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

The SABRE North experiment at Gran Sasso Laboratory

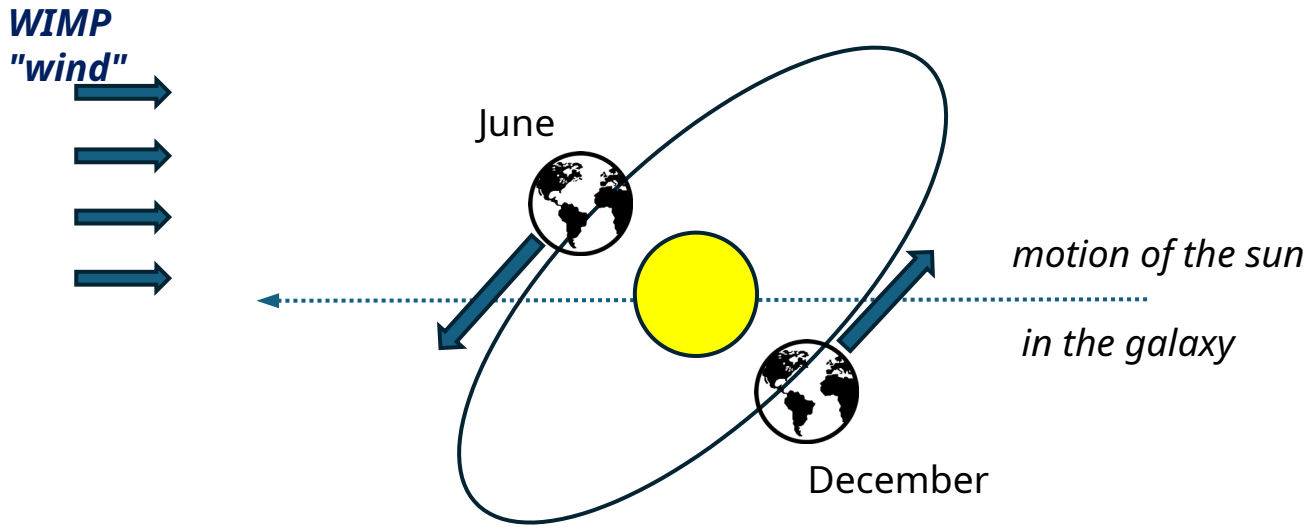
Krzysztof Szczepaniec
on behalf of Sabre North collaboration

TAUP
XICHANG

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

Frank Calaprice passed away on June 30, 2025.

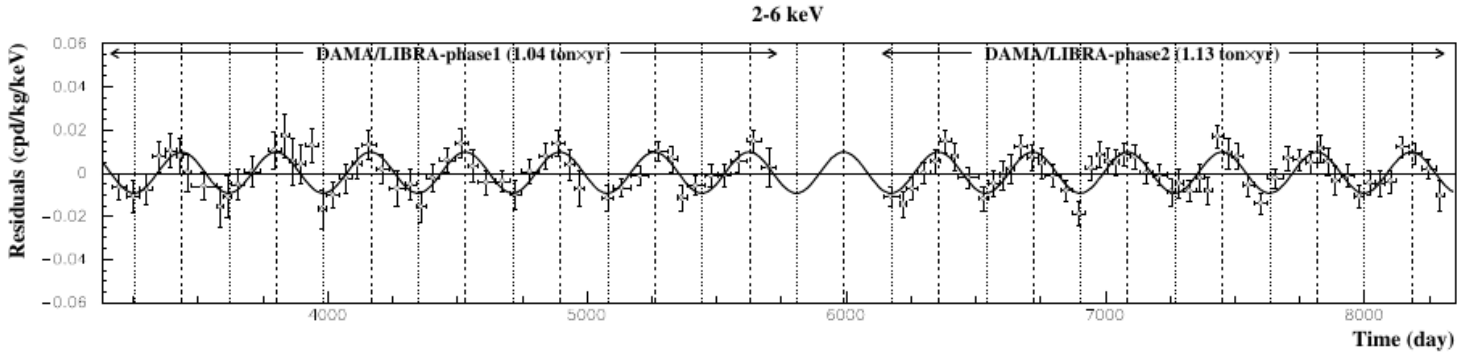
Dark Matter annual modulation



expected event rate
(if we are observing DM)

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

DAMA/NaI + DAMA/LIBRA



2-6 keV

$S_m = (0.0102 \pm 0.0008)$ [cpd/kg/keV]

13.7σ

jnpae2021.04.329

Dark Matter annual modulation

NaI-based detectors aiming to study annual modulation

Experiment	Location	Target	Mass [kg]	Status
DAMA/LIBRA	LNGS	NaI(Tl)	250	stopped
ANAIS-112	LSC	NaI(Tl)	112.5	running
COSINE-100	Y2L	NaI(Tl)	106/61.3	upgrading
COSINE-200	Yemilab	NaI(Tl)	~200	in preparation
SABRE North **SABRE South**	LNGS SUPL	NaI(Tl)	~50 ~50	in preparation
COSINUS	LNGS	NaI	~1	in preparation
PICOLON	Kamioka	NaI(Tl)	~50	in preparation

SABRE

Sodium-iodide with **A**ctive **B**ackground **R**ej**E**ction

GOAL: Model independent test of DAMA claim

-> Use the same material as DAMA

-> With background level lower than DAMA

- Eliminate non-DM effects

- Use ultra-pure NaI(Tl) crystals

SABRE

Sodium-iodide with **A**ctive **B**ackground **R**ej**E**ction

GOAL: Model independent test of DAMA claim

-> Use the same material as DAMA

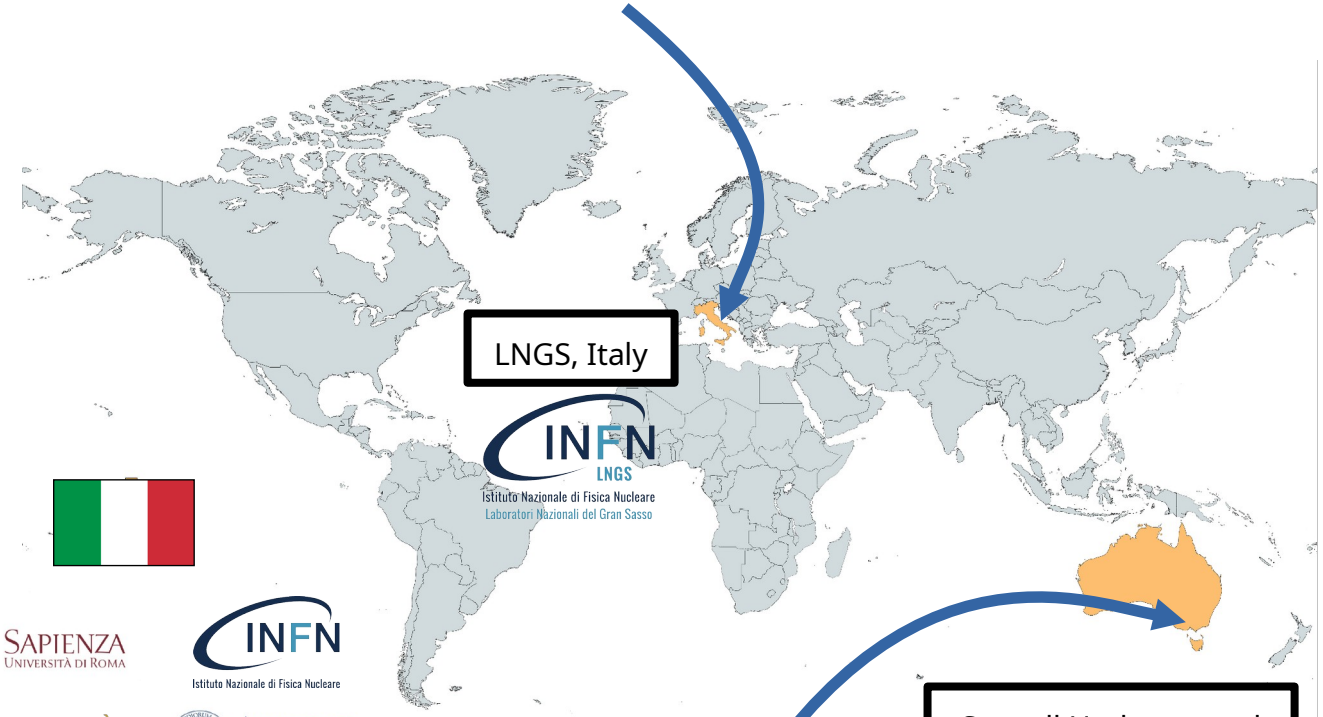
-> With background level lower than DAMA

