XIV International Conference on New Frontiers in Physics
17-31 July 2025, OAC, Kolymbari, Crete, Greece

Irene Bolognino

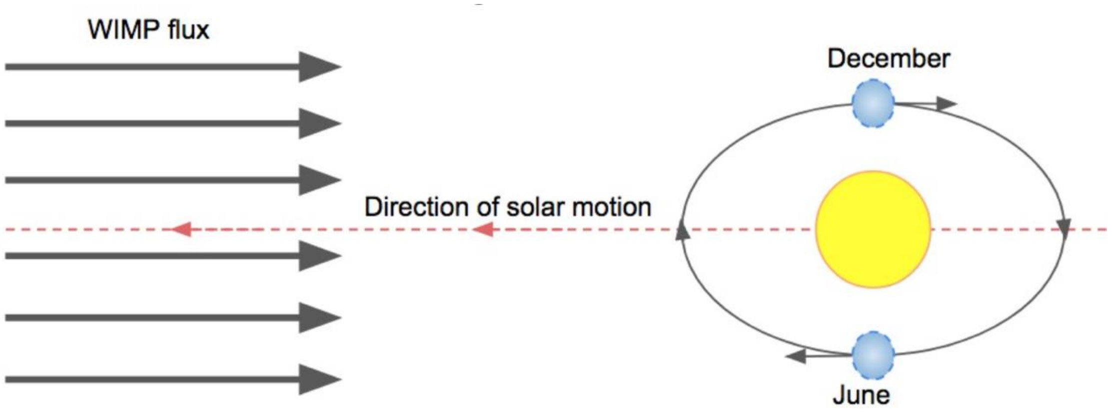
The University of Adelaide

ARC Centre for Dark Matter Particle Physics

INFN Milan

The SABRE South Experiment at the Stawell Underground Physics Laboratory

WIMP Wind– Annual Modulation Signal



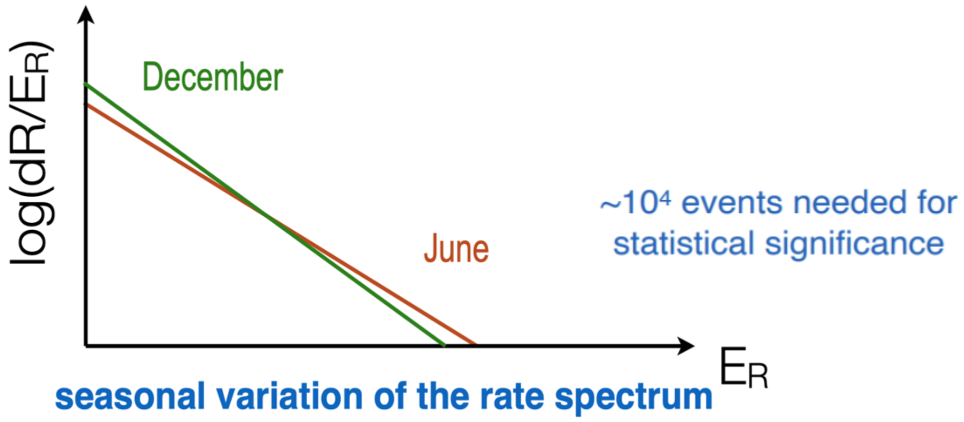
WIMP Rate $$\frac{dR}{dE_R}(t) = S_0(E_R) + S_m(E_R)\cos\omega(t - t_0)$$

Modulating component ~ 2-10% of R(t)

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 speed distribution

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

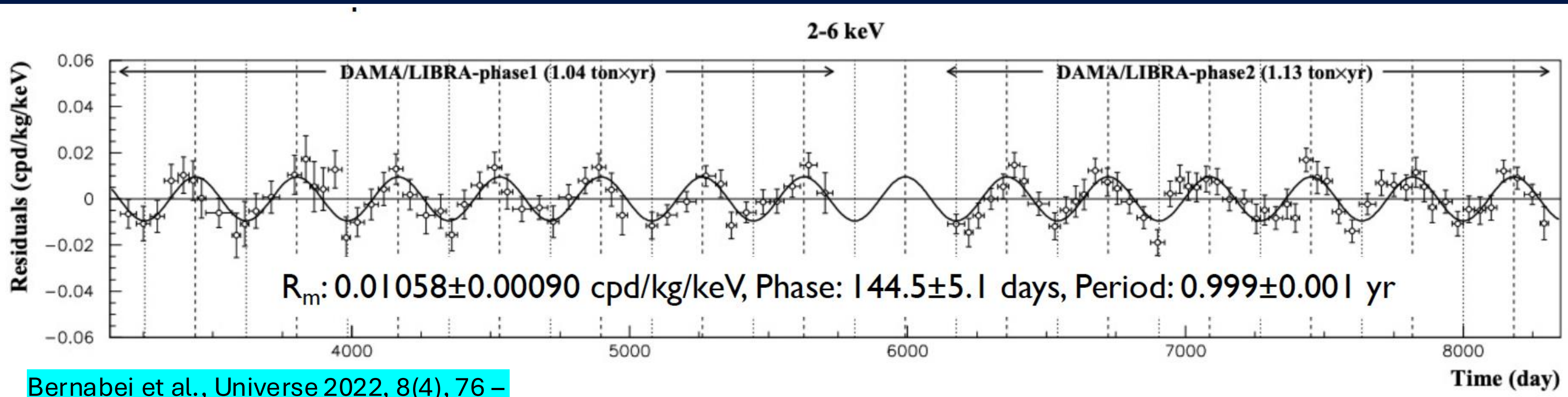


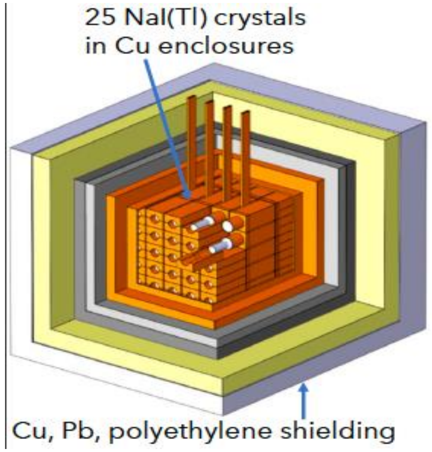
- Rare and low energy events.
- Low expected rate S_0 < 1 cpd/kg/keV (few% of which modulates, S_m).

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

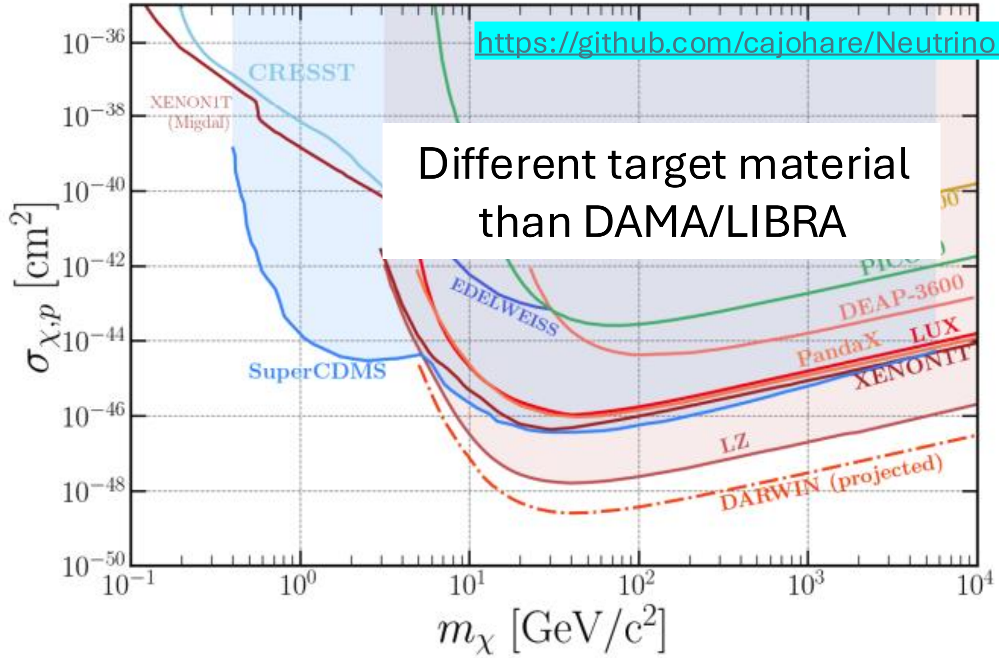
The control of modulating background is key

DAMA/LIBRA results





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



https://github.com/cajohare/NeutrinoFog

Different target material than DAMA/LIBRA

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.
- 13.7 σ significance.

