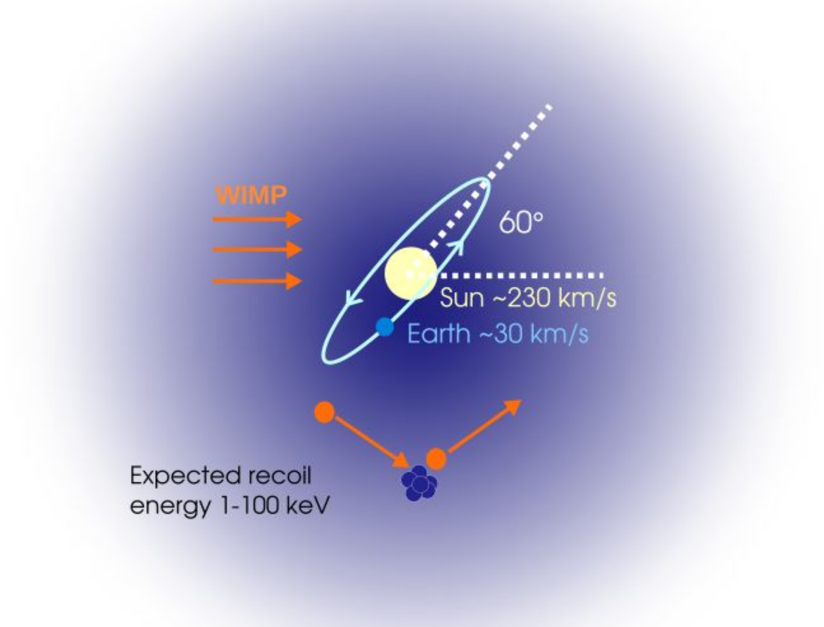
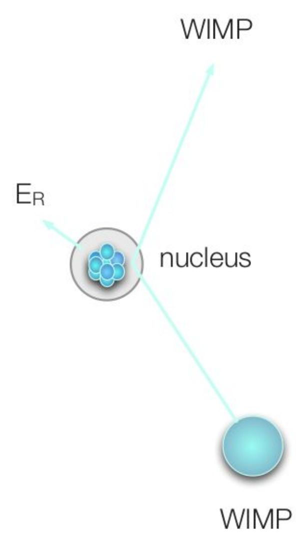
Background characterization of the SABRE experiment

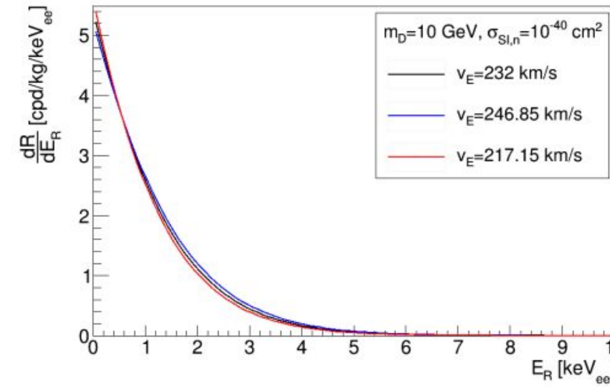
Giulia D’Imperio* on behalf of the SABRE collaboration
*INFN Roma 1

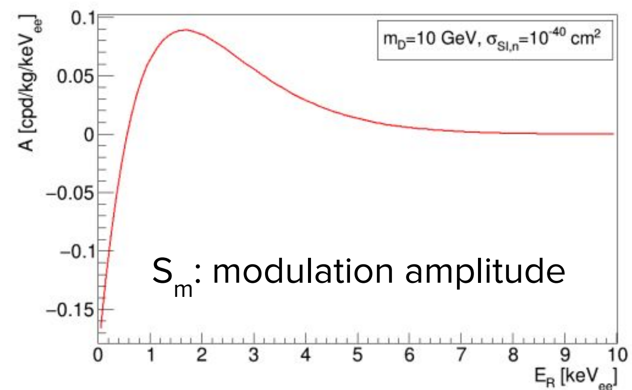
Low **R**adioactivity **T**echniques 2019
Laboratorio Subterráneo de Canfranc (LSC), Spain
21/05/2019

Dark matter search with SABRE



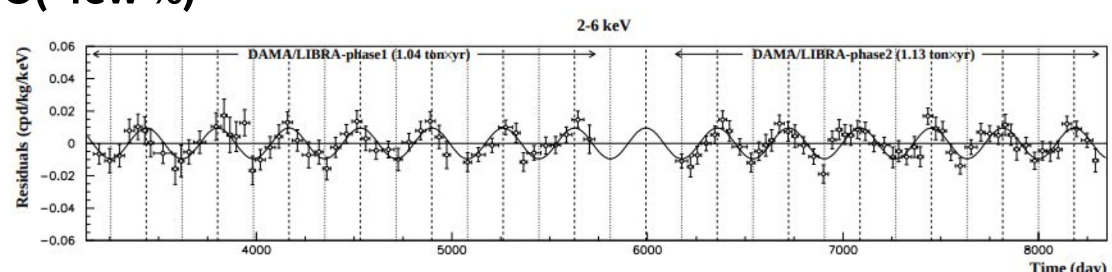






- Low recoil energy **1-100 keV**
- Differential rate of the order of **1 count/day/kg/keV** (cpd/kg/keV)
- Expected rate in an Earth-based detector is modulated
- Small modulation fraction **S_m/S_0 = O(~few %)**

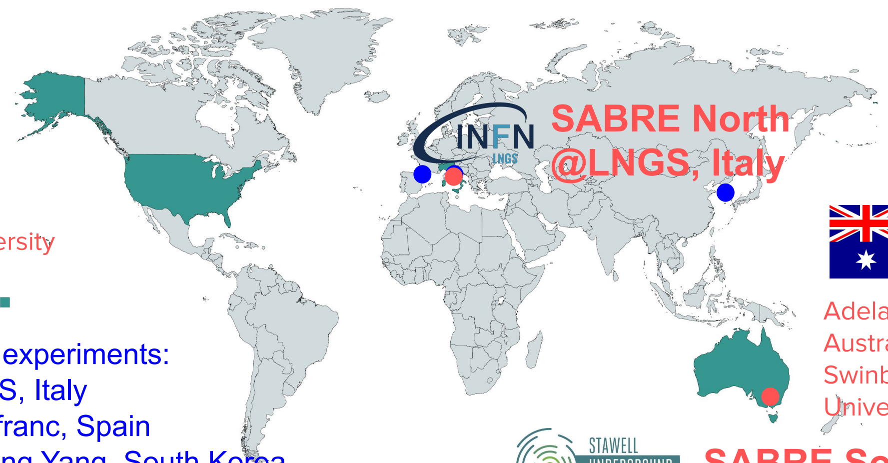
$$R = S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$



DAMA/LIBRA Phase 1 and 2 Nucl. Phys. At. Energy 19 (2018) 307-325

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

LLNL
PNNL
Princeton University



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

Current NaI(Tl) 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 from Sigma Aldrich (now Merck)
   - Clean crystal growth method developed by Princeton (PU) and RMD company
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

