Status of the SABRE Dark Matter experiment

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on behalf of the SABRE Collaboration

UCLA Dark Matter, 2023

Motivation of SABRE

Sodium-iodide with Active Background RejEction

- Probe DAMA/LIBRA **model-independent** finding with same target material and lower background
- Observed annual modulation ~ 0.01 cpd/kg/keV (dru) in ROI [1,6]keV
- Background ~ 1 dru in ROI
- **STRATEGY in SABRE**
  - Higher signal-to-background ratio by **ultra-high purity NaI(Tl) crystals**
    - ✓ aim to 0.1 dru in ROI
  - **North-South «twin» experiments** at LNGS(Italy) and SUPL(Australia)
    - ✓ Rule out seasonal effects
  - **Proof-of-Principle** (PoP) at LNGS
    - ✓ Exploit active background rejection with a liquid scintillator
    - ✓ Test crystals radio-purity

Ultra-high radio-purity NaI(Tl) detectors

- At the time SABRE was conceived by **Frank Calaprice** (Princeton Univ) (~2010) the main background sources under consideration were mainly **^{40}K** at DAMA/LIBRA level ~10-20ppb and ^{238}U, ^{232}Th, and ^{87}Rb

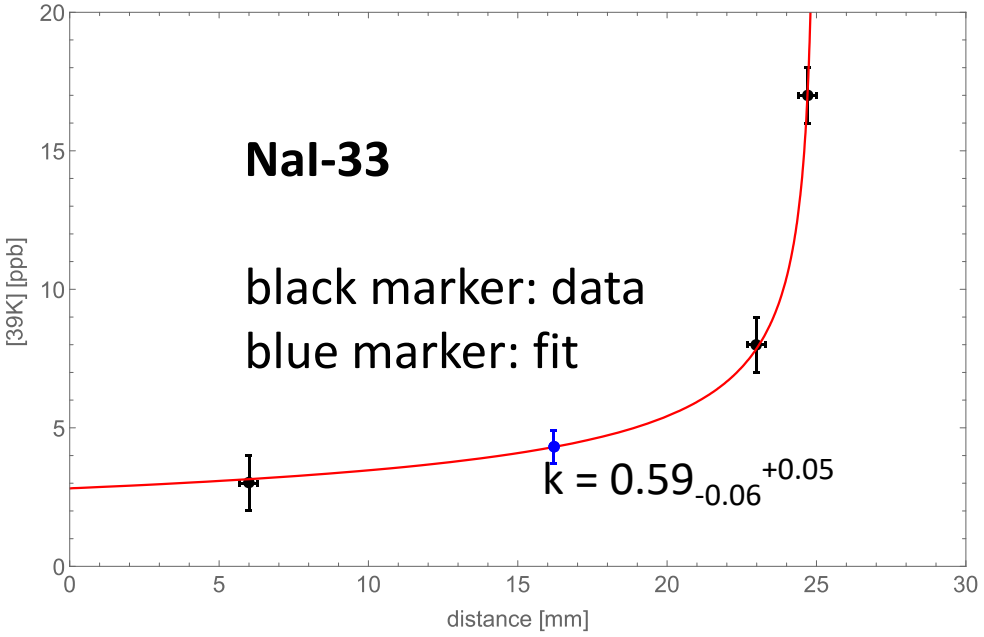
- Two considerations were driving the project
  - ✓ Grow crystals from a low potassium powder
  - ✓ Improve ^{40}K rejection by a high radio-purity liquid scintillator veto

- The effort made led to the following results
  - ✓ the Astro Grade NaI powder was developed in collaboration between Princeton University and Sigma-Aldrich with potassium < 10ppb after fractional crystallization purification
  - ✓ test crystals with potassium < 10ppb were grown
  - ✓ a PoP with the Borexino liquid scintillator was designed and built at LNGS showing 84% efficiency in rejection of ^{40}K

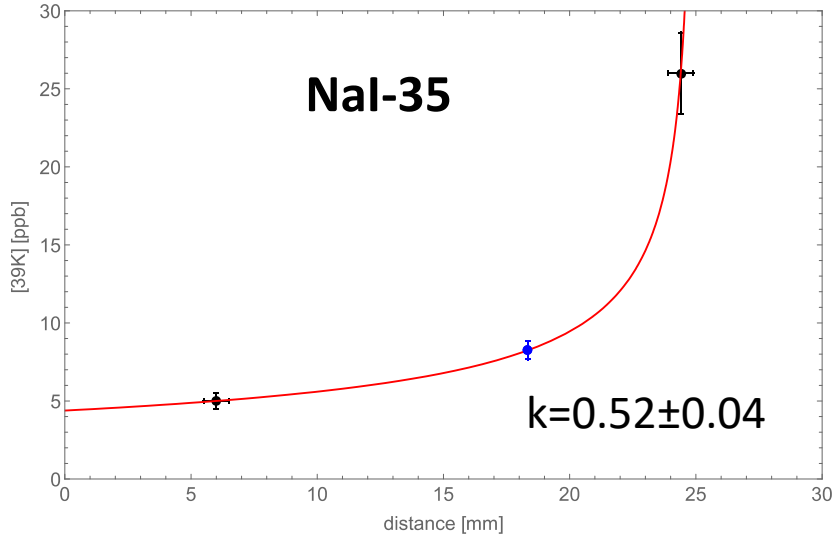
NaI(Tl) crystal production for SABRE

- Crystals are grown from Astro Grade
  - ✓ a few ppt in U, Th and a few ppb in K and Rb
- The Bridgman method has been selected to mitigate the risk of contamination during growth
  - ✓ molten material is sealed inside a cleaned crucible
- Crystal growth is performed by the industrial partner Radiation Monitoring Devices (RMD)
  - ✓ some quality controls are performed prior to underground counting

ICP-MS screening of tip and tail samples after growth

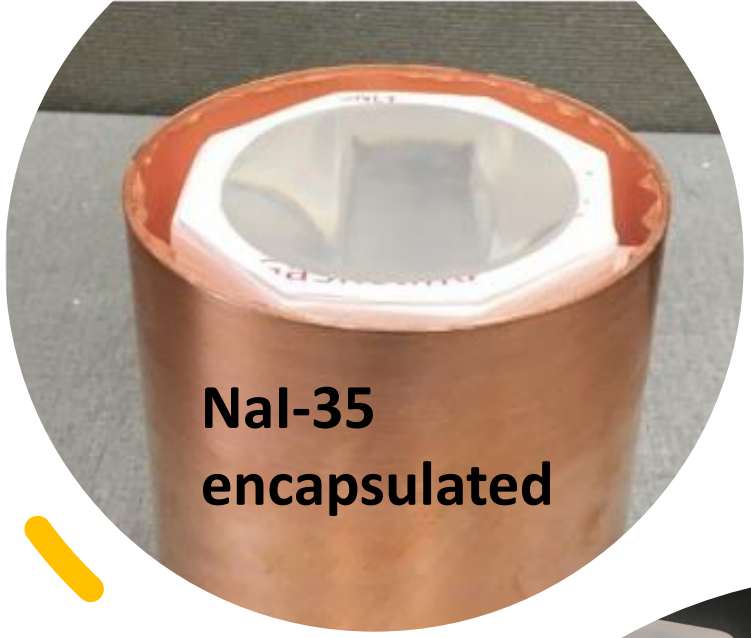


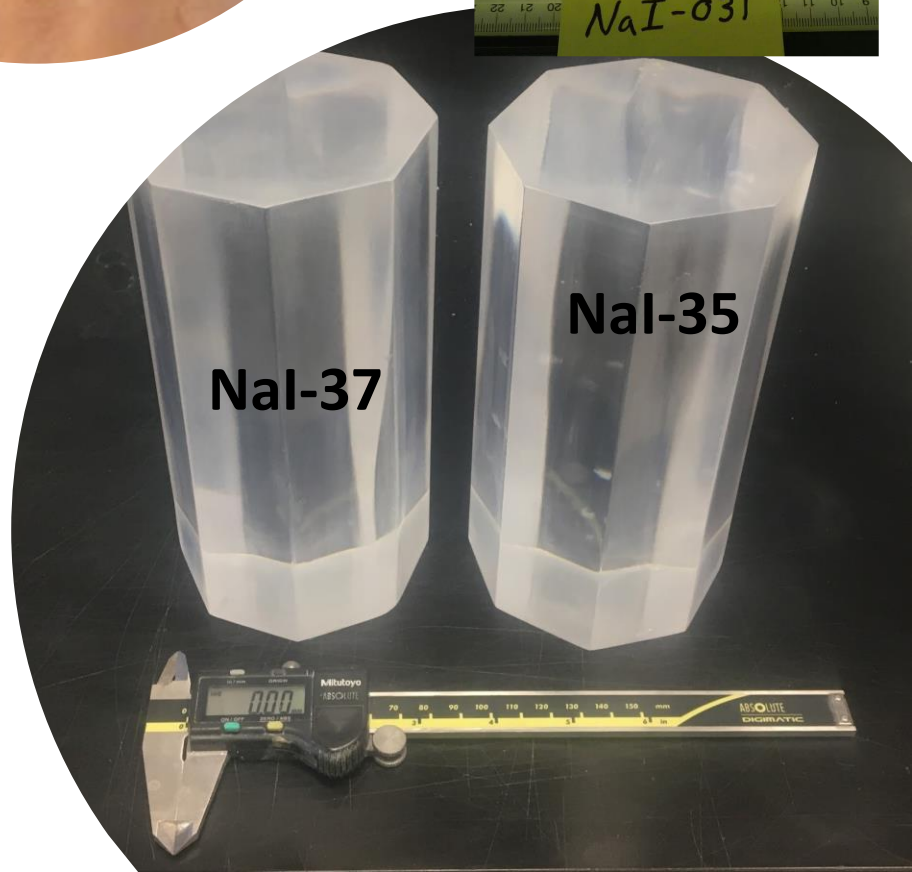
- radio-purity characterization is performed after growth on tip and tail samples to make a first assessment of the crystal quality
- ^{39}K < 10ppb, ^{85}Rb ~ 1ppb, U/Th < 0.1ppb
- These results to be compared with direct counting underground

