Dark matter search with the SABRE experiment

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for the SABRE collaboration

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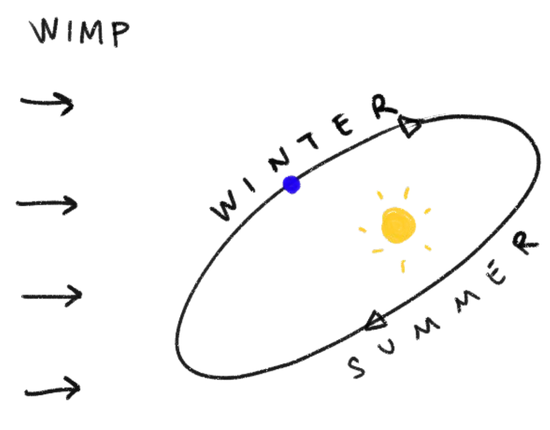
Dark matter detection through annual modulation

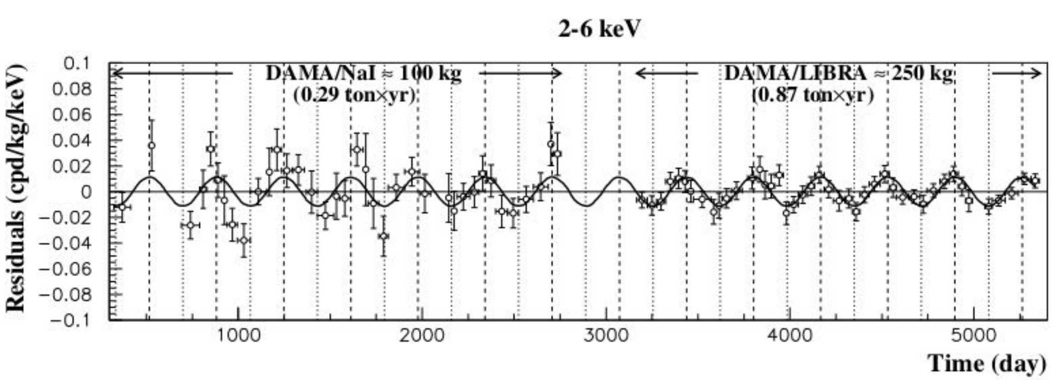
- **WIMP** is one of the most studied candidate for Dark Matter
- **Standard halo model**:
  - spherical DM halo around galaxy solidal to the galactic center
  - local energy density $\rho_\chi \sim 0.3$ GeV/cm^3
- **Rare and low energy** events
  - expected WIMP-nucleons xsec: 10^{-48} - 10^{-40} cm^2
    → **very low expected rate** < 1 count/day/kg
  - **expected recoil energy is 1-100 keV** for a WIMP of mass 10-1000 GeV/c
- **Annual modulation** of the WIMP flux on Earth
  - Period $2\pi/\omega$ = 1 year
  - Maximum of modulation at t_0 → June 2nd
  - **modulation signature is independent from the halo model**

WIMP rate: $$\frac{dR}{dE} \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$



- Sun velocity ~220 km/s
- WIMP velocity seen from Earth ~220 + 15 cos ω(t - t_0) km/s

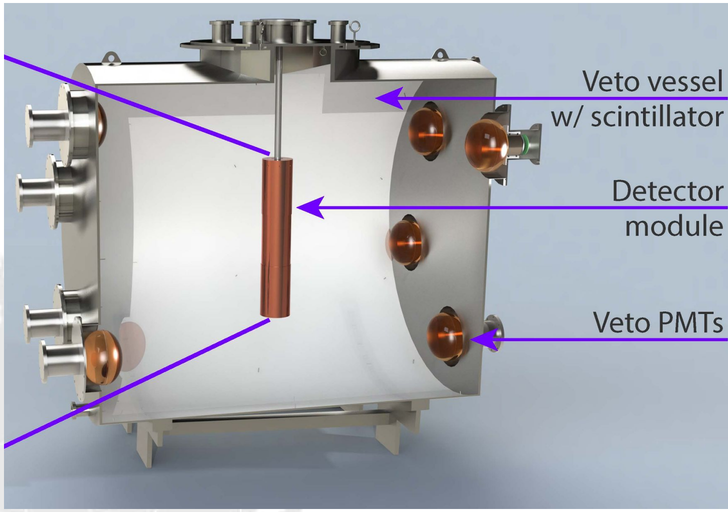
- **DAMA/LIBRA experiment** at LNGS observes a **9.3 σ annual modulation** in the region [2-6]keV$_{ee}$



Still missing an independent measurement with NaI target.
→ **SABRE** is a new experiment with **NaI detector** for annual modulation

SABRE (Sodium-iodide with Active Background REjection)

1. **Development of ultra-high purity NaI(Tl) crystals**
   - Ultra high purity NaI powder
   - Ultra 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**
   - Reduces any season-related background



Laboratori Nazionali del Gran Sasso (LNGS), Italy

Stawell Underground Physics Lab (SUPL), Australia

The SABRE collaboration

- Collaboration: 11 Institutions from **Italy, US, UK and Australia**

- Imperial College London

- Princeton University
- Lawrence Livermore National Laboratory (LLNL)
- Pacific Northwest National Laboratory (PNNL)

- INFN - Laboratori Nazionali del Gran Sasso
- Sapienza Università di Roma & INFN
- Università degli Studi di Milano & INFN

- Australian National University
- University of Adelaide
- University of Melbourne
- Swinburne University of Technology

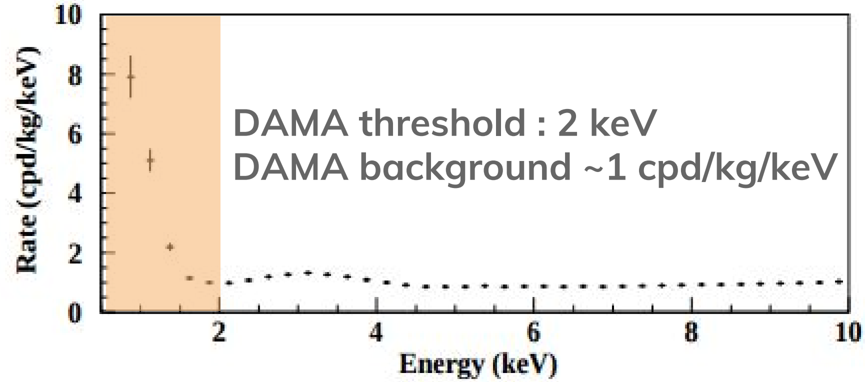
- Main background is due to crystal radioactivity: **^{40}K, ^{87}Rb, ^{232}Th, ^{238}U**
  - assumption confirmed by Monte Carlo simulations
- **Ultra pure NaI(Tl) crystals**
  - collaboration between Princeton and Sigma-Aldrich
  - low contamination Astrograde powder