- Eliminate non-DM effects
  > **Two-site experiment, on two hemispheres**

- Use ultra-pure NaI(Tl) crystals
  > **Use of purified NaI powder to grow crystals**

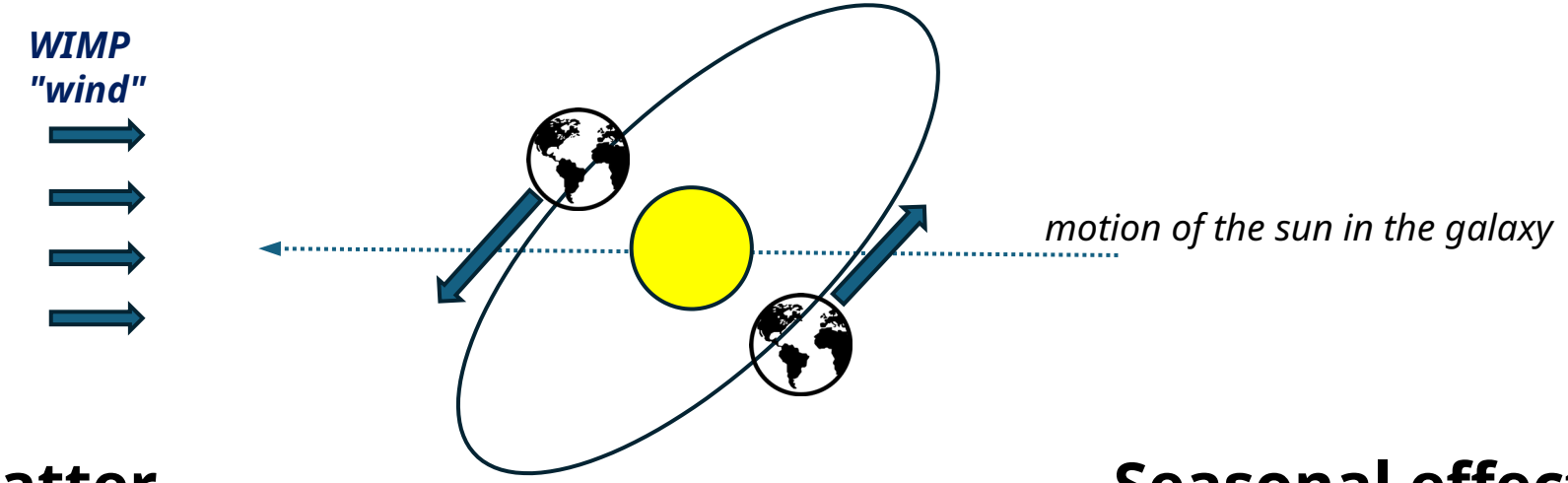
SABRE
TWO-SITE EXPERIMENT

SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy

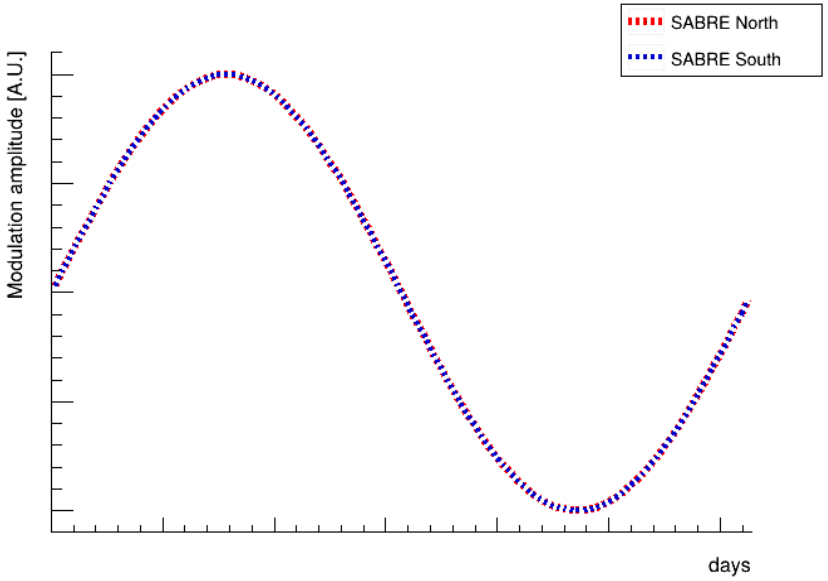


SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

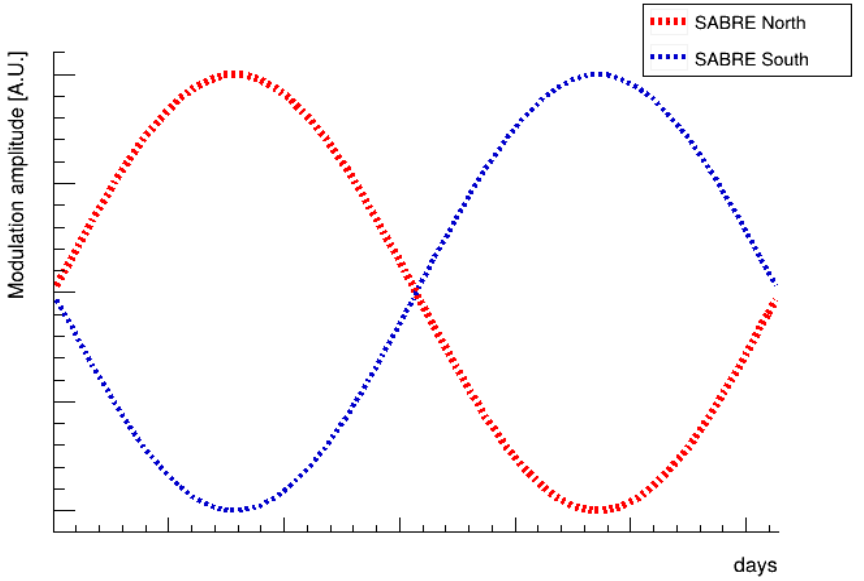
Why two locations?



Dark Matter



Seasonal effect

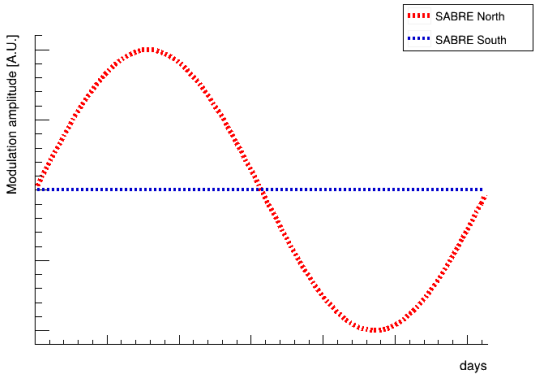


SABRE North location

DAMA/LIBRA

SABRE NORTH

Local effect



SABRE

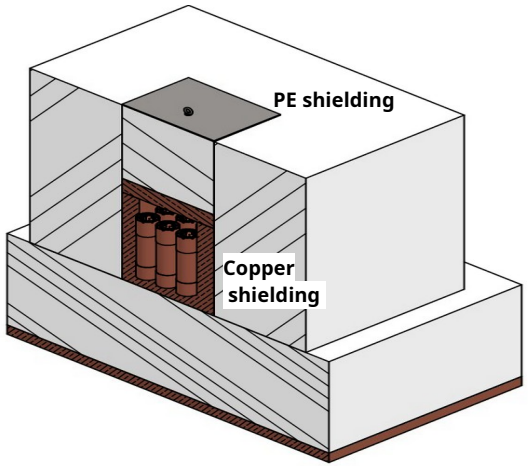
GOAL: background level lower than DAMA (~1 cpd/kg/keV) (in ROI)

- SABRE Proof-of-principle (PoP) and PoP-dry already achieved a background of **~ 1 cpd/kg/keV**
  We aim to reach ~ 0.5 cpd/kg/keV