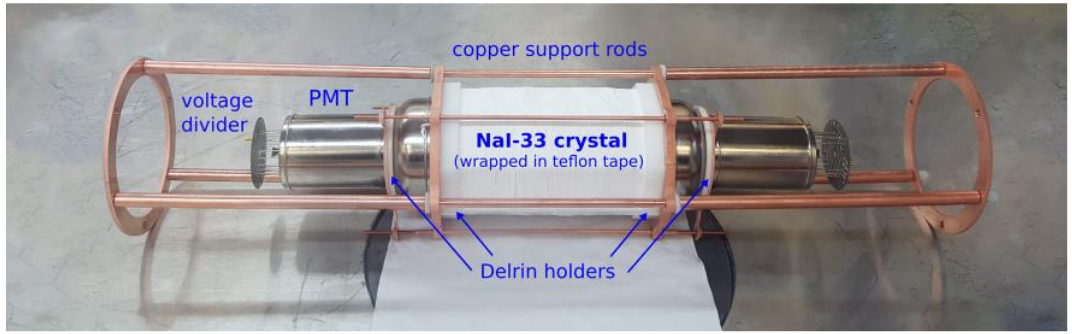


Grown crystals and underground at LNGS

- **NaI-31** at LNGS since April 2019
- **NaI-33** since August 2019, assembled in Princeton
- **NaI-35** since May 2022, assembled at RMD
- **NaI-37** since March 2022, naked and encapsulated at LNGS

