The SABRE North experiment: status and prospects

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on behalf of the SABRE North collaboration

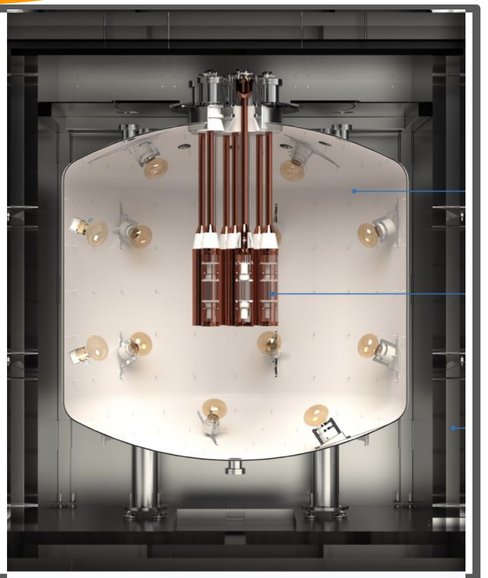
Zaragoza - June 1-5 2026

SABRE: Sodium-iodide with Active Background REjection

The goal of the 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

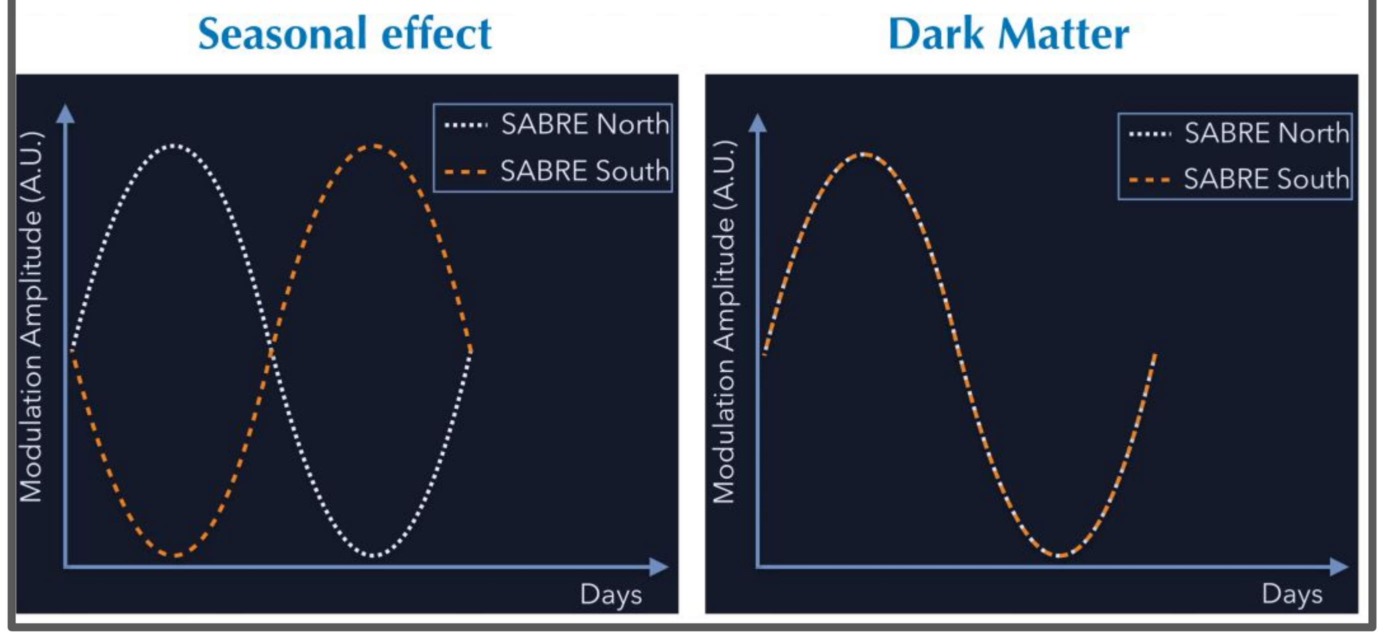
Active veto with liquid scintillator



@ SABRE South only

Double location:

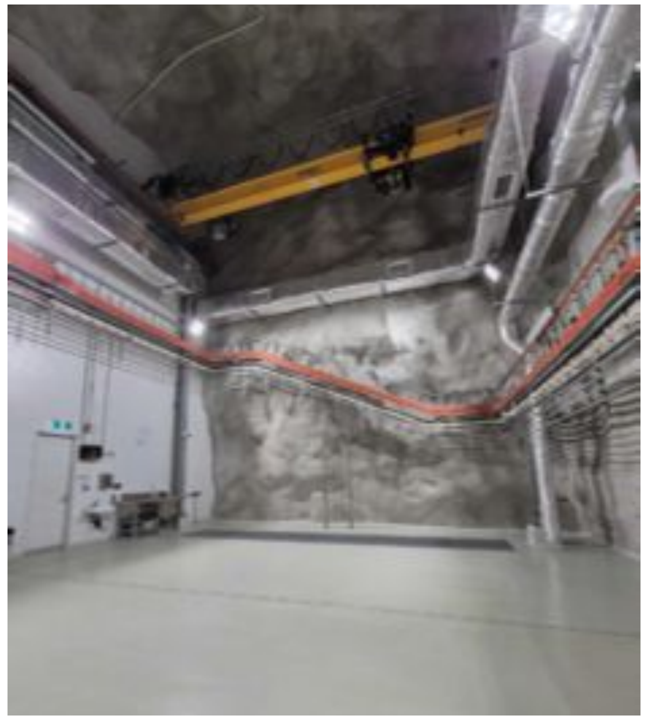
Northern and Southern hemisphere



see talk from Leonie Einfalt on SABRE South in this session

SABRE North and South

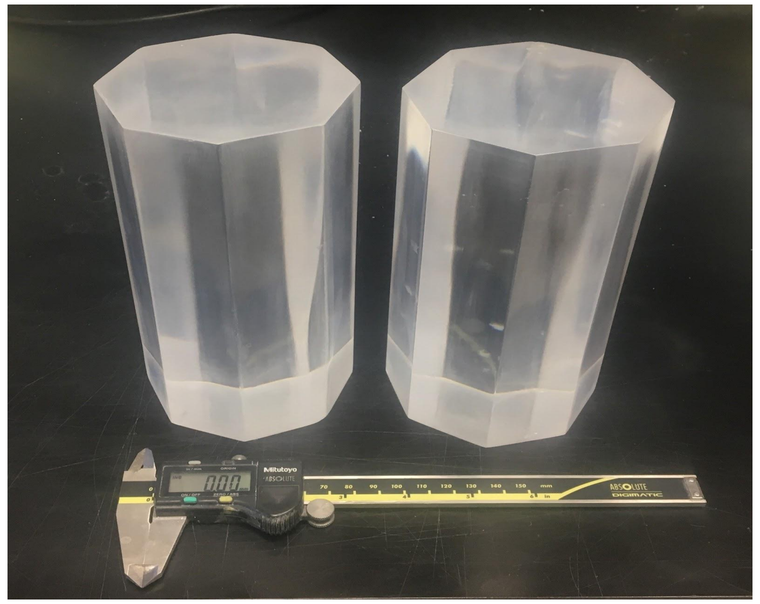
- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia



How to grow a radiopure NaI(Tl) crystal

Clean precursors: NaI powder, Tl dopant → **Powder drying** → **Doping** → **Clean growth** → **Cutting & polishing**

Zone Refining



The SABRE North recipe

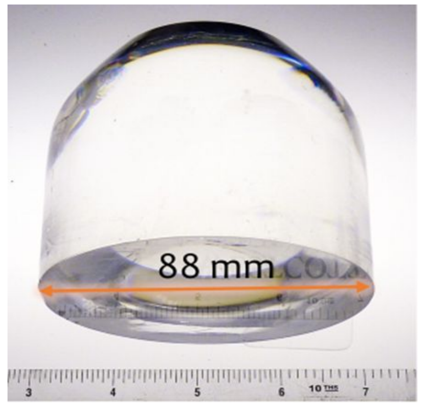
The collaboration between Princeton University and industrial partners led to:

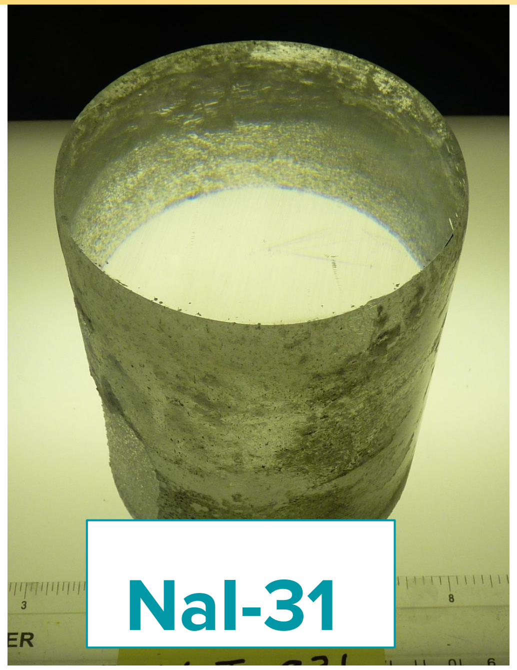
- clean NaI powder Astrograde by Sigma Aldrich now Merck, Germany
- clean crystals grown by RMD - Radiation Monitoring Devices, MA (USA)
    - Vertical Bridgman technique: the powder is placed inside a sealed ampoule, reducing the possibility of contamination during the growth phase

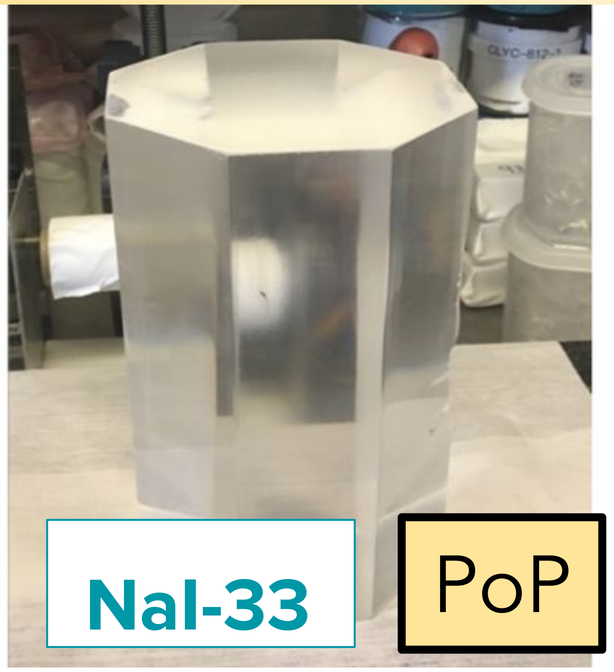
Radiopure NaI(Tl) crystals R&D

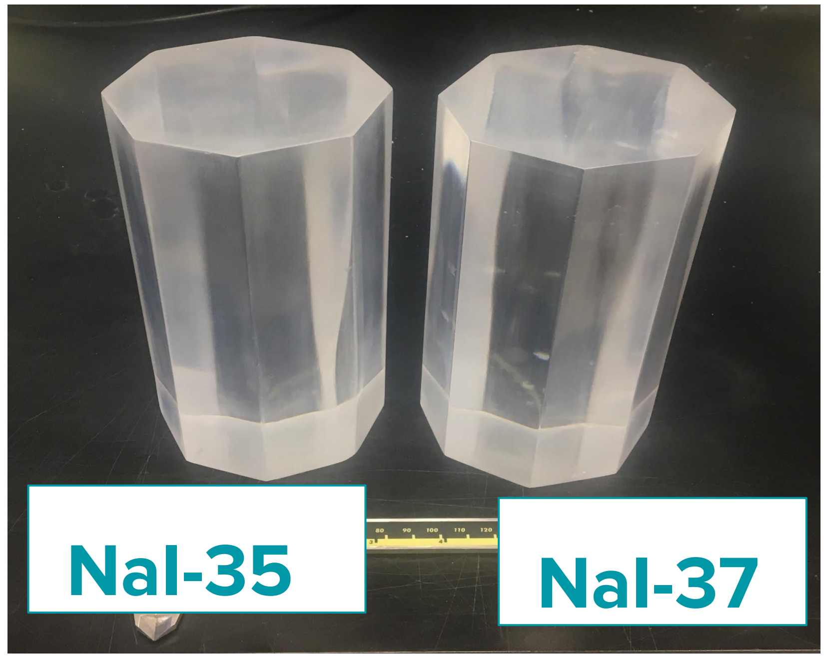
R&D carried out by PU, INFN and ARC Centre of Excellence for DM
Clean NaI powder Astrograde by Sigma Aldrich now Merck, Germany
Crystals grown by RMD - Radiation Monitoring Devices, MA (USA)

