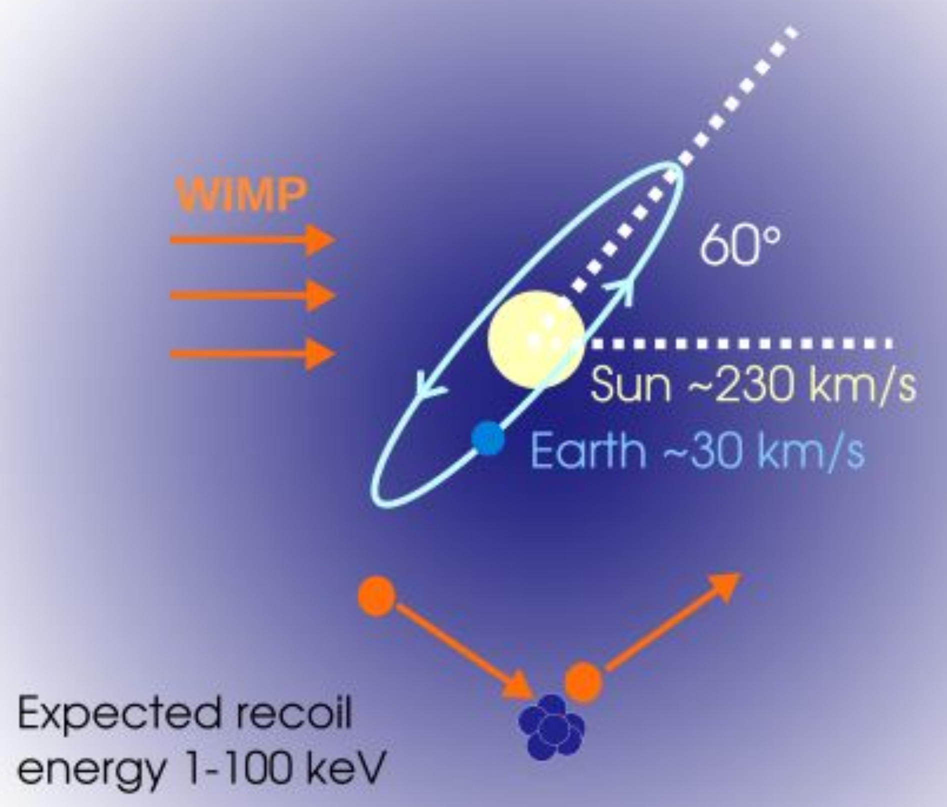
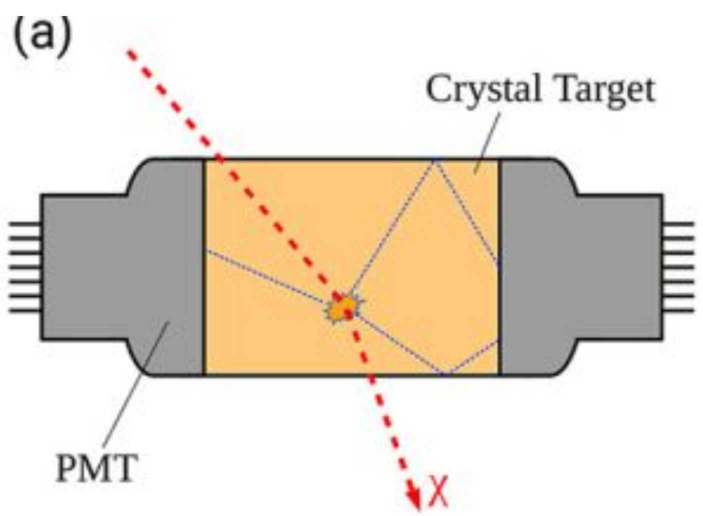
Status and prospects of SABRE North and South

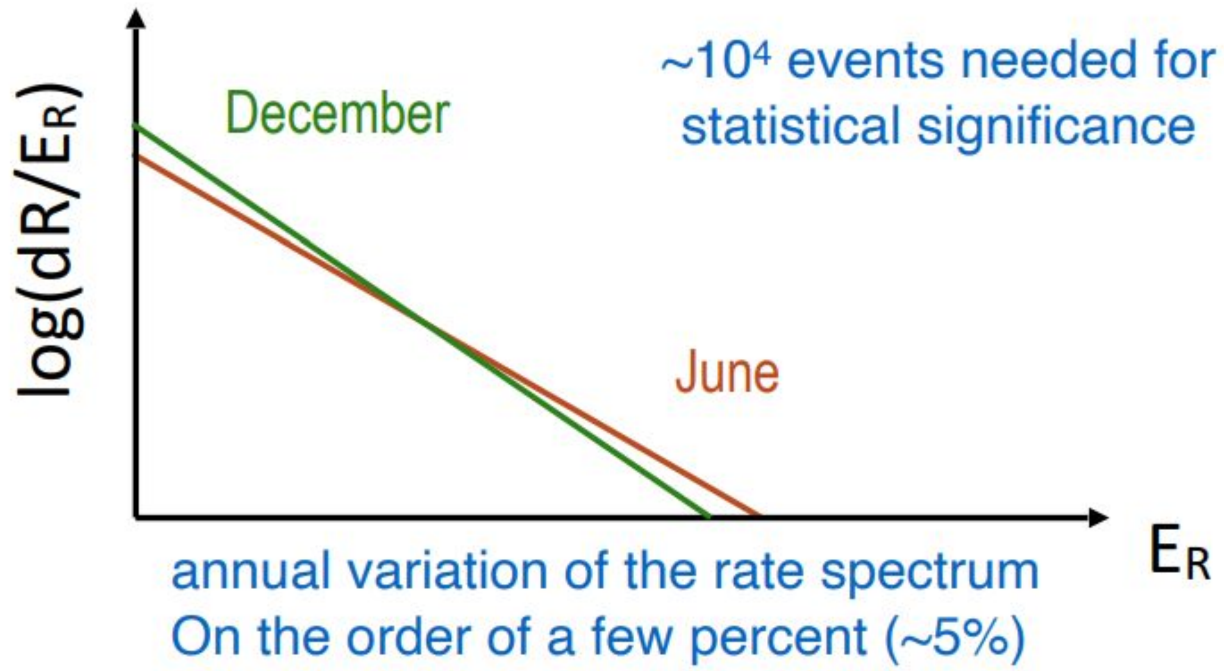
Giulia D'Imperio, INFN Roma
on behalf of SABRE North and SABRE South collaborations

Roma, 24/09/2024

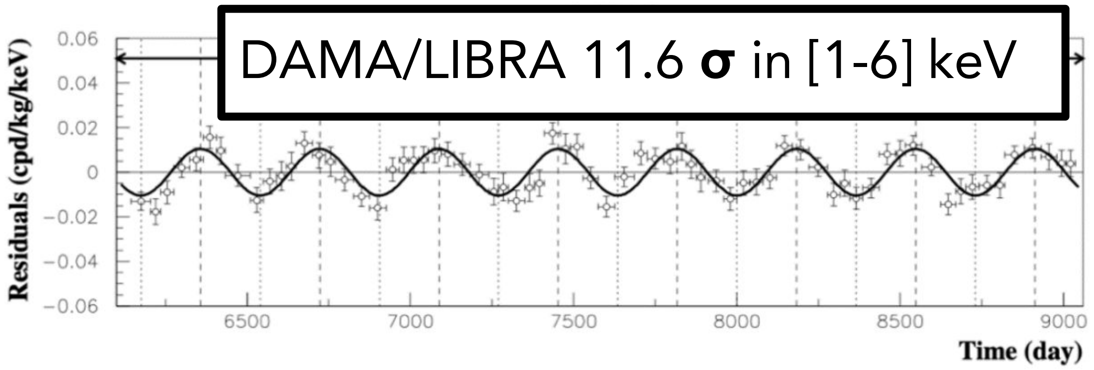
Dark Matter with annual modulation





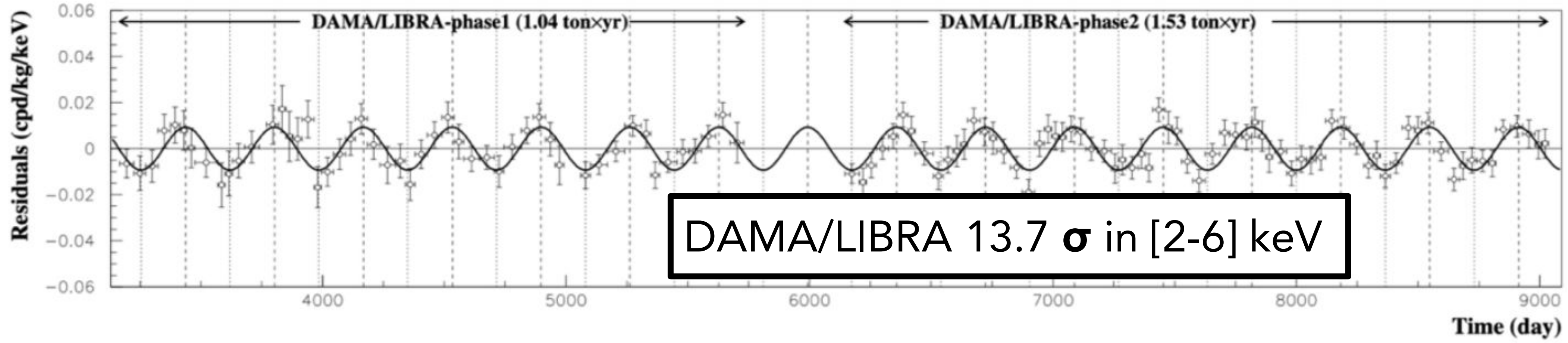


- Expected rate in an Earth-based detector is modulated
- Small modulation fraction S_m/S_0 = O(~few %)
- Region of interest [1-6] keV



Rate vs time

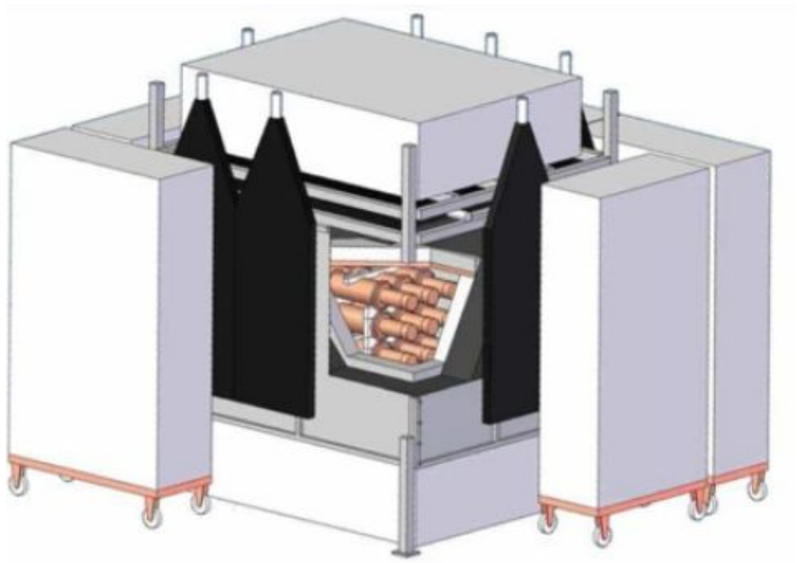
$$R = S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$



Nucl. Phys. At. Energy 22 (2021) 329-342

NaI experimental landscape

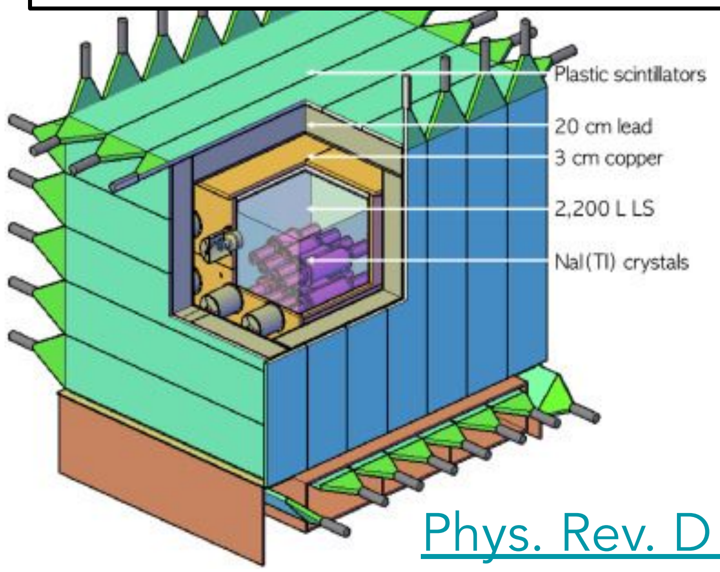
ANAIS @Canfranc, Spain



- 0.6 ton x yr in 7 years underground

Phys. Rev. D 103, 102005 (2021)

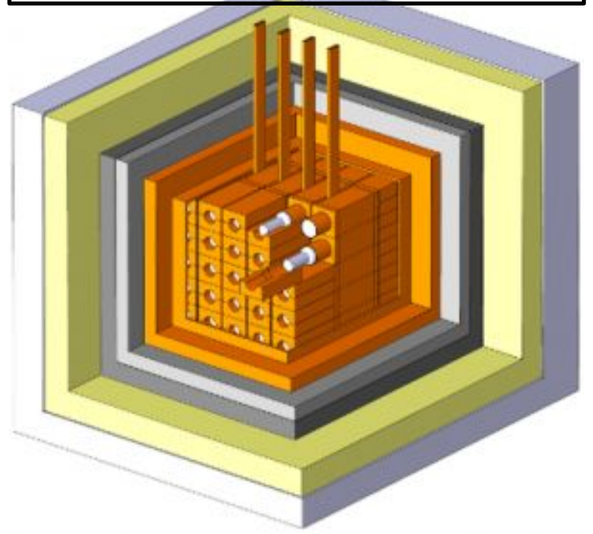
COSINE-100 @Yang Yang, South Korea



- 0.4 ton x yr in 8 years underground

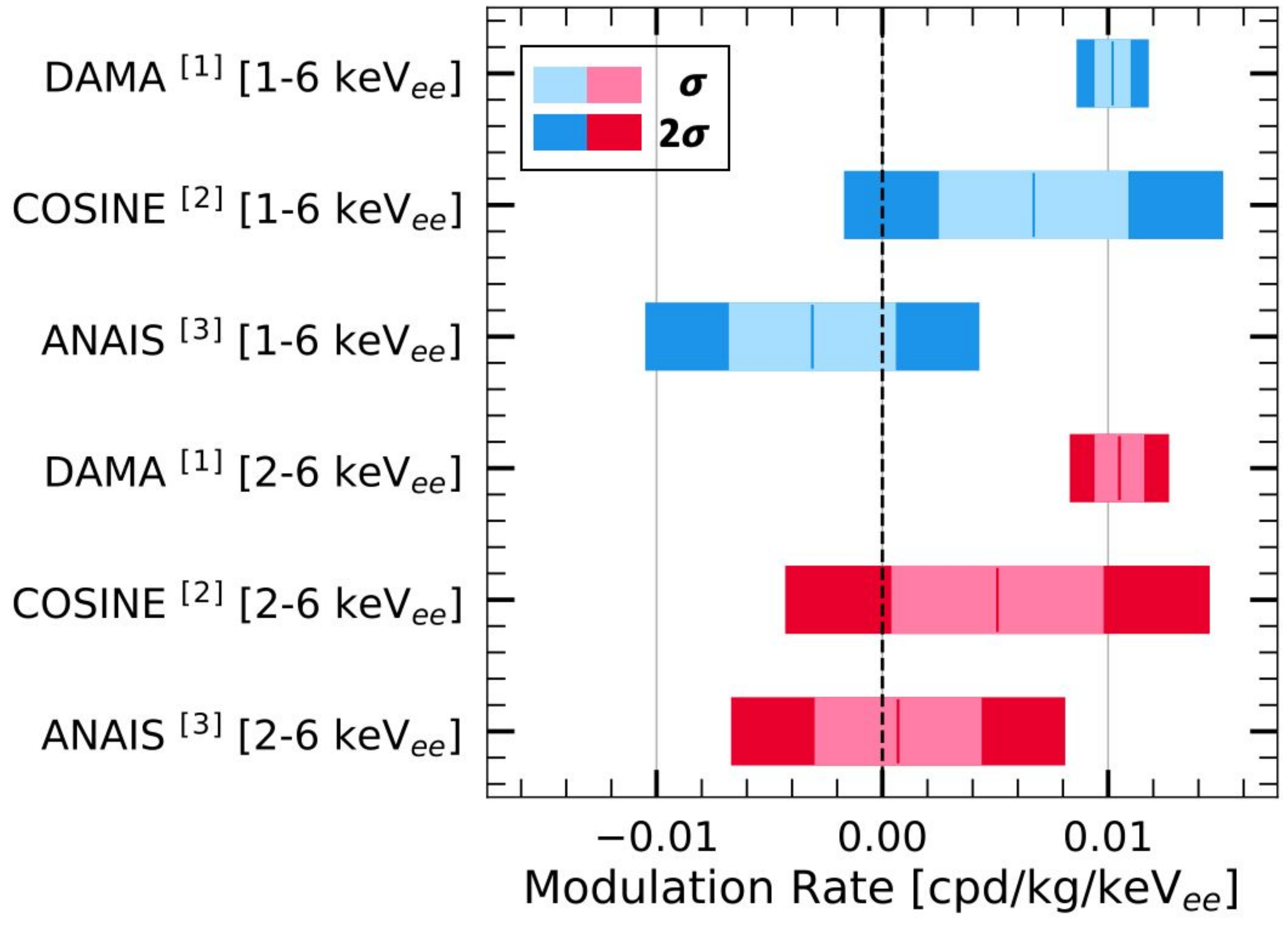
Phys. Rev. D 106, 052005 (2022)

