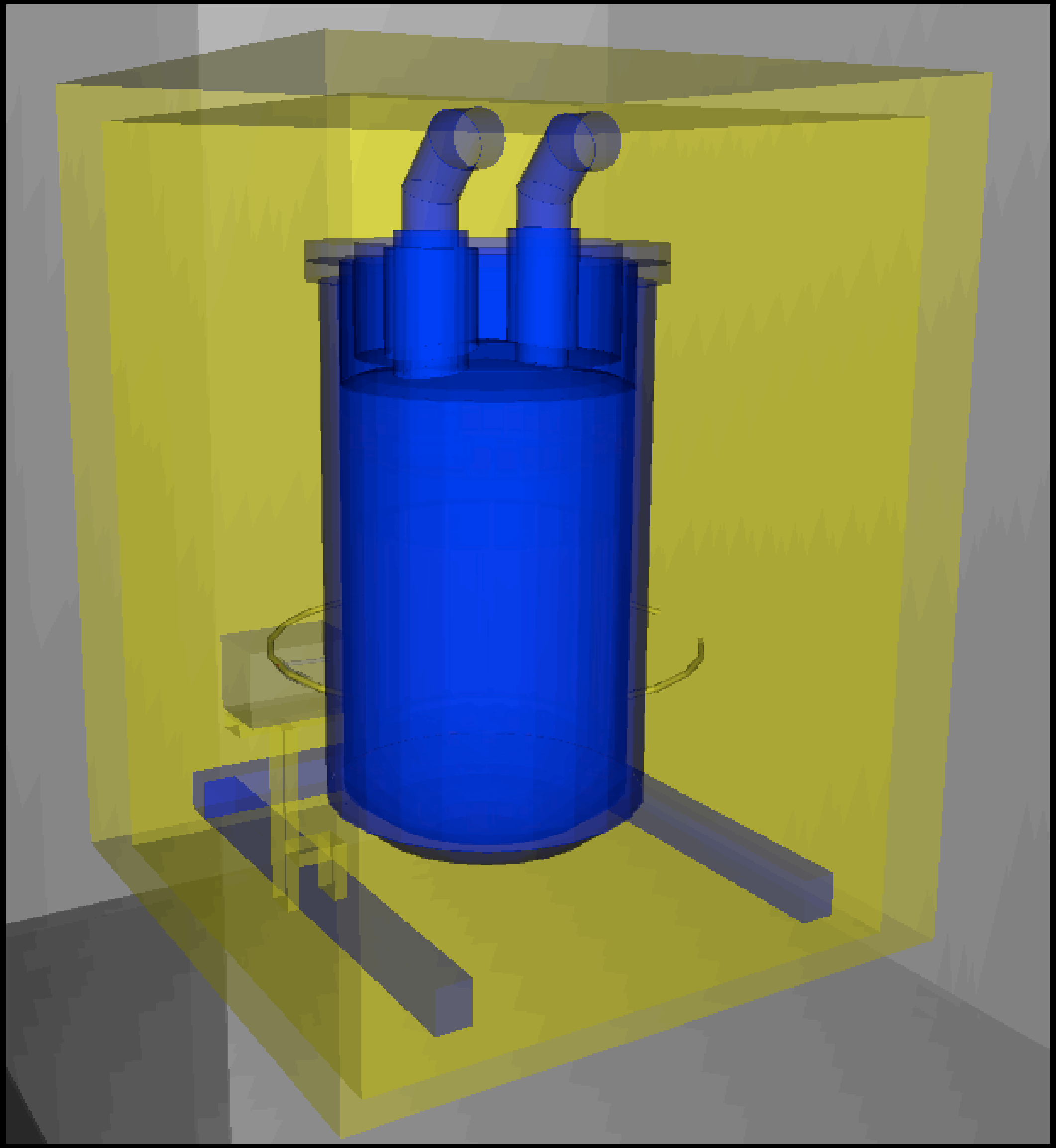
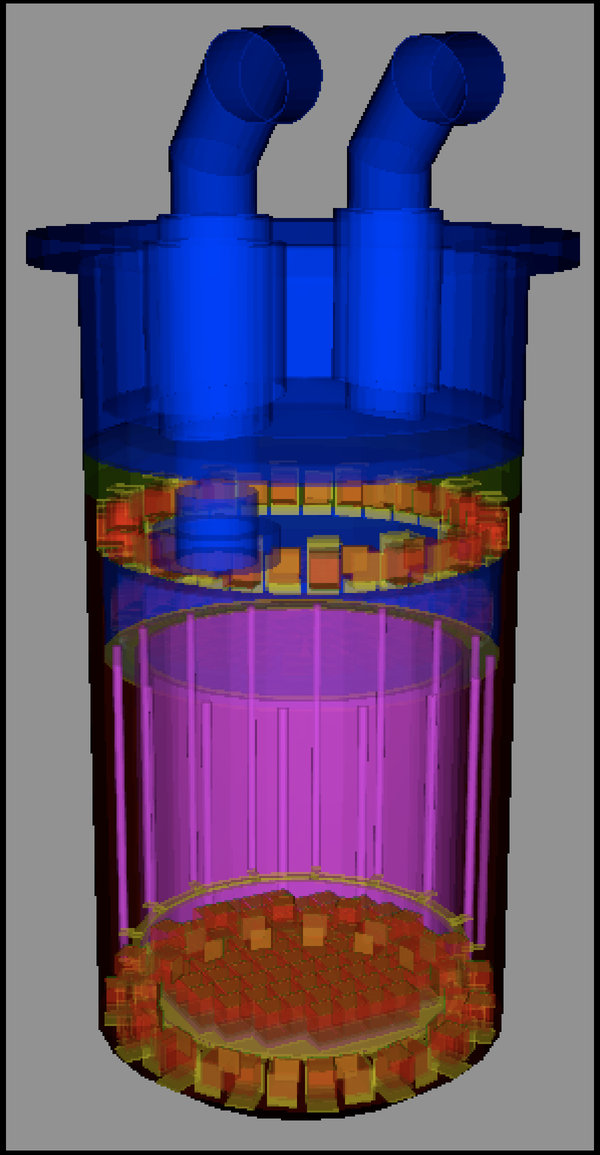
MonteCarlo simulations with Geant 4 for the XENON100 Detector





Alexander Kish,
University of Zürich

Outline

- Principle of the XENON dark matter search experiment
- XENON100 detector design
- Geant4 model of the detector
- Simulations of the optical response
- Simulations of the electron recoil background
- Simulations of the nuclear recoil background

XENON-100 collaboration

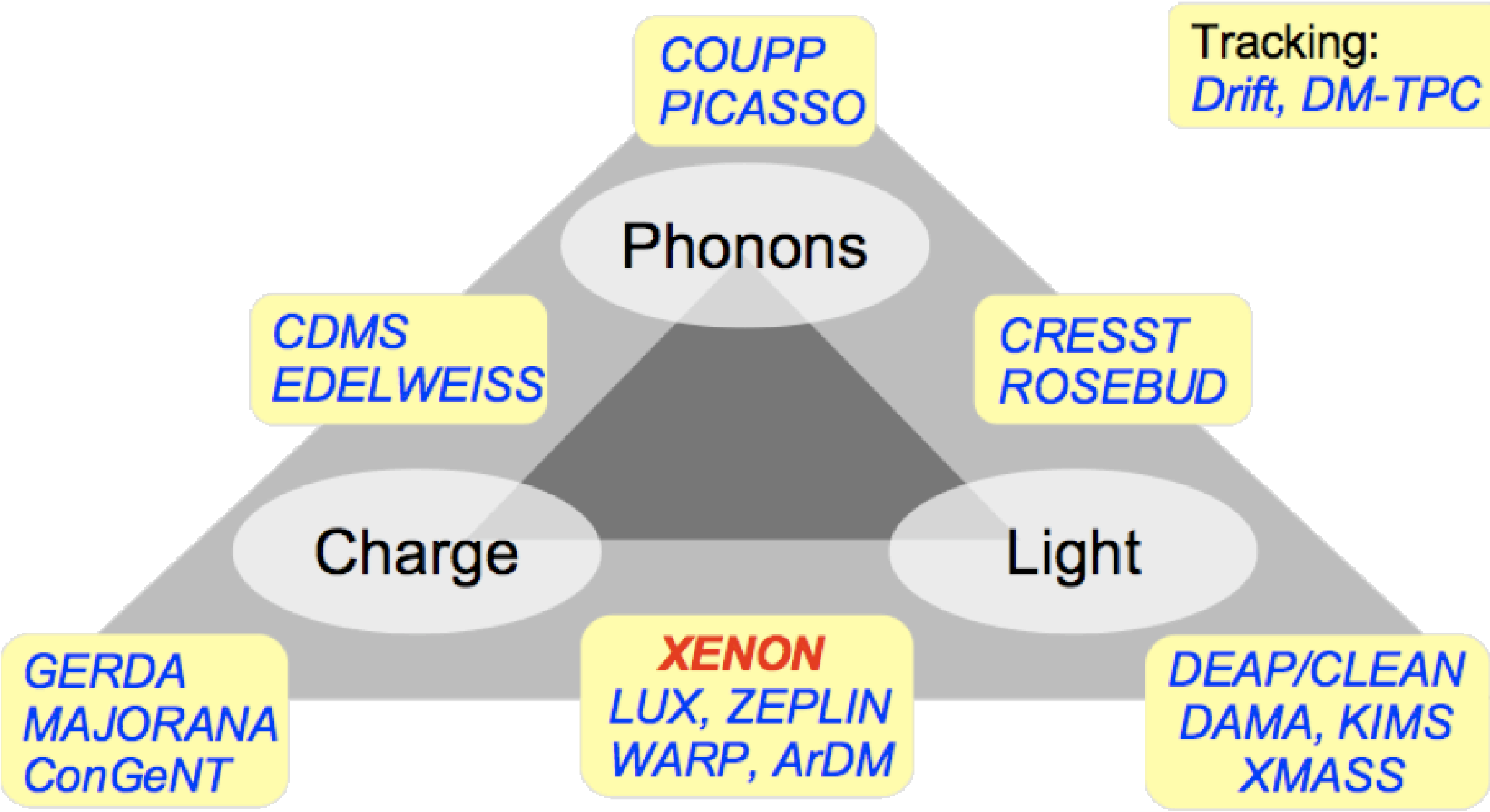
45 researchers (incl. 15 graduate students and 10 postdocs)

from

USA, Switzerland, Italy, Portugal, Germany, France, Japan, China

- **Columbia University**
- **University of Zürich**
- **Rice University**
- **Laboratori Nazionali del Gran Sasso**
- Westfälische Wilhelms-Universität Münster
- **University of California**
- **University of Coimbra**
- **Waseda University**
- **Shanghai Jiao Tong University**
- Subatech

