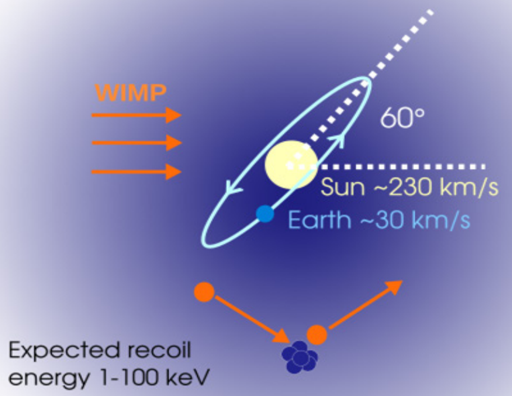
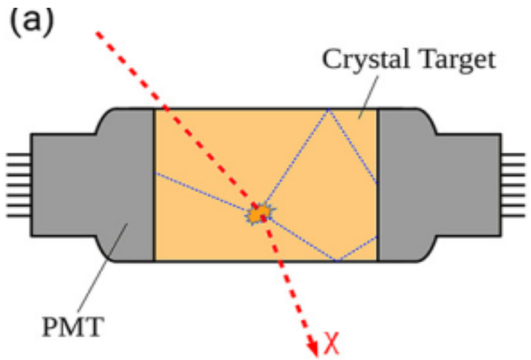
Status of SABRE North at LNGS and radiopurity of SABRE NaI(Tl) crystals

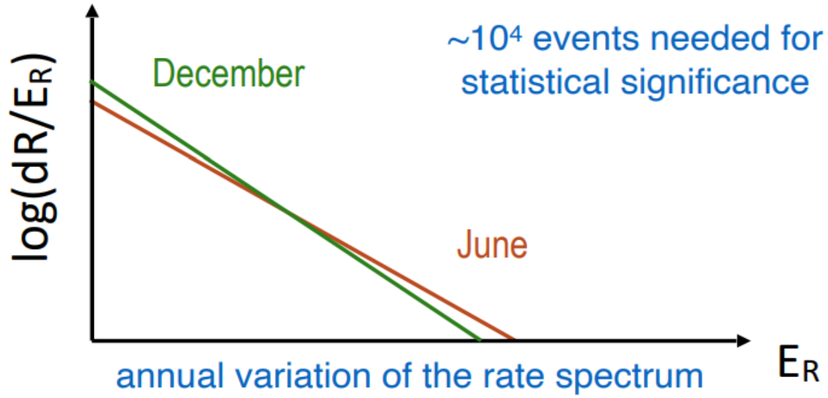
Gabriella Cataldi- INFN Lecce

on behalf of SABRE North Collaboration

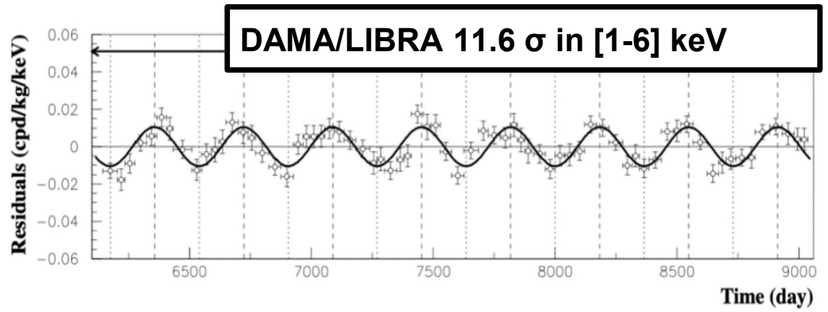
Dark Matter with annual modulation





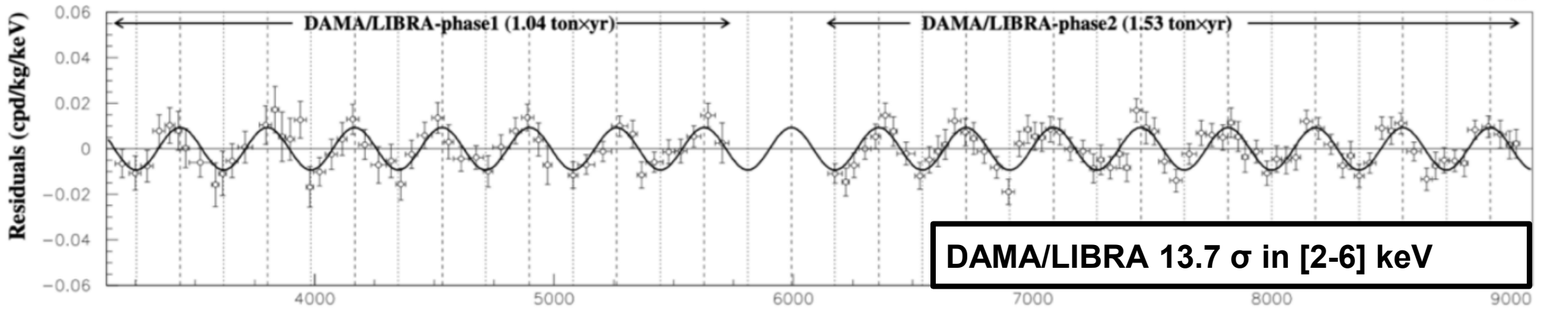


- ✓ Expected rate in an Earth-based detector is modulated
- ✓ Small modulation fraction $\mathbf{S_m/S_0 = O(\sim few\ \%)}$
- ✓ **Region of interest [1-6] keV**