DAMA/LIBRA @LNGS, Italy



- 3 ton x yr in 20 years
- closing data taking end of 2024

Nucl. Phys. At. Energy 22 (2021) 329-342



[1] PPNP 114, 103810 (2020)

[2] PRD 106, 052005 (2022)

[3] arxiv 2404.17348

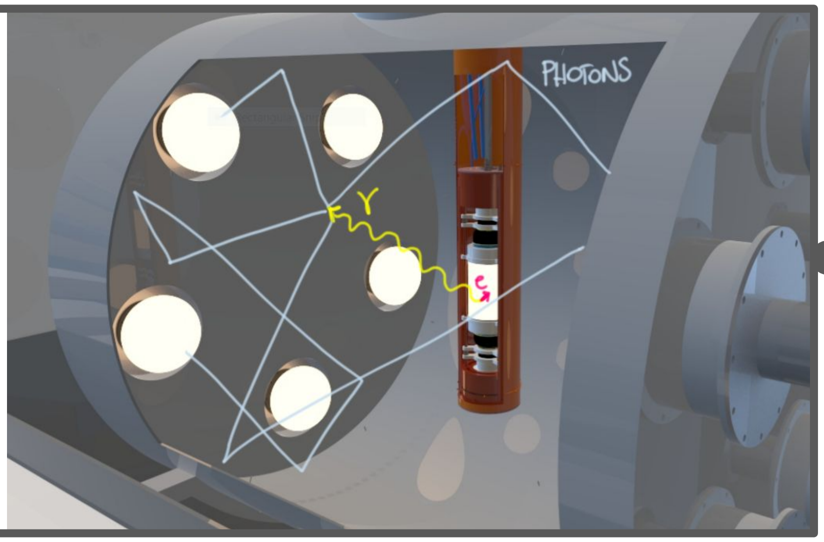
Sodium-iodide with Active Background REjection

The goal of SABRE experiment is to search for dark matter through **annual modulation** signature with **higher sensitivity (=lower background)** w.r.t. DAMA and other NaI(Tl) based experiments

Rate goal ~0.5 count/day/kg/keV

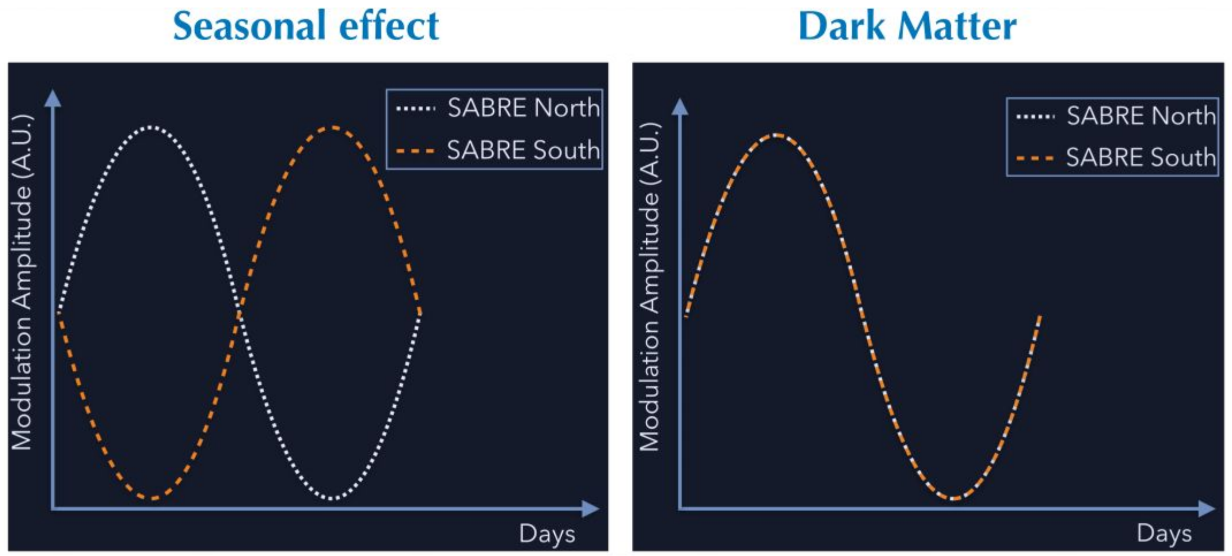
Ultra radio-pure crystals

Active veto with liquid scintillator



Double location:

Northern and Southern hemisphere

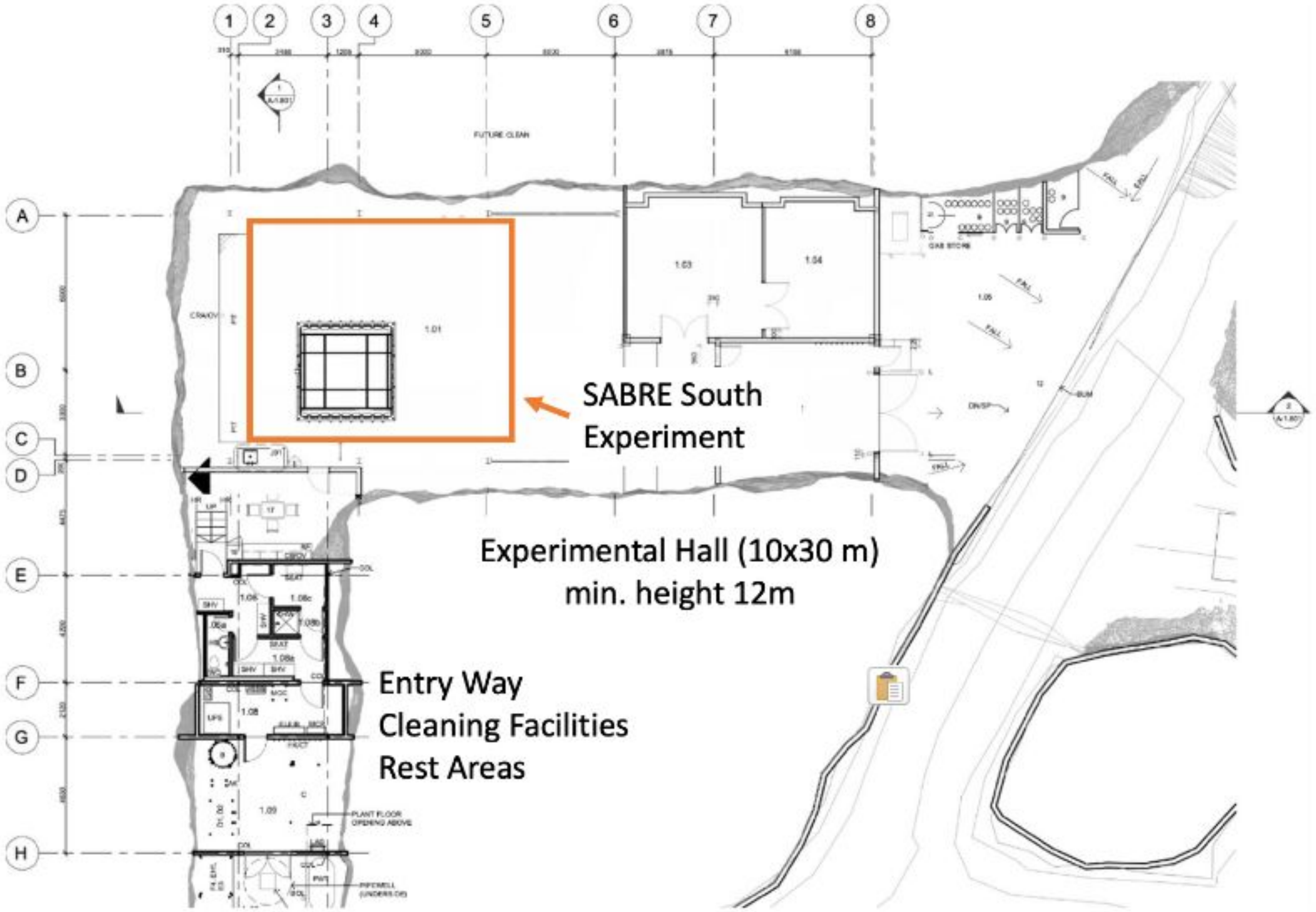


SABRE North and South

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

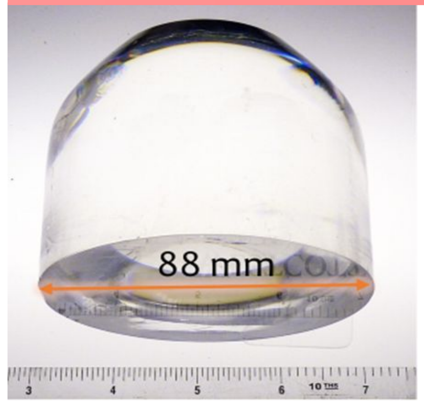
Stawell Underground Physics Lab (SUPL)

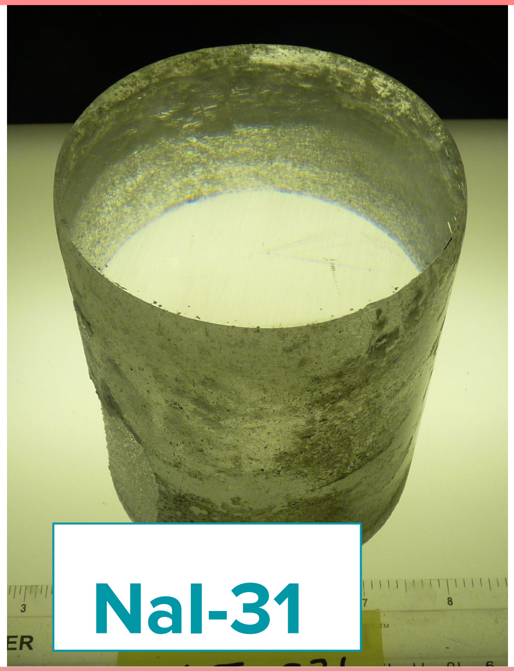
- First deep underground laboratory in the Southern Hemisphere
  - 1025 m deep (2900 m water equivalent) with flat overburden
- Located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia
- Stawell Underground Physics Laboratory completed, first detectors commissioned early 2024

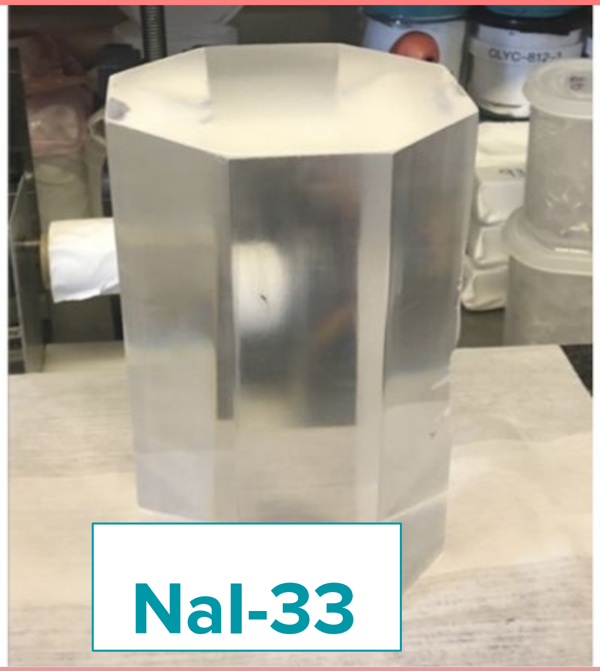


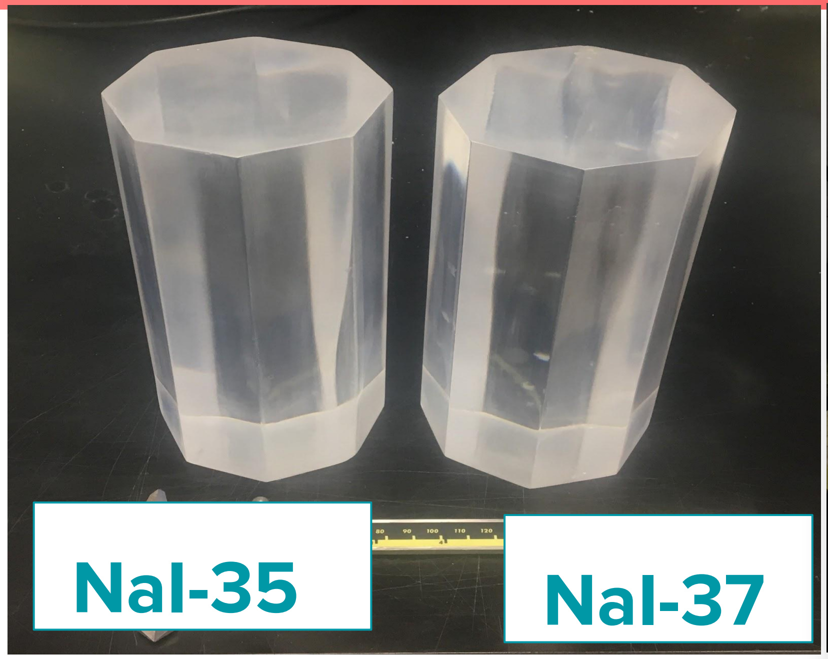
SABRE crystals R&D

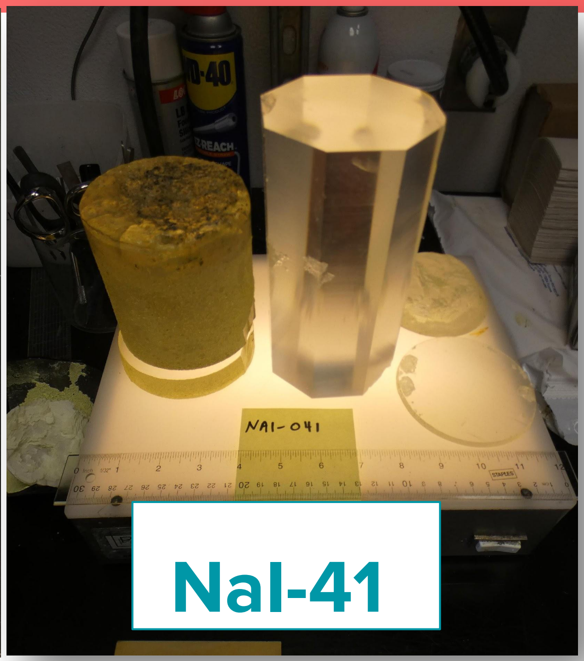
2015 — 2018 — 2019 — 2022 — 2023 — 2024











Expected @LNGS by 2024:
- NaI-42 grown after zone refining

	Powder Astro Grade batch	Mass [kg]	LY [phe/ keV]	^{39}K [ppb] powder	^{39}K [ppb] crystal	^{210}Pb [mBq/kg]	Rate ROI [dru]	^{238}U [ppt]	^{232}Th [ppt]
NaI-31	MKBW4911V	3.0	9	8.0	18.5±0.7 14.6±3.0 (PoP)	1.02±0.07	2.74±0.03	–	–
NaI-33	MKCC0371	3.4	11	4.3	4.4±0.6 2.1±1.4 (PoP)	0.51±0.02	0.95±0.05	0.47±0.05	0.40±0.07
NaI-35	MKCC0371	4.36	9	4.3	8.2±0.6	0.53±0.01	1.26±0.03	0.18±0.03	–
NaI-37	113065	4.35	7.8	17.7	8.0±0.6	0.79±0.01	2.57±0.05	0.61±0.05	0.27±0.06
NaI-40*	76650	-	-	6.7	5.8±0.7	-	-	-	-
NaI-41**	76650	4.27	10	6.7	5.7±0.9	0.60±0.02	1.8±0.4	0.48±0.05	0.39±0.07

