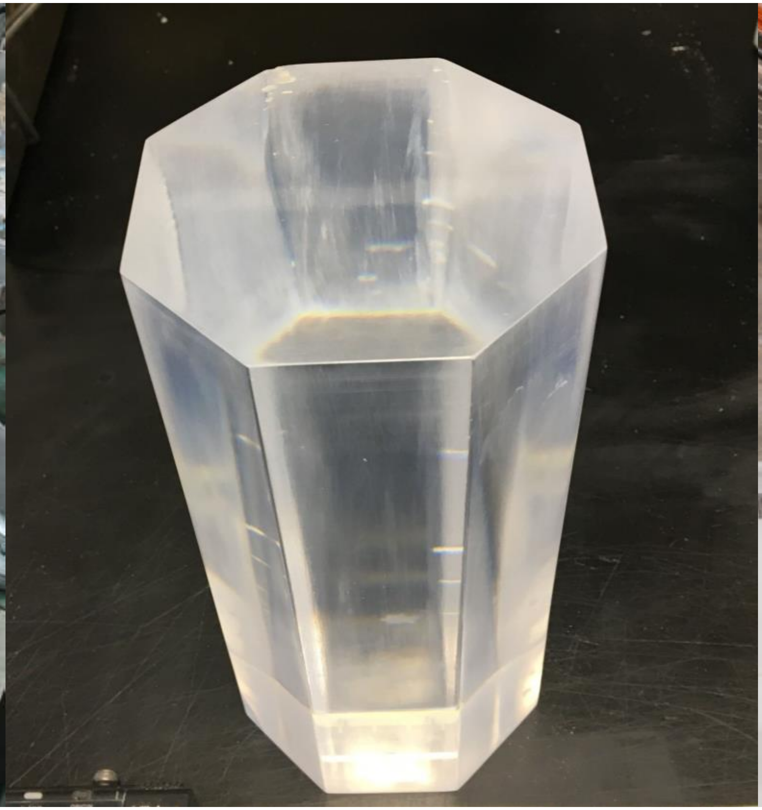




The SABRE South Experiment

at the Stawell Underground Physics Laboratory

Peter McNamara on behalf of the SABRE South Collaboration

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

Australian National University

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY of ADELAIDE

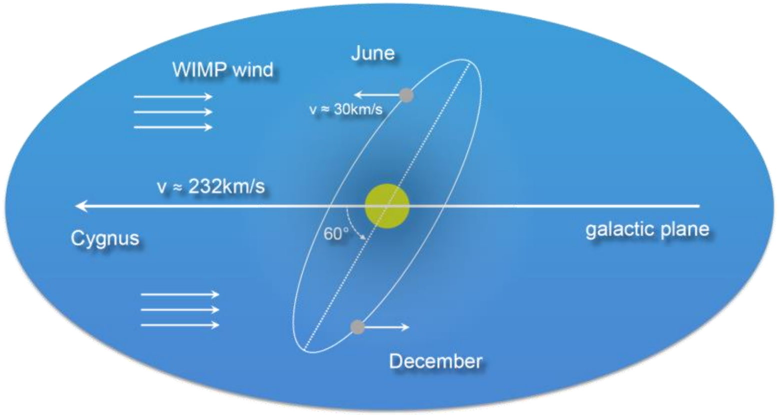
SABRE

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 energy

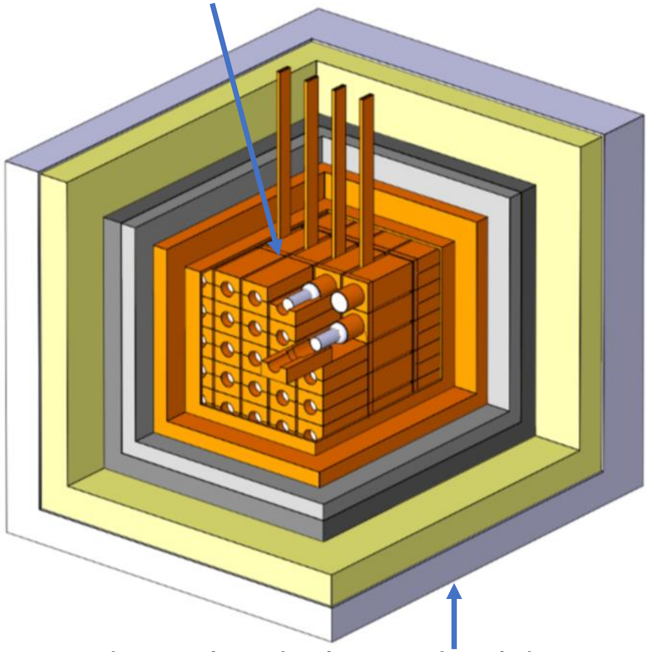
$$R(t) = B(t) + S_0 + S_m \cos\left(\frac{2\pi}{1\text{ year}}(t - t_0)\right)$$



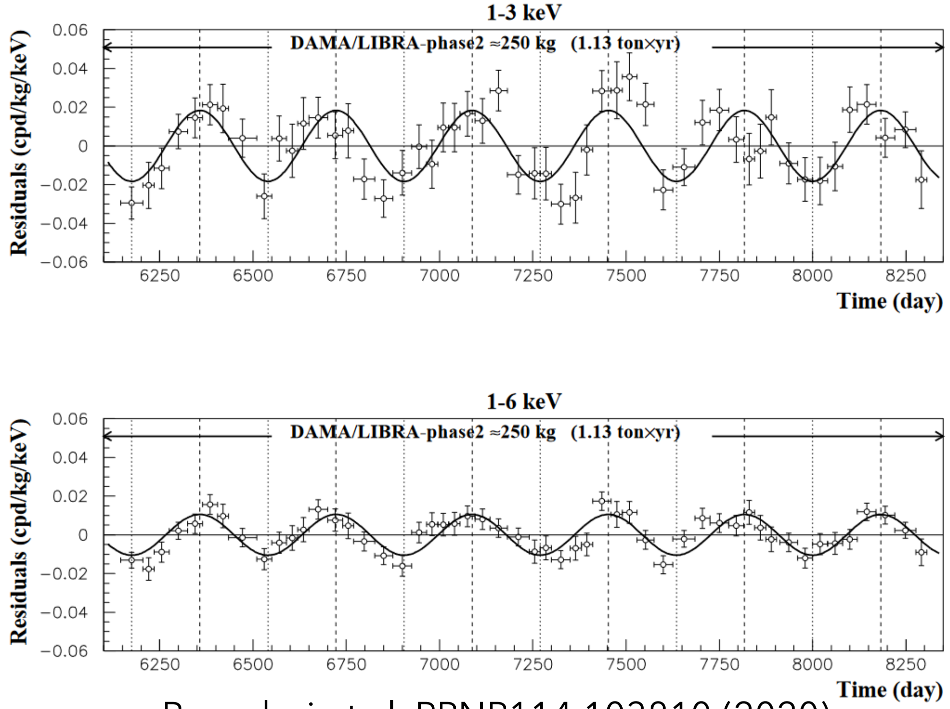
DAMA using NaI(Tl) crystals has observed a modulation consistent with these expectations for about 20 years with ~13σ CL

- Upper rate of ~0.8 cpd/kg/keV

25 NaI(Tl) crystals in Cu enclosures



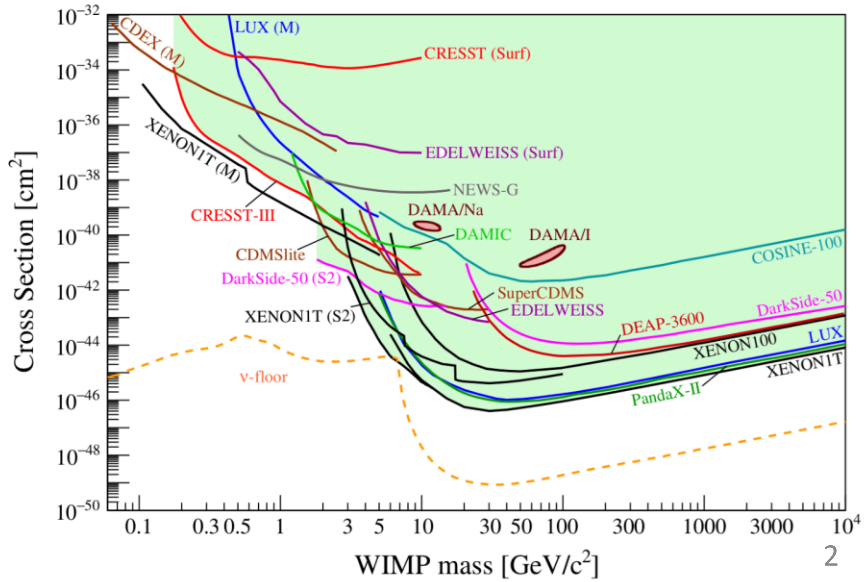
Cu, Pb, polyethylene shielding



Bernabei et al. PPNP114 103810 (2020)

