Jul 8-12 2024 L'Aquila (Italy)

# Status and prospects of the SABRE North experiment and NaI(Tl) crystal radiopurity

*D. D'Angelo*
Università degli Studi di Milano
Istituto Nazionale di Fisica Nucleare - sez. di Milano

**on behalf of the SABRE (North) collaboration**

**for SABRE (South) see talk by E. Barberio**

# SABRE motivation

**WHAT**

An experiment based on NaI(Tl) scintillating crystals and focused on the achievement of an ultra-low background

**WHERE**

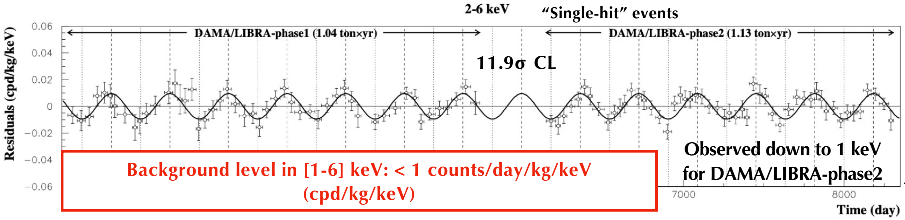
At the Gran Sasso National Laboratory (LNGS, Italy) and Stawell Underground Physics Laboratory (SUPL, Australia)

**WHY**

**Search for galactic dark matter (DM) through the annual modulation effect and perform a model-independent test of the long-standing DAMA result**

An annually modulated signal compatible with the DM hypothesis has been observed by the DAMA/LIBRA experiment at LNGS, in Italy.

250 kg of high purity NaI(Tl) crystals + passive shielding



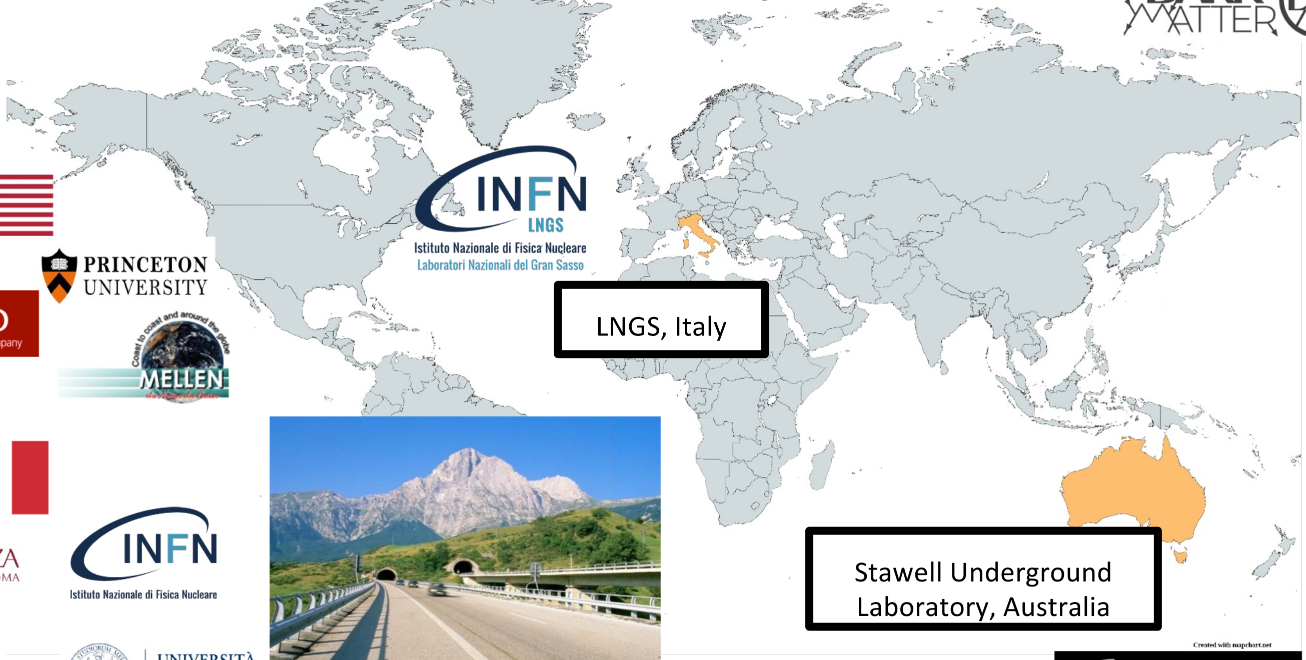

R. Bernabei et al., *Nuclear Physics and Atomic Energy*, 19(4):307–325, 2018.

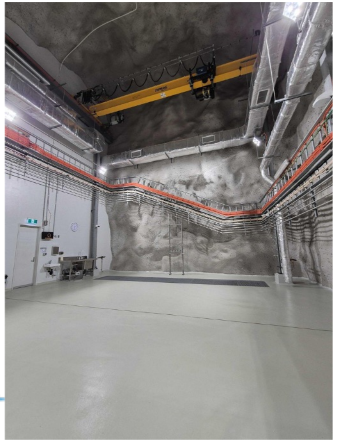
- Experiments using different target materials seem to exclude the interpretation of DAMA signal as due to spin-independent DM scattering off nuclei in the standard WIMP galactic halo hypothesis.
- Currently running experiments using the same target (ANAIS-112 and COSINE-100), have not yet reached the ultra-low background and sensitivity achieved by DAMA → A new high sensitivity and low background measurement with NaI(Tl) crystals is needed.

# SABRE: a dual site experiment

The ambitious program of SABRE foresees two detectors in two underground locations:

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



ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

Australian National University

THE UNIVERSITY of ADELAIDE

THE UNIVERSITY OF SYDNEY

SWIN BUR NE

KEK High Energy Accelerator Research Organization

PRINCETON UNIVERSITY

RMD A Dynasil Company

MELLEN

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEL SALENTO

UNIVERSITÀ DEGLI STUDI DI MILANO

STAWELL UNDERGROUND PHYSICS LAB

# 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 strategy

- SABRE Proof-of-principle (PoP) and PoP-dry achieved a background of ~1 cpd/kg/keV

  **We aim to ~ 0.5 cpd/kg/keV**

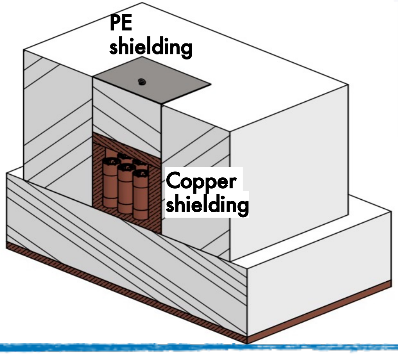
- Strategy to lower the **background:**
  - For internal backgrounds

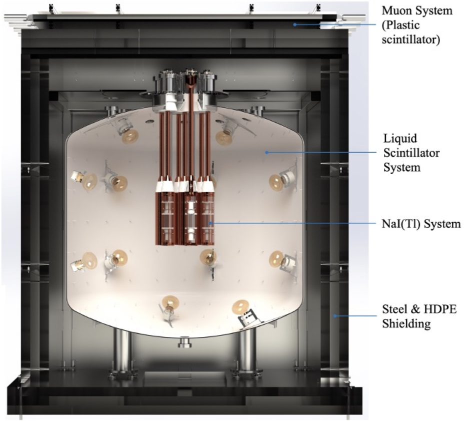
    → SABRE North & South: **zone refining**
    expected to reduce Pb of factor ~ 3, K of ~ 10
  - For external background:

    → SABRE North: improve passive shielding

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

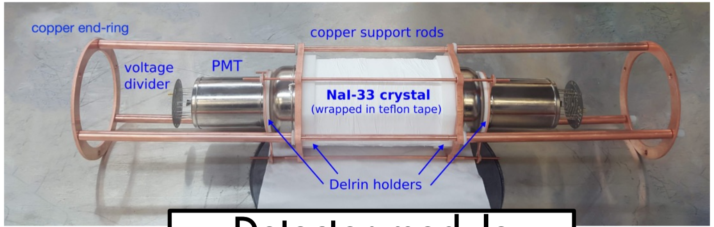
SABRE North



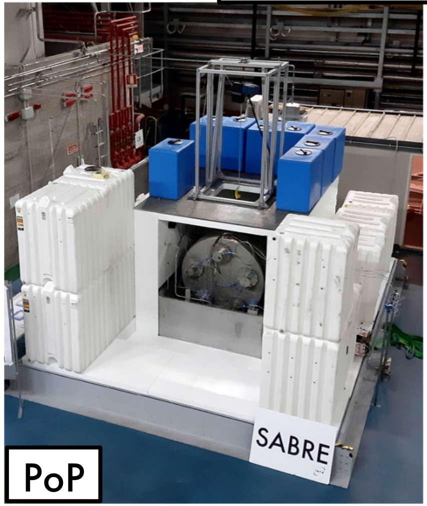




SABRE South

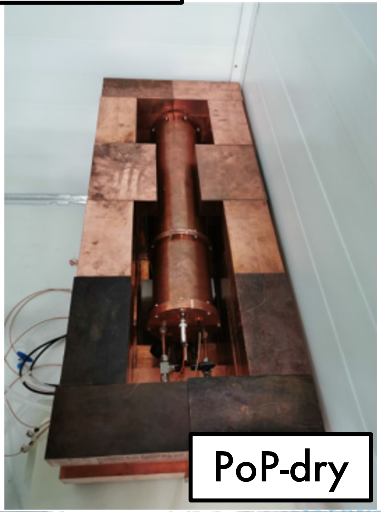
# The SABRE Proof-of-Principle
## @LNGS (2018-2022)




Detector module




PoP



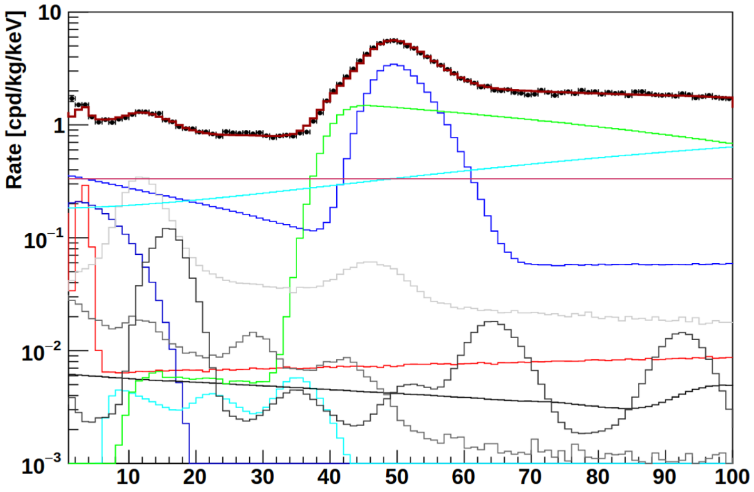
PoP-dry

- Run in 2020 with liquid scintillator and NaI-33 crystal
  - 2 tons active veto with 10 x 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 2021/22: passive shielding with additional layer of copper
  - confirmed background level

# SABRE background model (NaI-33)

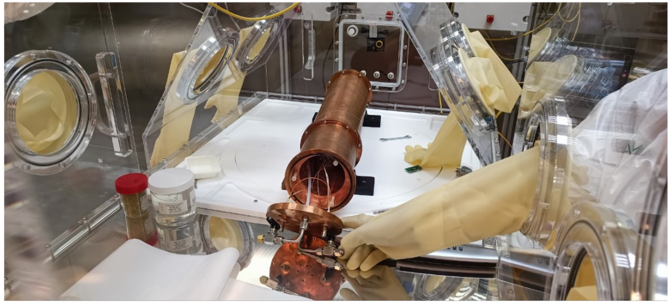
- Background model updated since Eur. Phys. J. C (2022) 82:1158
- Background from reflector is not dominant (now constrained from direct measurements)
- Dominant backgrounds: $^{210}$Pb in crystal bulk and external background

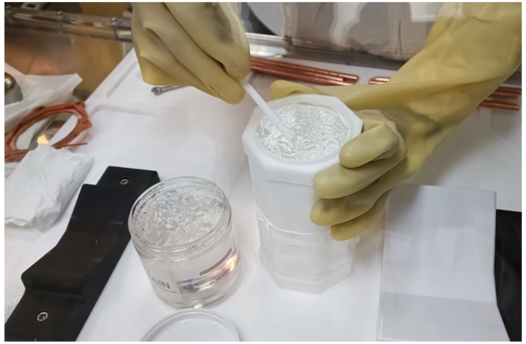
| Source | Rate in ROI [1,6] keV [cpd/kg/keV] | Activity from fit |
|---|---|---|
| 40K | 0.125 | 0.16±0.01 mBq/kg |
| 210Pb bulk | 0.333 | 0.49±0.05 mBq/kg |
| 210Pb reflector bulk | 0.054 | 11±1 mBq/kgPTFE |
| 210Pb reflector surface | 0.023 | <0.6 mBq/m2 |
| 3H | 0.198 | 24±2 mBq/kg |
| 129I | 0.0003 | 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 | |



# Crystal operations in glovebox (2022-23)

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



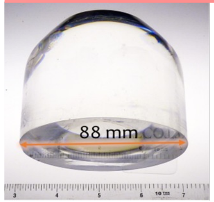


All operations successful and moisture level in the glove-box kept always below 5% RH

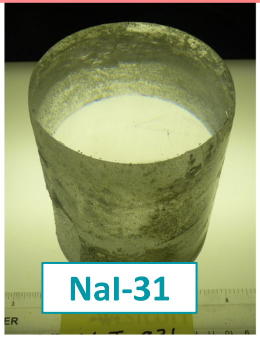
# SABRE crystals R&D

- R&D carried out by PU, INFN and ARC Centre of Excellence for DM
- Radioclean NaI powder *Astrograde* by Sigma Aldrich now Merck, Germany
- Crystals grown by RMD - Radiation Monitoring Devices, MA (USA)
    - Vertical Bridgeman method in fused silica vessels