Element	Sigma-Aldrich [ppb]	DAMA Powder [ppb]	DAMA Crystal [ppb]
K	3.5 (18)*	100	~13
Rb	0.2	n.a.	< 0.35
U	< 1.7 (< 10^{-3})**	~ 0.02	0.5 –7.5×10^{-3}
Th	< 0.5 (< 10^{-3})**	~ 0.02	0.7 –10×10^{-3}

* Independent measurement
** Preliminary measurement at PNNL; full validation needed.
Bernabei et al., NIM A592 (2008) 297-315

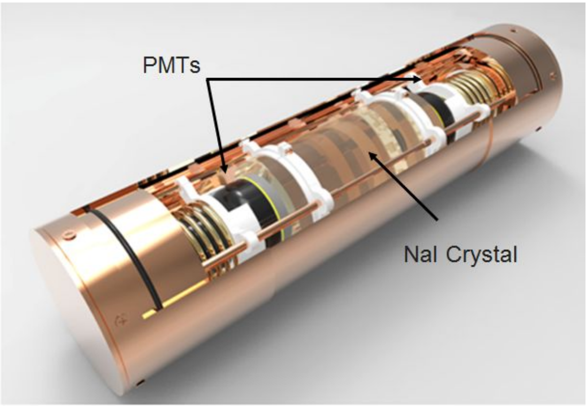
^{nat}K contamination 9 ppb
(DAMA crystal 13 ppb)

- Growth procedure tested
- **High-purity full-scale crystal in production**



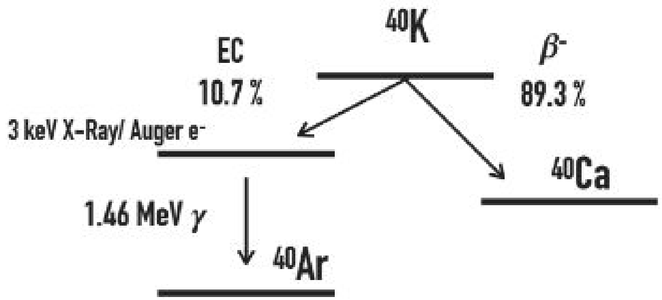
SABRE aims to achieve **low background and low threshold**:

- Hamamatsu R11065-20 3” PMTs: **high quantum efficiency and light yield**
- **direct PMT-Crystal coupling**
- **Low radioactivity**: ~1 mBq for U, Th; < 1 mBq for Co; <10 mBq for K

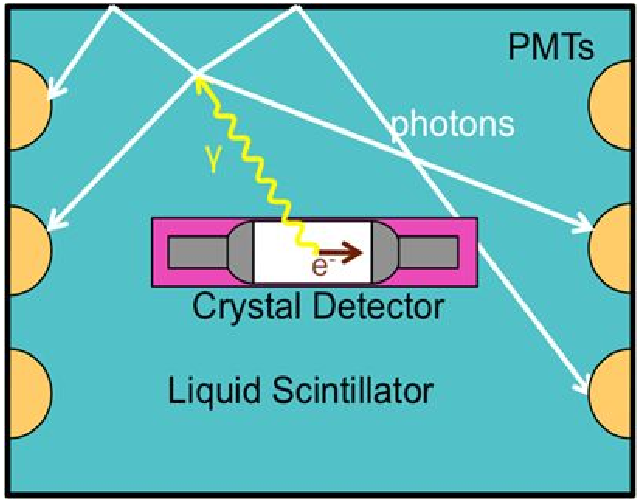


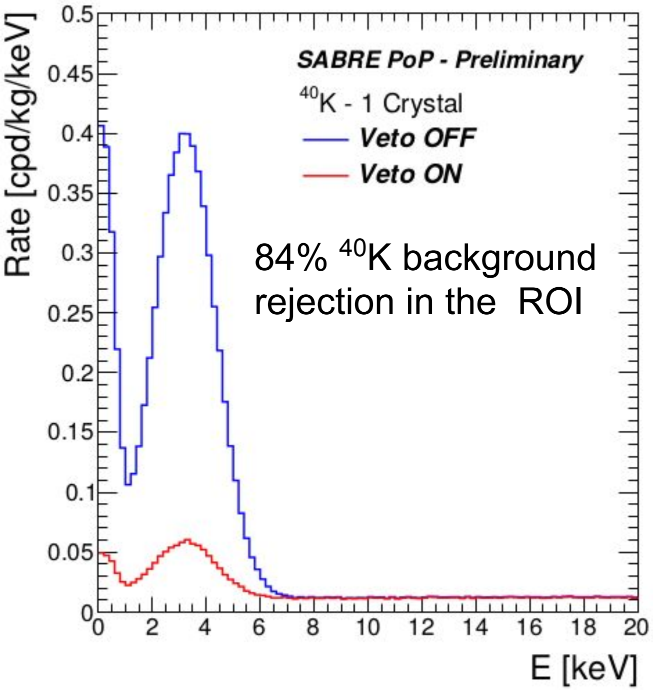
Active veto

- Crystals surrounded by a **liquid scintillator detector:**
  - **Reject external+intrinsic backgrounds** (radioactive and cosmic-induced processes) which deposit energy (>100 keV) in the liquid scintillator
  - 10 PMTs 8" Hamamatsu R5912



