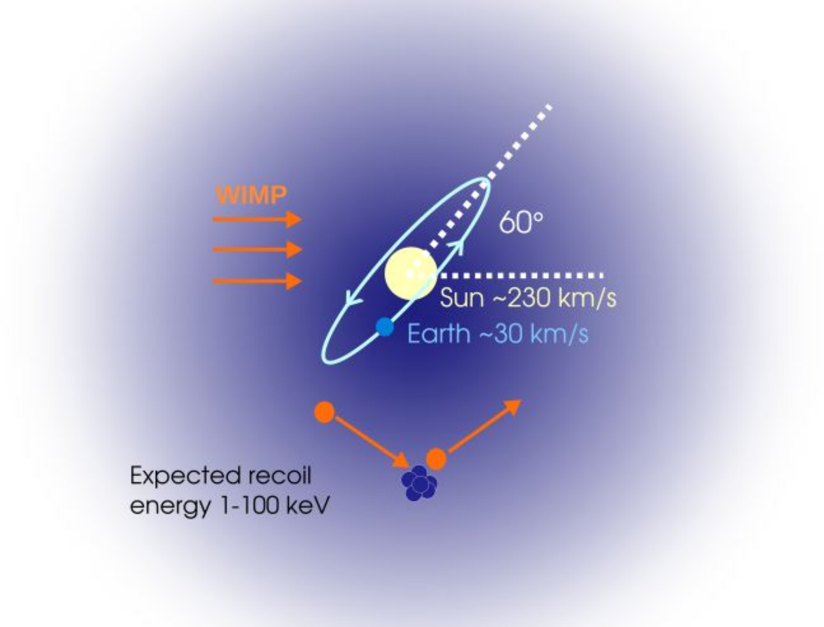
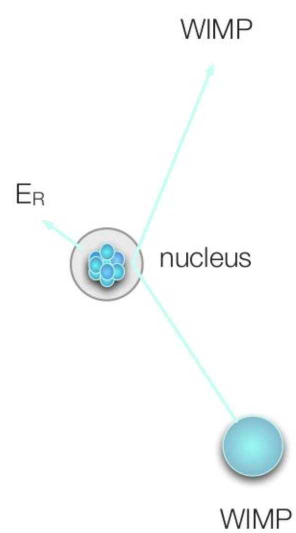
Background simulation of the SABRE experiment

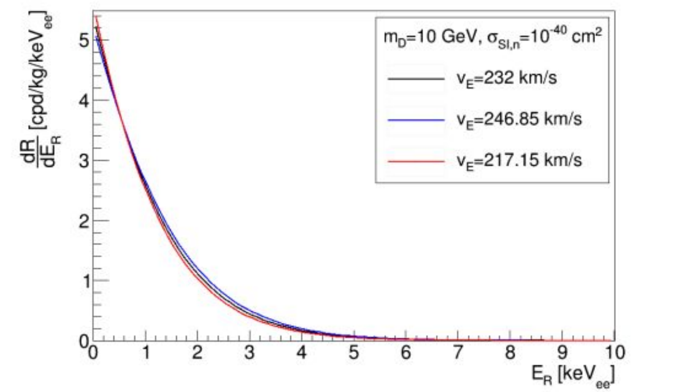
Giulia D'Imperio
INFN Roma

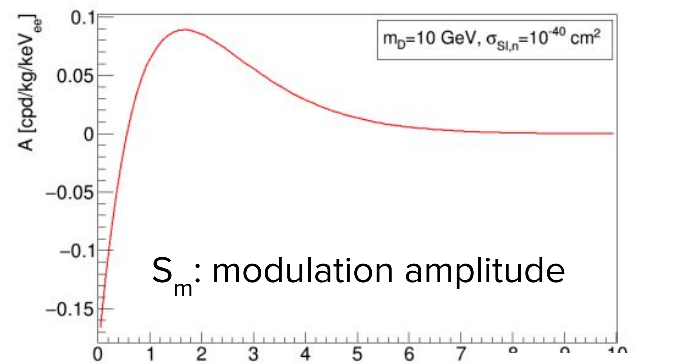
ENSAR2 workshop: GEANT4 in nuclear physics, CIEMAT Madrid, Spain
24-26 April 2019

Dark matter search with SABRE



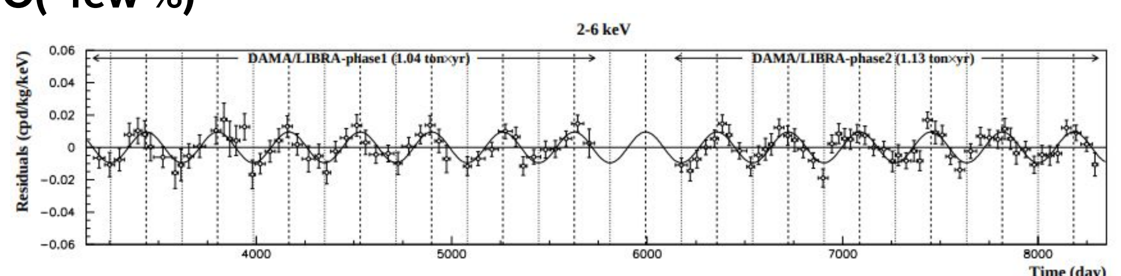






- Low recoil energy **1-100 keV**
- Differential rate of the order of **1 count/day/kg/keV** (cpd/kg/keV)
- Expected rate in an Earth-based detector is modulated
- Small modulation fraction **S_m/S_0 = O(~few %)**

$$\mathrm{R} = \mathrm{S}_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$



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

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

STAWELL UNDERGROUND PHYSICS LAB

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

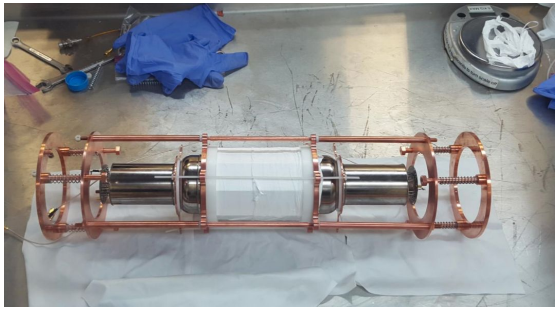
Experimental setup Proof-of-Principle (PoP)

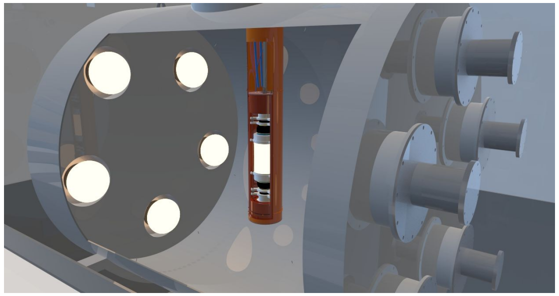
Layout:

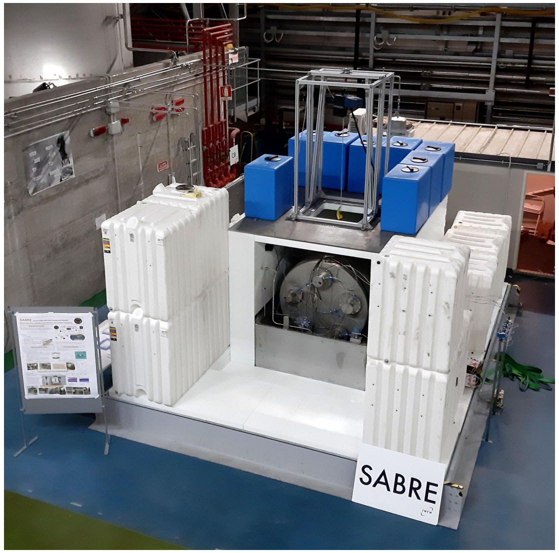
- 1 NaI(Tl) crystal (just arrived to LNGS from Princeton)
- Crystal and PMTs coupled directly with optical grease and sealed into a highly radio-pure copper enclosure
- Active veto:
  - Cylindrical vessel (⌀ x h) = (1.3 m x 1.5 m)
  - PC+PPO (3g/l) scintillator (mass ≃ 2 ton)
  - 10 Hamamatsu R5912-100 PMTs
- External shielding: combination of lead, polyethylene and water, sealed and filled with nitrogen

