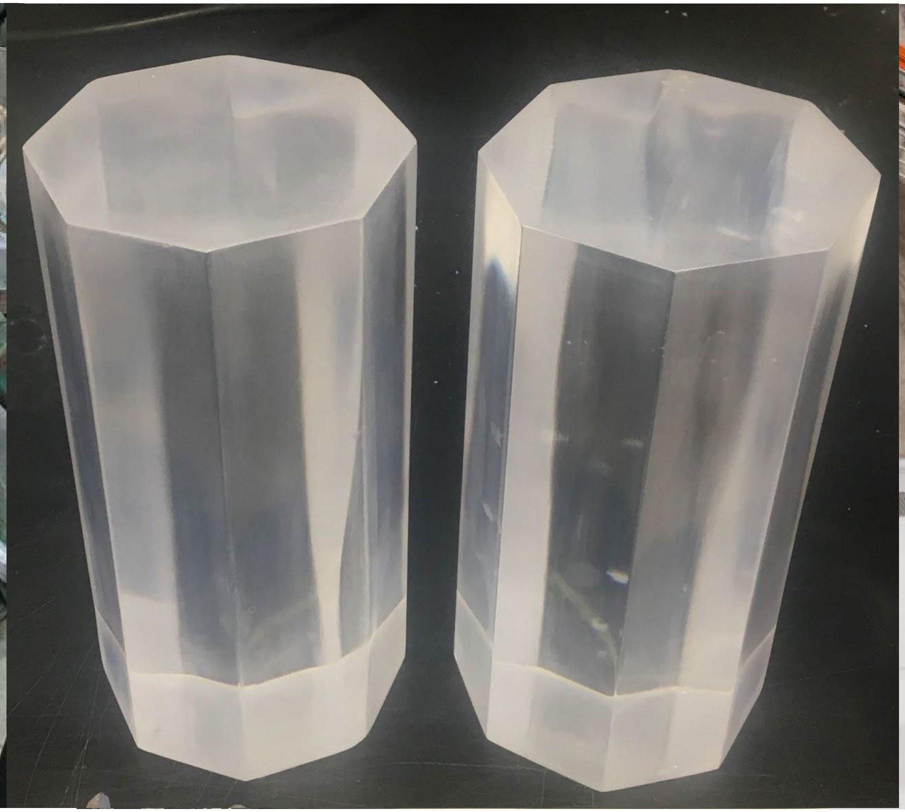
  

The SABRE South Experiment
at the Stawell Underground Physics Laboratory

Peter McNamara on behalf of the SABRE South Collaboration

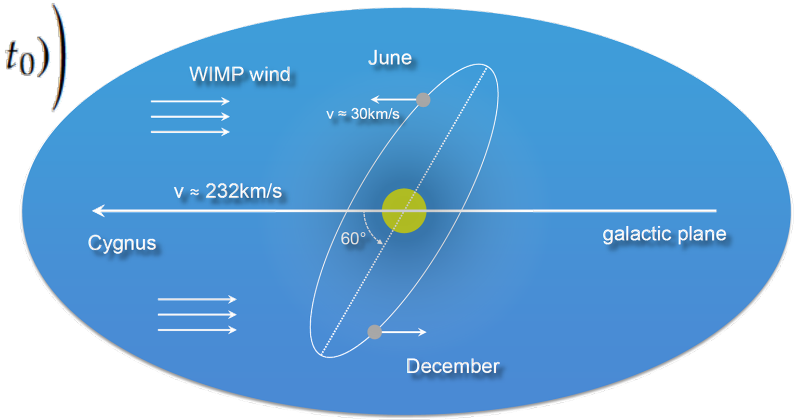
ARC Centre of Excellence for Dark Matter Particle Physics · The University of Adelaide · KEK High Energy Accelerator Research Organization · The University of Melbourne · Australian National University · The University of Sydney · Swinburne

Annual Modulation Signature – DAMA/LIBRA

Astrophysical predictions of DM distribution imply a modulating signal due to Earth's rotation around the Sun

- Period of a year with a peak in June
- Expected to be detected at low recoil energy (keV)

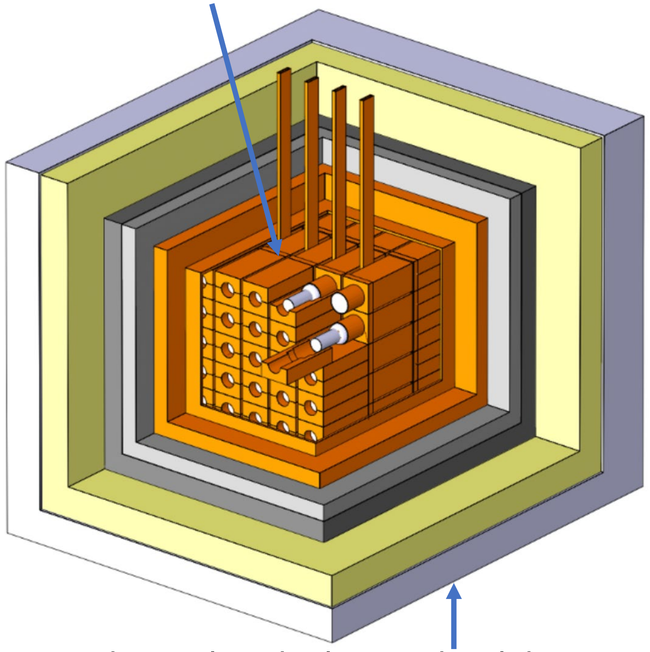
$$R(t) = B(t) + S_0 + S_m \cos\left(\frac{2\pi}{1\ \text{year}}(t - t_0)\right)$$



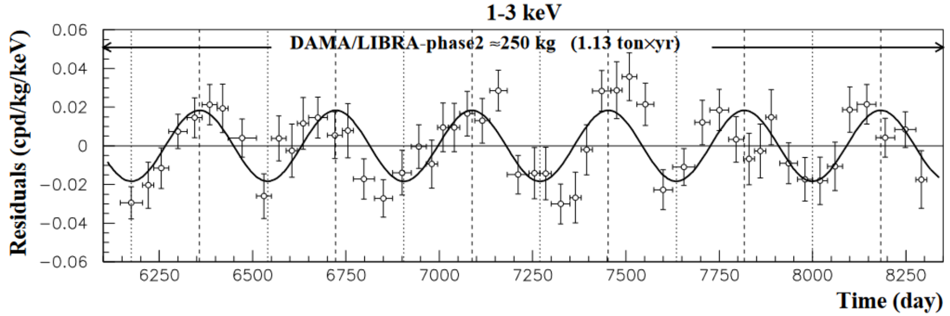
DAMA using NaI(Tl) crystals has observed a modulation consistent with these expectations for about 20 years with ~13σ CL

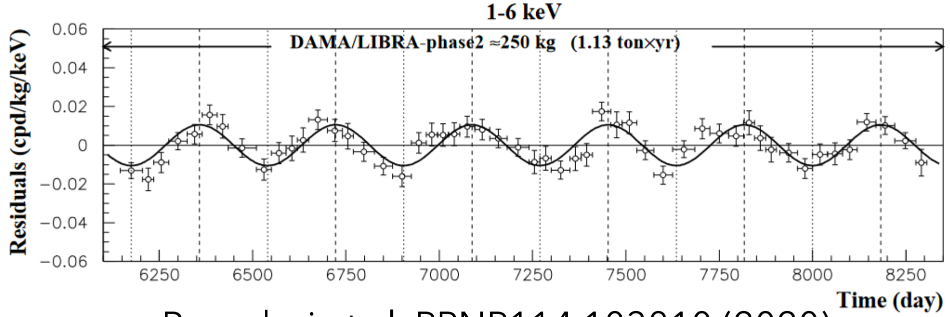
- Upper rate of ~0.8 cpd/kg/keV

25 NaI(Tl) crystals in Cu enclosures



Cu, Pb, polyethylene shielding

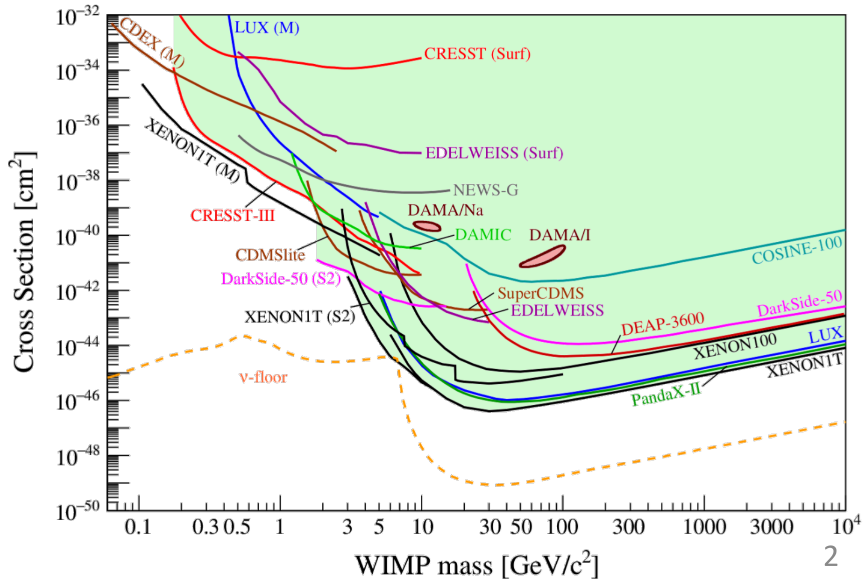




Bernabei et al. PPNP114 103810 (2020)

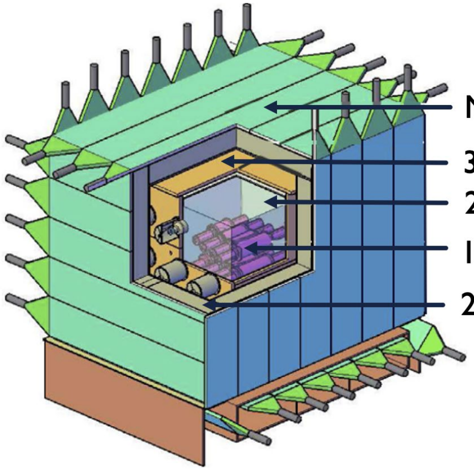
This result is constrained by null results from other experiments

- However need to use same target



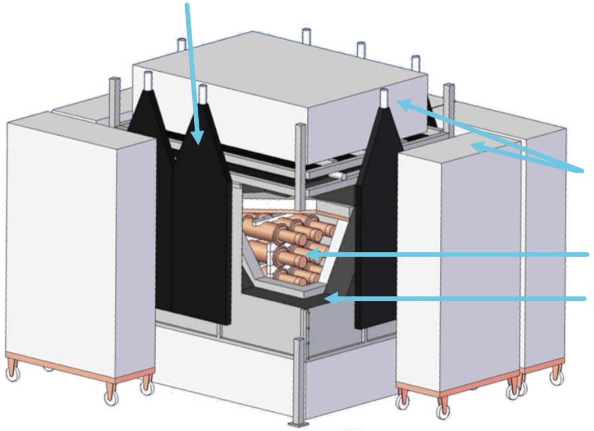
Other NaI(Tl) Experimental Results

COSINE

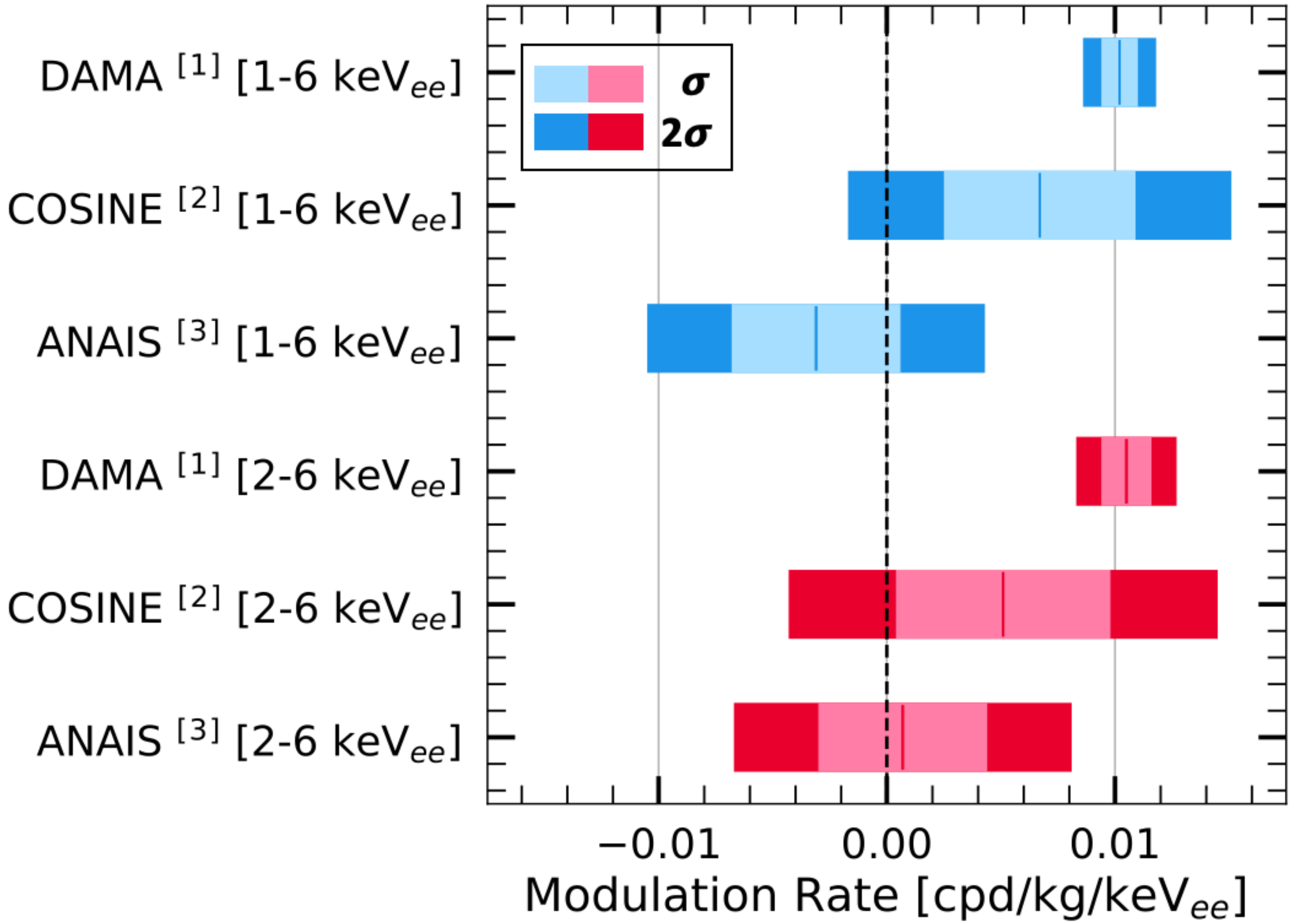


Phys. Rev. D 106,052005 (2022)

ANAIS



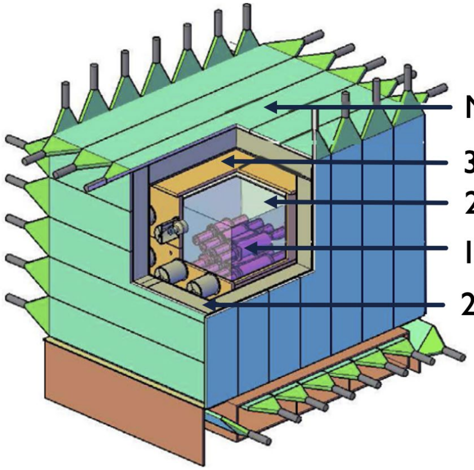
Phys.Rev.D 103 (2021) 10,102005



1] PPNP 114, 103810 (2020
[2] PRD 106, 052005 (2022)
[3] arxiv 2404.17348

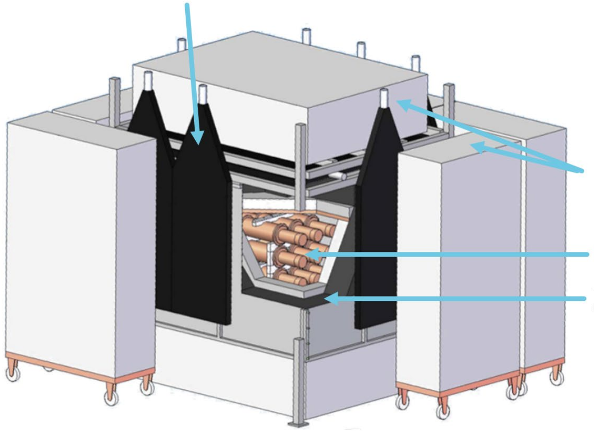
Other NaI(Tl) Experimental Results

COSINE

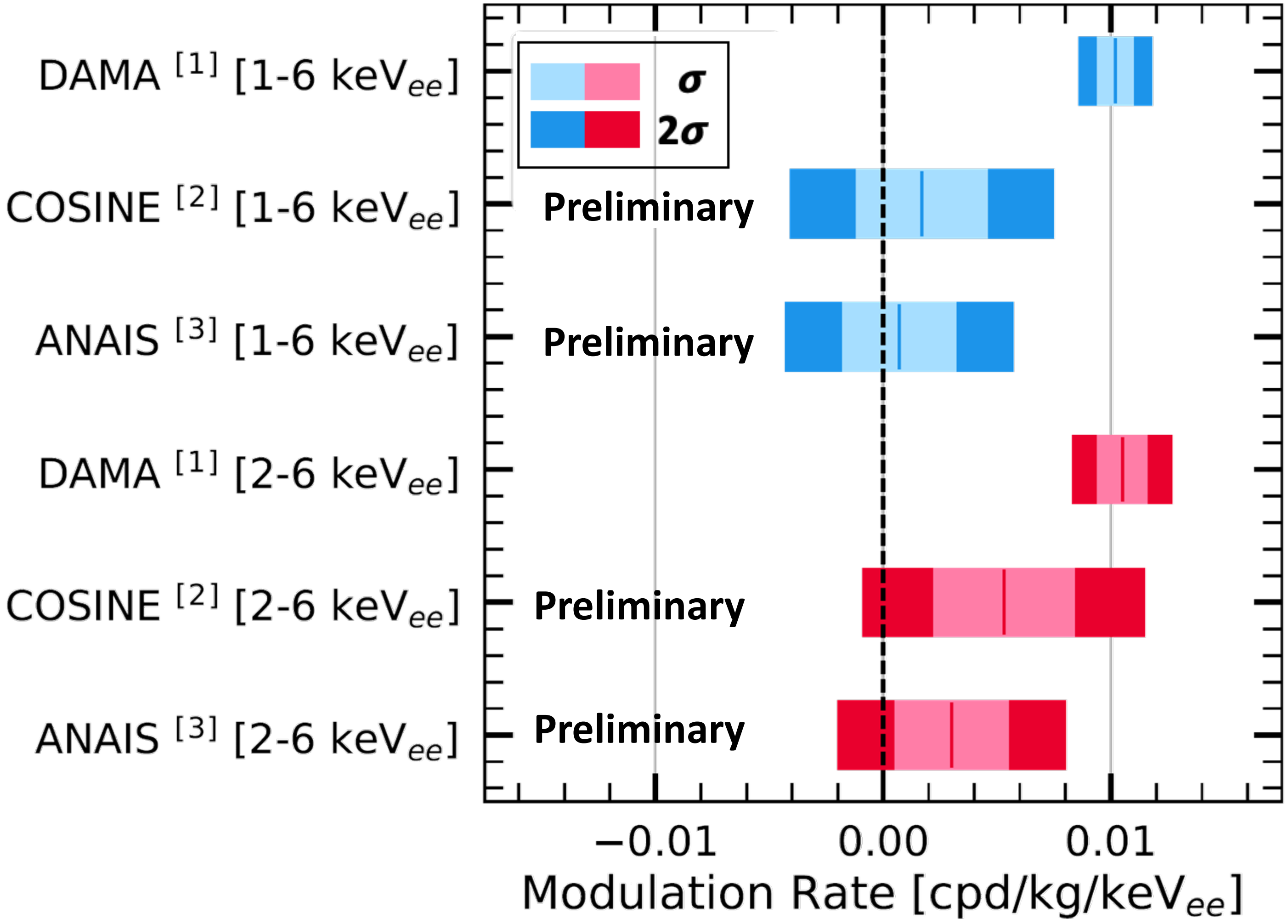


Phys. Rev. D 106,052005 (2022)

