The SABRE project and Status of the SABRE-PoP at LNGS

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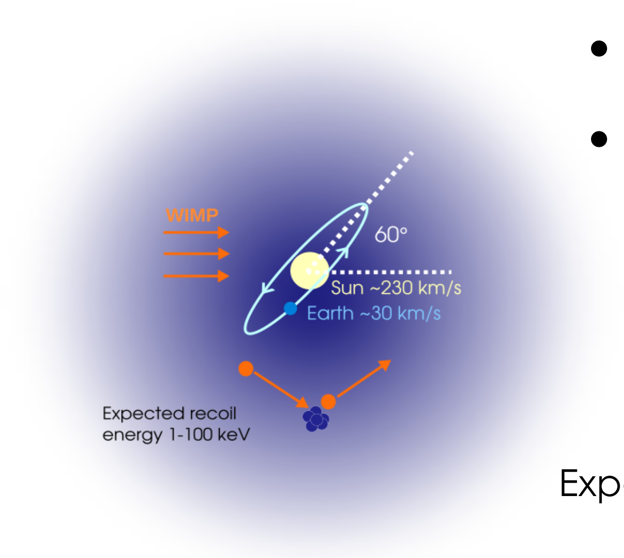
15TH MULTIDARK CONSOLIDER WORKSHOP, APRIL 3-5, 2019, ZARAGOZA

Dark matter via annual modulation



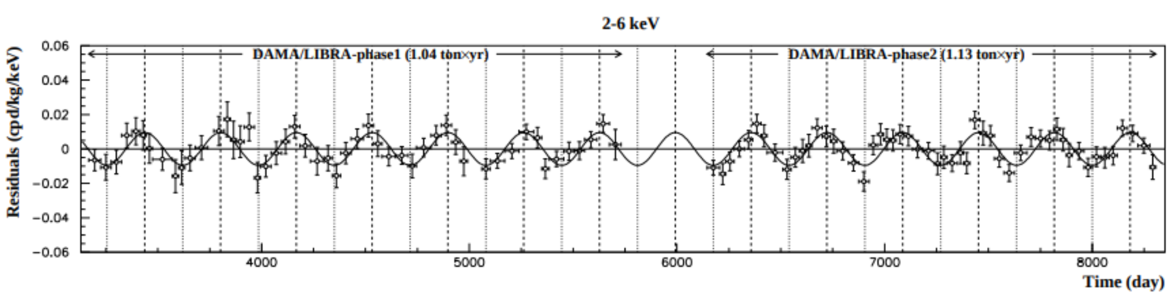
- Direct detection principle: dark matter scattering off detector nuclei
- Annual modulation of the count rate is a **model independent signature**
  - period 1 year
  - maximum of modulation around June 2nd

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

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**

Nuclear Physics and Atomic Energy 19 (2018) 307
arXiv:1805.10486

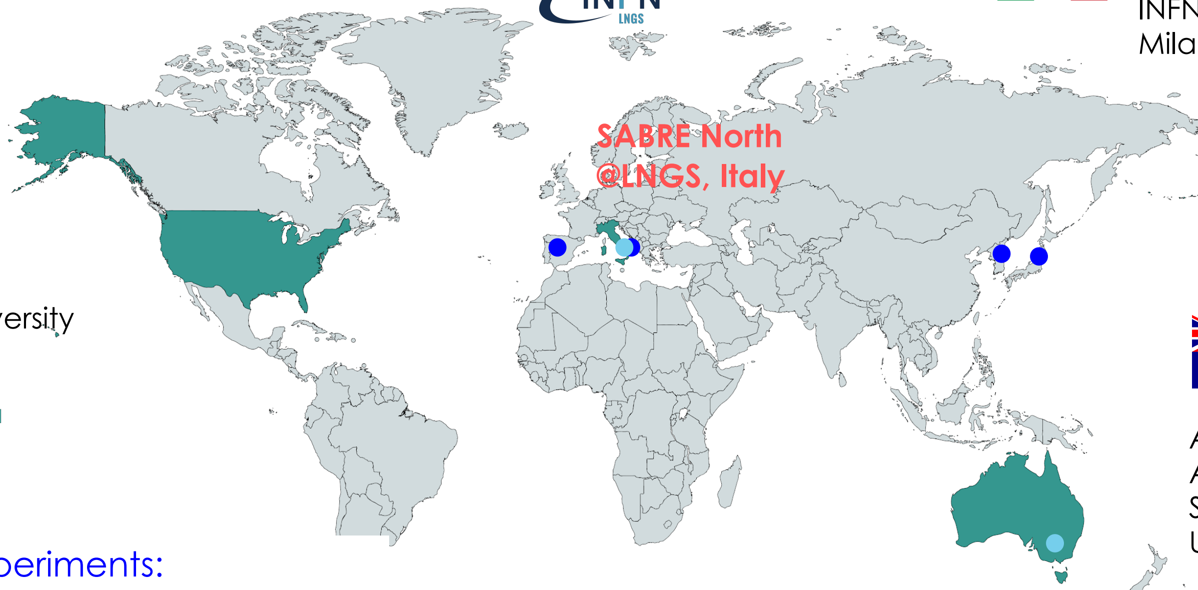


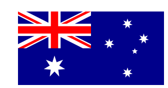
DAMA background ~1 cpd/kg/keV
DAMA modulation 0.0095 cpd/kg/keV
Modulation significance 11.9σ C.L.