Goals:

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







GEANT4 simulation

Study with Monte Carlo the **expected background**
GEANT4 version **10.2 patch 03**

- during the design phase optimize the choice of materials and geometry
- understand experimental background
- validate the SABRE strategy

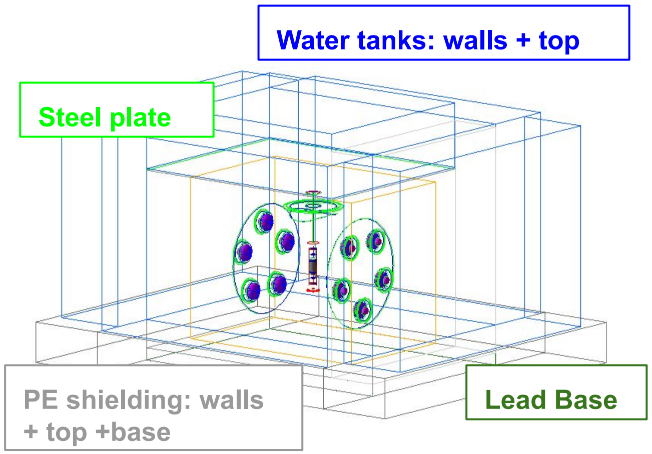
Radioactivity background

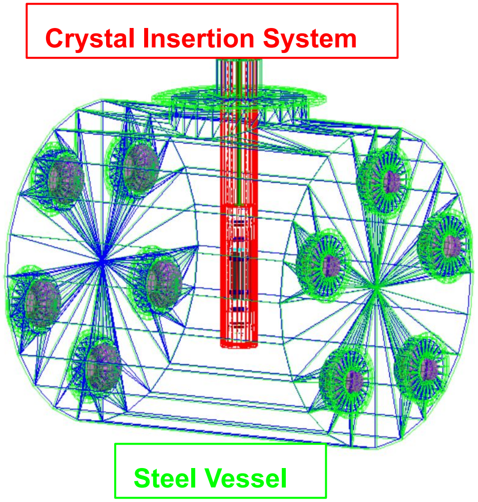
- **Radioactive decays**: `G4RadioactiveDecay`
- **Hadronic physics** list: `Shielding`
- **Electromagnetic physics** list: `G4EmStandardPhysics_option4`
  - Fluorescence, auger electron emission and particle induced atomic relaxation
- photo-nuclear reactions: `G4EmExtraPhysics`

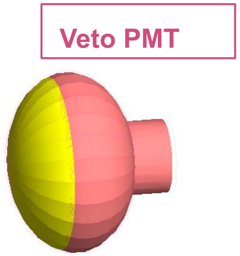
Further studies of **light collection**:

- production of **scintillation** and **cherenkov** photons: `G4OpticalPhoton`, `G4Cerenkov`, `G4Scintillation`
- **Refraction** and **Reflection** at medium boundaries: `G4OpBoundaryProcess`
- **Bulk absorption:** `G4OpAbsorption`
- **Rayleigh** scattering: `G4OpRayleigh`

Simulation of the PoP setup

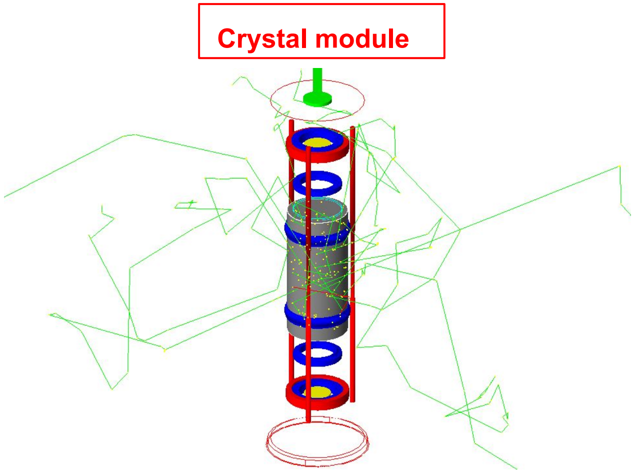






Geometry

- **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



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**: ^{40}K, ^{87}Rb, ^{232}Th, ^{238}U, ^{210}Pb out of equilibrium and **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

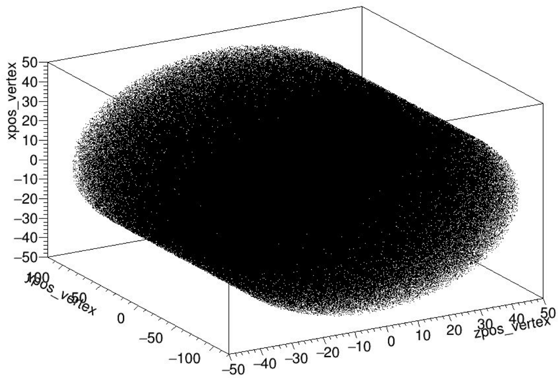
Simulation of radioactive decays in all the setup materials:

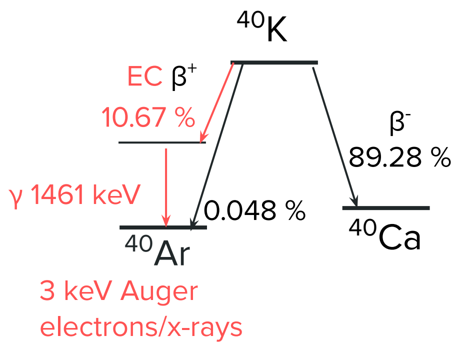
- input concentration of isotopes measured with **ICP-MS** or γ activity with **HPGe**:
  - NaI powder and crystals measured by SABRE
  - measurements of other materials available in literature
- calculations of **cosmogenic activation** with ACTIVIA software, 1 year exposure at sea level and 10 hours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

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

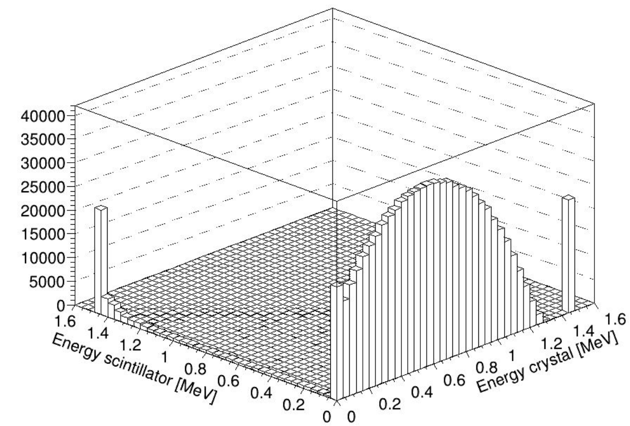
- Primary generator `G4GeneralParticleSource` (GPS)

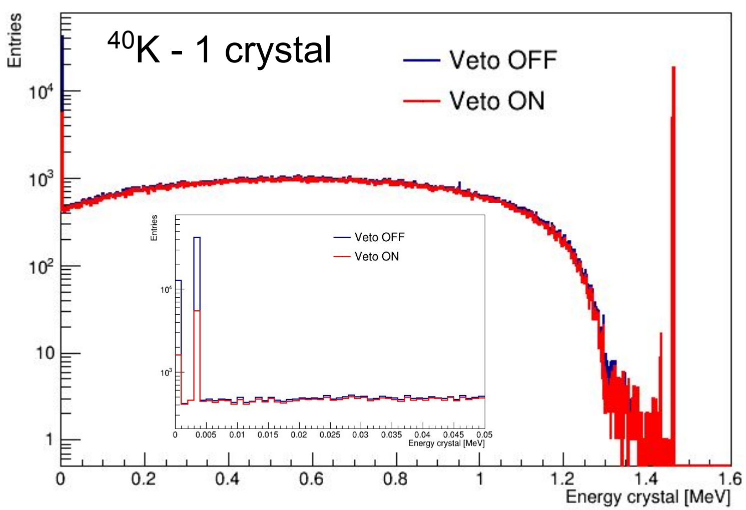
Radioactive decay positions confined into the crystal volume