Observation rates and detector dependence

Number of nuclear recoils as a function of nuclear recoil energy E_R

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

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

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

DM and target properties

- Target density
- Target mass
- DM density
- DM mass
- DM cross section

DM interaction model

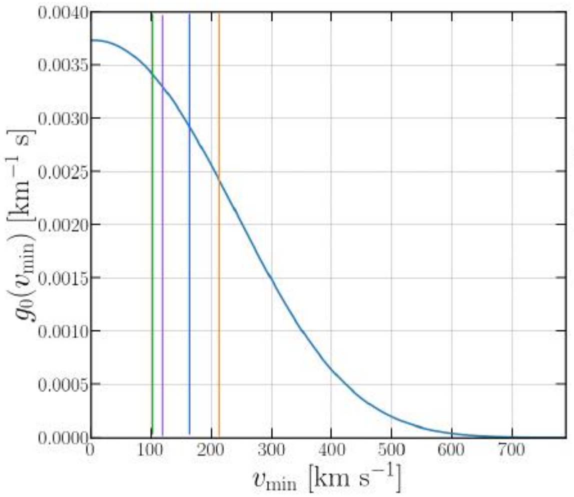
- Coupling constants
- DM Form factors
- Nuclear response functions

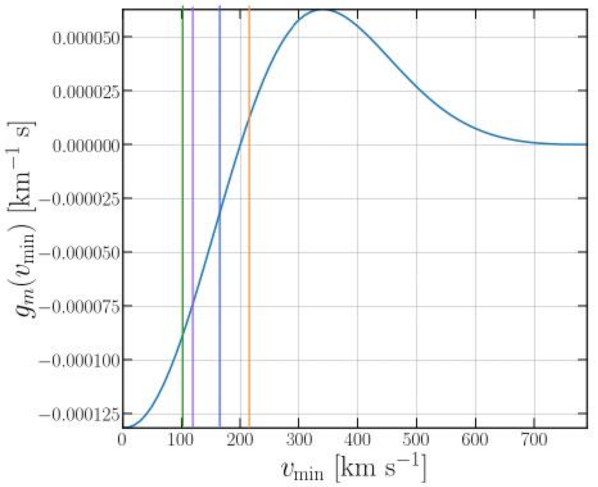
DM velocity distribution

- For chosen velocity distribution useful to express the integral as a function of minimum velocity.
- Minimum velocity for detection depends on target and DM mass. Modulation will be different depending on target.

For m_χ = 70 GeV/c²:

Target	v_{min}
Ge	101 km/s
Xe	117 km/s
I	174 km/s
Na	207 km/s





$$g(v_{\rm min}) = \int_{v_{\rm min}}^{v_{\rm esc}} v \; f_{\rm lab}(\vec{v}) \; dv \; d\Omega \qquad h(v_{\rm min}) = \int_{v_{\rm min}}^{v_{\rm esc}} v^3 \; f_{\rm lab}(\vec{v}) \; dv \; d\Omega \qquad v_{\rm min} = \sqrt{\frac{m_T E_R (m_\chi + m_T)^2}{2 m_\chi^2 m_T^2}}$$

Observation rates and detector dependence

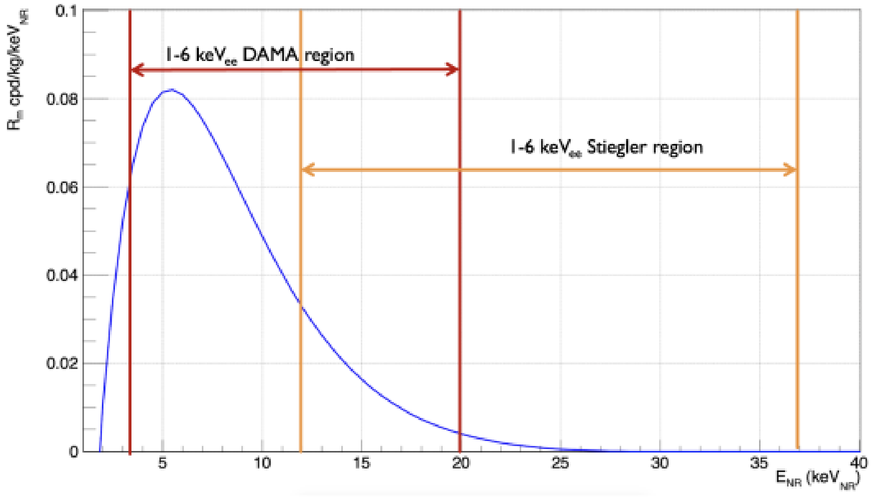
Number of events observed as a function of observed energy E_{ee}.

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

- **Efficiency/threshold** ($\epsilon(E')$): Imperfect/realistic detector setup
- **Interaction rate** ($\frac{dR}{dE_R}$): As per last slide
- **Quenching factor** ($\frac{dE_R}{dE_{ee}}$): Transformation from nuclear recoil energy to observable energy
- **Resolution** (Gaussian term): Ability to resolve fine details in energy spectrum

- Quenching factors 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 .