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

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

LLNL
PNNL
Princeton/University





Adelaide University
Australian National University
Swinburne University
University of Melbourne

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

SABRE South
@SUPL, Stawell gold mine, Australia

SABRE key features

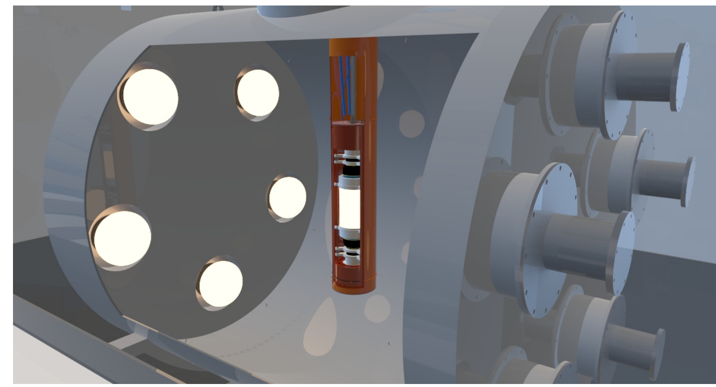
1. **Development of ultra-high purity NaI(Tl) crystals**
   - High purity NaI powder
   - Clean crystal growth method
2. **Low energy threshold**
   - High QE Hamamatsu PMTs directly coupled to the crystal
3. **Passive shielding + active veto**
   - Unprecedented background rejection and sensitivity 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

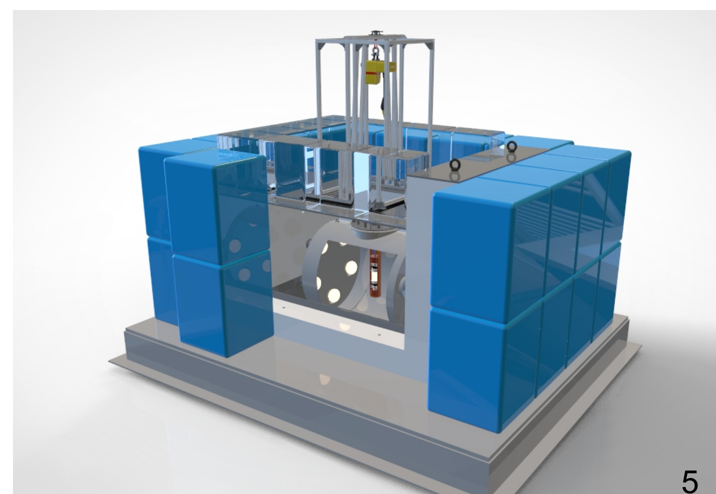
The SABRE phased approach

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 flushed with nitrogen

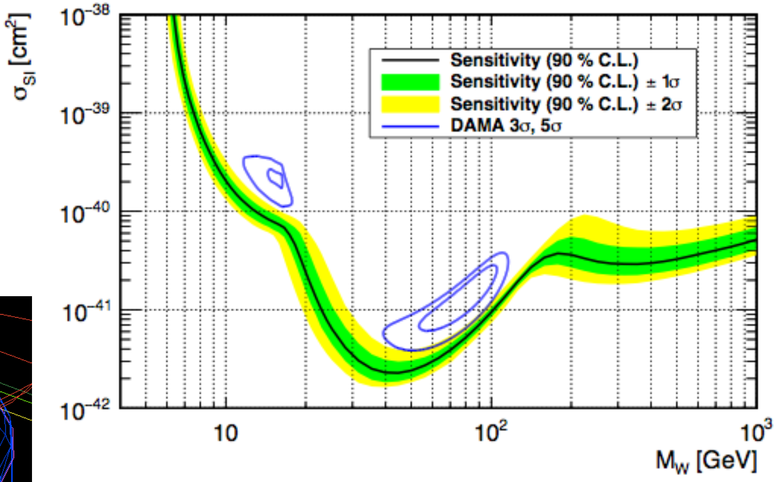




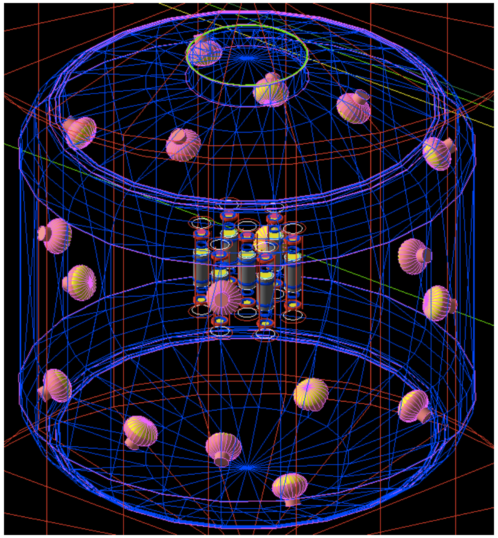
The SABRE phased approach

Full Scale Experiment (FSE)

Goals:
- Lowest background NaI experiment for Dark Matter search
- Confirm (reject) annual modulation with amplitude observed by DAMA/LIBRA



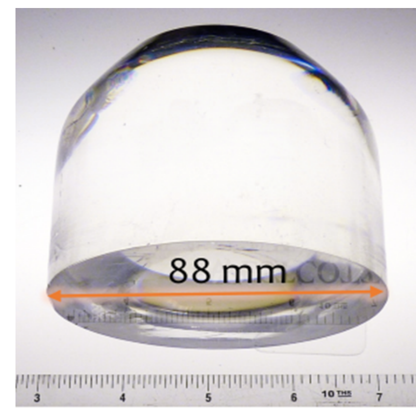
Layout:
- > 50 kg of NaI(Tl) crystal, active veto, external shielding, double location
- Final design and schedule depends on the outcome of PoP



Path to SABRE crystal

Ultra pure NaI(Tl) crystals
Astro Grade powder (Sigma Aldrich, now Merck)
Clean growth procedure: collaboration between Princeton and RMD, Boston

- Princeton University and industrial partner Sigma-Aldrich have produced ultra-high purity NaI powder (Astro Grade) with potassium levels consistently lower than 10 ppb and 1 ppt upper limit on U/Th content.
- NaI(Tl) crystals are grown by Radiation Monitoring Devices, Inc. using the vertical Bridgman-Stockbarger technique, where the powder is placed inside a sealed ampoule.
- To determine the best ampoule composition, several materials were prepared with different cleaning procedures and growth test with Astro Grade were performed. The optimum ampoule composition, together with a precision cleaning, showed no increase of the impurity levels inside the crystal with respect to the starting powder.



