SABRE North
the low radioactivity approach to dark matter annual modulation detection

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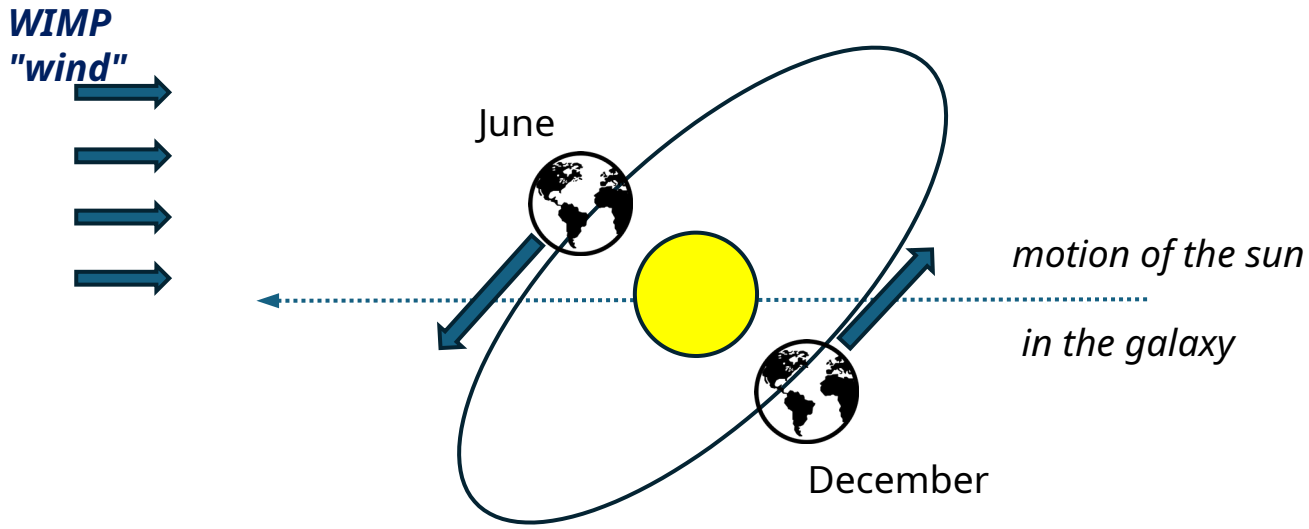
on behalf of Sabre North collaboration

LRT2026 workshop

september 21, 2026

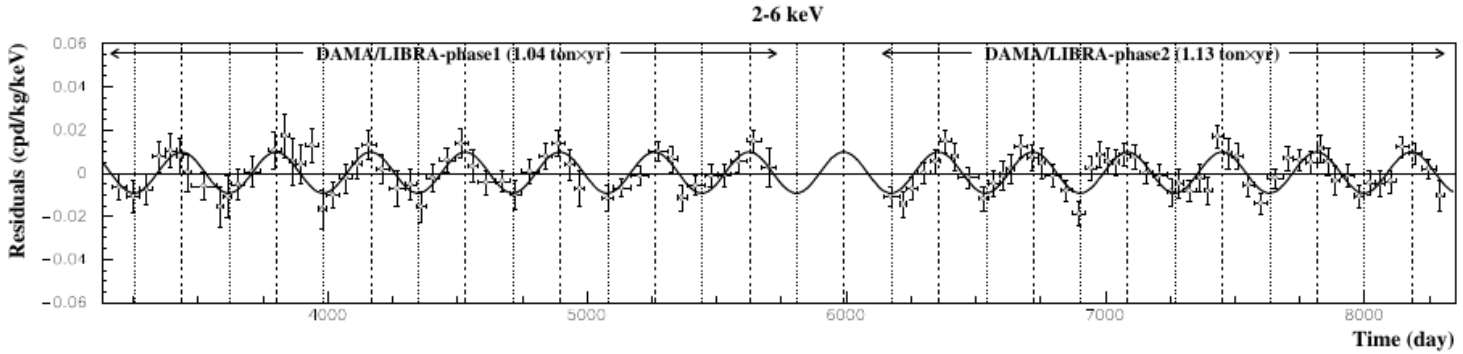
Dark Matter annual modulation



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

SABRE

SABRE: Sodium-iodide with Active Background REjection

GOAL: *Search for dark matter through annual modulation signature*

→ Test of DAMA/LIBRA claim

Use the same target material: NaI(Tl) crystals

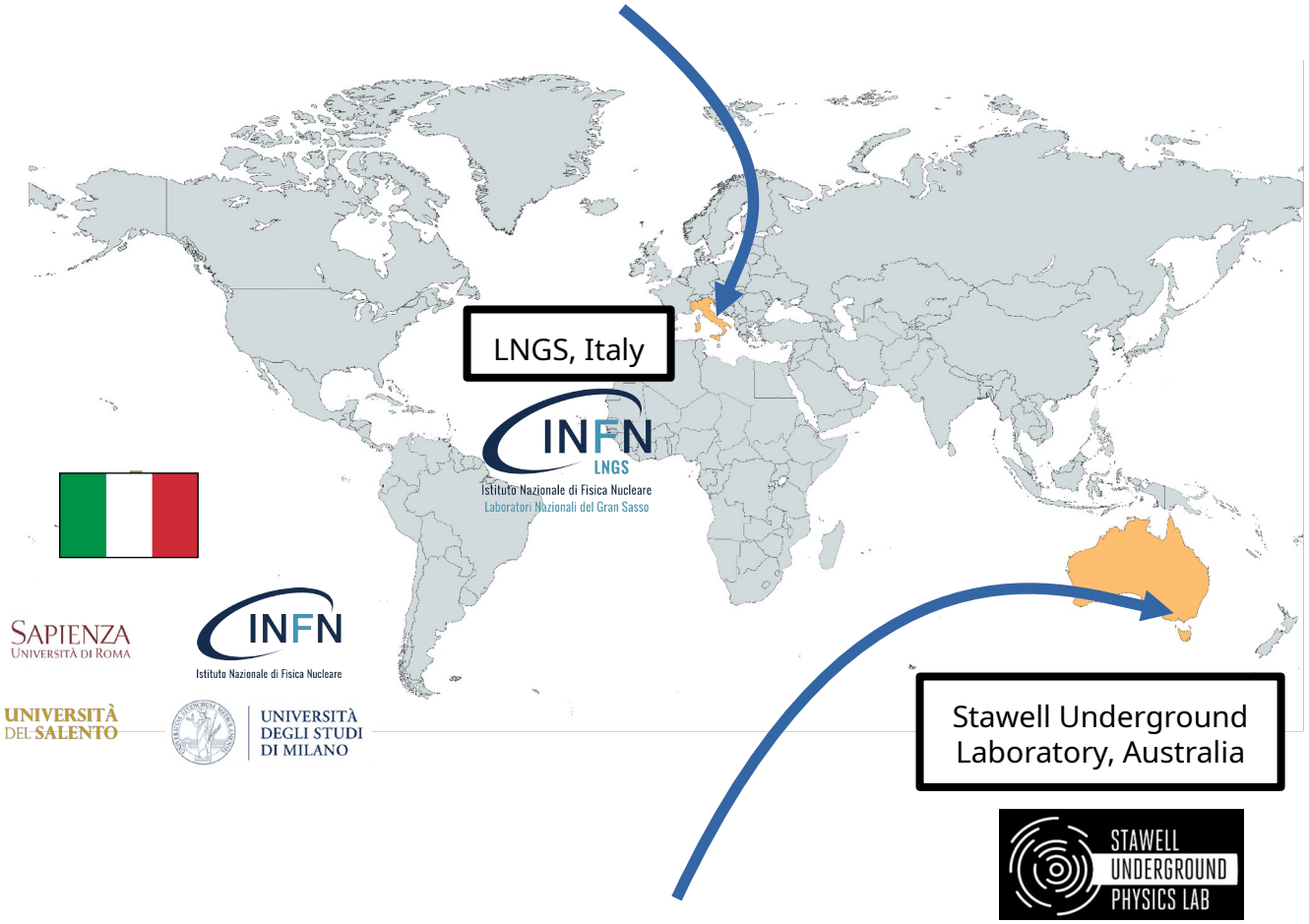
→ **We aim for lower background level w.r.t. DAMA/LIBRA**

