Testing Dark Matter models and Quantum Foundations with the SABRE experiment

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THE UNIVERSITY OF MELBOURNE

STAWELL UNDERGROUND PHYSICS LAB

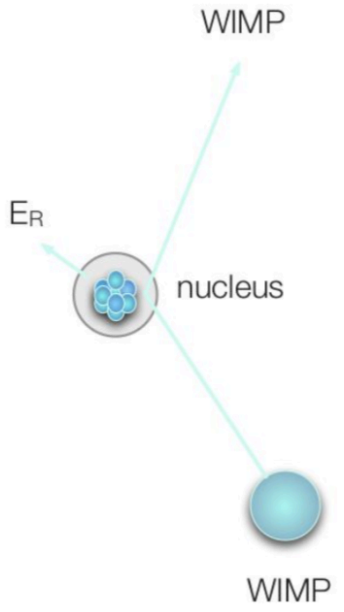
SABRE

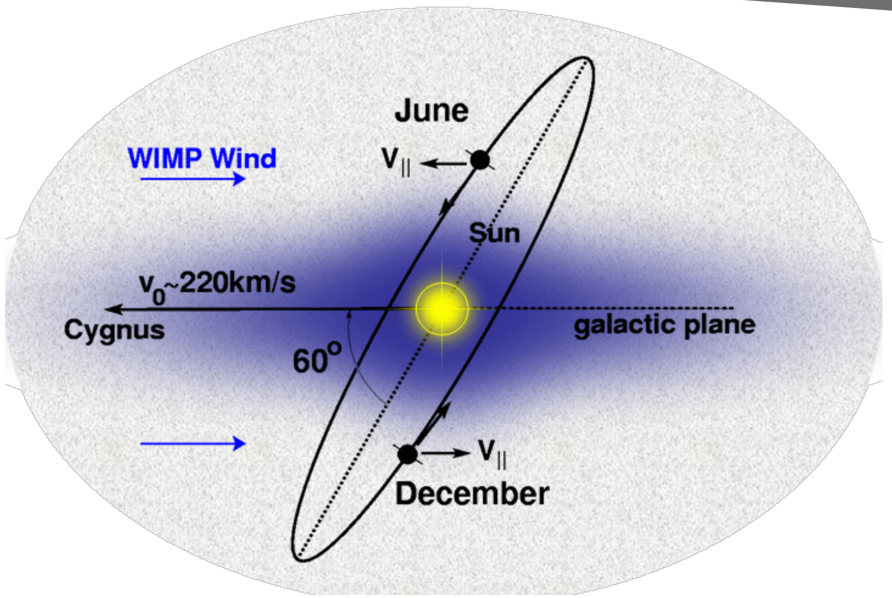
Direct detection of Dark Matter

- WIMP-like dark matter (DM) expected to occasionally interact with nuclei

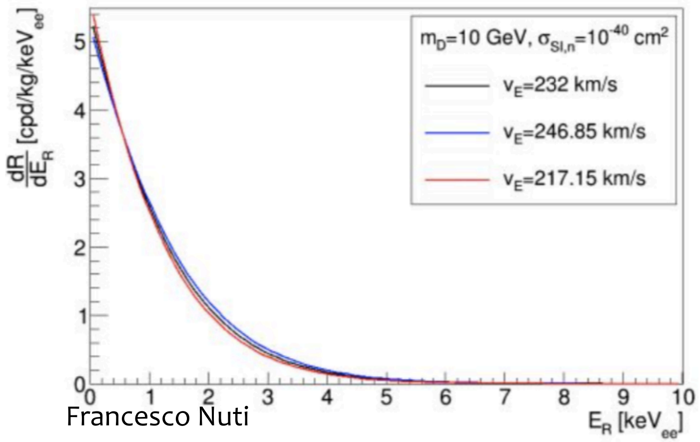
- Rate depends on the relative velocity DM-nucleus→ Annual modulation due to Earth change of speed during the year $S_m/S_0=O(10^{-2})$

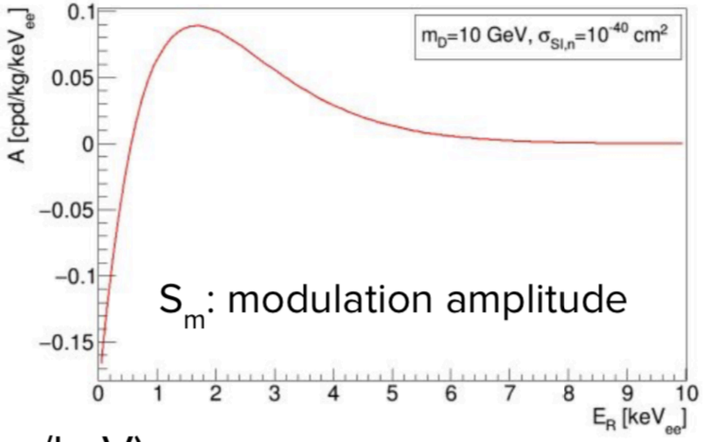
- For DM masses m_D > GeV recoil energies 1-100 keV





$$\frac{dR}{dE}(E,t) \simeq S_0(E) + S_m(E)\cos\omega(t-t_0)$$





THE CSL MODELS

- In quantum mechanics, the collapse of the wave function to a single state is unexplained (measurement problem)
- The transition Quantum-to-Classical worlds is also unclear
- The Continuous Spontaneous Localization (CSL) models address these questions introducing interactions with a stochastic non-linear noise field in the Schrödinger Equation

Mass density operator Noise field

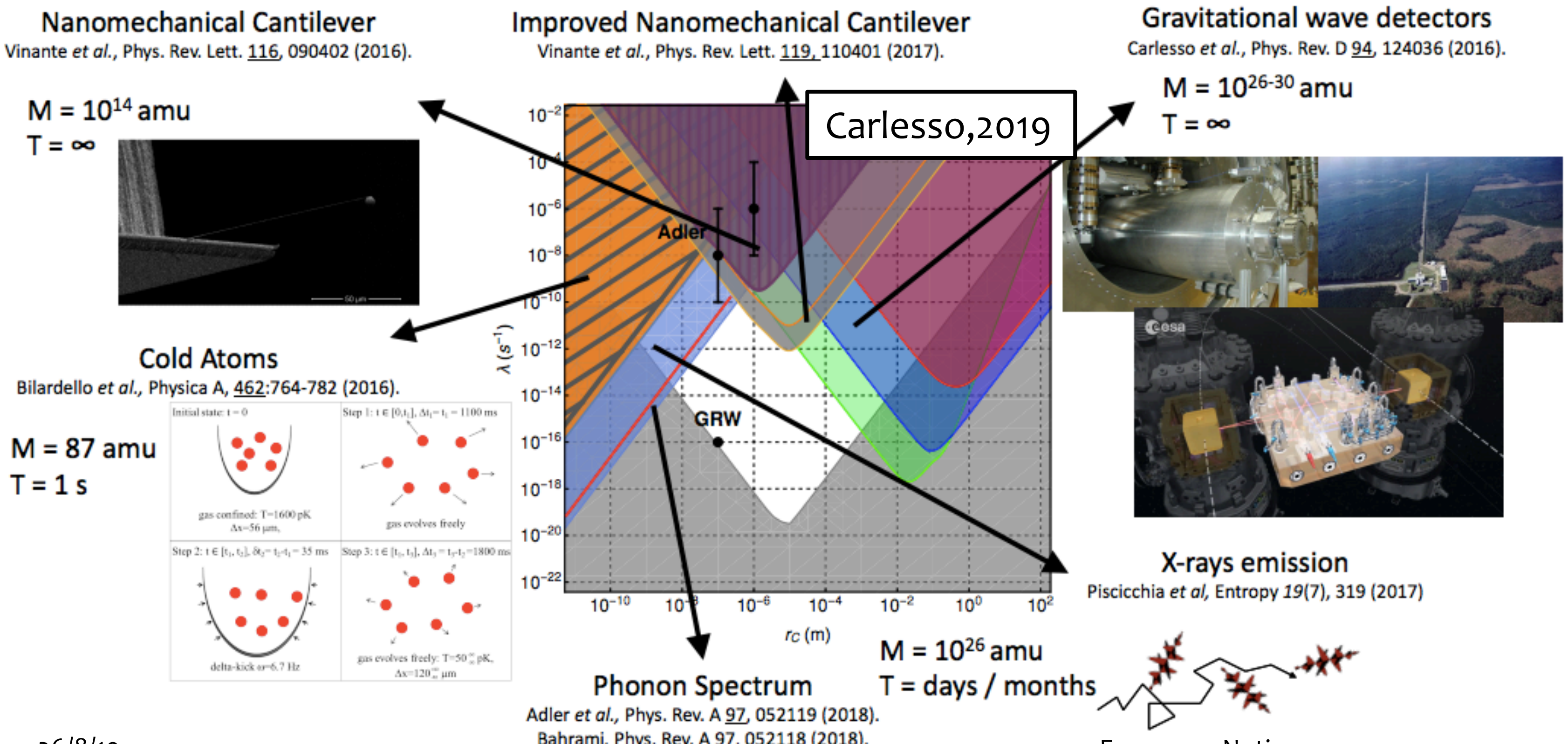
$$i\hbar\frac{\mathrm{d}|\psi(t)\rangle}{\mathrm{d}t} = \hat{H}|\psi(t)\rangle \longrightarrow i\hbar\frac{\mathrm{d}|\psi_t\rangle}{\mathrm{d}t} = \left[\hat{H} - \frac{\hbar\sqrt{\lambda}}{m_0}\int \mathrm{d}\mathbf{x}\,\hat{M}(\mathbf{x})w_t(\mathbf{x})\right]|\psi_t\rangle$$