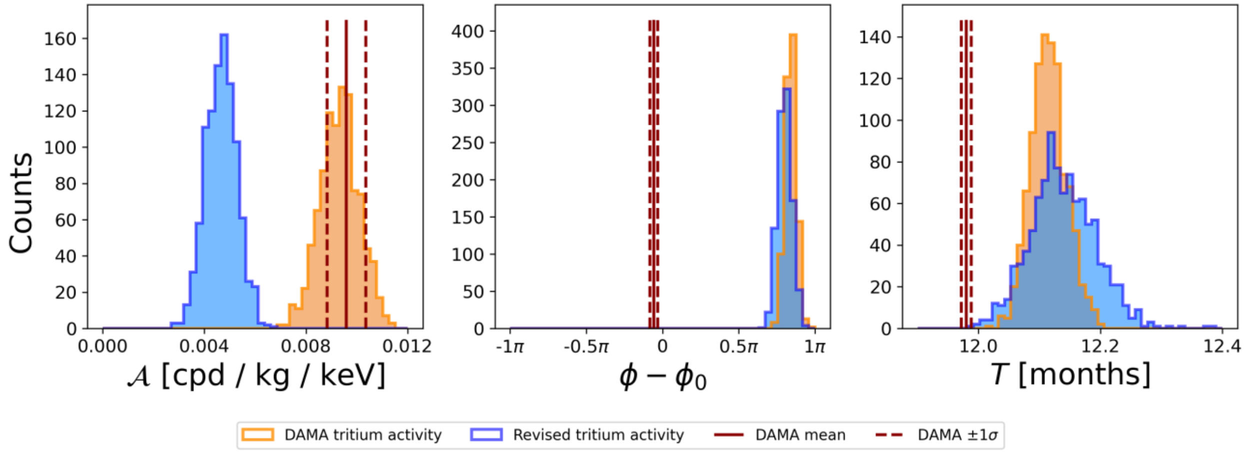
M. J. Zurowski, arXiv:2211.15861



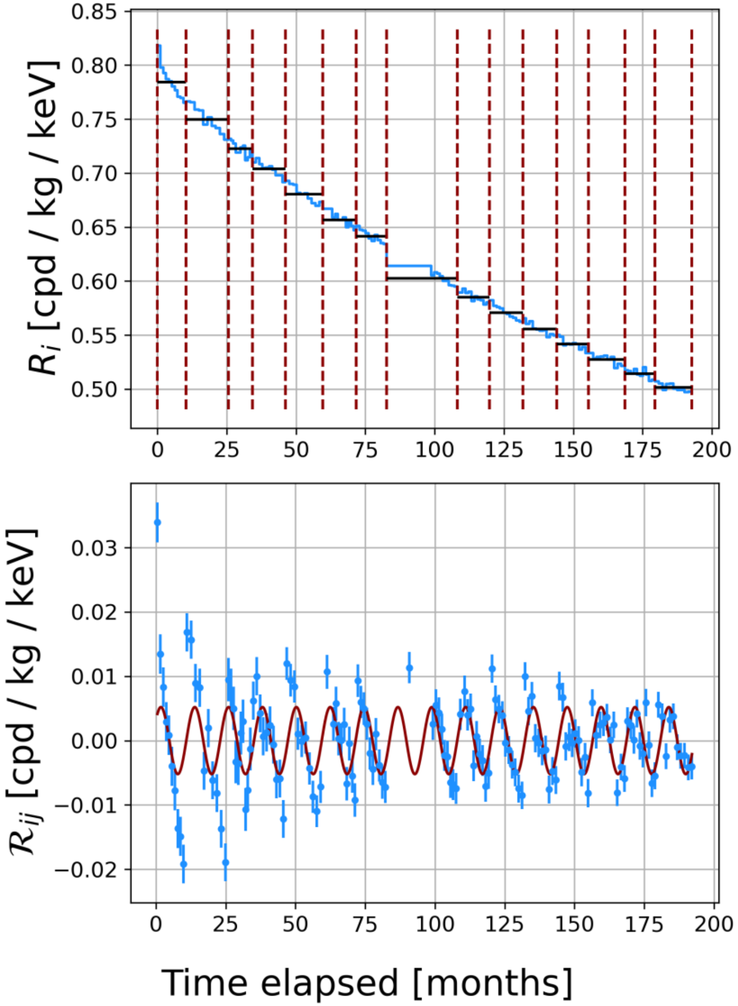
Induced Modulation

- DAMA analysis relied on subtracting average rate over ~ annual cycles.
- This procedure can induce a modulation effect consistent with their signal in the presence of a decaying background rate.
- DAMA tritium activity likely over-estimated.
  - Revised tritium activity found by using SABRE South crystal simulation
  - 210Pb taken from DAMA data

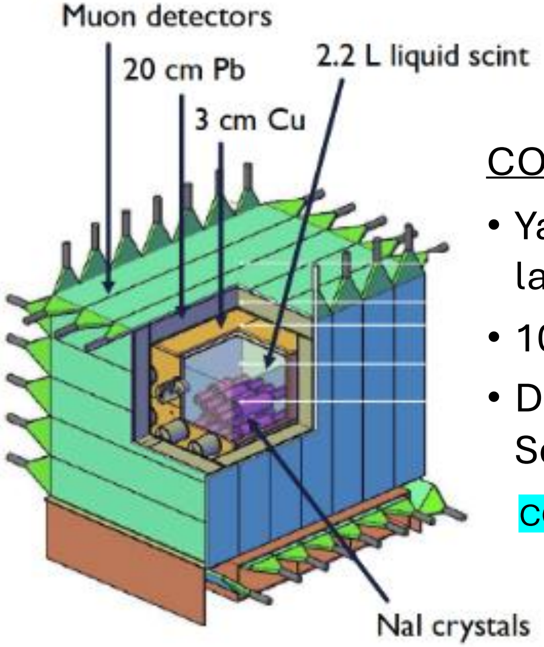
no sizeable induced modulation was observed with DAMA background subtraction. **DAMA background is low enough that shape of background/subtraction method doesn't matter, there is no induced modulation.**



A: Amplitude
Φ: Phase
T: Period



NaI(Tl) detectors: experiments results



COSINE-100:

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

COSINE-100, PRD 106 (2022)

1 dru = 1 cpd/kg/keV

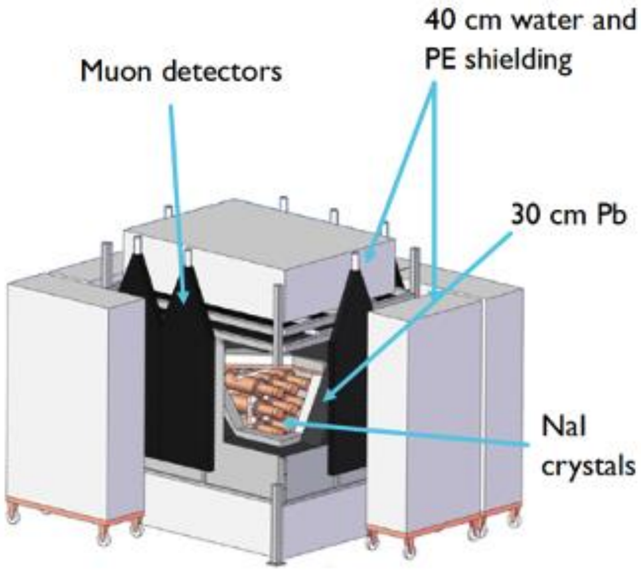
Setup	Mass (kg)	Bkg. (dru)	S_m (1–6 keV) (dru)	S_m (2–6 keV) (dru)
DAMA/LIBRA-phase2	250	0.8	0.0105 ± 0.0009	0.0093 ± 0.0009
COSINE	61.3	2.7	0.0017 ± 0.0029	0.0051 ± 0.0047
ANAIS	112.5	3.2	0.0007 ± 0.0025	0.0030 ± 0.0025

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

ANAIS:

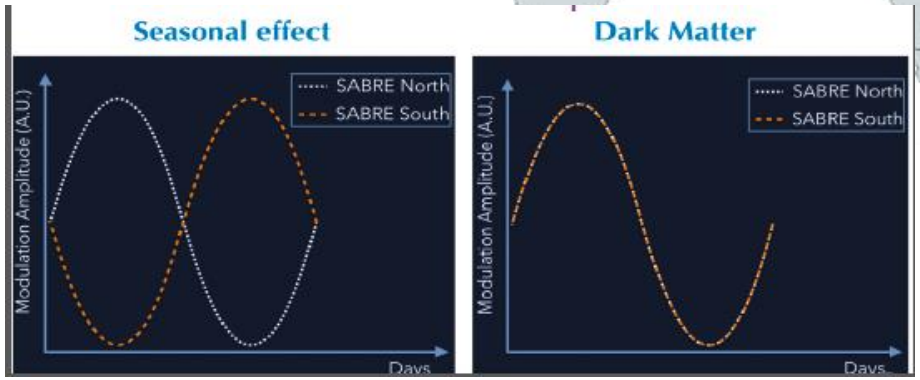
- Canfranc underground laboratory, Spain.
- 112.5 kg of NaI(Tl).
- Data taking from August 2017.

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



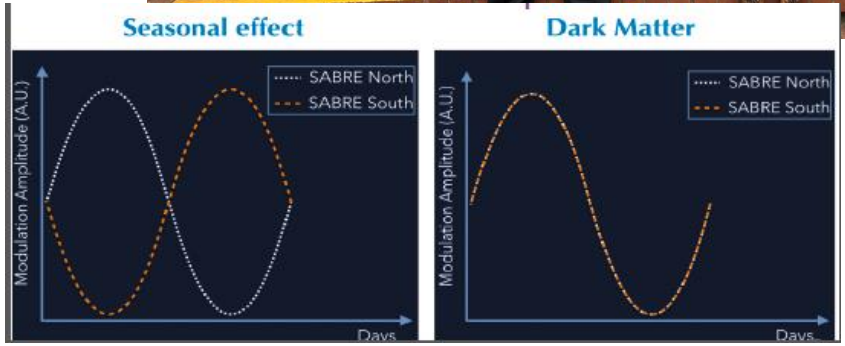
SABRE: a dual site experiment

Dual-site design - SABRE South (SUPL, Australia) and SABRE North (LNGS, Italy) - avoids seasonal effects.



