Status and prospects of the SABRE experiment for Dark Matter search in the two hemispheres

Claudia Tomei - INFN Roma

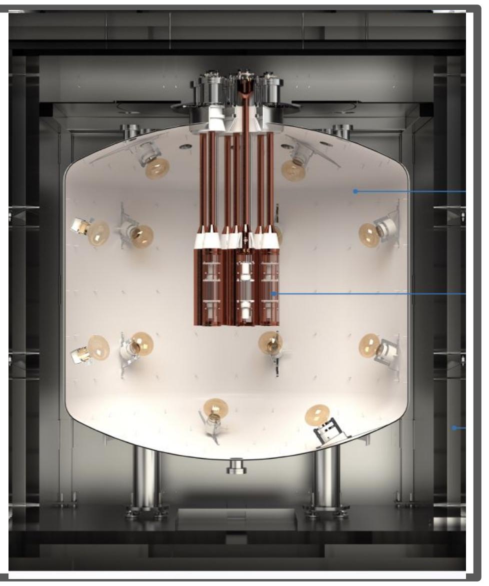
on behalf of SABRE North and SABRE South Collaborations

SABRE: 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

Ultra radio-pure crystals

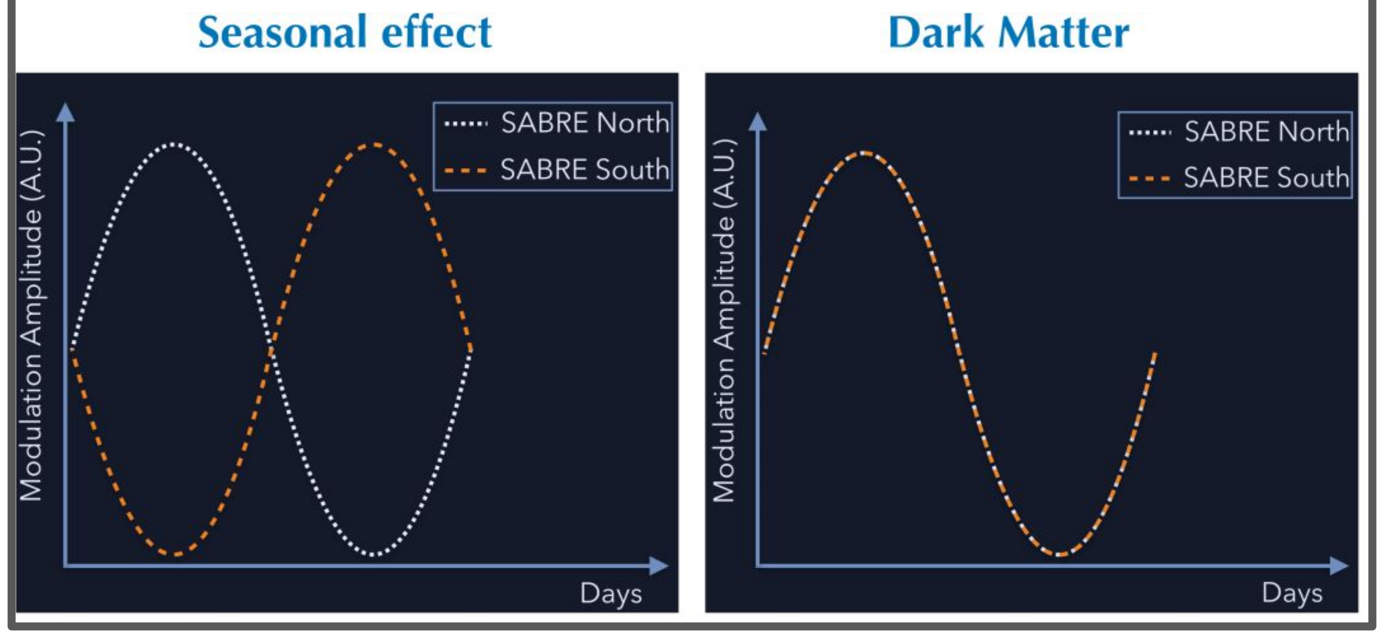
Active veto with liquid scintillator



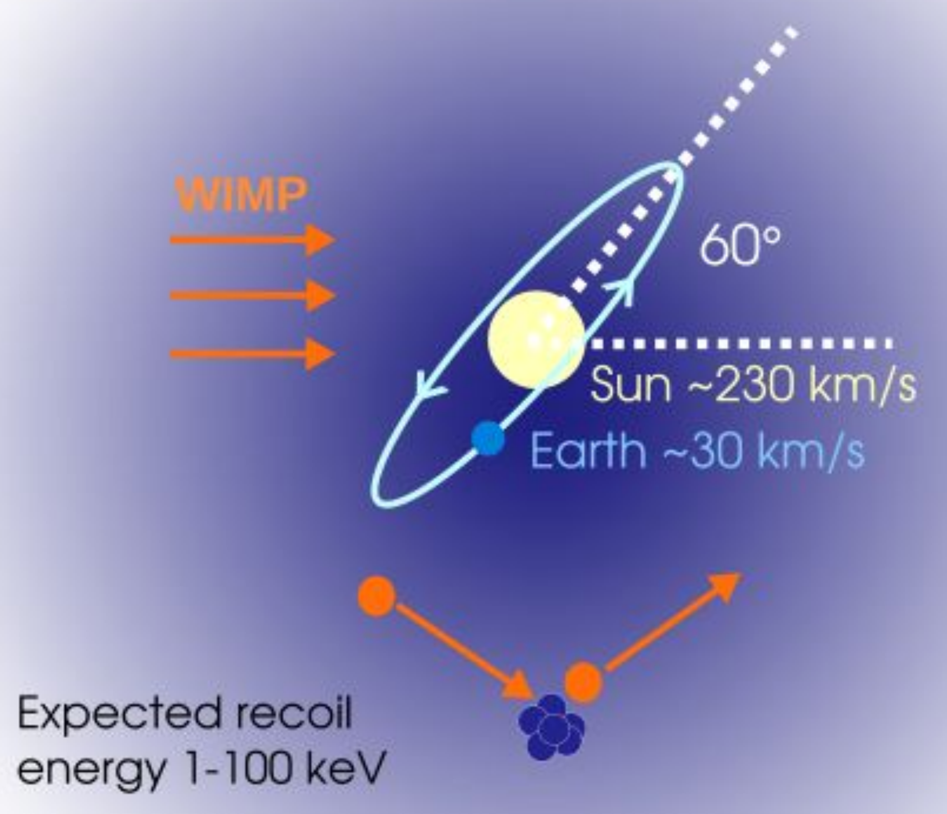
@ SABRE South only

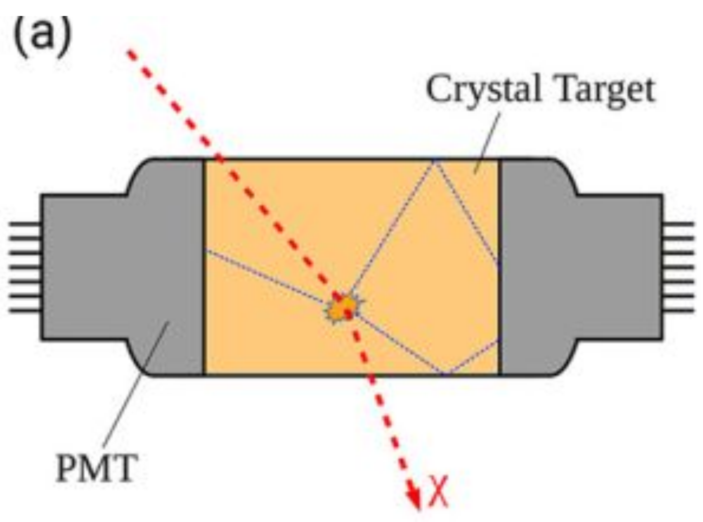
Double location:

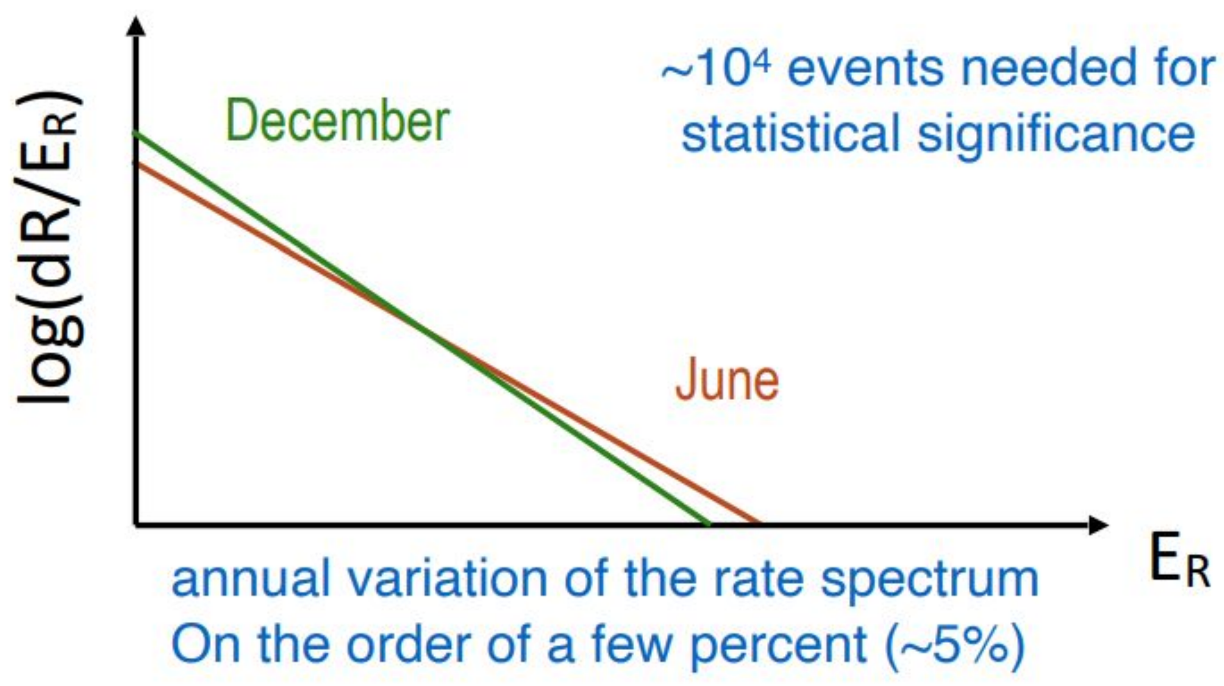
Northern and Southern hemisphere



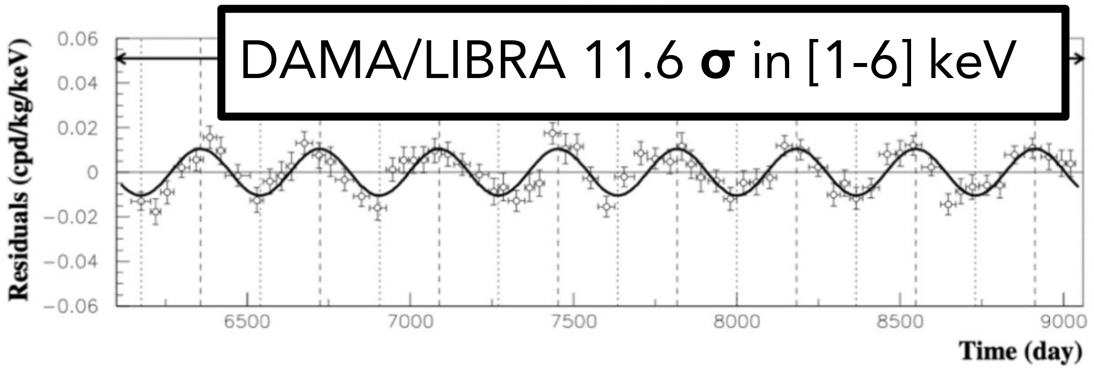
Dark Matter with annual modulation





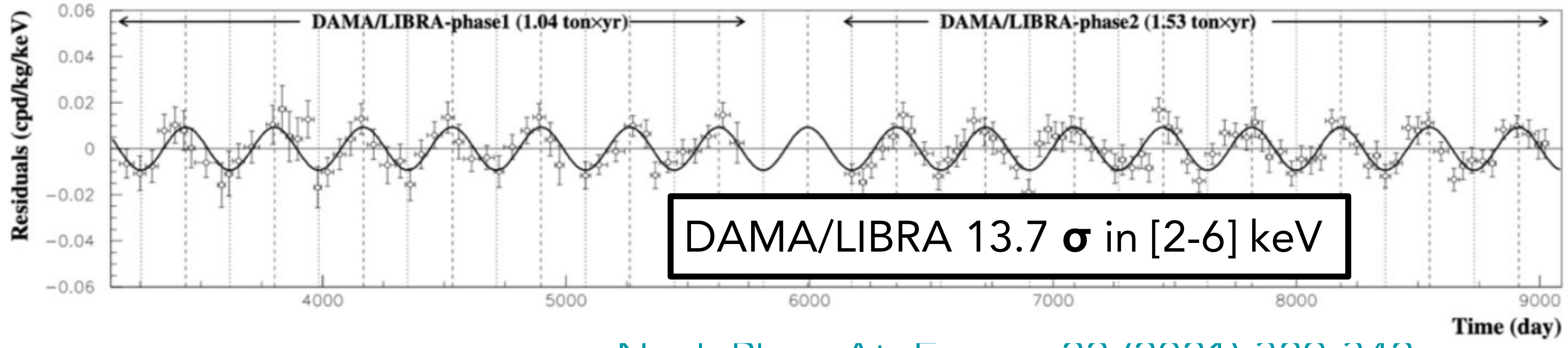


- Expected rate in an Earth-based detector is modulated
- Small modulation fraction S_m/S_0 = O(~few %)
- Region of interest [1-6] keV



Rate vs time

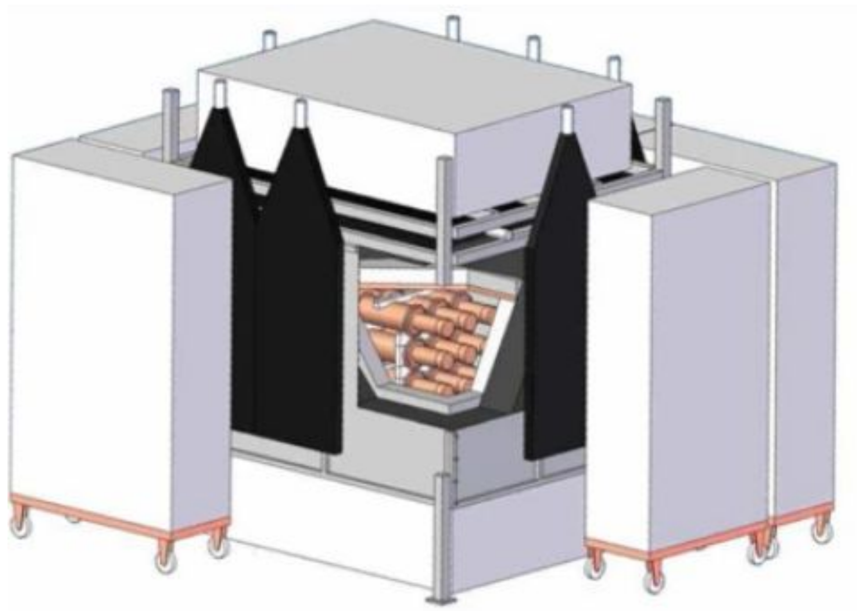
$$R = S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$



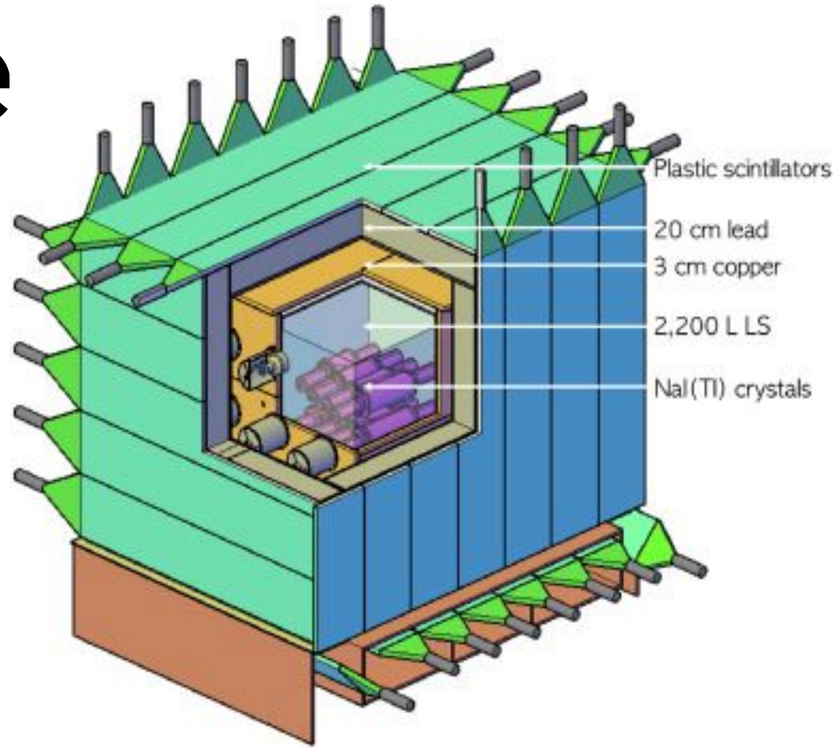
Nucl. Phys. At. Energy 22 (2021) 329-342