Rate vs time

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



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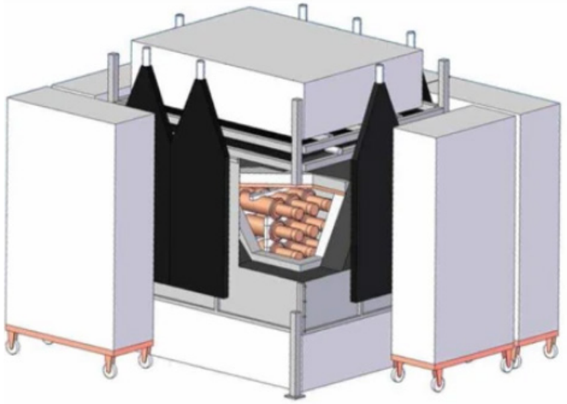
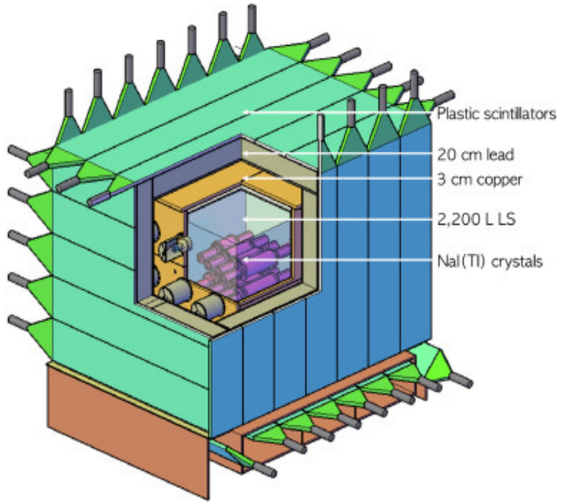
NaI(Tl) experimental landscape

ANAIS112
@Canfranc, Spain

M. Martinez @this session.

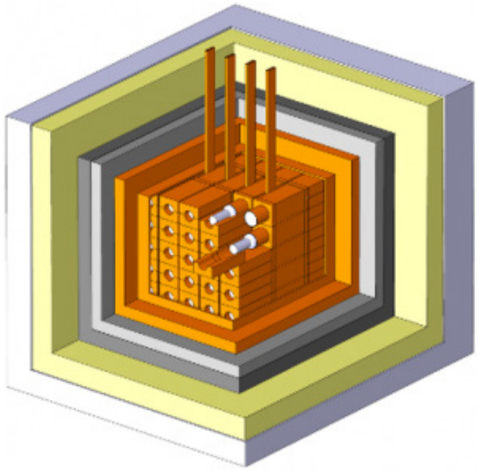




COSINE-100
@Yang Yang, South Korea

InSoo Lee @this session.

DAMA/LIBRA @LNGS, Italy



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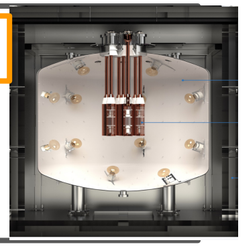
Ultra radio-pure crystals

@ SABRE South only

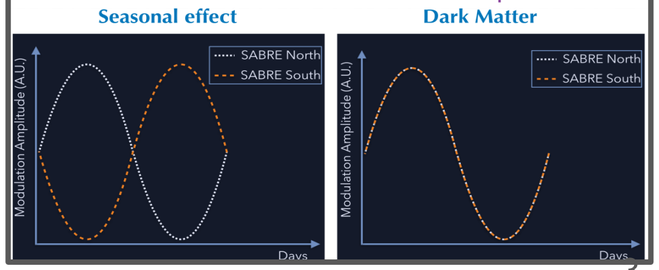
Active veto with liquid scintillator



SABRE South: L. Milligan@this session

Double location:

Northern and Southern hemisphere



SABRE North and South

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

SABRE North and South

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

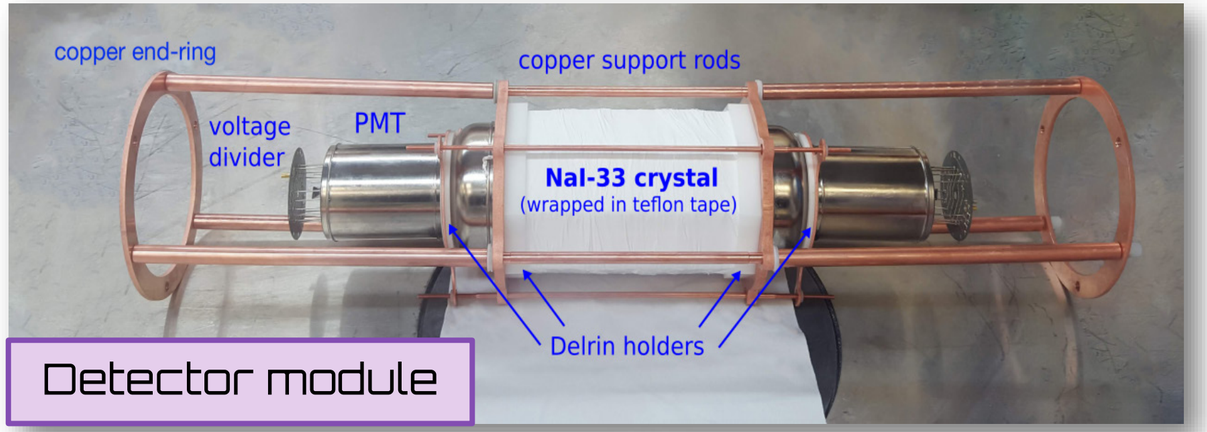
- Same crystal production and R&D.
- Same detector module concept (Ultra-pure crystals and HPK R11065 PMTs)
- Common simulation, DAQ and data processing frameworks
- Exchange of engineering know-how with official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN

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.

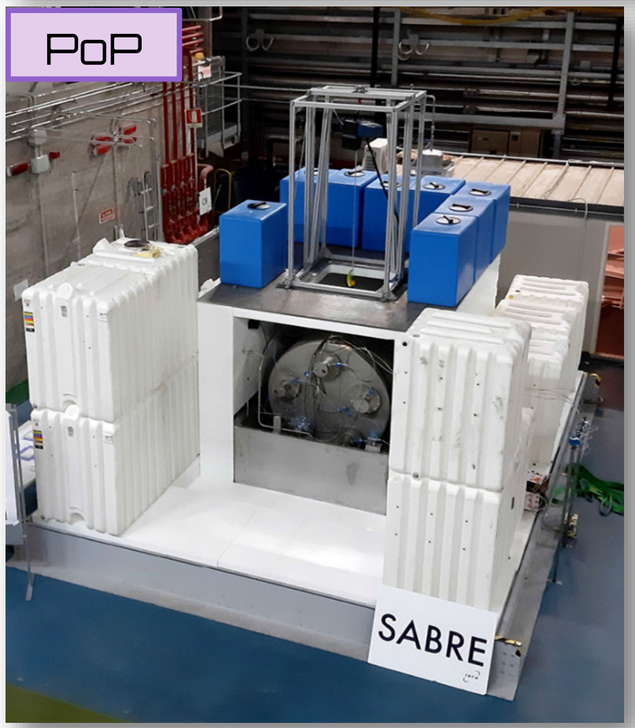
✓ SABRE South will be the first experiment in SUPL, the liquid scintillator will be used for in-situ evaluation and validation of the background in addition to background rejection and particle identification.

