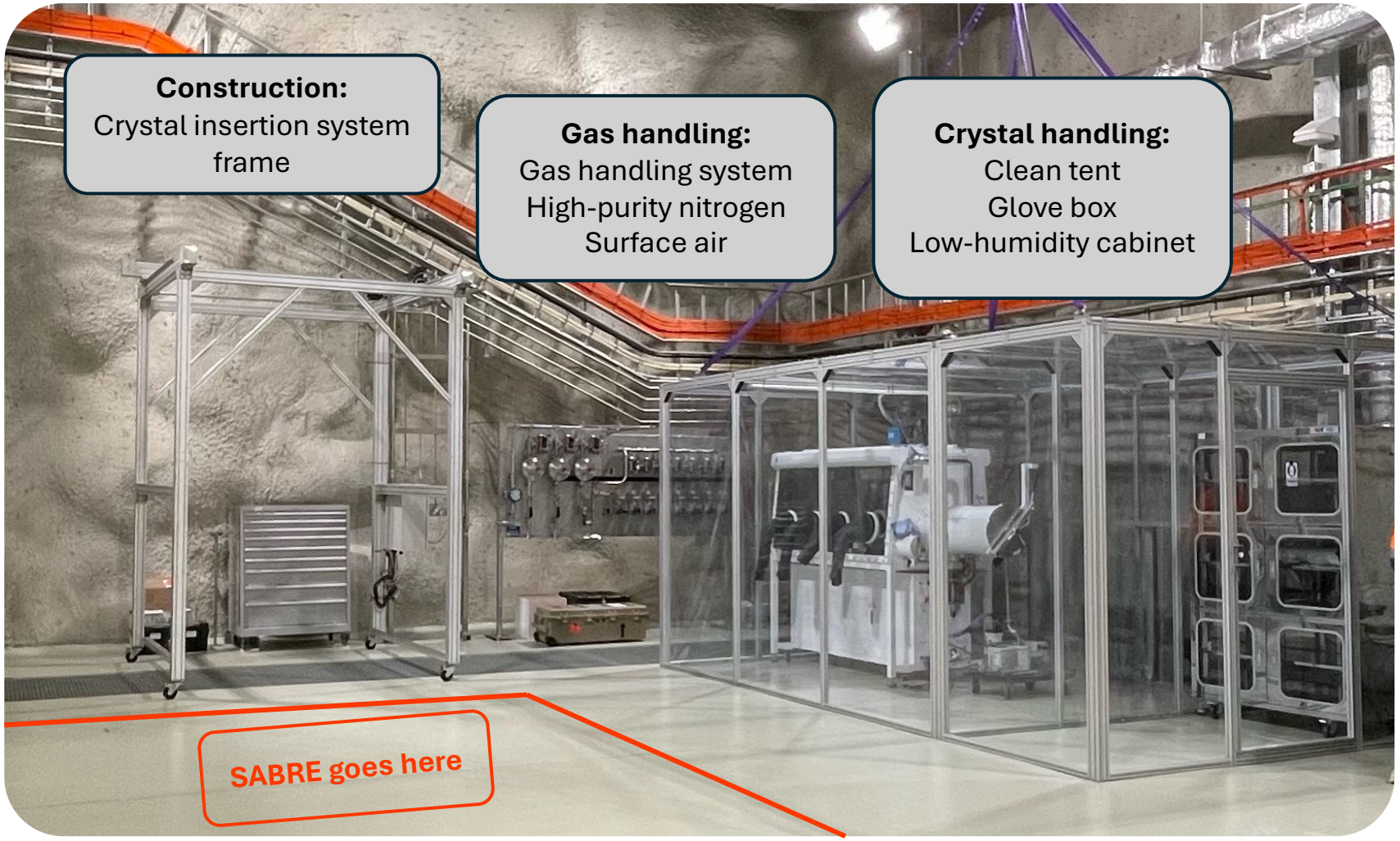
Astrograde crystals
*2x 0.5 kg Astrograde NaI(Tl) crystals will undergo **chemical and mechanical polishing** respectively to study impact on 210Pb surface contamination*

- **Recently shipped 20kg of NaI Astrograde powder to SICCAS to commence production**

Infrastructure

Testing:
Test crystal, inside copper enclosure
Steel castle for passive shielding