(see talk by Burkhant Suerfu this morning)

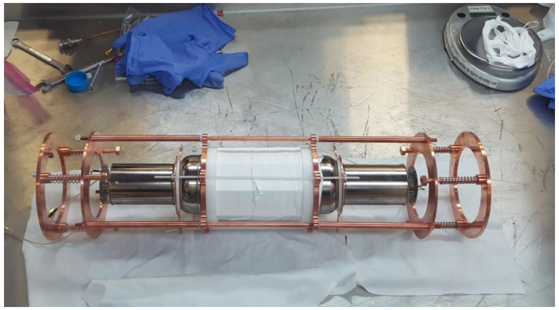
The Proof-of-Principle (PoP)

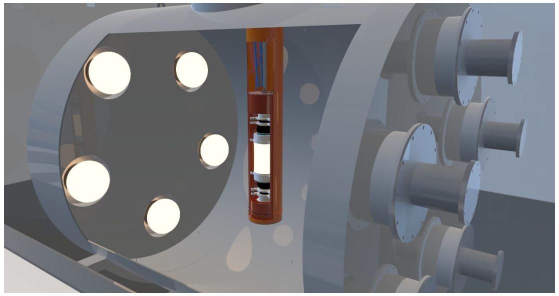
Layout:

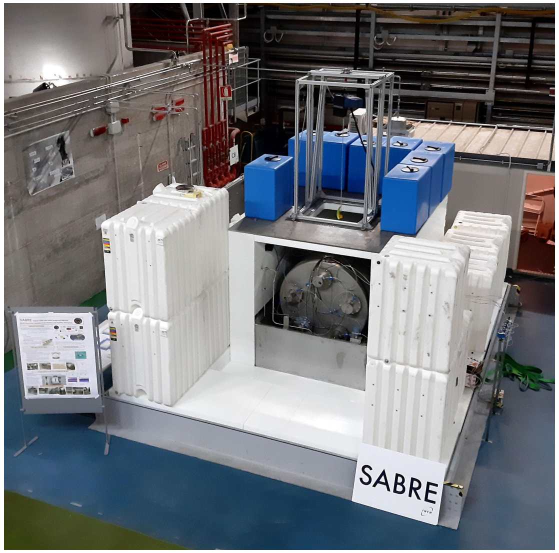
- 1 NaI(Tl) crystal of ~5 kg
- Crystal and PMTs coupled directly with optical grease and sealed into a OFHC copper enclosure
- Active veto:
  - Cylindrical vessel (∅ x h) = (1.3 m x 1.5 m)
  - PC+PPO (3g/l) scintillator (mass ≒ 2 ton)
  - 10 Hamamatsu R5912-100 PMTs
- External shielding: combination of lead, polyethylene and water, sealed and flushed with nitrogen

Goals:

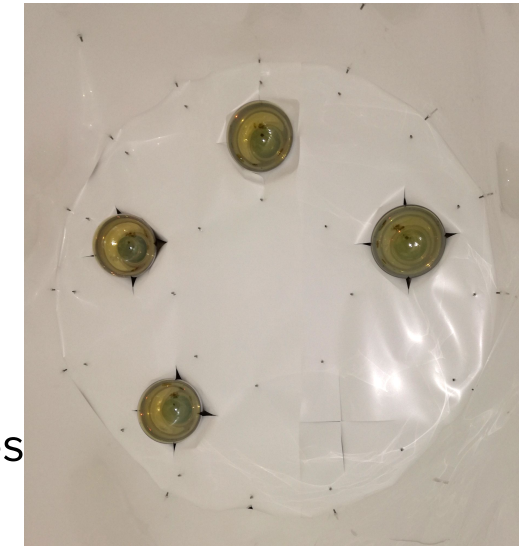
- Test active veto performance
- Fully characterize the intrinsic and cosmogenic backgrounds





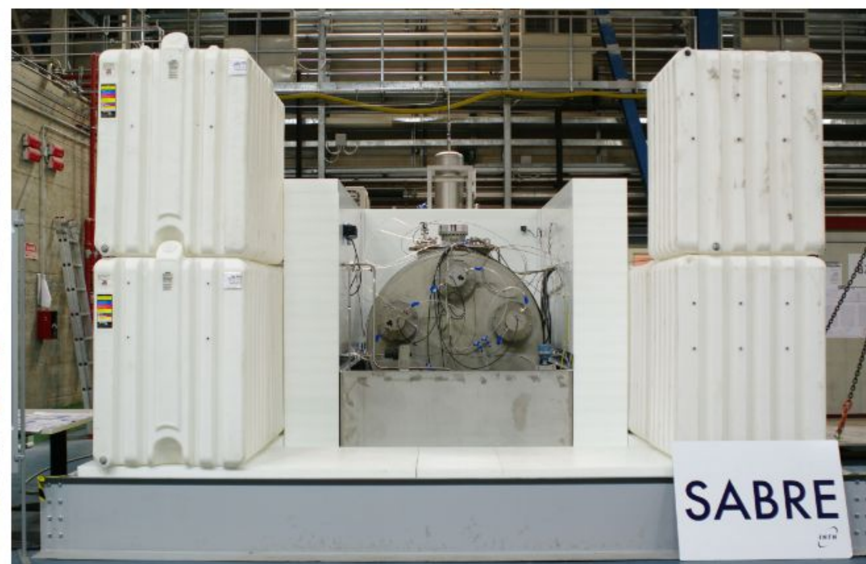


Status of the setup at LNGS (1/2)



The PoP setup in the **Hall C** at **LNGS** is complete

- vessel cleaned, lumirror reflector
- veto PMTs mounted and tested
- vessel placed inside the passive shielding
- all connections tested (cables for signal and HV, tubes and valves for fluid handling)



Status of the setup at LNGS (2/2)

- alignment of crystal insertion system done
- crystal NaI-31 already @LNGS
- NaI-33 ready for shipping by boat, will arrive in few weeks at LNGS

➔ Ready to start commissioning in **summer 2019**

Radioactivity of the setup

SABRE goal: achieve background **< 1 cpd/kg/keV** and **threshold of 1 keV**

The most important sources of background are:

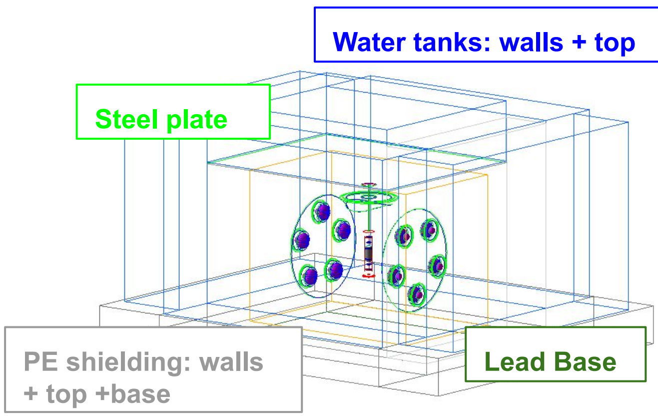
- radioactive contaminations in the **crystals**:
  - **intrinsic**: ^{40}K, ^{87}Rb, ^{232}Th, ^{238}U, ^{210}Pb out of equilibrium
  - long lived **cosmogenics**, in particular ^{3}H and ^{22}Na