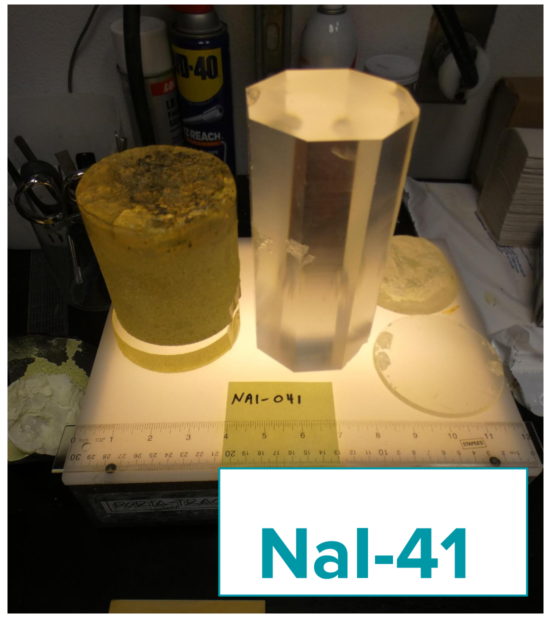
2015 **2018** **2019** **2022** **2023** **2025**











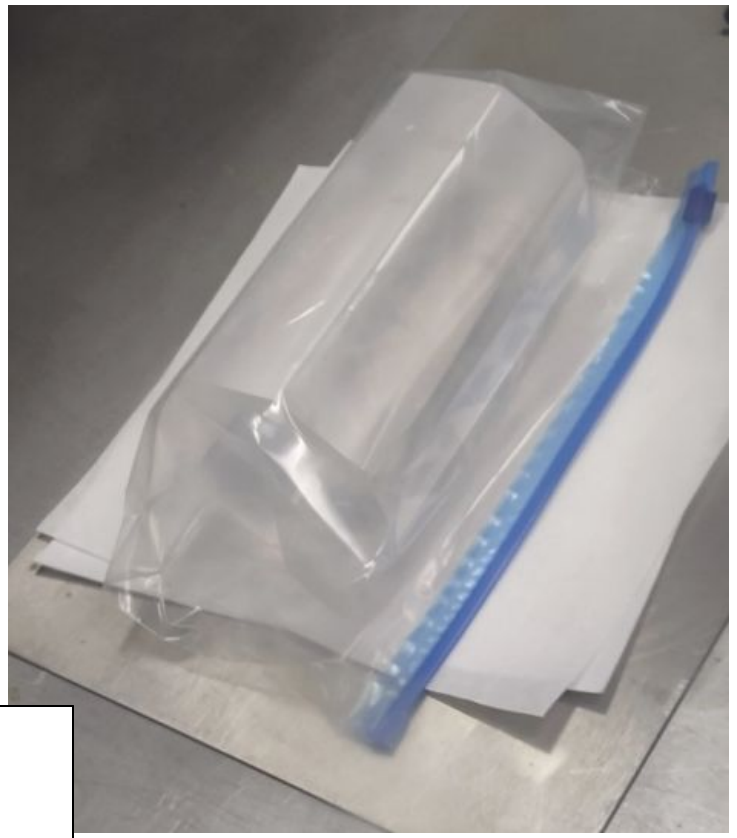
- NaI-33: Background ~1 cpd/kg/keV → at the level of DAMA/LIBRA Phase 1
- NaI-35, NaI-37: Reproducibility of clean growth within factor 2
- NaI-41: grown from chunks rather than powder
- NaI-47: grown out of powder from COSINE-200

NaI-42

The quest for clean powder

SABRE North started a procurement of Astro Grade powder produced by Merck (originally from Sigma Aldrich), however the company was not able to deliver powder with the needed purity.

In the framework of the INFN - IBS Global Research Center agreement, the COSINE collaboration provided powder to SABRE North to continue crystal production.



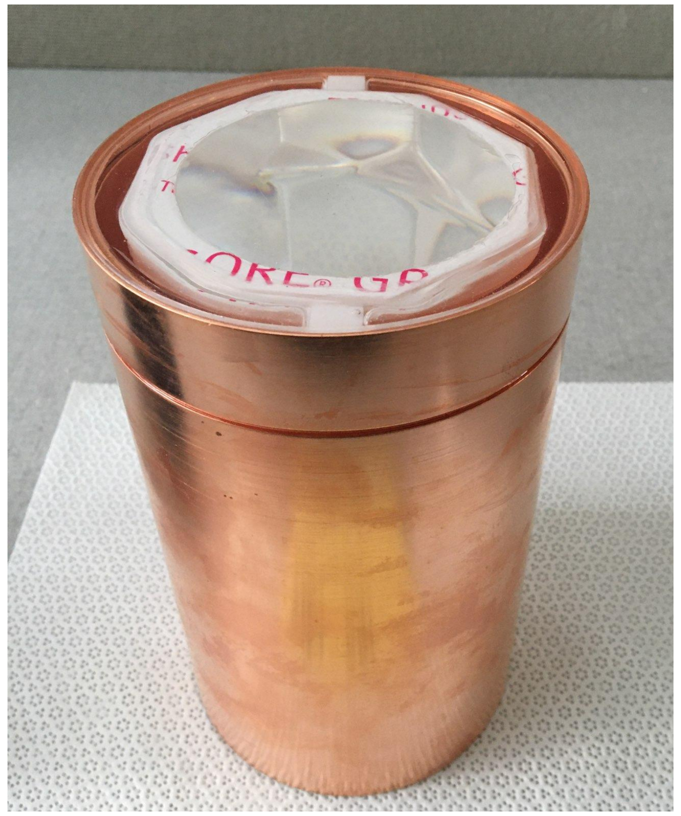
Crystal NaI-47

Powder	^{39}K [ppb]	^{88}Sr [ppb]	^{138}Ba [ppb]	^{208}Pb [ppb]
Cosine powder	6.4	0.1	0.8	0.3
Astrograde (SABRE)	~4-18	0.3	3.6	~1

ICP-MS @ Seastar

Crystal NaI-41

Crystal NaI-41 was grown @ RMD starting from chunks of a previous undoped crystal, named NaI-40 (Astrograde powder).



- Underground since December 2023
- Good scintillation properties: LY = 10.02 +/- 0.03 phe/keV, FWHM @59.6 keV → 15.7%
- α rate 0.49 +/-0.01 mBq/kg

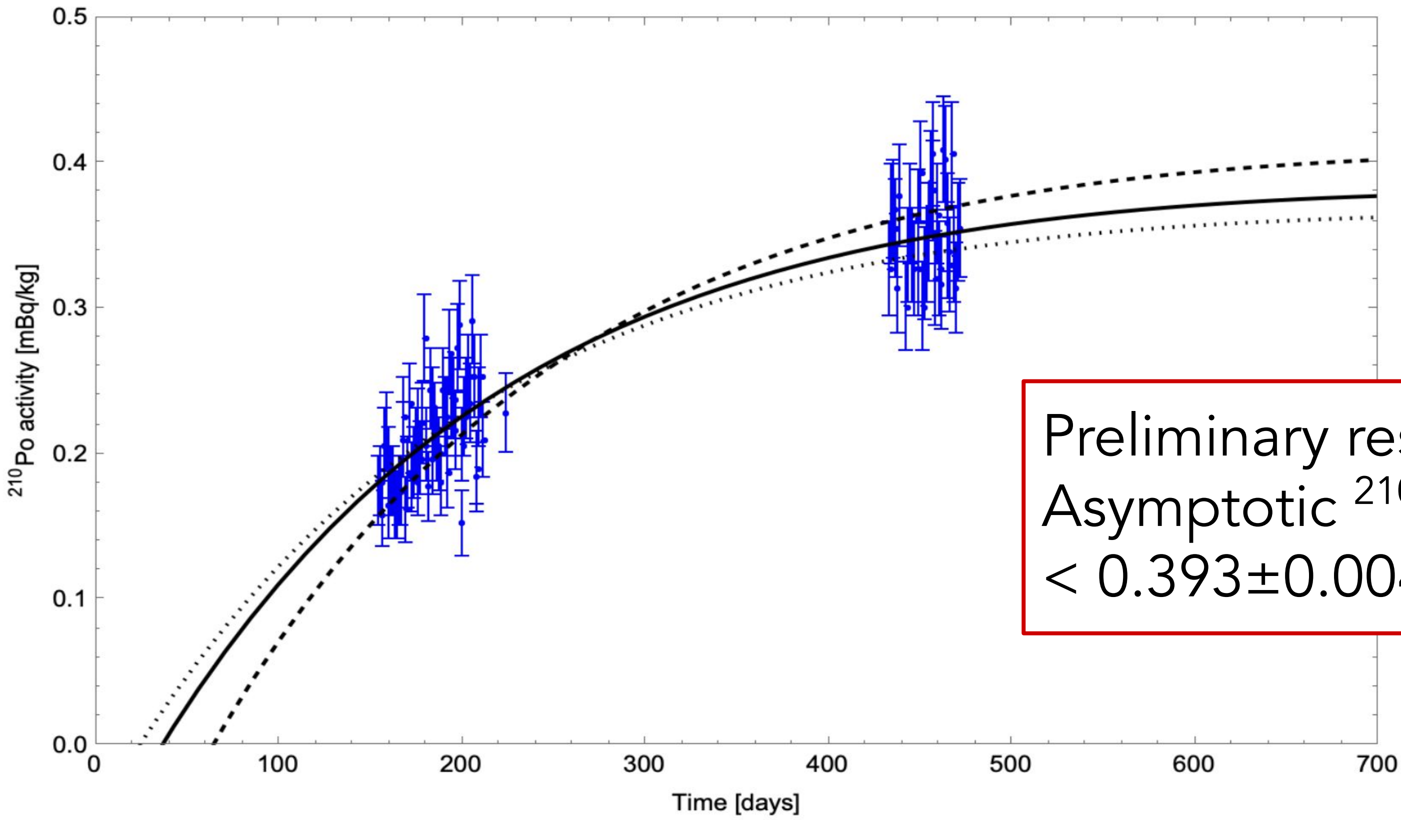
Average potassium contamination in the body of crystal NaI-40: 5.8±0.7 ppb

Compatible with that of NaI-41: the growth process does not introduce potassium contamination.