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



Detector module

PoP



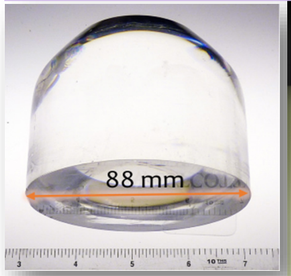
PoP-dry

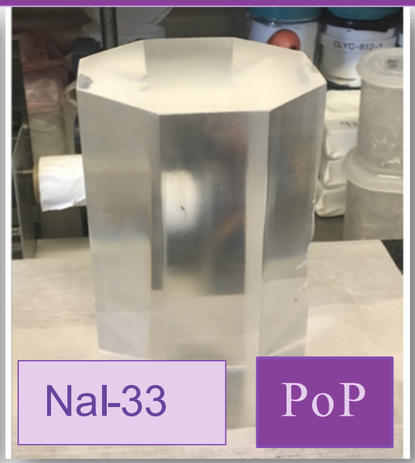
- ✓ Run in 2020 with Borexino liquid scintillator and NaI-33
  - ❖ 2 tons active veto with 10 8-inch PMTs + H_2O shielding
- ✓ Exploited successfully ^{40}K tagging with sensitivity at the level of 1 ppb
- ✓ Demonstration by direct counting of first crystal production after DAMA/LIBRA with **background in [1,6] keV of order 1 cpd/kg/keV**
- ✓ **PoP-dry run in 2021-2022:** passive shielding with additional layer of copper
  - ❖ confirmed background level

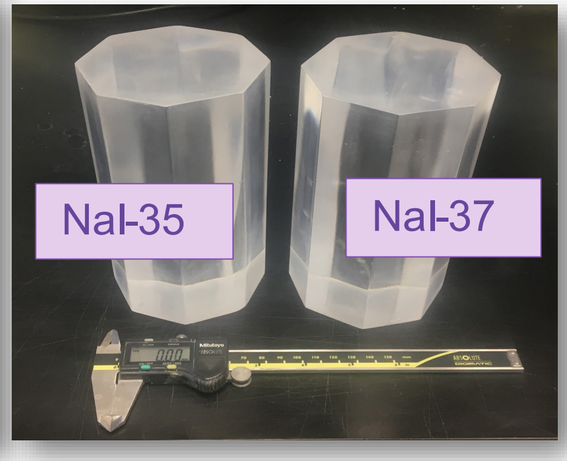
The SABRE crystals R&D

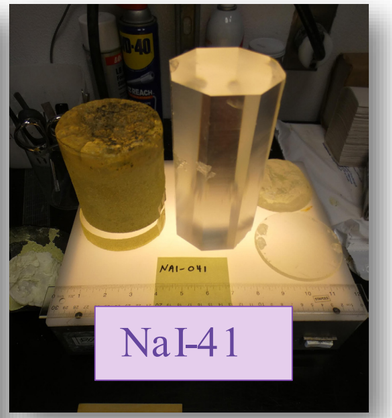
- ✓ R&D carried out by PU, INFN and ARC Centre of Excellence for DM
- ✓ Radioclean NaI powder *Astrograde* by Sigma Aldrich now Merck, Germany
- ✓ Crystals grown by RMD - Radiation Monitoring Devices, MA (USA)
  - ✓ Vertical Bridgman method in fused silica vessels

2015 2018 2019 2022 2023







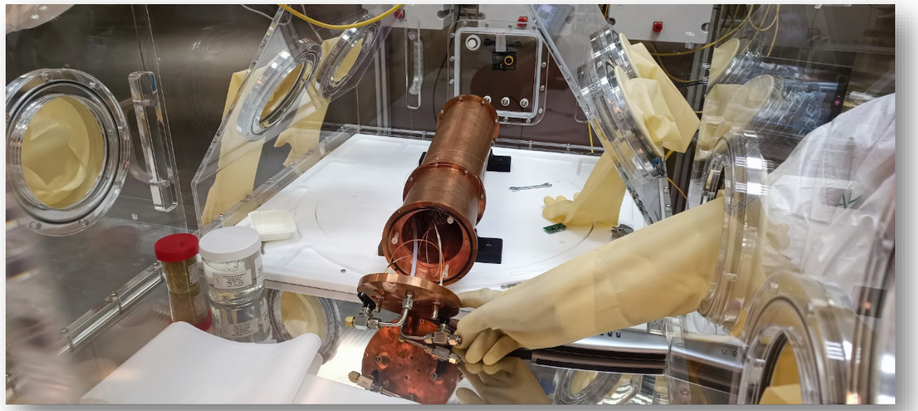


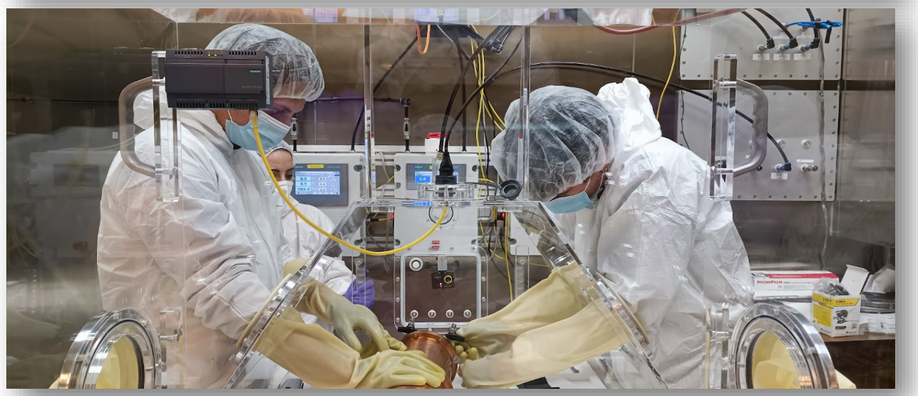
Expected in 2024@LNGS: NaI-42 grown after zone refining