ANAIS



Phys.Rev.D 103 (2021) 10,102005



[2,3] Preliminary numbers shown at IDM 2024
Numbers from NaI summary by A. Ianni t.ly/Lv3Np

SABRE: A Dual Site Experiment

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

SWINBURNE

RMD A Dynasil Company

MELLEN Coast to coast and around the globe

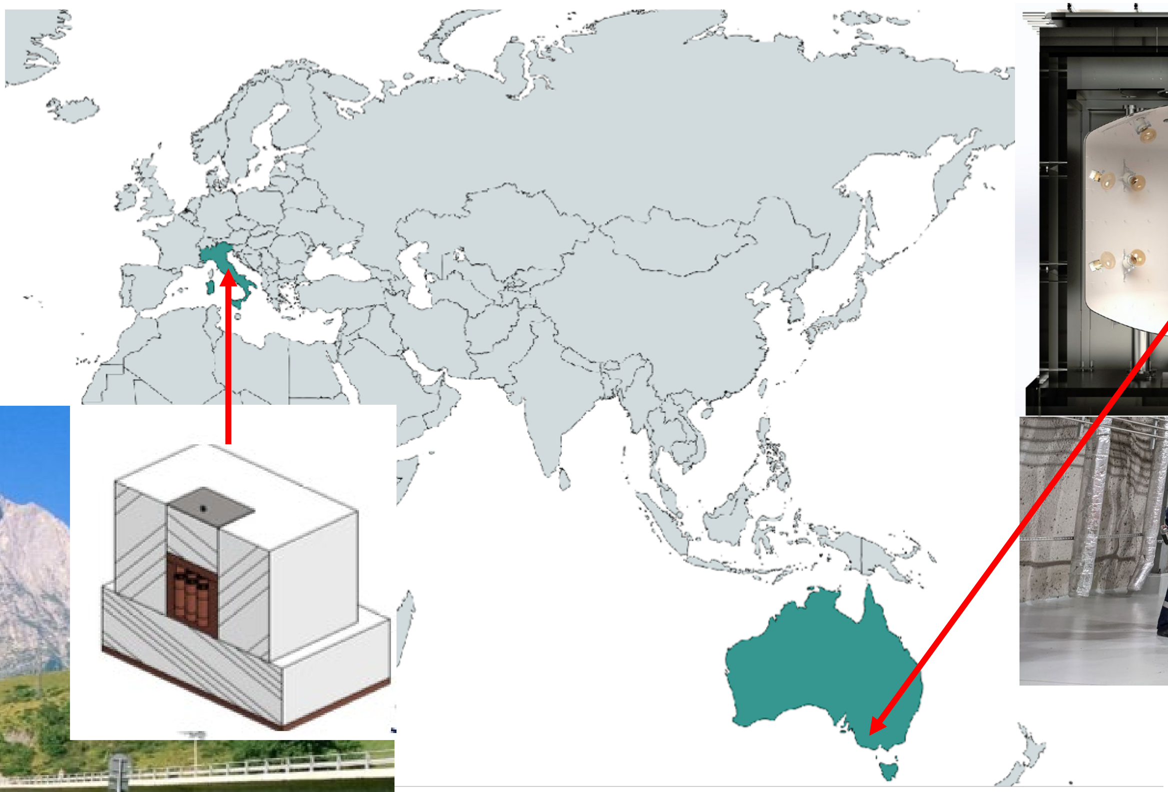
PRINCETON UNIVERSITY

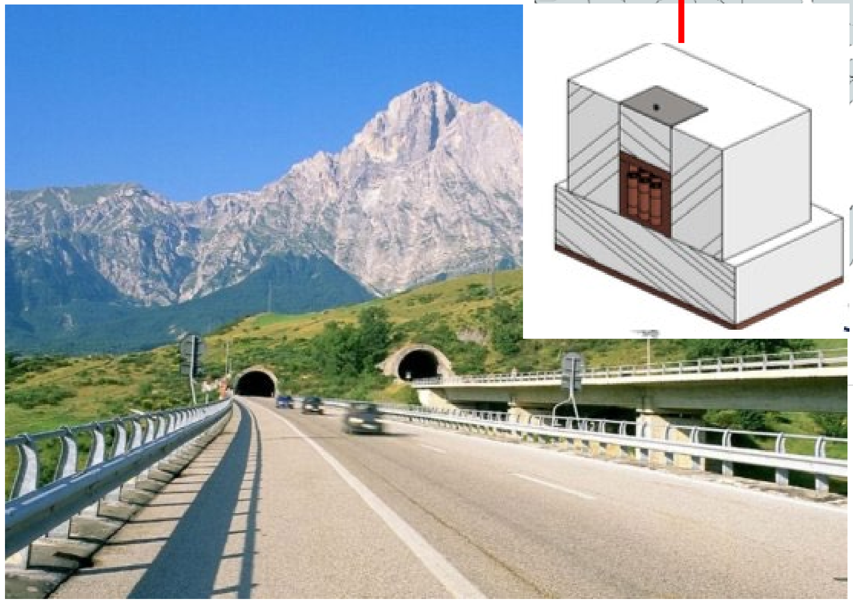
INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

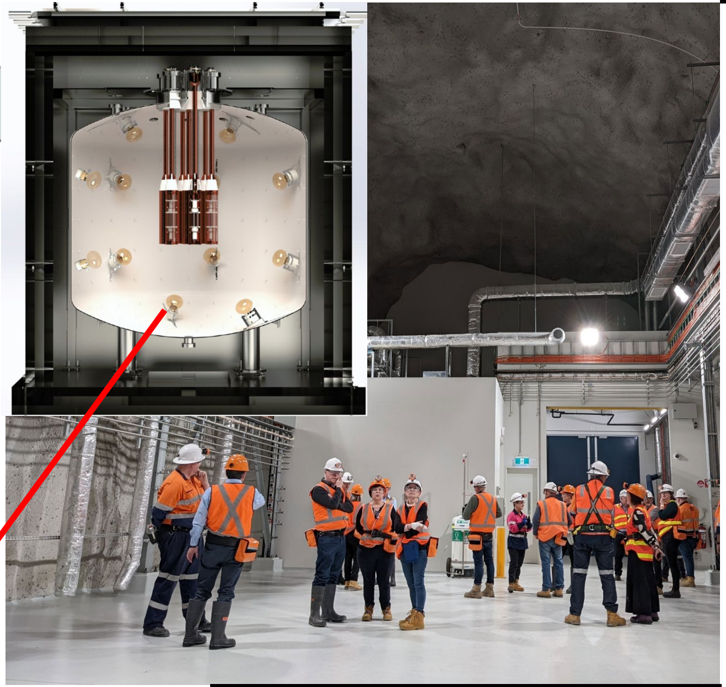
SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO

UNIVERSITÀ DEL SALENTO







STAWELL UNDERGROUND PHYSICS LAB

KEK High Energy Accelerator Research Organization

THE UNIVERSITY OF MELBOURNE

Australian National University

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY of ADELAIDE

The SABRE Collaboration

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

Stawell Underground Physics Lab (SUPL)

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

First deep underground laboratory in the Southern Hemisphere completed in 2022/2023

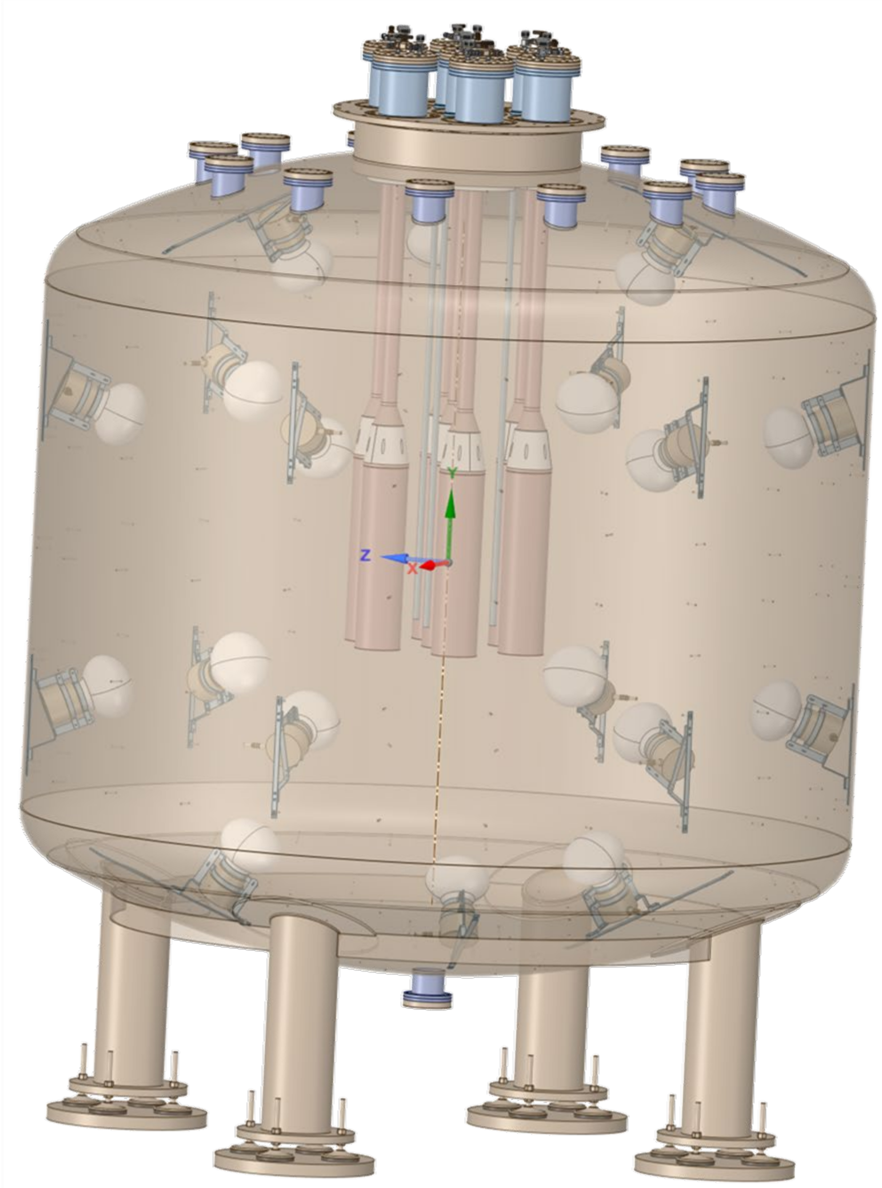
- 1025 m deep (2900 m water equivalent) with flat overburden

Located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia, Helical drive access

Muon detectors have been installed for muon flux measurements and are currently collecting data.
The first detectors set-up at SUPL:

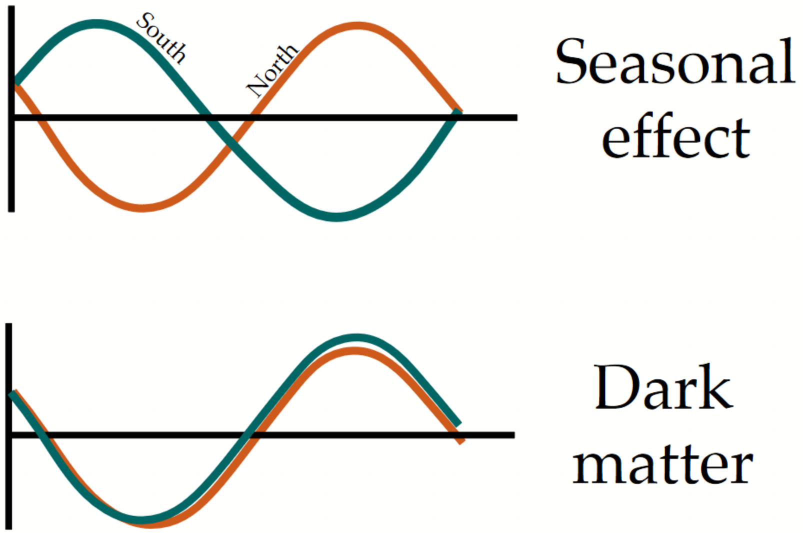
1. measure of muon flux and angular distributions;
2. provides the first test of the remote data acquisition system (DAQ) and processing pipelines

SABRE South



Key features:

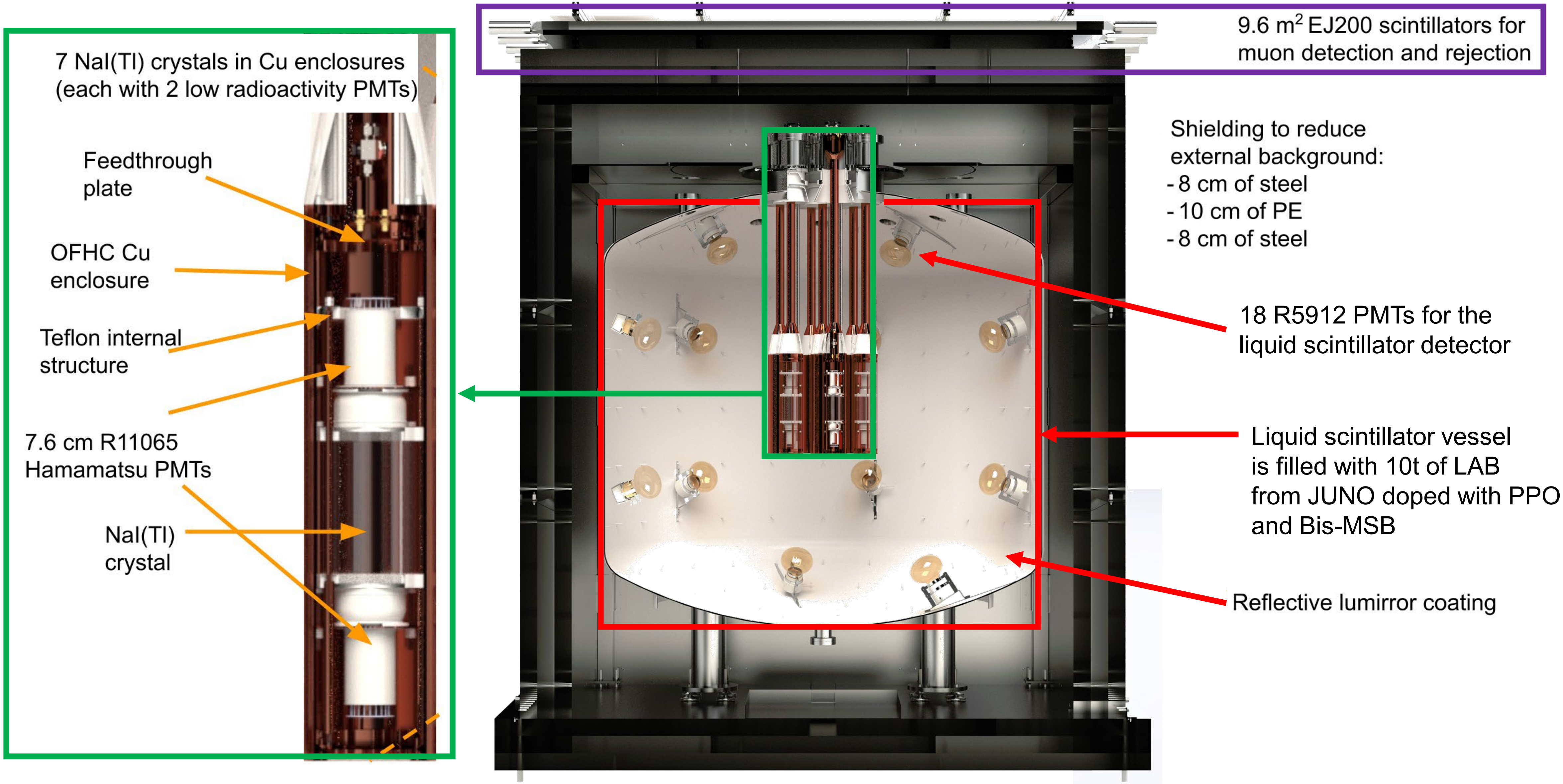
- High purity crystals
- Low energy threshold
- Active veto to detect & reject background
- Ability to measure background properties
- Southern hemisphere location



C. J. O'Hare

The SABRE South Experiment

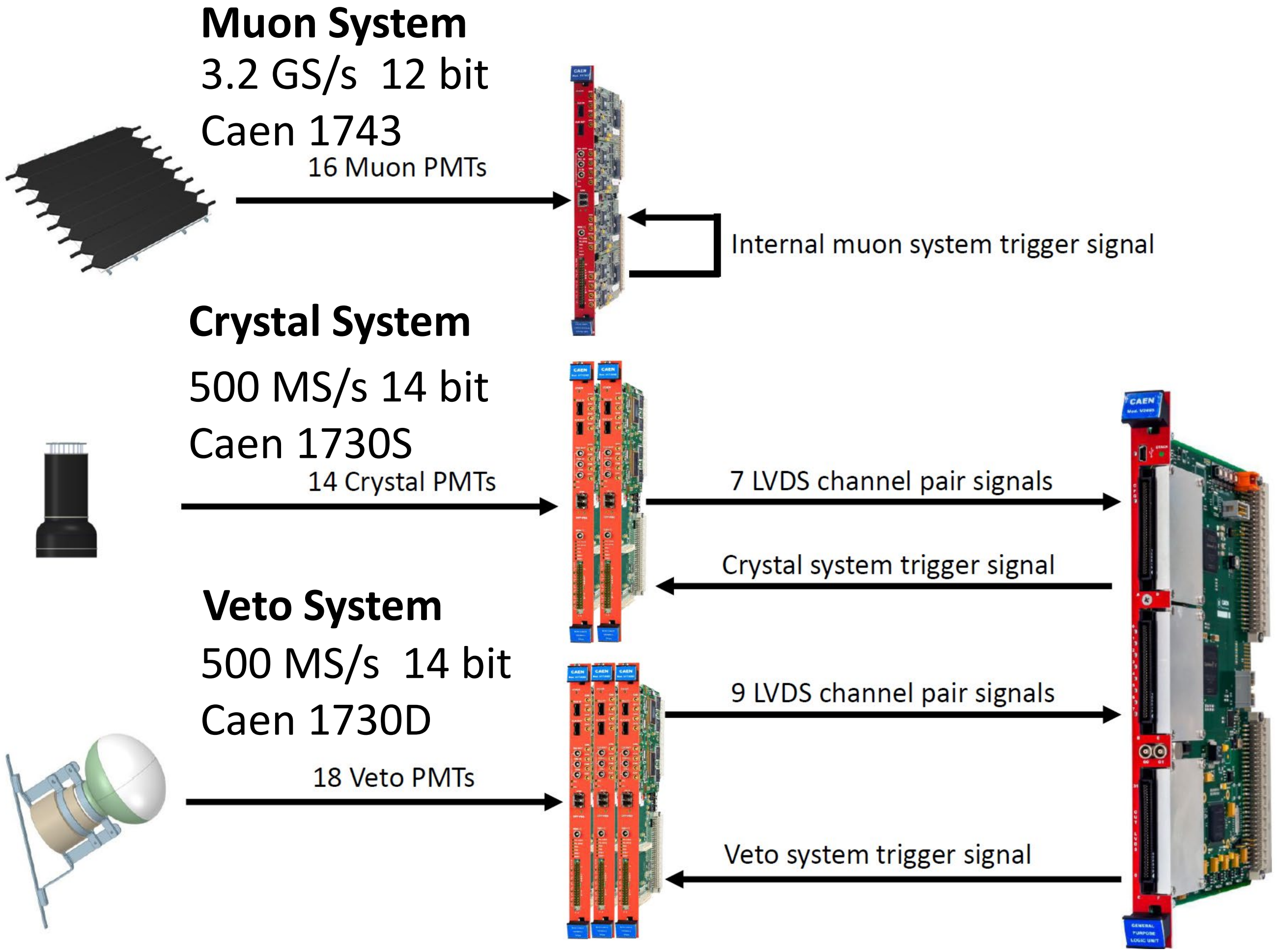
3 detector systems: **Crystal**, **Liquid Scintillator** and **Muon** detectors