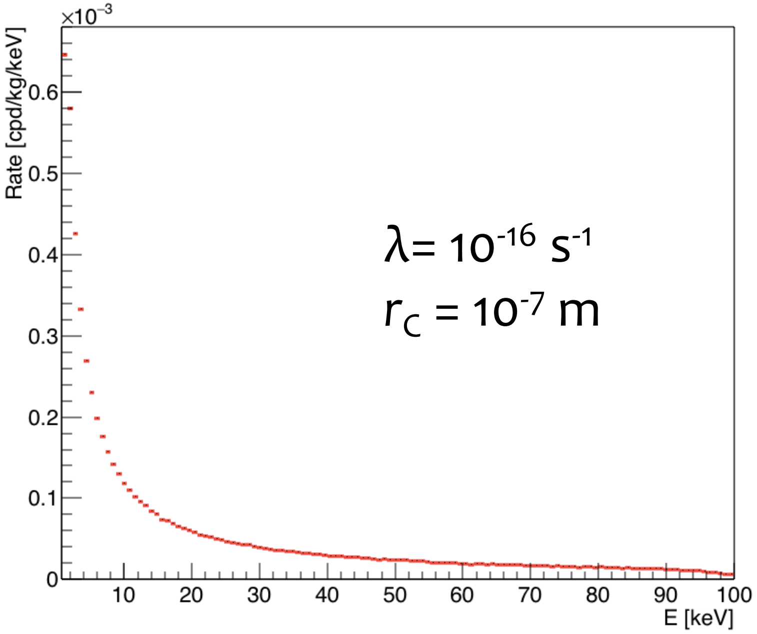
- Fundamental parameters of the theory: the collapse rate λ, the correlation length of the noise r_C

Adler, Bassi, 2007

SEARCH FOR SPONTANEOUS X-RAY EMISSION

- The CSL models have several implications that can be tested by different types of experiments
- CSL predicts spontaneous **x-ray emission** from charged particles that can be detected by DM direct detection experiments



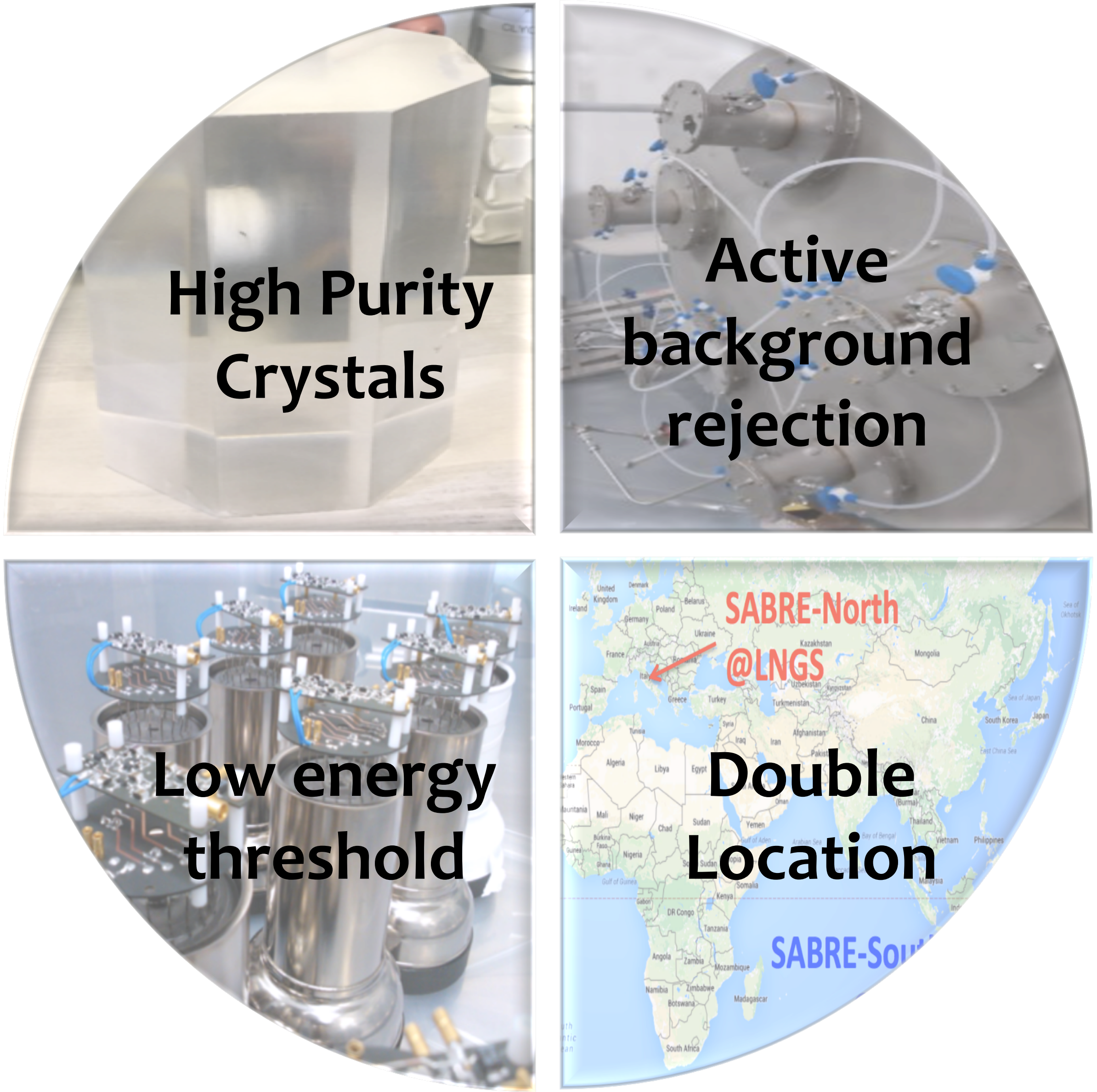


Spontaneous X-ray emission spectrum in NaI

Goals:

- Direct detection of DM in ultra-pure sodium-iodide (NaI) detectors in North and South hemispheres
- Model-independent verification/exclusion of DAMA/LIBRA annual modulation (see V. Caracciolo talk)