NaI experimental landscape

ANAIS
@Canfranc,
Spain



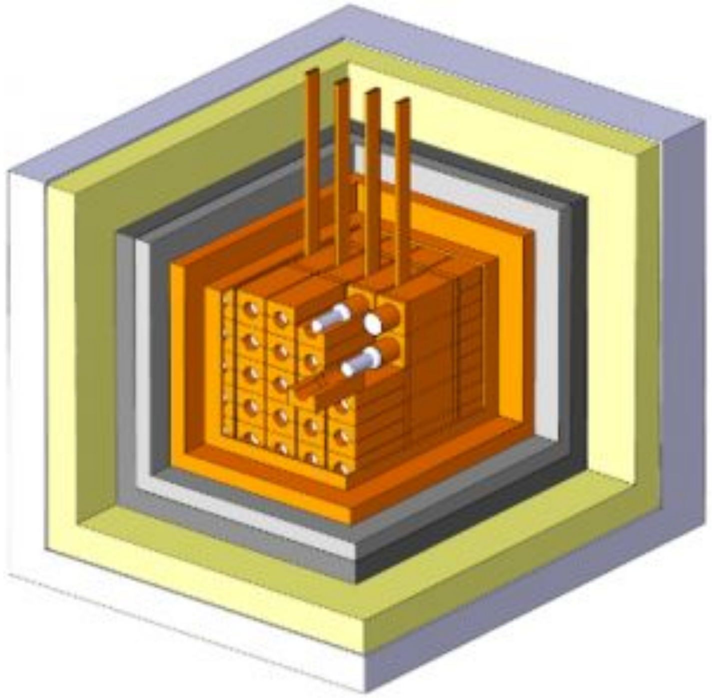
ANAIS, TAUP 2023



COSINE-100
@Yang Yang,
South Korea

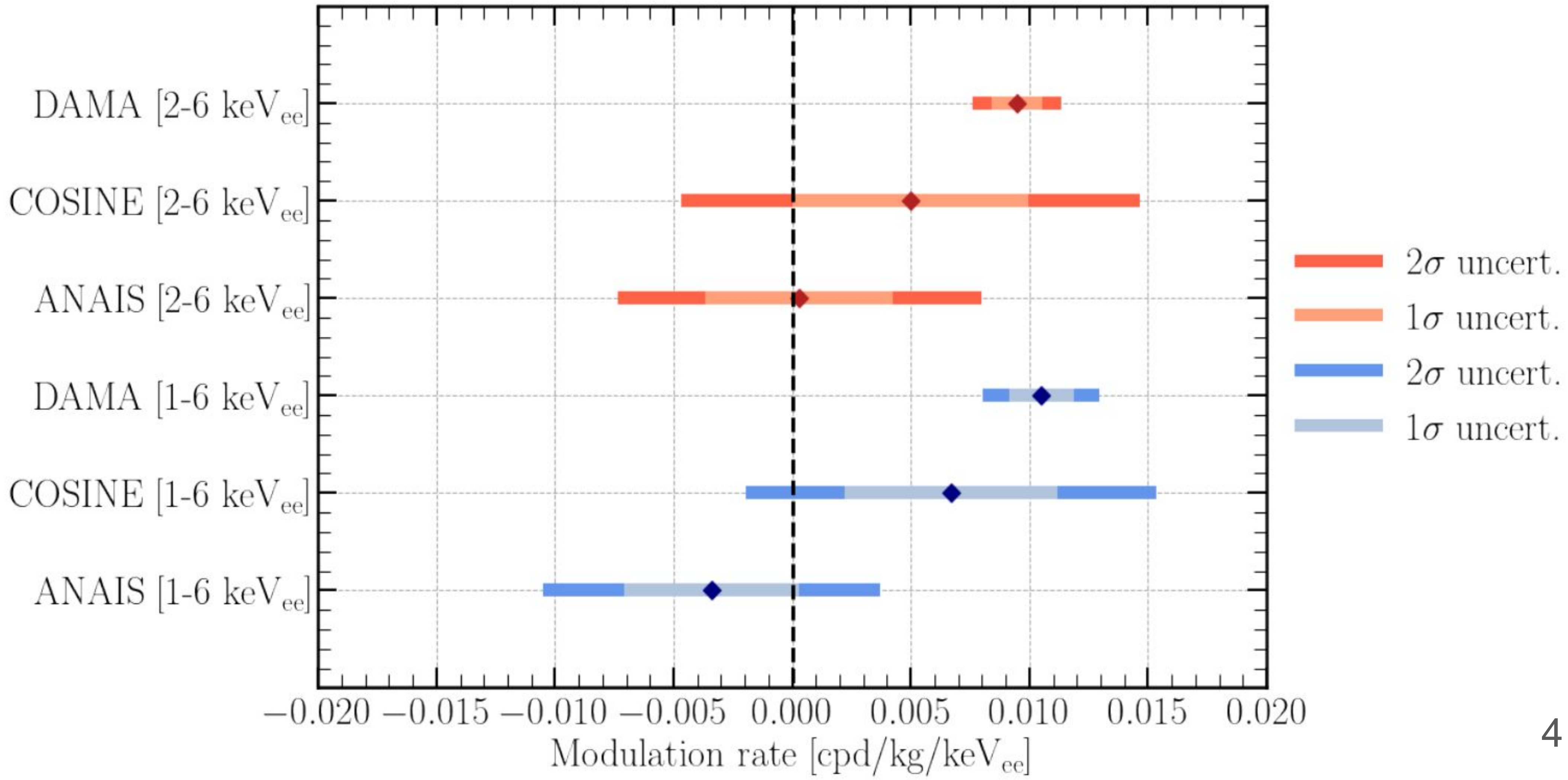
Phys. Rev. D 106, 052005 (2022)

DAMA/LIBRA @LNGS, Italy



arXiv: 2211.15861

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

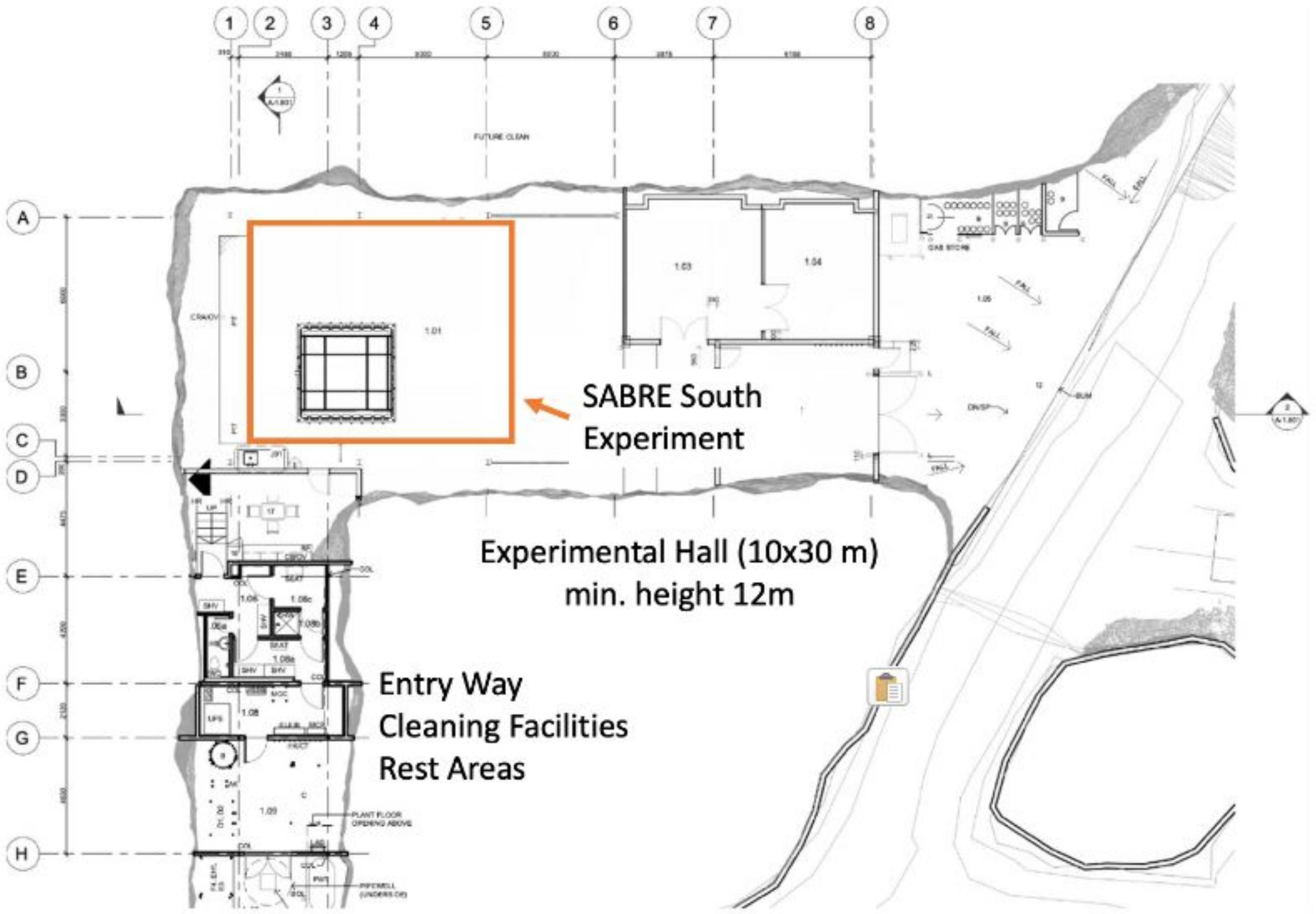


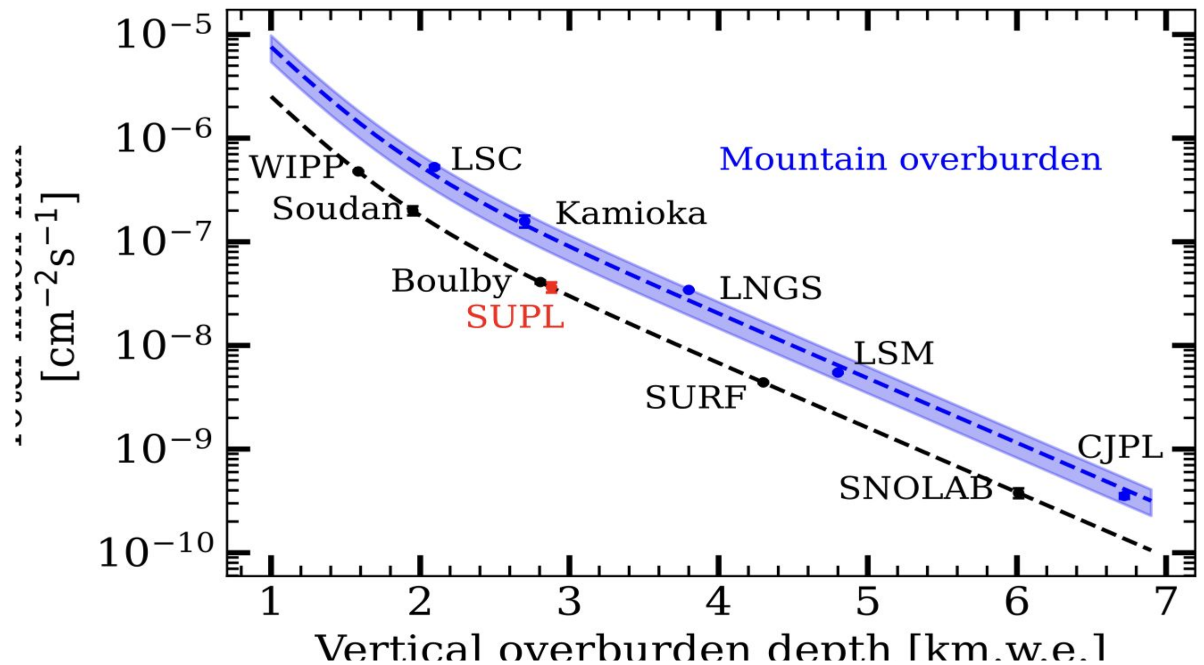
SABRE North and South

- 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
  - Helical drive access
- Lab completed in 2022. SABRE South assembly starting this year.





SABRE North and South synergy

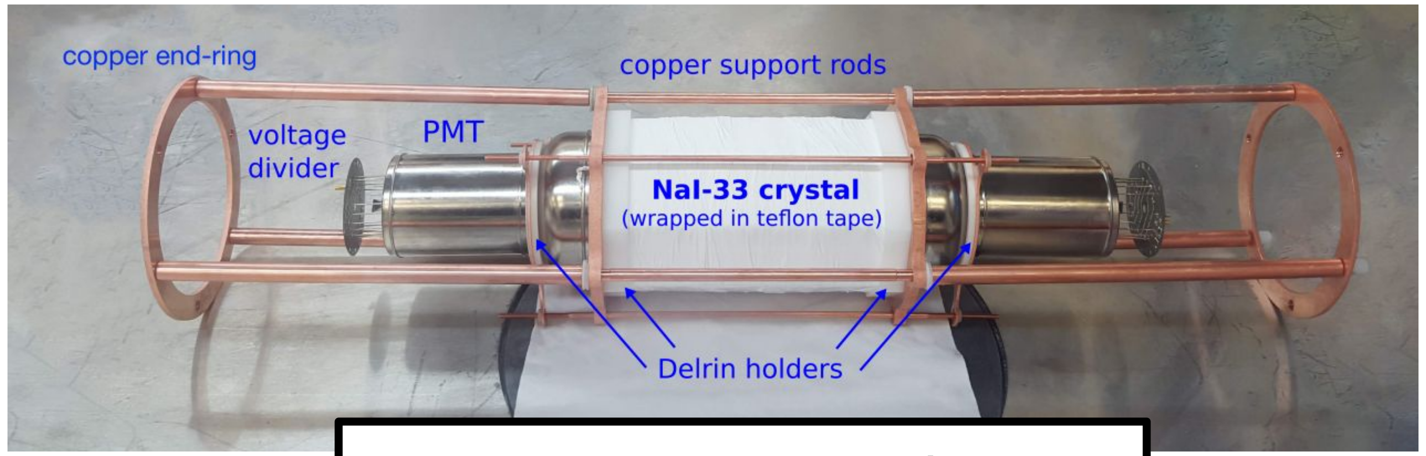
SABRE North and South detectors have **common core features:**

- 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

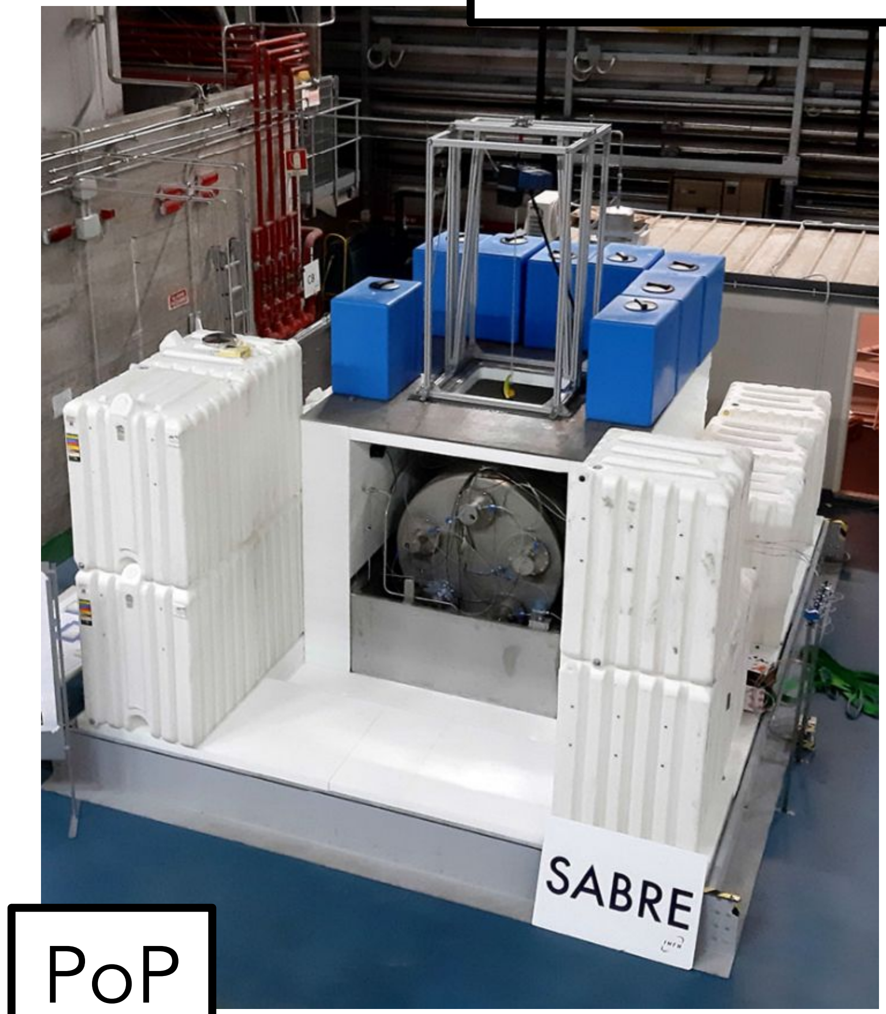
SABRE North and South detectors **have different shielding designs:**

- 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.