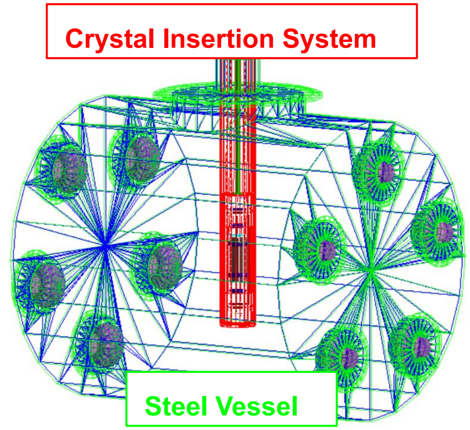
- radioactive contaminations in the **materials close to the crystals** (wrapping, PMTs, enclosure): ^{238}U and ^{232}Th decay chains, ^{40}K , ^{60}Co

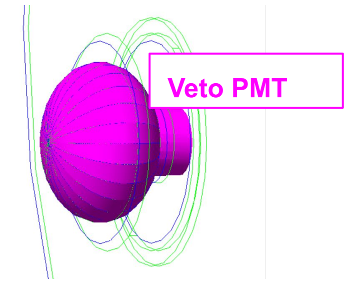
Simulation of radioactive decays in all the setup materials:

- input concentration of isotopes measured with **ICP-MS** or γ activity with **HPGe**:
  - NaI powder and crystals measured by SABRE
  - measurements of other materials available in literature
- calculations of **cosmogenic activation** with ACTIVIA software, 1 year exposure at sea level and 10 hours flight from US to Italy
- final background after 6 months underground

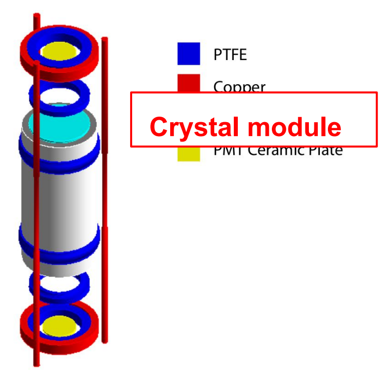
Simulation of the setup radioactivity







- 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 (only passive)



Crystal intrinsic radioactivity

- Input for radioactivity from ICP-MS on test crystal and powder

Isotope	Activity [mBq/kg]
^{40}K	0.31
^{238}U	$< 1.2 \cdot 10^{-2}$
^{232}Th	$< 4.1 \cdot 10^{-3}$
^{87}Rb	$< 8.9 \cdot 10^{-2}$
^{210}Pb	$< 3.0 \cdot 10^{-2}$
^{85}Kr	$< 1.0 \cdot 10^{-2}$

[1,2] ➔ 10 ppb from ICP-MS measurement on first test crystal

[1] ➔ <1 ppt from ICP-MS limits on Astrograde powder

[2] ➔ <0.1 ppb from ICP-MS limit on Astrograde powder

➔ assumed limit from DAMA, can be measured only with direct counting

[1] PNNL (Arnquist, I.J. et al. Methods Phys. Res., Sect. A, 2017. 851)
[2] Seastar

- Very low content and U, Th and K in the Astrograde powder

- Purification method and segregation in crystal growth works well with K and Rb ➔ long R&D by Princeton University and RMD
  (see talk by Burkhant Suerfu this morning)

- ^{210}Pb can be introduced later in cutting/polishing of grown crystal
  ➔ non vetoable contribution

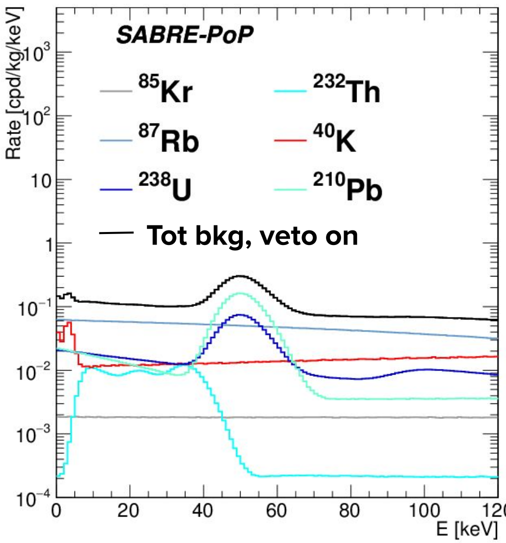
Crystal intrinsic background

Background in ROI: 2-6 keV

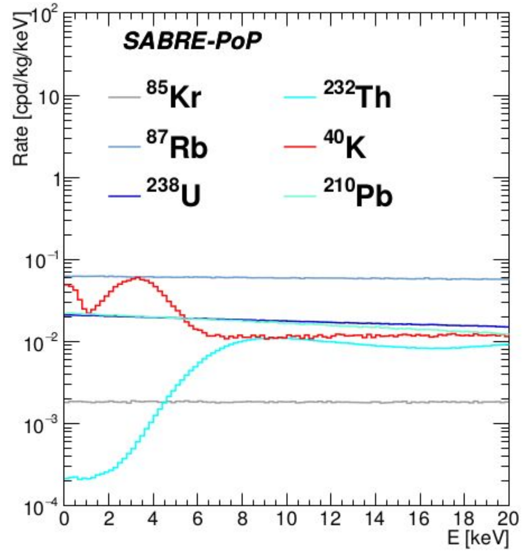
Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
	Intrinsic	
^{87}Rb	$6.1 \cdot 10^{-2}$	$6.1 \cdot 10^{-2}$
^{40}K	$2.5 \cdot 10^{-1}$	$4.0 \cdot 10^{-2}$
^{238}U	$2.0 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
^{210}Pb	$2.0 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
^{85}Kr	$1.9 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
^{232}Th	$1.9 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
Tot intrinsic	$3.5 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$

- actual value of **^{210}Pb** in SABRE crystal will be measured with direct counting
- **1 µBq/kg** of ^{210}Pb
  → background **0.67 ·10^{-3} cpd/kg/keV**
- assumed **30 µBq/kg** (DAMA upper limit)
  → background **2.0 ·10^{-2} cpd/kg/keV**

Veto on, threshold 100 keV



zoom to low energy



Crystal intrinsic background in ROI
0.14 cpd/kg/keV

Cosmogenic activation

ACTIVIA Simulation software http://universityofwarwick.github.io/ACTIVIA/

- Uses semi-empirical formulae from Silberberg and Tsao to calculate the isotope production cross section

