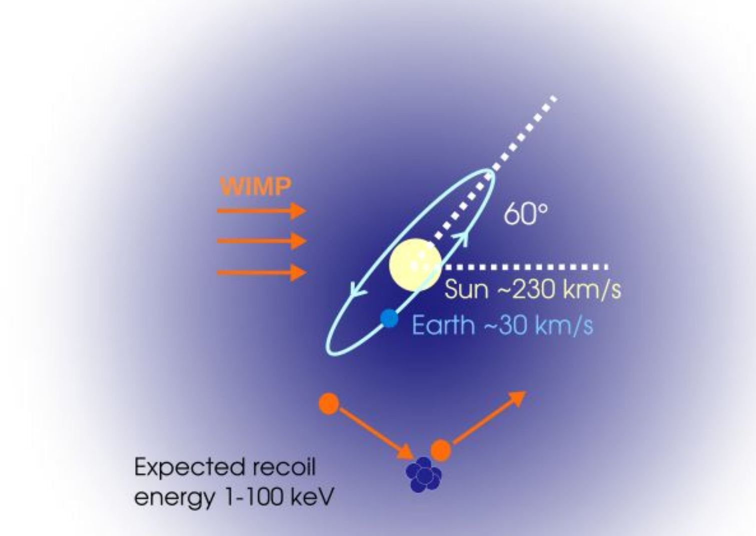
Dark matter search with the SABRE experiment

Giulia D’Imperio for the SABRE collaboration
XXXIX International Conference of High Energy Physics, Seoul, South Korea

07/07/2018

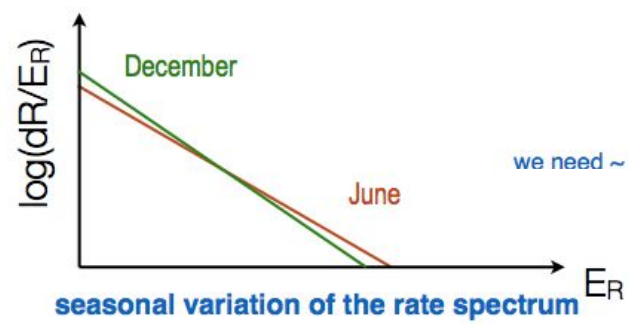
Dark matter through annual modulation



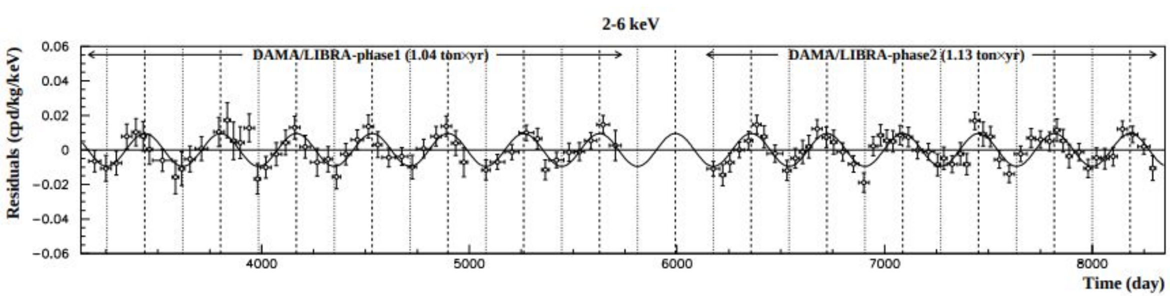
- WIMPs (Weakly Interacting Massive Particles) are promising candidates for dark matter
- Direct detection principle: dark matter scattering off detector nuclei
- Annual modulation of the count rate is a **model independent signature**
  - period 1 year
  - maximum of modulation around June 2nd

Expected rate in an Earth-based detector is modulated, small modulation fraction **S_m/S_0 ~O(1%)**

$$R \approx S_0 + S_m \cos(\frac{2\pi}{1\mathrm{yr}}(t - t_0))$$



DAMA/LIBRA experiment at LNGS modulation phase1 + phase2: total **exposure 2.17 ton x yr**



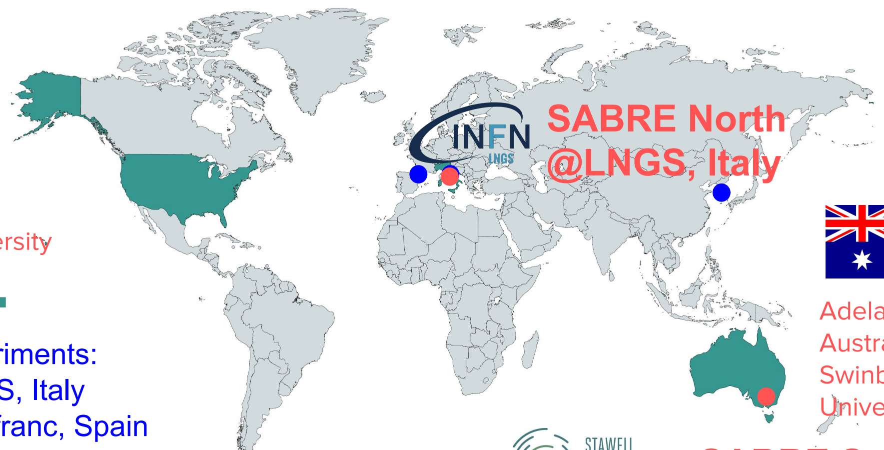
arXiv:1805.10486

DAMA background ~1 cpd/kg/keV
DAMA modulation 0.0095 cpd/kg/keV
Modulation significance 11.9σ C.L.