Eliminate non-DM effects

→ **Two-site experiment**

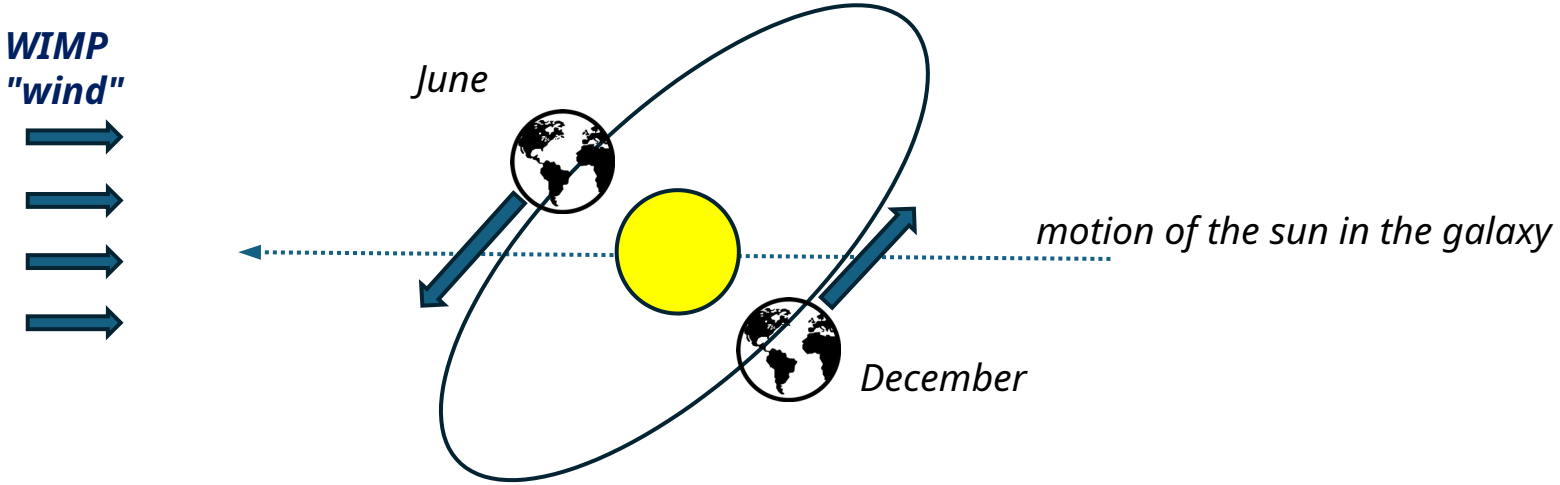
SABRE
TWO-SITE EXPERIMENT

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

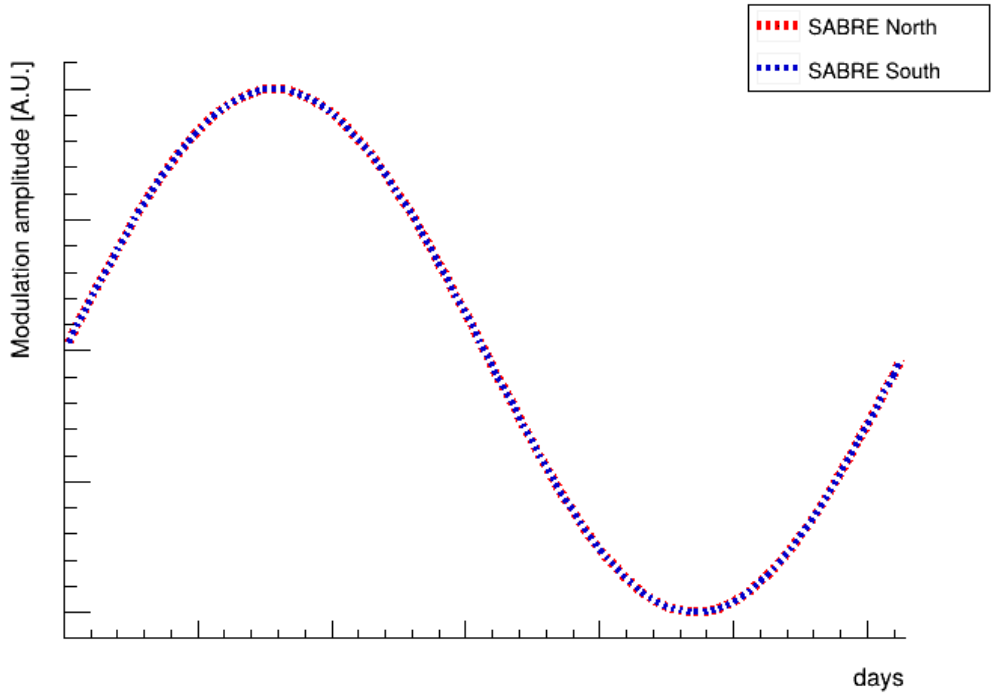


SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

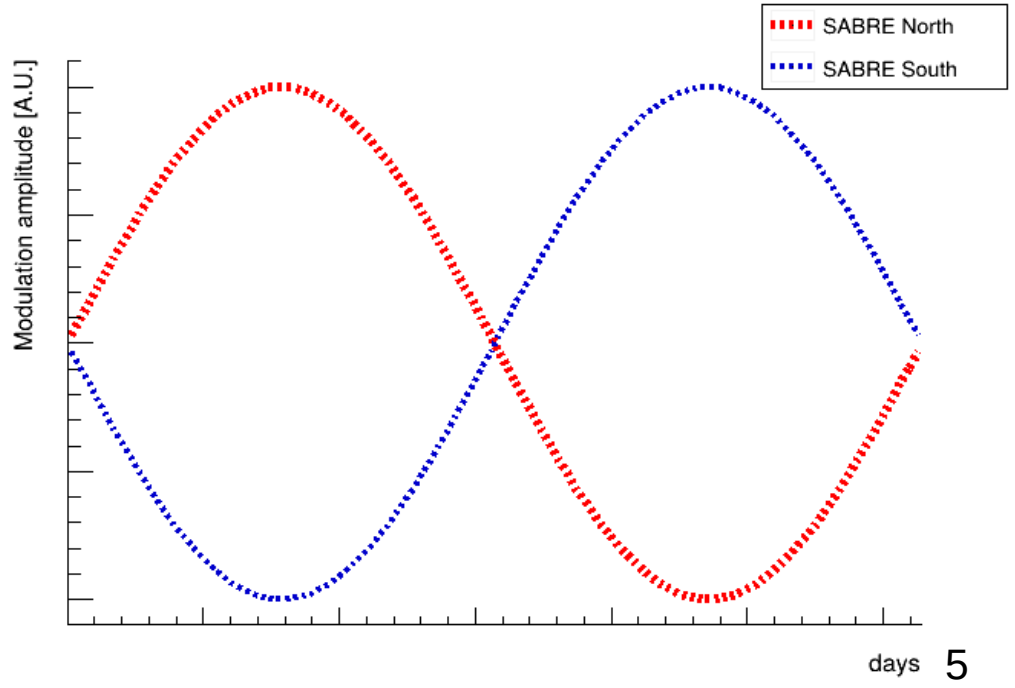
Why two locations?