Ongoing tests



Tests of mounting and assembly of veto PMTs



Tests of Lumirror mounting and cabling inside the vessel



Test assembly of steel shielding and vessel fit-test

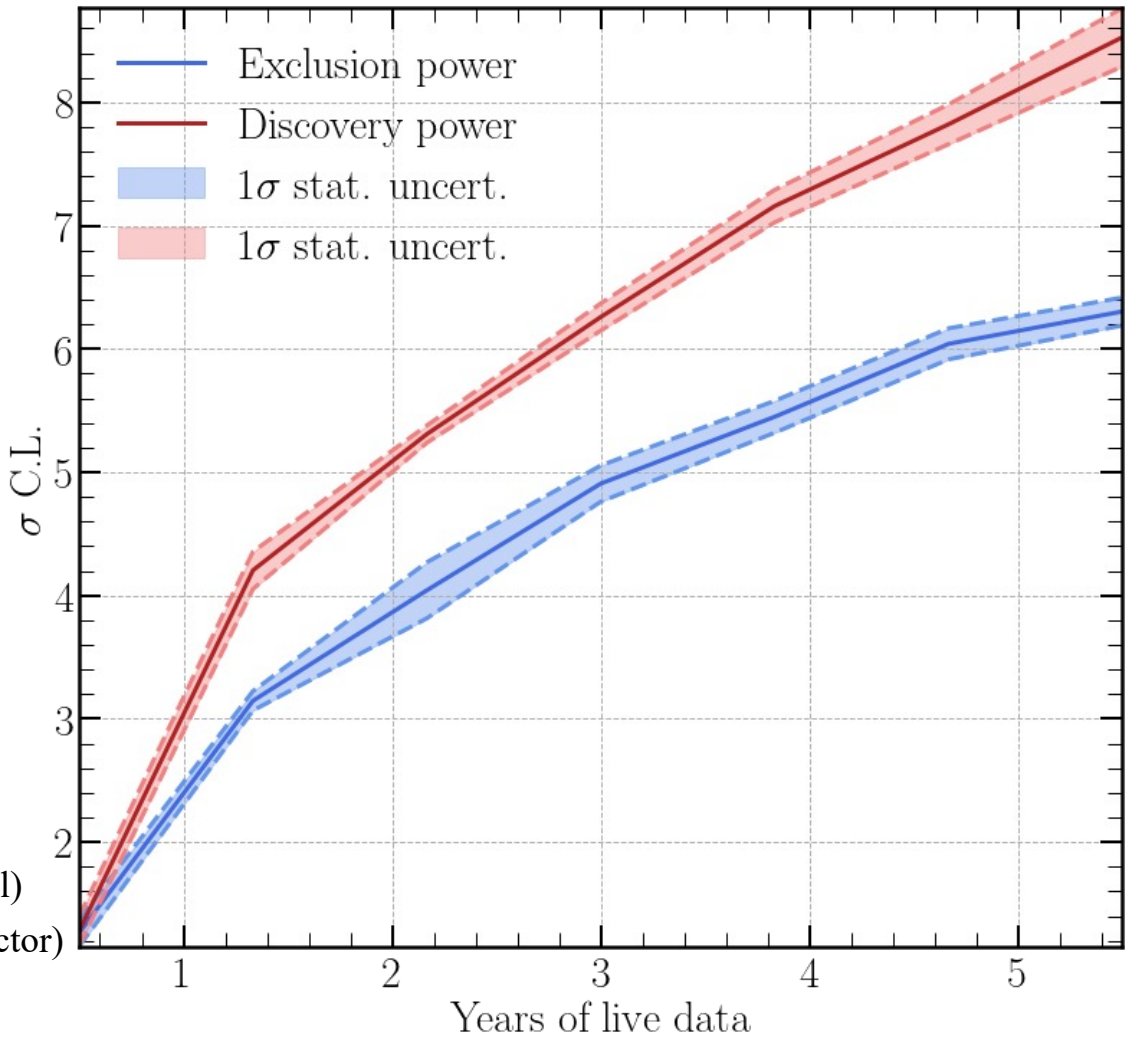
Sensitivity

For a DAMA/LIBRA-like modulation, we project:

- 3σ exclusion within 1.5 years, 5σ within 3 years
- 3σ discovery power within 1 year, 5σ in 2 years

Sensitivity improves over time as cosmogenic backgrounds decay.

Parameter	Value
Light yield (Crystal)	11.1 ± 0.2 PE/keV (PE = photoelectron)
Energy resolution	13.2% (FWHM/E) at 59.5 keV
Crystal energy threshold	1 keV (can access ROI, ≥ 1keV)
Veto energy threshold	50 keV (easily detects 1.46 MeV ^{40}K **γ**-ray)
Total active mass	≈ 50 kg (seven 7 kg crystals)
Background rate (PoP)	0.36 cpd/kg/keV (SABRE North, 1 crystal)
Background rate (South)	0.72 cpd/kg/keV (SABRE South full detector)

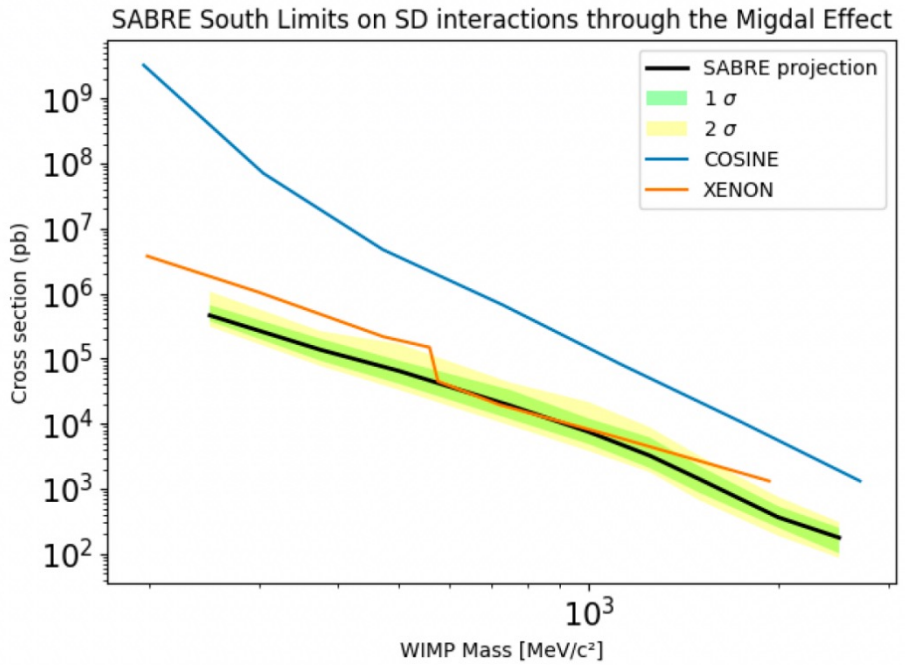


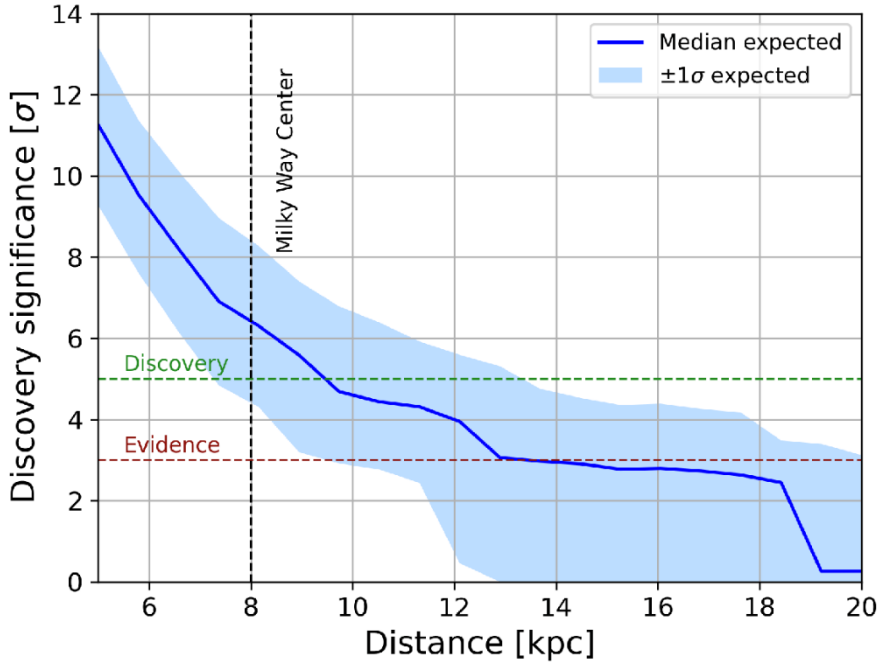
Physics beyond the annual modulation search