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

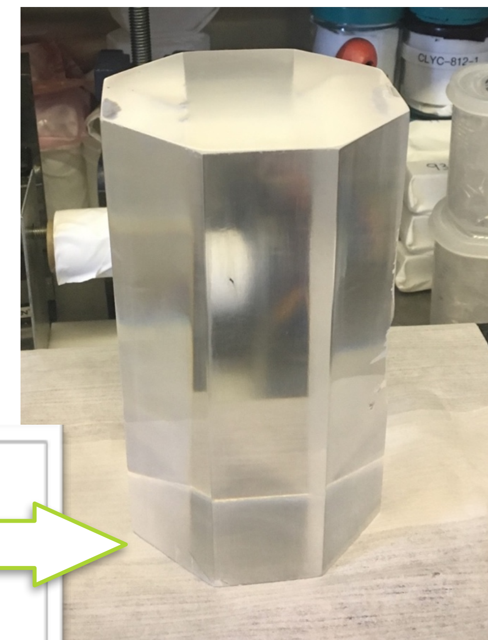
At the end of 2015, the optimal procedure was used to grow a 2-kg crystal with average K level of 9 ± 1 ppb

Status of SABRE PoP Crystals

Ultra pure NaI(Tl) crystals
Astro Grade powder (Sigma Aldrich, now Merck)
Clean growth procedure: collaboration between Princeton and RMD, Boston

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

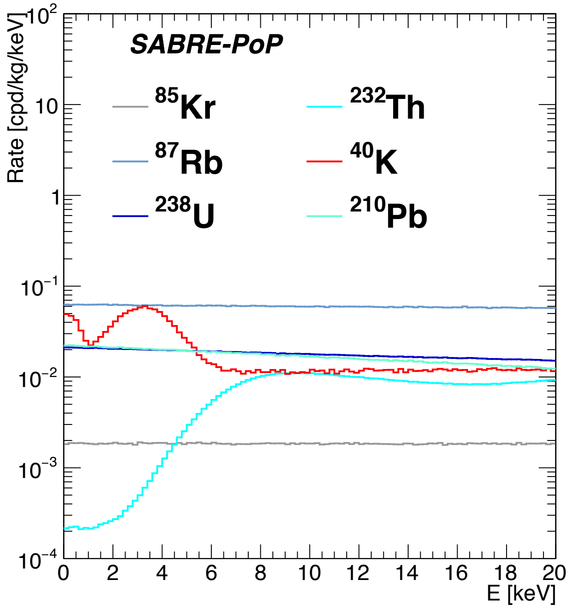


Path to SABRE crystal - intrinsic contaminations

Potassium and U/Th are not the only worrisome intrinsic contaminations of the crystals
Goal of the PoP: Fully characterise the intrinsic and cosmogenic background

Intrinsic	
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	$< 1.0 \cdot 10^{-2}$

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	$3.5 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$

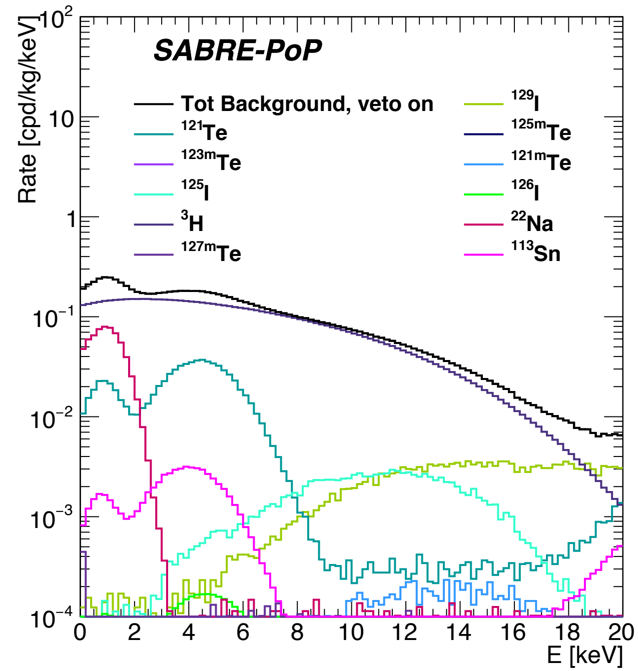


- ^{210}Pb contamination not yet measured in our crystals, assumed the highest among the DAMA values (0.03 mBq/kg);
- Simulation of intrinsic (not cosmogenic) background in the crystal give a contribution of **~0.15 cpd/kg/keV** in [2-6] keV with veto ON
- This contribution is dominated by Rb (upper limit), with the above assumptions.

Path to SABRE crystal - cosmogenic activation

Cosmogenic activation rate calculated with ACTIVIA assuming 1 year of activation at sea level and 8 hours flight.