This result is constrained by null results from other experiments

- However need to use same target

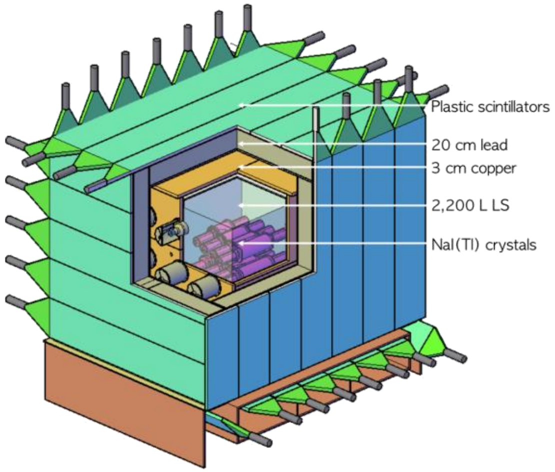


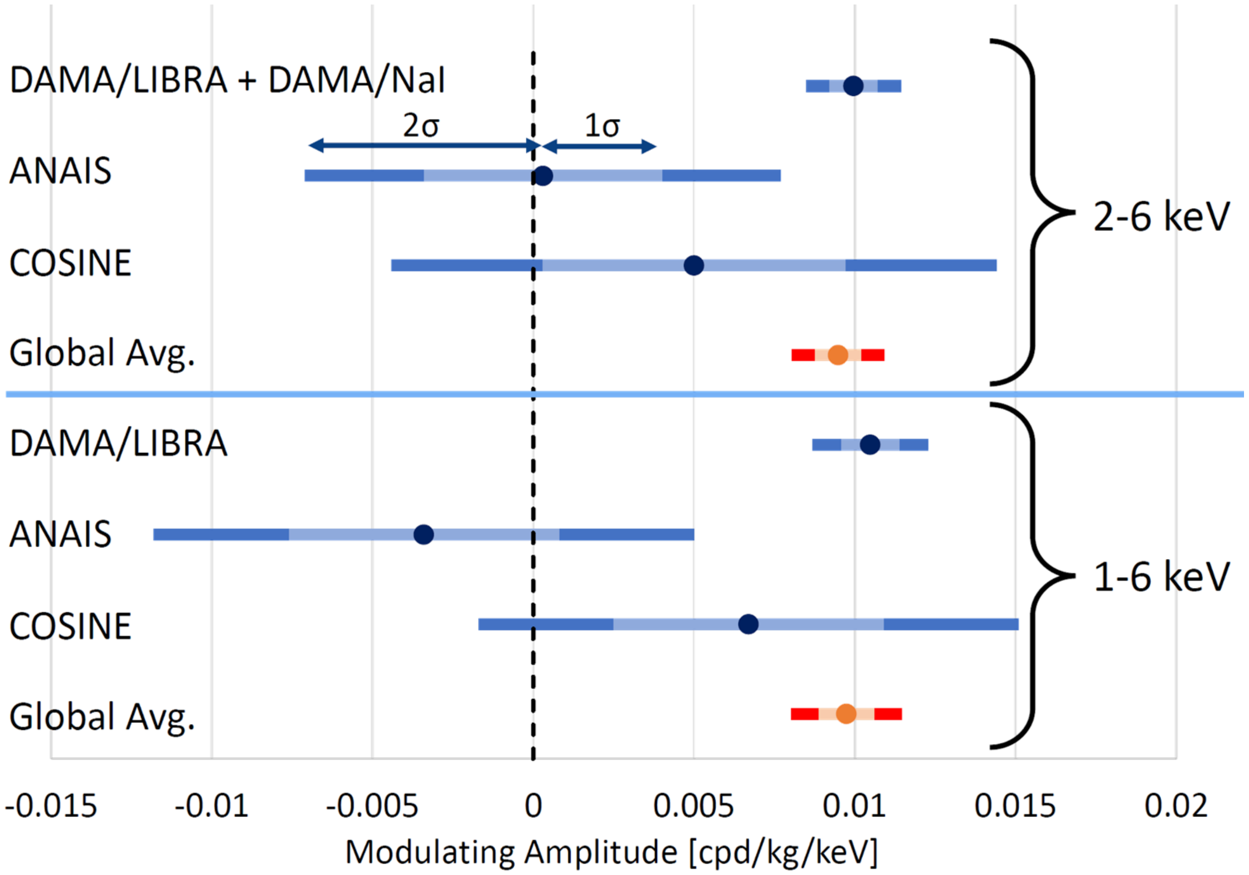
Other NaI(Tl) Experiments & Results

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

Yangyang underground lab

Adhikari et al. arxiv:2111.08863

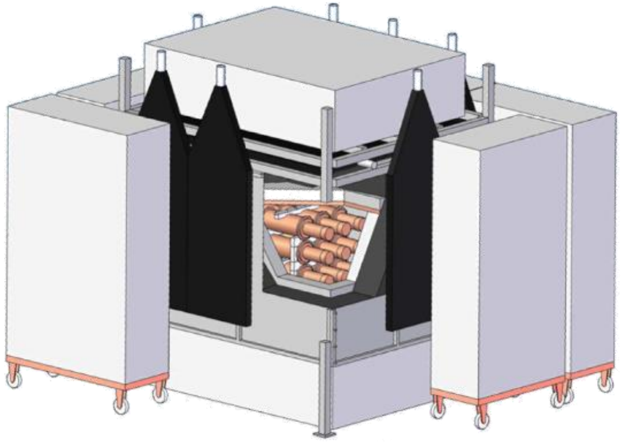




ANAIS
- 110 kg of NaI(Tl)
- Muon veto
- ~3-4 cpd/kg/yr background

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

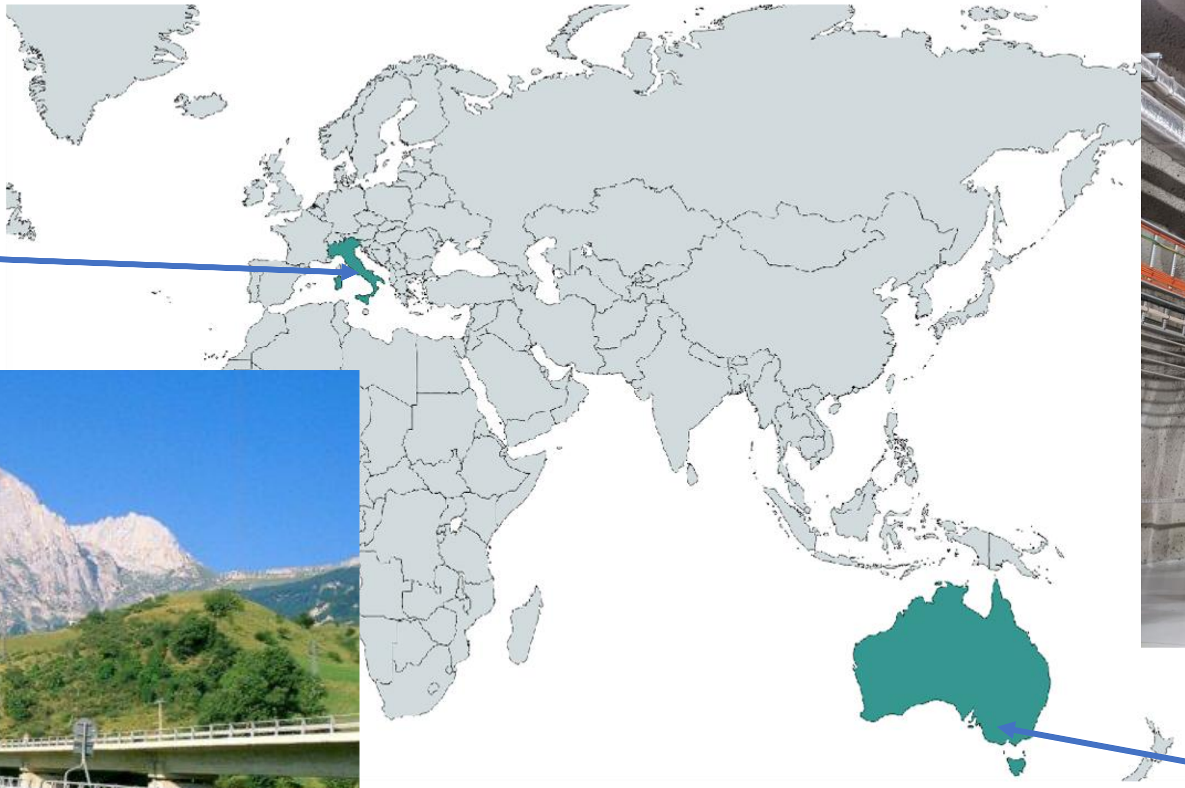
DAMA results: Bernabei et al. PPNP114 103810 (2020)

SABRE: A Dual Site Experiment

Experimental program to test the DAMA modulation based around detectors placed in two different locations:

- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

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



STAWELL UNDERGROUND PHYSICS LAB

The SABRE Collaboration

SABRE North and South detectors have **common core features**, both employing:

- Same detector module concept (Ultra-pure crystals and HPK R11065 PMTs)
- Common simulation, DAQ and software frameworks
- Exchange of engineering know-how with official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN

SABRE North and South detectors have **different shielding designs**:

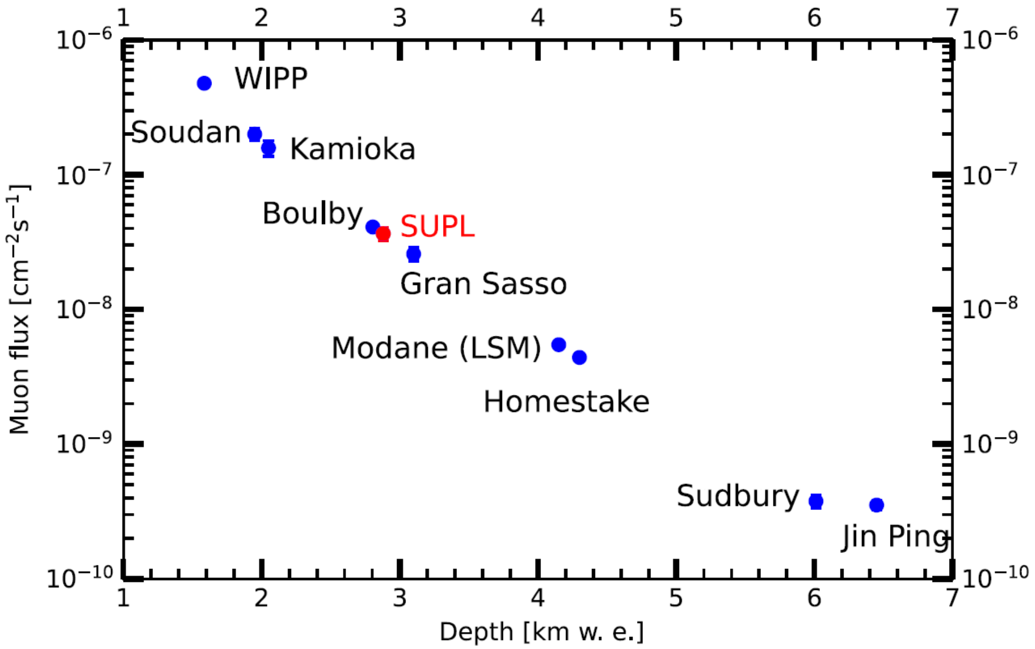
- SABRE North has opted for a fully passive shielding due to the phase out of organic scintillators at LNGS. Direct counting and simulations demonstrate that this is compliant with the background goal of SABRE North at LNGS.
- SABRE South will be the first experiment in SUPL, the liquid scintillator will be used for in-situ evaluation and validation of the background in addition of background rejection and particle identification.

