The SABRE South experiment at the Stawell Underground Physics Laboratory

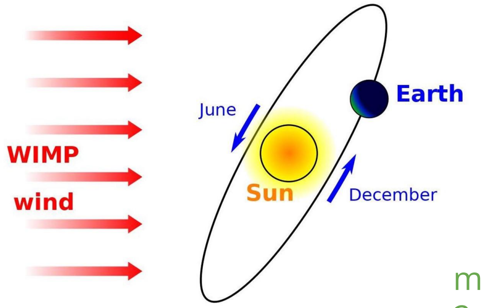
Robert James on behalf of the SABRE South Collaboration
The University of Melbourne

PASCOS 2024, Quy Nhon, Vietnam

Annual modulation of galactic dark matter

- Scattering rate of galactic dark matter in terrestrial detector depends on velocity distribution and relative velocity at Earth
- Expected annual variation in velocity of ~6% → modulation in event rate
- Event rate consistent with this variation would be ‘smoking gun’ evidence of galactic dark matter signal: requires solid understanding of seasonally-varying backgrounds

$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int_{v_{\min}}^{\infty} v f(\vec{v} + \vec{v}_e) \frac{d\sigma}{dE_R} d^3v$$



maximal on 2nd June

$$R_{\Delta E}(t) \approx R_{0,\Delta E} + R_{m,\Delta E} \cos[\omega(t - t_0)]$$

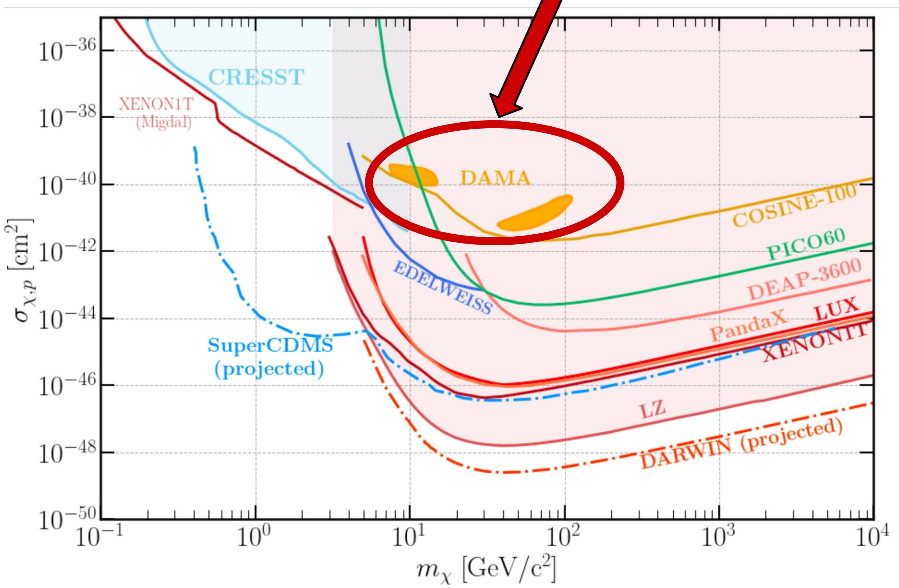
energy window

period of 1 year

WIMPs: the experimental landscape

- Weakly interacting massive particles (WIMPs) are a favoured dark matter candidate: neutral, stable, cold and non-baryonic
- Parameter space widely probed by currently leading technology: liquid xenon time-projection chambers. No hint of WIMP-like signals
- Non-null result from only one experiment...

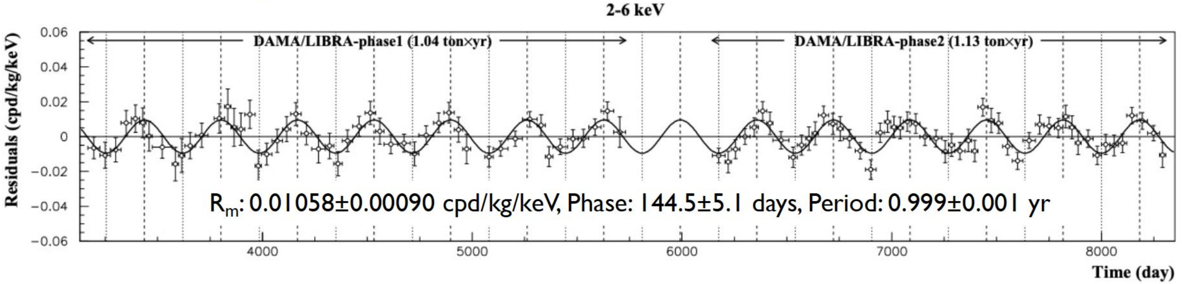
What is happening here?



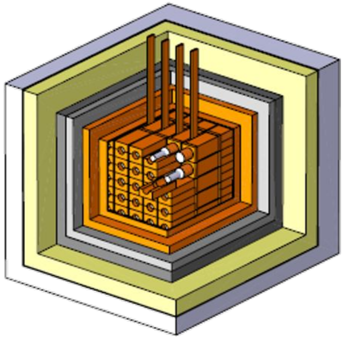
https://github.com/cajohare/NeutrinoFog

The DAMA/LIBRA signal

- DAMA/LIBRA experiment: ultra-low background NaI(Tl) scintillator crystals located at Laboratori Nazionali del Gran Sasso (LNGS), Italy
- Modulation in event rate observed: period and phase consistent with galactic dark matter
- Residual modulation of ~0.01 cpd/kg/keV observed over 2-6 keV energy region (combined Phase I and Phase II) @ 12.6 σ significance; 1-6 keV (phase II) @ 11.8 σ significance
- Phase 1 + Phase II corresponds to ~15 years of data collection



R. Bernabei et al., Nucl. Phys. Atomic Energy 22, 329 (2021)



250 kg NaI(Tl): 25 crystals

Cu, Pb, PE shielding

The DAMA/LIBRA signal: explanations?