Dark Matter



Seasonal effect

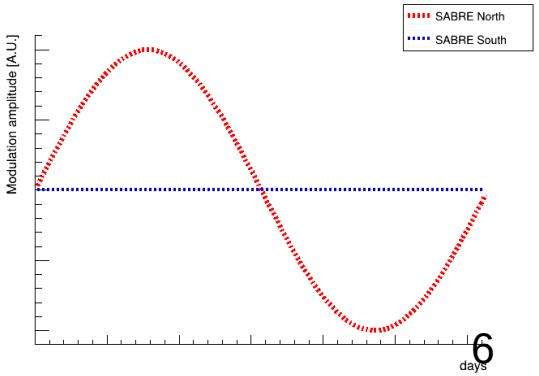


SABRE North location

DAMA/LIBRA

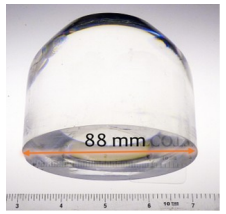
SABRE NORTH

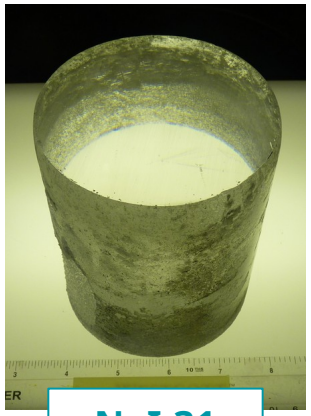
local effect



SABRE CRYSTALS

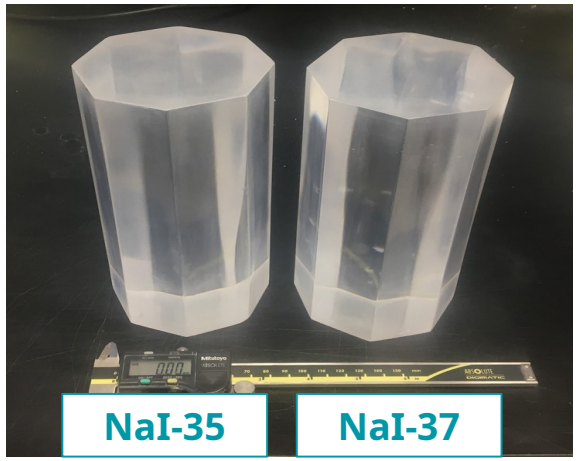
2015 2018 2019 2022 2023 2025 2026



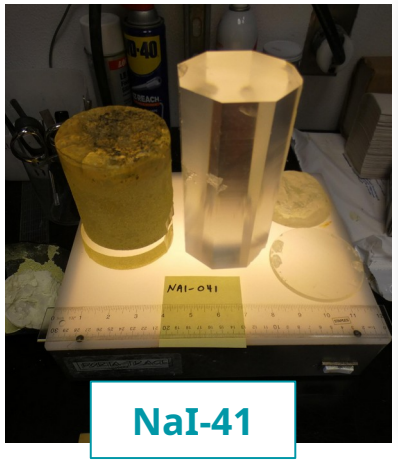


NaI-31

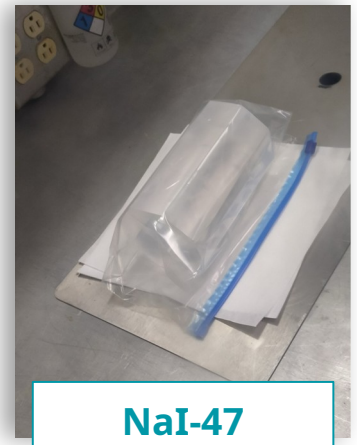
NaI-33



NaI-35 NaI-37



NaI-41



NaI-47

NaI-42

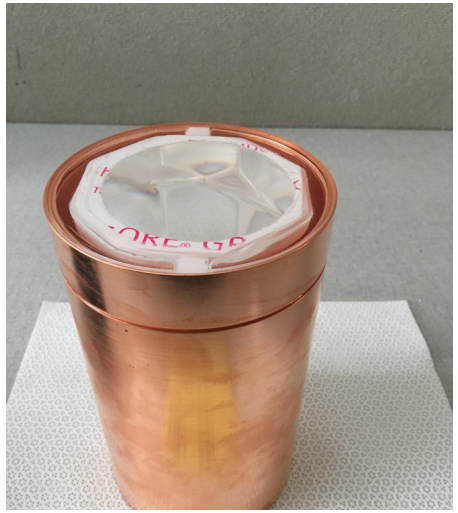
background **~ 1 cpd/kg/keV**
→ first NaI crystal since DAMA/LIBRA with such low background

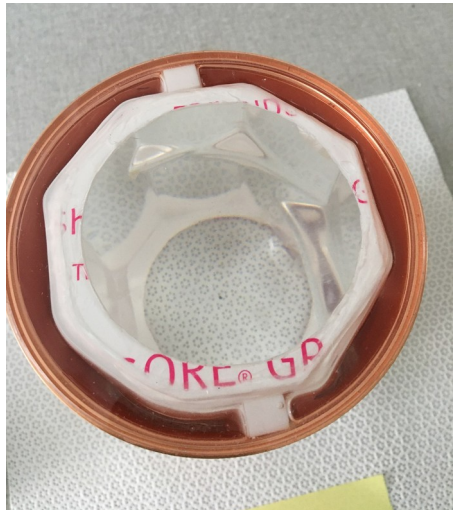
grown from chunks rather than powder

grown from COSINE-200 powder

grown from zone refined powder

NaI-41





- After zone refining process, NaI will not be in powder form anymore (but chunks).
- RMD grown undoped crystal, named NaI-40, which was broken into chunks.
- From these chunks full size (4.3kg) crystal NaI-41 was grown.
- ICP-MS: average potassium contamination in NaI-40: **5.8±0.7 ppb**
- Compatible with that of NaI-41:
  → the growth process does not introduce potassium contamination
- LY and energy resolution:
  → same as crystals grown from powder

important result for zone-refining

Problems with NaI powder

SABRE planned to grow crystals using **Astro Grade** powder produced by **Merck**
(originally from *Sigma Aldrich*)

Last year Merck comunicated to us
they were not able to produce powder with specified purity

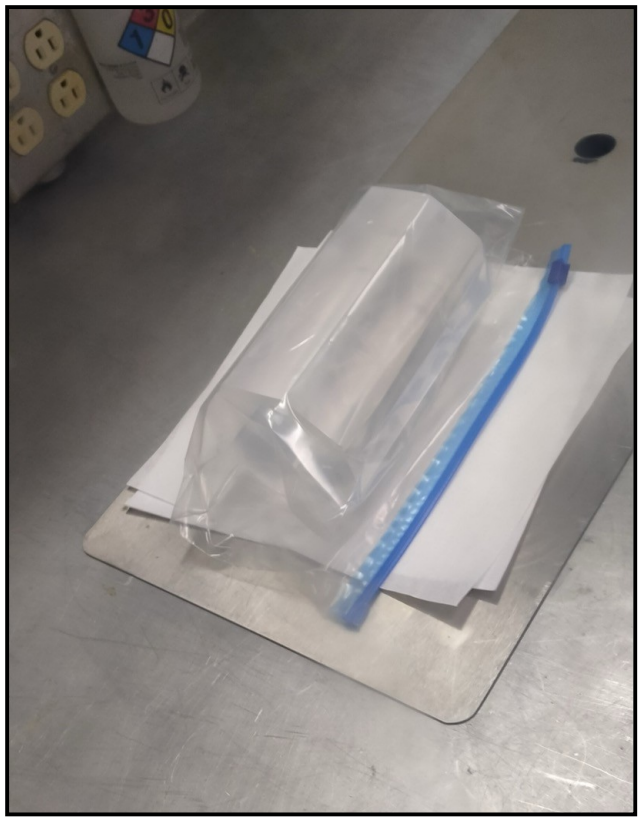
COSINE-200 collaboration provided powder to SABRE North
within the **INFN - IBS Global Research Center** agreement.

SABRE North will grow crystals from this powder

NaI-47

First crystal grown from powder provided by COSINE-200 Collaboration.

For testing yield and purity with our growth method.



Crystal after cutting & polishing

Final mass: 3.65 kg

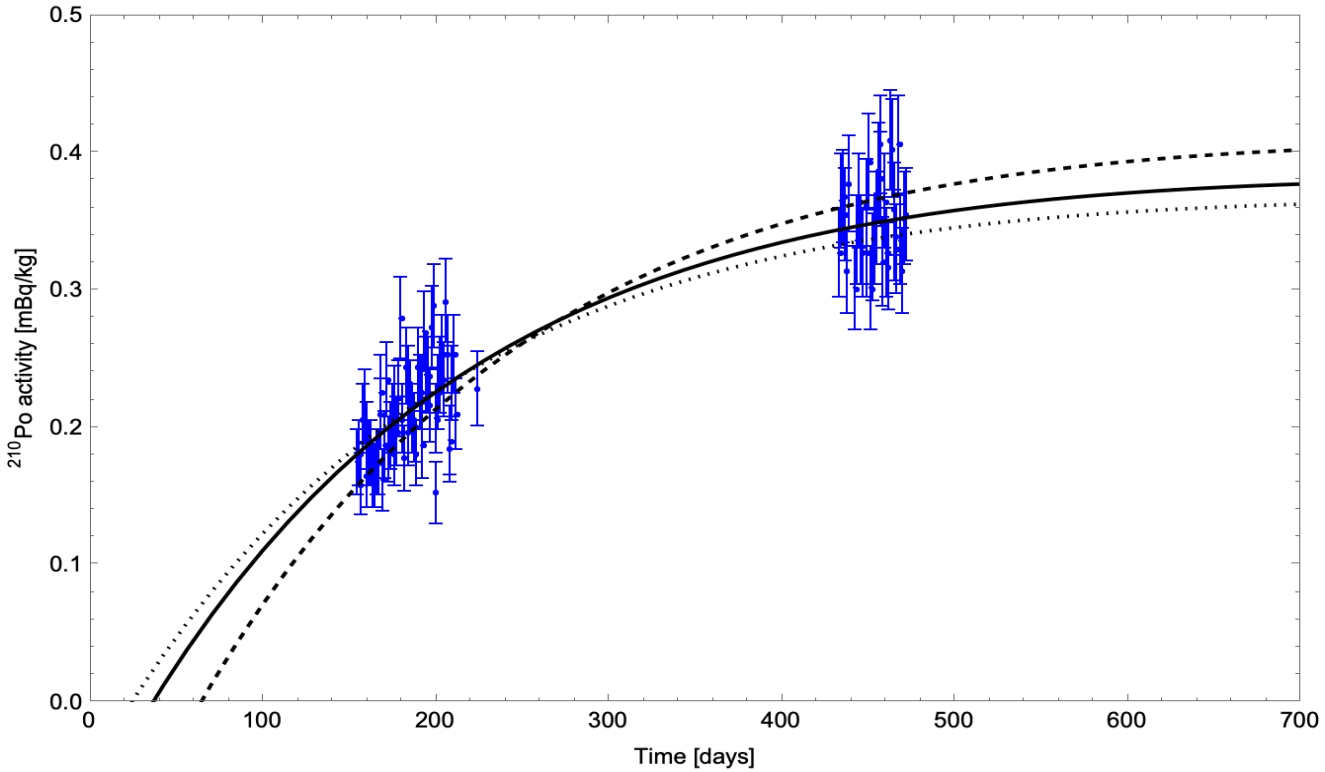
Powder	^{39}K [ppb]	^{88}Sr [ppb]	^{138}Ba [ppb]	^{208}Pb [ppb]
COSINE-200 powder	6.4	0.1	0.8	0.3
Astro Grade	~4-18	0.3	3.6	~1