Sodium-iodide with **A**ctive **B**ackground **RE**jection

LLNL
PNNL
Princeton/University

Other NaI experiments:
- DAMA @LNGS, Italy
- ANAIS @Canfranc, Spain
- COSINE @Yang Yang, South Korea



SABRE North @LNGS, Italy

LNGS & GSSI
INFN Roma & Sapienza University
INFN Milano and University of Milano

Adelaide University
Australian National University
Swinburne University
University of Melbourne

STAWELL UNDERGROUND PHYSICS LAB

SABRE South @SUPL, Stawell gold mine, Australia

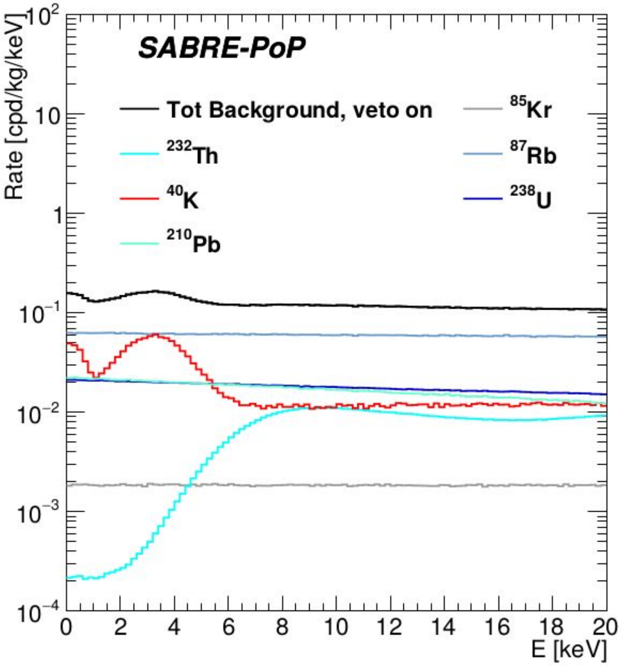
1. **Development of ultra-high purity NaI(Tl) crystals**
   - High purity NaI powder
   - Clean crystal growth method
2. **Low energy threshold**
   - High QE Hamamatsu PMTs directly coupled to the crystal
3. **Passive shielding + active veto**
   - Unprecedented background rejection and sensitivity with a NaI(Tl) experiment
4. **Two identical detectors in northern and southern hemispheres**
   - seasonal backgrounds have opposite phase in northern and southern hemispheres
   - dark matter signal has same phase

The SABRE crystal

Ultra pure NaI(Tl) crystals

- Astro Grade powder (Sigma Aldrich)
- clean growth procedure: collaboration between Princeton and RMD, Boston
- a crystal of 3.6 kg (6 kg before cut) has been produced recently (131 mm length x 98 mm diameter)

- Internal background in the crystal **~0.15 cpd/kg/keV** in [2-6] keV
- dominated by Rb, but upper limit



Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal (*) [ppb]
K	100	~13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	~0.02	0.5-7.5×10^{-3}	<10^{-3}	<10^{-3}
Th	~0.02	0.7-10×10^{-3}	<10^{-3}	<10^{-3}

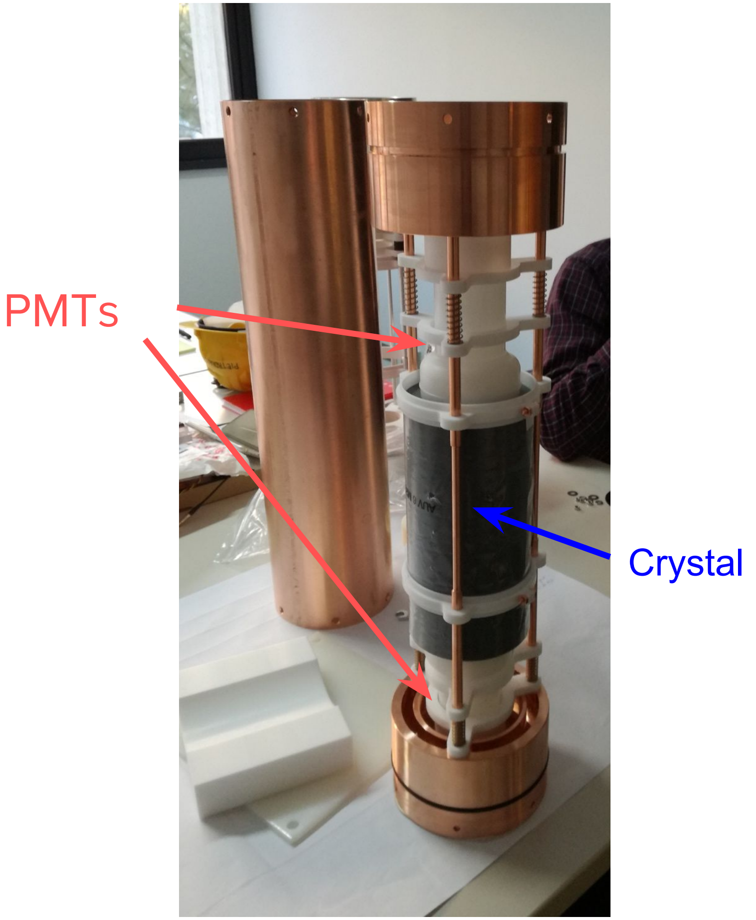
(*) 2 kg test crystal grown from Astro Grade powder with same technique