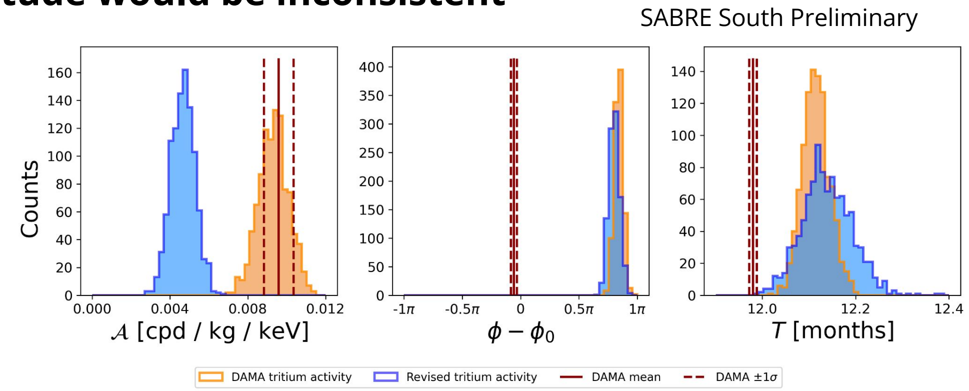
- **Artefact of the analysis procedure**
- **Seasonal background or systematic effect** (muon-induced neutrons? Something else?)
- **Dark matter signal with complex interaction mechanism** (to explain lack of detection elsewhere)

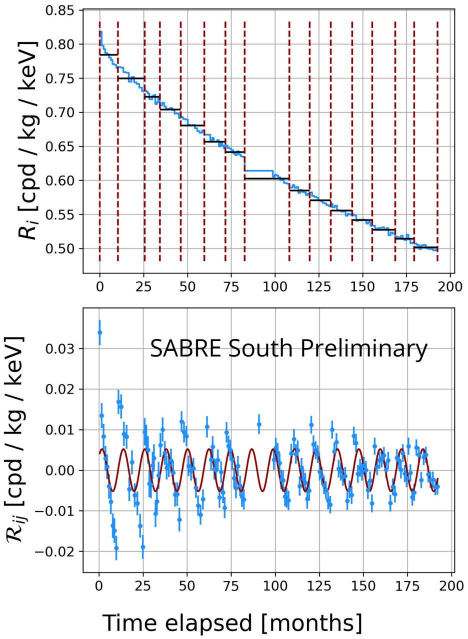
From APPEC: *The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material.*

The DAMA/LIBRA signal: analysis artefact?

$$\mathcal{R}_{ij} = \mathcal{R}_i = \langle \mathcal{R}_i \rangle_j$$

- DAMA/LIBRA analysis relied on subtracting average rate over approximately annual cycles to calculate ‘residuals’
- Claims that this procedure can induce a modulation effect consistent with their signal in the presence of a decaying background rate
- Whilst the amplitude could be consistent if the levels of ^{3}H and ^{210}Pb reflected their reported upper limits, the **phase is opposite**
- A re-assessment of the likely ^{3}H background shows that **even the amplitude would be inconsistent**

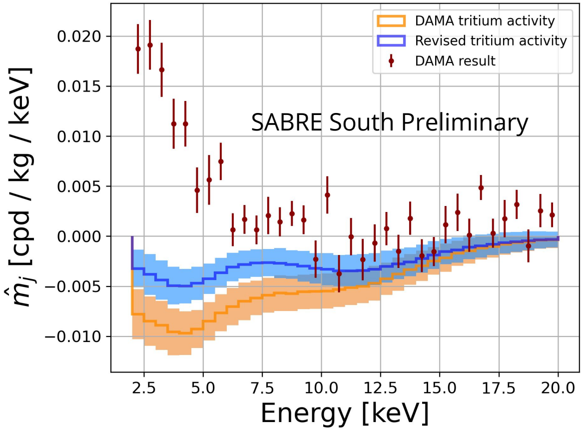


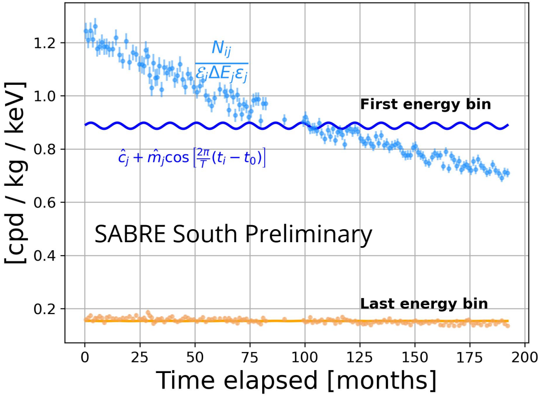


The DAMA/LIBRA signal: analysis artefact?

- Alternative analysis performs maximum likelihood fit in energy bins (0.5 keV width between 2-20 keV)
- DAMA claim that the presence of modulation in the lowest energy bins only consistent with WIMP-like signal
- Presence of decaying background rate cannot explain this behaviour

$$L_j = \prod_i \frac{e^{-\mu_{ij}} \mu_{ij}^{N_{ij}}}{N_{ij}!}$$





$$\mu_{ij} = \left[c_j + m_j \cos\left(\frac{2\pi}{T}(t_i - t_0)\right)\right] \mathcal{E}_i \Delta E_j \epsilon_j$$

The DAMA/LIBRA signal: explanations?

- **Artefact of the analysis procedure** → *this seems unlikely*

- **Seasonal background or systematic effect** (muon-induced neutrons? Something else?) → *need alternative tests that can discriminate against this*

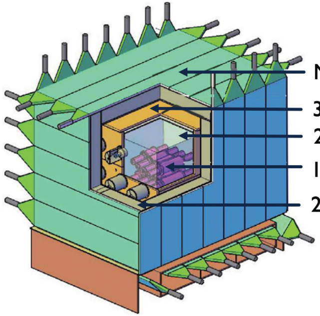
- **Dark matter signal with complex interaction mechanism** (to explain lack of detection elsewhere) → *require alternative tests utilising the same target material*

From APPEC: *The long-standing claim from DAMA/LIBRA [...] needs to be independently verified using the same target material.*

Other recent NaI(Tl) experiments

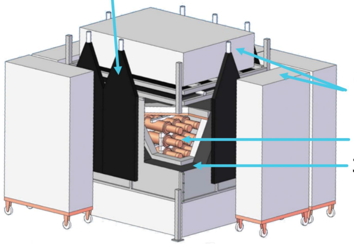
COSINE-100

- Operations at Yangyang Underground Laboratory (Y2L), South Korea, from 2016-2023
- Utilises muon detectors + liquid scintillator for active background rejection