Preliminary sensitivity studies performed on

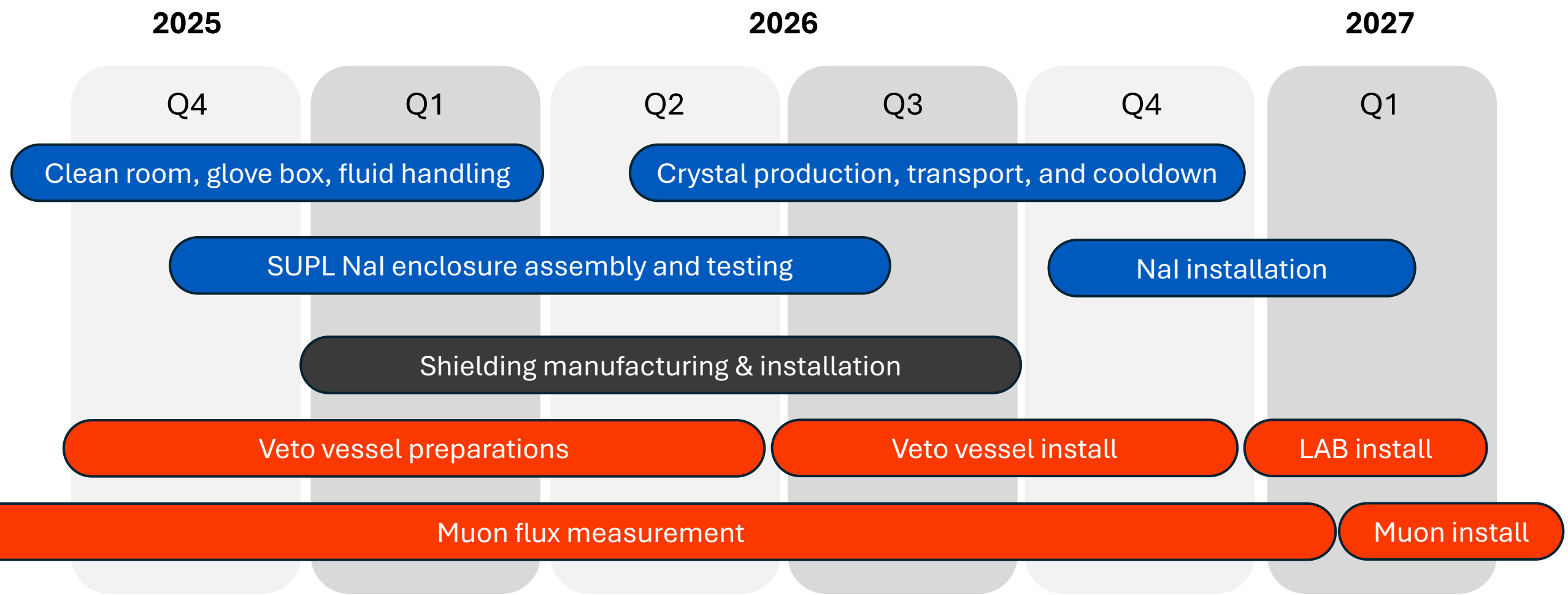
- Migdal effect (all SABRE target nuclei have spin, so sensitive to spin-dependent DM interaction, whereas half of Xenon isotopes have no spin. Also Na is lighter and so more sensitive to light DM Migdal-type signals).
- Bosonic super-WIMPs (entire rest mass energy of boson deposited in the detector).
- Some sensitivity to (very nearby) supernova neutrinos – yielding the possibility that SABRE South could join a Supernova Early Warning System (SNEWS).

The SABRE South technical design report executive summary, E. Barberio et al 2025 JINST 20 T04001





Timeline


2025
2026
2027
Q4
Q1
Q2
Q3
Q4
Q1
Clean room, glove box, fluid handling
Crystal production, transport, and cooldown
SUPL NaI enclosure assembly and testing
NaI installation
Shielding manufacturing & installation
Veto vessel preparations
Veto vessel install
LAB install
Muon flux measurement
Muon install

Summary

- **SABRE South is fully funded and currently under** construction at SUPL.
- **Focus on ultra-high-purity NaI(Tl) detectors**: strong progress on crystal production and low-background enclosures
- Mechanical **test crystal available** and 20k of astrograde powder recently shipped to SICCAS for first crystal production.
- Projected **total background: 0.72 cpd/kg/keV**.
- 120-tonne steel **shielding ready for installation**.
- **Access to SUPL has commenced**; muon detectors operational since February 2024.
- **Pre-calibration of PMTs** for crystal and veto systems **completed**; publications on JINST.
- **Gas handling, insertion system, and liquid scintillator veto ready for deployment**.
- **Ongoing development of software, DAQ, computing, and database systems**.
- Discovery or exclusion results expected **within two years of data taking** (from the SABRE South site).