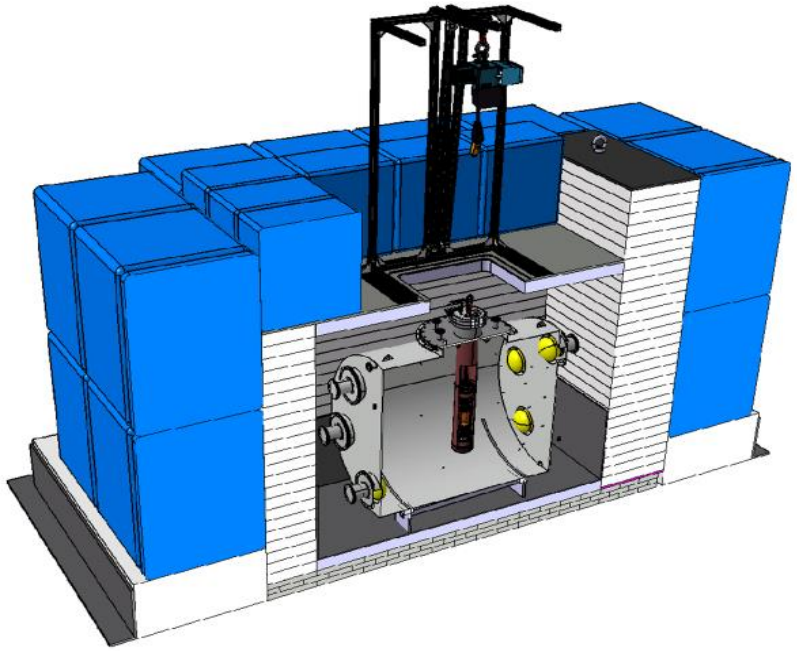


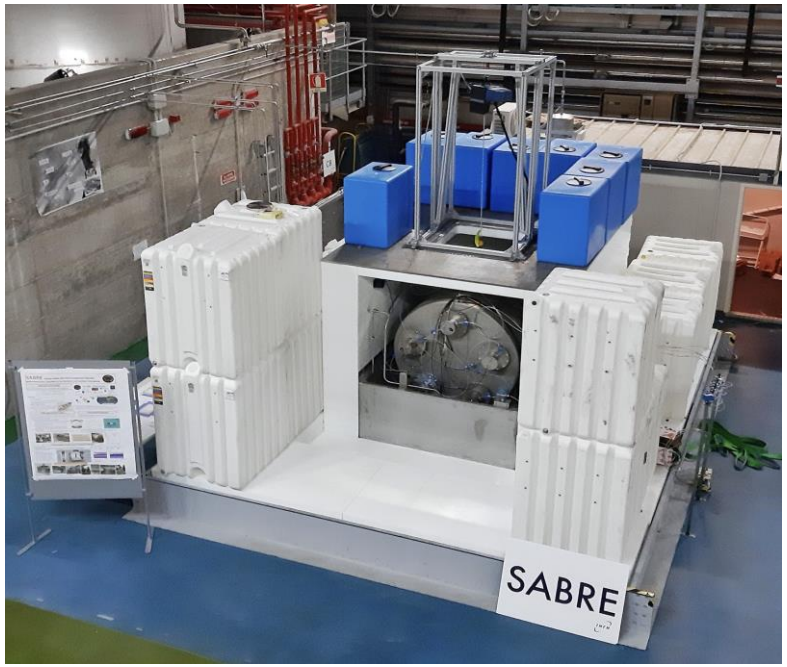




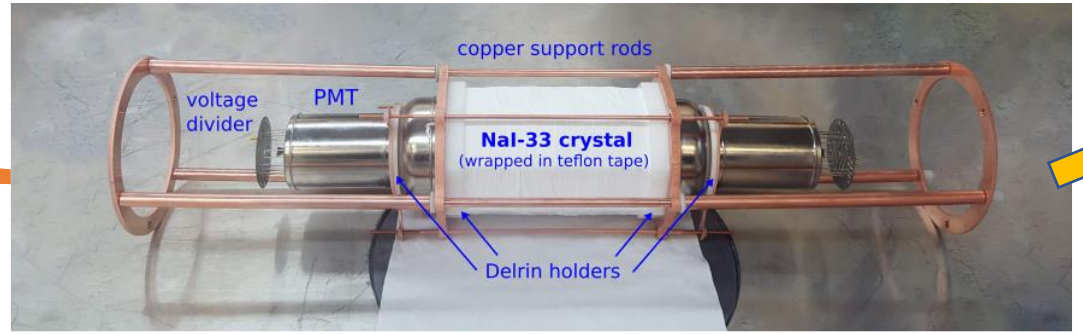
PoP at LNGS

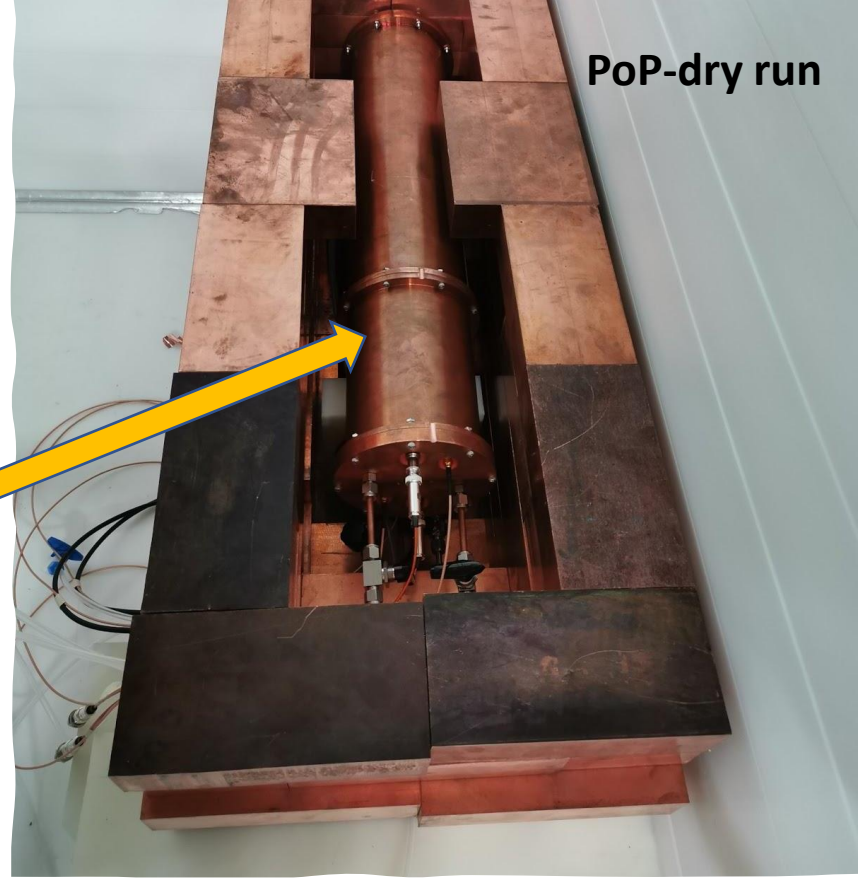
- Run in 2020 with Borexino liquid scintillator and NaI-33
  - ✓ 2 tons LS active veto with 10 8-inch PMTs + H_2O shielding
- Exploited successfully ^{40}K tagging with sensitivity at the level of 1ppb
- **Demonstration by direct counting of first crystal production after DAMA/LIBRA with background in [1,6]keV of order 1dru**
- Identified main background sources:
  - ✓ ^{210}Pb in crystal bulk equal to 0.51±0.02 mBq/kg
  - ✓ Confirmed ICP-MS estimation for ^{40}K contamination





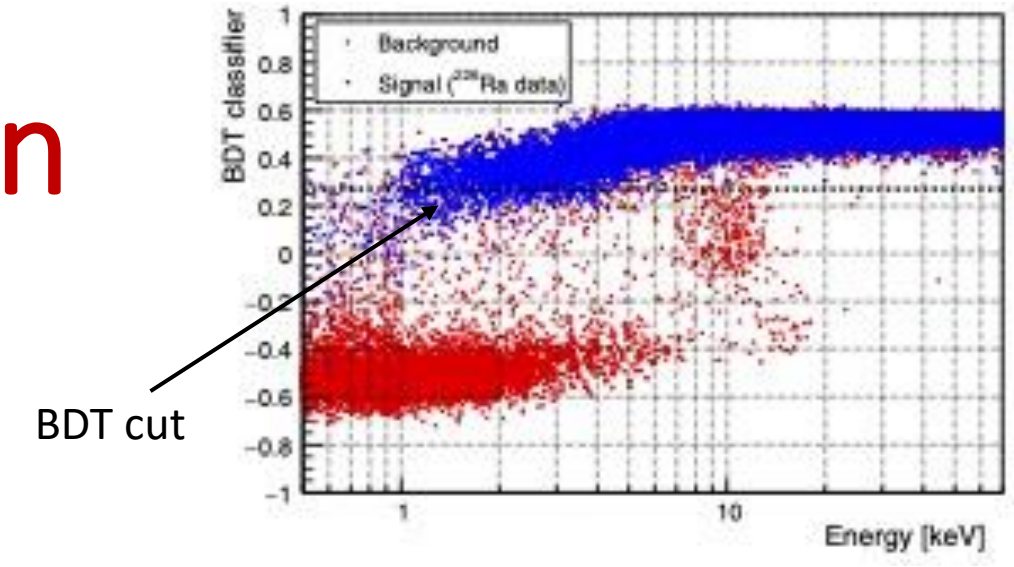
Beyond the PoP run

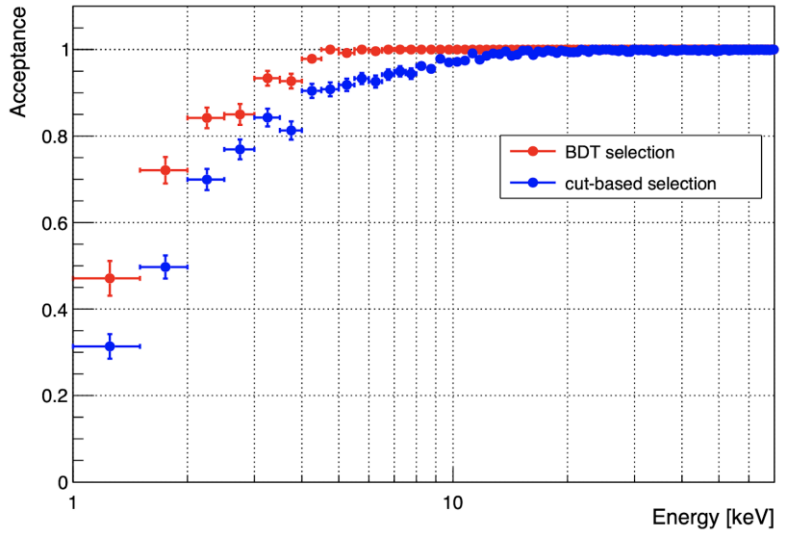




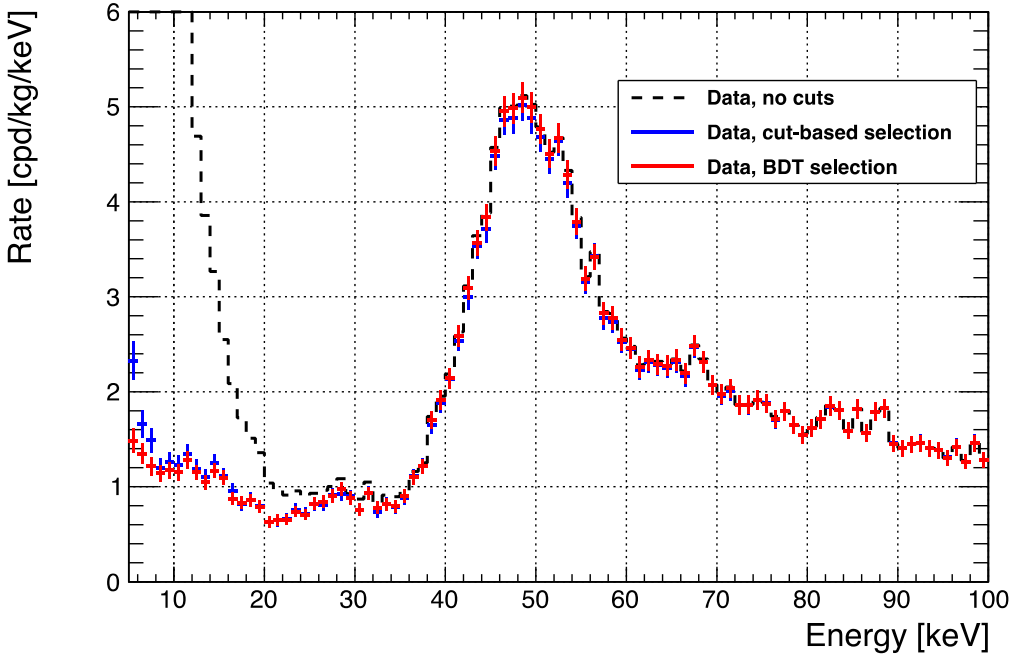
- The low potassium level wrt to the original 10-20ppb assumed and restrictions at LNGS for LS use, led us to consider a passive shielding design for SABRE-North
- To elaborate this idea we have taken data with NaI-33 inside the PoP w/o LS with an improved Cu shielding (**PoP-dry run**)
- After PoP set-up desommissiong we have built a full low ^{210}Pb Cu shielding (30cm) set-up for crystal characterization

PoP-dry run





- 891 kg x day exposure with NaI-33
- Noise reduction by BDT
- Rate in ROI dominated (60%) by external background
- ^{40}K in ROI only 10% of total rate
- Rate in ROI = 1.39±0.03 dru

