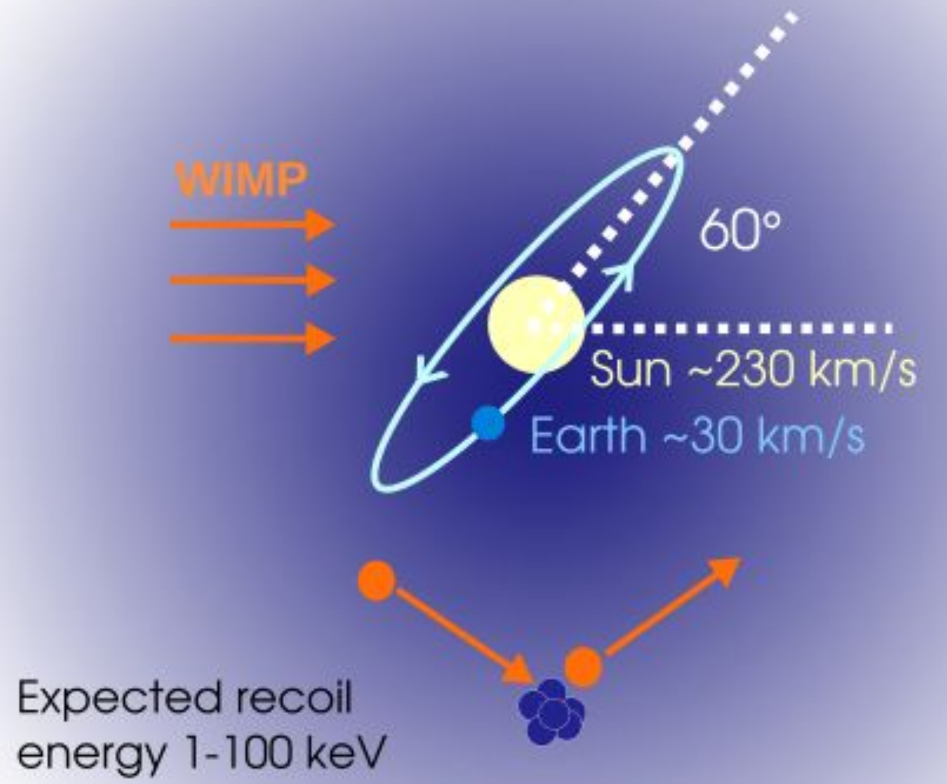
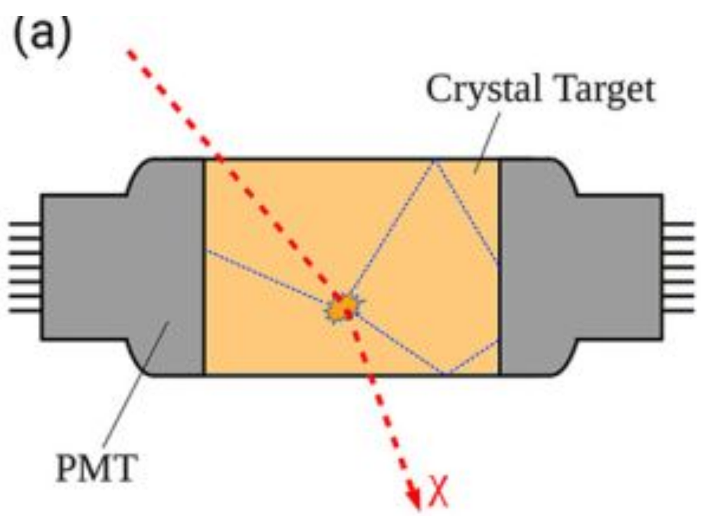
Status and prospects of SABRE North and South

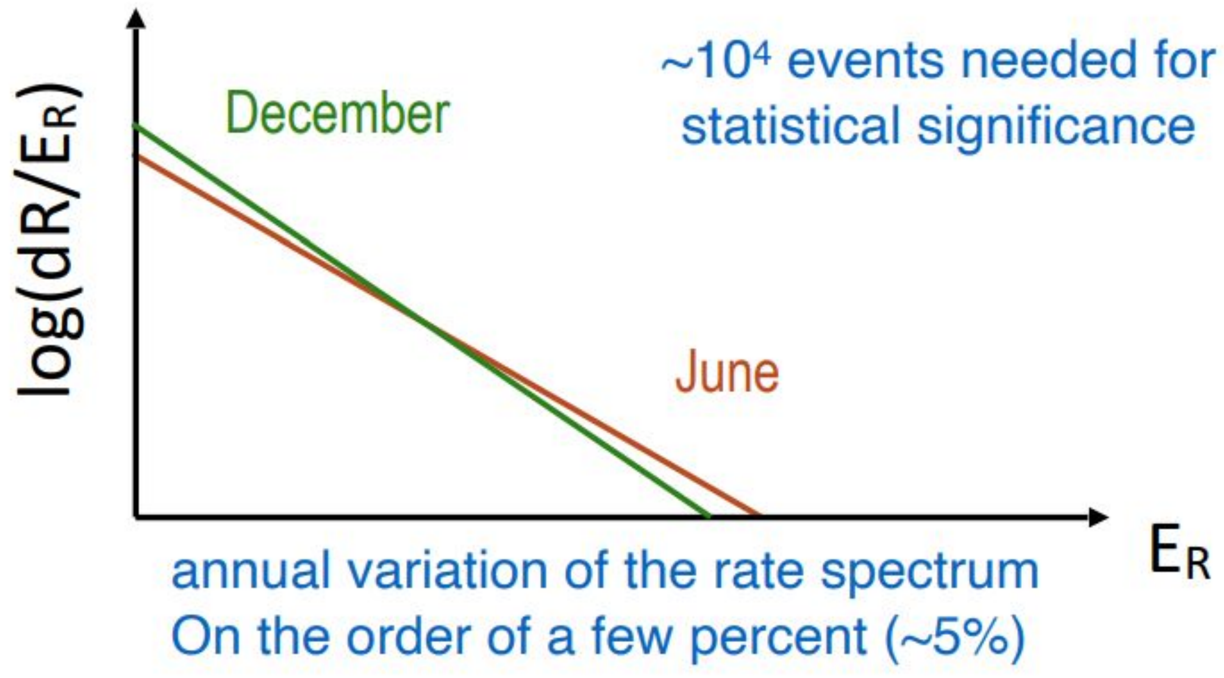
Giulia D'Imperio, INFN Roma
on behalf of SABRE North and SABRE South collaborations

TAUP VIENNA 2023

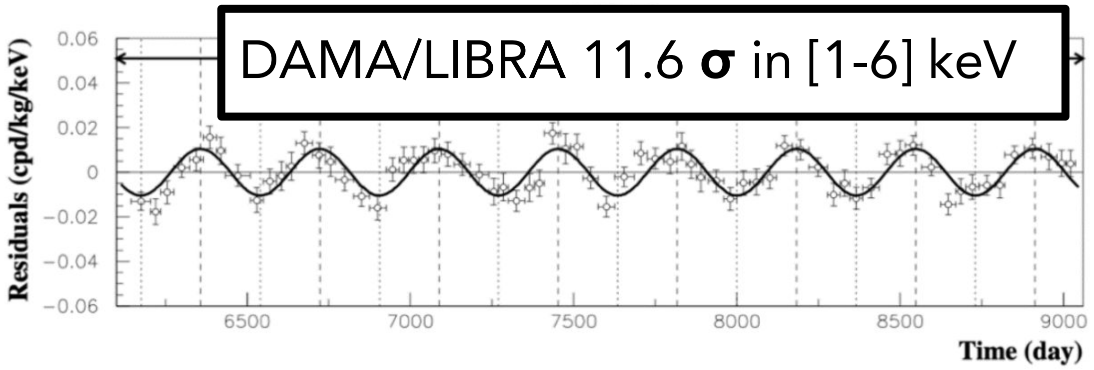
Dark Matter with annual modulation





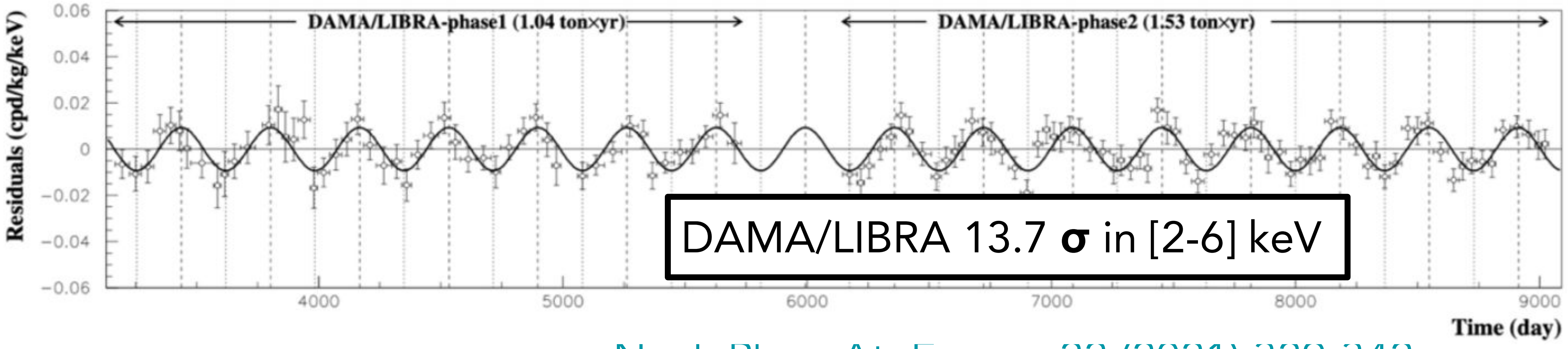


- Expected rate in an Earth-based detector is modulated
- Small modulation fraction S_m/S_0 = O(~few %)
- Region of interest [1-6] keV



Rate vs time

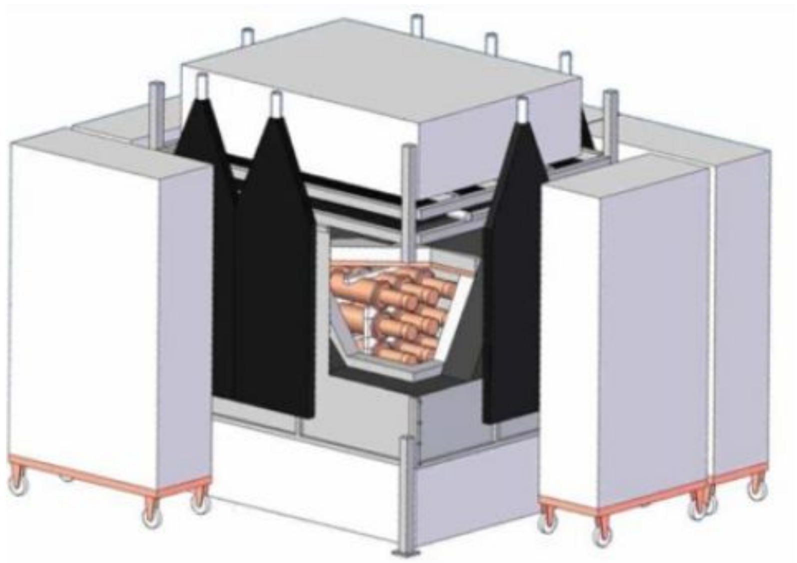
$$R = S_0 + S_m \cos(\frac{2\pi}{T}(t - t_0))$$



Nucl. Phys. At. Energy 22 (2021) 329-342

NaI experimental landscape

ANAIS
@Canfranc,
Spain

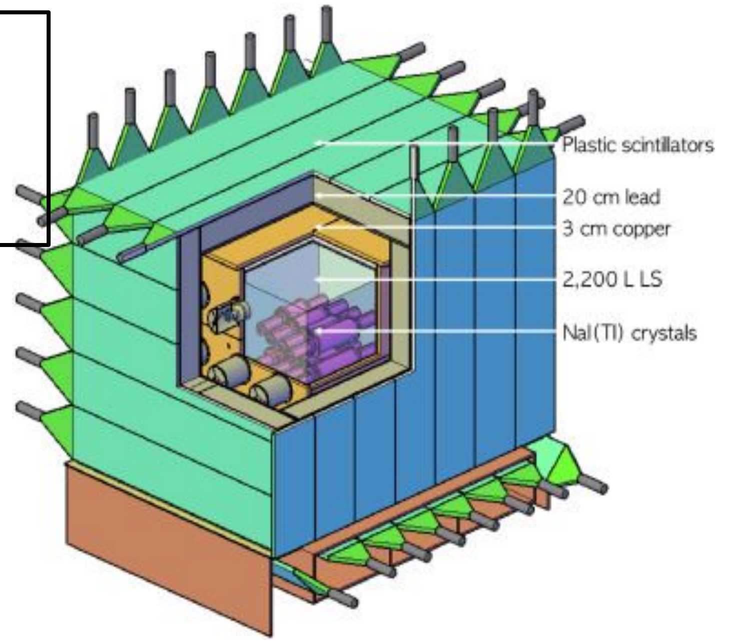


see talk by I. Coarasa on Thursday 31

Phys. Rev. D 103, 102005 (2021)

