Dark matter search with the SABRE experiment

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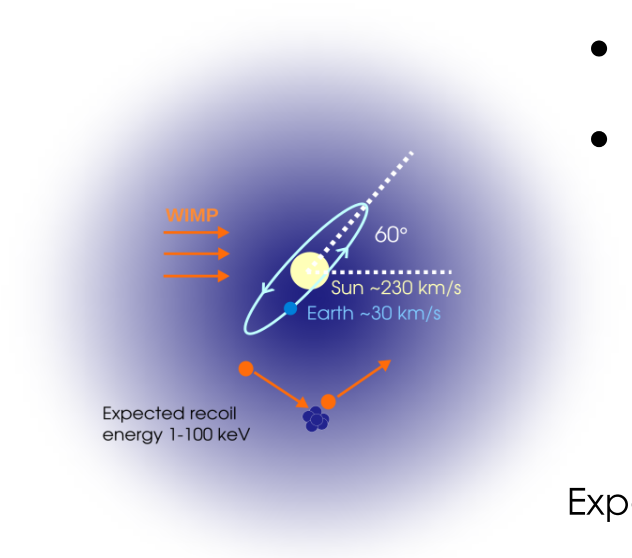
Dark matter via annual modulation

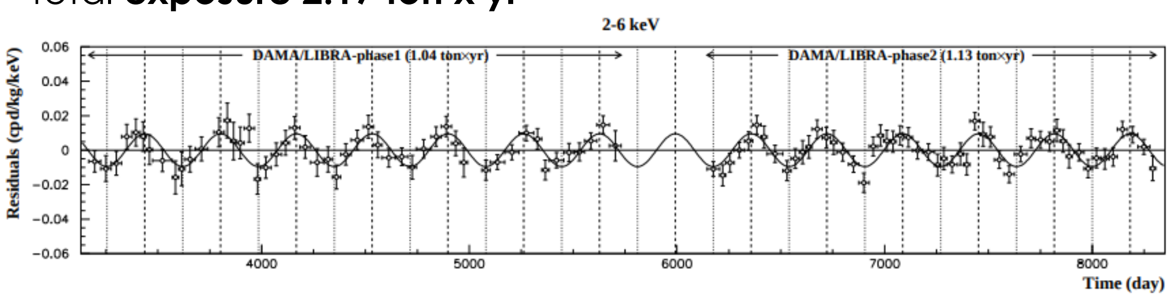


- Direct detection principle: dark matter scattering off detector nuclei
- Annual modulation of the count rate is a **model independent signature**
  - period 1 year
  - maximum of modulation around June 2nd

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

Expected rate in an Earth-based detector is modulated: $\mathbf{S_m/S_0 \sim O(1\%)}$

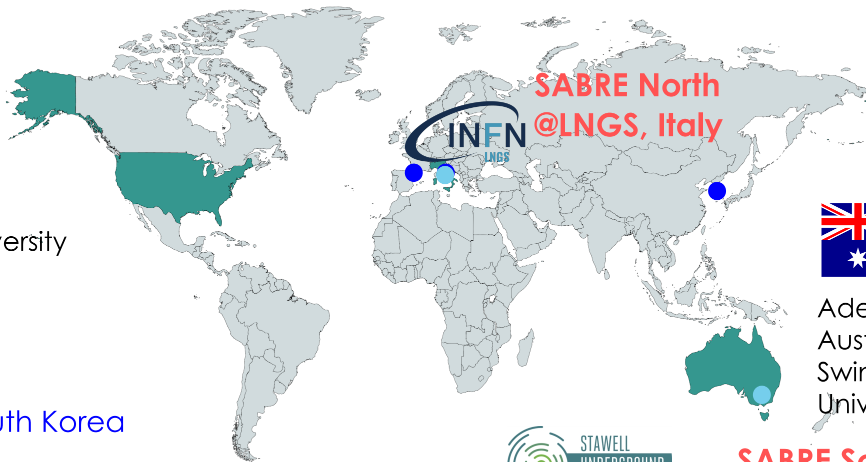
DAMA/LIBRA experiment at LNGS modulation phase1 + phase2:
total **exposure 2.17 ton x yr**



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

arXiv:1805.10486

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



LLNL
PNNL
Princeton/University

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

Adelaide University
Australian National University
Swinburne University
University of Melbourne