Crystal NaI-47

Powder from COSINE-200 Collaboration
Final mass: 3.65 kg

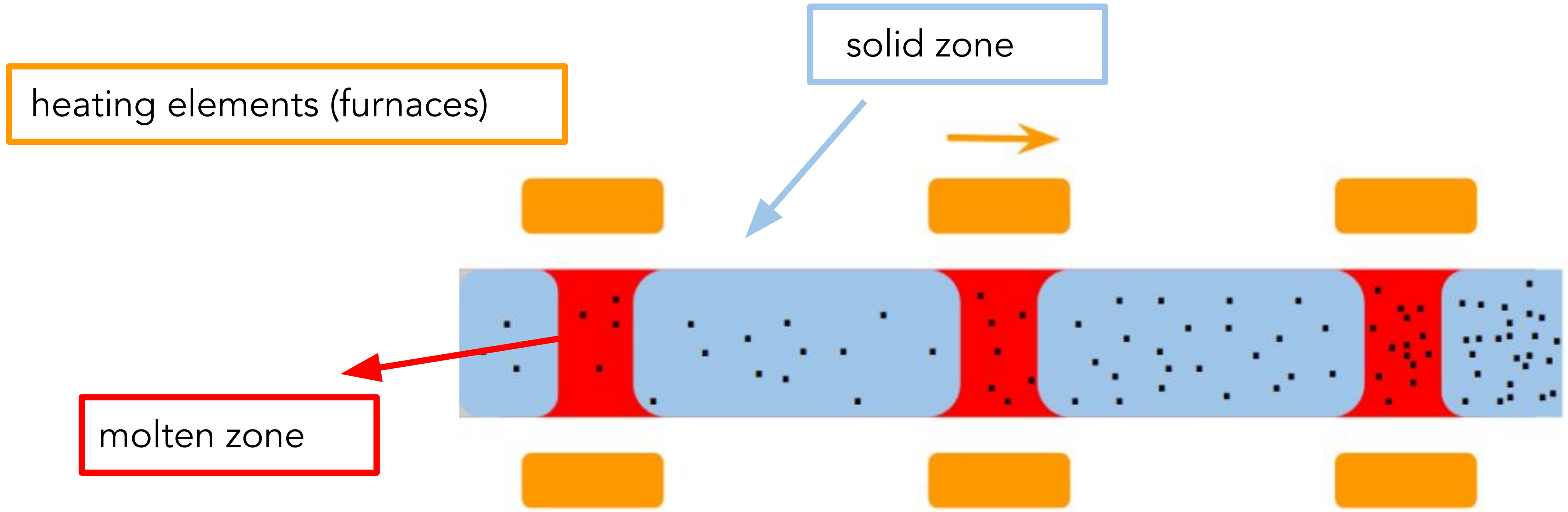
- Solid bold line: zero ^{210}Po activity at t_0 (free par) after growth start
- Dotted line: zero ^{210}Po activity at growth start
- Dashed line: zero ^{210}Po activity at growth end



Preliminary results:
Asymptotic ^{210}Po (from ^{210}Pb) < 0.393±0.004 [mBq/kg]

Adding a step: Zone refining

- Technique successfully used in semiconductor industry
- A narrow region of an ingot is melted, and the molten zone is moved along the crystal's axis
  - The segregation coefficient of an impurity (ratio of the concentration in the solid phase with respect to the liquid phase) is usually less than one
  - Impurities will diffuse into the liquid phase and will be segregated to one side of the ingot by the moving ovens
- The process can be repeated until the desired level of purity is met
- The refined crystal is obtained discarding the end part along with all the impurities



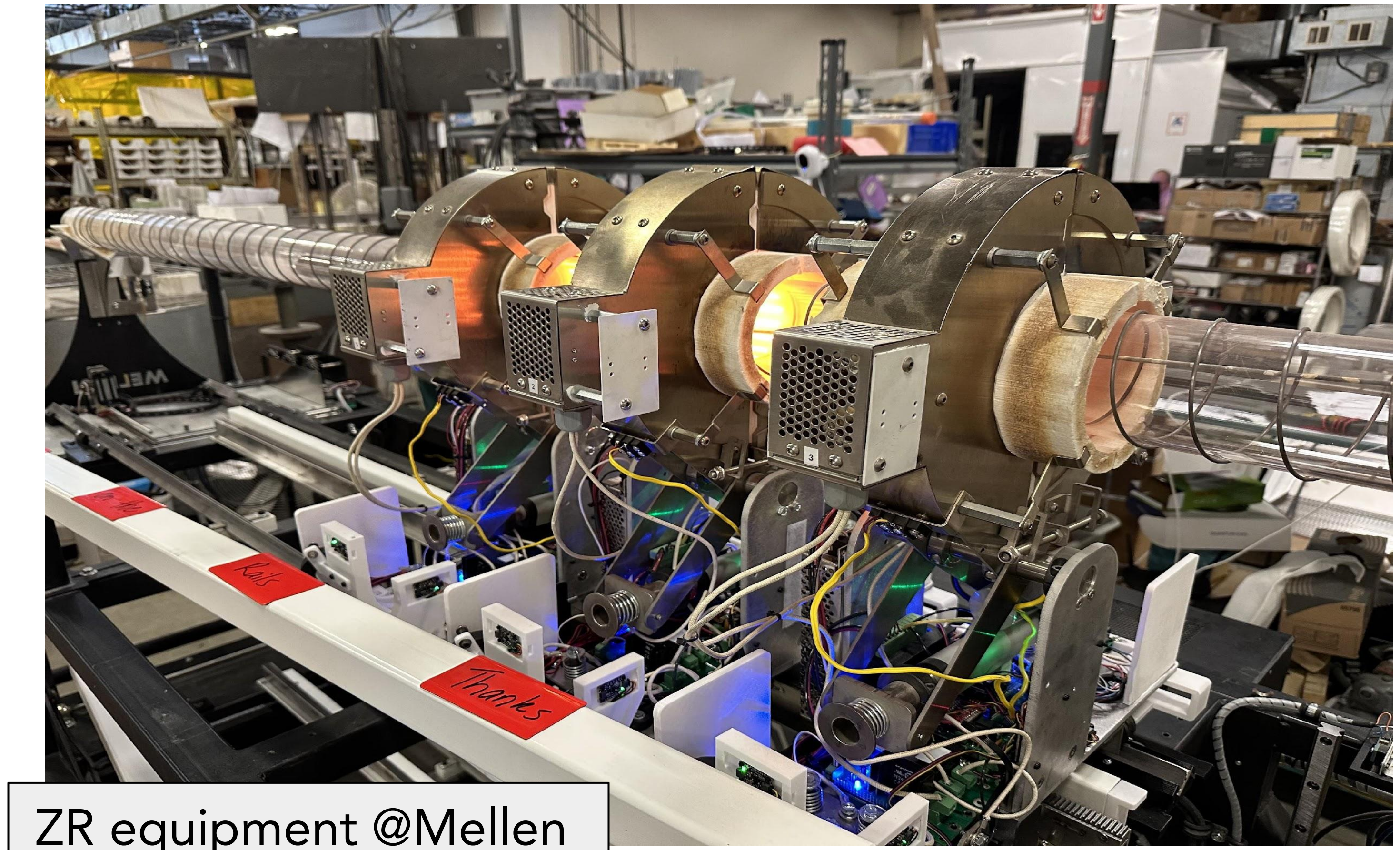
This same technique can be applied directly to an ampoule containing pre-melted NaI powder, to obtain a purified ingot out of which the final NaI(Tl) crystal will be later grown.

Zone refining

Tested on NaI Astro grade powder

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

Phys. Rev. Applied 16, 014060 (2021)



ZR equipment @Mellen

A zone refiner with three furnaces was designed by the SABRE Princeton group in collaboration with our industrial partner MELLEN, NH USA.

Refurbished and upgraded in 2023.

- Unique instrument: large enough for the production of kg size crystals.
- Continuous mode of operation:
  - The three annular furnaces move simultaneously on a motorised track along the ingot and perform multiple zone-refining steps (passes).
- Adjustable speed and number of passes.

Zone refining (2023 - now)

Four runs with 900 gr of Astro Grade NaI powder have been performed at MELLEN from 2023 to 2025.

- Finalized protocol: use of $SiCl_4$ to avoid sticking

Five runs with increasing mass of Astro Grade NaI powder have been performed from 2025 to April 2026.

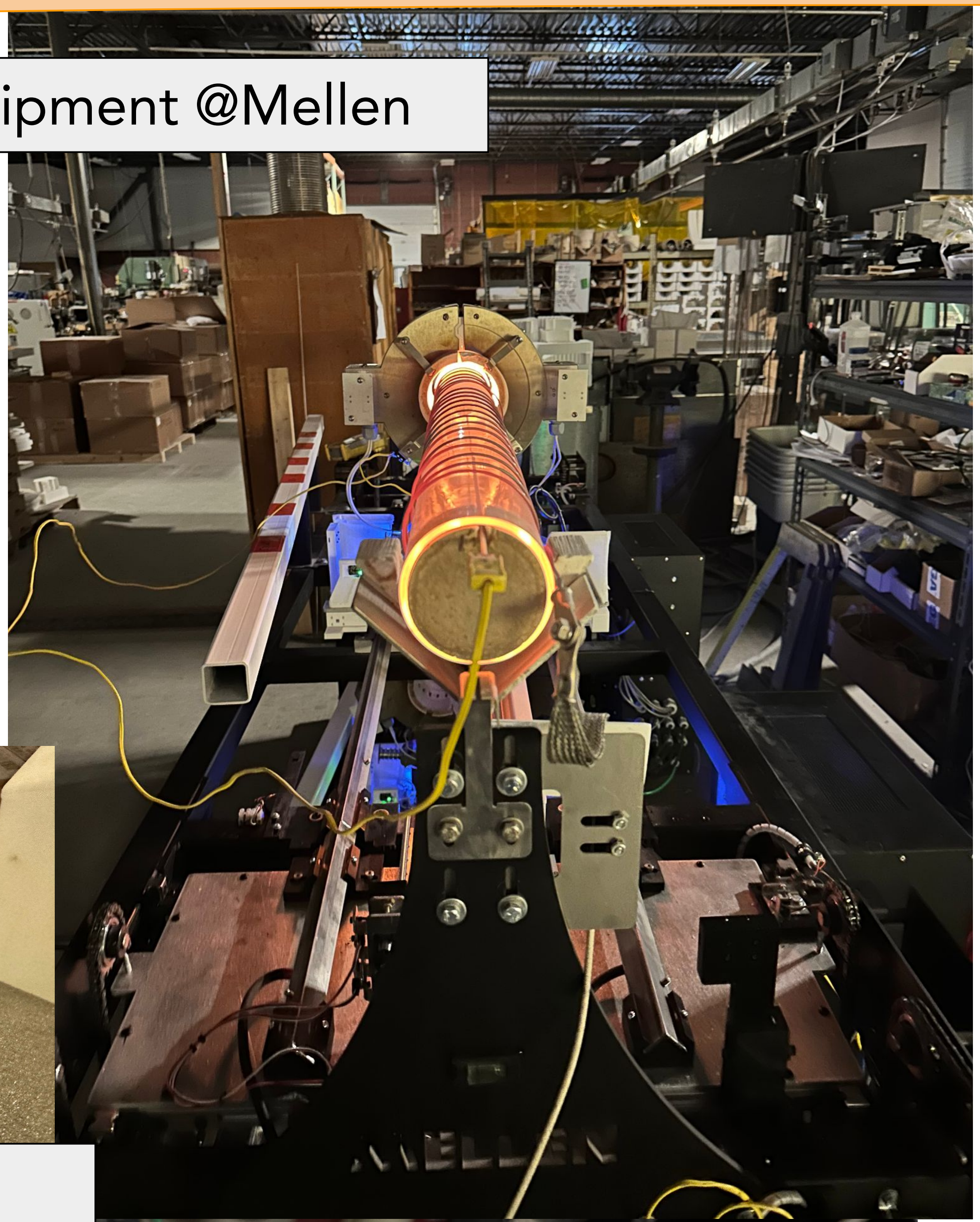
ZR RUN	Mass [kg]	^{39}**K** in powder [ppb]	^{39}**K** after ZR [ppb]
ZR-011	2	6.8	1.6
ZR-012	1.9	8	1.9
ZR-013	2	8	1.9
ZR-014	3	6.8	1.6
ZR-015	3.8	17.7	2.5