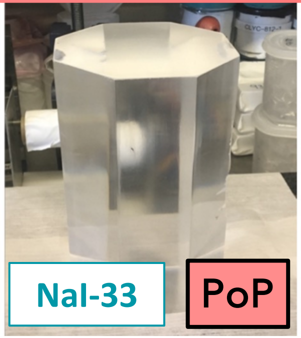
**2015**



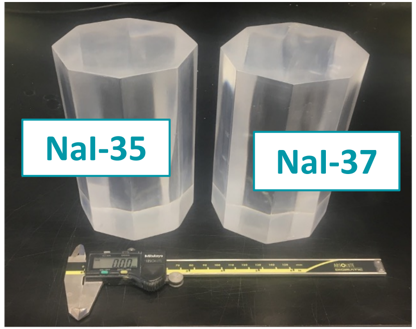

**2018**



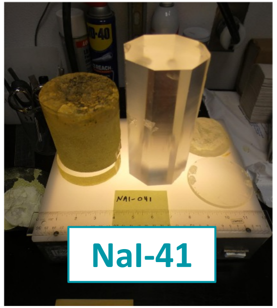

**2019**




**2022**



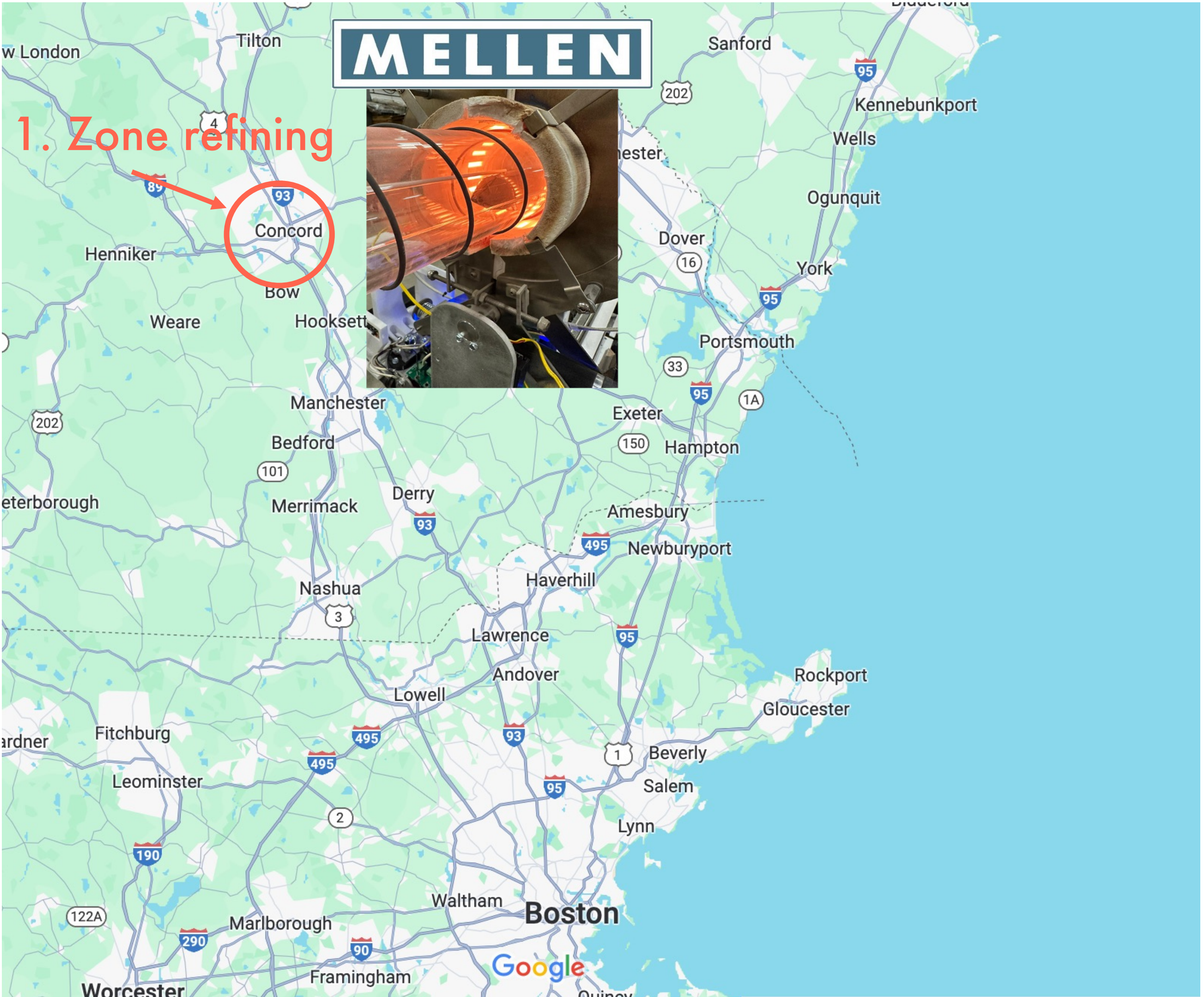

**2023**



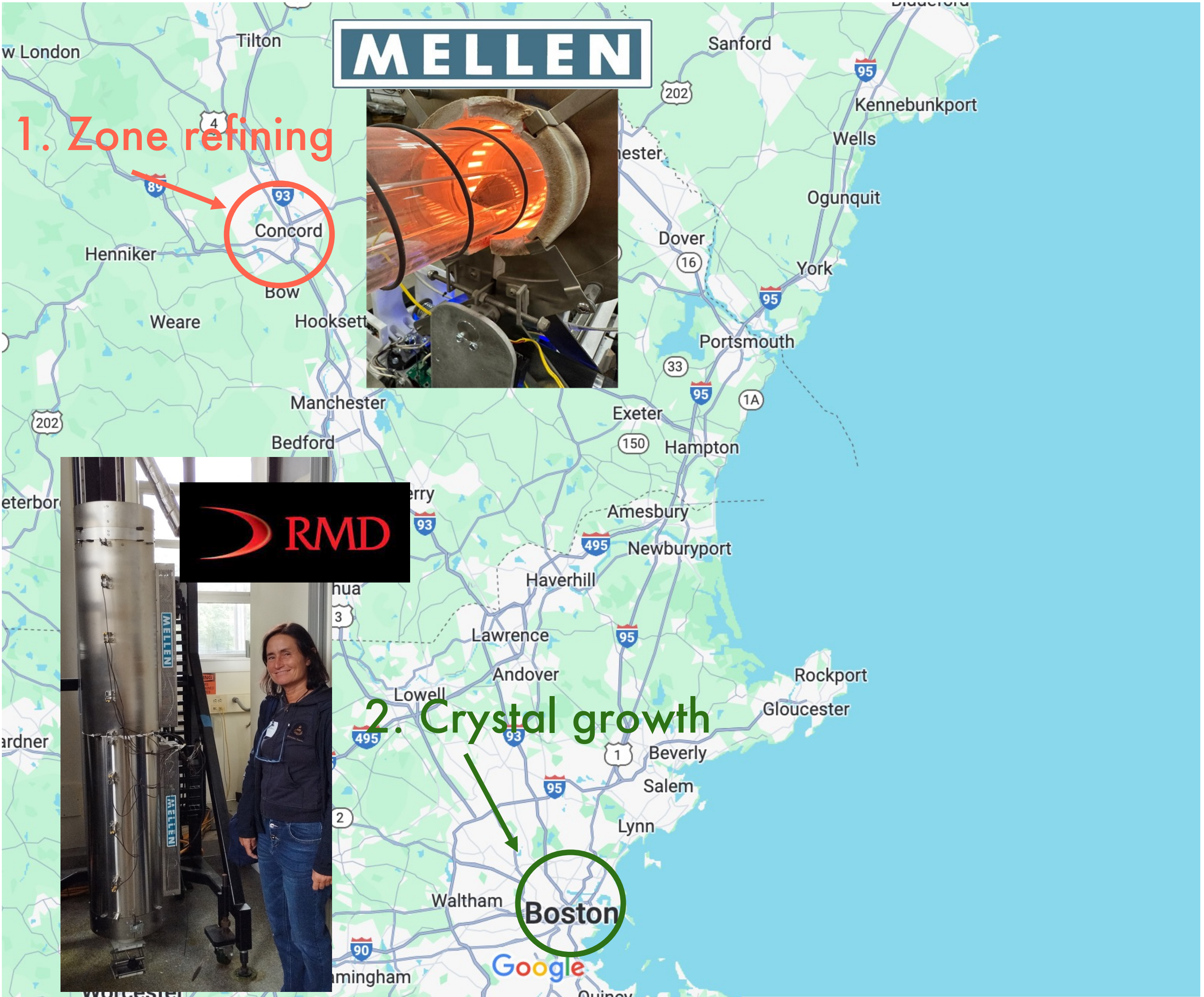

Expected in 2024: NaI-42 grown after zone refining

- NaI-33: background ~ 1 cpd/kg/keV → close to DAMA/LIBRA Phase 1
- NaI-35, NaI-37: reproducibility within factor 2
- NaI-41: grown from chuncks rather than powder → demonstrated same optical quality