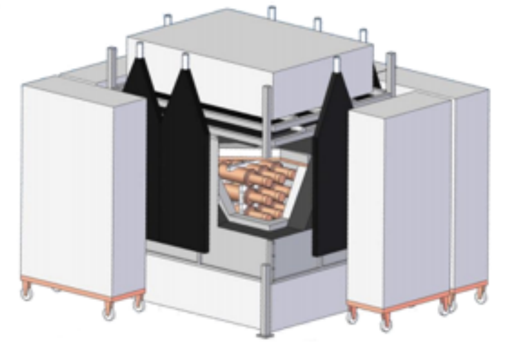
Other NaI experiments:
- DAMA @LNGS, Italy
- ANAIS @Canfranc, Spain
- COSINE @Yang Yang, South Korea

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

Other NaI experiments worldwide

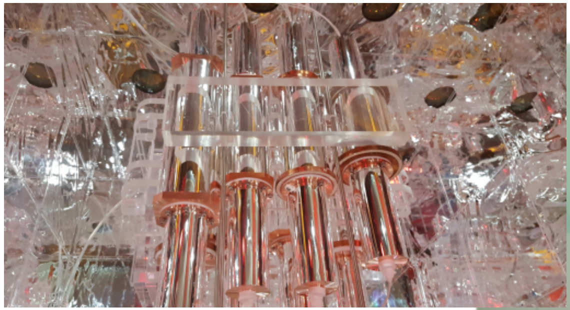
ANAIS-112 @ Canfranc (Spain)
Setup: 9 x 12.5 kg crystals (112.5 kg).
Muon tagging. Gamma (lead, also ancient), Anti-Rn box and neutron (PE) shielding. Data taking started Aug 2017.



3x3 matrix of 12.5 kg cylindrical NaI(Tl) modules
(**112.5 kg** of active mass)

- Alpha Spectra crystals: ^{40}K and ^{22}Na peaks and ^{210}Pb (bulk+surface) and ^{3}H continua are the most significant contributions in the very low energy region. Bkg ~ 4 cpd/kg/keV (single hit)
- Outstanding light collection: ~15 phe/keV
- Threshold: 1 keV (trigger), 2 keV (sensitivity)

COSINE-100 @ YangYang (South Korea)
Joint collaboration between DM-Ice and KIMS
Setup: 8 crystals (106 kg).
Muon tagging. Gamma (3cm Cu + 20 cm Pb) shield, LS veto (~ 2000 l LAB). Data taking started Sep 2016.



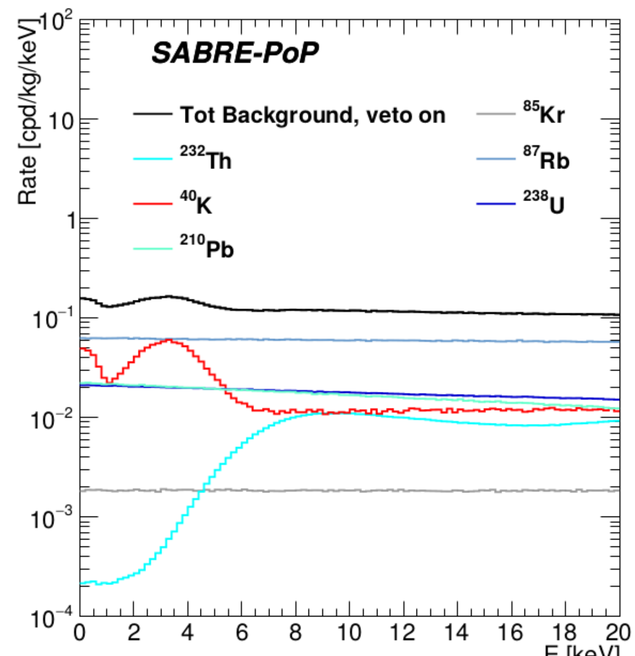
- Alpha Spectra crystals. Bkg 2-4 cpd/kg/keV (single hit)
- Threshold: 2 keV (goal is 1 keV)
- R&D for COSINE-200 powder purification and crystal growth facility @ IBS in Korea (mass production facility for purification under construction)

The SABRE crystal

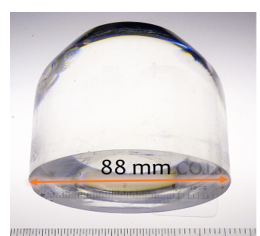
Ultra pure NaI(Tl) crystals

- 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)

- Simulation show that the internal background in the crystal can be as low as **~0.15 cpd/kg/keV** in [2-6] keV
- dominated by Rb (upper limit)
- provided that ^{210}Pb, ^{3}He and cosmogenics are kept under control.



Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb] (*)
K	100	$\sim$13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	$\sim$0.02	$0.5\text{-}7.5\times10^{-3}$	$<10^{-3}$	$<10^{-3}$
Th	$\sim$0.02	$0.7\text{-}10\times10^{-3}$	$<10^{-3}$	$<10^{-3}$



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

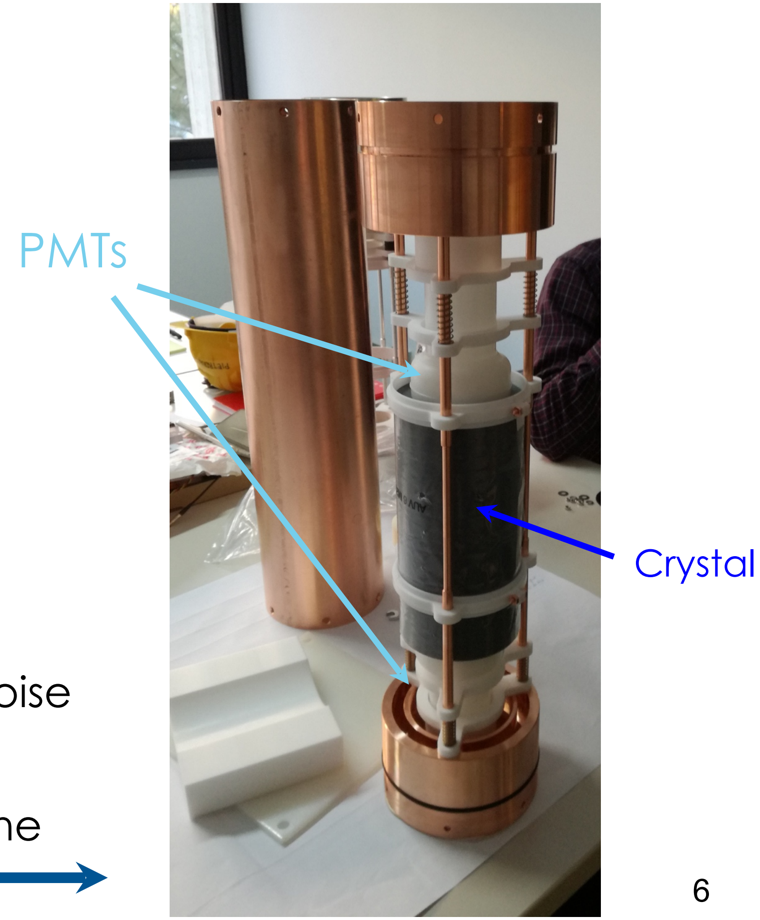
Low energy sensitivity

SABRE aims to be sensitive to the energies in the range between [1-6] keV_{ee}

Current Design:

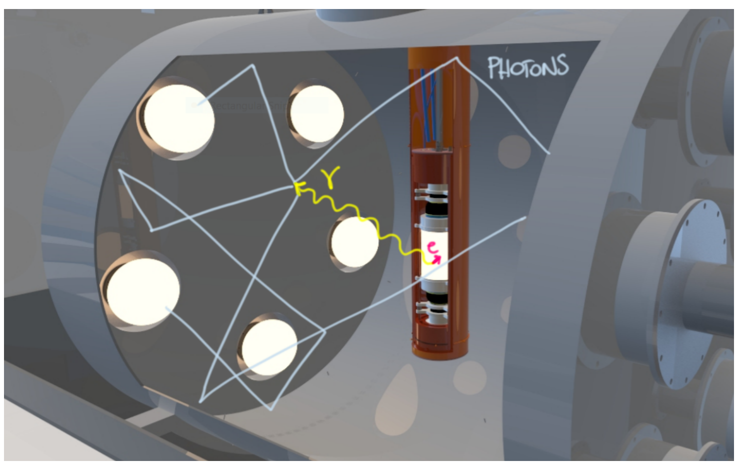
- 2 x Hamamatsu R11065-20 3" PMTs per crystal with High QE: >35% and low contaminations
- Direct PMT-Crystal coupling for maximal light yield
- Custom preamplifiers and super bialkali photocathodes → less afterglow and dark noise