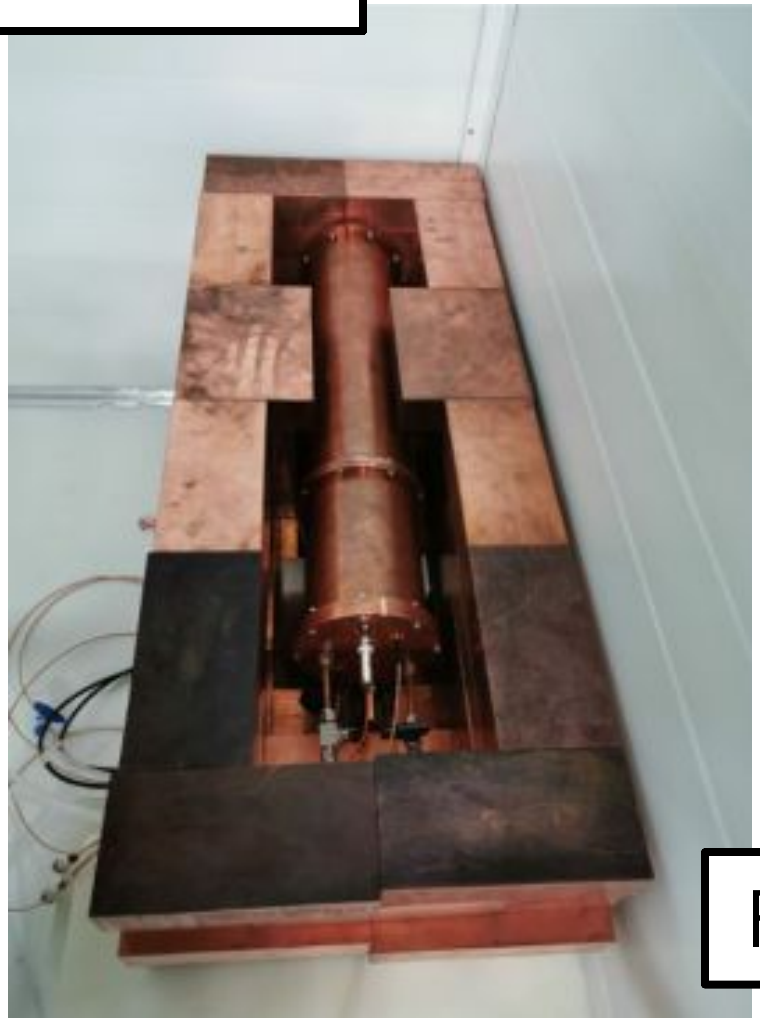
The SABRE Proof-of-Principle @LNGS (2018-2022)



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

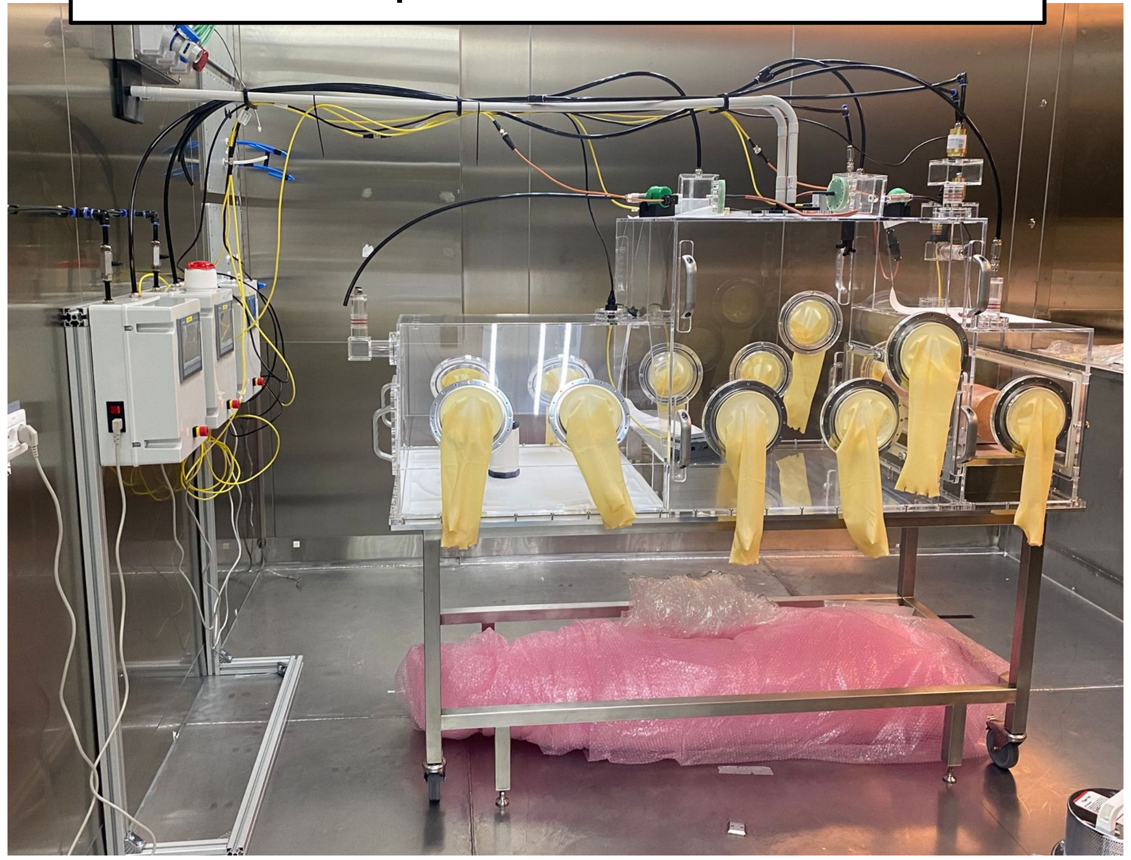
SABRE North facilities @LNGS (2022-2023)

- Two passive shielding setups for crystal characterization
- A clean room with SABRE glovebox for crystal assembling

- 10 cm Cu + 15 cm of Pb
- Host 1 detector module
- Lexan box flushed with N2

- 30 cm Cu shielding
- Host 1-3 detector modules
- Flushed with N2

SABRE glovebox
for the handling of
hygroscopic NaI(Tl) crystals.

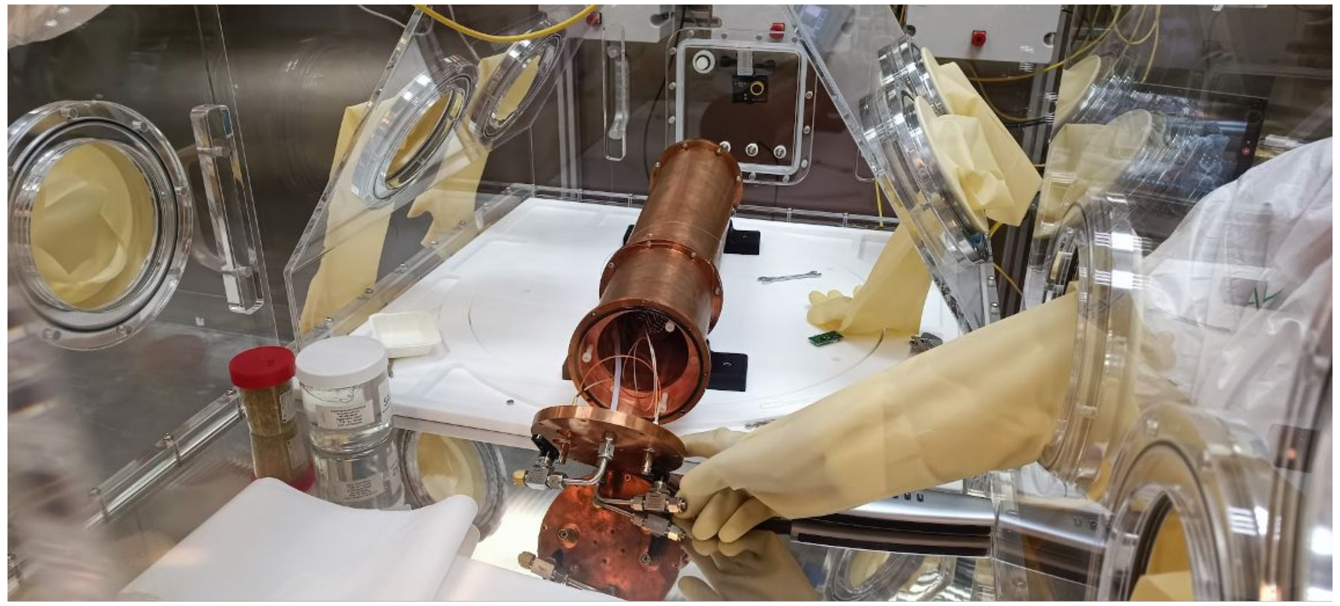


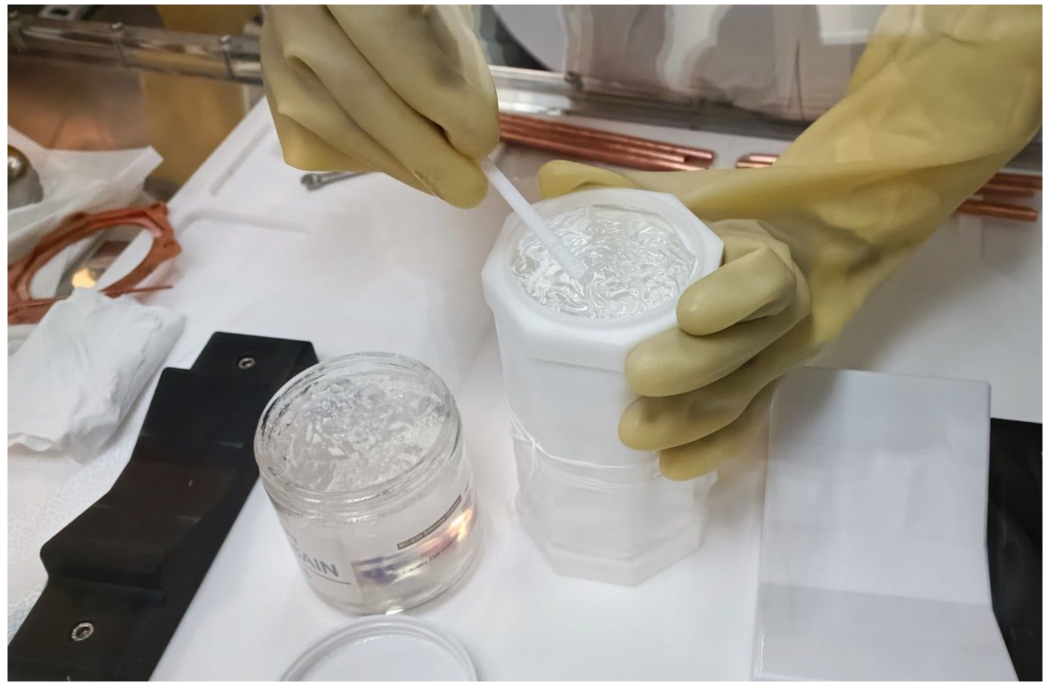
- A new site for SABRE North has been identified at LNGS.
- Moving of the equipment in progress.

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



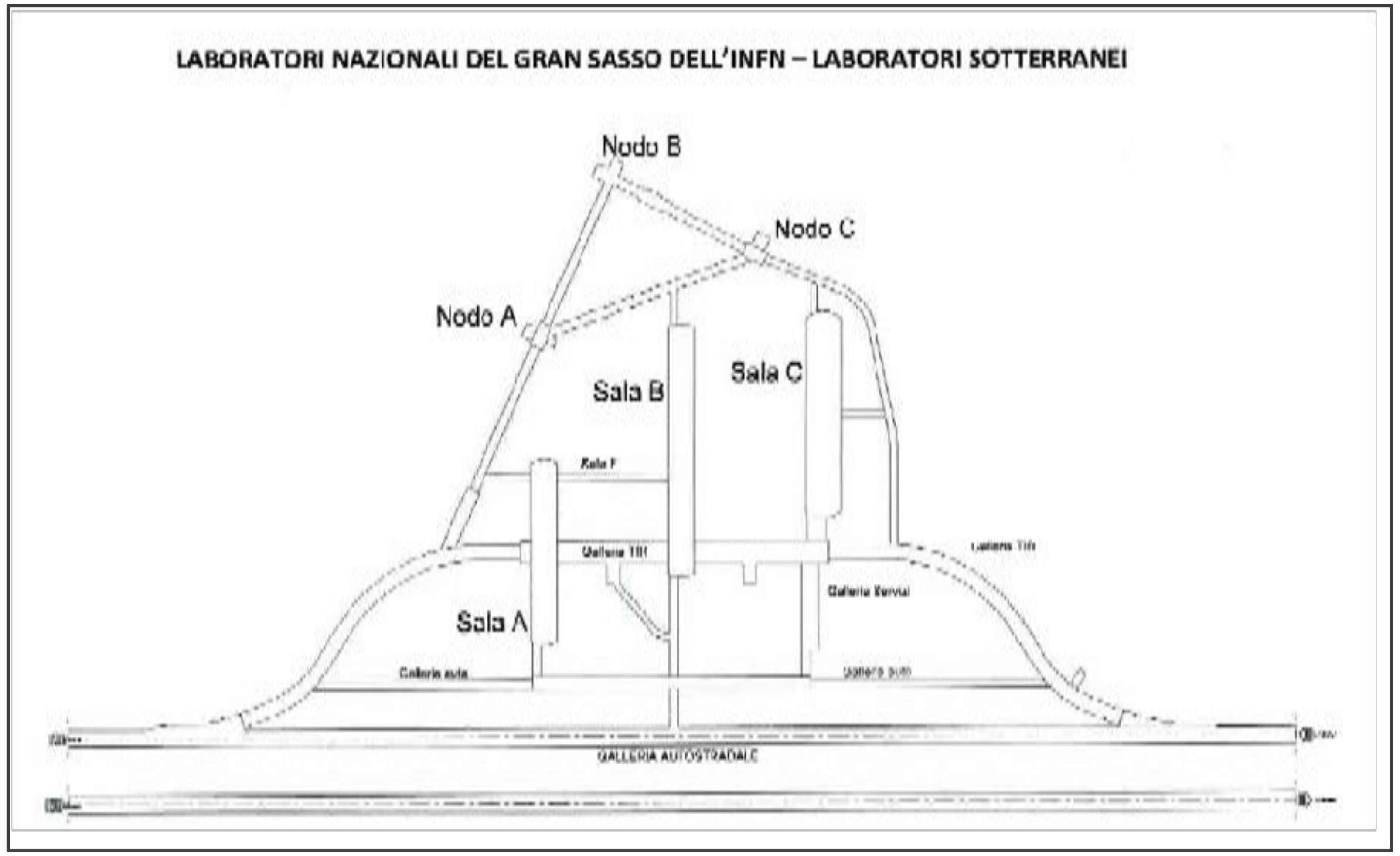


SABRE North facilities @LNGS (2024)

New SABRE experimental area in the corridor between Hall B and Hall A.