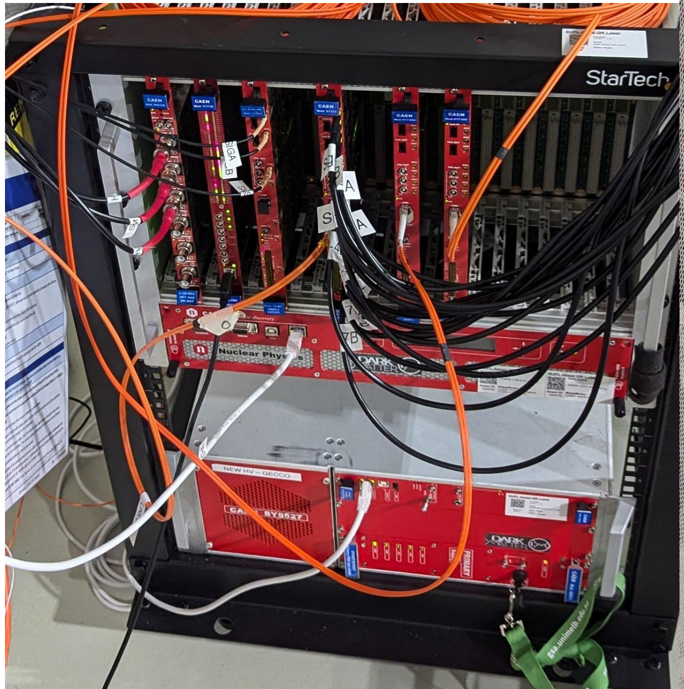
SABRE South Data Acquisition

Designed to acquire PMT waveforms at high rates

- Hardware trigger followed by transfer to and processing on dedicated computers



Already 3 DAQ instances operational in SUPL for muon and crystal measurements



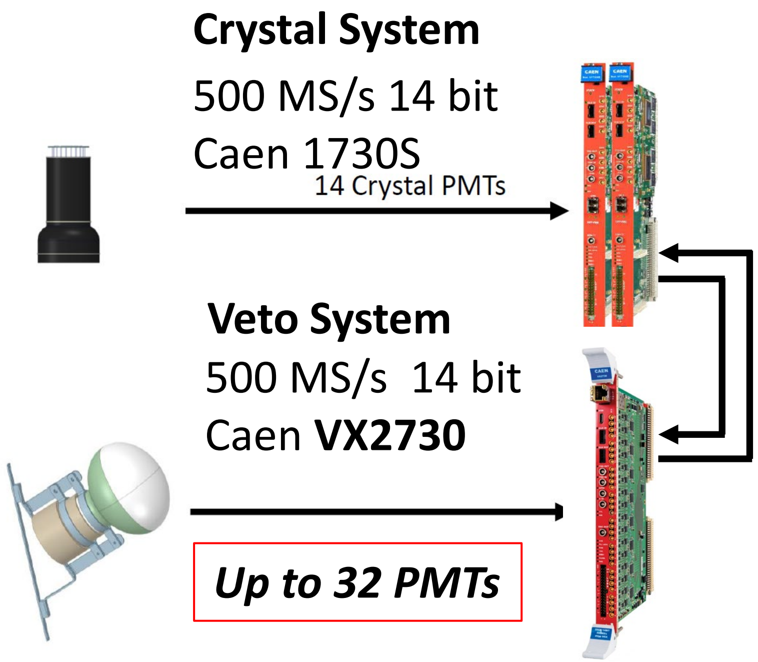
SABRE South - Improvements

New digitizer has been obtained for the liquid scintillator veto

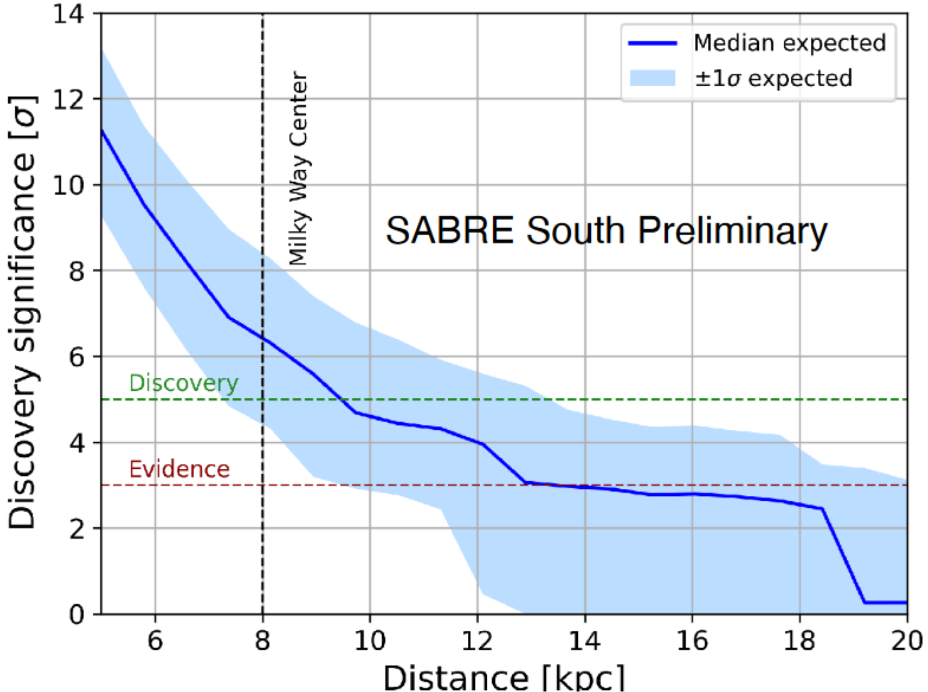
- More channels (32) allows additional PMTs (from Daya Bay experiment)
- FPGA allows for custom signal processing and triggering onboard

Investigating new trigger strategies for:

- Better background measurement using the liquid scintillator at SUPL
- Other non-WIMP physics processes such as galactic supernova neutrinos



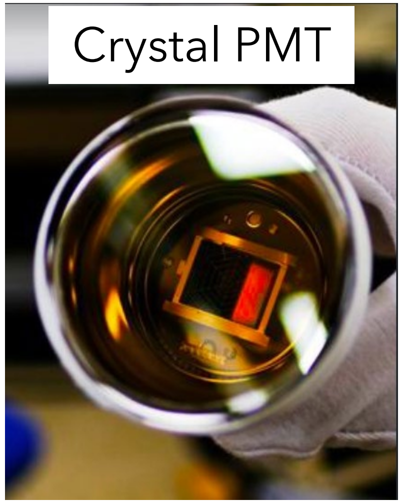
Preliminary sensitivity studies are being performed



PMT Pre-Characterisation

Extensive program to test and pre-characterise PMTs

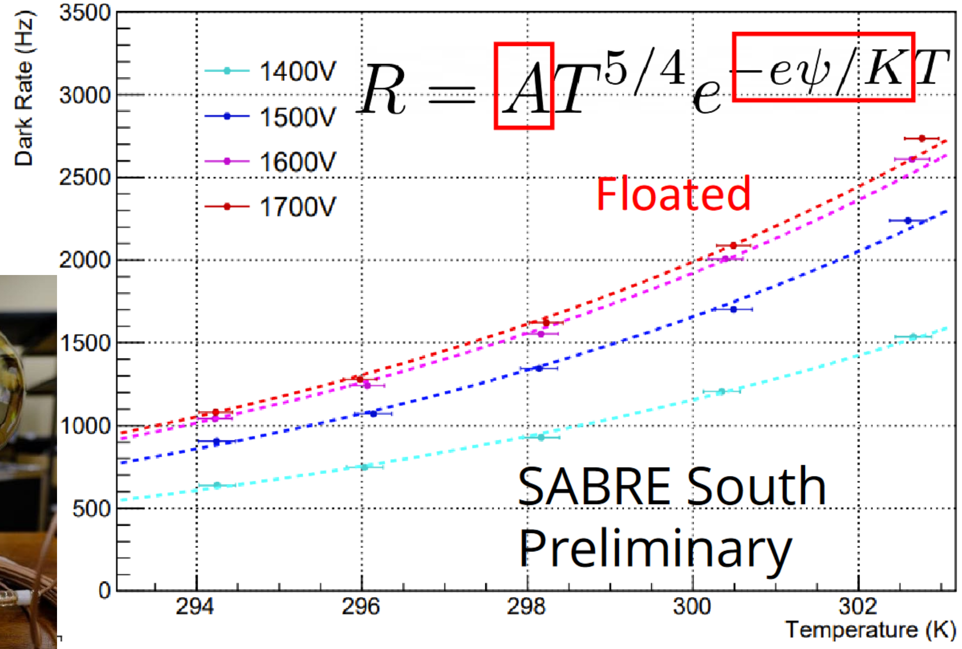
- Understand response of PMTs and their noise characteristics
  - Important for achieving reliable results and low thresholds (~kev, 12 phe)



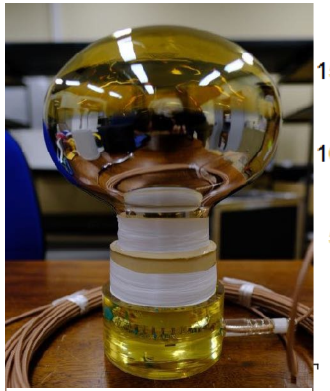
Crystal PMT

Measuring / Testing:

- Quantum efficiency
- Single phe response and gain
- Dark rate and temperature dependence
- Linearity/saturation
- Afterpulsing
- Dynamic range



Developing noise classifiers



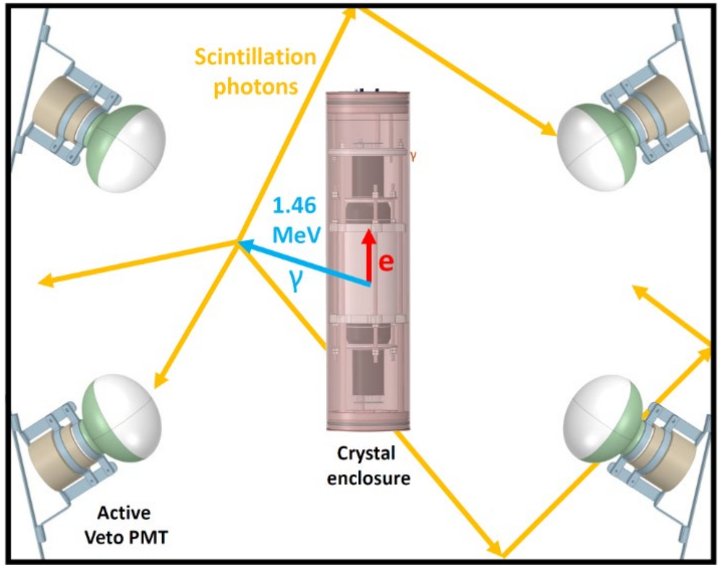
Veto PMT

Paper coming soon

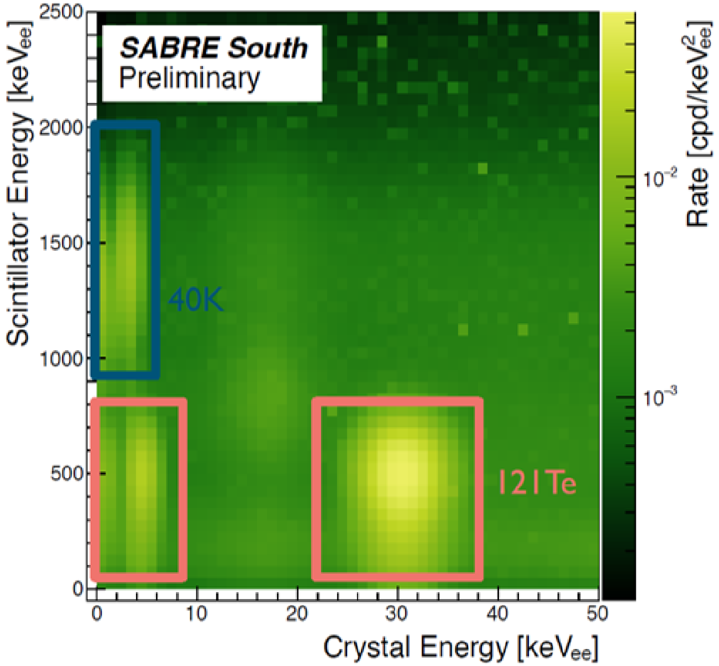
Liquid Scintillator Detector, an Active Veto

Liquid scintillator surrounds the crystal detectors

- Primary purpose is to detect particles or decay products that interact with both the crystals and liquid scintillator
  - For example ^{40}K decays ~ factor of 10 reduction
- Average light yield of about 0.12 phe/keV
- Small scale prototype used to study the properties
- Possible to use for particle ID as well as some position info
  - Combined crystal + LS can do in situ measurements



Bulk tank of LAB from JUNO ready for use



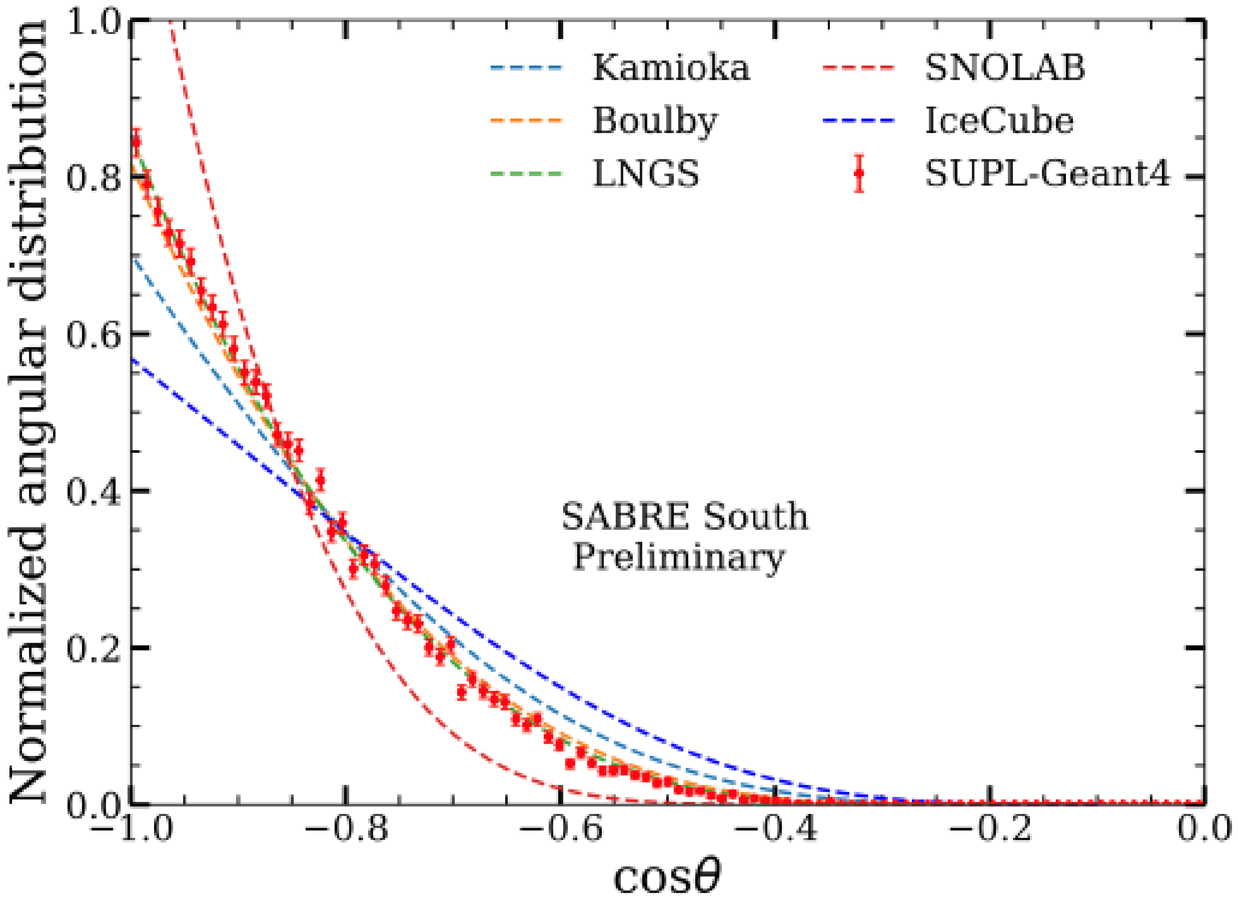
Muon Detector

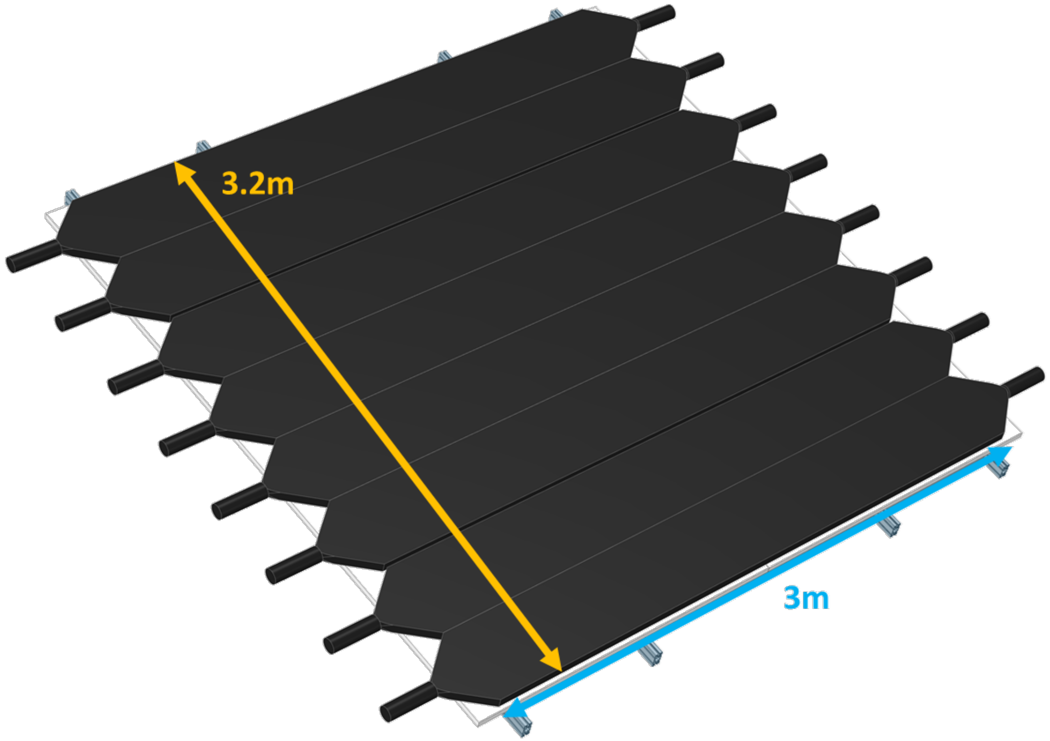
Eight 3m long detector paddles, PMTs at each end

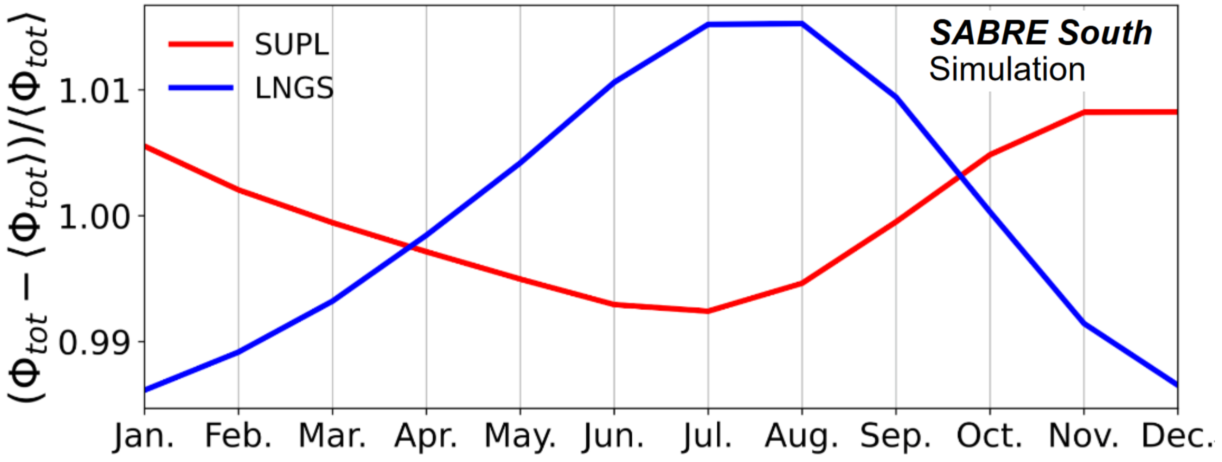
Used to veto majority of cosmic rays & for particle ID