Low-radioactivity copper enclosure now @ PU for the assembly of the detector module →



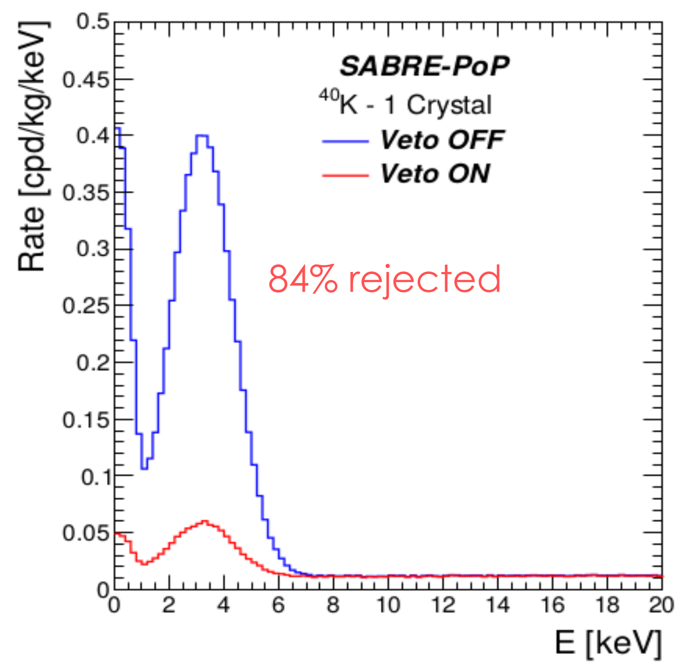
Active veto system

- 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



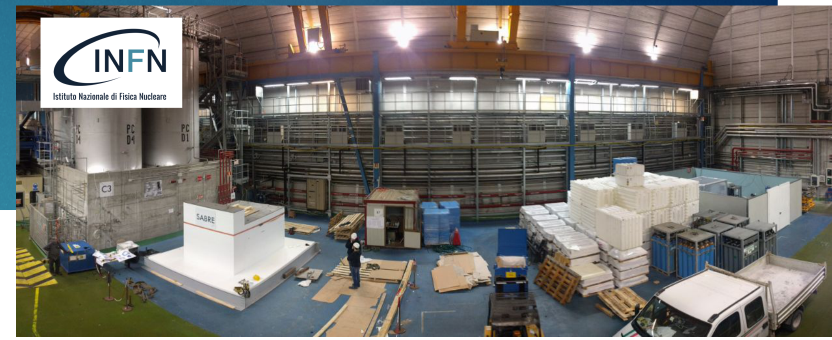
^{40}K (11% BR) decays through electron capture to ^{40}Ar

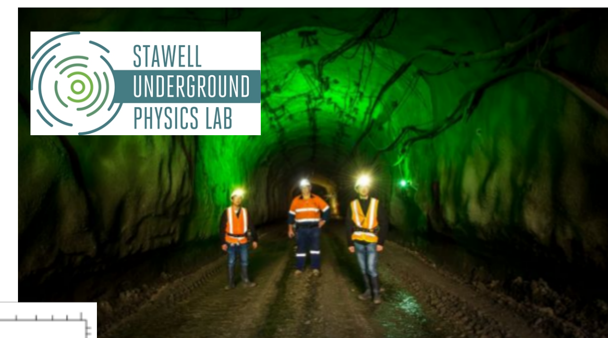
- γ 1460 keV
- X-rays, Auger electrons 3 keV