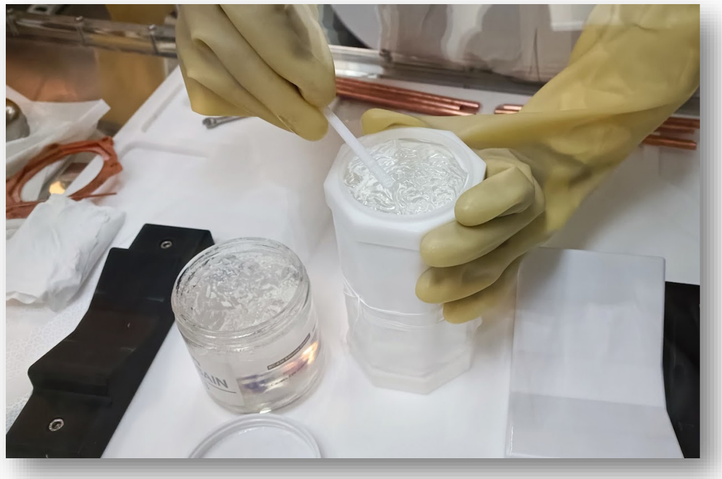
- NaI-33: background ~ 1 cpd/kg/keV → close to DAMA/LIBRA Phase 1
- NaI-35, NaI-37: reproducibility within factor 2
- NaI-41: grown from chuncks rather than powder → demonstrated same optical quality

Crystal Operations in glovebox 2022-2023

- 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





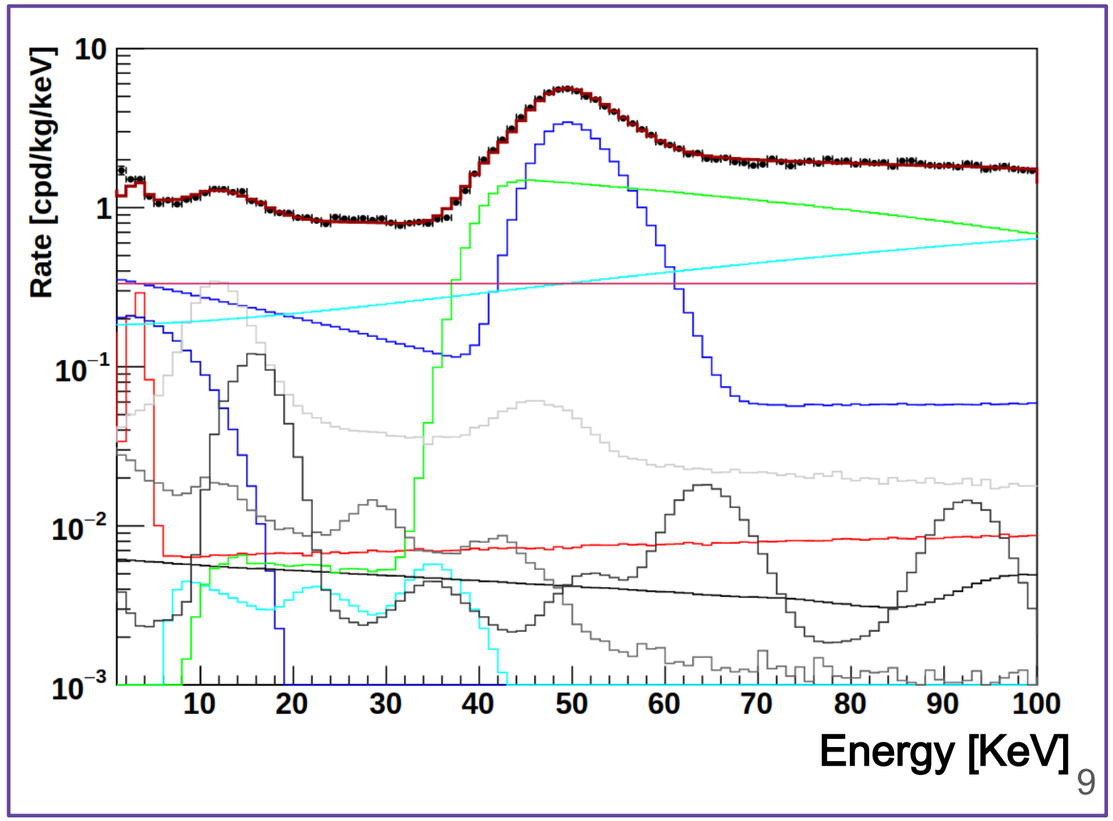


All operations successful and moisture level in the glove-box kept always below 5% RH

SABRE Background model (NaI-33)

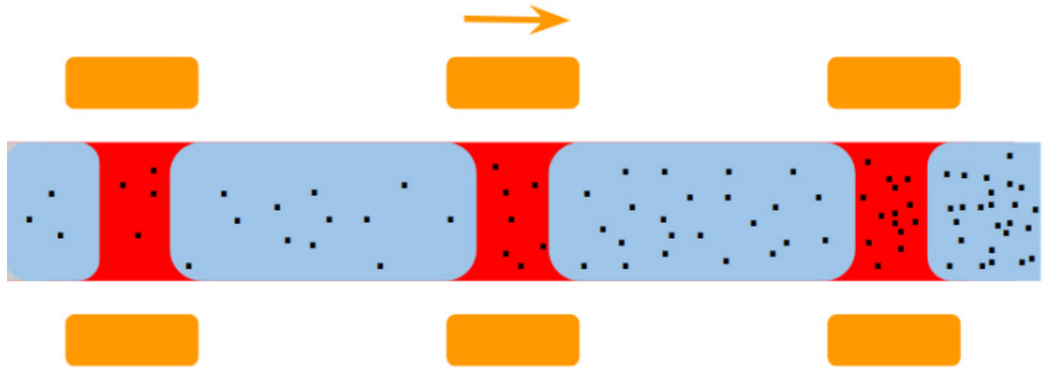
- Background model updated since Eur. Phys. J. C (2022) 82:1158
- Background from reflector is not dominant (now constrained from direct measurements)
- Dominant backgrounds: ^{210}Pb in crystal bulk and external background