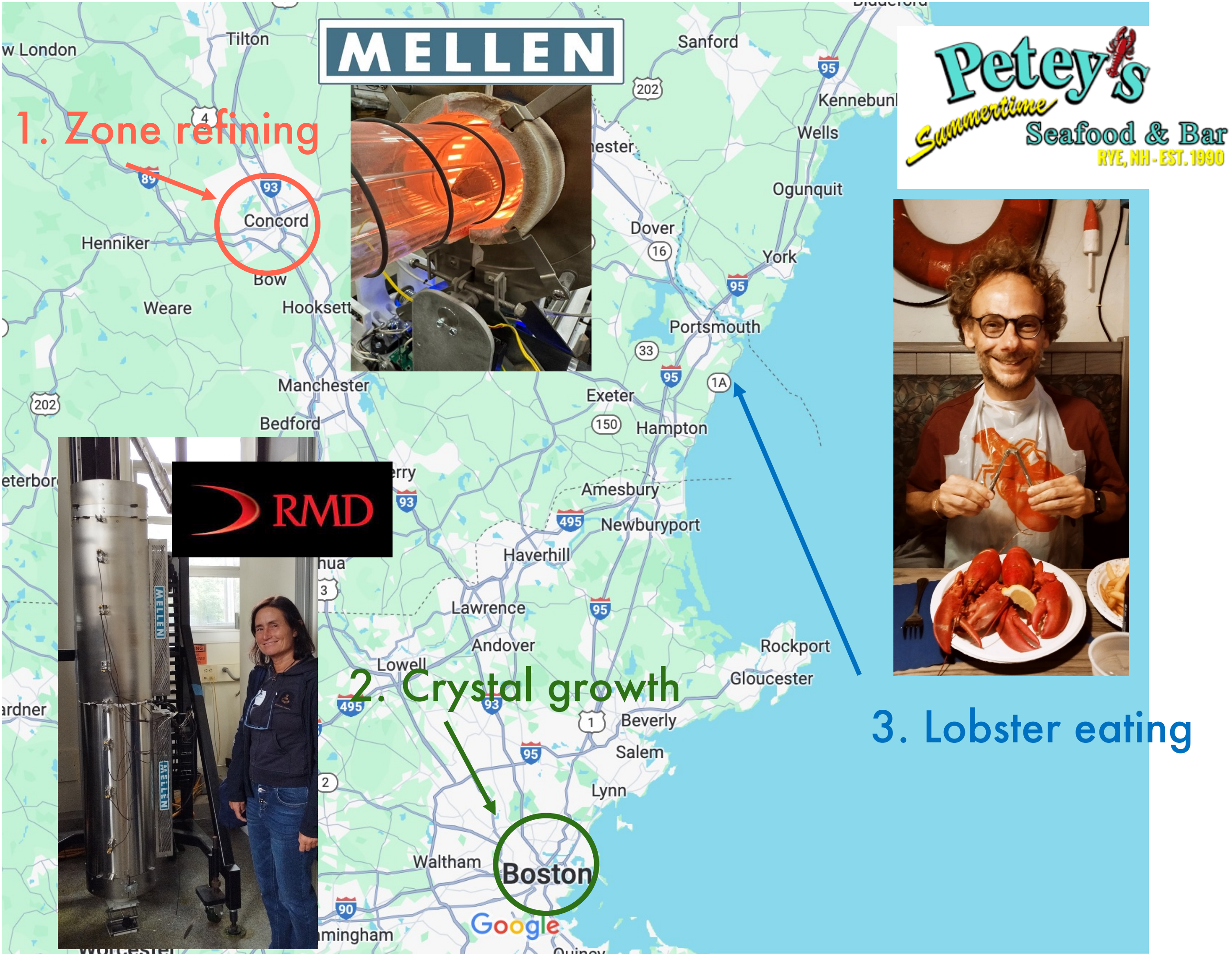
# The SABRE strategy



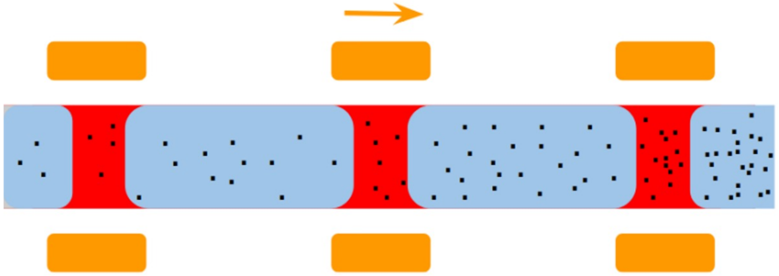
# The SABRE strategy



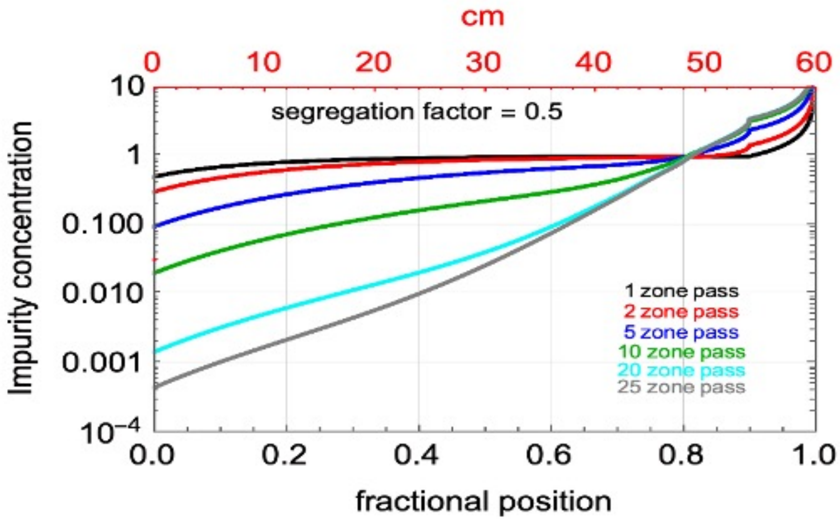
# The SABRE strategy



# 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)




| 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 |

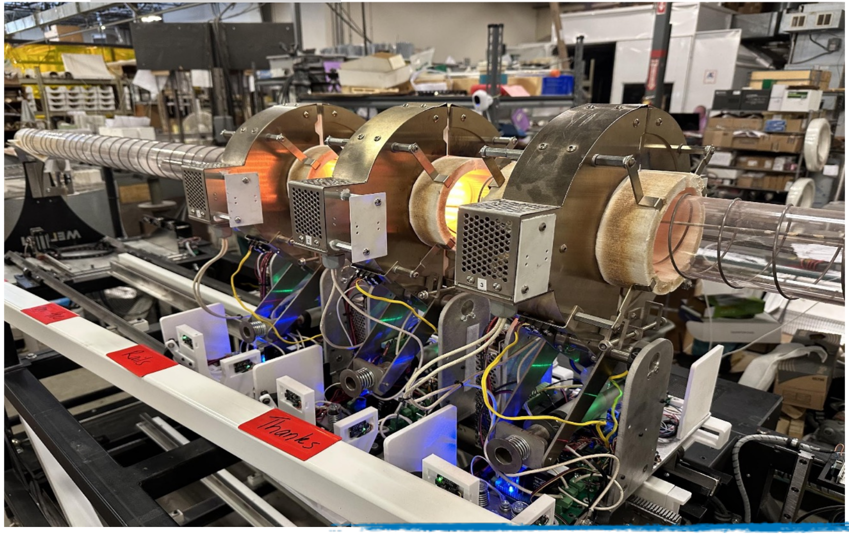
Phys. Rev. Applied 16, 014060 (2021)