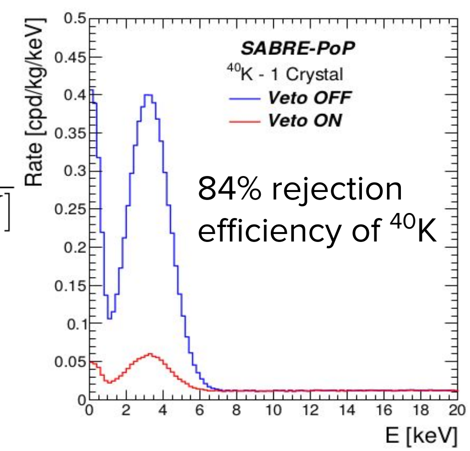
Energy in the crystal vs energy in the liquid scintillator





Resolution smearing

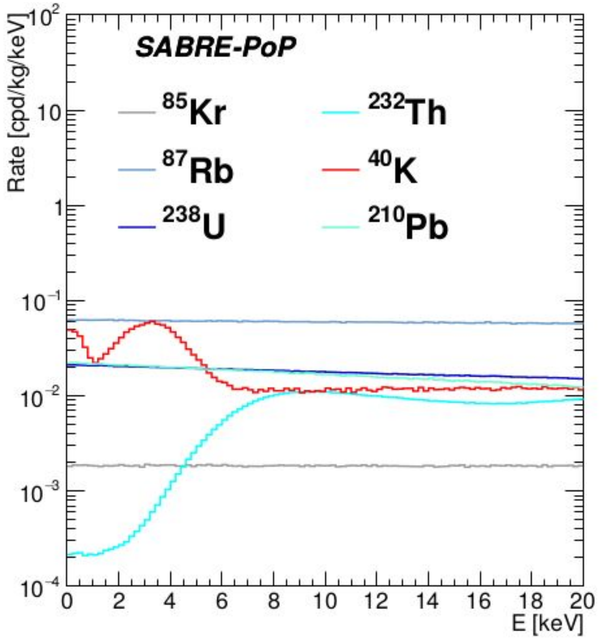
$$\sigma(E)/E = 0.02\sqrt{E[\mathrm{MeV}]}$$



Crystal intrinsic background

- Generate radioactive decays
- For decay chains, generate all the isotopes in the chain
- Normalize each spectrum to counts/day/kg/keV
- 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	$3.5 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$

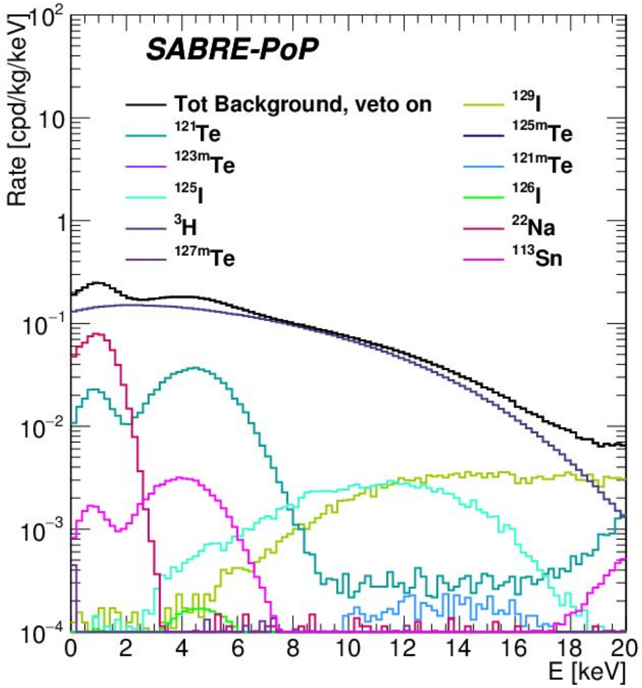
Astroparticle Physics
Volume 106, March 2019, Pages 1-9

Crystal cosmogenic background

Cosmogenic activation 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: E(Scint) < 100 keV



ROI: 2-6 keV

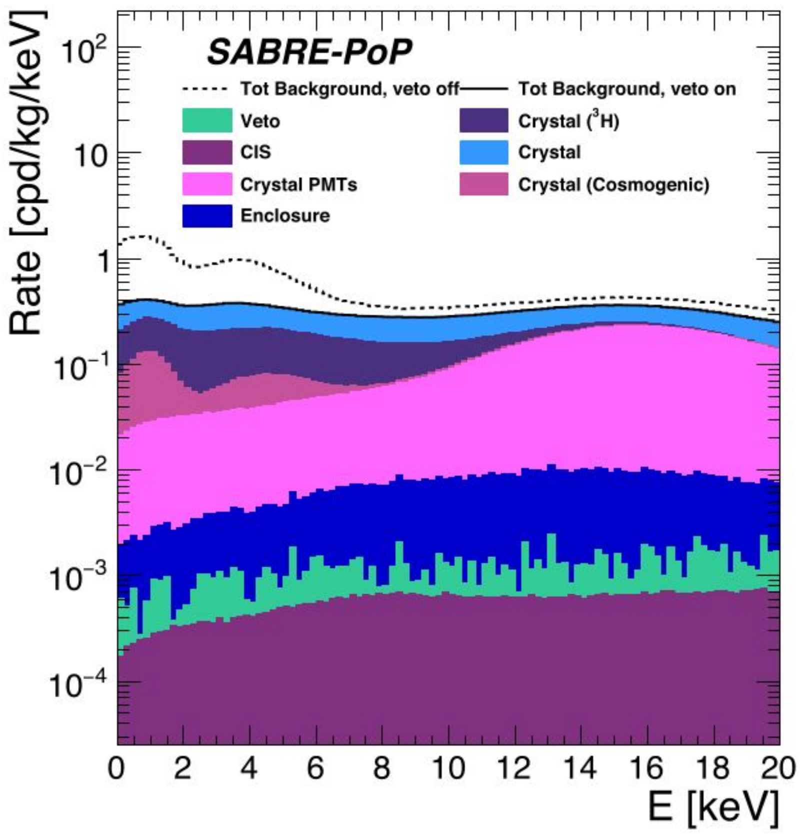
Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Cosmogenic		
^{3}H	$1.4 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$
^{121}Te	$2.0 \cdot 10^{-1}$	$2.6 \cdot 10^{-2}$
^{113}Sn	$1.2 \cdot 10^{-2}$	$2.2 \cdot 10^{-3}$
^{22}Na	$2.1 \cdot 10^{-2}$	$1.5 \cdot 10^{-3}$
^{125}I	$4.4 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$
^{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)	$3.8 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$

Astroparticle Physics
Volume 106, March 2019, Pages 1-9

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

- **Veto rejection is ~56%**
- Total background **0.36 cpd/kg/keV**
- If confirmed with data, **lowest background with NaI(Tl)** detector

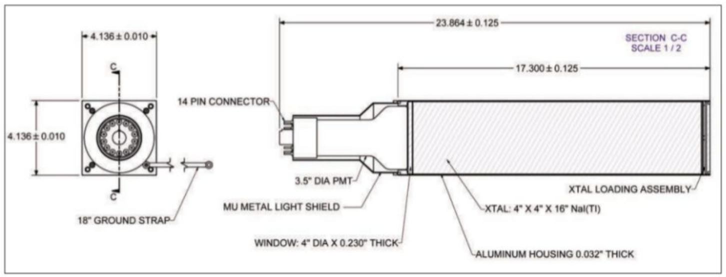
Astroparticle Physics
Volume 106, March 2019, Pages 1-9