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	



Zone refining technique

- ✓ 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)

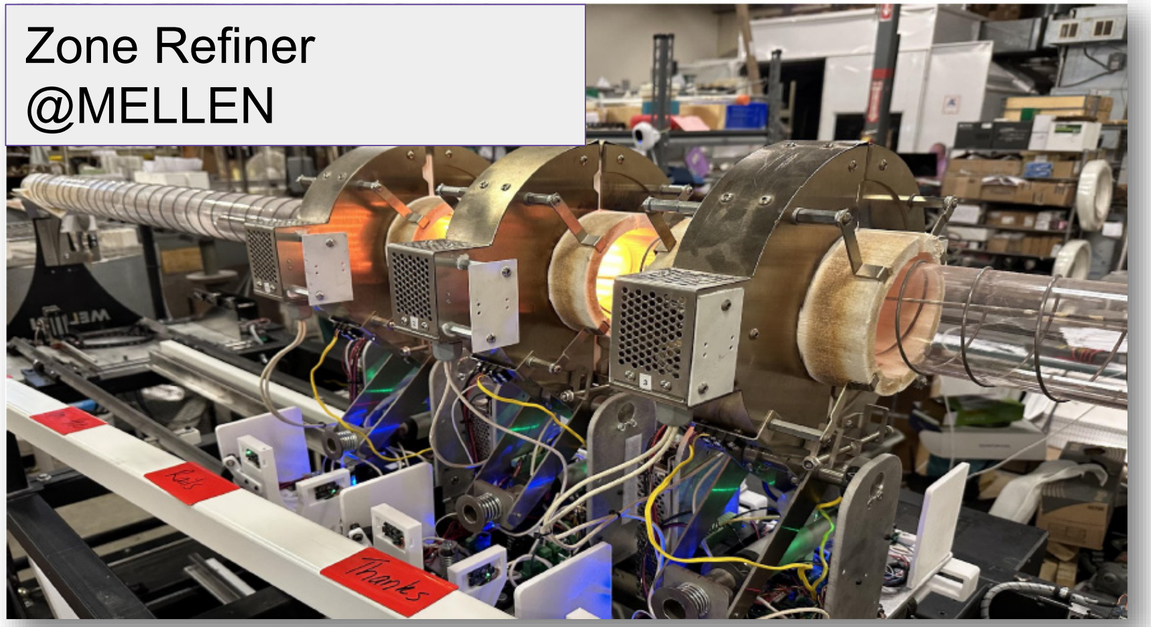
Zone refining activities 2023-2024

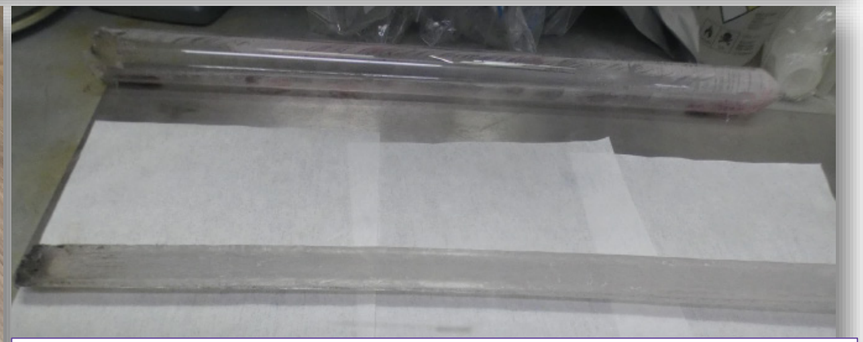
Four runs with 900 gr of AstroGrade NaI powder have been performed at MELLEN, NH, USA

