Studio del background dell'esperimento SABRE

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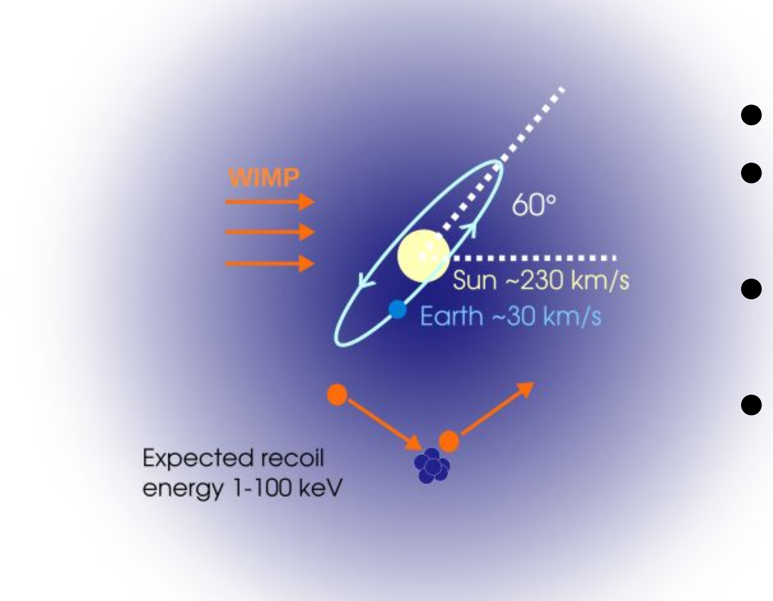
Università di Roma, La Sapienza
26/06/2018

Dark matter through annual modulation

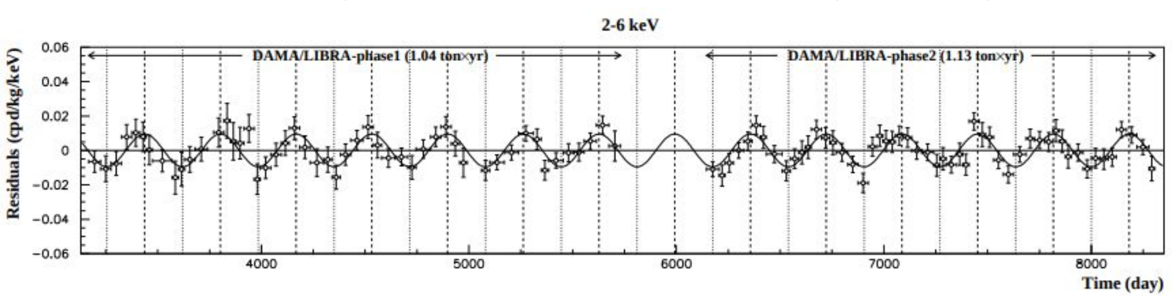


- About 85% of matter in the Universe is "dark"
- WIMPs (Weakly Interacting Massive Particles) are promising candidates for dark matter
- Direct detection principle: dark matter scattering off detector nuclei
- Annual modulation of the count rate is a model independent signature
  - period 1 year
  - maximum of modulation around June 2nd

Expected rate in an Earth-based detector

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

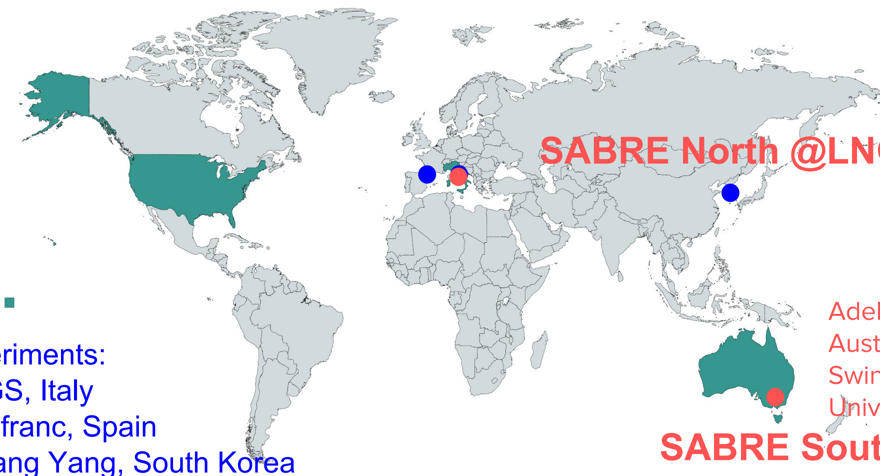
DAMA/LIBRA experiment at LNGS modulation phase1 + phase2: total **exposure 2.17 ton x yr**



arXiv:1805.10486

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

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



SABRE North @LNGS, Italy

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

SABRE South @SUPL, Stawell gold mine, Victoria, Australia

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

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

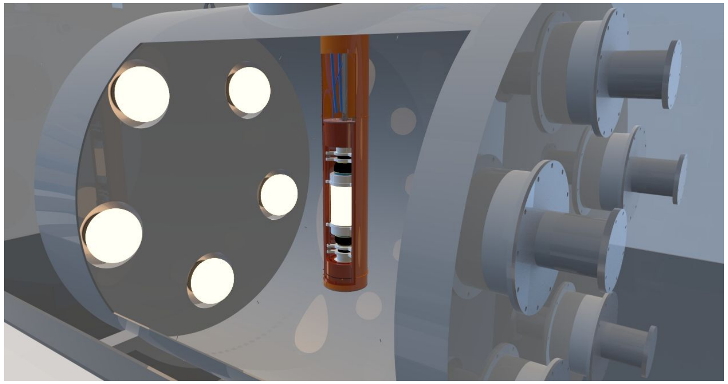
The SABRE Proof-of-Principle

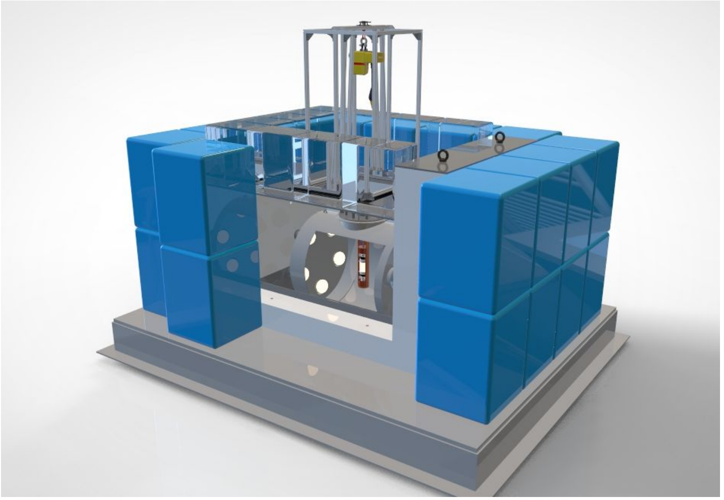
Goals:

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

Layout:

- 1 NaI(Tl) crystal (~5 kg)
- Crystal and PMTs will be coupled directly with optical coupling gel and sealed into a highly radiopure copper enclosure
- Active veto:
  - Cylindrical vessel (⌀ x h) = (1.4 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 Proof-of-Principle @ LNGS

Status:

- Shielding and vessel mounted in Hall C
- 5 kg crystal in Princeton, will be put in the enclosure and shipped to LNGS
- SABRE-PoP data taking foreseen in 2018

Background sources

SABRE goal: achieve background of 0.1 cpd/kg/keV and threshold of 1 keV

- **Internal**: radioactivity from all the setup materials
    - natural radioactivity: ^{238}U and ^{232}Th decay chains, ^{40}K
    - cosmogenic: ^{121}Te, ^{121m}Te, ^{125m}Te, ^{127m}Te, ^{125}I, ^{126}I, ^{129}I, ^{22}Na, ^{3}H

- **External**: natural radioactivity in LNGS rocks and concrete, muons
    - gammas from ^{238}U, ^{232}Th and ^{40}K in the rock, muon induced
    - neutrons (radiogenic, muon induced)

The most important sources of background for SABRE are the <u>intrinsic contaminations in the crystals:</u> ^{40}K, ^{87}Rb, ^{232}Th, ^{238}U

Low background is achieved with:

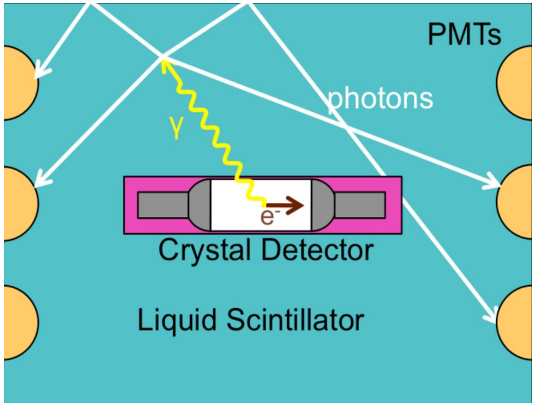
- **High purity crystals**
- **Active veto**: reduces external and internal background (ex. ^{40}K in the crystals)

The low background challenge

- **Ultra pure NaI(Tl) crystals**
  - Astro Grade powder (Sigma Aldrich)
  - clean growth procedure: collaboration between Princeton and RMD, Boston
  - test crystal of 2 kg
  - full scale crystal (4” diameter, 5 kg) now in Princeton, will be shipped to LNGS

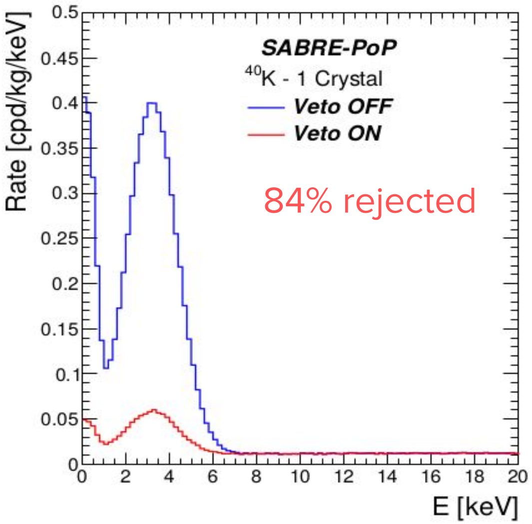
Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb]
K	100	~13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	~0.02	0.5-7.5×10^{-3}	<10^{-3}	<10^{-3}
Th	~0.02	0.7-10×10^{-3}	<10^{-3}	<10^{-3}

- A **liquid scintillator veto** surrounding the NaI detector at 4π allows to reduce
  - external backgrounds
  - internal backgrounds: ^{40}K



