Search for Dark Matter with the SABRE experiment

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for the SABRE Collaboration

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Picture by M. Volpi

THE UNIVERSITY OF MELBOURNE

STAWELL UNDERGROUND PHYSICS LAB

SABRE

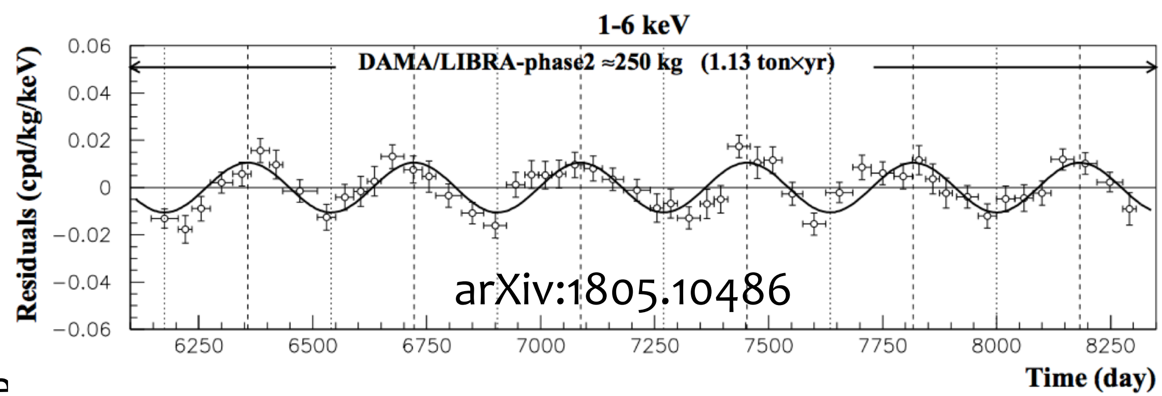
Sodium-iodide with Active Background REjection

Goal: search for annual modulation compatible with Galactic Dark Matter interactions

Strong modulation observed by DAMA/LIBRA with 250 kg of NaI(Tl) crystals

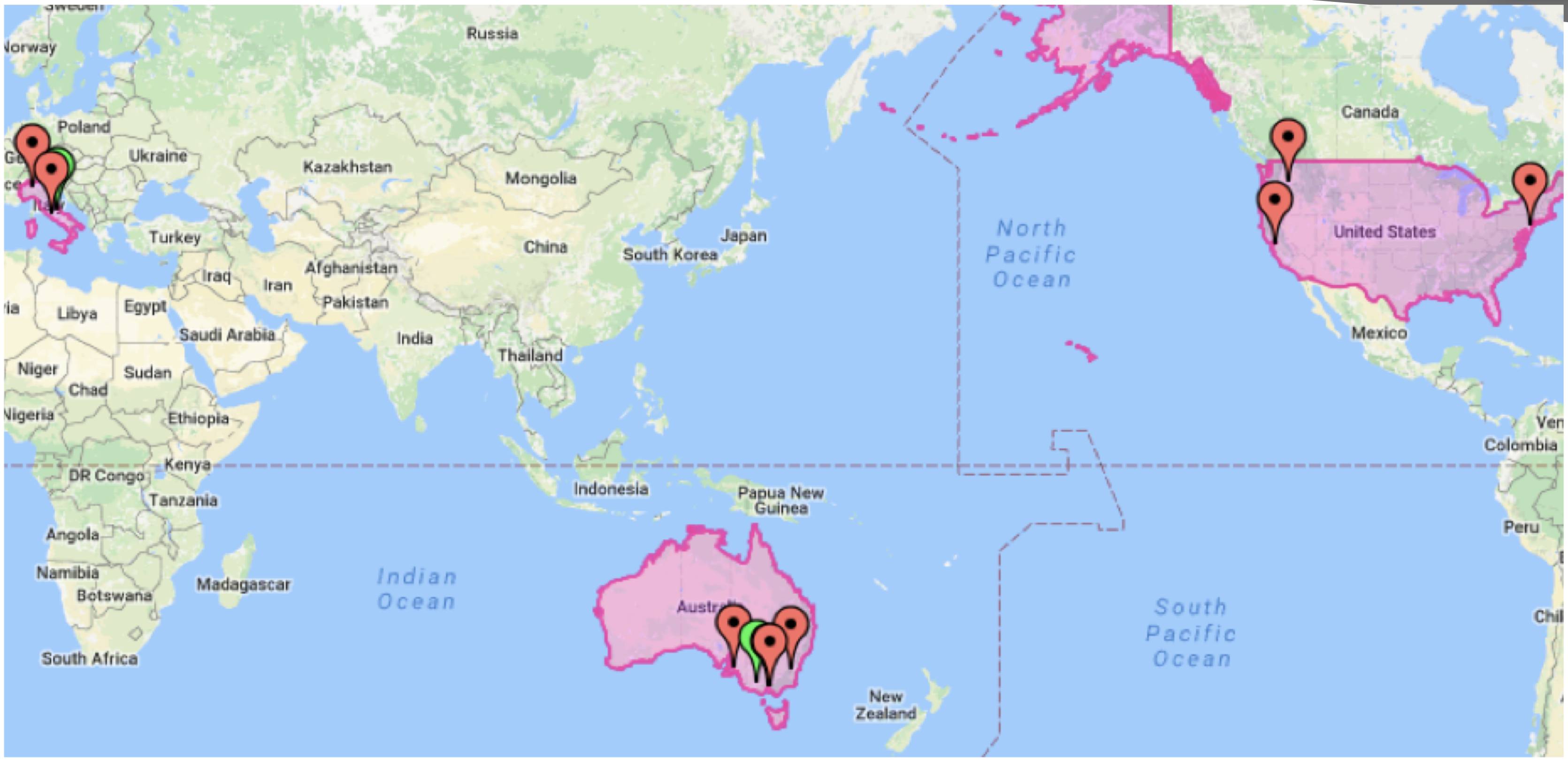
- Energy ∈ [1,6] keV
- Phase 148 ± 6 days
- Amplitude ≈ **10^{-2}** cpd/kg/keVee
- Background ≈ **1** cpd/kg/keVee

Null results with other techniques (see Xenon1T/LUX results)



SABRE can perform a model-independent verification/confutation of DAMA/LIBRA results