SABRE: a dual site experiment

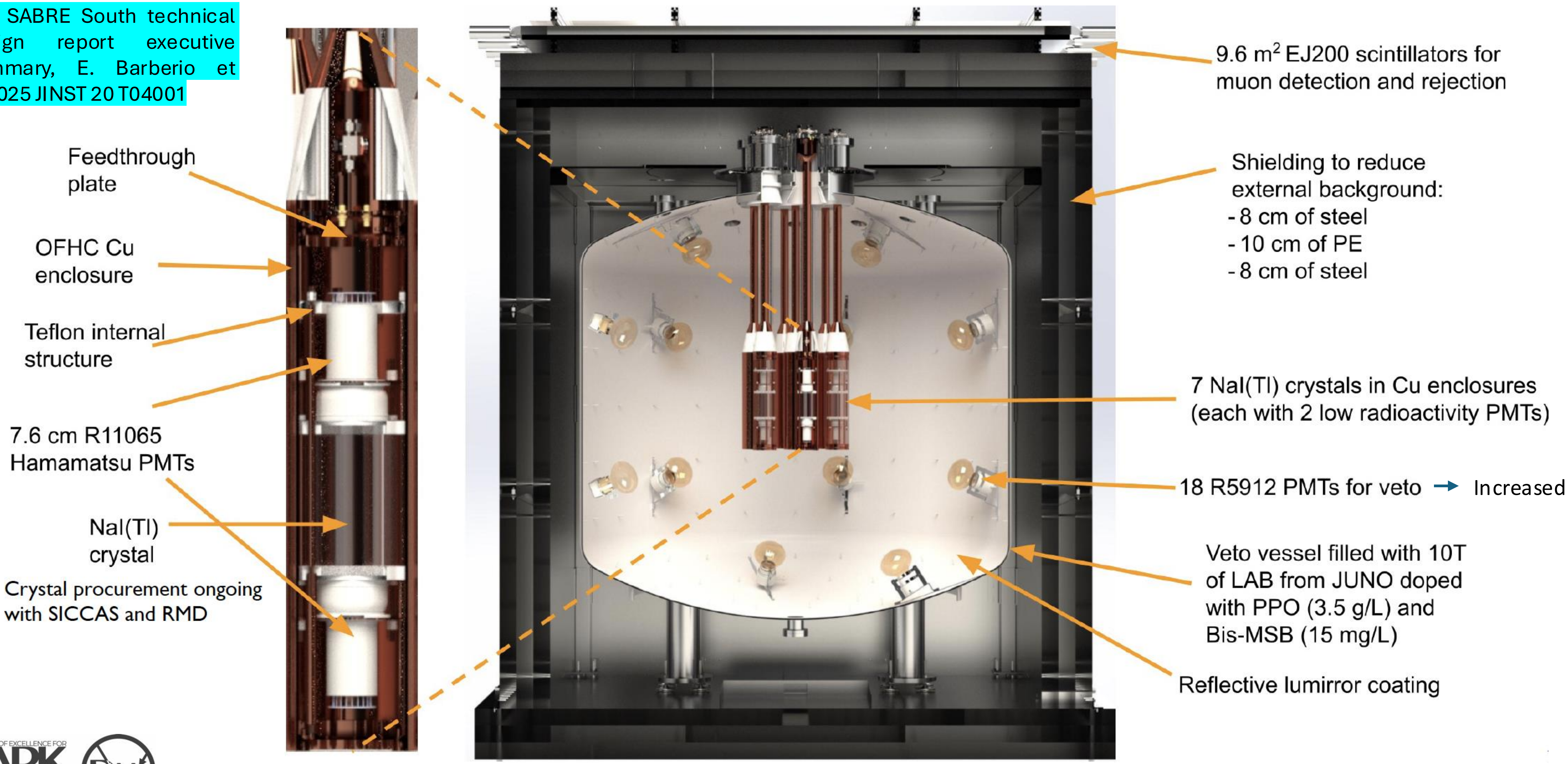
SABRE
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS
THE UNIVERSITY of ADELAIDE



DARK MATTER
THE UNIVERSITY of ADELAIDE
THE UNIVERSITY OF MELBOURNE
Australian National University
SWIN BUR NE
THE UNIVERSITY OF SYDNEY
KEK

SABRE (Sodium iodide with Active Background REjection) South

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



→ Increased to 32

NaI(Tl) crystals production

- Ultra-pure Astrograde NaI powder.
- R&D with two different providers to achieve the highest purity: SICCAS (Shanghai, China) and RMD (Boston, US).

	^{nat}K [ppb]	^{238}U [ppt]	^{232}Th [ppt]	^{210}Pb [mBq / kg]	Mass [kg]
SABRE NaI-33 [1]	4.3 ± 0.8	0.4 ± 0.05	0.20 ± 0.07	0.46 ± 0.01	3.4
DAMA [2]	13	0.3 - 2	0.5 - 7.5	(5 - 30) x 10^{-3}	10.0
COSINE-100 [3]	35.1	<0.12	0.4 - 2.4	0.7 - 3	13.3
ANAIS [4]	31	<0.81	0.1 - 1.0	0.7 – 3.2	12.5

[1] B. Suerfu et al., Phys. Rev. Research 2, 013223 (2020)
[2] R. Bernabei et al., NIMA 592(3) (2008)
[3] P. Adhikari et al., Phys. Rev. Lett. 123, 031302 (2019)
[4] J. Amare et al., EPJC 79 412(2019)

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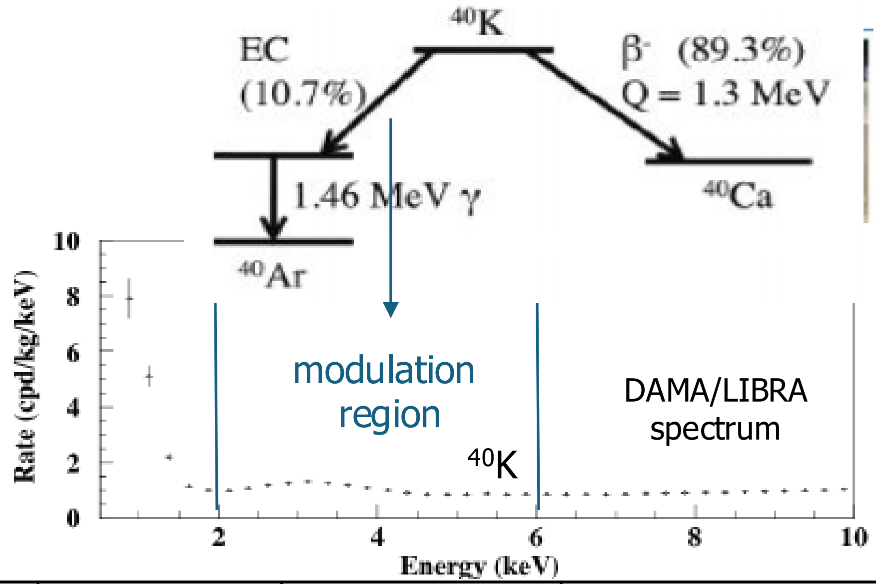

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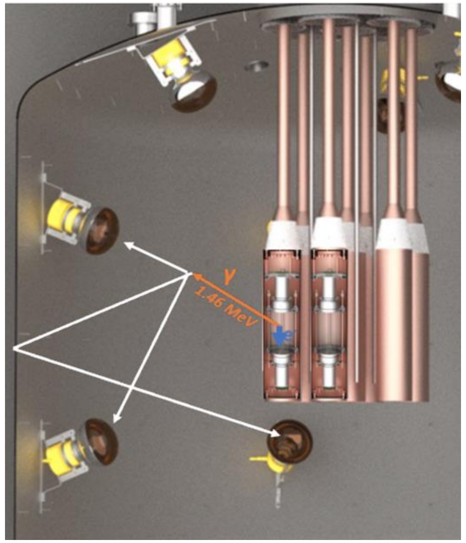
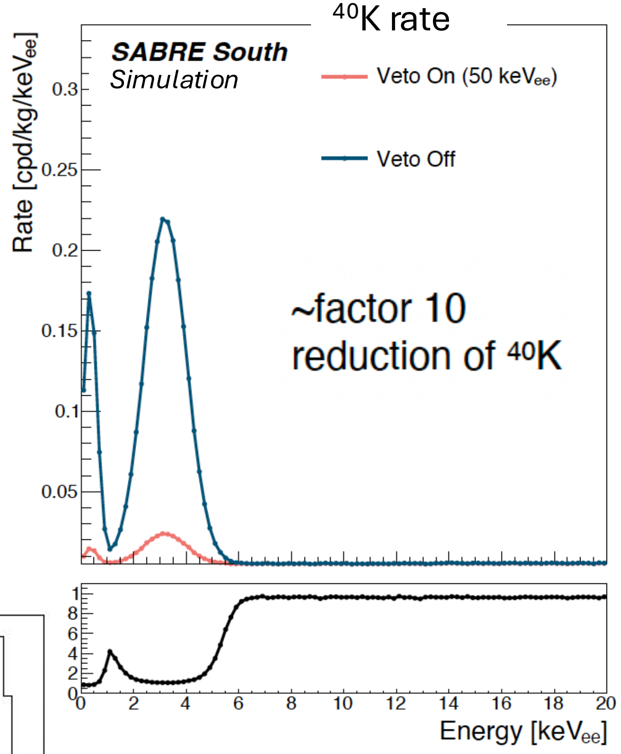
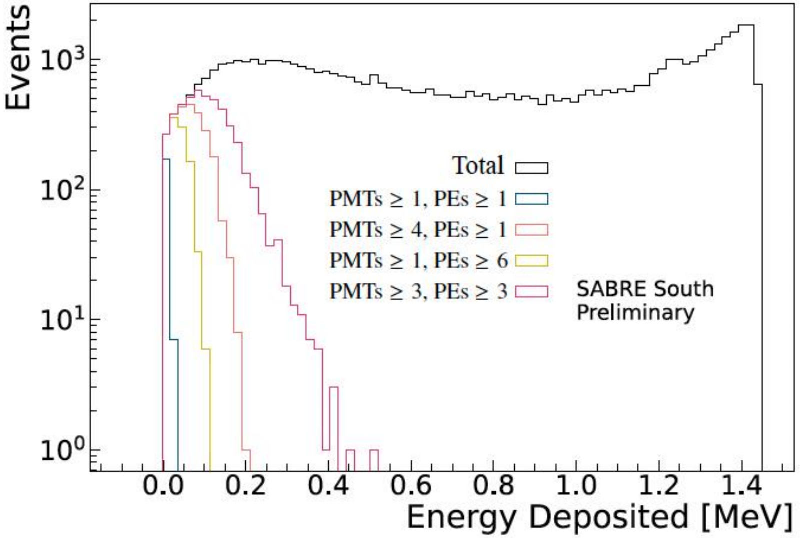
Active Background Rejection