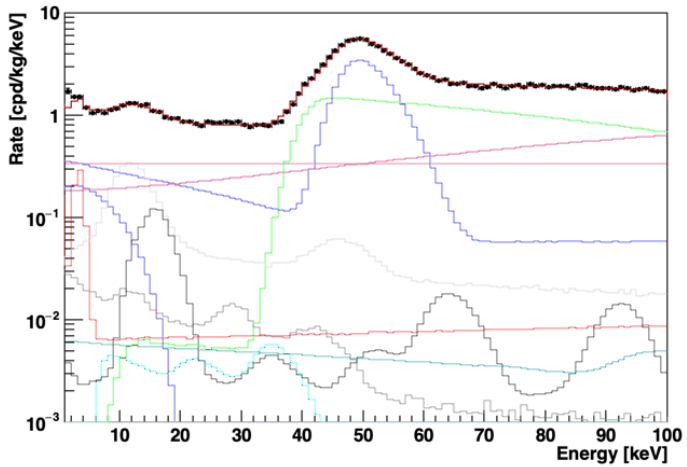


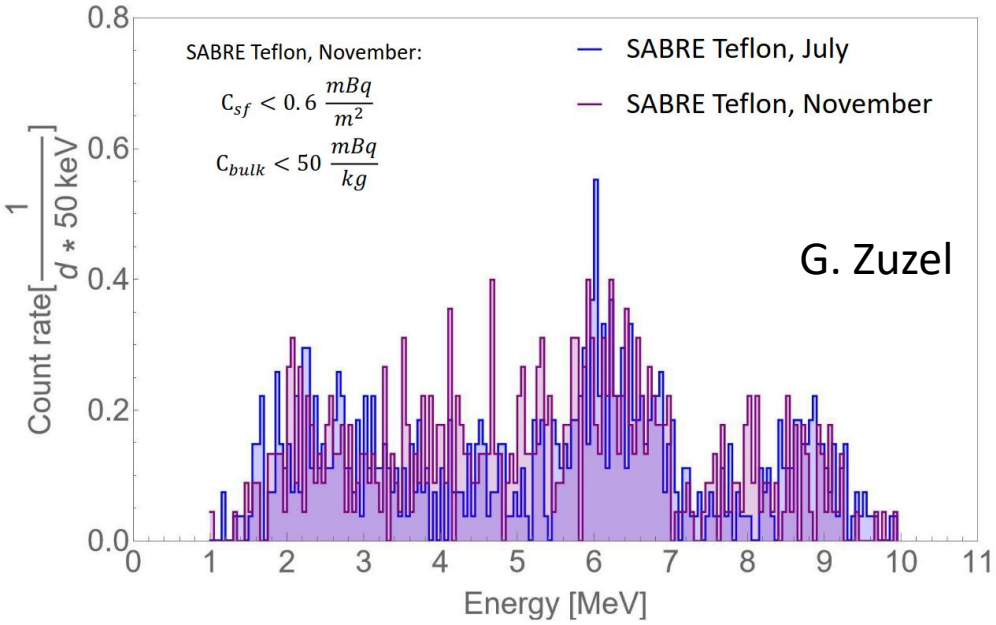
PRELIMINARY

PoP-dry background breakdown

- ^{3}H expected 37±10 μBq/kg for 10 months surface exposure and 24 months underground
  - ✓ Possible reduction due to storage in B level below ground at Princeton
- ^{210}Pb in PTFE reflector within upper limits by α spectroscopy
- ^{210}Pb in bulk consisted with α tagging by PSD based on amplitude-weighed mean time

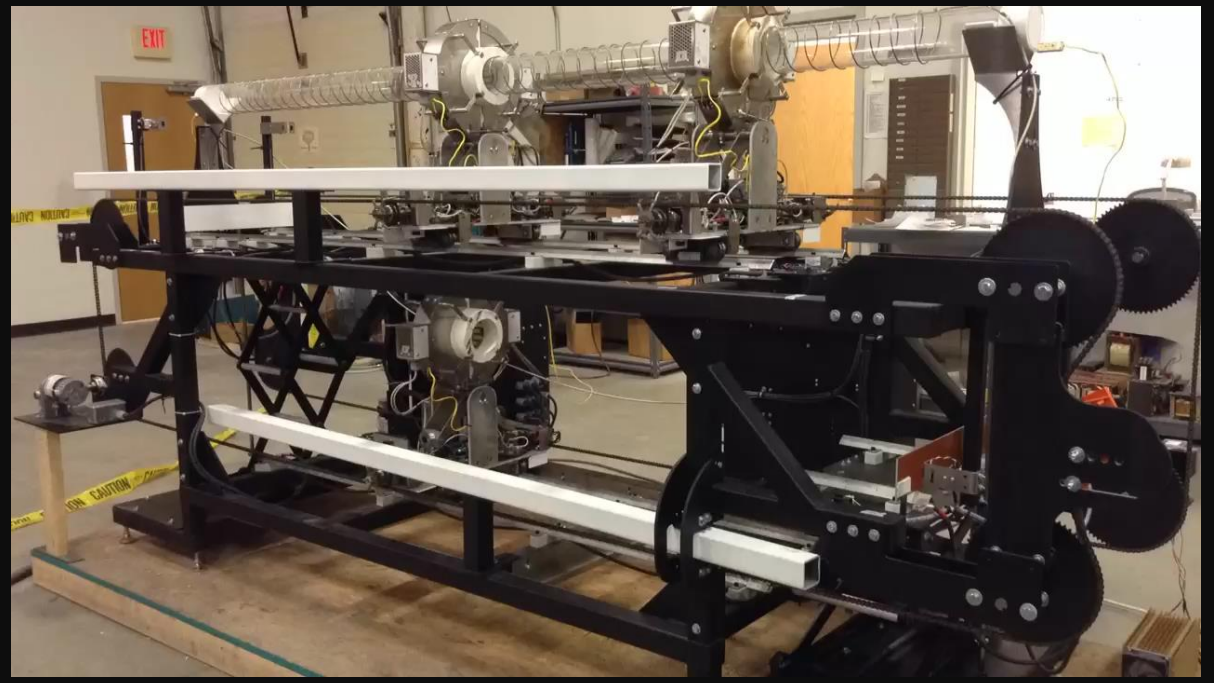
Source	Rate in ROI [1,6]keV in cpd/kg/keV	Fit results
^{40}K	0.125	0.16±0.01 mBq/kg
^{210}Pb bulk	0.333	0.49±0.05 mBq/kg
^{210}Pb reflector bulk	0.054	11±1 mBq/kg$_{PTFE}$
^{210}Pb reflector surface	0.023	<0.6 mBq/m^2
^{3}H	0.198	24±2 μBq/kg
^{129}I	0.0003	1.03±0.05 mBq/kg
^{238}U	0.006	5.9±0.6 μBq/kg
^{232}Th	0.0003	1.6±0.3 μBq/kg
PMT	0.003	1.9±0.4 mBq/PMT
External	0.185	0.89±0.05
Other β's	0.333	297±15
TOTAL	**1.26±0.27**	



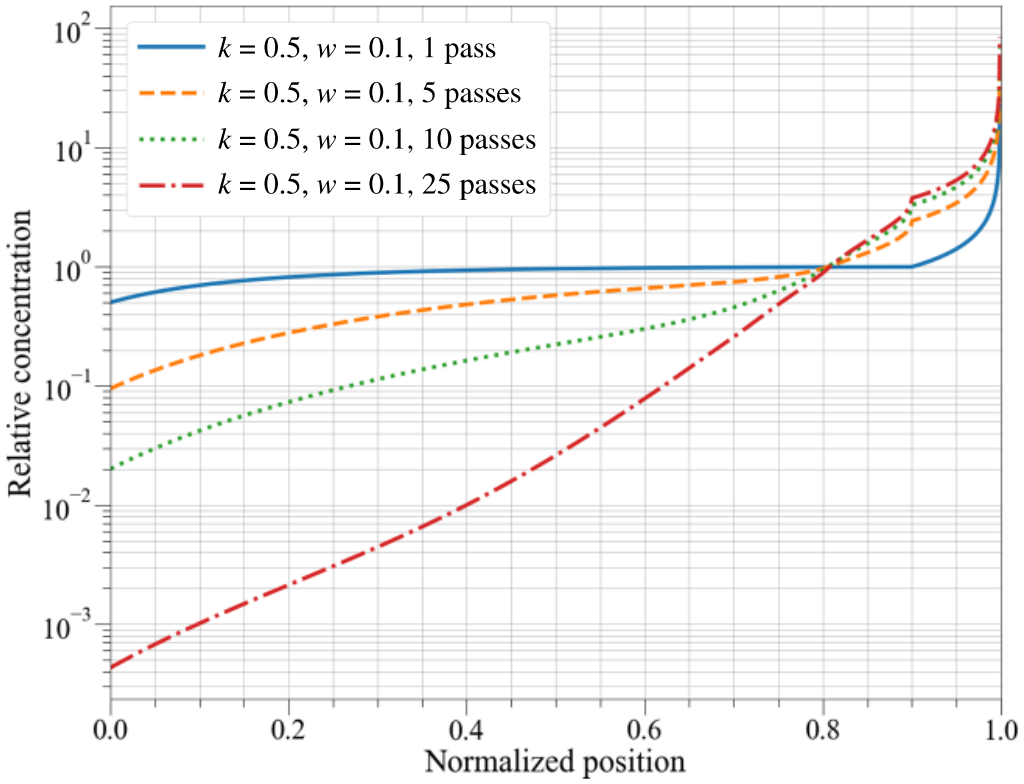


Zone refining purification in SABRE

- Strategic and unique to the SABRE project is the idea to zone refine the powder prior to growth
- A zone refiner suitable for order of 100 kg crystal production has been built in collaboration with MELLEN
- The zone refiner is being moved to RMD for growing a test crystal by the end of the summer