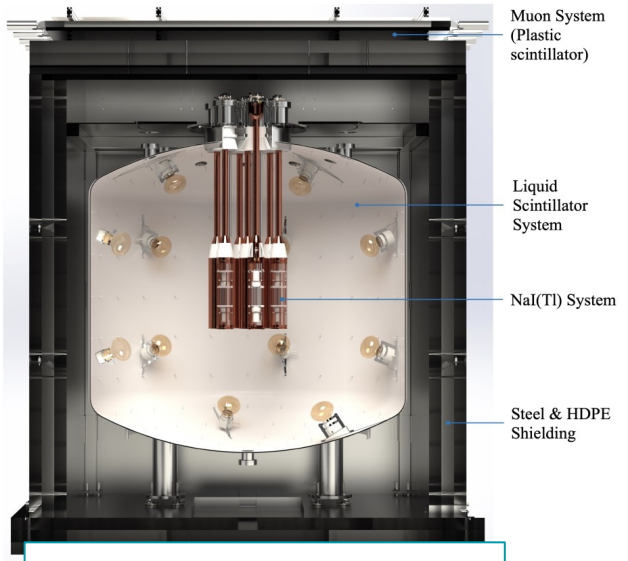
- Strategy to lower the **background:**
  - For internal backgrounds: → **zone refining**

  - For external background:
    → **SABRE North**: improved passive shielding
    (LNGS restrictions on liquid scintillators use)

    → **SABRE South**: Liquid Scintillator (LAB) + Muon Veto



SABRE North

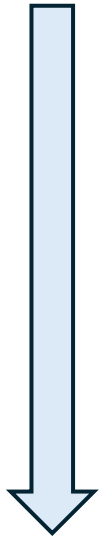


SABRE South

SABRE CRYSTALS

POWDER

Astrograde powder developed in collaboration with Sigma-Aldrich (now Merck). Now available commercially



CRYSTAL

Vertical Bridgman method for clean crystal growth - optimized in collaboration with Radiation Monitoring Devices Inc. (RMD). Crystal grows in fused silica vessel.

SABRE CRYSTALS

POWDER

Astrograde powder developed in collaboration with Sigma-Aldrich (now Merck). Now available commercially

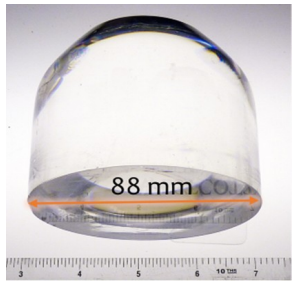
ZONE REFINING as a method to purify NaI powder further.

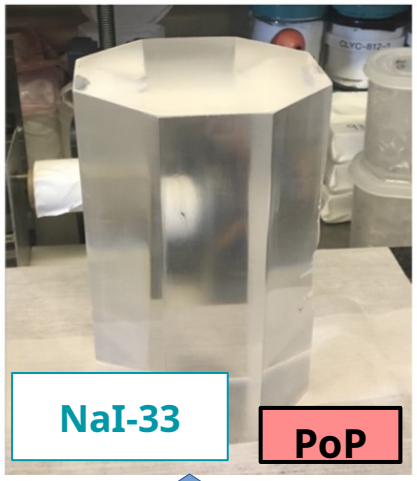
CRYSTAL

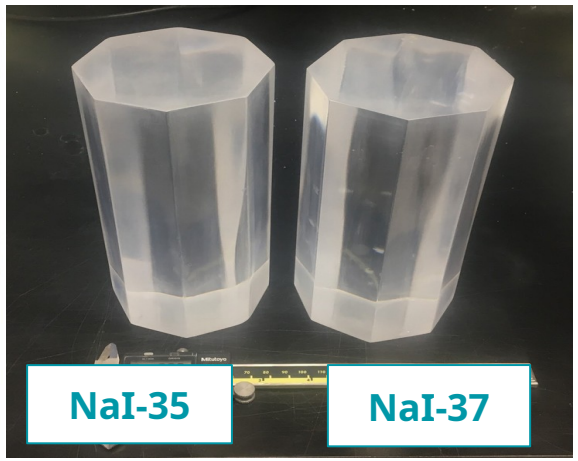
Vertical Bridgman method for clean crystal growth - optimized in collaboration with Radiation Monitoring Devices Inc. (RMD). Crystal grows in fused silica vessel.

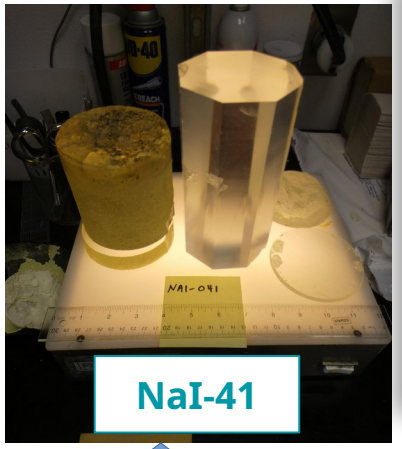
SABRE CRYSTALS

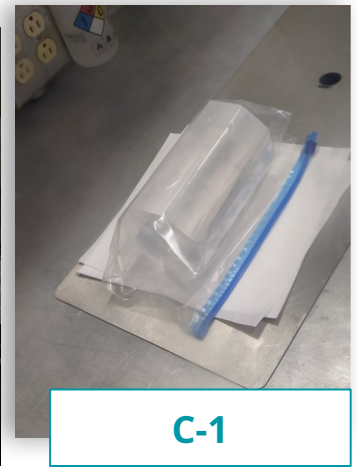
2015 | 2018 | 2019 | 2022 | 2023 | 2025











background **~ 1 cpd/kg/keV**
→ first NaI crystal since DAMA/LIBRA with such low background

grown from chunks (NaI-40) rather than powder
→ demonstrated same optical quality
→ important result for zone-refining

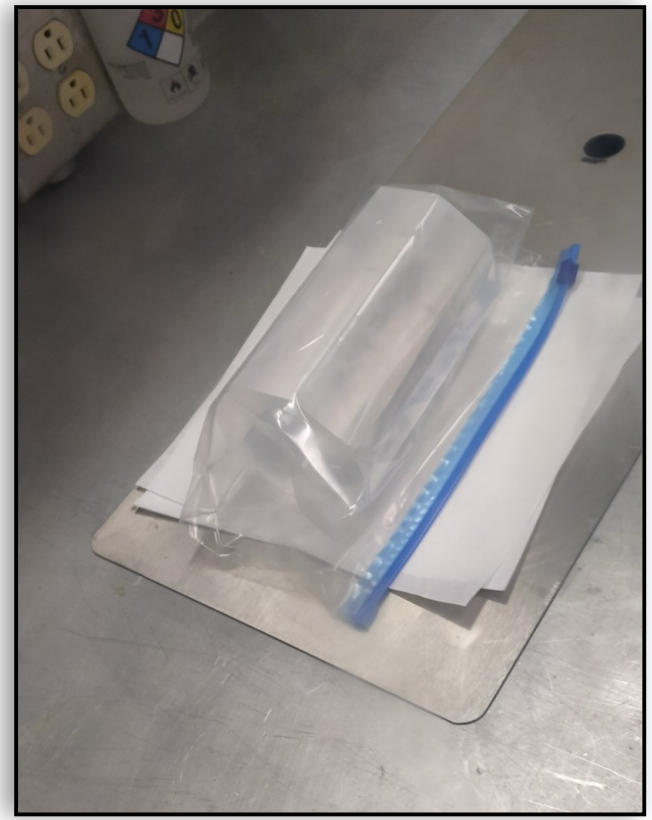
NaI-42

grown without **ZR**

powder after **ZR**
→ first crystal for physics run

C-1 crystal

15 kg of pure NaI powder given in-kind from COSINE-200 Collaboration



Crystal after cutting & polishing

Final mass: 3.65 kg

Powder	^{39}K [ppb]	^{88}Sr [ppb]	^{85}Rb [ppb]	^{133}Cs [ppb]	^{138}Ba [ppb]	^{65}Cu [ppb]	^{208}Pb [ppb]
Cosine-200	12.5	<0.8	<0.3	6	1.2	82±3.5	0.6
Astrograde (SABRE)	~4-18	0.3	< 0.4	< 1	3.6	79.4±2.8	~1