- 12 kL of linear alkyl benzene (LAB) procured from JUNO production line, doped with PPO and bisMSB.
- Average number of observed PE ~0.75/keV, photon attenuation > 20m.
- 18 R5912 PMTs oil proof, sampled at 500 MS/s +14 from Daya Bay decommissioning.





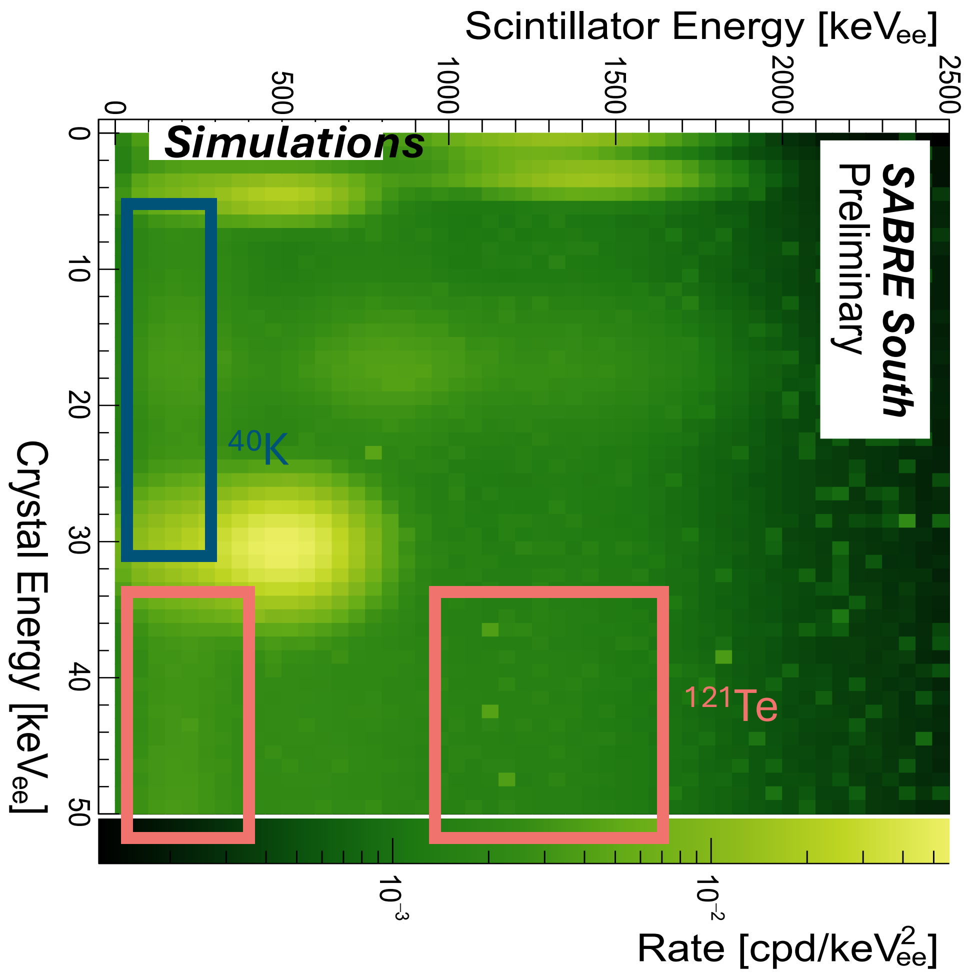
PSD (particle ID) framework developed and tested on small scale prototype.



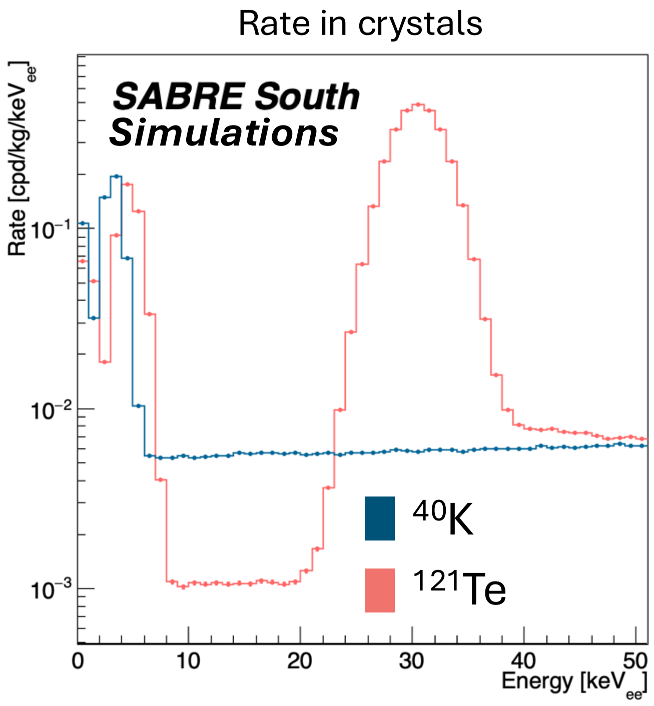
"Photomultiplier Requirements and Pre-Calibration for the SABRE South Liquid Scintillator Veto". 2025. Accepted to JINST, https://arxiv.org/abs/2505.10353