ICP-MS @ Seastar

NaI-47

Preliminary results:

Asymptotic ^{210}Pb **<0.393±0.004** [mBq/kg]



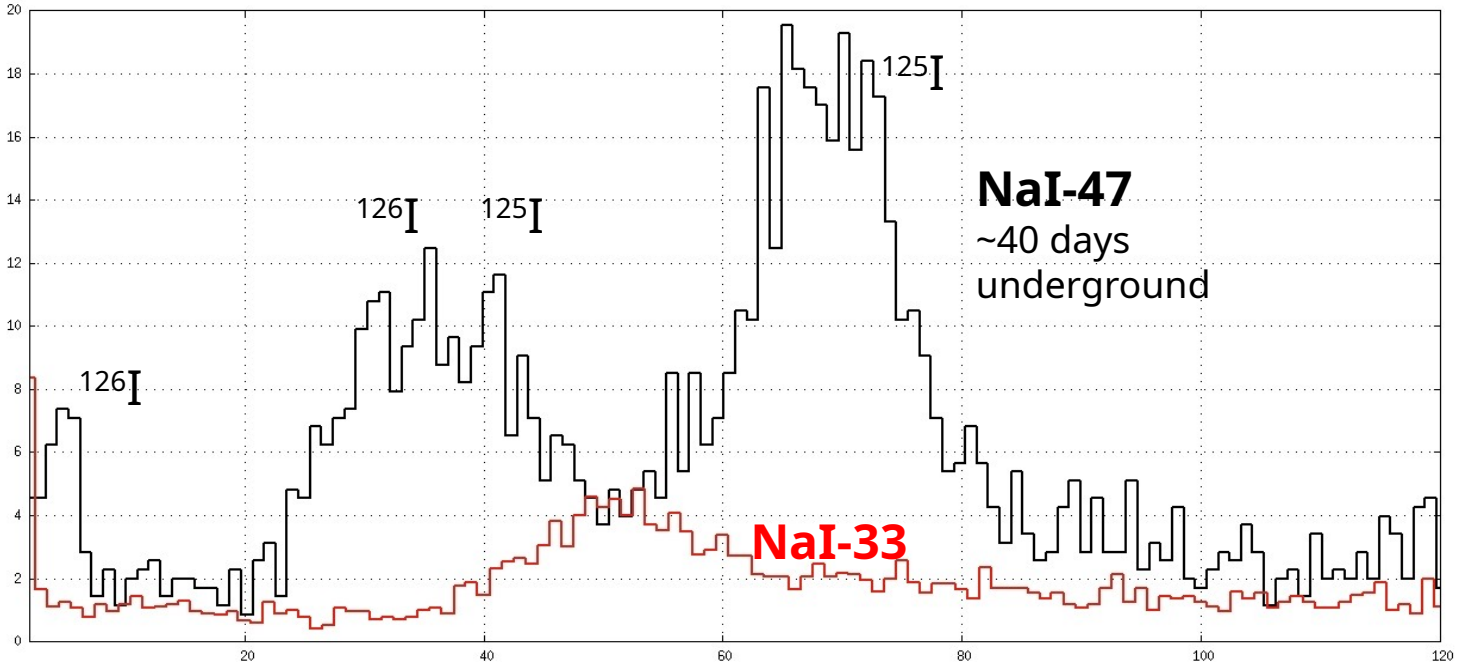
Solid bold line: ^{210}Po zero till some t_0 (free par) after growth start, χ^2/Ndof = 1.05
Dotted line: ^{210}Po activity is zero at growth start, χ^2/Ndof = 1.11
Dashed line: ^{210}Po activity is zero at growth end, χ^2/Ndof = 1.32

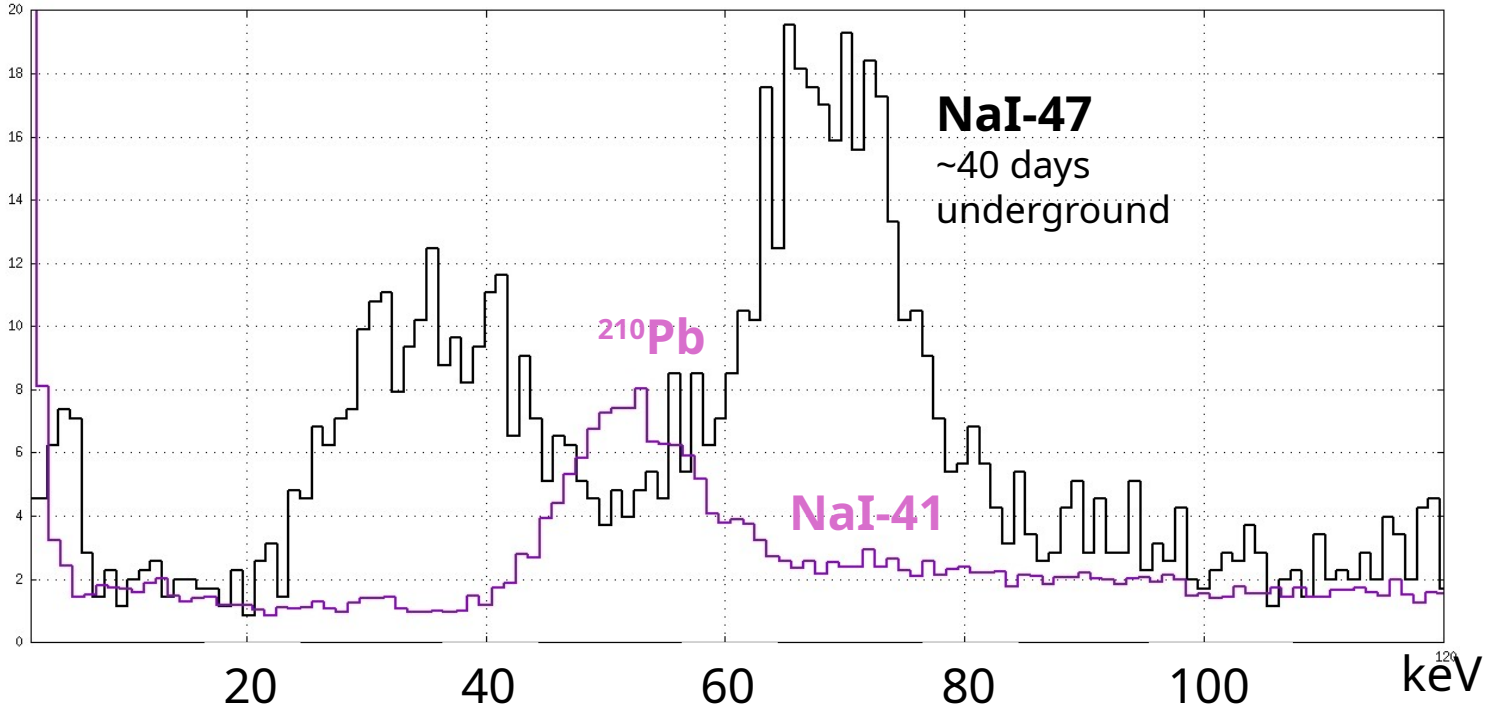
crystal encapsulated by RMD
and shipped to LNGS