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

The SABRE South technical design report executive summary, E. Barberio et al 2025 JINST 20 T04001

Acknowledgements

Crystals

RMD
A Dynasil Company

Since 1928
SICCAS

Screening

Science and Technology Facilities Council
Boulby Underground Laboratory

Australian Government
ANSTO

UCL

SABRE

South

Australian Government
Australian Research Council

Adelaide University

SWINBURNE

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

MACQUARIE University

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

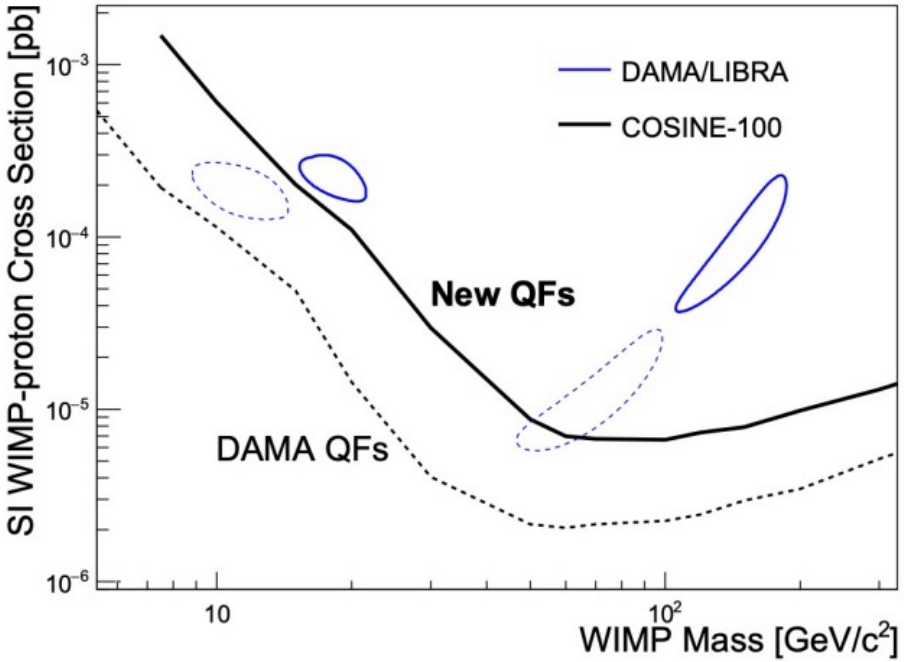
Veto LS & PMTs

Institute of High Energy Physics
Chinese Academy of Sciences

Extra Slides

Quenching Factor Impact

Can use results presented by COSINE [1] to understand how different QF combinations impact exclusion of DAMA

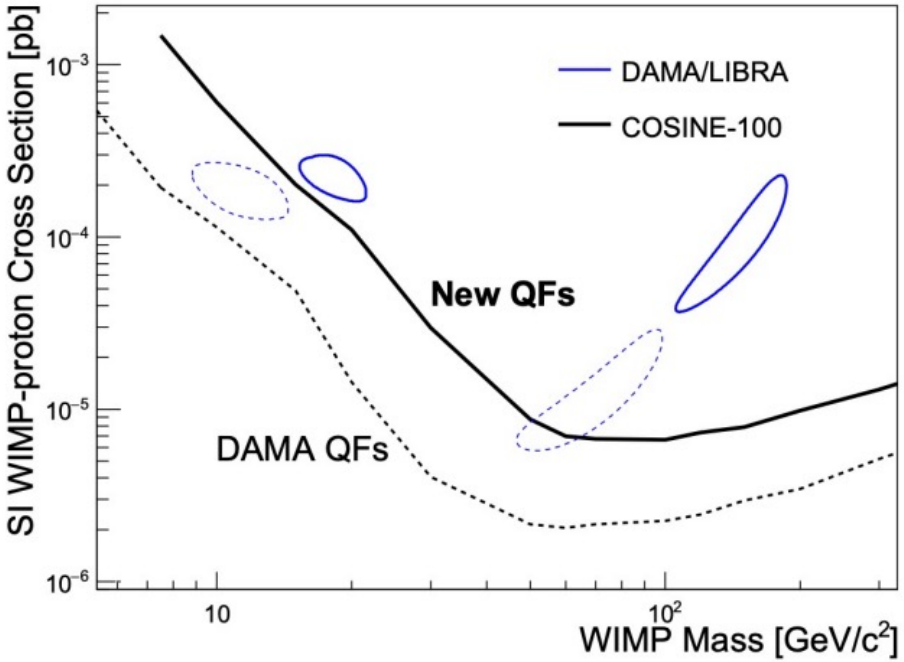


Assuming detectors have the same QF (either the solid or dotted lines)

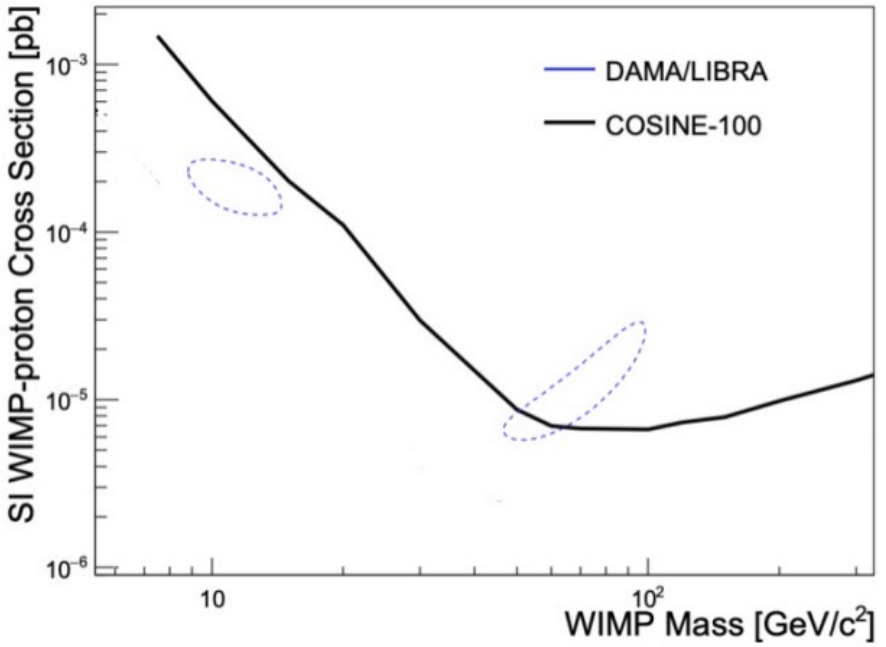
[1] Adhikari et al. JCAP 11 (2019)