Performance of ZR purification

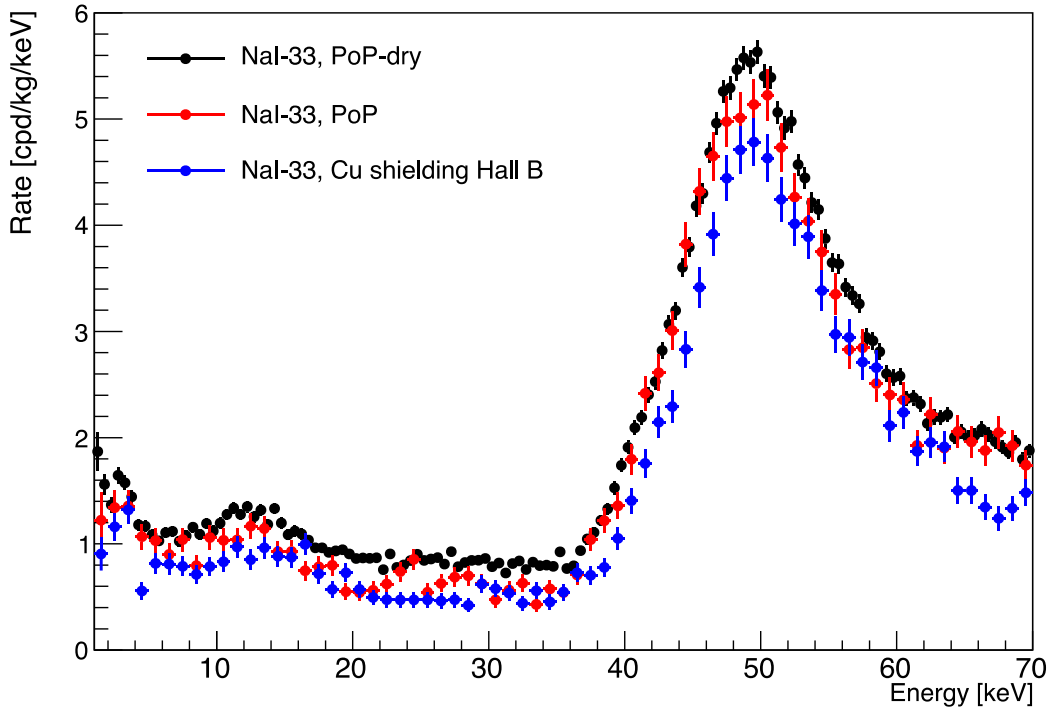


744 g of AG powder and 53 passes at ~ 6 cm/h

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
^{208}Pb	1.0	0.4	0.4	<0.4	0.5	0.5
^{85}Rb	<0.2	<0.2	<0.2	<0.2	<0.2	0.7
^{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

Different segregation coefficients (k<1) of impurities in molten vs solid phase

impurities are pushed to the end of the refining tube at different level and eliminated from the material selection before the growth



preliminary

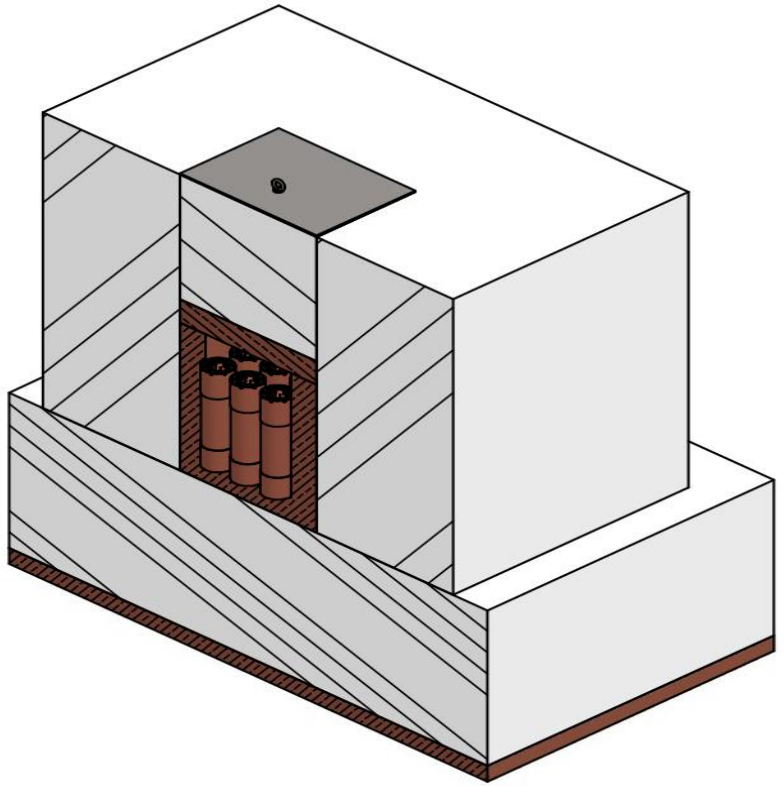
	Mass [kg]	LY**** [pe/keV]	^{39}K [ppb]	^{210}Pb [mBq/kg]	Rate ROI [1,6]keV
NaI-31	3.00	9.1±0.1	16.5±1.1	1.02±0.07	2.74±0.03
NaI-33*	3.40	12.1±0.2	4.3±0.6	0.51±0.02	1.20±0.05
NaI-33**	3.40	11.1±0.2	4.3±0.6	0.51±0.02	1.39±0.03
NaI-33***	3.40	11.1±0.2	4.3±0.6	0.51±0.02	0.95±0.05
NaI-35	4.36	~9	8.3±0.6	0.49±0.2	-
NaI-37	4.35	~8	8.0±0.6	0.80±0.01	-

Data from tested crystals

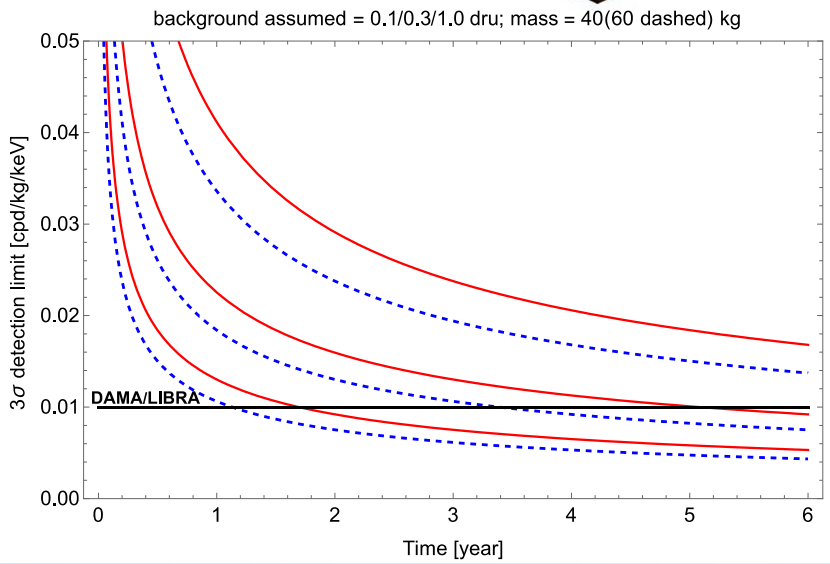
- * PoP run
- ** PoP-dry run
- *** NaI-33 in 30cm Cu shielding
- **** from ^{241}Am (59.5 keV)