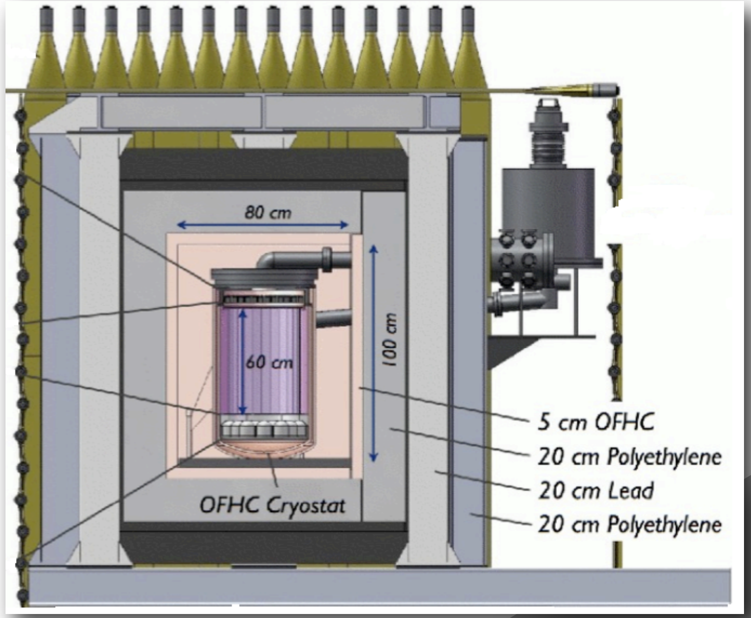
Dark Matter Searches



The XENON WIMP Search Program

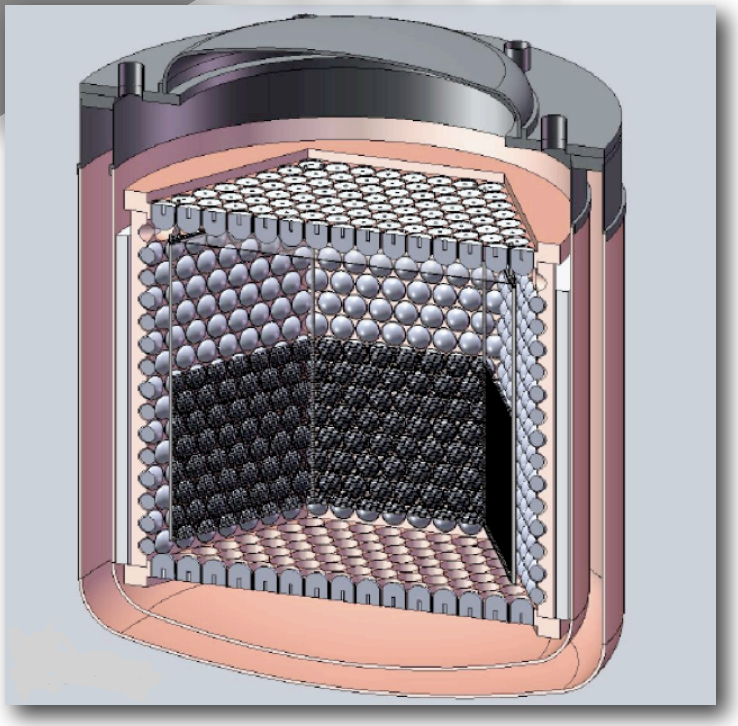
Target Volume ~100 kg
Muon Veto
QUPIDs

2010 - 2012



XENON 100+

XENON 1T



2013 - 2015

2005 - 2007

XENON 10

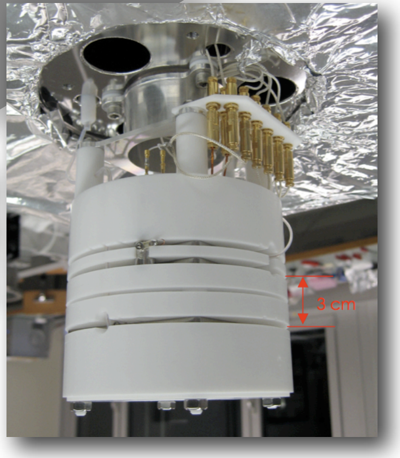
Target Volume ~10 kg

XENON 100

2007 - ongoing...

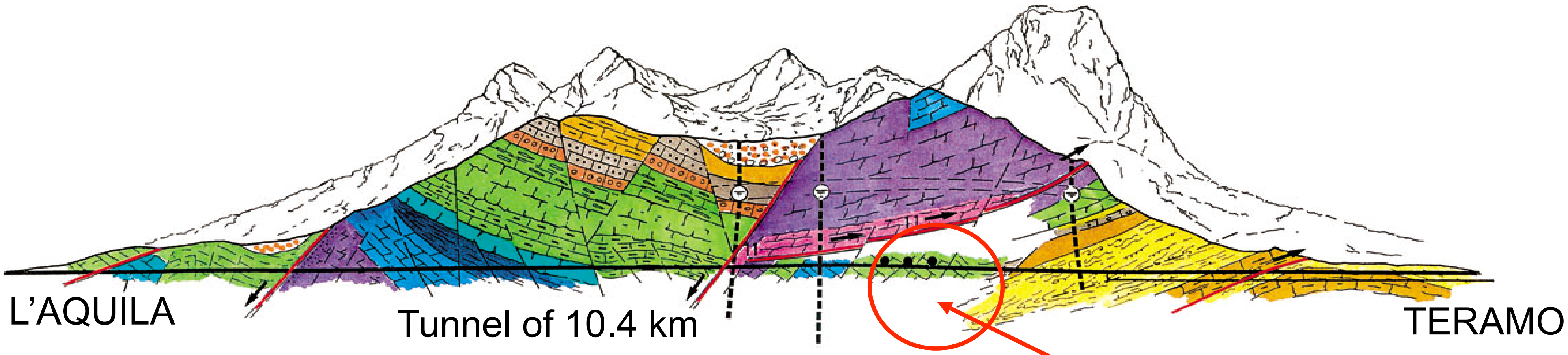
Target Volume 65 kg
Total 170 kg of LXe

R&D

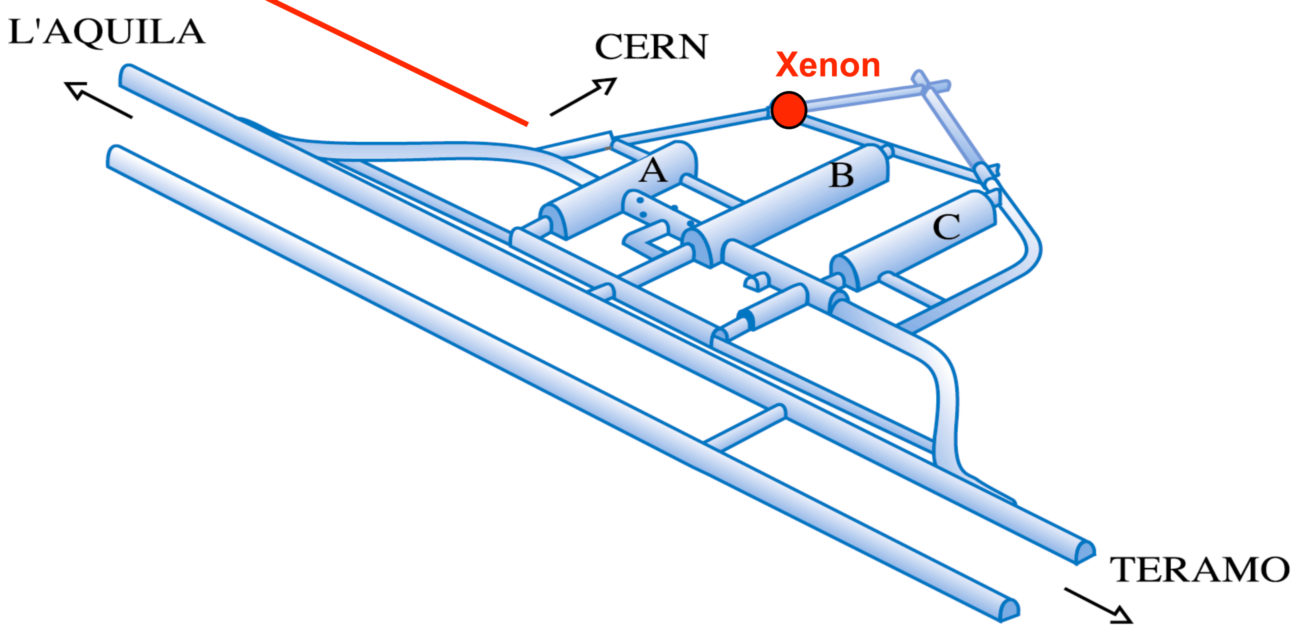


ongoing...