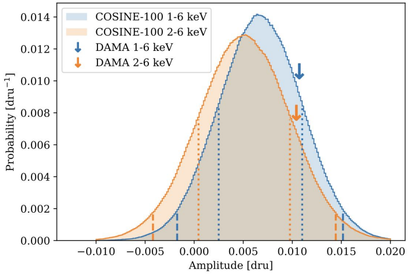
ANAIS-112

- Operations at Canfranc Underground Laboratory, Spain, from 2017-present
- Utilises muon veto system for active background rejection



Other recent NaI(Tl) experiments: results

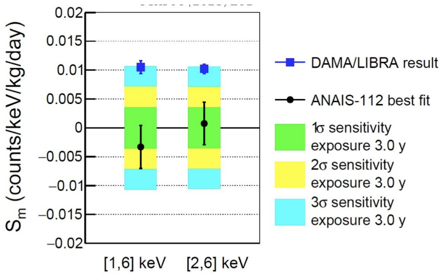
COSINE-100

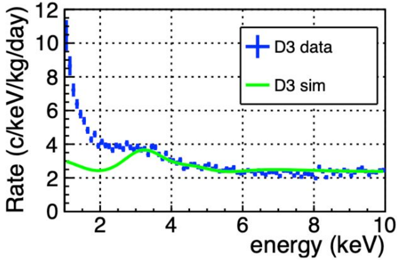


- COSINE-100 results compatible with both 0 modulation *and* the DAMA signal at ~1 σ
- Measurement limited by high crystal background rate → need ultra-low background crystals

COSINE-100 Collaboration, Phys. Rev. D 106, 052005 (2022)

ANAIS-112

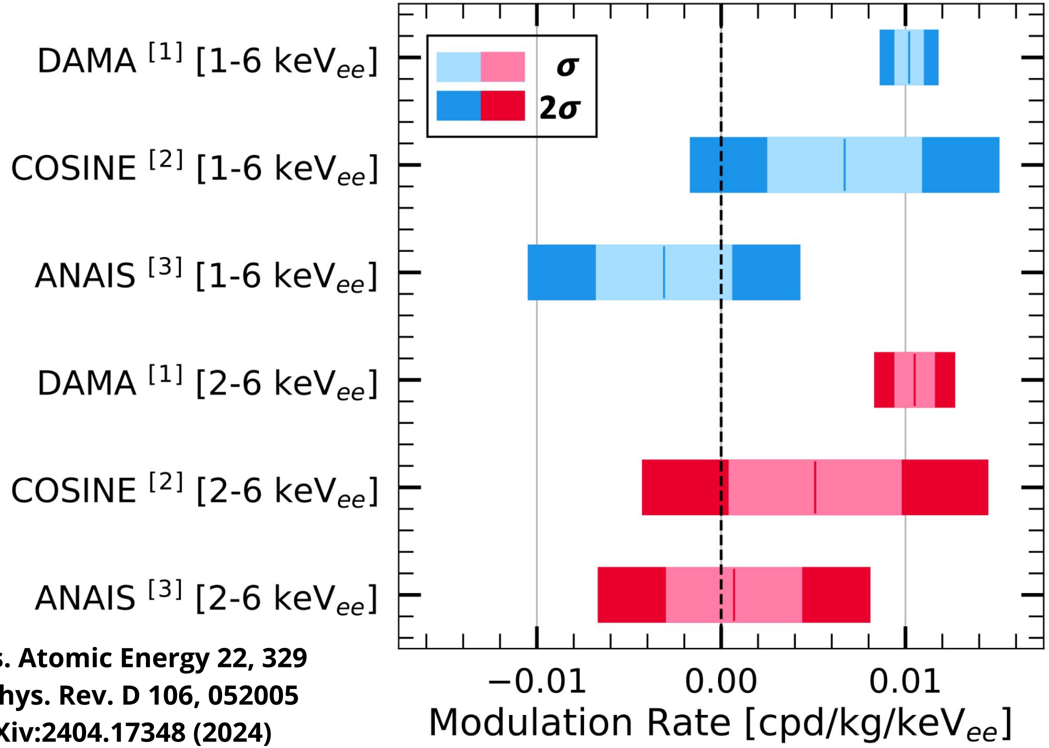




- ANAIS-112 results appear to be in tension with the DAMA result
- Model and data disagreement below ~3 keV → need to model near-threshold effects

ANAIS-112 Collaboration, arXiv:2404.17348 (2024)

Summary of the NaI(Tl) experimental landscape



[1] R. Bernabei et al., Nucl. Phys. Atomic Energy 22, 329 (2021)
[2] COSINE-100 Collaboration, Phys. Rev. D 106, 052005 (2022)
[3] ANAIS-112 Collaboration, arXiv:2404.17348 (2024)

The SABRE project

PRINCETON UNIVERSITY

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO

UNIVERSITÀ DEL SALENTO

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

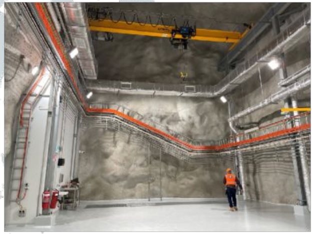
SABRE North

Dual-site experiment in opposite hemispheres enables ruling out of seasonal effects

SABRE South
(this talk)

STAWELL UNDERGROUND PHYSICS LAB

Australian Government
Australian Research Council



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THE UNIVERSITY of ADELAIDE

Australian National University

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

SABRE North/South

Common features

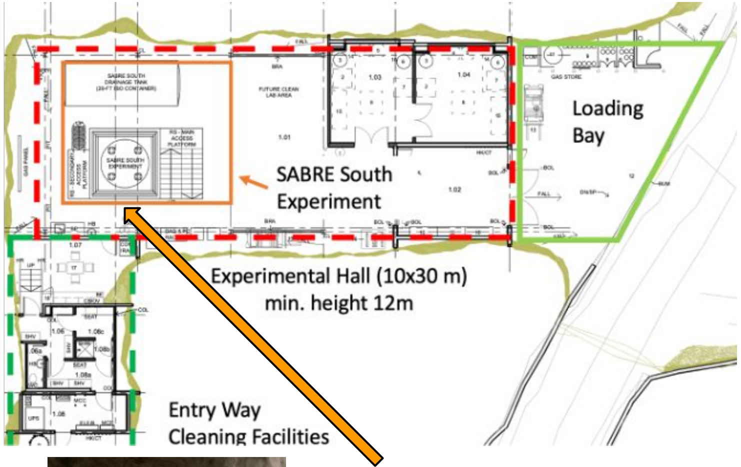
- Will use the same crystal growth powder and crystal PMTs (HPK R11065)
- Will share simulation, DAQ and software frameworks
- Exchange of engineering knowledge: collaborative agreements between INFN and ARC Centre of Excellence for Dark Matter Particle Physics