The Collaboration

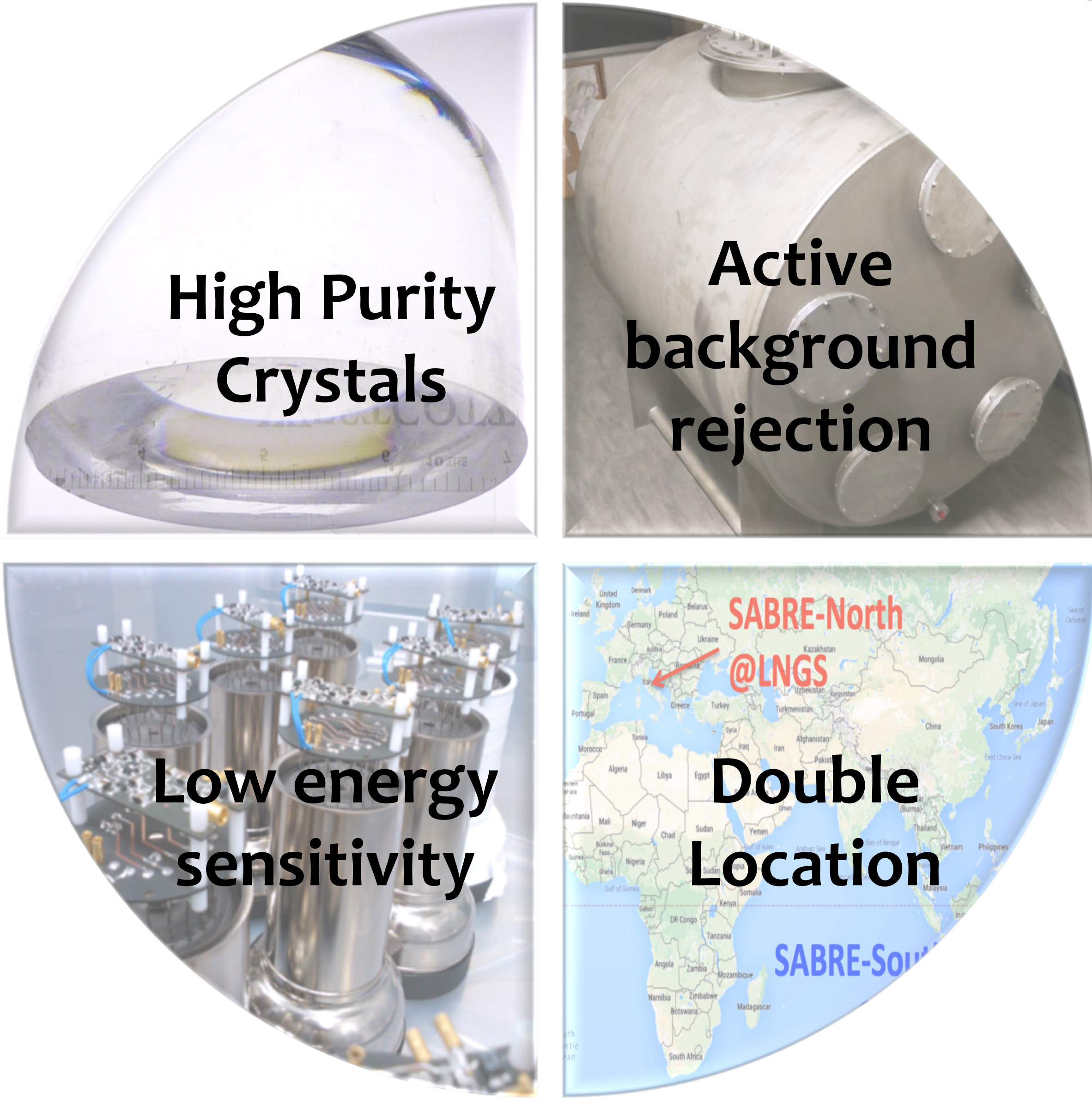


Adelaide University,
Australian National University
Swinburne University
University of Melbourne

LNGS & GSSI
INFN Rome & Sapienza
University of Milano &INFN

LLNL
PNNL
Princeton University

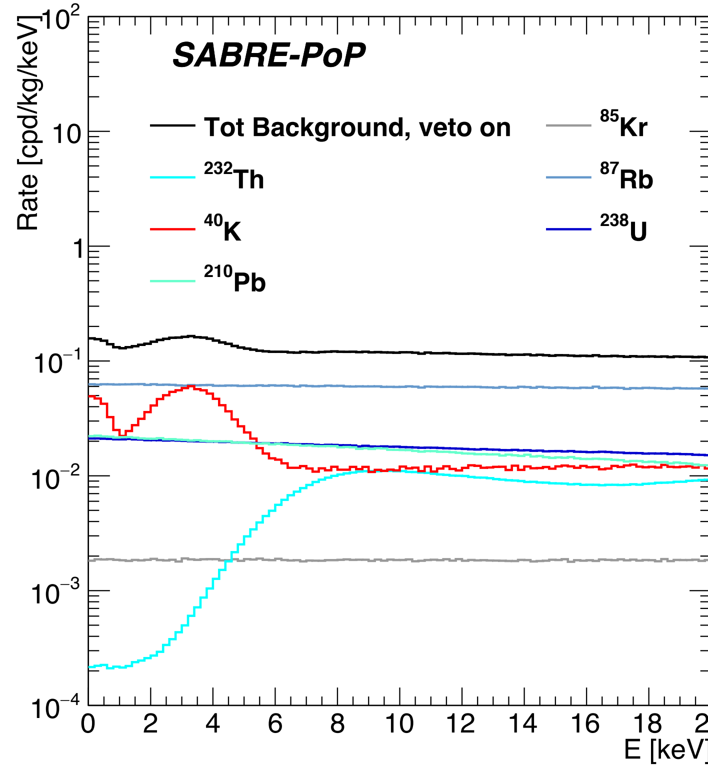
THE SABRE PRINCIPLES



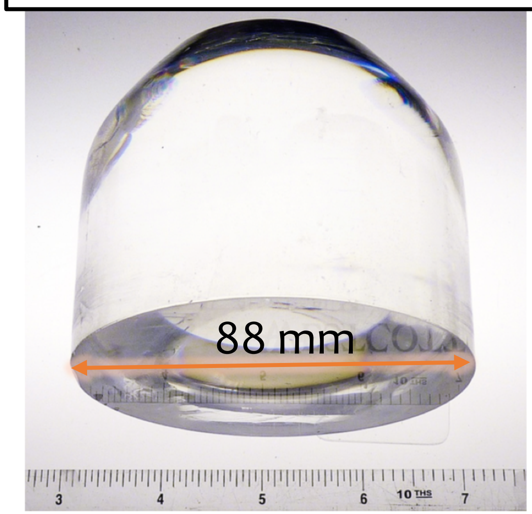
Unprecedented background rejection and sensitivity with a NaI(Tl) experiment

ULTRA PURE CRYSTALS

- Crystal radioactivity is the experiment's main background: ^{40}K, ^{87}Rb, ^{238}U, ^{232}Th, ^{210}Pb
- Collaboration with Merck (former Sigma-Aldrich) to produce Astro-grade powder with reduced contaminations
- Growth procedure tested with minimal contamination
- High-purity full-scale crystal in production



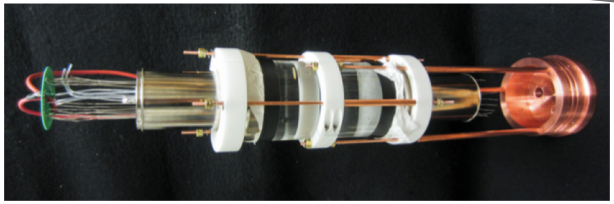
First large crystal (≈ 2 kg)

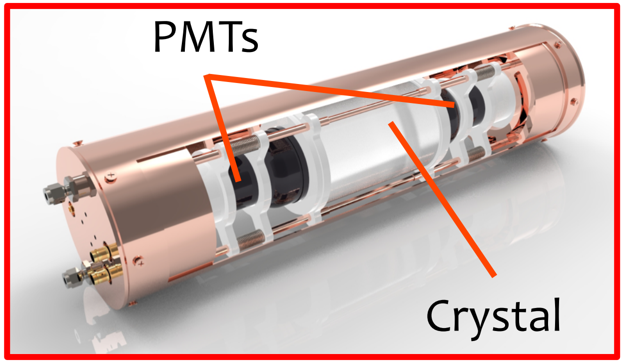


Element	NaI Powder	Crystal	DAMA Crystal
^{nat}K	3.5 - 18 ppb	9 ± 1 ppb	13 ppb
^{238}U	< 1 ppt	< 1 ppt	0.7 – 7.5 ppt
^{232}Th	< 1 ppt	< 1 ppt	1 ppt
^{87}Rb	0.2 ppb	< 0.1 ppb	< 0.35 ppb