Location of the XENON-100 experiment

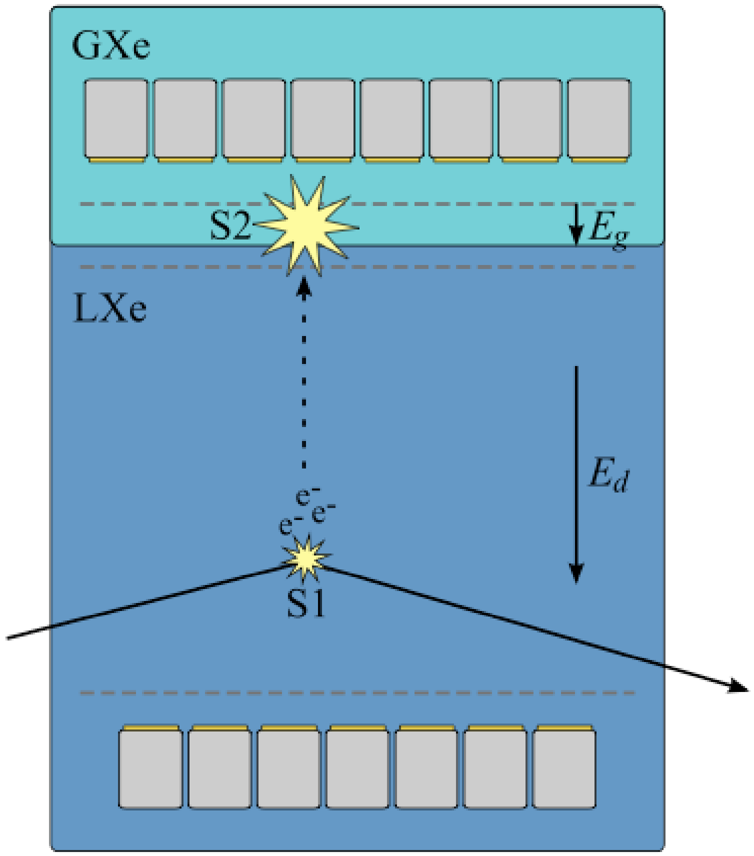


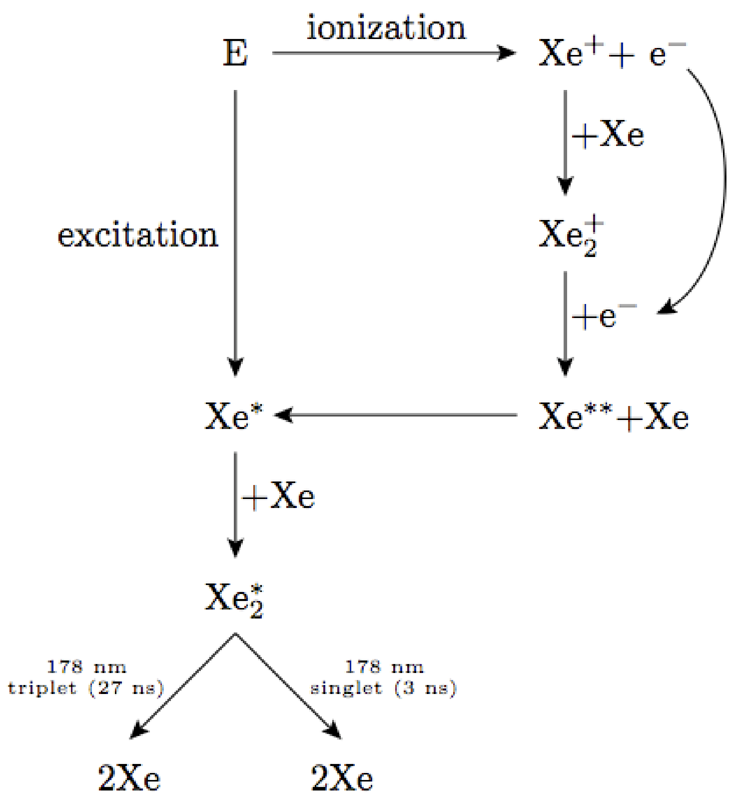
Laboratori Nazionali del Gran Sasso

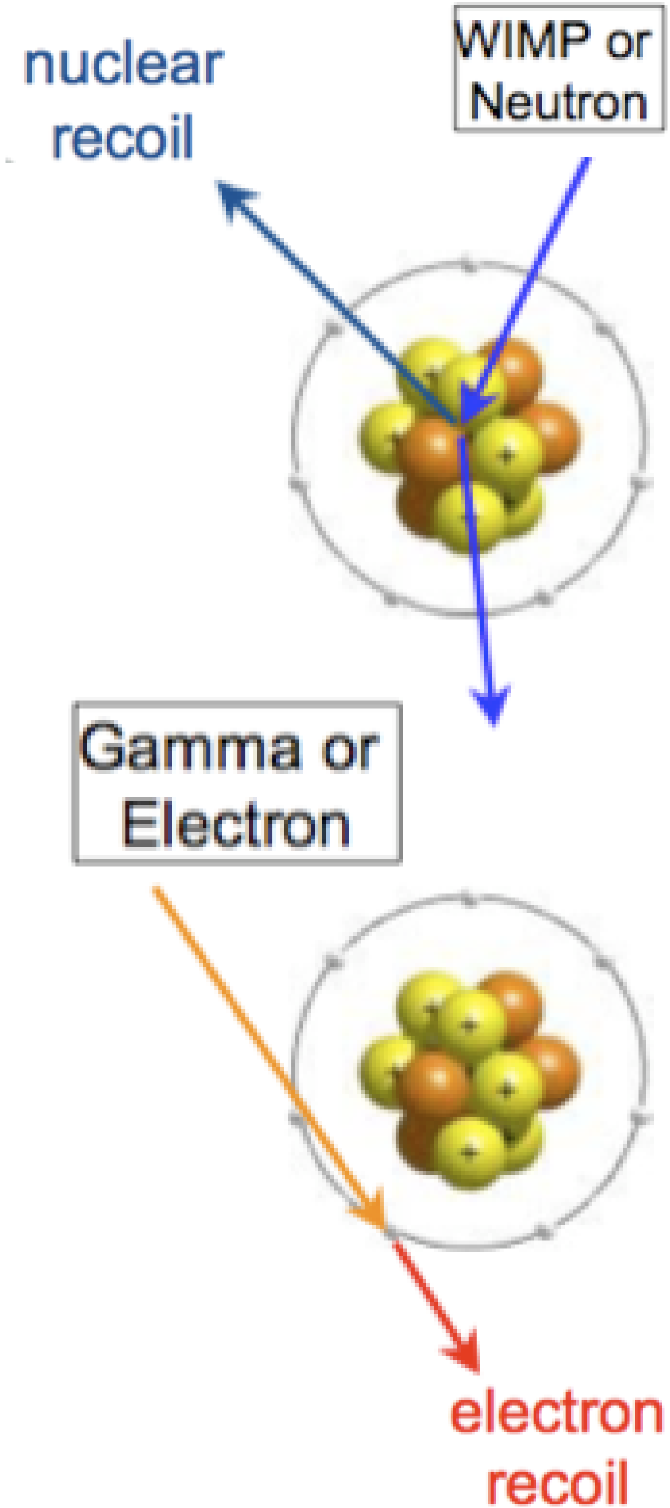


1.4 km rock
=
3100 meters water equivalent shielding from cosmic rays

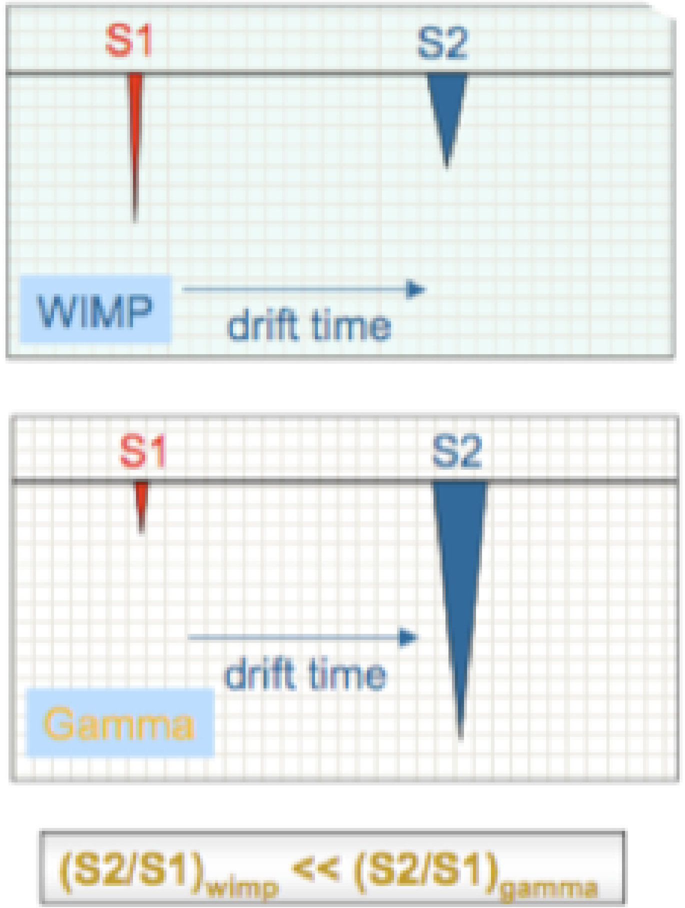
The Principle of the XENON experiment



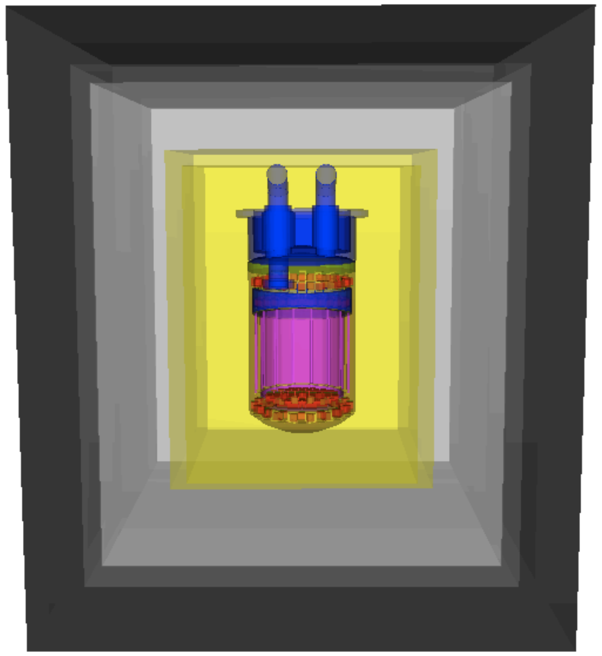




Electron/nuclear recoils discrimination based on S2/S1 ratio



XENON-100 Design

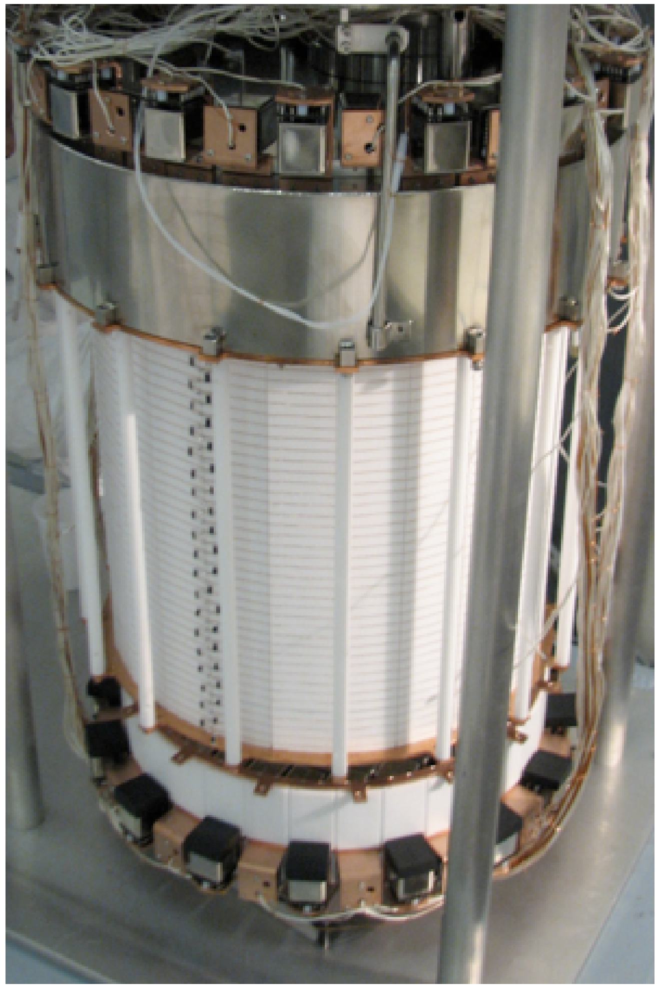


Shield:
- lead, 33T
- polyethylene, 1.6T
- copper, 2T

Cryostat:
- double walled (1.5 mm thick)