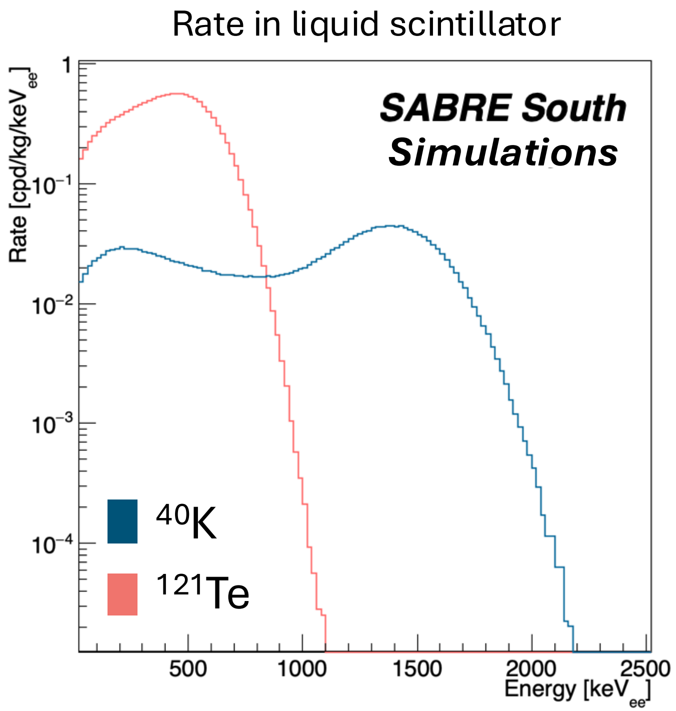
Particle Identification

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



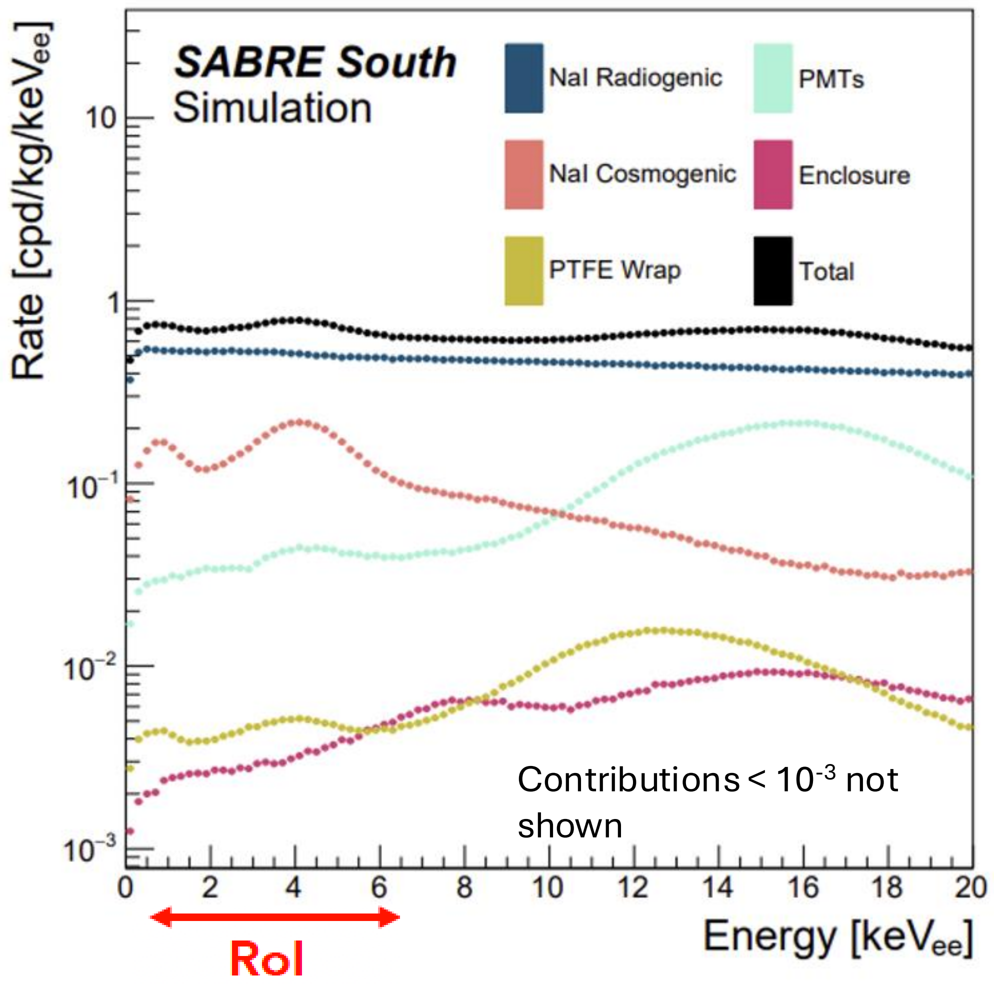


SABRE South Collab. arxiv:2205.13849

Total Background Model

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

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

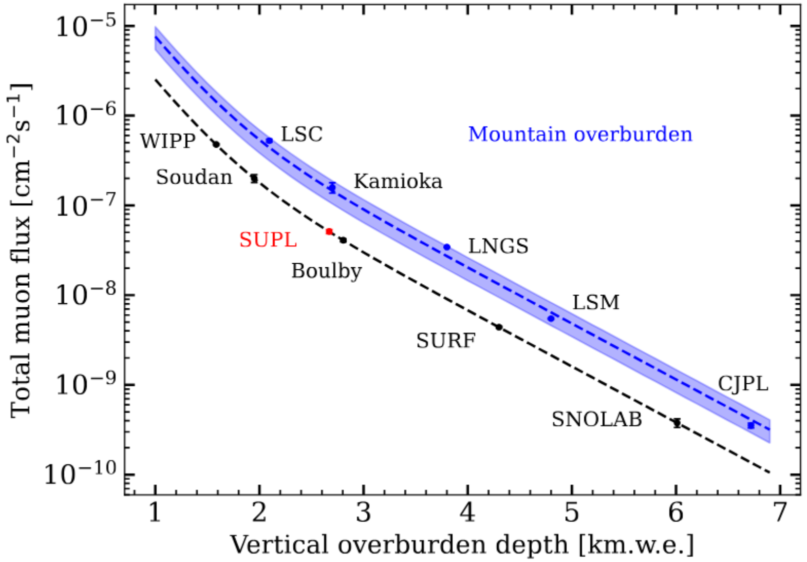


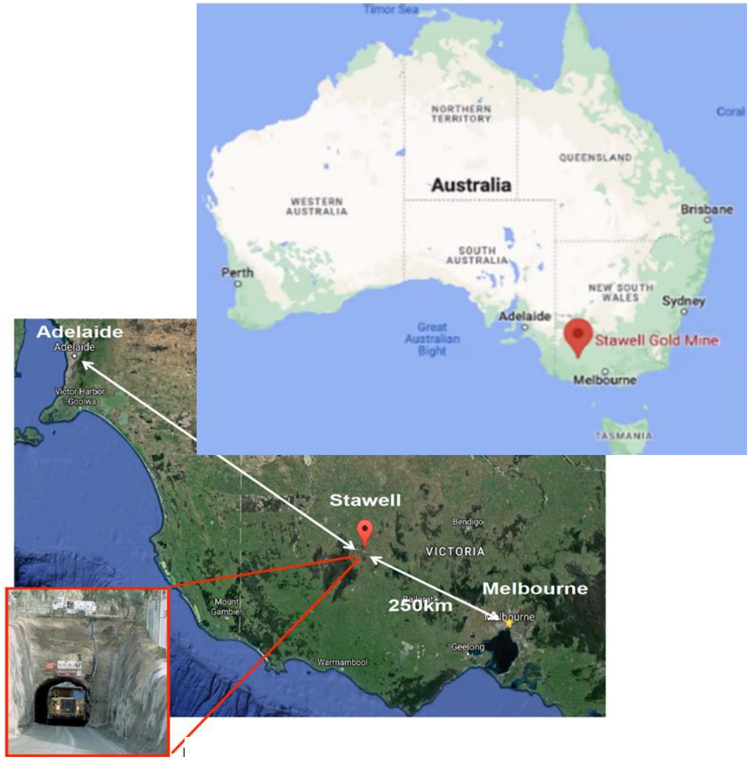
< 10% of background from non-crystal sources.

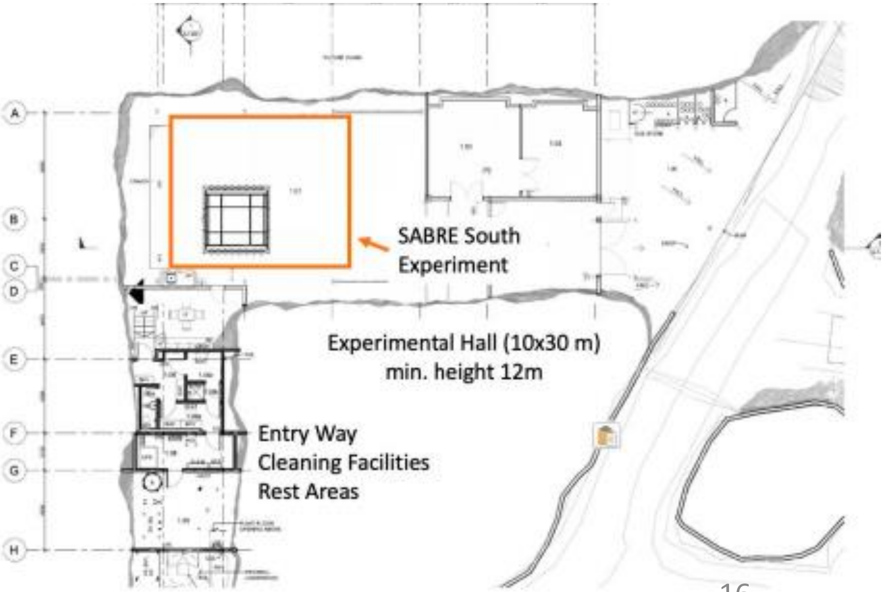
Component	Rate (cpd/kg/keV$_{ee}$)	Veto efficiency (%)
Crystal intrinsic	<5.2×10^{-1}	13
Crystal cosmogenic	1.6×10^{-1}	45
Crystal PMTs	3.8×10^{-2}	57
Crystal wrap	4.5×10^{-3}	11
Enclosures	3.2×10^{-3}	85
Conduits	1.9×10^{-5}	96
Steel vessel	1.4×10^{-5}	>99
Veto PMTs	1.9×10^{-5}	>99
Shielding	3.9×10^{-6}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