Quenching Factor Impact

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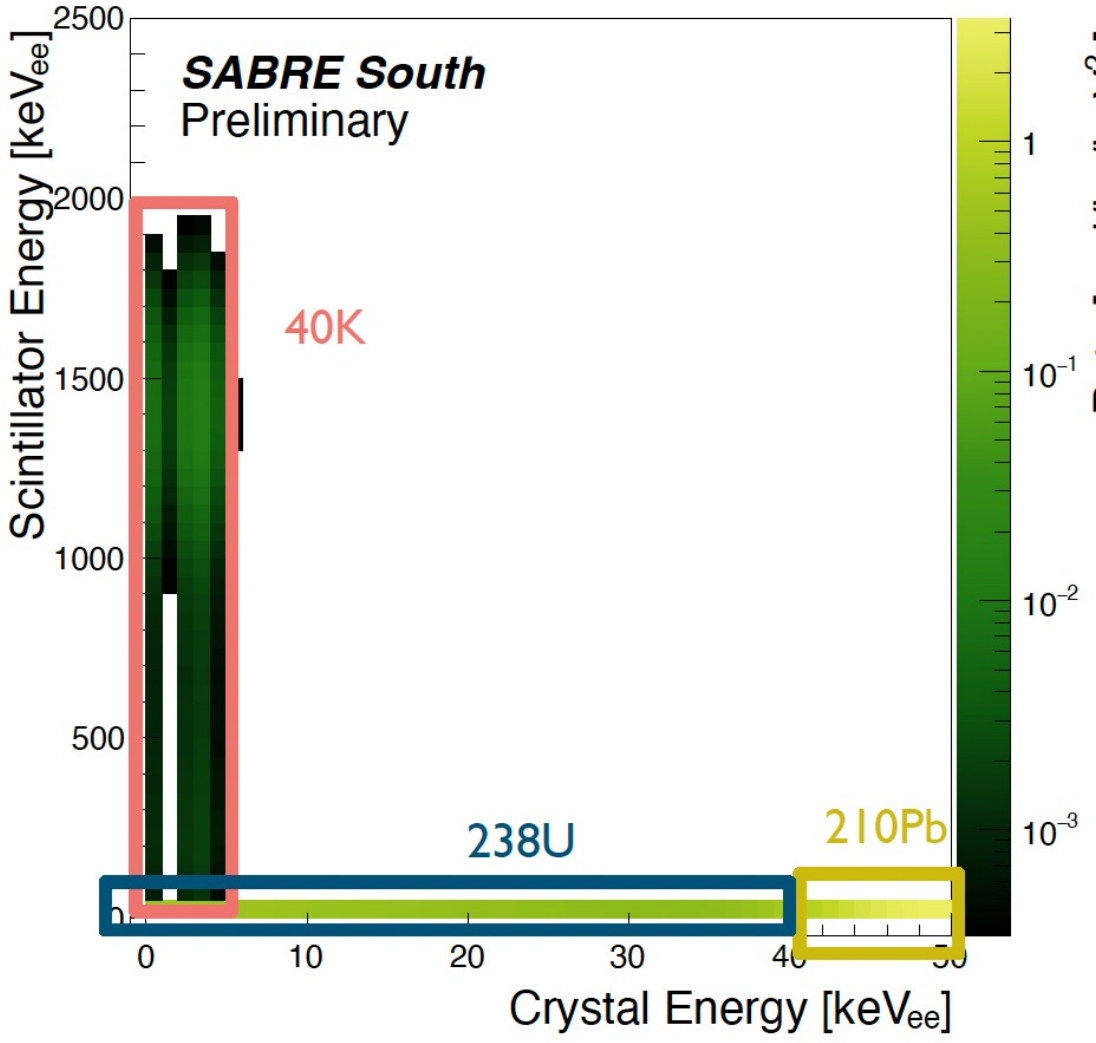


Assuming detectors have different QFs

[1] Adhikari et al. JCAP 11 (2019)