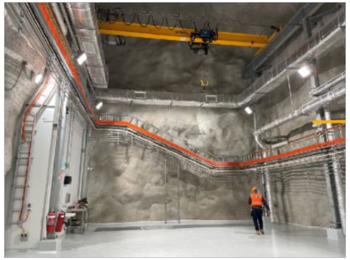
Differences

- Phase-out of organic scintillators at LNGS → SABRE North will use fully passive shielding. Will achieve required low background levels through zone refining process
- SABRE South will use LAB liquid scintillator for active background rejection → less stringent requirements on crystal background levels

The Stawell Underground Physics Laboratory

- First deep underground laboratory in the Southern Hemisphere
- Situated in Stawell, Victoria, Australia, ~250 km from Melbourne
- Located 1025 m below ground (2900 m water equivalent overburden) with the Stawell Gold Mine
- Ongoing lab access since late 2023
- SABRE South is paving the way for SUPL: CELLAR cryogenic lab will host a dilution refrigerator, enabling low-mass dark matter searches





The SABRE South collaboration

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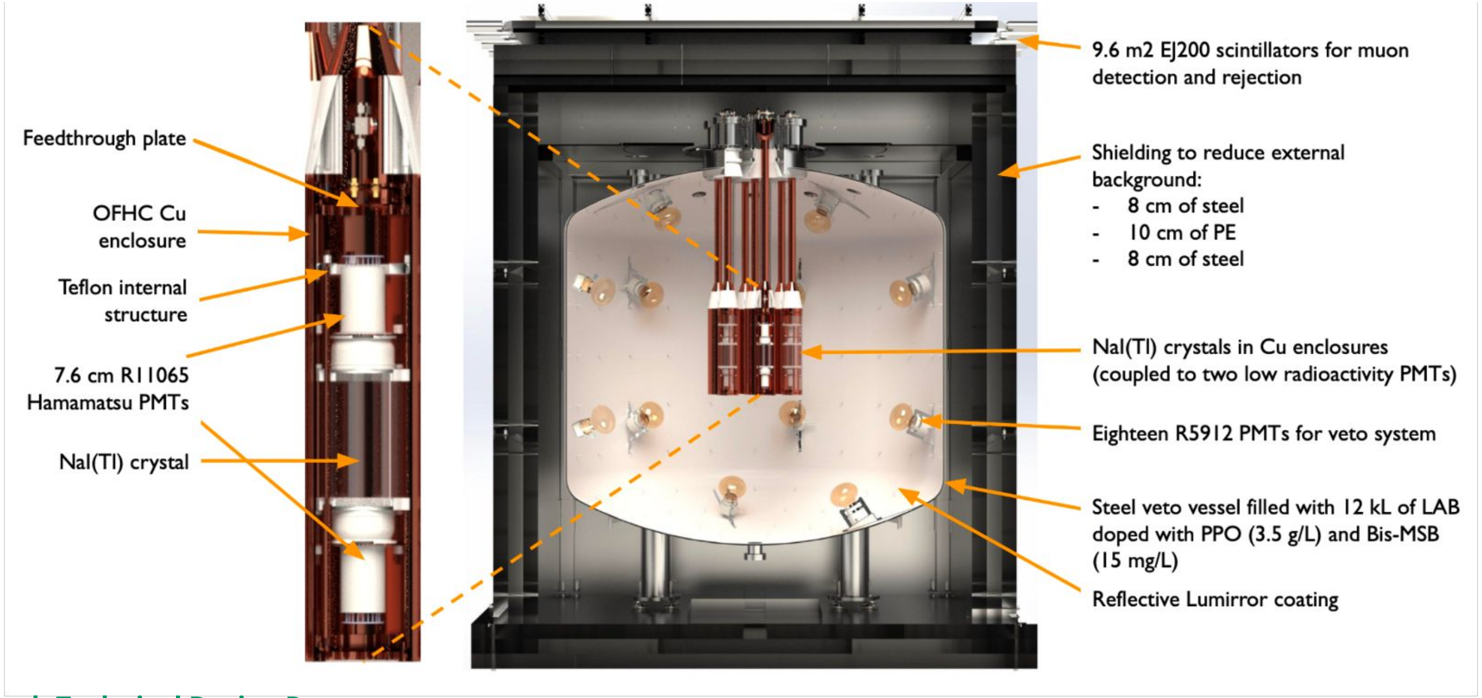
The SABRE South detector



[The SABRE South Technical Design Report]

SABRE South crystal production

- SABRE South NaI(Tl) crystals will be grown from ultra-pure "Astrograde" powder from Princeton-Sigma-Aldrich (now MERCK)

- SABRE South will utilise 7 crystal modules. Crystals encapsulated in copper/PTFE enclosures and directly coupled to two Hamamatsu R11065 PMTs. Assembly process currently being finalised using glove box

- 5 x ~3.5 kg test crystals grown by RMD in collaboration with SABRE North: all at or near the required purity. Final ~50 kg crystal production will proceed via partners SICCAS and RMD. Crystals will be characterised in a lead castle setup at SUPL later this year