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

Veto on: E(Scint) < 100 keV



Background simulations with Geant4

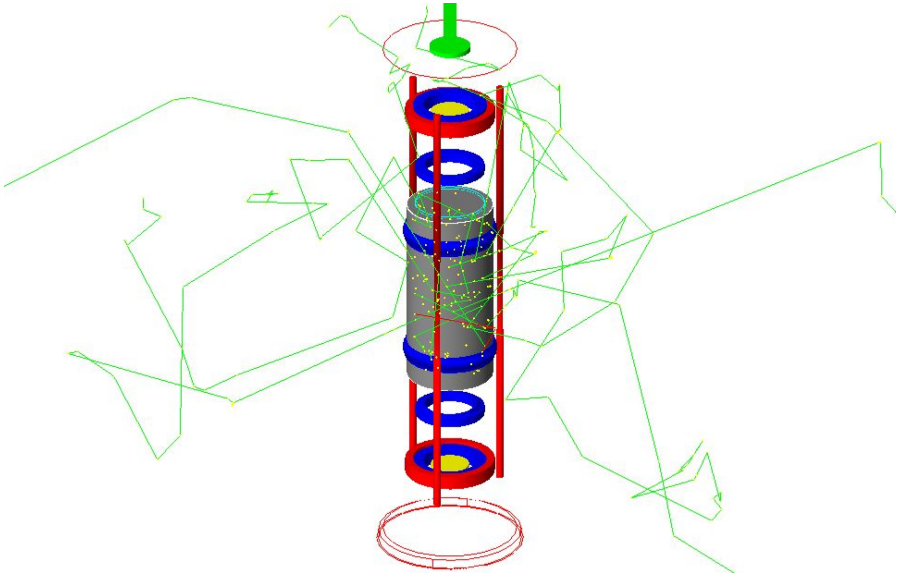
How does Geant4 work

Toolkit contains

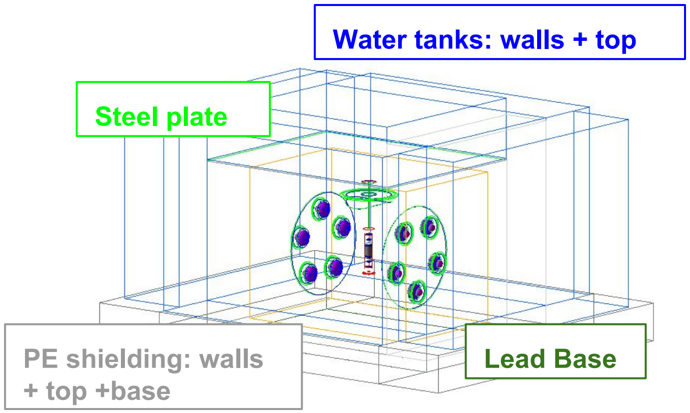
- physics of particle interaction and transport
- physics data (particle properties, cross sections, radioactive decays, ...)
- materials

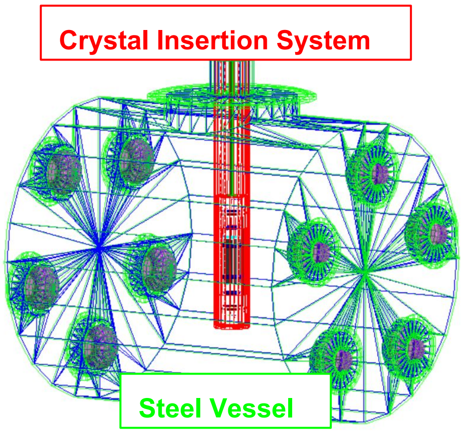
User defines:

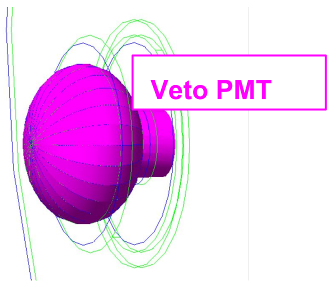
- detector geometry
- particles to be generated
- scoring of results



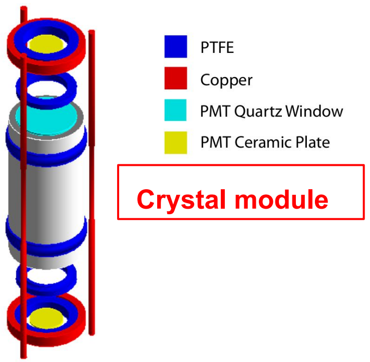
Internal Background (radioactivity in the setup materials)







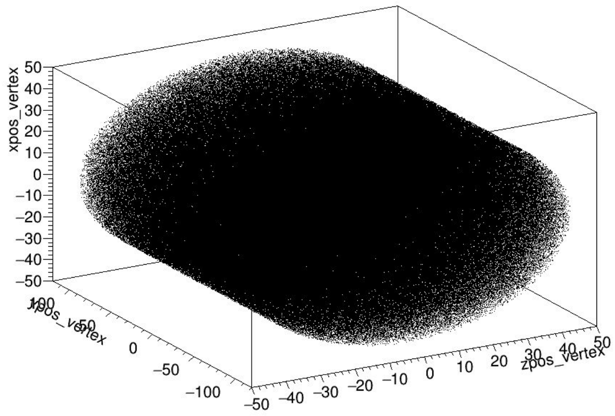
- GEANT4 based code with detailed geometry implementation
  - **Crystal**
  - **Crystal PMTs**: quartz window + body + feedthrough
  - **Enclosure**: wrapping, copper enclosure and small components inside
  - **Crystal Insertion System (CIS)**: copper tube, steel bar
  - **Veto**: steel vessel + liquid scintillator + 10 veto PMTs
  - **Shielding**: water + polyethylene + steel + lead (only passive)



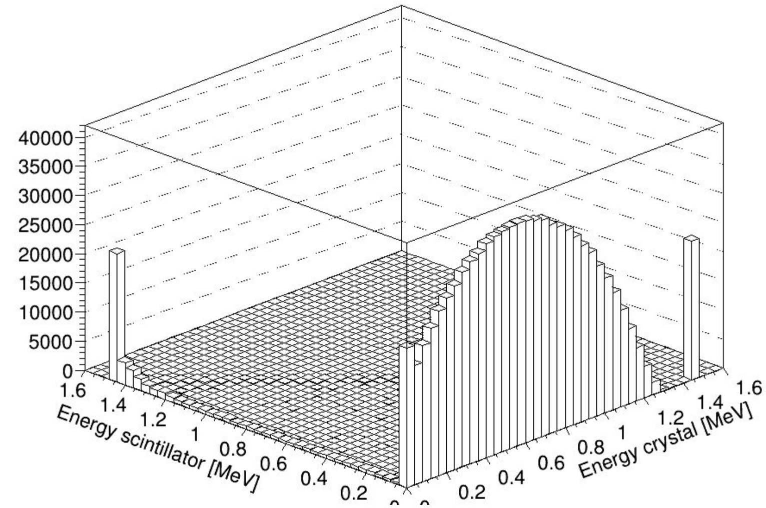
- GEANT4 v10.2.p03
  - Hadronic physics list: Shielding
  - EM physics list: G4EmStandardPhysics_option4
  - Fluorescence, auger electron emission and particle induced atomic relaxation accounted
  - G4EmExtraPhysics