Stawell Underground Physics Lab (SUPL)

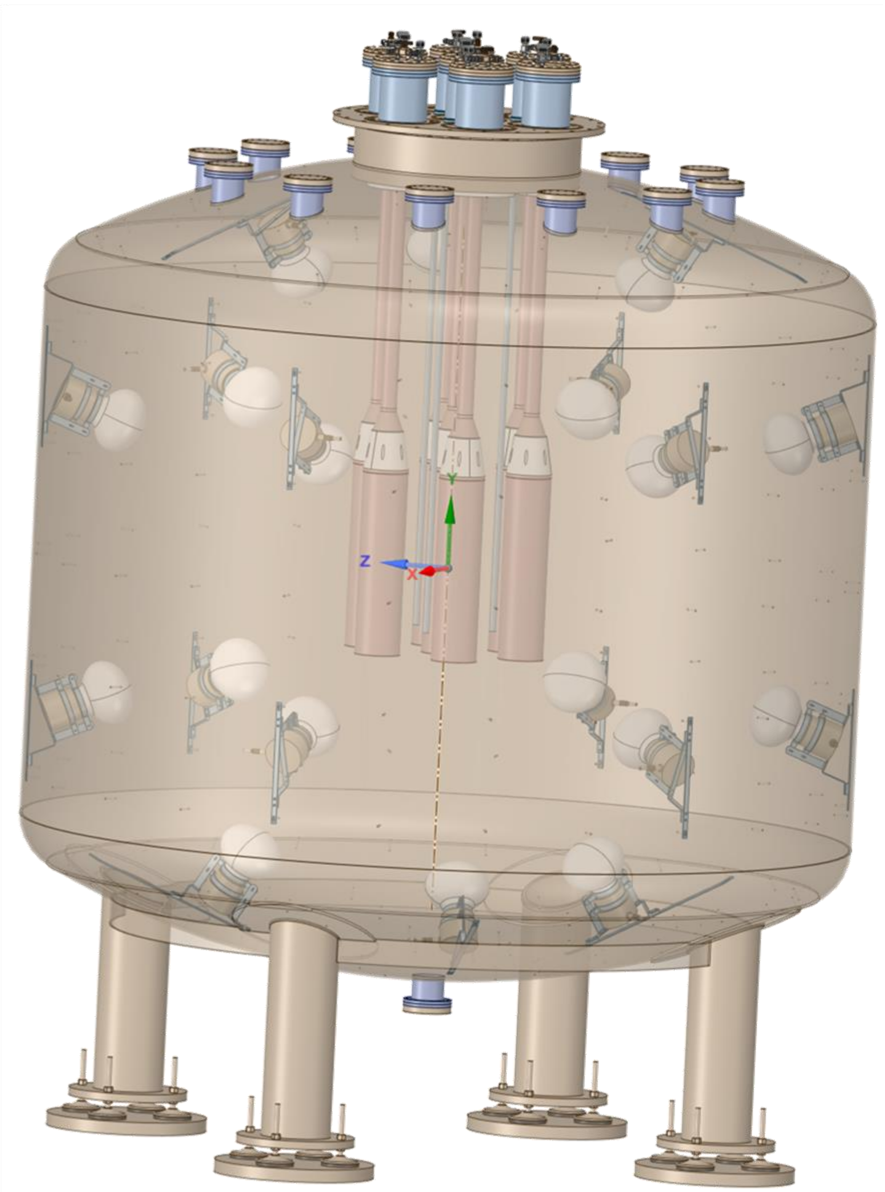
First deep underground laboratory in the Southern Hemisphere

- 1025 m deep (2900 m water equivalent) with flat overburden
- Helical drive access
- Low background screening facilities

Construction is complete with operations starting very soon

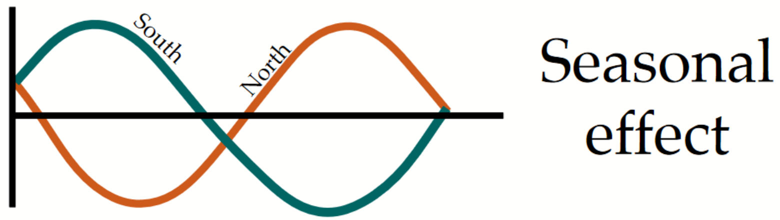


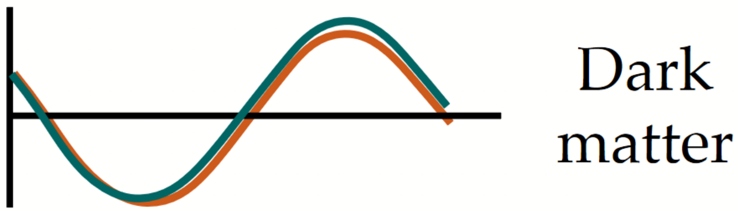
SABRE South



Key features:

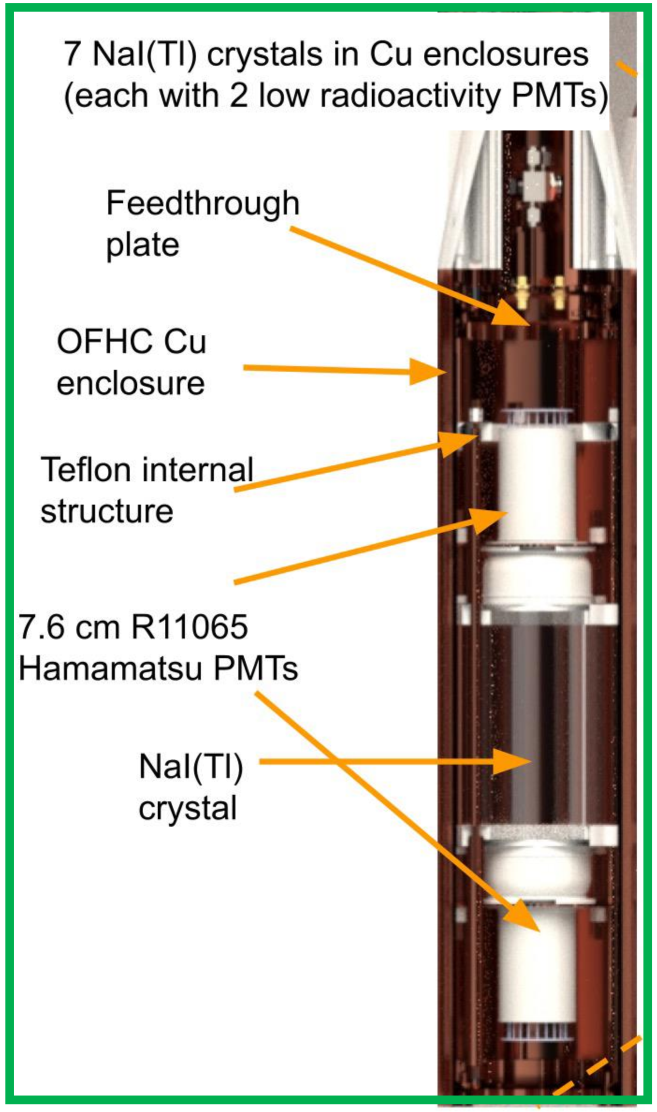
- Active veto to detect & reject background
- Low energy threshold
- High purity crystals
- Ability to measure background properties
- Southern hemisphere location