- Now measuring angular muon flux in SUPL

400 ps timing resolution gives ~5cm position resolution





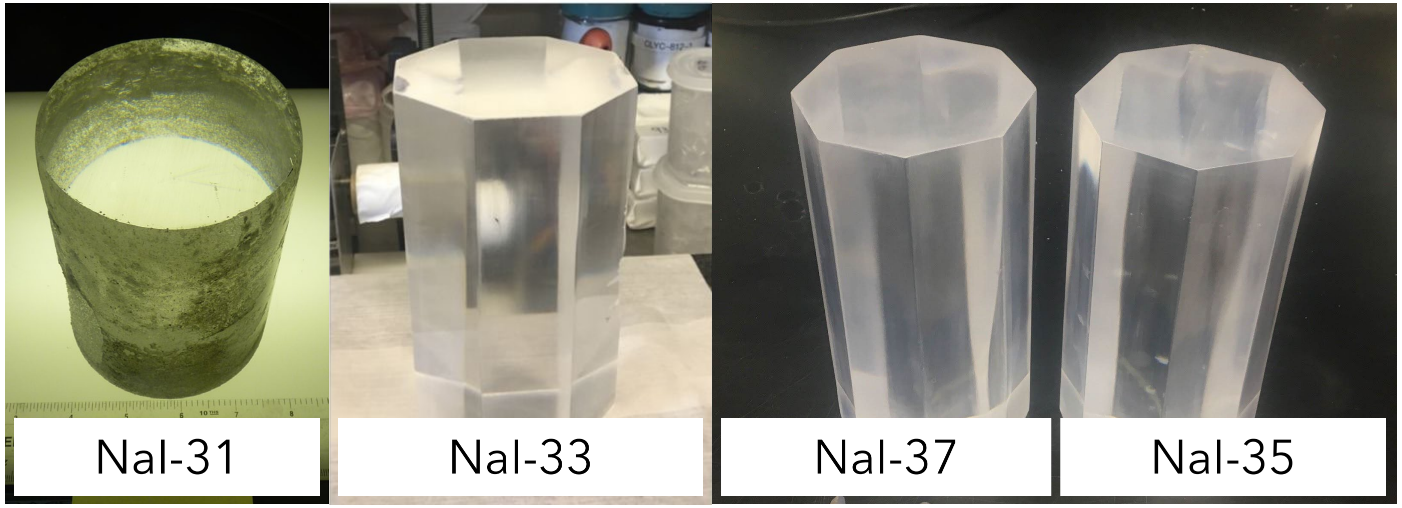


High Purity NaI(Tl) Crystals

Ultra pure Astro Grade NaI powder from R&D with Merck

A number of test crystals have been grown, and tested at LNGS

- Light yield 9-12 phe/keV



SABRE have developed some of the lowest background crystals

	^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)
DAMA [1]	13	0.7-10	(5-30) x 10^{-3}	0.5-7.5
ANAIS [2]	31	< 0.81	1.5	0.36
COSINE [3]	35.1	< 0.12	1-1.7	<2.4
SABRE [4]	4.3	0.4	0.51	0.2
PICOLON [5]	<20	-	< 5.7 x 10^{-3}	-

[1] NIMA 592 (3) (2008), [2] EPJC 79 412 (2019), [3] EPJC 78 490 (2018)
[4] Phys. Rev. Research 2, 013223 (2020), Eur Phys.J.C 81 (2021) 4, 299, Phys. Rev. D 104, 021302 (2021)
[5] PTEP 4 043F01 (2021)

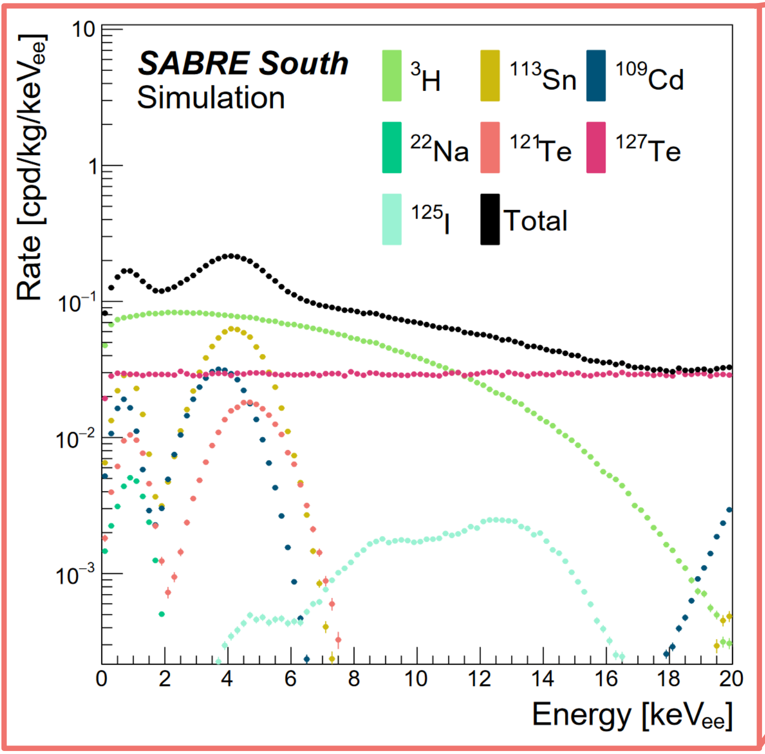
High Purity NaI(Tl) Crystals

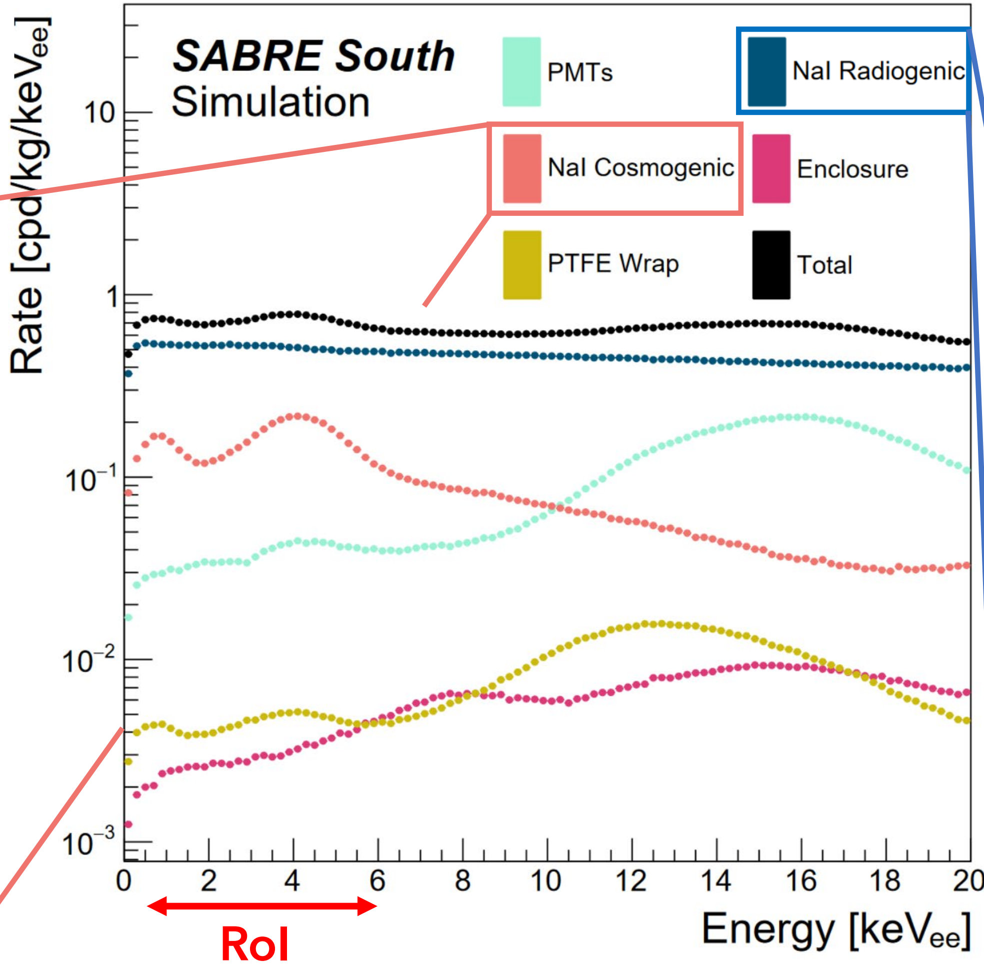
Eur.Phys.J.C 83 (2023) 9, 878

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

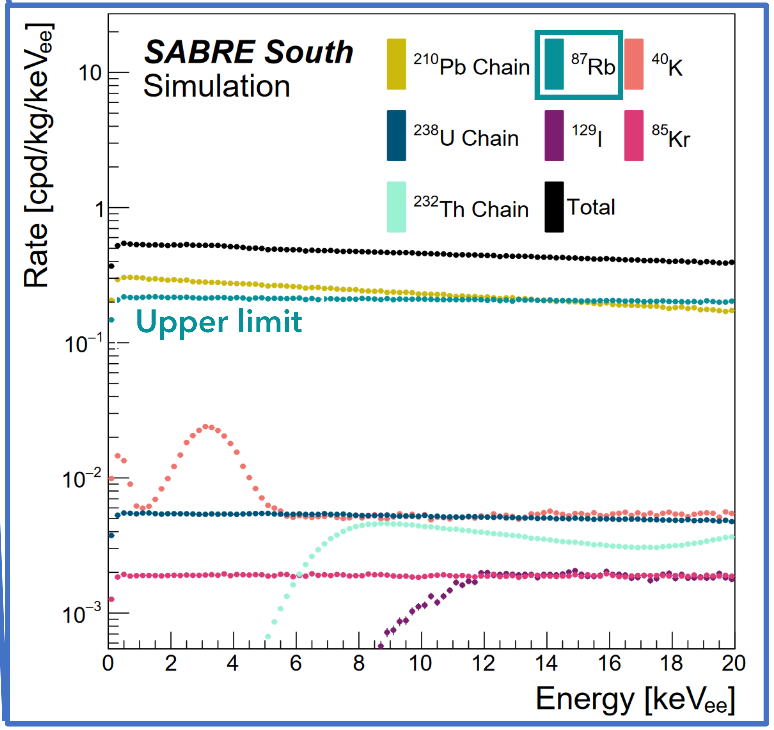
Crystal background is ~94% of the total

Cosmogenic background is ~22%, dominated by ^{3}H





Radiogenic background is ~72% of the total

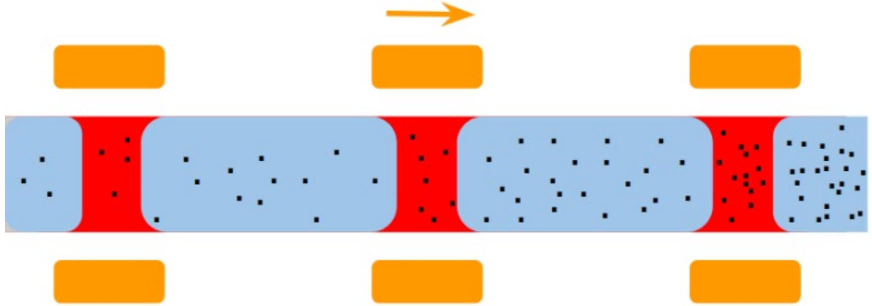


Key contaminants: ^{3}H, ^{40}K, ^{210}Pb

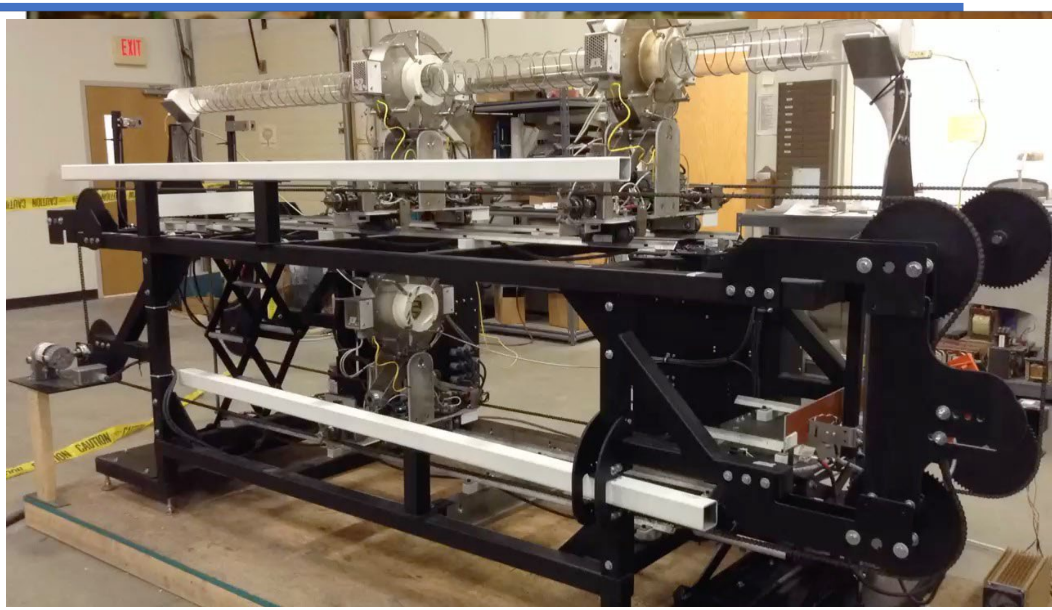
*After 6 month cool down

Higher Purity NaI(Tl) Crystals - Zone Refining

- Aim to further reduce impurities by zone refining the powder prior to growth
- Impurities are segregated to one side of the ingot by the moving ovens



- Tested on NaI Astro Grade powder by Princeton group at Mellen.
- Ampoule preparation and handling by RMD
- Zone refining will reduce significantly internal background components.

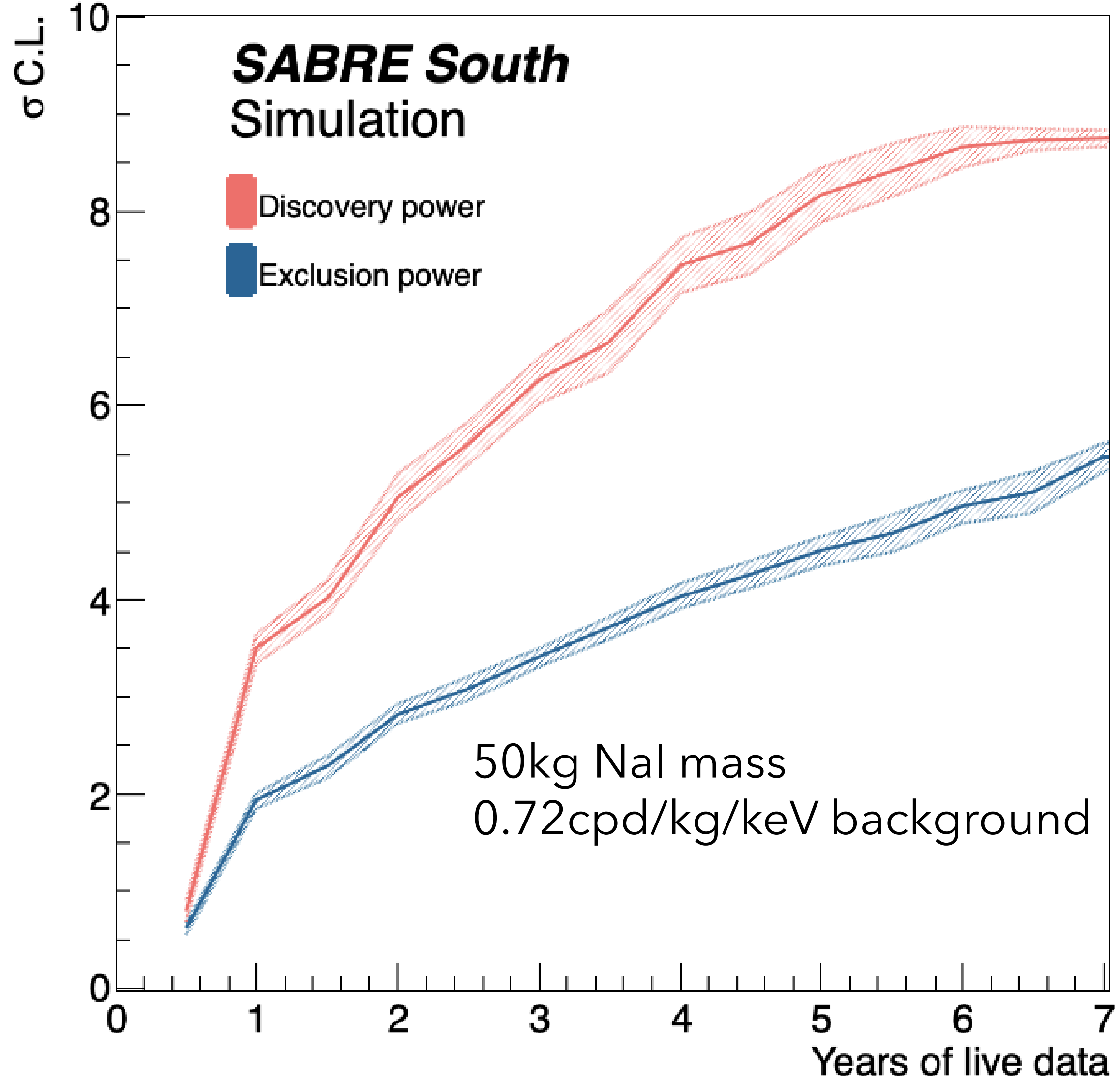


Isotope	Impurity Concentration (ppb)					
	Powder	S_1	S_2	S_3	S_4	S_5
^{39}K	7.5	<0.8	<0.8	1	16	460
^{208}Pb	1.0	0.4	0.4	<0.4	0.5	0.5
^{85}Rb	<0.2	<0.2	<0.2	<0.2	<0.2	0.7
^{24}Mg	14	10	8	6	7	140
^{133}Cs	44	0.3	0.2	0.5	3.3	760
^{138}Ba	9	0.1	0.2	1.4	19	330