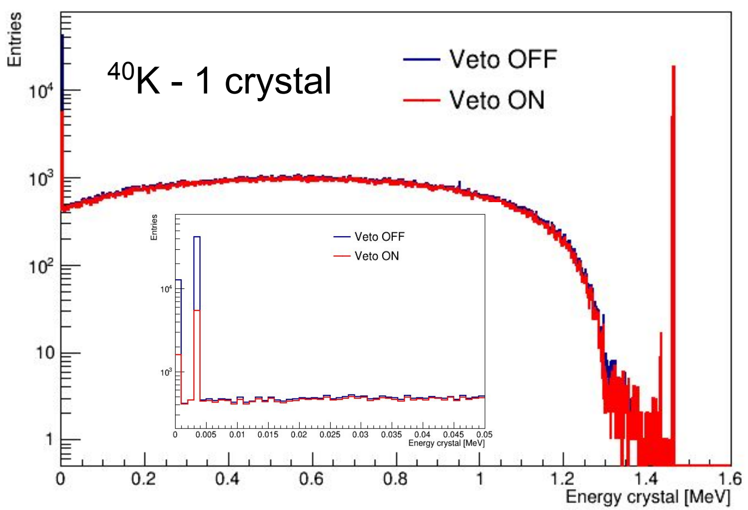
An Example: simulation of ^{40}K decay in the SABRE crystal

Radioactive decay positions

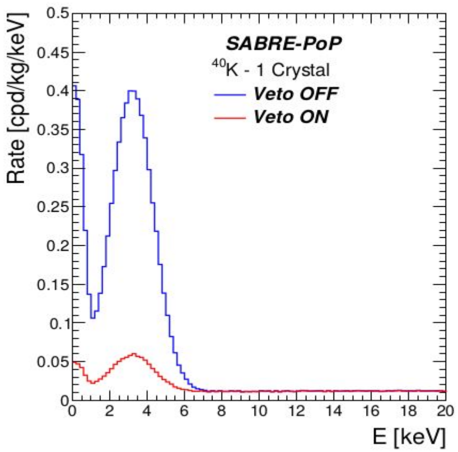


Lego plot: energy in the crystal vs energy in the liquid scintillator





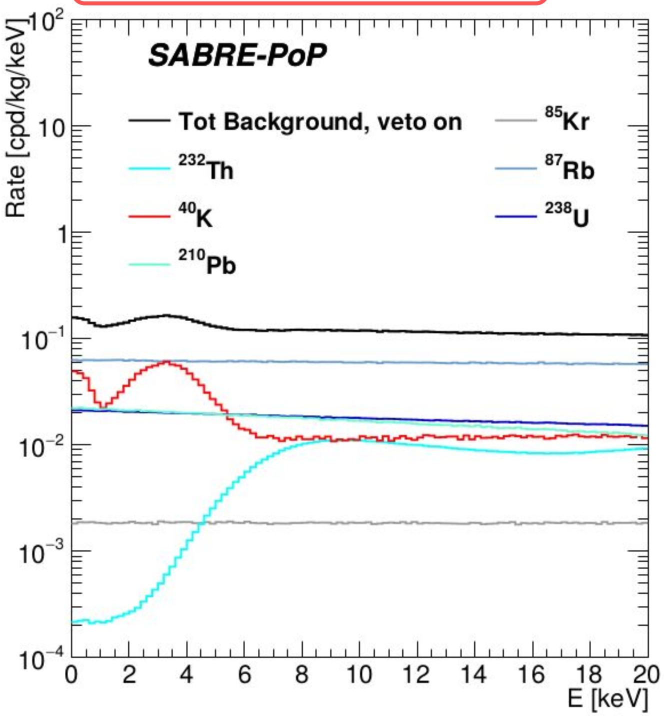
with resolution smearing applied



Crystal intrinsic background

- Generate all radioactive decays as explained in slide 11
- For decay chains, generate all the isotopes in the chain
- Normalize each spectrum to counts/day/kg/keV using the activity measured on the SABRE crystal test or powder
- Sum the contributions

Veto on: E(Scint) < 100 keV



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	$3.5 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$

arXiv:1806.09344

Cosmogenic backgrounds

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

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

- Activation Rate depends on the activation cross section and the cosmic ray flux

$$R \propto \int \phi_x(E)\sigma_x(E)dE$$

- CR flux should be corrected for Altitude, Geomagnetic cutoff and solar activity

$$\phi = \phi_0 F_{alt}(d) \cancel{F_{BSYD}(R_c, d, I)}$$

neglected, should have a small effect if the plane does not follow the polar route

$$F_{alt}(0\ \mathrm{m}) = 1$$

$$F_{alt}(11.000\ \mathrm{m}) \approx 455$$

Summary of crystal activation

Use the following assumptions:

- exposure at sea level for 1 year
- back and forth Italy/USA via plane or ship
- ship does not contribute w.r.t 1 year of previous exposure

Isotope	Half life (days)	Plane (µBq/kg)	Ship (µBq/kg)	Ratio plane/ship
^{3}H	4500	43	23	1.9
^{22}Na	949	980	500	2
^{113}Sn	115	249	89	2.8
^{121}Te	154	1295	475	2.7
^{125}I	59	5270	1170	4.5

Transportation of crystals by boat can reduce significantly cosmogenic background