Powder screening at LSC by ICP-MS

This collaboration program is part of the MoU between Center for Underground Physics at IBS (CUP-IBS) in South Korea and INFN

fphy.2023.1142849

C-1 crystal

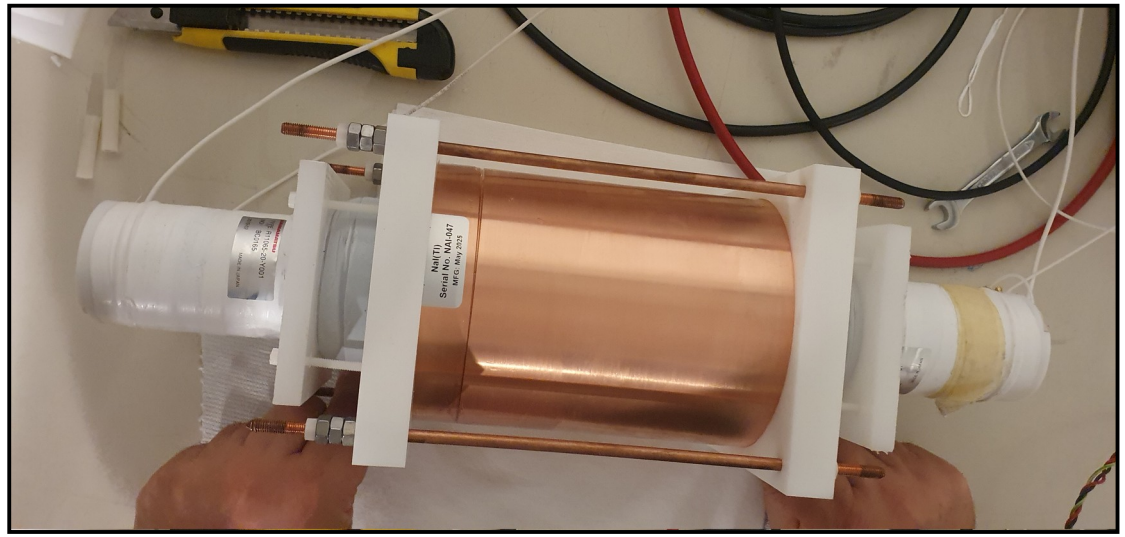
Preliminary results:

Asymptotic ^{210}Po **<0.47** [mBq/kg]

^{214}Bi-Po: U eq ~ **0.7** [ppt]

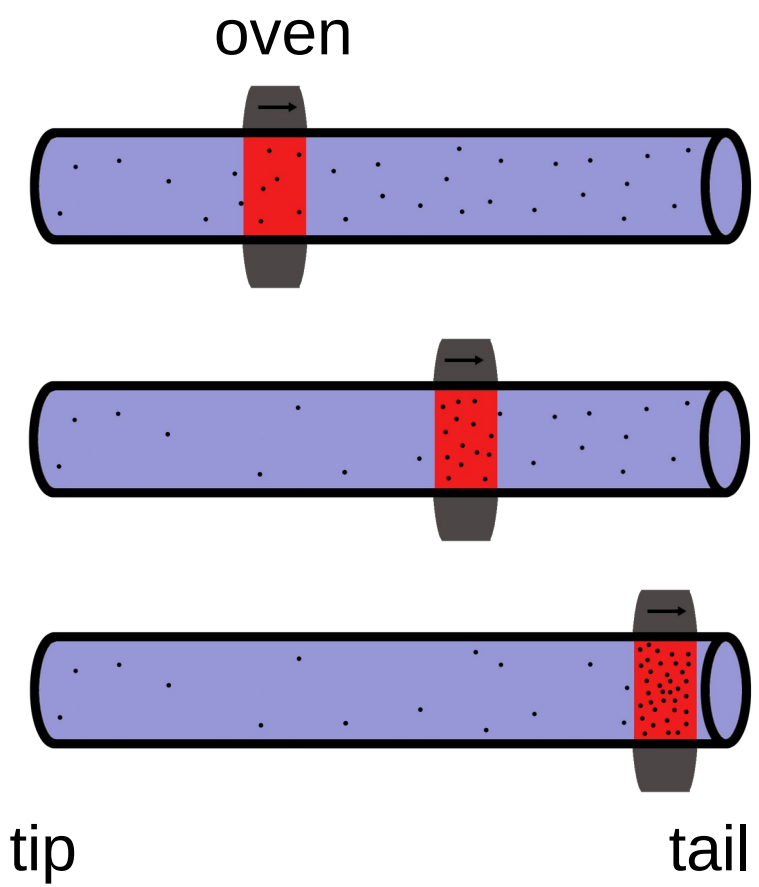
^{212}Bi-Po: Th eq ~ **0.2** [ppt]

Crystal is currently under measurement @LNGS
- still active cosmogenics



Crystal encapsulated by RMD
and shipped to LNGS

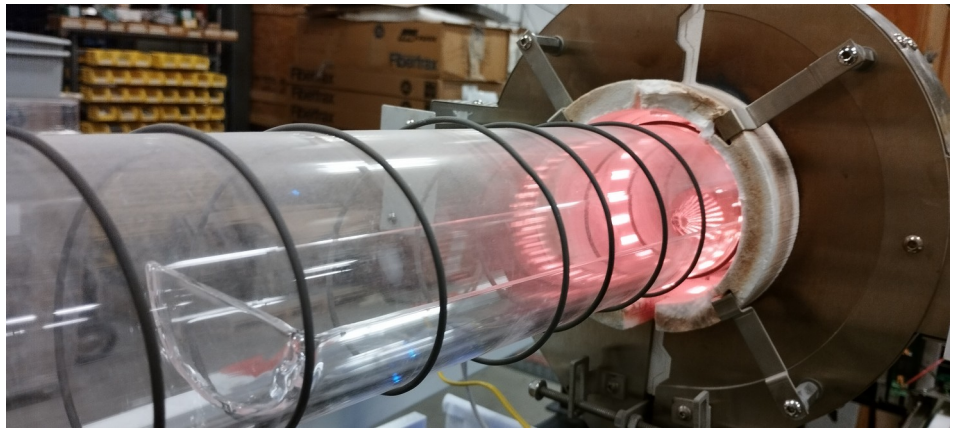
ZONE REFINING



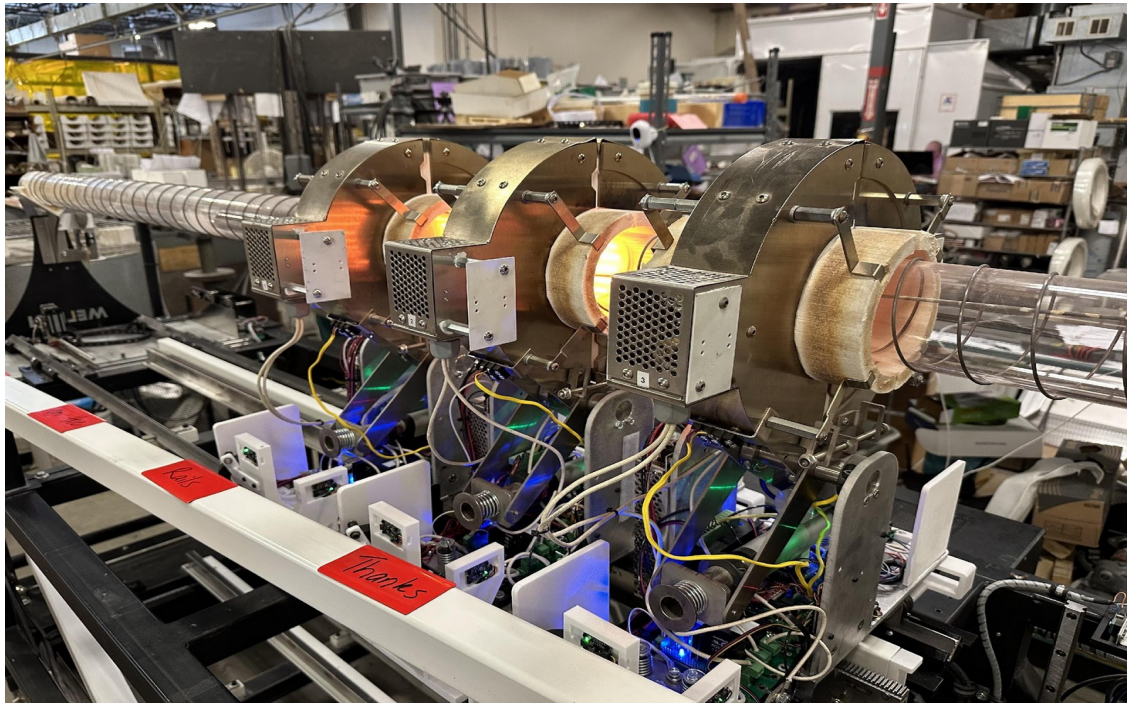
- Zone refining technique successfully used in semiconductor industry
- Impurities are segregated to one side of the ingot by moving annular ovens
- Tested on NaI ***Astrograde*** powder by Princeton group at Mellen company, Concord, NH (USA)