Low energy sensitivity

SABRE aims to be sensitive to the energies covered by DAMA/LIBRA [1-6] KeV_{ee} and below

Current Design:

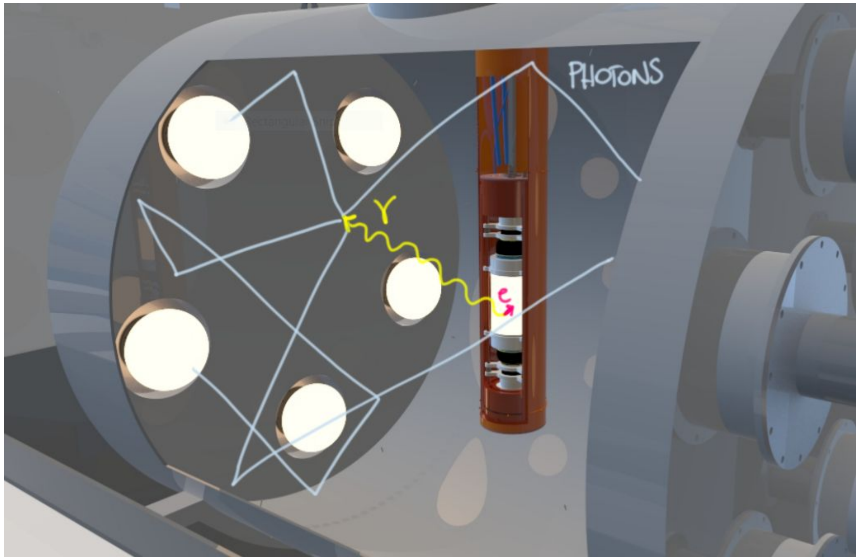
- 2 x Hamamatsu R11065-20 3” PMTs per crystal with High QE: >35% and minimal contaminations
- Direct PMT-Crystal coupling for maximal light yield
- Custom preamplifiers and super bialkali photocathodes ➔ less afterglow and dark noise

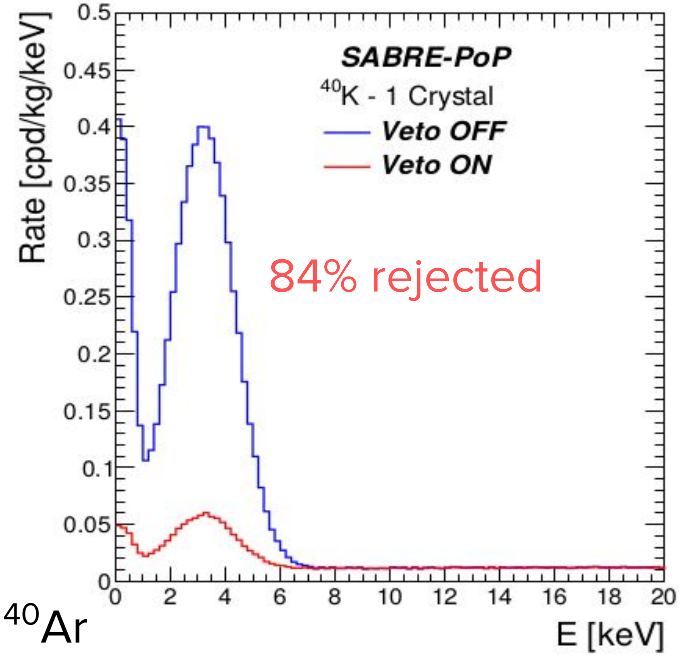


Isotope	Activity [mBq/PMT]		
	Body	Window	Ceramic plate
^{40}K	<5.9	<0.48	6.5
^{60}Co	0.65	<0.042	<0.19
^{238}U	<0.52	<1.8	13
^{226}Ra	<0.29	0.040	0.29
^{232}Th	<0.0098	<0.037	0.70
^{228}Th	<0.41	<0.015	0.13

Active veto system

- A **liquid scintillator veto (PC+PPO 3g/l)** surrounding the NaI detector at 4π
- Veto events with E > 100 keV in the liquid scintillator
- Strongly reduce
  - external backgrounds
  - internal backgrounds that release energy also in the liquid scintillator: ^{40}K