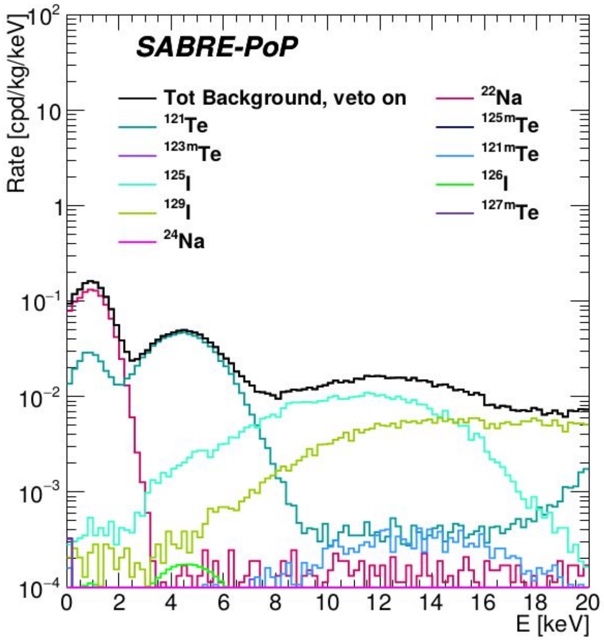
Crystal cosmogenic background

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

➜ compatible with ACTIVIA simulations for crystals that flew from US

Veto on: E(Scint) < 100 keV
6 months underground



ROI: 2-6 keV

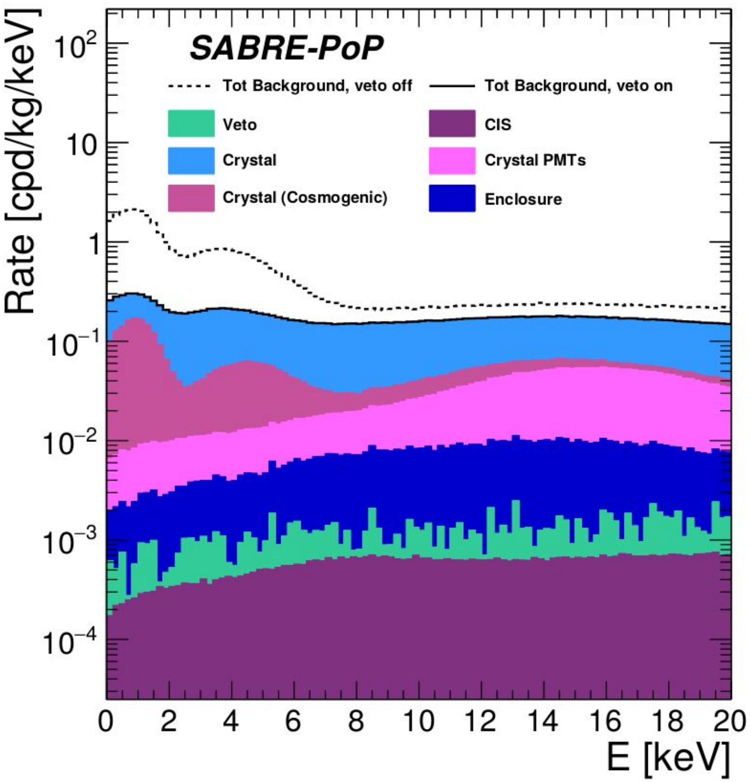
Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Cosmogenic		
^{121}Te	$2.6 \cdot 10^{-1}$	$3.3 \cdot 10^{-2}$
^{22}Na	$3.6 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$
^{125}I	$1.8 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$
^{129}I	$3.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$
^{126}I	$2.0 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$
^{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)	$3.0 \cdot 10^{-1}$	$3.9 \cdot 10^{-2}$

arXiv:1806.09344

Total internal backgrounds

Summary of the total internal backgrounds

Veto on: E(Scint) < 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 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	$7.4 \cdot 10^{-1}$	$2.2 \cdot 10^{-1}$

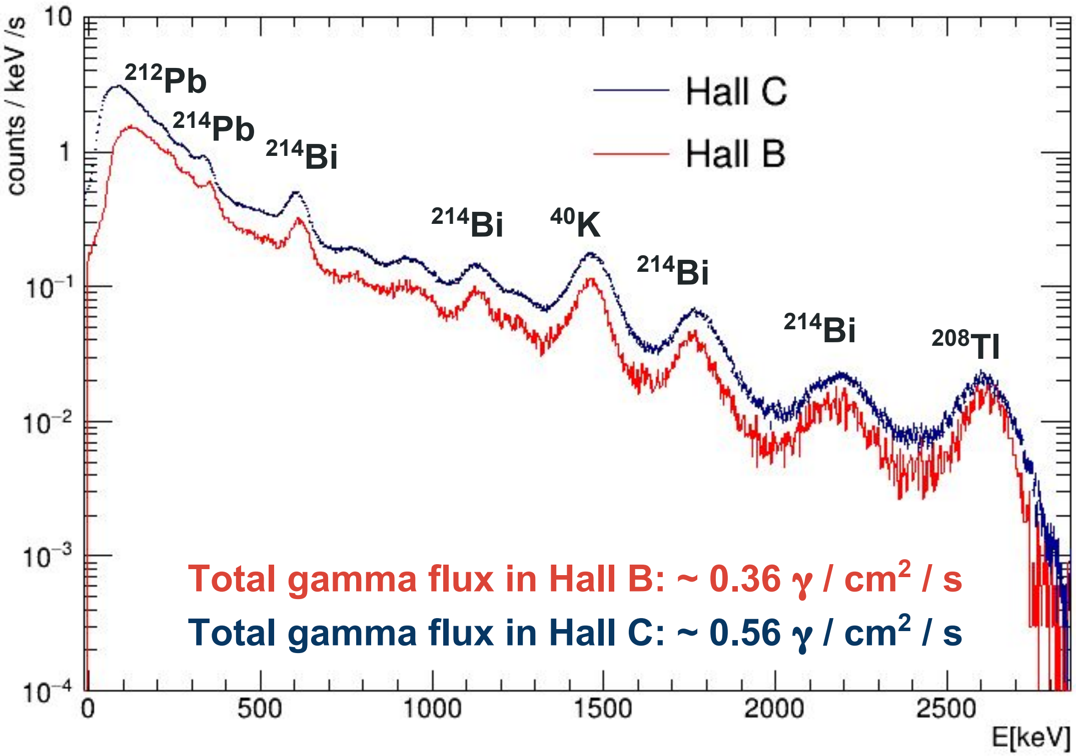
- **Veto rejection is ~70%**
- **Total background 0.22 cpd/kg/keV**, 5 times lower than DAMA background
- Highest contribution from Rb in the crystal, but we used the the upper limit contamination