NaI-33 (growth 2019):
Astro Grade by Sigma-Aldrich

NaI-47 (growth 2025):
COSINE powder

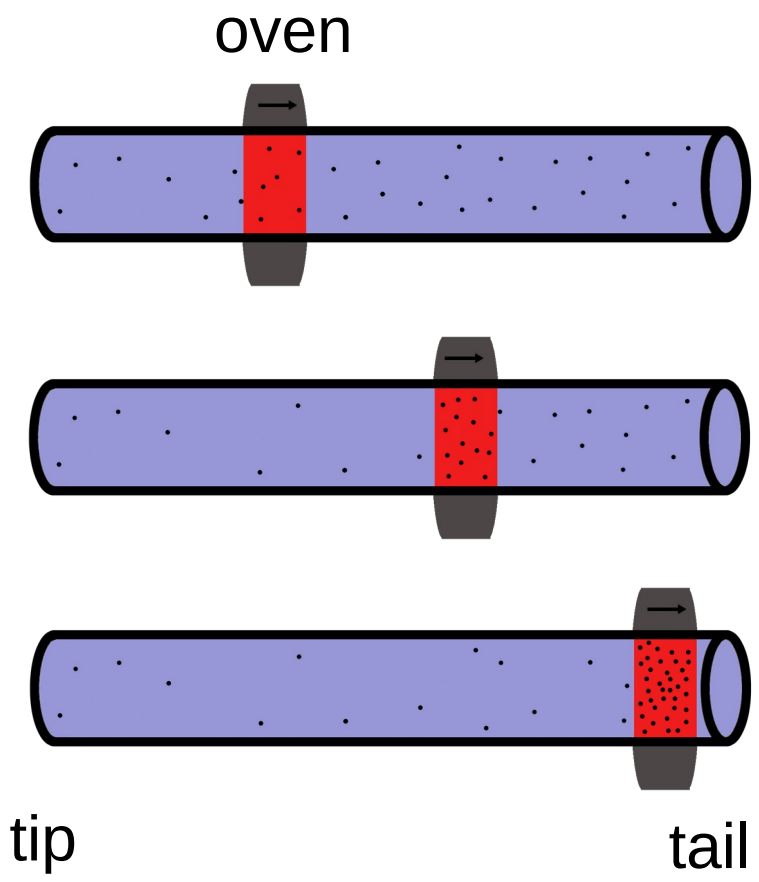
NaI-41 (growth 2023):
Astro Grade by Merck





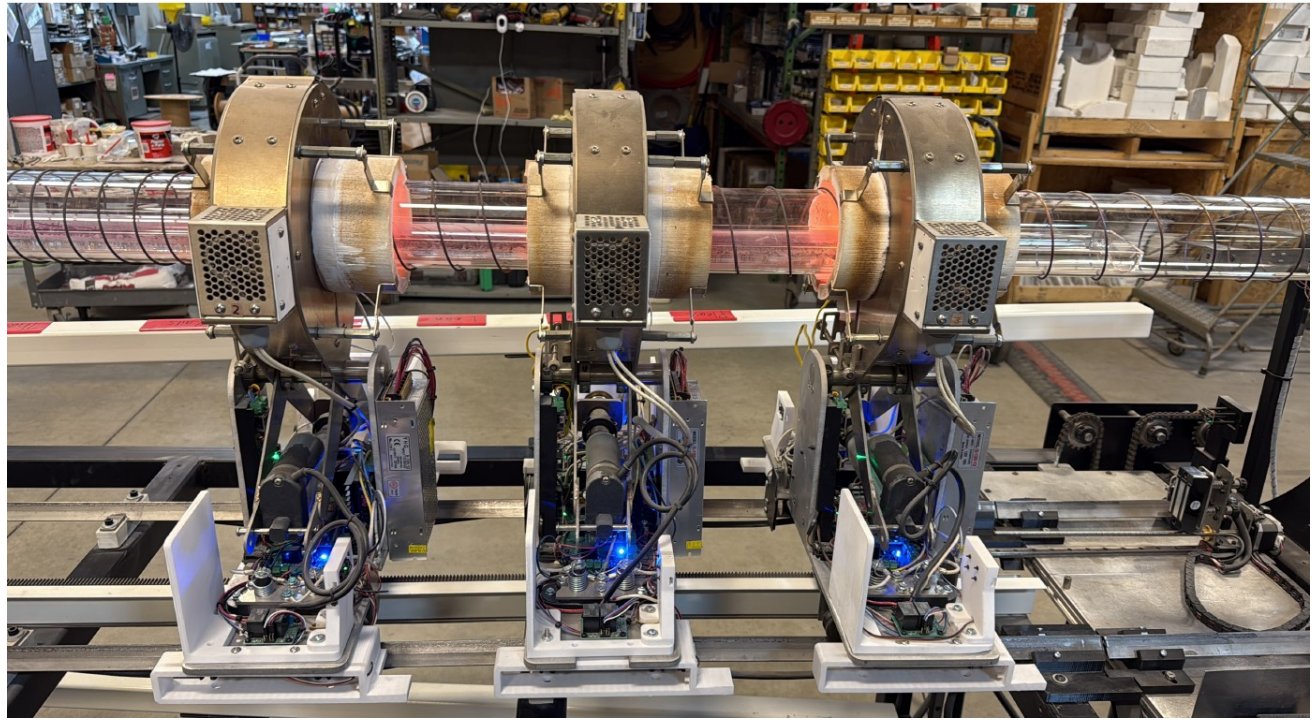
ZONE REFINING

NaI powder → zone refining → crystal growth

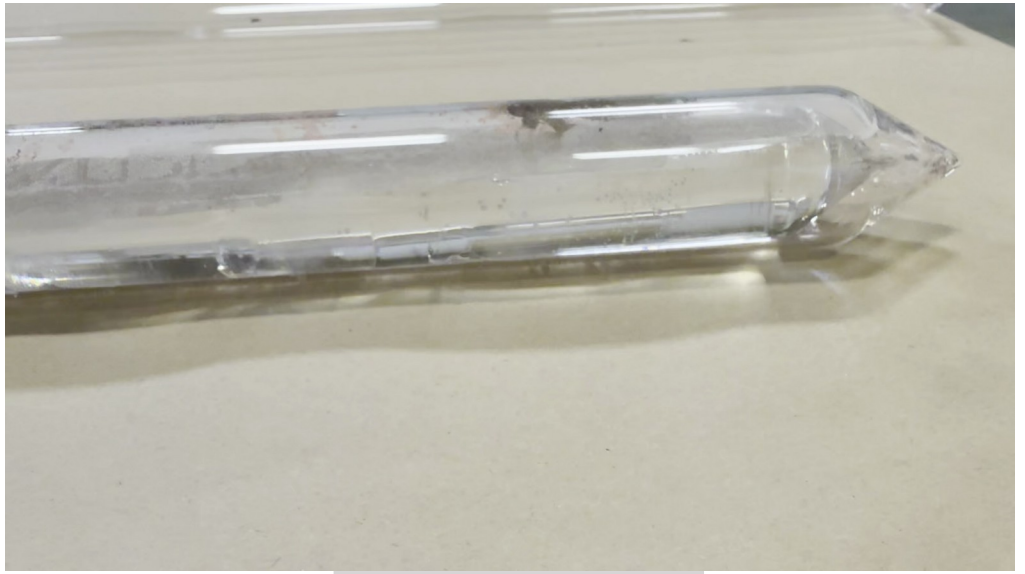


- Zone refining technique successfully used in semiconductor industry
- Some contaminants prefer to stay in molten zone
- Impurities are segregated to one side of the ingot by moving annular ovens
- Tested on NaI ***Astro Grade*** powder by Princeton group at Mellen company, Concord, NH (USA)

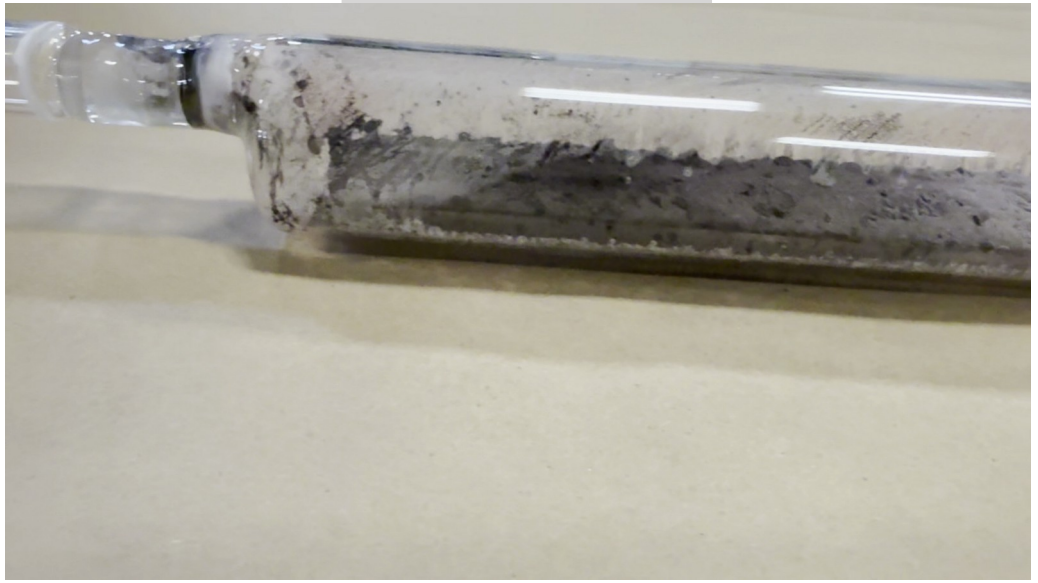
ZONE REFINING



Zone refiner



Ingot after ZR



We use $SiCl_4$ during ZR runs to prevent sticking

ZONE REFINING

for **NaI-42**
performed on Astro Grade powder (from Merck) we already had
(4 different batches)