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

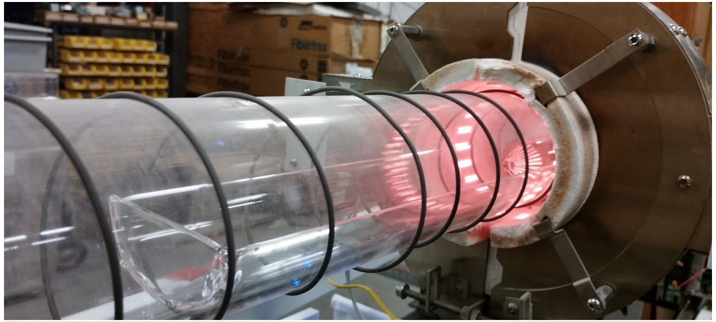
# Zone refining
## (2023 - 2024)

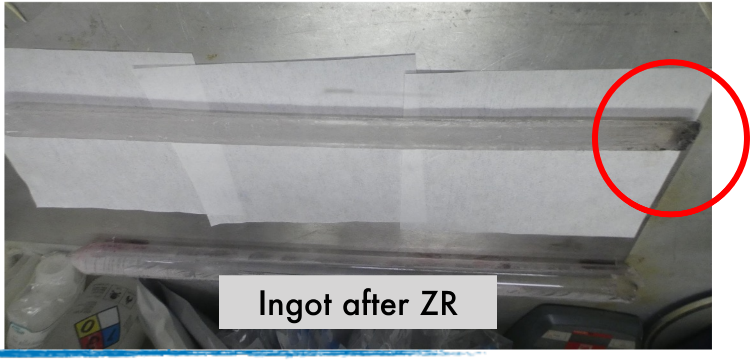
4 runs with *Astrograde* NaI powder performed at MELLEN, Concord NH, USA.

Zone refiner









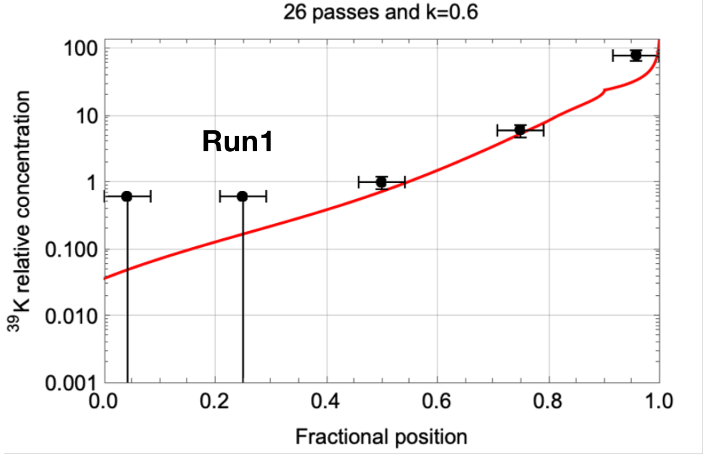
# Zone refining
## (2023 - 2024)

| run | Date | Ampoule | Astrograde lot # | Loaded Mass [gr] | ZR speed [mm/h] | # passes |
|---|---|---|---|---|---|---|
| 1 | set/oct 23 | C coating | 76650 | 893 | 38 | 26 |
| 2 | oct/nov-23 | C coating | 76650 | 900 | 38 | 51 |
| 3 | gen-24 | with $SiCl_4$ | MKCC0371 | 900 | 50 | 60 |
| 4 | feb/apr-24 | with $SiCl_4$ gas removed | MKCC0371 | 900 | 50 | 56 |

Could be our preferred option

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

# Zone refining test results



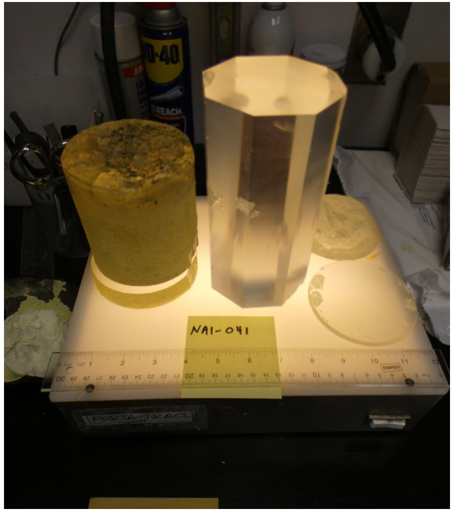

| Sample Run4 | $^{39}$K [ppb] | $^{65}$Cu [ppb] | $^{85}$Rb [ppb] | $^{133}$Cs [ppb] | $^{138}$Ba [ppb] | $^{208}$Pb [ppb] |
|---|---|---|---|---|---|---|
| powder | 7 | 5 | <0.2 | 1 | 3.6 | 1.1 |
| Zone 1 | <4 | <4 | <0.8 | <0.3 | <0.3 | 2.0±0.3 |
| Zone 2 | <4 | <4 | <0.8 | <0.3 | 1.2±0.3 | 1.6±0.2 |
| 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 |

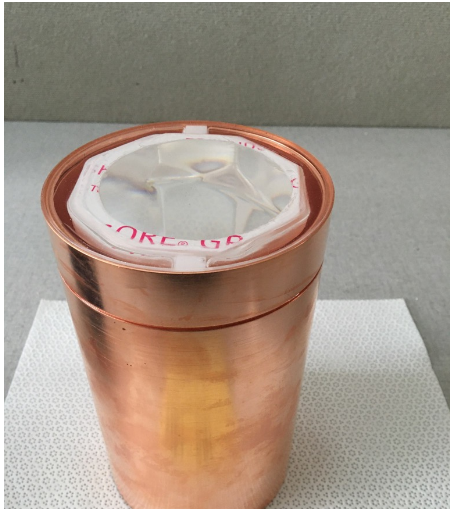
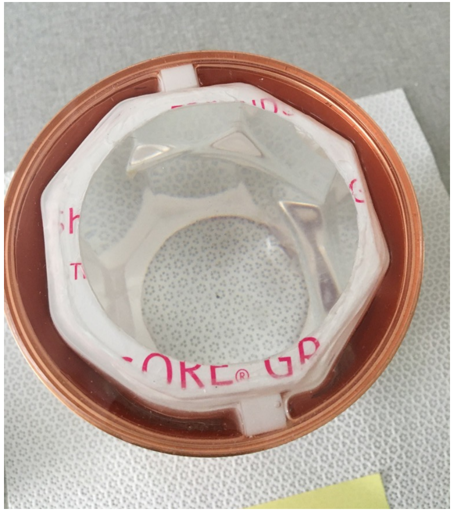
# Strategy for Pb reduction

1. Glove box:
   - Pb contamination probably occurred in the glove box used so far at RMD for material handling
   - Now dedicated glove box from Princeton University
   - Reburbished and instrumented with a pipe for crystal insertion
2. Purging:
   - Pb compounds are highly volatile at the temperature of ZR
   - Under study the possibility to gas purge the volume during ZR

# NaI-41

- Full size (4.3 kg) crystal grown <u>from chunks</u> from NaI-40
- *LY and energy resolution: same as crystals grown from powder!*
- K at 5 ppb
  - By ICP-MS interpolating three samples: tip, tail and far tail.
- alpha background: similar to previous crystals