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)	$3.8 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$

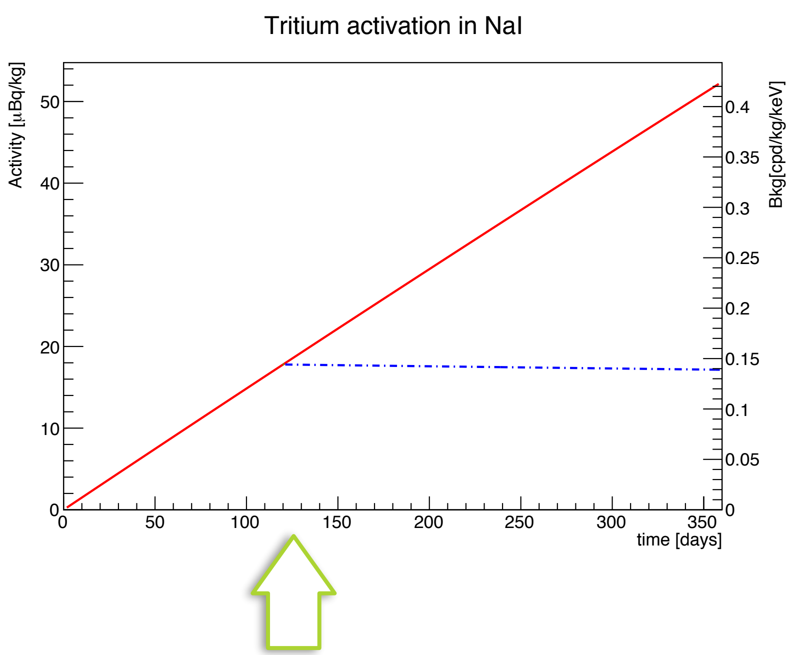


- Simulation of cosmogenic background in the crystal give a contribution of **~0.17 cpd/kg/keV** in [2-6] keV with veto ON (after 180 days underground).
- This contribution is dominated by ^{3}H at the level of 0.018 mBq/kg (see next slide).

Path to SABRE crystal - ^3H

ACTIVIA production rate on Iodine = 31 nuclei/kg day. The calculations from the ANAIS group give a tritium production rate at sea level of about a factor 4 higher than ACTIVIA's

[J.Amare' et al., Cosmogenic production of tritium in dark matter detectors, Astropart. Phys. 97, 96 (2018)]



Assuming the production rate calculated by the ANAIS group (84 nuclei/kg day), 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).

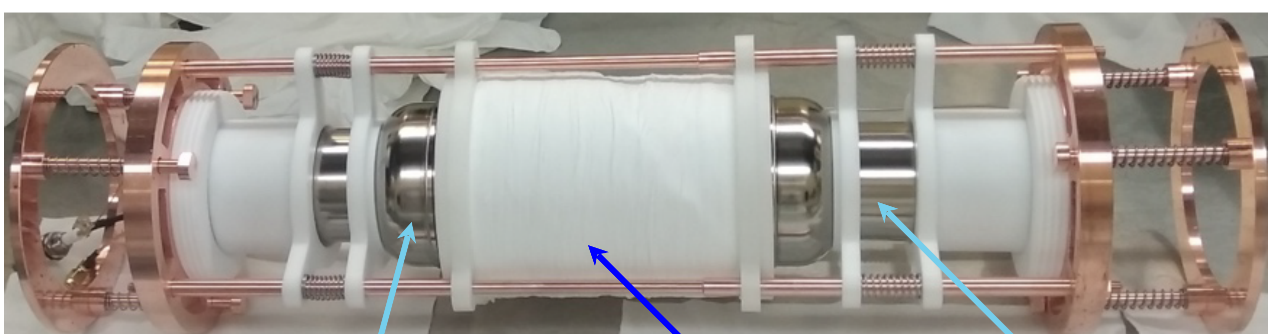
SABRE PoP detector module

SABRE aims to be sensitive to energies in the range [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