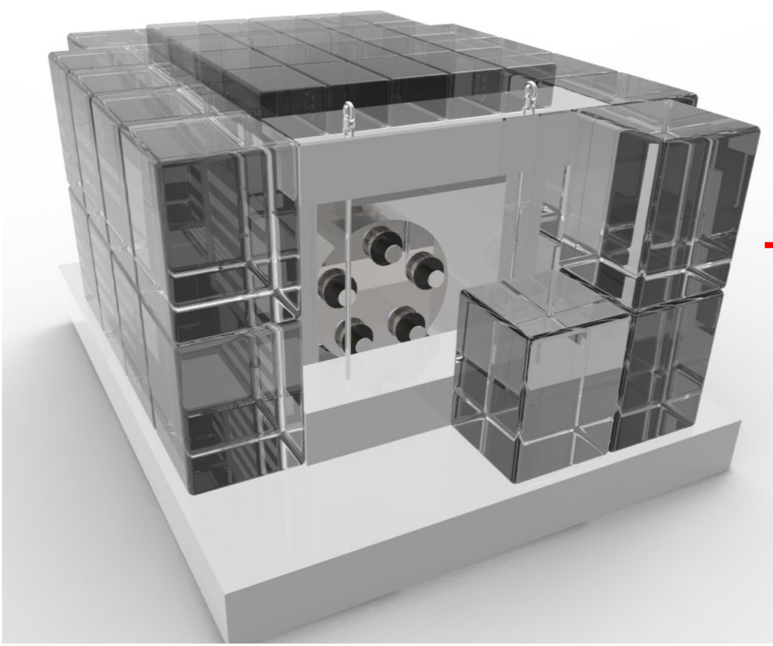
- Additional **passive shielding** against external backgrounds
  - **Bottom**: 15 cm **Lead** + 10 cm **PE**
  - **Sides**: 40 cm **PE** + 90 cm **water**
  - Top:10 cm **PE** + 2cm **Stainless Steel** plate + 80 cm **water**)





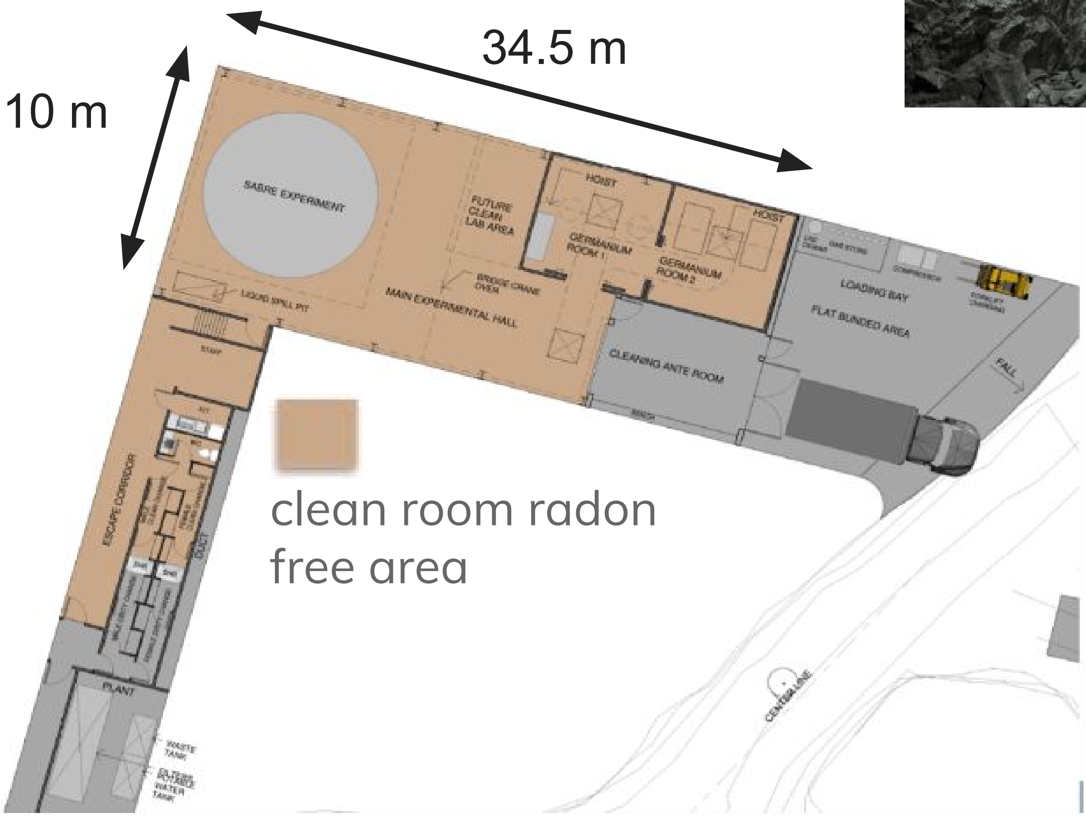
Status of SABRE Proof of Principle @LNGS

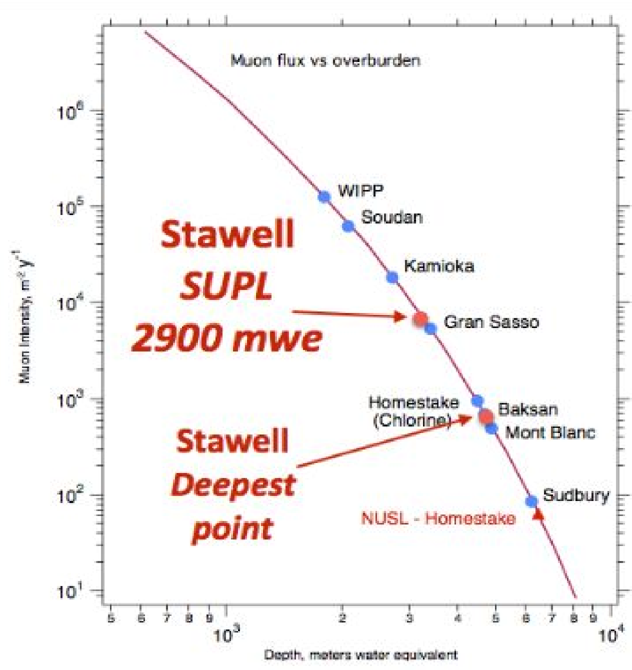
- First Phase : Proof of Principle (PoP)@LNGS:
  - Setup with **1 crystal of 5kg** inside liquid scintillator (**~ 2 tons PC + PPO** 3 g/l)
  - Goals: measure **crystal background, veto efficiency** and **validate SABRE concept**
- Steel vessel with 10 PMTs in a temporary area in Hall B
  - done tests of veto PMTs and DAQ
  - run with water planned before moving to Hall C
- Final location Hall C:
  - refurbishment completed + lead shielding installed
  - shielding completion ~end of summer 2017