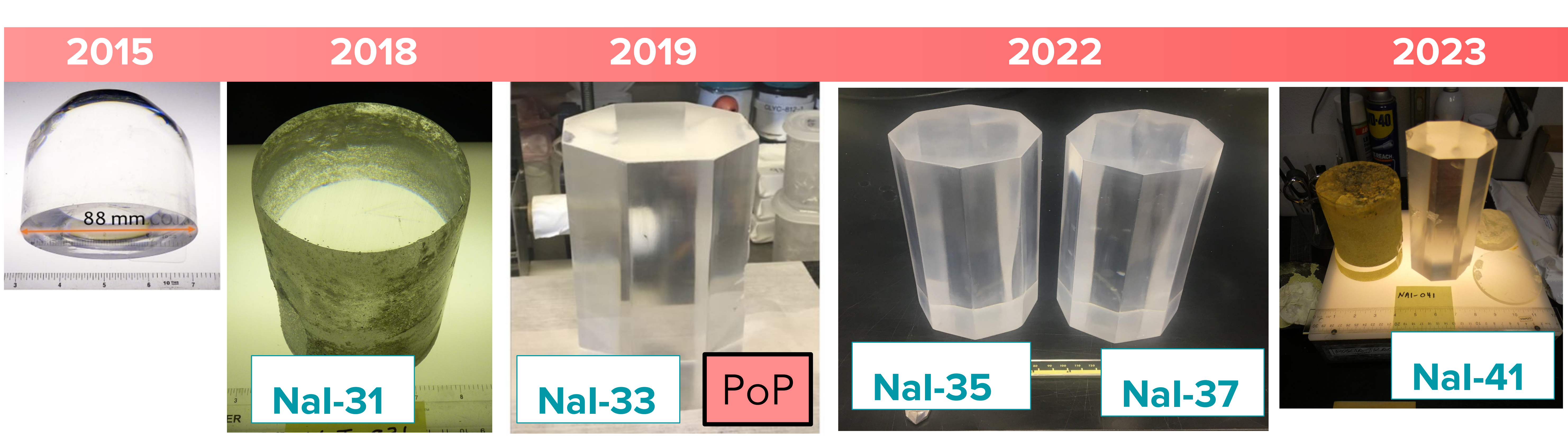
Consists of a two storeys building:

1. Ground floor (PT): set-up SABRE NORTH
2. First floor (P1). DAQ & counting room



SABRE crystals R&D

R&D carried out by PU, INFN and ARC Centre of Excellence for DM
Clean NaI powder Astrograde by Sigma Aldrich now Merck, Germany
Crystals grown by RMD - Radiation Monitoring Devices, MA (USA)



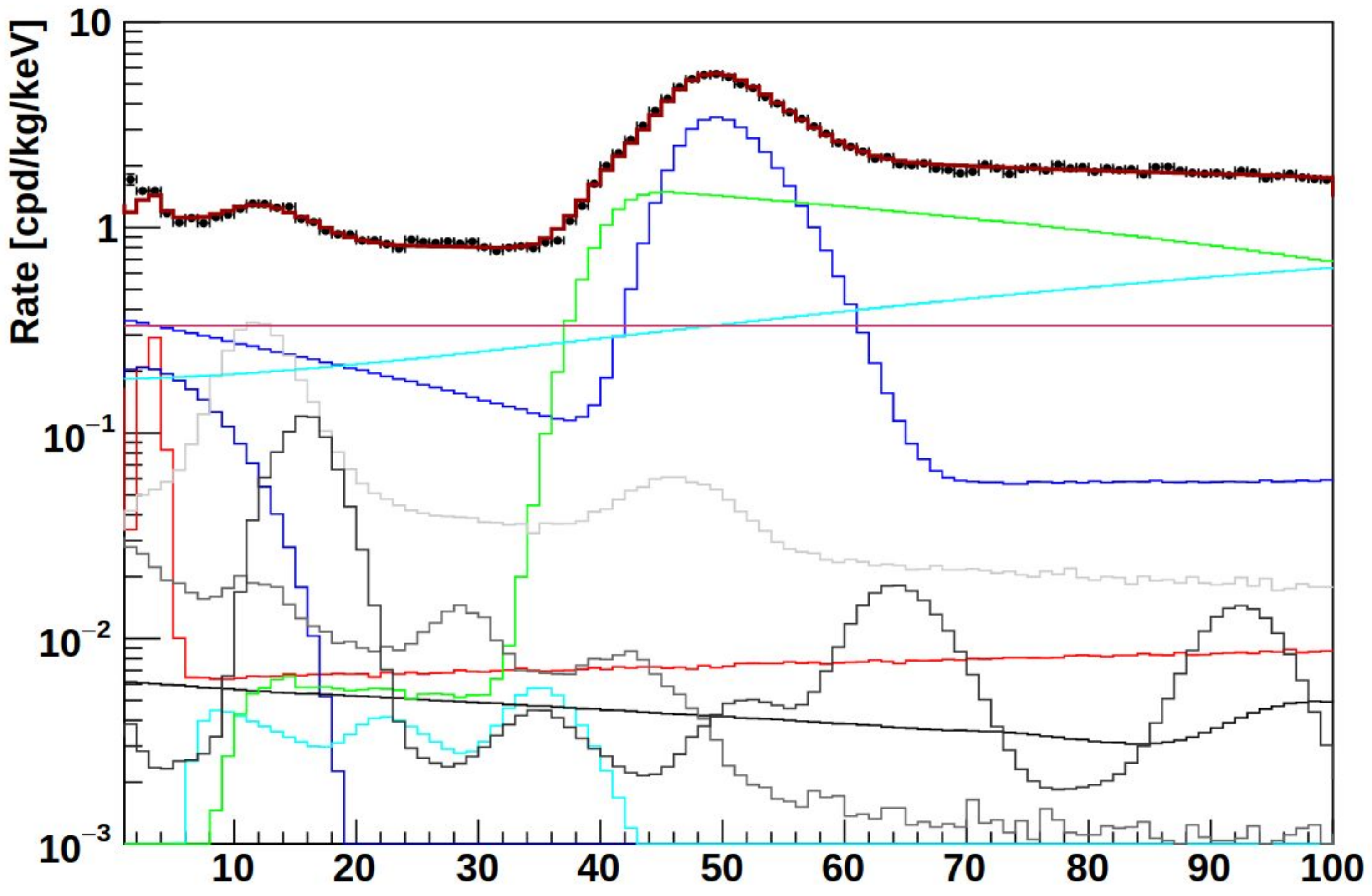
Expected in 2024:
NaI-42 grown
after zone refining

- NaI-33: Background ~1 cpd/kg/keV →close to DAMA/LIBRA Phase 1
- NaI-35, NaI-37: Reproducibility of clean growth within factor 2
- NaI-41: Zone Refining R&D activity (see next slides)

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 and 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) and PoP-dry achieved a background of ~1 cpd/kg/keV

- Strategy to lower the background
  - For ^{210}Pb and other internal backgrounds

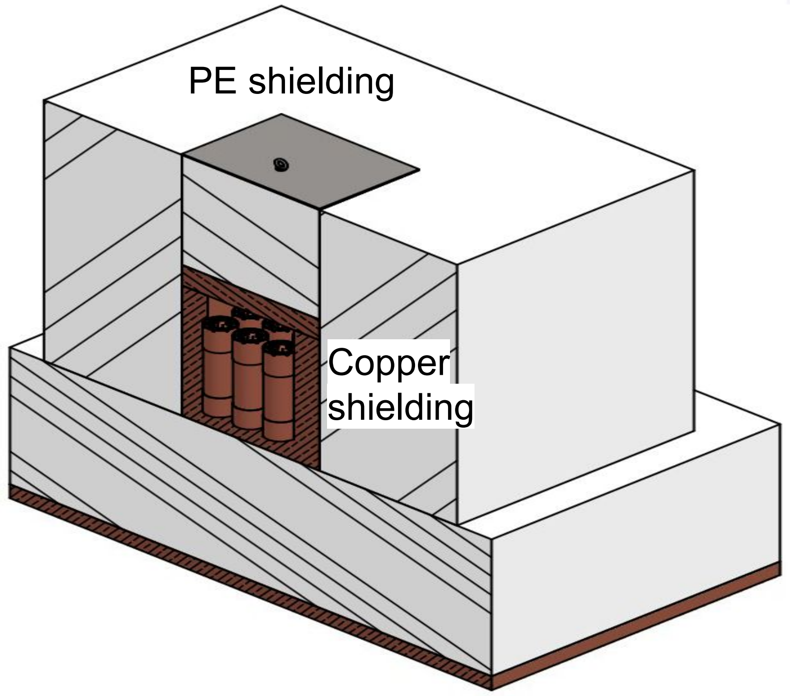
    →SABRE North & South: zone refining
    → Reduce Pb of factor ~3, K of ~10
    [Phys. Rev. Applied 16, 014060 (2021)]
  - For external background:

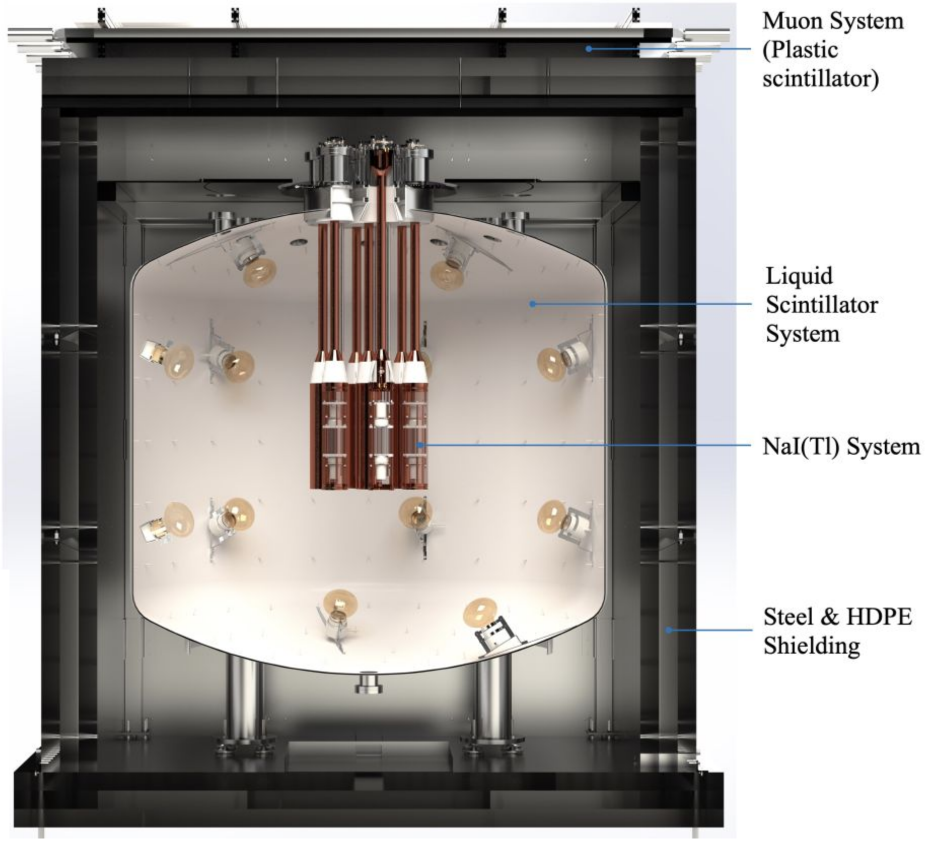
    →SABRE North: improve passive shielding

    →SABRE South: Liquid Scintillator (LAB)

    + Muon Veto

SABRE North

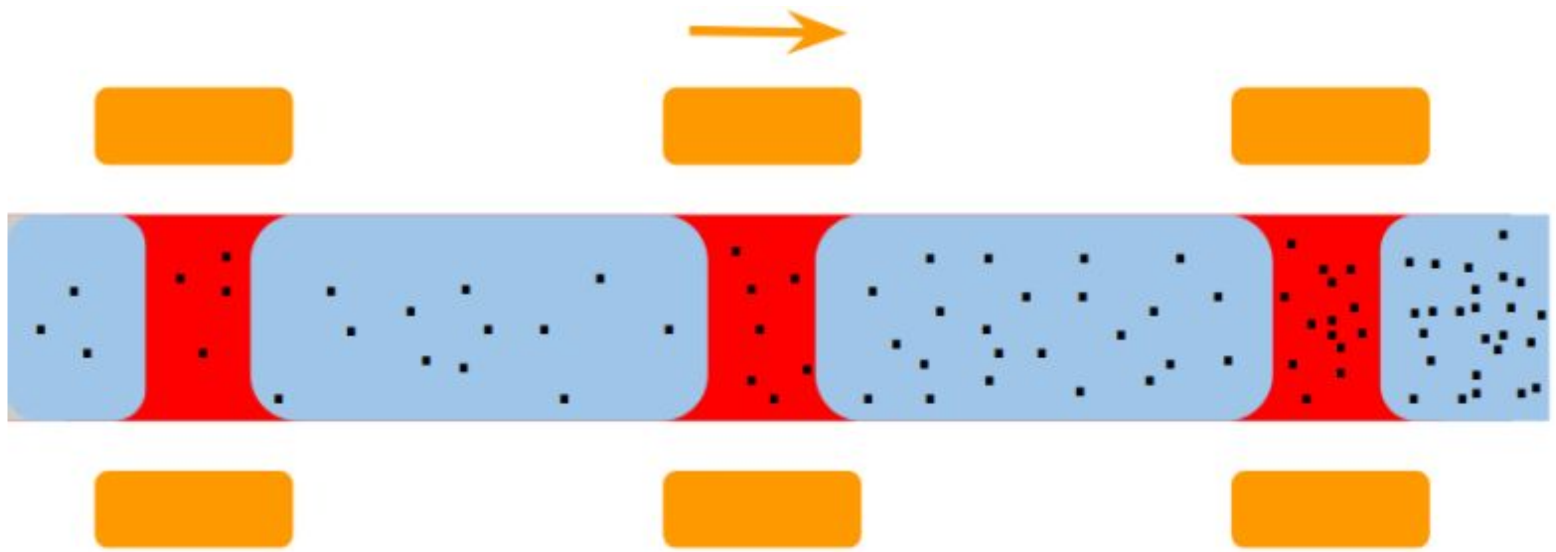




SABRE South

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, Concord, NH (USA)



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

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

Phys. Rev. Applied 16, 014060 (2021)

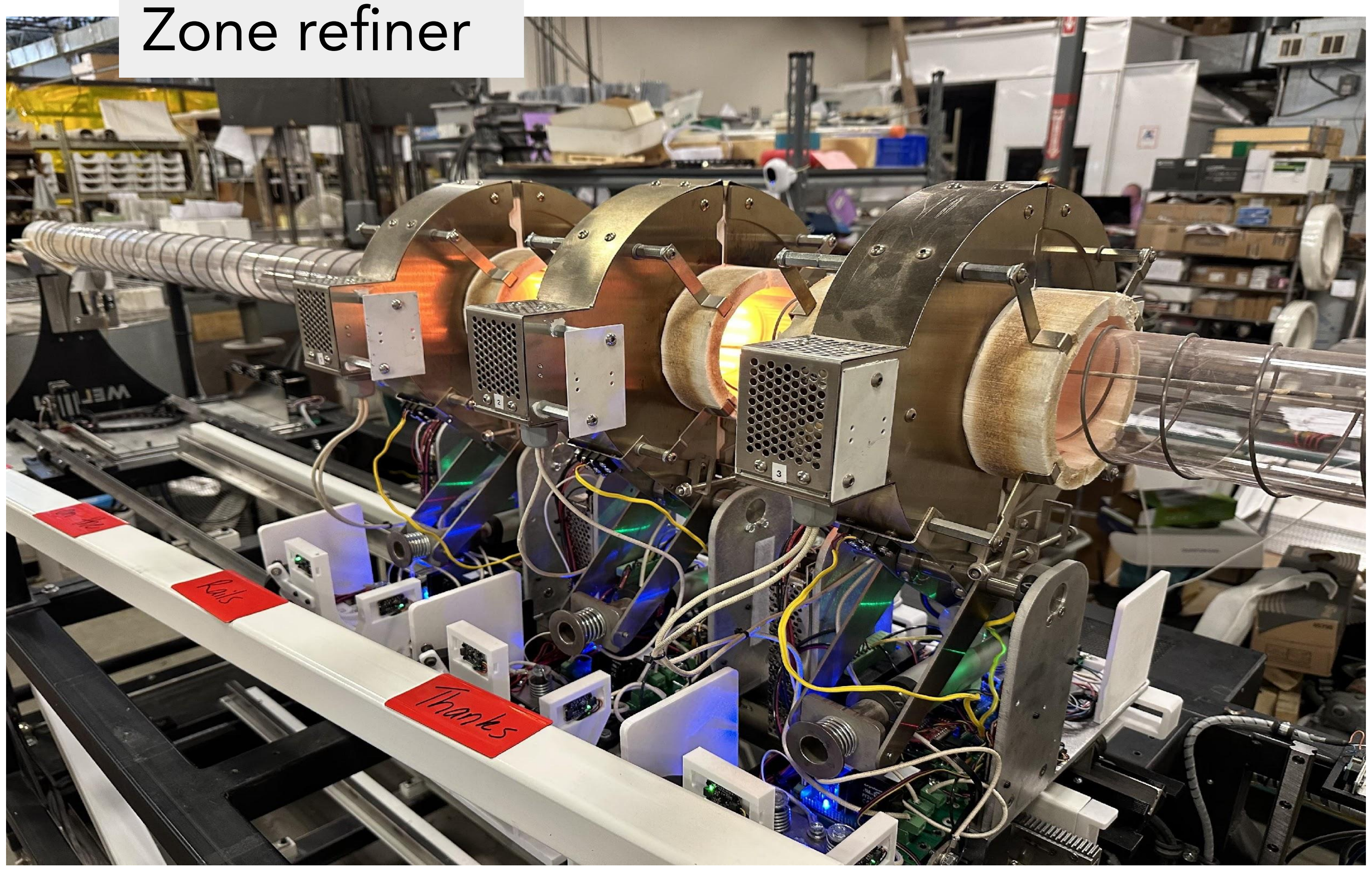
Zone refining (2023 - 2024)