Stawell Underground Physics Lab

- SUPL is the first deep underground lab in Southern Hemisphere (37°South) located in western Victoria 240 km from Melbourne.
- Lab is 1025 m (~2900 m water equivalent) below ground with flat over burden within the Stawell Gold Mine.
- Helical drive access.
- Completed in 2023. First access & major detector installation in Jan/Feb 2024.

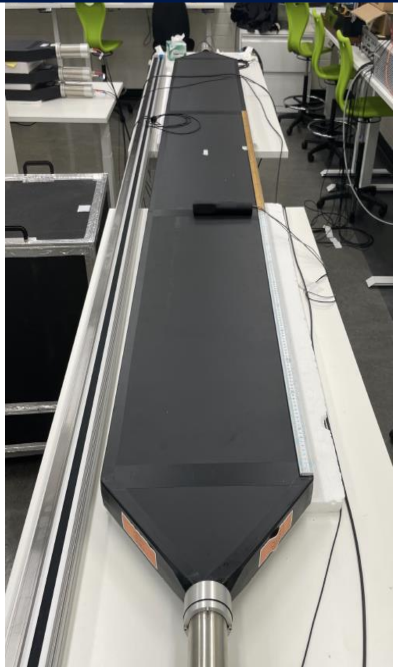


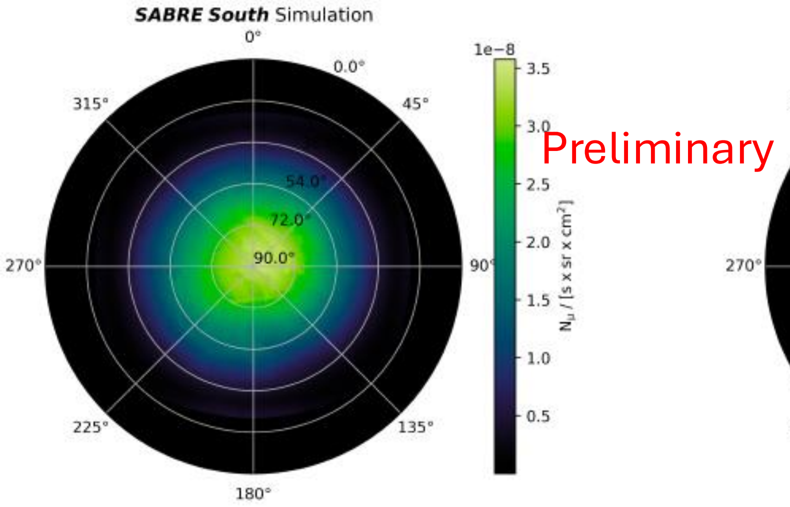


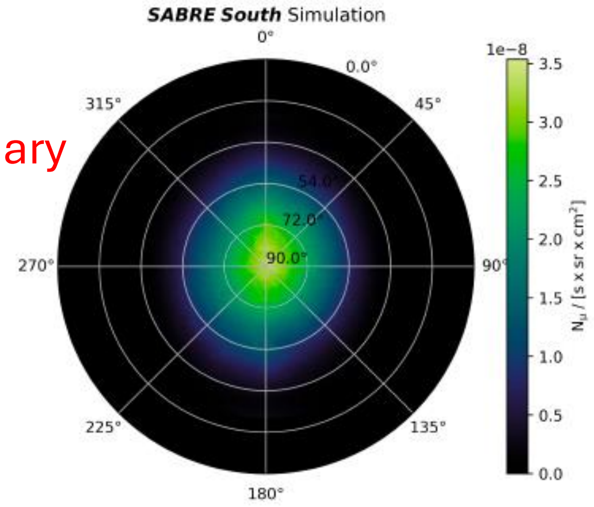


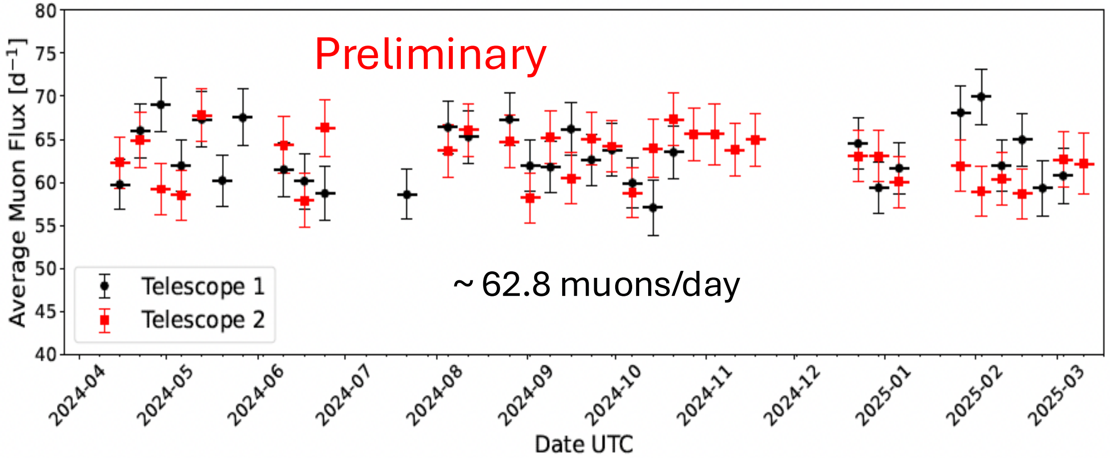
Stawell Underground Physics Lab

- First detectors commissioned early 2024 in SUPL.
- Eight 5 cm-thick EJ-200 plastic scintillator panels deployed in telescope configuration to measure muon flux and angular distribution.
- Muon flux simulations include realistic overburden modelling and seasonal effects.
- Observed rate consistent with predictions based on atmospheric models and site-specific geology.
- Seasonal modulation studies (with PUMAS) are ongoing to characterise atmospheric effects on the underground muon flux.