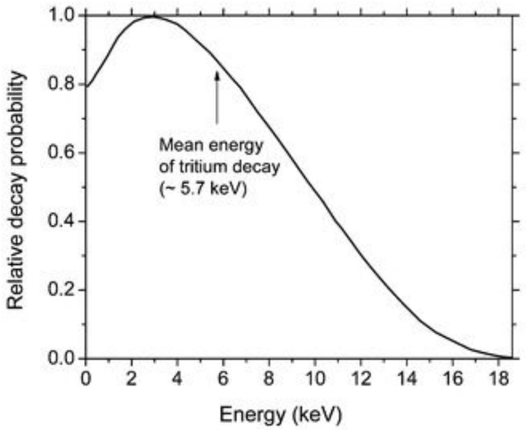
- Production rate depends on the activation cross section σ and the cosmic rays flux ϕ

$$R \propto \int \phi_x(E)\sigma_x(E)dE$$ [nuclei/kg day]

- Assumptions on crystal exposure:
  - 1 year of exposure at sea level
  - + 10 hours flight from US (crystal production in Boston/Princeton) to Italy
  - 6 months underground

Tritium activation

- Long-lived (4503 days) pure β^- decaying isotope with very low Q-value (18.6 keV)
- active veto not effective



Activation rate on NaI → **26 nuclei/kg day**

- From simulations, **1 μBq/kg** of ^{3}H in the crystal → **$8 \cdot 10^{-3}$ cpd/kg/keV**
- Assuming **1 year@sea level + 10h flight**: **18 μBq/kg** → **0.14 cpd/kg/keV**

The calculations from the ANAIS group give a tritium production rate (independent on height) of about a factor 4 higher than ACTIVIA's

`J.Amarè et al. Astropart. Phys. 97, 96 (2018)`

→ To have the same activation level of simulations we need to **limit the exposure at sea level to a few months** and **avoid transportation by flight**

Crystal activation in flight

- Assumptions on crystal exposure:
  - 1 year of exposure at sea level
  - **10 hours flight** from US (crystal production in Boston/Princeton) to Italy
  - 1 week by boat does not contribute w.r.t. **1 year@sea level**

Isotope	Half life (days)	1 year sea level (mBq/kg)	1y@sea + 10h plane (mBq/kg)	Ratio plane+1y@sea / 1y@sea
^{3}H	4500	0.011	0.018	1.6
^{22}Na	951	0.076	0.12	1.6
^{113}Sn	115	0.045	0.096	2.1
^{121m}Te	154	0.24	0.50	2.1
^{123m}Te	120	0.14	0.31	2.2
^{125m}Te	58	0.21	0.69	3.2
^{127m}Te	109	0.22	0.54	2.4
^{125}I	59	0.59	1.92	3.2
^{126}I	13	0.38	4.14	10.1

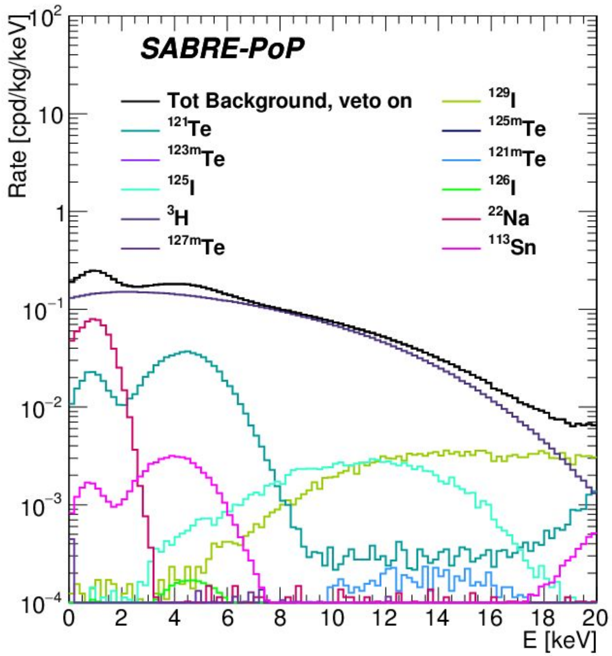
Transportation of crystals by boat can **reduce cosmogenic background of ~40%**

Crystal cosmogenic backgrounds

Calculation with **ACTIVIA** and assumptions:

- **1 year** of exposure at **sea level**
- + **10 hours flight** from US (crystal production in Boston/Princeton) to Italy
- **6 months underground**

Veto on, threshold 100 keV



ROI: 2-6 keV

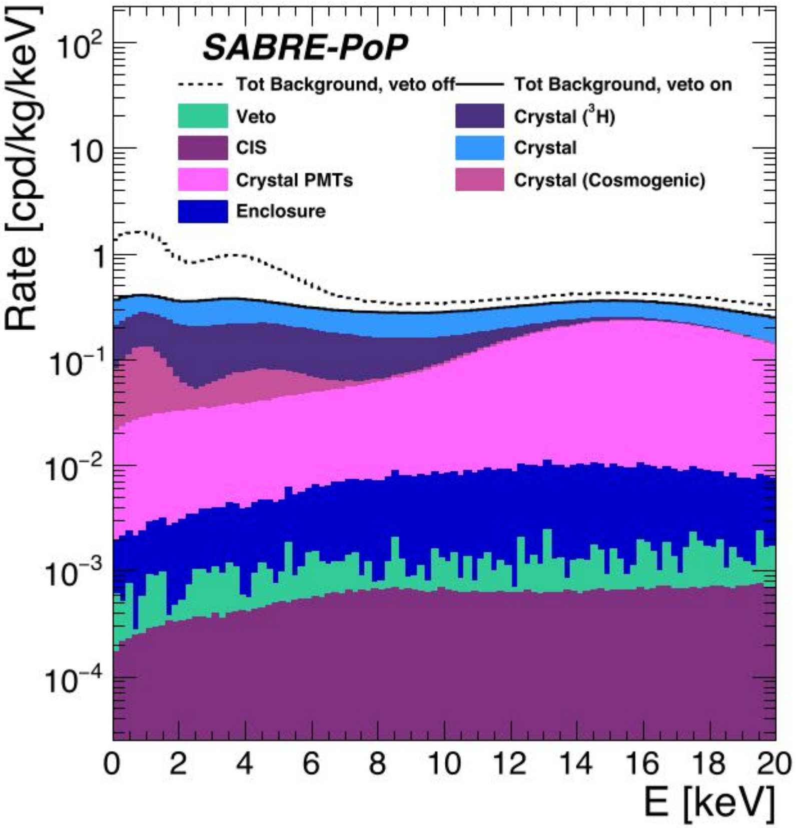
Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
	Cosmogenic	
^{3}H	$1.4 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$
^{121}Te	$2.0 \cdot 10^{-1}$	$2.6 \cdot 10^{-2}$
^{113}Sn	$1.2 \cdot 10^{-2}$	$2.2 \cdot 10^{-3}$
^{22}Na	$2.1 \cdot 10^{-2}$	$1.5 \cdot 10^{-3}$
^{125}I	$4.4 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$
^{129}I	$1.9 \cdot 10^{-4}$	$1.9 \cdot 10^{-4}$
^{126}I	$1.8 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$
^{127m}Te	$6.4 \cdot 10^{-5}$	$6.4 \cdot 10^{-5}$
^{121m}Te	$7.1 \cdot 10^{-5}$	$3.7 \cdot 10^{-5}$
^{123m}Te	$1.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$
^{125m}Te	$3.8 \cdot 10^{-6}$	$3.7 \cdot 10^{-6}$
Tot Cosmogenic (180 days)	$3.8 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$

The most important cosmogenic background is ^{3}H, but can be **significantly reduced avoiding flight** and **minimizing exposure at sea level**

Total internal backgrounds

Summary of the total background from the experimental setup.