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

Expected average K contamination ~ 2 ppb

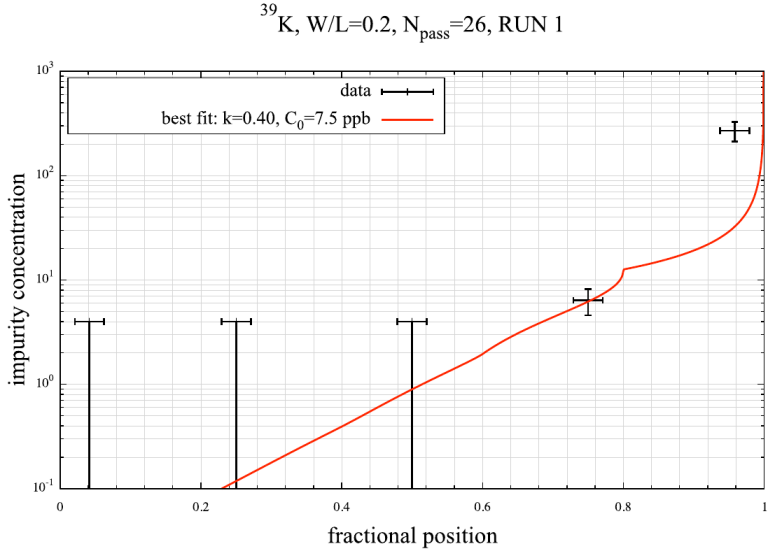
ZONE REFINING

Efficiency of zone refining from commissioning and production runs

$f_{pur} = \overline{C}/C_0$

	^{138}Ba	^{44}Ca	^{39}K	^{24}Mg	^{208}Pb
coeff. of purification	0.06	1.21	0.24	1	1.1
1 σ range	0.03-0.14	1.20-1.22	0.13-0.31	0.94-1.04	1.08-1.13
Average residual concentration of contaminants [ppb]	0.018	45.1	**1.55** (7 in origin)	1.97	1.98

on Astro Grade powder



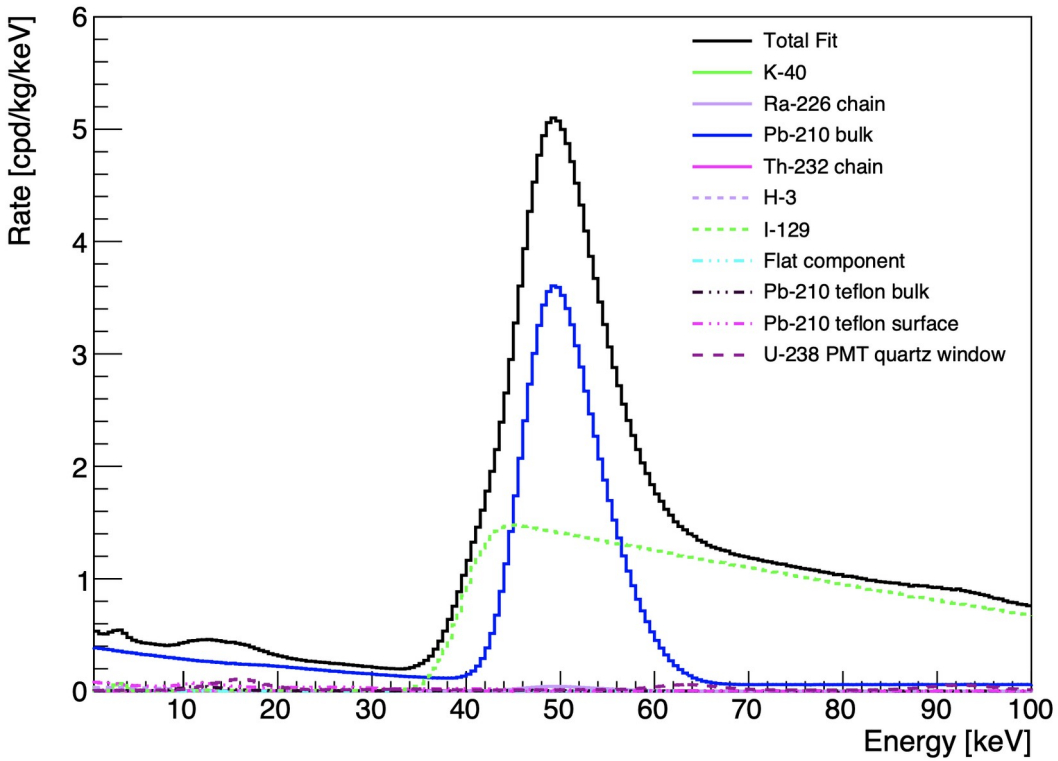
Our paper on ZR: **2601.15998**

ZONE REFINING

Expected background in SABRE North 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

NaI-42

April 2026: ampoule for crystal growth loaded with ZR chunks

Filled with 9 kg of chunks from zone refined powder + 39 g of zone refined TlI (0.4%)

NaI-42

cut & polished

encapsulated &
shipped to LNGS

Our very first full-size crystal grown from zone refined powder!

grown with zone-refined Astro Grade from 4 different batches

Mass: 3.43 kg
LY ~ 9.6 phe/keV and $\Delta E/E$ ~ 15% @ 59.5 keV

NaI-42

- ICP-MS measurements after zone refining showed good results on benchmark impurities or proxy (^{39}K, ^{85}Rb, ^{138}Ba, ^{238}U, ^{232}Th)

- Preliminary underground measurement on ^{210}Po build-up indicates ^{210}Pb contamination at the level of a few mBq/kg (higher than expected)