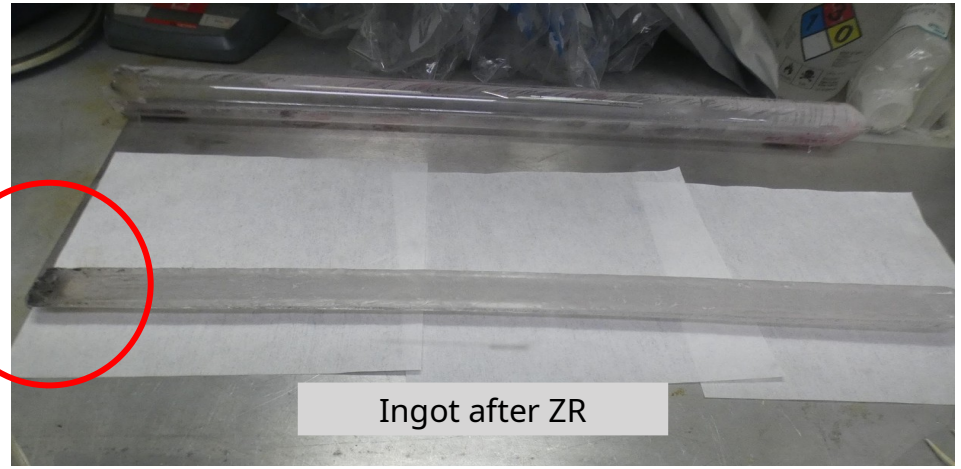
ZONE REFINING

test runs with *Astrograde* NaI powder have been performed at MELLEN, Concord NH, USA.



Zone refiner

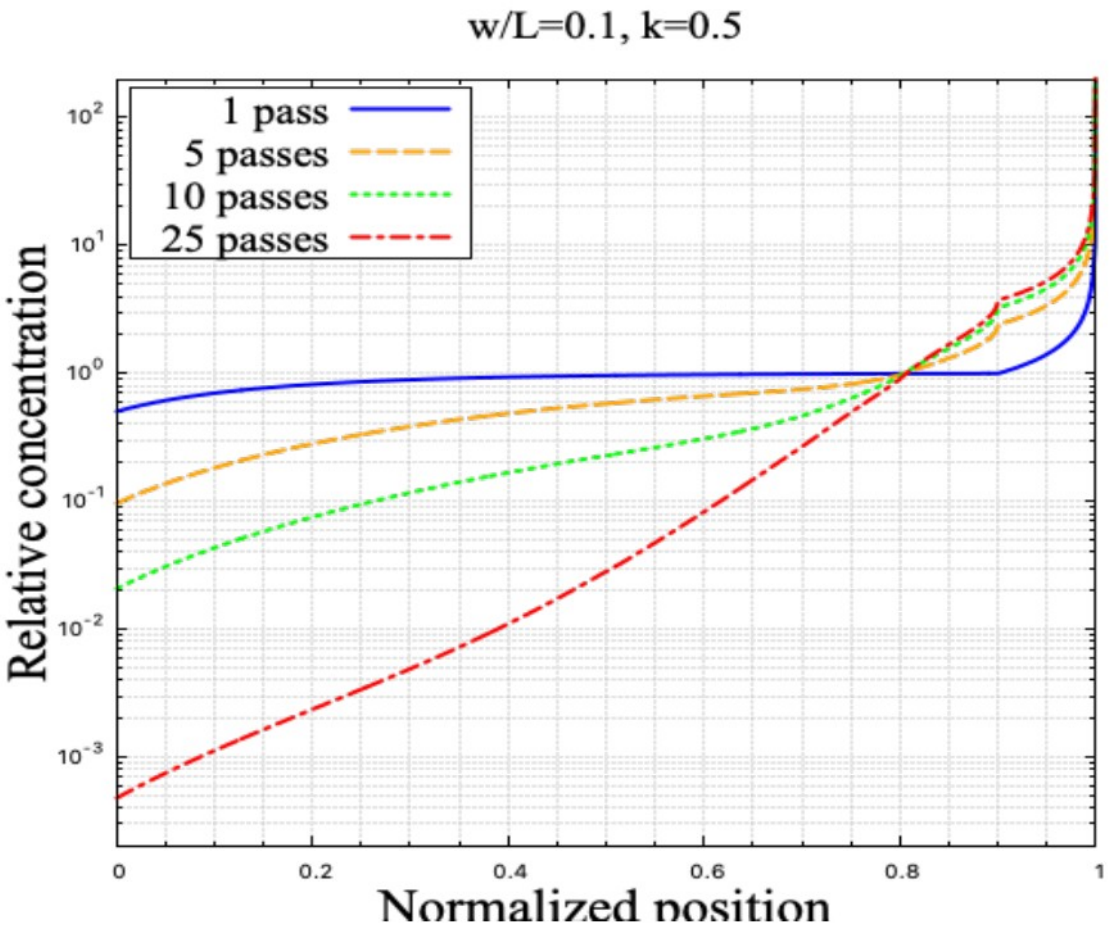




ZONE REFINING

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

tip tail



tip tail

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ZONE REFINING

Sample	^{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

ZR test Run4

ZONE REFINING

Test runs 2023-2024

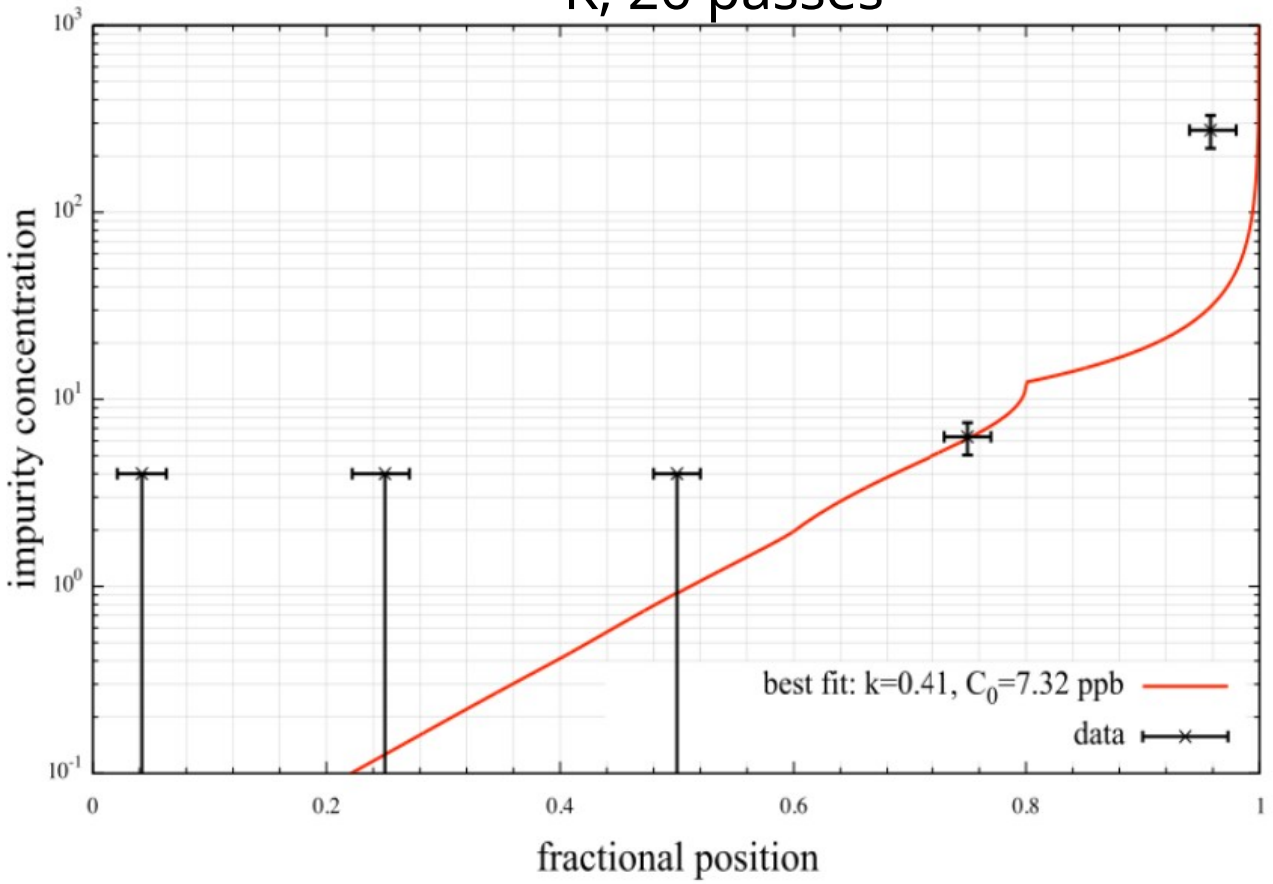
Distribution coefficient, $k = C_s / C_l$