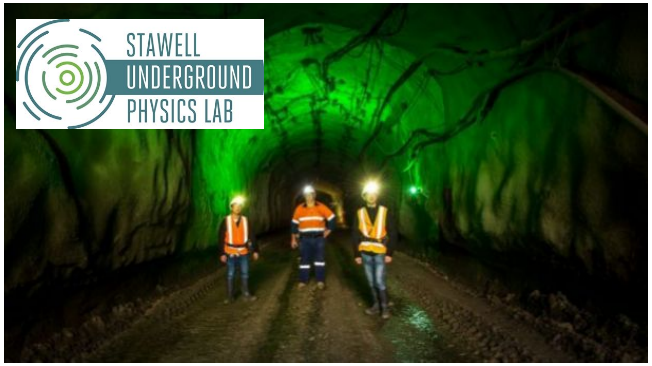


^{40}K (11% BR) decays through electron capture to ^{40}Ar

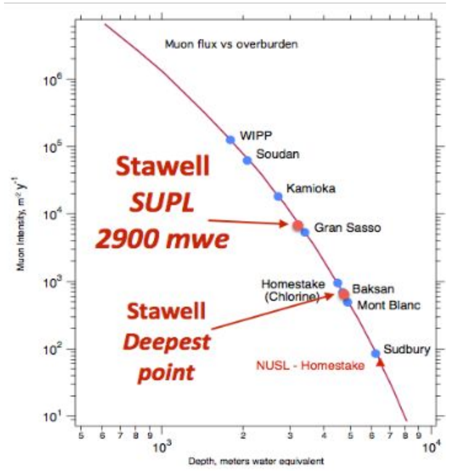
- γ 1460 keV
- X-rays, Auger electrons 3 keV

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



- Hosted in the **Stawell Gold Mine, Victoria, Australia**
- Construction second half of 2018
- Will host SABRE and other experiments



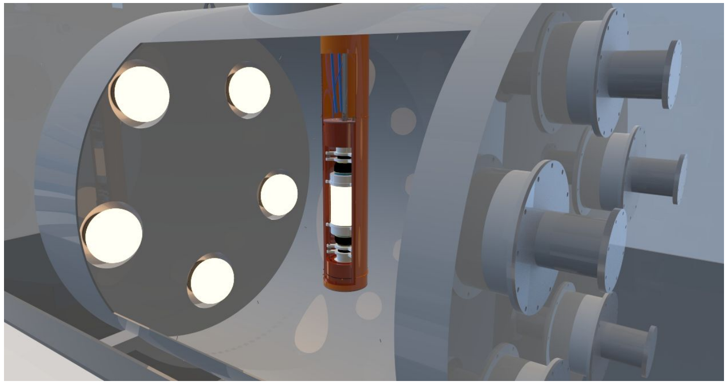
The SABRE Proof-of-Principle

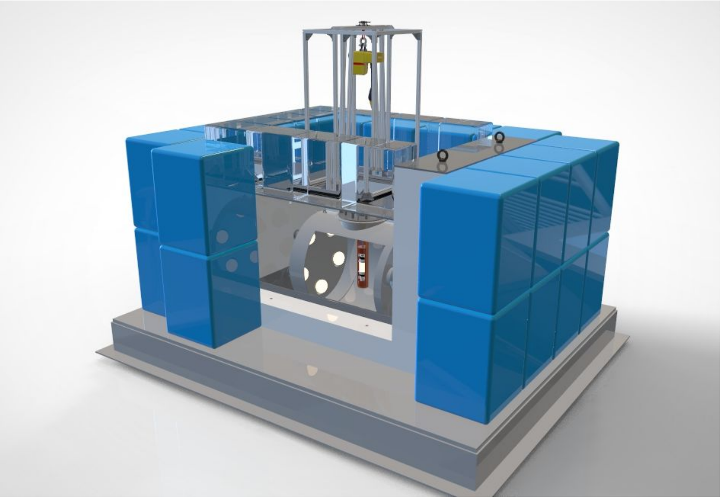
Goals:

- Test active veto performance
- Fully characterize the intrinsic and cosmogenic backgrounds

Layout:

- 1 NaI(Tl) crystal
- Crystal and PMTs will be coupled directly with optical coupling gel and sealed into a highly radiopure copper enclosure
- Active veto:
    - Cylindrical vessel (⌀ x h) = (1.3 m x 1.5 m)
    - PC+PPO (3g/l) scintillator (mass ≈ 2 ton)
    - 10 Hamamatsu R5912-100 PMTs
- External shielding: combination of lead, polyethylene and water, sealed and filled with nitrogen





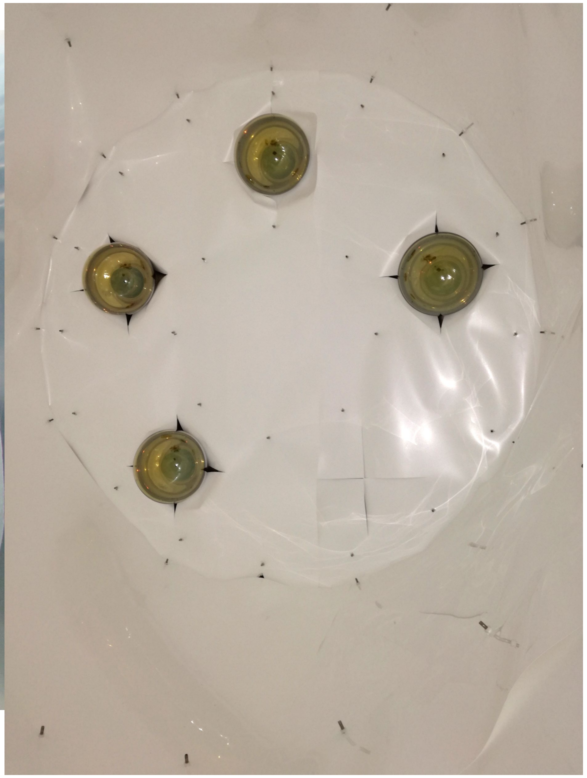
Status of the SABRE Proof-of-Principle @ LNGS