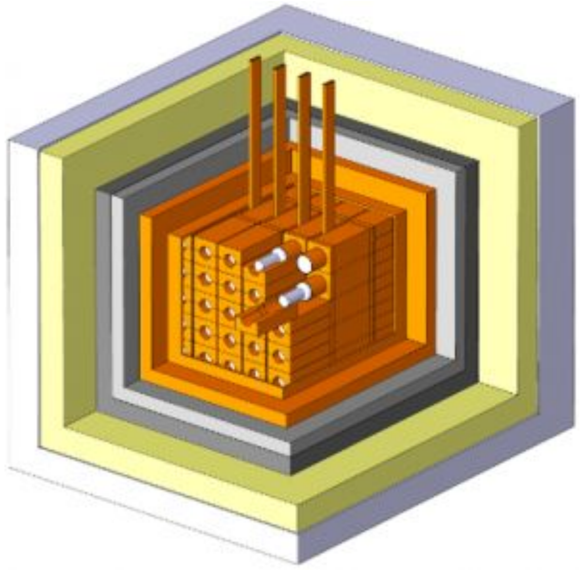
COSINE-100 @Yang Yang, South Korea

see talk by H. S. Lee on Thursday 31

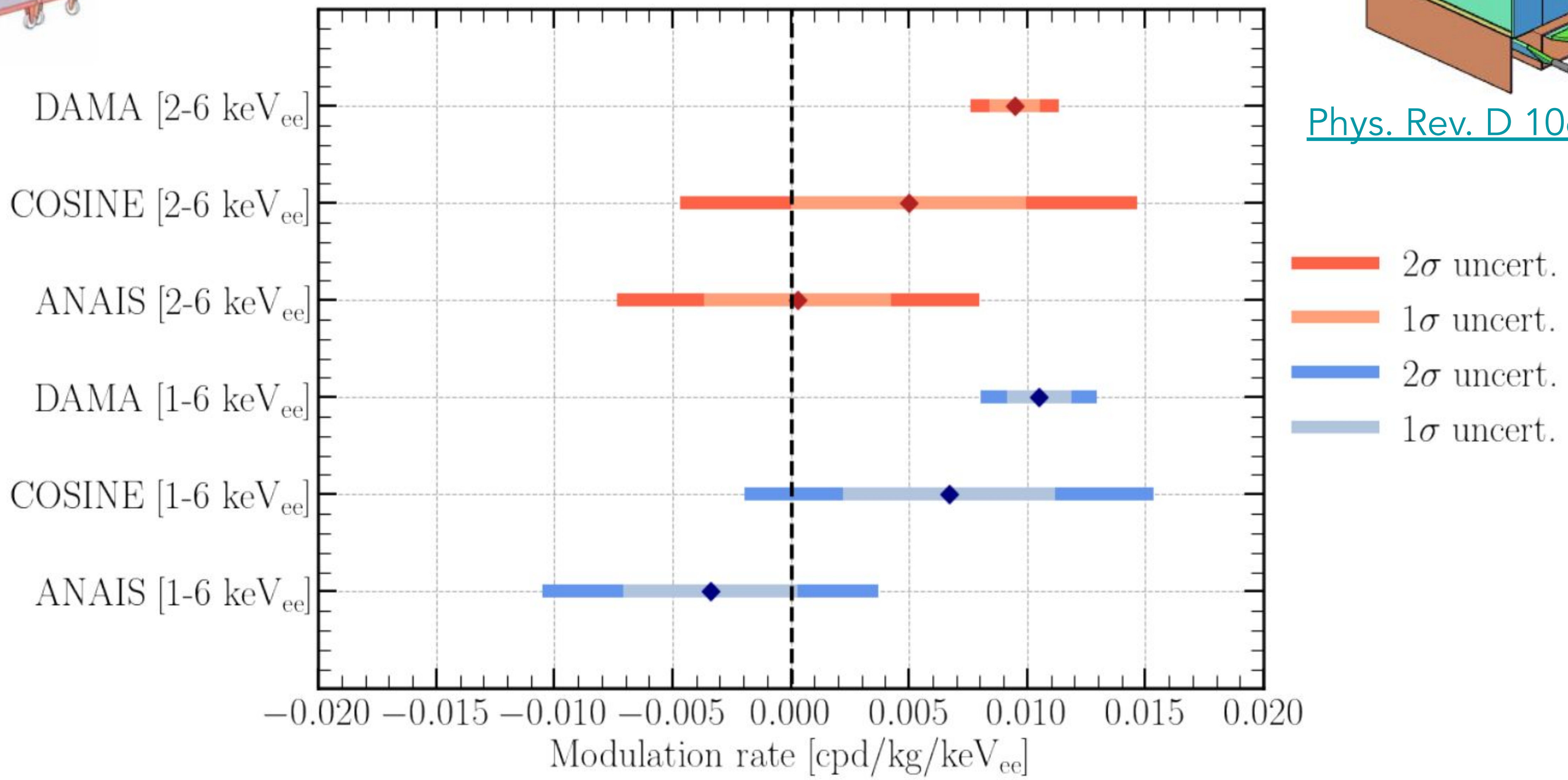


Phys. Rev. D 106, 052005 (2022)

DAMA/LIBRA
@LNGS, Italy



Nucl. Phys. At. Energy 22 (2021) 329-342



arXiv: 2211.15861

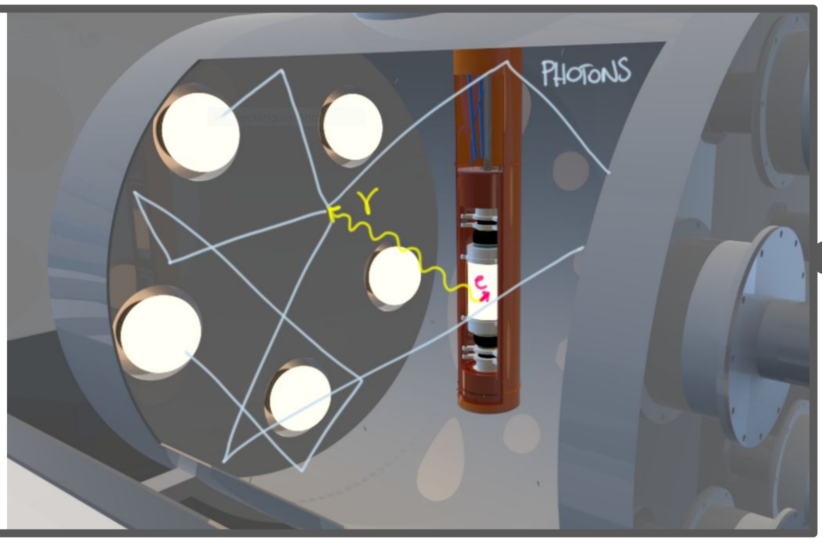
Sodium-iodide with Active Background REjection

The goal of SABRE experiment is to search for dark matter through **annual modulation** signature with **higher sensitivity (=lower background)** w.r.t. DAMA and other NaI(Tl) based experiments

Rate goal ~0.5 count/day/kg/keV

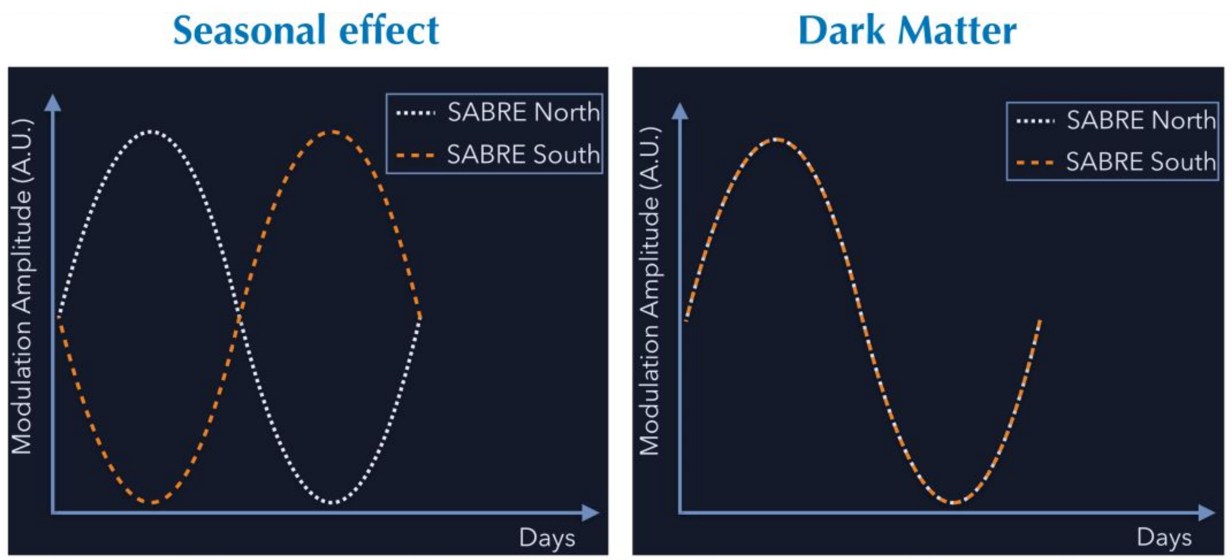
Ultra radio-pure crystals

Active veto with liquid scintillator



Double location:

Northern and Southern hemisphere

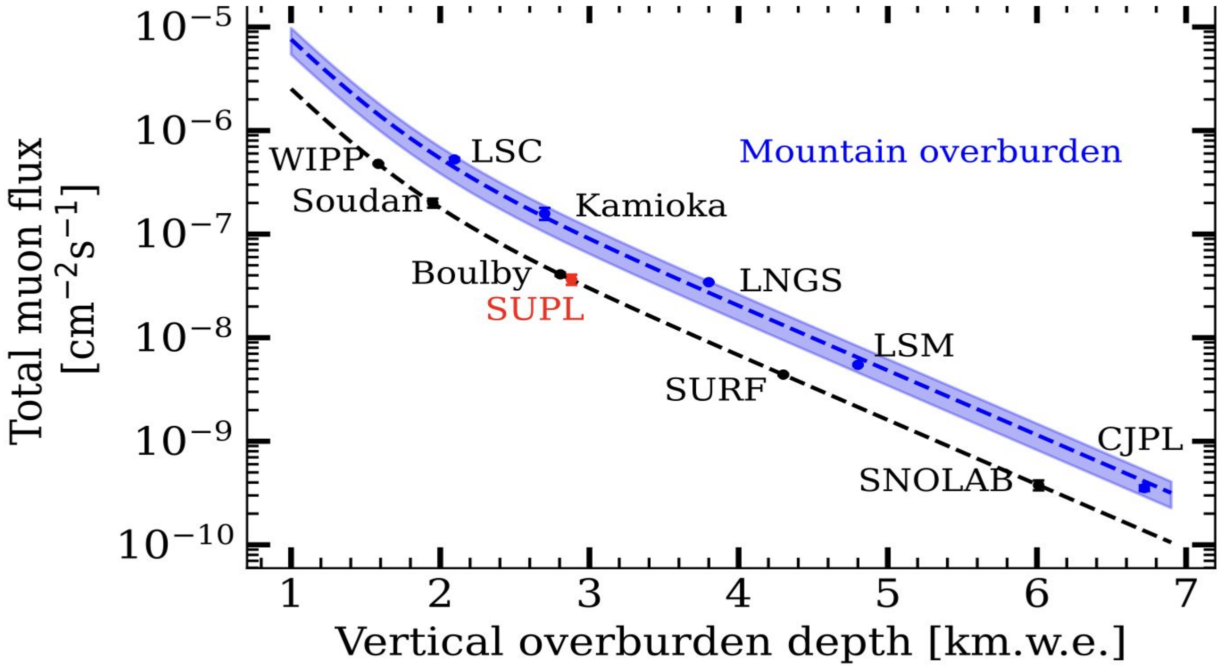


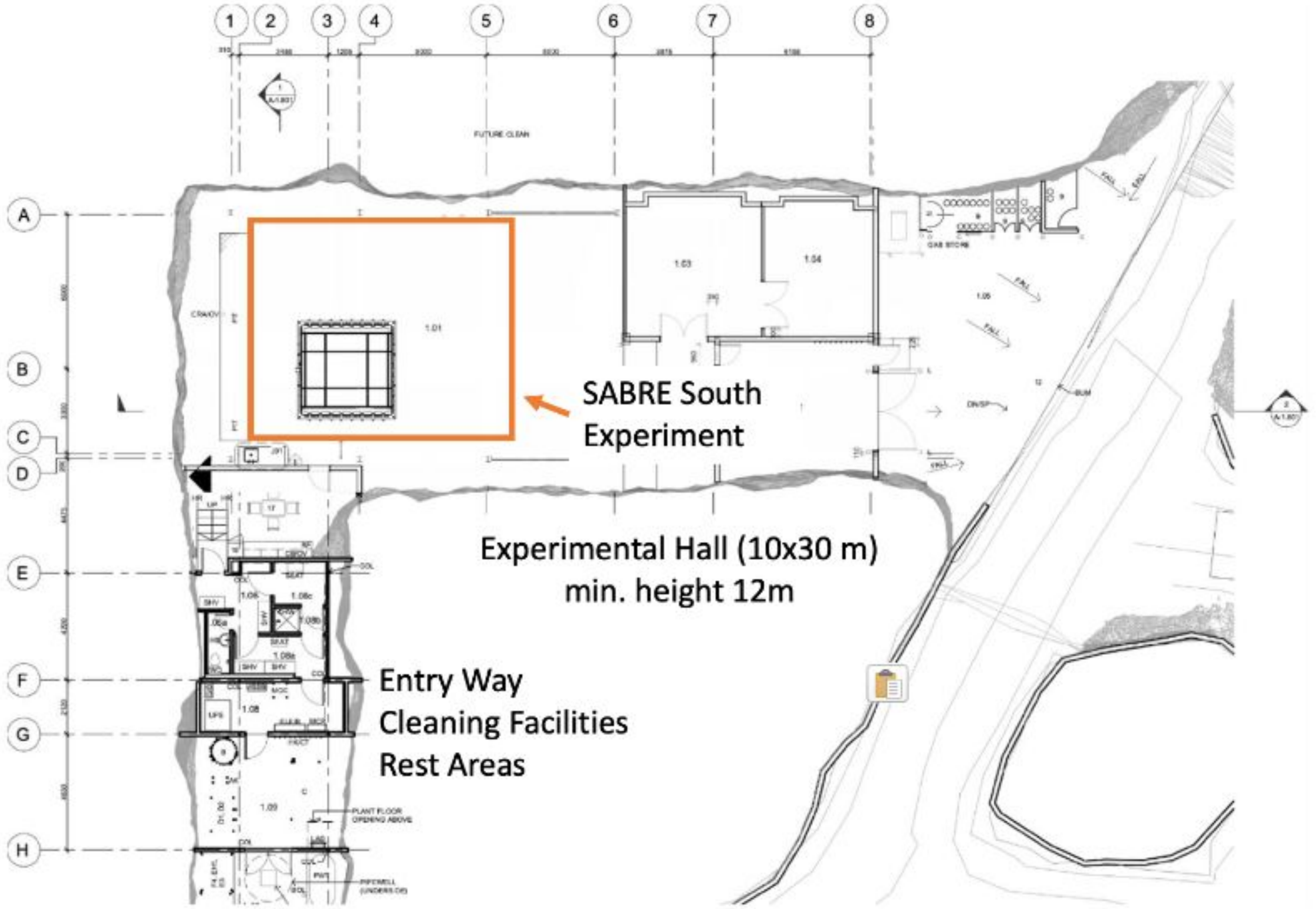
SABRE North and South

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

Stawell Underground Physics Lab (SUPL)

- First deep underground laboratory in the Southern Hemisphere
  - 1025 m deep (2900 m water equivalent) with flat overburden
- Located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia
  - Helical drive access
- Lab completed in 2022. SABRE South Assembled 2023-24.