Concentration in solid phase

Concentration in liquid phase

If k<1 – solute "prefers" to stay in liquid phase

^{39}K, 26 passes



From test data we can fit the **distribution coefficients** (k) of different isotopes (K, Pb, Ba, Kr, Sr, Mg) for concentrations much lower than literature data (10-100ppm)

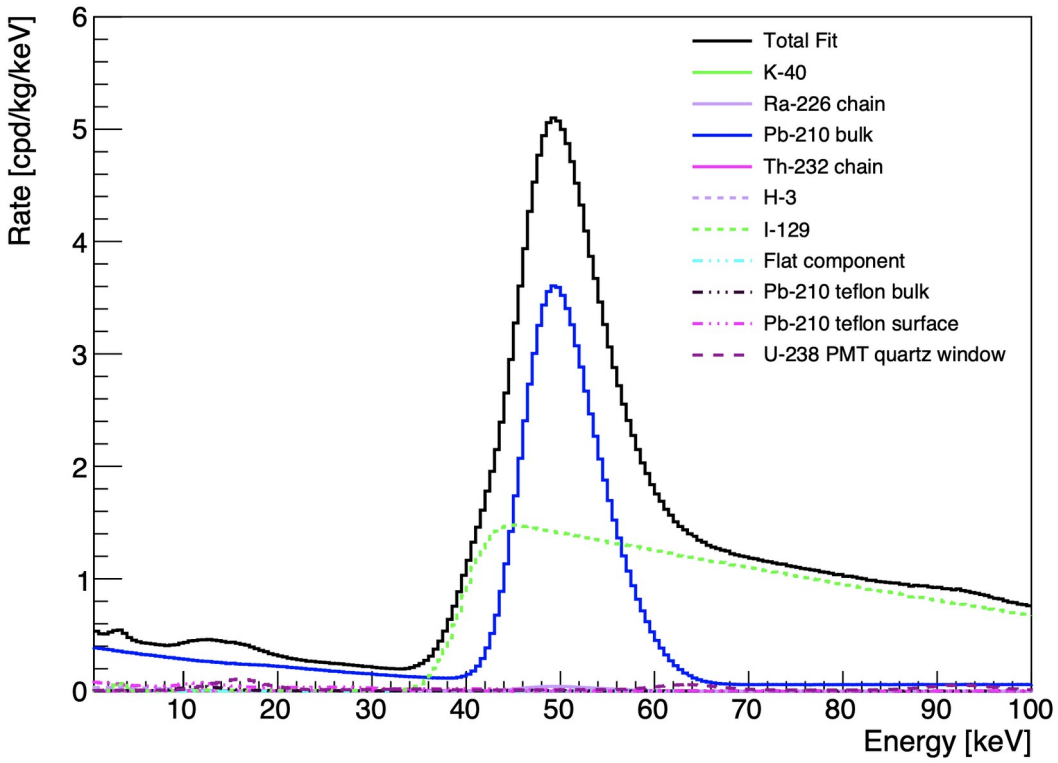
Paper on ZR in preparation

ZONE REFINING

Expected background in SABRE crystals

Source	Rate in ROI [1,6] keV [cpd/kg/keV]
^{40}K	0.025
^{210}Pb bulk	0.353
^{210}Pb reflector bulk	0.005
^{210}Pb reflector surface	0.060
^{3}H	0.033
^{129}I	0.003
^{238}U	0.005
^{232}Th	0.0004
PMT	0.009
Other backgrounds	0.01
TOTAL	0.50

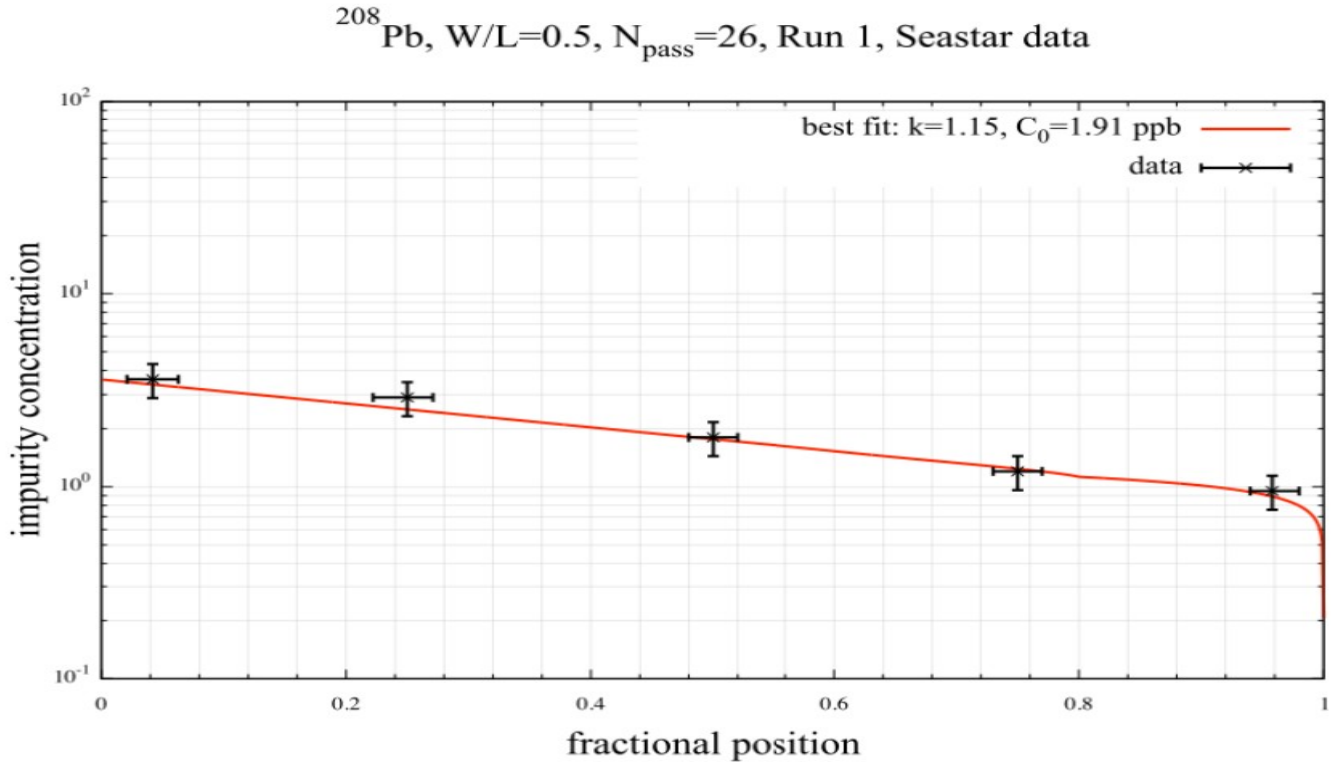
~ 0.5 cpd/kg/keV



- Using spectral fit from NaI-33 measurements
- With applied reduction from zone refining
- Spectrum from Monte Carlo