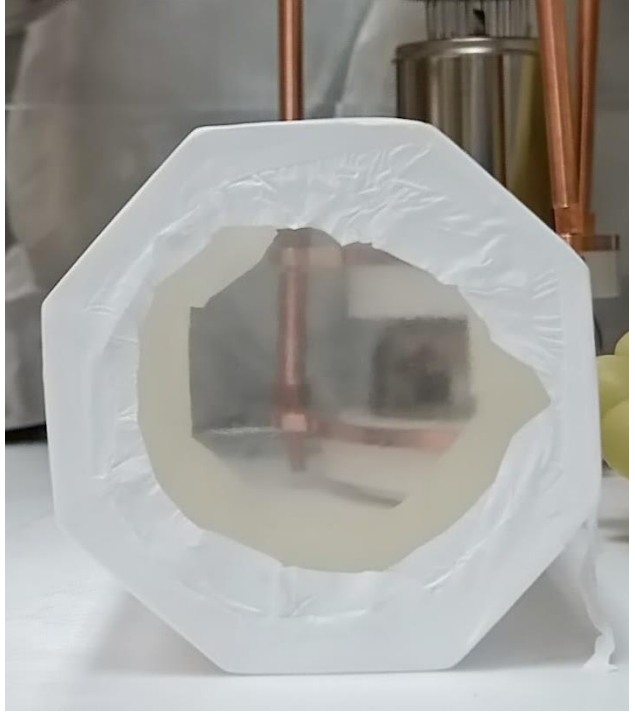
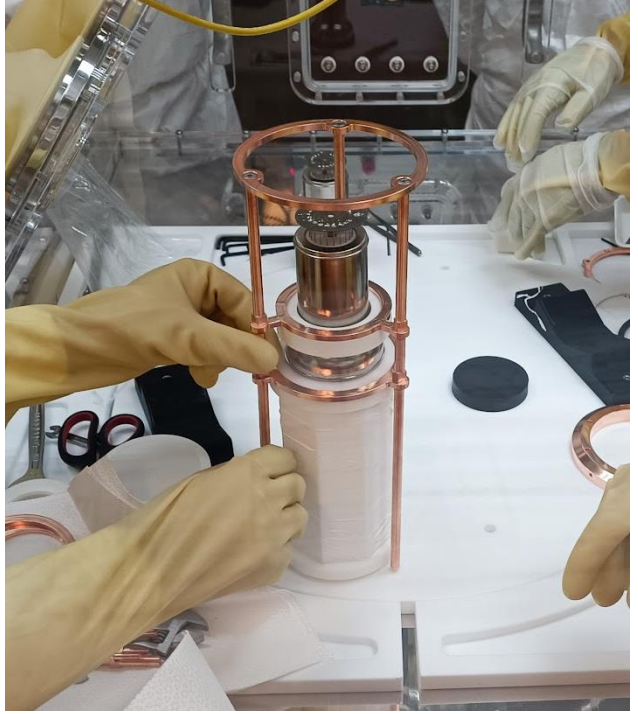
Preliminary design of SABRE-North

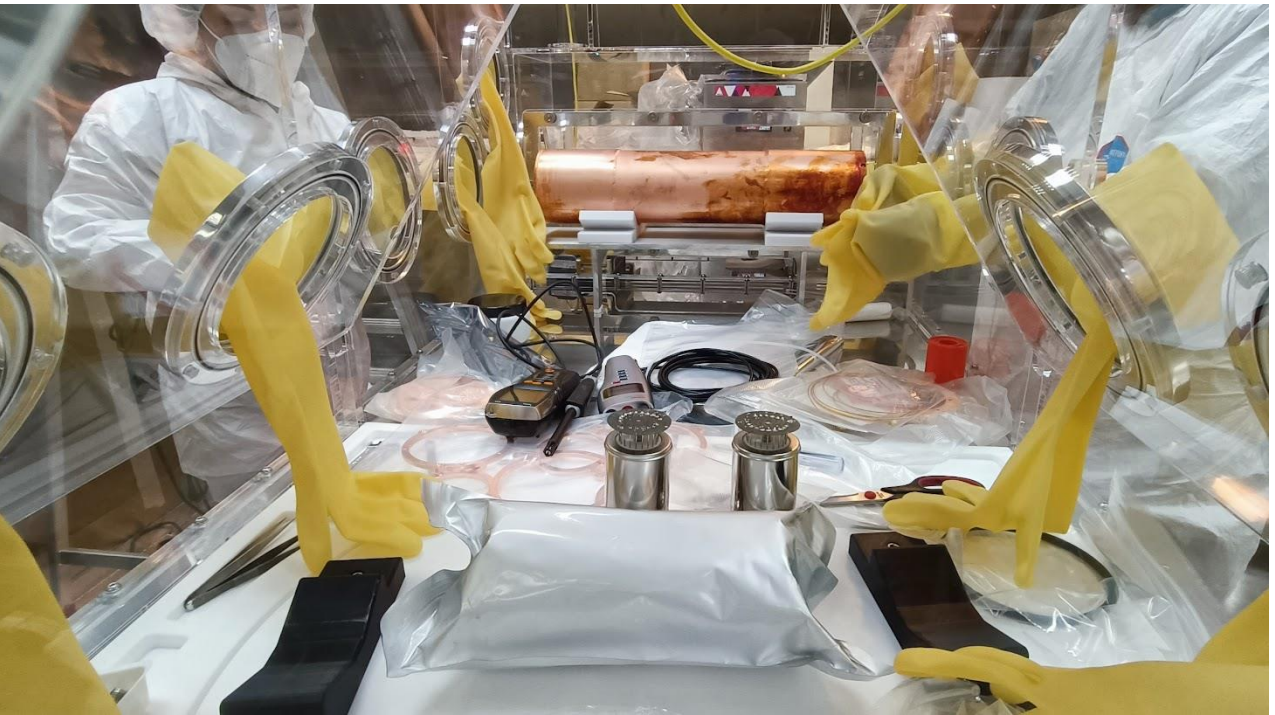
- 3 x 3 matrix of ≈ 5 kg NaI detectors
- Inner 5 mm thick Cu box
- Vertical crystal deployment
- 15 cm Cu and 80 cm PE shielding structure
- 10 cm Cu basement
- MC predicted background from environmental gamma and neutrons ~0.01dru in the ROI
- Overall shielding dimensions and mass:
  3 x 3 x 3 m³, ≈30 t