- low r/activity stainless steel
- total weight 70 kg

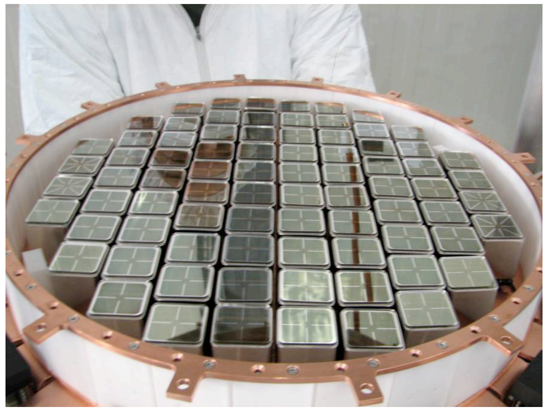
Target:
- 65 kg of LXe
(total amount 170 kg)
- 30 cm diameter,
- 30 cm height

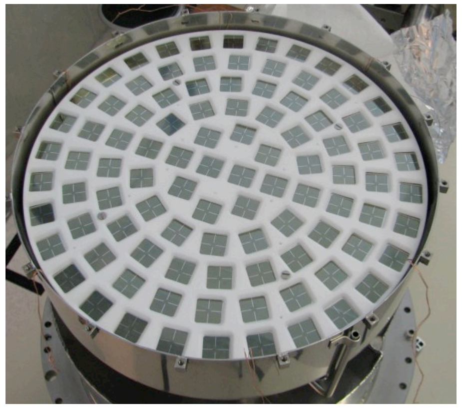
Active veto:
- 65 kg of LXe
- 30 cm diameter,
- 30 cm height



Bell:
- stainless steel
- weight 3.6 kg

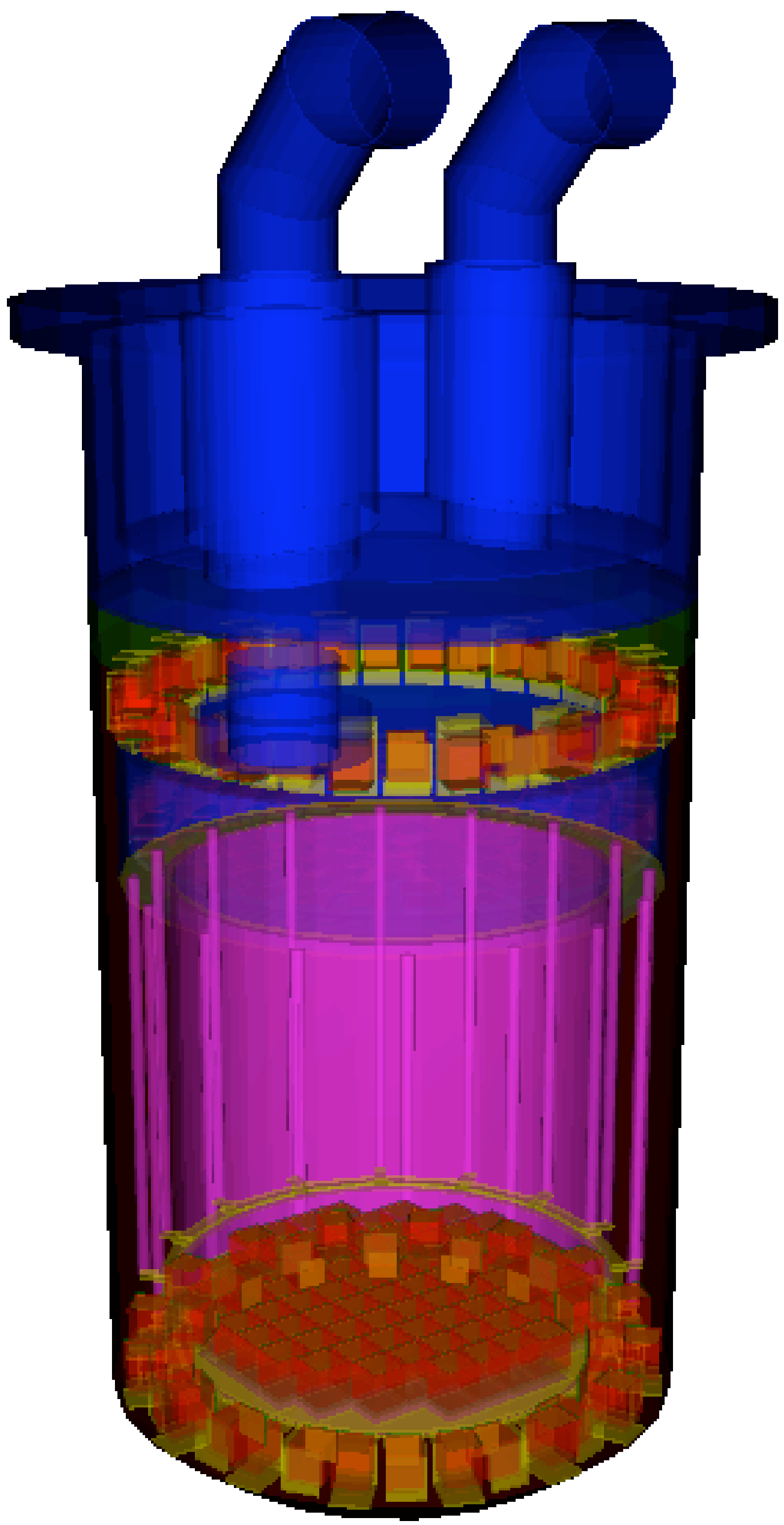
PTFE structure:
- 24 interlocking panels
- enclose target volume
- support field shaping rings
- total weight of teflon 12 kg
- UV light reflector





80 PMTs on the bottom,
98 PMT in the top array,
64 PMTs in the active veto

Simulation of the Optical Response



Teflon reflection:

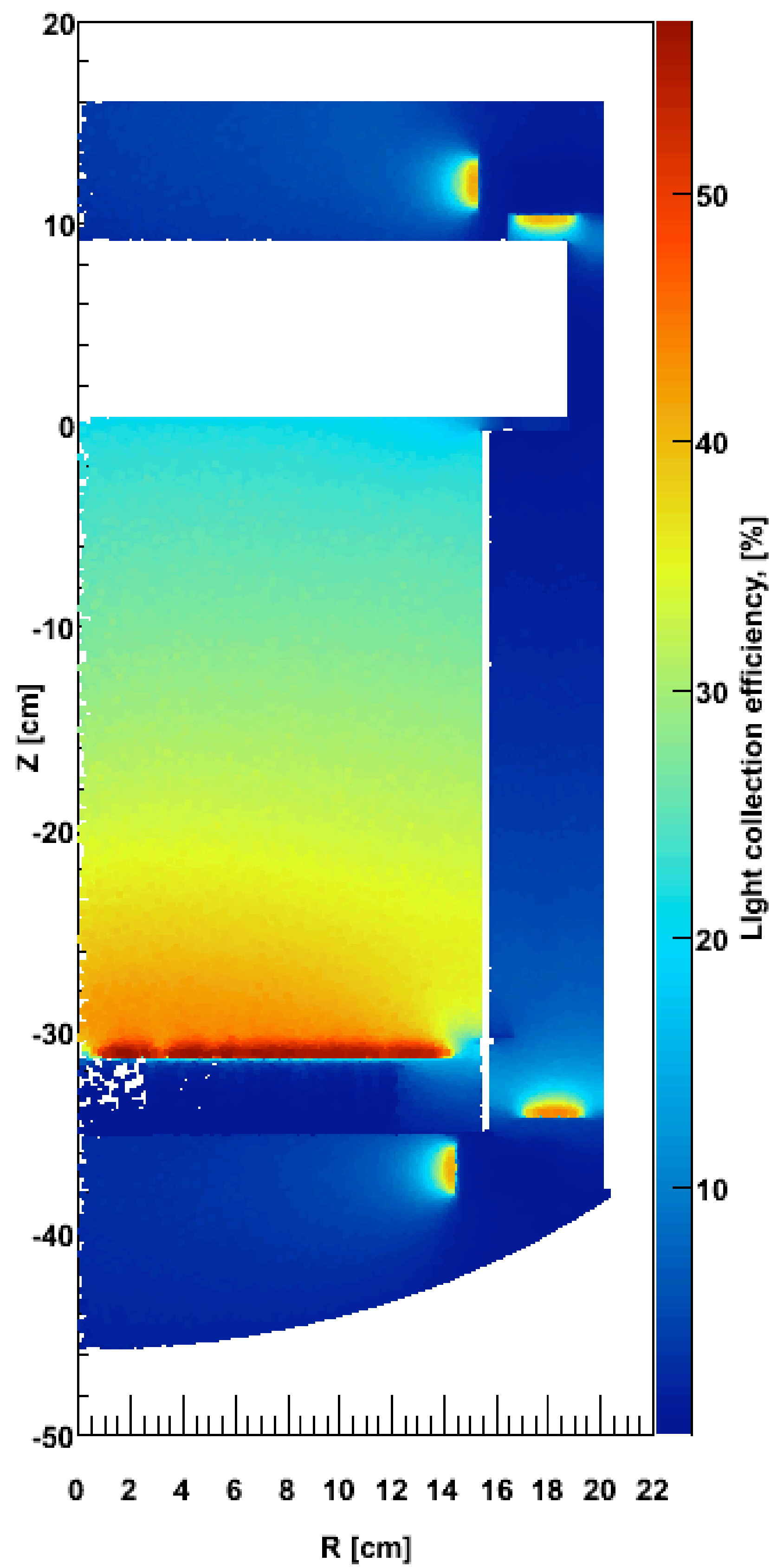
added specular component upon the Lambertian shape. Set the surface to ‘dielectric-metal’ and ‘groundbackpainted’, in order to have full control on the parameters of the specular lobe

Optical parameters:

Liquid Xenon Absorption Length	1 m
Liquid Xenon Rayleigh Scattering Length	30 cm
Gaseous Xenon Absorption Length	100 m
Gaseous Xenon Rayleigh Scattering Length	100 m
Photocathode Refractive Index	1.50
Photocathode Absorption Length	1 nm
Quartz Refractive Index	1.50
Quartz Absorption Length	30 m
Teflon Refractive Index	1.63
Teflon Reflectivity	95 %
Steel Reflectivity	20 %
Copper Reflectivity	20 %

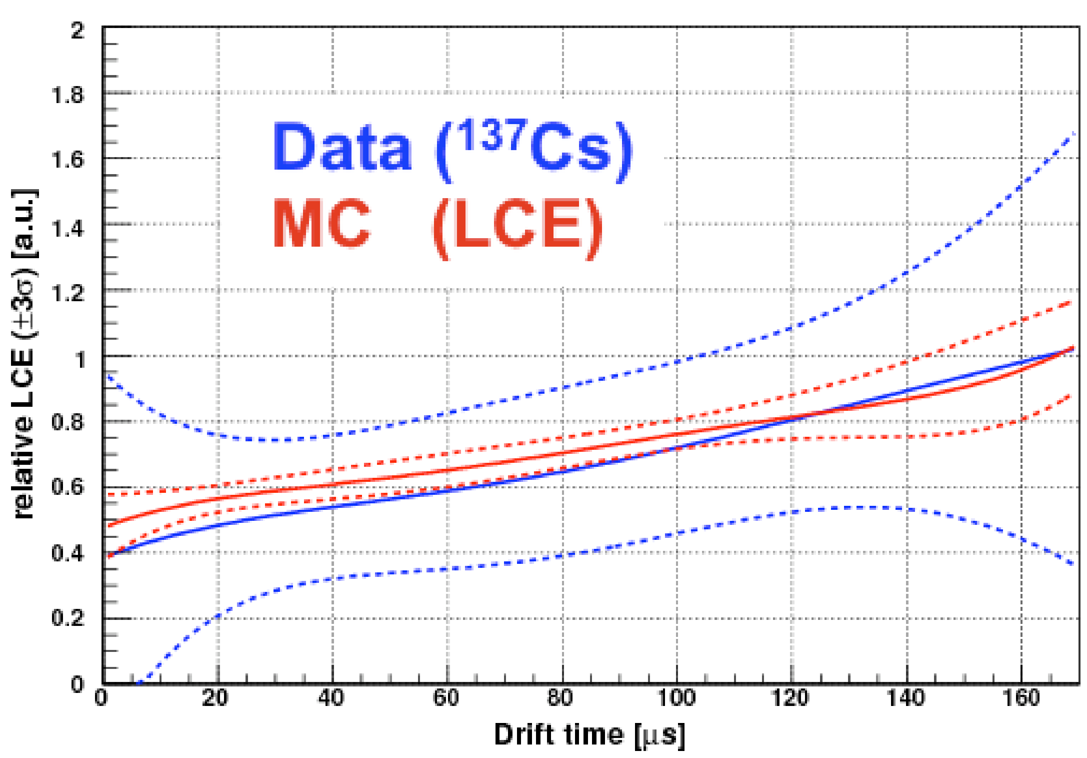
The electrode meshes are simulated as absorption discs -> good agreement with detailed azimuthal-averaged square mesh calculation

Light Collection Efficiency Simulation



$$LCE = \frac{N\ detected\ photons}{N\ emitted\ photons} \cdot 100 \quad [\%]$$

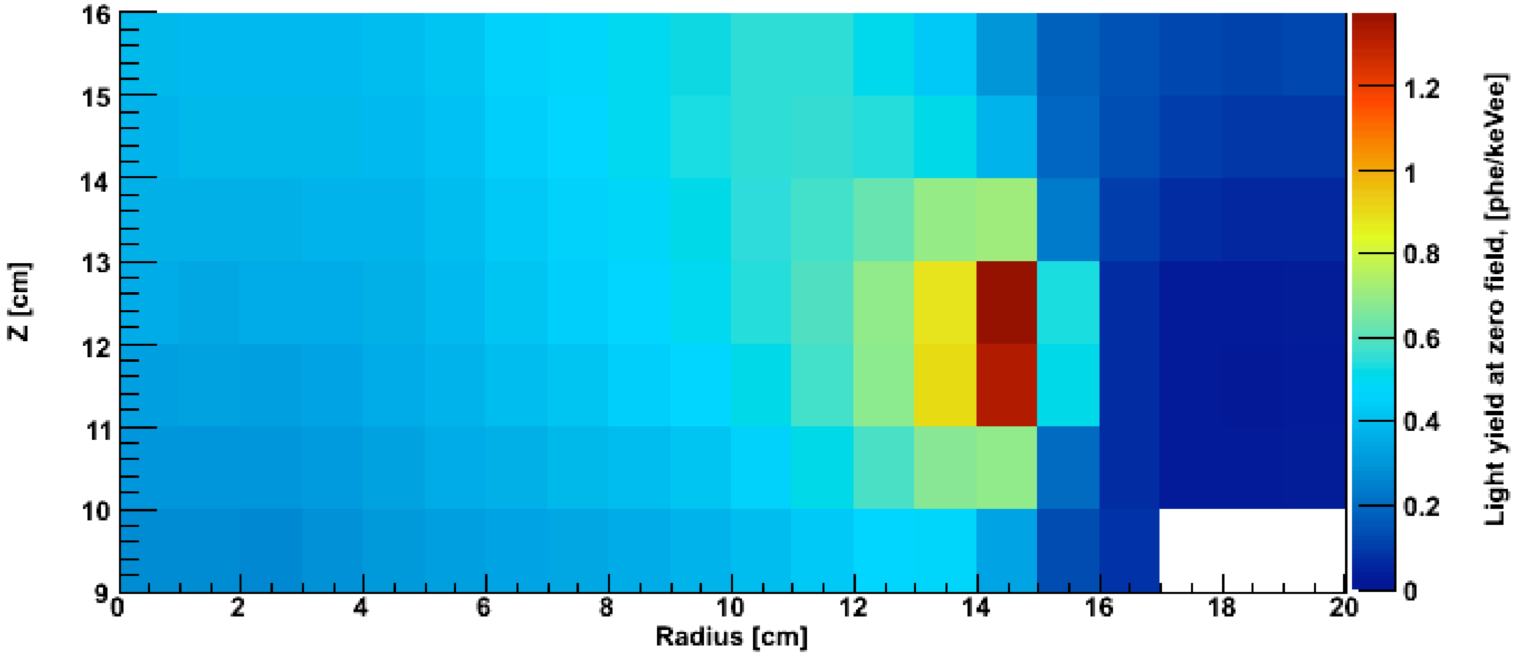
- **Average LCE in the target volume:**
  24%, 3.2 pe/keVee at zero field;
  nuclear recoil detection efficiency 100% at 5 keVr
- **Average LCE in the active veto volume:**
  4.7%
- **Relative LCE in the target volume, scaled to the maximum value in the target volume**