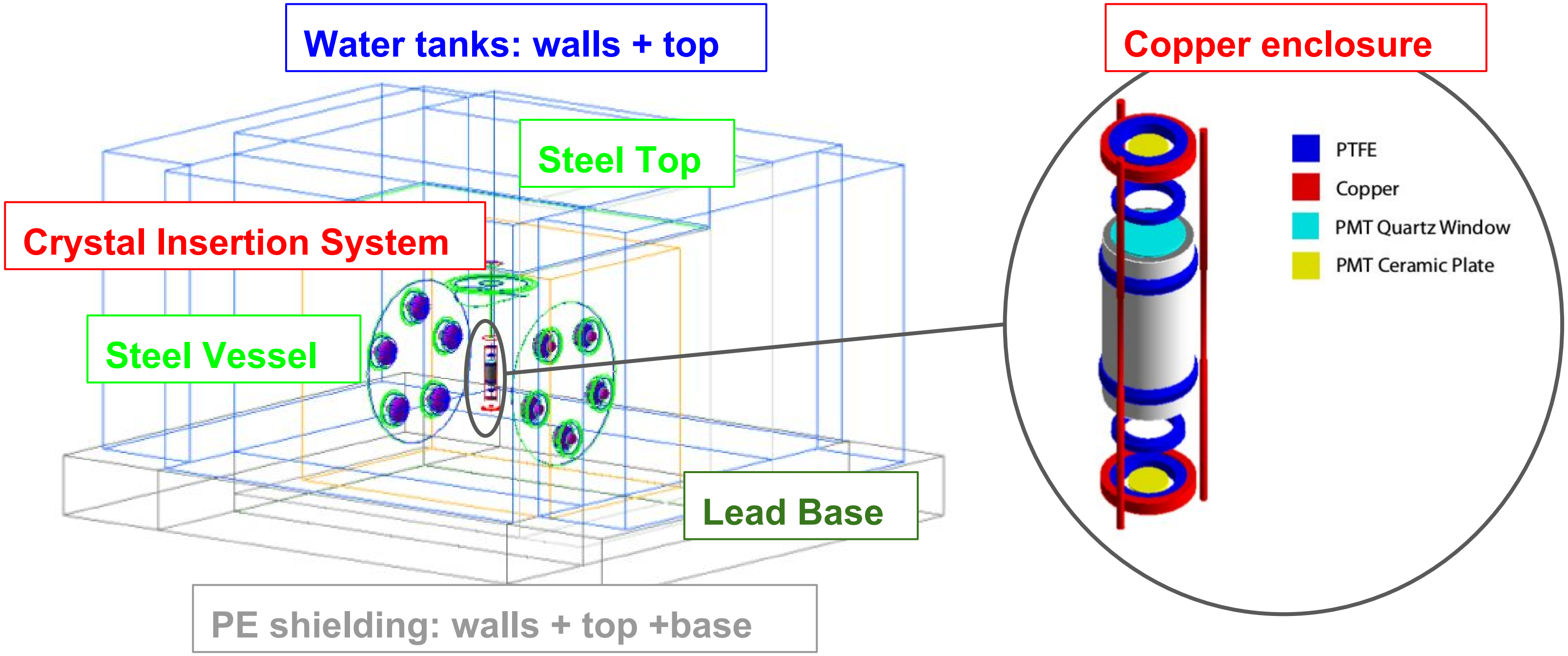
SUPL laboratories in Australia

- Hosted in the **Stawell Gold Mine, Victoria, Australia**
- Construction to start in second half of 2017
- Depth 1025 m (2900 m w.e.)
- 34.5 m X 10 m clean room and radon free area
- Will host SABRE and other experiments





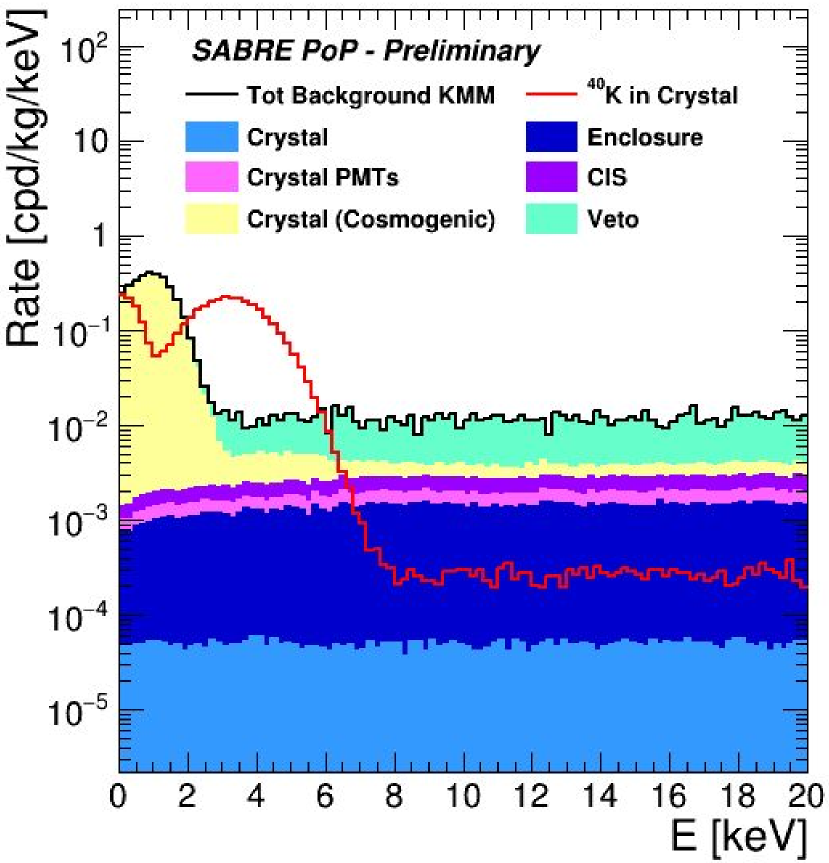
Full background simulation of the PoP



- **GEANT4** based code with **detailed geometry** implementation
  - External shielding: water + PE + Pb + Steel
  - Steel vessel filled with liquid scintillator + 10 PMTs 8”
  - Crystal insertion system: copper tube + steel bar
  - Copper enclosure with **crystal** and 2 PMTs 3”
- Contaminations from available **measurements** or **literature**
- **Comparison with previous independent simulations** gives results in good agreement for the major bkg contributions

K measurement

- **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(Scintillator) ∈ [1280,1640] keV
E(Crystal) ∈ [2,4] keV