- Investigation of the source of such contamination is underway

→ Next crystal is already growing, from zone-refined COSINE-200 powder

→ *Expected in LNGS end of October*

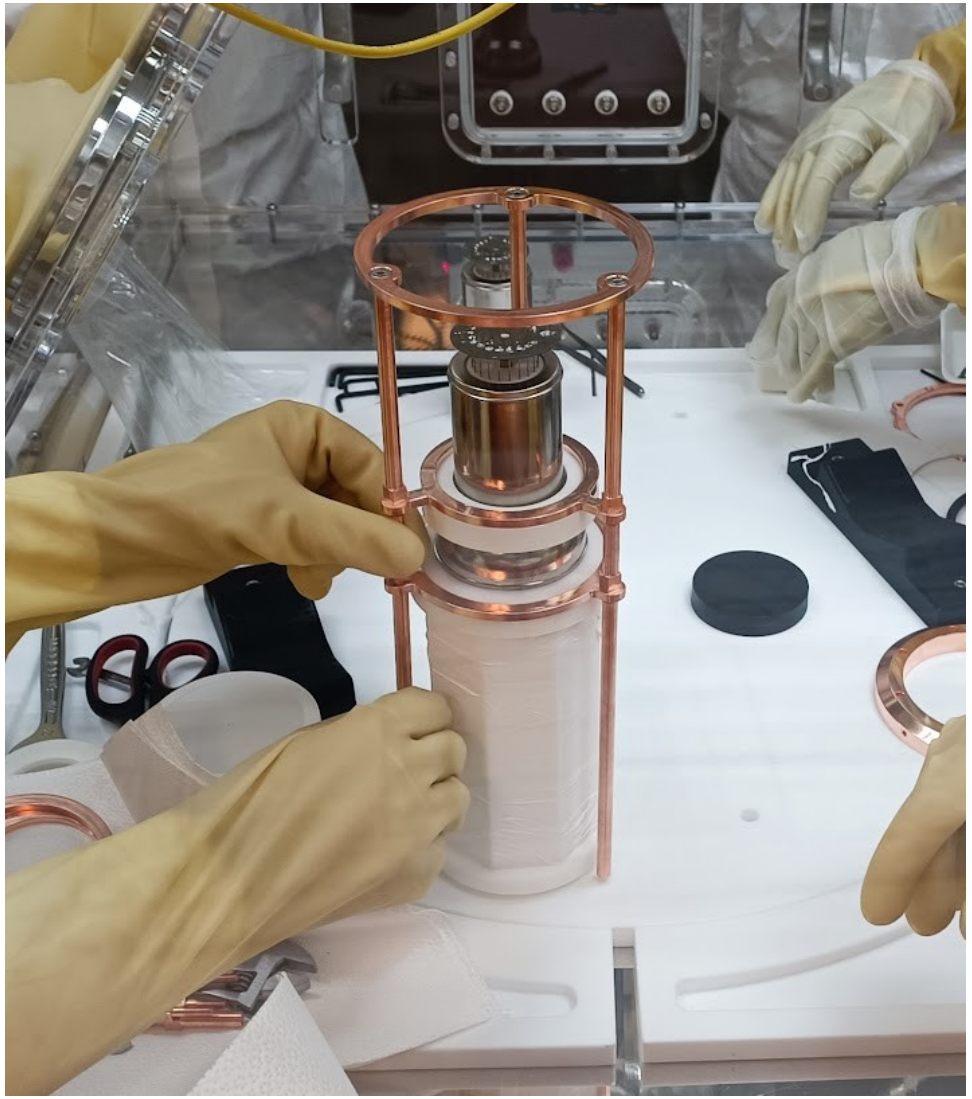
SUMMARY

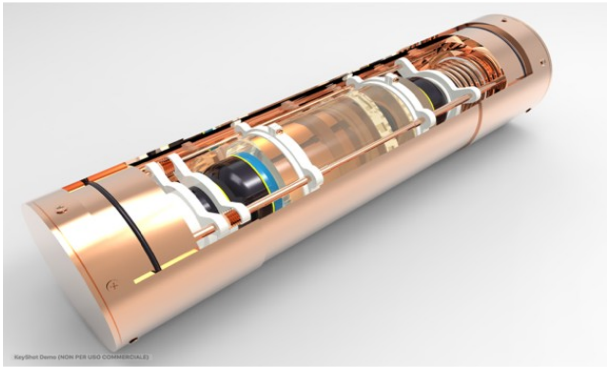
- Goal of SABRE experiment is to search for annual modulation with two NaI(Tl) detectors in the Northern and Southern Hemisphere.
- SABRE North will grow crystals from COSINE-200 collaboration powder.
  → ICP-MS characterization will be performed at LNGS with <1 ppb sensitivity on K
- First crystal from zone-refined powder - NaI-42 is ready, but not as good as we expected.
- We are already growing a crystal from zone-refined powder provided by COSINE collaboration.
- Background level of ~0.5 cpd/kg/keV is within reach with ZR
- Physics data taking will start in 2028
  → We expect to exclude/confirm annual modulation within 3-5 years

Thank you for your attention!

backup slides

Enclosure





ZONE REFINING

Test runs 2023-2024

Distribution coefficient, $k = C_s / C_l$

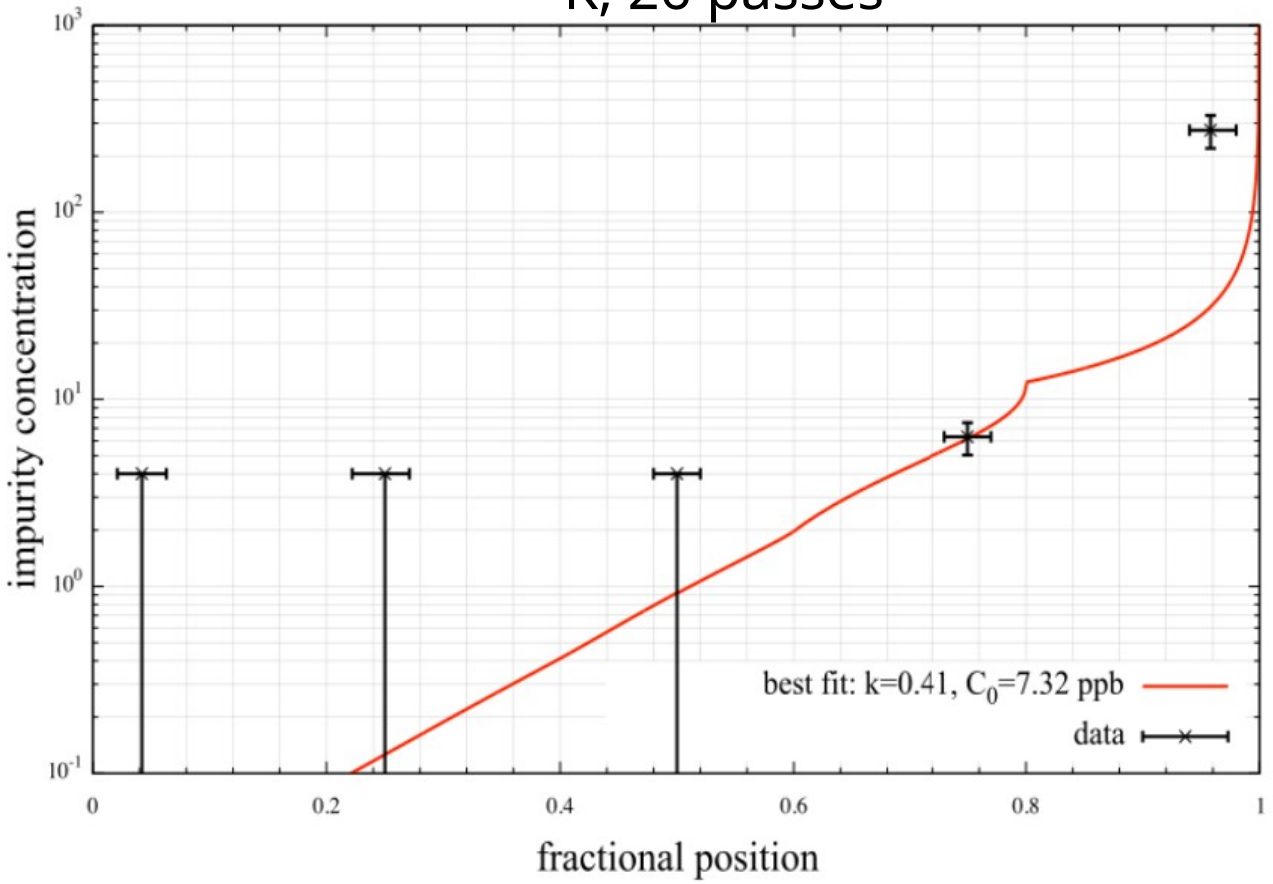
Concentration in solid phase

Concentration in liquid phase

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

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)