Four runs with 900 gr of Astro Grade NaI powder have been performed at MELLEN, NH, USA

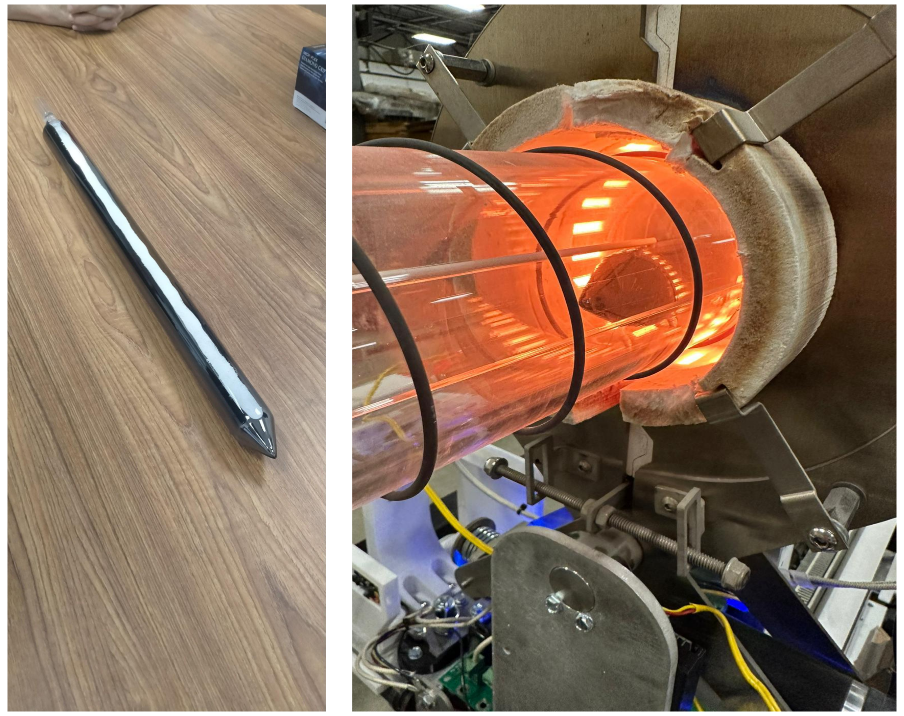
- RUN1: Carbon coated ampoule
- RUN2: Carbon coated ampoule with increased number of passes
- RUN3: No coating + use of $SiCl_4$ to avoid sticking
- RUN4: No coating + use of $SiCl_4$
  - Ampoule sealed without gas inside
  - Could be our preferred option

For each run taken 5 samples from ingot of length equal to 60 cm taken and shipped to Canfranc Laboratory and Seastar for ICPMS measurements.

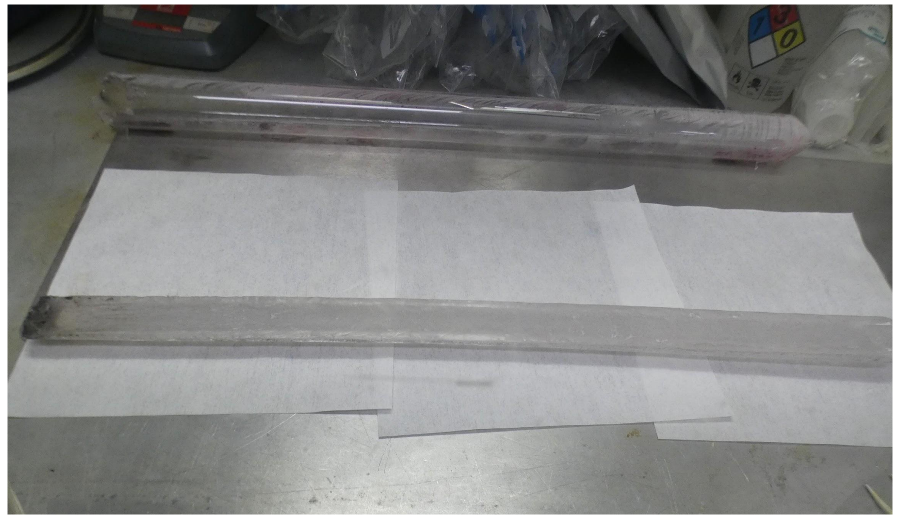
Zone refiner



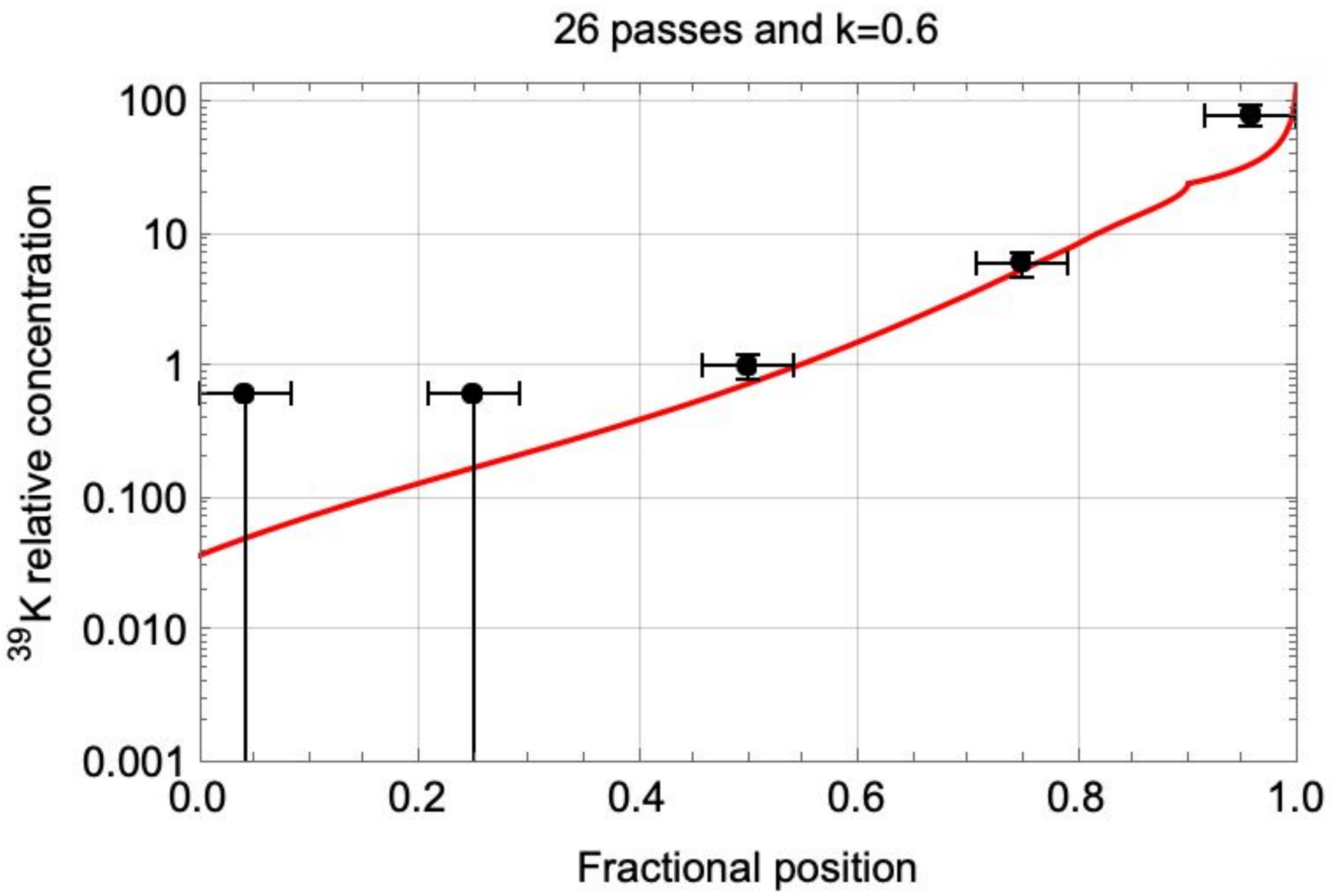
Carbon coated ampoule

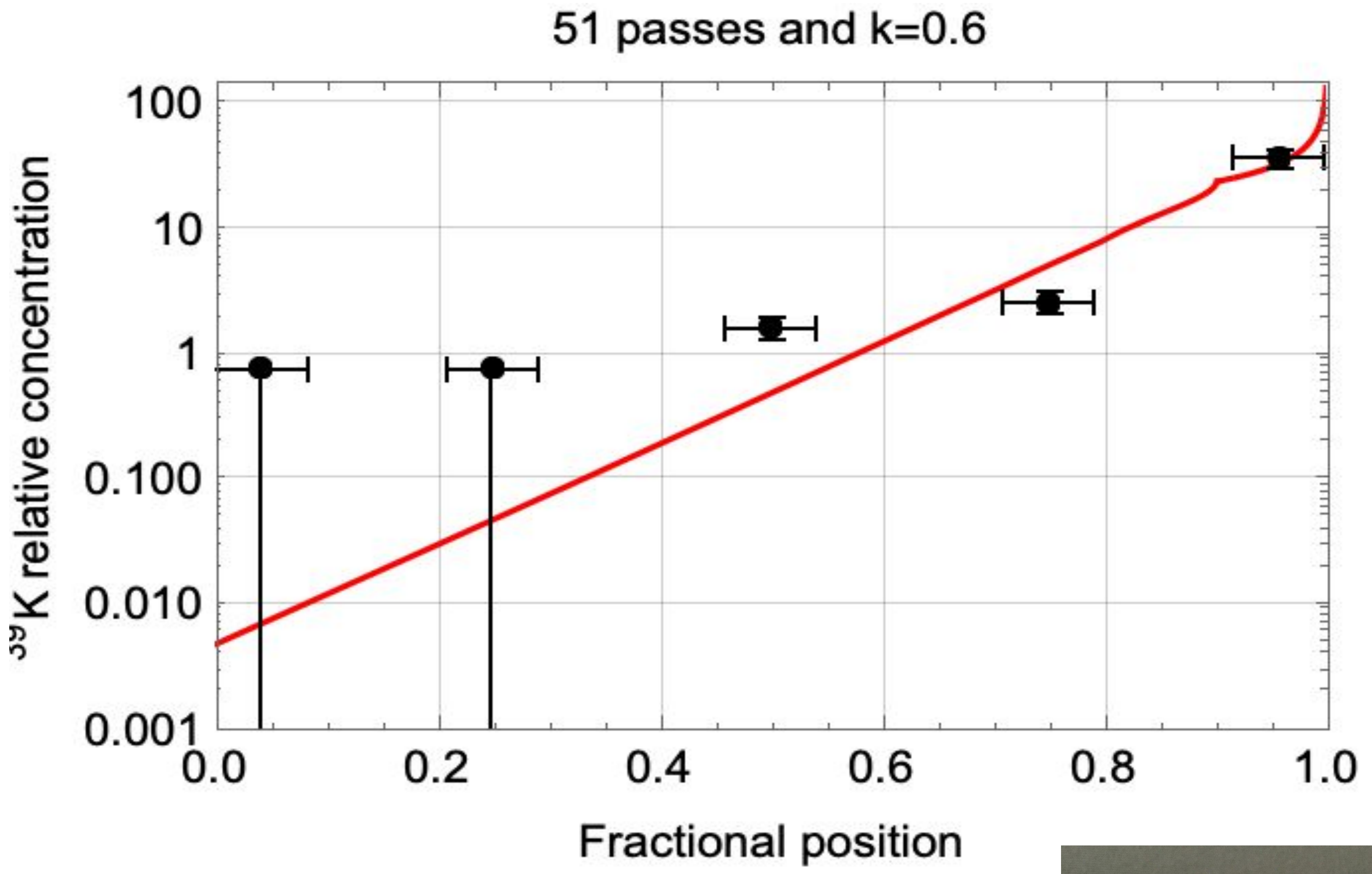


Ingot after ZR

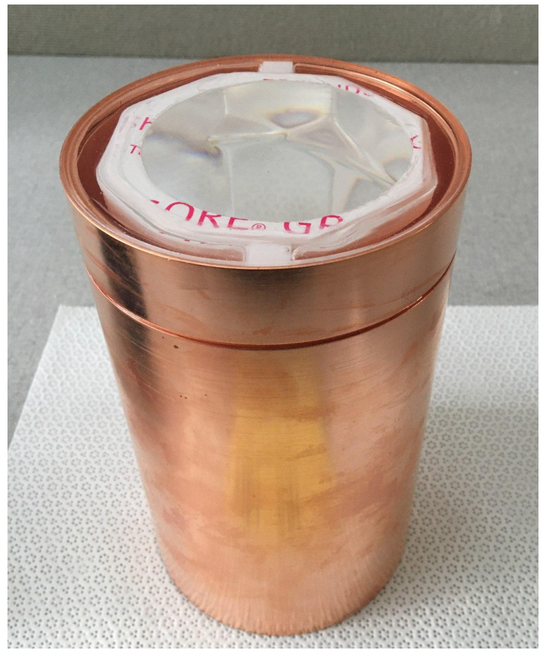


Zone refining preliminary results





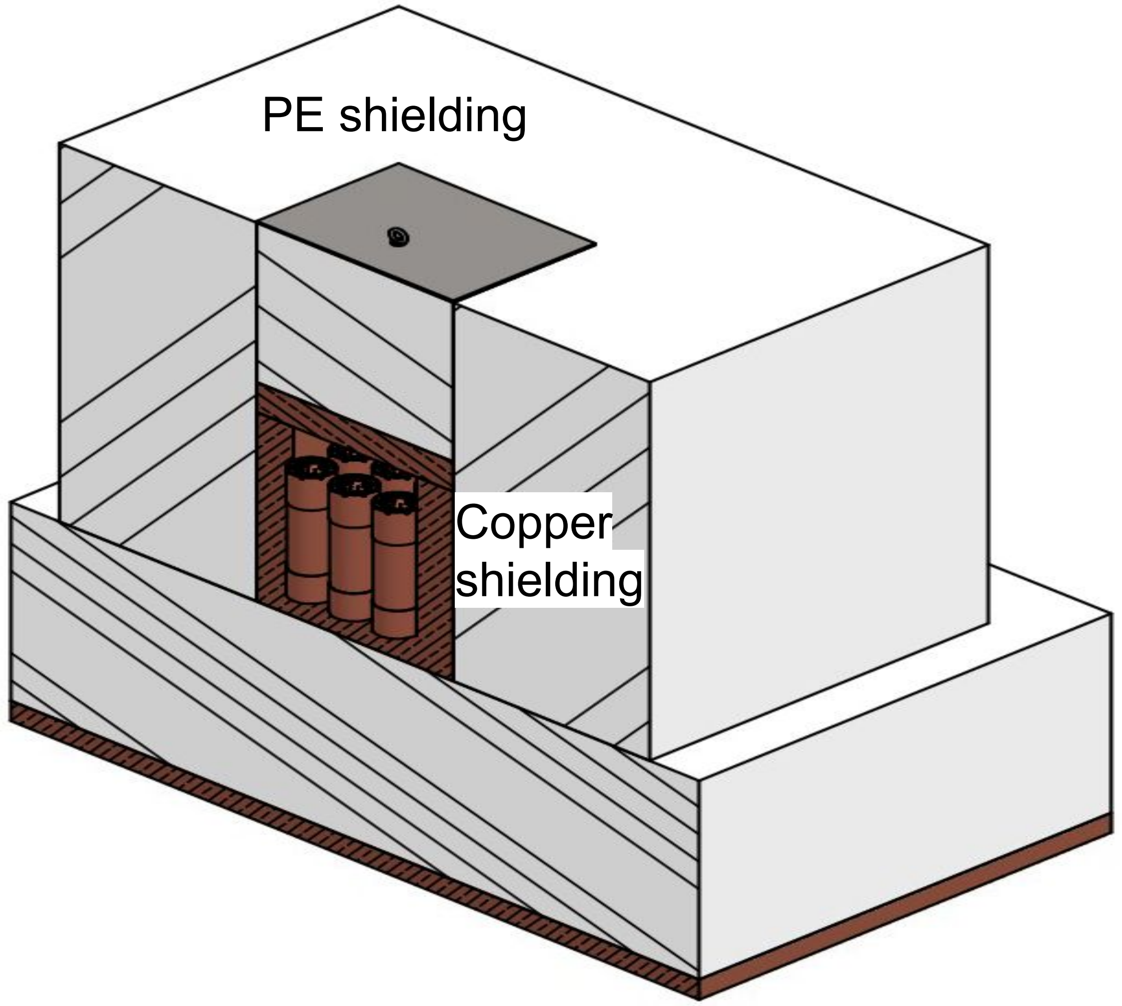
These preliminary results confirm our prediction that going from 26 to 51 passes does not significantly improve the average purification.
More work ongoing to better understand results.
The successful growth of crystal NaI-41 (grown from chunks) and its good optical properties marks a critical step in our strategy to grow high radiopurity crystals.