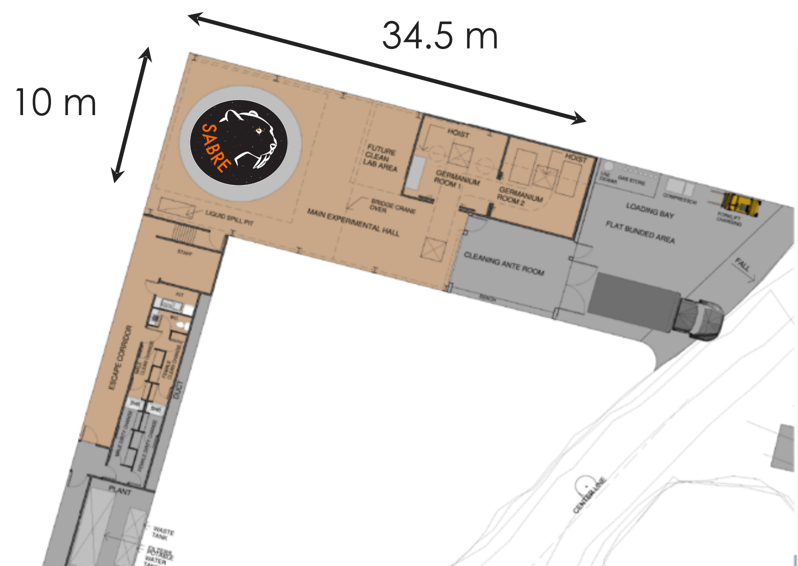


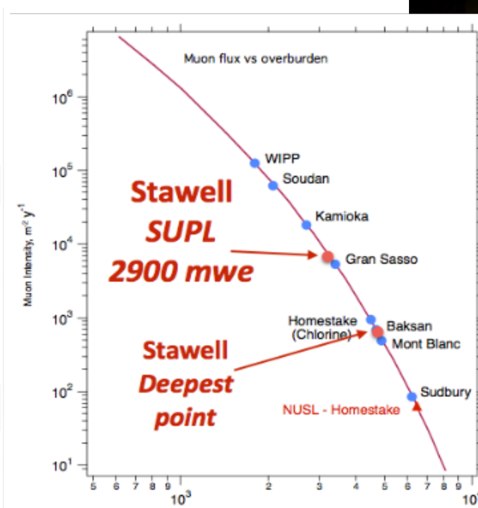
Double location

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







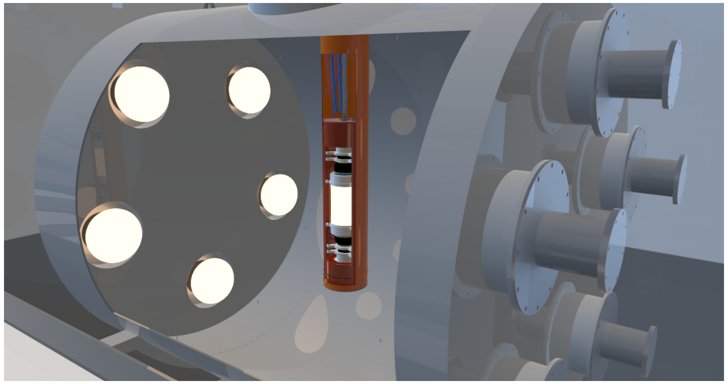


- Hosted in the **Stawell Gold Mine, Victoria, Australia**
- Construction second half of 2018
- Will host SABRE and other experiments

The SABRE Proof-of-Principle (PoP)

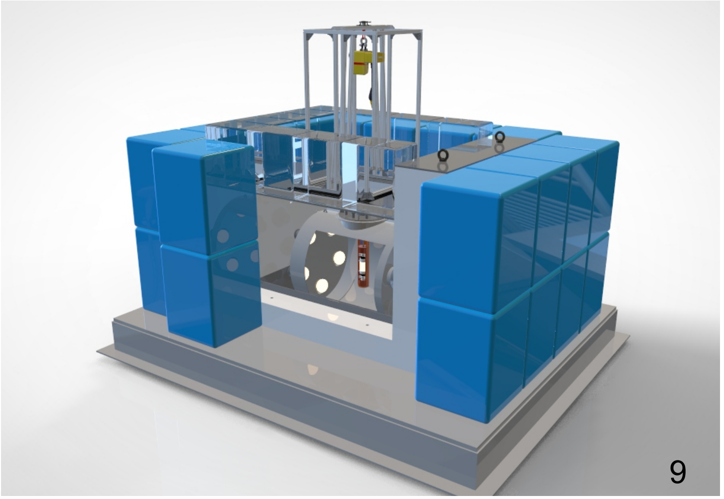
Goals:

- Test active veto performance
- Fully characterise 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 radio-pure 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

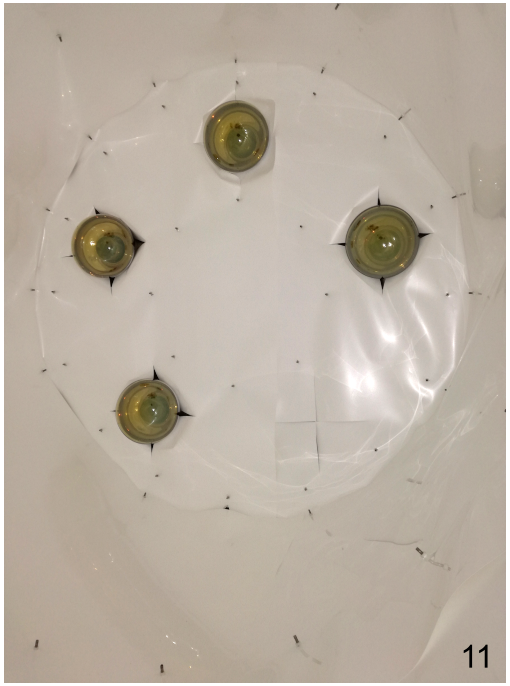


Status of the SABRE PoP @ LNGS

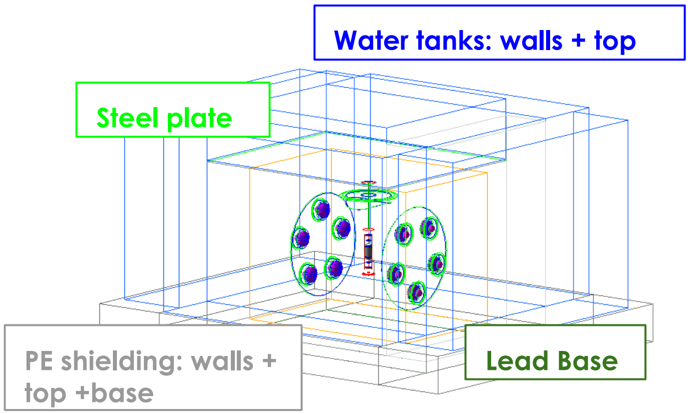
Shielding and vessel mounted in Hall C

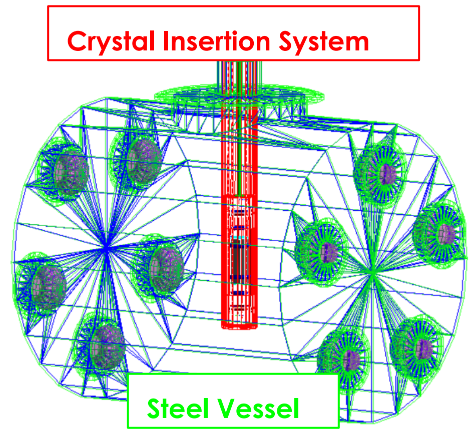
Status of the SABRE PoP @ LNGS

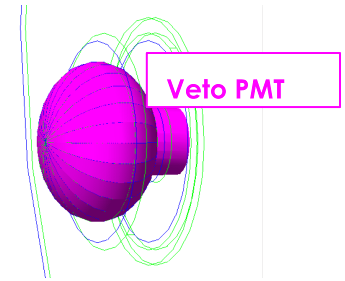
- Shielding assembled
- Veto tank cleaned, internally covered with Lumirror® and equipped with PMTs
- Crystal and enclosure in Princeton, will be mounted and shipped to LNGS
- Data taking with PoP foreseen in the second half of 2018