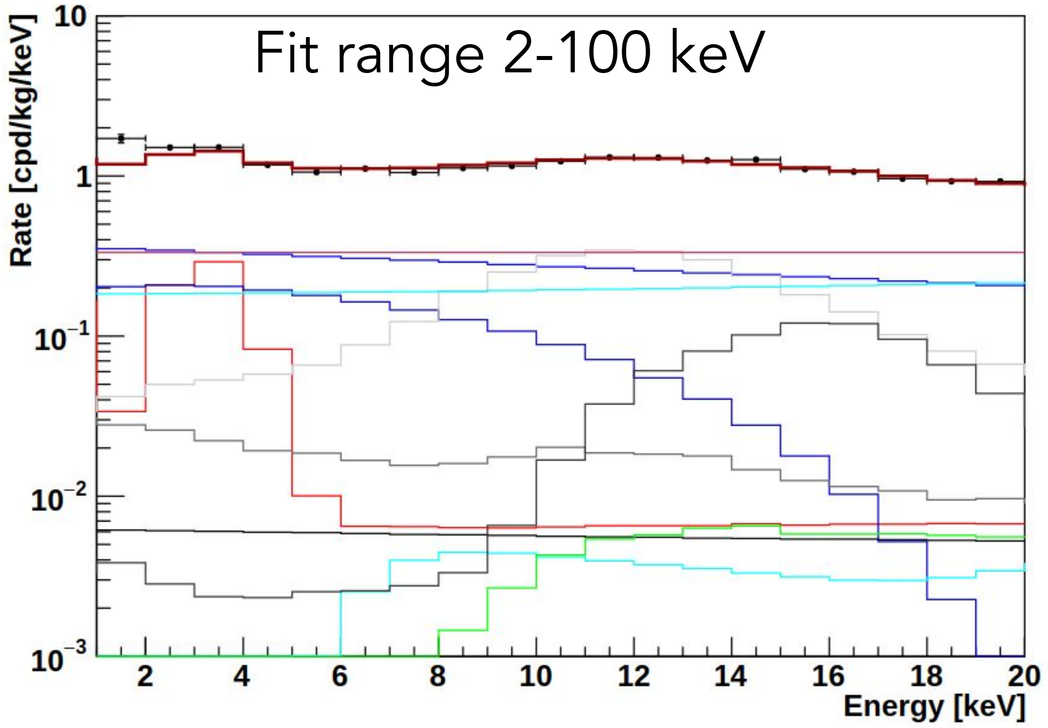
- Crystals grown at RMD
- Background ~1 cpd/kg/keV
- Reproducibility of clean growth from clean powder
- Clean growth from chunks (NaI-41)

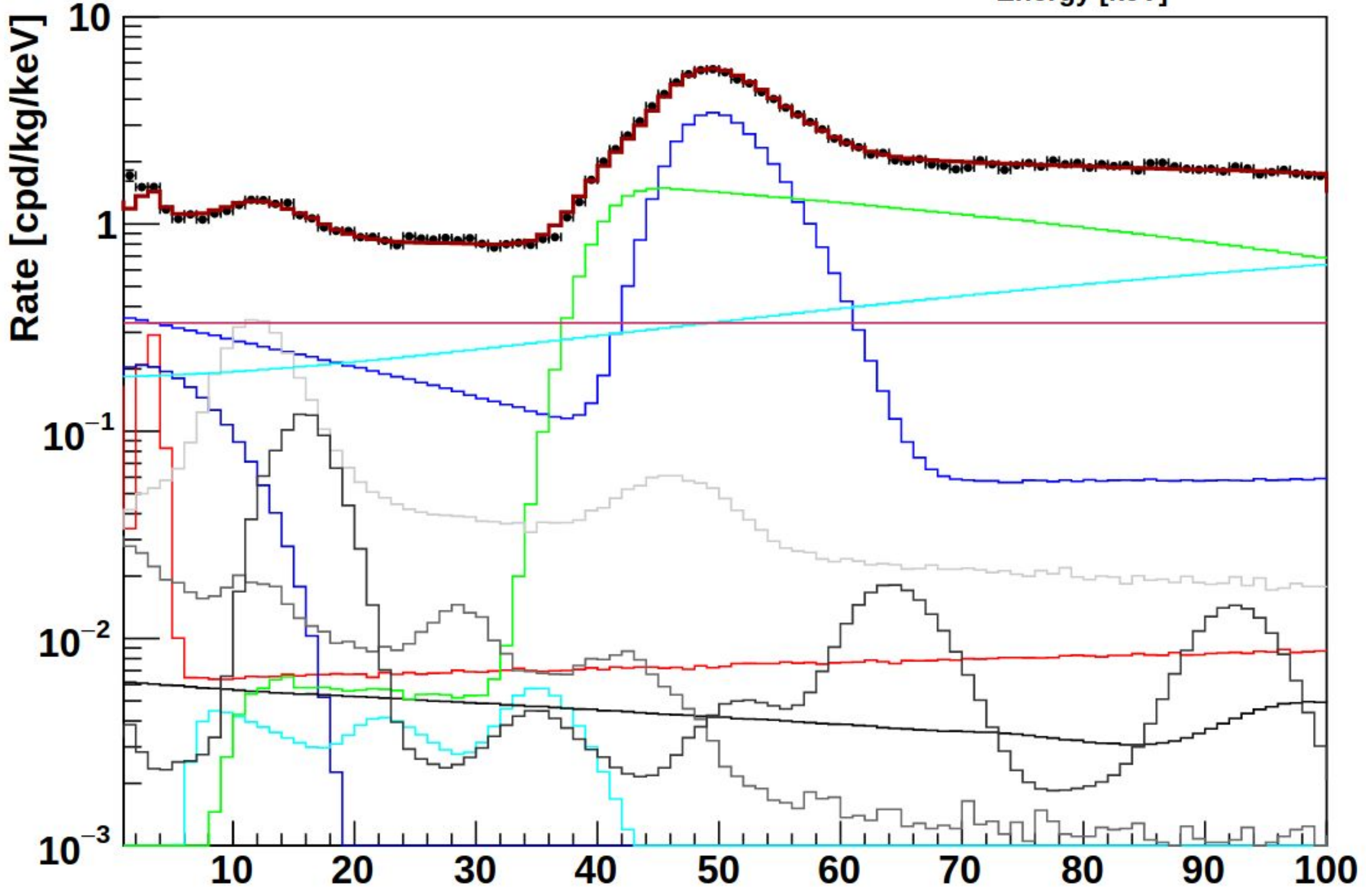
*Destroyed to grow NaI-41 from chunks
**Still affected by cosmogenics

SABRE background model (NaI-33)

- Background model updated since Eur. Phys. J. C (2022) 82:1158
- Background from reflector is not dominant (now constrained from direct measurements)
- Dominant backgrounds: ^{210}Pb in crystal bulk, internal beta emitters, external background

Source	Rate in ROI [1,6] keV [cpd/kg/keV]	Activity from fit
40K	0.125	0.16±0.01 mBq/kg
210Pb bulk	0.333	0.49±0.05 mBq/kg
210Pb reflector bulk	0.054	11±1 mBq/kgPTFE
210Pb reflector surface	0.023	<0.6 mBq/m2
3H	0.198	24±2 mBq/kg
129I	0.0003	1.03±0.05 mBq/kg
238U	0.006	5.9±0.6 mBq/kg
232Th	0.0003	1.6±0.3 mBq/kg
PMT	0.003	1.9±0.4 mBq/PMT
External	0.185	0.89±0.05 relative unit to reference spectrum
Other b's	0.333	297±15 counts
TOTAL	1.26±0.27	



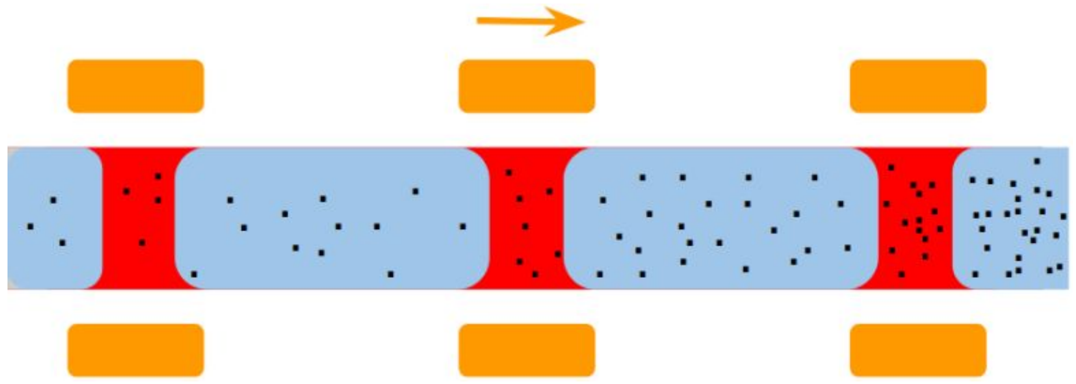


The SABRE strategy

- SABRE Proof-of-principle (PoP, with active veto) and PoP-dry (only passive shielding) at LNGS achieved a background of ~1 cpd/kg/keV

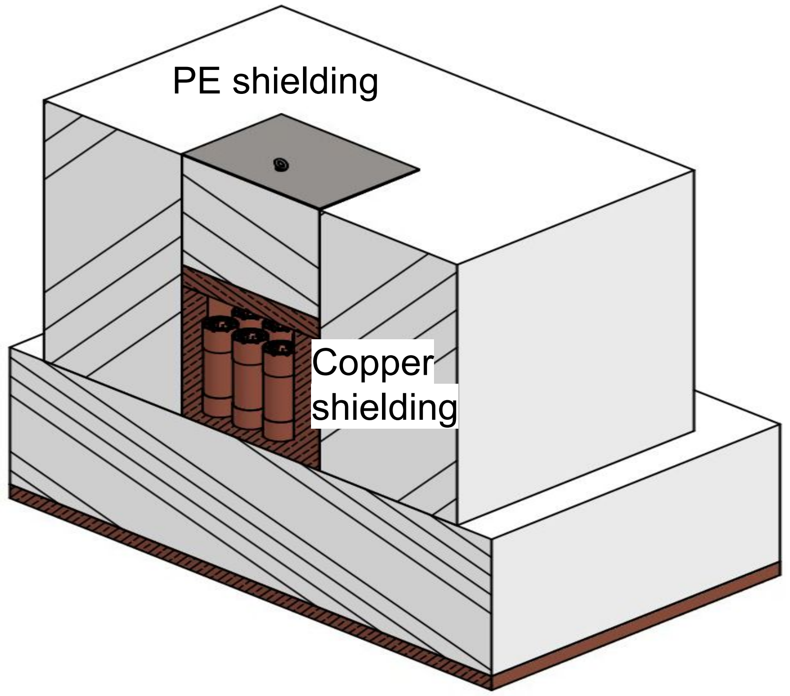
- Strategy to reach the background goal of ~0.5 cpd/kg/keV
  - For internal backgrounds

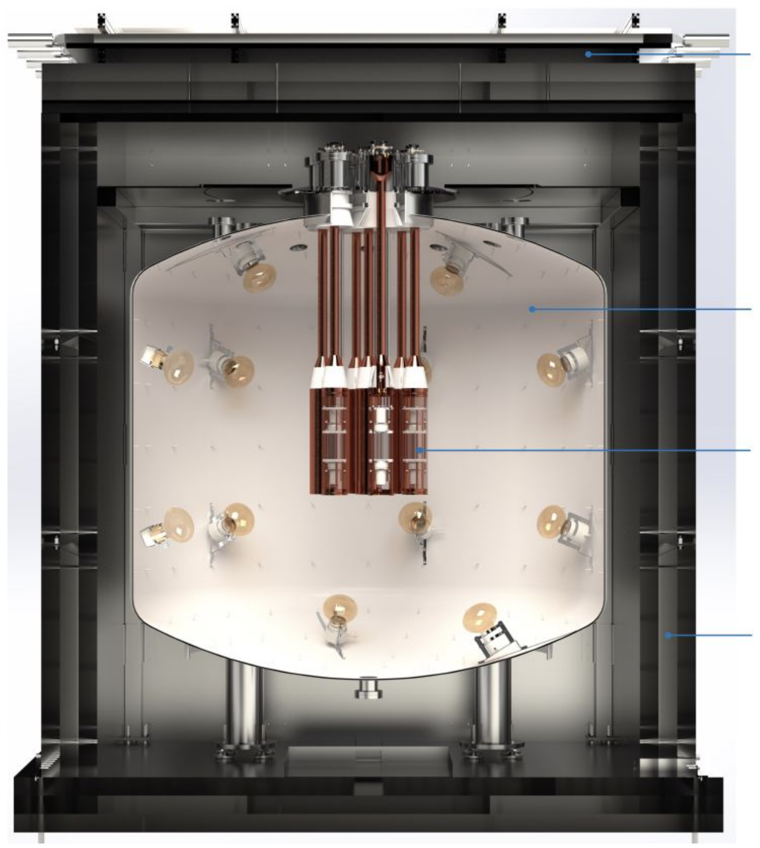
    →SABRE North & South: zone refining
    → Reduce K of ~10, Pb of ~3
    Phys. Rev. Applied 16, 014060 (2021)



  - For external background:

    →SABRE North: improve passive shielding
    →SABRE South: Liquid Scintillator (LAB)
    + Muon Veto