Crystal NaI31 assembled in the copper enclosure inside the PU glove box



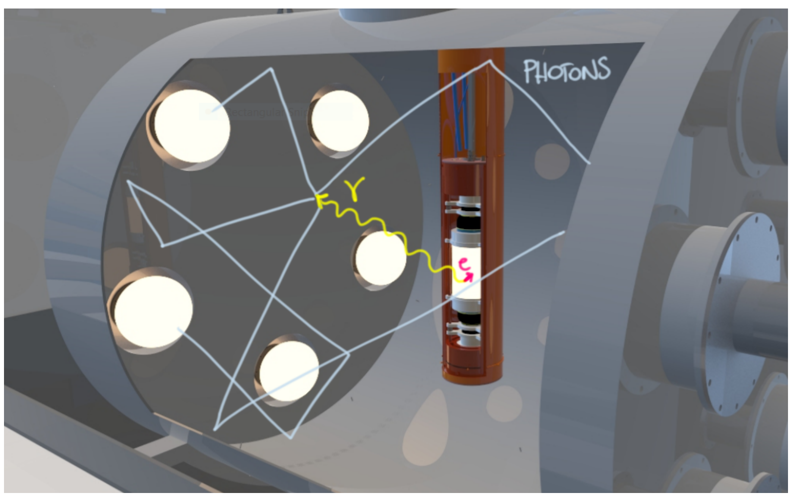
PMT

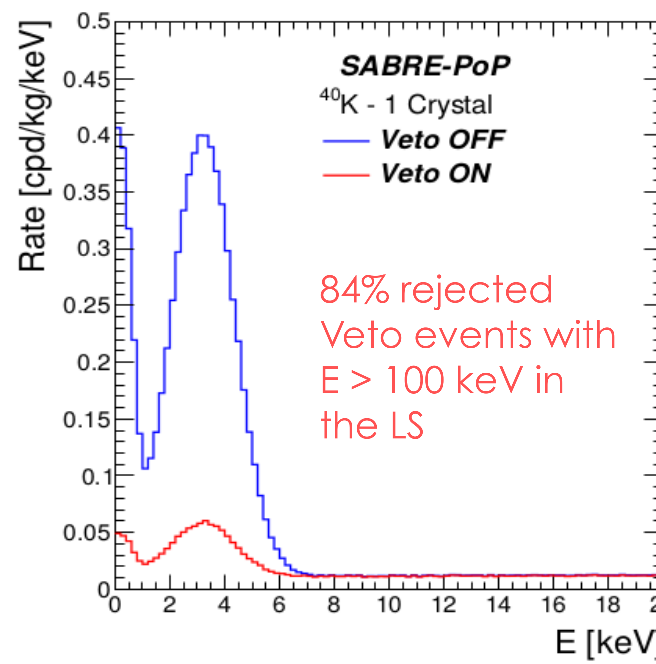
Crystal

PMT

Active veto system

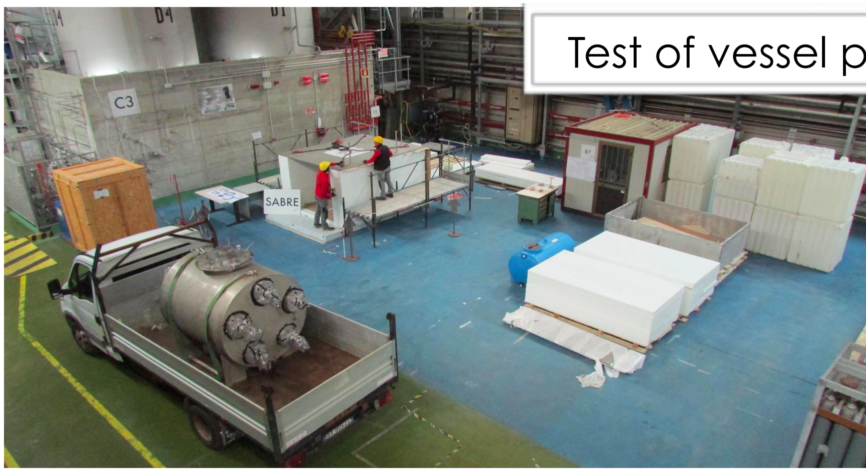
- A **liquid scintillator veto (PC+PPO 3g/l)** surrounding the NaI detector at 4π
- Strongly reduce:
  - external backgrounds
  - internal backgrounds that release energy also in the liquid scintillator: ^{40}K





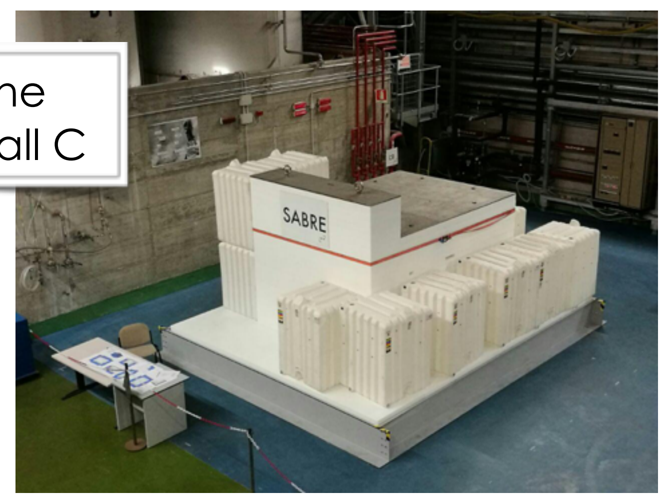
^{40}K (11% BR) decays through electron capture to ^{40}Ar
- γ 1460 keV
- X-rays, Auger electrons 3 keV

Status of the SABRE PoP @ LNGS



Test of vessel positioning

Mounting the shielding in Hall C



Status of the SABRE PoP @ LNGS

SABRE clean area in Hall C, equipped with a forced air circulation system through filters.

Veto tank cleaned, internally covered with Lumirror® and equipped with PMTs

Status of the SABRE PoP @ LNGS

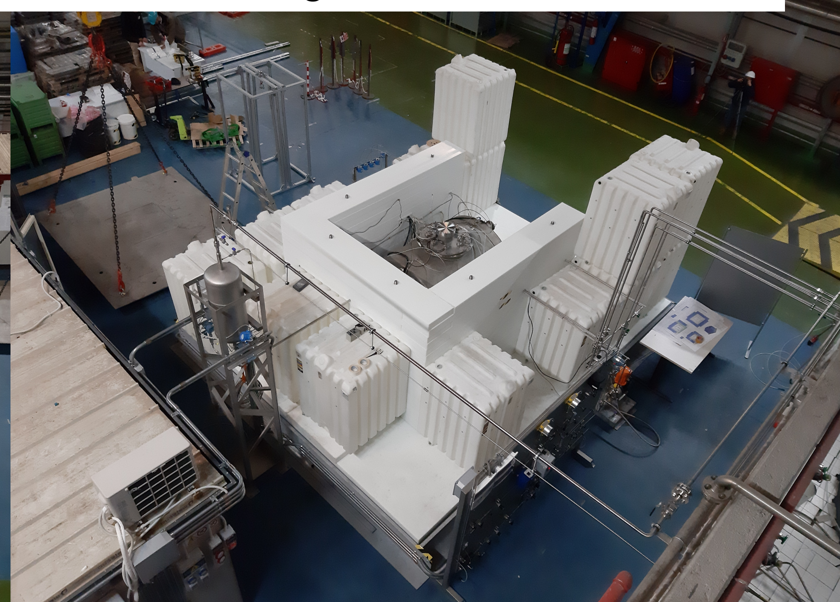
The SABRE PoP setup in Hall C @ LNGS is READY!