Giulia D'Imperio - TAUP 2023

SABRE North facilities @LNGS (2022-2023)

- Two passive shielding setups for crystal characterization in Hall B
- A clean room with SABRE glovebox for crystal assembling in Hall C

- 10 cm Cu + 15 cm of Pb
- Host 1 detector module
- Lexan box flushed with N2

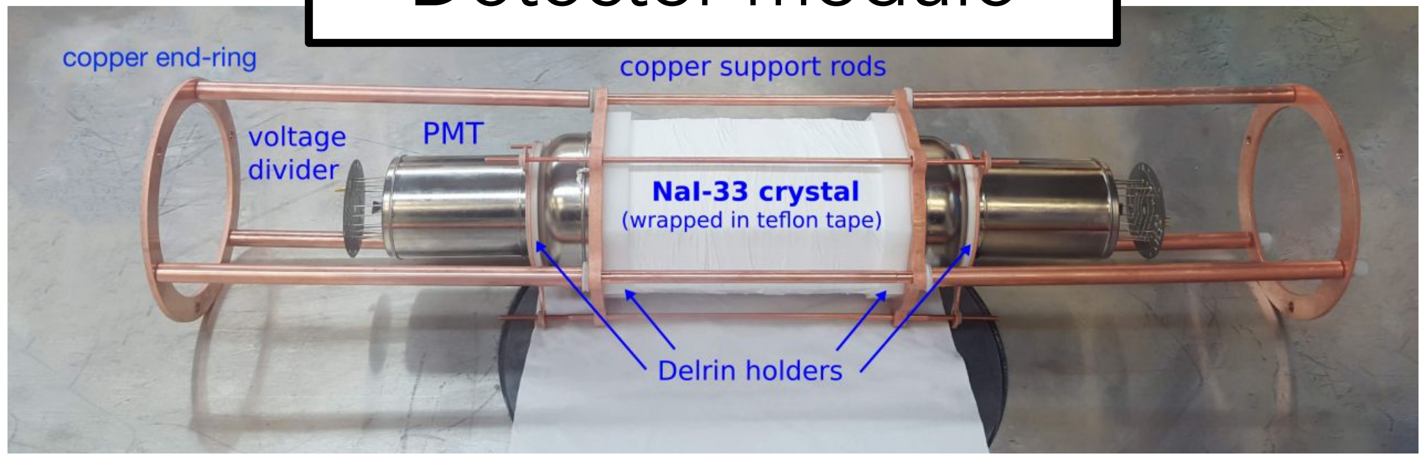
- 30 cm Cu shielding
- Host 1-3 detector modules
- Flushed with N2

SABRE glovebox

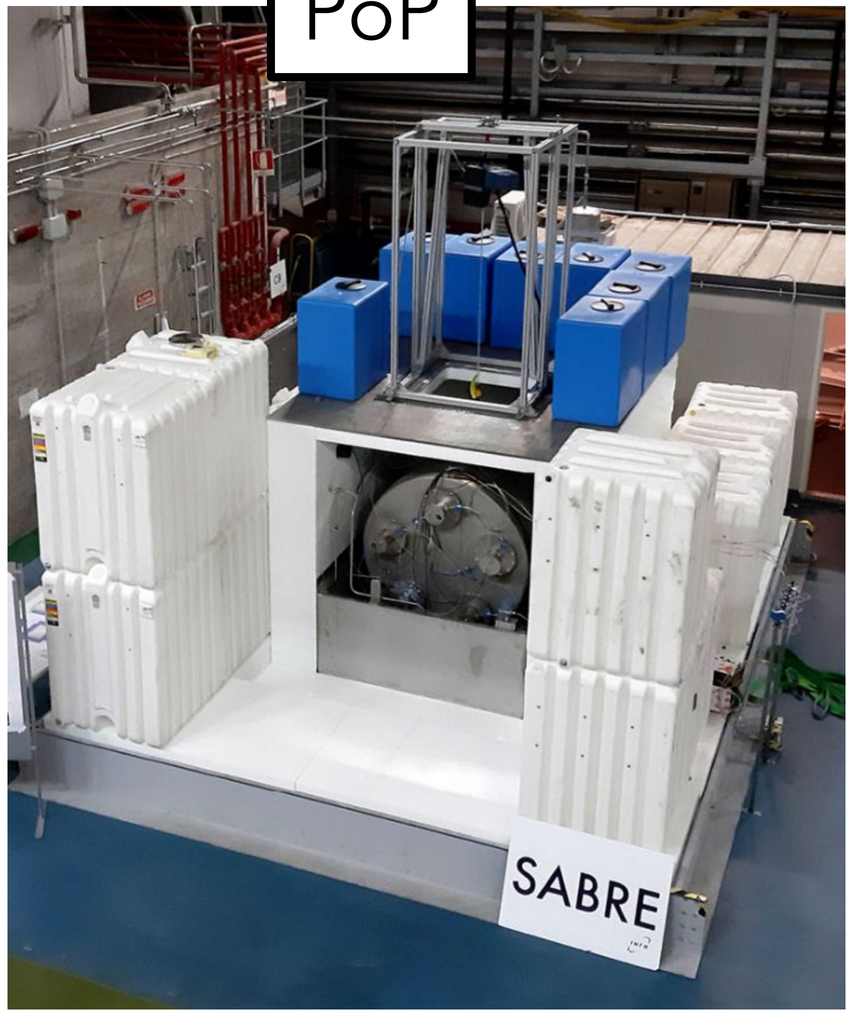
- A new site for SABRE North has been identified at LNGS. Development of a refurbishment plan and new outfitting in 2024 in collaboration with the Technical Division of LNGS

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

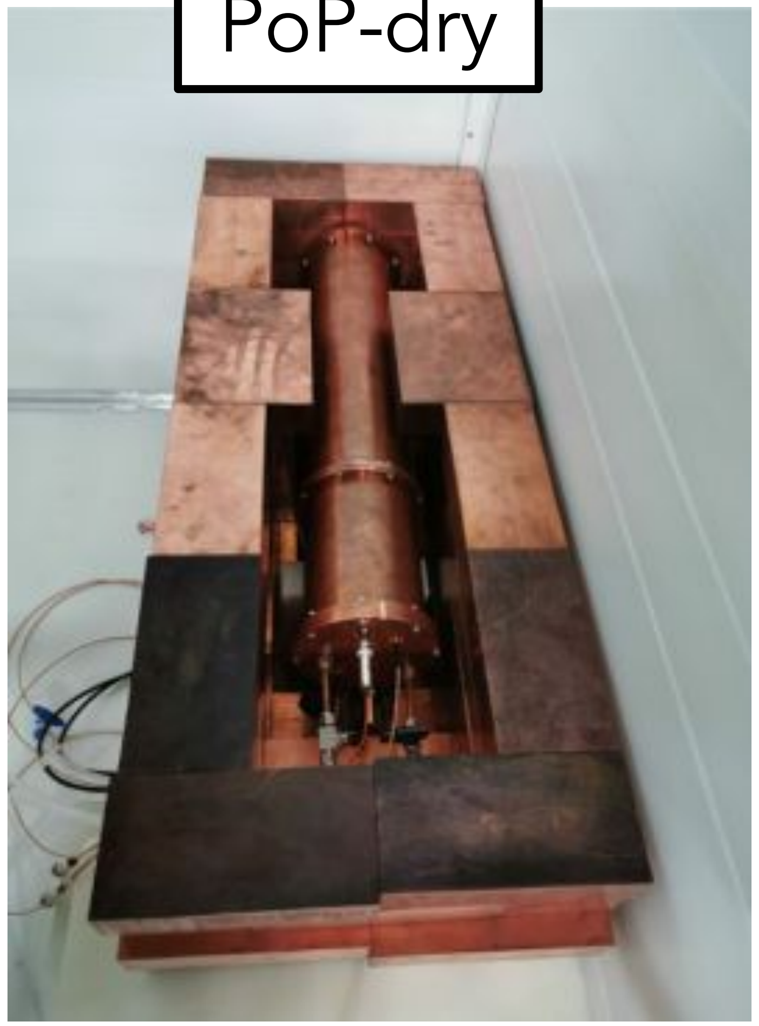
Detector module



PoP

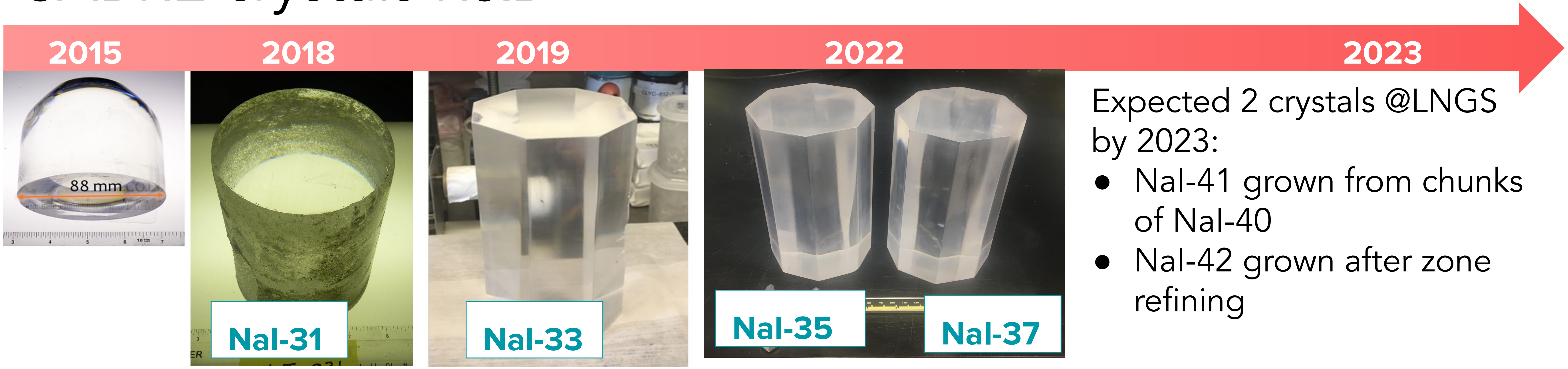


PoP-dry



- 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: passive shielding with additional layer of copper
  - confirmed background level

SABRE crystals R&D



Expected 2 crystals @LNGS by 2023:

- NaI-41 grown from chunks of NaI-40
- NaI-42 grown after zone refining

	Mass [kg]	LY [pe/keV]	^{39}K [ppb]	^{210}Pb [mBq/kg]	^{238}U [ppb]	^{232}Th [ppb]	Rate [1-6] keV [cpd/kg/keV]	Exposure [kg day]
NaI-31	3.00	9.1±0.1	16.5±1.1	1.02±0.07	-	-	2.74±0.03	786
NaI-33 (*)	3.40	12.1±0.2	4.3±0.6	0.51±0.02	0.47±0.05	0.40±0.07	1.20±0.05	90
NaI-33 (**)	3.40	11.1±0.2	4.3±0.7	0.51±0.02	0.47±0.05	0.40±0.07	1.39±0.03	891
NaI-33 (***)	3.40	11.1±0.2	4.3±0.8	0.53±0.01	0.47±0.05	0.40±0.07	0.95±0.05	95.2
NaI-35	4.36	8.7±0.1	8.3±0.6	0.51±0.03	0.18±0.03	-	1.26±0.35 (****)	35.6
NaI-37	4.35	7.8±0.2	8.0±0.6	0.79±0.01	0.61±0.05	0.27±0.06	2.71±0.05 (****)	243.6

Crystals grown by RMD
R&D carried out by PU, INFN and ARC Centre of Excellence for DM

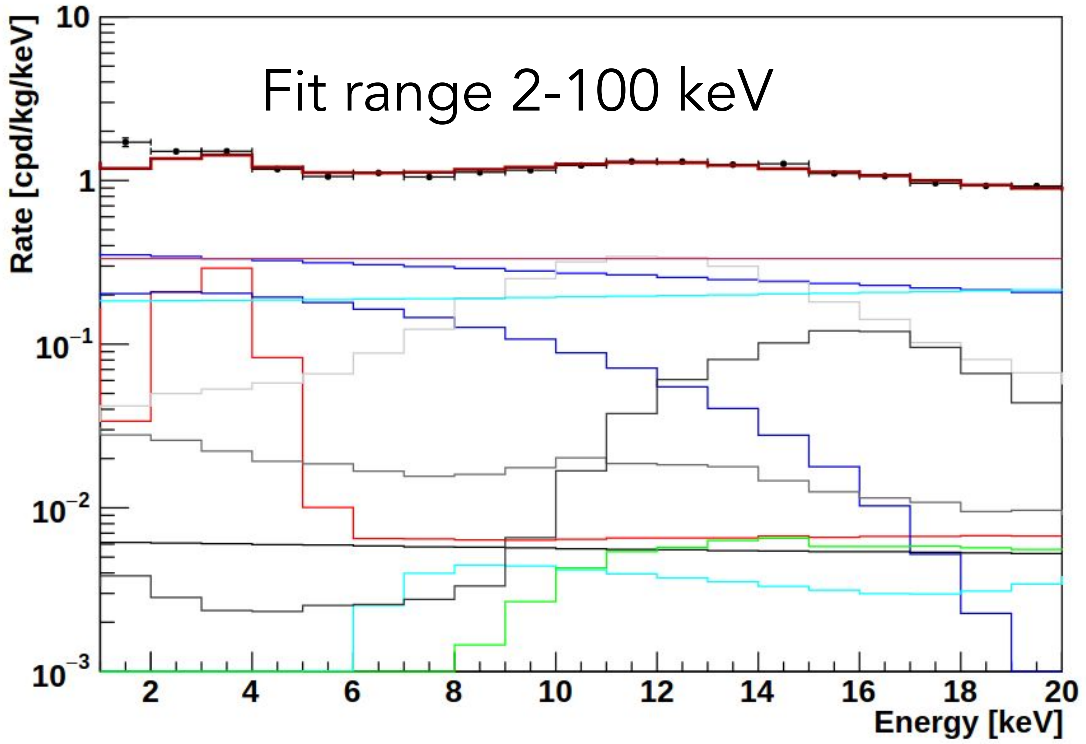
(*) SABRE PoP
(**) SABRE PoP-dry
(***) SABRE PoP-dry in new shielding
(****) Preliminary rate in [2,6] keV ROI