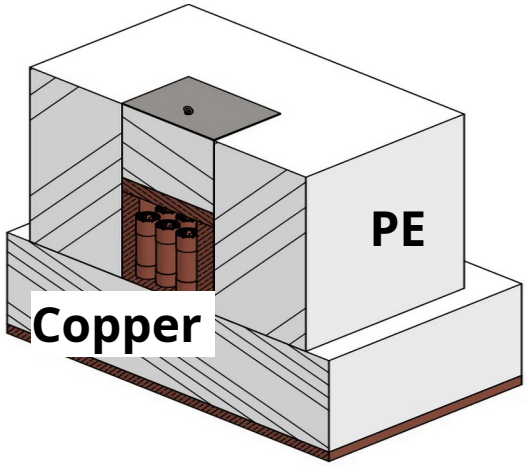
Problem with Pb

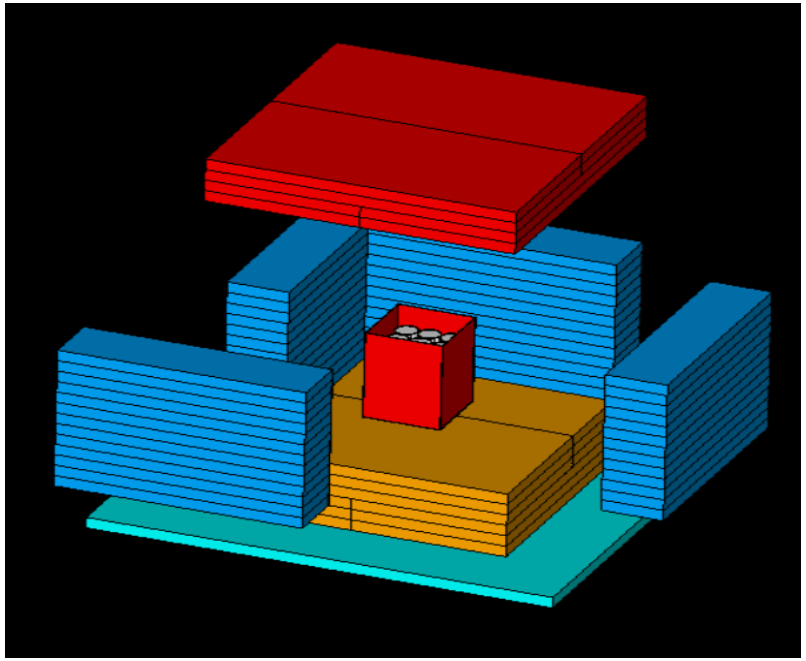
From data **k >~ 1** → **Pb cannot be removed with ZR**

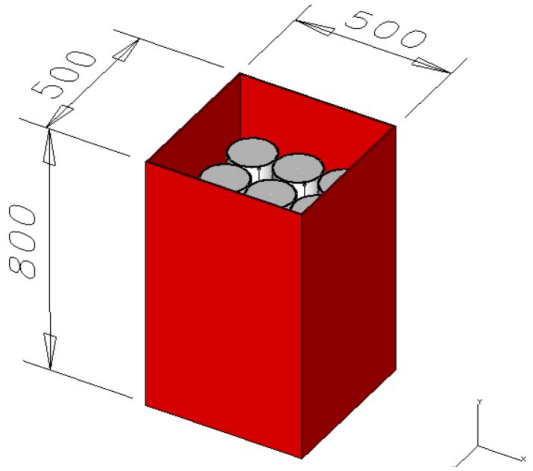


Best fit
k = 1.15 ± 0.03

SABRE NORTH SHIELDING



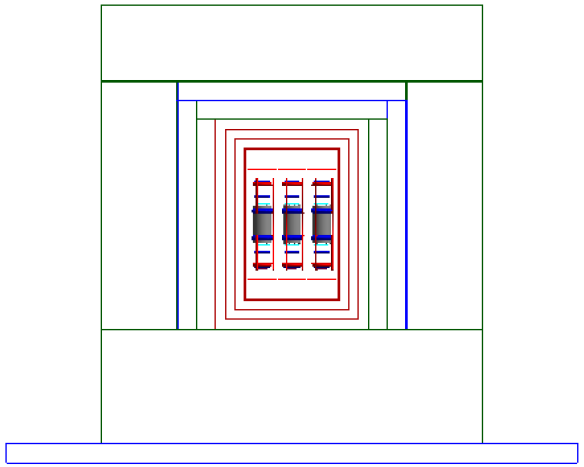




- Experimental area @LNGS is ready
- Shielding design is ready
- Array of 9 x 5 kg crystals
- Each crystal in a Cu enclosure
- Crystals inside a Cu box 5mm thick
- Flushed with HPN_2

- 3 Cu layers with decreasing radiopurity
- One 10 cm thick PE U-shaped layer
- One 10 cm thick Cu U-shaped layer
- Outer PE slabs 40 cm on top and sides and 60 cm on the bottom
- 3m x 3m Cu basement with 10 cm thickness

SABRE NORTH SHIELDING

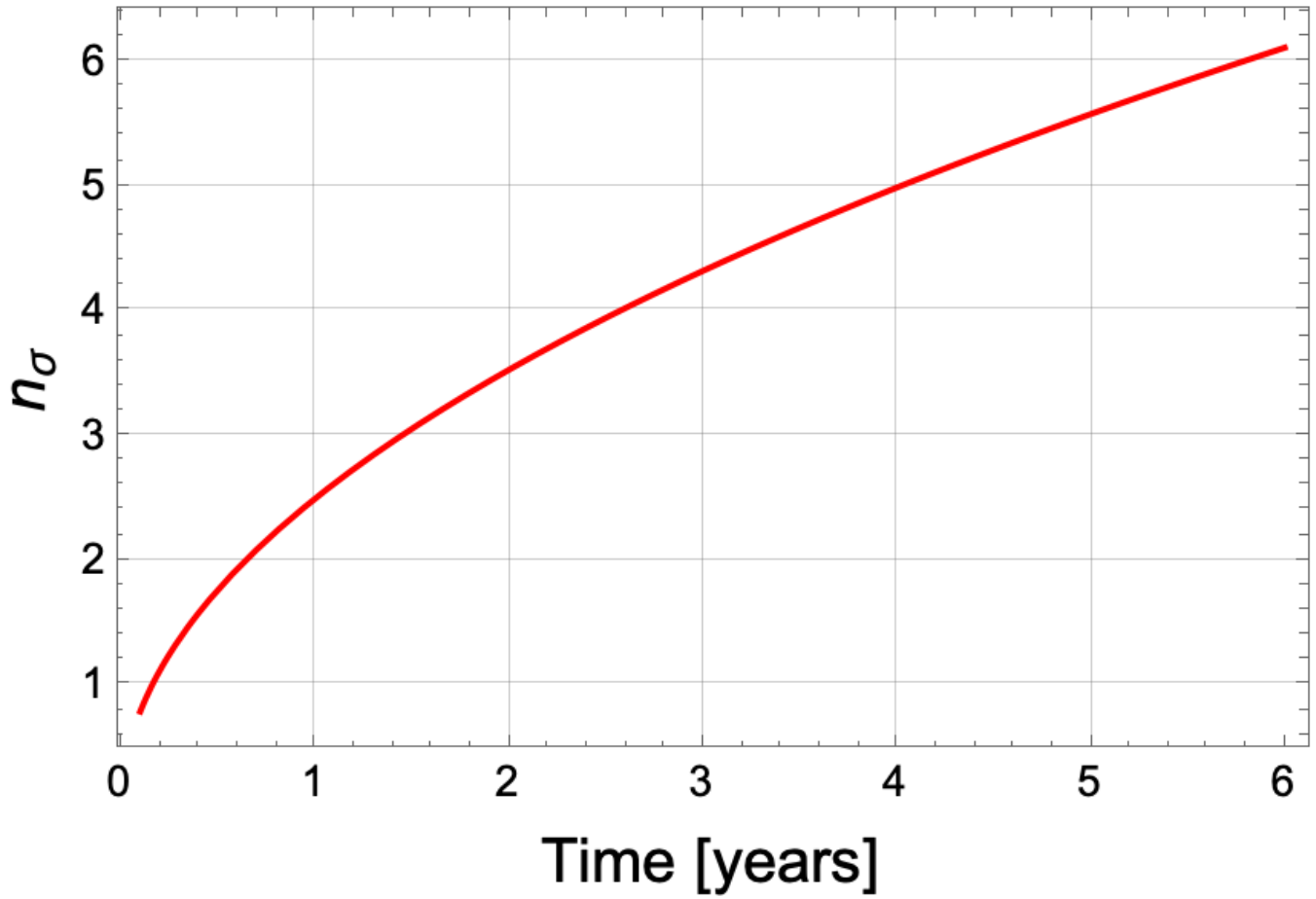


Source	Contribution in the ROI (1-6 keV) [dru]
Internal: NaI + PMTs + PTFE	0.5
Enclosure: Copper + Delrin parts	0.032
Shielding: Inner copper + Outer copper (negligible) + PE (negligible)	0.01
External gammas + neutrons (negligible)	0.001