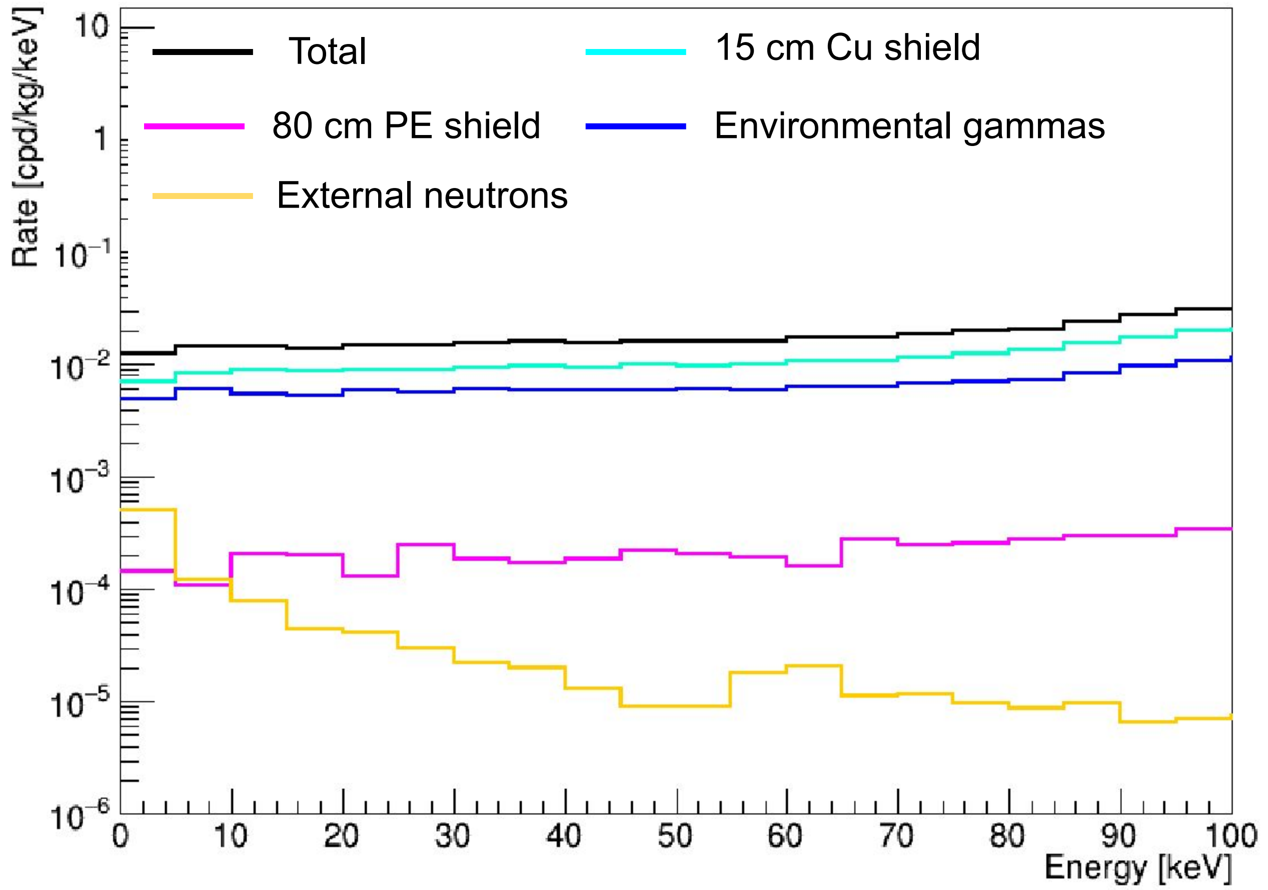
SABRE North status

- Conceptual design report presented in July 2021, TDR due in summer 2024
- 3 x 3 matrix of crystals of ~5 kg mass each
- Fully passive shielding design: 15 cm copper + 80 cm PE
  → enough shielding power and negligible contribution to the total background
- Expected background 0.5 cpd/kg/keV (with ZR) or 1 cpd/kg/keV (w/o ZR)

3x3 NaI matrix with 15 cm copper and 80 cm polyethylene



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



Conclusions

- SABRE goal is to search for annual modulation with two similar NaI(Tl) detectors in the Northern and Southern Hemispheres
- Crystals current result @LNGS: ~1 cpd/kg/keV background
  - R&D effort ongoing to understand the improvement achievable with ZR
- In 2024:
  - SABRE-North new underground site outfitting by 2024
  - SABRE-South setup entering SUPL
- SABRE expected to exclude/confirm annual modulation in 3-5 years of operation

...thanks for your attention!

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

THE UNIVERSITY OF SYDNEY

Australian National University

THE UNIVERSITY OF MELBOURNE

Extra slides

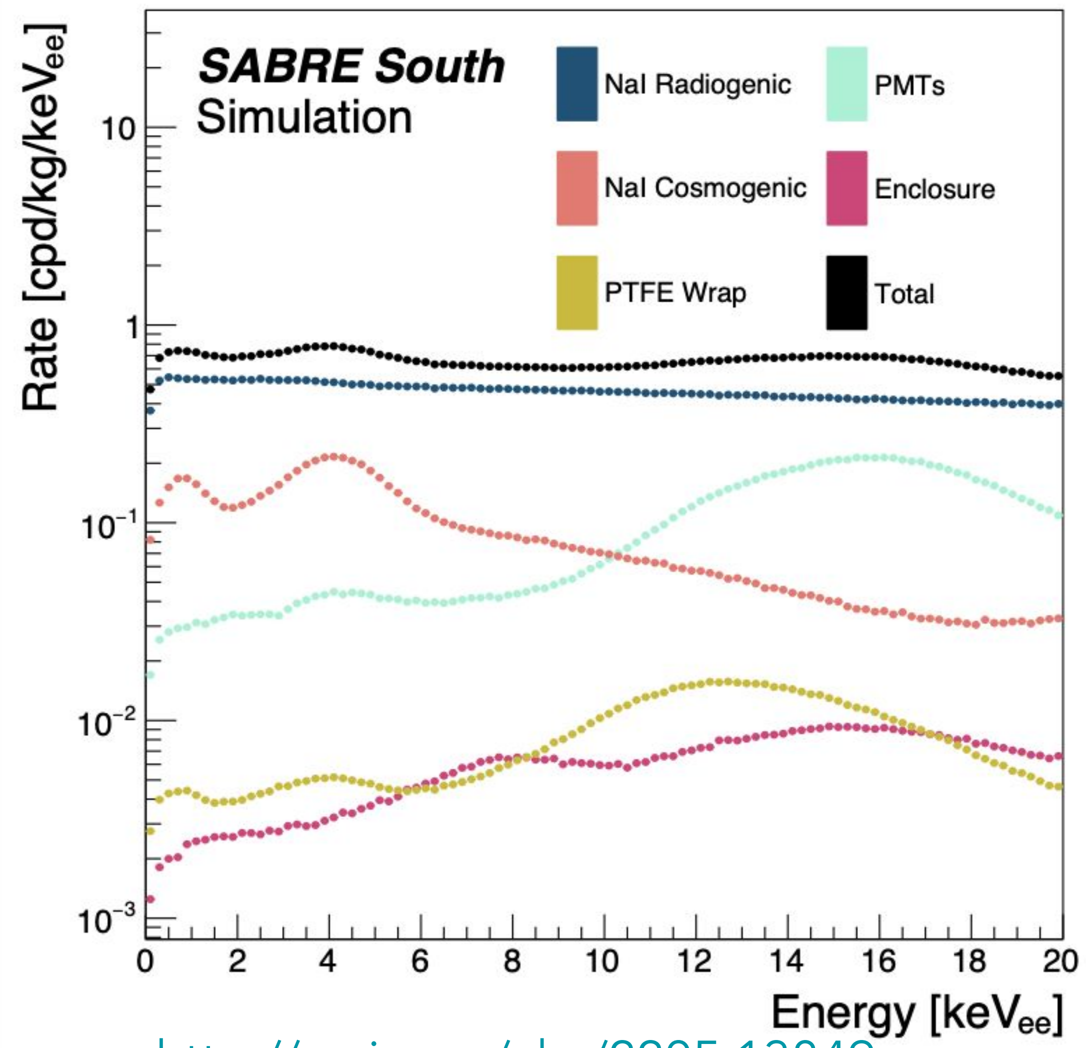
ICPMS Preliminary results

RUN1	39K [ppb]		65Cu [ppb]		85Rb [ppb]		133Cs [ppb]		138Ba [ppb]		208Pb [ppb]	
	LSC	Seast.	LSC	Seast.	LSC	Seast.	LSC	Seast.	LSC	Seast.	LSC	Seast.
powder	14.4	6.7	<5	<4	<0.8	<0.4	11	19	<0.6	0.18	2	1.6
Zone 1	<4		<5		<0.8		<0.3		<0.5		<1	
Zone 2	<4		<5		<0.8		<0.3		0.8		<1	
Zone 3	6.7		<5		<0.8		0.4		0.8		<1	
Zone 4	40		<5		<0.8		0.4		3.8		<1	
Zone 5	540		234		1.3		447		10		<1	

RUN2	39K [ppb]		65Cu [ppb]		85Rb [ppb]		133Cs [ppb]		138Ba [ppb]		208Pb [ppb]	
	LSC	Seast.	LSC	Seast.	LSC	Seast.	LSC	Seast.	LSC	Seast.	LSC	Seast.
powder	14.4	6.7	<5	<4	<0.8	<0.4	11	19	<0.6	0.18	2	1.6
Zone 1	<5		<5		<0.8		<0.3		<0.2			
Zone 2	<5		<5		<0.8		<0.3		<0.2			
Zone 3	10.7		<5		<0.8		<0.3		0.4		ongoing	
Zone 4	17		<5		<0.8		<0.3		0.4			
Zone 5	243		261		<0.8		309		4.5			

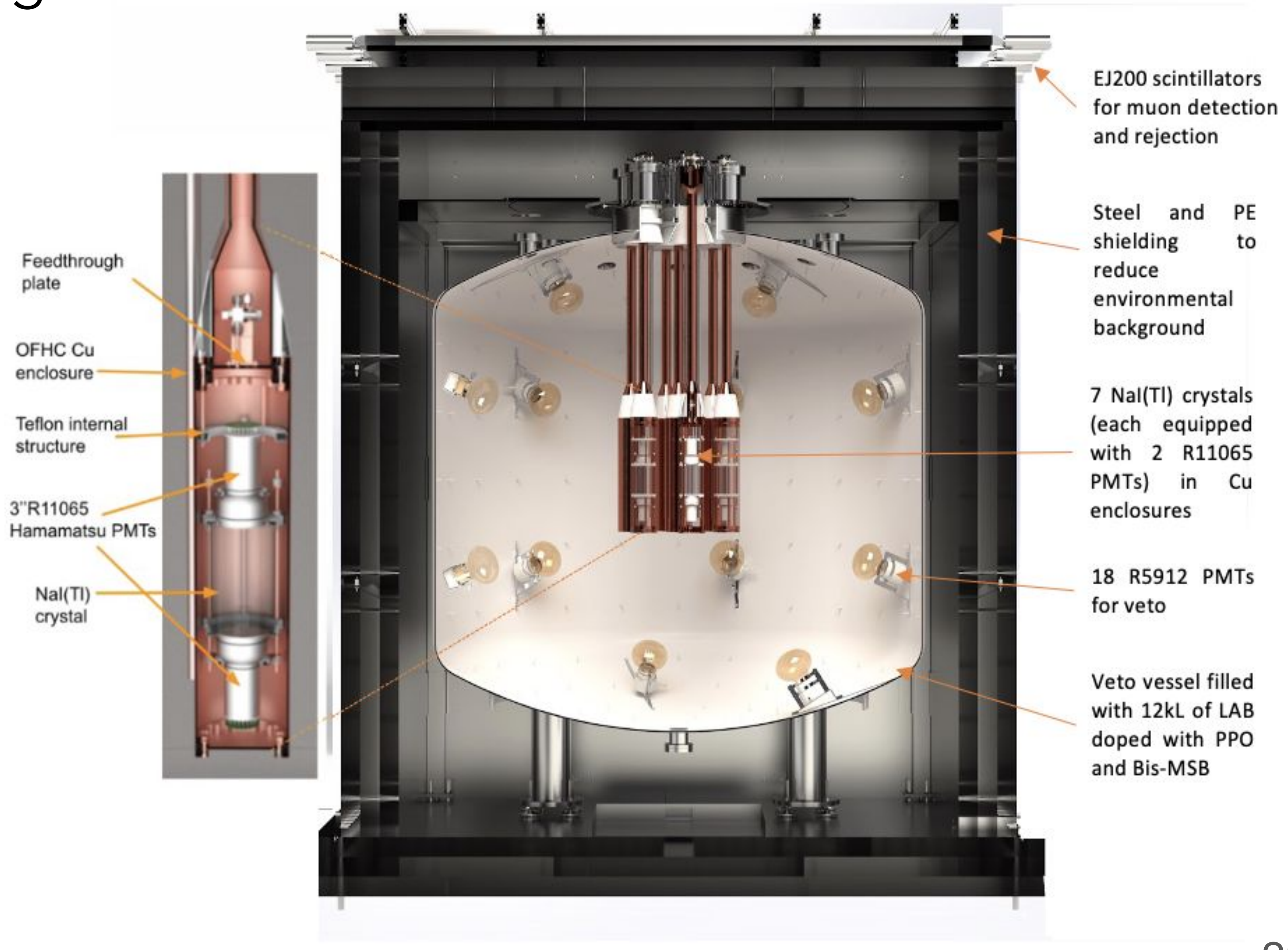
SABRE South status

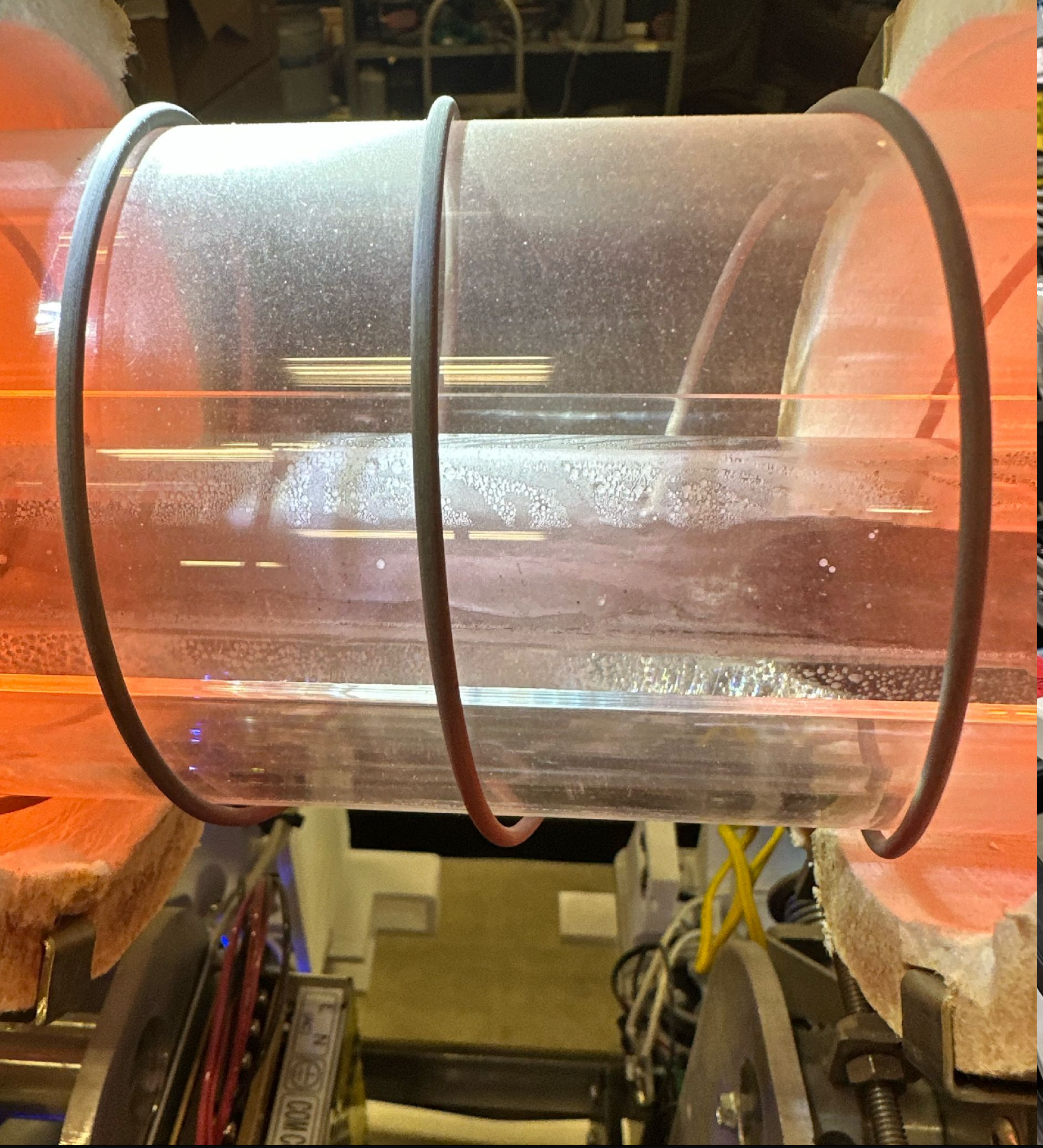
- Design: 7 crystals array of ~5-7 kg mass (SABRE South TDR available online)
- Vessel + LAB, PMTs, muon detector, DAQ electronics, Crystal insertion system ... all ready.
- Crystal procurement in synergy with SABRE North
- Highest purity crystals and largest active veto: 0.72 cpd/kg/keV.