- **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 @MELLEN

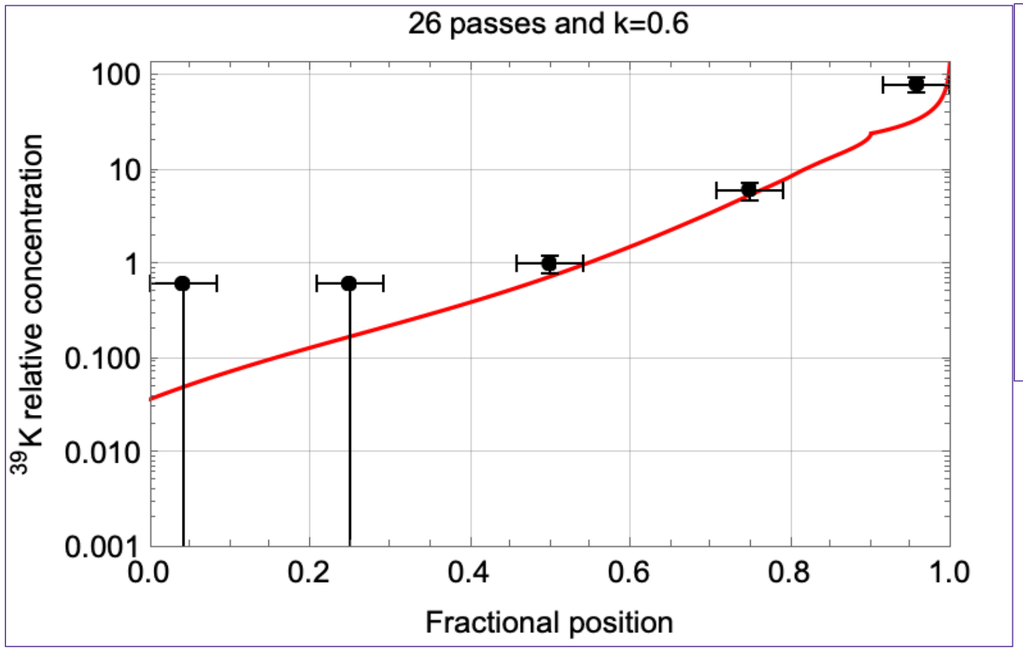




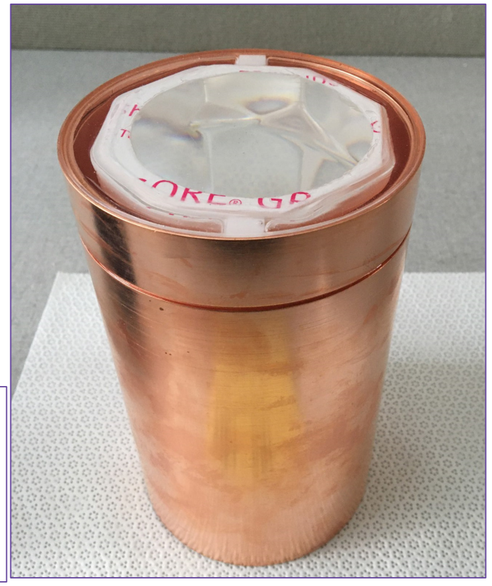
Ingot processed by Zone Refining (RUN3)

Carbon coated ampoule (RUN1)

Zone refining preliminary results



Comparison with the data from Run 1 with the model using a segregation factor of 0.6 for Potassium.
The comparison is not based on a fit. Below the fractional position of 0.75, the average purification is approximately 87%, i.e. a contamination level of 10 ppb is reduced to about 1 ppb.



The successful growth of the NaI-41 crystal from chunks and its excellent optical properties represents an important step in our approach to producing high radiopurity crystals.

The SABRE strategy

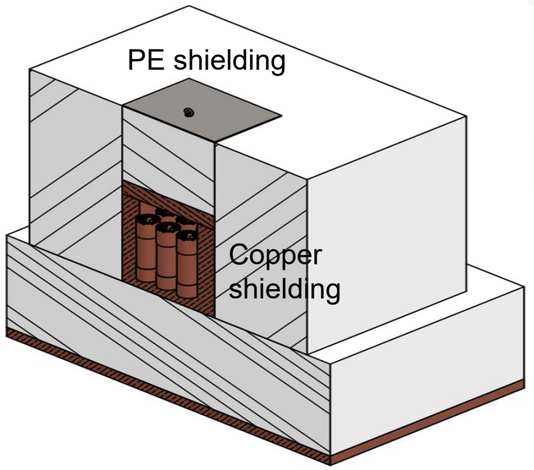
- **SABRE Proof-of-principle (PoP) and PoP-dry** achieved a background of **~1 cpd/kg/keV**

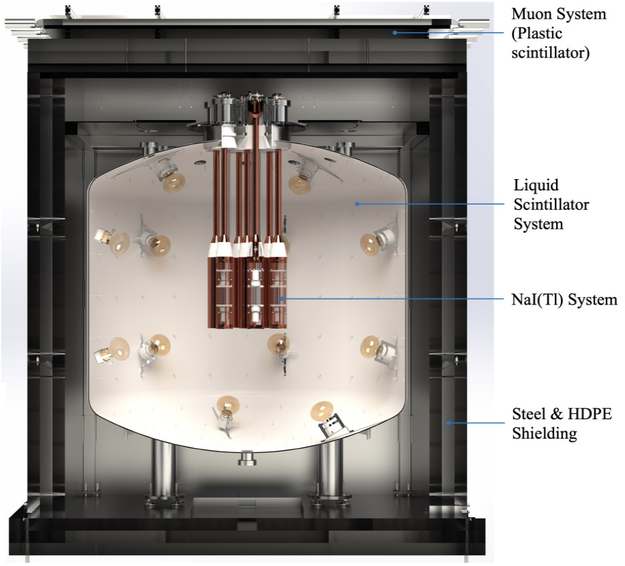
- Strategy to lower the **background**
  - **zone refining**

  - For external background:
    - **→SABRE North: improve passive shield**
    - **→SABRE South: Liquid Scintillator (LAB)**