- Shielding and vessel mounted in Hall C

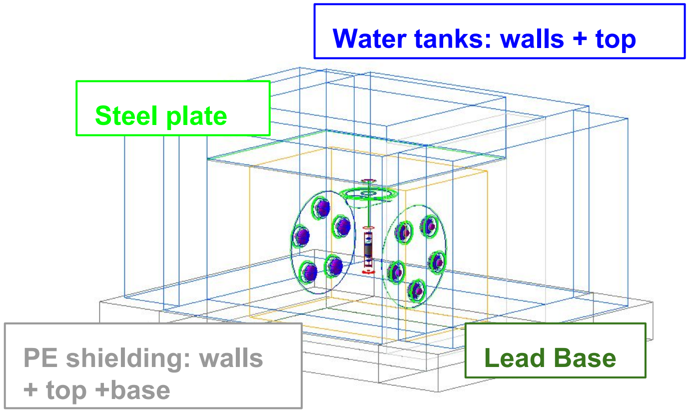
Status of the SABRE Proof-of-Principle @ LNGS

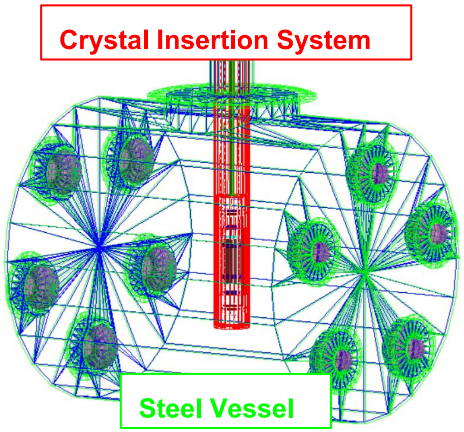
- The veto tank has been cleaned, internally covered with lumirror® and equipped with PMTs
- Crystal and enclosure in Princeton, will be mounted and shipped to LNGS
- Data taking with PoP foreseen in the second half of 2018

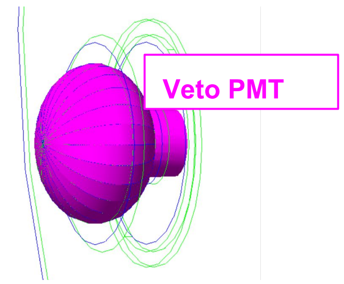




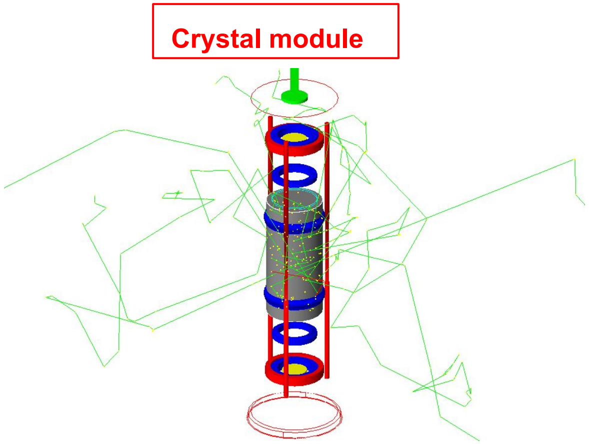
Monte Carlo simulation of the background





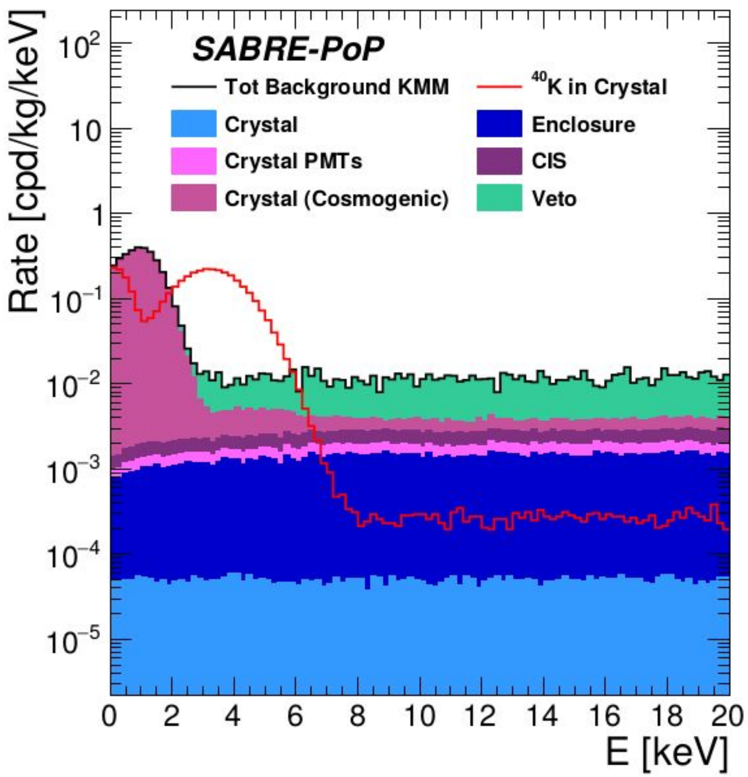


- GEANT4 based code with detailed geometry implementation
  - **Crystal**
  - **Crystal PMTs**: quartz window + body + feedthrough
  - **Enclosure**: wrapping, copper enclosure and small components inside
  - **Crystal Insertion System (CIS)**: copper tube, steel bar
  - **Veto**: steel vessel + liquid scintillator + 10 veto PMTs
  - **Shielding**: water + polyethylene + steel + lead