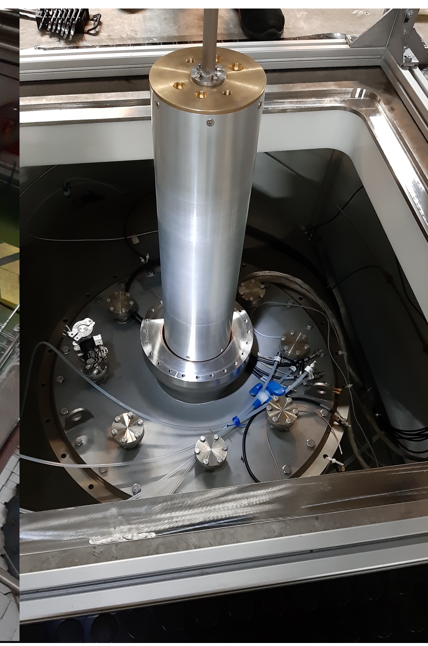
accomplished

Shielding and all the accessory infrastructure such as the fluid handling system, the slow control system, the power plant, the control room, and the safety plant are assembled;
Veto tank cleaned, internally covered with Lumirror® and equipped with PMTs;

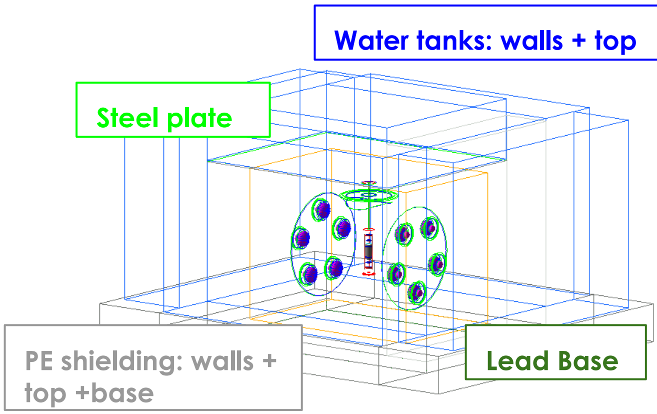
upcoming

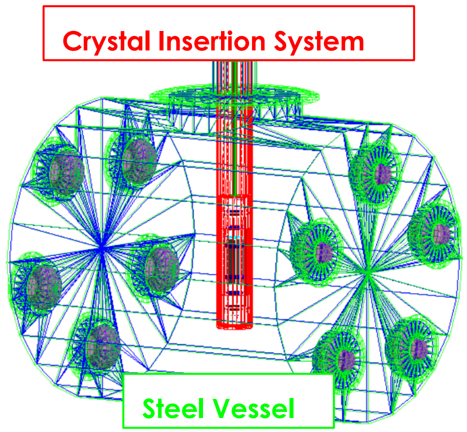
Crystals and enclosures mounted and shipped to LNGS;
Vessel filling and commissioning;

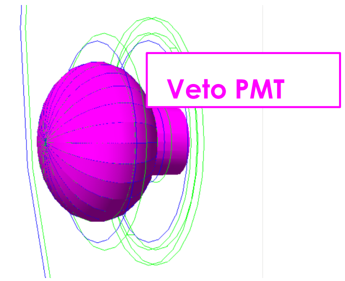


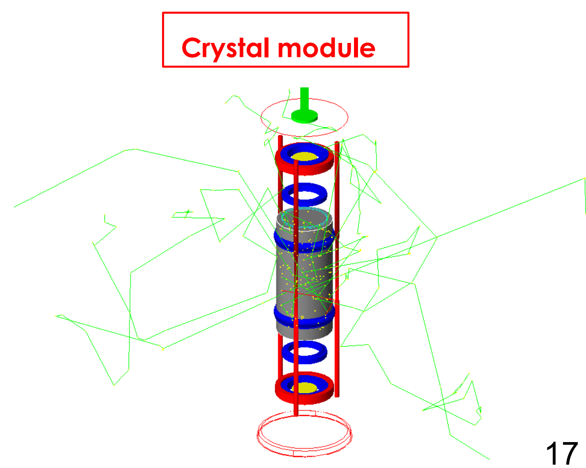


Monte Carlo simulation of the background





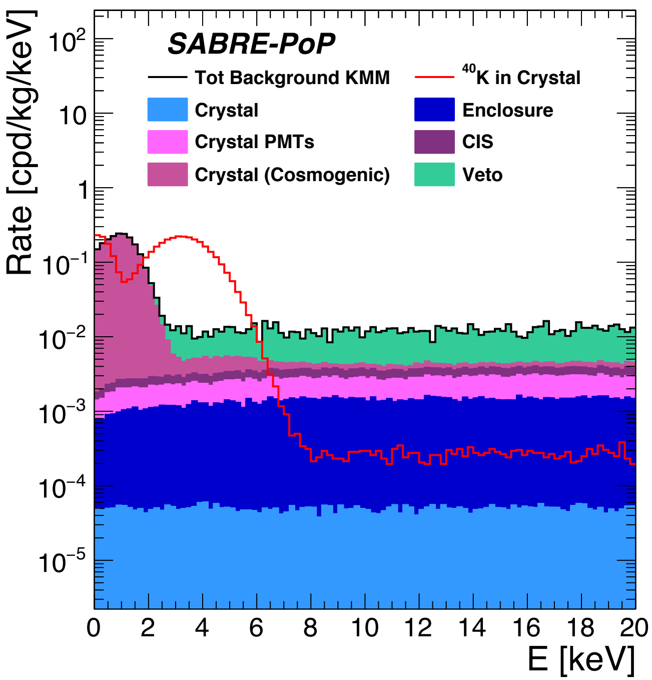




- GEANT4 based code with detailed geometry implementation
  - **Crystal**
  - **Crystal PMTs**: quartz window + body + feedthrough
  - **Enclosure**: wrapping, copper enclosure and small components inside
  - **Crystal Insertion System (CIS)**: copper tube, steel bar
  - **Veto**: steel vessel + liquid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