NaI-41 is an enabling step in our strategy to grow high radiopurity crystals

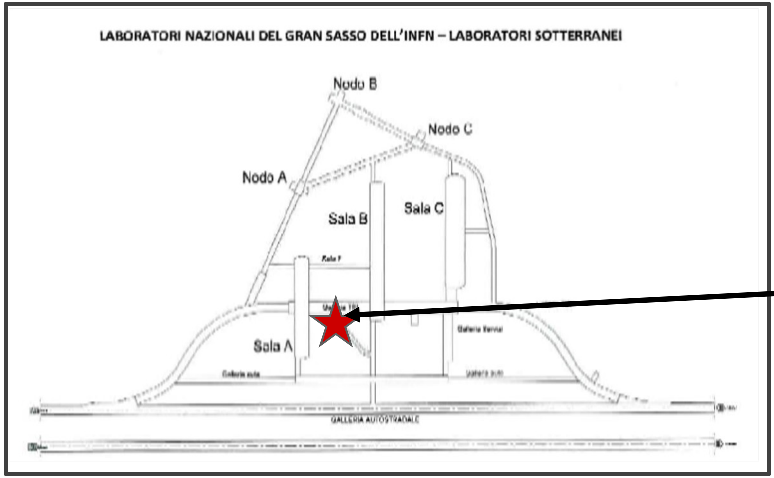
# SABRE North new area @LNGS (2024)

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

(formerly hosting COBRA and Heidelberg/Moscow $\beta\beta$-deacy experiments)

Consists of a two storeys building:

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

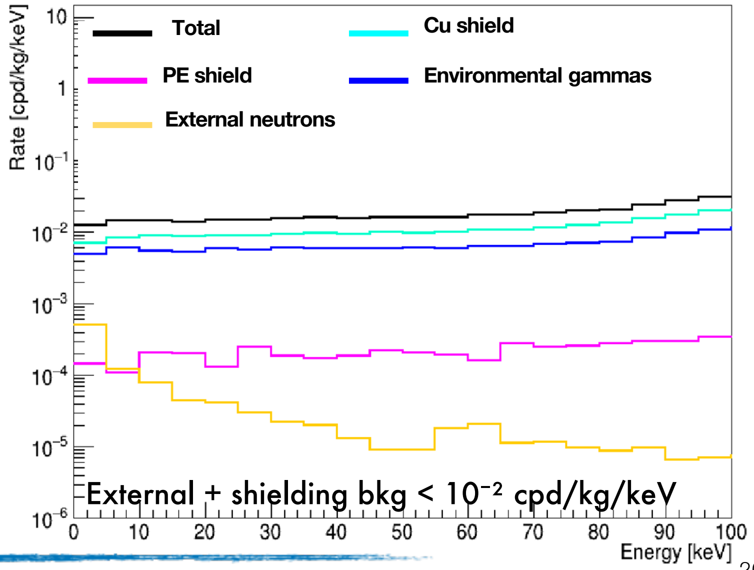



PoP-dry refurbished and moved in

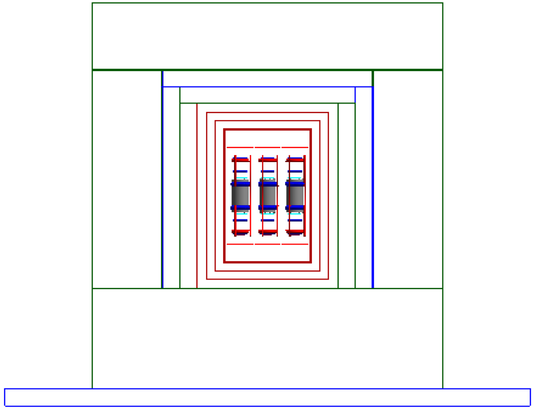
# SABRE-North status

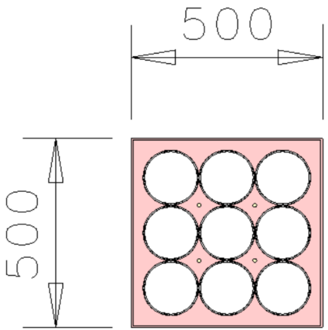
- NaI-42 crystal grown after Zone Refining coming this year!
- TDR presented June 2024 for the physics phase detector
  - 3x3 crystal matrix, ~ 5 kg each
  - Fully passive shielding: 25 cm Cu + 50 cm PE
    - enough shielding power
    - negligible background contribution
- Expected background: ~ 0.5 cpd/kg/keV (with ZR)
- Schedule:
  - First crystal delivered end of 2025
  - Last beginning of 2027

| Source | Contribution in [1,6] keV units dru |
|---|---|
| Internal: NaI + PMTs + PTFE | 0.5 |
| Enclosure: Copper + Delrin | 0.032 |
| Shielding: Cu + PE | 0.01 |
| External gammas + neutrons | 0.001 |

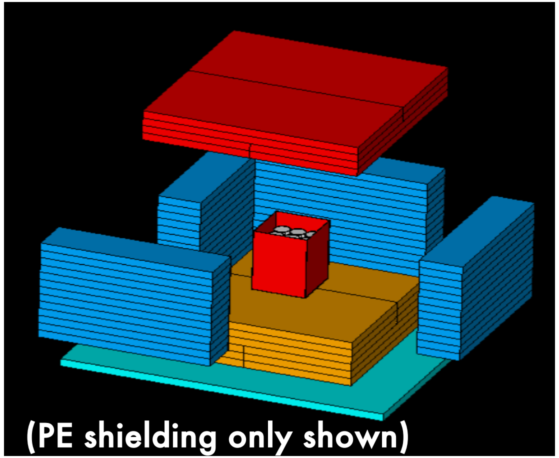


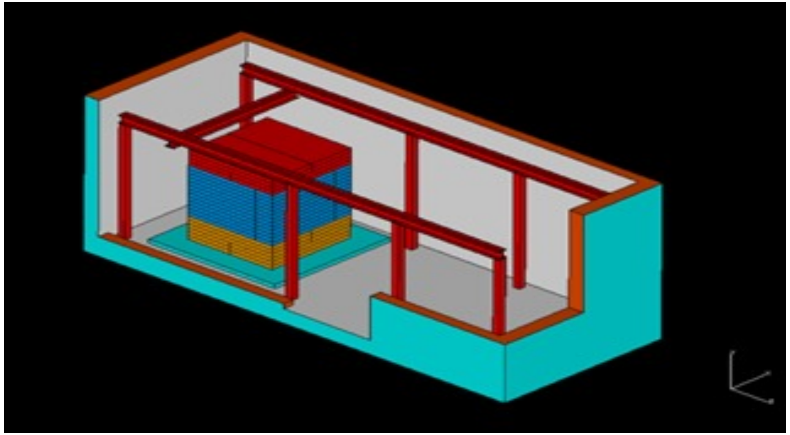
# The SABRE North detector design






3x3 crystal matrix



# Conclusions

**Past:**

- SABRE PoP and PoP-dry demonstrated a background of ~ 1.2 cpd/kg/keV [1-6] keV ROI
  - **NaI-33 crystal is a <u>breakthrough</u> for radio-purity after DAMA/LIBRA**
- vetoable backgrounds, such as $^{40}$K, are low enough: a background rate lower than DAMA/LIBRA is at hand also with a passive shielding

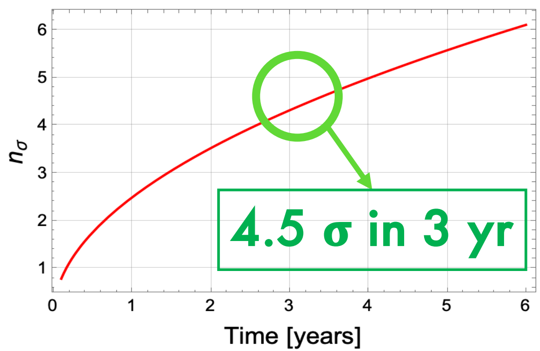
**Present:**

- Zone Refining of *Astrograde* powder has been perfected across 4 tests: successful reduction of key backgrounds
- SABRE facilities now installed into the final location at LNGS
- Technical Design Report presented to INFN CSN2 in June 2024
- NaI-42 grown after Zone Refining coming this year

**Future:**

- An array of 9 crystals for a total mass of ~ 45 kg:
  - within a multi-layer passive shielding
- Projected background ~ 0.5 cpd/kg/keV
- Schedule: late 2025 (first crystal) to early 2027 (last crystal)

45 kg, 0.5 dru




SABRE-North only!