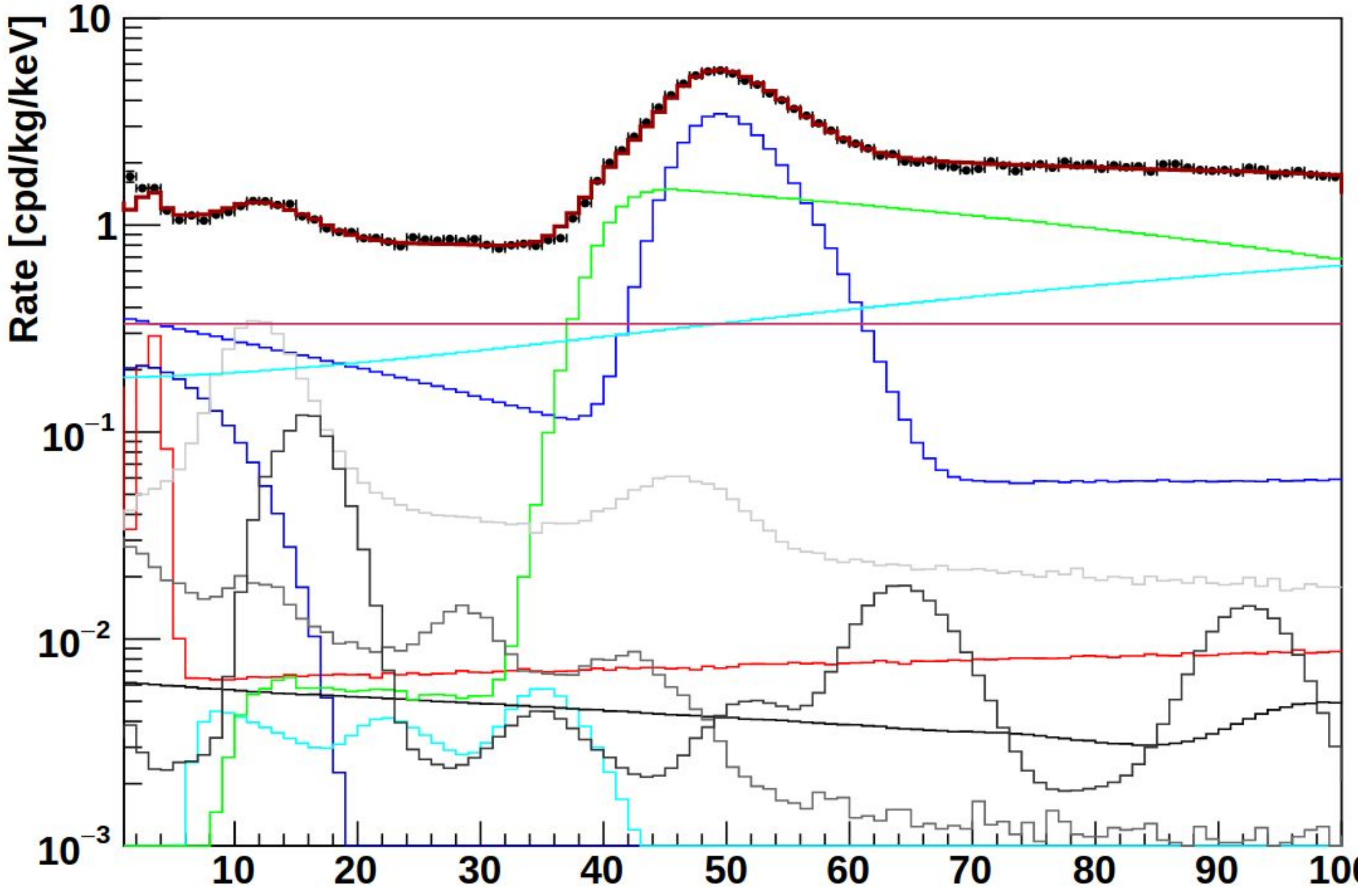
- Background ~1 cpd/kg/keV →close to DAMA/LIBRA Phase 1
- Reproducibility of clean growth within factor 2

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	





The SABRE strategy

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

- Strategy to reach the background goal of ~0.5 cpd/kg/keV
  - For ^{210}Pb and other internal backgrounds

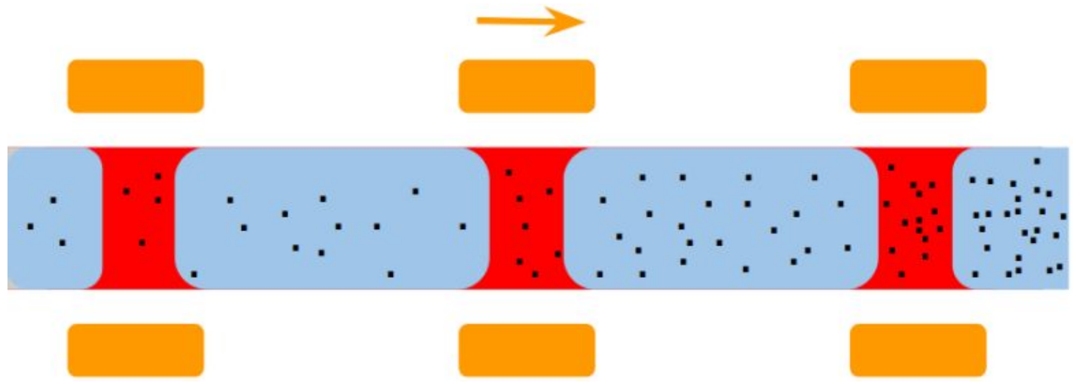
    →SABRE North & South: zone refining
    → Reduce Pb of factor ~3, K of ~10
    Phys. Rev. Applied 16, 014060 (2021)

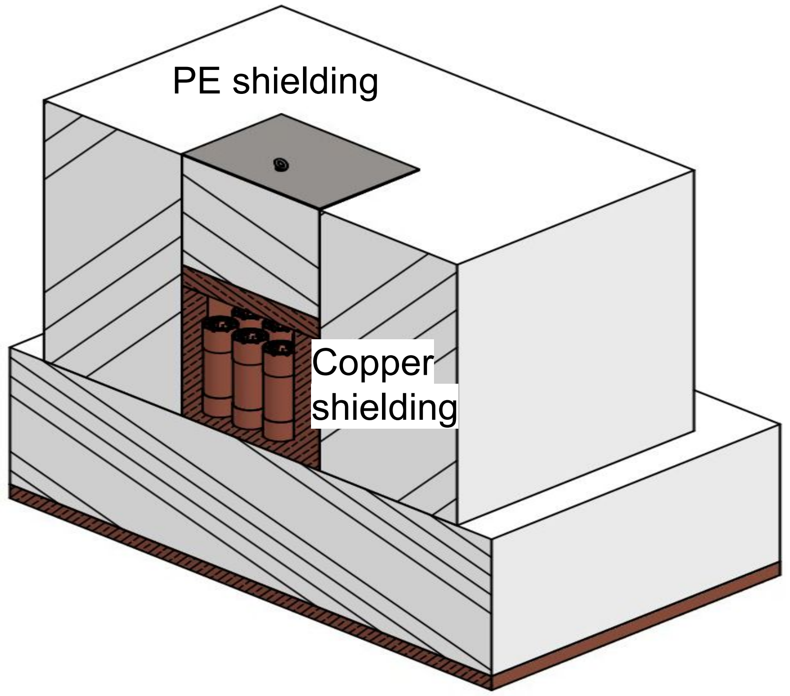
  - For external background:

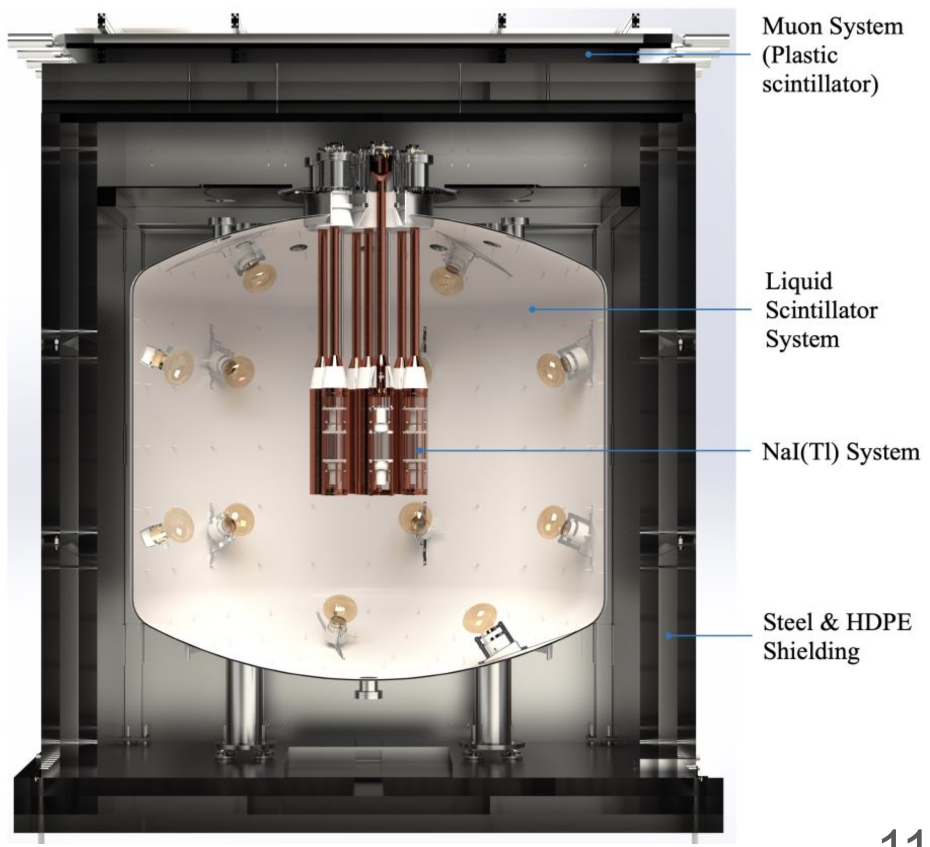
    →SABRE North: improve passive shielding

    →SABRE South: Liquid Scintillator (LAB)