Veto on, threshold 100 keV
6 months underground



ROI: 2-6 keV

	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Crystal	$3.5 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$
Crystal (^{3}H)	$1.4 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$
Crystal cosmogenic	$2.4 \cdot 10^{-1}$	$3.1 \cdot 10^{-2}$
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	$8.2 \cdot 10^{-1}$	$3.6 \cdot 10^{-1}$

crystal → 89%

other setup → 11%

- **Veto rejection is ~56%** (heavily affected by non vetoable contribution from ^{3}H)
- Total background **0.36 cpd/kg/keV**
- If confirmed with data, **lowest background with NaI(Tl)** detector

Astroparticle Physics
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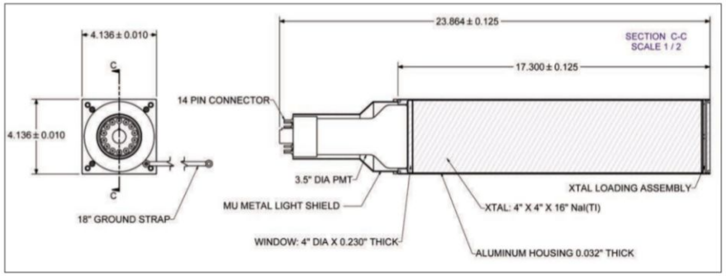
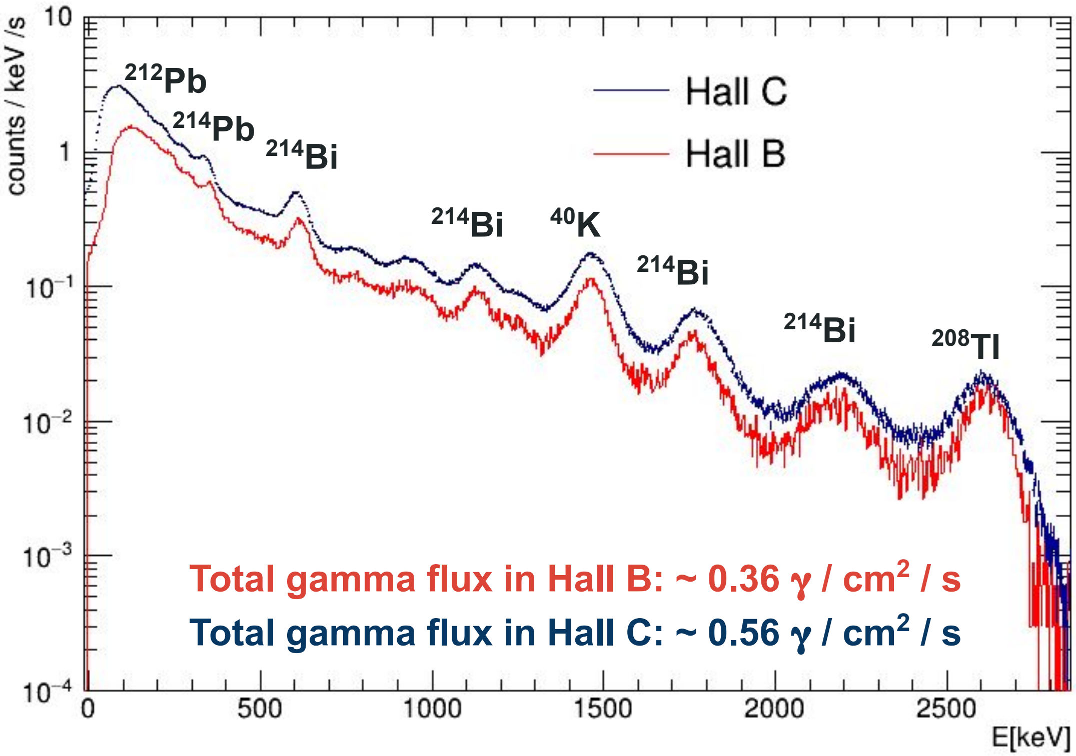
Radioactivity of surroundings: external γ

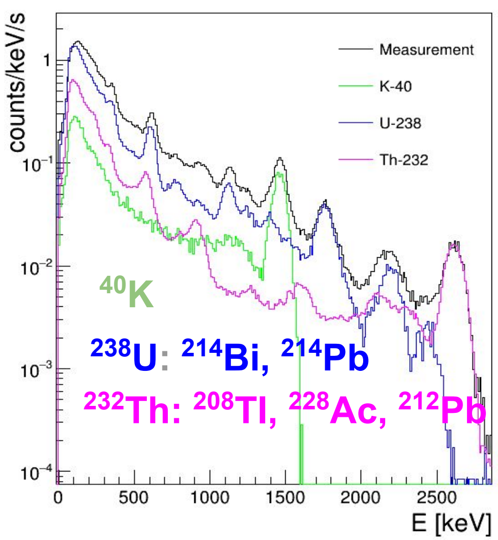
External background in **Hall B** and **Hall C** of LNGS has been measured with a standard grade NaI(Tl) crystal.

➜ Use Monte Carlo to deconvolve the spectrum and obtain U, Th and K contamination in the rocks

905-16 NaI Scintillation detector, 4x4x16 in. crystal, 3.5 in. tube







$$f(E) = c_K \times f_K(E) + c_U \times f_U(E) + c_{Th} \times f_{Th}(E)$$

External γ background

- Simulation of U, Th and K in the LNGS rocks and propagate in SABRE geometry

	Hall B [ppm]	**Hall C [ppm]**
K	7068 ± 90	12780 ± 70
U	0.56 ± 0.01	0.966 ± 0.004
Th	0.54 ± 0.01	0.840 ± 0.006

In agreement with values in literature
(**H. Wulandari et al. Astroparticle Physics 22 (2004) 313–322**)

	Rate in [2-6] keV [cpd/kg/keV]
Gamma Hall B	< $4.0 \cdot 10^{-3}$ (99% CL)
Gamma Hall C	< **$5.4 \cdot 10^{-3}$** (99% CL)
Total internal	**0.36**

Gamma external background including shielding and veto effect is **O(100) lower than internal backgrounds**

- Preliminary study on radiogenic neutrons show that the contribution is ~10^{-4} cpd/kg/keV in the signal region
- Next step: study muon background