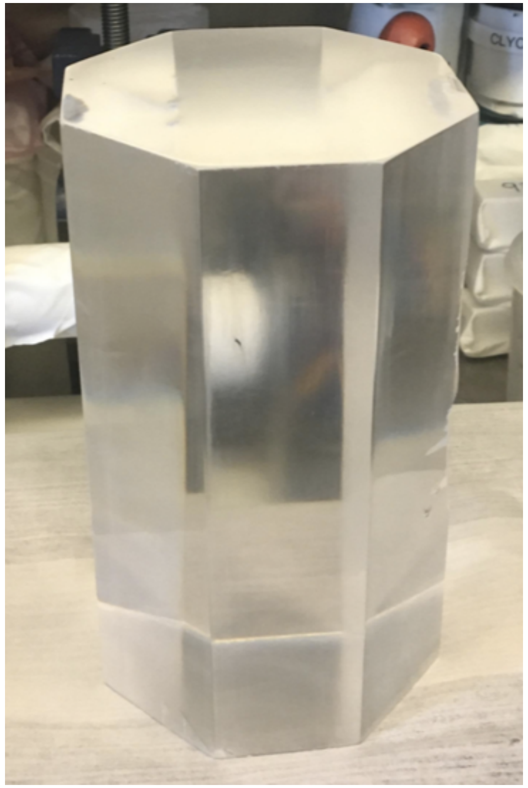
SABRE KEY FEATURES

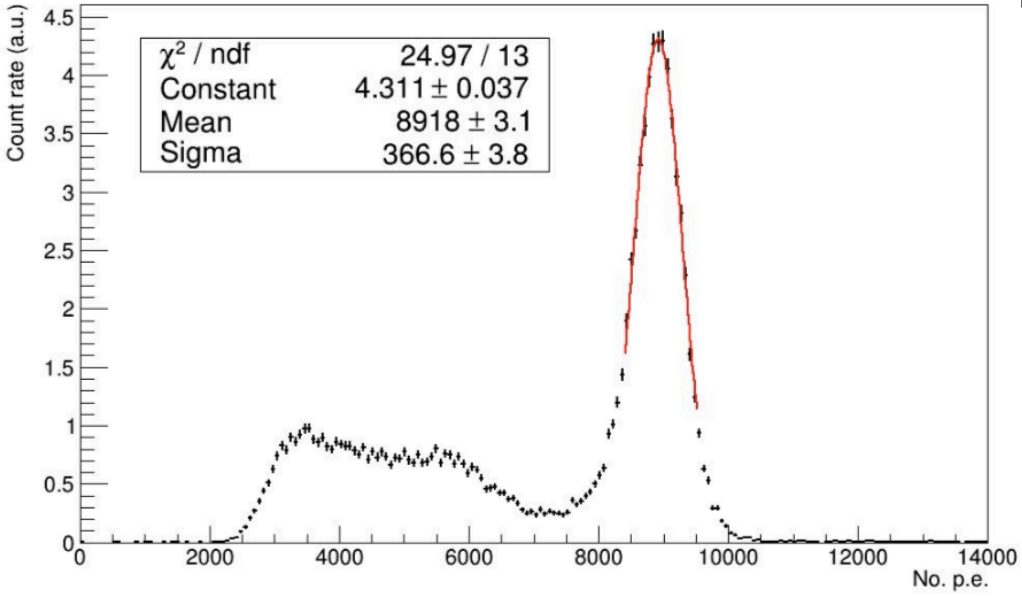


Unprecedented low-background and sensitivity for a NaI(Tl) experiment

ULTRA-PURE CRYSTALS

- The crystal radiopurity is the most critical aspect for NaI detectors
- SABRE uses
  - High purity Astro-grade powder produced by Merck (former Sigma-Aldrich)
  - Clean crystal growth method developed by Princeton and RMD
- Two octagonal 3.5 kg crystals have been grown



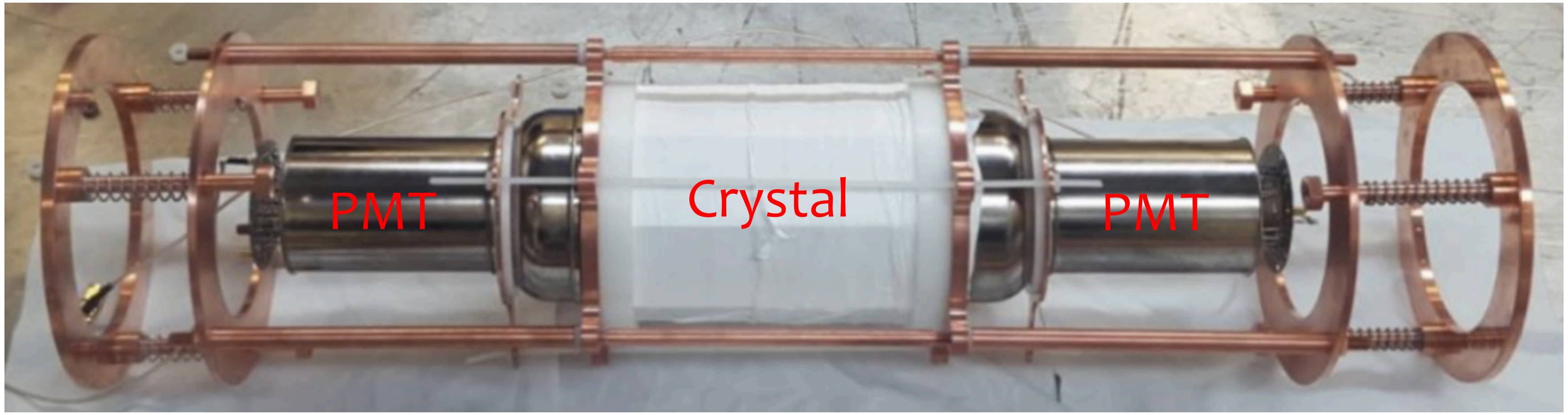


Light-yield 13.5 p.e./keV with ^{137}Cs

Element	NaI Powder	Crystal	DAMA Crystal
^{nat}K	3.5 - 18 ppb	4.3 ± 0.9 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 threshold

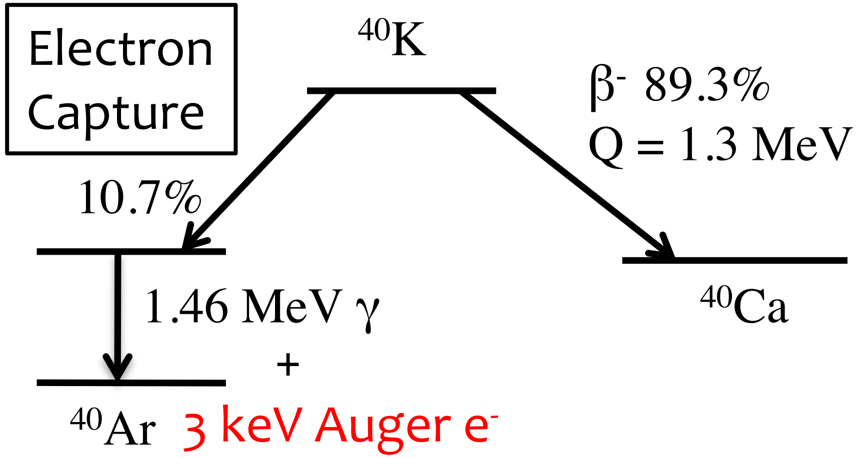
- SABRE aims to be sensitive to the energies covered by DAMA/LIBRA 1-6 KeVee and below
- Current Design:
  - 2 x Hamamatsu R11065-20 3" PMTs per crystal with High QE: > 35% and minimal contaminations
  - Direct PMT-Crystal coupling for maximal light yield
  - Custom pre-amplifiers and super bialkali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