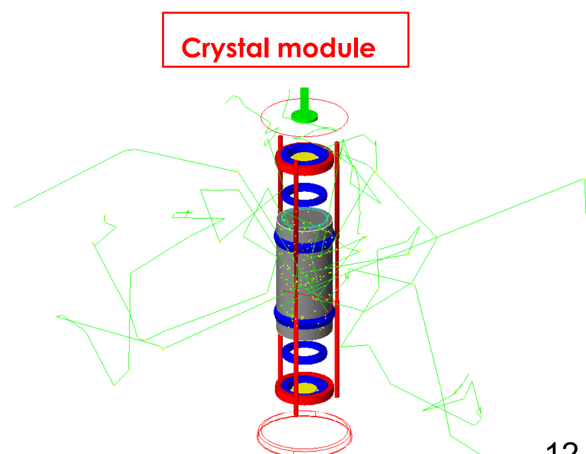


Monte Carlo simulation of the background





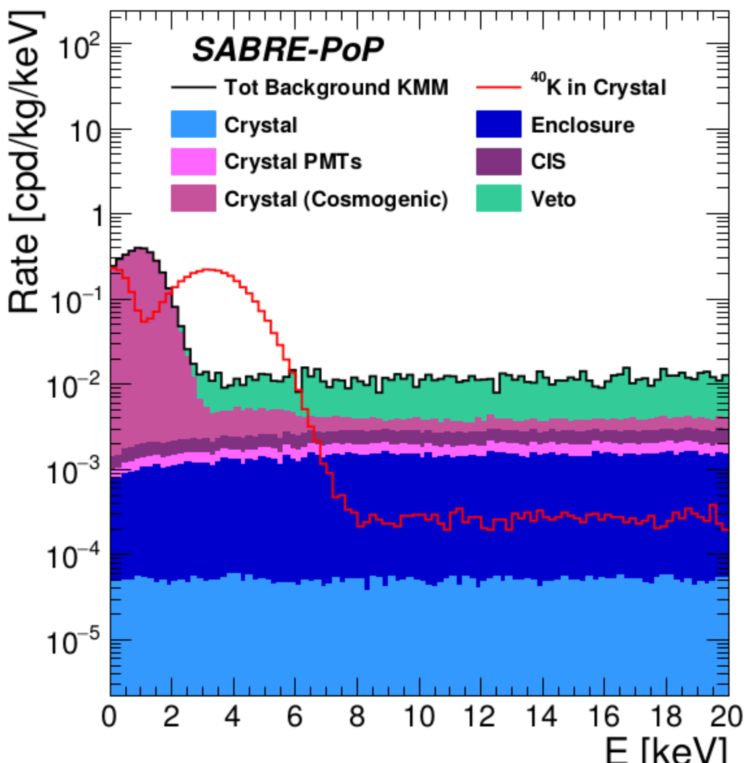




- GEANT4 based code with detailed geometry implementation
  - **Crystal**
  - **Crystal PMTs**: quartz window + body + feedthrough
  - **Enclosure**: wrapping, copper enclosure and small components inside
  - **Crystal Insertion System (CIS)**: copper tube, steel bar
  - **Veto**: steel vessel + liquid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



arXiv:1806.09344

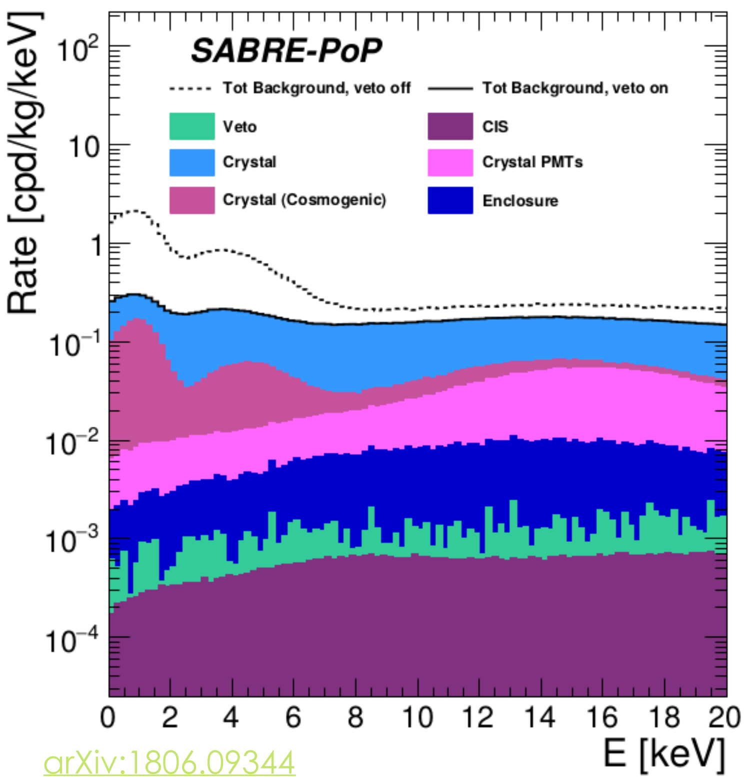
E_{VETO}:
[1280 < 1640]keV
E_{CRYS} : [2,4] keV
2 months underground