Low Energy Sensitivity

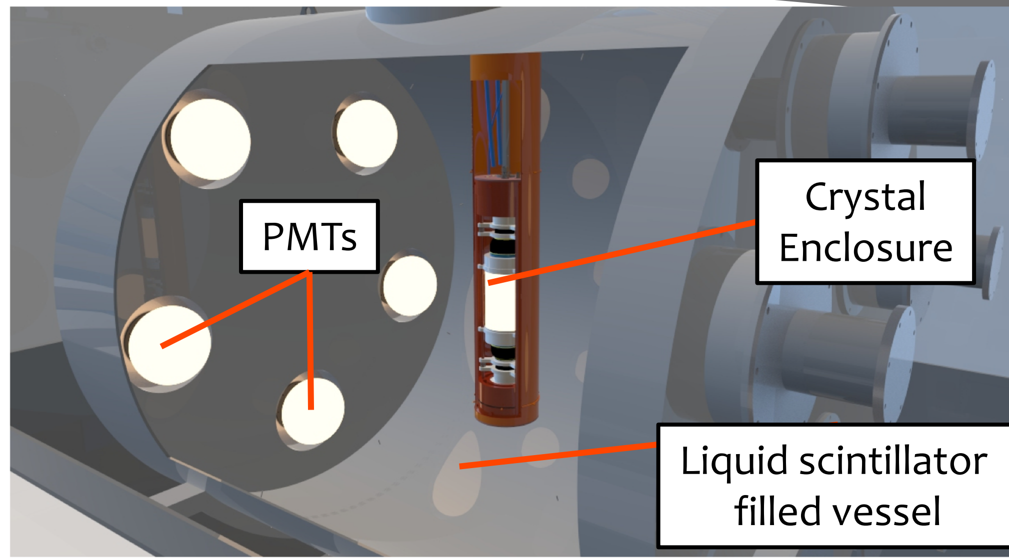
- SABRE aims to be sensitive to the energies covered by DAMA/LIBRA 1-6 KeVee and below
- Current Design:
  - 2 x Hamamatsu R11065-20 3" PMTs per crystal with High QE: > 35% and minimal contaminations
  - Direct PMT-Crystal coupling for maximal light yields
  - Custom pre-amplifiers and super bialkali photocathodes → less after-glow and dark noise

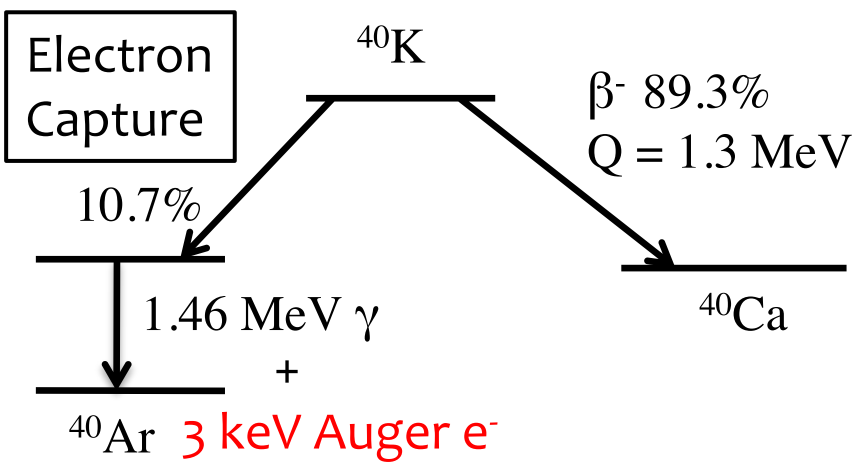


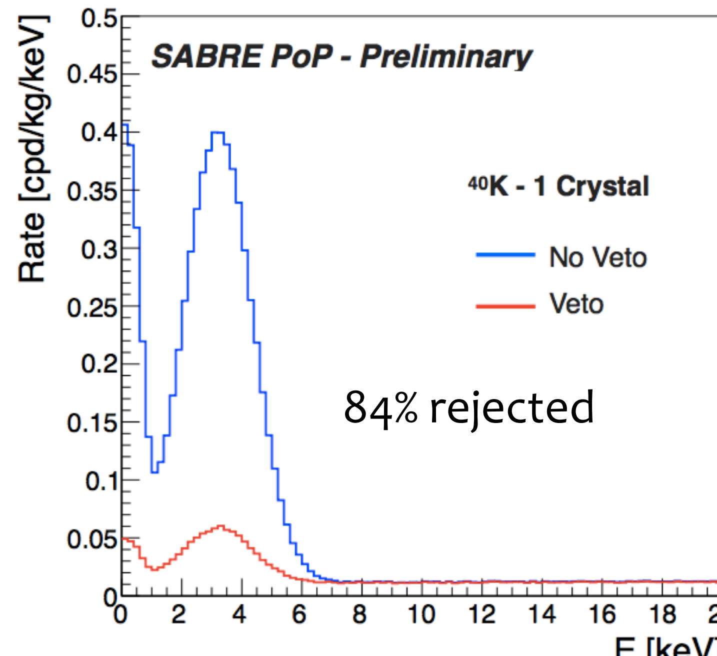


Element	Contamination (mBq/ PMT)
^{nat}K	< 10
^{238}U	~ 15
^{232}Th	~ 1
^{60}Co	< 1

- Crystals surrounded by a liquid scintillator detector
- Veto processes with energy > 100 keVee
- Goal: reject external and intrinsic backgrounds
- Very effective in rejecting ^{40}K crystal events

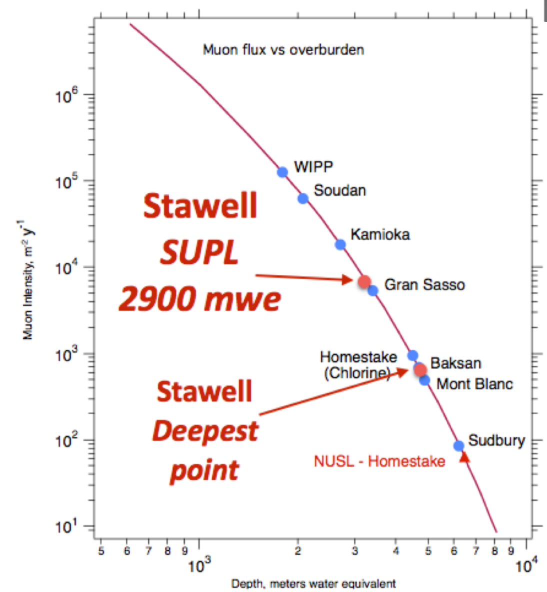




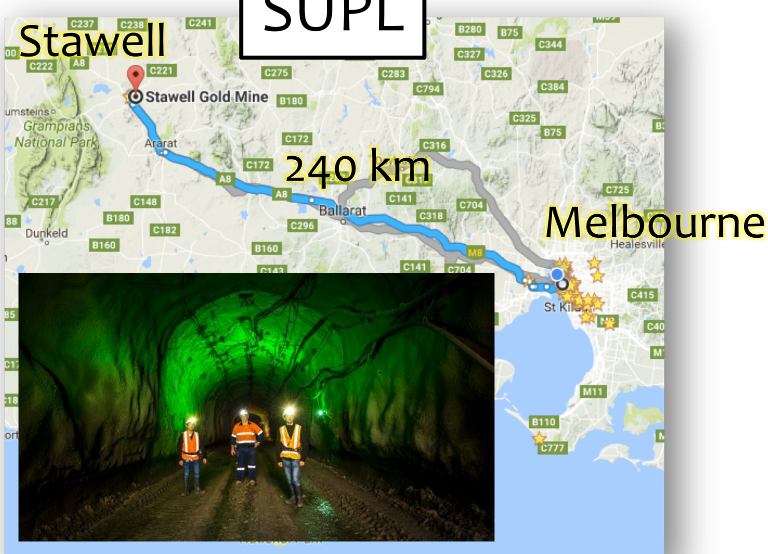


DOUBLE LOCATION

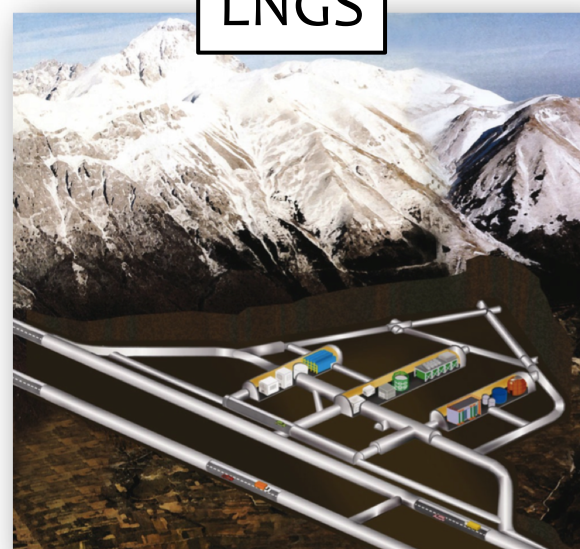
- Twin experiments:
  - LNGS (Italy)
  - SUPL (Australia)
- Different environmental conditions:
  - Seasonal effects with opposite phase
  - Rock composition and radiopurity
  - Independent radon, temperature, pressure control systems and power supply