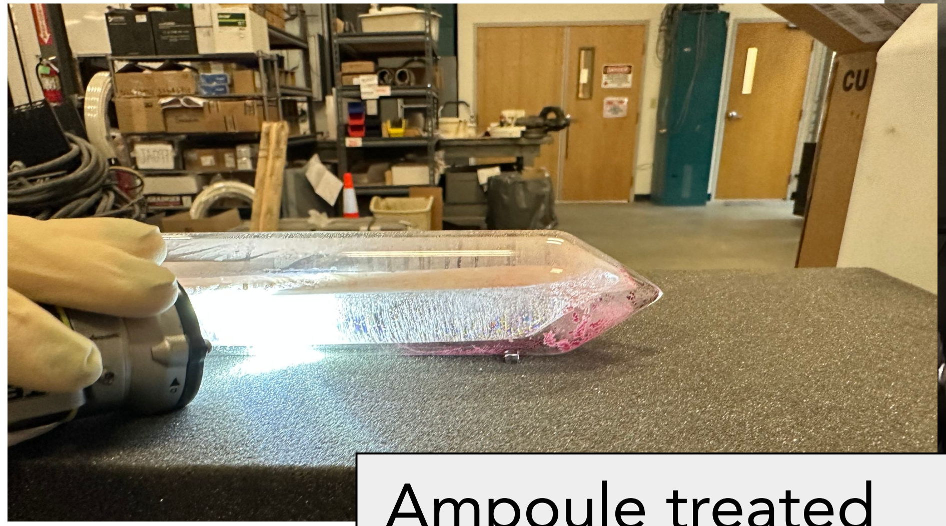
ICP-MS @ Seastar

The zone refined powder has been used for the growth of crystal NaI-42

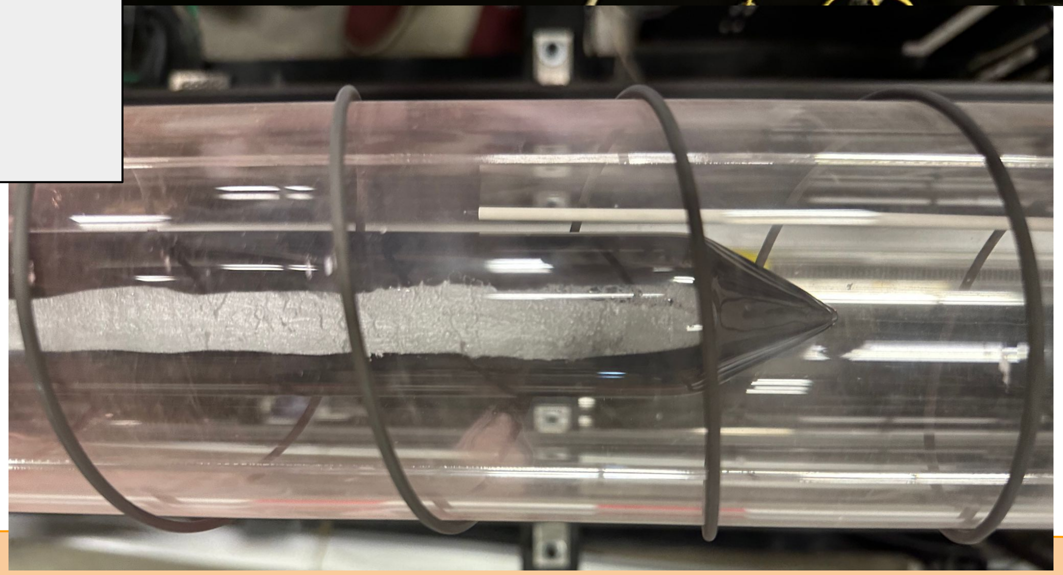
Expected average ^{40}K ~ 2 ppb

ZR equipment @Mellen





Ampoule treated with $SiCl_4$ during and after a ZR

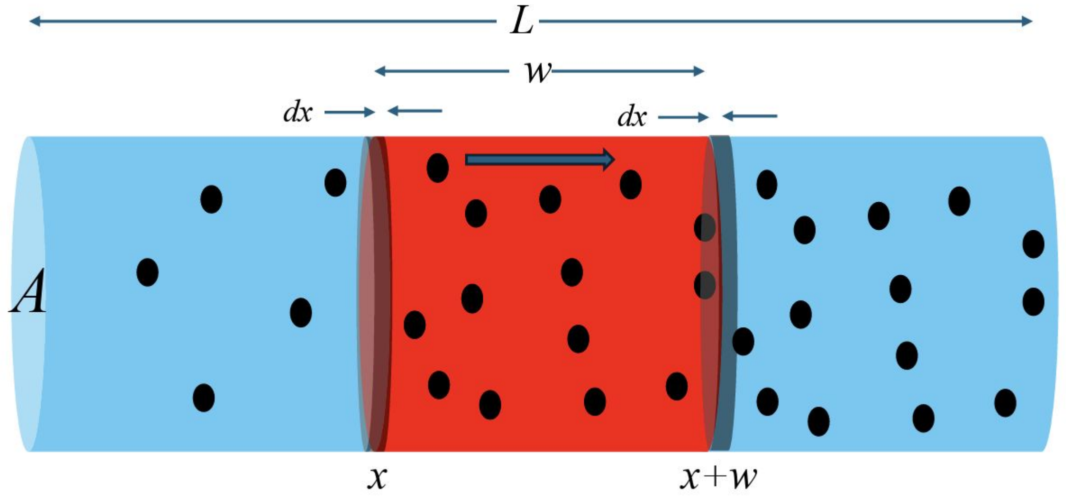


Understanding and optimizing ZR

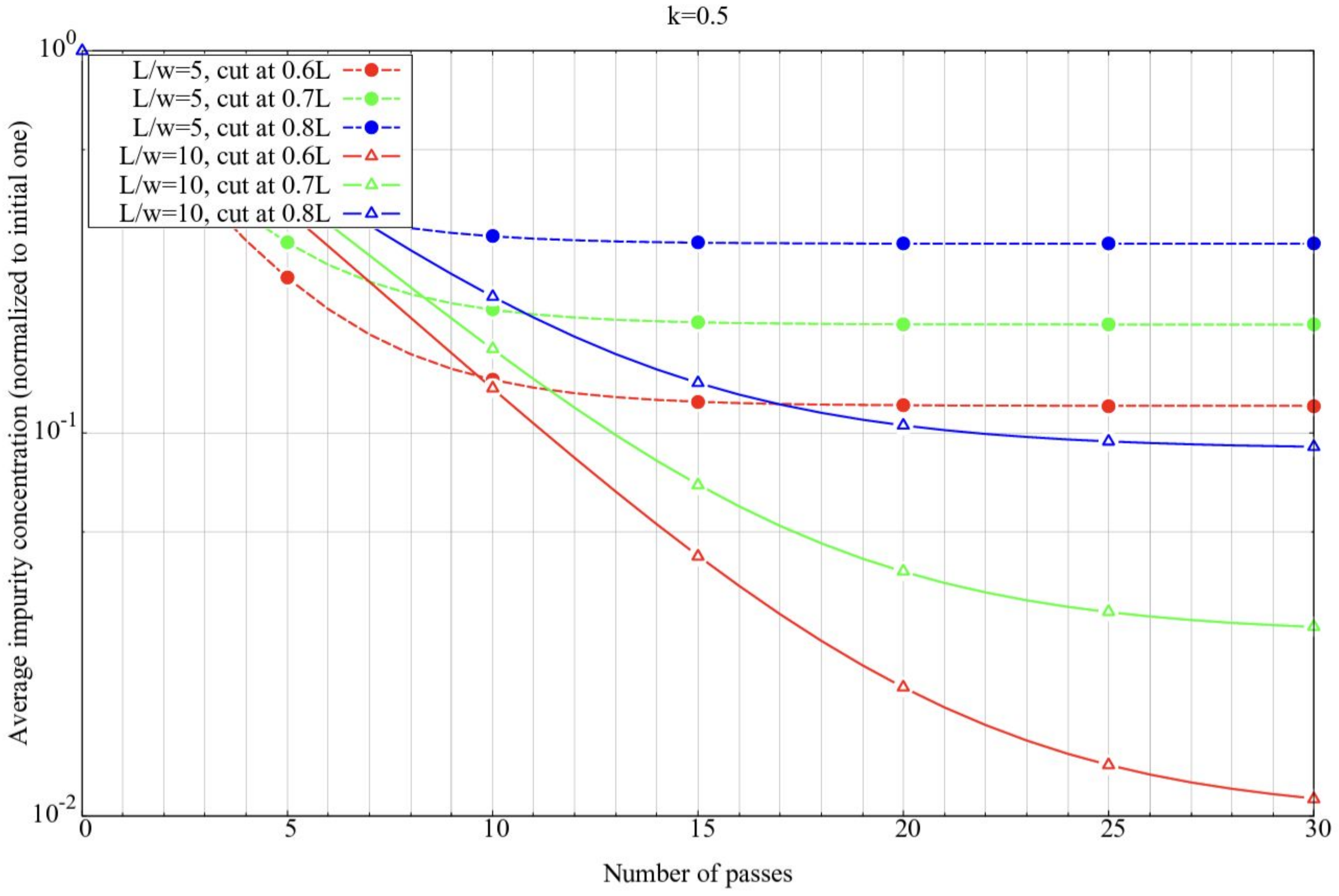
SABRE North developed a mathematical model to describe the ZR purification process:

- distribution coefficients determined for various impurities, by comparing the model to the results of the commissioning and production runs
- for the first time on concentration level at the parts-per-billion (ppb) level
- study of the impurity distribution resulting from ZR when varying the experimental parameters: number of passes, L/w in the ampoule, etc…

SABRE North ZR paper on ArXiv



see poster from Daniele Montanino: *Application of zone refining to the development of NaI(Tl) detectors for SABRE North*



NaI-42: full test of the ZR-based growth of SABRE North crystals

NaI-42 is the first SABRE North crystal, entirely grown out of ZR NaI powder (Astrograde)

The C-coated growth ampoule was filled with 9052 g of chunks from zone refined powder + 39 g of zone refined TlI (0.4%)

growth started at RMD on April 14th

Crystal is ready as of May 28th

SABRE North facilities @LNGS

- New SABRE North experimental between Hall B and Hall A
  - Copper passive shielding for crystal testing, enclosed in a anti-radon box
- Glovebox facility for NaI(Tl) crystal handling

Shielding for crystal testing

SABRE North

SABRE glovebox

SABRE North status

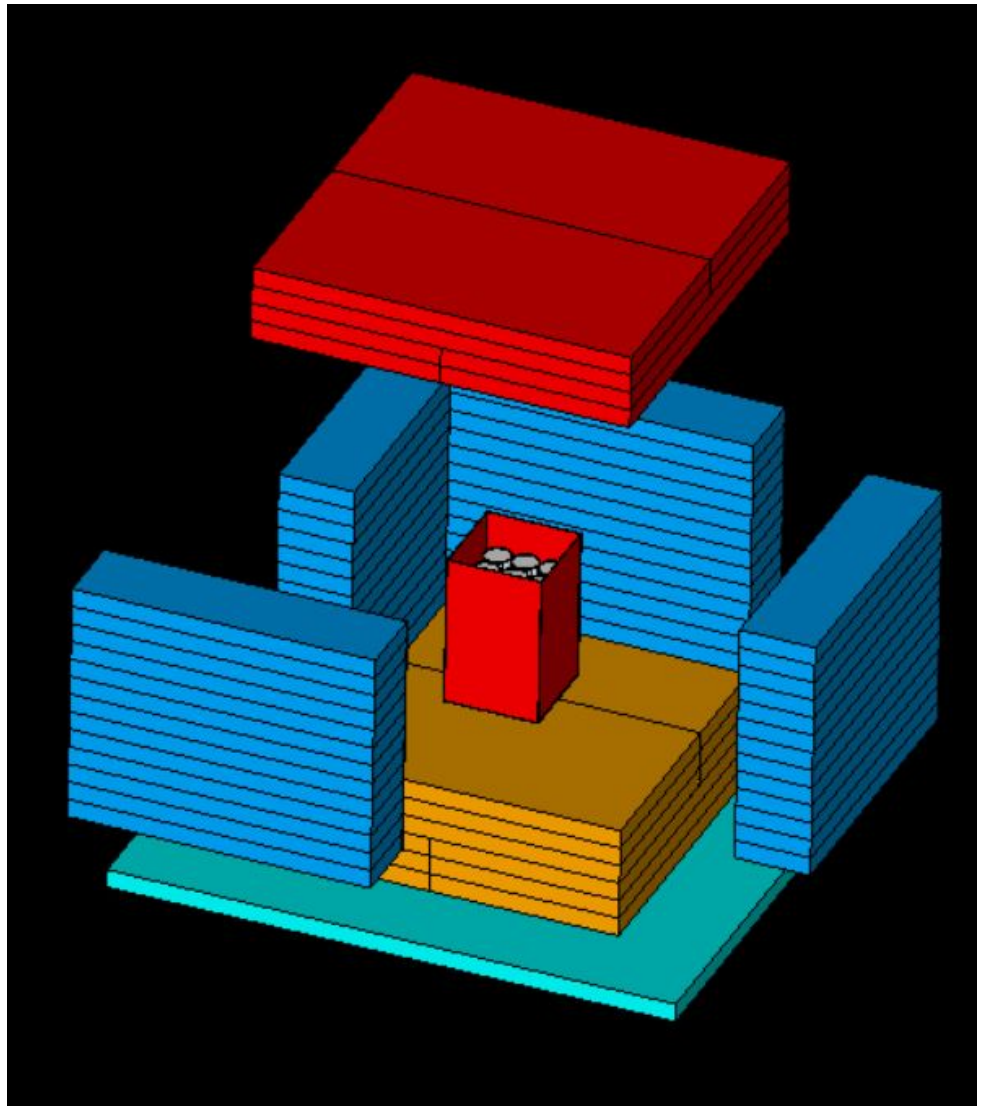
Milestones

- Conceptual design report presented in July 2021
- TDR presented in summer 2024
- TDR approved by INFN CSN2
- NaI-42 crystal ready: the first full size crystal of the SABRE North array
- ZR of new powder in progress for future growths