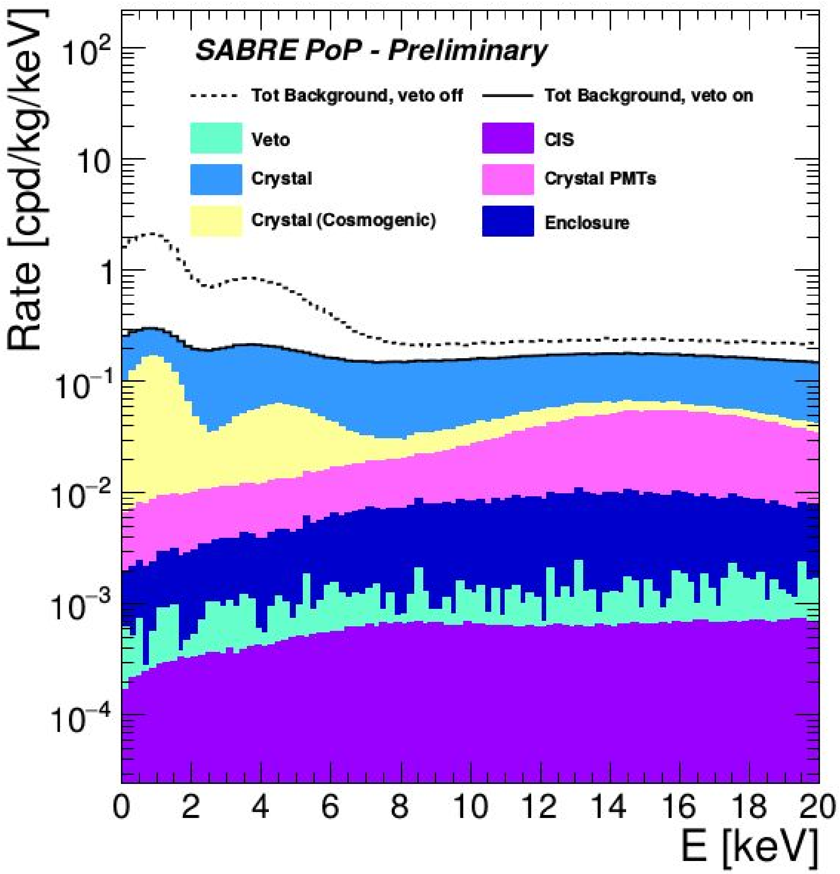
	Rate KMM [cpd/kg/keV]
Veto	$6.2 \cdot 10^{-3}$
CIS(*)	$7.7 \cdot 10^{-4}$
Crystal	$5.1 \cdot 10^{-5}$
Crystal Cosmogenic(*)	$1.8 \cdot 10^{-2}$
CrystalPMTs	$4.3 \cdot 10^{-4}$
Enclosure(*)	$1.3 \cdot 10^{-3}$
Total	$2.7 \cdot 10^{-2}$
Crystal ^{40}K	$1.9 \cdot 10^{-1}$

(*) after 60 days underground

- Largest bkg contribution from ^{22}**Na mostly below threshold of 2 keV**

Background for Dark Matter detection

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



veto: E(Scintillator) > 100 keV
E(Crystal) ∈ [2,6] keV

	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Veto	$3.0 \cdot 10^{-2}$	$5.7 \cdot 10^{-4}$
CIS(*)	$3.7 \cdot 10^{-3}$	$4.6 \cdot 10^{-4}$
Crystal	$3.5 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$
Crystal Cosmogenic(*)	$3.0 \cdot 10^{-1}$	$3.9 \cdot 10^{-2}$
CrystalPMTs	$1.3 \cdot 10^{-2}$	$8.3 \cdot 10^{-3}$
Enclosure(*)	$9.5 \cdot 10^{-3}$	$3.6 \cdot 10^{-3}$
Total	$7.1 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$

(*) after 180 days underground

- Expected BKG **0.2 cpd/kg/keV in the ROI**
- Total veto rejection of internal bkg: **factor 3.5**
- **Crystal is the main source** of background
  - contaminations in the crystal measured with ICP-MS
  - dominant bkg ^{40}K → measured independently with ICP-MS at Seastar and PNNL
  - other bkg do not change the overall picture
- Next step → simulate full-scale experiment

Expected sensitivity

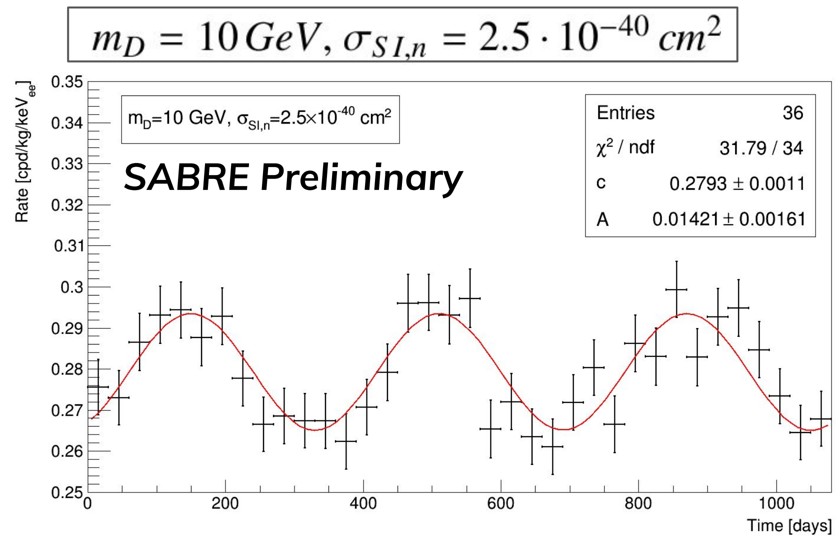
Preliminary study of SABRE sensitivity using the following assumptions:

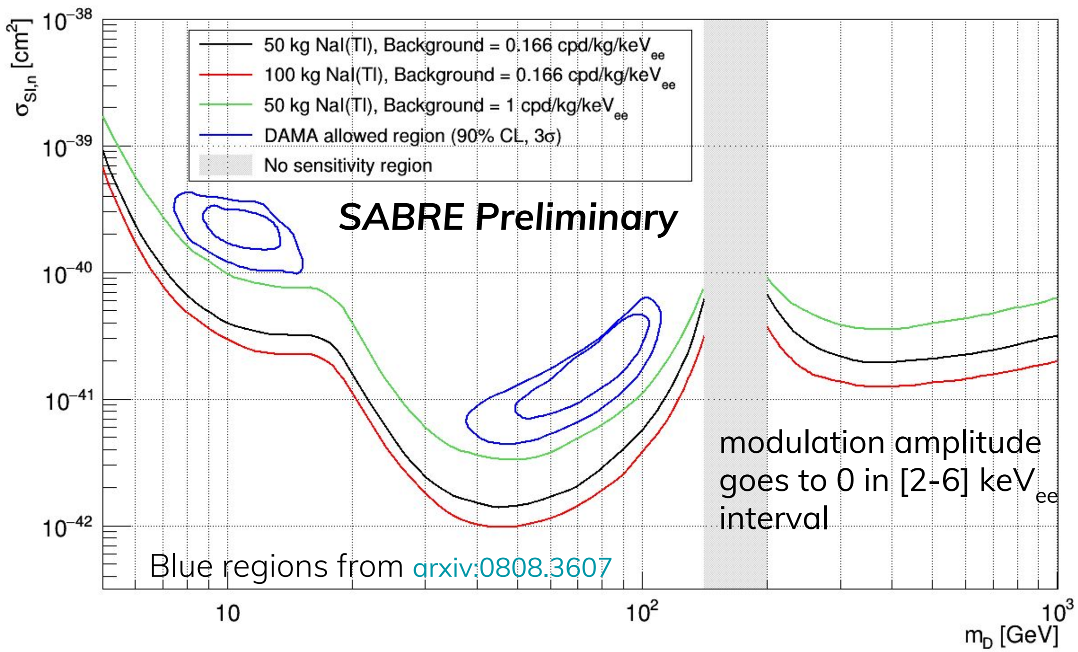
- DM **standard halo model** arxiv:1209.3339
- region of interest **[2-6] keV$_{ee}$**
- **50 kg** of ultrapure NaI(Tl) crystals (black curve)
- **3 years** exposure
- **Bkg** from simulation ~**0.2 cpd/kg/keV**

- quenching factors from DAMA
  - QF(Na) = 0.3, QF(I)=0.09
  - new measurements indicate that Na QF is significantly lower

- detector efficiency/resolution not yet included

3 years x 50 kg exposure sufficient to confirm or exclude the DAMA modulation signal





Conclusions

- Verification of the DAMA/LIBRA results with high sensitivity
  - **High purity** crystals
  - **Low energy t**hreshold
  - **Active LS Veto**
  - 2 twin experiment in **both hemispheres**

- Proof of principle (PoP) detector is being deployed @ LNGS
  - Preliminary tests on the DAQ, trigger logic, veto PMTs ongoing
  - Validation of the crystals and veto efficiency
  - Data taking in the second half of 2017

- Monte Carlo Simulations
  - BKG in DMM **~0.20 cpd/kg/keV**
  - active **veto rejection factor ~3.5**
  - coincidence mode will allow measurement of potassium and other intrinsic BKGs that give energy release in the LS

- Full Scale experiment under design
  - Confirm/Reject DAMA/LIBRA modulation before 3 years

Backup Slides

Simulated contaminations: crystal

Isotope	Activity/Concentration		Ref.
Intrinsic			
^{nat}K	10 ppb		SABRE, in preparation
^{238}U	1 ppt		SABRE: arxiv:1601.05307
^{232}Th	1 ppt		
^{nat}Rb	0.1 ppb		
^{210}Pb	0.03 mBq/kg		DAMA: arxiv:0804.2738
Cosmogenic			
Isotope	Activity [mBq/kg]	Half life [days]	Ref.
^{22}Na	0.80	949	LNGS: M. Laubenstein
^{126}I	4.30	13	
^{24}Na	2.60e-04	0.625	DAMA: arxiv:0804.2738
^{129}I	0.95	-	
^{121}Te	1.27	17	ANAIS: arXiv:1604.05587
^{125}I	7.20	59	
^{121}mTe	0.89	154	
^{123}mTe	1.17	119	
^{125}mTe	0.92	57	
^{127}mTe	0.37	107	

Simulated contaminations

PFTE wrapping

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

XENON: arxiv:1207.5988

Copper

Isotope	Activity/Concentration
^{40}K	0.7 mBq/kg
^{238}U	0.065 mBq/kg
^{232}Th	0.002 mBq/kg

CUORE-0: Eur. Phys. J. C

Copper activation

Isotope	T1/2 [days]	Activity [μBq/kg]
^{60}Co	1925	340
^{58}Co	71	798
^{57}Co	272	519
^{56}Co	77	108
^{54}Mn	312	154
^{46}Sc	84	27
^{59}Fe	44	47
^{48}V	16	39

XENON Eur. Phys. J. C

Crystal PMTs Hamamatsu R11410 3”

PMT component	Isotope	Activity[mBq/PMT]
Kovar Body	^{40}K	<0.99
Kovar Body	^{60}Co	7e-02
Kovar Body	^{238}U	<0.095
Kovar Body	^{226}Ra	<0.26
Kovar Body	^{232}Th	<0.0032
Kovar Body	^{228}Th	<0.34
Quartz Window	^{40}K	<8.1e-02
Quartz Window	^{60}Co	<4.5e-03
Quartz Window	^{238}U	<0.33
Quartz Window	^{226}Ra	0.036
Quartz Window	^{232}Th	<1.2e-02
Quartz Window	^{228}Th	<1.2e-02
Ceramic Feedthrough	^{40}K	1.1
Ceramic Feedthrough	^{60}Co	<0.02
Ceramic Feedthrough	^{235}U	0.11
Ceramic Feedthrough	^{238}U	2.4
Ceramic Feedthrough	^{226}Ra	0.26
Ceramic Feedthrough	^{232}Th	0.23
Ceramic Feedthrough	^{228}Th	0.11

XENON1T : Eur. Phys. J. C

Simulated contaminations

PFTE

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

XENON100: Astroparticle Physics

Stainless steel

Lot Number	Thickness [inch]	U [ppb]	Th [ppb]	K [ppb]
S536	3/8	0.3	<0.1	4
T915	1/4	0.04	0.02	<1

SABRE: GDMS method

Veto PMTs Hamamatsu R5912 8”