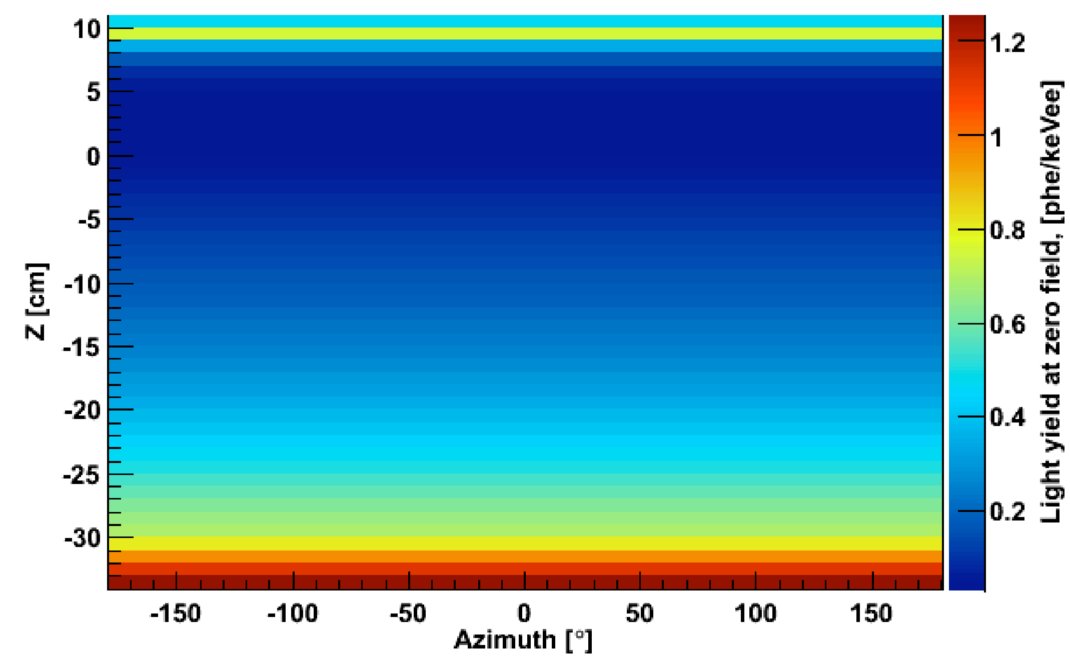
Prediction of the Detected Light Yield in the Veto Volume

$$LY = \frac{average\ LY\ in\ the\ target\ volume\ (data)}{average\ LCE\ in\ the\ target\ volume\ (MC)} \cdot LCE,\ [phe/keVee]$$

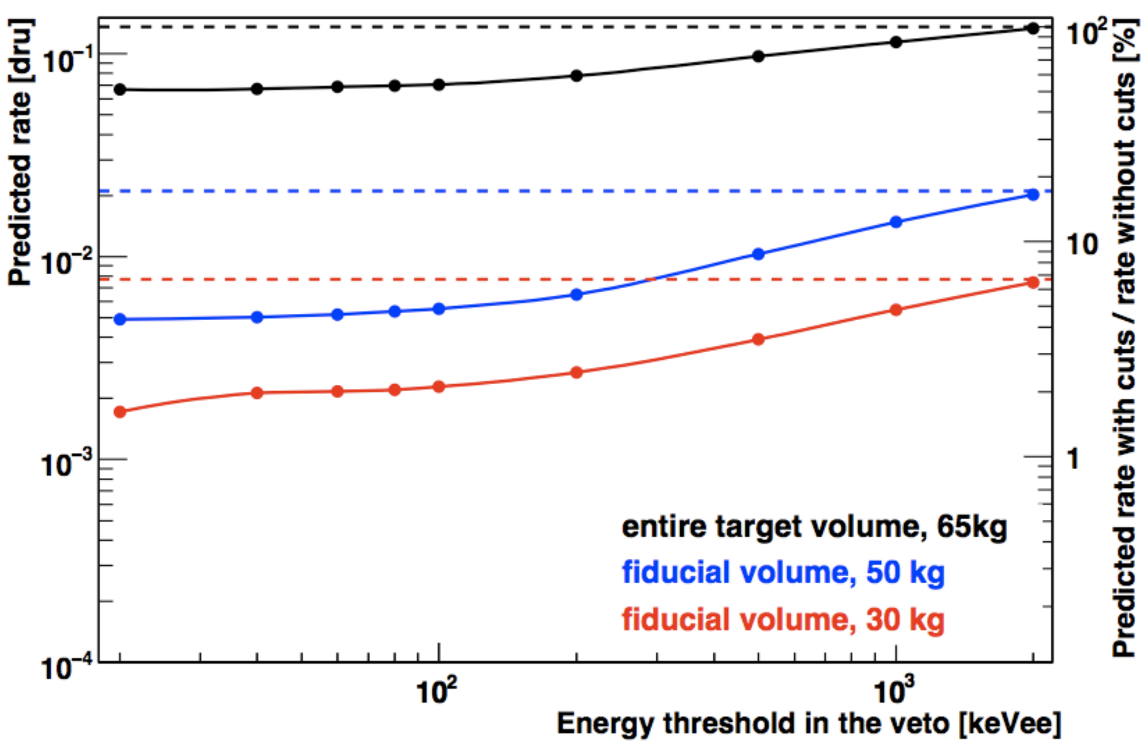
- **Predicted LY in the top veto**



- **Predicted LY in the side veto**



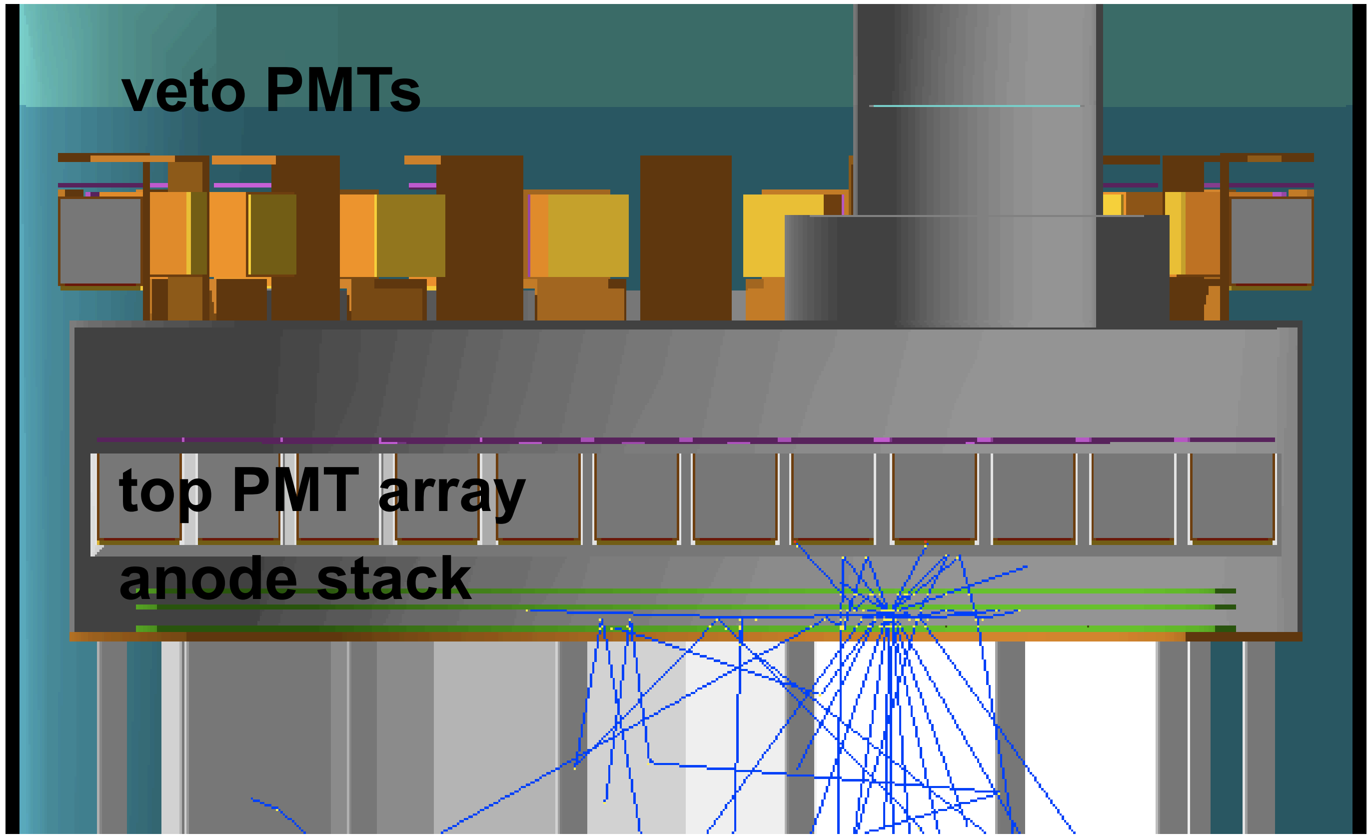
- **Energy threshold in the active veto 5-100 keVee**

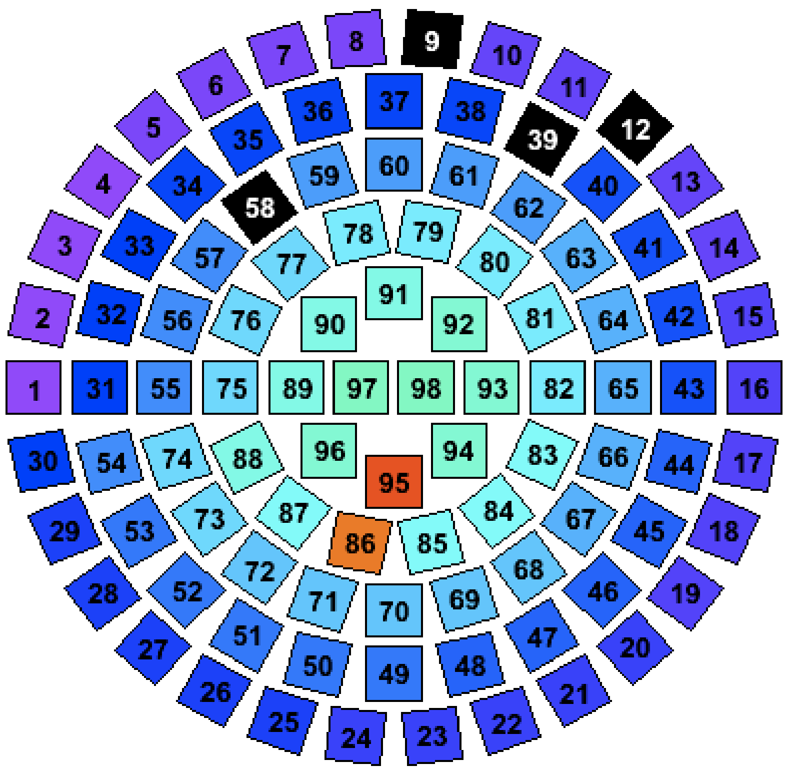


Fiducial volume and active veto cuts: up to 95-99% efficiency for electron recoil background rate reduction