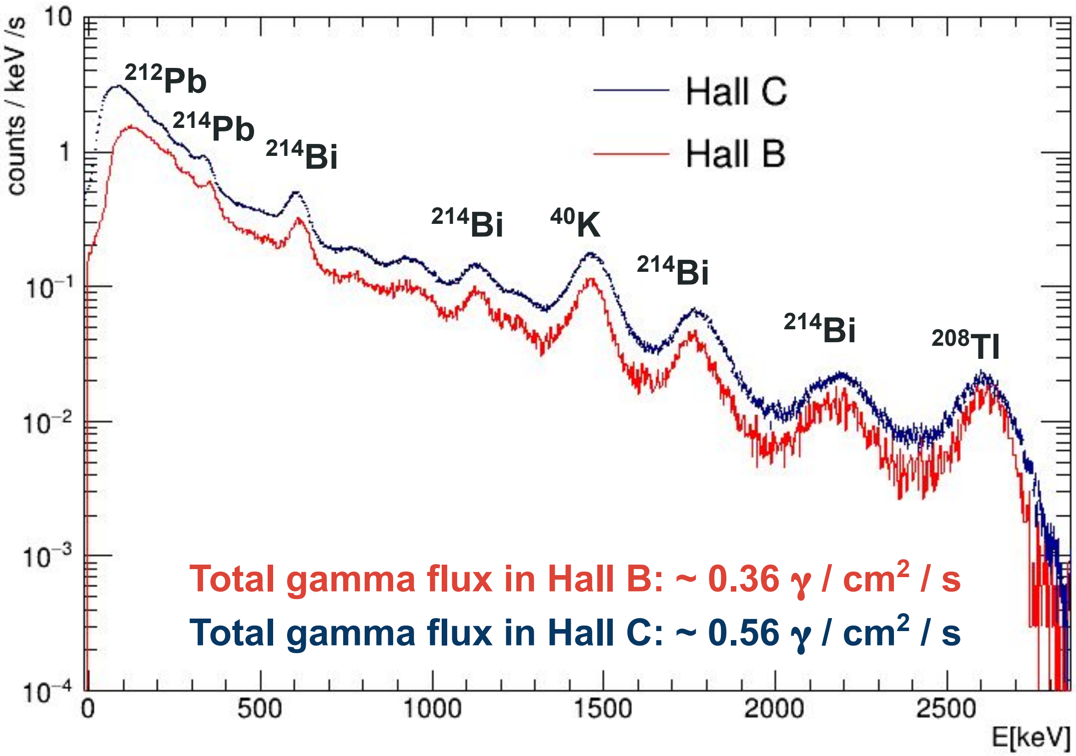
Radioactivity of surroundings: external γ

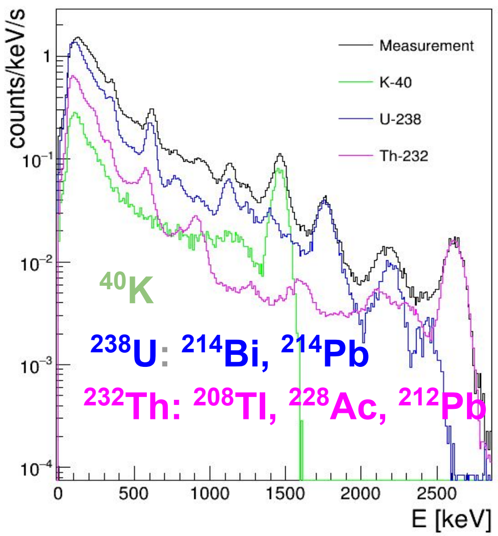
External background in Hall B and Hall C of LNGS has been measured with a standard grade NaI(Tl) crystal.

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

905-16 NaI Scintillation Detector, 4- x 4-in. crystal, 3-in. tube







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

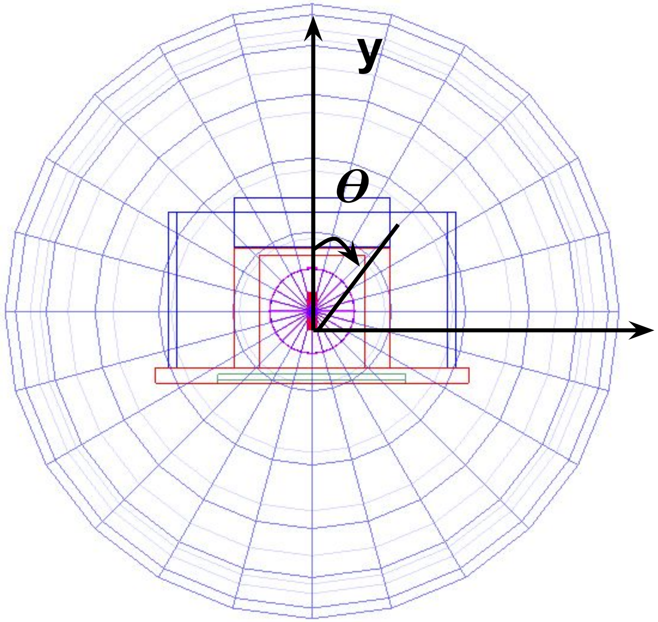
External γ simulation

- 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**)

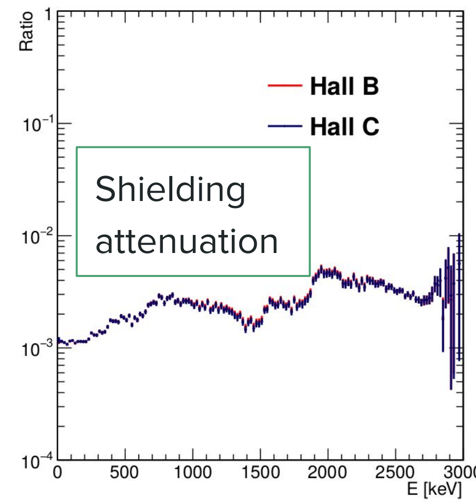
Front view

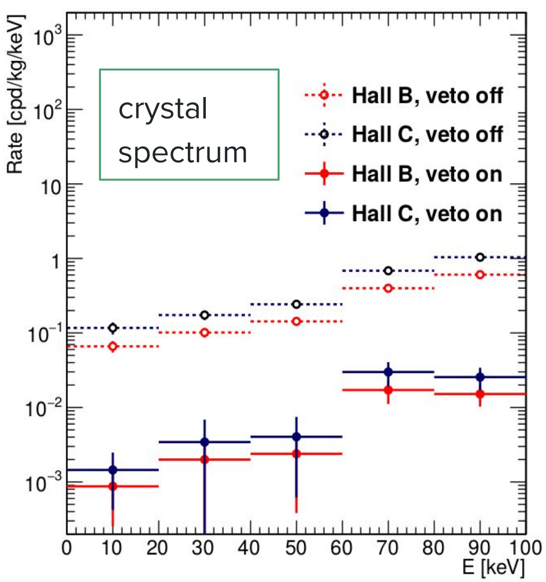


- Rock cavern simplified
  ➔ rock spherical shell of 40 cm thickness and 4.5 m internal radius in order to contain the shielding
- Input contaminations of ^{40}K, ^{238}U and ^{232}Th in the rock shell from the table

External γ background

- **Shielding attenuation vs energy** is estimated from the ratio of spectra with and without shielding in **liquid scintillator**
- Attenuation is applied to crystal spectrum





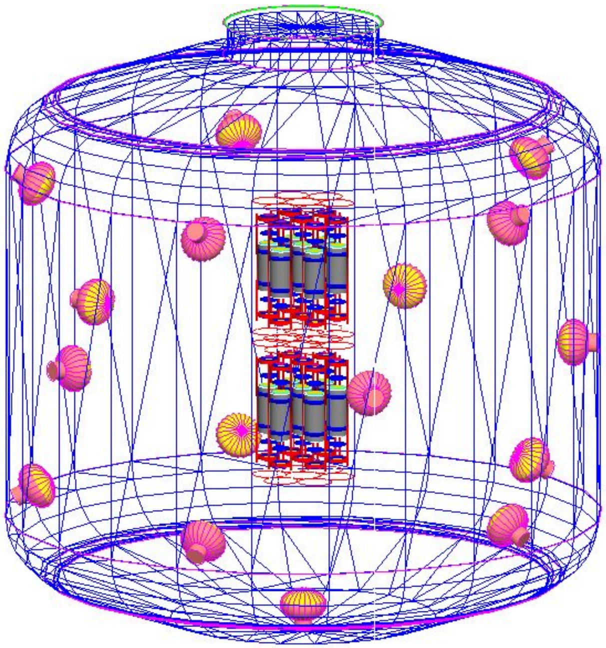
	Rate in [2-6] keV [cpd/kg/keV]
Gamma Hall B	< 4.0 10^{-3} (99% CL)
Gamma Hall C	**< 5.4 10^{-3}** (99% CL)
Total internal	**0.36**

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; muon background not yet studied.