B. Suerfu, Phys. Rev. Applied 16, 014060 (2021)

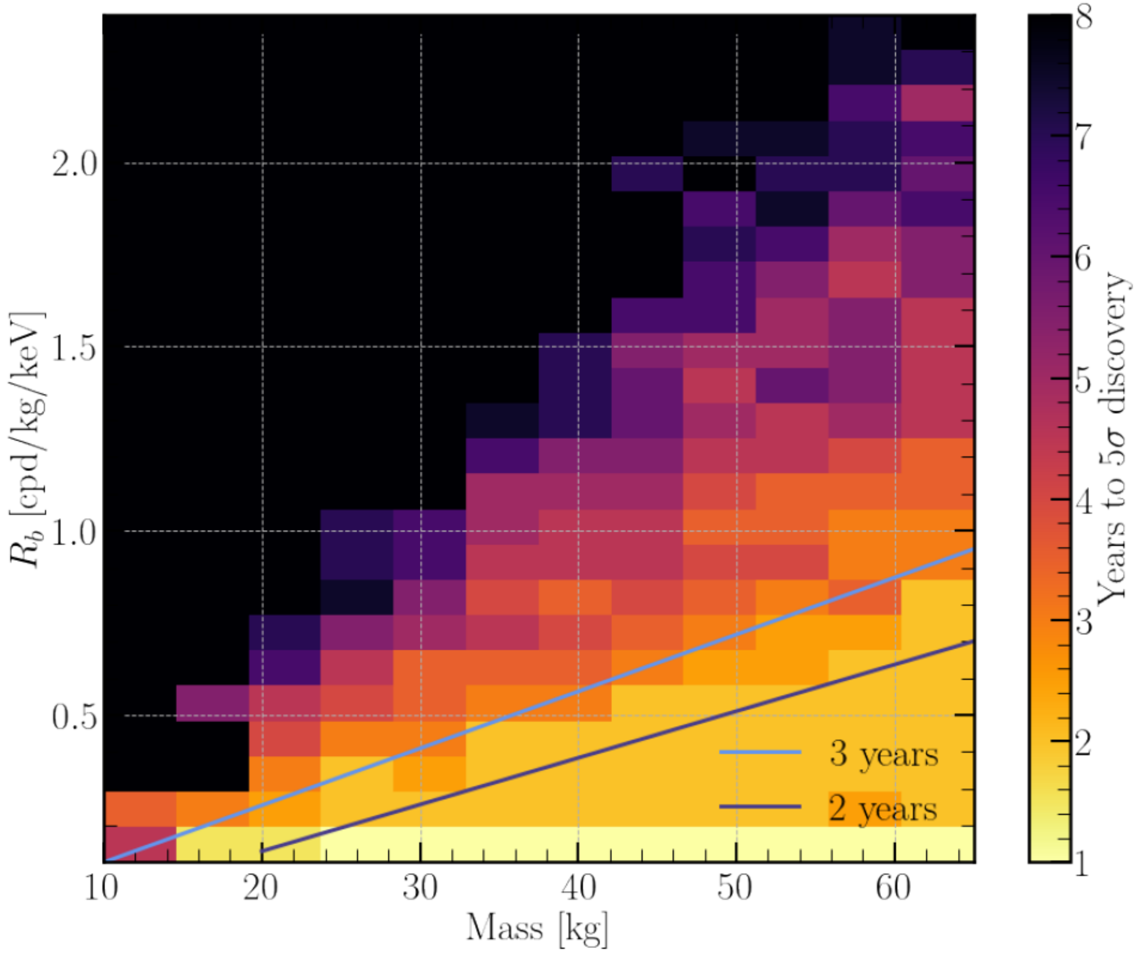
SABRE Sensitivity

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



Scales approximately as $\sqrt{M_E/R_b}$

For similar performance 35kg of NaI would require <0.5 cpd/kg/keV



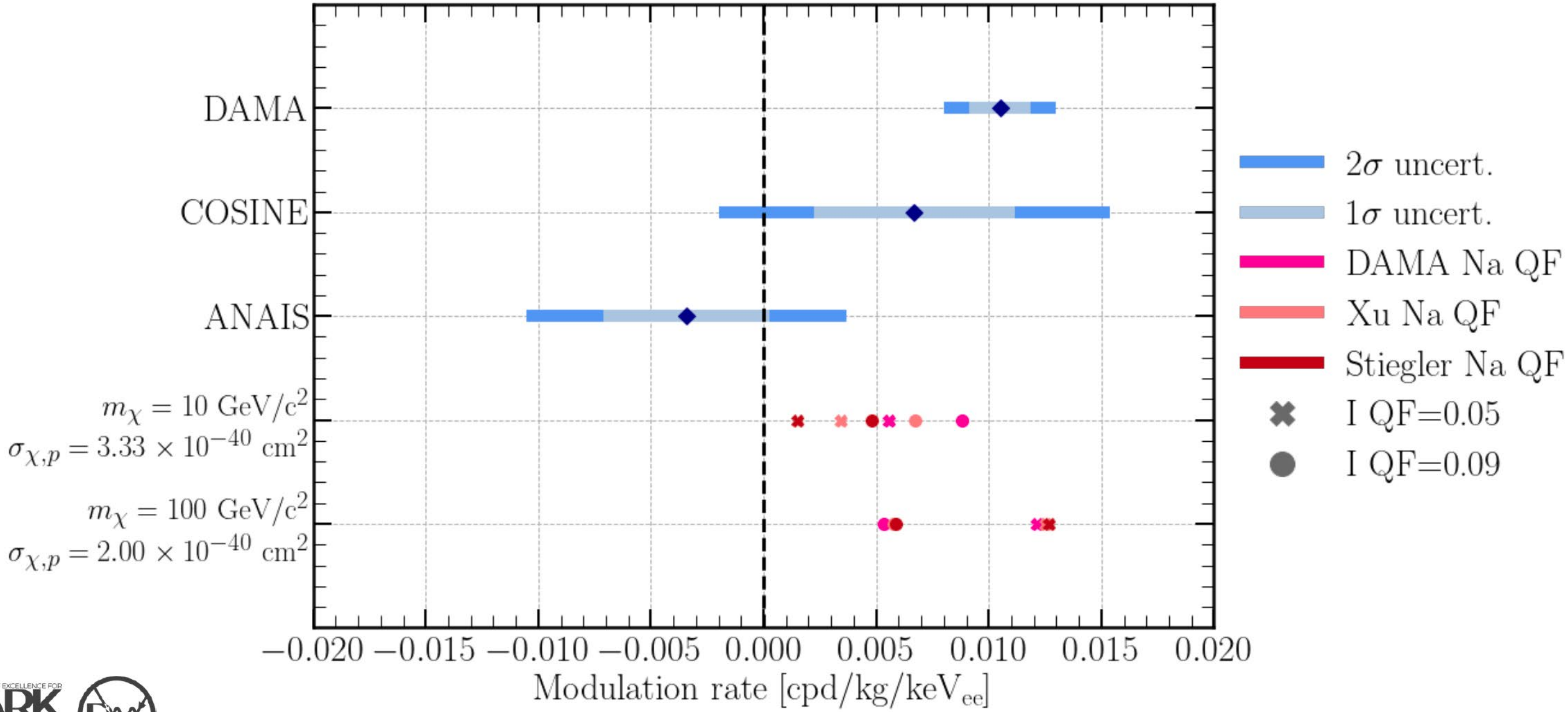
Summary

- SABRE is a dual site experiment with two very similar detectors
  - SABRE North at LNGS in Italy
  - SABRE South at SUPL in Australia
- Focusing on ultra-high purity NaI(Tl) crystals
- Taking data underground in SUPL, starting early this year
- SABRE South construction to start towards the end of this year, full deployment in 2025
  - Vessel, LAB, PMTs, gas handling and crystal insertion system all ready
  - Muon detectors and DAQ already in use underground
- Expect discovery or exclusion results after about 2.5 years of continuous operation (with a single site)
  - SABRE South TDR
  - Background paper
  - Induced modulation study

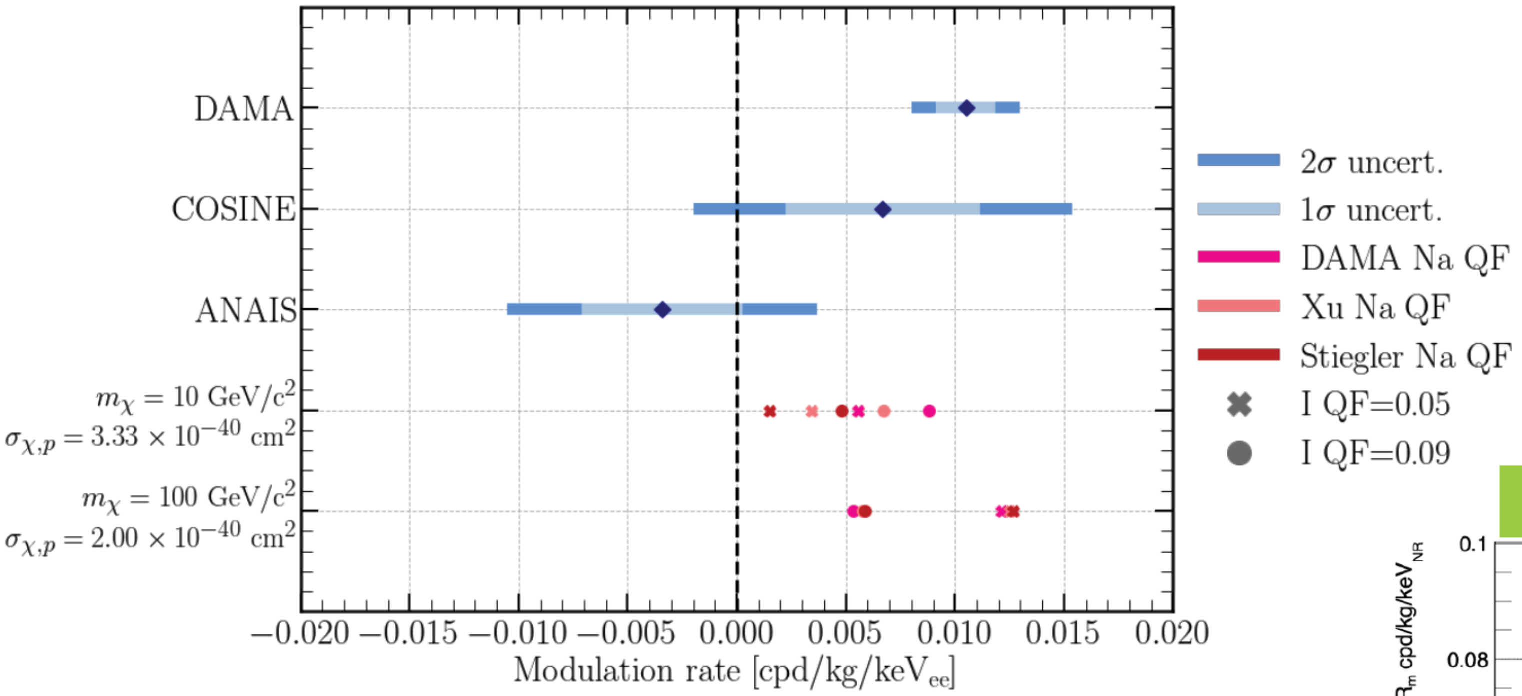
https://www.sabre-experiment.org.au

Backup

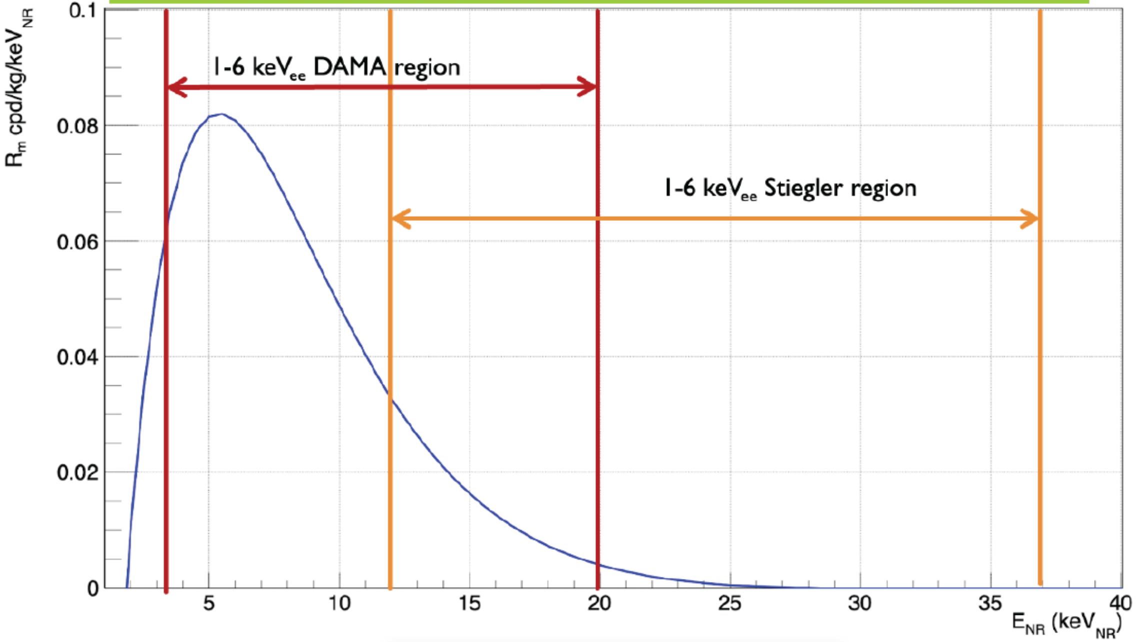
M. Zurowski, SciPost Phys.Proc. 12 (2023) 027



M. Zurowski, arXiv: 2211.15861



WIMP NR in NaI(Tl) with $\sigma \sim 3.33 \times 10^{-40}$ cm^2



SABRE publications

1. E. Shields et al., SABRE: A New NaI(T1) Dark Matter Direct Detection Experiment, Physics Procedia 61 (2015) 169 – 178
2. M. Antonello et al., The SABRE project and the SABRE Proof-of-Principle, Eur.Phys.J.C 79 (2019) 4, 363
3. M. Antonello et al., Monte Carlo simulation of the SABRE PoP background, Astropart.Phys. 106 (2019) 1-9
4. B. Suerfu et al., Growth of ultra-high purity NaI(Tl) crystals for dark matter searches, Phys.Rev.Res. 2 (2020) 1, 013223
5. M. Antonello et al., Characterization of SABRE crystal NaI-33 with direct underground counting, Eur.Phys.J.C 81 (2021) 4, 299
6. F. Calaprice et al., High sensitivity characterization of an ultrahigh purity NaI(Tl) crystal scintillator with the SABRE proof-of-principle detector, Phys.Rev.D 104 (2021) 2, L021302
7. B. Suerfu et al., Zone Refining of Ultrahigh-Purity Sodium Iodide for Low-Background Detectors, Phys.Rev.Applied 16 (2021) 1, 014060
8. F. Calaprice et al., Performance of the SABRE detector module in a purely passive shielding, Eur.Phys.J.C 82 (2022) 12, 1158
9. E. Barberio et al., Simulation and background characterisation of the SABRE South experiment, arXiv:2205.13849 (accepted by EPJ-C)

SABRE North status

Proof-of-Principle phase (1 crystal + active veto) concluded

- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, **lowest since DAMA/LIBRA**.

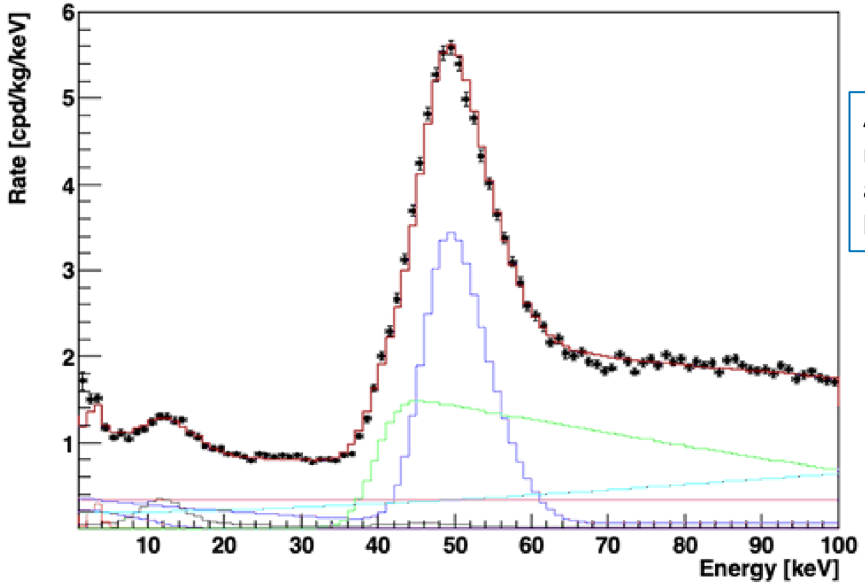
Goals for near future:

- Test reproducibility of crystal radiopurity
- Demonstrate lower background with zone refining of NaI powder

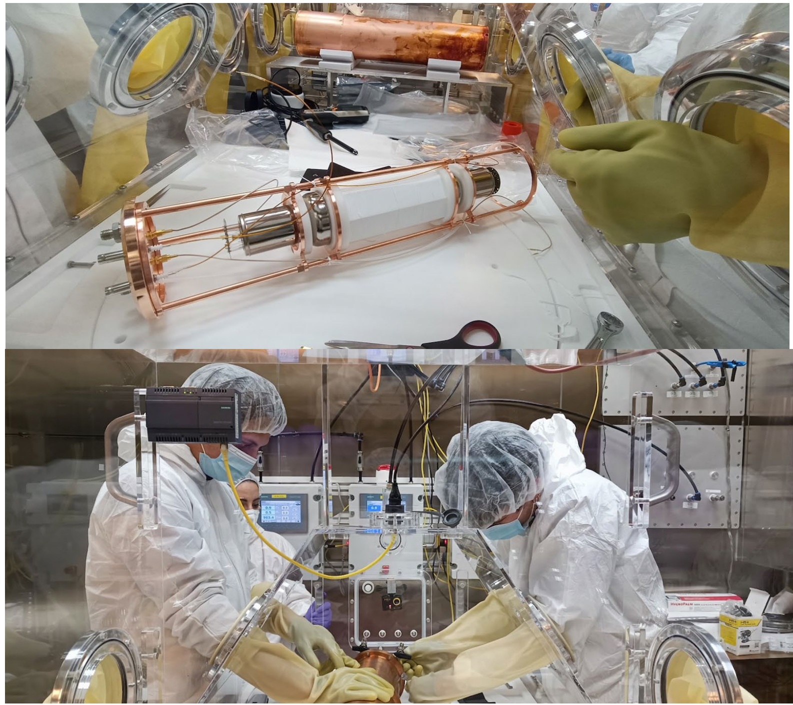
High radiopurity copper shielding in SABRE area @LNGS Hall B

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

Full Monte-Carlo simulation model of crystal NaI-33 to identify background components



Assembly of detector modules at LNGS with a new custom glove box



SABRE North status

Two low background NaI(Tl) crystals (NaI-31 and NaI-33) tested and characterised.

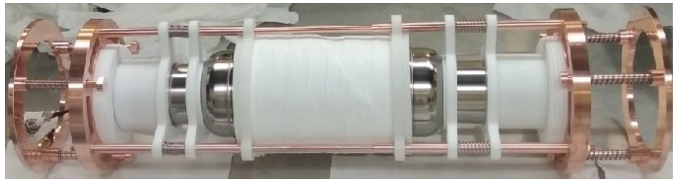
Proof-of-principle phase (1 crystal + active veto) concluded.

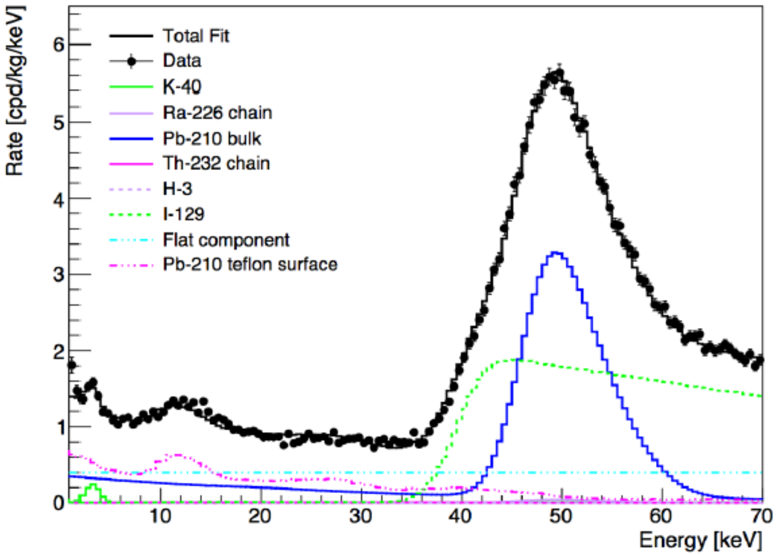
Results:

- 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.