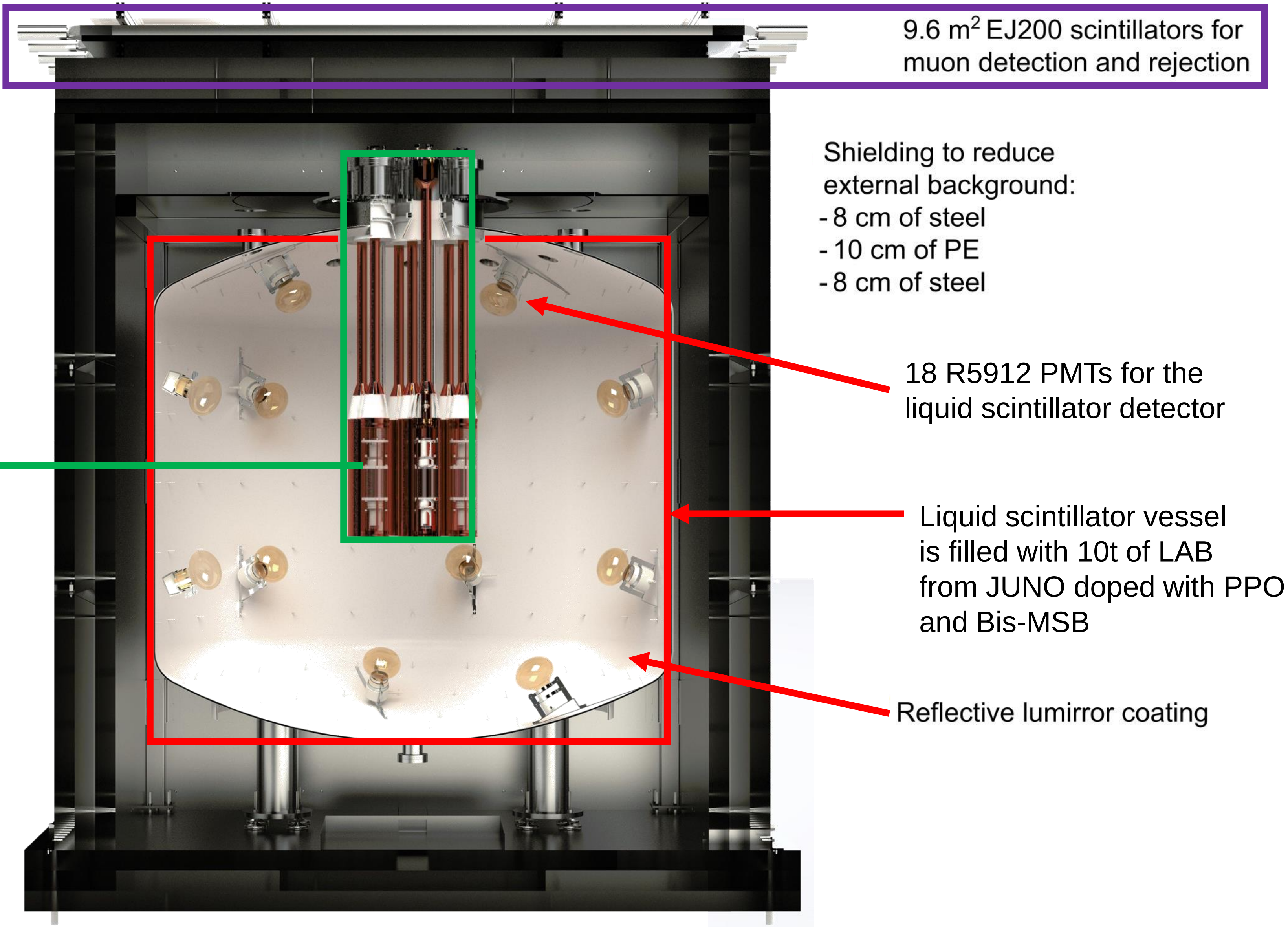




The SABRE South Experiment

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

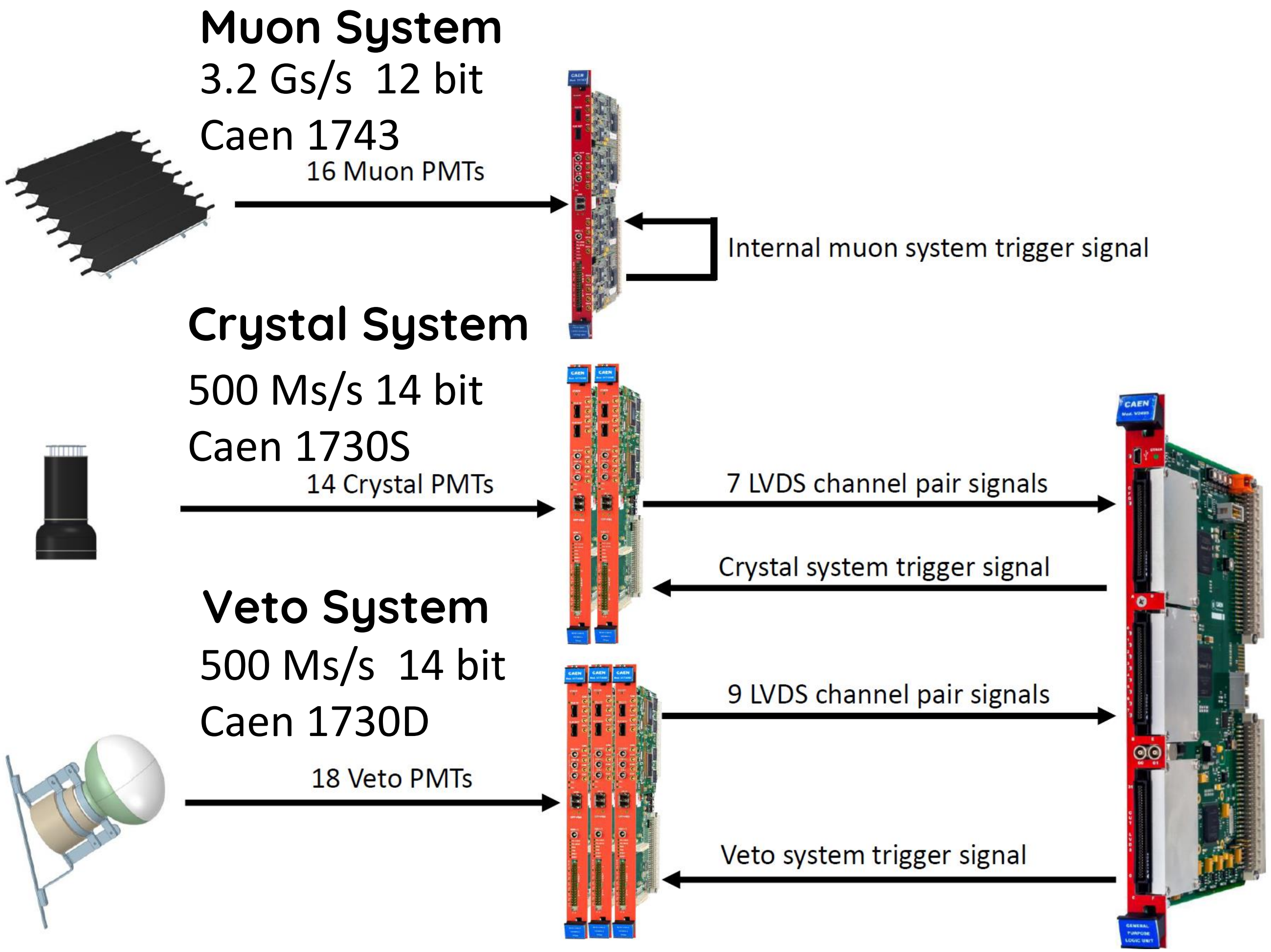




SABRE South Data Acquisition

Designed to acquire PMT waveforms at high rates

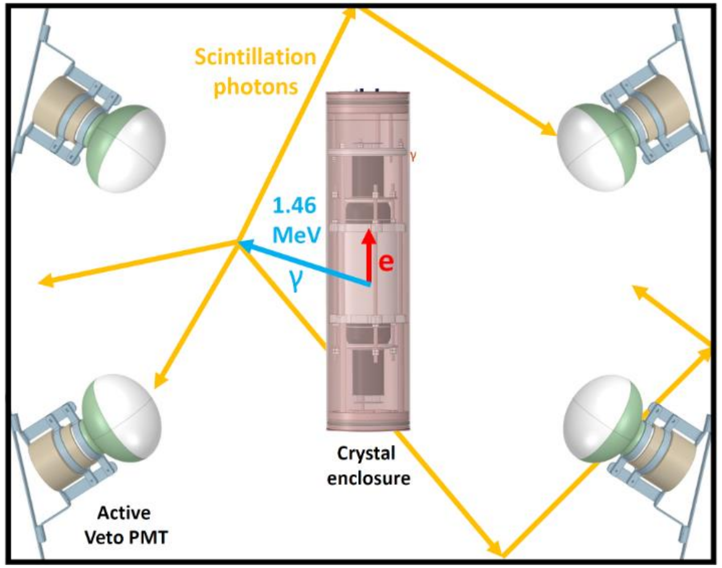
- Hardware trigger followed by transfer to and processing on dedicated computers

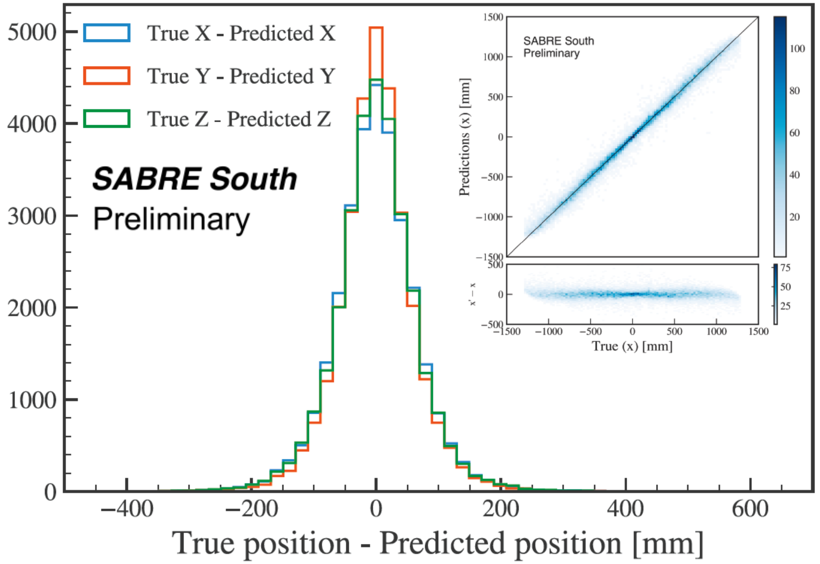


Liquid Scintillator Detector, an Active Veto

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

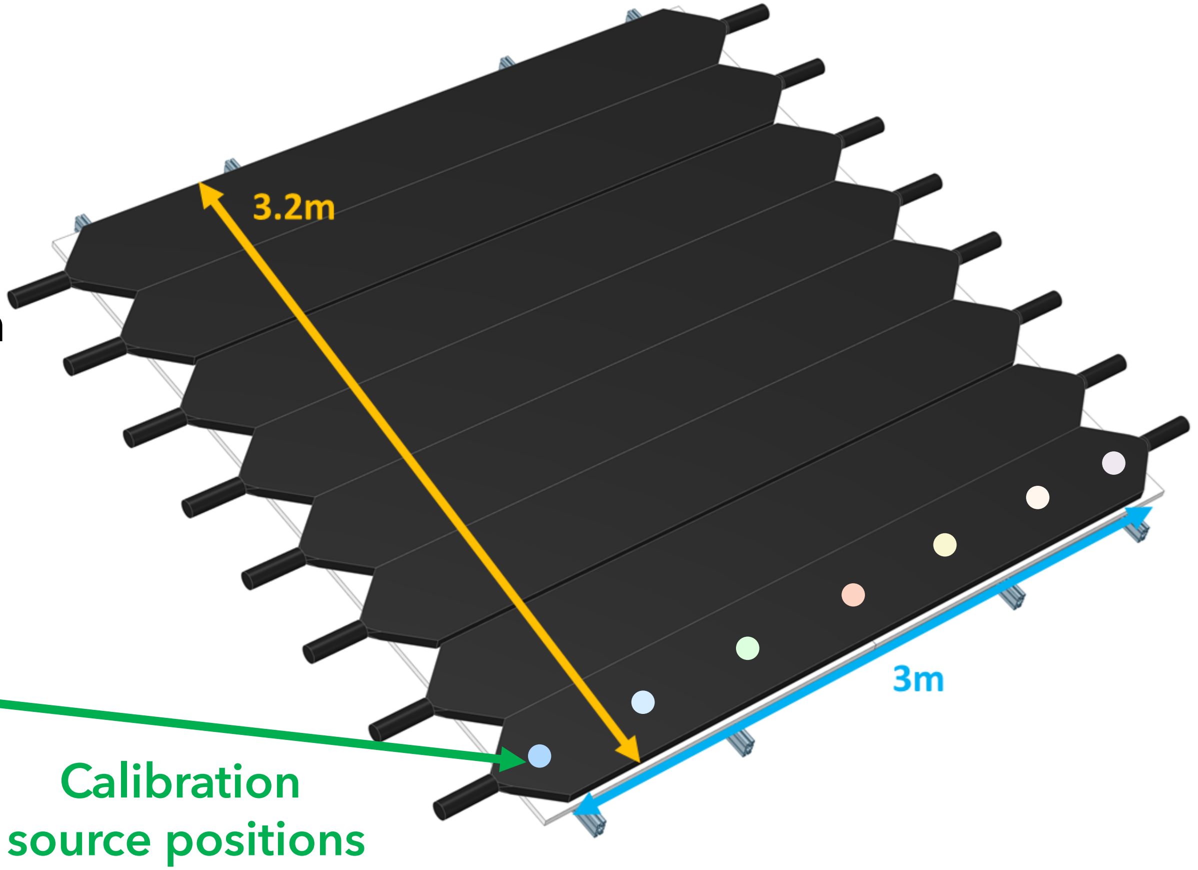
Eight 3m long detector paddles, PMTs at each end