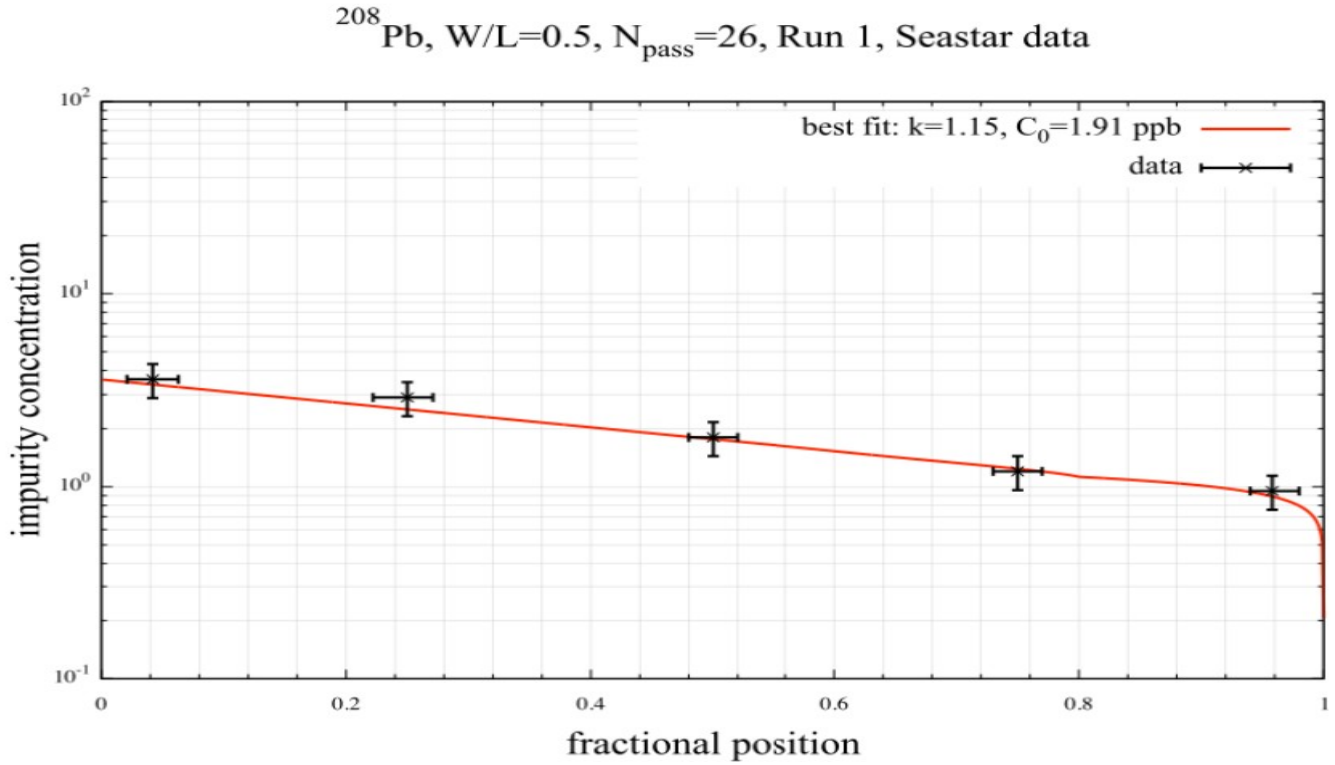
^{39}K, 26 passes



ZONE REFINING

Problem with Pb

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

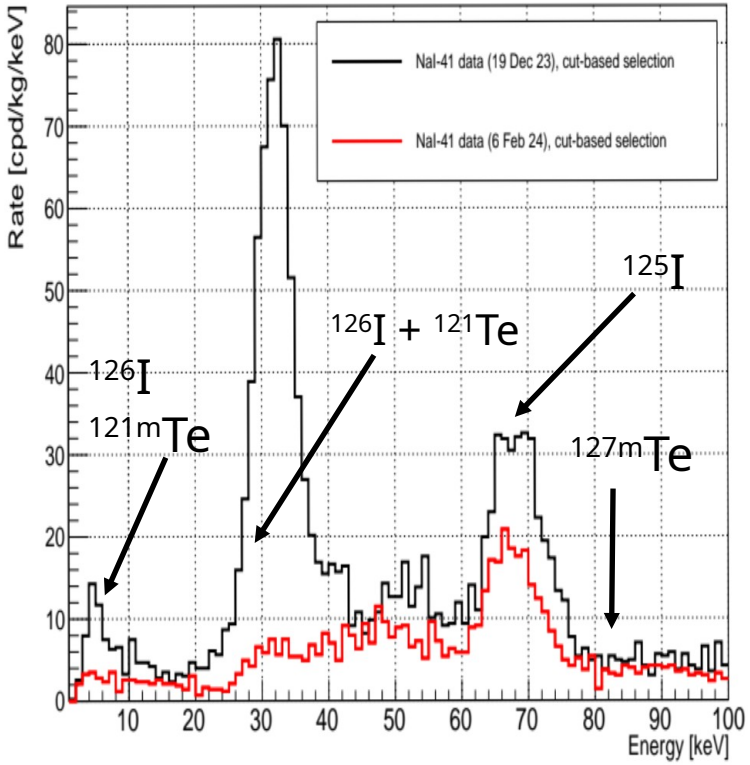


Best fit
k = 1.15 ± 0.03

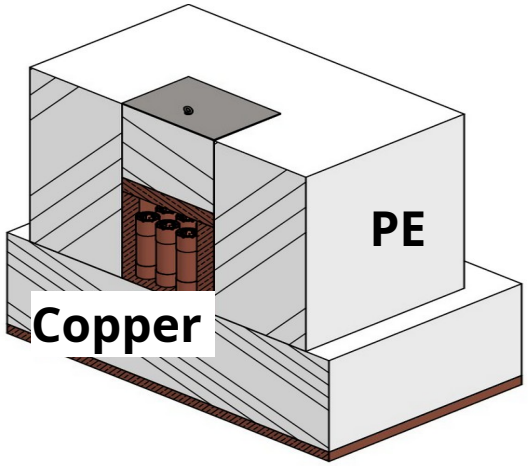
Cosmogenic backgrounds

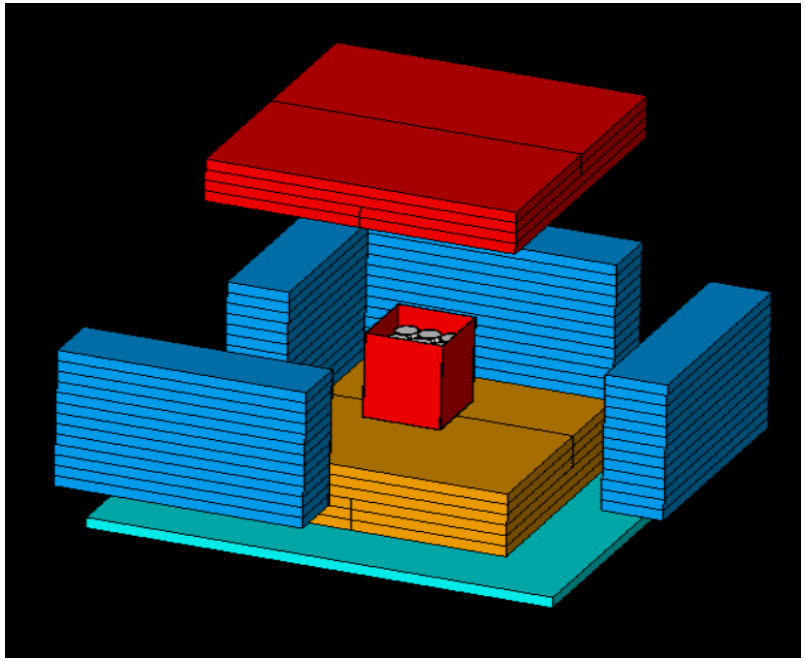
Isotope	$T_{1/2}$
^{129}I	1.57×10^7 yr
^{3}H	12.3 yr
^{22}Na	2.6 yr
^{109}Cd	1.3 yr
^{121m}Te	164 d
^{113}Sn	115 d
^{123m}Te	119 d
^{127m}Te	106 d
^{125}I	59 d
^{125m}Te	57 d
^{121}Te	19 d
^{126}I	12.1 d

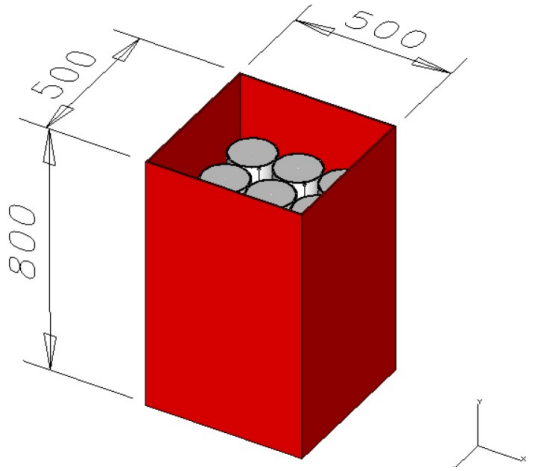
- Cosmogenic activation in the ROI mainly comes from ^{3}H, ^{113}Sn, ^{109}Cd, ^{22}Na
- Can be used for low energy calibrations: 0.87 keV (^{22}Na), 25.5 keV, 3.5 keV (^{109}Cd), 30.5 keV (^{121}Te), 67.8 keV (^{125}I)
- Minimum 1 year of “cooling” underground is required



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

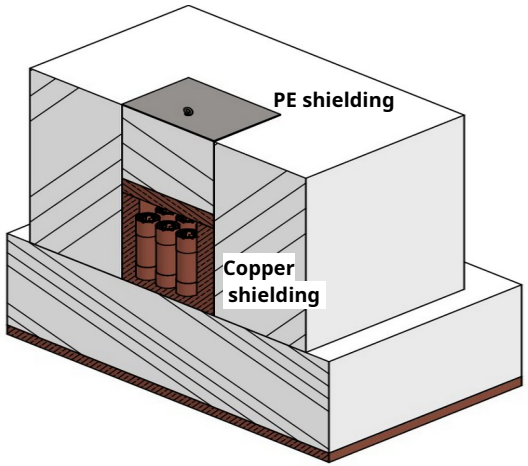
GOAL: background level lower than DAMA (~1 cpd/kg/keV) (in ROI)

- 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

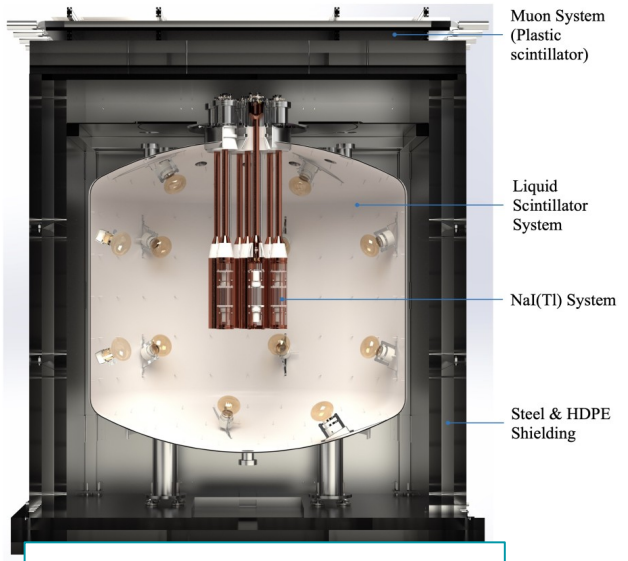
- Strategy to lower the **background:**
  - For internal backgrounds: → **zone refining**

  - 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