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

DarkSide-50: arXiv:1512.07896

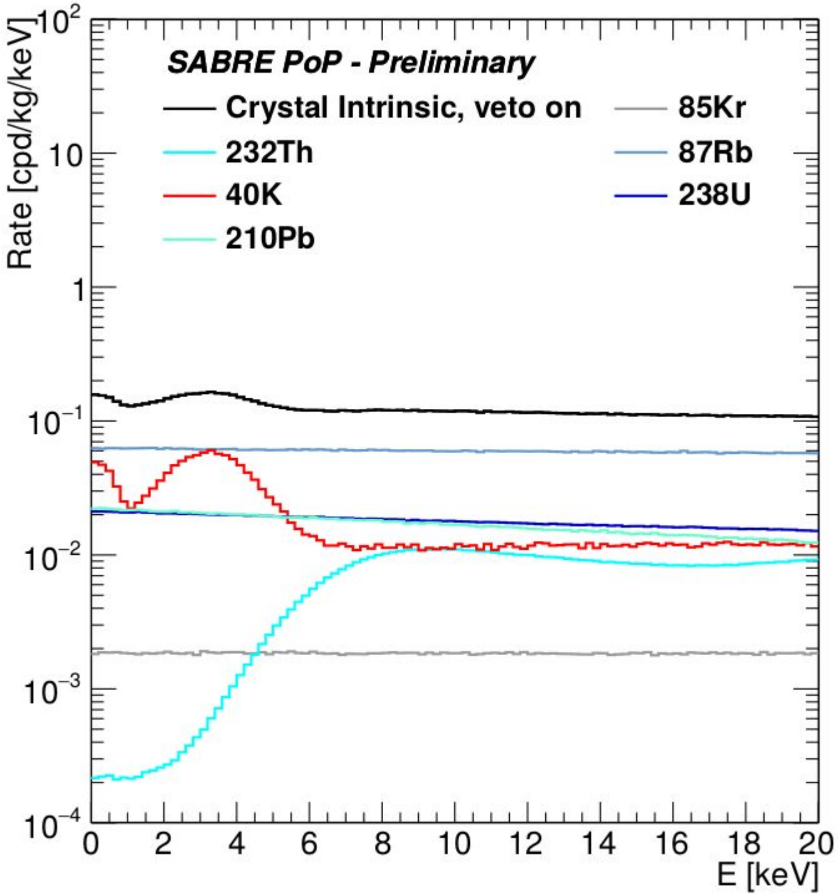
Liquid scintillator

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	$3.5 \cdot 10^{-7}$

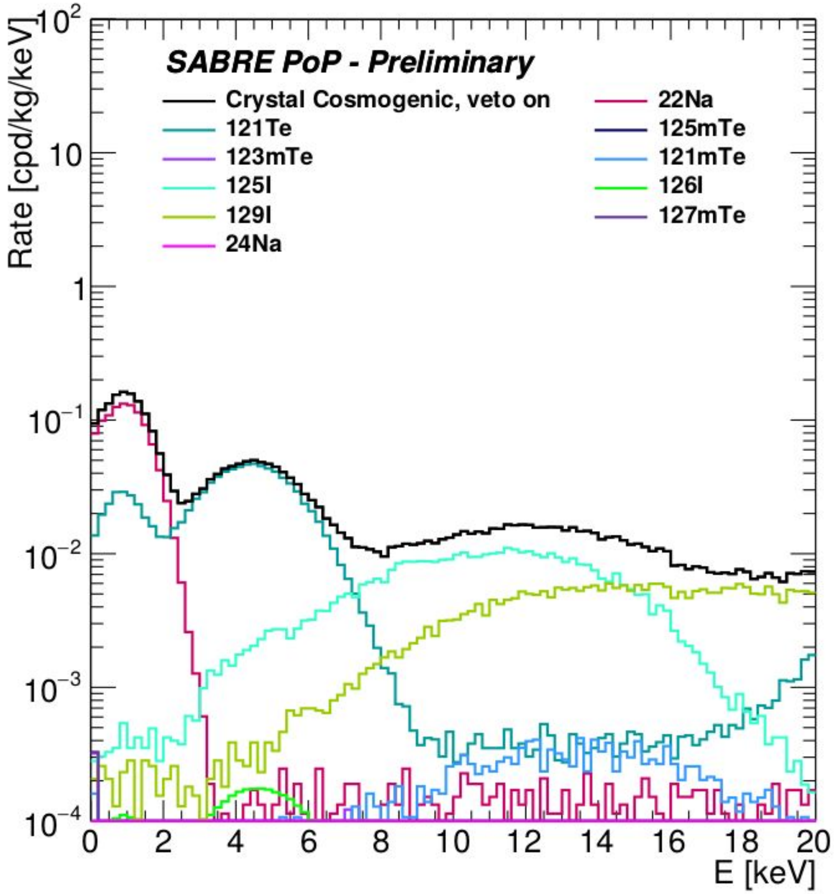
Borexino: Nucl. Instr. & Meth.