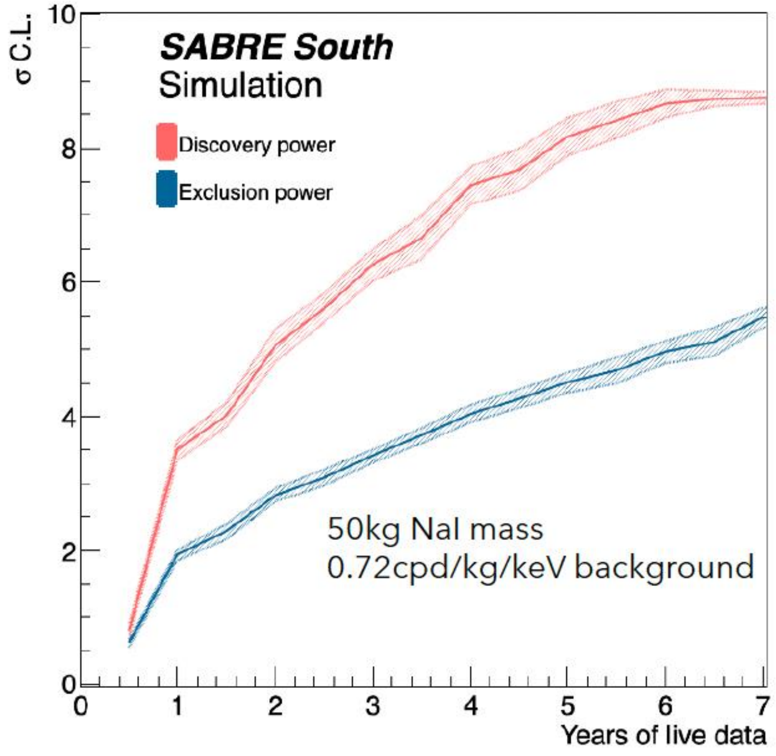


Sensitivity Performance

SICCAS and/or RMD likely to provide suitable crystals that meet requirements

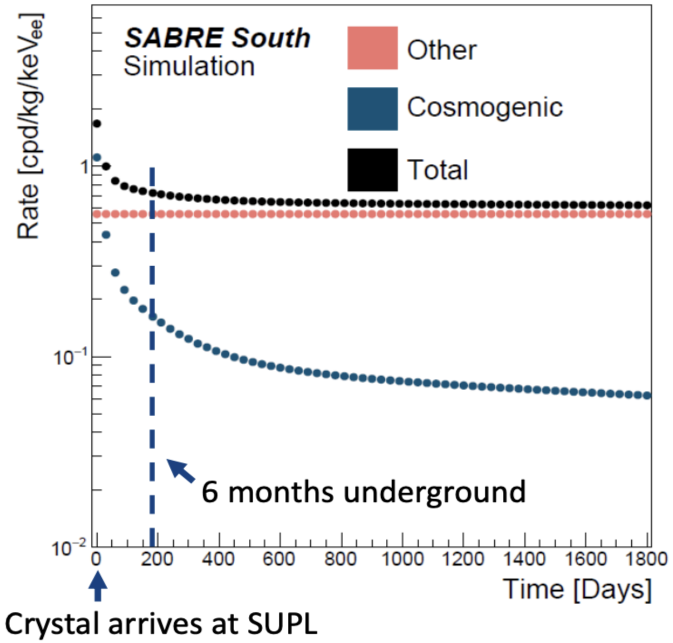
https://www.sabre-experiment.org.au

Parameter	Value
Light yield	11.1 ± 0.2 PE/keV
Energy resolution	13.2% (FWHM/E) at 59.5 keV
Efficiency	
Crystal energy threshold	1 keV
Veto energy threshold	50 keV
Total active mass	35 - 50 kg
Background rate (PoP)	0.36 cpd/kg/keV
Background rate (South)	0.72 cpd/kg/keV



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

Cosmogenic background ^{3}H (half life 12.4 yrs), ^{109}Cd (half life 463 days) and ^{113}Sn (half life 115 days) after 180 days



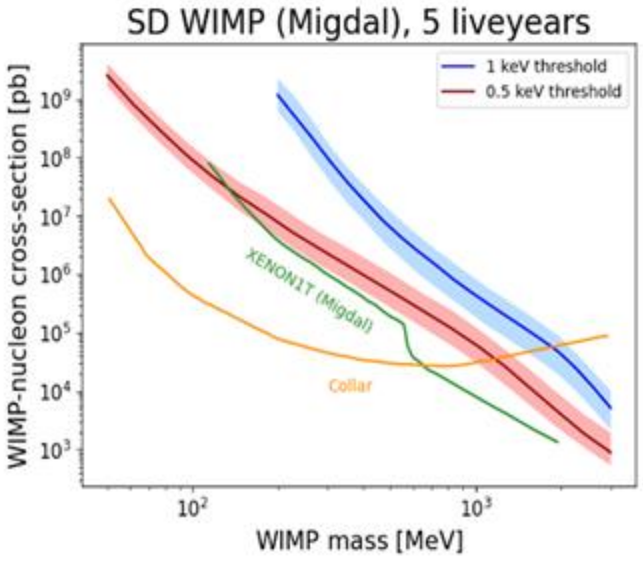
Physics Program

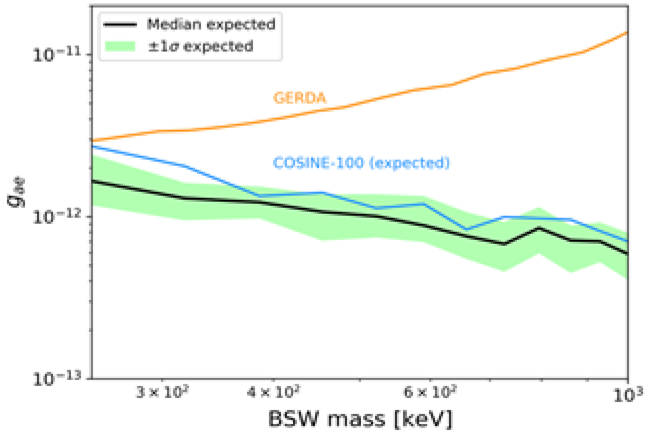
SABRE South has been exploring different types of physics detector can exploit

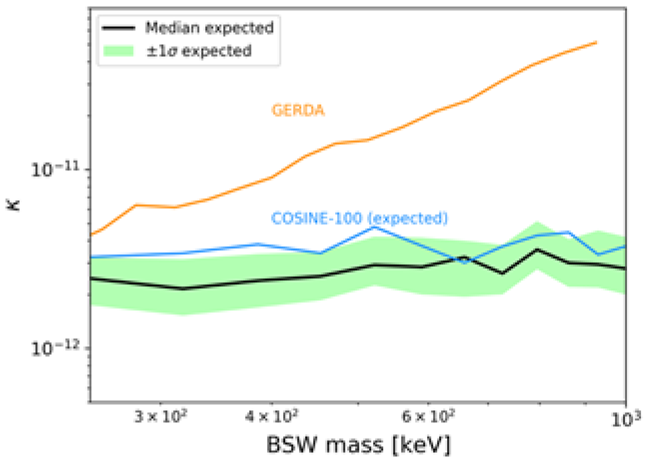
- Both crystal detectors and veto detector

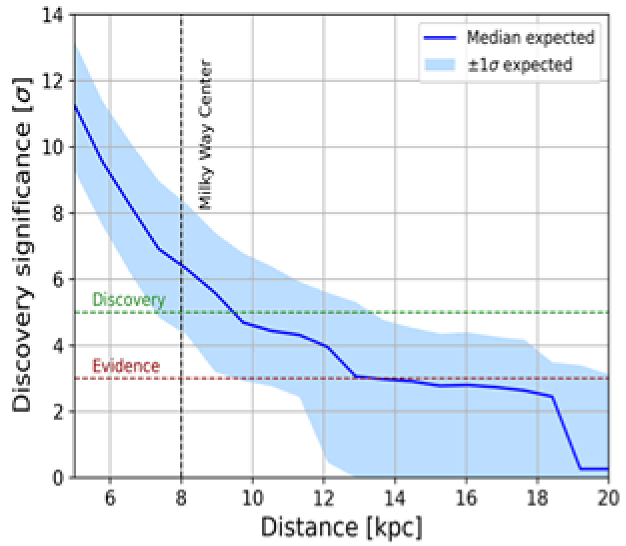
Preliminary sensitivity studies performed on

- Migdal effect
- Bosonic super-WIMPs
- Sensitivity to supernova neutrinos – yielding the possibility of SABRE South could join a Supernova Early Warning System (SNEWS)









SABRE South Status

- Fully funded and under construction at SUPL through 2025.
- Focus on ultra-high-purity NaI(Tl) detectors: strong progress on crystal production and low-background enclosures.
- Projected total background: 0.72 cpd/kg/keV.
- 120-tonne steel shielding ready for installation in Q3 2025.
- Access to SUPL has commenced; muon detectors operational since February 2024.
- Pre-calibration of PMTs for crystal and veto systems completed; publication submitted to 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 (with a single 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

SICCAS Since 1928

Screening

UKRI Science and Technology Facilities Council

Boulby Underground Laboratory

Australian Government ANSTO

UCL

SABRE

South

Australian Government
Australian Research Council

KEK-JAPAN

SWINBURNE

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY of ADELAIDE

Australian National University

North

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

INFN
Istituto Nazionale di Fisica Nucleare

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SAPIENZA UNIVERSITÀ DI ROMA

PRINCETON UNIVERSITY

UNIVERSITÀ DEL SALENTO

Veto LS & PMTs

Institute of High Energy Physics
Chinese Academy of Sciences