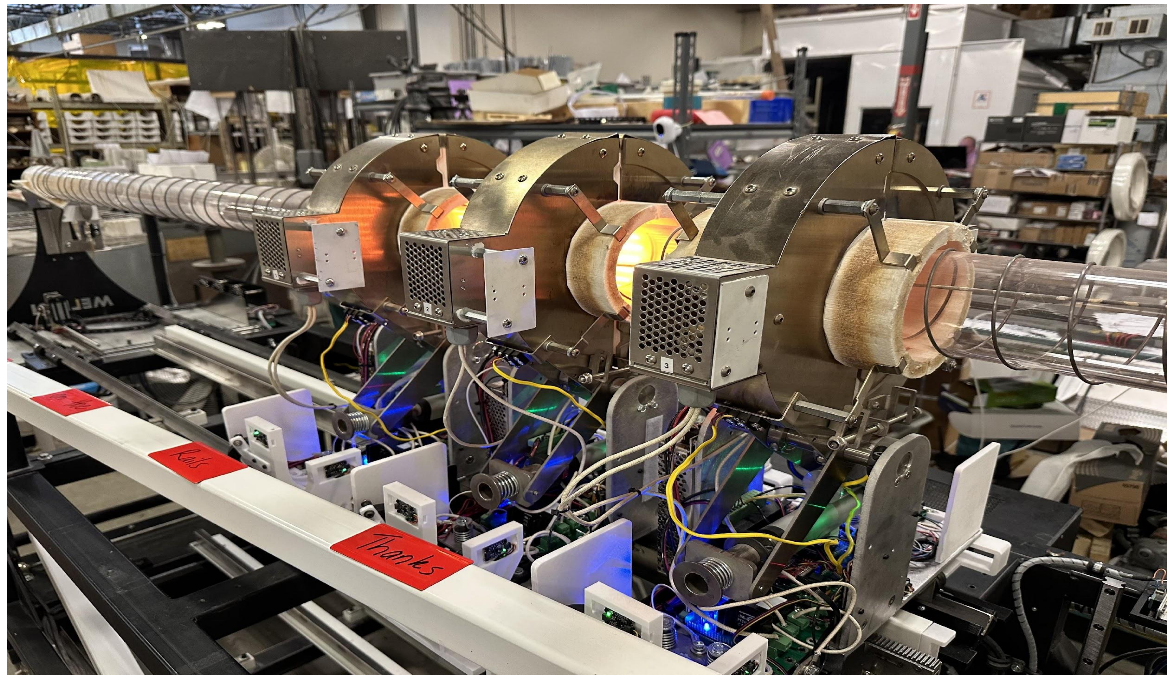




Zone refining activities 2023-2024

Four runs with 900 gr of AstroGrade NaI powder have been performed at MELLEN, NH, USA between September 2023 and February 2024

- RUN1: Carbon coated ampoule
- RUN2: Carbon coated ampoule with increased number of passes
- RUN3: No coating + use of $SiCl_4$ to avoid sticking
- RUN4: No coating + use of $SiCl_4$ (gas in the ampoule pumped out)

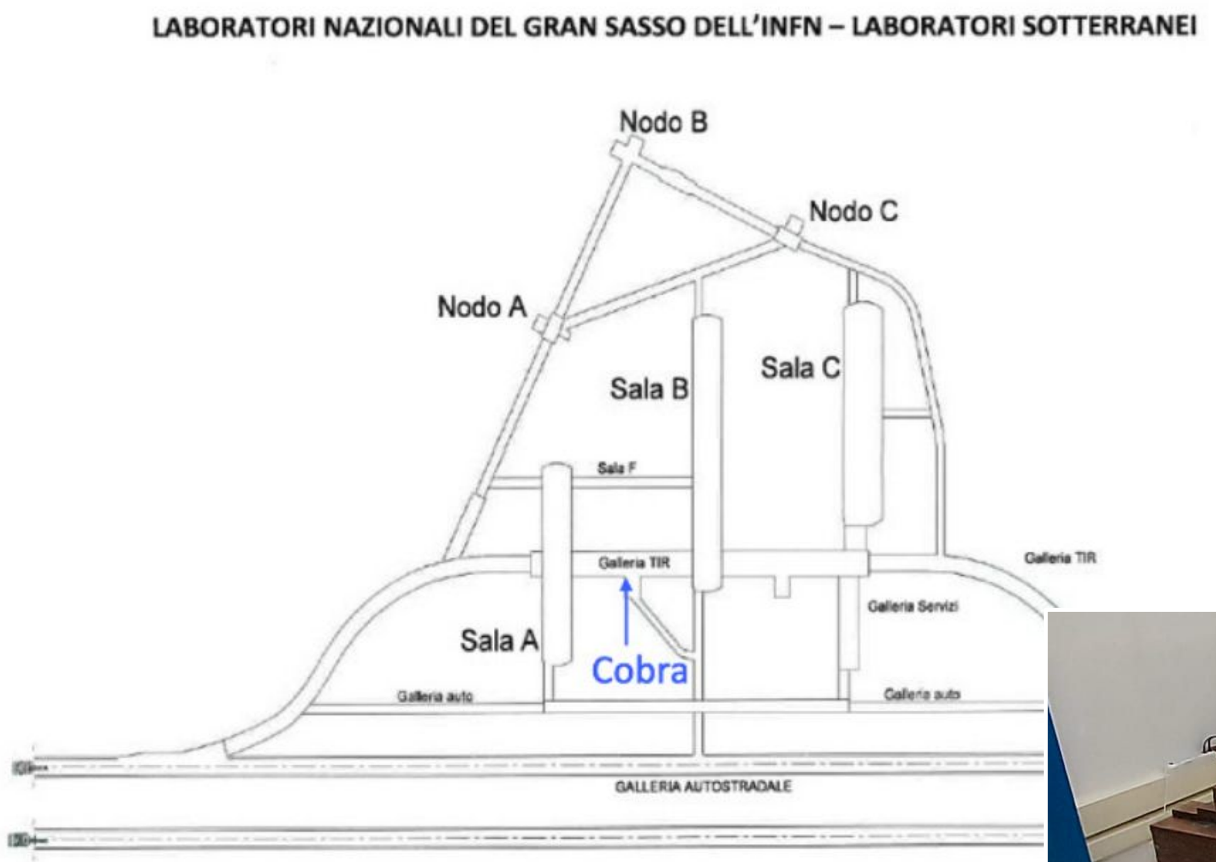


Sample Run4	^{39}K [ppb]	^{65}Cu [ppb]	^{85}Rb [ppb]	^{133}Cs [ppb]	^{138}Ba [ppb]	^{208}Pb [ppb]
	LSC	LSC	LSC	LSC	LSC	LSC
powder	7	5	0.2	1	3.6	1.1
Zone 1	<4	<4	<0.8	<0.3	<0.3	2.0±0.3
Zone 2	<4	<4	<0.8	<0.3	1.2±0.3	1.6±0.2
Zone 3	10.1±0.6	<4	<0.8	<0.3	2.7±0.2	1.6±0.3
Zone 4	21.5±0.7	<4	<0.8	1.1±0.1	8.1±0.5	1.9±0.3
Zone 5	68±2	10±1	<0.8	203±6	17±0.9	1.2±0.3

The successful growth of the NaI-41 crystal from chunks and its excellent optical properties represents an important step in our approach to producing high radiopurity crystals.

SABRE North facilities @LNGS (2024)

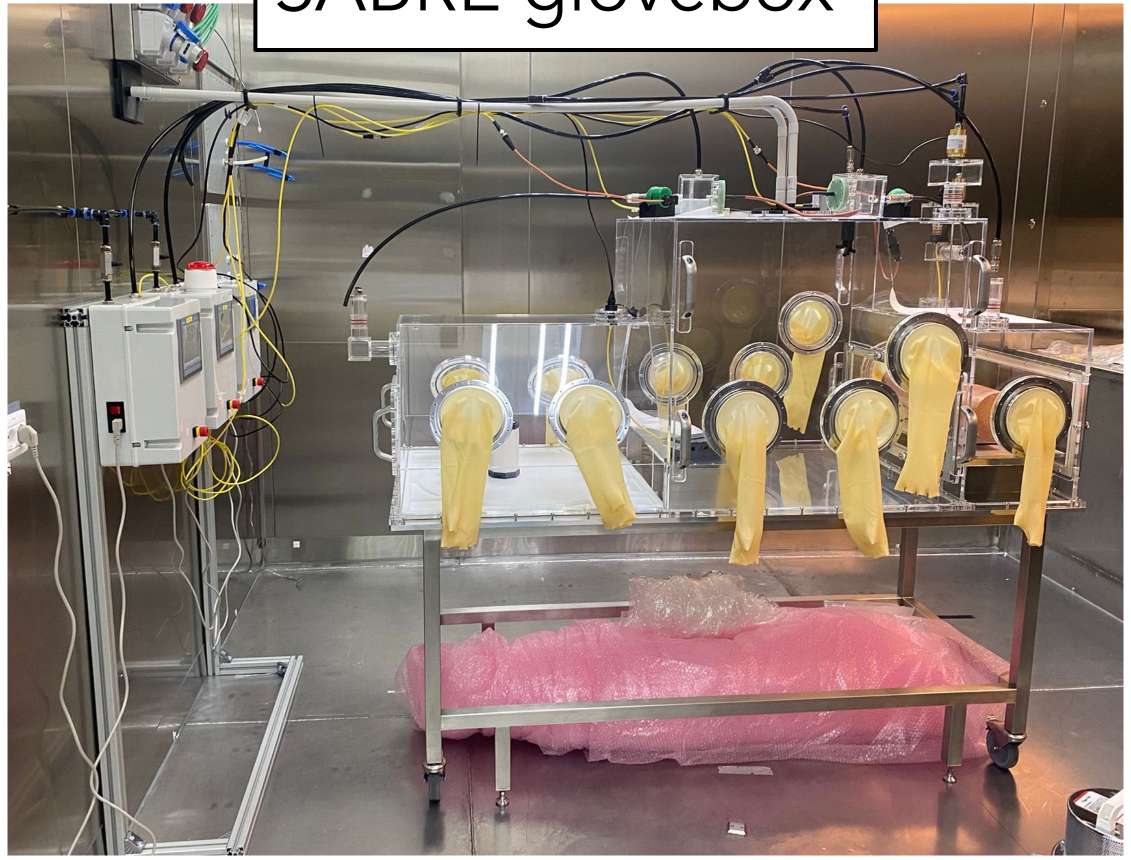
- Recently decommissioned the SABRE area in Hall B (May 2024)
- New SABRE experimental area in the corridor between Hall B and Hall A ("Cobra area")
- Glovebox facility for crystal handling in the clean Room in Hall C



Cobra area

Shielding for crystal testing

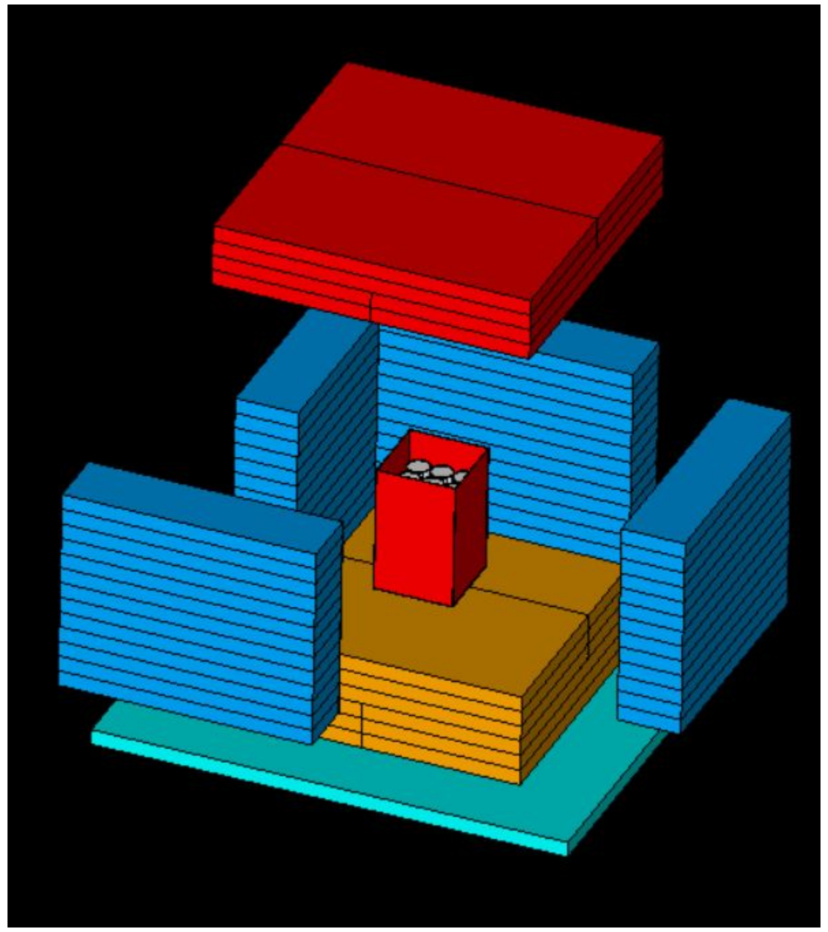
SABRE glovebox

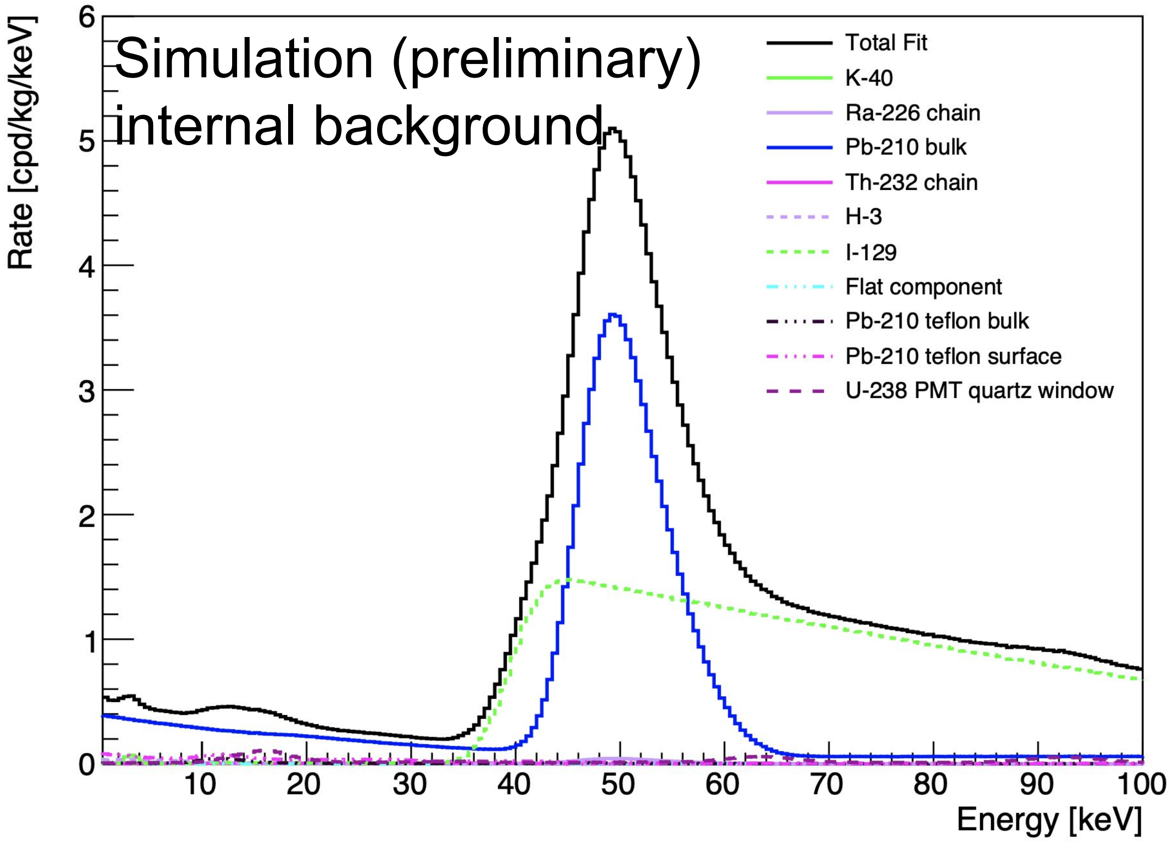


SABRE North status

- Technical Design Report presented in July 2024
  - just approved by INFN
- 3 x 3 matrix of crystals of ~5 kg mass each
- Fully passive shielding design: 15 cm copper + 40 cm PE
  → enough shielding power and negligible contribution to the total background
- Expected background 0.5 cpd/kg/keV

3x3 NaI matrix with 15 cm copper shielding + 40 (60) cm polyethylene lateral and top (bottom)