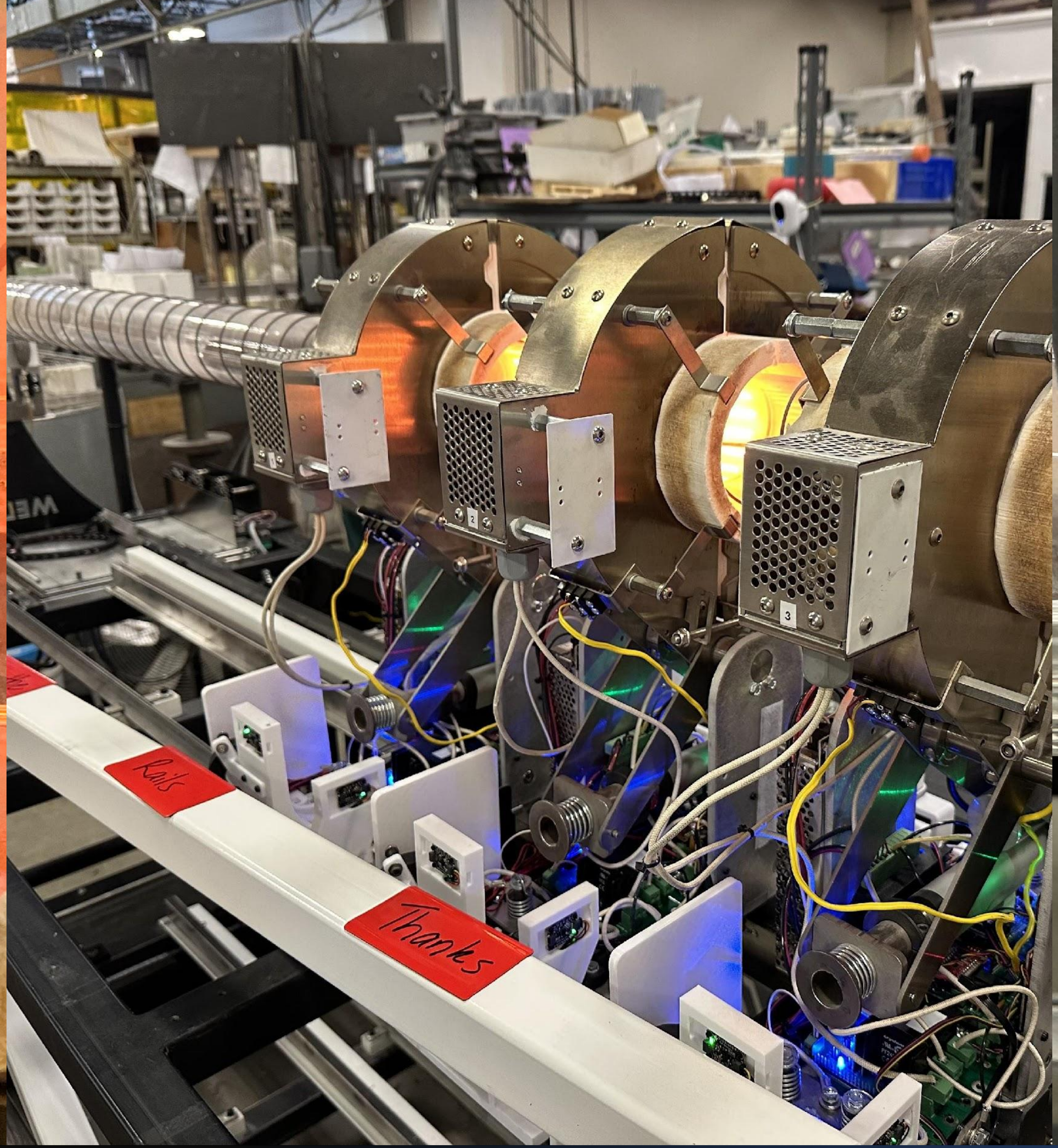


http://arxiv.org/abs/2205.13849
(accepted to EPJC)

- SABRE South detector deployment starting in 2024
- Expect exclusion or discovery results after 2.5-3 years of continuous operation.