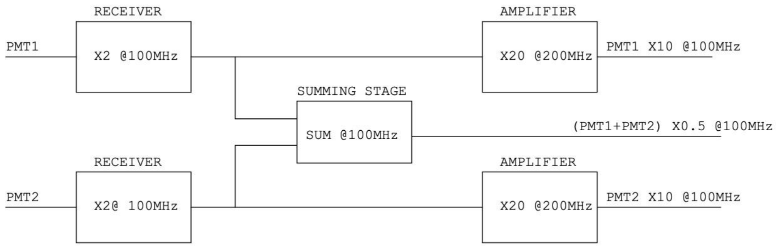
Dual site SABRE North+South analysis will yield a faster result

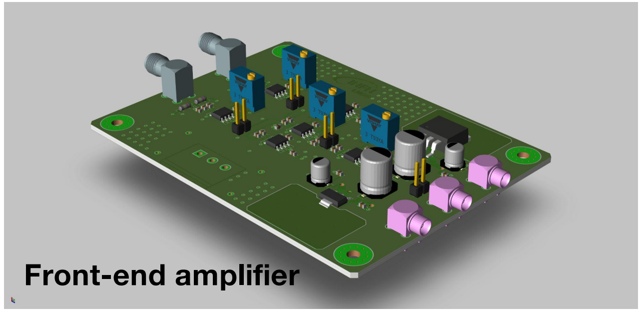
# Backup

# Summary of crystals characterization

| | Powder Astro Grade batch | Mass [kg] | LY [phe/keV] | 39K [ppb] powder | 39K [ppb] crystal | 210Pb [mBq/kg] | Rate ROI [dru] | 214Bi-Po [ppt] (238U) | 212Bi-Po [ppt] (232Th) |
|---|---|---|---|---|---|---|---|---|---|
| NaI-31 | MKBW4911V | 3.0 | 9 | 8.0 | 18.5±0.7<br>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<br>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 | 0.49±0.01<br>(initial activity) | - | - | - |

# Electronics and DAQ

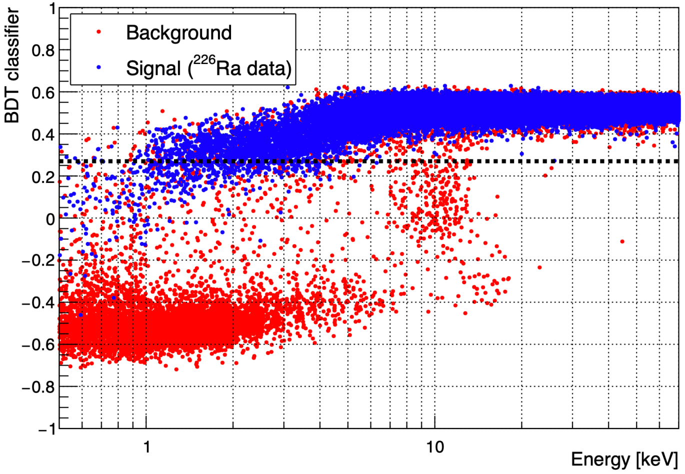




Front-end amplifier

- Waveform digitizers CAEN v1730 8-channels boards
- 500 Msa/s, 14-bit resolution
- Acquisition: 8-10 μs and no dead time
- Self triggering

# Low energy data analysis

*A more innovative Boosted Decision Trees (BDT) approach used to maximize the acceptance of scintillation events at very low energies while efficiently rejecting noise.*



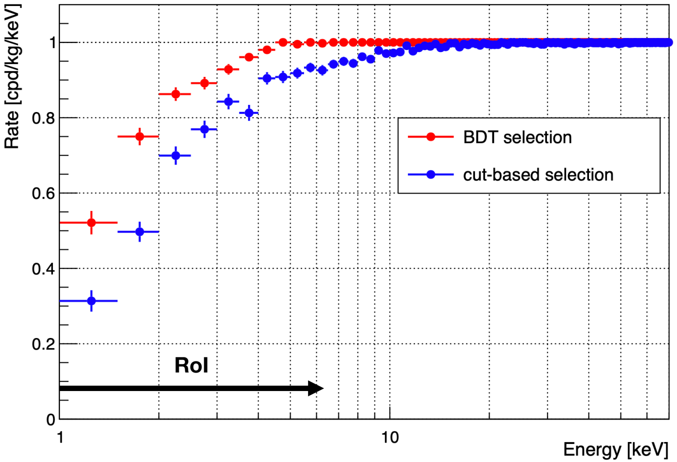

Lower scores → noise-like events.

Higher scores → signal-like events.

BDT cut threshold (black dashed line) chosen based on data acquired with the $^{226}$Ra source to have an average event acceptance in the RoI > 90%.

**Training samples:**

- Signal: $^{226}$Ra source data acquired by triggering only on coincidences between the two crystals, selecting events in the 0.5-10 keV energy region;
- Noise: background runs selecting events in the 0.5-4 keV energy region (dominated by noise).




NaI-33 PoP-dry data

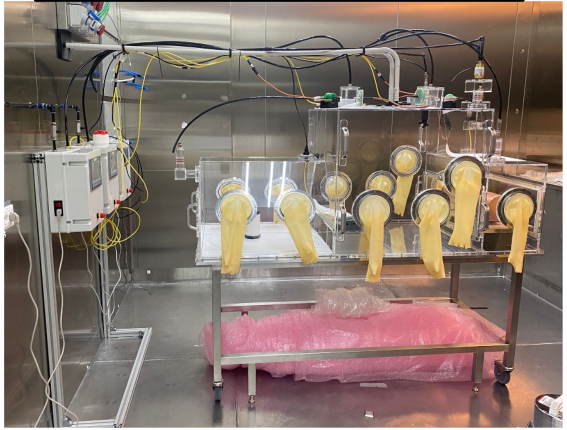
# SABRE North facilities @LNGS (2022-2023)

- 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 3 detector modules
- Flushed with N2

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



# SABRE high-purity NaI(Tl) crystals

The main background in the 1-6 keV energy region of interest (ROI) for DM search is due to crystal intrinsic contaminants: $^{238}U$, $^{232}Th$, $^{40}K$, $^{87}Rb$, $^{210}Pb$.

Extensive R&D program carried out by the SABRE Collaboration and industrial partners to develop high-purity NaI(Tl) scintillating crystals.