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

	Rate KMM [cpd/kg/keV]
Crystal Cosmogenic	$9.8 \cdot 10^{-3}$
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	$2.5 \cdot 10^{-2}$
Crystal ^{40}K	$1.9 \cdot 10^{-1}$

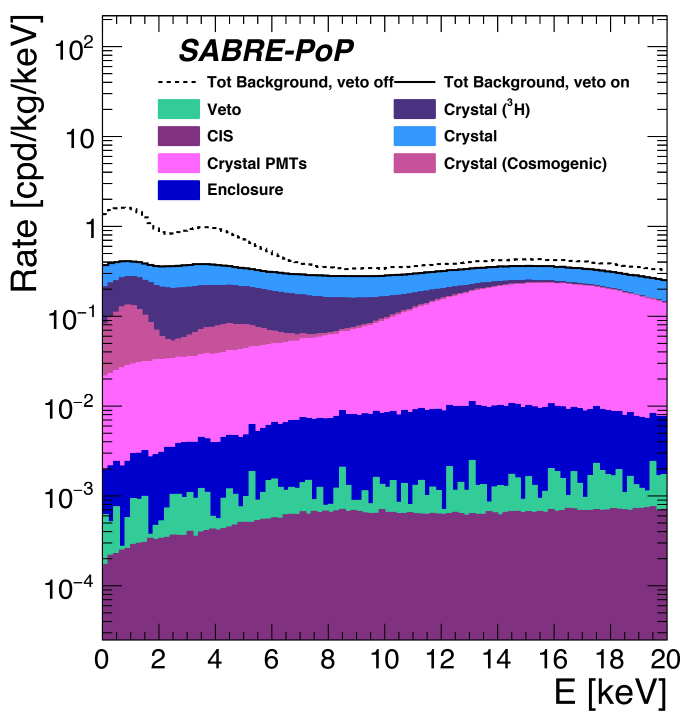
- Largest bkg contribution from **^{22}Na mostly below threshold of 2 keV**
- 10 ppb of K can be directly measured at 1 ppb precision in ~2 months

[Astroparticle Physics, 106 (2019) 1-9](#)
[arXiv:1806.09340](#)

Dark matter measurement mode

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

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 (^{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	$8.2 \cdot 10^{-1}$	$3.6 \cdot 10^{-1}$

- **Overall veto rejection is ~44% (^{3}H cannon be vetoed)**
- **Total background 0.36 cpd/kg/keV**, lower than DAMA background
- Highest contribution from ^{3}H and ^{210}Pb in the crystal have to be assessed by the PoP measurement

Astroparticle Physics, 106 (2019) 1-9
arXiv:1806.09340

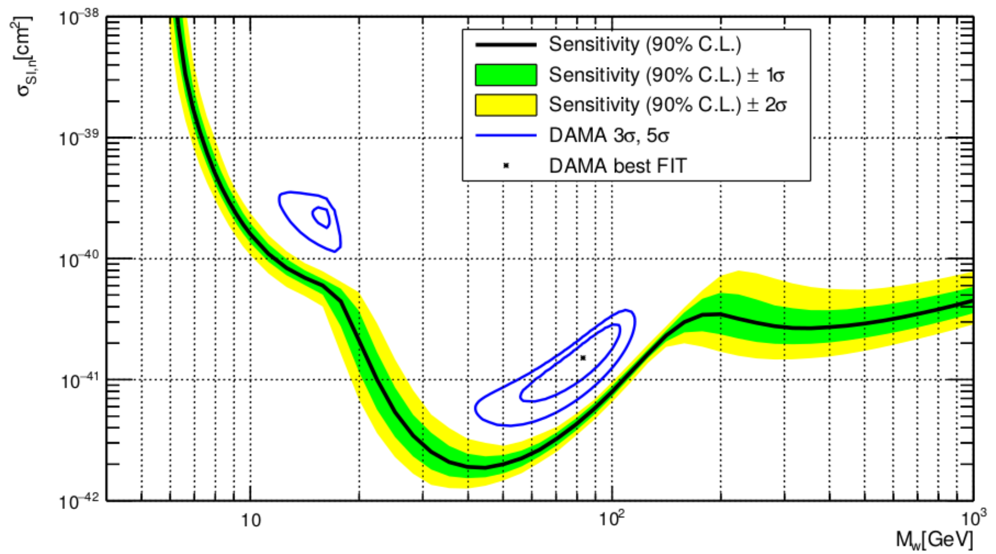
SABRE expected sensitivity

Assumptions:

- 3 years exposure, 50 kg of NaI(Tl) crystals
- average background 0.36 cpd/kg/keV in [2-6] keV region
- systematic uncertainties: energy resolution, detection efficiency, Na and I QF, and the background level

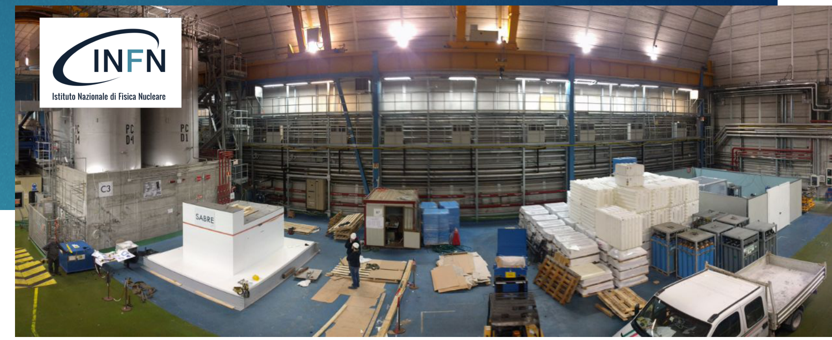
The blue curves represent the 3 and 5 σ confidence regions we obtained interpreting the DAMA Phase-1 results in the framework of the standard WIMP model.