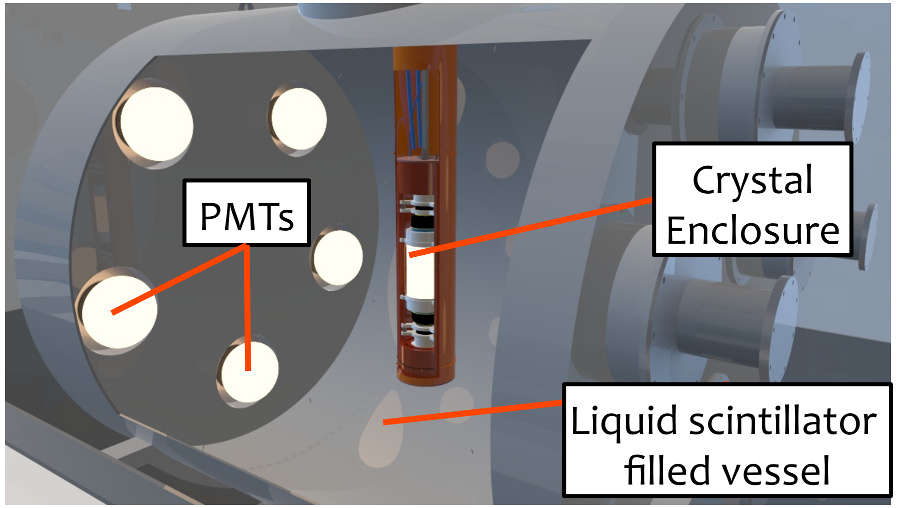


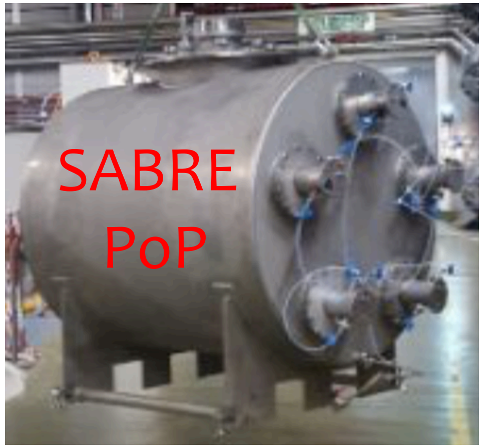
Element	Contamination (mBq/ PMT)
^{nat}K	< 10
^{238}U	~ 15
^{232}Th	~ 1
^{60}Co	< 1

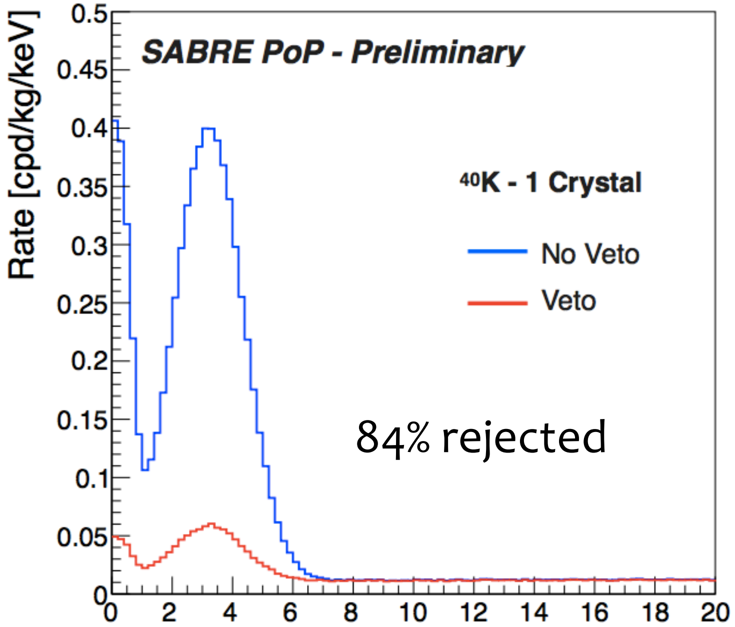
Active Background Rejection

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



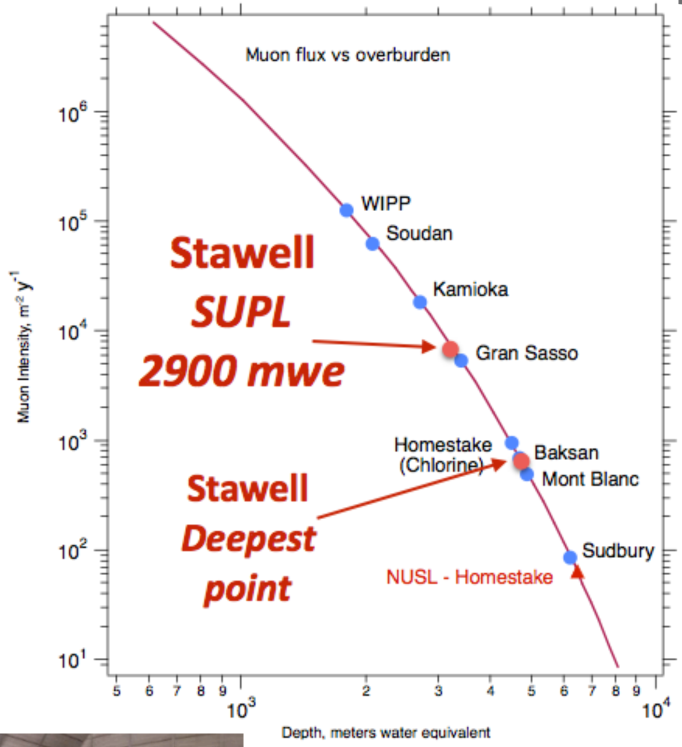






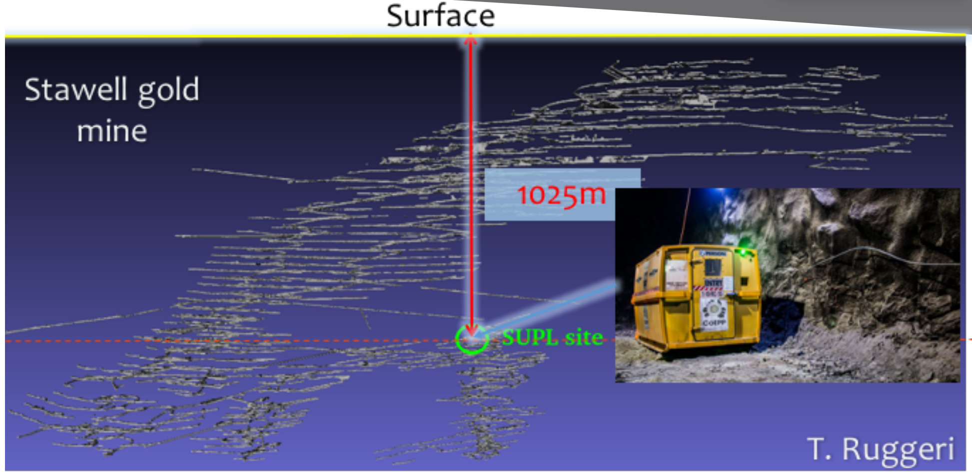
Double location

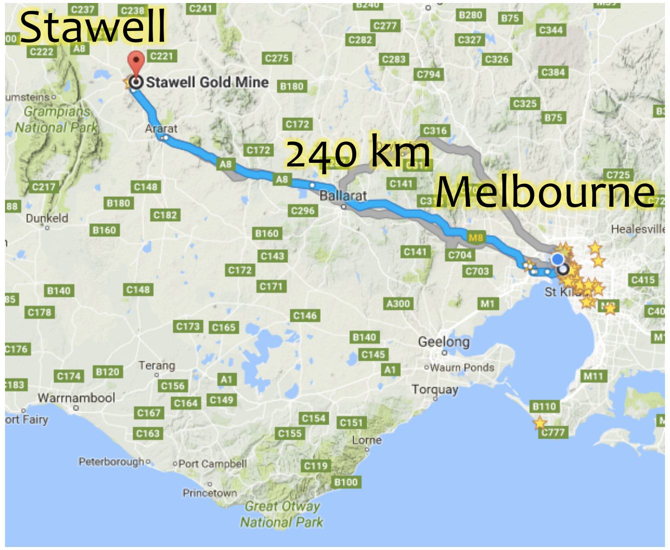
- Twin experiments in opposite hemispheres allow to:
  - rule out potential seasonal modulations and local effects
  - reduce biases thanks to independent systems