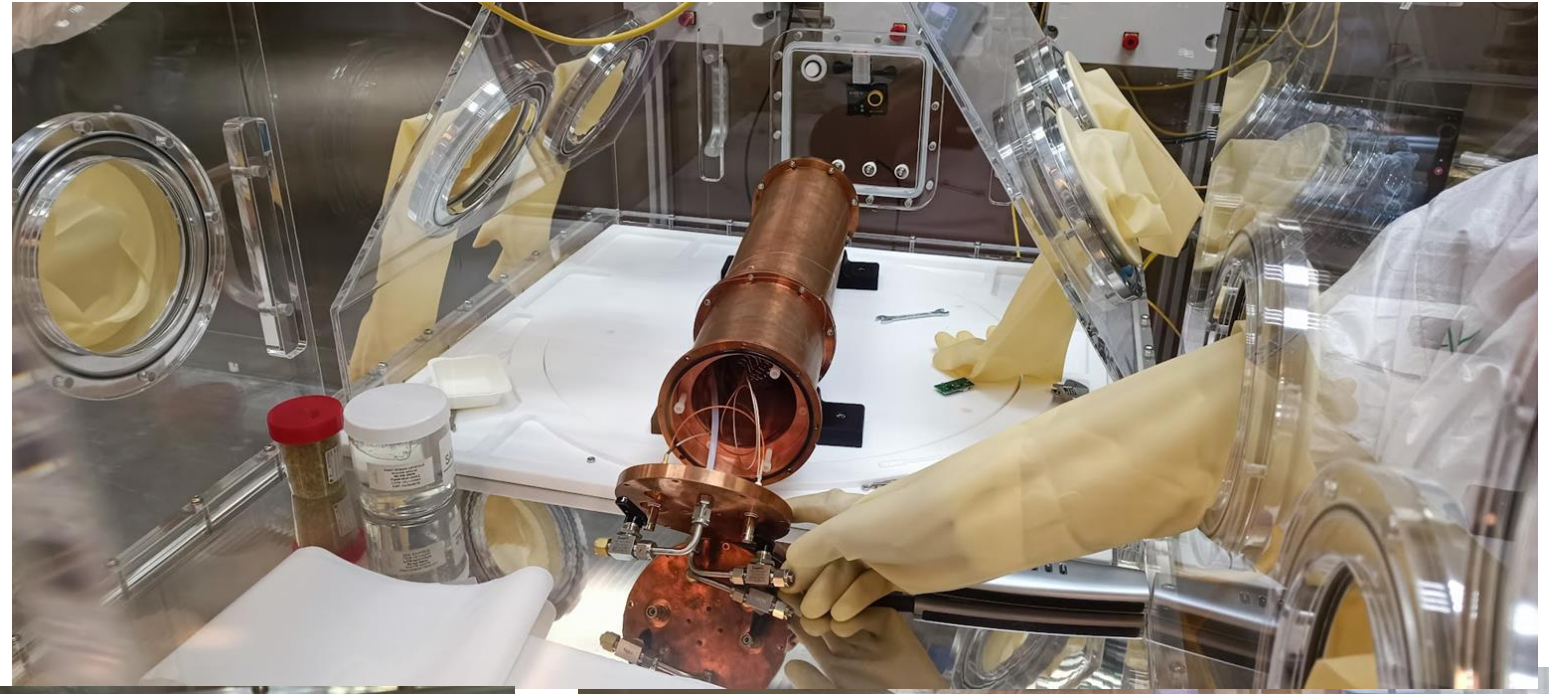
Sensitivity to annual modulation





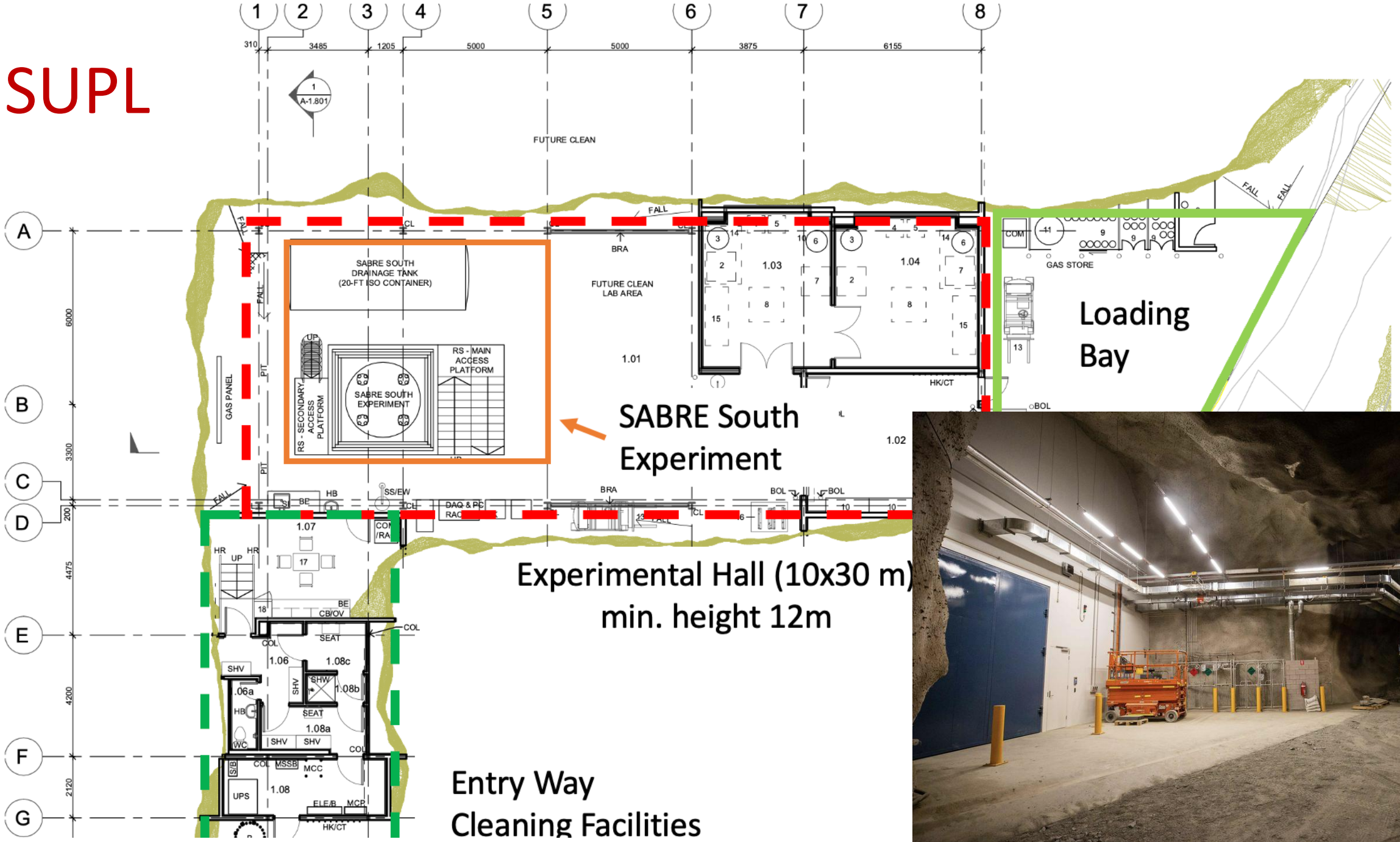
Operation for NaI-37 in underground Radon-free clear room (400mBq/m^3) previously built for DarkSide-50



Stawell Underground Physics Laboratory (SUPL) and SABRE-South

- SUPL is in an advanced outfitting phase with 2900 m.w.e. overburden
- SABRE-South
  - ✓ Same detector module concept
  - ✓ Common DAQ and simulations
  - ✓ Same crystals
  - ✓ Active veto with LAB from JUNO
    - From MC simulations efficiency to reject ^{40}K is 85.4%
    - <10% background from non-crystal sources in ROI

SUPL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C
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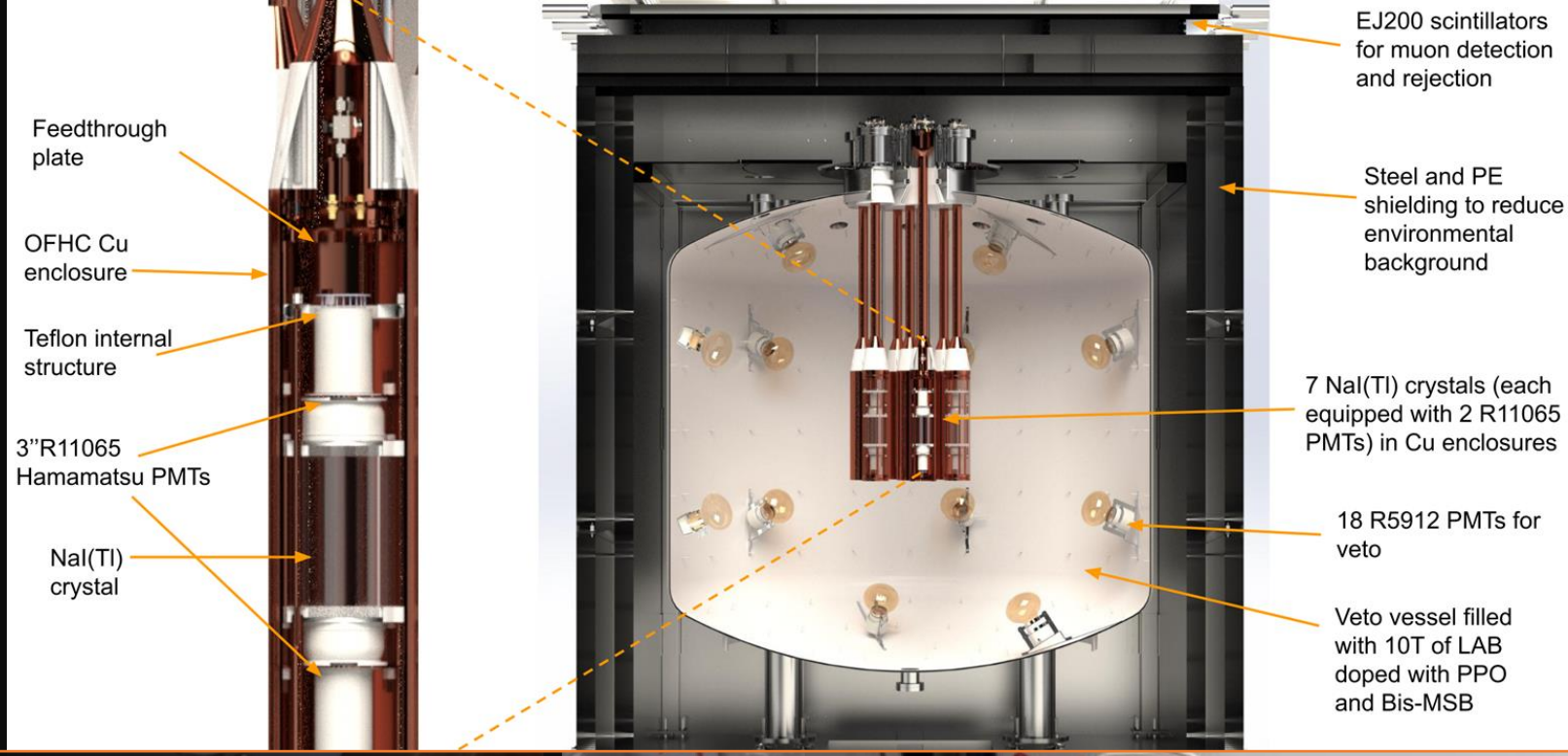
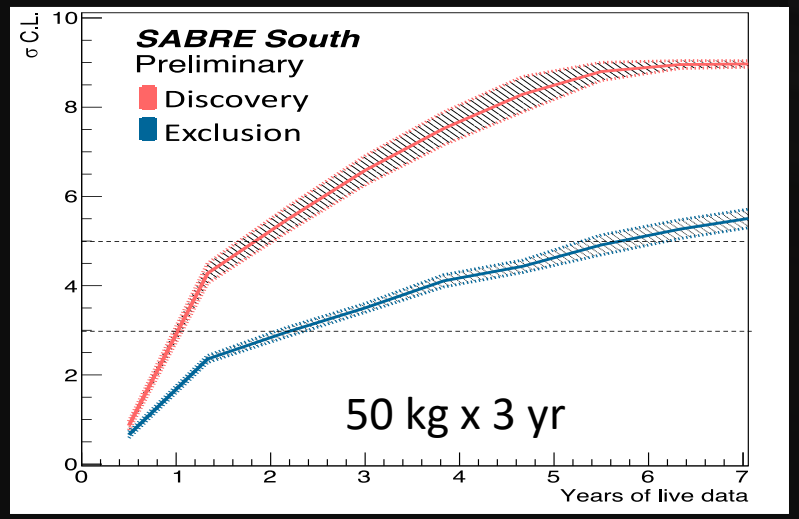
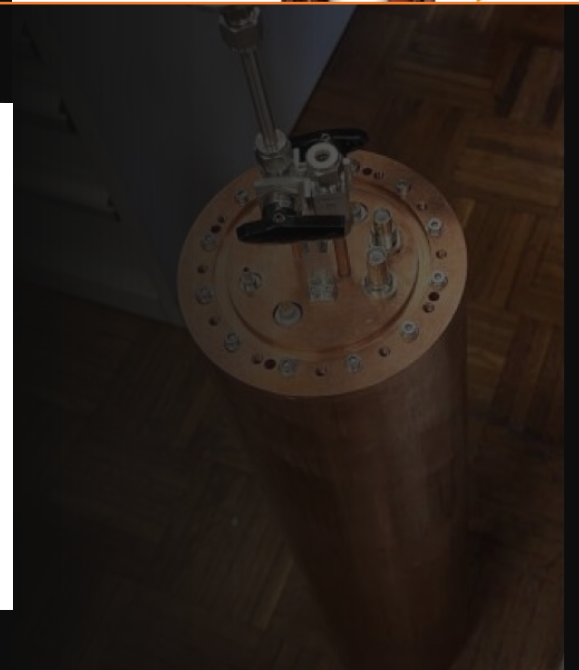
6000
3300
200
4475
4200
2120
FUTURE CLEAN
SABRE SOUTH
DRAINAGE TANK
(20-FT ISO CONTAINER)
SABRE SOUTH
EXPERIMENT
RS - MAIN
ACCESS
PLATFORM
RS - SECONDARY
ACCESS
PLATFORM
GAS PANEL
FUTURE CLEAN
LAB AREA
1.01
1.02
1.03
1.04
1.07
1.06
1.08
1.08a
1.08b
1.08c
HK/CT
GAS STORE
COM
Loading
Bay
SABRE South
Experiment
Experimental Hall (10x30 m)
min. height 12m
Entry Way
Cleaning Facilities