      + Muon Veto

SABRE North

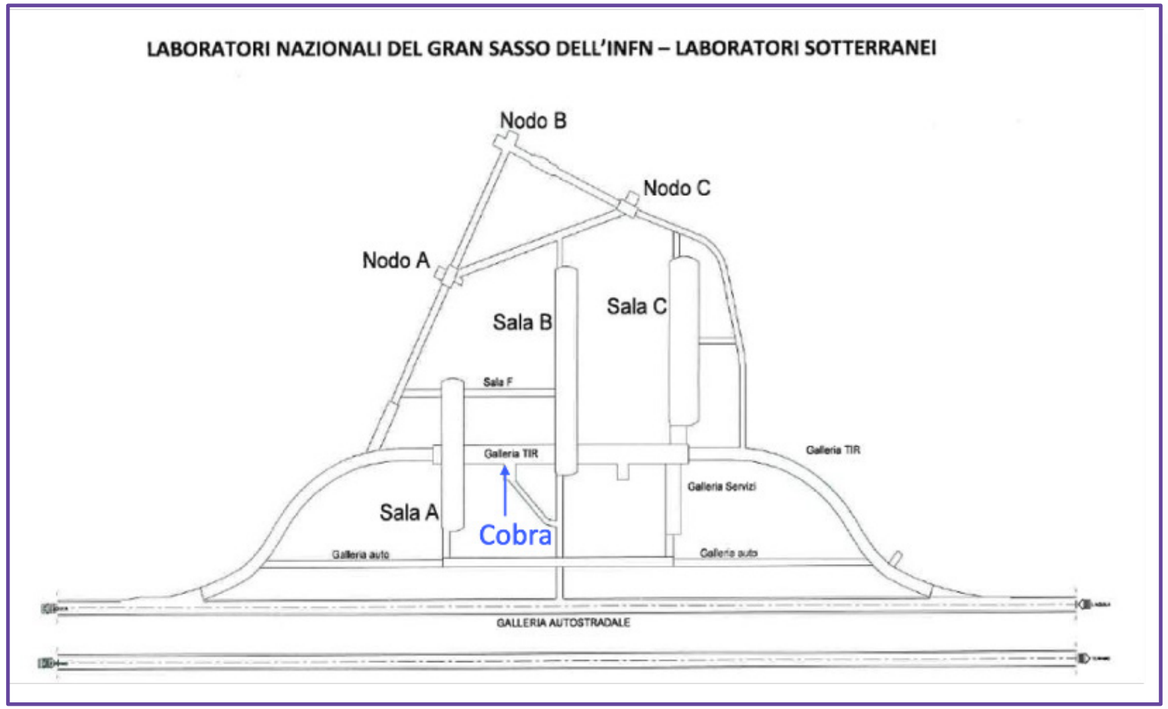




SABRE South

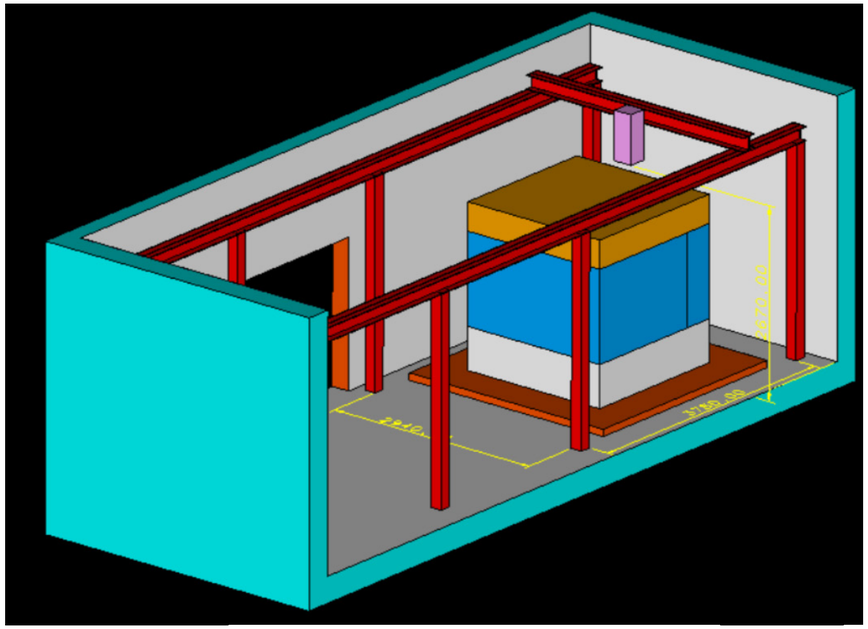
SABRE Facilities @ LNGS (2024)

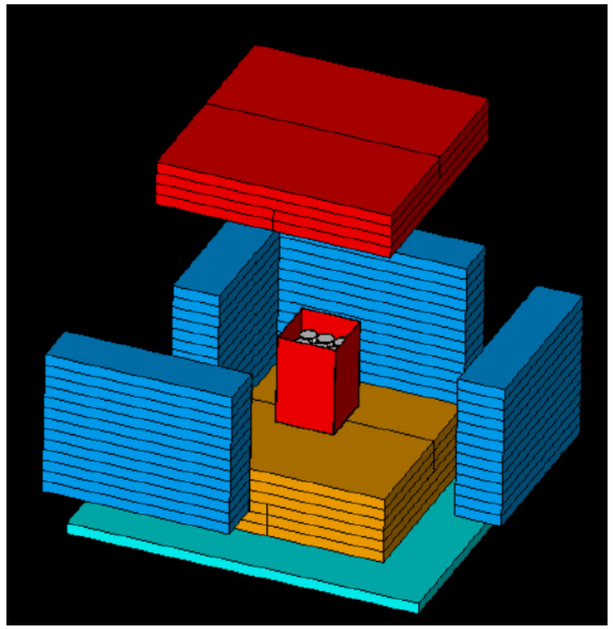
New SABRE experimental area is in the corridor between Hall B (Sala B) and Hall A (SALA A), in the so called «Cobra area».

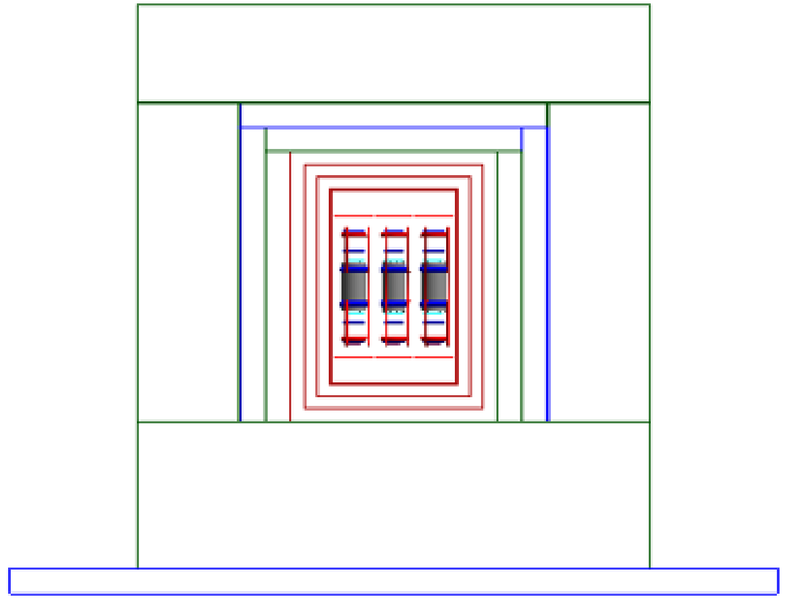


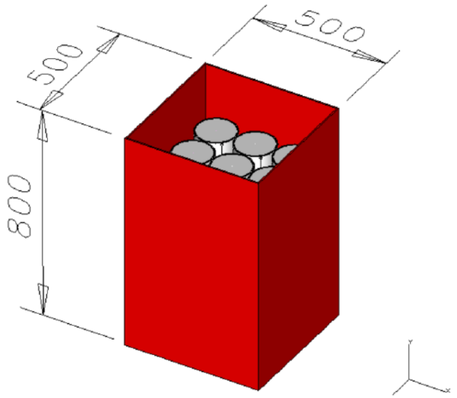
It consists of a two storeys building:
Ground floor (PT): set-up SABRE NORTH
First floor (P1). DAQ & counting room