Background of the full scale detector

- 7 + 7 crystal array, total weight ~70 kg



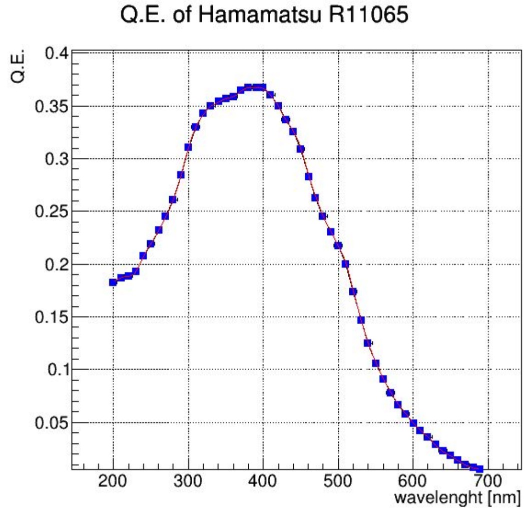
	Bkg single-hit & veto-on crystal array [cpd/kg/keV]	Bkg veto-on SABRE-PoP [cpd/kg/keV]	Ratio array/PoP [cpd/kg/keV]
Crystal	$1.35\ 10^{-1}$	$1.45\ 10^{-1}$	0.93
PMT window	$1.07\ 10^{-2}$	$1.12\ 10^{-2}$	0.95
Enclosure	$2.38\ 10^{-3}$	$1.93\ 10^{-3}$	1.23
Total	**$1.48\ 10^{-1}$**	**$1.58\ 10^{-1}$**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

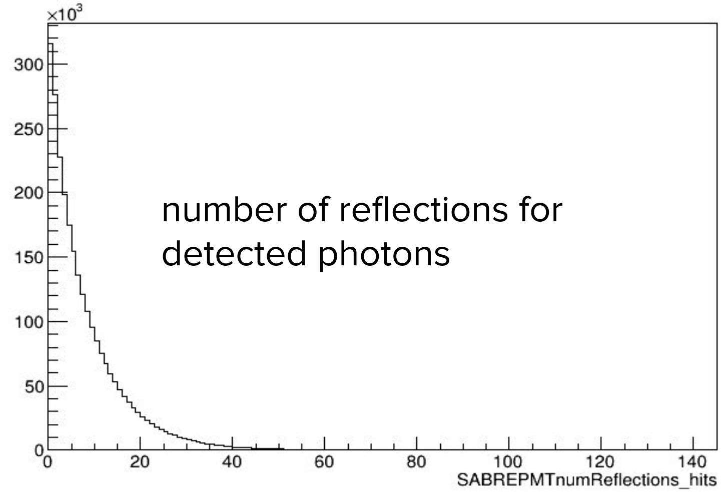
- Internal backgrounds are of the **same order of magnitude in the single-crystal and crystal-array geometry**

Light collection in the crystals

- NaI(Tl) light yield 40000 photons/MeV
- Emission spectrum peaked @420 nm
- Teflon reflector, diffusive reflection
- **Expected light collection 9 p.e./keV**
  - 22.9 % detected photons
  - 44.1 % absorbed because of PMT QE
  - 5.7 % absorbed in crystal
  - 22.6 % absorbed in wrapping
  - 4.7 % other

On average 5-6 reflections before being detected/absorbed





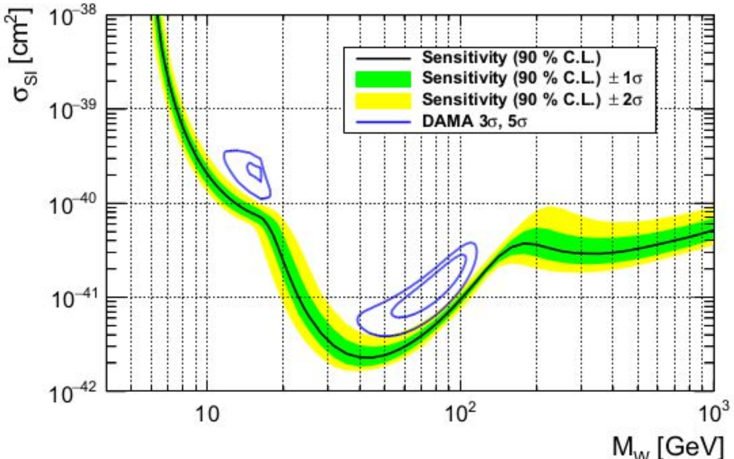
Summary of SABRE Monte Carlo simulations

Monte Carlo fundamental in the design phase

- In the near future we expect to:
  - use Monte Carlo to understand background sources
  - validate SABRE strategy and learn precious informations for the next phase
- In progress:
  - preliminary background simulations for the full scale experiment
  - preliminary radiogenic neutron external background, muon-induced neutrons to be done

If Monte Carlo prediction confirmed with data:

- lowest background among NaI(Tl) based detectors for dark matter (DM)
- double location in opposite hemispheres will discriminate DM from background
- with 3 years and 50 kg the DAMA result can be tested at 5σ sensitivity



arXiv:1806.09340
(accepted by EPJC)

Conclusions

- SABRE simulations use standard classes and physics lists of GEANT4
  - Radioactive decay
  - EM and hadronic interactions
  - save total energy deposited in the crystals and the veto
  - track optical photons and study light collection

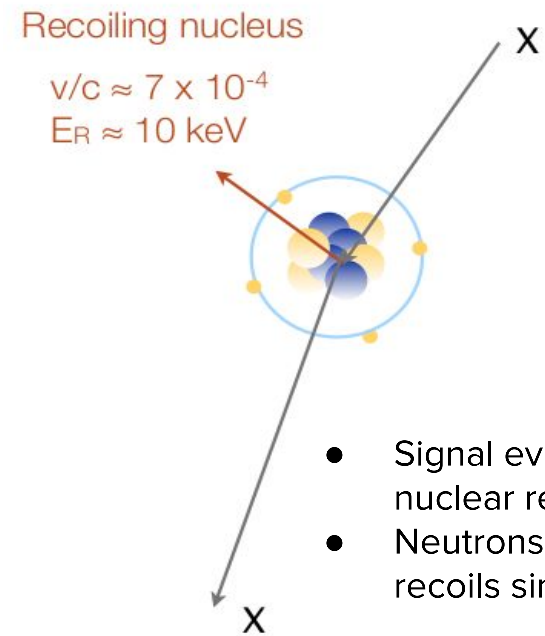
- Messages/requests for GEANT4 community:
  - **Generation of a primary from a complex volume**, large surface and small volume: the use of gps with the confine method often fails. Possibility to set the number of iterations before the code ignore the confine command and generate something in the volume defined for generation.

  - **General recommendations** for generating **flux of particles with isotropic direction** through a detector, for example to study detector acceptance or the background as in slide 14. Partly addressed by Marc Verderi in his talk.

  - Standard procedure to **remove optical photons** from the account of energy deposited.