K measurement mode

- **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
- Coincidences Cystal+Scintillator allow to study other intrinsic BKGs that give a energy release in the scintillator



[1280 < E(Scintillator) < 1640] keV
ROI : [2,4] keV
2 months underground

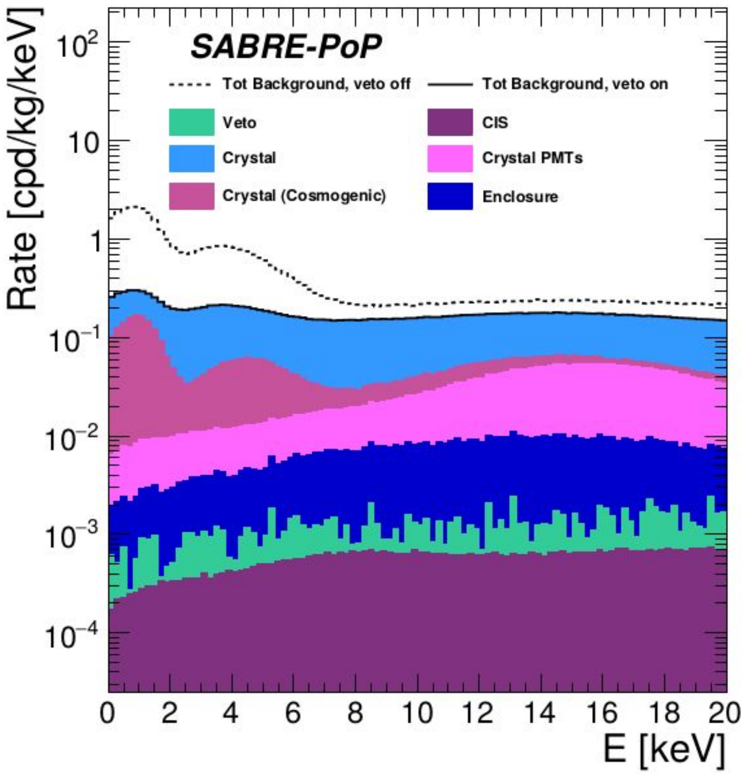
	Rate KMM [cpd/kg/keV]
Crystal Cosmogenic	$1.8 \cdot 10^{-2}$
Veto	$6.2 \cdot 10^{-3}$
Enclosure	$1.3 \cdot 10^{-3}$
Crystal PMTs	$1.1 \cdot 10^{-3}$
CIS	$7.7 \cdot 10^{-4}$
Crystal (no ^{40}K)	$5.1 \cdot 10^{-5}$
Total	$2.7 \cdot 10^{-2}$
Crystal ^{40}K	$1.9 \cdot 10^{-1}$

- Largest bkg contribution from **^{22}Na mostly below threshold of 2 keV**
- 10 ppb of K can be directly measured at 1 ppb precision in ~2 months

arXiv:1806.09344

Dark matter measurement mode

- Test the **active veto rejection power** of the liquid scintillator system and the
- **Measure background level** after veto in the crystal



Veto on: E(Scintillator) < 100 keV
ROI: [2,6] keV
6 months underground

	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Crystal	$3.5 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$
Crystal Cosmogenic	$3.0 \cdot 10^{-1}$	$3.9 \cdot 10^{-2}$
Crystal PMTs	$4.3 \cdot 10^{-2}$	$3.5 \cdot 10^{-2}$
Enclosure	$9.5 \cdot 10^{-3}$	$3.6 \cdot 10^{-3}$
Veto	$3.0 \cdot 10^{-2}$	$5.7 \cdot 10^{-4}$
CIS	$3.7 \cdot 10^{-3}$	$4.6 \cdot 10^{-4}$
Total	$7.4 \cdot 10^{-1}$	$2.2 \cdot 10^{-1}$

- **Veto rejection is ~70%**
- **Total background 0.22 cpd/kg/keV**, 5 times lower than DAMA background
- Highest contribution from Rb in the crystal, but we used the the upper limit contamination

arXiv:1806.09344

SABRE expected sensitivity

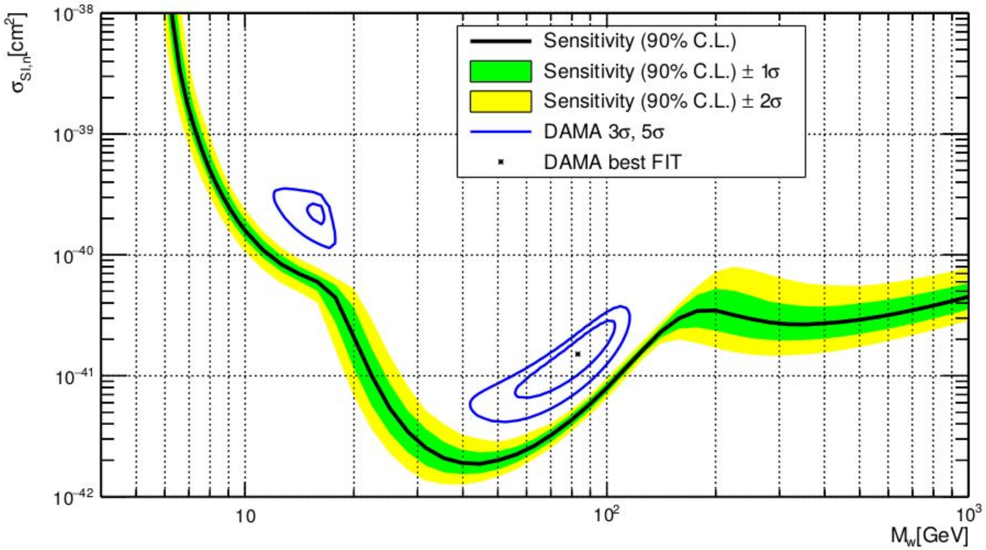
Assuming:

- 3 years exposure
- 50 kg of NaI(Tl) crystals
- average background 0.22 cpd/kg/keV in [2-6] keV region
- Quenching factor for Na: $0.13 < Q_{Na} < 0.21$, for I $Q_I = 0.09$

The SABRE full scale can:

- Confirm modulation with amplitude observed by DAMA at 6σ
- Refute it at 5σ
- Exclude spin independent WIMP-nuclear scattering as strong as 10^{-42} cm^2

arXiv:1806.09340



Summary and conclusions

- 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) annual modulation with amplitude observed by DAMA/LIBRA with 3 years of data at 6 (5) sigma.

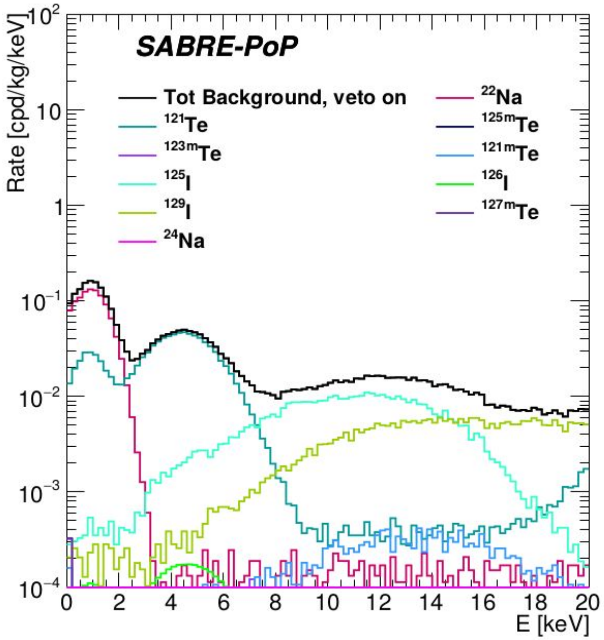
Backup slides

Crystal cosmogenic background

Cosmogenic activation assumptions:

- ^{22}Na and ^{126}I measured at LNGS on Astro Grade powder
- ^{24}Na and ^{129}I measured from DAMA collaboration on their crystals
- other isotopes measured from ANAIS collaboration on their crystals

Veto on: E(Scint) < 100 keV
6 months underground



ROI: 2-6 keV

Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Cosmogenic		
^{121}Te	$2.6 \cdot 10^{-1}$	$3.3 \cdot 10^{-2}$
^{22}Na	$3.6 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$
^{125}I	$1.8 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$
^{129}I	$3.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$
^{126}I	$2.0 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$
^{121m}Te	$1.3 \cdot 10^{-4}$	$7.0 \cdot 10^{-5}$
^{123m}Te	$7.6 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
^{127m}Te	$5.0 \cdot 10^{-5}$	$4.9 \cdot 10^{-5}$
^{125m}Te	$5.3 \cdot 10^{-6}$	$5.1 \cdot 10^{-6}$
^{24}Na	-	-
Tot Cosmogenic (180 days)	$3.0 \cdot 10^{-1}$	$3.9 \cdot 10^{-2}$

arXiv:1806.09344

Radioactivity of materials
arXiv:1806.09344

Crystal

Intrinsic			
Isotope	Activity [mBq/kg]		Ref.
^{40}K	0.31		[14]
^{238}U	$< 1.2 \cdot 10^{-2}$		[14]
^{232}Th	$< 4.1 \cdot 10^{-3}$		[14]
^{87}Rb	$< 8.9 \cdot 10^{-2}$		[14]
^{210}Pb	$< 3.0 \cdot 10^{-2}$		[24]
^{85}Kr	$< 1.0 \cdot 10^{-2}$		[24]
Cosmogenic			
Isotope	Activity [mBq/kg]	Half life [days]	Ref.
^{22}Na	0.80	949	[29]
^{126}I	4.30	13	[29]
^{24}Na	$2.6 \cdot 10^{-4}$	0.625	[24]
^{129}I	0.95	-	[24]
^{121}Te	1.27	17	[28]
^{125}I	7.20	59	[28]
^{121m}Te	0.89	154	[28]
^{123m}Te	1.17	119	[28]
^{125m}Te	0.92	57	[28]
^{127m}Te	0.37	107	[28]

[14] M. Antonello, et al., The SABRE project and the SABRE PoParXiv:1806.09340.
[24] R. Bernabei, et al., *The DAMA/LIBRA apparatus*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 592 (3) (2008) 297 – 315. doi:http://dx.doi.org/10.1016/j.nima.2008.04.082.
[28] J. Amaré, et al., Cosmogenic radionuclide production in NaI(Tl) crystals, JCAP 1502 (02) (2015) 046. arXiv:1411.0106, doi:10.1088/1475-7516/2015/02/046.
[29] M. Laubenstein, HPGe screening at LNGS.