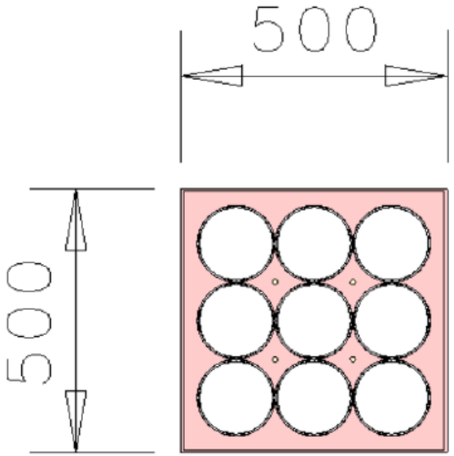
SABRE North Experimental Area







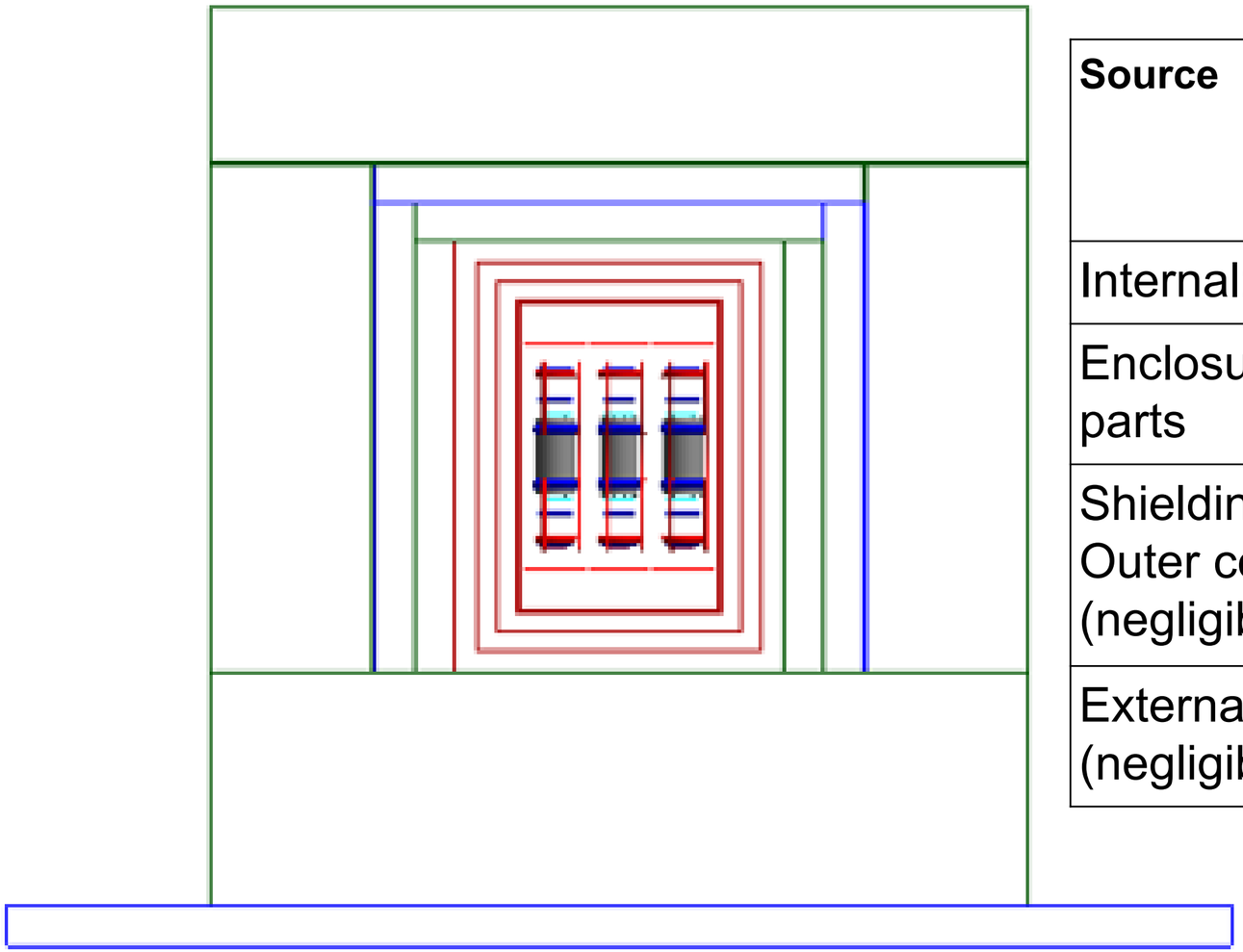




3x3 NaI matrix with 25 cm copper and 50 cm polyethylene

SABRE North-Background contributions

Background contributions from Monte Carlo simulations



Source	**Contribution in the ROI [1,6] keV units 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

SABRE North status and Conclusion

- Conceptual design report presented in July 2021
- SABRE North TDR presented in June 2024 for the physic phase detector
- 3 x 3 matrix of crystals of ~5 kg mass each
- Fully passive shielding design: 25 cm copper + 50 cm PE
  → enough shielding power
  → negligible contribution to the total background
- Zone refining of Astro Grade has been tested across four runs with a reduction of some of the key background sources
- SABRE facilities are now installed in the final site at LNGS
- NaI-42 grown after zone refining will come to LNGS in 2024
- SABRE goal is to search for annual modulation with two similar NaI(Tl) detectors in the Northern and Southern Hemispheres
- SABRE expected to exclude/confirm annual modulation in 3-5 years of operation

THANKS FOR YOUR ATTENTION!

SABRE North

Istituto Nazionale di Fisica Nucleare

SABRE South

BACKUP SLIDES

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 N_2

- 30 cm Cu shielding
- Host 1-3 detector modules
- Flushed with N_2

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