The SABRE North apparatus

- 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)

The DESIGN: 3x3 NaI matrix
15 cm copper shielding
40 (60) cm polyethylene lateral and top (bottom)



Remembering Frank Calaprice

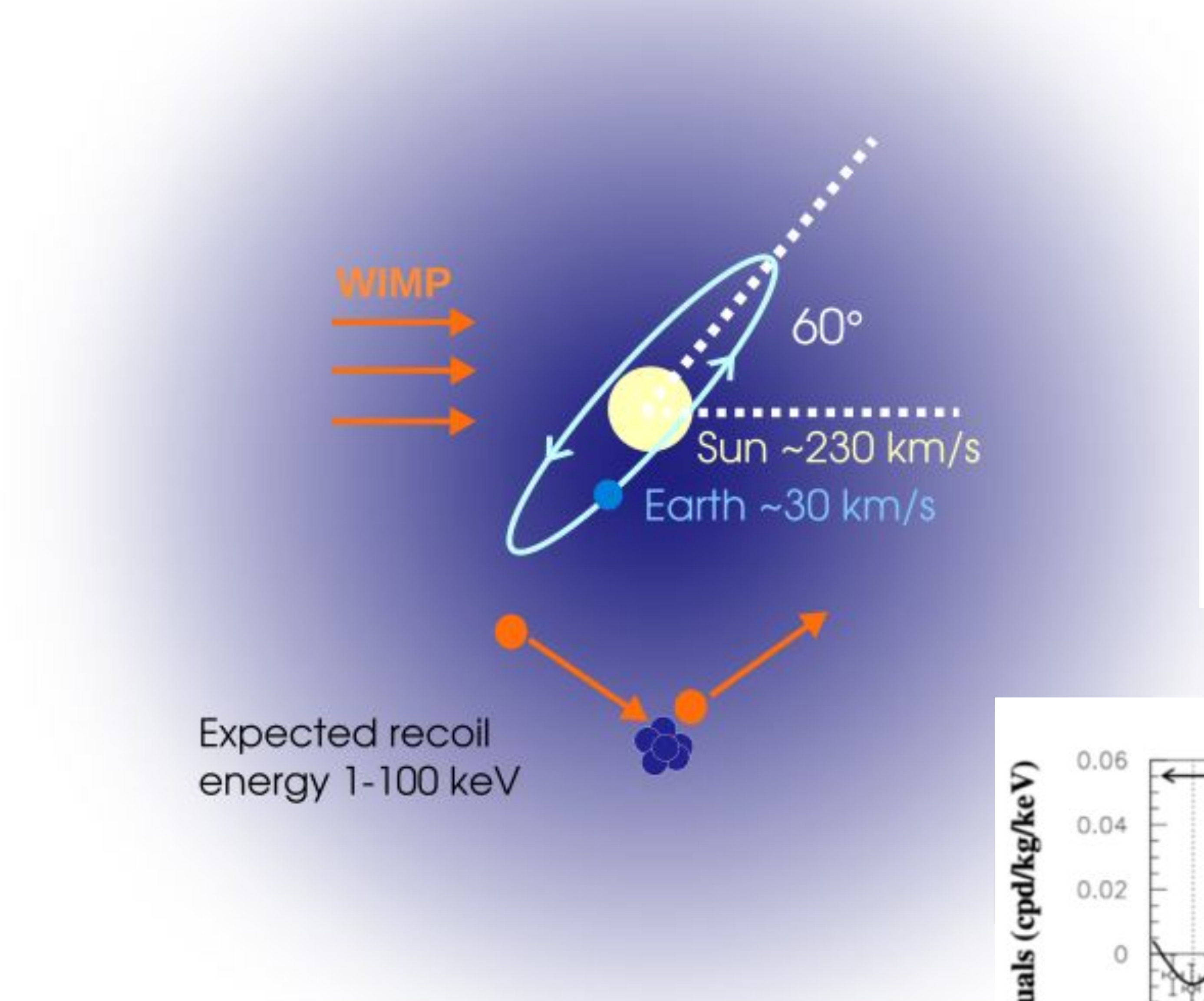
The Frank Paul Calaprice Memorial
took place on Friday 29 May 2026
at Princeton University

The SABRE collaboration remembers the invaluable contributions of Professor Frank Calaprice, who played a fundamental role in shaping the SABRE experiment.

Extra slides

Dark Matter with annual modulation

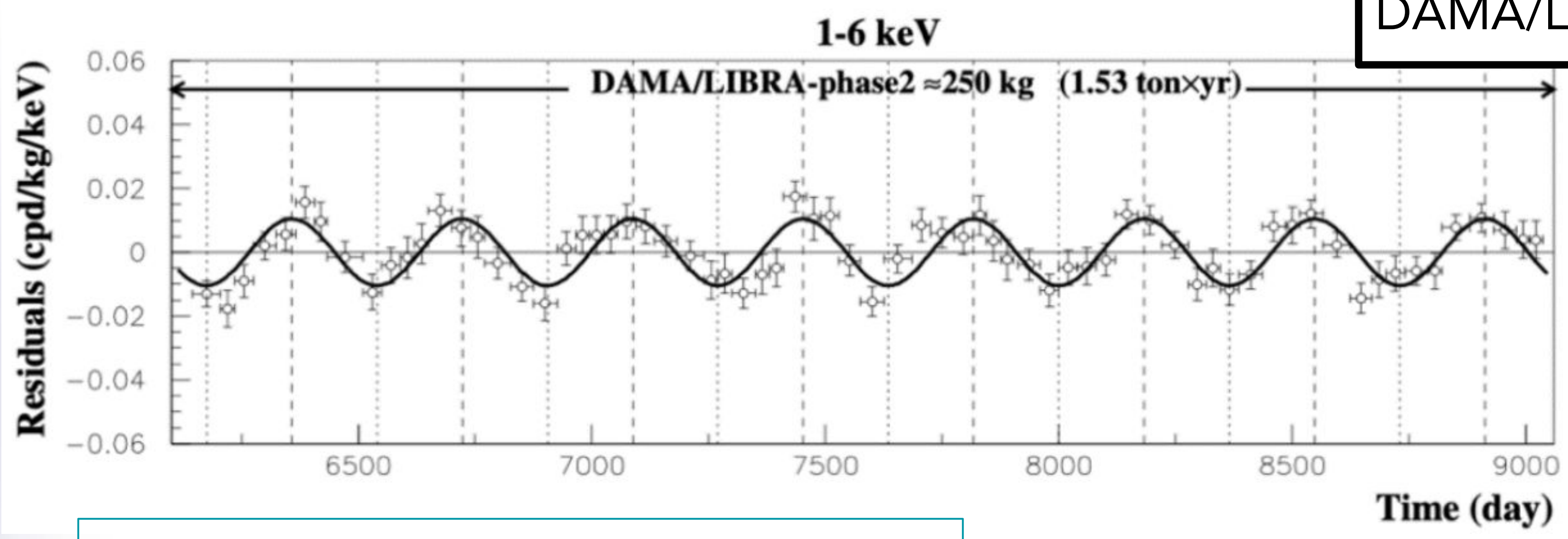
$$R = S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$



The modulation observed by DAMA/LIBRA satisfies the criteria expected of a DM-induced signal.

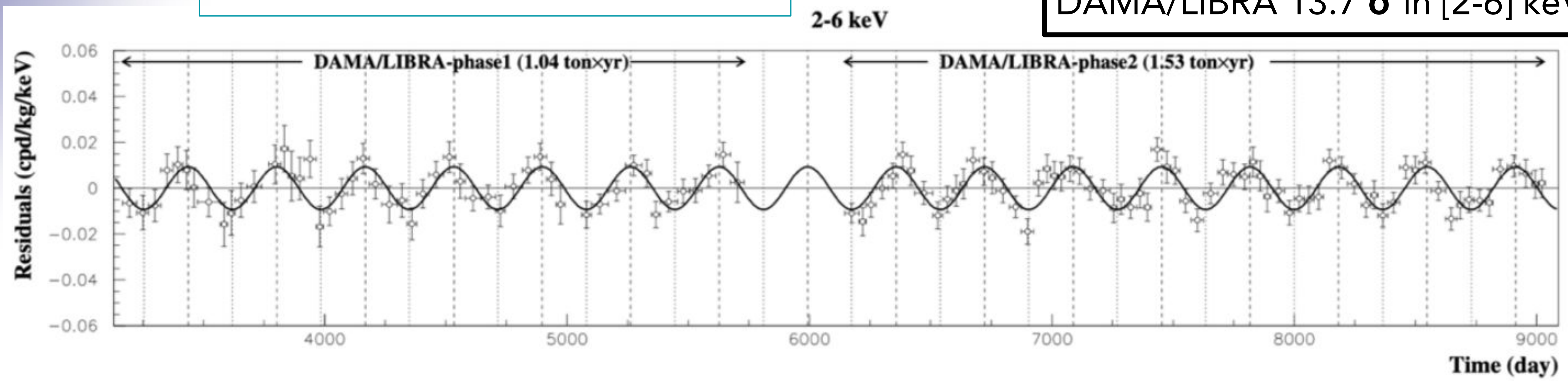
- Expected rate in an Earth-based detector is modulated
- Small modulation fraction S_m/S_0 = O(~few %) on a background at the level of 1 cpd/kg/keV (1 dru)
- Region of interest [1-6] keV

DAMA/LIBRA 11.6 **σ** in [1-6] keV



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

DAMA/LIBRA 13.7 **σ** in [2-6] keV



Zone refining preliminary results

Sample Run4	^{39}K [ppb]	^{65}Cu [ppb]	^{85}Rb [ppb]	^{133}Cs [ppb]	^{138}Ba [ppb]	^{208}Pb [ppb]
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

Clear segregation visible for Potassium and Rubidium (both contributing to background in the DM ROI).

The results on Pb may seem to indicate a contamination during the handling of the material.

Credits to Laura Cid-Barrio and the Canfranc ICP-MS lab for the extensive measurement campaign!