Conclusions

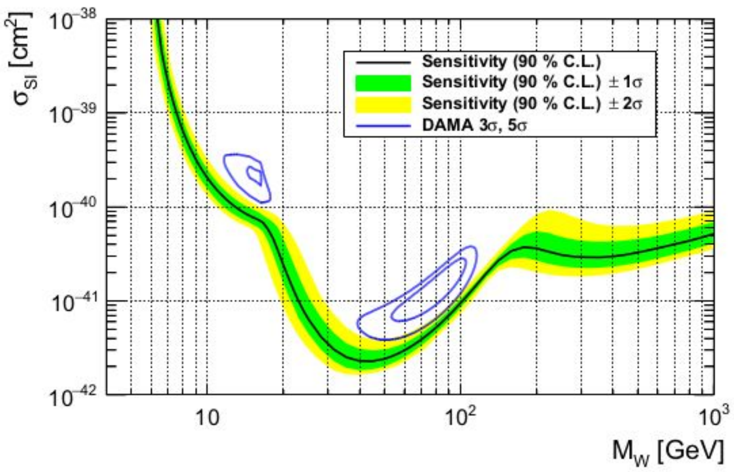
Status of the SABRE experiment:

- **Crystal NaI-31** arrived at **LNGS** in April 2019
- **Transportation by plane** for **NaI-31** from PU to LNGS was safe and fast
- **Crystal NaI-33** (**best crystal**, grown with optimal procedure developed by Princeton/RMD ready for shipping by **boat**
- Ready to start the **data taking** of the PoP in **summer 2019**
- South laboratory (**SUPL**) excavation will start in 2019
  → laboratory ready in 2020

If Monte Carlo prediction confirmed with data:

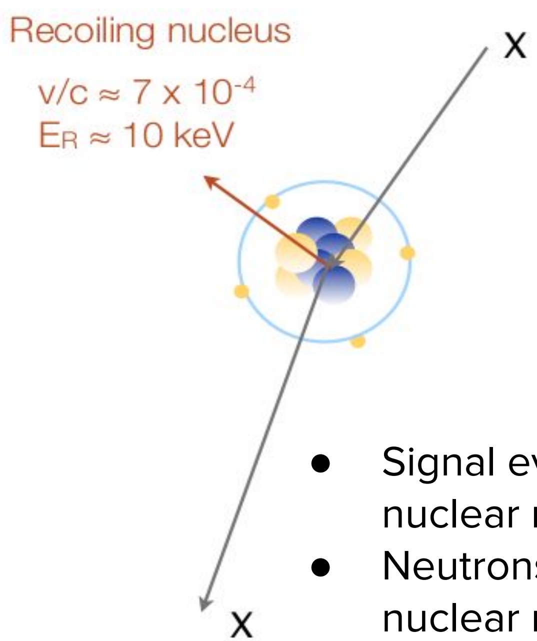
- **lowest background among NaI(Tl)** based detectors for dark matter (DM)
- **double location** in opposite hemispheres will help to discriminate annual modulation signal from DM interactions wrt. seasonal effects
- with **3 years** and **50 kg** the DAMA result can be tested at **5 σ** sensitivity

Eur. Phys. J. C (2019) 79: 363



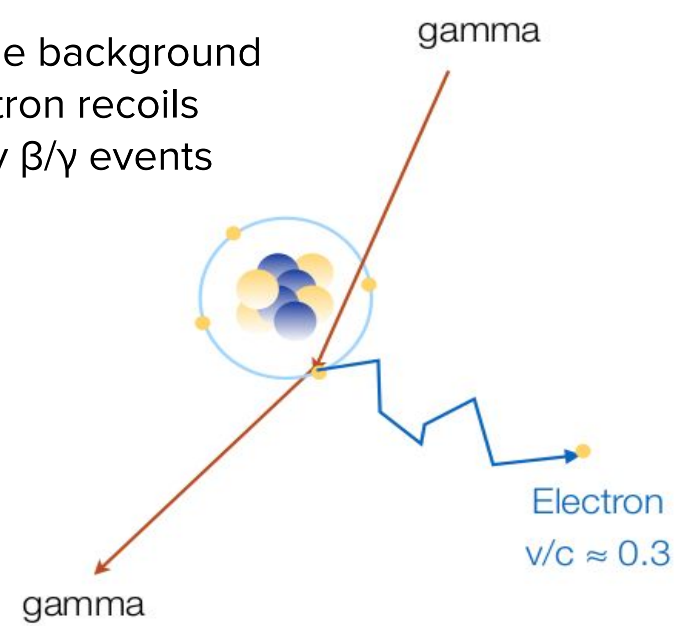
Backup

Signal and backgrounds



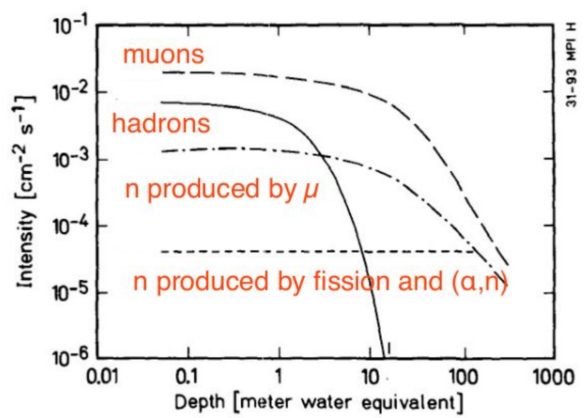
- Signal events produce nuclear recoil
- Neutrons produce nuclear recoils similar to a WIMP

- Most of the background from electron recoils caused by β/γ events



Background sources:

➔ **Radioactivity** of **detector** and shield materials
➔ **Radioactivity** of **surroundings** (laboratory environment)
➔ **Cosmic rays** and **secondary** reactions
(need to go **underground**, LNGS 3700 mwe)



The SABRE crystals

Ultra pure NaI(Tl) crystals

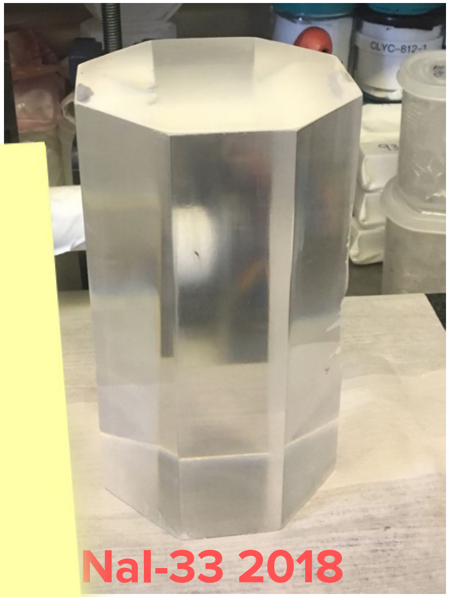
- Astro Grade powder (Sigma Aldrich, now Merck)
- clean growth procedure: collaboration between Princeton and RMD, Boston
- Small crystal (2 kg) grown with optimal procedure in 2015

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	$0.7\text{-}10\times10^{-3}$	$<10^{-3}$	$<10^{-3}$

- Crystal NaI-31, grown in a standard quartz crucible.
- Mass: ~3.5 kg after polishing.