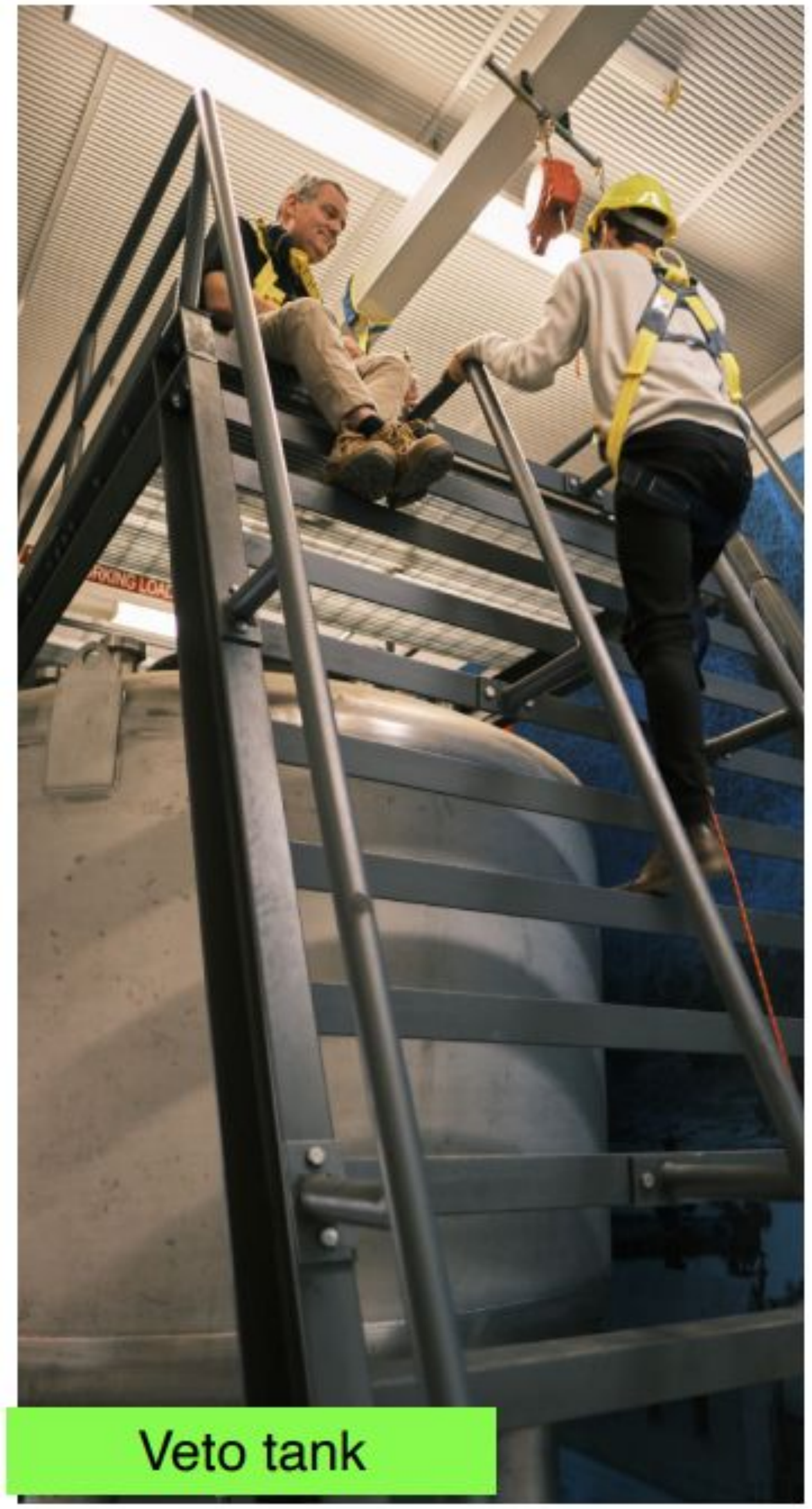




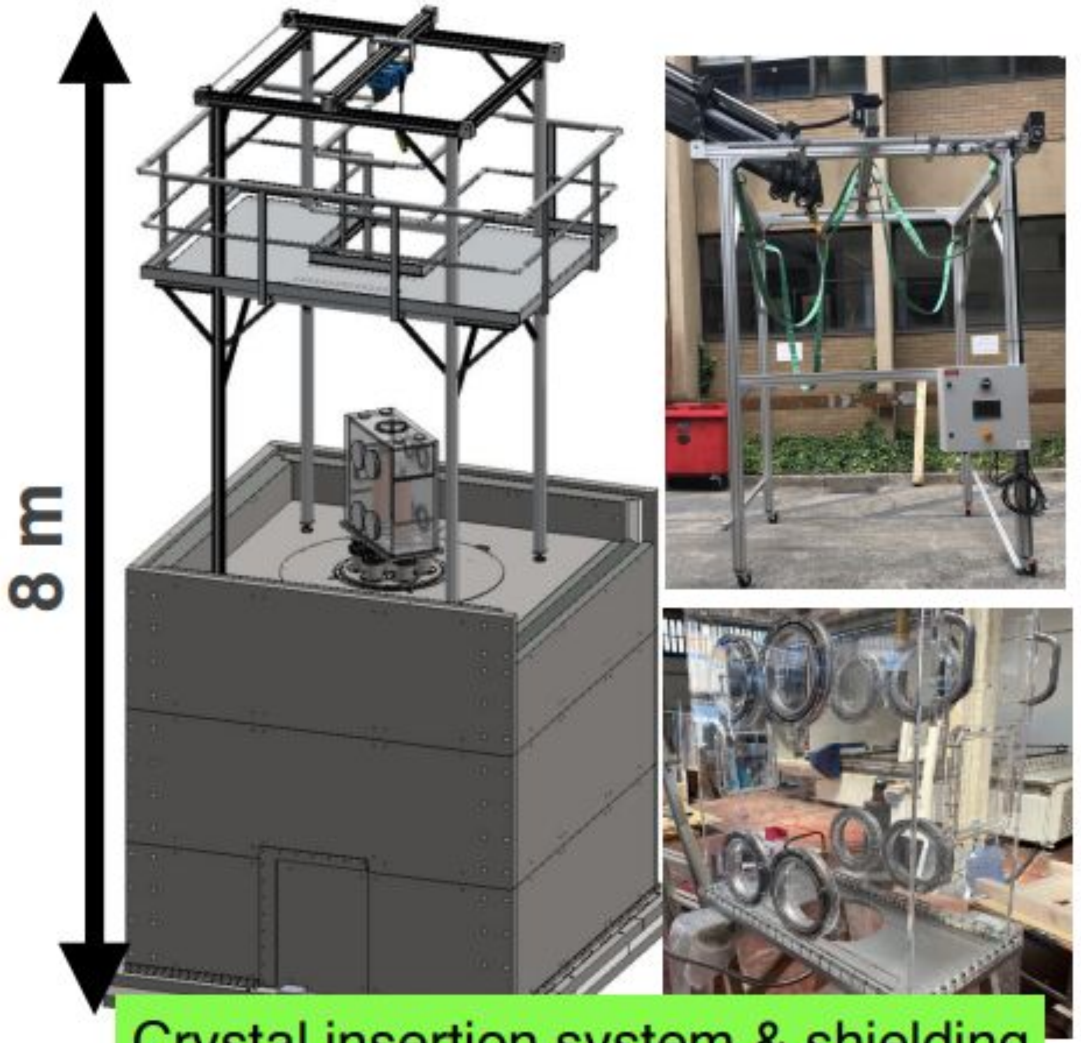


Zone Refining RUN3

SABRE South status

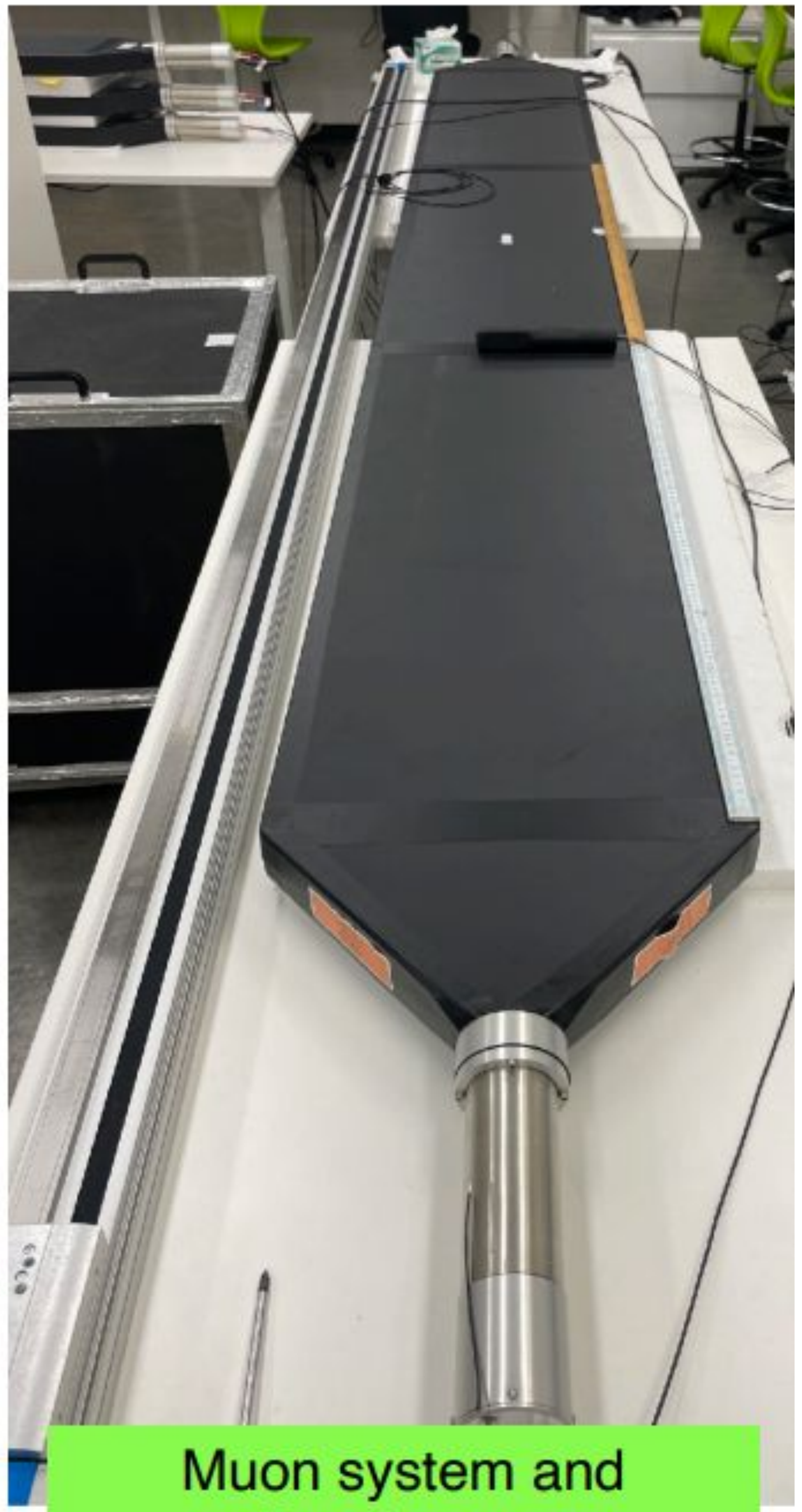


Veto tank



Crystal insertion system & shielding

Liquid Scintillator from JUNO



Muon system and calibration stage

NaI crystals background comparison

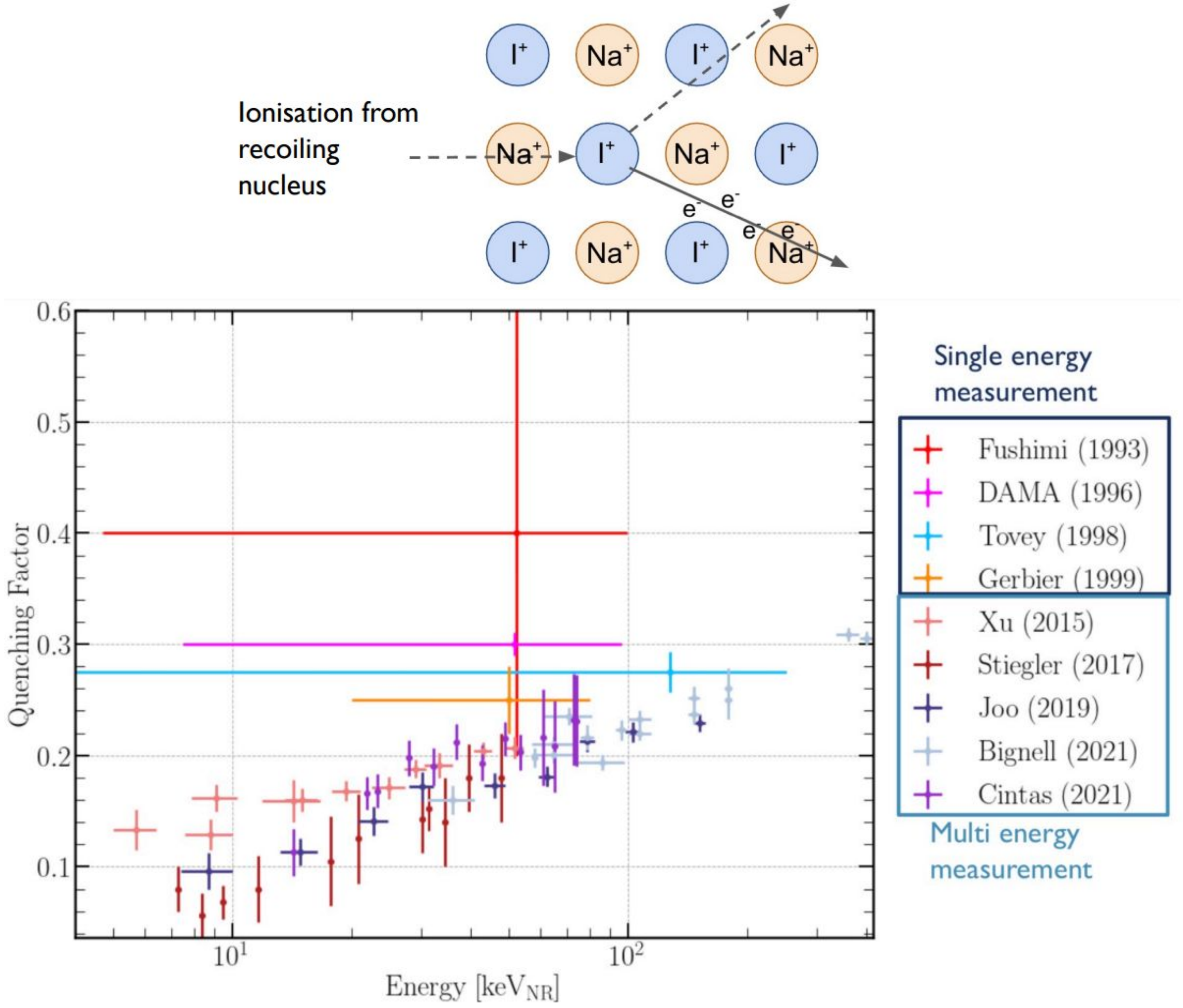
Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)	Active mass (kg)
DAMA [1]	13	0.7-10	$(5\text{-}30)\times10^{-3}$	0.5-7.5	250
ANAIS [2]	31	<0.81	1.5	0.36	112
COSINE [3]	35.1	<0.12	1-1.7	<2.4	~60
SABRE [4]	4.3	0.4	0.49	0.2	~35+40=75 (total goal)
PICOLON [5]	<20	-	$<5.7\times10^{-3}$	-	~20 (goal)

[1] Nucl.Instrum.Meth.A 592 (2008) 297-31
[2] Eur.Phys.J.C 79 (2019) 5, 412
[3] Eur.Phys.J.C 78 (2018) 490
[4] Eur.Phys.J.C 81 (2021) 4, 299, Phys.Rev.D 104 (2021) 2, L021302, Eur.Phys.J.C 82 (2022) 12, 1158
[5] PTEP 2021 (2021) 4, 043F01

Interpretation of results: the quenching factor (QF)

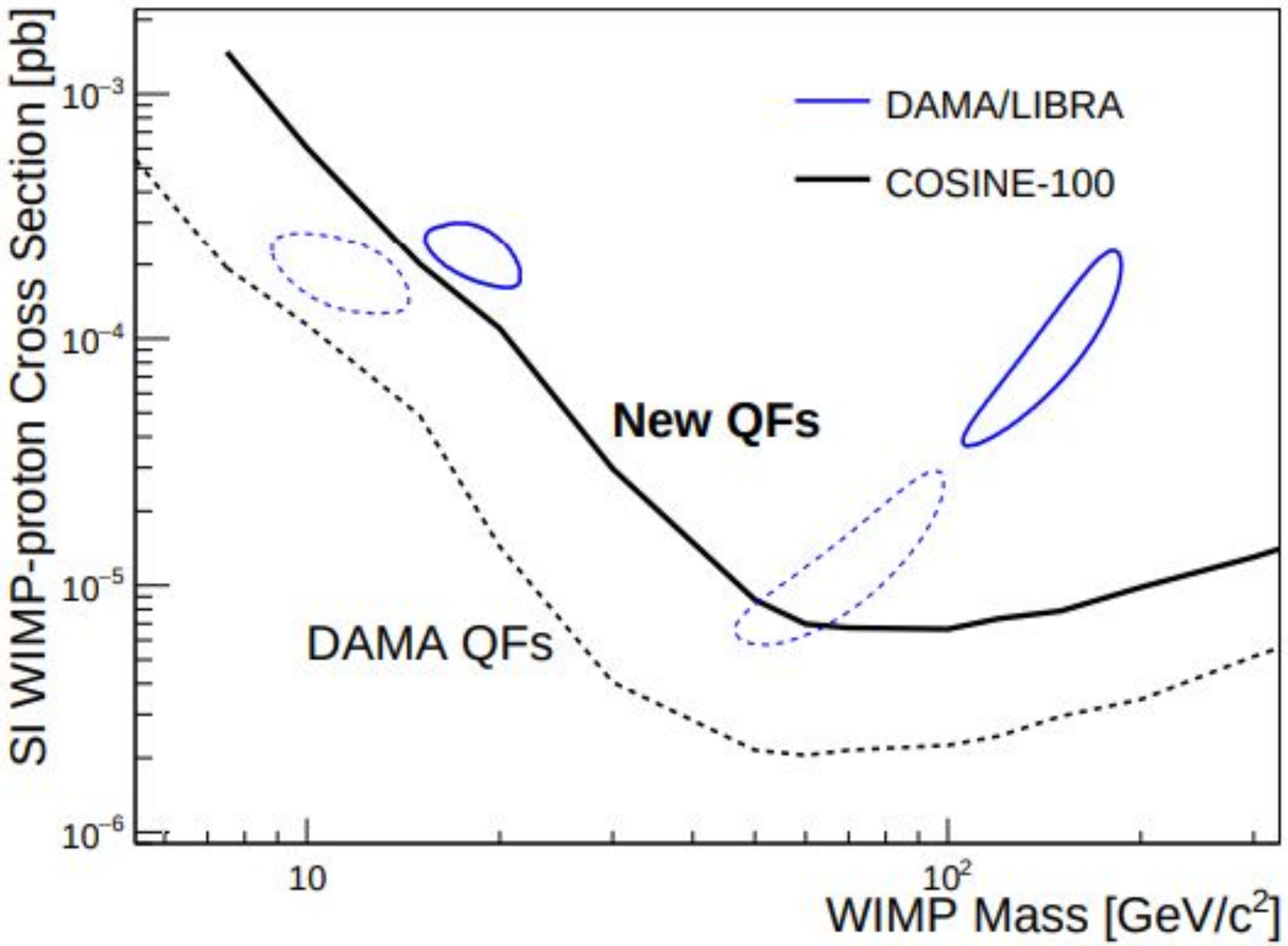
- Part of the energy released by the nuclear recoil is not transformed in scintillation light → quenching
- Observable is the energy in keV_{ee} (electron-equivalent)
- Measurements on different crystals not in good agreement
- QF affects both the energy range and amplitude of the modulation

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

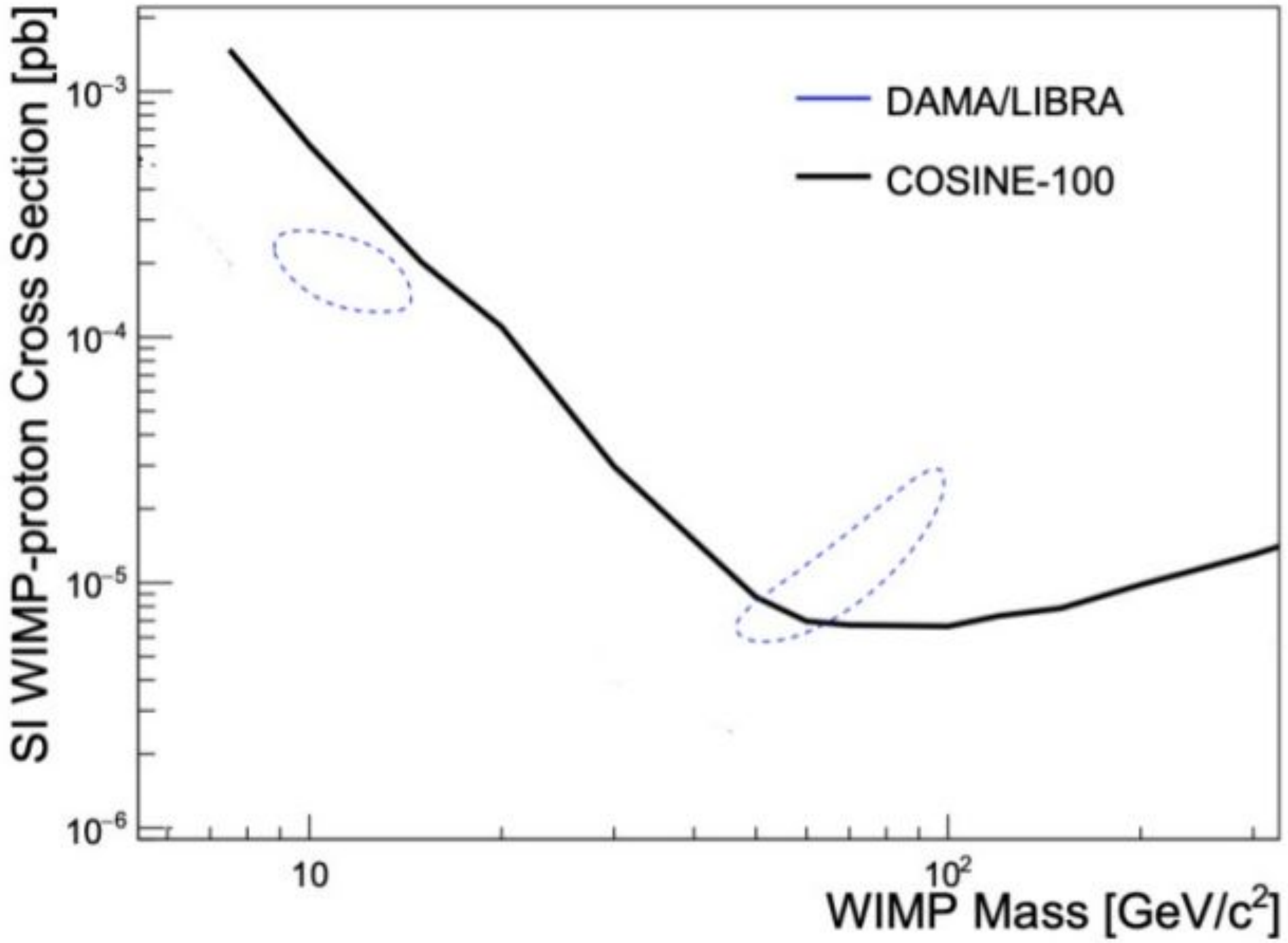


Quenching factor impact

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



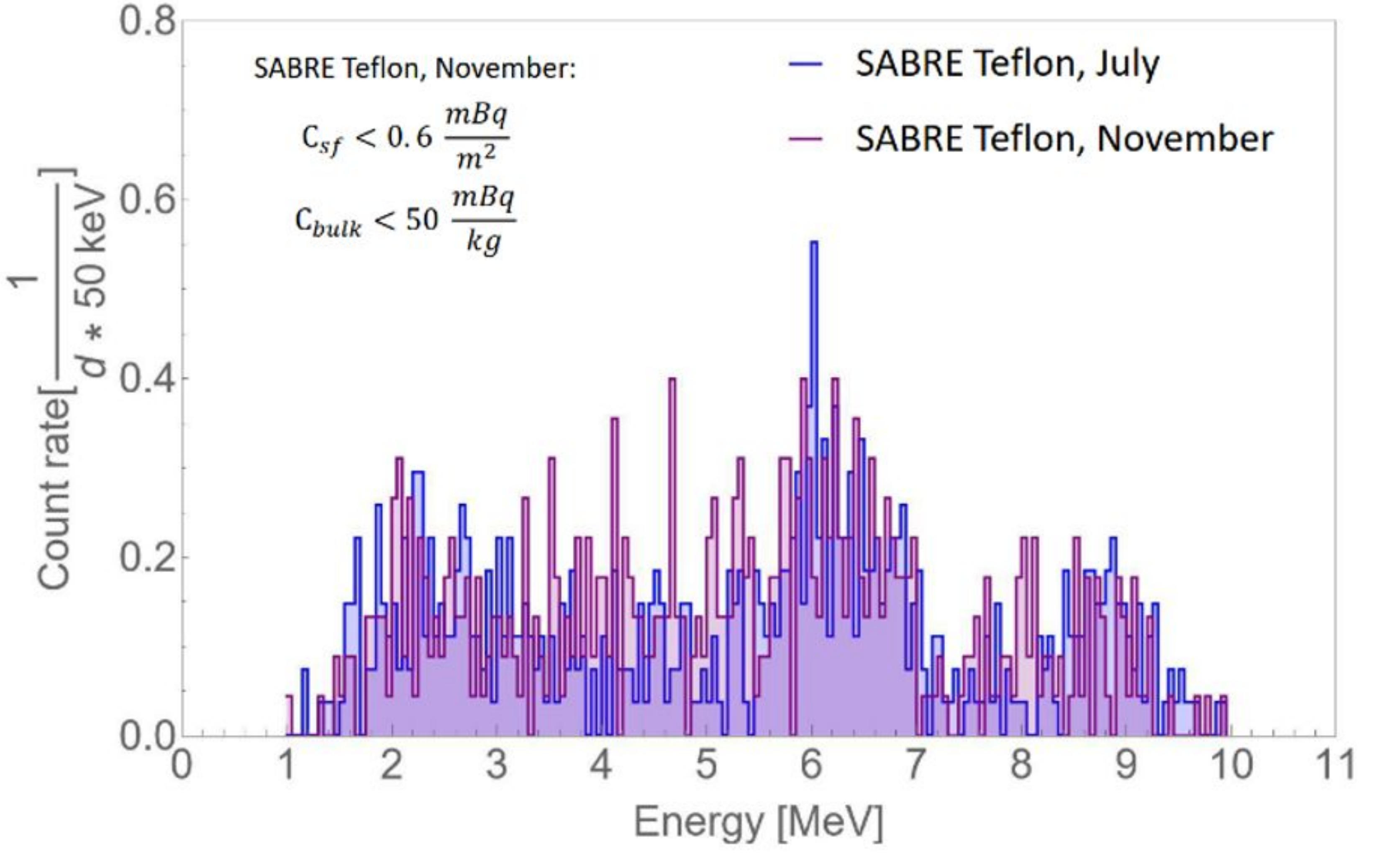
Assuming detectors have the same quenching factor (dashed lines or solid lines)



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