Crystal PMTs Hamamatsu R11065

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

E. Aprile, et al., Lowering the radioactivity of the photomultiplier tubes for the XENON1T dark matter experiment, European Physical Journal C 75 (2015) 546. doi:10.1140/epjc/s10052-015-3657-5.

PFTE reflector foil

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

PFTE holders inside enclosure

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

E. Aprile, et al., Material screening and selection for XENON100, Astroparticle Physics 35 (2) (2011) 43 – 49. doi:http://dx.doi.org/10.1016/j.astropartphys.2011.06.001.

Radioactivity of materials

arXiv:1806.09344

Copper parts: enclosure, CIS

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

L. Baudis, et al., Cosmogenic activation of xenon and copper, The European Physical Journal C 75 (10) (2015) 485. doi:10.1140/epjc/s10052-015-3711-3.

Steel vessel

Isotope	Activity [mBq/kg]	
	Lot n.S536 Thickness 3/8"	Lot n.T915 Thickness 1/4"
^{40}K	0.12	< 0.03
^{238}U	3.7	0.49
^{232}Th	$<$0.41	0.082

E. Shields, SABRE: A search for dark matter and a test of the DAMA/LIBRA annual-modulation result using thallium-doped sodium-iodide scintillation detectors, Ph.D. Thesis Princeton University.

Veto PMTs Hamamatsu R5912

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

P. Agnes, et al., The veto system of the DarkSide–50 experiment, JINST P03016. doi:https://doi.org/10.1088/1748-0221/11/03/P03016

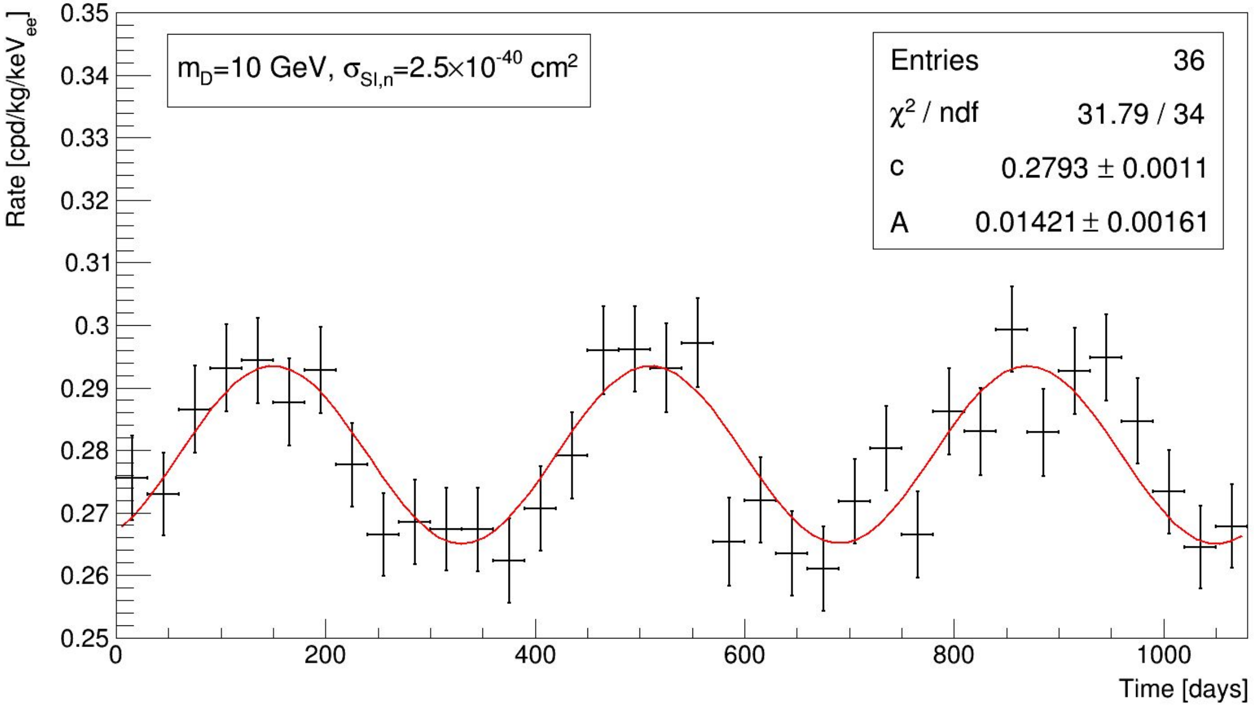
Liquid scintillator

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	$3.5 \cdot 10^{-7}$

G. Alimonti, et al., The liquid handling systems for the Borexino solar neutrino detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 609 (1) (2009) 58 – 78. doi:http://dx.doi.org/10.1016/j.nima.2009.07.028.

SABRE expected modulation

$$m_D = 10\,GeV, \sigma_{SI,n} = 2.5 \cdot 10^{-40}\,cm^2$$



Geant 4 details

- GEANT4 v10.2.p03
  - Hadronic physics list: Shielding
  - EM physics list: G4EmStandardPhysics_option4
  - Fluorescence, auger electron emission and particle induced atomic relaxation accounted
  - G4EmExtraPhysics