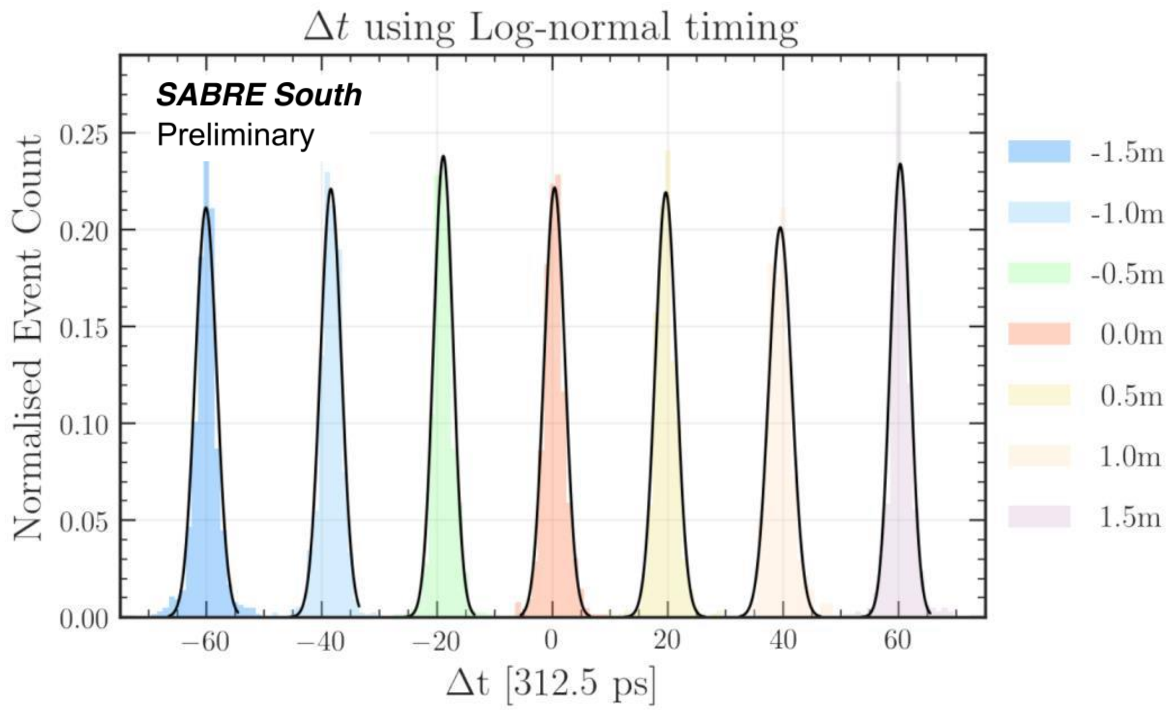
Used to veto majority of cosmic rays & for particle ID

- 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)

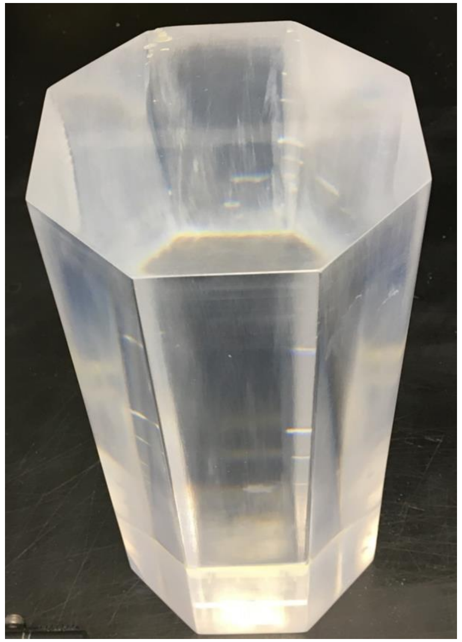
Currently the SABRE South test Crystal (NaI-35) is being tested at LNGS