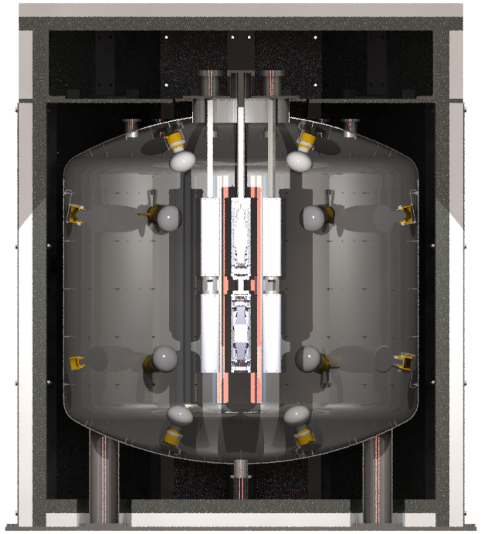
STAWELL UNDEGROUND PHYSICS LABORATORY

- Clean laboratory at the Stawell Gold Mine 1025 m underground
- Project fully funded with A$10 millions
- Construction to start in September 2019
- SABRE @ SUPL around the end of 2020





Clean-room, low radon areas



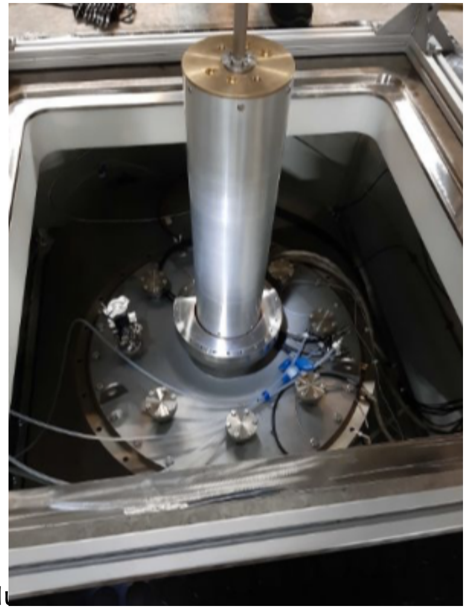
PROOF OF PRINCIPLE

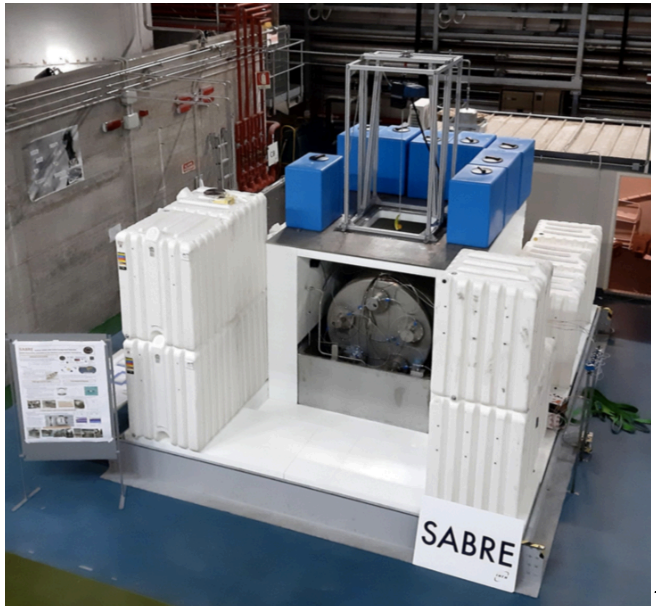
At LNGS, SABRE Proof of Principle (PoP) phase is ready for commissioning:

- Single 3.5 kg crystal
- Active veto with 2 ton PC+PPO (3g/l) scintillator and 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

Goals:

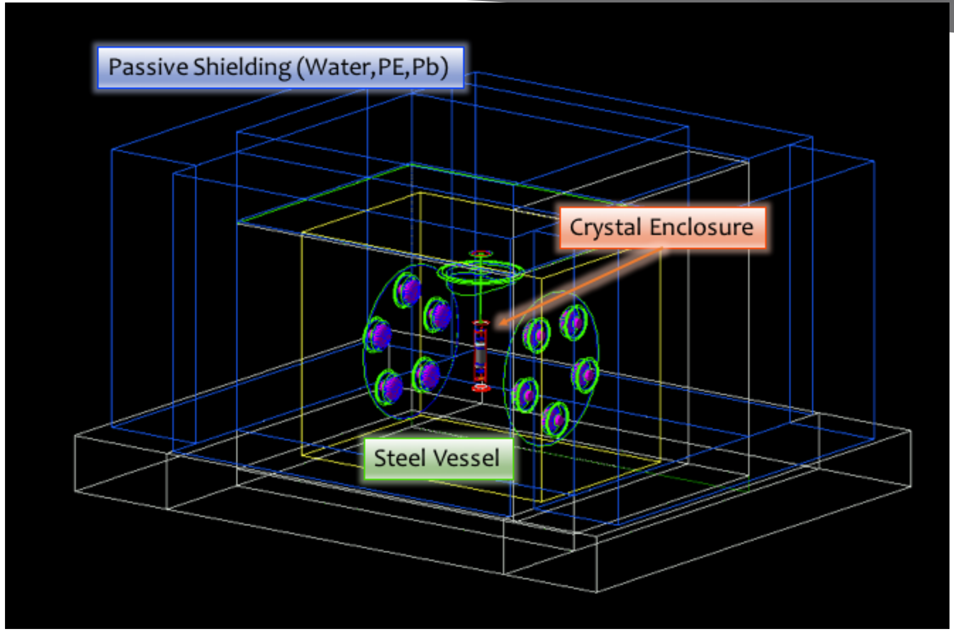
- Characterize crystal contaminations, particularly ^{40}K, ^{3}H, ^{210}Pb
- Test active veto performance

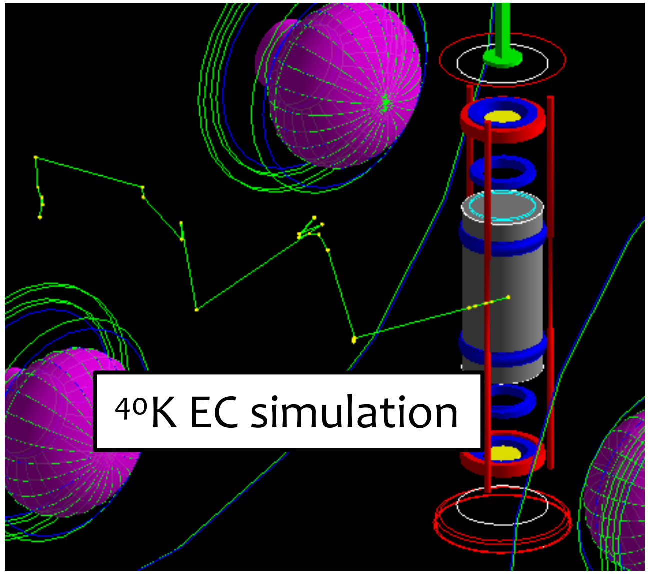




SABRE SIMULATION

- GEANT4 simulation of the PoP detector and estimate of the expected background
- Considered radiogenic and cosmogenic 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)
- Expected external background below 5E-03 cpd/keV/kg