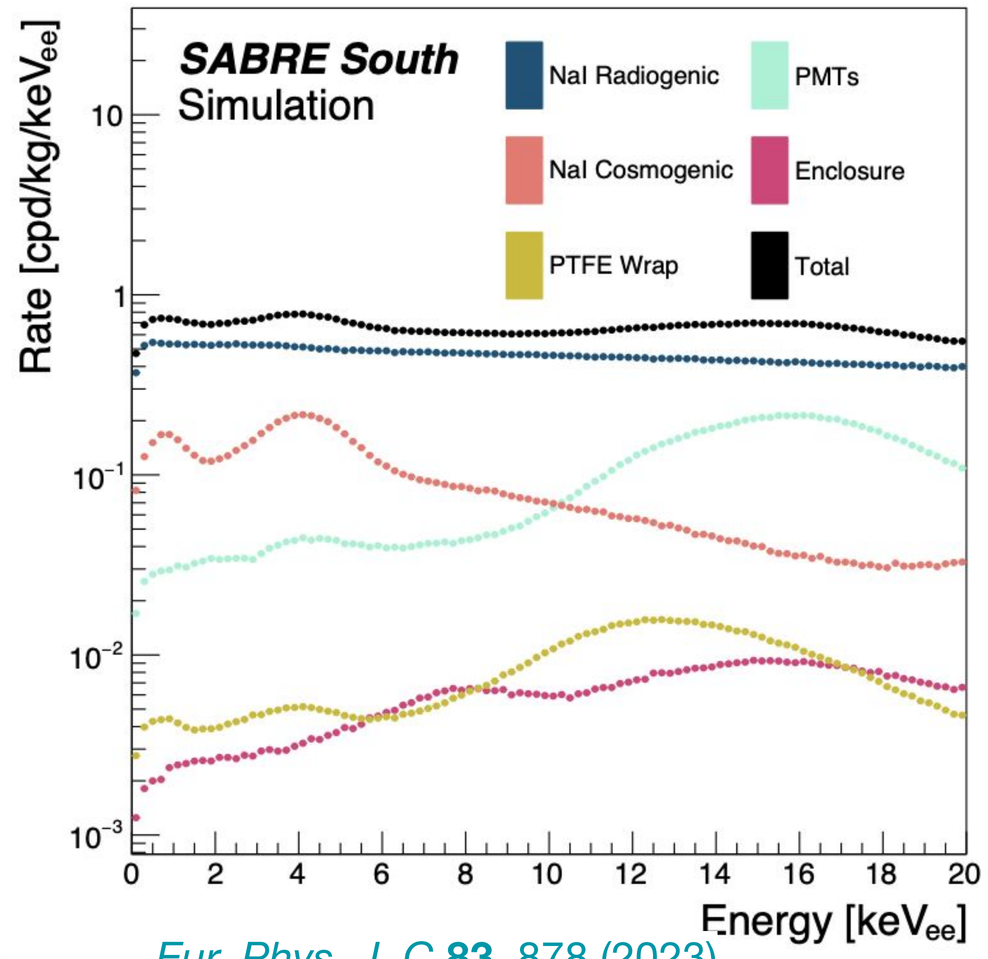


External +shielding bkg $<10^{-2}$ cpd/kg/keV

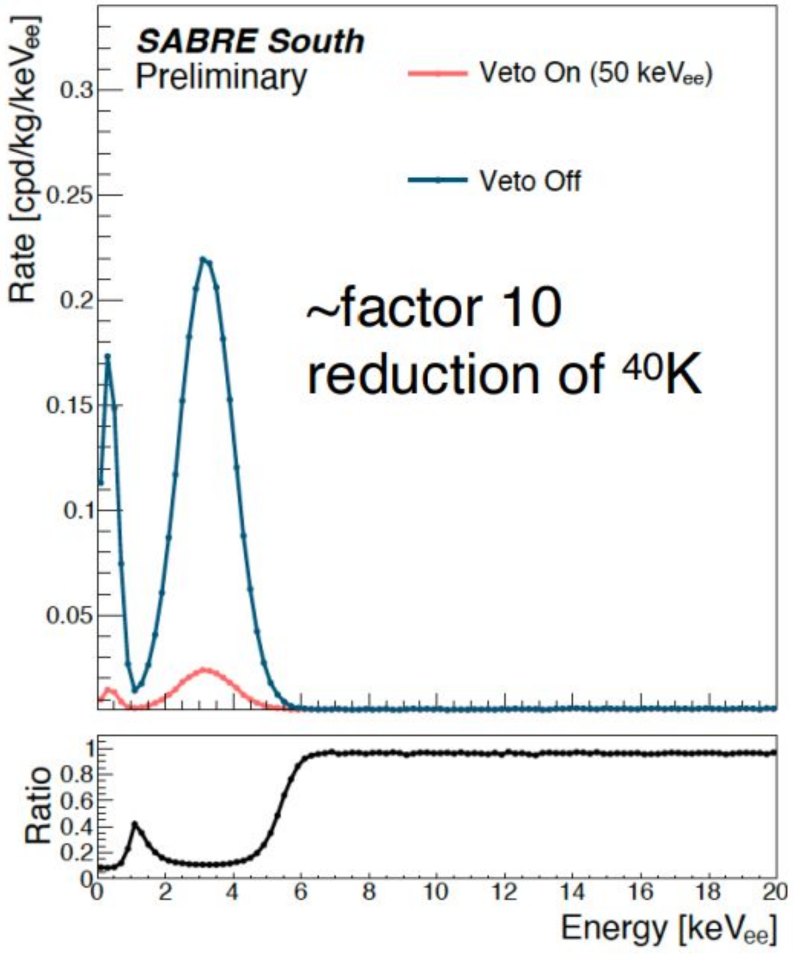
SABRE South status

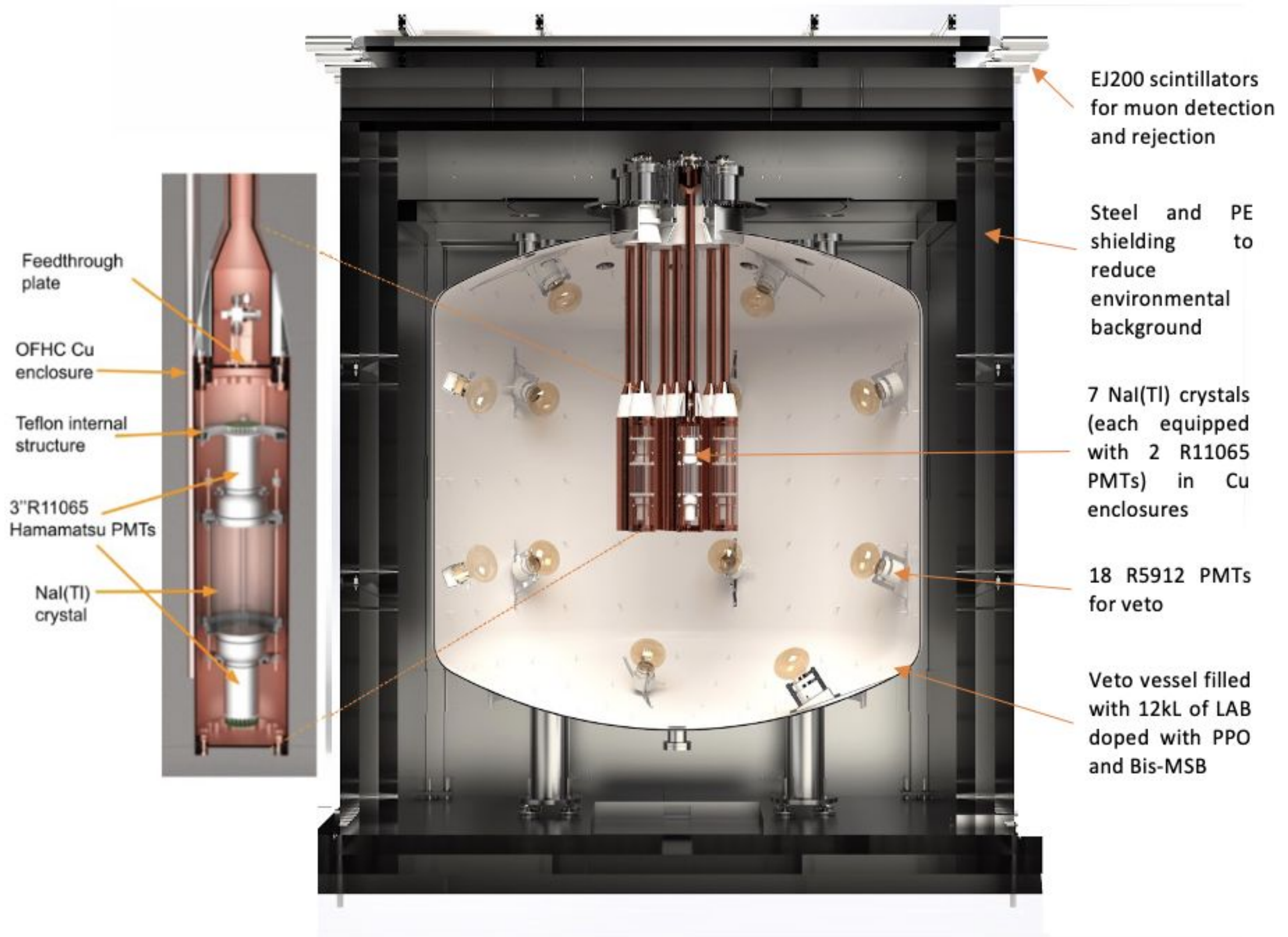
- Design: 7 crystals array of ~5-7 kg mass (SABRE South TDR available online)
- Vessel + LAB, PMTs, muon detector, DAQ electronics, Crystal insertion system … all ready.
- Crystal procurement in synergy with SABRE North
- Highest purity crystals and largest active veto: 0.72 cpd/kg/keV.

SABRE South assembling started in early 2024, aiming for completion in 2025

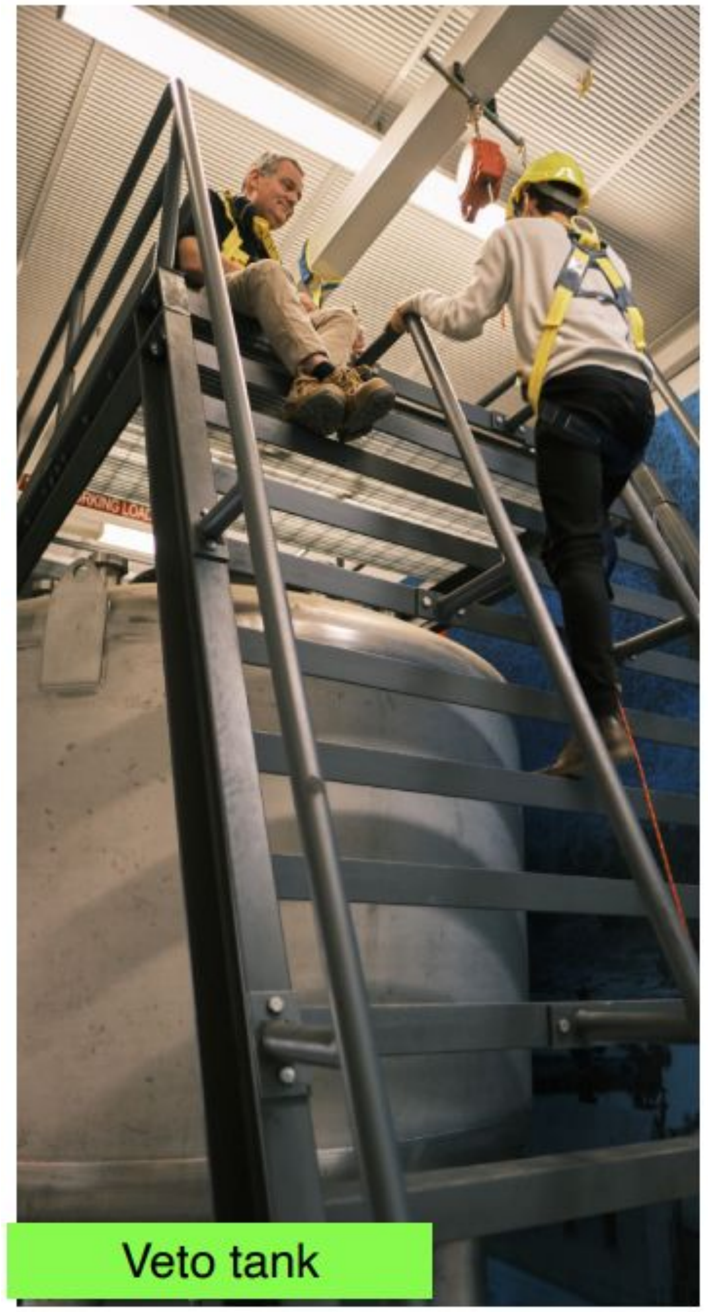


Eur. Phys. J. C **83**, 878 (2023)