SUPL

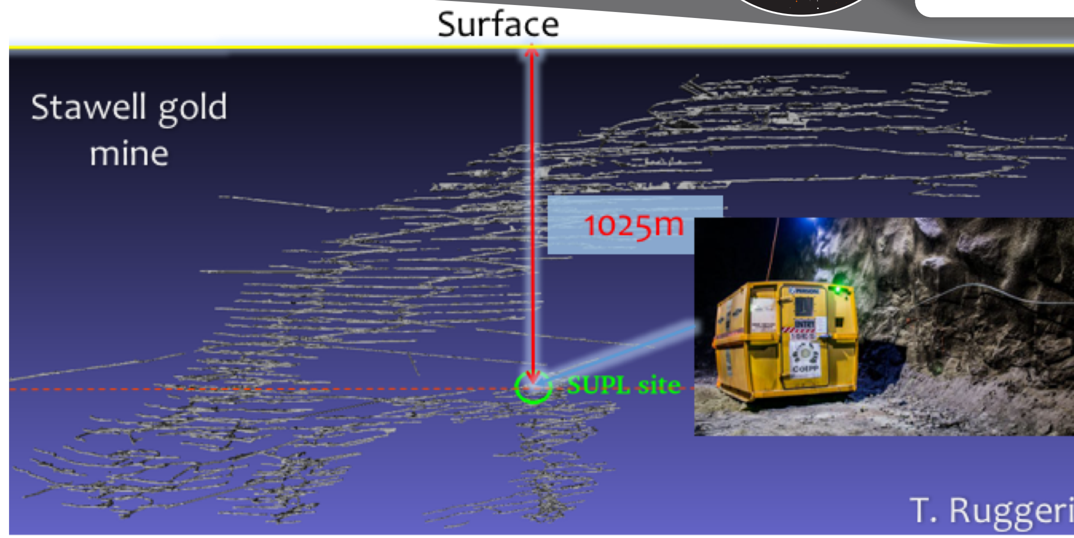


LNGS

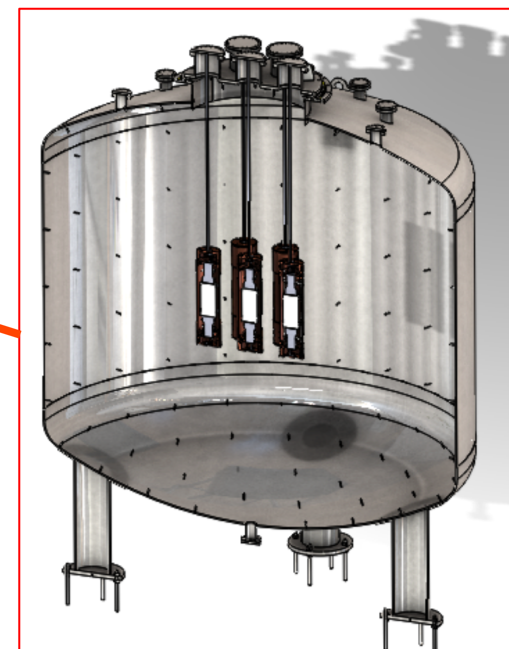


Stawell Undeground Physics Laboratory

- Clean laboratory @ 1025m in the Stawell gold mine
- Construction to start in second half of 2018
- Host SABRE and other experiments



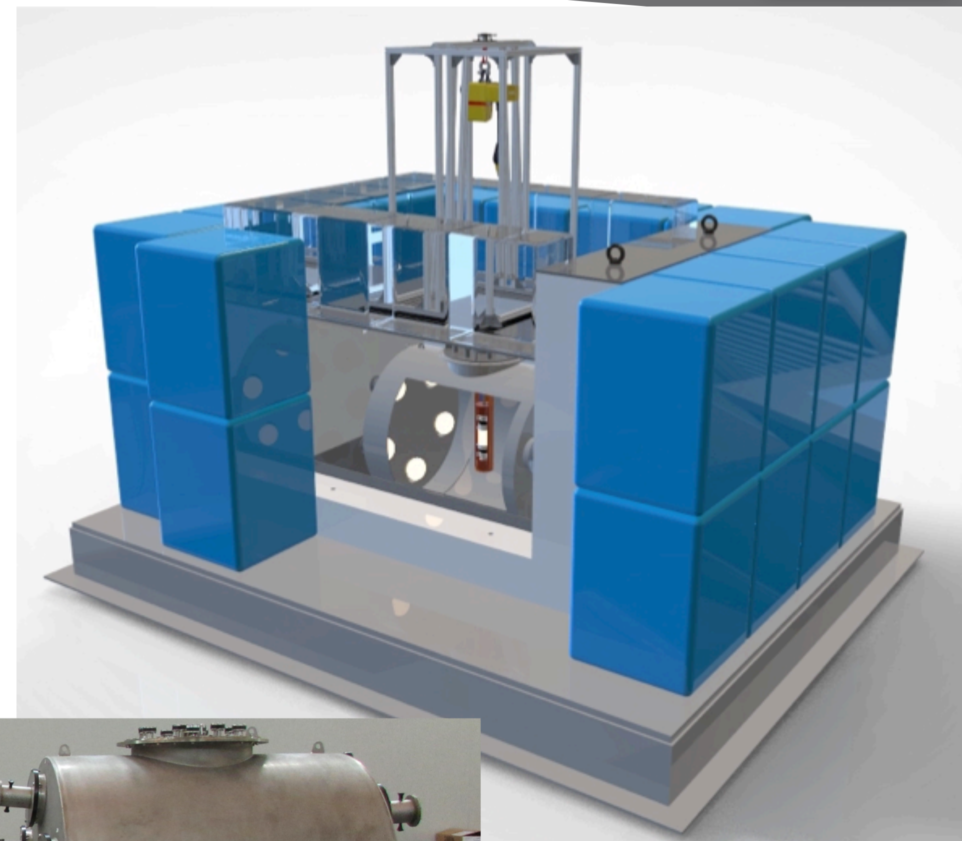
Clean-room, low radon areas



Proof of Principle

A Proof of Principle (PoP) phase of the experiment is in preparation @ LNGS

- 1 NaI(Tl) crystal (~5kg)
- Active veto:
  - Cylindrical vessel (Ø x h) = (1.35 m x 1.50 m)
  - PC+PPO (3g/l) scintillator (mass ≈ 2 ton)
  - 10 Hamamatsu R5912-100 PMTs
- Hybrid passive shielding:
  - Bottom: 15 cm Pb + 10 cm PE
  - Sides: 40 cm PE + 90 cm water
  - Top: 10 cm PE + 2cm Stainless Steel +80cm water
  - Internal volume flushed with N_2 to remove radon