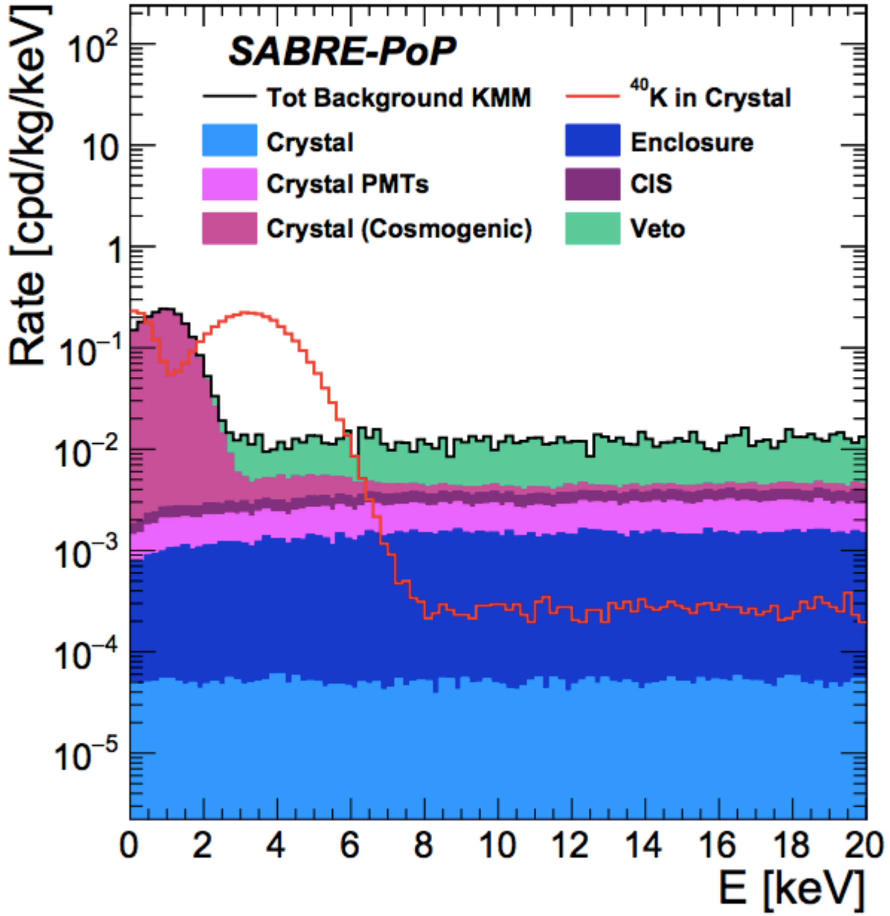
^{40}K MEASUREMENT MODE (KMM)

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

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

	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	$1.9 \cdot 10^{-1}$

* After 2 months underground



Probably possible to measure ^{22}Na background below 2 keV

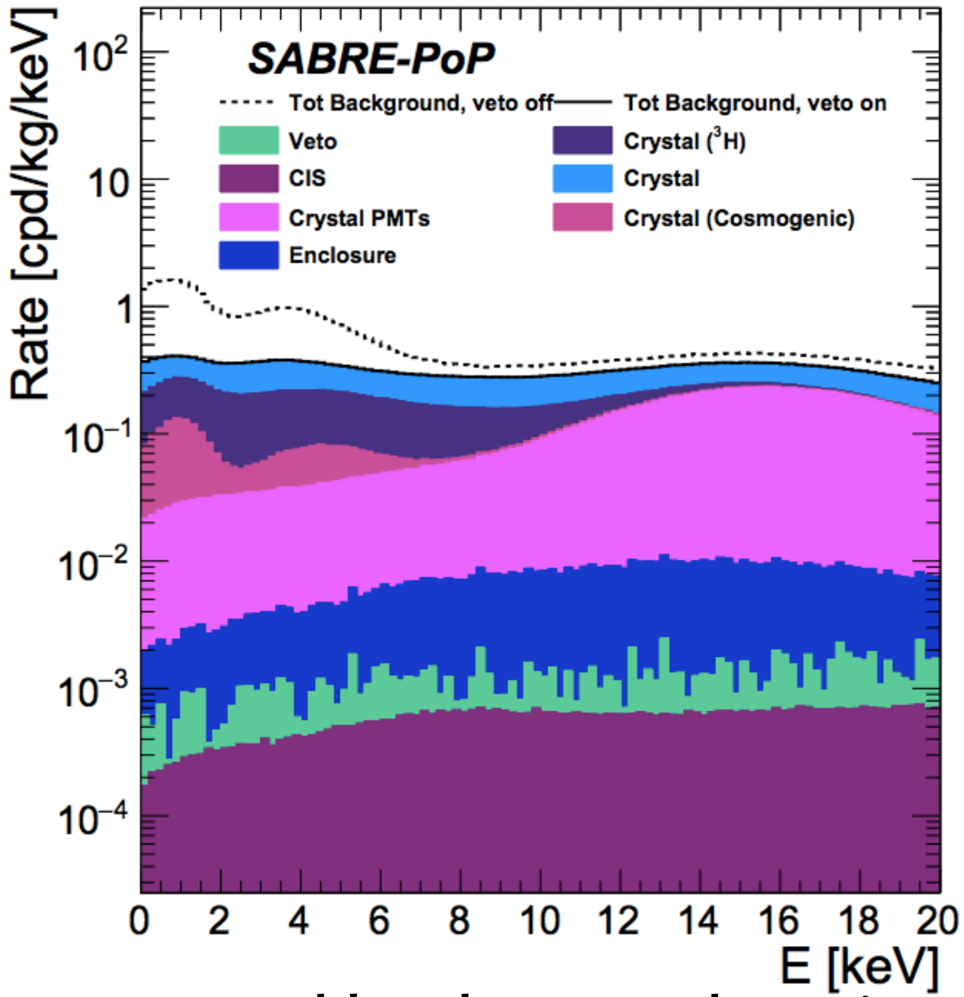
Dark Matter mode (DMM)

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

Selection:
E(Scintillator) < 100 keVee
E(Crystal) ∈ [2,6] keVee

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

* After 6 months underground



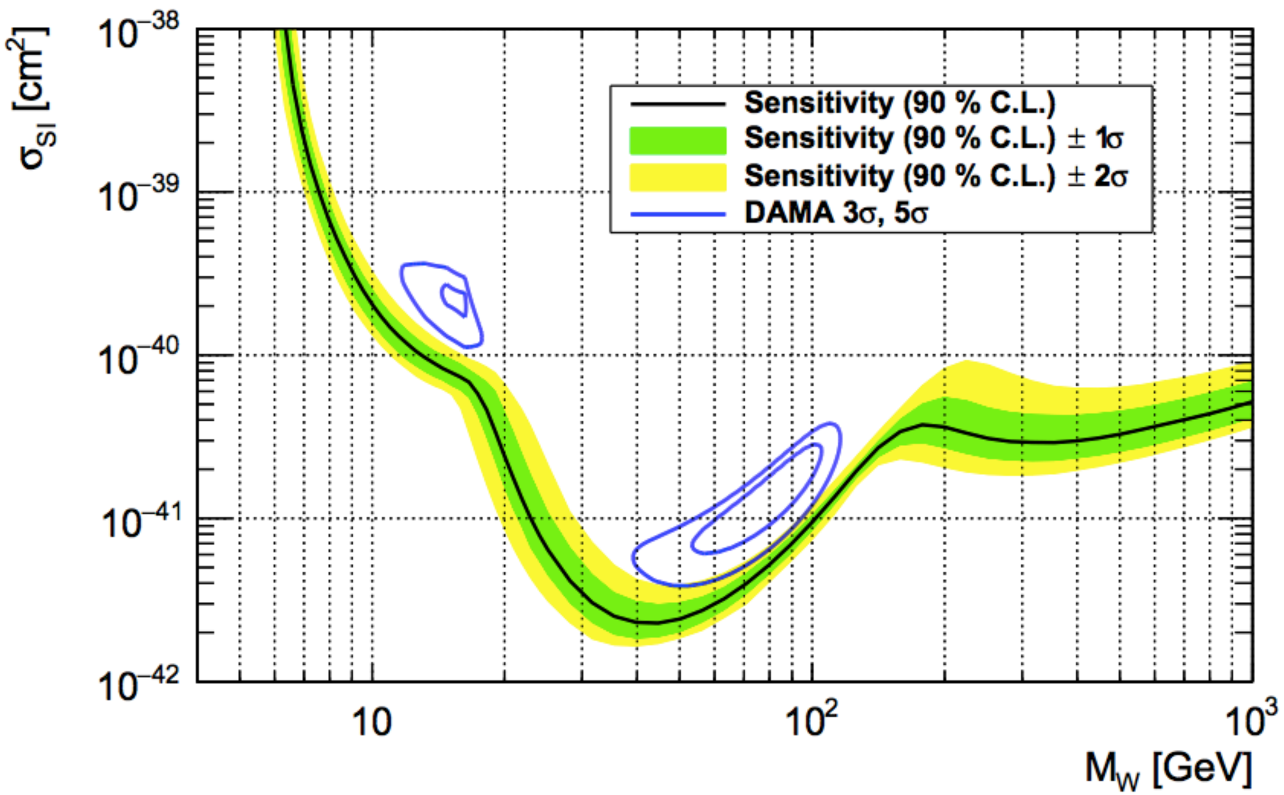
Expected background ~3 times smaller than DAMA/LIBRA