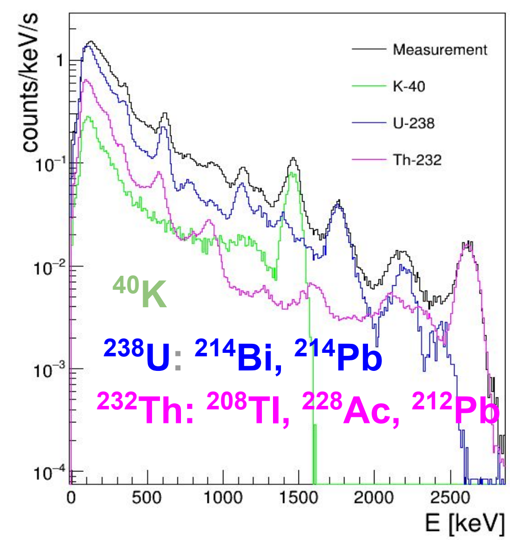
arXiv:1806.09344

External gamma background

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





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

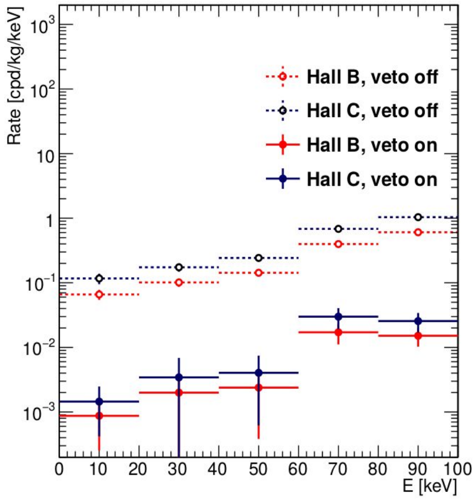
External gamma background

- Values obtained from deconvolution of experimental spectrum

	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**)

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



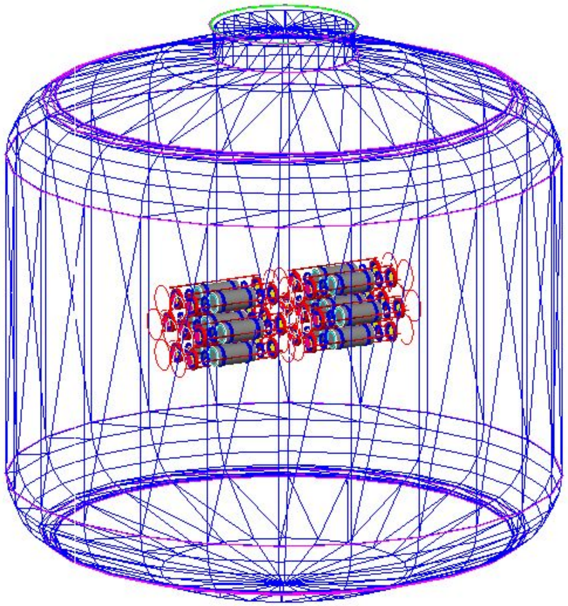
	Rate in [2-6] keV [cpd/kg/keV]
Gamma Hall B	< 4.0 10^{-3} (99% CL)
Gamma Hall C	< 5.4 10^{-3} (99% CL)
Total internal	0.22

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; muon background not yet studied.

Background using a crystal array (full scale detector)

- 7 + 7 crystal array



	Bkg single-hit & veto-on crystal array [cpd/kg/keV]	Bkg veto-on SABRE-PoP [cpd/kg/keV]	Ratio array/PoP [cpd/kg/keV]
Crystal	$1.35\ 10^{-1}$	$1.45\ 10^{-1}$	0.93
PMT quartz	$1.07\ 10^{-2}$	$1.12\ 10^{-2}$	0.95
Enclosure	$2.38\ 10^{-3}$	$1.93\ 10^{-3}$	1.23
Total	**$1.48\ 10^{-1}$**	**$1.58\ 10^{-1}$**	**0.93**

- All the internal backgrounds are of the **same order of magnitude in the single-crystal and crystal array geometry**

Conclusions

- The SABRE activity in Roma strongly focused on the Monte Carlo simulations of the background (arXiv:1806.09344)

- Guide the design of the experiment towards minimizing the background

- Will serve as a tool for interpreting the real background when experimental data become available

- According to the simulations we expect a background of ~0.22 cpd/kg/keV in the PoP
    - similar for the full scale experiment

- With 50 kg of NaI and 3 years of data taking we expect to confirm (refute) the presence of an annual modulation signal with the amplitude observed by DAMA at 6 (5) sigma (arXiv:1806.09340).

Backup slides

Radioactive decays in GEANT4

Decay library based on ENSDF database: half life, decay modes, branching ratios
https://www.nndc.bnl.gov/ensdf/

- Decay an unstable nucleus
  - Sample discrete decay emission: alpha, neutrinos (EC)
  - Sample continuous decay emission: Beta-Fermi-function (e, neutrinos)
  - Generate daughter nucleus
  - Take care of kinematics: energy- and momentum conservation

- Deexcite daughter nucleus
  - Sample gamma, X-rays and conversion electrons resulting from nuclear deexcitation
  - Sample fluorescence and Auger-electrons due to shell vacancies

- Per-decay simulation

The decay products are propagated in the detector according to the physics lists used by the user's simulation

SABRE expected sensitivity

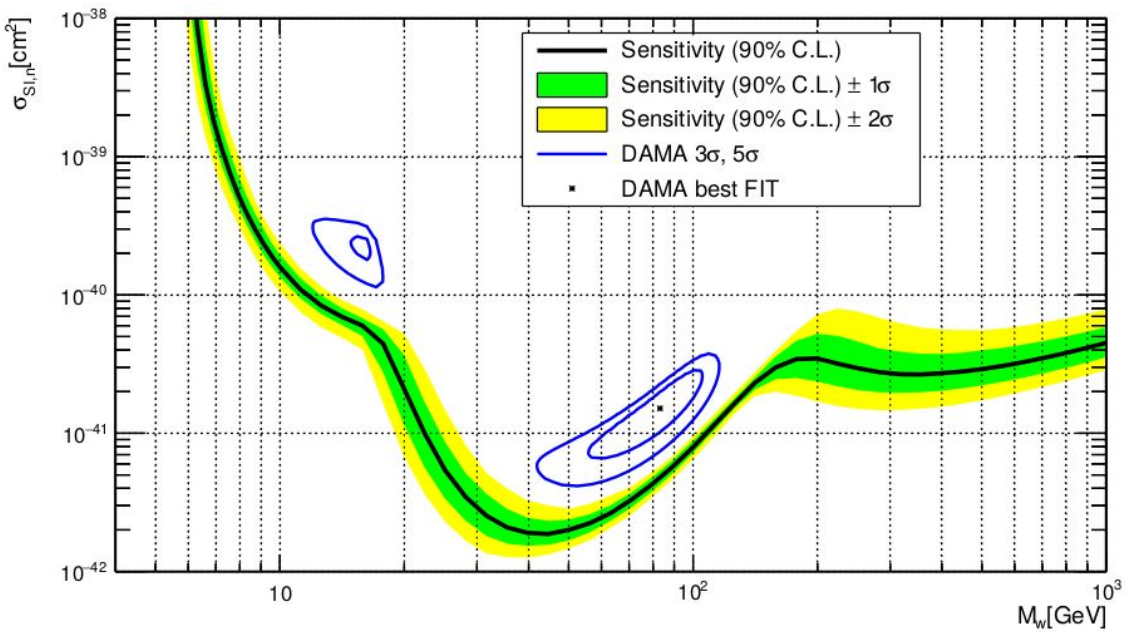
Assuming:

- 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 $Q_I = 0.09$

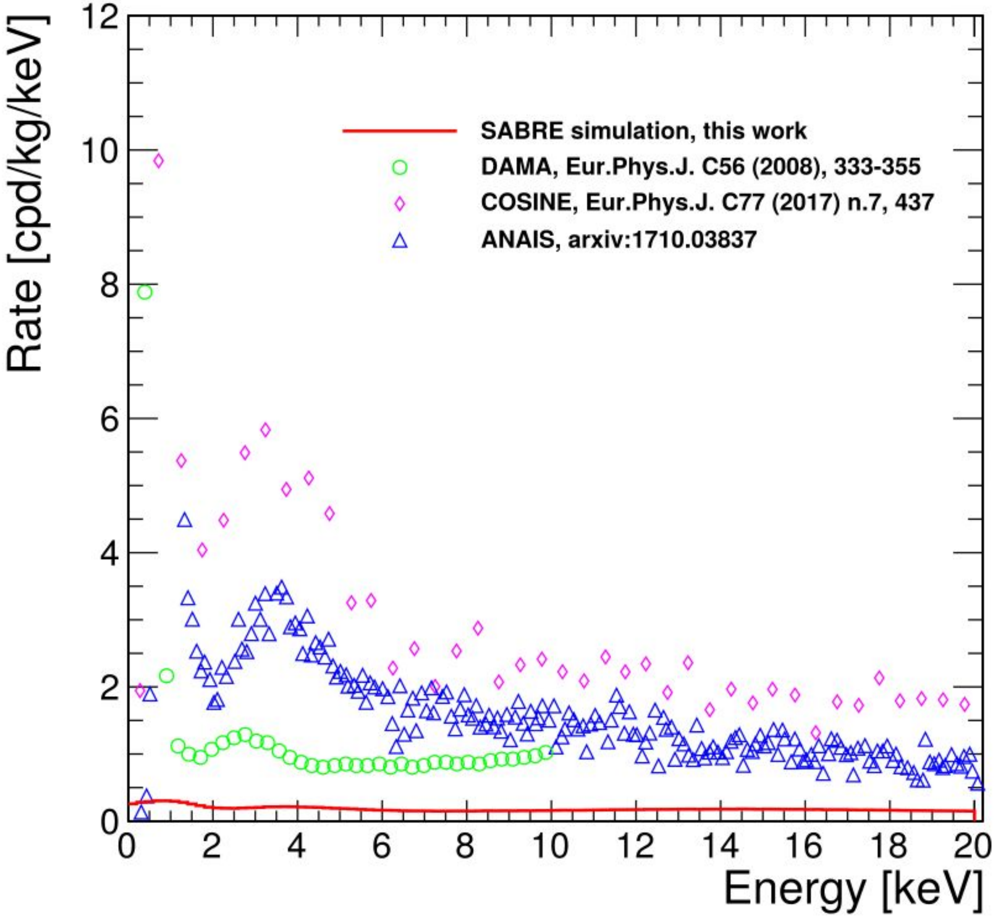
The SABRE full scale can:

- Confirm modulation with amplitude observed by DAMA at 6σ
- Refute it at 5σ
- spin independent WIMP-nuclear scattering limits as strong as 10^{-42} cm^2

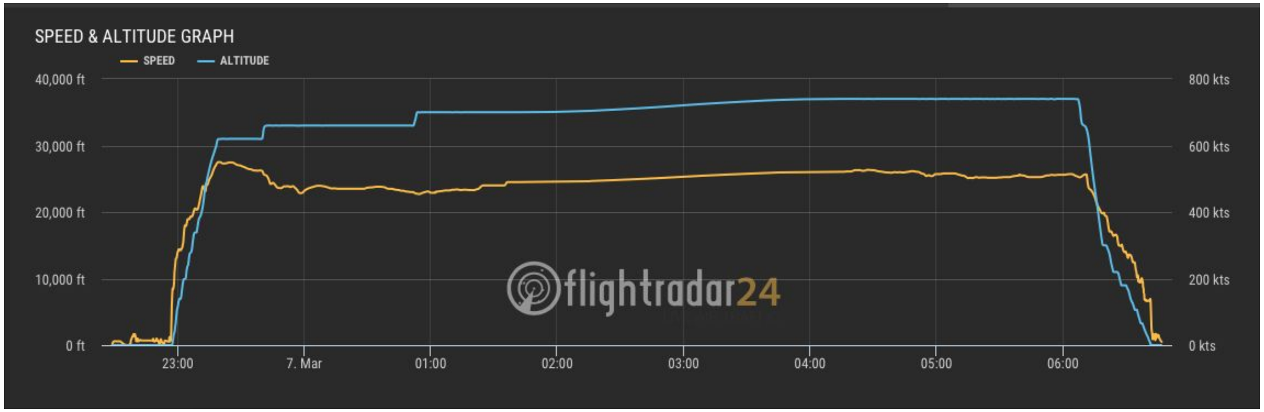
arXiv:1806.09340



Background of other NaI experiments



Altitude dependence



A flight from New York to Rome travels for ~8 hours at 11.000 m

$$F_{alt}(d) = \exp\left[\frac{d_{ref} - d}{L_n}\right]$$

- d_{ref} = 1033.7 g/cm^2 is the atmospheric depth of sea level
- L_n = 131.3 g/cm^2 is the attenuation length hof neutrons above 10 MeV
- An altitude of 11.000 m corresponds to an atmospheric depth of 230 g/cm^2

$$F_{alt}(0\text{ m}) = 1 \qquad F_{alt}(11.000\text{ m}) \approx 455$$

Geomagnetic and solar correction factors

$$F_{BSYD}(R_c, d, I) = N\left[1 - exp\left(\frac{-\alpha}{R_c^k}\right)\right]$$