Fully passive shielding design: 25 cm copper + 50 cm PE
→ enough shielding power
→ negligible contribution to the total background

Expected sensitivity on S_m

→ Assuming background 0.5 dru in ROI and negligible cosmogenics contribution



45 kg mass allows 4σ statistical sensitivity to DAMA-like signal in 3 years assuming negligible cosmogenic activity

SUMMARY

- Goal of SABRE experiment is to search for annual modulation with two nearly identical NaI(Tl) detectors in the Northern and Southern Hemisphere
- Background level of ~0.5 cpd/kg/keV is within reach with ZR
- Crystal production is ongoing
  → first crystal expected early 2026
- Physics data taking will start in 2028
- We expect to exclude/confirm annual modulation within 3-5 years

Thank you for your attention!

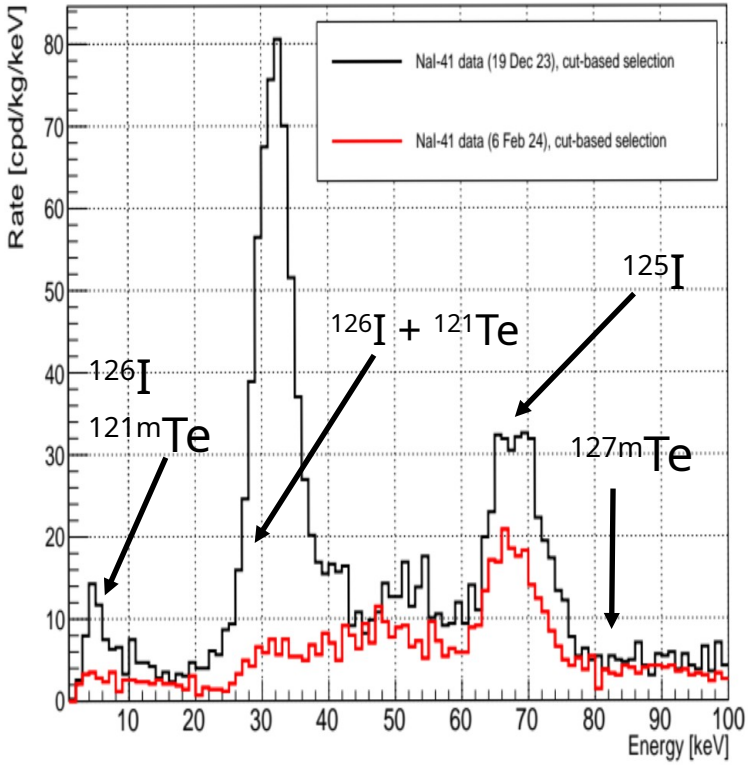
← *See also the poster*

backup slides

Cosmogenic backgrounds

Isotope	$T_{1/2}$
^{129}I	1.57×10^7 yr
^{3}H	12.3 yr
^{22}Na	2.6 yr
^{109}Cd	1.3 yr
^{121m}Te	164 d
^{113}Sn	115 d
^{123m}Te	119 d
^{127m}Te	106 d
^{125}I	59 d
^{125m}Te	57 d
^{121}Te	19 d

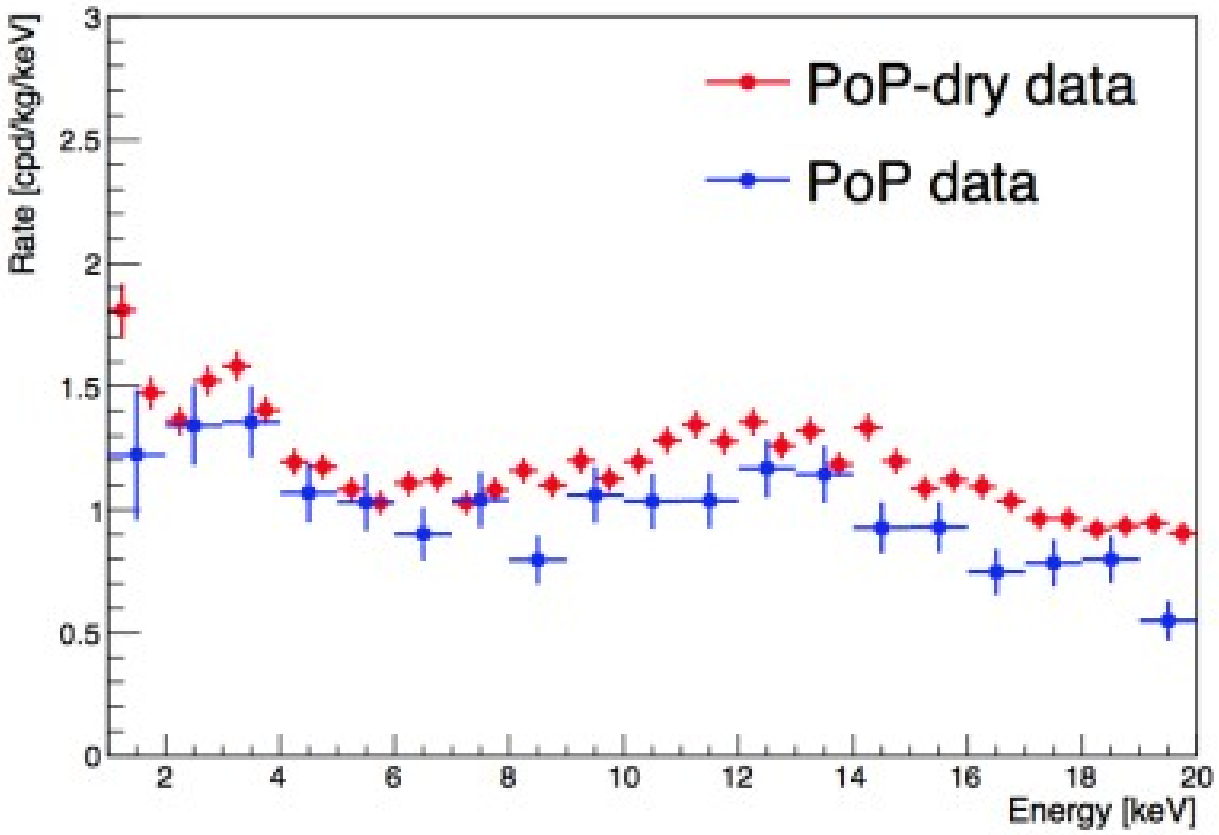
- Cosmogenic activation in the ROI mainly comes from ^{3}H, ^{113}Sn, ^{109}Cd, ^{22}Na
- Can be used for low energy calibrations: 0.87 keV (^{22}Na), 25.5 keV, 3.5 keV (^{109}Cd), 30.5 keV (^{121}Te), 67.8 keV (^{125}I)
- Minimum 1 year of “cooling” underground is required
- In the future: underground growth?



SABRE NORTH PASSIVE SHIELDING

NaI-33 was measured with and without the LS active veto

K-40 contamination of less than a few ppb does not require necessarly the LS active veto



PoP-dry: only Cu shielding (30 cm)