EXPECTED SENSITIVITY (DM)

If PoP data confirm the simulated background estimate → SABRE full scale can test DAMA/LIBRA at 5σ sensitivity in few years

90% CL limits for spin-independent WIMP nuclear scattering are obtained assuming:

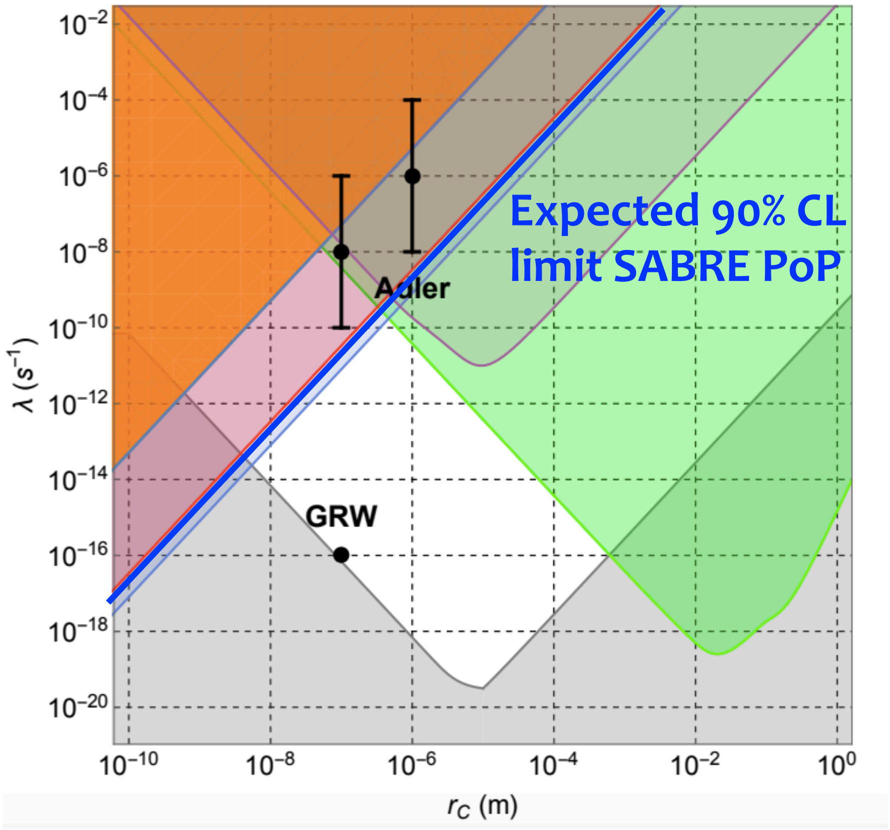
- 50 kg of total crystal mass
- 3 years of exposure
- $0.13 < Q_{Na} < 0.21$ and $Q_I = 0.09$



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

Expect sensitivity (QM)

- The PoP setup can be used to search for spontaneous x-ray emission
- Limits on the CSL parameters λ and r_C found assuming:
  - the background rate from simulation
  - an uncertainty on the overall background magnitude of 10%
  - 6 months of data taking with a single 3.5 kg crystal
- SABRE PoP sensitivity is comparable with that of the current leading experiment for spontaneous X-ray emission
- Could potentially set the strongest limit

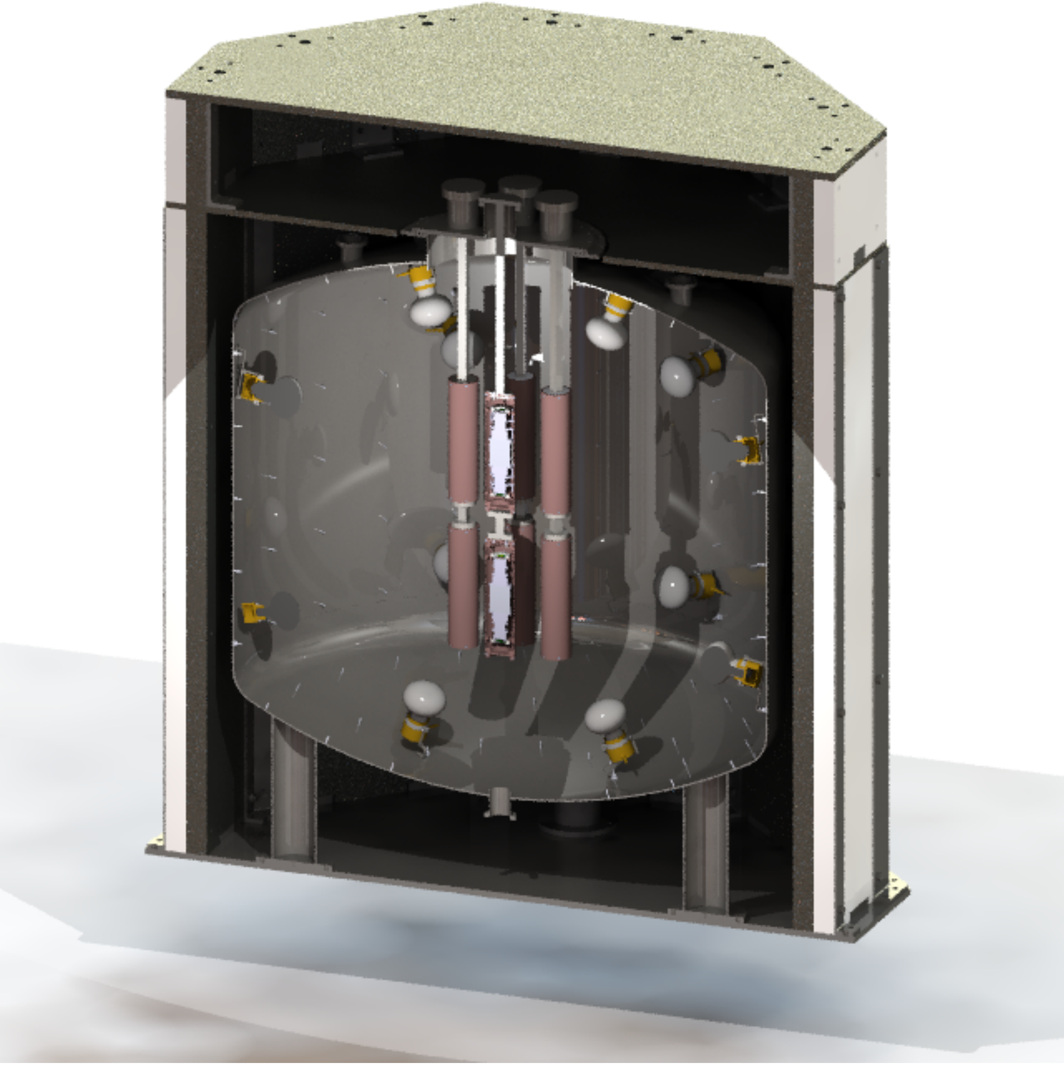


Carlesso, 2019

Proposed theoretical values (Dots) and exclusion from:
LISA Pathfinder, cold atoms, phonon excitations in crystals, X-ray emission (IGEX), nanomechanical cantilever, theory

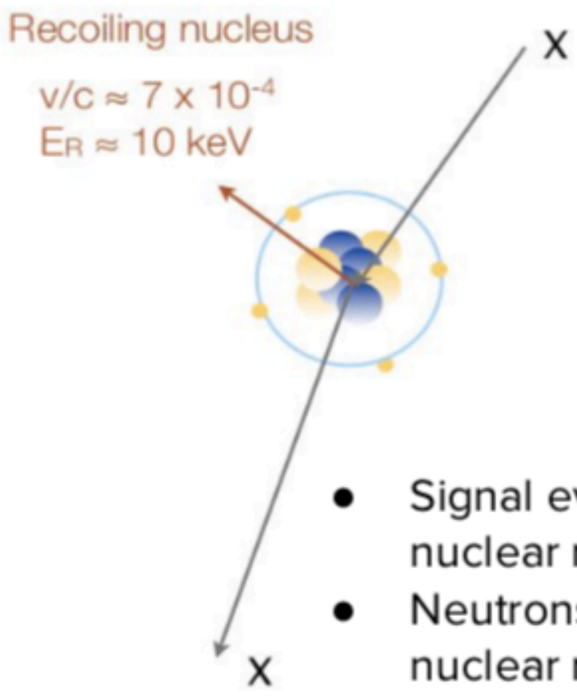
CONCLUSION

- SABRE can:
  - achieve the lowest background among NaI(Tl) detectors
  - perform a model-independent 5σ verification of the DAMA/LIBRA modulation
  - exclude any local effects thanks to double location
  - compete with the current x-ray emission detectors to set the strongest limits on the CSL models
- Proof of Principle phase is in commissioning
- SABRE @ SUPL is expected by the end of 2020