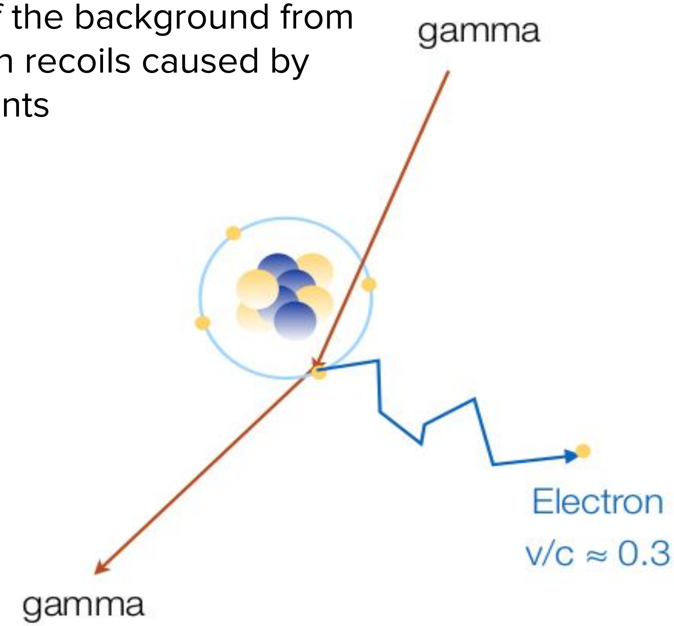
Backup

Signal and backgrounds



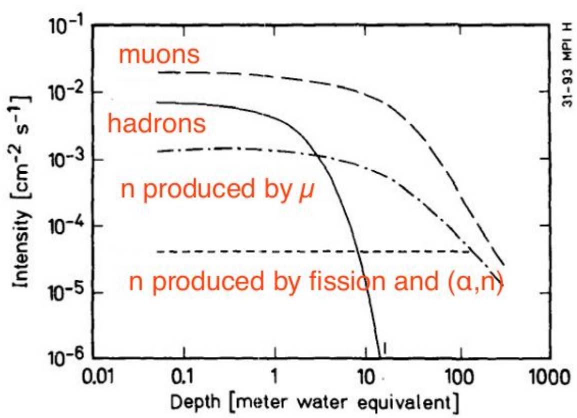
- Signal events produce nuclear recoil
- Neutrons produce nuclear recoils similar to a WIMP

- 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

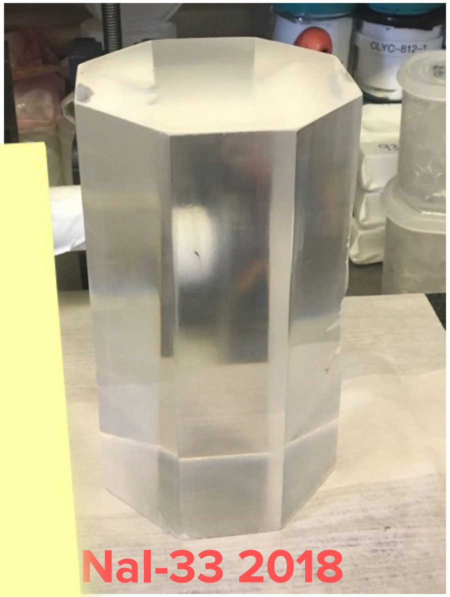
- Astro Grade powder (Sigma Aldrich, now Merck)
- clean growth procedure: collaboration between Princeton and RMD, Boston
- Small crystal (2 kg) grown with optimal procedure in 2015

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.

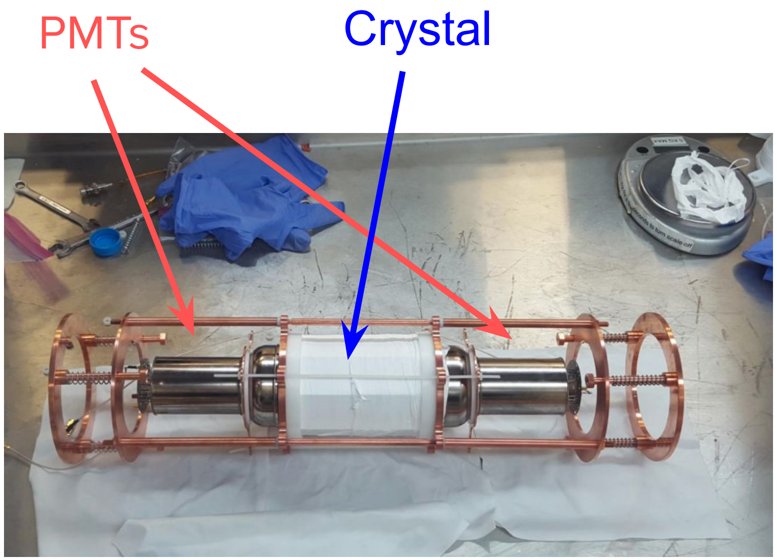
Average K level higher than the value of 9 ppb that was achieved in the crystal grown in 2015-2016.

- 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



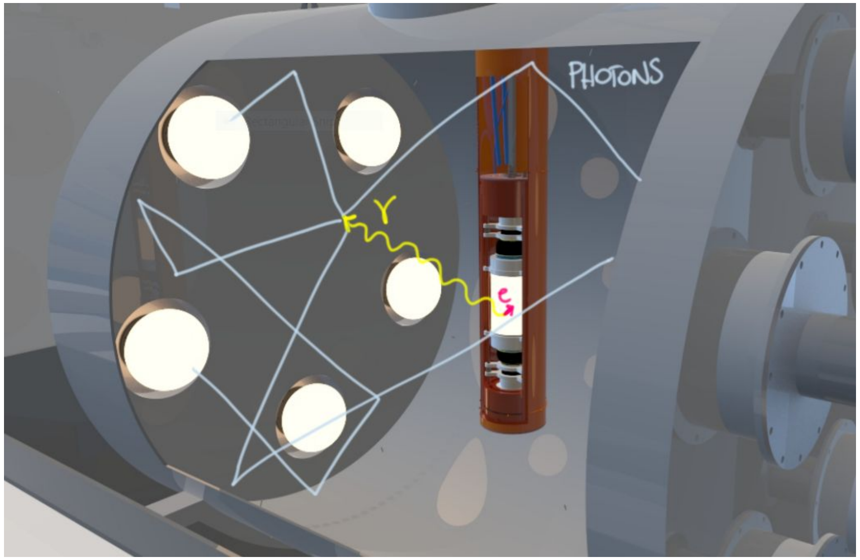
Current Design:

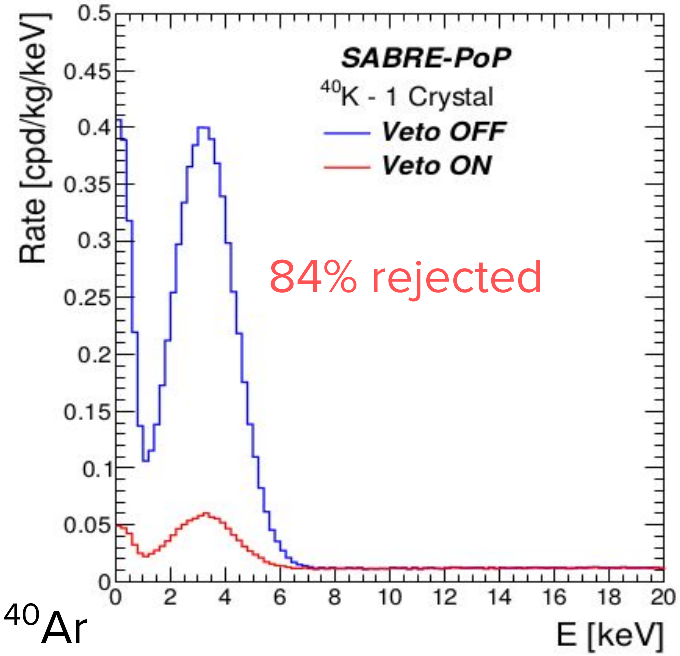
- 2 x Hamamatsu R11065-20 3” PMTs per crystal with High QE >35% and minimal contaminations
- Direct PMT-Crystal coupling for maximal light yield
- Custom preamplifiers and super bialkali photocathodes → less afterglow and dark noise