    \+ Muon Veto



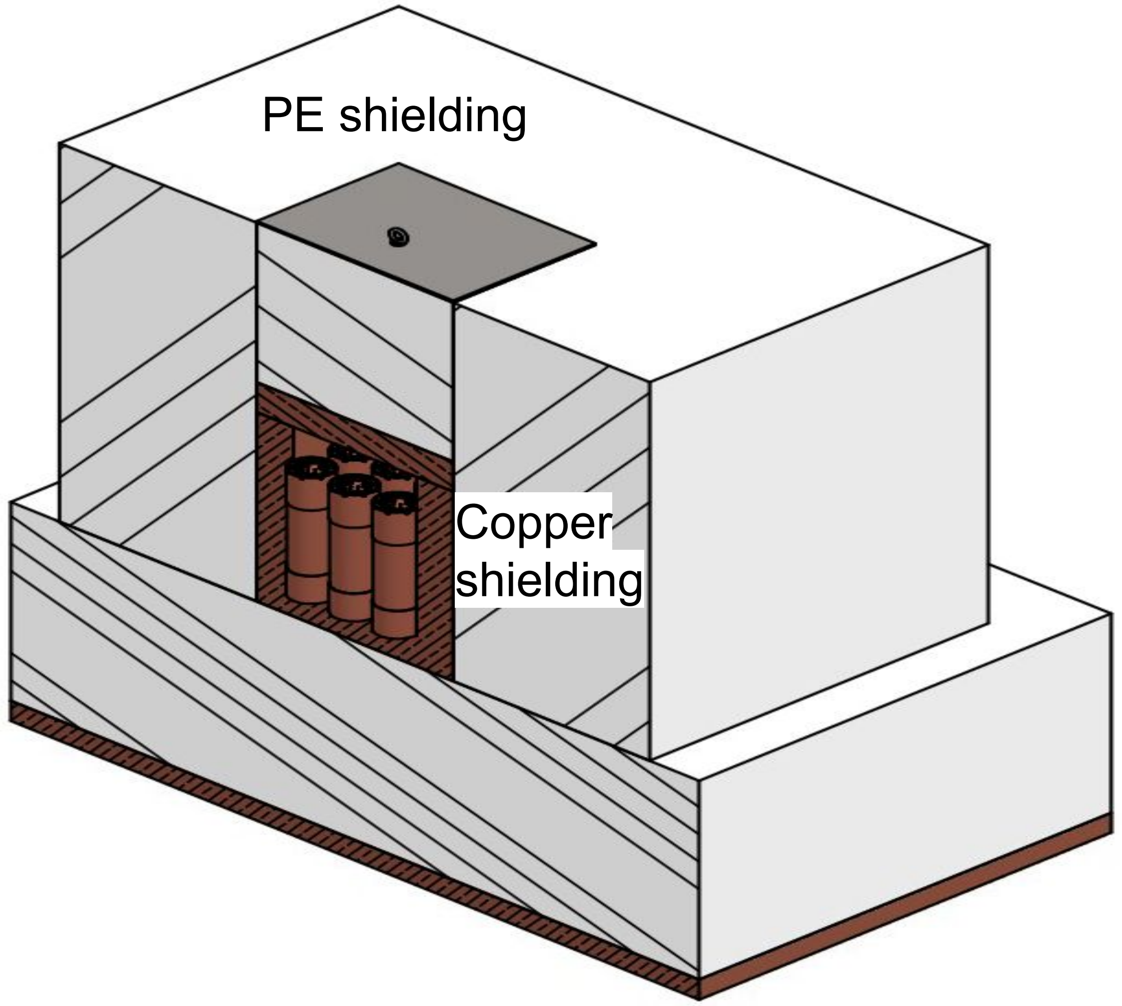




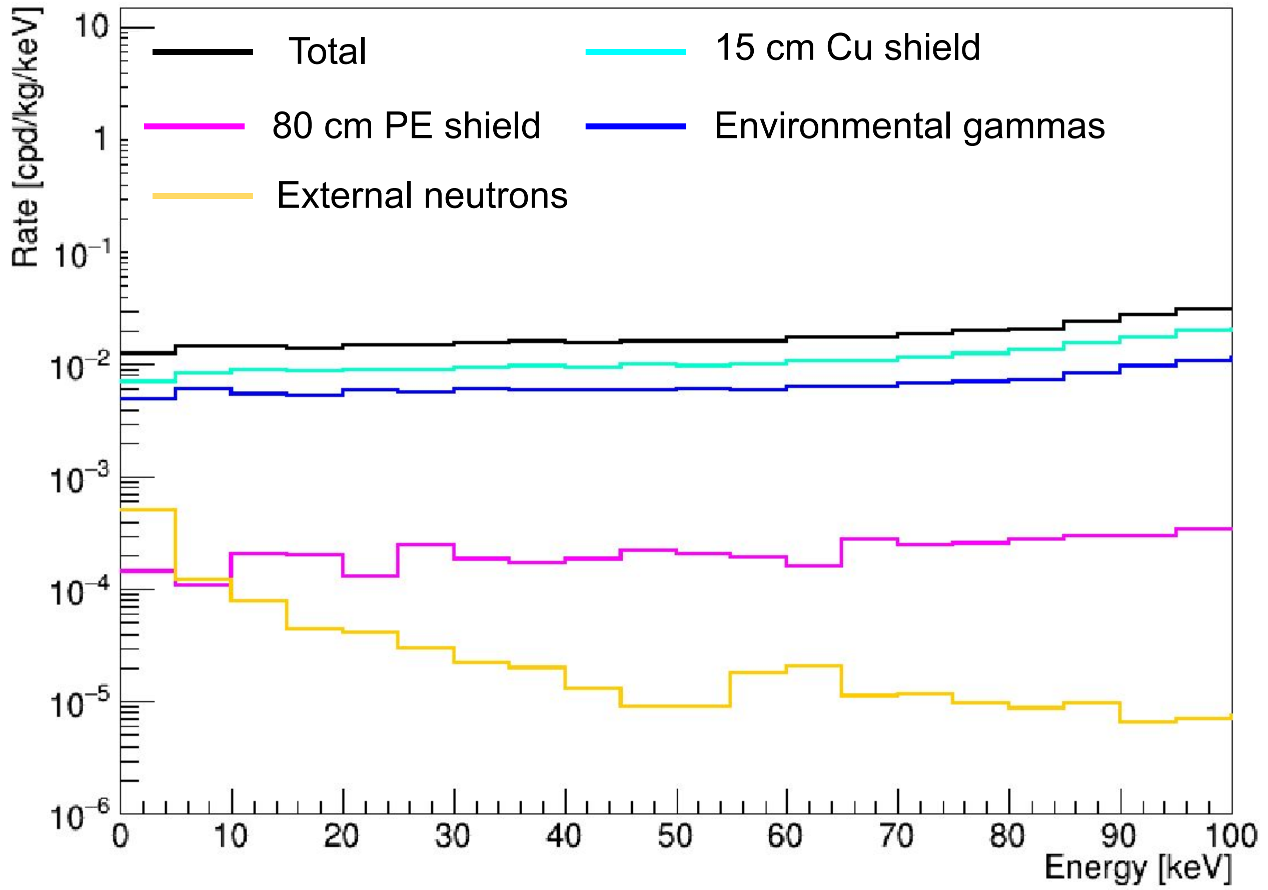
SABRE North status

- Conceptual design report presented in July 2021, TDR due in summer 2024
- 3 x 3 matrix of crystals of ~5 kg mass each
- Fully passive shielding design: 15 cm copper + 80 cm PE
  → enough shielding power and negligible contribution to the total background
- Expected background 0.5 cpd/kg/keV (with ZR) or 1 cpd/kg/keV (w/o ZR)

3x3 NaI matrix with 15 cm copper and 80 cm polyethylene

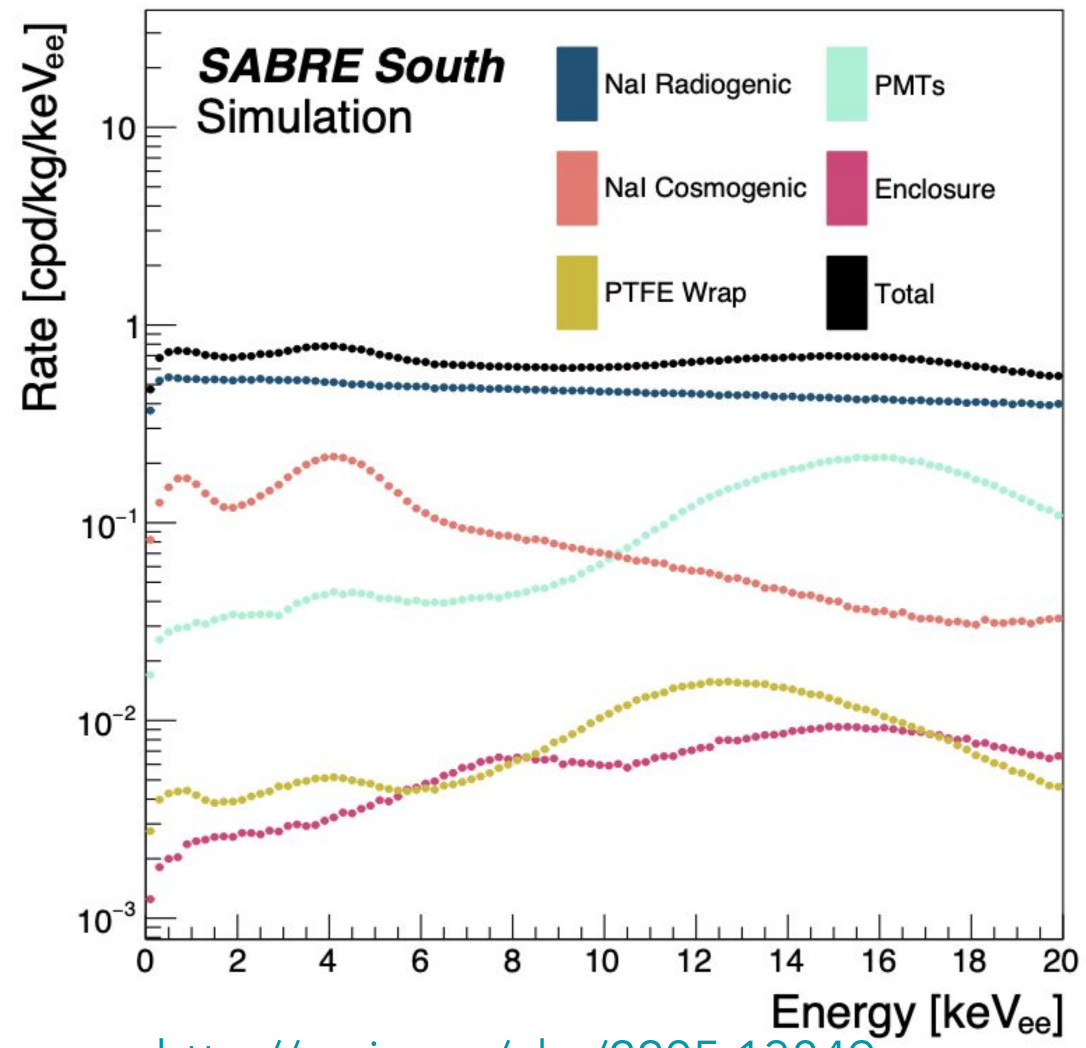


External +shielding bkg ~10^{-2} cpd/kg/keV



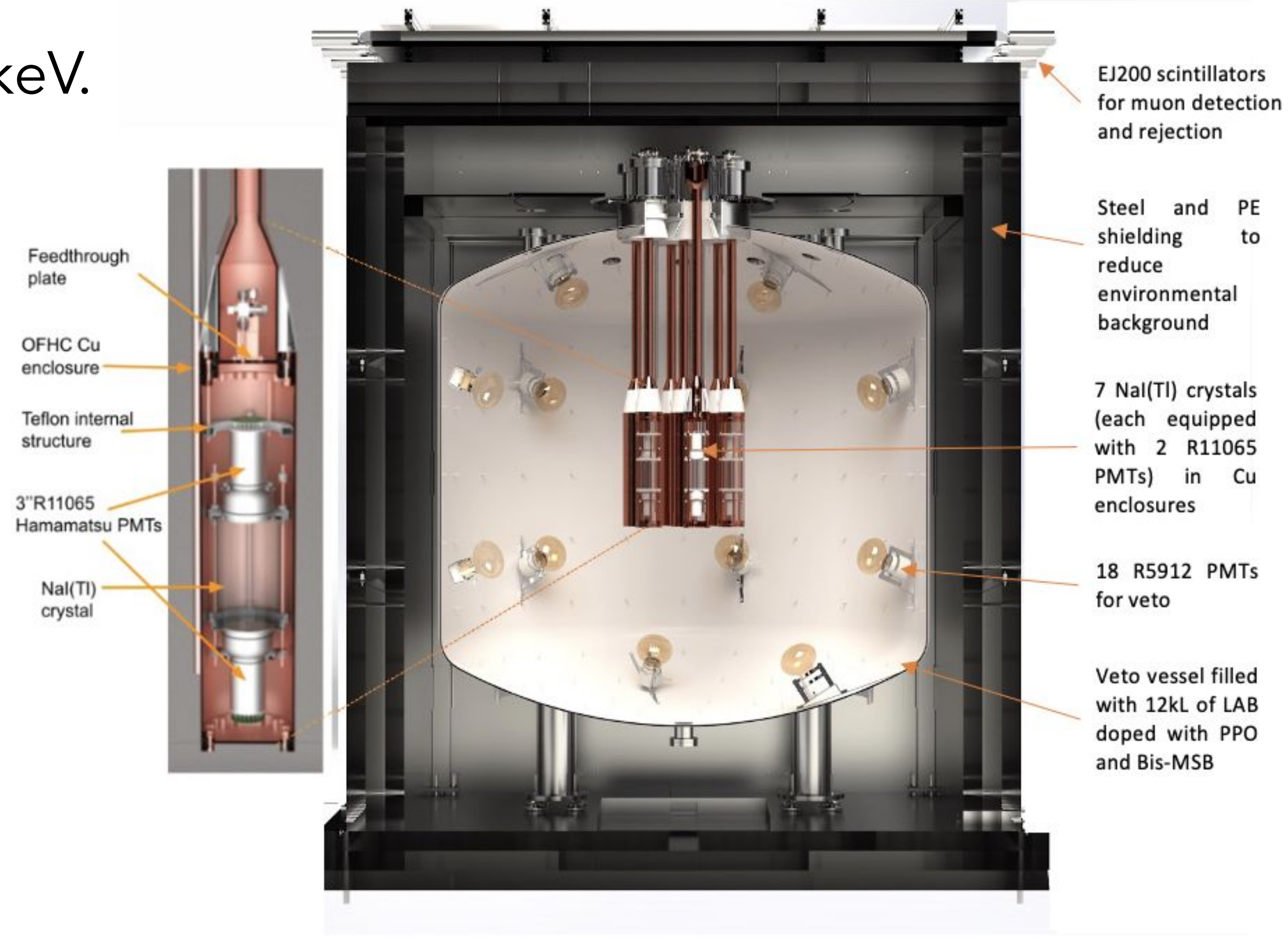
SABRE South status

- Design: 7 crystals array of ~5-7 kg mass (SABRE South TDR available online)
- Vessel + LAB, PMTs, muon detector, DAQ electronics, Crystal insertion system ... all ready.
- Crystal procurement in synergy with SABRE North
- Highest purity crystals and largest active veto: 0.72 cpd/kg/keV.