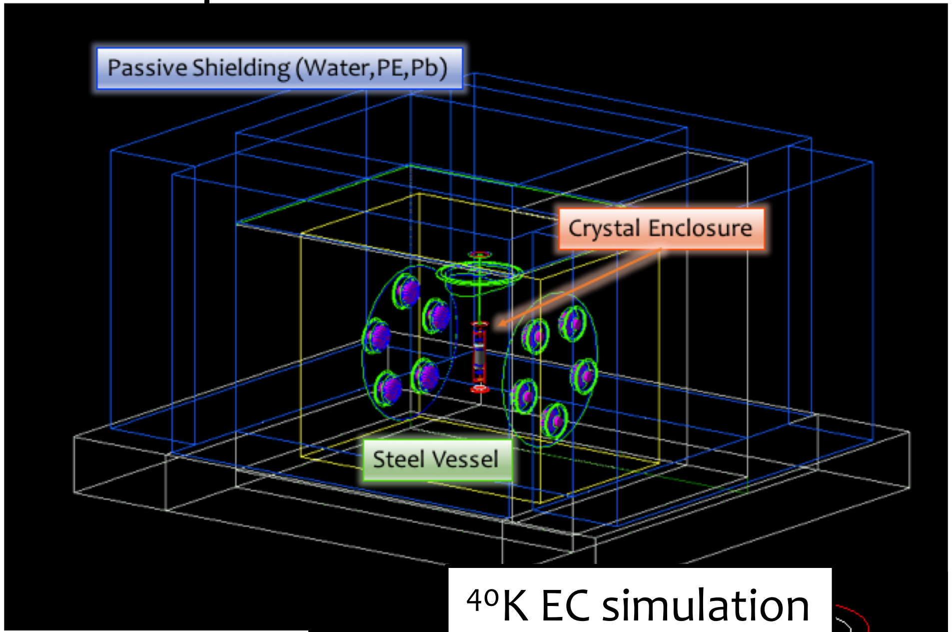


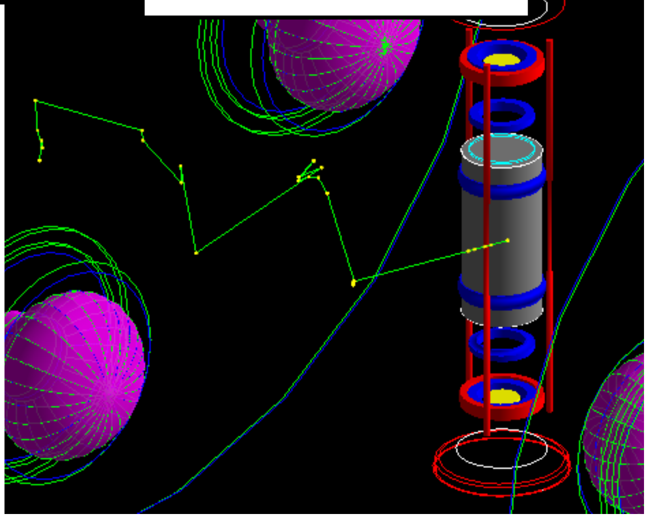
Goals:

- Characterize crystal contaminations, particularly ^{40}K
- Test active veto performance

SABRE SIMULATION

- GEANT4 simulation of the Proof of Principle detector and estimate of the expected background
- Considered contaminations in
  - NaI(Tl) crystals
  - Crystal wrapping + PMTs
  - Crystal enclosure
  - Crystal insertion system (CIS)
  - Vessel, Liquid Scintillator, vessel PMTs (Veto)





- Activity values from preliminary measurements and literature (see backup)
- Results validated by independent simulations within the collaboration
- Additional studies on shielding and external backgrounds on going

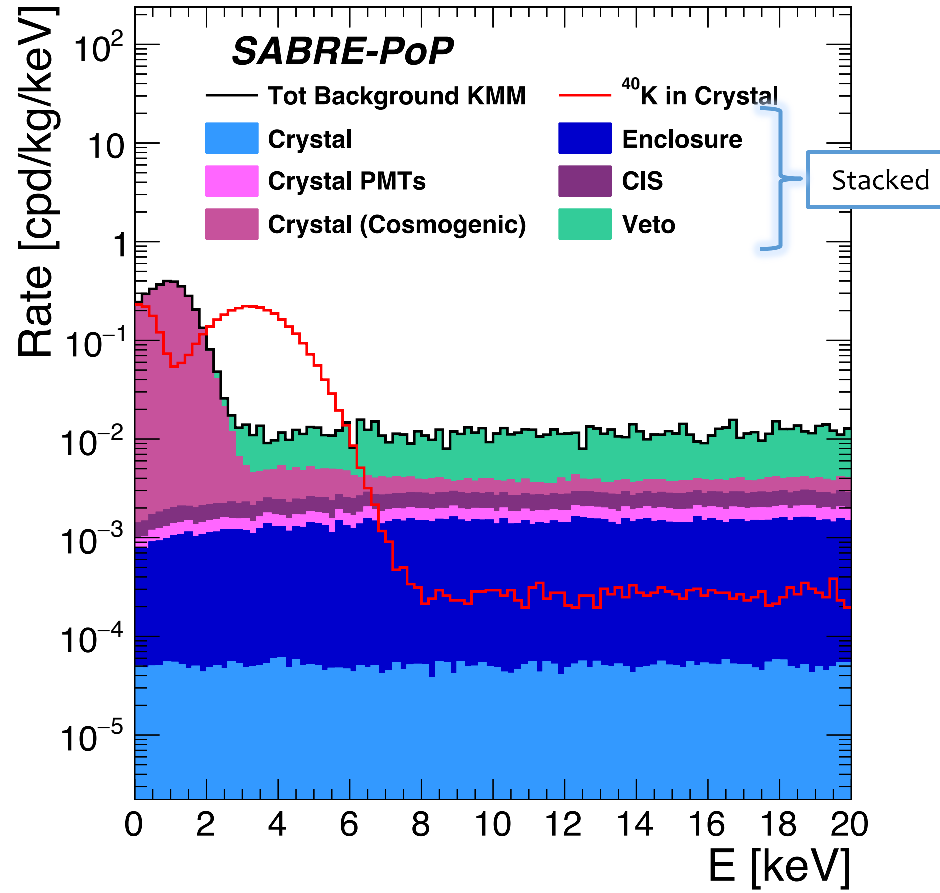
^{40}K MEASUREMENT MODE (KMM)

Target ^{40}K electron capture (3 keV auger e^{-} + 1.46 MeV γ) in the crystal and other processes with large energy deposits in the scintillator

E(Scintillator) ∈ [1280,1640] keVee
E(Crystal) ∈ [2,4] keVee

Element	Expected rate [cpd/kg/keV]
Crystal (other radiogenic)	5.1E-05
Crystal (cosmogenic*)	1.8E-02
Crystal PMTs	1.1E-03
Enclosure	1.3E-03
CIS	7.7E-04
Veto	6.2E-03
Total background	2.7 E-02
^{40}K in Crystal	1.9E-01

* After 2 months underground



- Large cosmogenic ^{22}Na background for E < 2 keV
- Main background in the region of interest from Veto