SABRE-South detector







Conclusions

- The main goal of SABRE is to deploy two nearly identical detectors in the Northern and Southern Hemispheres

- SABRE aims to focus on ultra-high purity NaI(Tl) detectors (0.1-0.3 dru in the ROI)
  - ✓ Currently, four crystals underground at LNGS
  - ✓ Two more crystals foreseen by 2023 to complete crystal characterization prior to production

- By 2023 finalize the strategy for crystals mass production for both SABRE-North and SABRE-South
  - ✓ We aim to demonstrate that ZR is a key technique for ultra-high radio-purity NaI-based detectors

- SABRE-South full detector deployment by mid 2024

- SABRE-North new underground site outfitting by 2024

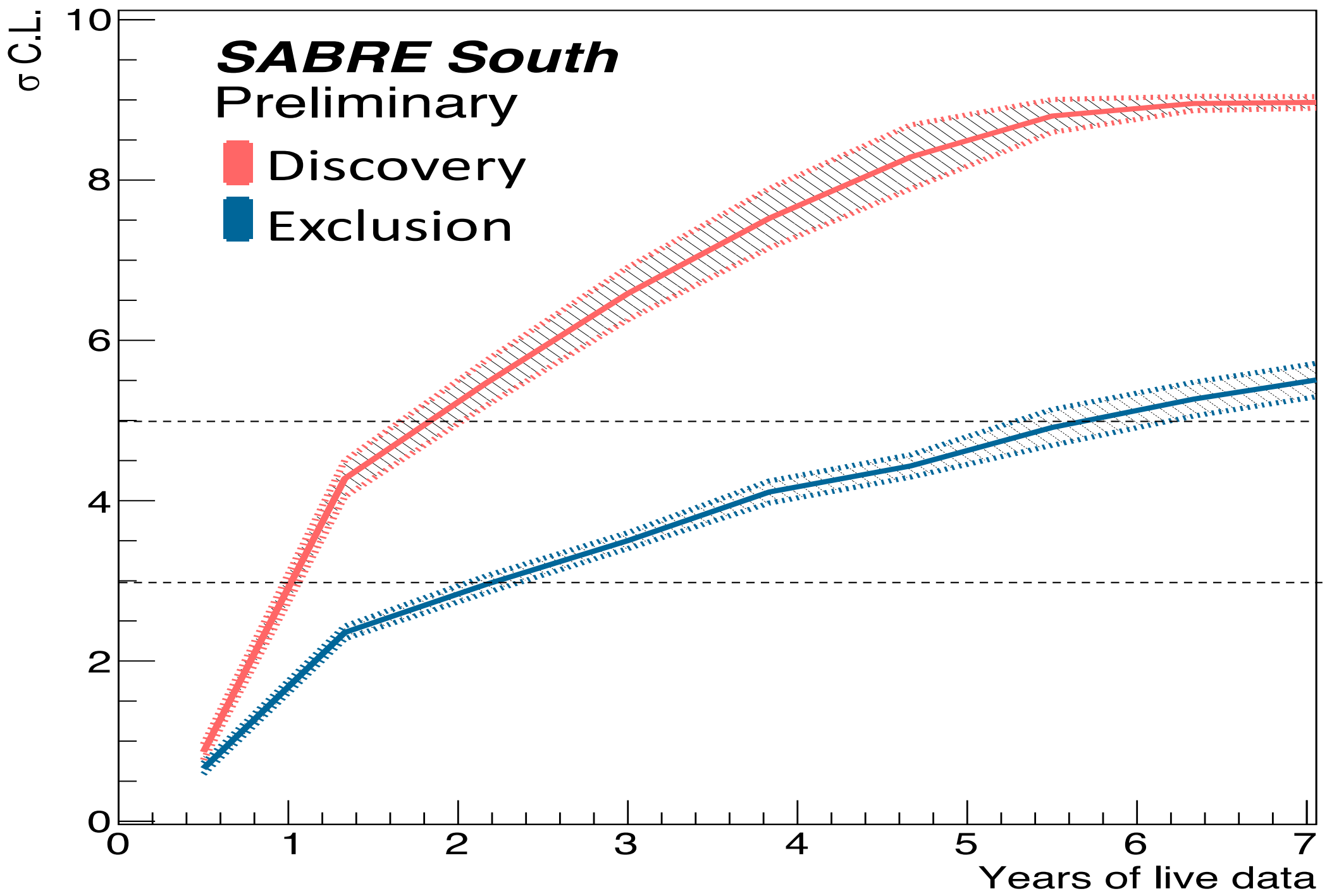
Publications

- SABRE: A new NaI(Tl) dark matter direct detection experiment, Physics Procedia 61 (2015) 169 – 178
- The SABRE project and the SABRE Proof-of-Principle, *Eur.Phys.J.C* 79 (2019) 4, 363
- Monte Carlo simulation of the SABRE PoP background, *Astropart.Phys.* 106 (2019) 1-9
- Growth of ultra-high purity NaI(Tl) crystals for dark matter searches, *Phys.Rev.Res.* 2 (2020) 1, 013223
- Characterization of SABRE crystal NaI-33 with direct underground counting, *Eur.Phys.J.C* 81 (2021) 4, 299
- Zone Refining of Ultrahigh-Purity Sodium Iodide for Low-Background Detectors, *Phys.Rev.Applied* 16 (2021) 1, 014060
- High sensitivity characterization of an ultrahigh purity NaI(Tl) crystal scintillator with the SABRE proof-of-principle detector, *Phys.Rev.D* 104 (2021) 2, L021302
- Performance of the SABRE detector module in a purely passive shielding, *Eur.Phys.J.C* 82 (2022) 12, 1158
- SABRE-South simulation paper submitted to EPJC. https://arxiv.org/abs/2205.13849

Thank you!

Ongoing activities for 2023

- Characterization of NaI-35 and NaI-37 at LNGS
- Performed several assembly activities to test different PTFE reflectors and enclosure design in an underground Radon-free clean room
- Ugrade of zone refiner at MELLEN
- Outfitting laboratory space at RMD for zone refining and tests for growth after zone refining
- Start feasibility study with APL Engineered Materials, Inc. for high-purity powder production
- Outfitting of SUPL and deployment of SABRE-South detector, almost completed
- Fluid handling and shielding construction for SABRE-South


σ C.L.
SABRE South
Preliminary
Discovery
Exclusion
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Years of live data