Average K level higher than the value of 9 ppb that was achieved in the crystal grown in 2015-2016.

- Crystal NaI-33, grown in a high purity crucible
- produced @ Princeton.
- Mass: ~3.5 kg after polishing
- ICP-MS measurements on samples from three positions of the crystal indicate that the K concentration is very low!

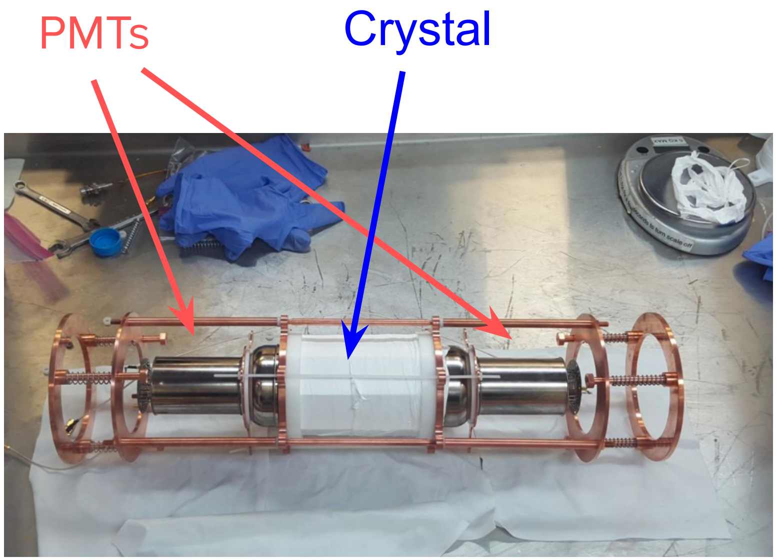


Low energy sensitivity

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

Current Design:

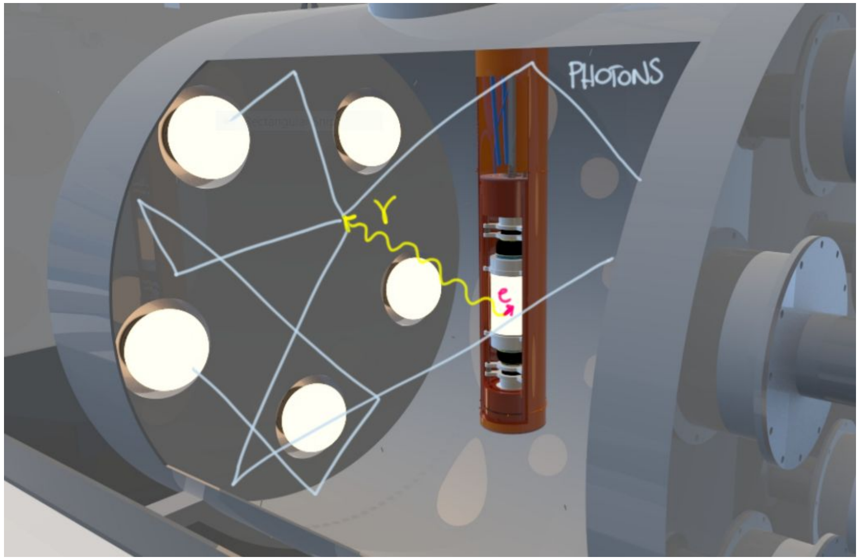
- 2 x Hamamatsu R11065-20 3” PMTs per crystal with High QE >35% and minimal contaminations
- Direct PMT-Crystal coupling for maximal light yield
- Custom preamplifiers and super bialkali photocathodes → less afterglow and dark noise

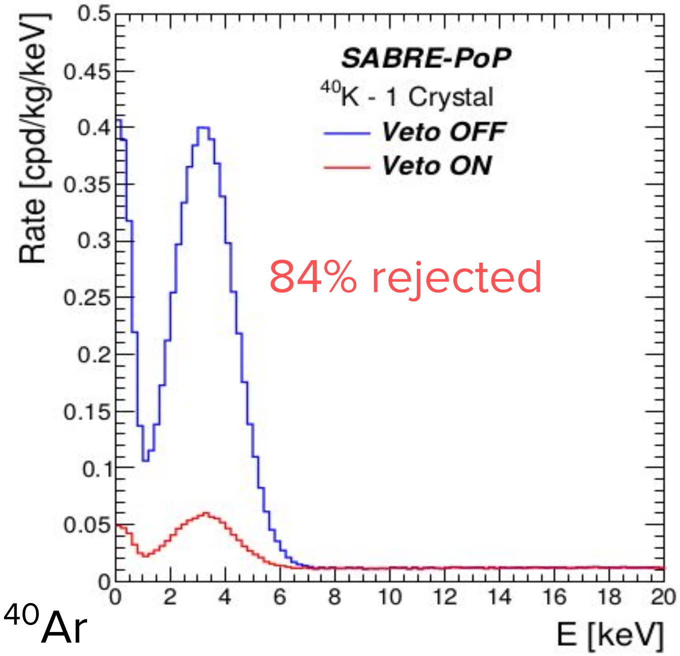


Isotope	Activity [mBq/PMT]		
	Body	Window	Ceramic plate
^{40}K	<5.9	<0.48	6.5
^{60}Co	0.65	<0.042	<0.19
^{238}U	<0.52	<1.8	13
^{226}Ra	<0.29	0.040	0.29
^{232}Th	<0.0098	<0.037	0.70
^{228}Th	<0.41	<0.015	0.13

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



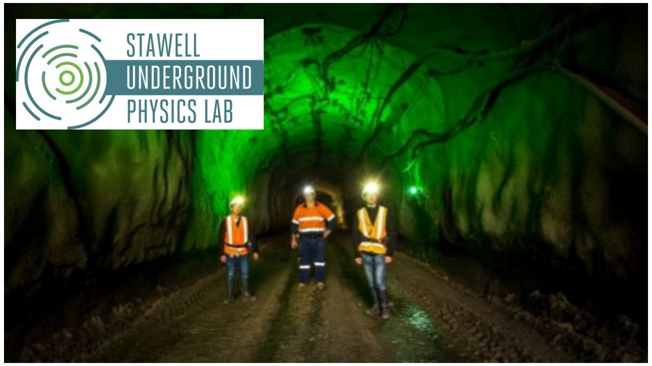


^{40}K (11% BR) decays through electron capture to ^{40}Ar

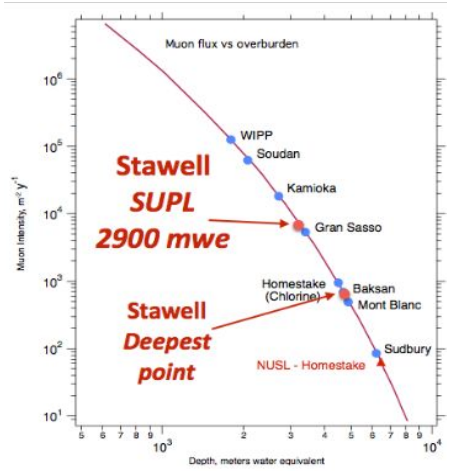
- γ 1460 keV
- X-rays, Auger electrons 3 keV