- 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

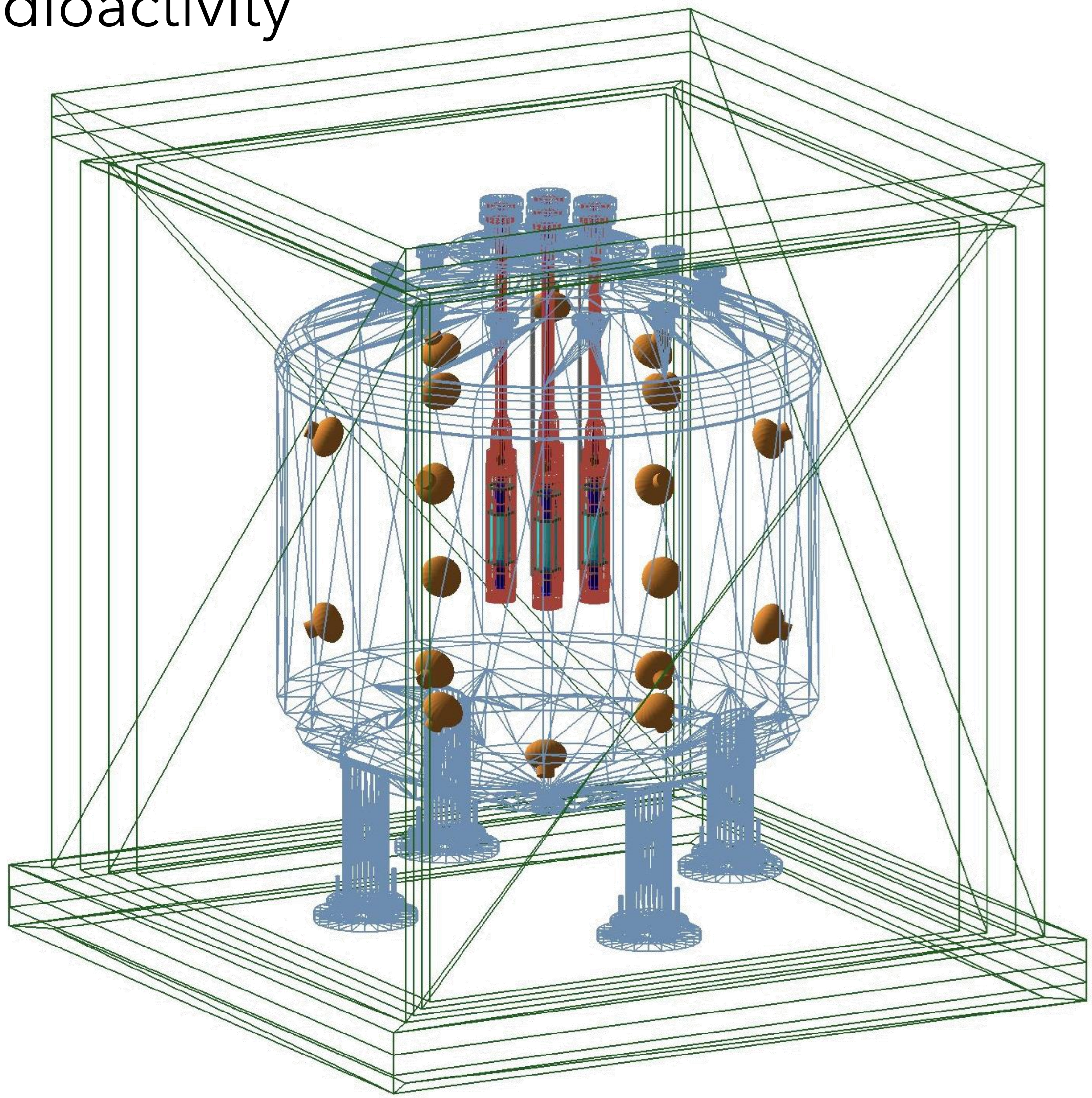
NaI-35

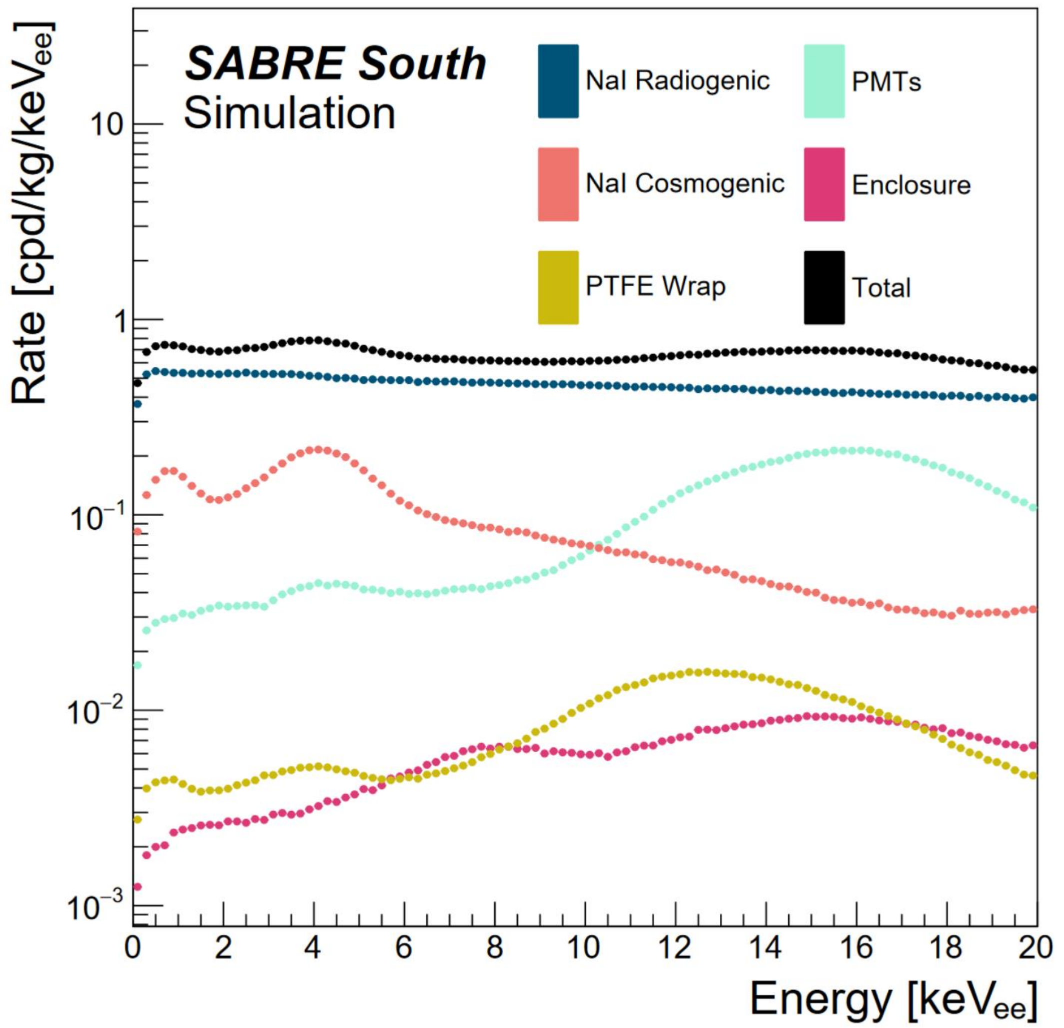


Background Simulation

Arxiv 2205.13849

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



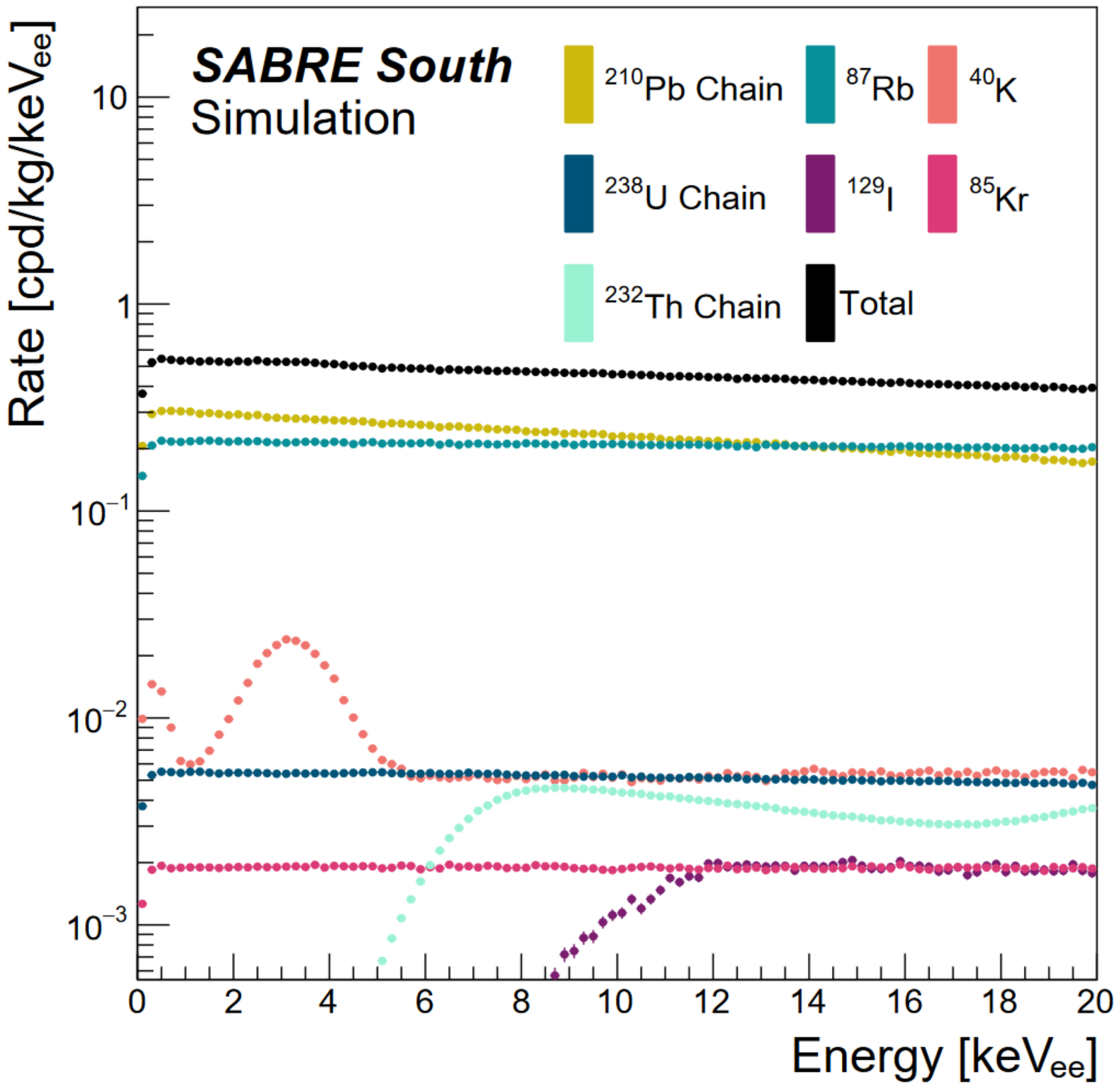


In total expect 0.72cpd/kg/keV (1-6keV)

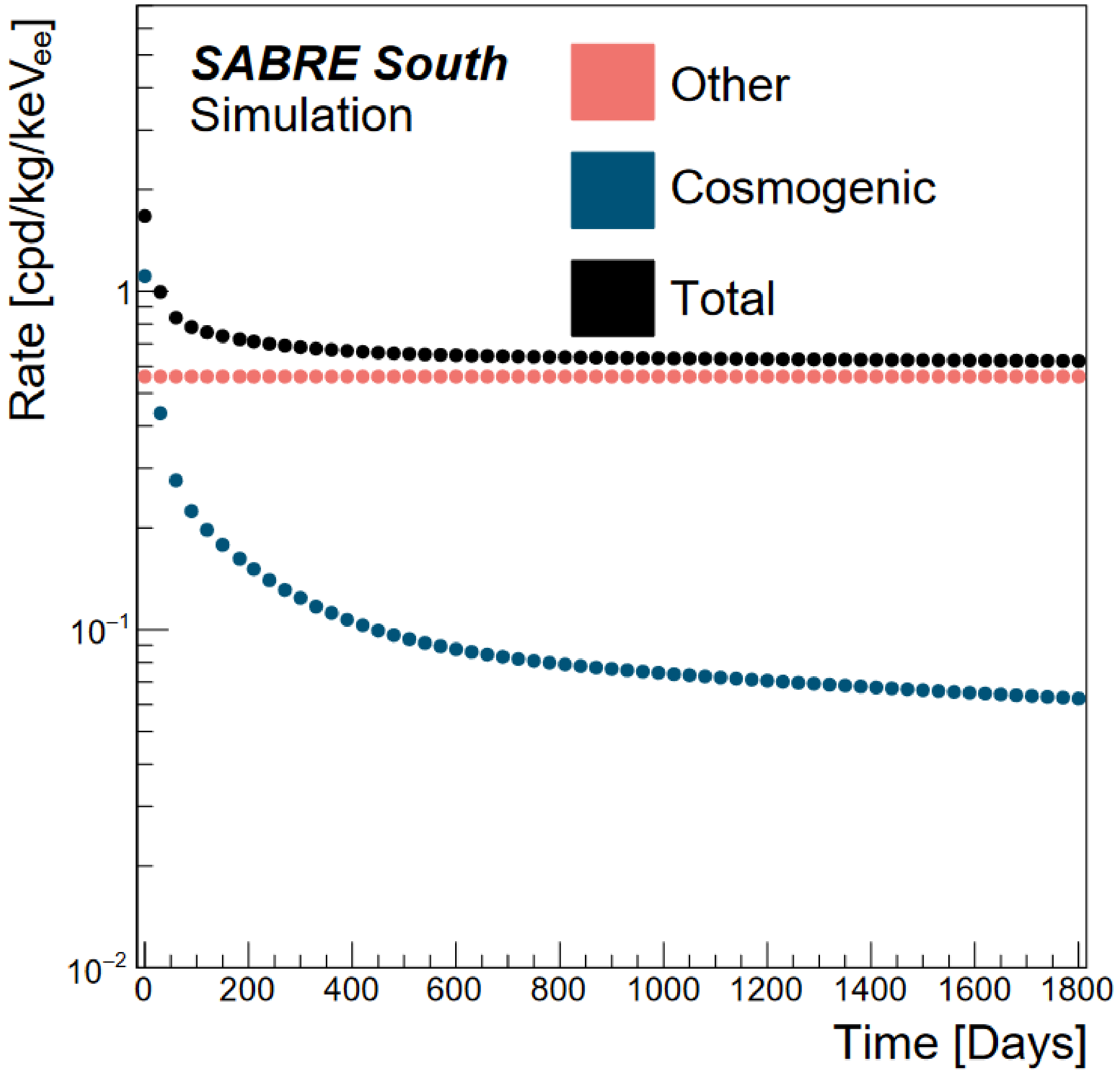
Crystal Radiation

Arxiv 2205.13849

Breakdown of isotope contributions (radiogenic crystal)



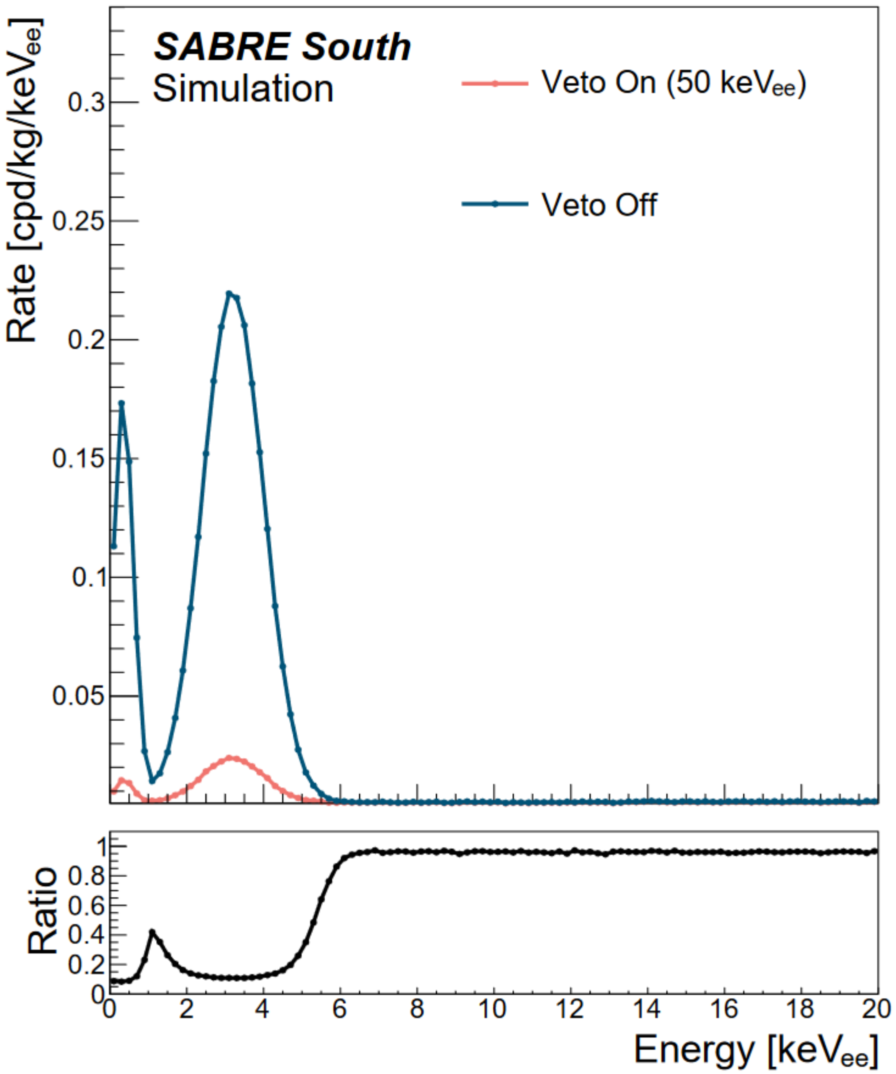
Time-dependent background rate (1-6 keV)