<u>Key ingredients:</u>

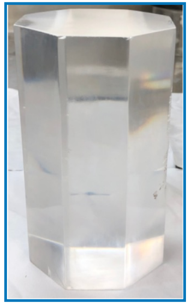
A. Ultra-high purity NaI powder

- **AstroGrade powder** developed in collaboration with **Sigma-Aldrich.** Now the standard powder for NaI-based low background experiments.

| Isotope | **AstroGrade NaI powder [ppb]** |
|---|---|
| $^{nat}K$ | 9.7 |
| $^{238}U$ | $0.6 \times 10^{-3}$ |
| $^{232}Th$ | $0.5 \times 10^{-3}$ |
| $^{87}Rb$ | 0.2 |

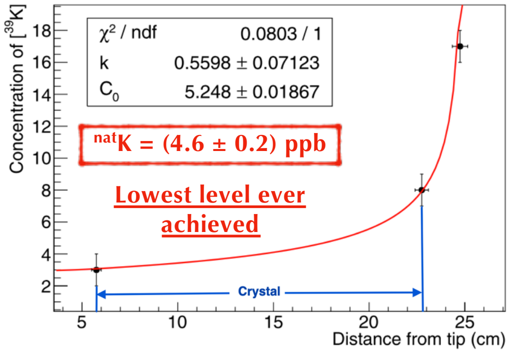
B. Ultra-clean crystal growth method

- **Vertical Bridgman (VB)** method optimized in collaboration with **Radiation Monitoring Devices Inc. (RMD).**



NaI-33 after cut and polishing

$^{39}K$ distribution as a function of distance from tip in NaI-33 (measured by ICP-MS)




B. Suerfu et al., *Phys. Rev. Research*, 2:013223, 2020.

# Potassium direct counting with SABRE PoP

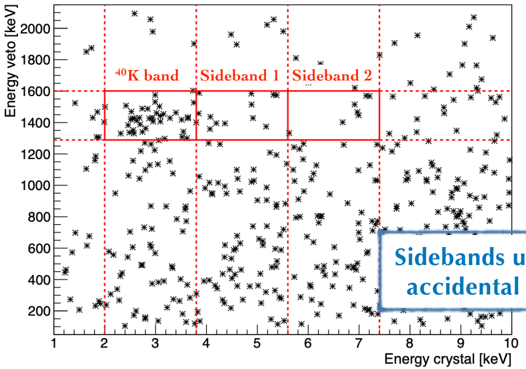
**Coincidence analysis between crystal and veto detector**

**Requirements:**

- A crystal energy deposition within $\pm 1\sigma_c$ around the 3.2 keV peak ($\sigma_c$ energy resolution of the crystal);
- A veto energy deposition within $\pm 2\sigma_v$ around the 1461 keV $\gamma$ peak ($\sigma_v$ energy resolution of the veto).

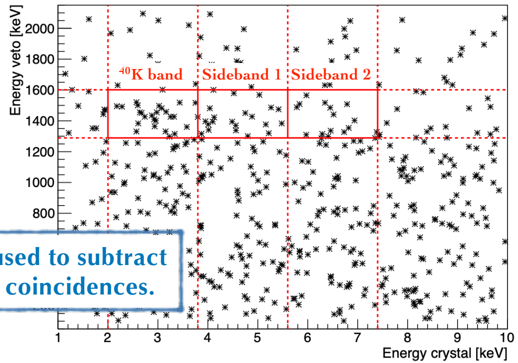
**Efficiency of the selection (calculated by Monte Carlo) taken into account in the analysis.**

**NaI-31**




**Exposure: ~60 kg · days**

**NaI-33**




**Exposure: ~90 kg · days**

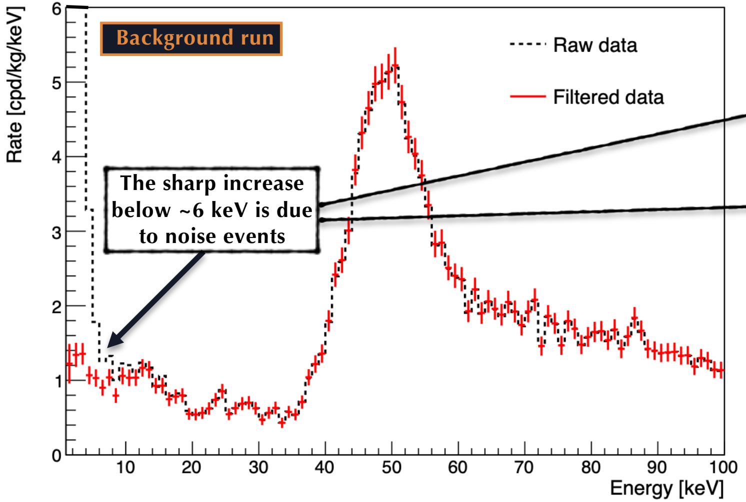
Sidebands used to subtract accidental coincidences.

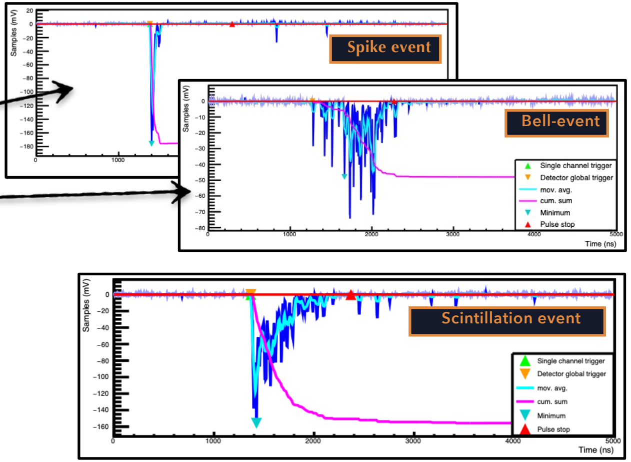
| | NaI-31 | NaI-33 |
|---|---|---|
| **$^{40}$K activity [mBq/kg]** | 0.49 ± 0.10 | 0.07 ± 0.05 |
| **$^{nat}$K contamination [ppb]** | 15.7 ± 3.2 | 2.2 ± 1.5 |
| **$^{nat}$K contamination by ICP-MS [ppb]** | 17.7 ± 1.1 | 4.6 ± 0.2 |

**Upper limits for NaI-33 (90% CL):**

- **$^{40}$K activity:** < 0.15 mBq/kg;
- **$^{nat}$K contamination:** < 4.7 ppb.

# NaI-33 low energy data analysis




**Pulse Shape Discrimination (PSD) parameters used to select scintillation events**

# PSD parameters

- **Amplitude weighted Mean Time:** $< t >_{600} = \frac{\sum_{t_i<600ns} h_i t_i}{\sum_{t_i<600ns} h_i}$

  time of the i-th sample (starting from the trigger $t_0$)

  pulse amplitude in mV

  Rejects events that are too long or too short, such as tail-events following very high energy interactions and Cherenkov light emission in PMTs, respectively.

- **Charge over Maximum:** $CoM = \frac{C_{(0,1000)}}{h_{max}}$

  pulse area between 0 and 1000 ns

  absolute value of the maximum pulse amplitude in mV

  Rejects mainly PMTs noise, such as spike events.

- **Head-to-middle pulse shape:** $C_2/C_1 = \frac{C_{(200,400)}}{C_{(0,200)}}$

  pulse area between 200 and 400 ns

  pulse area between 0 and 200 ns

- **Middle-to-tail pulse shape:** $C_3/C_2 = \frac{C_{(400,600)}}{C_{(200,400)}}$

  pulse area between 400 and 600 ns

  pulse area between 200 and 400 ns

  Reject events that do not have the proper shape of a scintillation pulse, such as bell events.

- **Trigger Time Delay:** TTD: Time delay between the signals of the two PMTs.

  Reject afterglows in PMTs.