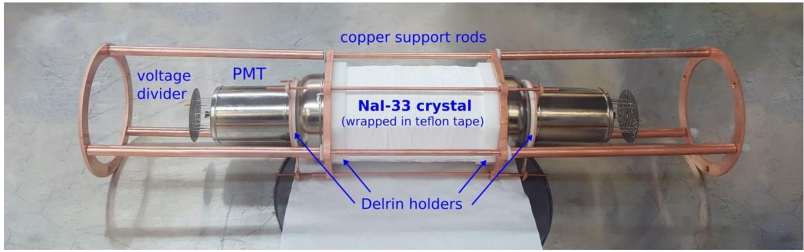
RMD A Dynasil Company

SICCAS Since 1928

NaI-33

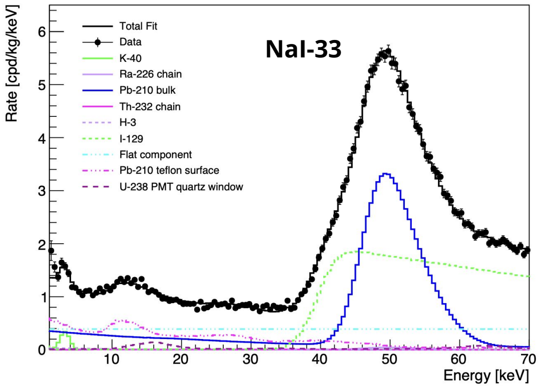
NaI-35

NaI-37

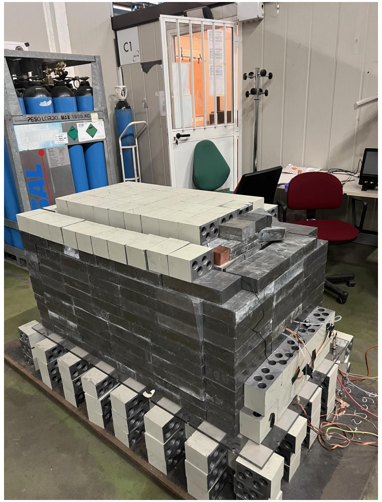


SABRE South crystal characterisation

- A number of test crystals have been characterised at LNGS: via a lead castle and in a proof-of-principle setup
- Radioactive contaminant levels used to inform the first SABRE South background model (see slide 23)
- Targeting an effective light yield of 12 phe / keV for final crystals to enable an energy threshold of 1 keV



SABRE Collaboration, Eur. Phys. J. C 81, 299 (2021)



NaI-33 characterisation

^{nat}K [ppb]	^{238}U [ppt]	^{232}Th [ppt]	^{210}Pb [mBq / kg]	Mass [kg]
4.3 ± 0.8	0.47 ± 0.05	0.40 ± 0.07	0.46 ± 0.01	3.40

Liquid scintillator veto system

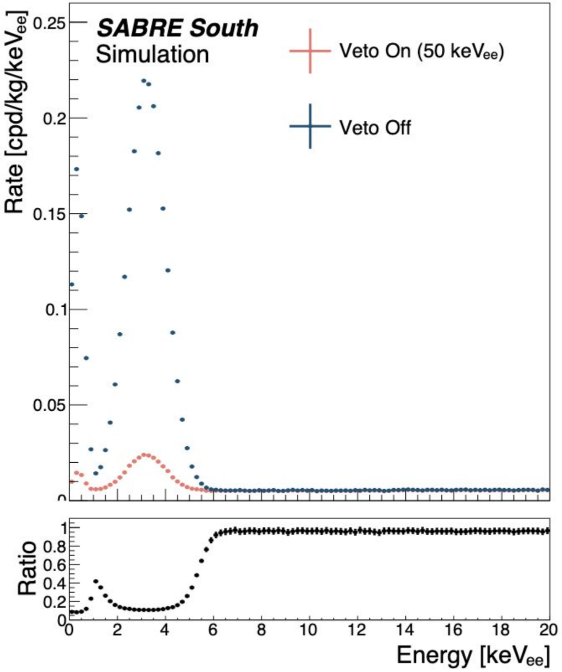
SABRE South Collaboration, Eur. Phys. J. C 83, 878 (2023)

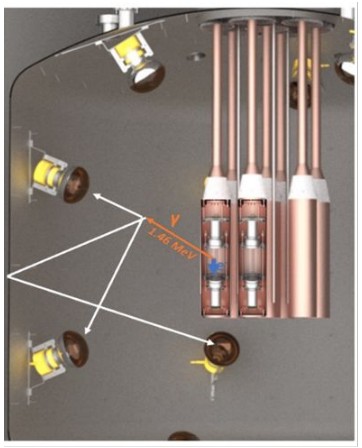
- 12 kL of linear alkyl benzene (LAB) sourced from JUNO experiment. Doped with PPO and Bis-MSB

- LAB fills vessel surrounding the crystal modules. Imaged with (nominally) 18 Hamamatu R5912 PMTs providing 4π coverage. Additional PMTs have been sourced from Daya Bay experiment and may be utilised in final setup

- Average effective light yield of ~0.12 phe / keV. Veto system provides a total background reduction of ~25%, and a reduction of ~85% for ^{40}K electron capture background events

^{40}K background

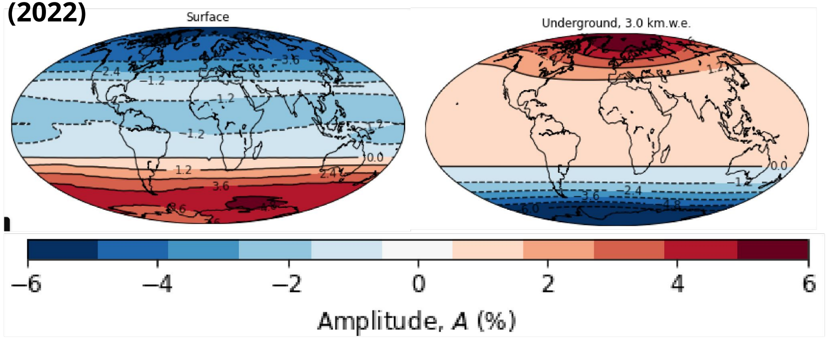




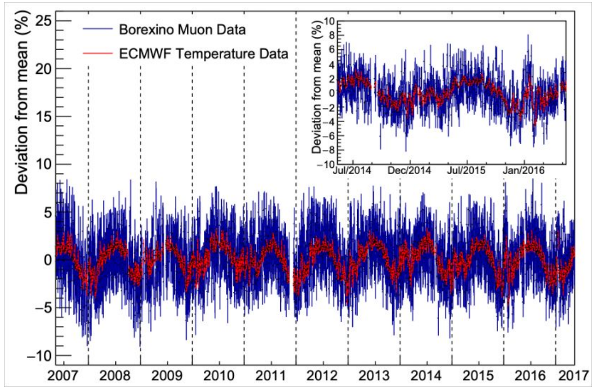
Muon veto system

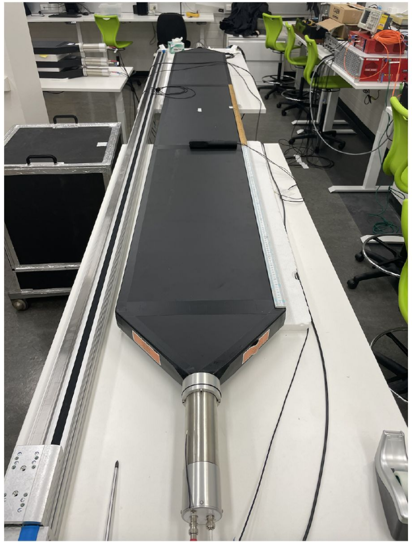
- Underground cosmic ray muon flux is known to modulate annually
- Muon interactions in cavern rock and detector materials can produce neutrons via spallation processes: these can act as background in the NaI(Tl) detectors with an annually modulating signature
- SABRE South will utilise 8 muon panels (9.6 m^2 area) above the detector. Panels made of EJ200 organic scintillator, each coupled to 2 PMTs at opposing ends
- Will act to veto crystal interactions coincident with detected muon hits