Simulated Veto Performance

Arxiv 2205.13849

^{40}K decays in the crystal

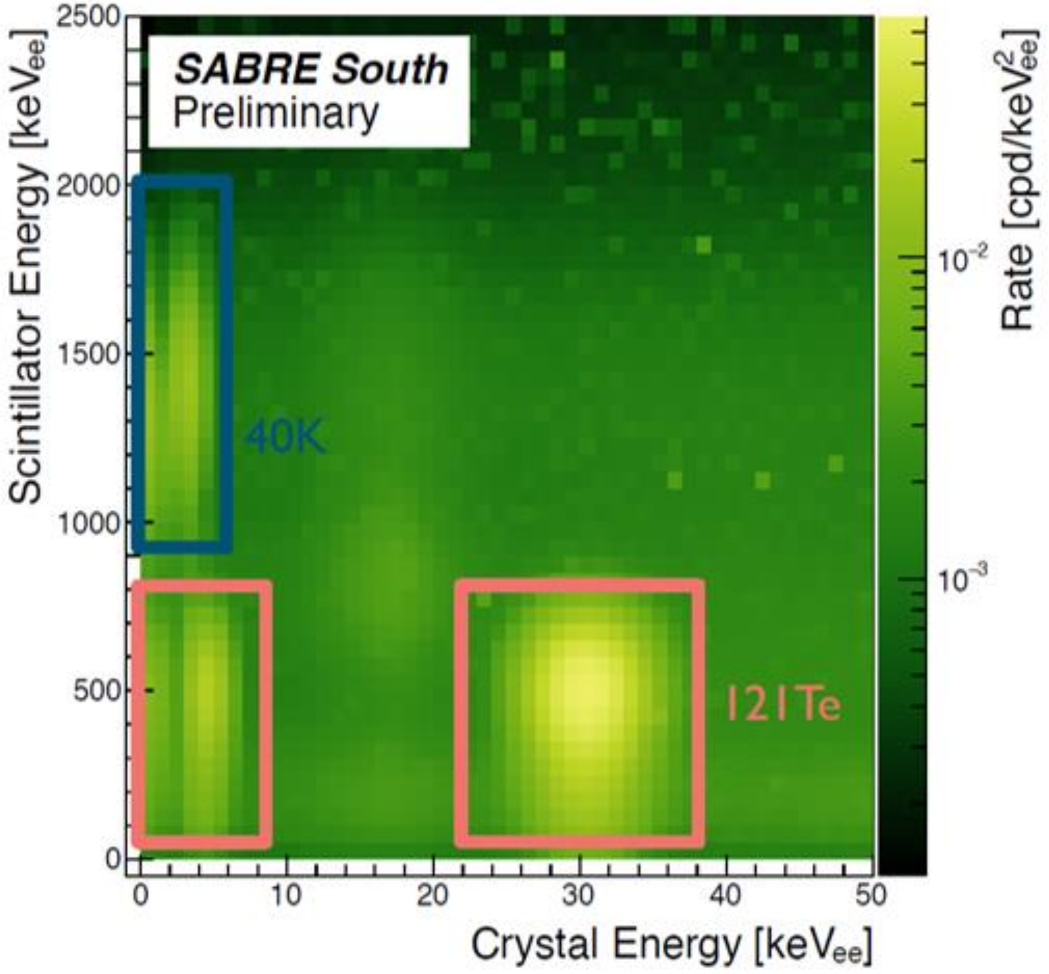


Component	Rate (cpd/kg/keV)	Veto efficiency (%)
Crystal intrinsic	<5.2 x 10^{-1}	13
Crystal cosmogenic	1.6 x 10^{-1}	45
Crystal PMTs	3.8 x 10^{-2}	57
Crystal wrap	4.5 x 10^{-3}	11
Enclosures	3.2 x 10^{-3}	85
Conduits	1.9 x 10^{-5}	96
Steel vessel	1.4 x 10^{-5}	>99
Veto PMTs	1.9 x 10^{-5}	>99
Shielding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

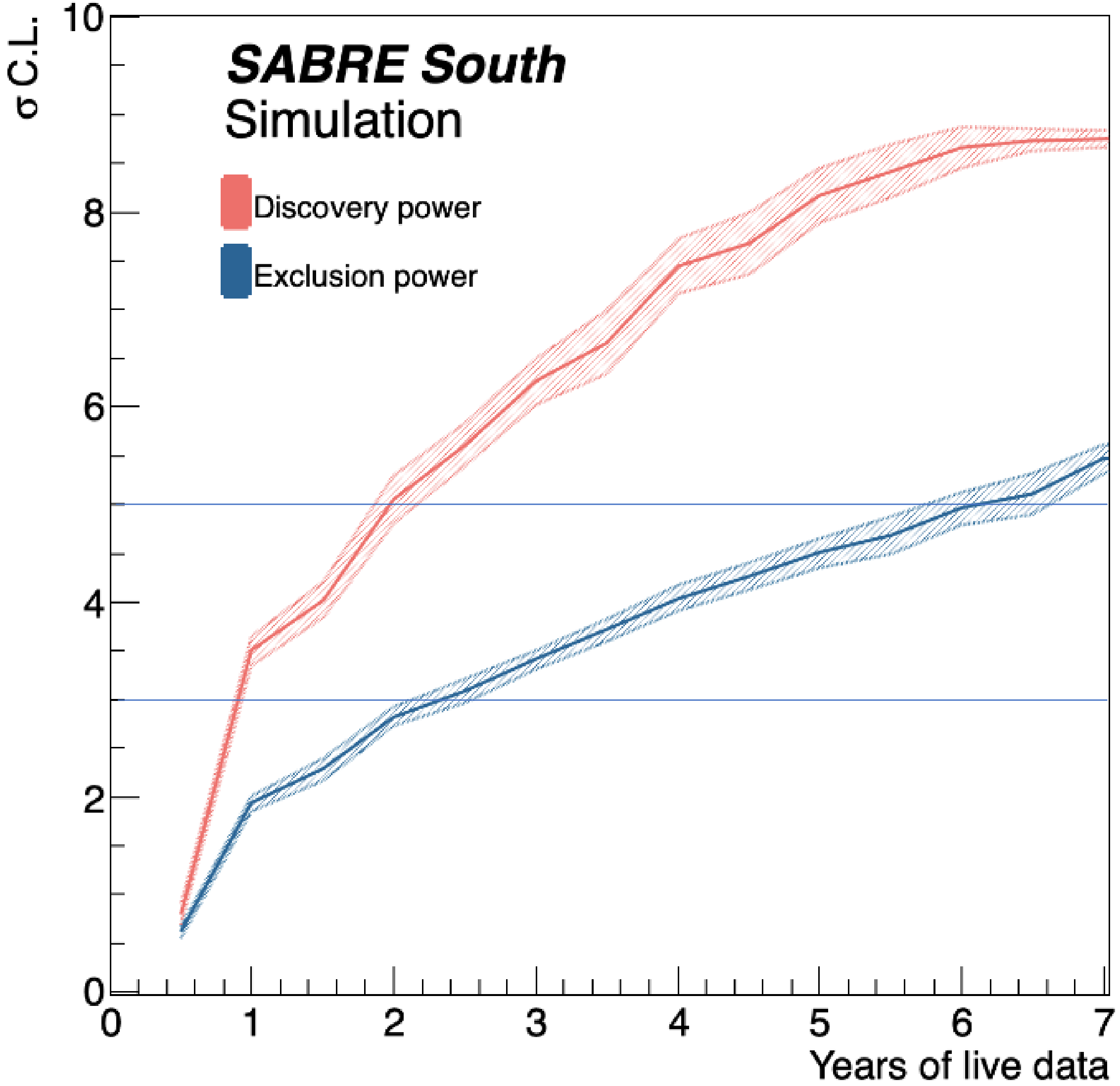
Particle ID and Expected Sensitivity

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

SABRE North

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

Backup

SABRE North status

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

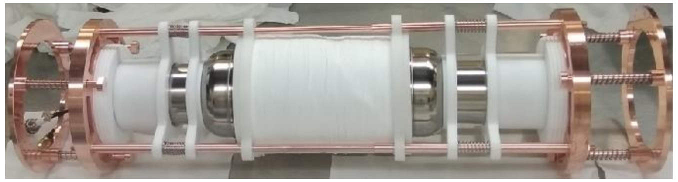
Proof-of-principle phase (1 crystal + active veto) concluded.

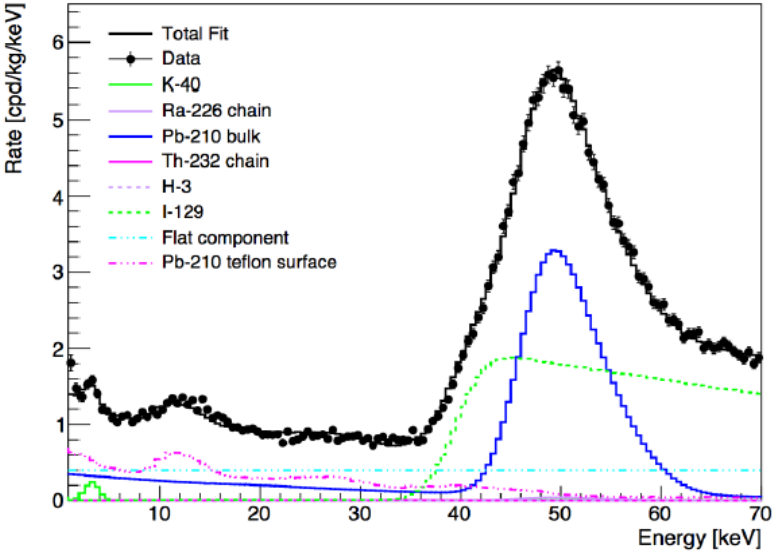
Results:

- 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.