Understanding Zone refining

Values of f_{pur} for the six contaminants previously analyzed for the best fit value of k (1σ range uncertainty in k)

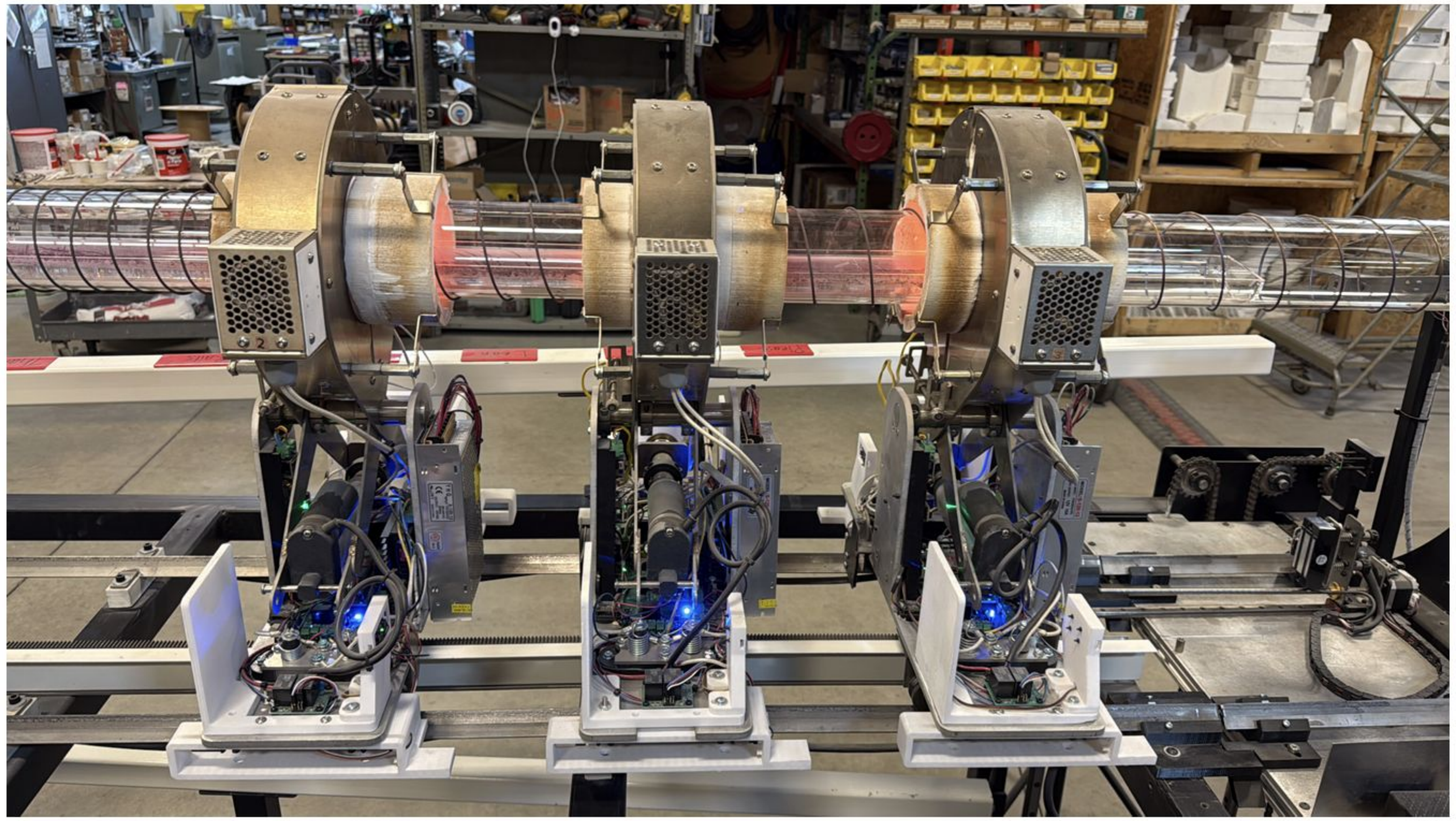
Since also the value of C_0 is uncertain, we show the value of C_{bar} for the best fit values of k and C_0 and the maximum and minimum values varying (k, C_0) in the 1σ allowed zone in the parameter space.

	^{138}Ba	^{44}Ca	^{39}K	^{24}Mg	^{208}Pb	^{88}Sr (RUN2)
$f_{\rm pur}$, best $k \in 1\sigma$ range	0.06 0.03÷0.14	1.21 1.20÷1.22	0.24 0.13÷0.31	1. 0.94÷1.04	1.1 1.08÷1.13	1.23 1.22÷1.24
$\overline{C}$, best (ppb) $(k, C_0) \in 1\sigma$ allow.	0.018 0.008÷0.036	45.1 38.6÷51.7	1.55 0.64÷1.80	1.97 1.76÷2.0	1.98 1.78÷2.18	0.61 0.61÷0.62

TABLE VIII. Coefficient of purification and final average concentration of contaminants for 80% cut initial part of the ingot. For ^{88}Sr we have used only the RUN2 data.

Glove box @ RMD
recently upgraded with recirculation system, dehumidifier, and sensors (T, P)

Wavefront Zone Refiner @ Mellen



Radiopurity of NaI powder

	DAMA-NaI (Saint Gobain)	DAMA/LIBRA (Saint Gobain)	SABRE - Astrograde (Merck)
^{238}U	0.56±0.04 ppb	0.02 ppb	<0.07 ppb
^{232}Th	0.21±0.01 ppb	0.02 ppb	<0.08 ppb
^{nat}K	<4.8 ppm	<0.1 ppm	~3-10 ppb
^{85}Rb			< 0.4 ppb
^{208}Pb			~1 ppb

Astrograde vs DAMA

For Dama-NaI
https://link.springer.com/article/10.1007/BF03035868

For DAMA/LIBRA:
https://doi.org/10.1016/j.nima.2008.04.082

SABRE CRYSTALS

Astrograde vs itself

variability in the powder batch

	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-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

*NaI-41 still affected by cosmogenics

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/cm² (spectral fit)	0.8-1.6 μBq/cm² (from ^{210}Po)	~ 3 mBq/detector for D3 and D4	~ 1 μBq/cm² (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	

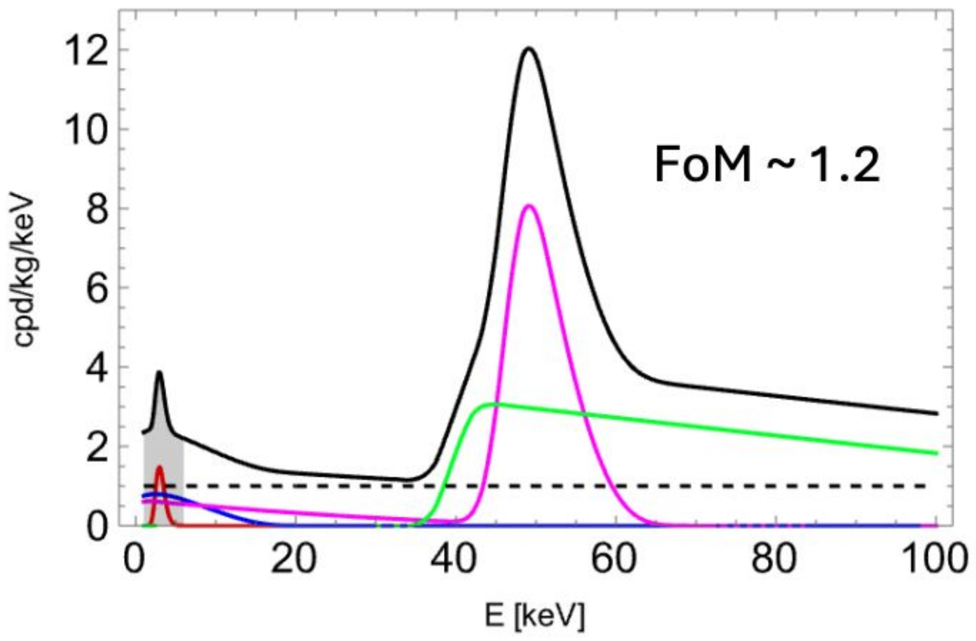
Internal backgrounds in NaI(Tl) crystals

The case of ^{210}Pb:

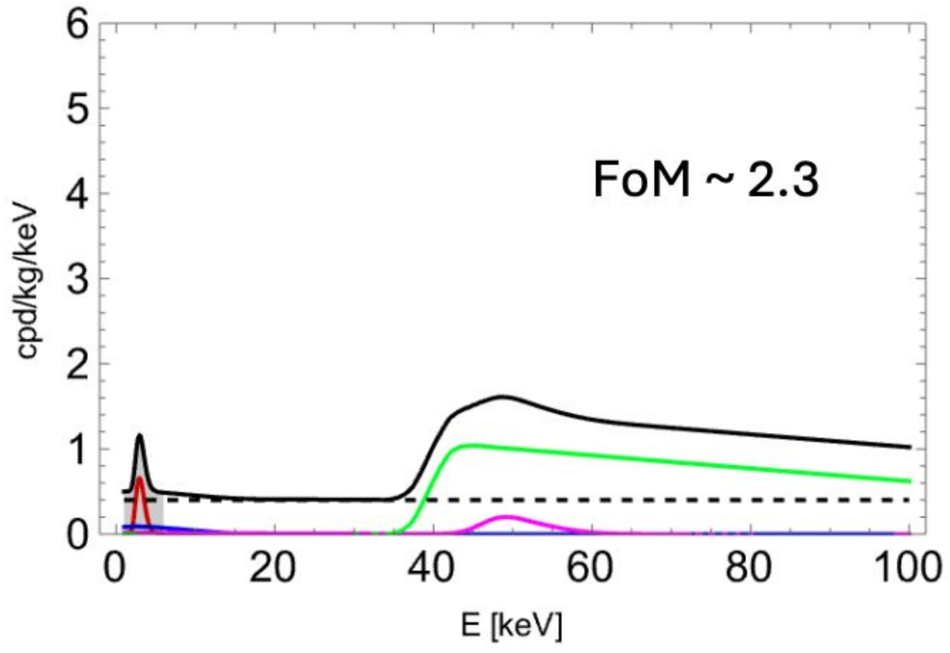
- it can originate from the crystal bulk or it can be implanted on the surface from the ^{222}Rn decay chain
- it can be present in the reflector around the crystal
- the contribution to the background in the ROI depends on the depth distribution

The case of ^{3}H:

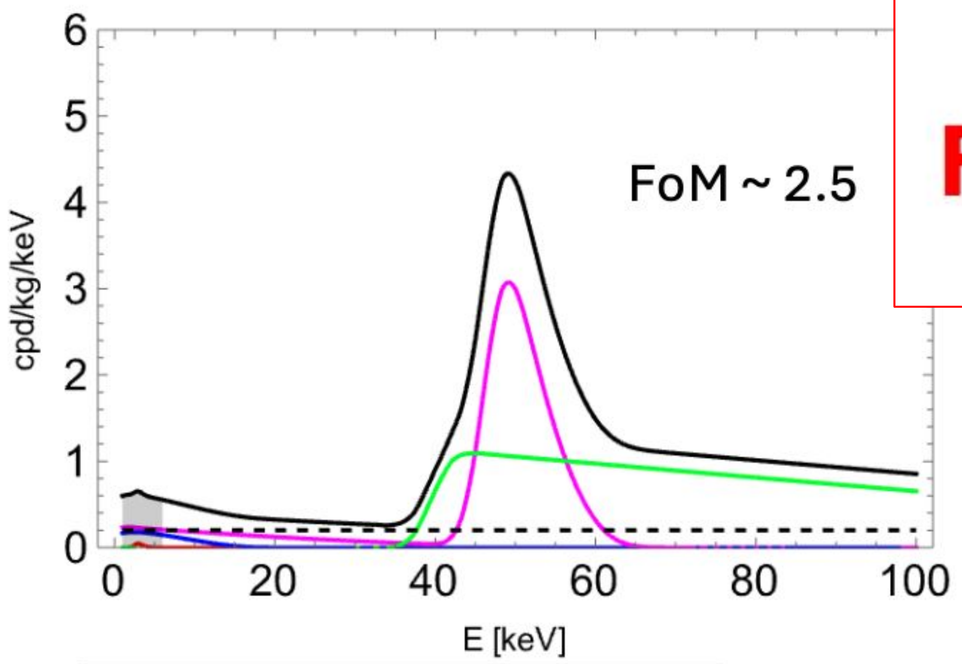
- relevant background source in the ROI
  - pure beta emitter with Q = 18.591 keV and $T_{1/2}$ ~ 12 years
- its activity in the crystal depends on the exposure on surface



^{210}Pb ~ 20% (1 mBq/kg)
K ~ 15% (32 ppb)
^{3}H ~ 28% (90 µBq/kg)



^{210}Pb ~ 4% (26 µBq /kg)
K ~ 26% (14 ppb)
^{3}H ~ 12% (10 µBq/kg)