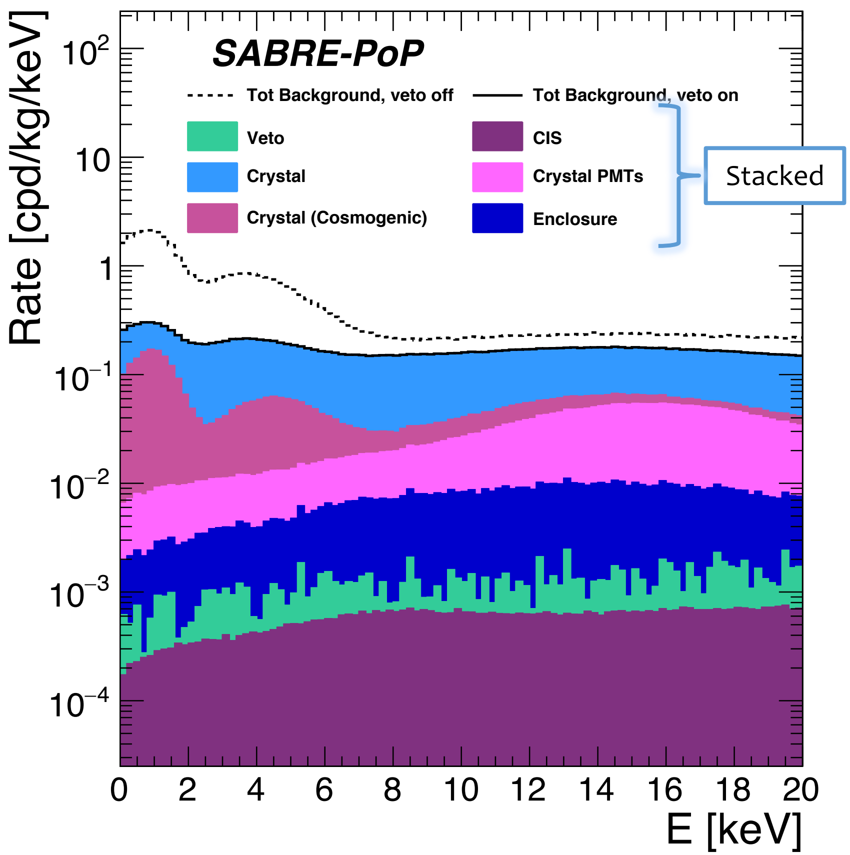
DARK MATTER MODE (DMM)

Test the active rejection power of the liquid scintillator system and the expected background in the crystal

Veto: E(Scintillator) < 100 keVee
Region of Interest: E(Crystal) ∈ [2,6] keVee

Element	Expected rate [cpd/kg/keV]
Crystal (radiogenic)	1.5E-01
Crystal (cosmogenic*)	3.9E-02
Crystal PMTs	3.5E-02
Enclosure	3.6E-03
CIS	4.6E-04
Veto	5.7E-04
Total	2.2E-01
Total (Veto off)	7.4E-01

* After 6 months underground

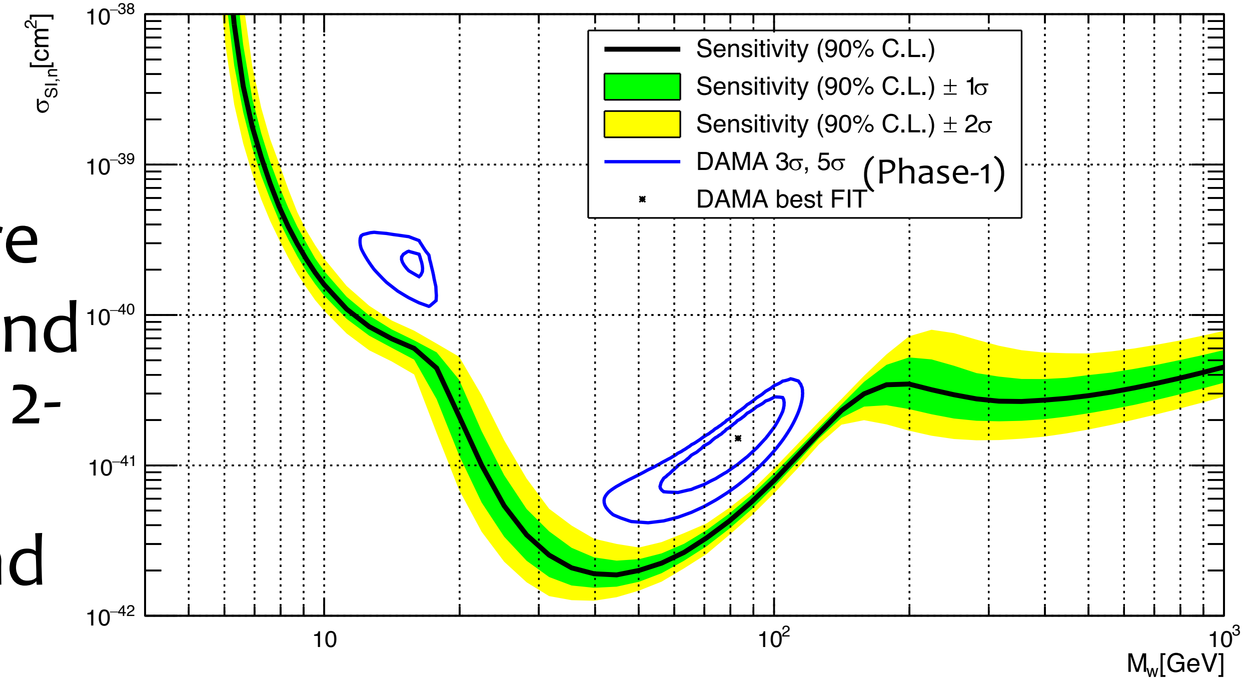


- Overall veto rejection power ~3
- Expected background ~5 times smaller than DAMA/LIBRA

Expected Sensitivity

Assuming

- 50 kg total crystal mass
- 3 years of exposure
- Average background 0.22 cpd/kg/keV in 2-6 keVee
- $0.13 < Q_{Na} < 0.21$ and $Q_I = 0.09$



The 90% C.L. limit (black), the 1σ (green) and 2σ (yellow) bands, and the DAMA Phase-1 3σ and 5σ confidence regions (blue)

The SABRE full scale can:

- Confirm DAMA/LIBRA at 6σ
- Refute it at 5σ
- spin-independent WIMP nuclear scattering limits as strong as 10^{-42} cm^2

Conclusion

- SABRE can perform an *independent high sensitivity* verification of the DAMA/LIBRA modulation
- SABRE features:
  - High-purity NaI(Tl) crystals
  - Low energy sensitivity
  - Active background rejection
  - Twin detectors
- Proof of Principle phase in preparation and expected to run in the second half of 2018
- Background levels evaluated with GEANT4 simulations:
  - 0.027 cpd/kg/keV for KMM (^{40}K excluded)
  - 0.22 cpd/kg/keV for DMM
- Full scale experiment can confirm/reject DAMA/LIBRA results with 3 years of data