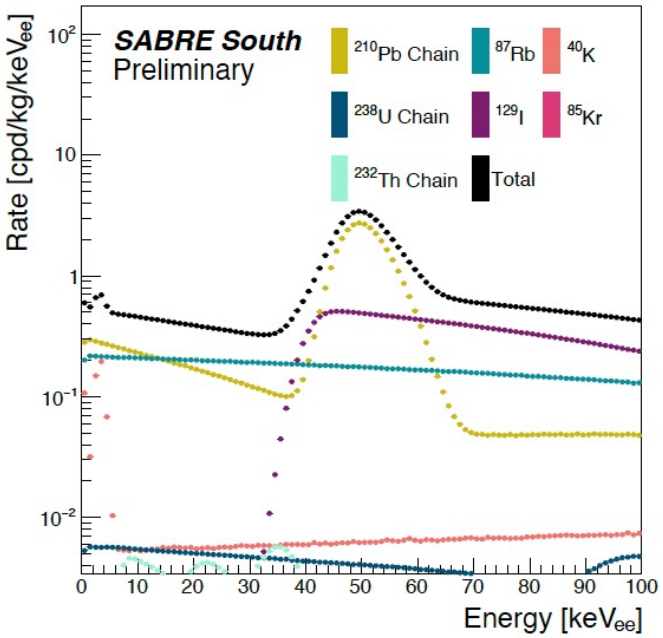
Intrinsic Radiation

SABRE Eur. Phys. J. C (2023) 83:878

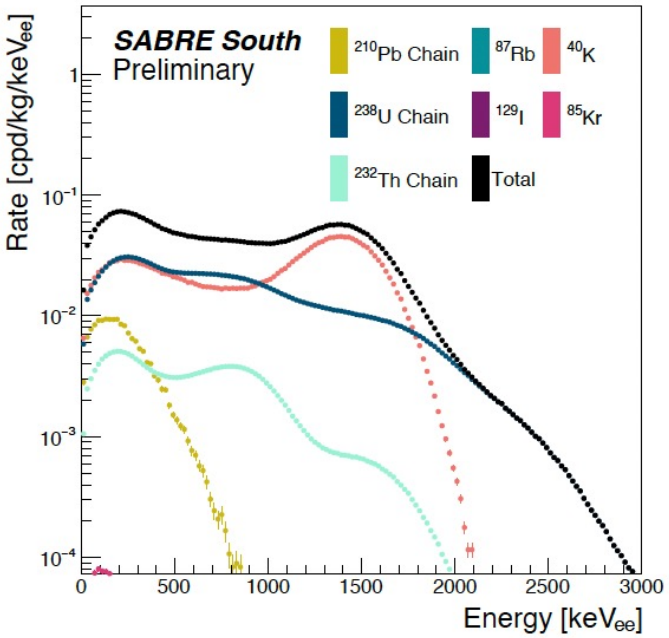


Contamination from intrinsic radiation of crystals

Deposition in crystal

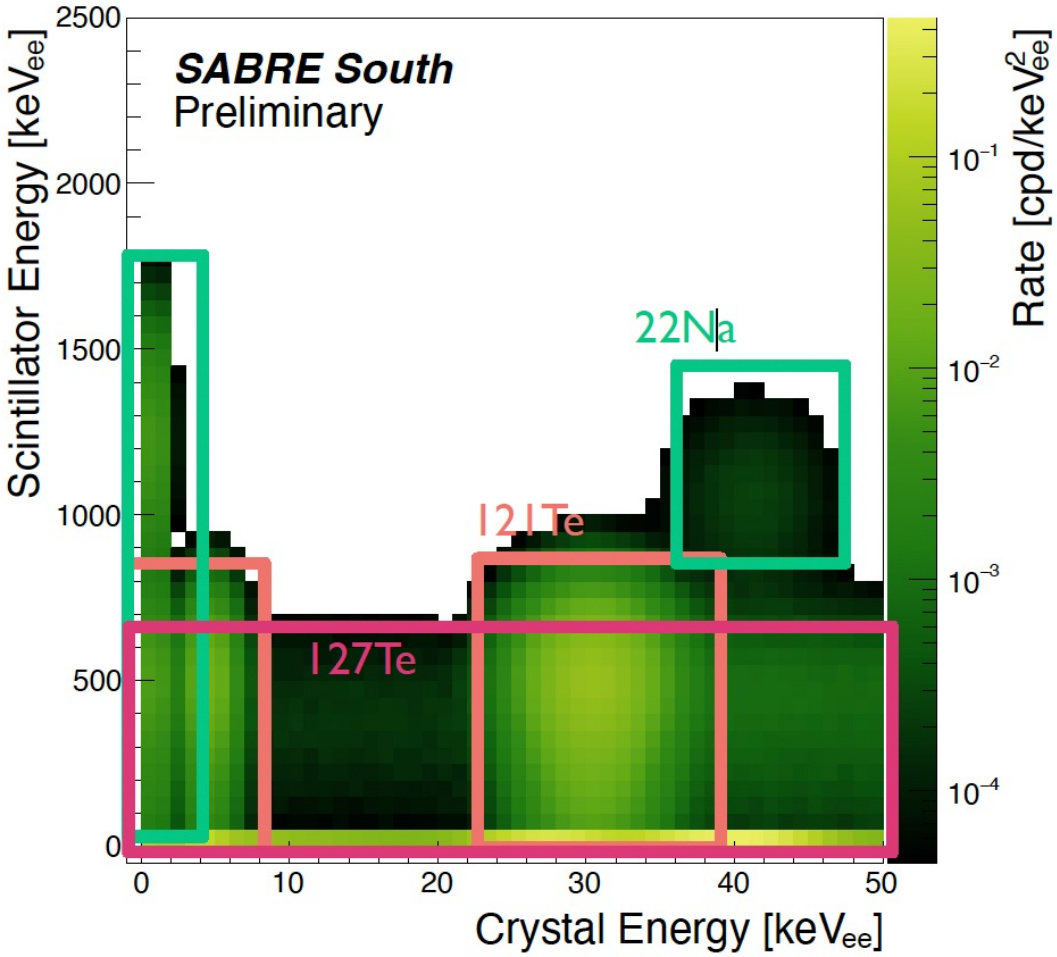


Deposition in veto



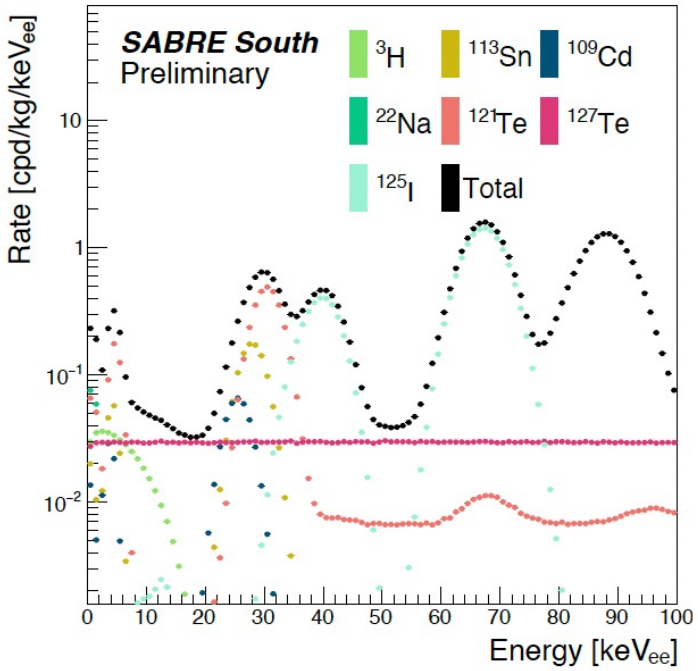
Cosmogenic activation

SABRE Eur. Phys. J. C (2023) 83:878

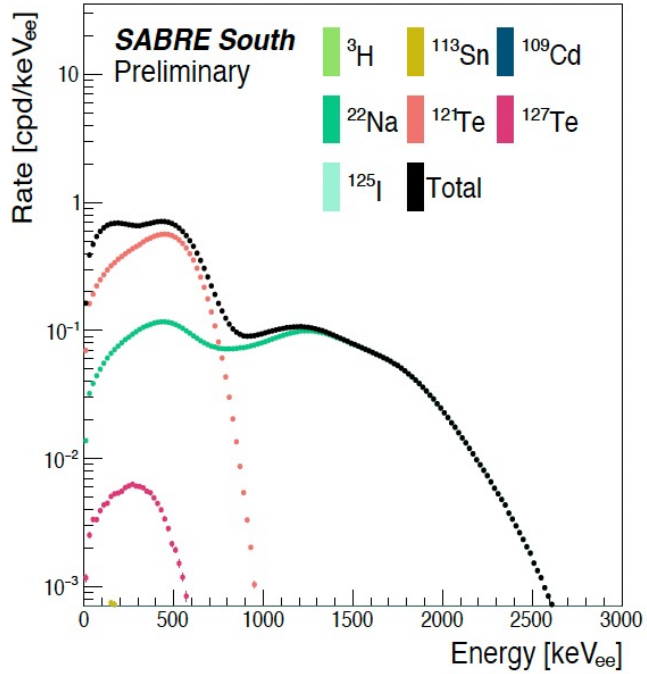


Contamination from cosmogenic activation of crystals

Deposition in crystal



Deposition in veto

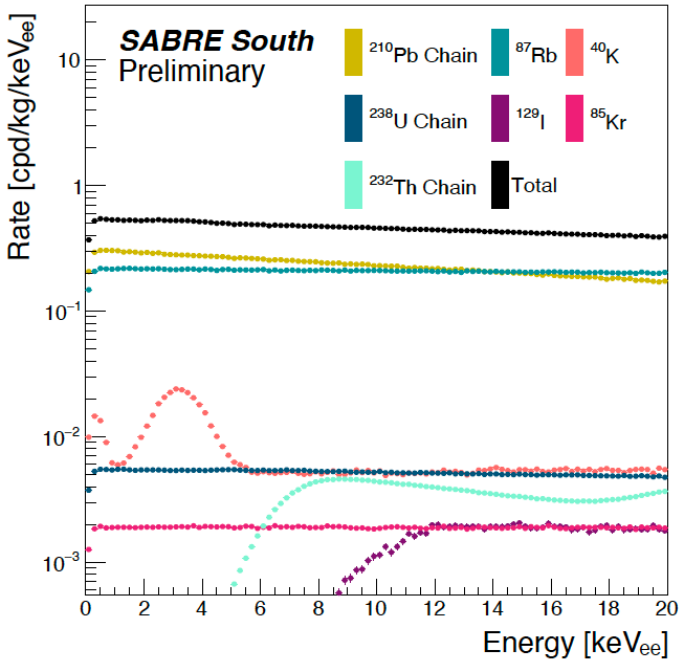