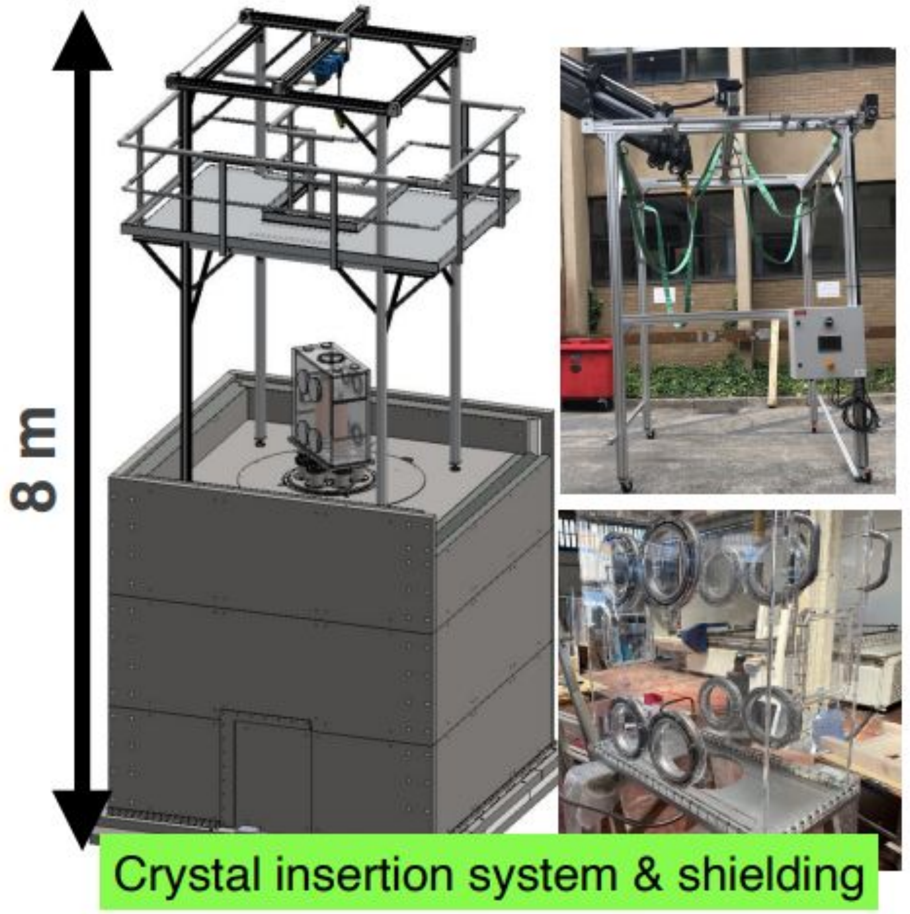




SABRE South status

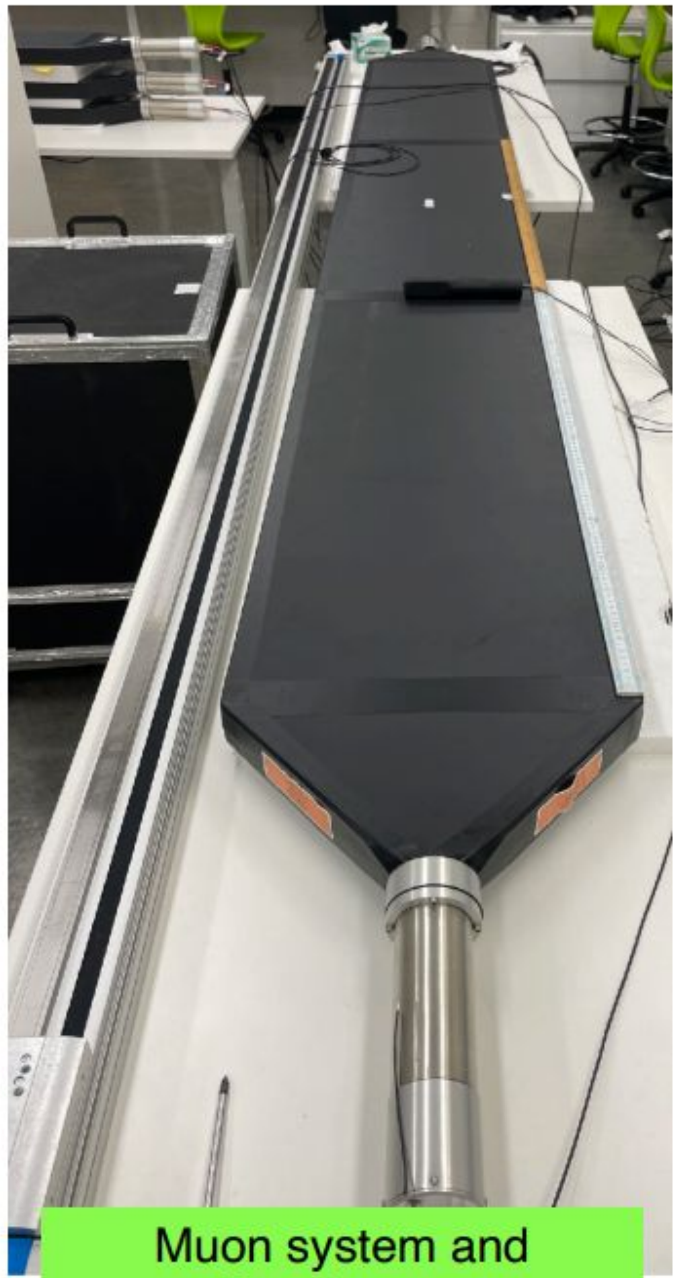


Veto tank



Crystal insertion system & shielding

Liquid Scintillator from JUNO



Muon system and calibration stage

SABRE DAQ and muon system underground

Gas panel

Veto PMTs installation

Conclusions

- SABRE goal is to search for annual modulation with two nearly identical NaI(Tl) detectors in the Northern and Southern Hemispheres
- Crystals current result @LNGS: ~1 cpd/kg/keV background
  - Goal is ~0.5 cpd/kg/keV → within reach with ZR
  - Demonstrated successful growth from chunks with NaI-41
  - NaI-42 expected @LNGS by 2024 → first full-size crystal produced after ZR
- SABRE-South installation started 2024 aiming for completion in 2025
- SABRE-North TDR just approved by INFN,
  - start powder procurement and crystal production in 2025 (complete in 2027)
- SABRE expected to exclude/confirm annual modulation in 3-5 years of operation

SABRE

INFN

SABRE North

UNIVERSITÀ DEL SALENTO

INFN Istituto Nazionale di Fisica Nucleare

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI MILANO

SAPIENZA UNIVERSITÀ DI ROMA

SABRE South

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY of ADELAIDE

SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian National University

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY OF SYDNEY

…thanks for the attention!

Extra slides

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

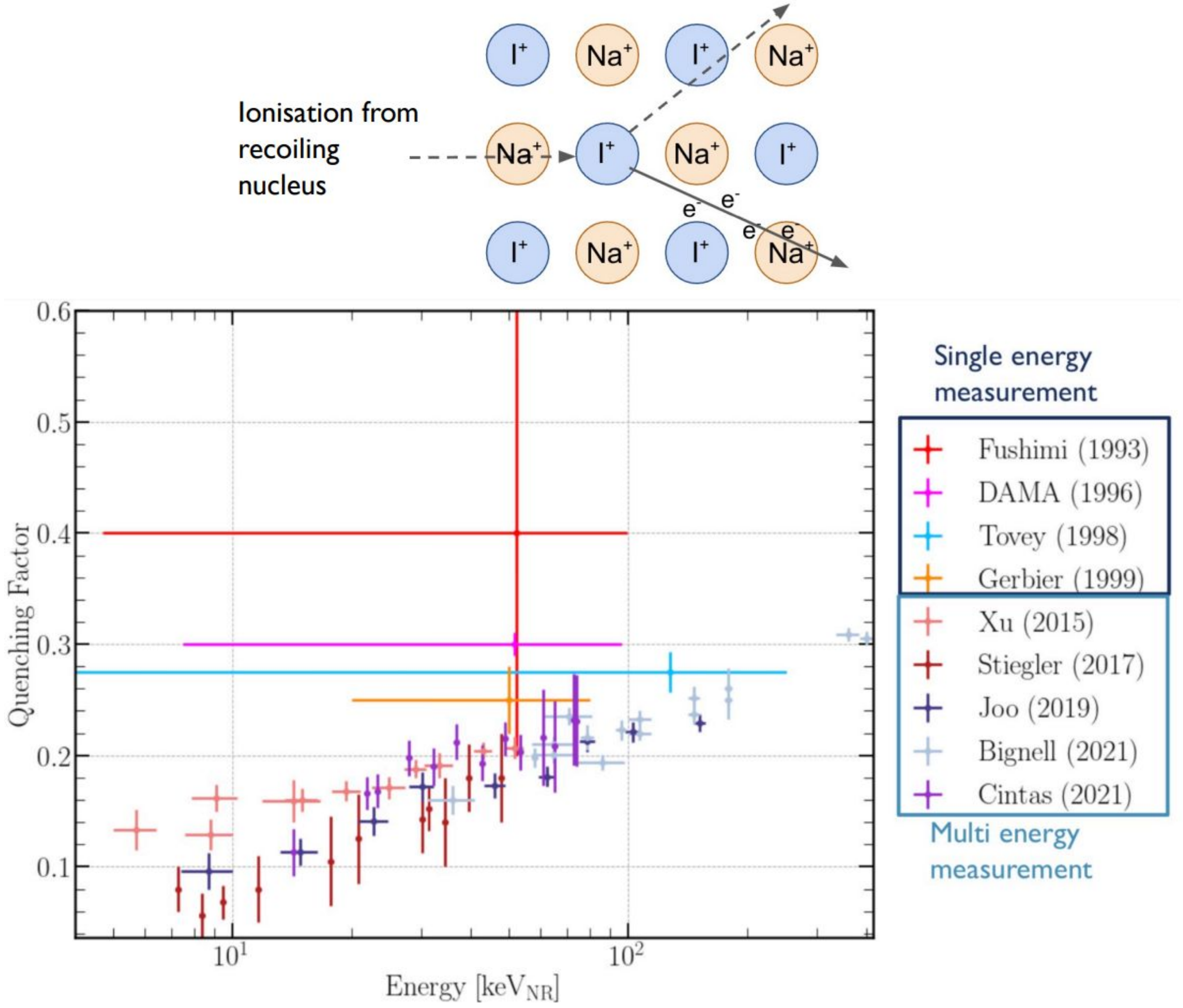
NaI crystals background comparison

	DAMA/LIBRA	COSINE-100	ANAIS-112	SABRE	COSINUS
^{238}U	0.3-2 ppt	< 0.12 ppt	0.2-0.8 ppt	0.2-0.6 ppt	< 1ppb
^{232}Th	0.5-7.5 ppt	0.4-2.4 ppt	0.1-1 ppt	0.3-0.4 ppt	< 1ppb
^{nat}K	$\lesssim$ 20 ppb	17-82 ppb	17-43 ppb	2-8 ppb	6-22 ppb
^{210}Pb	5-30 μBq/kg	0.7-3 mBq/kg	0.7-3.2 mBq/kg	0.5-0.8 mBq/kg	
^{210}Pb reflector	~ 5 μBq/cm^2 (spectral fit)	0.8-1.6 μBq/cm^2 (from ^{210}Po)	~ 3 mBq/detector for D3 and D4	~ 1 μBq/cm^2 (spectral fit)	
^{3}H	< 90 μBq/kg	100-250 μBq/kg	90-200 μBq/kg	24±2 μBq/kg	
^{87}Rb	< 0.3 mBq/kg	-	-	< 0.4 mBq/kg	
^{22}Na	< 15 μBq/kg	0.4-0.8 mBq/kg	0.5-2 mBq/kg	-	
Rate in ROI [1,6]keV	~ 0.7 dru	~ 3 dru	~ 3.5 dru	~ 1 dru	

Interpretation of results: the quenching factor (QF)

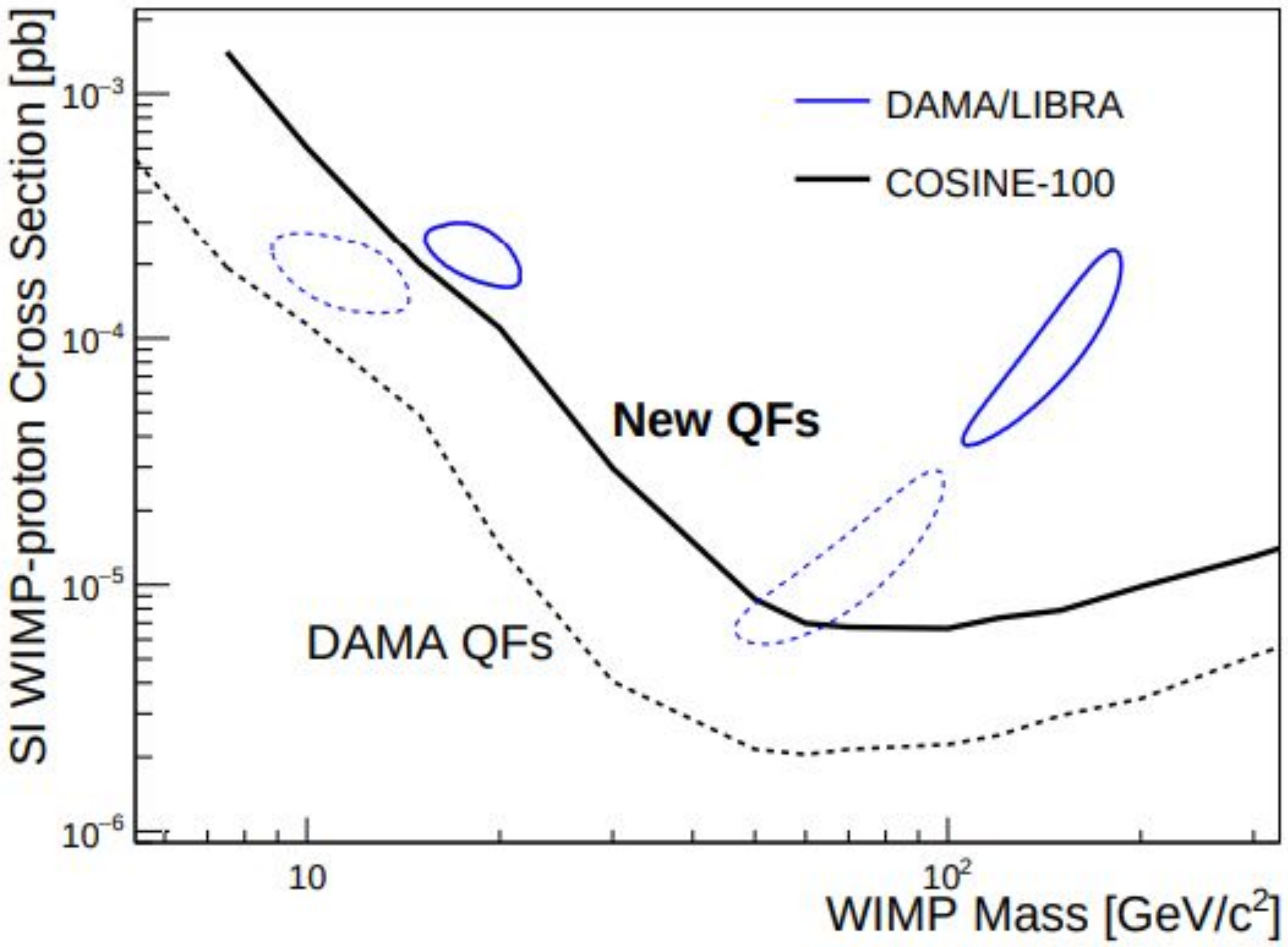
- Part of the energy released by the nuclear recoil is not transformed in scintillation light → quenching
- Observable is the energy in keV_{ee} (electron-equivalent)
- Measurements on different crystals not in good agreement
- QF affects both the energy range and amplitude of the modulation

Is annual modulation search with different NaI(Tl) crystals really model independent?