A. Fedynitch et al., ApJ 928, 27 (2022)



M. Agostini et al., JCAP02, 046 (2019)



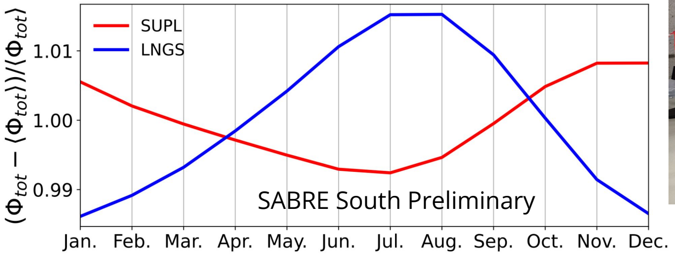


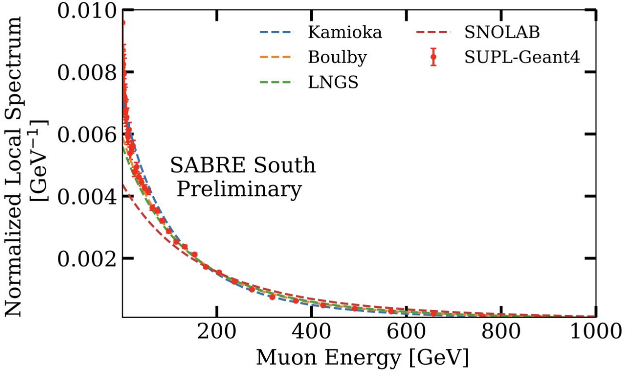
Towards muon flux measurement at SUPL

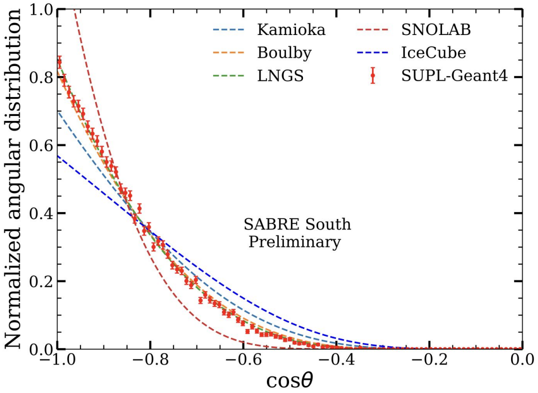
- Muon detectors should tag muons with ~99 % efficiency

- Important to characterise the muon flux precisely for background modelling. Currently taking data from muon detectors in 2 layer configuration to measure angular distribution of muon flux: map the overburden

- Long term, will also measure muon flux modulation. This information will be used to build up a detailed background model for muon-induced neutrons

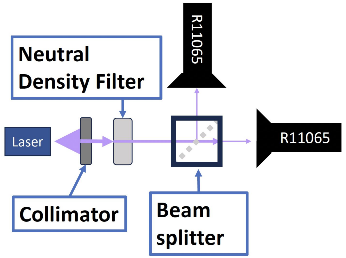


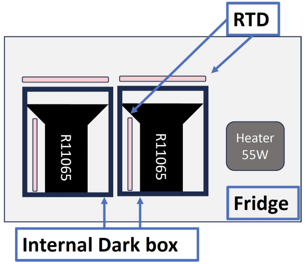


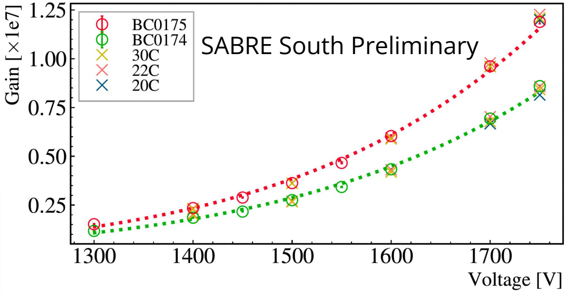


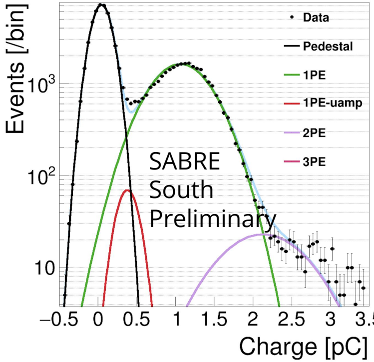
PMT characterisation

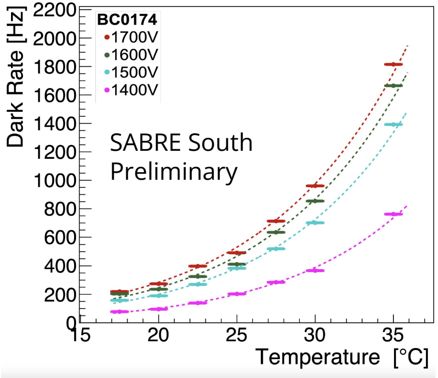
- Characterisation of PMT-related parameters such as gain, dark rate and transit time is needed for accurate modelling of PMT noise backgrounds relevant near the ROI threshold
- Characterisation performed and in-situ method of gain tracking via dark rate developed and verified
- Machine learning-based framework has been developed to reject PMT noise events
- Detailed waveform simulation framework also developed → train machine learning framework, quantify trigger selection efficiencies