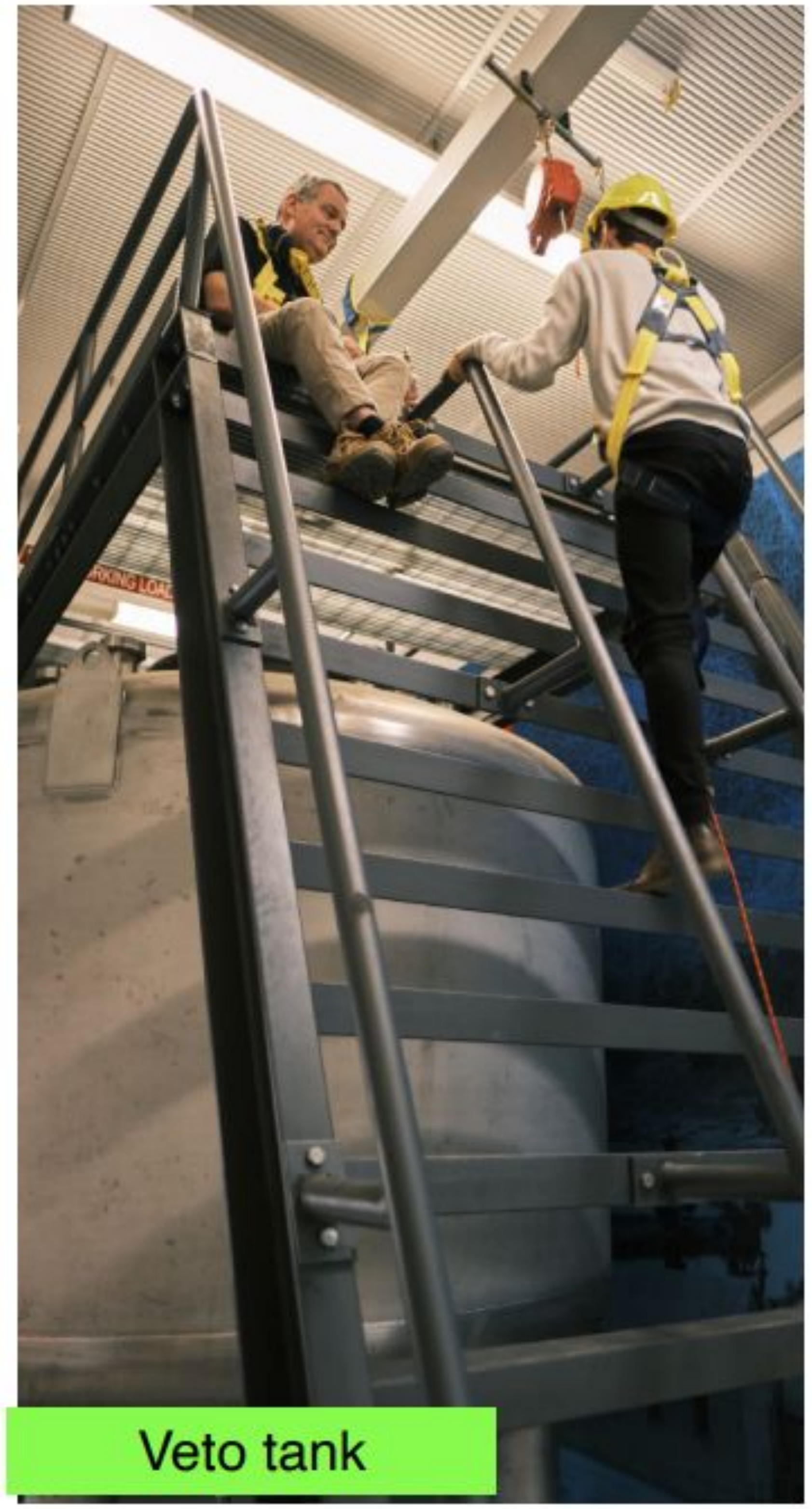


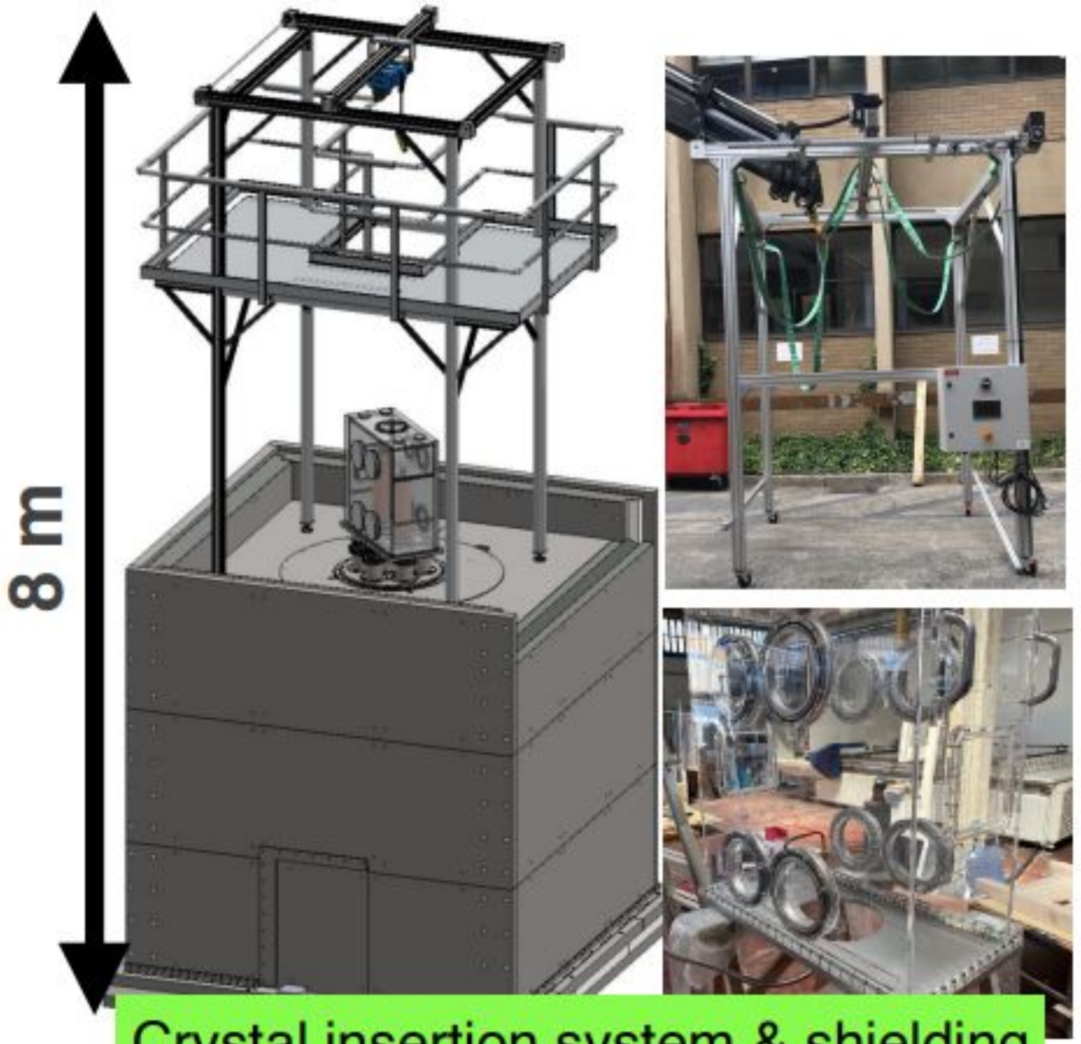
http://arxiv.org/abs/2205.13849
(accepted to EPJC)

- SABRE South will be assembled in 2023 → full detector deployment by end of 2024
- Expect exclusion or discovery results after 2.5-3 years of continuous operation



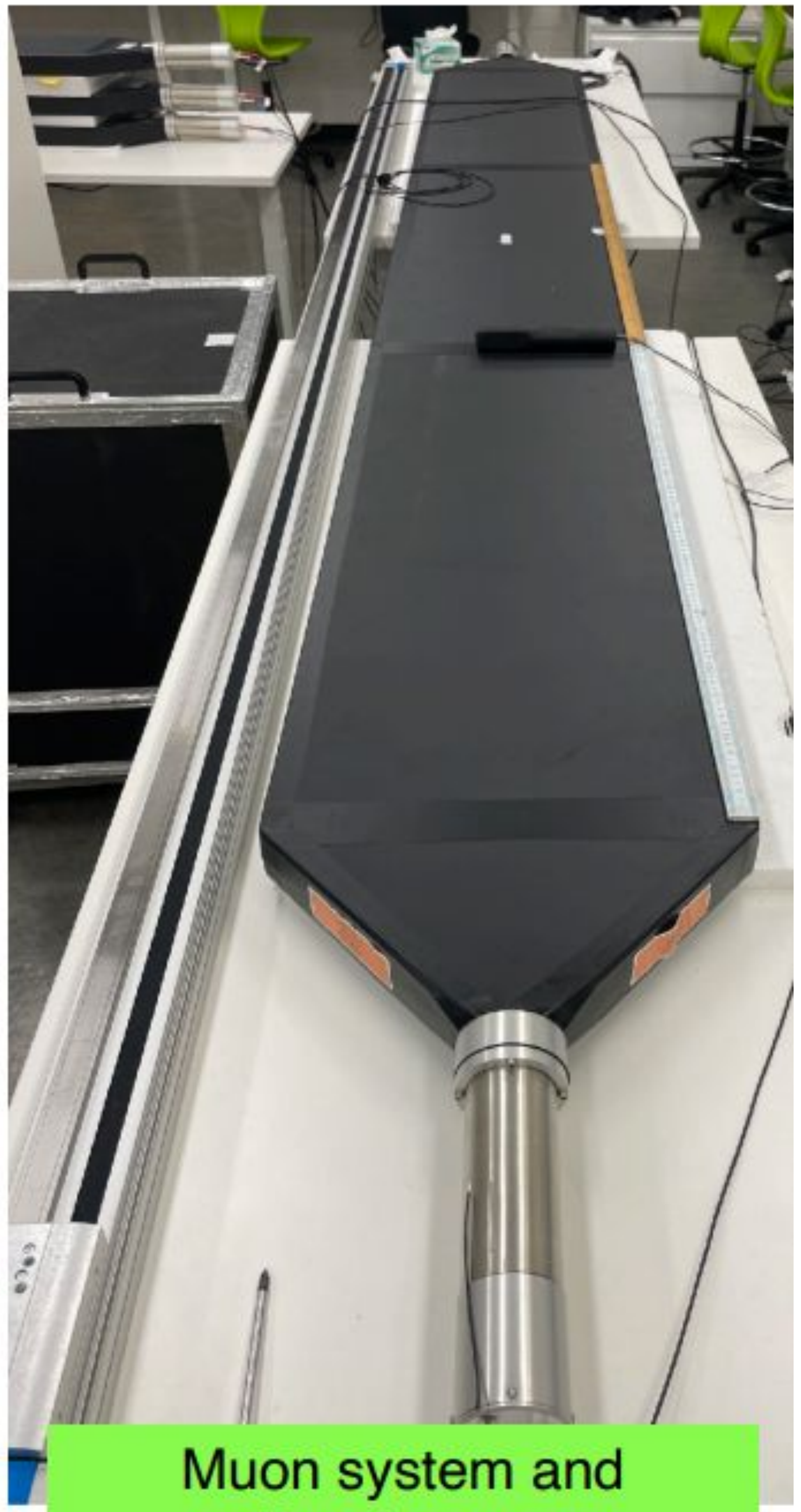
SABRE South status


Veto tank



Crystal insertion system & shielding


Liquid Scintillator from JUNO


Muon system and calibration stage

Conclusions

- SABRE goal is to search for annual modulation with two nearly identical NaI(Tl) detectors in the Northern and Southern Hemispheres
- Crystals current result @LNGS: ~1 cpd/kg/keV background
  - Goal is ~0.5 cpd/kg/keV → within reach with ZR
- SABRE-South full detector deployment by end of 2024
- SABRE-North new underground site outfitting by 2024
- SABRE expected to exclude/confirm annual modulation in 3-5 years of operation

…thanks for the attention!

SABRE North

UNIVERSITÀ DEL SALENTO

INFN Istituto Nazionale di Fisica Nucleare

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI MILANO

SAPIENZA UNIVERSITÀ DI ROMA

SABRE South

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY of ADELAIDE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF SYDNEY

Australian National University

THE UNIVERSITY OF MELBOURNE

Extra slides

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SABRE publications

1. E. Shields et al., SABRE: A New NaI(T1) Dark Matter Direct Detection Experiment, Physics Procedia 61 (2015) 169 – 178
2. M. Antonello et al., The SABRE project and the SABRE Proof-of-Principle, Eur.Phys.J.C 79 (2019) 4, 363
3. M. Antonello et al., Monte Carlo simulation of the SABRE PoP background, Astropart.Phys. 106 (2019) 1-9
4. B. Suerfu et al., Growth of ultra-high purity NaI(Tl) crystals for dark matter searches, Phys.Rev.Res. 2 (2020) 1, 013223
5. M. Antonello et al., Characterization of SABRE crystal NaI-33 with direct underground counting, Eur.Phys.J.C 81 (2021) 4, 299
6. F. Calaprice et al., 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
7. B. Suerfu et al., Zone Refining of Ultrahigh-Purity Sodium Iodide for Low-Background Detectors, Phys.Rev.Applied 16 (2021) 1, 014060
8. F. Calaprice et al., Performance of the SABRE detector module in a purely passive shielding, Eur.Phys.J.C 82 (2022) 12, 1158
9. E. Barberio et al., Simulation and background characterisation of the SABRE South experiment, arXiv:2205.13849 (accepted by EPJ-C)

NaI crystals background comparison

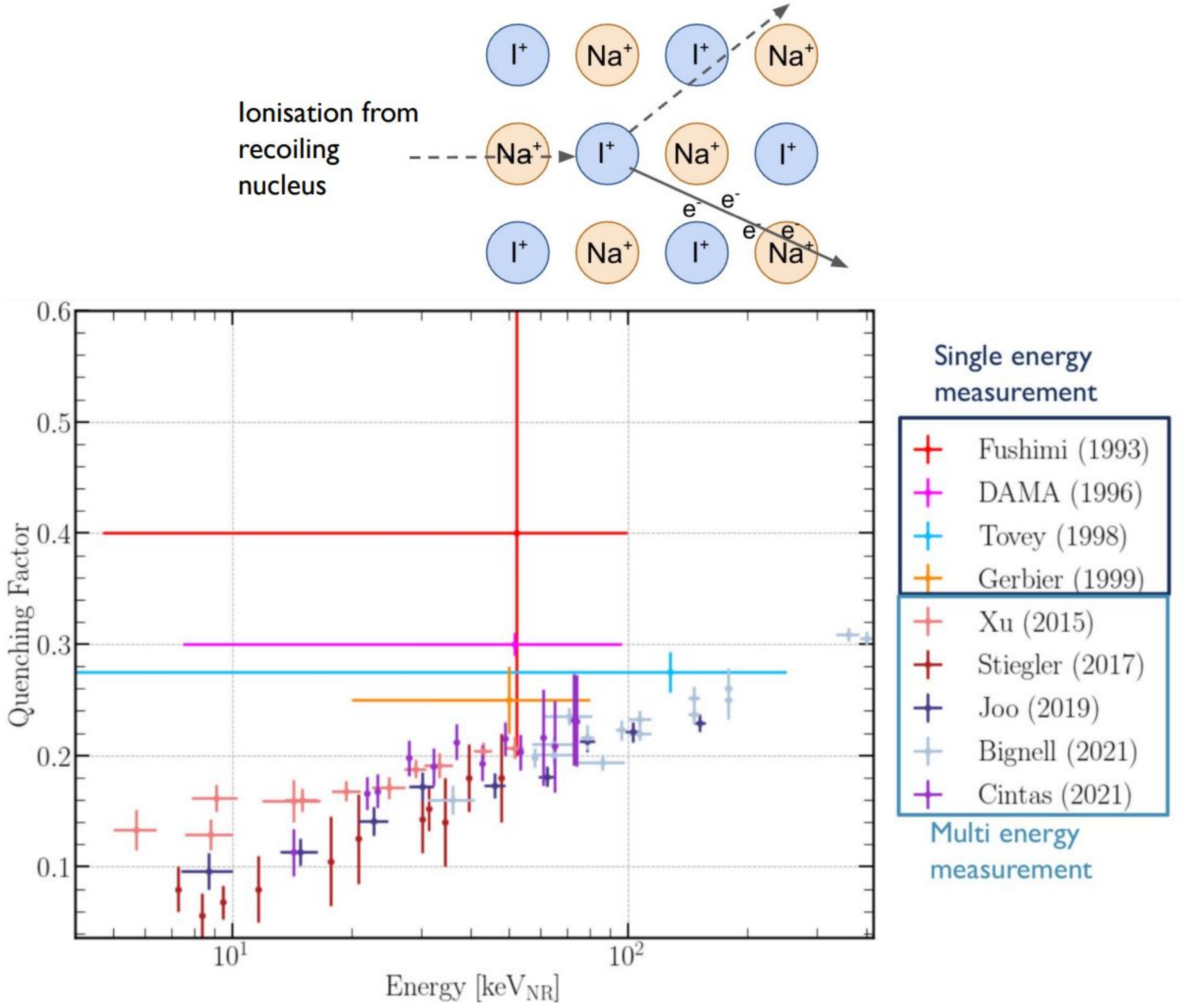
Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)	Active mass (kg)
DAMA [1]	13	0.7-10	$(5\text{-}30)\times10^{-3}$	0.5-7.5	250
ANAIS [2]	31	<0.81	1.5	0.36	112
COSINE [3]	35.1	<0.12	1-1.7	<2.4	~60
SABRE [4]	4.3	0.4	0.49	0.2	~35+40=75 (total goal)
PICOLON [5]	<20	-	$<5.7\times10^{-3}$	-	~20 (goal)