NaI(Tl) Background Simulations

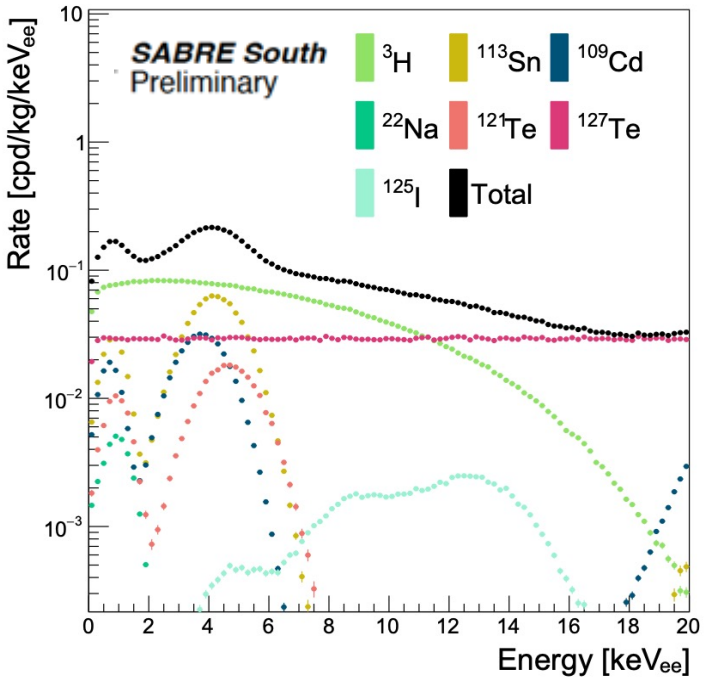
- Background of SABRE South crystal have been both simulated and directly measured (on NaI-33) with Inductively coupled plasma mass spectrometry (ICP-MS).
- Main radiogenic background represented by ^{210}Pb, ^{87}Rb (very conservative upper limit). No ^{87}Rb was found with the ICP-MS measurement, and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

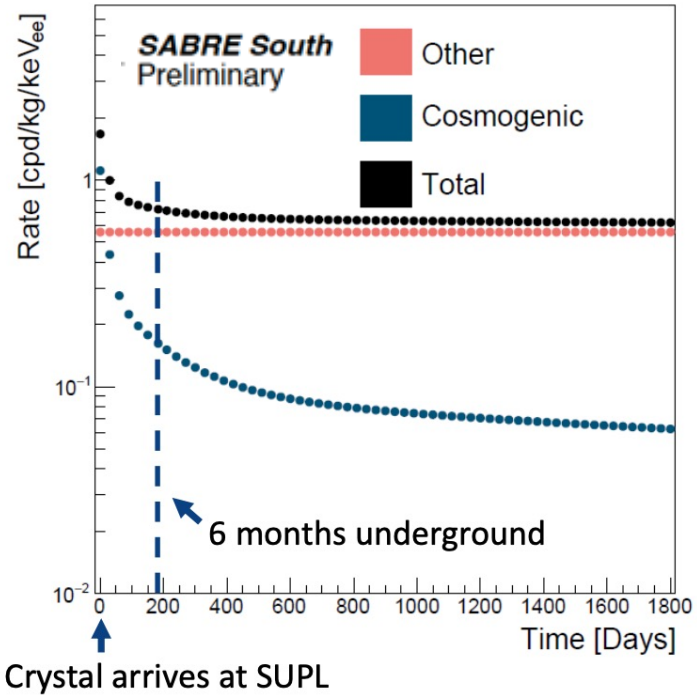
Radiogenic Background



Cosmogenic Background
(6 months underground)