Backup

DAMA/LIBRA Phase-1

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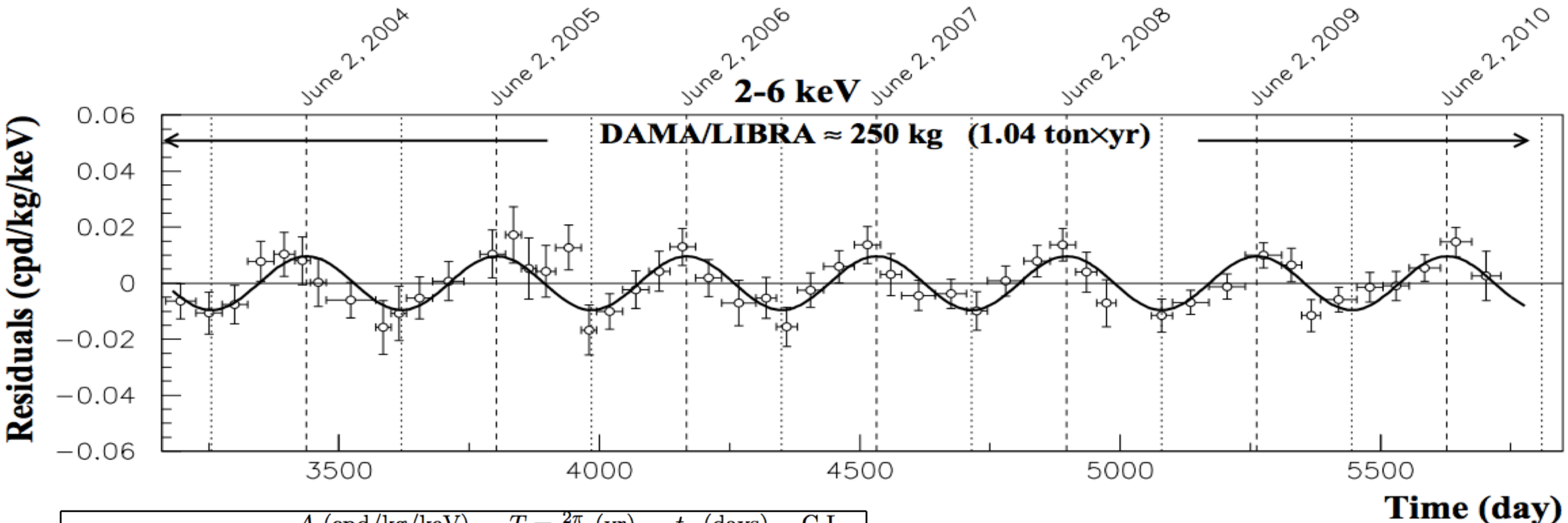
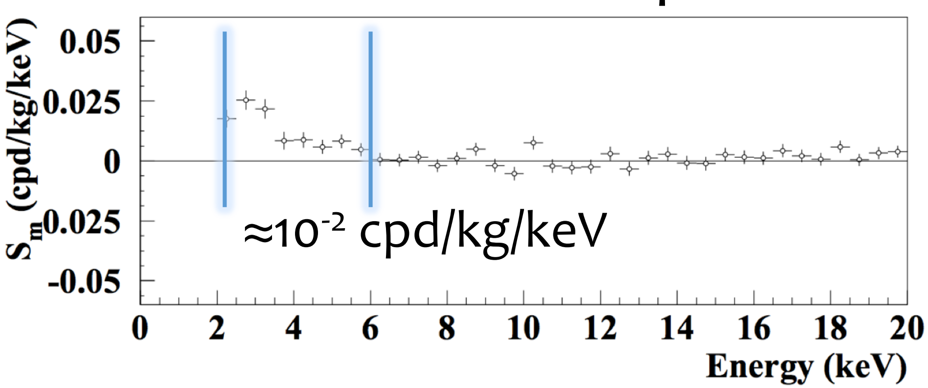


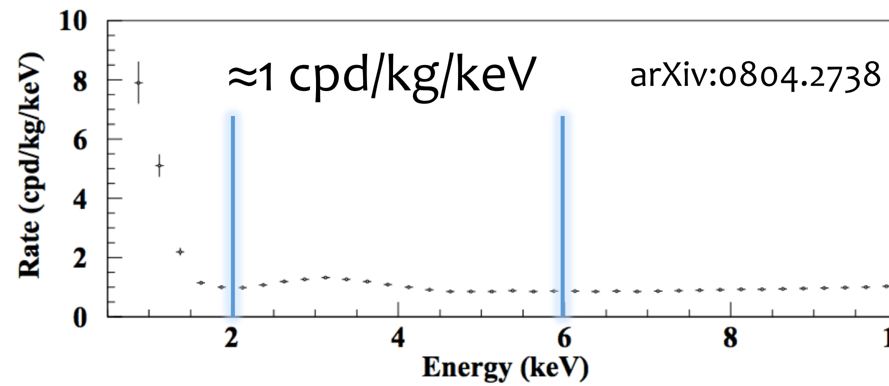
	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (days)	C.L.
DAMA/NaI & DAMA/LIBRA–phase1				
2-4 keV	(0.0190±0.0020)	(0.996±0.002)	134±6	9.5 σ
2-5 keV	(0.0140±0.0015)	(0.996±0.002)	140±6	9.3 σ
2-6 keV	(0.0112±0.0012)	(0.998±0.002)	144±7	9.3 σ

arXiv:1308.5109v2

Modulation amplitude



Background



SUPL CHARACTERISTICS

- Clean lab similar to SNOLab
- Rn activity < 100 Bq/m^3 in "clean area". Surface coating to inhibit Rn.
- Temp.: 19±2 °C, Relative humidity 40% - 50%, remote monitoring & control.
- Low radiation concrete and finishing; sampling all sand and cement.

	Gran Sasso Lab. Reference	Stawell
Neutron Flux	4 x 10^{-6} n/s/	<7 x 10^{-6} n/s/cm^2 UL
Gamma-ray flux below 3 MeV	0.73 γ/s/cm^2	<2.5 γ/s/cm^2 UL
Radioactivity levels of rock		
Rock ^{238}U (ppm) @ 880m SUPL	2.63	0.64
Rock ^{232}Th (ppm) @ 880m SUPL	0.72	1.63
Refuge Radon Bq/m^3 (12 day accumulation, ventilated)	*O*(50)	36±5 21°C, 1056 kPa, 21% humidity

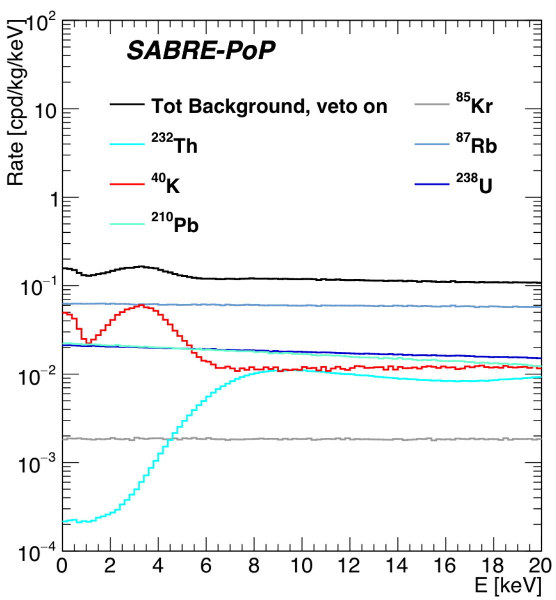
CRYSTAL BACKGROUND

Radiogenic

Nuclide	Activity	Reference
^{40}K	10 ppb	**SABRE (in preparation)**
^{238}U	< 1 ppt	**SABRE** (arXiv:1601.05307)
^{232}Th	< 1 ppt	
^{87}Rb	< 0.1 ppb	
^{210}Pb	0.03 mBq/kg	**DAMA** (arXiv:0804.2738)

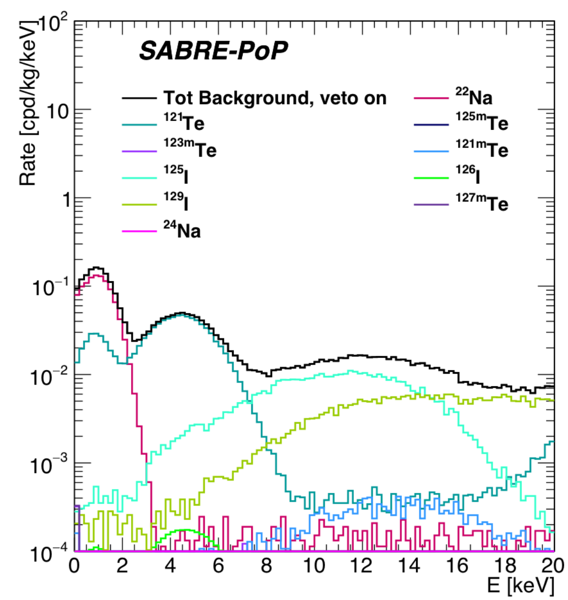
Cosmogenic after 6 months

Nuclide	Activity [mBq/kg]	Reference
^{22}Na	0.8	**LNGS (M.Laubenstein)**
^{126}I	4.3	
^{24}Na	2.6E-04	**DAMA** (arXiv:0804.2738)
^{129}I	0.95	
^{125}I	7.2	**ANAIS** (arXiv:1604.05587)
^{121}Te	1.27	
^{121m}Te	0.89	
^{123m}Te	1.17	
^{125m}Te	0.92	
^{127m}Te	0.37	