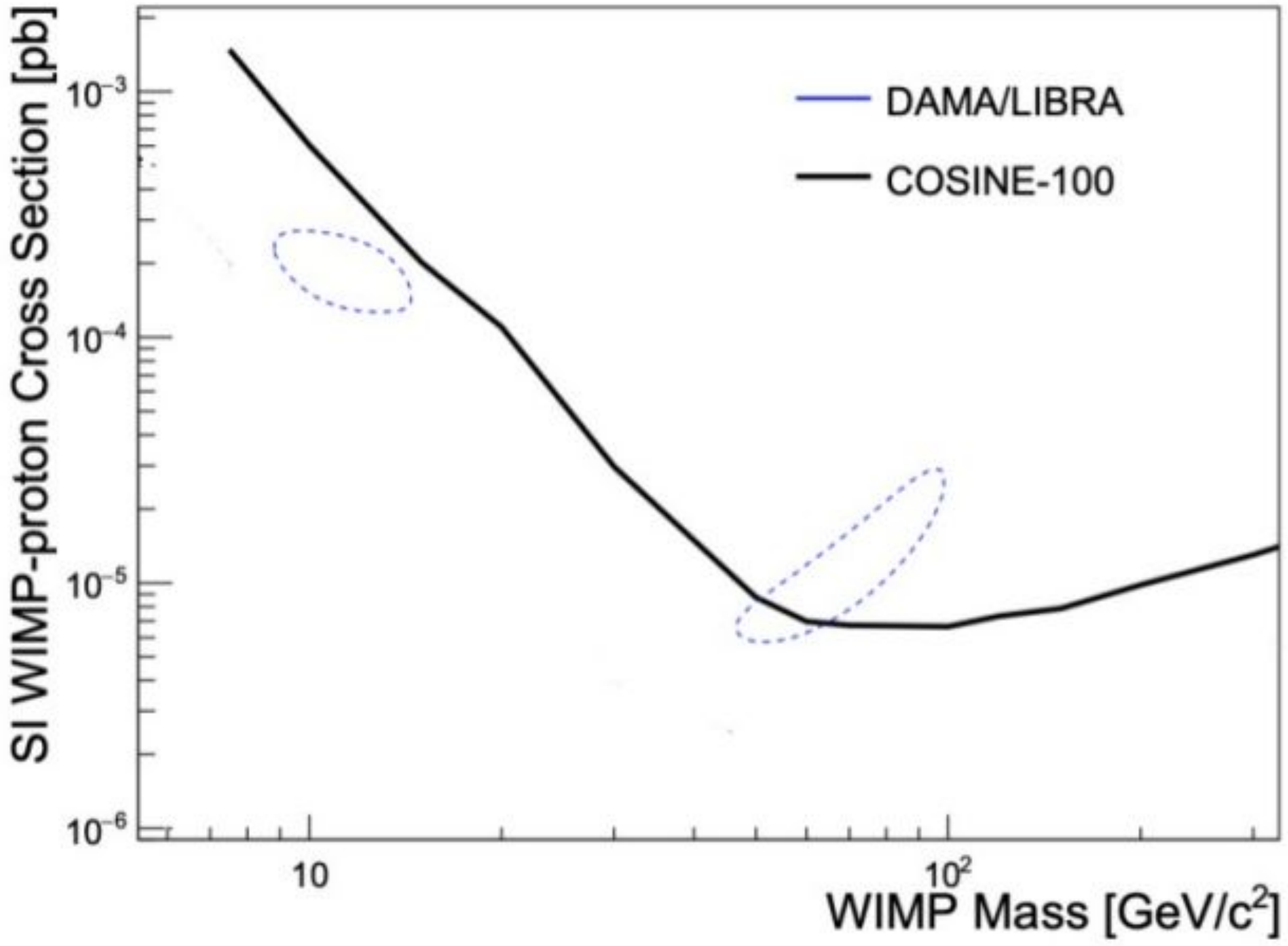


Quenching factor impact

Y.J. Ko et al JCAP11(2019)008



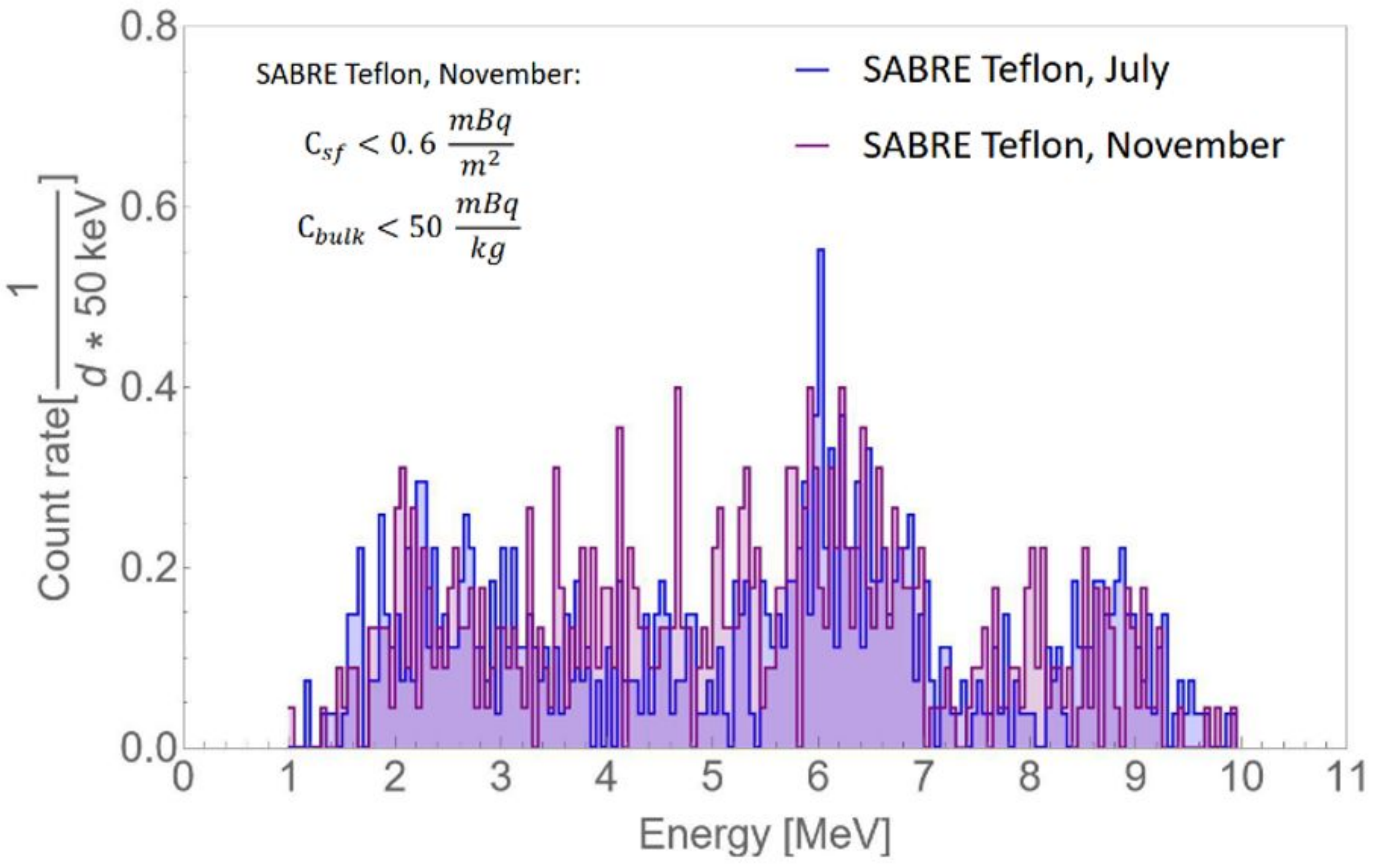
Assuming detectors have the same quenching factor (dashed lines or solid lines)



Assuming detectors have the different quenching factors the DAMA signal region is not totally excluded

SABRE reflector radioactivity assay

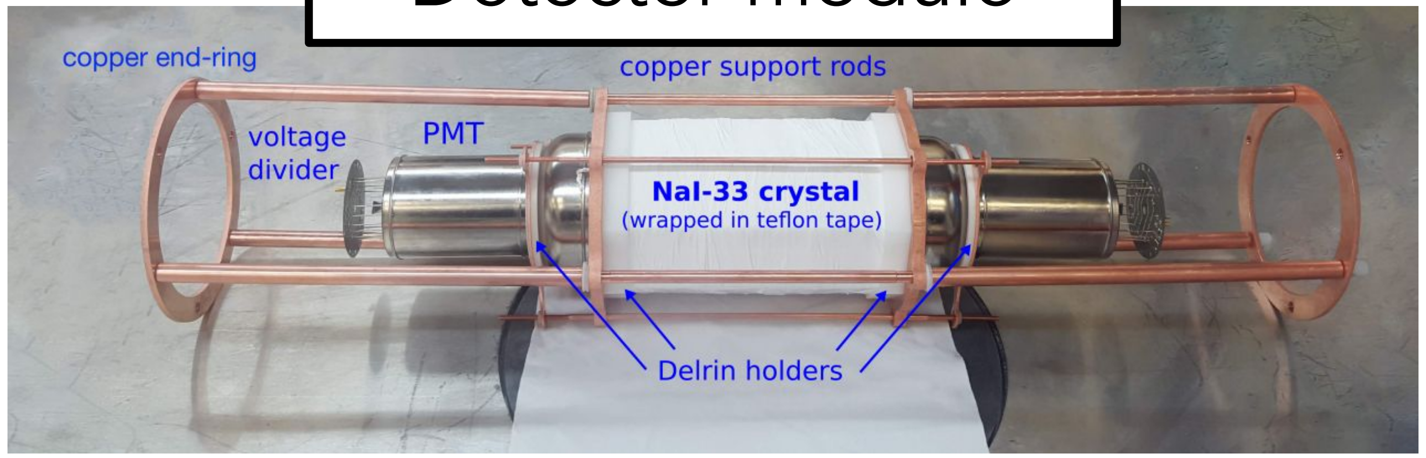
- Procured virgin teflon foils
- Samples tested with HPGe at LNGS
- Alpha counting with XIA spectrometer
  → ^{210}Pb contamination at level of detector's sensitivity
    - surface contamination: < 0.6 mBq/m^2
    - bulk contamination: < 50 mBq/kg



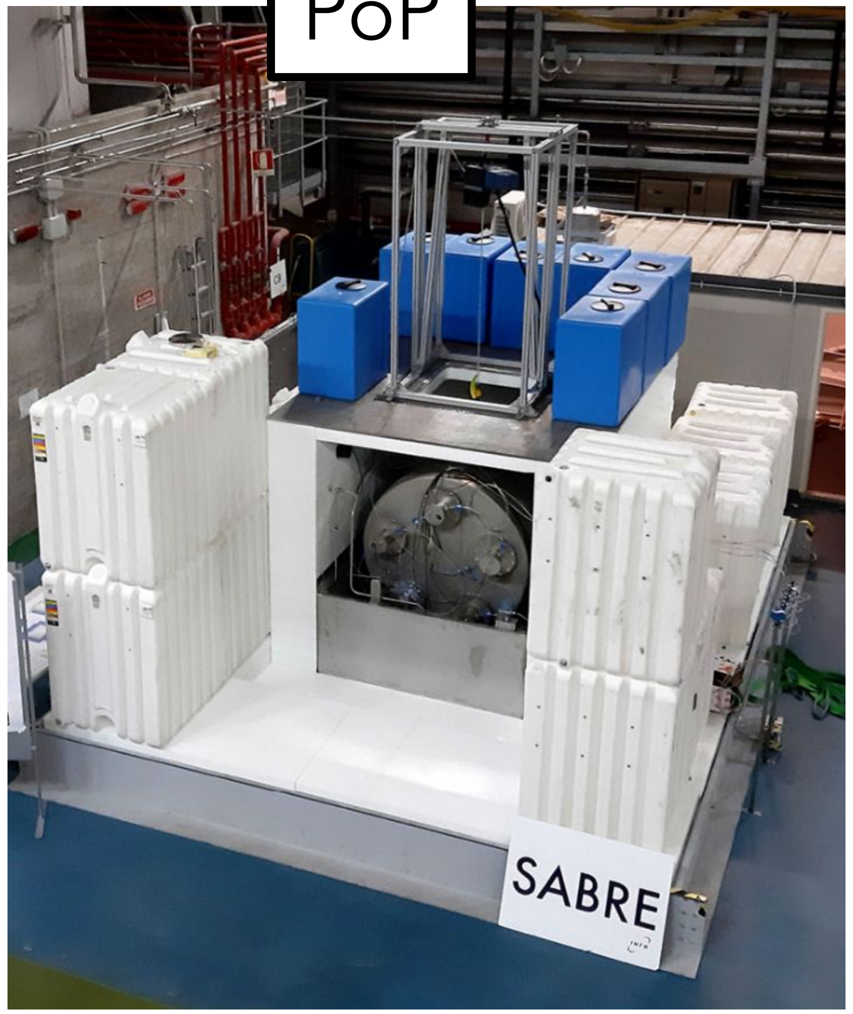
G. Zuzel

The SABRE Proof-of-Principle @LNGS (2018-2022)

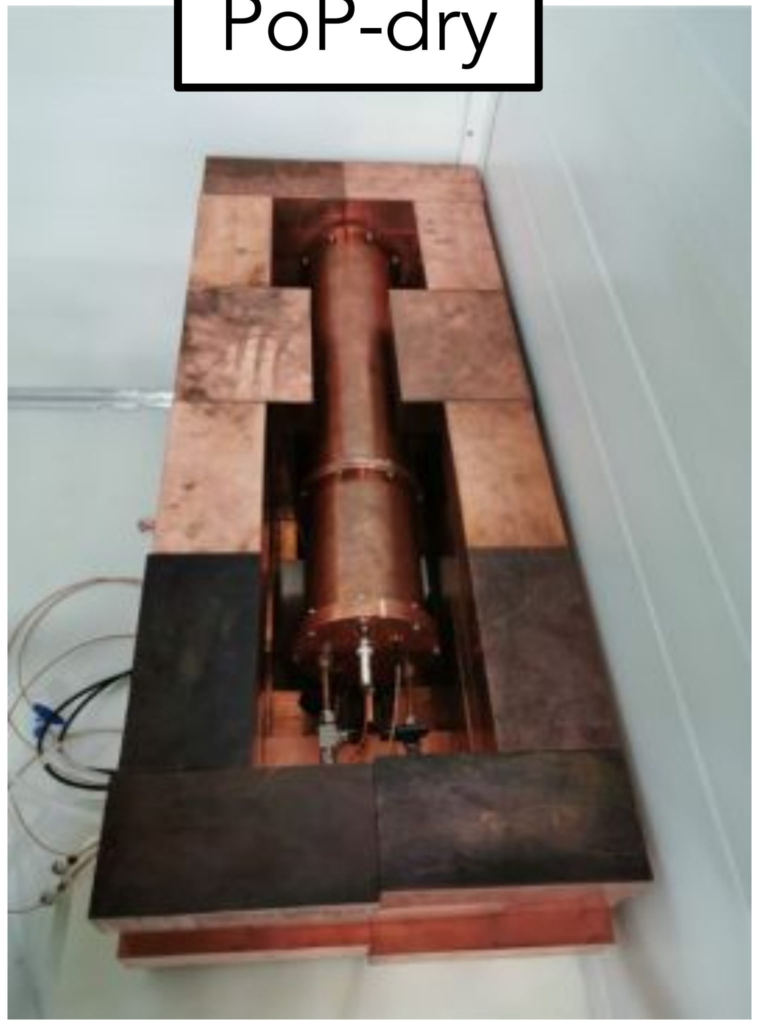
Detector module



PoP



PoP-dry

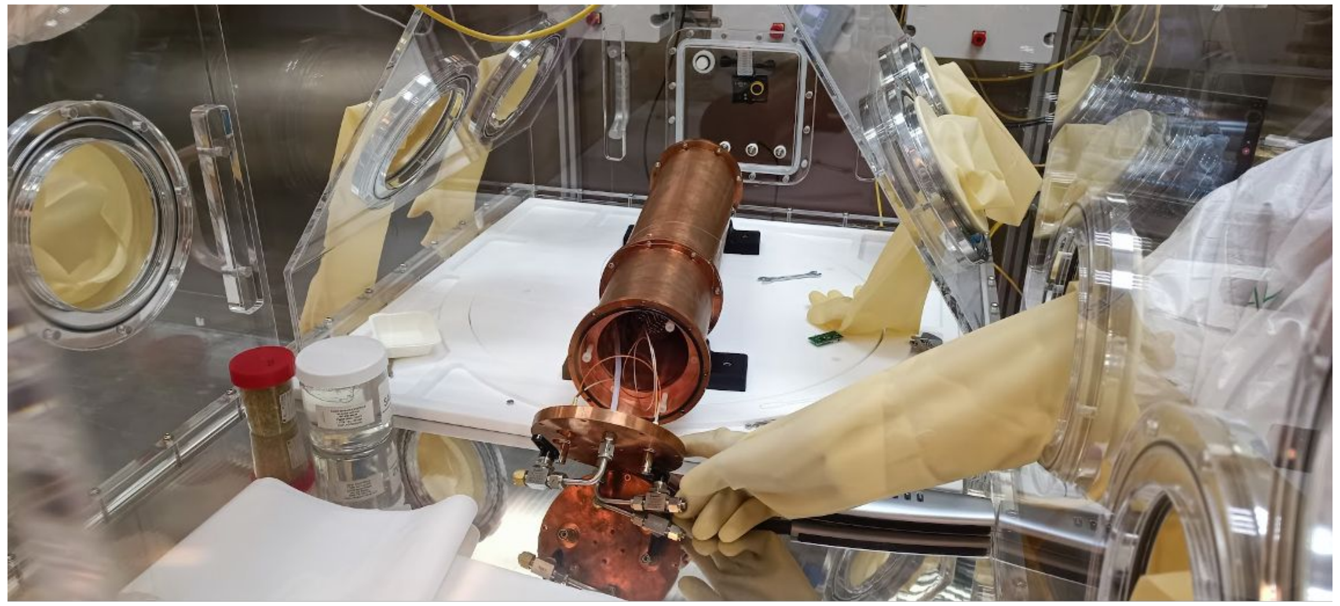


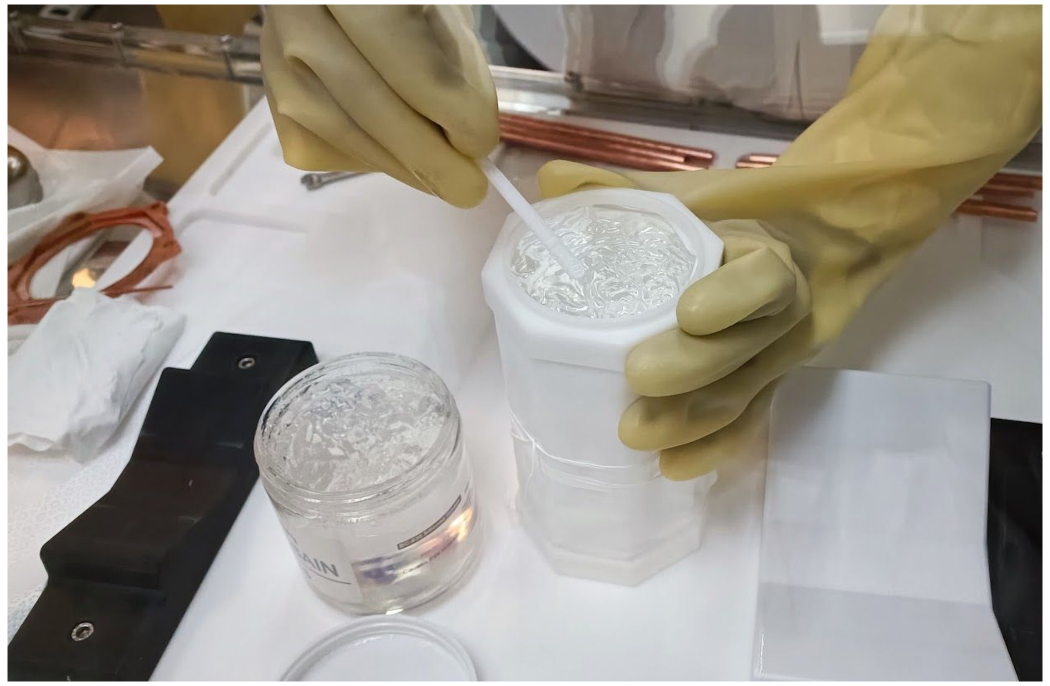
- Run in 2020 with Borexino liquid scintillator and NaI-33
    - 2 tons active veto with 10 8-inch PMTs + H_2O shielding
- Exploited successfully ^{40}K tagging with sensitivity at the level of 1 ppb
- Demonstration by direct counting of first crystal production after DAMA/LIBRA with background in [1,6] keV of order 1 cpd/kg/keV
- PoP-dry run in 2021: passive shielding with additional layer of copper
    - confirmed background level