Further reduction by a factor of 100 with S2/S1 discrimination

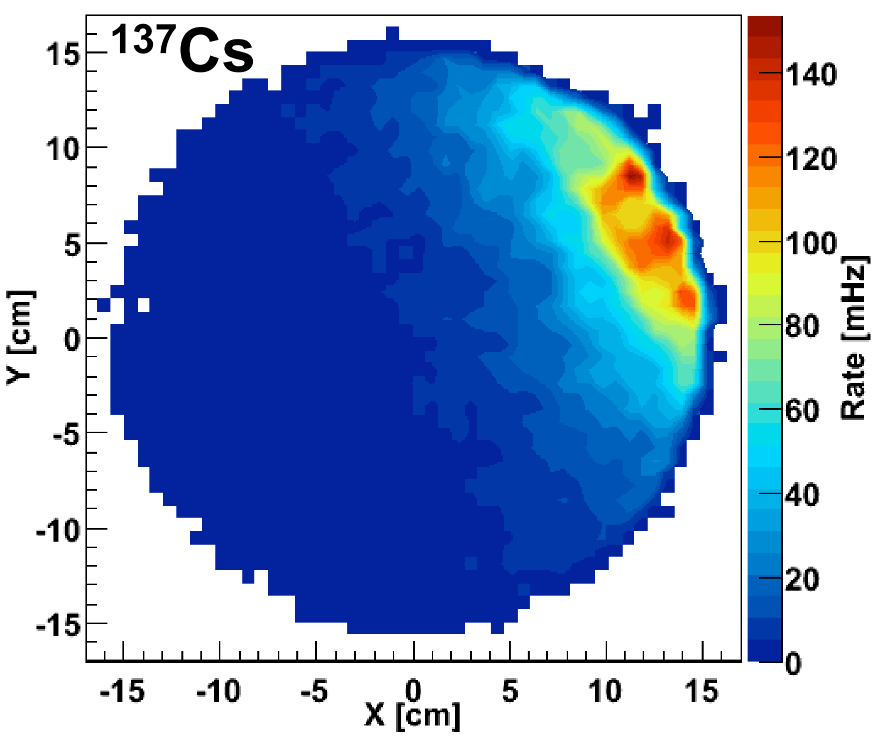
S2 Simulation for XY Position Reconstruction

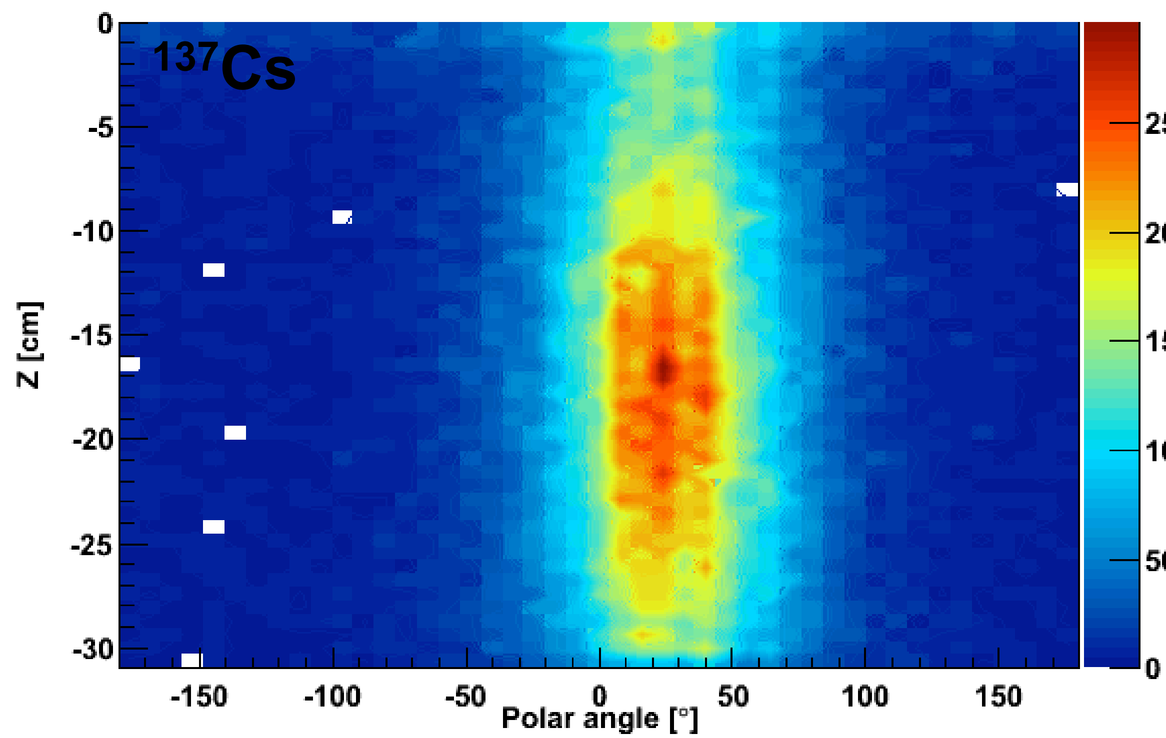




XY reconstruction algorithms with support vector machines, neural networks, and χ2 minimization

Z-position inferred by the delay time between the S1 and S2





Backgrounds Prediction

SOURCES OF ELECTRON RECOIL BACKGROUND:

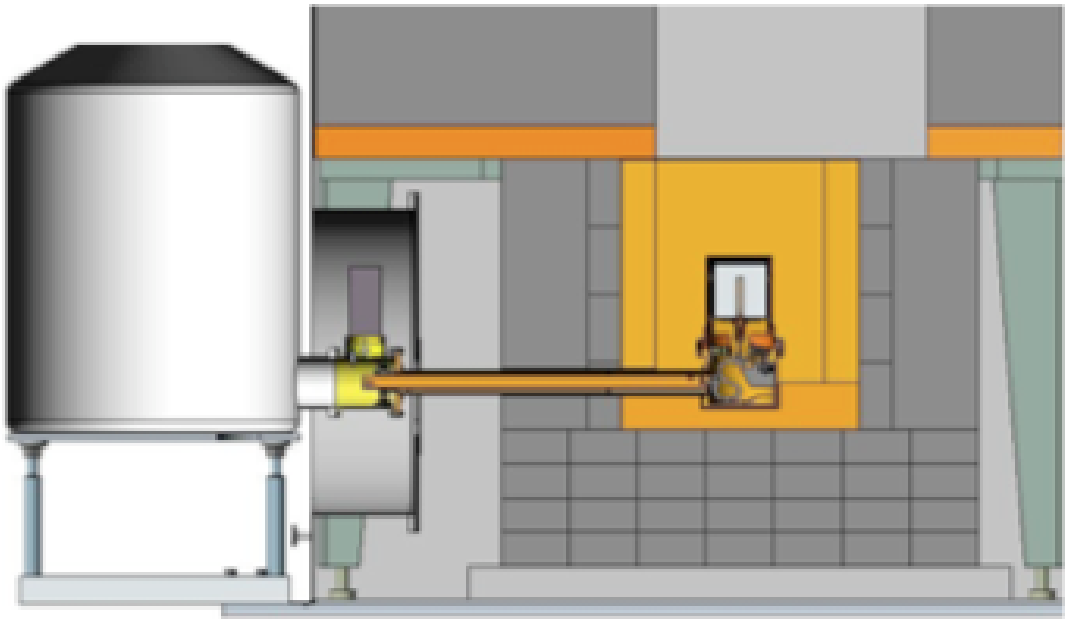
- radioactive contamination in the detector and shield materials (^{232}Th, ^{238}U, ^{60}Co, ^{40}K);
- contamination in liquid xenon (^{232}Th, ^{238}U, ^{85}Kr);
- ^{222}Rn contamination in the shield cavity.

SOURCES OF NUCLEAR RECOIL BACKGROUND:

- (α,n) reactions from ^{232}Th, ^{238}U and ^{235}U decay chains, and spontaneous fission of ^{238}U (contamination in detector and shield materials, local radioactivity in the rock and concrete surrounding the experimental site);
- muon-induced neutrons.