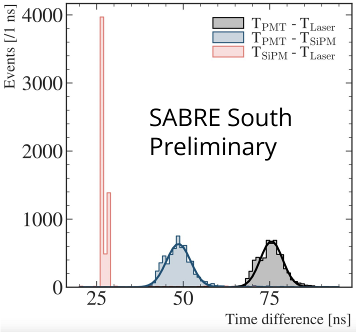












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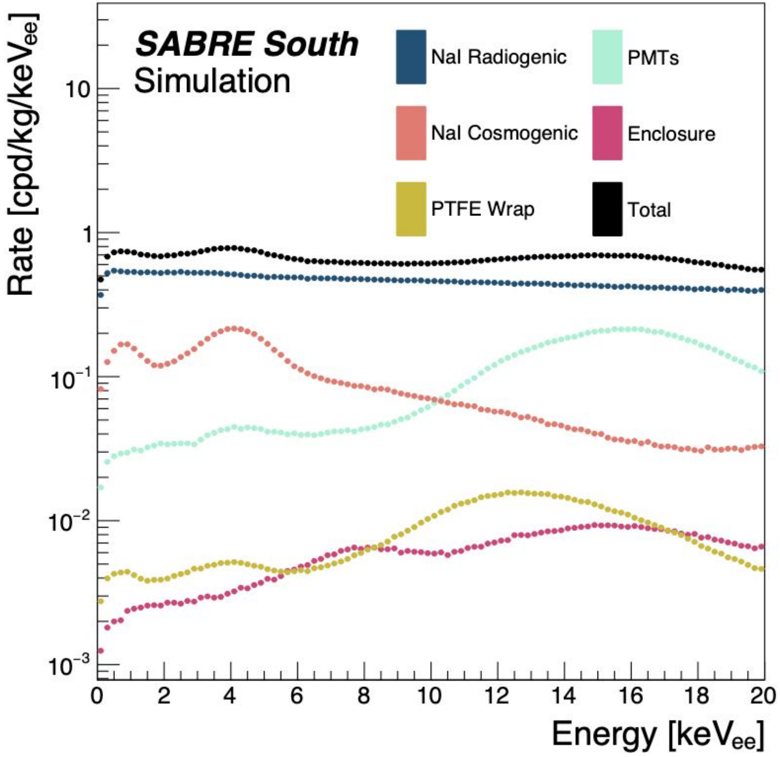
Background model

- GEANT4 simulation of SABRE South used to build preliminary background model for the experiment. Input activities informed by NaI-33 spectral fits (slide 18)

- Radiogenic background dominated by ^{210}Pb and ^{87}Rb (current conservative over-estimate). ^{40}K efficiently tagged by veto
- Will reduce cosmogenic background by minimising activation during production and transport and giving a 6 month cooldown period after crystals brought underground

- More detailed simulation framework currently in development: detailed detector responses, systematic uncertainties and modelling of calibration sources

SABRE South Collaboration, Eur. Phys. J. C 83, 878 (2023)

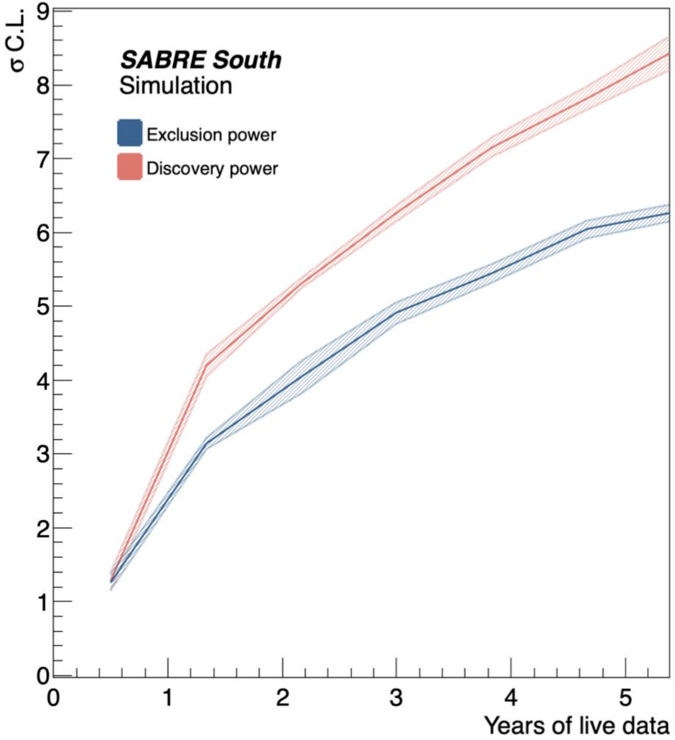


Projected sensitivity for modulation analysis

SABRE South Collaboration, Eur. Phys. J. C 83, 878 (2023)

- SABRE South alone will provide 5 σ exclusion of the DAMA/LIBRA modulation in ~2.5 years of data taking (~1.5 years for confirmation of a modulating signal) for 50 kg crystal mass and the background model of slide 23

- SABRE South will utilise a detailed background model and a frequentist inference methodology to properly account for systematic uncertainties as nuisance parameters

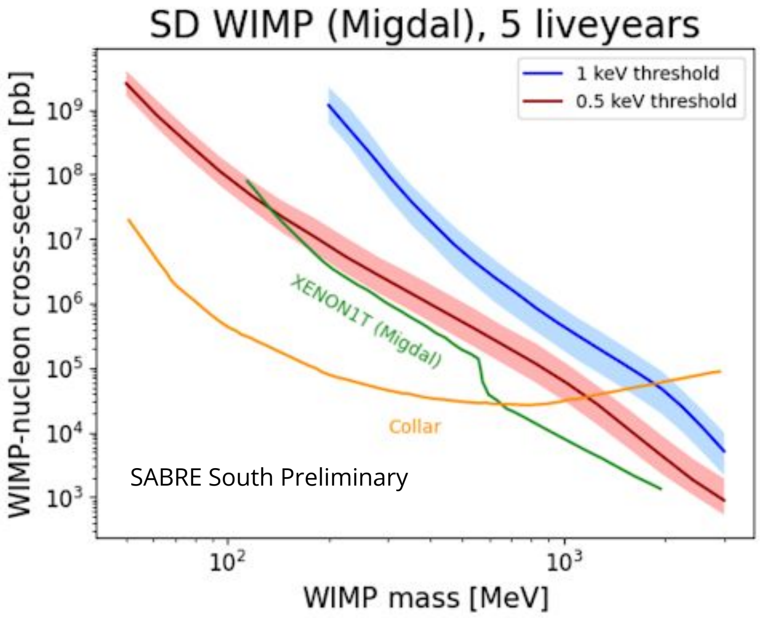


Sensitivity to spin-dependent WIMPs

- Odd number of protons in both sodium and iodine: NaI target is particularly sensitive to spin-dependent WIMP scattering