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



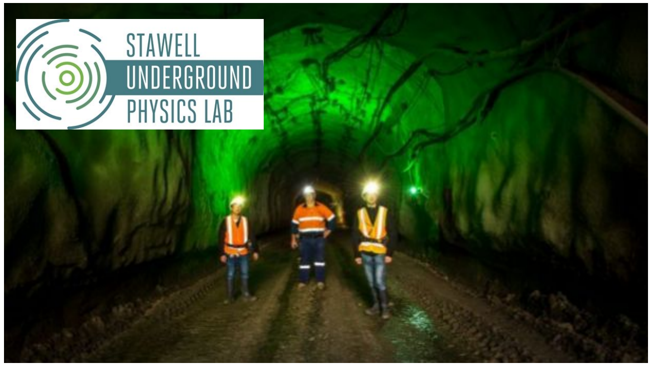


^{40}K (11% BR) decays through electron capture to ^{40}Ar

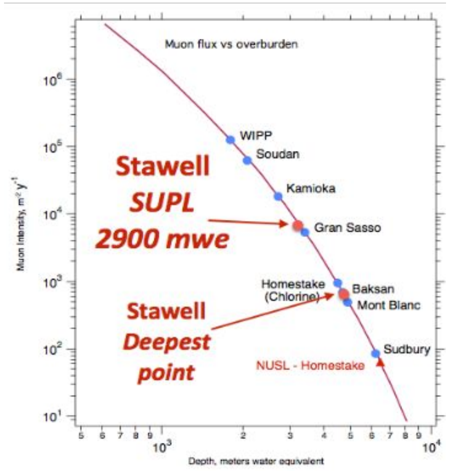
- γ 1460 keV
- X-rays, Auger electrons 3 keV

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 2018
- Will host SABRE and other experiments



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

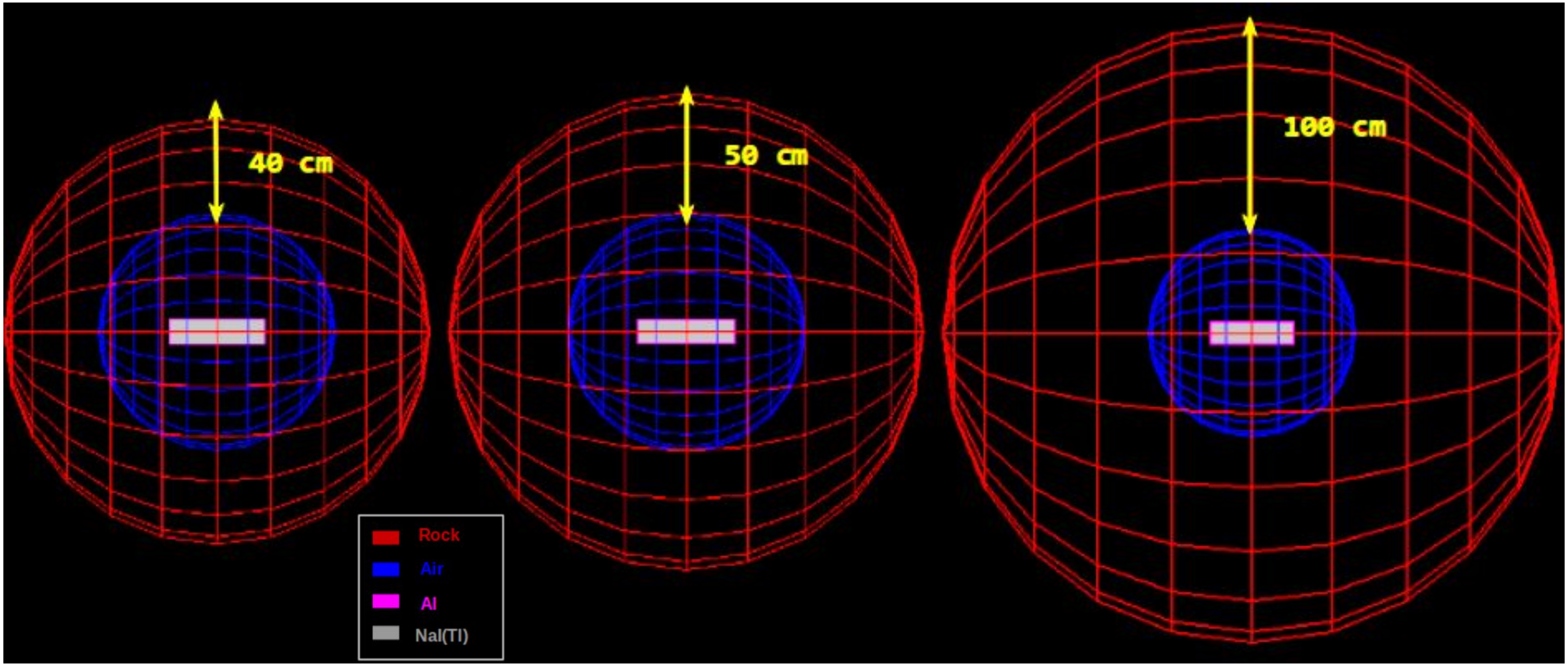
$$\phi = \phi_0 F_{alt}(d) F_{BSYD}(R_c, d, I)$$

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

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

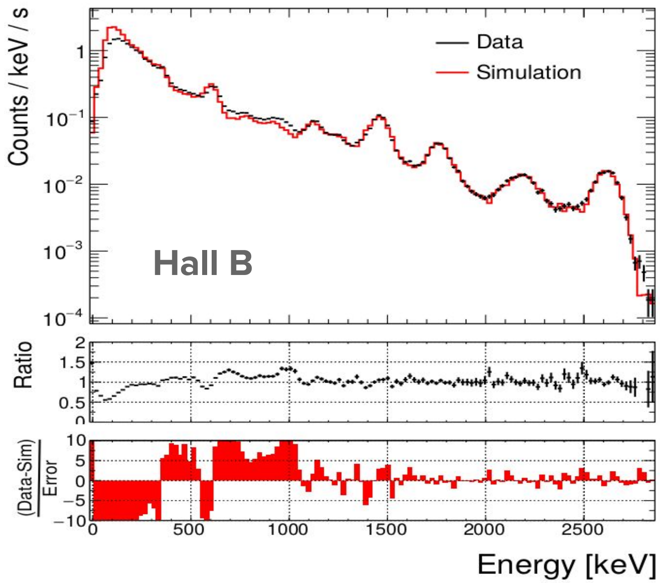
NaI simulation

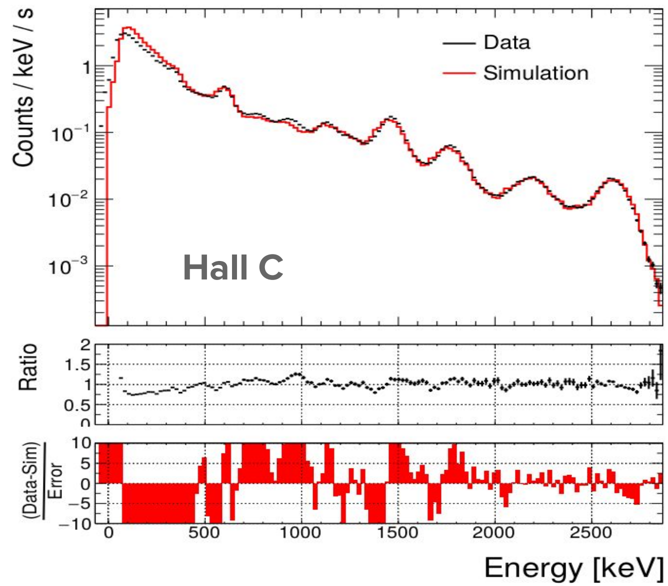
- Rock spherical shell
- NaI crystal of 4"× 4"×16" in aluminium case
- Test of spectrum dependency vs thickness and internal radius in order to maximize statistics
  ➜ difference between configurations within 10%
  ➜ use R_{int} = 50 cm and thickness = 40 cm