[1] Nucl.Instrum.Meth.A 592 (2008) 297-31
[2] Eur.Phys.J.C 79 (2019) 5, 412
[3] Eur.Phys.J.C 78 (2018) 490
[4] Eur.Phys.J.C 81 (2021) 4, 299, Phys.Rev.D 104 (2021) 2, L021302, Eur.Phys.J.C 82 (2022) 12, 1158
[5] PTEP 2021 (2021) 4, 043F01

Interpretation of results: the quenching factor (QF)

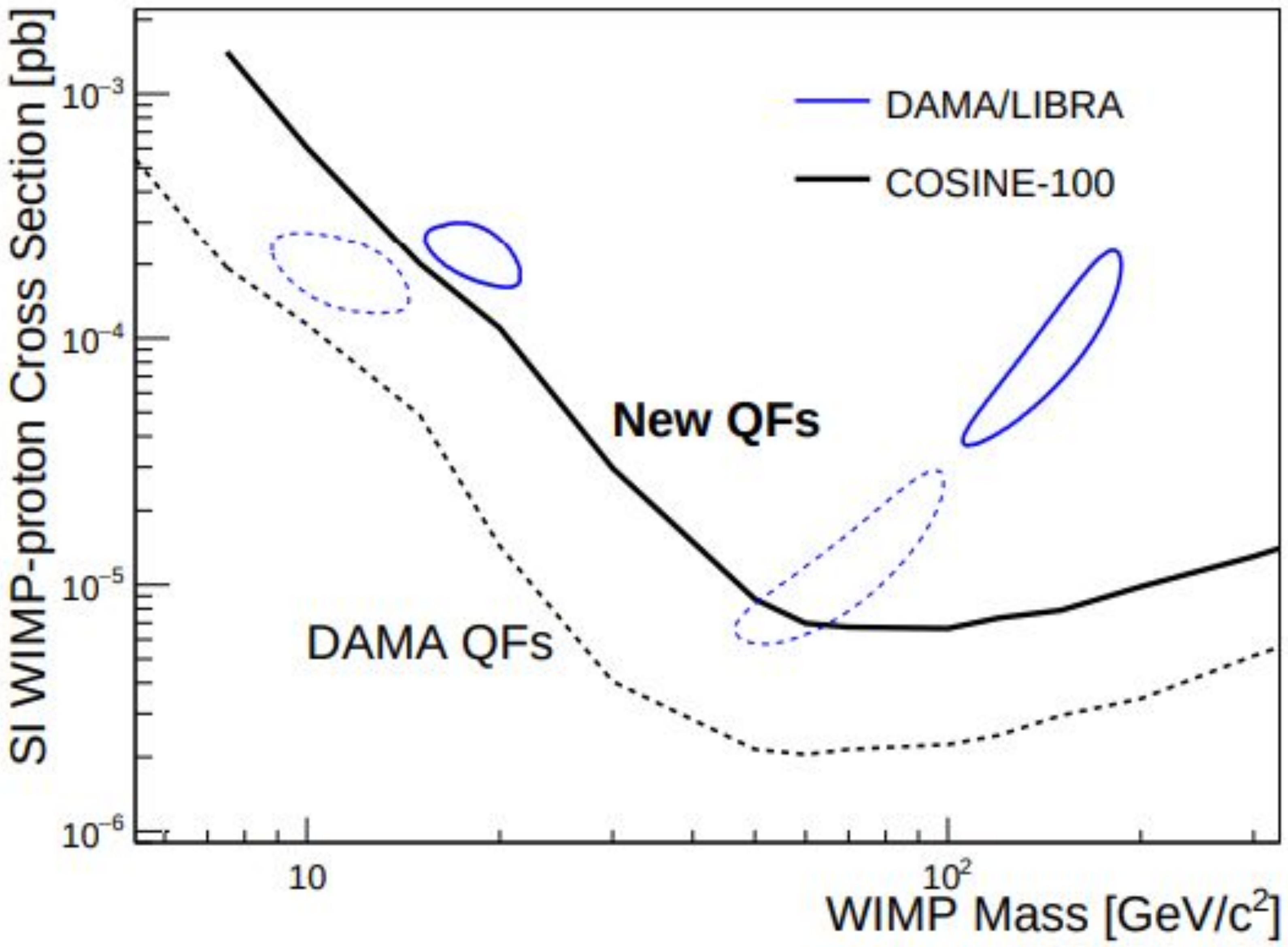
- Part of the energy released by the nuclear recoil is not transformed in scintillation light → quenching
- Observable is the energy in keV_{ee} (electron-equivalent)
- Measurements on different crystals not in good agreement
- QF affects both the energy range and amplitude of the modulation

Is annual modulation search with different NaI(Tl) crystals really model independent?

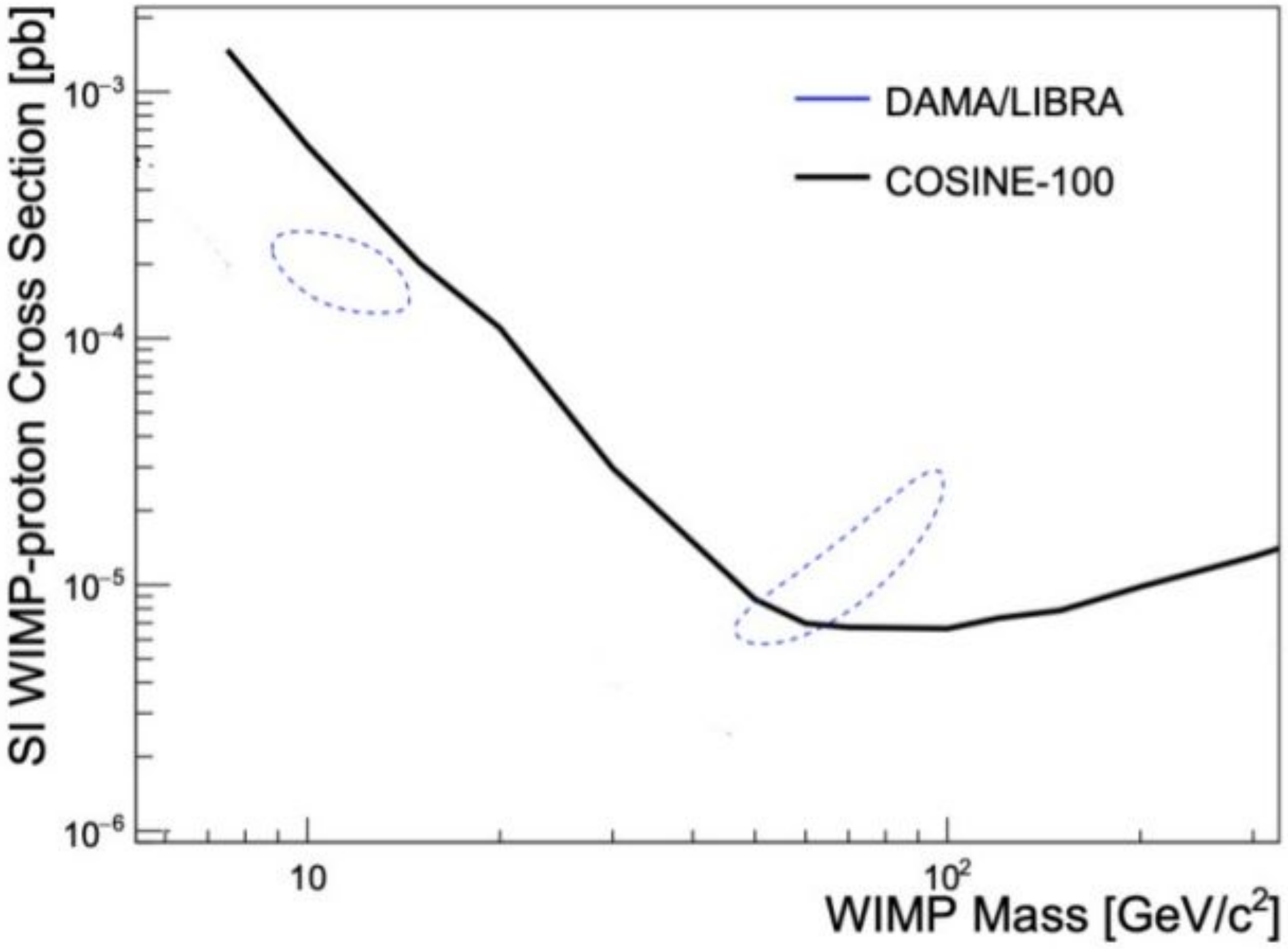


Quenching factor impact

Y.J. Ko et al JCAP11(2019)008



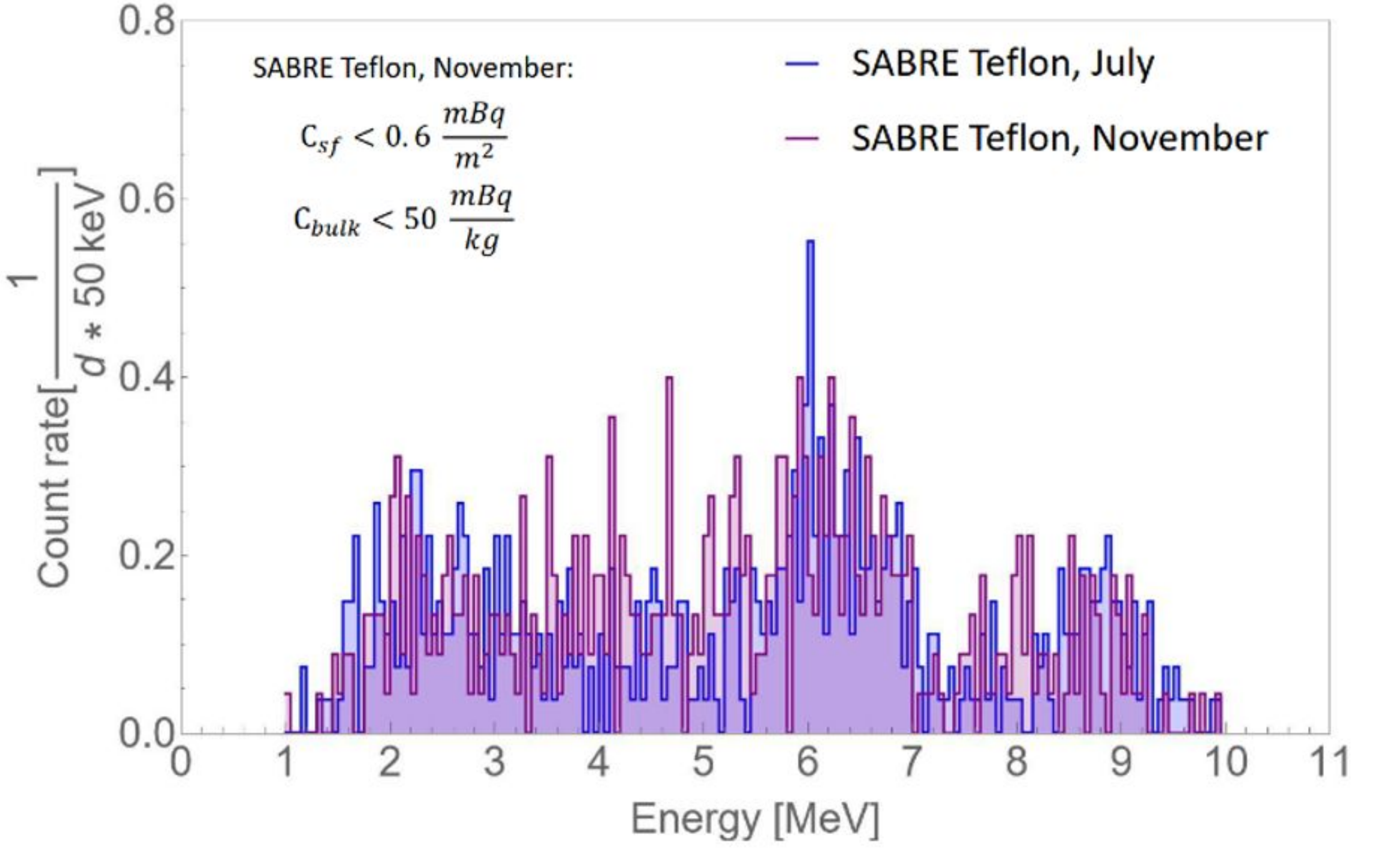
Assuming detectors have the same quenching factor (dashed lines or solid lines)



Assuming detectors have the different quenching factors the DAMA signal region is not totally excluded

SABRE reflector radioactivity assay

- Procured virgin teflon foils
- Samples tested with HPGe at LNGS
- Alpha counting with XIA spectrometer
  → ^{210}Pb contamination at level of detector's sensitivity
  - surface contamination: < 0.6 mBq/m^2
  - bulk contamination: < 50 mBq/kg