The SABRE full scale experiment can: confirm or refute the modulation with amplitude observed by DAMA at 5 σ.

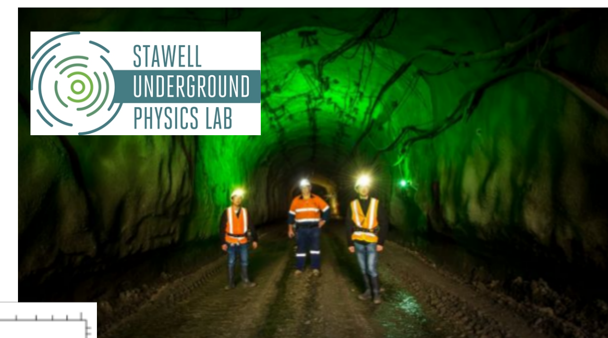


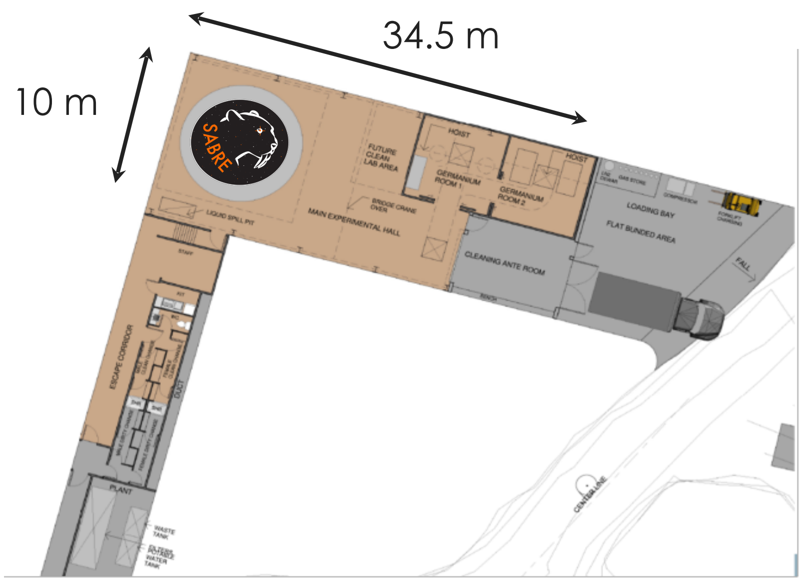
[arXiv:1806.09340, submitted to EPJC](arXiv:1806.09340)

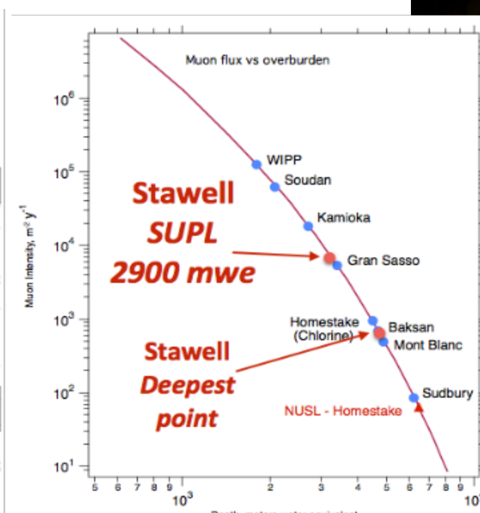
Double location



- 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



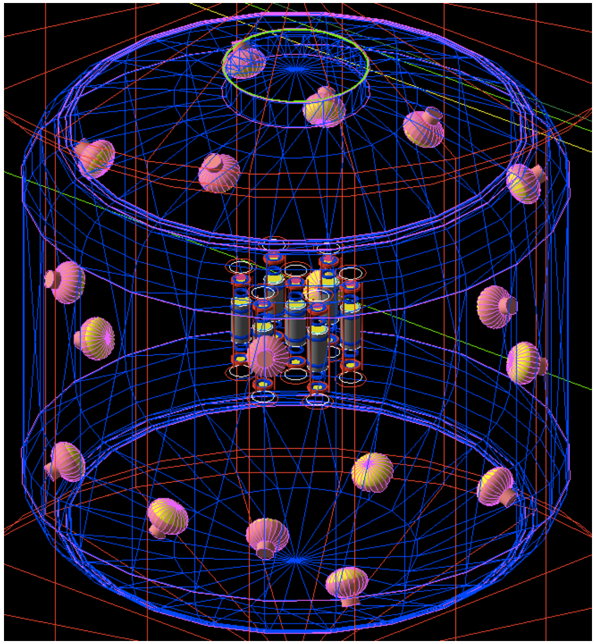




- Hosted in the **Stawell Gold Mine, Victoria, Australia**
- Construction just funded with additional 5M AUD
- Will host SABRE and other experiments

SABRE South activities

- 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.



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 coming months.

Full scale experiment can confirm (reject) annual modulation with amplitude observed by DAMA/LIBRA with 3 years of data at 6 (5) sigma.