Spectrum fit

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

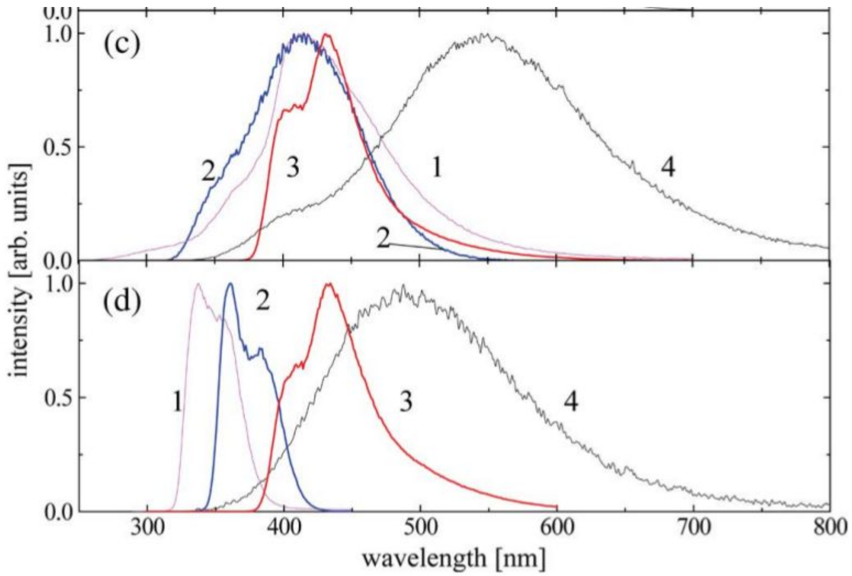




	Measurements		H. Wulandari et al. Astroparticle Physics 22 (2004) 313–322			
	Hall B [ppm]	Hall C [ppm]	Hall B [ppm]		Hall C [ppm]	
			Rock	Concrete	Rock	Concrete
K	7068 ± 90	12780 ± 70	10272	5377	10272	5377
U	0.56 ± 0.01	0.966 ± 0.004	0.42	0.66	0.66	0.66
Th	0.54 ± 0.01	0.840 ± 0.006	0.062	1.05	0.066	1.05

Optical properties of NaI

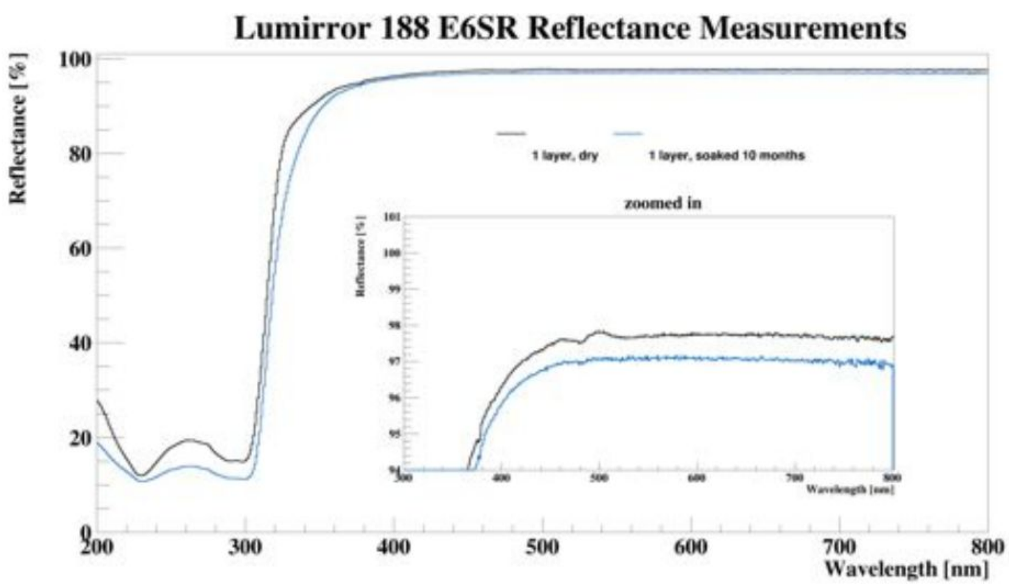
- Light yield: 40000 photons/MeV
- emission spectrum ➜ grab data with Data Thief from
  "Advances in Yield Calibration of Scintillators", Johan T. M. de Haas and Pieter Dorenbos, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 55, NO. 3, JUNE 2008
- time constant 250 ns
- R-index = 1.8
- attenuation length 10 m (i.e. negligible attenuation)

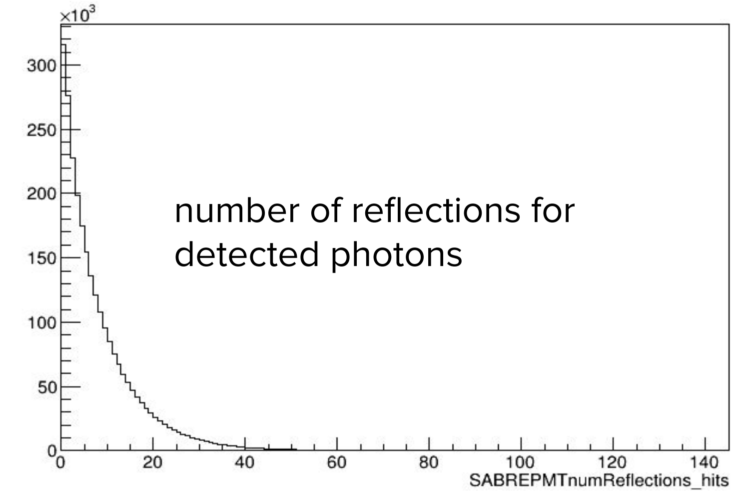


NaI emission is the blue line in the upper plot (2c)

Surface between crystal and reflector

- The reflector covers both the round part of the crystal, and the flat parts not coupled to the PMT
- Dielectric - metal interface
- raw surface (Lambertian reflection)
- Use Lumirror reflectivity
- on average ~5-6 reflection before being detected or absorbed





Physics lists

```
//Radioactive decays
#include "G4DecayPhysics.hh"
#include "G4RadioactiveDecayPhysics.hh"
#include "SABRETritiumPhysics.hh" //this is the class to make the tritium decay

//EM lists
#include "G4EmStandardPhysics.hh"
#include "G4EmStandardPhysics_option4.hh"
#include "G4EmLivermorePhysics.hh"
#include "G4EmPenelopePhysics.hh"
#include "G4EmLowEPPhysics.hh"
#include "G4EmExtraPhysics.hh"
#include "G4EmProcessOptions.hh"

//Hadronic lists
#include "G4HadronPhysicsShielding.hh"
#include "G4HadronPhysicsFTFP_BERT_HP.hh"
#include "G4HadronPhysicsQGSP_BERT_HP.hh"
#include "G4IonPhysics.hh"
#include "G4IonQMDPhysics.hh"
#include "G4IonElasticPhysics.hh"
#include "G4StoppingPhysics.hh"
#include "G4HadronElasticPhysicsHP.hh"
#include "G4HadronElasticPhysicsLEND.hh"

//Optical photons
#include "G4OpticalPhysics.hh" //this is for scintillation light: eV energies
#include "G4Cerenkov.hh"
#include "G4Scintillation.hh"
#include "G4OpAbsorption.hh"
#include "G4OpRayleigh.hh"
#include "G4OpMieHG.hh"
#include "G4OpBoundaryProcess.hh"
#include "G4EmSaturation.hh"
#include "G4OpWLS.hh"
#include "G4OpticalPhoton.hh"
```