- So-called Migdal effect predicts enables a lower threshold: portion of the nuclear recoil energy is deposited in the electron recoil channel (not quenched)

- Here, we project the 90% C.L. expected upper limit over 5 live years with 50 kg crystal mass for the nominal 1 keV threshold as well as a 0.5 keV threshold that may be within reach with advanced PMT noise rejection techniques

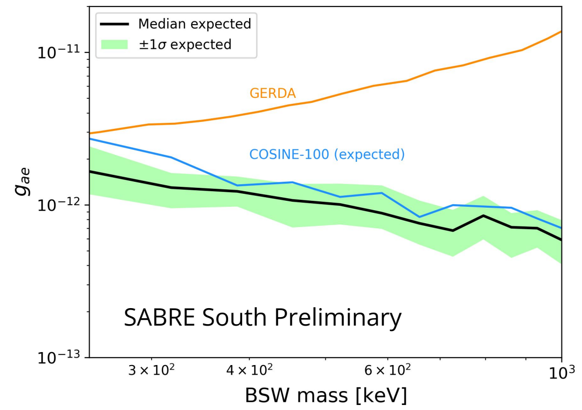


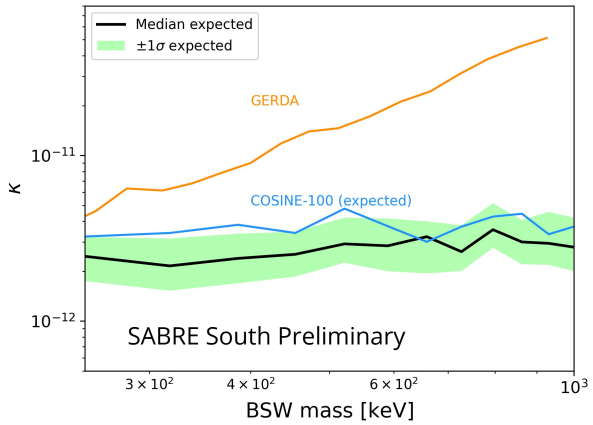
Sensitivity to bosonic super-WIMPs

- Viable keV-scale pseudoscalar and vector bosonic dark matter candidates can be proposed in EFT extensions of the Standard Model. In a bosonic scenario, couplings consistent with astrophysical bounds are accessible to direct detection experiments

- Interactions in NaI(Tl) experiments can take place via either absorption (considered here) or Compton-like scattering (deferred to future work)

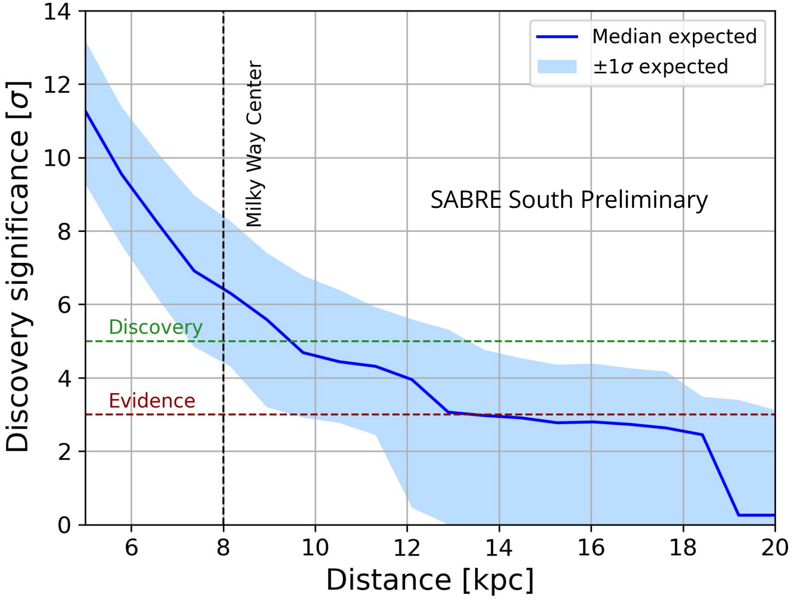
- For ~100 kg year exposure SABRE South could set world-leading constraints on these channels (current world-leading constraints from COSINE-100 [1])





Supernova neutrino detection

- LAB liquid scintillator veto system could be used as a detector for supernova neutrino scattering
- Core-collapse supernova explosion produces an intense flux of neutrinos over ~10 s
- Projected sensitivity of the SABRE South veto system to a typical (27 solar masses) core-collapse supernova explosion at different distances: currently assuming nominal number of PMTs (18)
- Potential for SABRE South to become part of the supernova early warning system (SNEWS)



Further expanding the physics programme

Model	Comments
Boosted DM (inelastic and elastic)	MeV-scale signal: multiple-scatter in the inelastic case. Certain parameter values would enable exploration of unprobed dark photon parameter space
Solar axions	Bragg-Primakoff photoconversion in crystal lattice
Pauli Exclusion Principle violation	Search for exotic nuclear transitions that would only be allowed given a small level of PEP violation. Direct muon hits dominant background, muon veto will aid this search
Upscattered MIDM	Currently has no direct experimental constraints – signal from upscattering of MIDM in the Earth's crust, then a decay into a photon in the detector volume. Scales with volume not mass, so promising channel via the LS veto

The SABRE South Technical Design Report

Summary and outlook

- SABRE dual-site project will deploy NaI(Tl) detectors in the Northern and Southern Hemispheres to enable a model-independent test of the DAMA/LIBRA modulation in a way that can negate seasonal effects
- SABRE South currently undergoing commissioning at the Stawell Underground Physics Laboratory in VIC, Australia. Full deployment expected by end of 2025
- Exclusion of discovery results expected 2-3 years after data taking begins
- SABRE North TDR submitted for review; if approved, installation will begin in 2025
- MoU under draft between SABRE North/South, COSINE and ANAIS collaborations to work towards a sharing of knowledge and potential joint analyses

Acknowledgements

SABRE South

Australian Government
Australian Research Council

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