Crystal operations in glovebox 2022-23

- 27/09/2022 change of teflon reflector in NaI-33
- 29/11/2022 change of tefon reflector in NaI-33
- 7/12/2022 first assembly of NaI-37
- 24/01/2023 second assembly of NaI-37

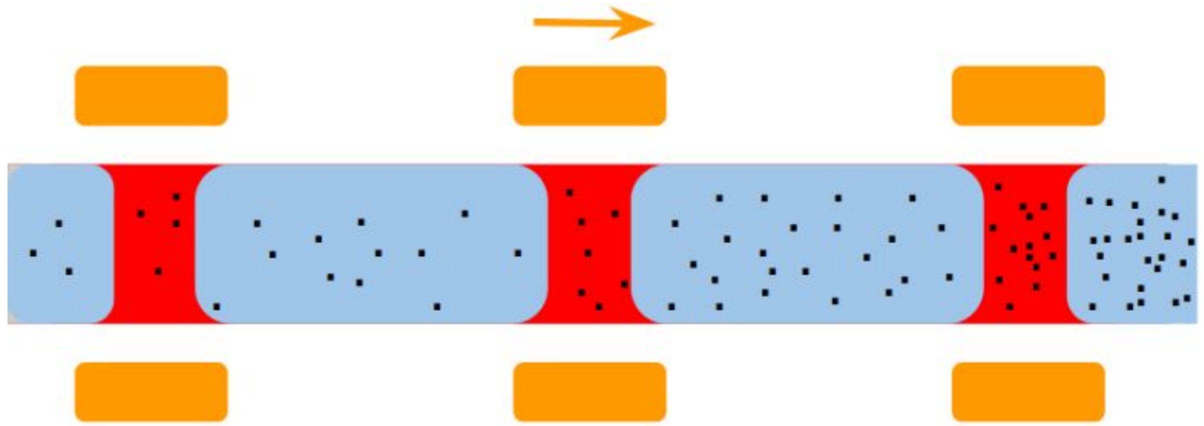
All operations successful and moisture level in the glove-box kept always below 5% RH





Zone refining

- Zone refining technique successfully used in semiconductor industry
- Impurities are segregated to one side of the ingot moving the ovens
- Tested on NaI Astro grade powder by Princeton group at Mellen company



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
^{85}Rb	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.7
^{208}Pb	1.0	0.4	0.4	< 0.4	0.5	0.5
^{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

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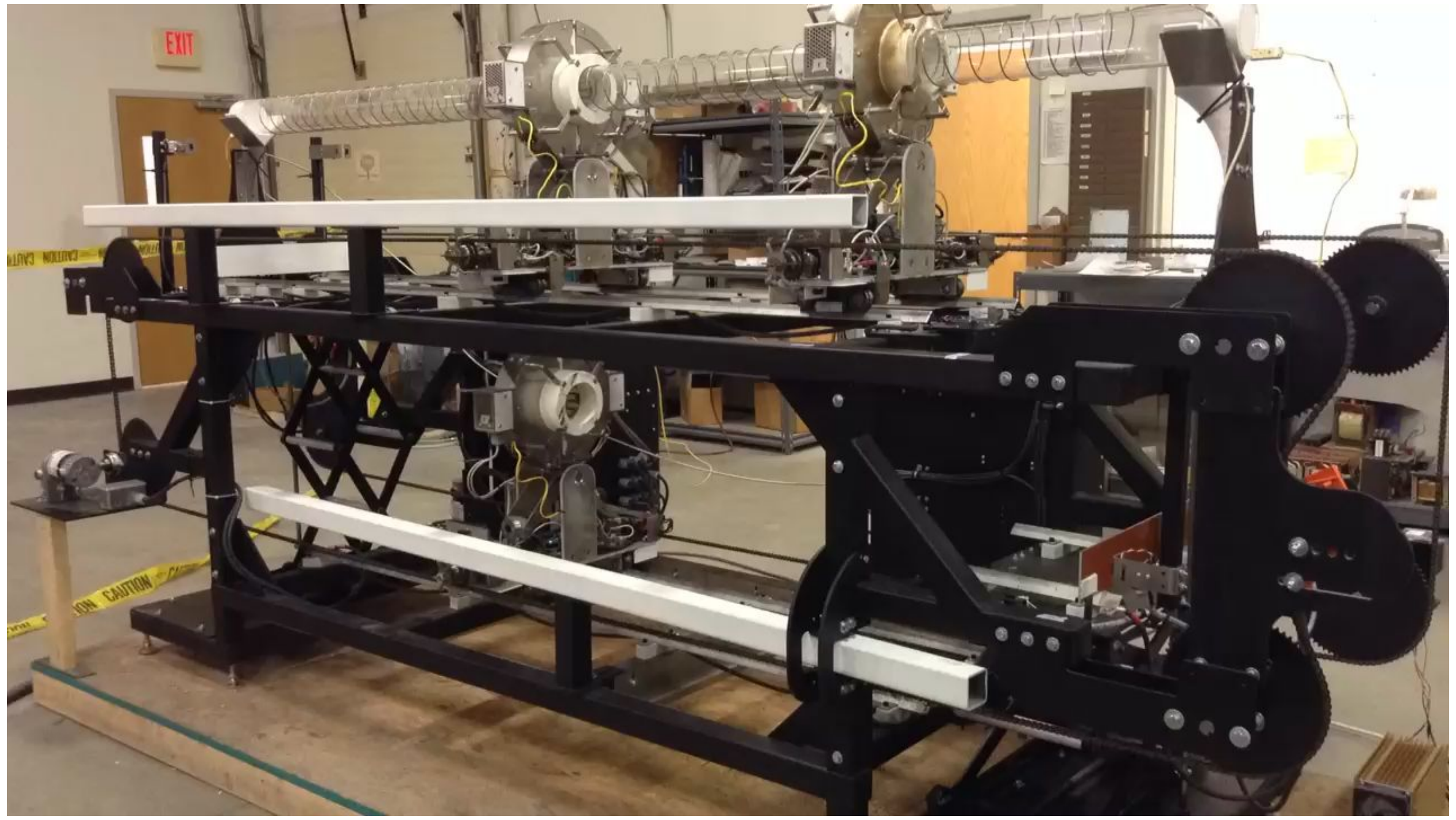
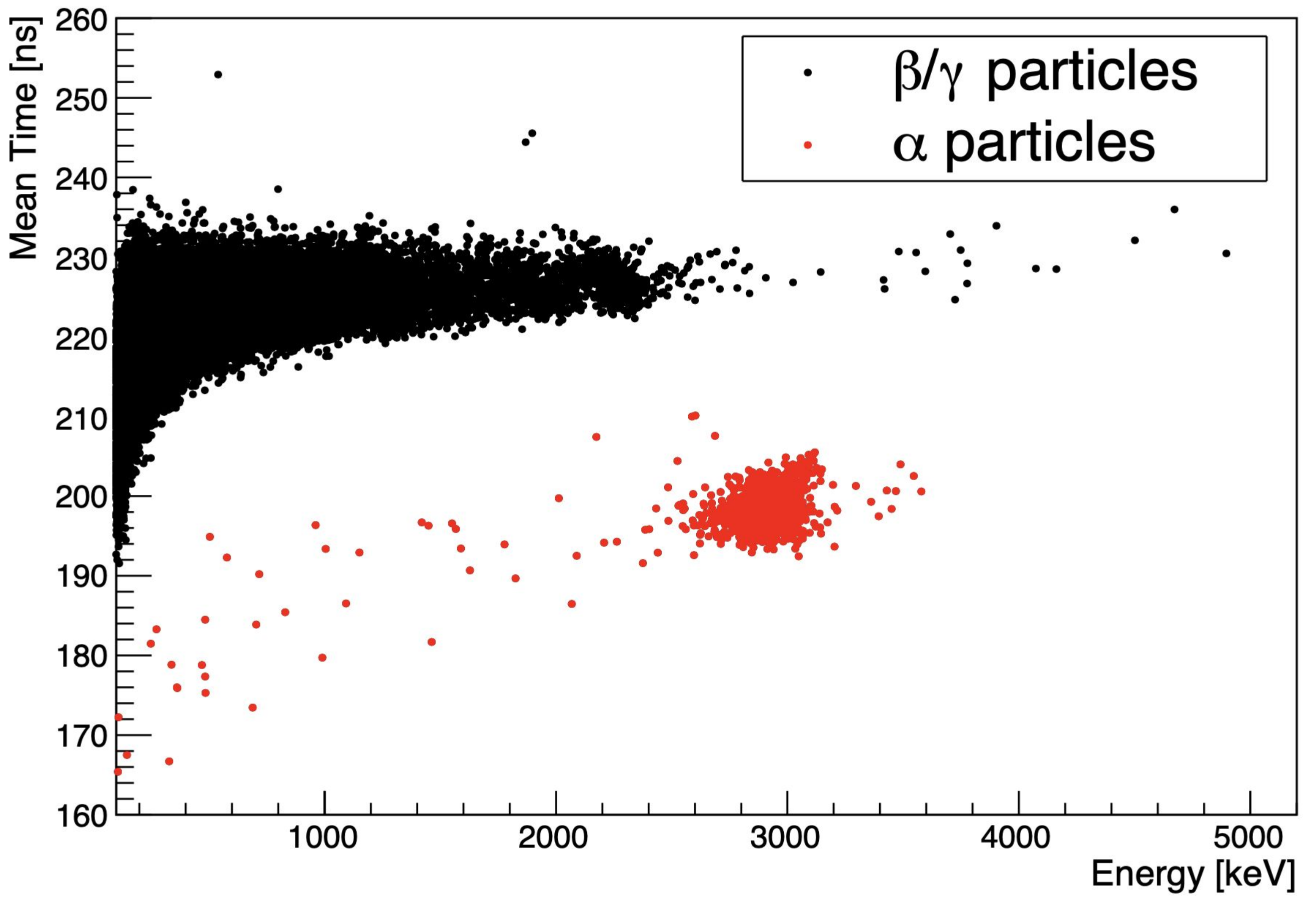


Zone refinement equipment at Mellen, now transferred to RMD

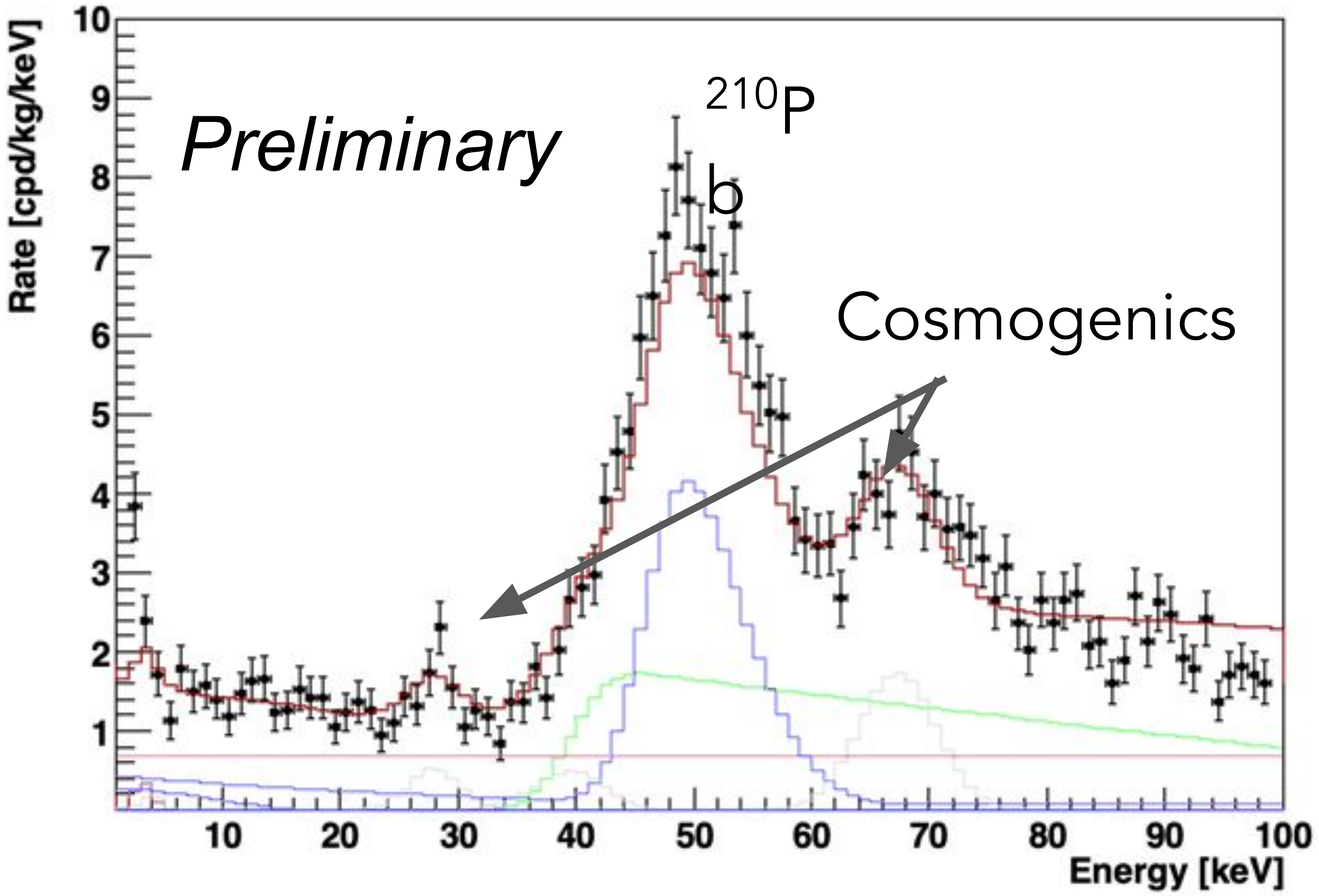
Zone refining could reduce to about 1/3 the Pb content, almost 1 order of magnitude K and possibly other internal contaminants like Rb

NaI-41

- Grown from chunks of NaI-40 undoped crystal (grown from Astograde powder)
- Underground since December 15th, 2023
- Good scintillation properties: LY = 10.02 +/- 0.03 phe/keV, FWHM @59.6 keV → 15.7%
- Alpha rate 0.49 +/-0.01 mBq/kg



Mean time against energy to identify the ^{210}Po background as a proxy of ^{210}Pb



Low energy spectrum of NaI-41 after 8 months underground

SABRE North and South synergy

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.

A MoU for the full SABRE experiment has been drafted