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 2019
- Will host SABRE and other experiments



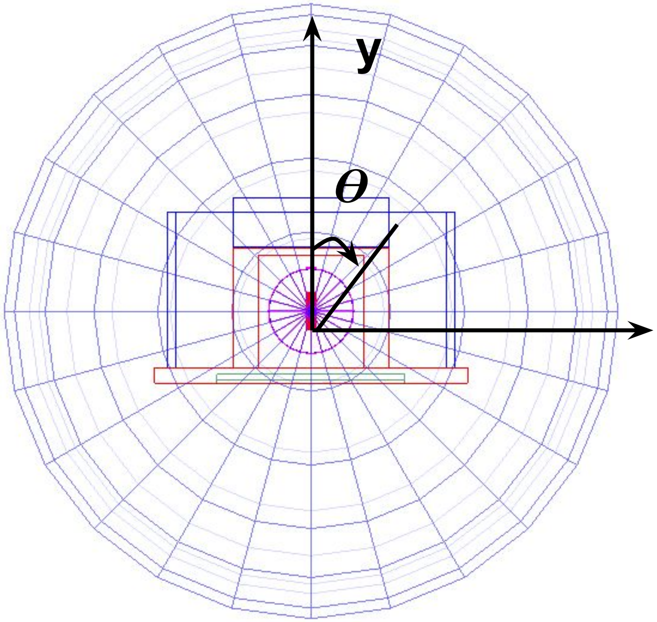
External γ simulation

- Simulation of U, Th and K in the LNGS rocks and propagate in SABRE geometry

	Hall B [ppm]	Hall C [ppm]
K	7068 ± 90	12780 ± 70
U	0.56 ± 0.01	0.966 ± 0.004
Th	0.54 ± 0.01	0.840 ± 0.006

In agreement with values in literature
(**H. Wulandari et al. Astroparticle Physics 22 (2004) 313–322**)

Front view



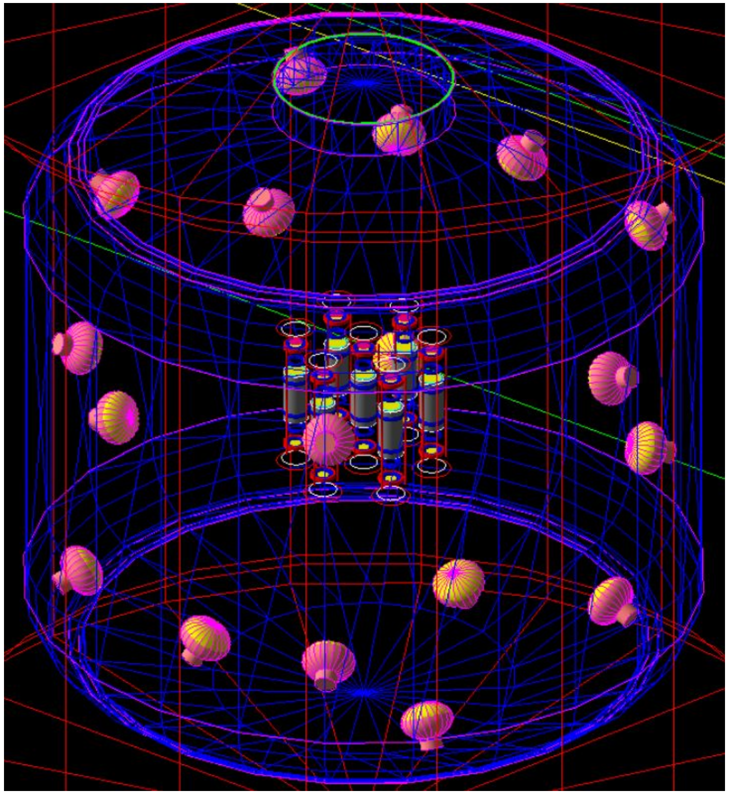
- Rock cavern simplified
  ➔ rock spherical shell of 40 cm thickness and 4.5 m internal radius in order to contain the shielding
- Input contaminations of ^{40}K, ^{238}U and ^{232}Th in the rock shell from the table

SABRE South

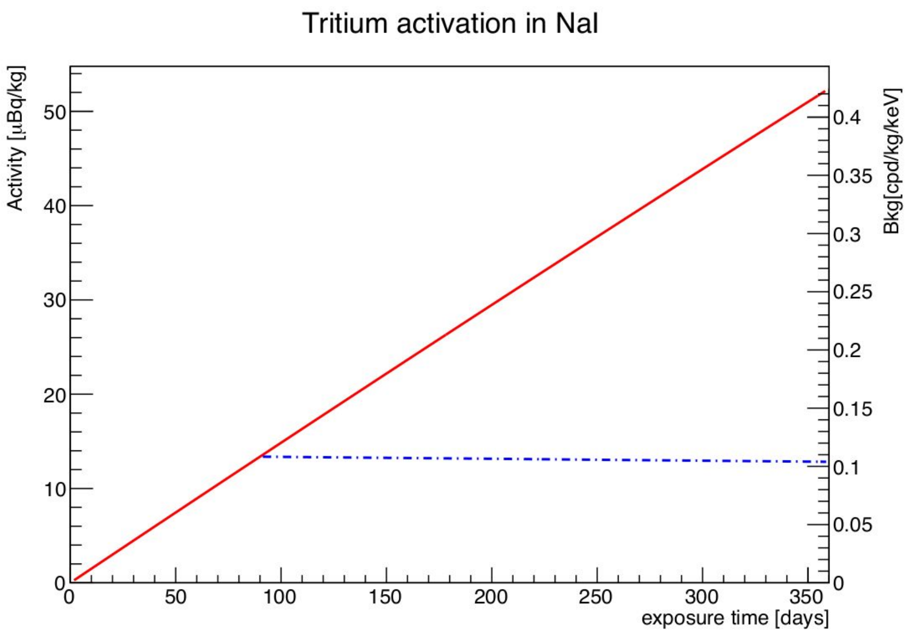
Preparation of Stawell Underground Physics Laboratory (SUPL) continues, with underground construction expected to begin this year.

On-going SABRE research activities include:

- Monte Carlo simulations,
- DAQ development and PMT testing,
- Scintillator (LAB) testing,
- Quenching factor measurements



Tritium activation



Assuming the production rate calculated by the ANAIS group the only way to maintain the Tritium background lower is to limit the exposure time at sea level to a few months and do not transport by flight.

This assumes that the Tritium build-up starts at the moment when the crystal is grown, meaning that our growth procedure efficiently removes any prior Tritium content in the powder.

Production rate from ANAIS calculations 84 nuclei/kg/day

`J.Amarè et al. Astropart. Phys. 97, 96 (2018)`