Crystal backgrounds in DMM

Intrinsic background



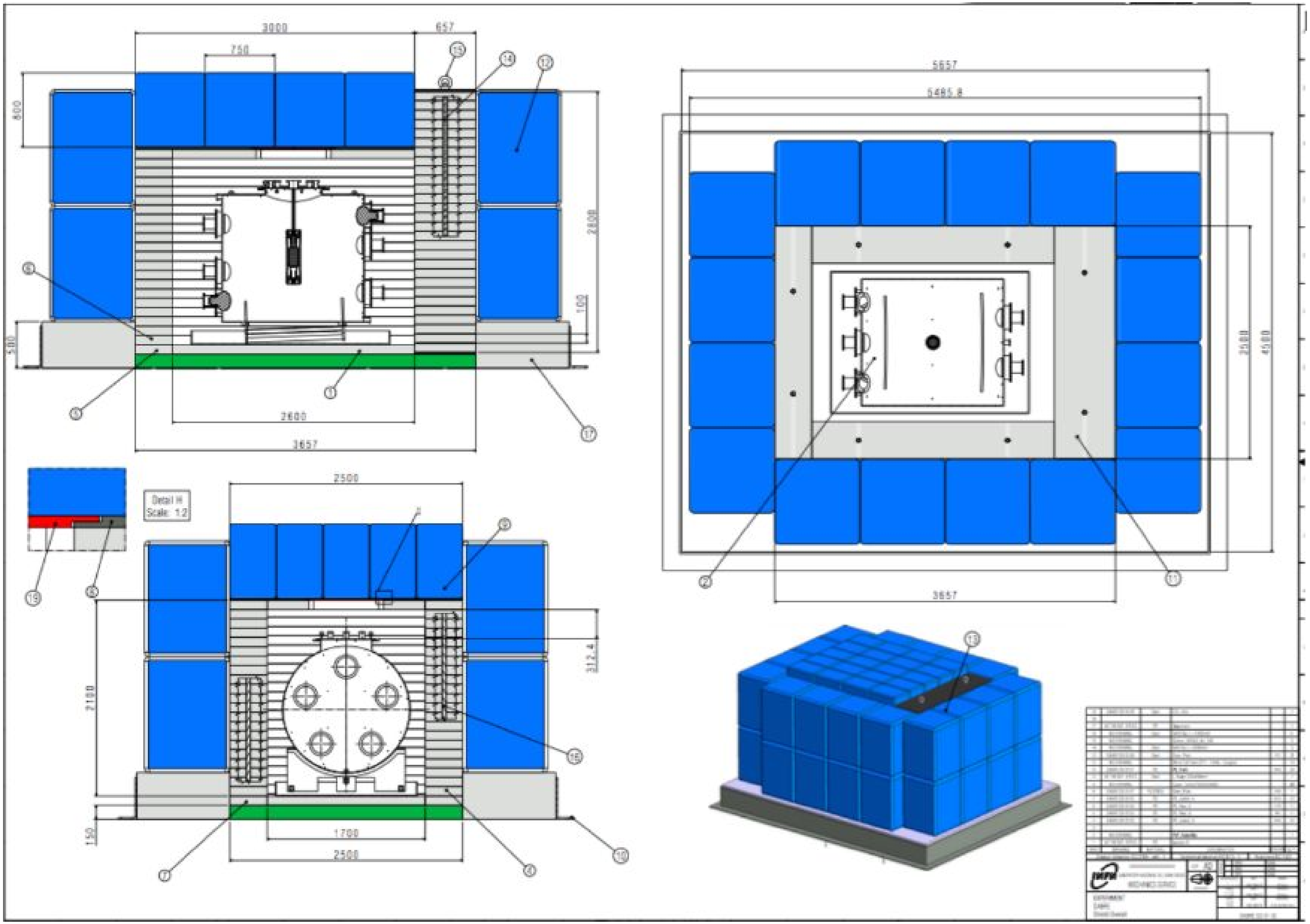
Cosmogenic background after
6 months underground



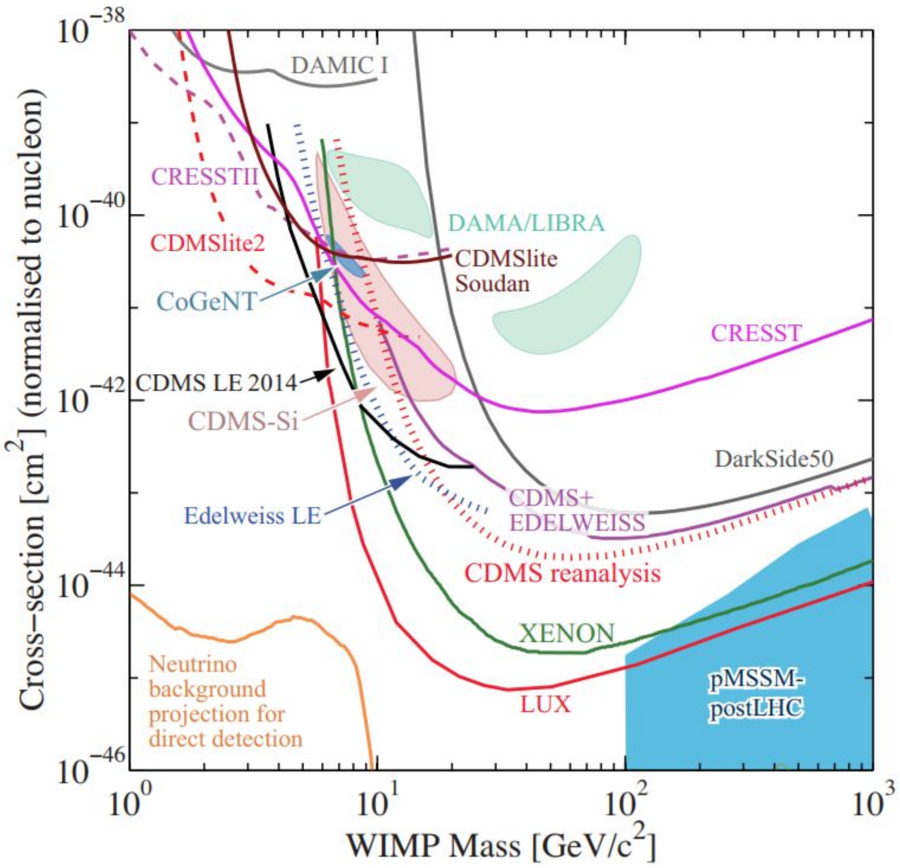
Crystal backgrounds in DMM

Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Intrinsic		
^{40}K	$2.5 \cdot 10^{-1}$	$4.0 \cdot 10^{-2}$
^{238}U	$2.0 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
^{232}Th	$1.9 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
^{87}Rb	$6.1 \cdot 10^{-2}$	$6.1 \cdot 10^{-2}$
^{210}Pb	$2.0 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
Tot Intrinsic	$3.5 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$
Cosmogenic		
^{22}Na	$3.6 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$
^{121}Te	$2.6 \cdot 10^{-1}$	$3.3 \cdot 10^{-2}$
^{125}Te	$5.3 \cdot 10^{-6}$	$5.1 \cdot 10^{-6}$
^{123m}Te	$7.6 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
^{121m}Te	$1.3 \cdot 10^{-4}$	$7.0 \cdot 10^{-5}$
^{125}I	$1.8 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$
^{126}I	$2.0 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$
^{129}I	$3.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$
^{127m}Te	$5.0 \cdot 10^{-5}$	$4.9 \cdot 10^{-5}$
^{24}Na	-	-
Tot Cosmogenic	$3.0 \cdot 10^{-1}$	$3.9 \cdot 10^{-2}$

PoP shielding design



Dark matter direct search panorama



- DAMA/LIBRA observes a modulation using 250 kg of NaI detector
- When interpreted in the WIMP framework (model dependent), tension with other results from experiments using different targets (XENON, LUX, CDMS, etc...)