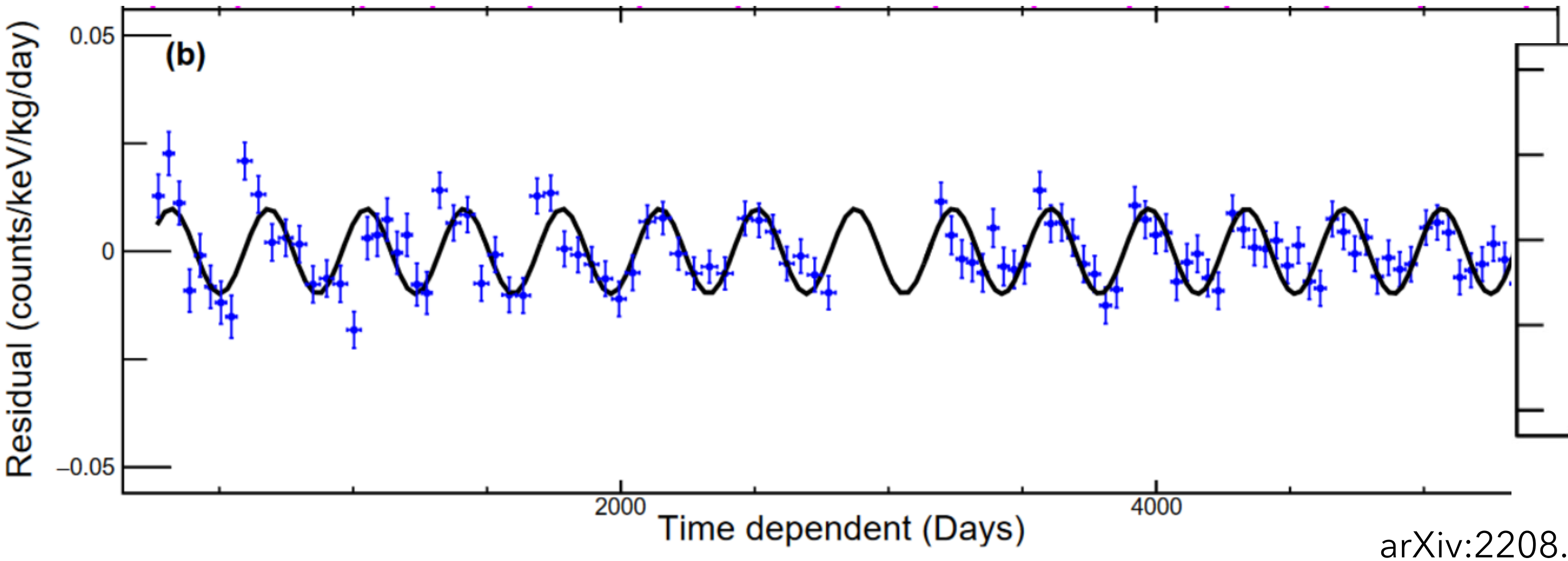
Goals for near future:

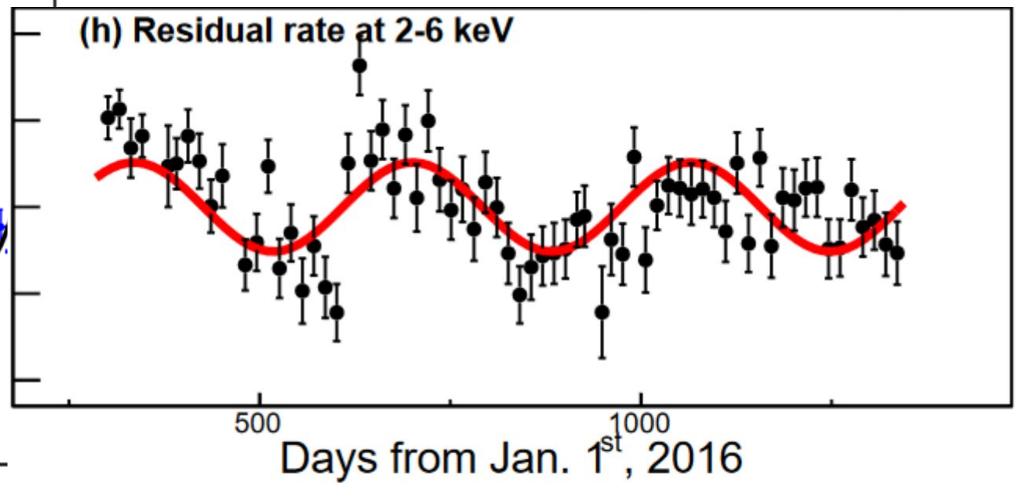
- Test the same crystal (NaI-33) with a lower radioactivity reflector
- Test reproducibility of crystal radiopurity
- Assembly of detector modules at LNGS with a new custom glove box.



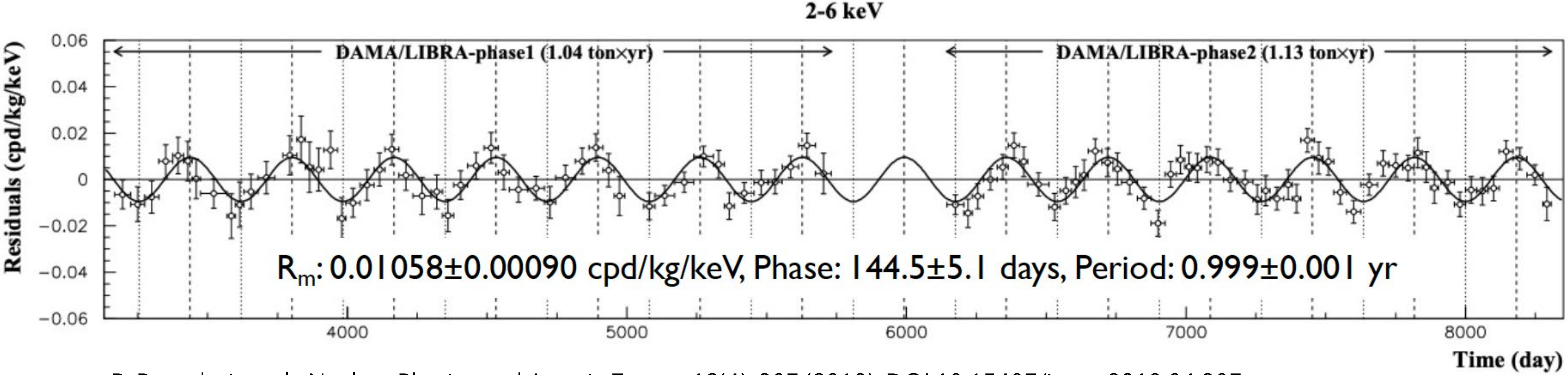


Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding





arXiv:2208.05158



R_m: 0.01058±0.00090 cpd/kg/keV, Phase: 144.5±5.1 days, Period: 0.999±0.001 yr

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

Simulation

Radiogenic Crystal Activity

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

Cosmogenic Crystal Activity

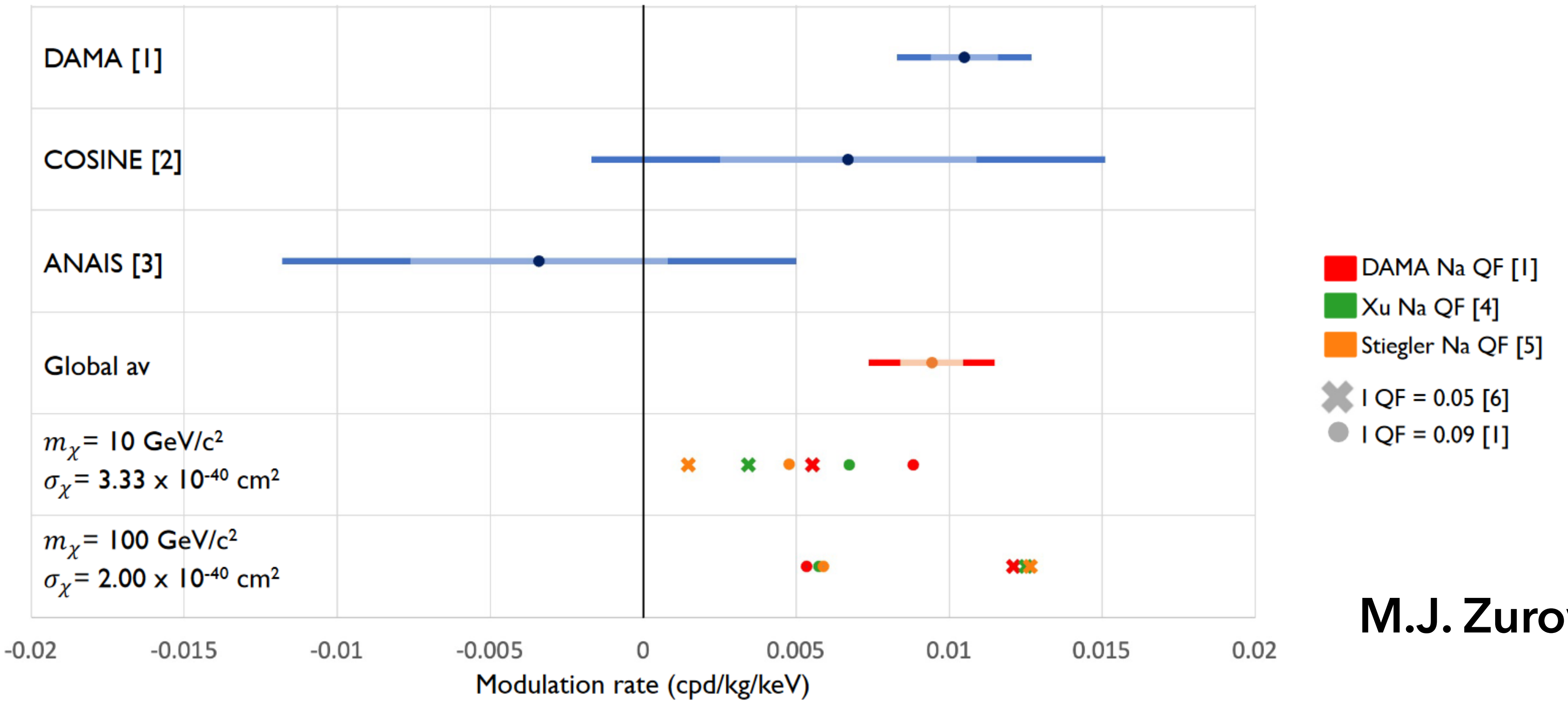
Isotope	Activity [mBq/kg]	Half life [days]
^{3}H	$9.4 \cdot 10^{-3}$	4496.8
^{22}Na	$4.3 \cdot 10^{-2}$	949.7
^{109}Cd	$5.3 \cdot 10^{-3}$	461.4
^{109m}Ag	$5.3 \cdot 10^{-3}$	$4.6\ 10^{-4}$
^{113}Sn	$1.44 \cdot 10^{-2}$	115.1
^{113m}In	$1.41 \cdot 10^{-2}$	0.07
^{121m}Te	0.16	164.2
^{121}Te	0.16	19.2
^{123m}Te	$8.35 \cdot 10^{-2}$	119.2
^{125m}Te	$5.96 \cdot 10^{-2}$	57.4
^{127m}Te	0.14	106.1
^{127}Te	0.14	0.39
^{125}I	0.19	59.4
^{126}I	$1.0 \cdot 10^{-4}$	12.9

https://indico.cern.ch/event/922783/contributions/4892679/attachments/2481816/4261597/idm22-zurowski.pdf

QUENCHING FACTOR IMPACT

[1] Bernabei et al. PPNP114 103810 (2020)
[2] Adhikari et al. arxiv:2111.08863
[3] Amare et al. PRD 103, 102005 (2021)
[4] Xu et al. 2015 PRC 92.015807
[5] Stiegler et al. 2017 arxiv:1706.07494
[6] Bignell et al 2021 JINST 16 P07034

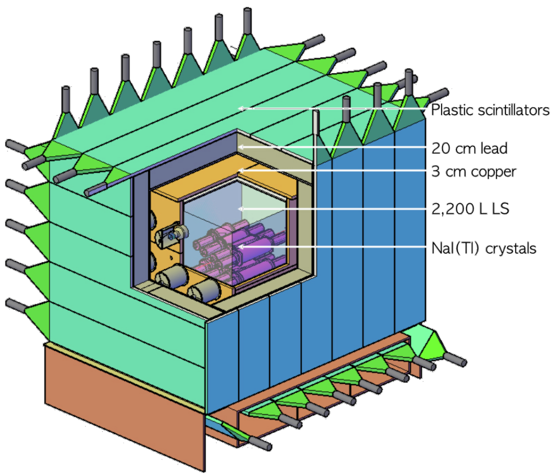
This toy model w/ different QFs can produce modulation amplitudes more consistent with other observations
Effect is strongly dependent on DM model and mass ⇒ model independent test is impossible



M.J. Zurowski

Other NaI(Tl) Experiments & Results

COSINE



Adhikari et al. arxiv:2111.08863

- 100 kg of NaI(Tl)
- Muon veto
- Liquid scintillator veto
- ~3 cpd/kg/yr background

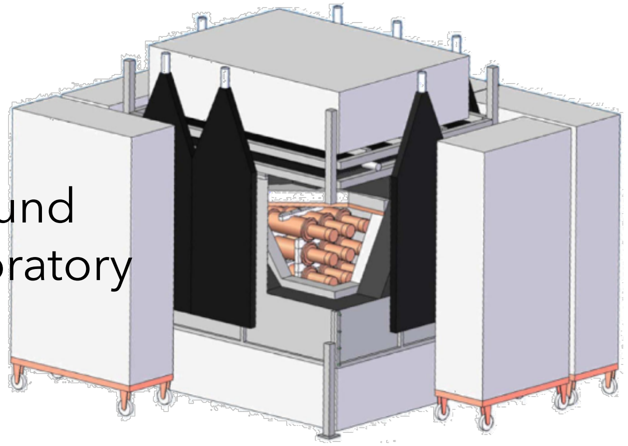
Yangyang underground lab

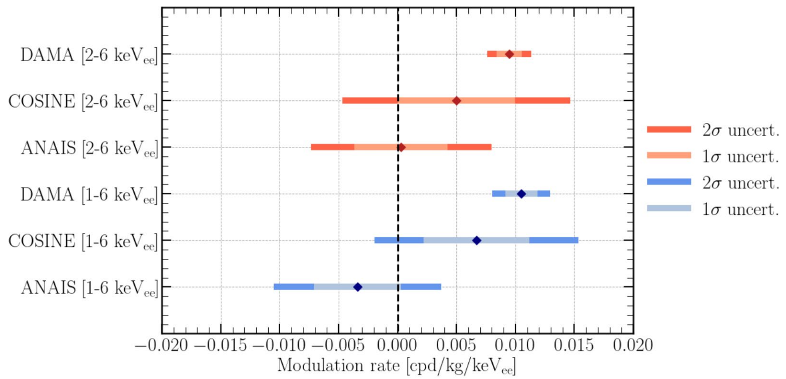
ANAIS

- 110 kg of NaI(Tl)
- Muon veto
- ~3-4 cpd/kg/yr background

Canfranc underground laboratory

Amare et al. PRD 103, 102005 (2021)





Some tension between ANAIS and DAMA

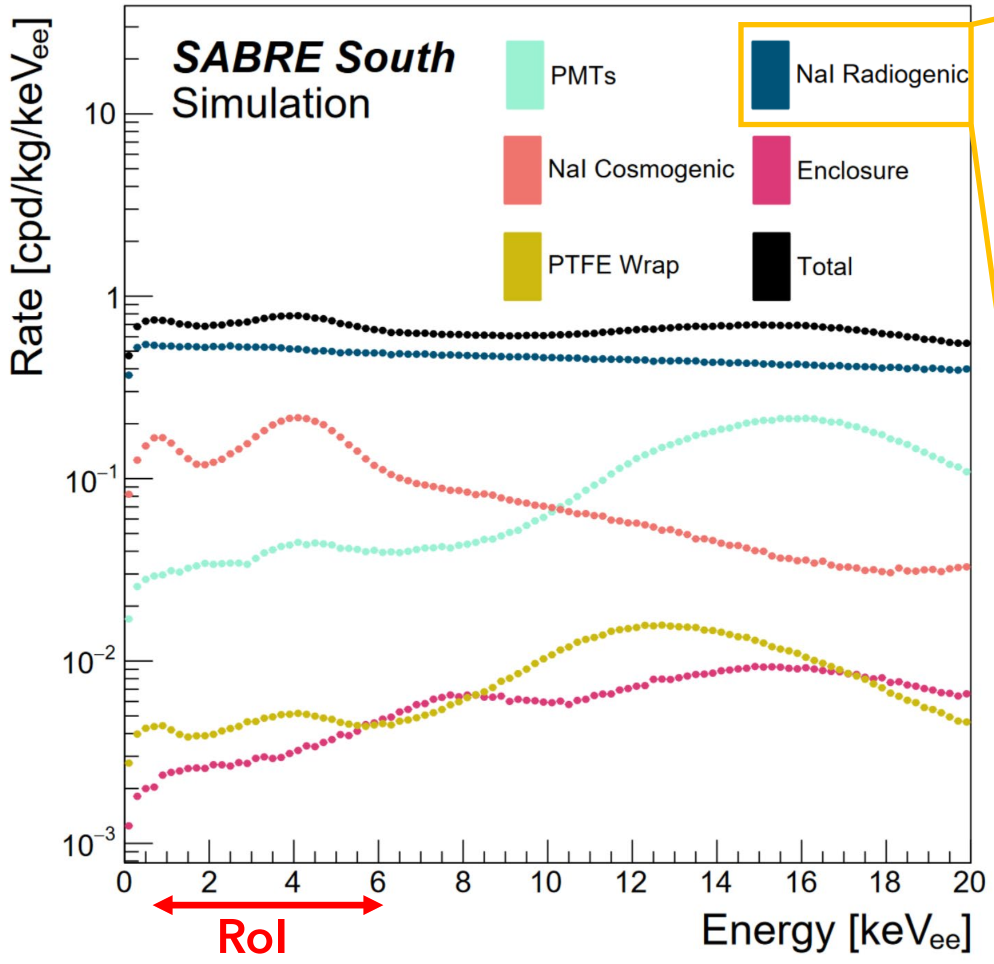
No significant discovery or exclusion of DAMA so far

Motivation for an additional search with lower background rate

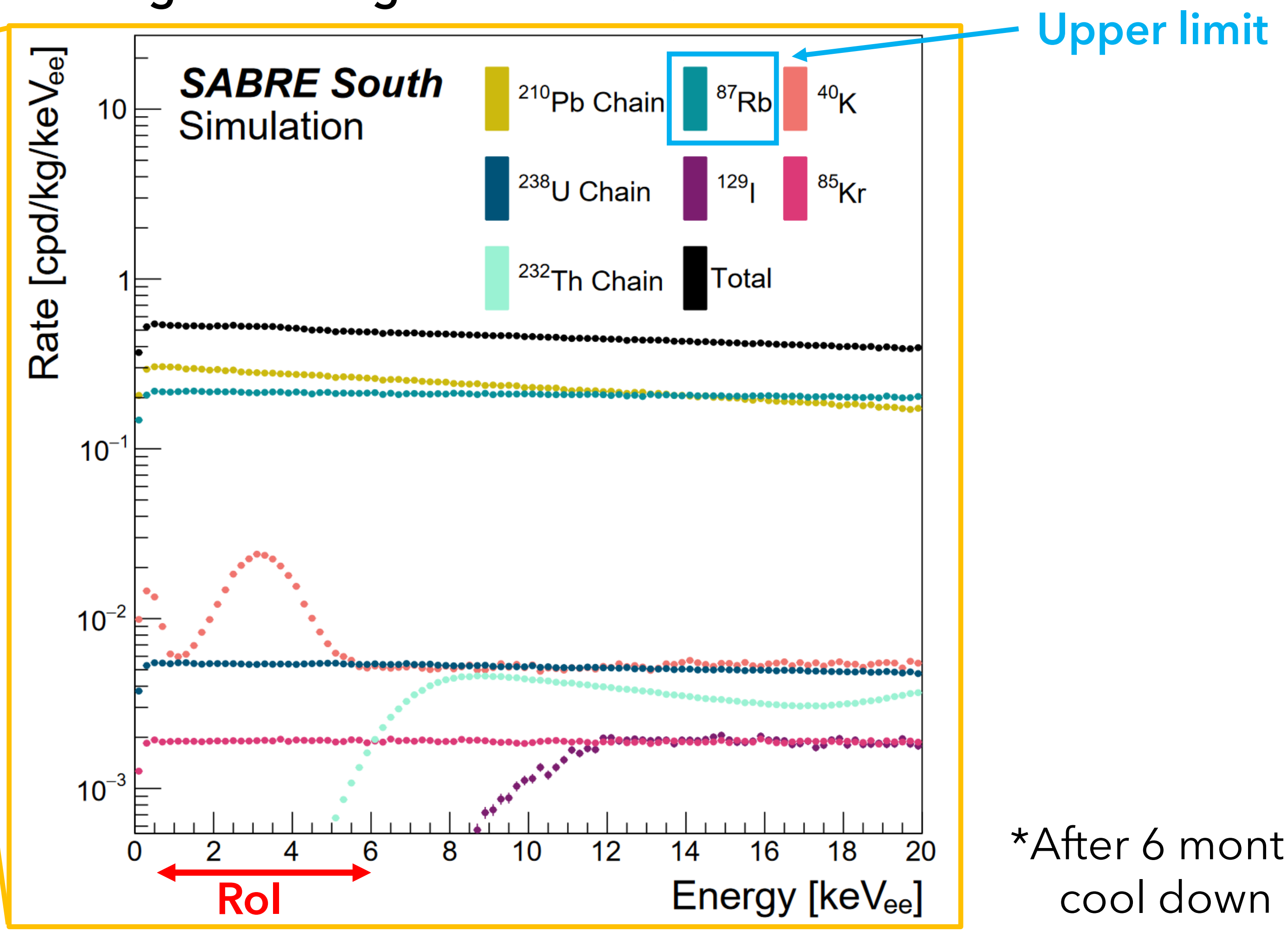
- Southern hemisphere experiment to better separate backgrounds