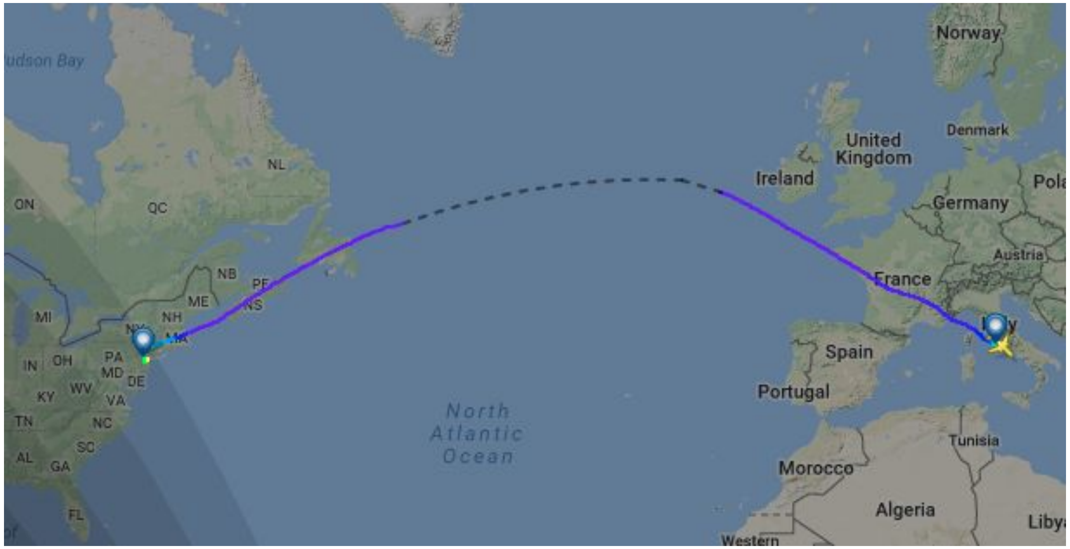
- R_c is the geomagnetic cutoff
- d is the atmospheric depth
- N is a normalization factor

At solar minimum

$$\alpha = \exp\left[1.84 + 0.094h - 0.09\exp(-11h)\right]$$

$$k = 1.4 - 0.56h + 0.24\exp(-8.8h) \quad ,$$

At this level this factor has been neglected. It may have a large impact on the results if the plane travels a polar route (not the case for flights from US to Italy).



Radioactivity of materials

arXiv:1806.09344

Crystal

Intrinsic			
Isotope	Activity [mBq/kg]		Ref.
^{40}K	0.31		[14]
^{238}U	$< 1.2 \cdot 10^{-2}$		[14]
^{232}Th	$< 4.1 \cdot 10^{-3}$		[14]
^{87}Rb	$< 8.9 \cdot 10^{-2}$		[14]
^{210}Pb	$< 3.0 \cdot 10^{-2}$		[24]
^{85}Kr	$< 1.0 \cdot 10^{-2}$		[24]
Cosmogenic			
Isotope	Activity [mBq/kg]	Half life [days]	Ref.
^{22}Na	0.80	949	[29]
^{126}I	4.30	13	[29]
^{24}Na	$2.6 \cdot 10^{-4}$	0.625	[24]
^{129}I	0.95	-	[24]
^{121}Te	1.27	17	[28]
^{125}I	7.20	59	[28]
^{121m}Te	0.89	154	[28]
^{123m}Te	1.17	119	[28]
^{125m}Te	0.92	57	[28]
^{127m}Te	0.37	107	[28]

[14] M. Antonello, et al., The SABRE project and the SABRE PoParXiv:1806.09340.
[24] R. Bernabei, et al., *The DAMA/LIBRA apparatus*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 592 (3) (2008) 297 – 315. doi:http://dx.doi.org/10.1016/j.nima.2008.04.082.
[28] J. Amaré, et al., Cosmogenic radionuclide production in NaI(Tl) crystals, JCAP 1502 (02) (2015) 046. arXiv:1411.0106, doi:10.1088/1475-7516/2015/02/046.
[29] M. Laubenstein, HPGe screening at LNGS.

Crystal PMTs Hamamatsu R11065

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

E. Aprile, et al., Lowering the radioactivity of the photomultiplier tubes for the XENON1T dark matter experiment, European Physical Journal C 75 (2015) 546. doi:10.1140/epjc/s10052-015-3657-5.

PFTE reflector foil

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

PFTE holders inside enclosure

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

E. Aprile, et al., Material screening and selection for XENON100, Astroparticle Physics 35 (2) (2011) 43 – 49. doi:http://dx.doi.org/10.1016/j.astropartphys.2011.06.001.

Radioactivity of materials [arXiv:1806.09344]

Copper parts: enclosure, CIS

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

L. Baudis, et al., Cosmogenic activation of xenon and copper, The European Physical Journal C 75 (10) (2015) 485. doi:10.1140/epjc/s10052-015-3711-3.

Steel vessel

Isotope	Activity [mBq/kg]	
	Lot n.S536 Thickness 3/8"	Lot n.T915 Thickness 1/4"
^{40}K	0.12	$<$ 0.03
^{238}U	3.7	0.49
^{232}Th	$<$0.41	0.082

E. Shields, SABRE: A search for dark matter and a test of the DAMA/LIBRA annual-modulation result using thallium-doped sodium-iodide scintillation detectors, Ph.D. Thesis Princeton University.

Veto PMTs Hamamatsu R5912

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

P. Agnes, et al., The veto system of the DarkSide–50 experiment, JINST P03016. doi:https://doi.org/10.1088/1748-0221/11/03/P03016

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	$3.5 \cdot 10^{-7}$

G. Alimonti, et al., The liquid handling systems for the Borexino solar neutrino detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 609 (1) (2009) 58 – 78. doi:http://dx.doi.org/10.1016/j.nima.2009.07.028.