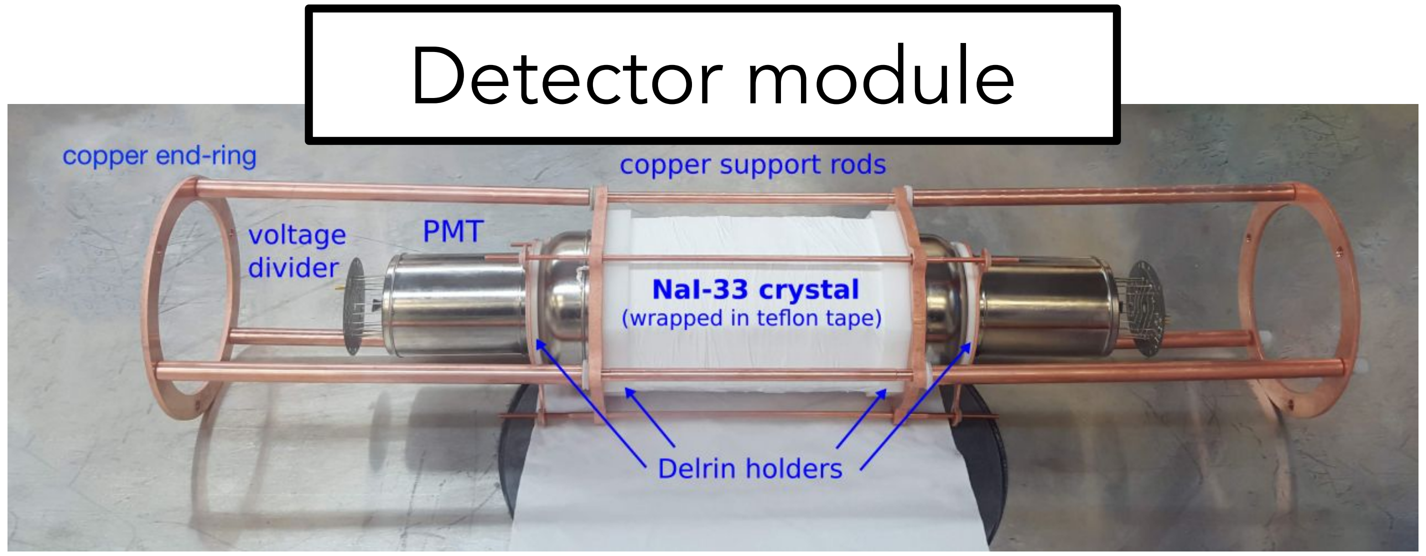
^{210}Pb ~ 37% (0.4 mBq/kg)
K ~ 2% (1 ppb)
^{3}H ~ 28% (20 µBq/kg)

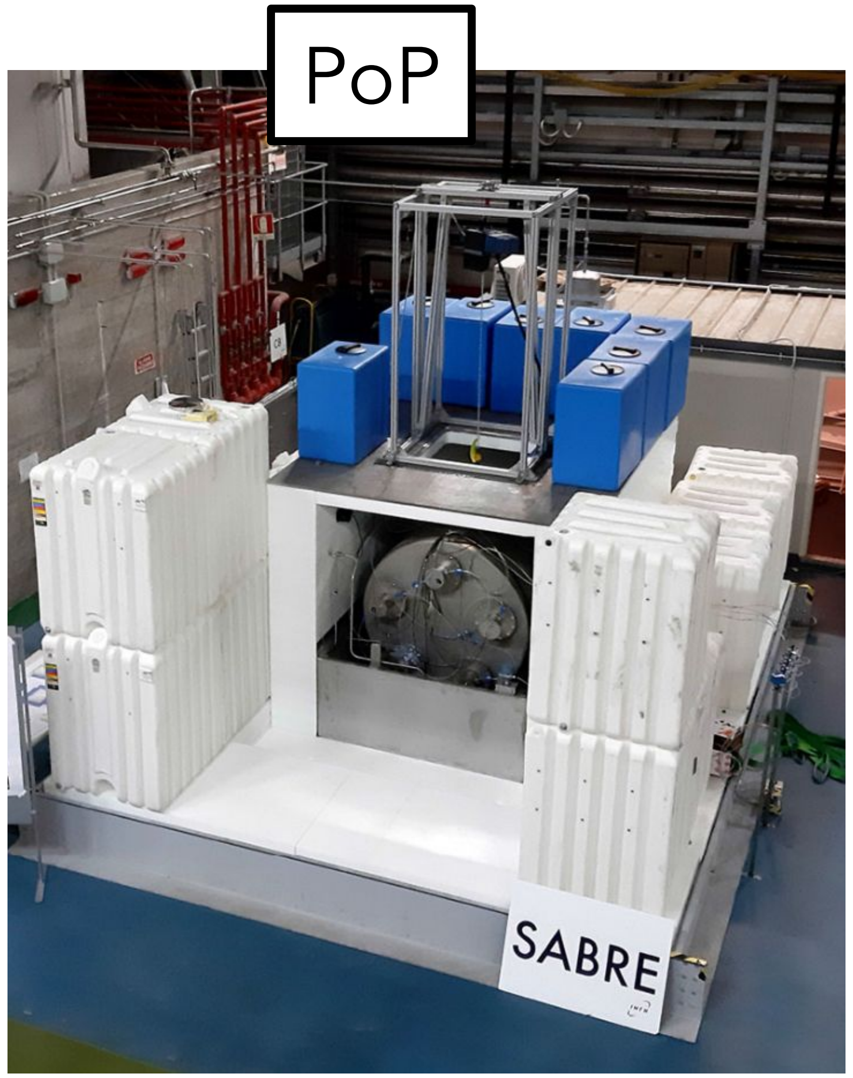
$$\mathrm{FoM} = \frac{S_m}{\sqrt{2}} \sqrt{\frac{M\,t}{S_0+B}}$$

assume an exposure of 1000 kg x yr and Sm = 0.01 dru

credit: A. Ianni - IDM 2024

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



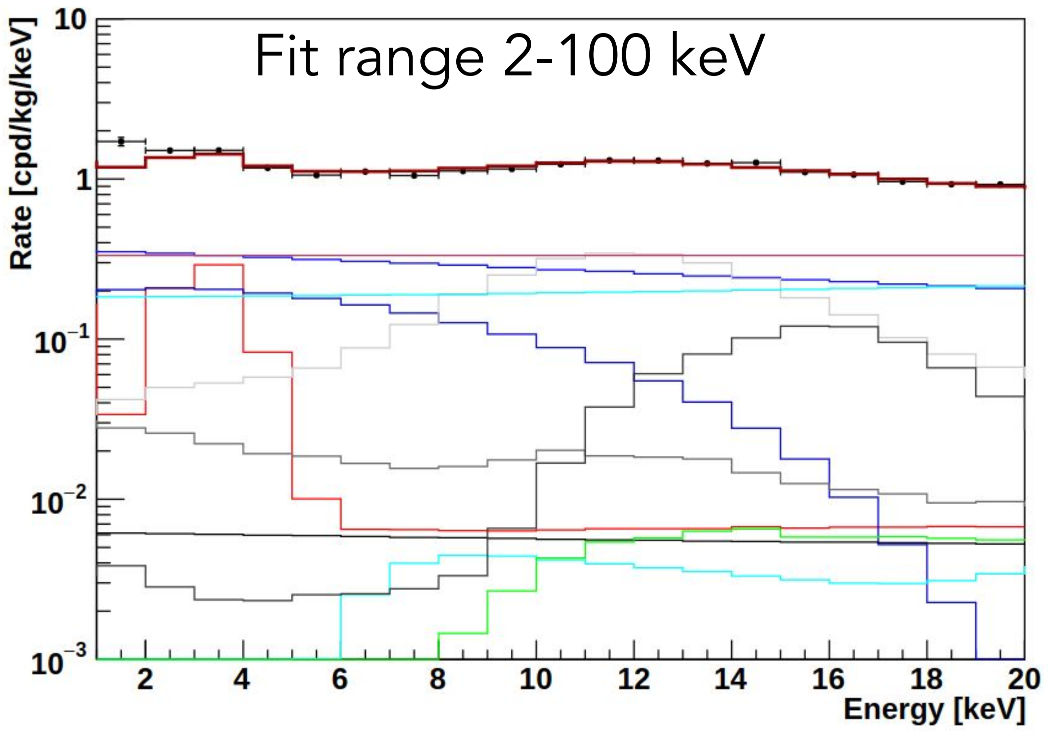


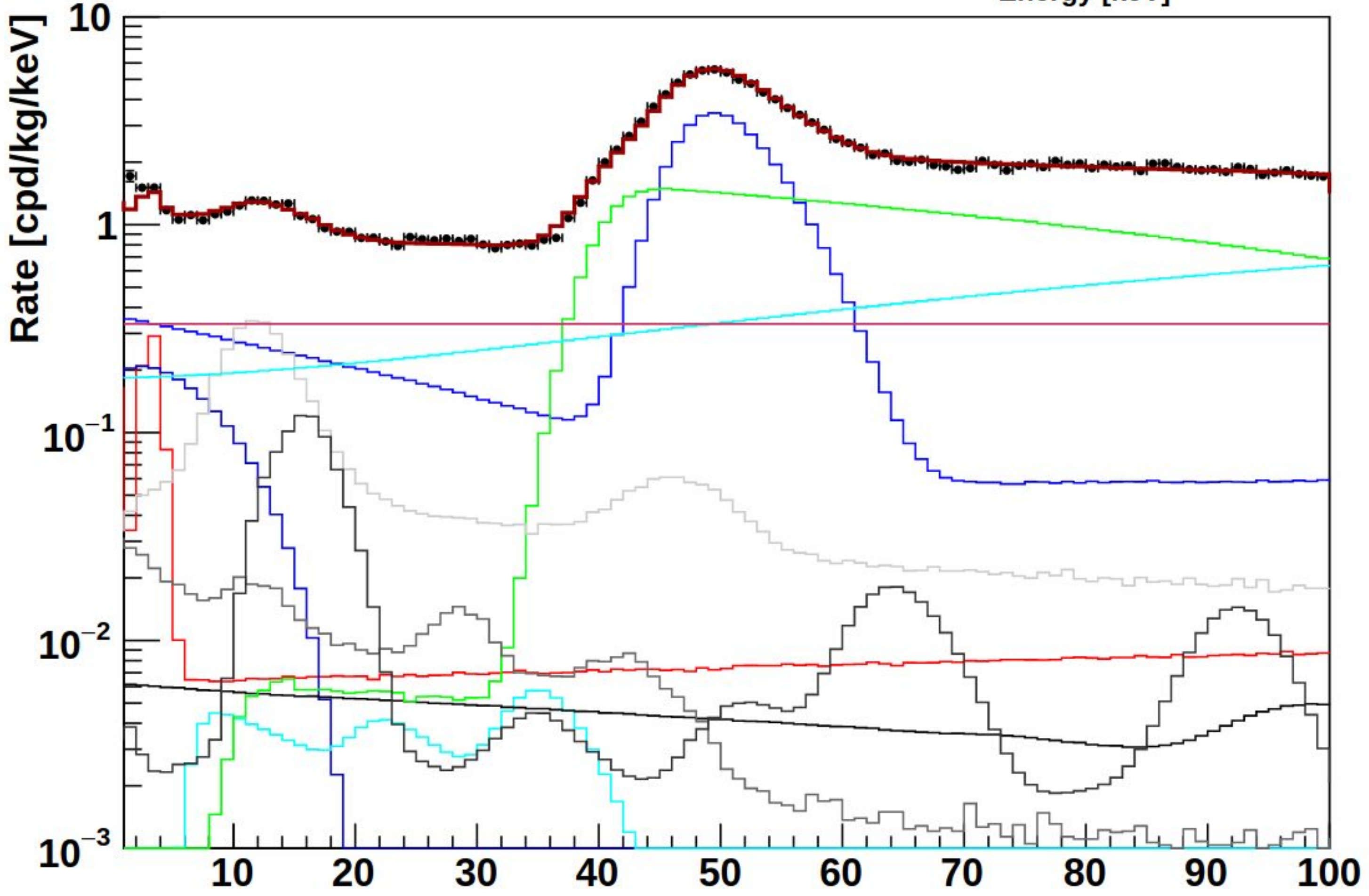
- Run in 2020 with Borexino liquid scintillator and NaI-33
  - 2 tons active veto with 10 8-inch PMTs + H_2O shielding
- Exploited successfully ^{40}K tagging with sensitivity at the level of 1 ppb
- Demonstration by direct counting of first crystal production after DAMA/LIBRA with background in [1,6]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