Time Dependence of Background



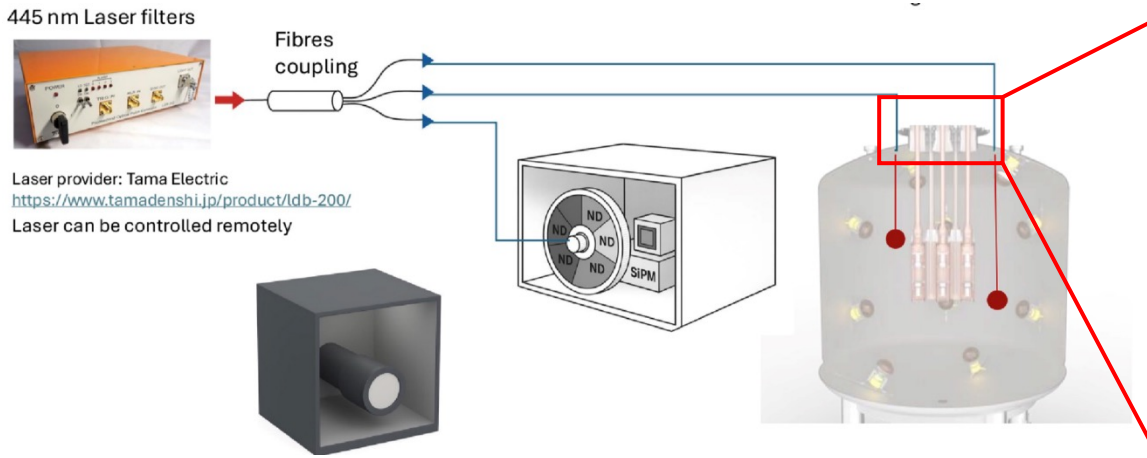
SABRE CALIBRATION SYSTEMS

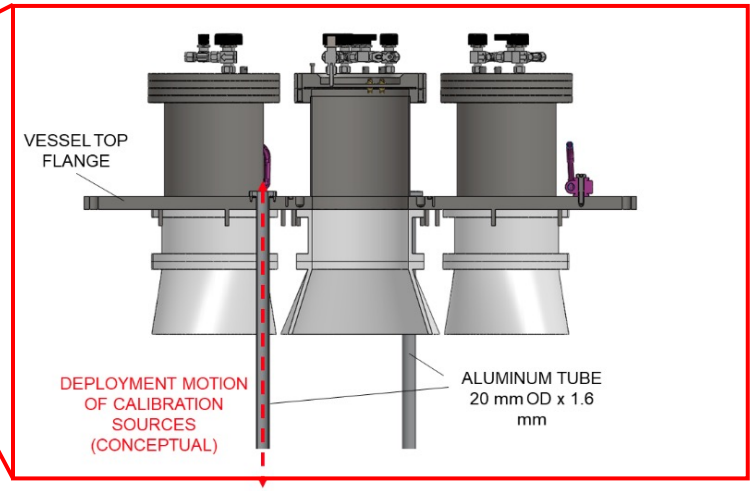
Optical calibration

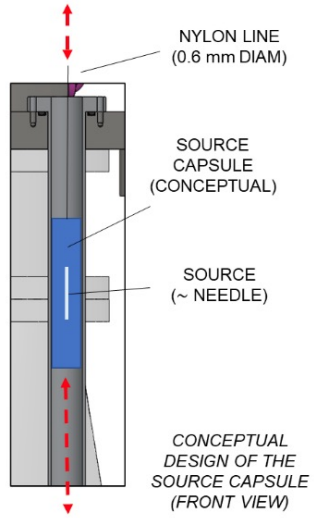
- Laser balls permanently lowered into LAB on optical fibres
- Successfully tested and procurement is ongoing

Radioactive calibration

- Automatic deployment of various radioactive sources into the veto vessel
- Available sources: ^{137}Cs, ^{207}Bi, ^{22}Na, ^{241}Am, and ^{109}Cd

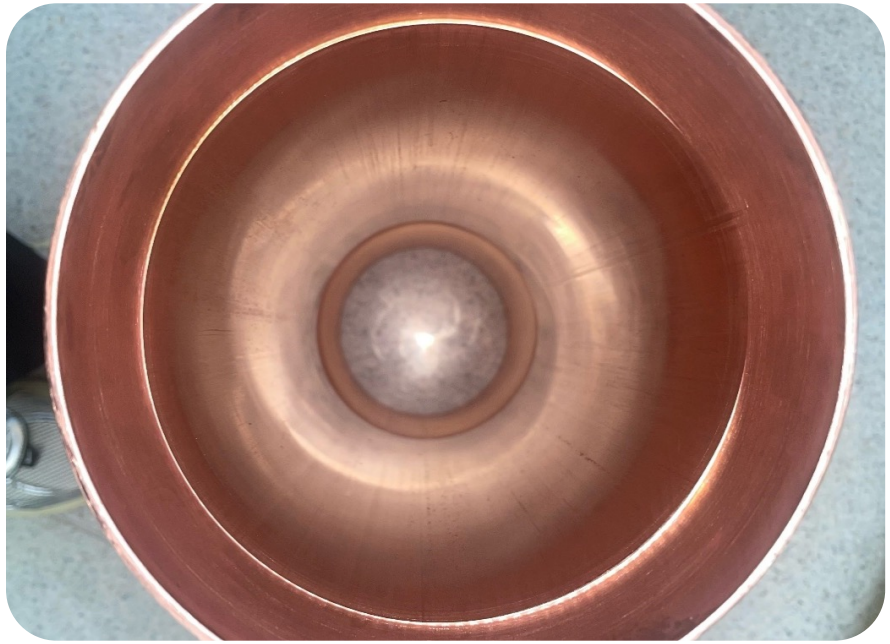






PRECISION CLEANING

- Workflow developed for copper enclosures and PTFE components
- Cleaning of veto PMT brackets
- Crystal PMT and base cleaning procedures under assessment
- Industry engaged for veto vessel cleaning





DAQ & CONDITIONS

Muon detector:
1x V1743, 16-channel, 3.2 GS/s, 12-bit ADC

Crystal detector

2x V1730, 8-channel, 500 MS/s, 14-bit ADC

Liquid detector

1x V2730, 32-channel, 500 MS/s, 14-bit ADC