	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

Dark matter measurement mode

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



arXiv:1806.09344

Veto on: E_{VETO} < 100 keV
E_{CRYS}: [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

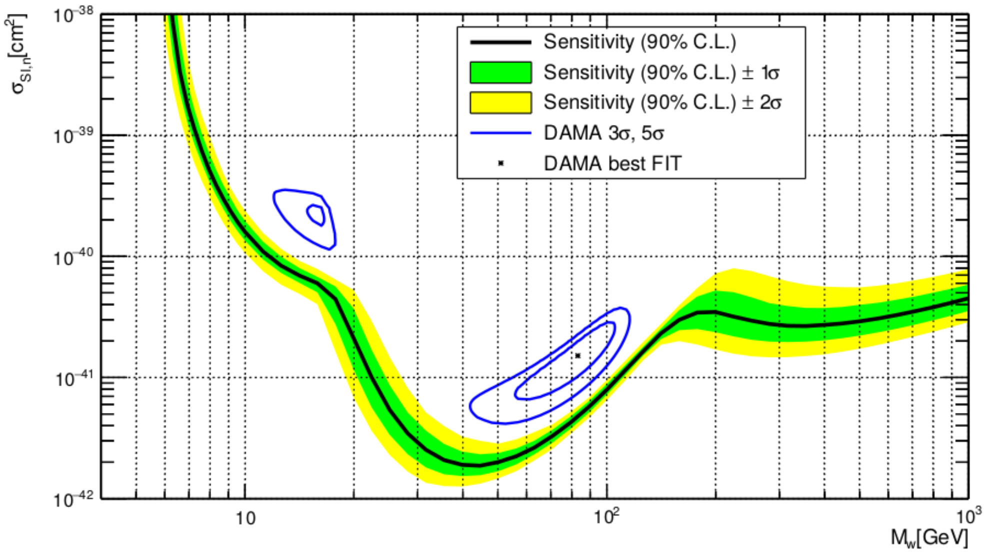
SABRE expected sensitivity

Assumptions:

- 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

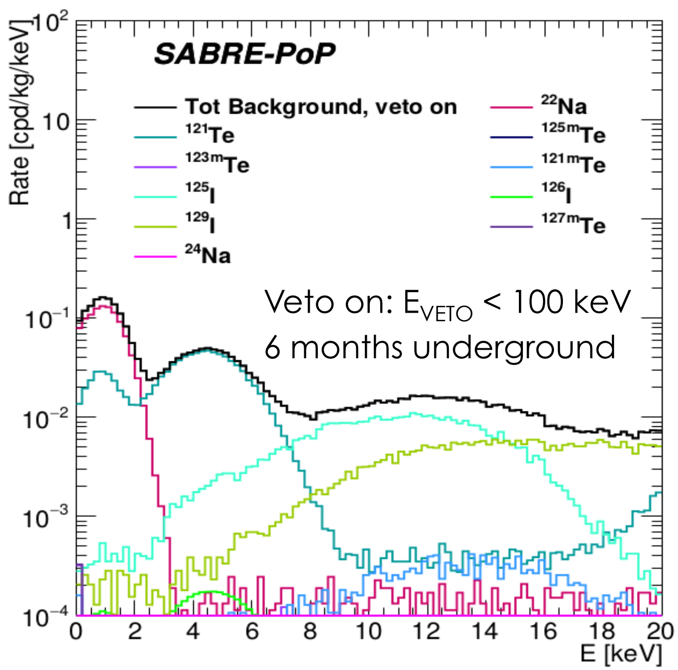
Crystal cosmogenic background

arXiv:1806.09344

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

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)	$3.0 \cdot 10^{-1}$	$3.9 \cdot 10^{-2}$

SABRE expected modulation

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