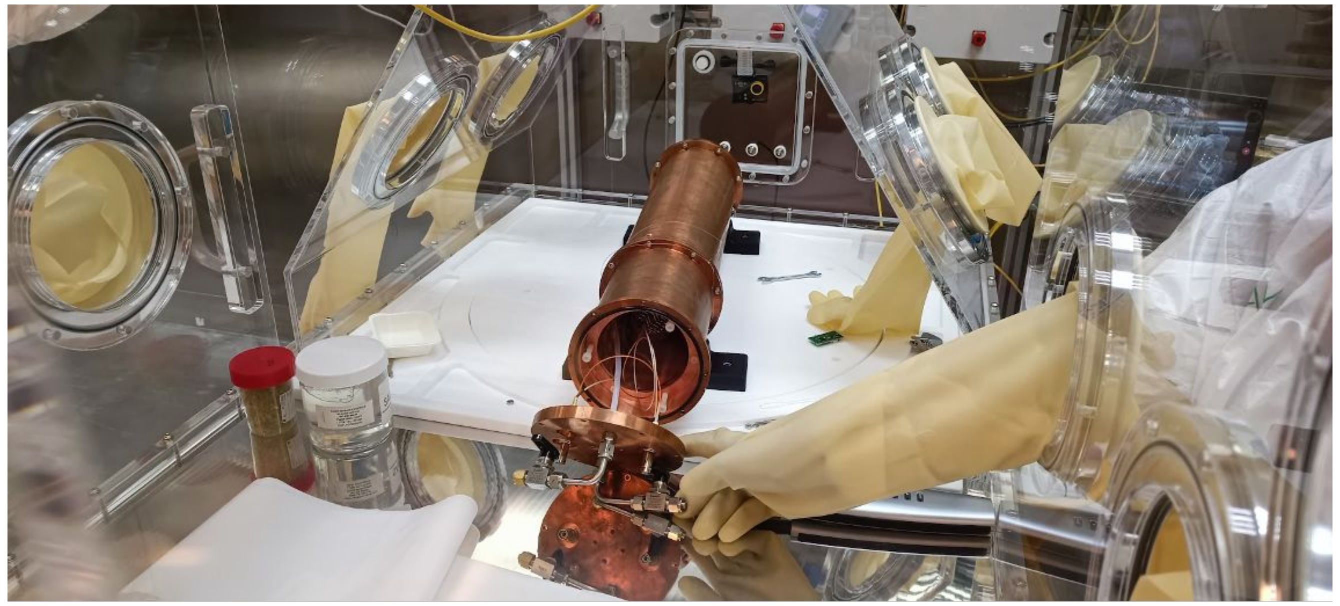


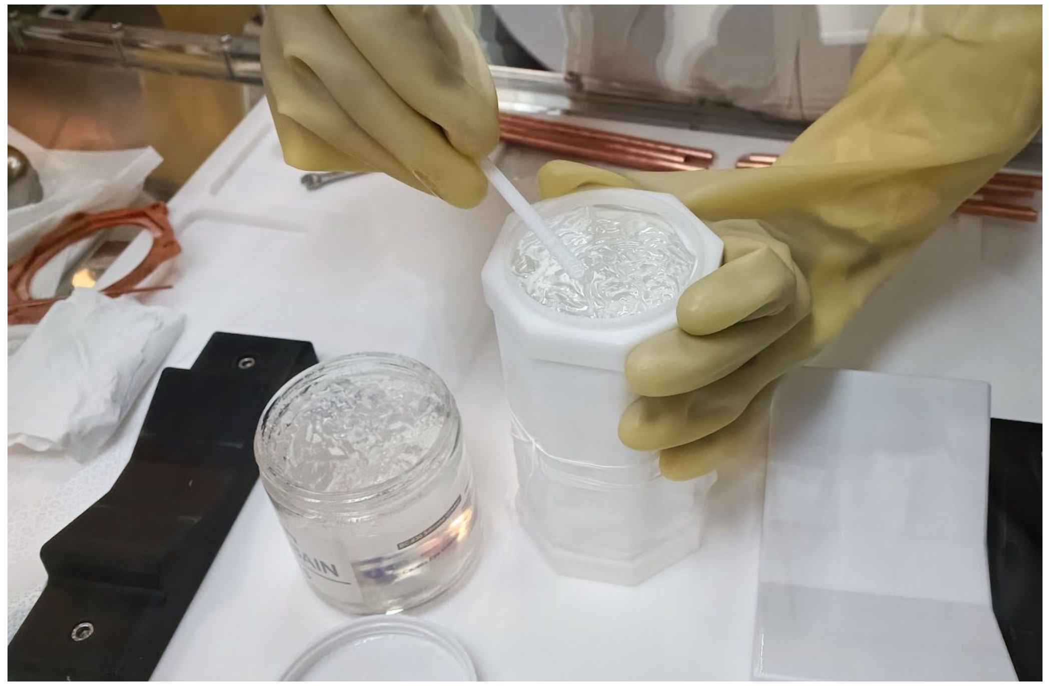
G. Zuzel

Crystal operations in glovebox 2022-23

- 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



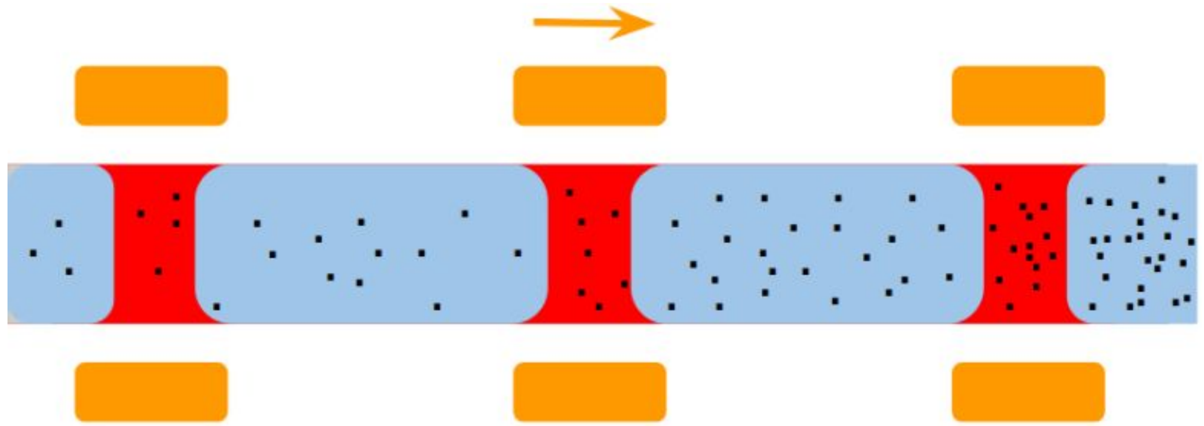


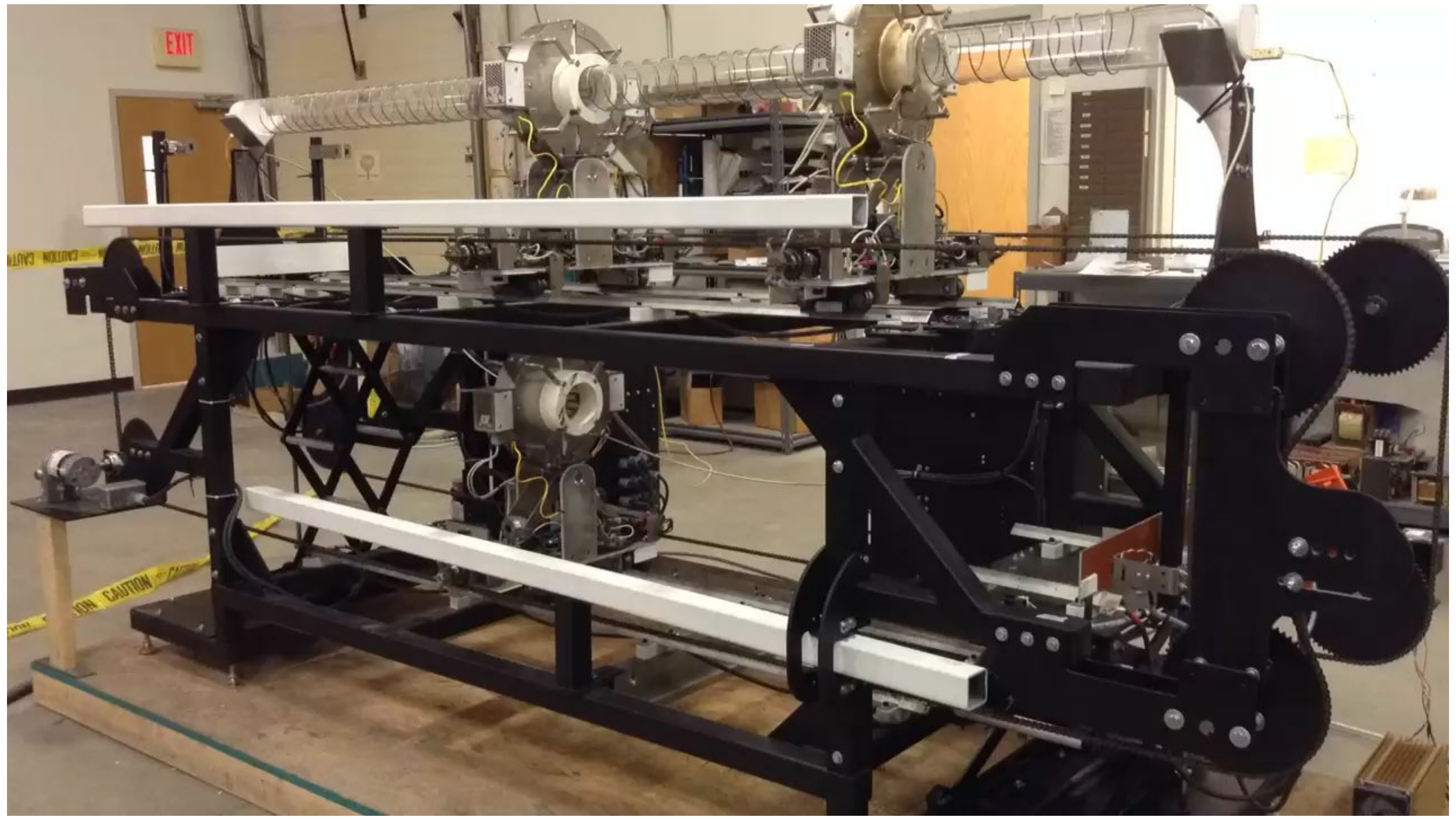

Zone refining

- 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

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 refinement equipment at Mellen, now transferred to RMD

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

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

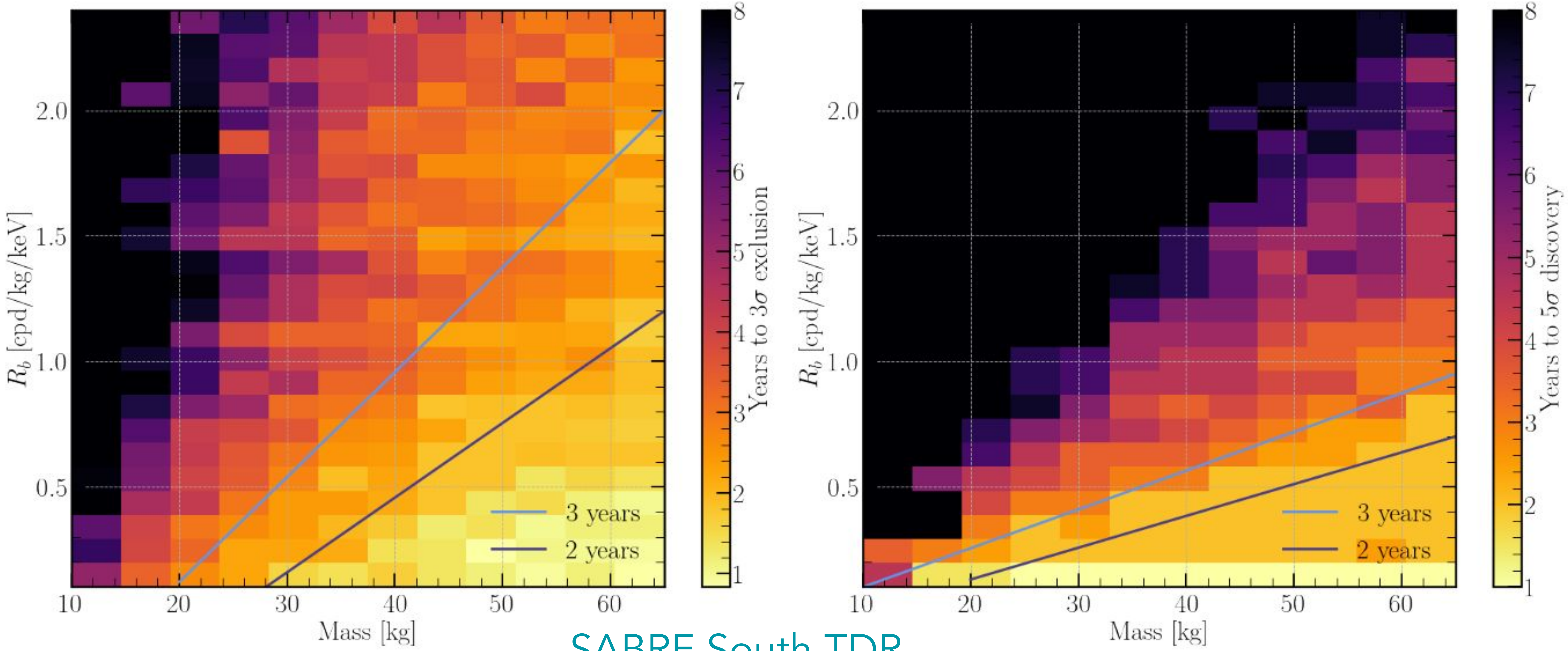
SABRE North and South detectors **have different shielding designs:**

- 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.

A MoU for the full SABRE experiment has been drafted and will be in the following months

SABRE sensitivity



[SABRE South TDR]

The time in years required for SABRE to reach 3σ exclusion (left) and 5σ discovery (right) for the DAMA modulation signal as a function of exposure mass and total background