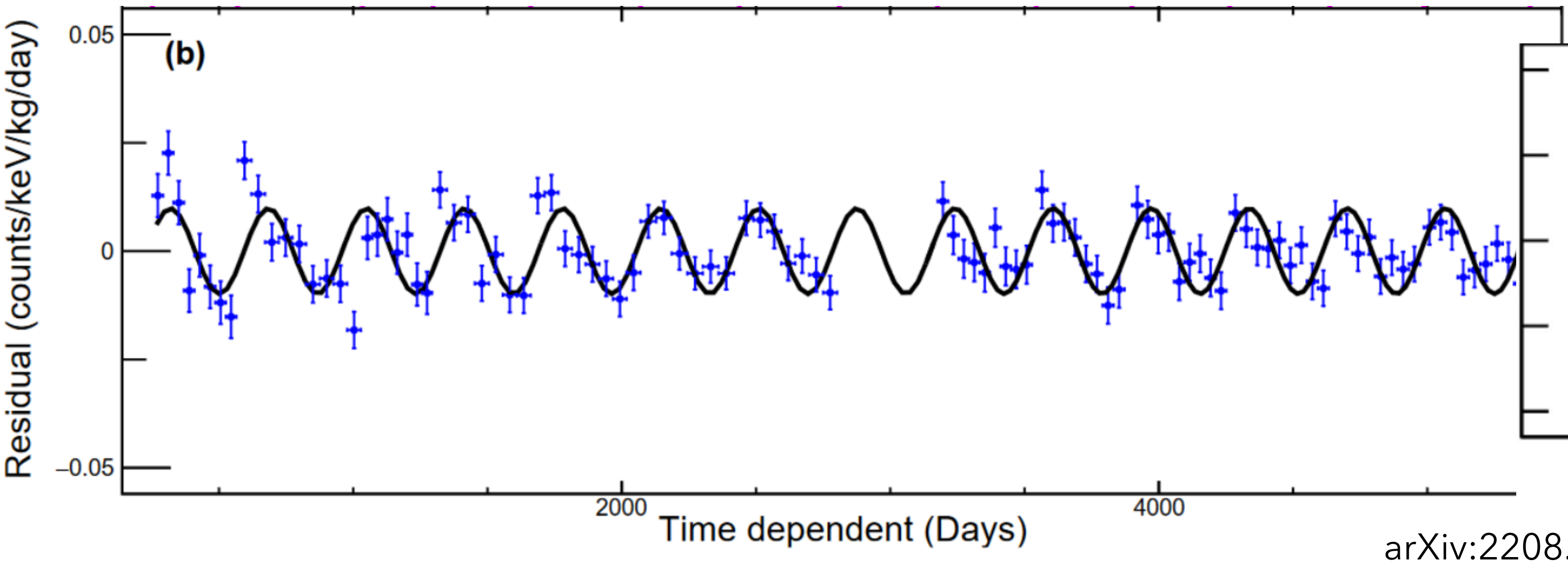
Goals for near future:

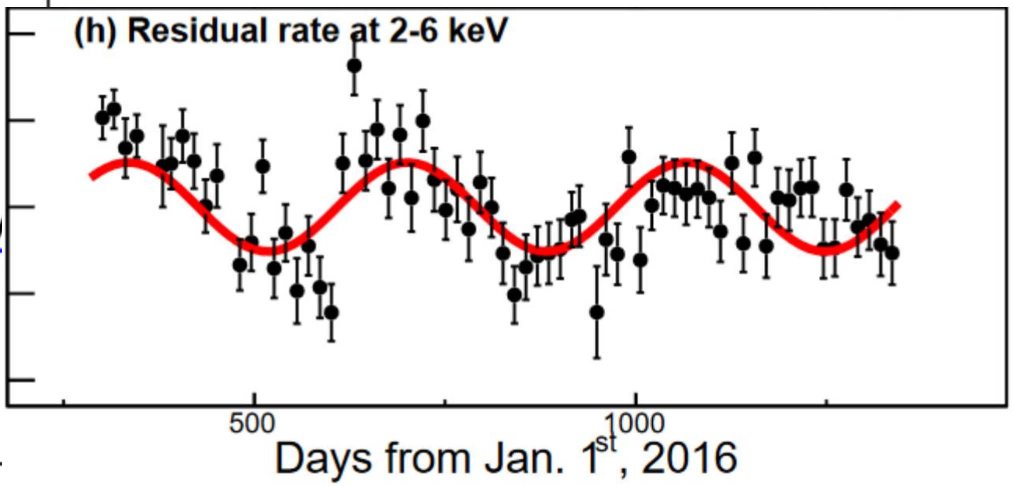
- Test the same crystal (NaI-33) with a lower radioactivity reflector
- Test reproducibility of crystal radiopurity
- Assembly of detector modules at LNGS with a new custom glove box.



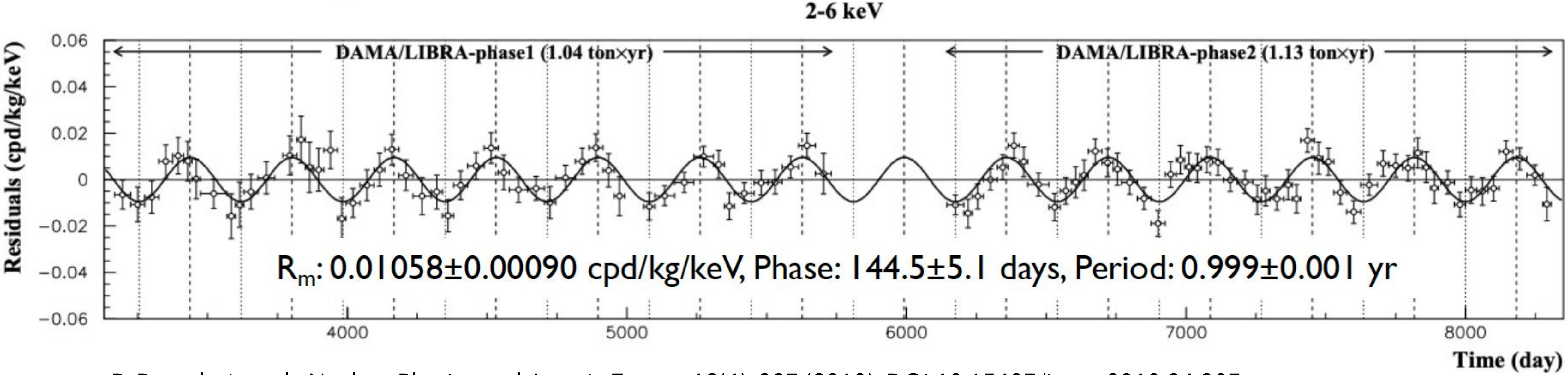


Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding





arXiv:2208.05158



R. 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

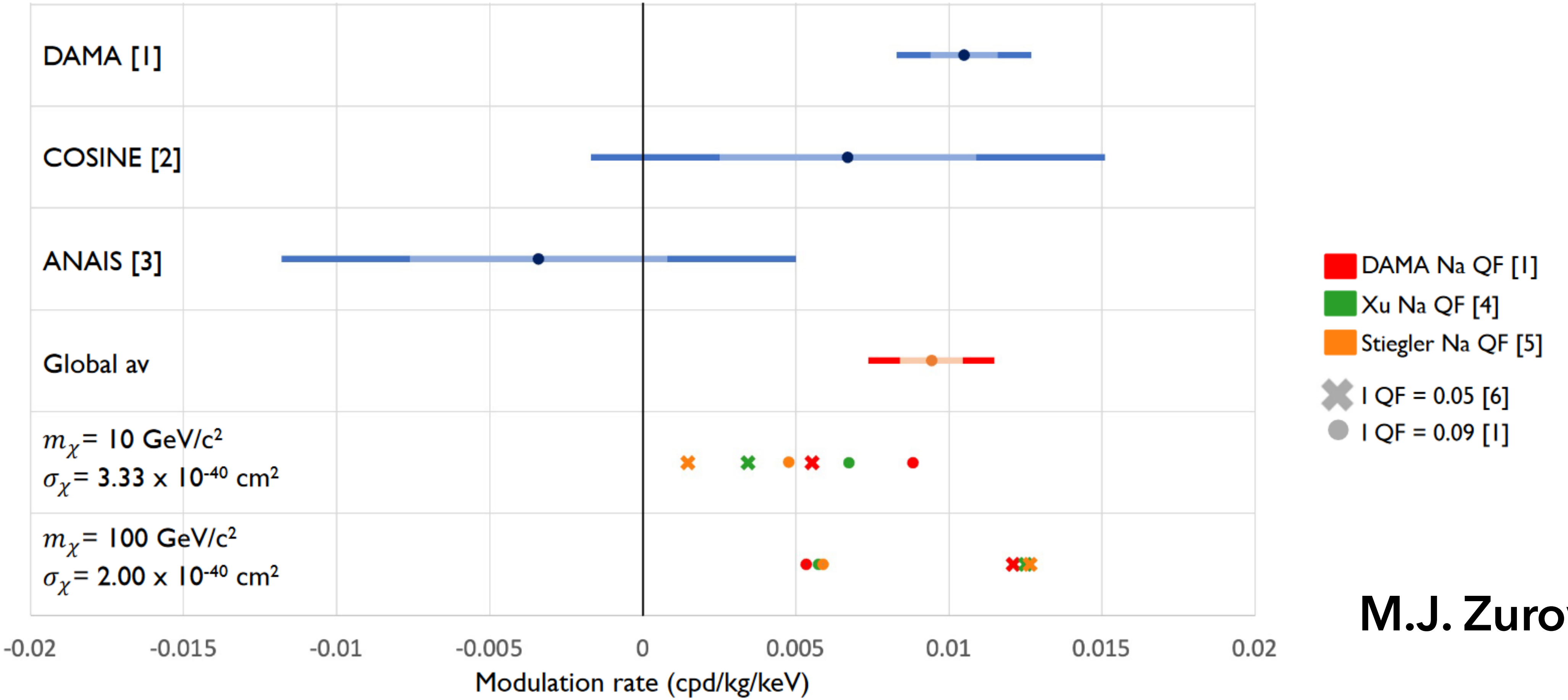
Isotope	Activity [mBq/kg]	Half life [days]
^{3}H	$9.4 \cdot 10^{-3}$	4496.8
^{22}Na	$4.3 \cdot 10^{-2}$	949.7
^{109}Cd	$5.3 \cdot 10^{-3}$	461.4
^{109m}Ag	$5.3 \cdot 10^{-3}$	$4.6\ 10^{-4}$
^{113}Sn	$1.44 \cdot 10^{-2}$	115.1
^{113m}In	$1.41 \cdot 10^{-2}$	0.07
^{121m}Te	0.16	164.2
^{121}Te	0.16	19.2
^{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