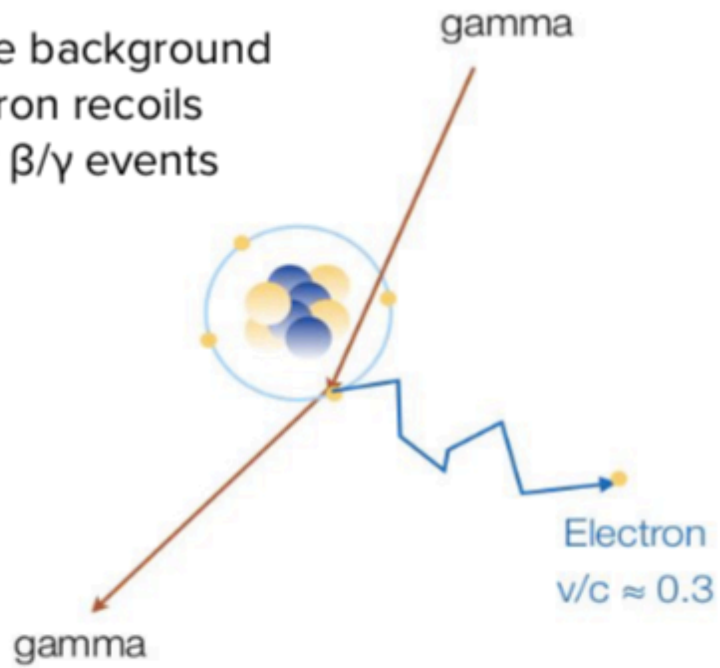
Backup

BACKGROUNDS



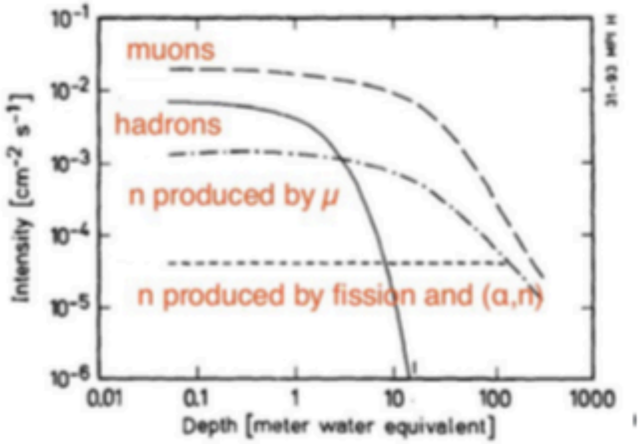
- Signal events produce nuclear recoil
- Neutrons produce nuclear recoils similar to a WIMP

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



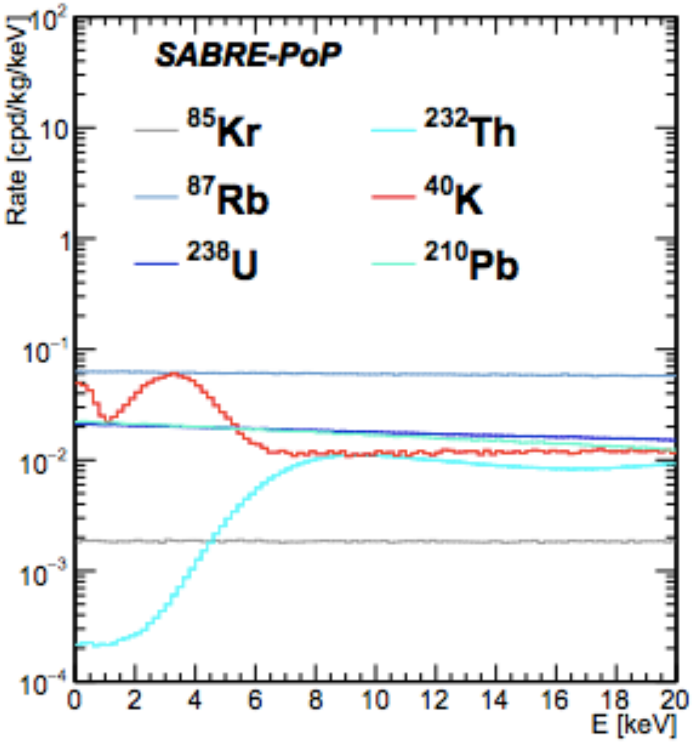
Background sources:

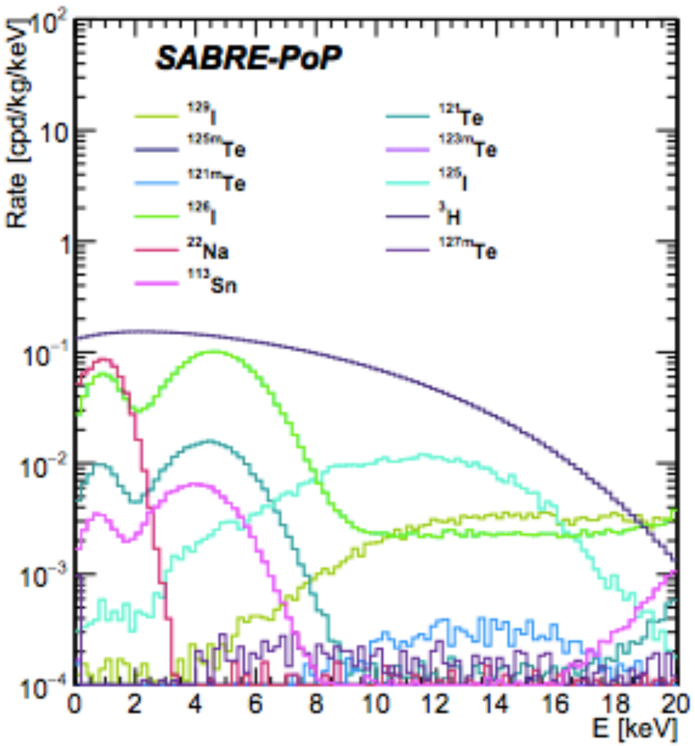
→ **Radioactivity** of **detector** and shield materials
→ **Radioactivity** of **surroundings** (laboratory environment)
→ **Cosmic rays** and **secondary** reactions
(need to go **underground**, LNGS 3700 mwe)



CRYSTAL BACKGROUND (DMM)

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	$3.5 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$
	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)	$3.8 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$





Cosmogenic activation:

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**

External 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 10^{-3} (99% CL)
Gamma Hall C	< **5.4** 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

CONTAMINATIONS (1/2)

Isotope	Activity	Reference
^{40}K	10 ppb	**SABRE (arXiv:1806.09344)**
^{238}U	< 1 ppt	
^{232}Th	< 1 ppt	
^{87}Rb	< 0.1 ppb	
^{210}Pb	<0.03 mBq/kg	**DAMA (arXiv:0804.2738)**
^{85}Kr	<0.01 mBq/kg	

Radiogenic

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

Isotope	Activity [mBq/kg]	Reference
^{3}H	0.018	**Activia simulation software**
^{22}Na	0.48	
^{126}I	4.1	
^{129}I	0.57	
^{113}Sn	0.096	
^{125}I	1.9	
^{121}Te	1.27	
^{121}mTe	0.50	
^{123}mTe	0.31	
^{125}mTe	0.69	
^{127}mTe	0.50	

Cosmogenic after 6 months

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	$3.5 \cdot 10^{-7}$