SABRE 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	

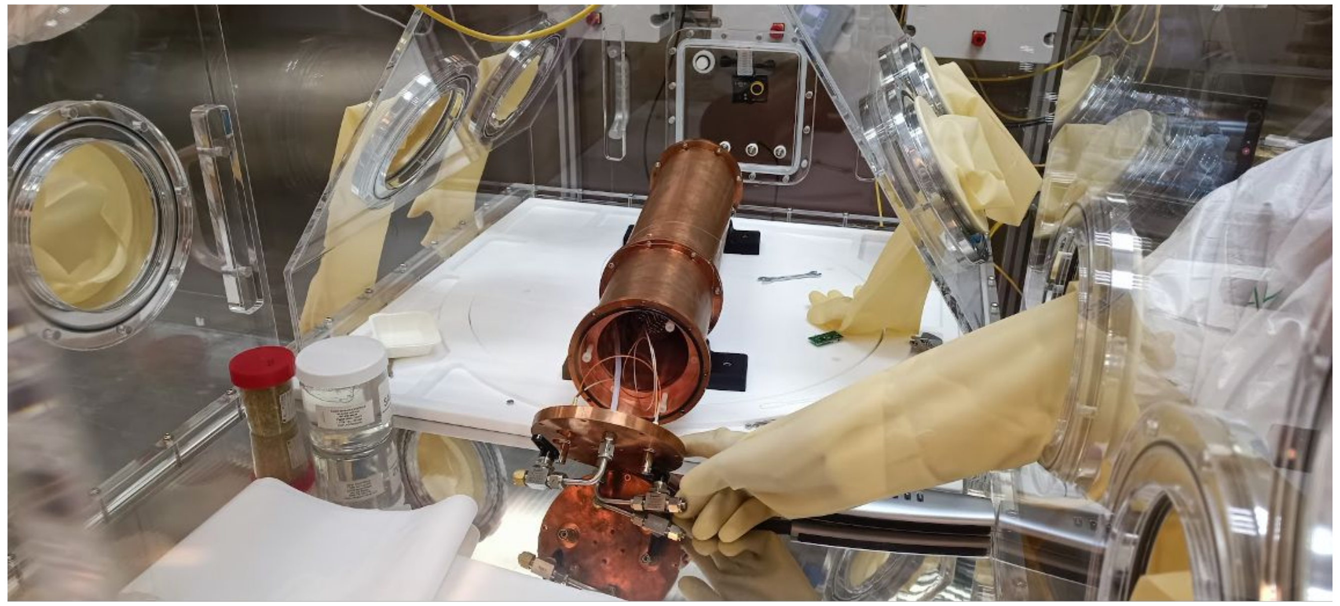


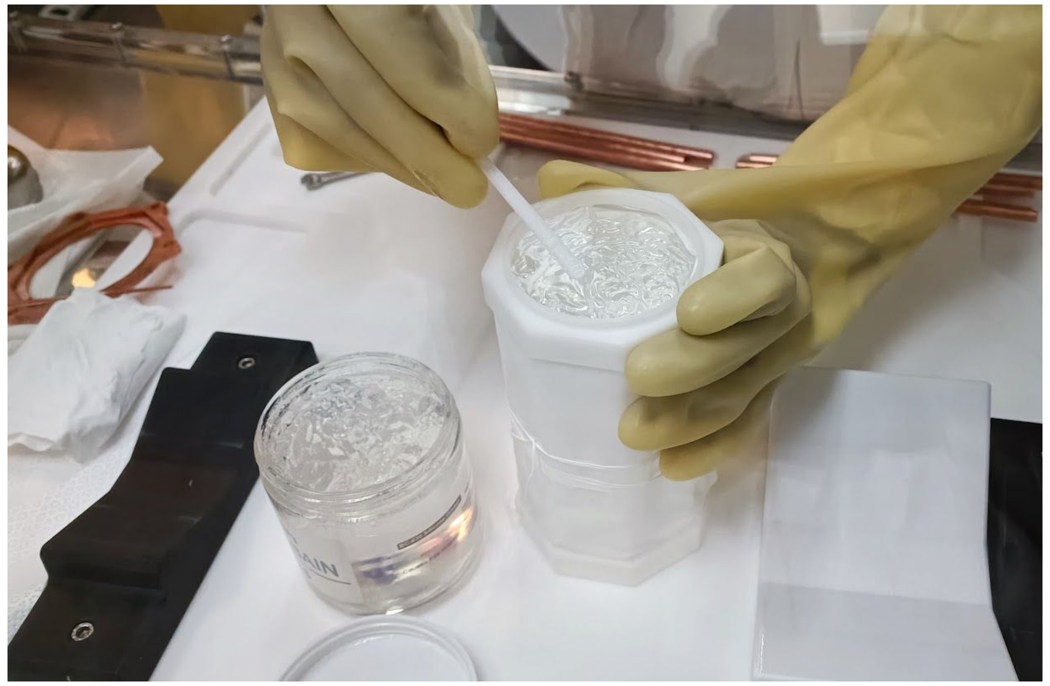


Crystal operations in glovebox 2022-23

- 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

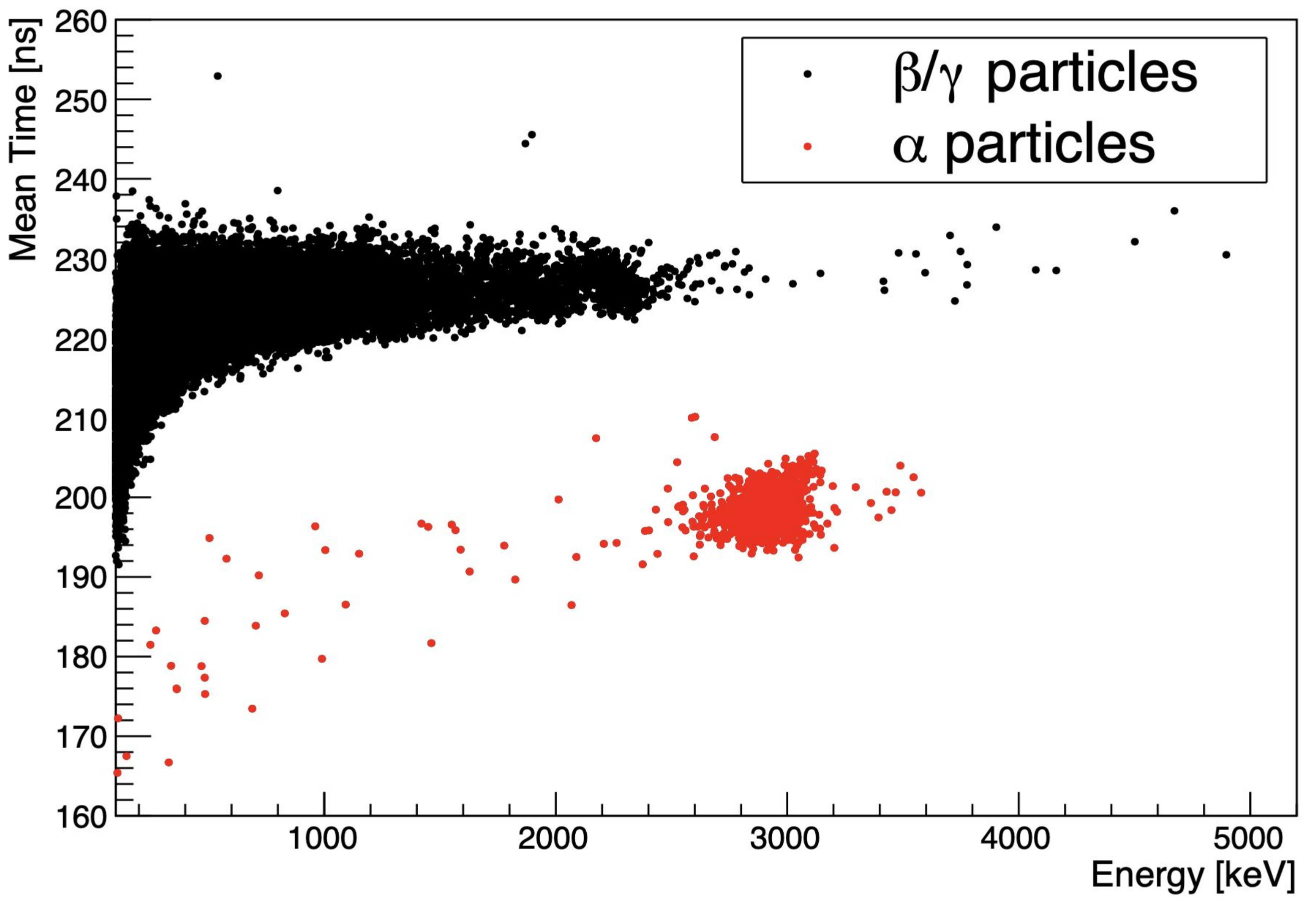
All operations successful and moisture level in the glove-box kept always below 5% RH



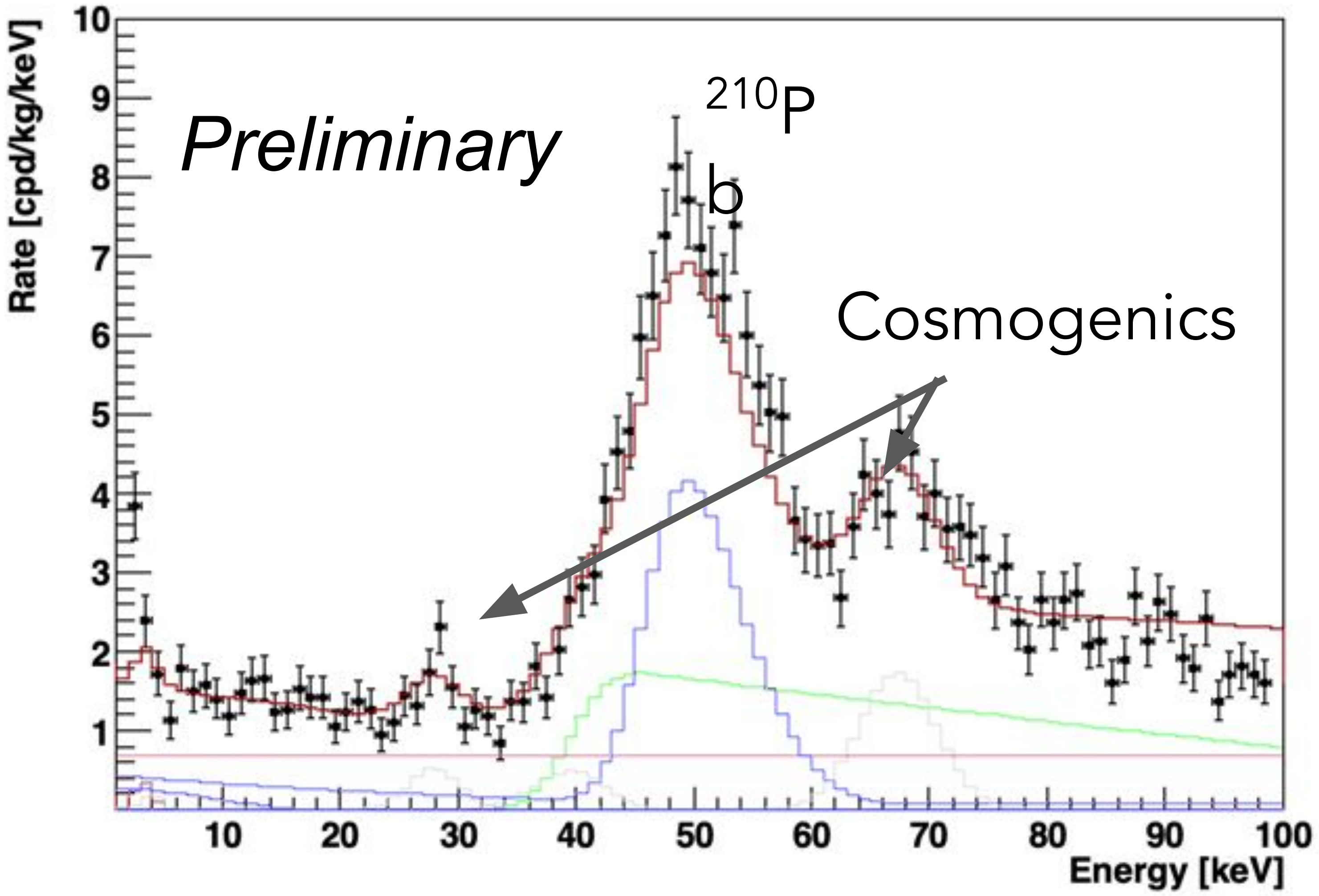



NaI-41

- 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