High Purity NaI(Tl) Crystals

Crystal background is ~95% of the total



Radiogenic background is ~72% of the total



*After 6 month cool down

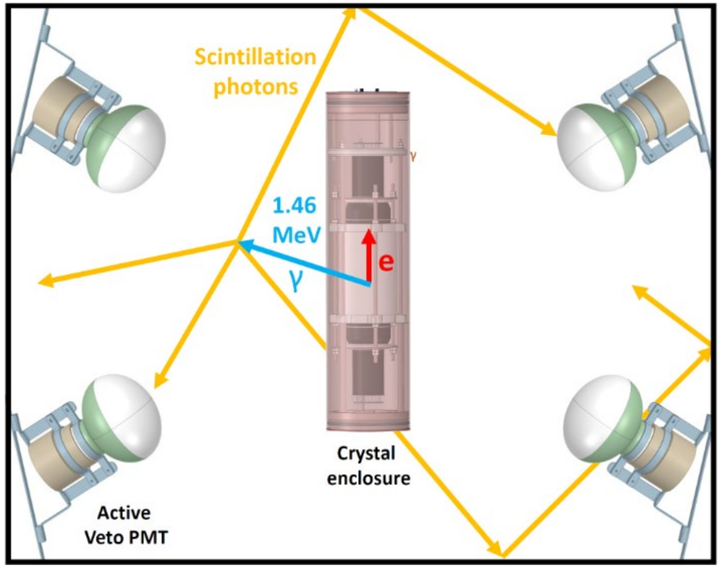
Key contaminants

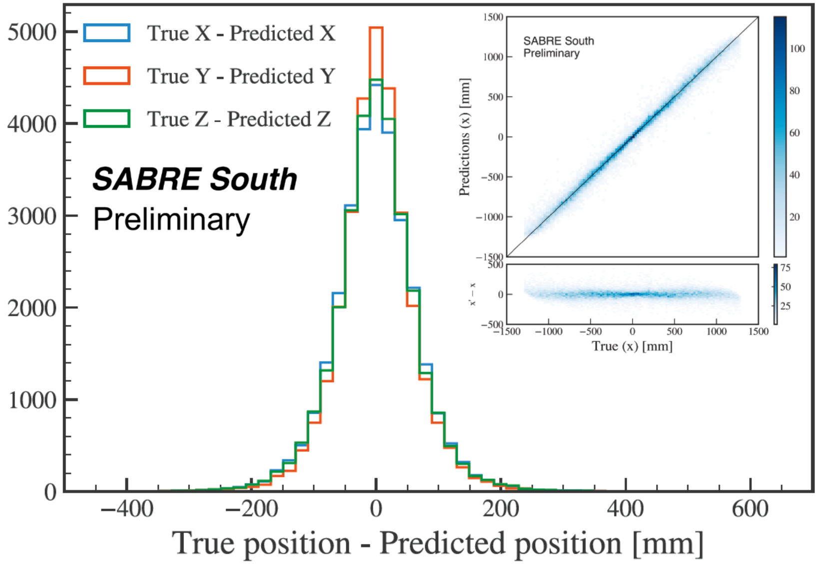
- 40K
- 210Pb

Liquid Scintillator Detector, an Active Veto

Liquid scintillator completely surrounds the crystal detectors

- Primary purpose is to detect particles or decay products that interact with both the crystals and liquid scintillator
  - For example ^{40}K decays
- Average light yield of about 0.12 phe/keV but is position dependent
- Small scale prototype used to study the properties
- Possible to use for particle identification as well as extracting position information
  - Promising early results using a boosted regression model with simulated data





Bulk tank of LAB ready for use

Muon Detector

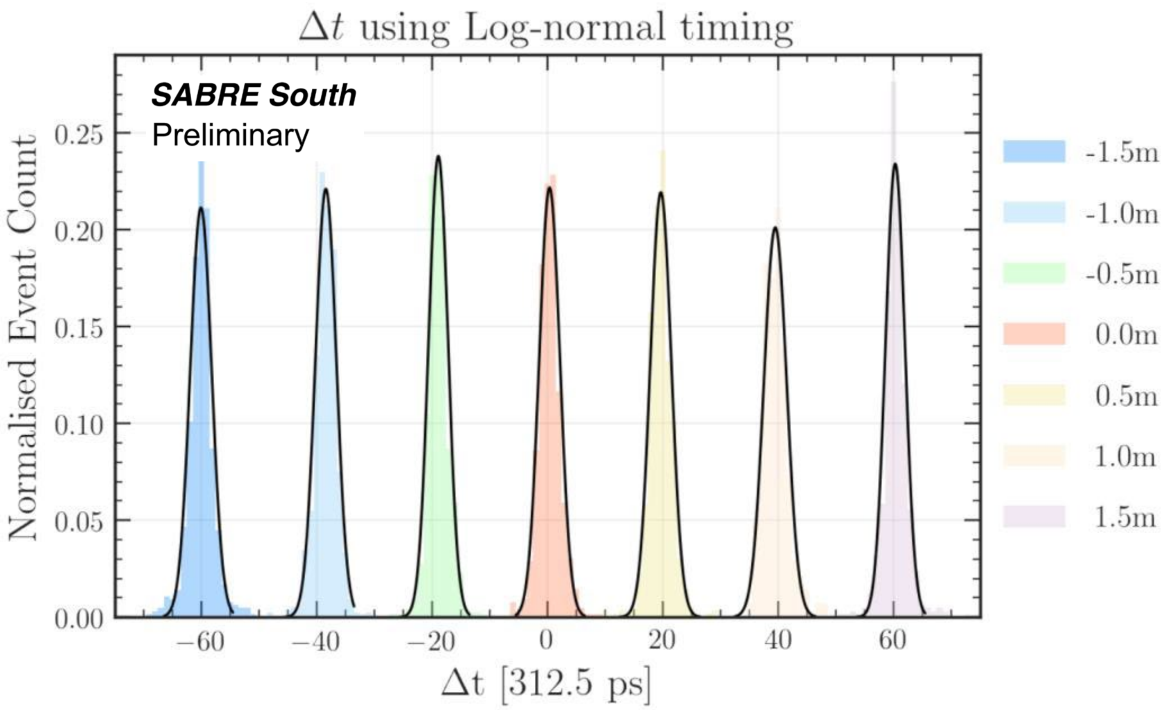
Eight 3m long detector paddles, PMTs at each end

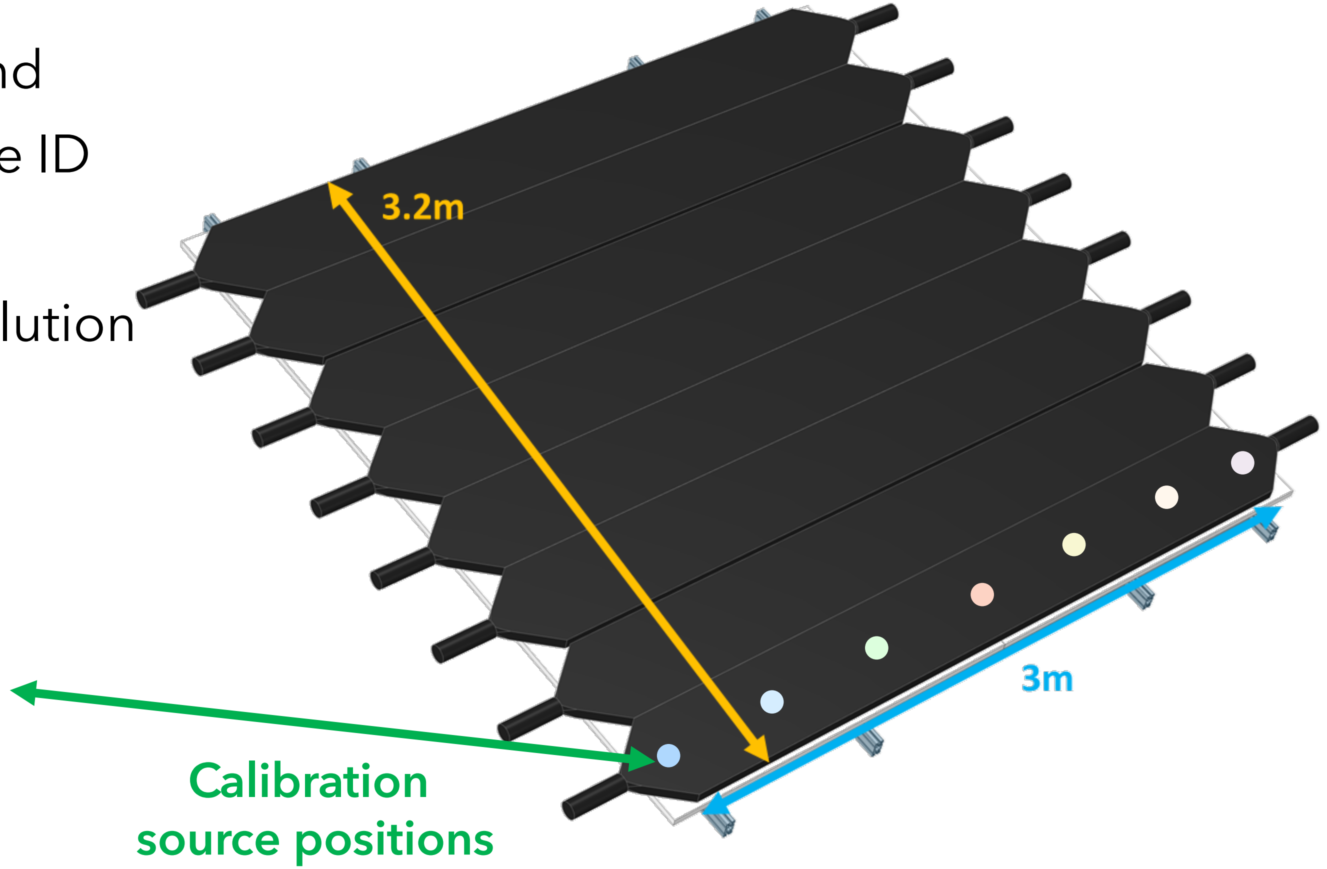
Used to veto majority of cosmic rays & for particle ID

- Will measure long-term muon flux in SUPL

400 ps timing resolution gives 5cm position resolution

Ongoing work characterising each paddle1





High Purity NaI(Tl) Crystals

The background in the region of interest (low energy 1-6 keV) for these dark matter searches is mostly due to intrinsic contaminants. ^{87}Rb, ^{40}K, ^{210}Pb …

SABRE have developed some of the lowest background crystals in the world

Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{226}Ra (μBq/kg)	^{210}Pb (μBq/kg)	^{232}Th (μBq/kg)
DAMA [1]	13	0.7-10	8.7-124	5-30	2-31
ANAIS [2]	31	<0.81	-	1530	0.4-4
COSINE [3]	<42	<0.12	8-60	10-420	7-35
SABRE [4]	2.2±1.5	0.4	5.9±0.6	410±20	1.6±0.3
PICOLON [5]	<20	-	13±4	<5.7	1.2±1.4

[1] R. Bernabei et al., NIMA 592(3) (2008)
[2] J. Amare et al., EPJC 79 412(2019)
[3] P. Adhikari et al., EPJC 78 490 (2018)
[4] F. Calaprice et al., PRD 104 (2021)
[5] K. Fushimi et al., PTEP 4 043F01 (2021)

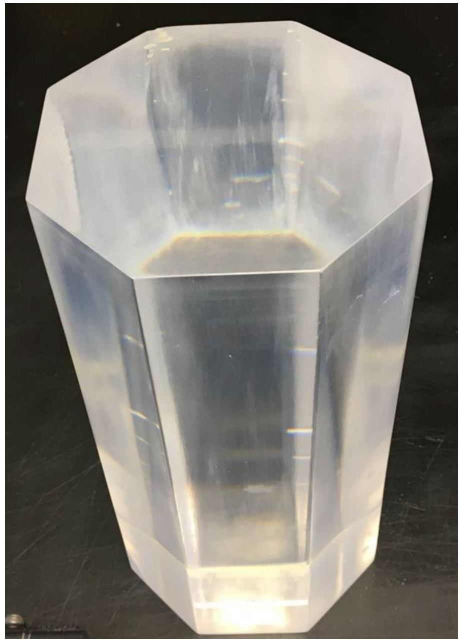
Currently the SABRE South test Crystal (NaI-35) is being tested at LNGS

- Early results show comparable backgrounds and light yield to NaI-33
  - Light yield is approximately 11.6 phe/keV

Quenching factor for both tip and tail have also been measured

- Test if quenching factor is uniform

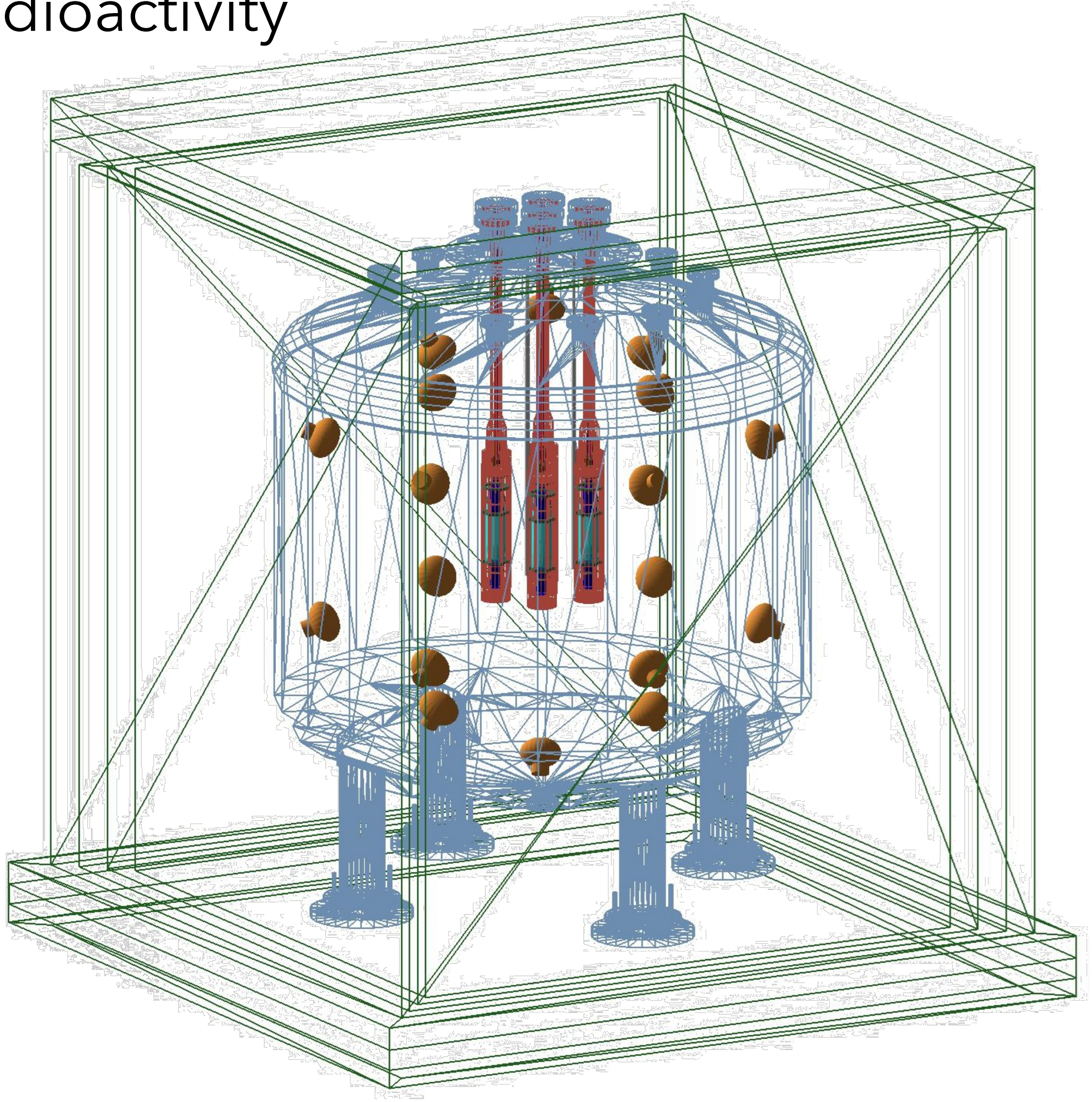
NaI-35

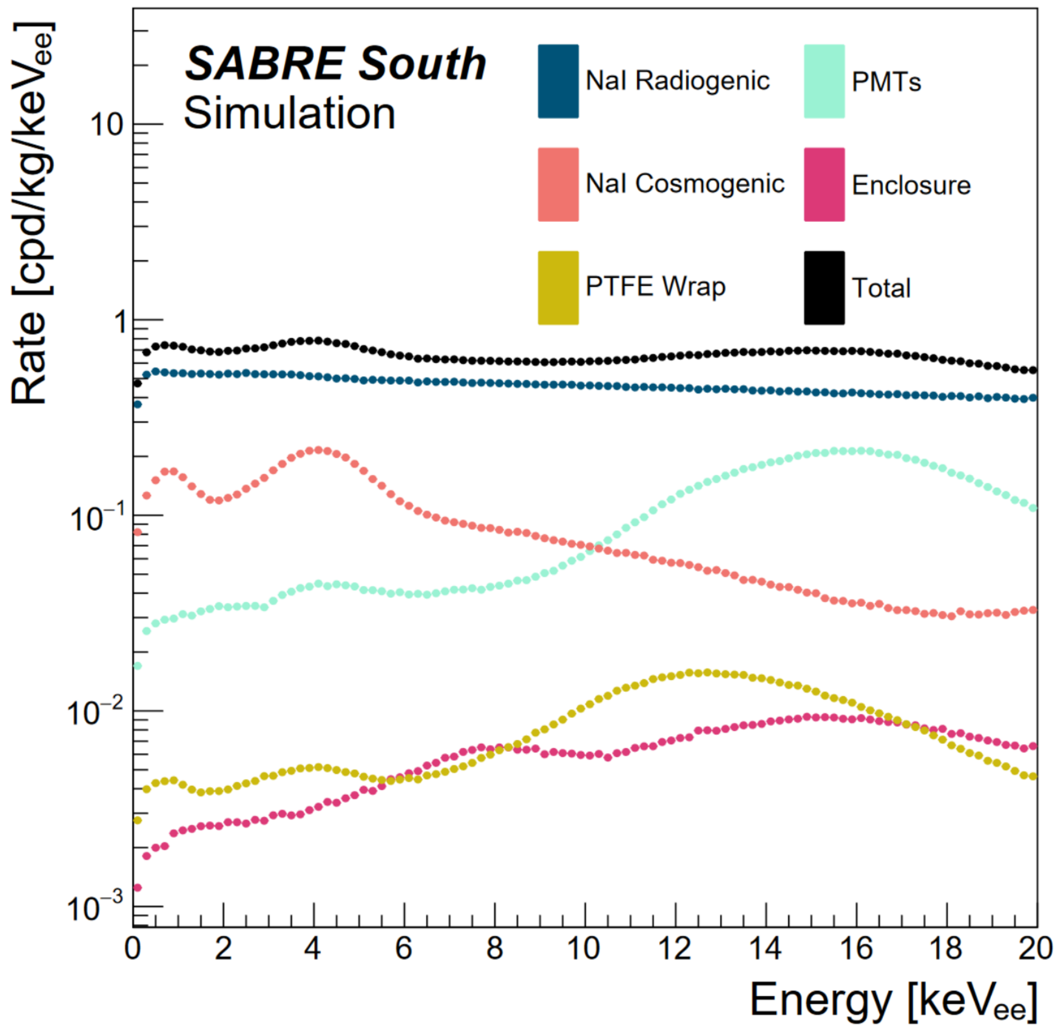


Background Simulation

Arxiv 2205.13849

A Full Geant4 simulation has been performed to understand the background radioactivity