^{40}K and ^{87}Rb (upper limit) contaminations are dominant in DMM

the largest background from cosmogenic activation is due to 121Te



CONTAMINATIONS (1/2)

Crystal

Radiogenic

Isotope	Activity	Reference
^{40}K	10 ppb	**SABRE (in preparation)**
^{238}U	< 1 ppt	**SABRE (arXiv:1601.05307)**
^{232}Th	< 1 ppt	
^{87}Rb	< 0.1 ppb	
^{210}Pb	0.7 mBq/kg	**ANAIS (arXiv:1604.05587)**

Cosmogenic after 6 months

Isotope	Activity [mBq/kg]	Reference
^{22}Na	0.8	**LNGS (M.Laubenstein)**
^{126}I	4.3	
^{24}Na	2.6 E-4	**DAMA (arXiv:0804.2738)**
^{129}I	0.95	
^{121}Te	1.27	**ANAIS (arXiv:1604.05587)**
^{121m}Te	0.89	
^{123m}Te	1.17	
^{125m}Te	0.92	
^{127m}Te	0.37	

Crystal PMTs
(XENON1T arXiv:1503.07698)

Isotope	Activity [mBq/PMT]		
	Body	Window	Ceramic plate
^{40}K	<5.9	<0.48	6.5
^{60}Co	0.65	<0.042	<0.19
^{238}U	<0.52	<1.8	13
^{226}Ra	<0.29	0.040	0.29
^{232}Th	<0.0098	<0.037	0.70
^{228}Th	<0.41	<0.015	0.13

PTFE crystal wrapping
(XENON100 arXiv:1207.5988)

Isotope	Activity [mBq/kg]
^{40}K	3.1
^{238}U	0.25
^{232}Th	0.5

CONTAMINATIONS (2/2)

PTFE parts of enclosure
(XENON100 arXiv:1103.5831)

Isotope	Activity [mBq/kg]
^{40}K	<2.25
^{238}U	<0.31
^{232}Th	<0.16
^{60}Co	<0.11
^{137}Cs	<0.13

Steel vessel
(SABRE GDMS method)

Isotope	Activity/Concentration
40K	4 ppb
238U	0.3 ppb
232Th	< 0.1 ppb

Veto PMTs
(DarkSide-50 arXiv:1512.07896)

Isotope	Activity[mBq/PMT]
40K	649
238U	883
232Th	110
235U	41

Copper parts of enclosure
(Cuore-0 arXiv:1609.01666)

Isotope	Half life [days]	Activity [mBq/kg]
^{40}K		0.7
^{238}U		0.065
^{232}Th		0.002
^{60}Co	1925	0.340
^{58}Co	71	0.798
^{57}Co	272	0.519
^{56}Co	77	0.108
^{54}Mn	312	0.154
^{46}Sc	84	0.027
^{59}Fe	44	0.047
^{48}V	16	0.039

1507.03792

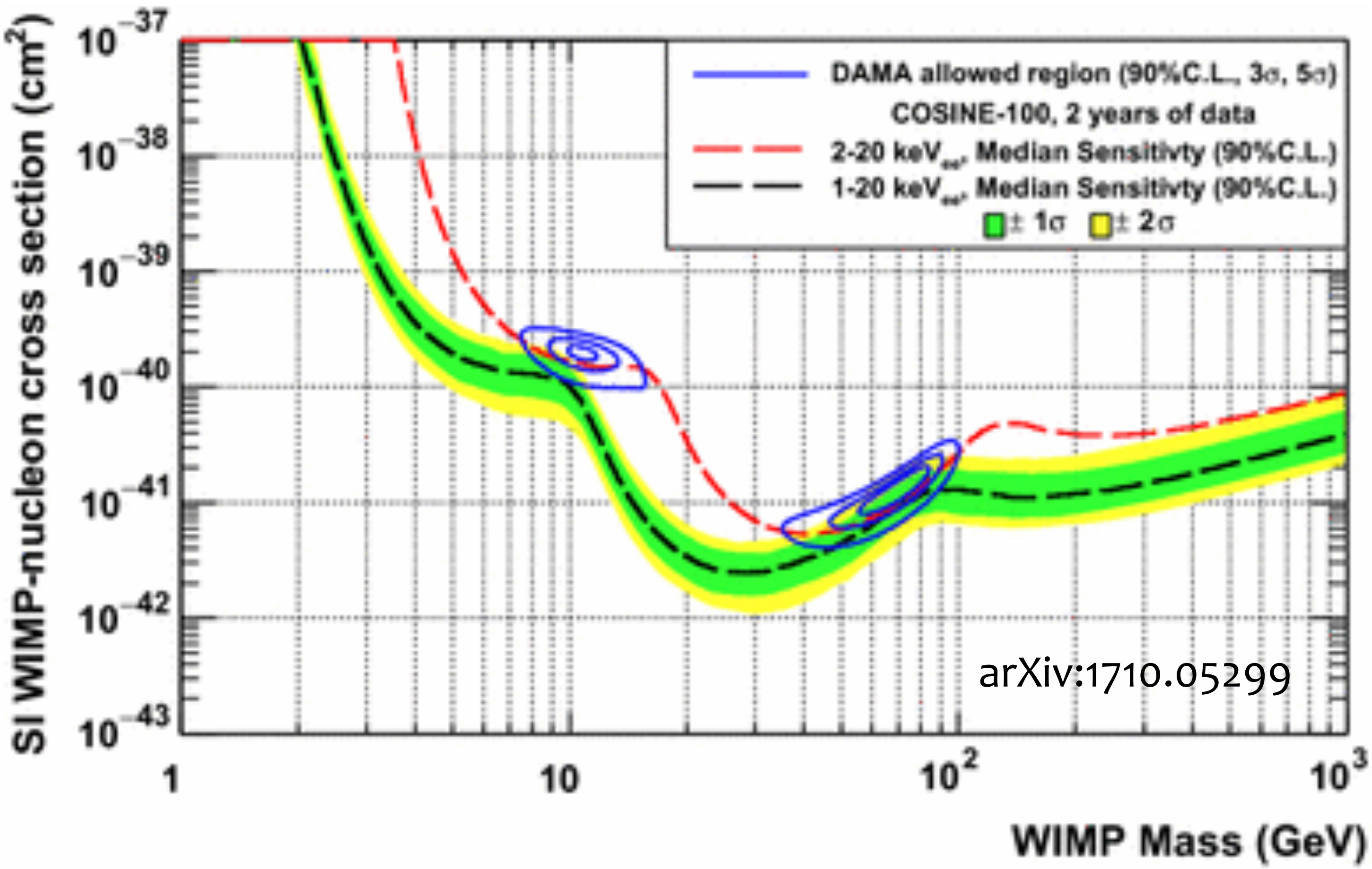
Liquid scintillator
(Borexino Nucl. Instr. & Meth. A609 (2009) 58)

Isotope	Activity [mBq/kg]
^{40}K	$3.5 \cdot 10^{-7}$
^{238}U	$< 1.2 \cdot 10^{-6}$
^{232}Th	$< 1.2 \cdot 10^{-6}$
^{210}Pb	$1.7 \cdot 10^{-6}$
^{210}Bi	$1.7 \cdot 10^{-6}$
^{7}Be	$< 1.2 \cdot 10^{-6}$
^{14}C	$4.1 \cdot 10^{-1}$
^{39}Ar	$3.5 \cdot 10^{-6}$
^{85}Kr	$3.5 \cdot 10^{-7}$

SIMULATION SETTINGS

- GEANT 4 10.2.p03
- Hadronic physics list: Shielding
- EM physics list:
  - G4EmStandardPhysics_option4
  - Fluorescence, auger electron emission and particle induced atomic relaxation accounted
  - G4EmExtraPhysics

COSINE-100 PREDICTIONS



Based on a total exposure of 212 kg·year and flat representative background of 4.3 cpd/kg/keV