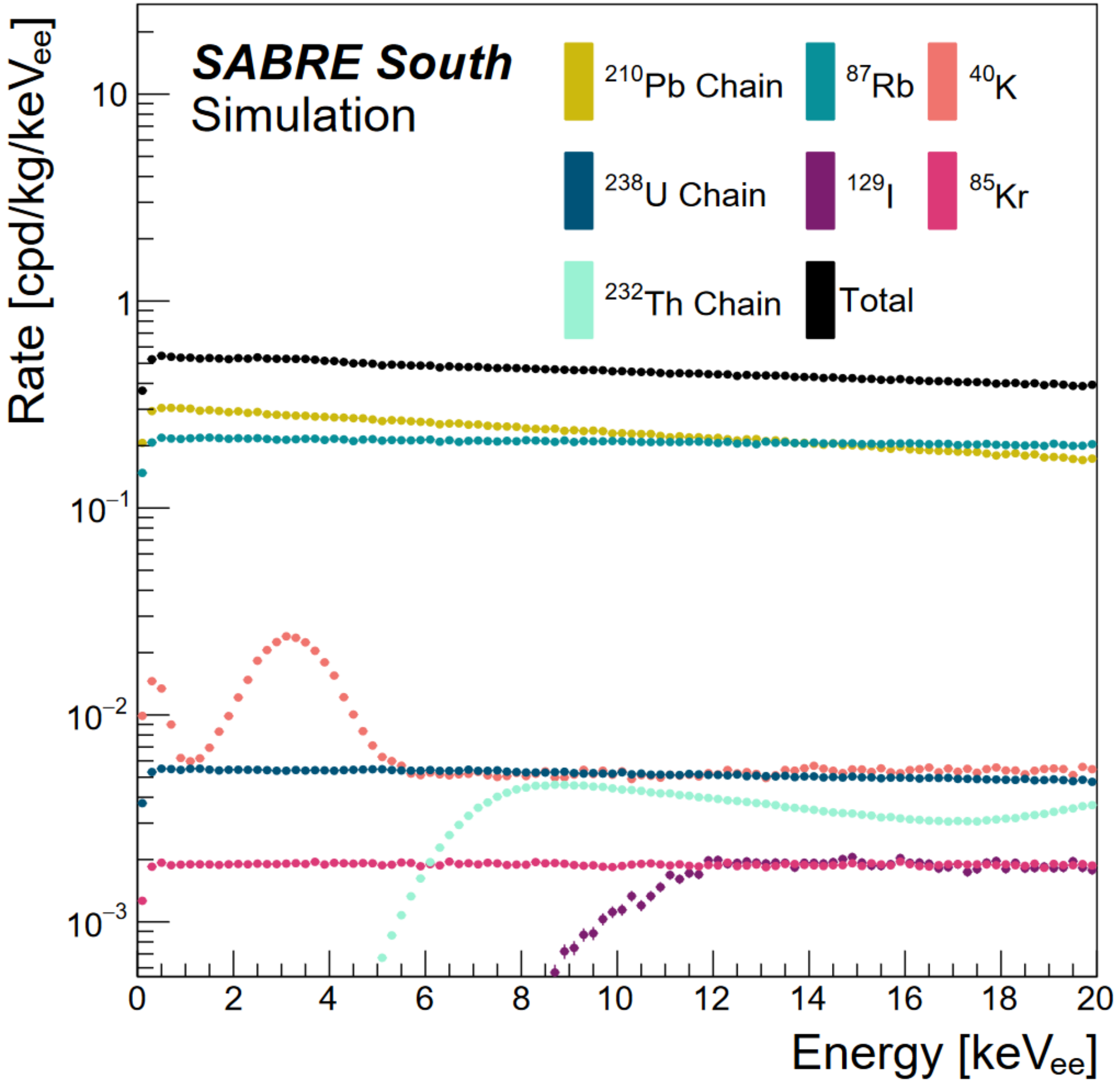


In total expect 0.72cpd/kg/keV (1-6keV)

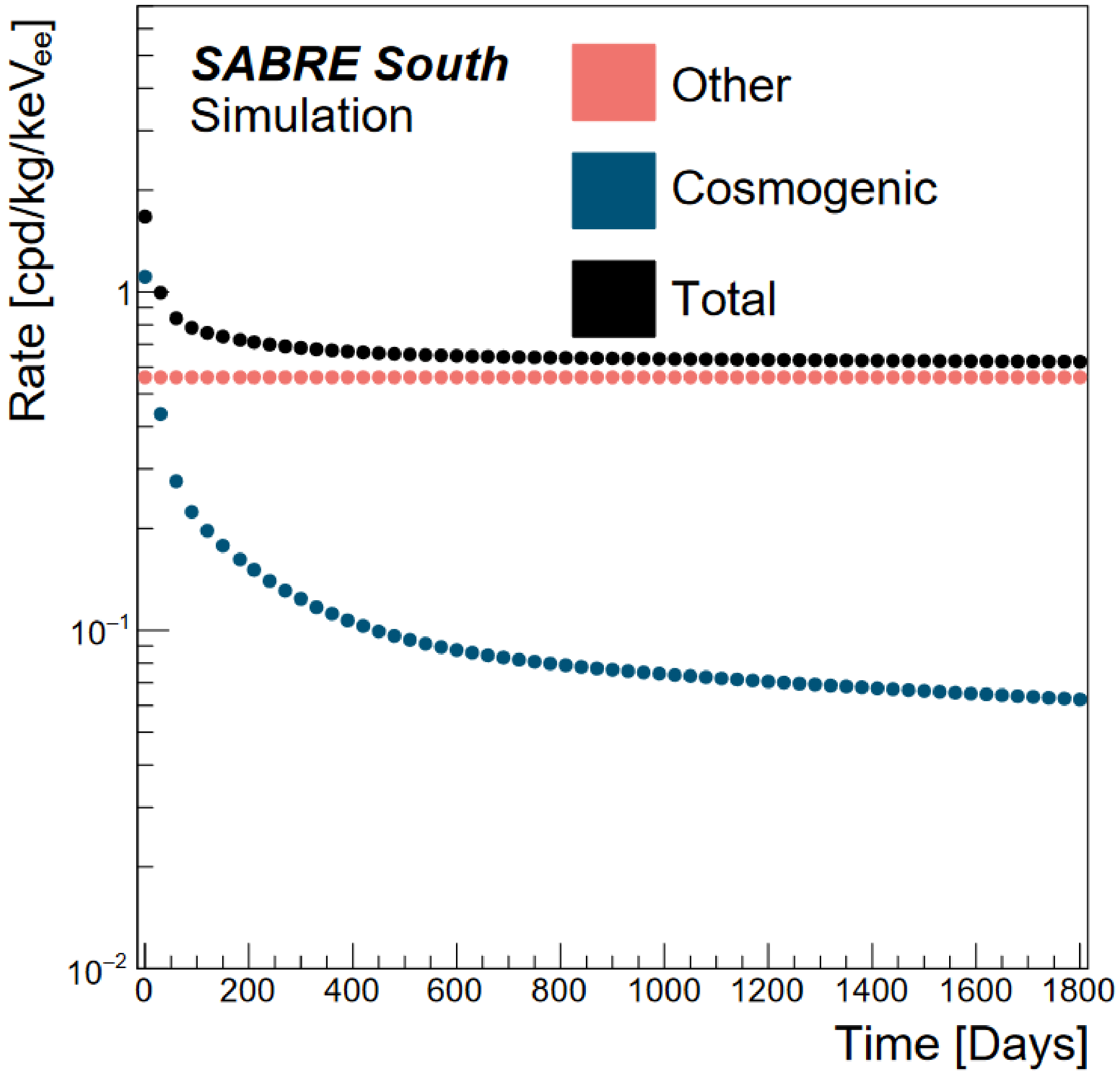
Crystal Radiation

Arxiv 2205.13849

Breakdown of isotope contributions (radiogenic crystal)



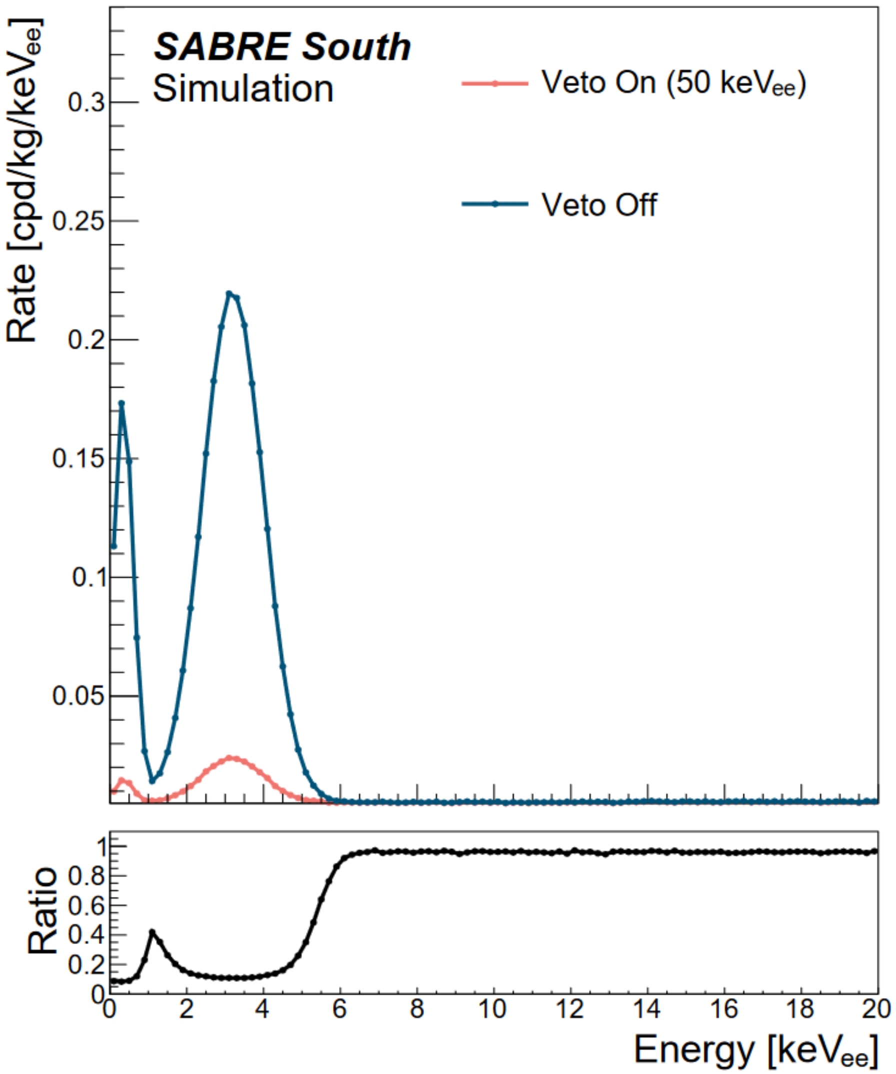
Time-dependent background rate (1-6 keV)



Simulated Veto Performance

Arxiv 2205.13849

^{40}K decays in the crystal

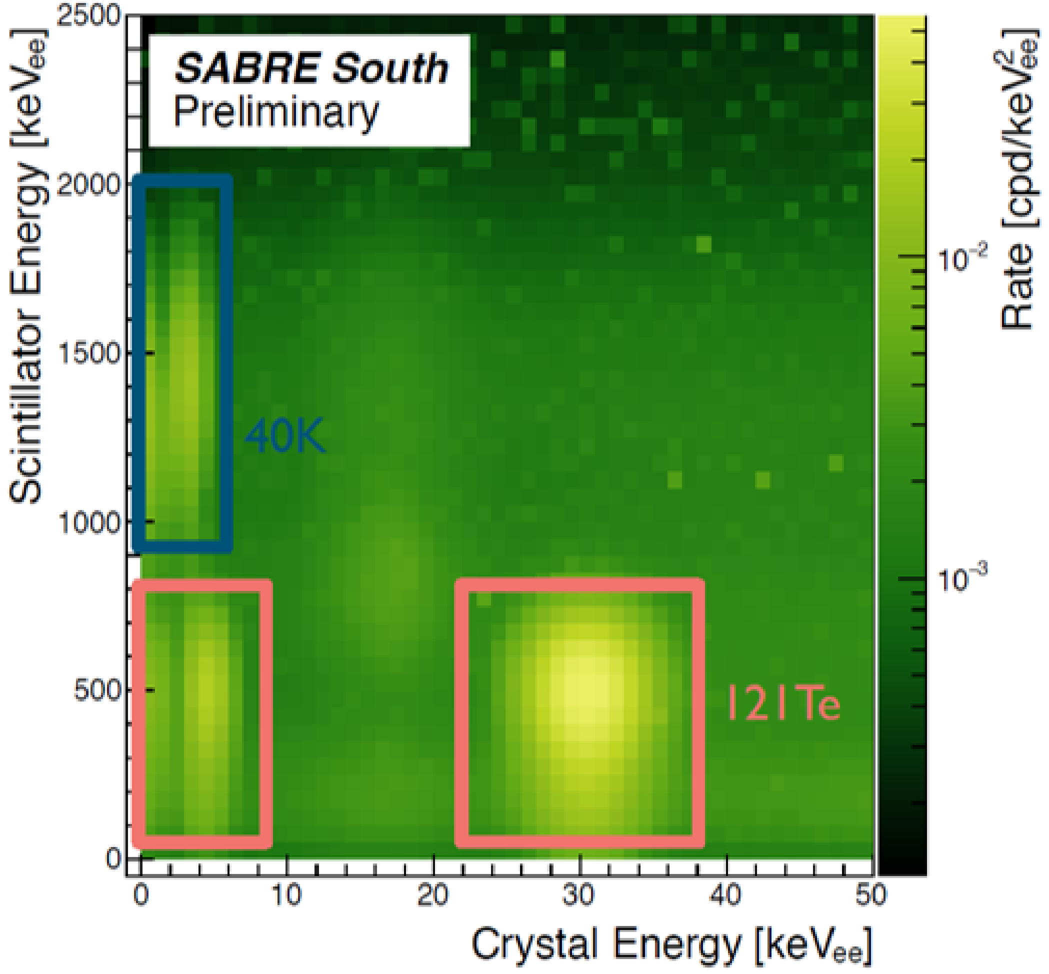


Component	Rate (cpd/kg/keV)	Veto efficiency (%)
Crystal intrinsic	$<5.2 \times 10^{-1}$	13
Crystal cosmogenic	1.6×10^{-1}	45
Crystal PMTs	3.8×10^{-2}	57
Crystal wrap	4.5×10^{-3}	11
Enclosures	3.2×10^{-3}	85
Conduits	1.9×10^{-5}	96
Steel vessel	1.4×10^{-5}	>99
Veto PMTs	1.9×10^{-5}	>99
Shielding	3.9×10^{-6}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

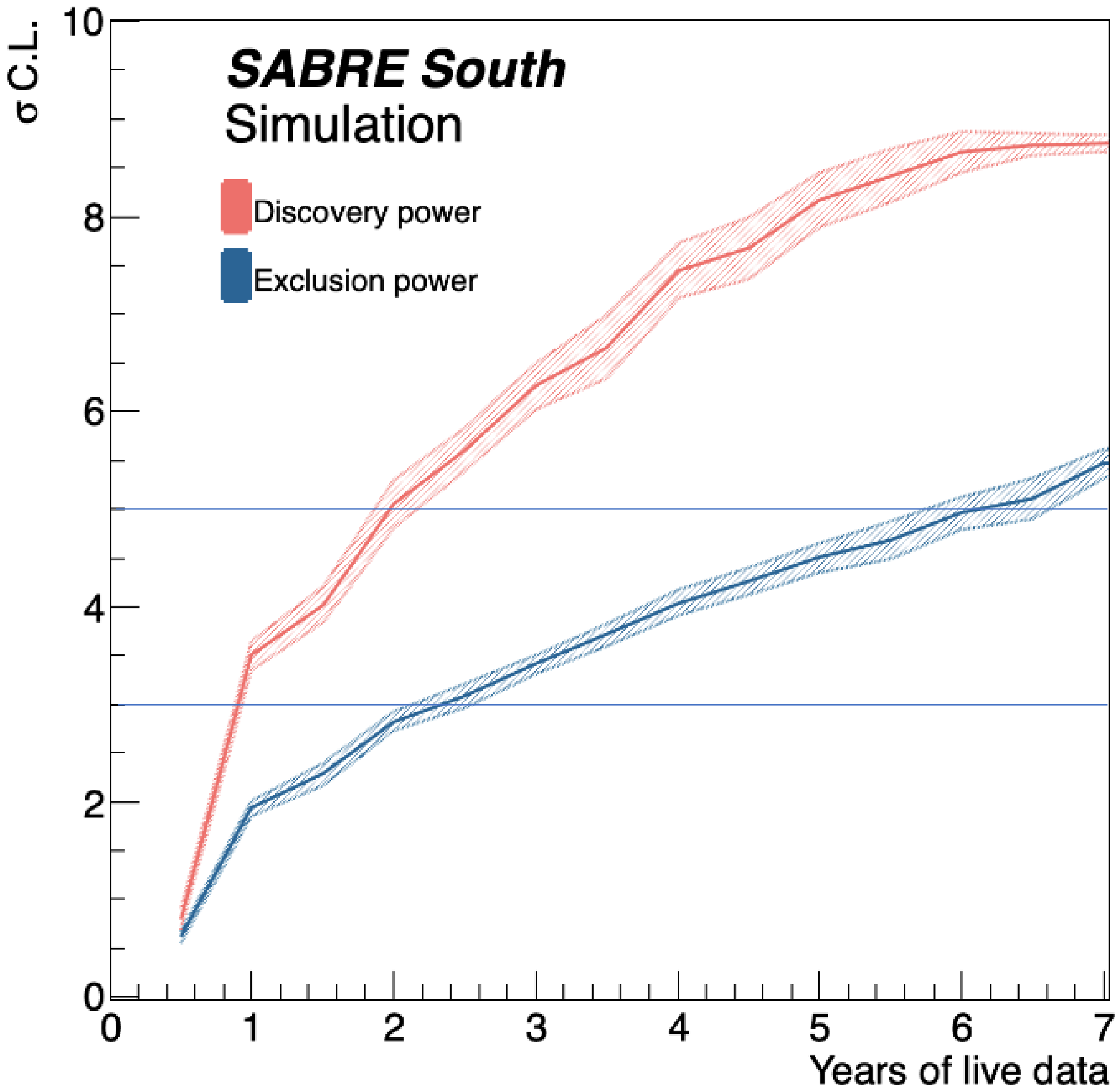
Particle ID and Expected Sensitivity

Arxiv 2205.13849

Combining measurements of the liquid scintillator and crystals allows for in situ particle ID and measurement



SABRE South will have 5σ discovery (3σ exclusion) power to a DAMA-like signal with little over 2 years of data taking.



Summary

- SABRE South is part of the SABRE Collaboration which will test DAMA-like modulation signals
- High purity crystals and a large active veto achieve an ultra-low background (~0.72 cpd/kg/keV)
- This allows for 3σ exclusion or 5σ discovery with little over two annual cycles of data
- SUPL is a new underground physics lab 1025 m underground & is now operational
- SABRE South will be commissioned over the next 12 months, with data taking anticipated to start in mid/late 2023

SABRE South

ARC Centre of Excellence for Dark Matter Particle Physics
The University of Adelaide
The University of Melbourne
Swinburne University of Technology
Australian National University
Australian Government

SABRE North

INFN LNGS – Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso
Pacific Northwest National Laboratory
INFN – Istituto Nazionale di Fisica Nucleare
Princeton University
RMD – A Dynasil Company
Sapienza Università di Roma
Università degli Studi di Milano

More questions? contact peter.mcnamara@anu.edu.au

Summary

- SABRE South is part of the SABRE Collaboration which will test DAMA-like modulation signals
- High purity crystals and a large active veto achieve an ultra-low background (~0.72 cpd/kg/keV)
- This allows for 3σ exclusion or 5σ discovery with two and a half annual cycles of data
- SUPL is a new underground physics lab 1025 m underground & is now operational
- Full detector deployment by mid 2024

SABRE South

SABRE North

Summary