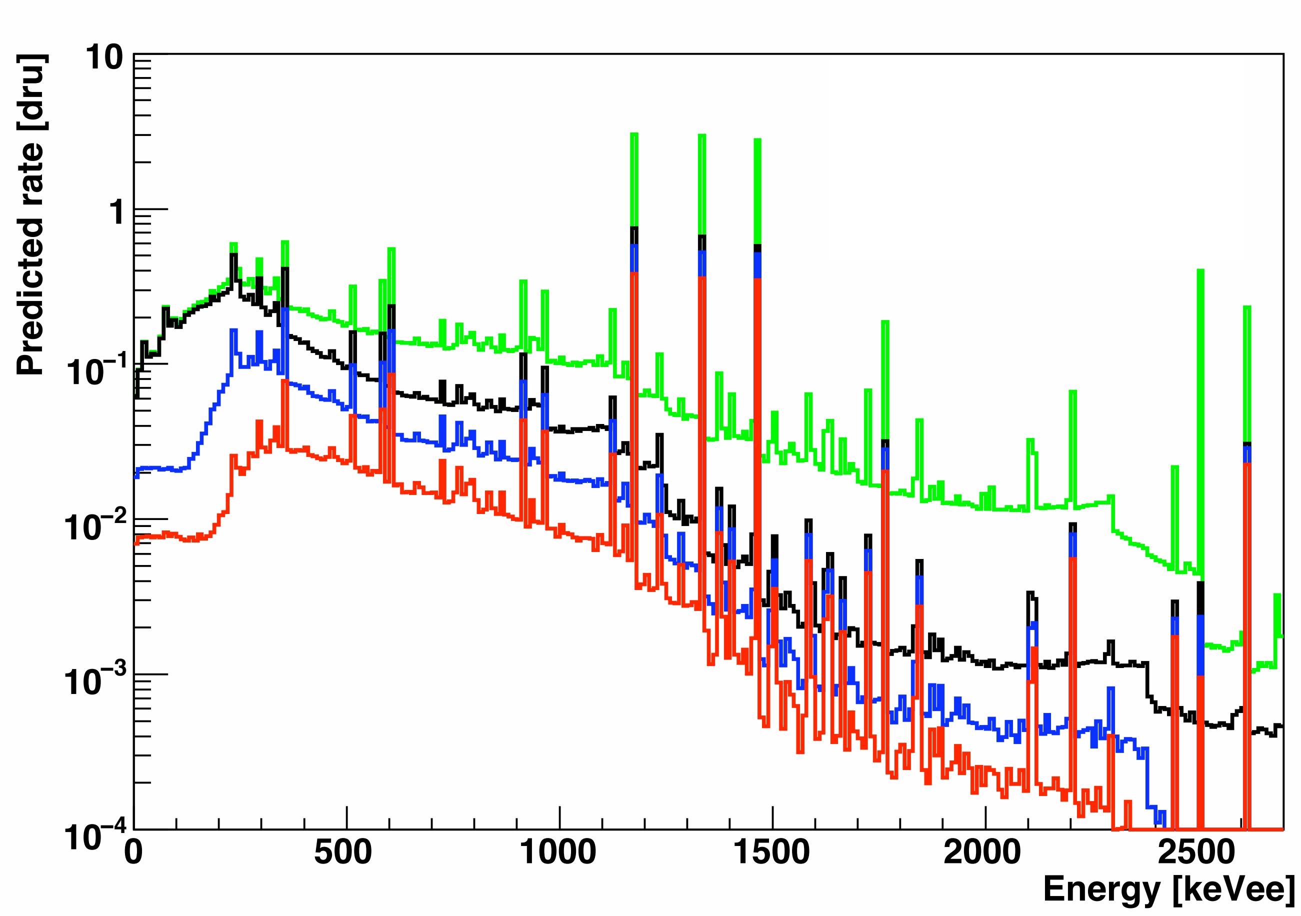
Materials Screening

Material	Unit	^{238}U [mBq/unit]	^{232}Th [mBq/unit]	^{60}Co [mBq/unit]	^{40}K [mBq/unit]	^{210}Pb [Bq/unit]
Stainless steel	kg	< 1.7	< 1.9	5.5±0.6	< 9.0	
PTFE	kg	< 0.31	< 0.16	< 0.11	< 2.25	
PMTs	piece	0.15±0.02	0.17±0.04	0.6±0.1	11±2	
PMT bases	piece	0.16±0.02	0.07±0.02	<0.01	<0.16	
Support bars (steel)	kg	< 1.3	2.9±0.7	1.4±0.3	< 7.1	
Copper (inside)	kg	< 0.22	< 0.16	0.20±0.08	< 1.34	
Resistor chain	piece	0.027±0.004	0.014±0.003	< 0.003	0.19±0.03	
Cathode support ring	kg	3.6±0.8	1.8±0.5	7.3±1.3	< 4.92	
Top grids support rings	kg	< 2.7	< 1.5	13±1	< 12	
PMT signal cables	kg	< 1.6	3.7±1.8	< 0.69	35±13	
Polyethylene shield	kg	0.23±0.05	< 0.094	< 0.89	0.7±0.4	
Copper shield	kg	< 0.07	< 0.03	< 0.0045	< 0.06	
Lead shield (outer)	kg	< 0.92	< 0.72	< 0.12	14±3	530±70
Lead shield (inner)	kg	< 0.66	< 0.55	< 0.11	< 1.46	26±6



- All materials used in the experiment are screened for the radioactive contamination with a 2.2 kg high purity Ge detector (“Gator” @ LNGS)
- The screening results are used for material selection and as an input for the MonteCarlo simulations

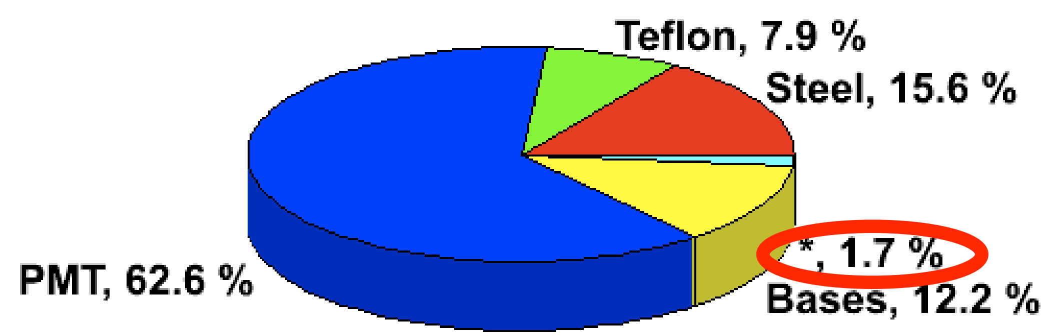
Predicted Electron Recoil Background from Detector Materials



all events in the entire target volume (65 kg)
single scatter events in the target volume
single scatters in the 50 kg fiducial volume
single scatters in the 30 kg fiducial volume

Rate in differential rate units:
dru = events / (kg·day·keV)

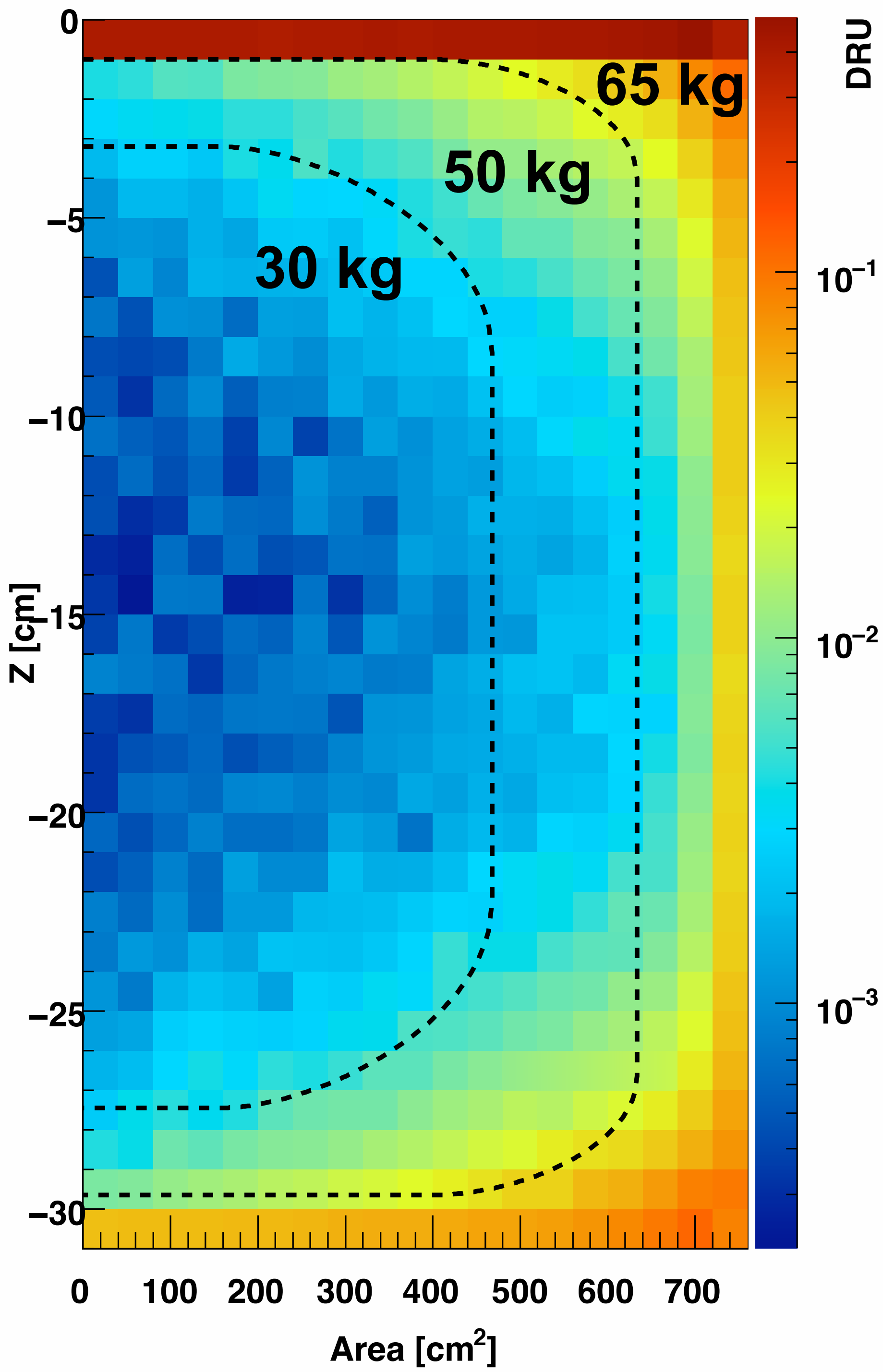
Material	Single electron recoils [mdru] in		
	target volume (65 kg)	50 kg FV	30 kg FV
Steel	< 19.3	< 3.98	< 1.68
PTFE	< 9.8	< 0.24	< 0.09
PMT	< 77.7	< 14.55	< 5.21
PMT bases	< 15.2	< 1.61	< 0.49
Polyethylene	< 0.31	< 0.07	< 0.005
Support bars	< 1.0	< 0.28	< 0.12
Copper (inside)	< 0.29	< 0.04	< 0.02
Cathode	< 0.3	< 0.02	< 0.02
Top grids	< 11.45	< 0.09	< 0.03
Resistor chain	$< 1.6\times10^{-3}$	$< 4.4\times10^{-6}$	$< 1.6\times10^{-6}$
Total	**< 135.9**	**< 21.01**	**< 7.73**



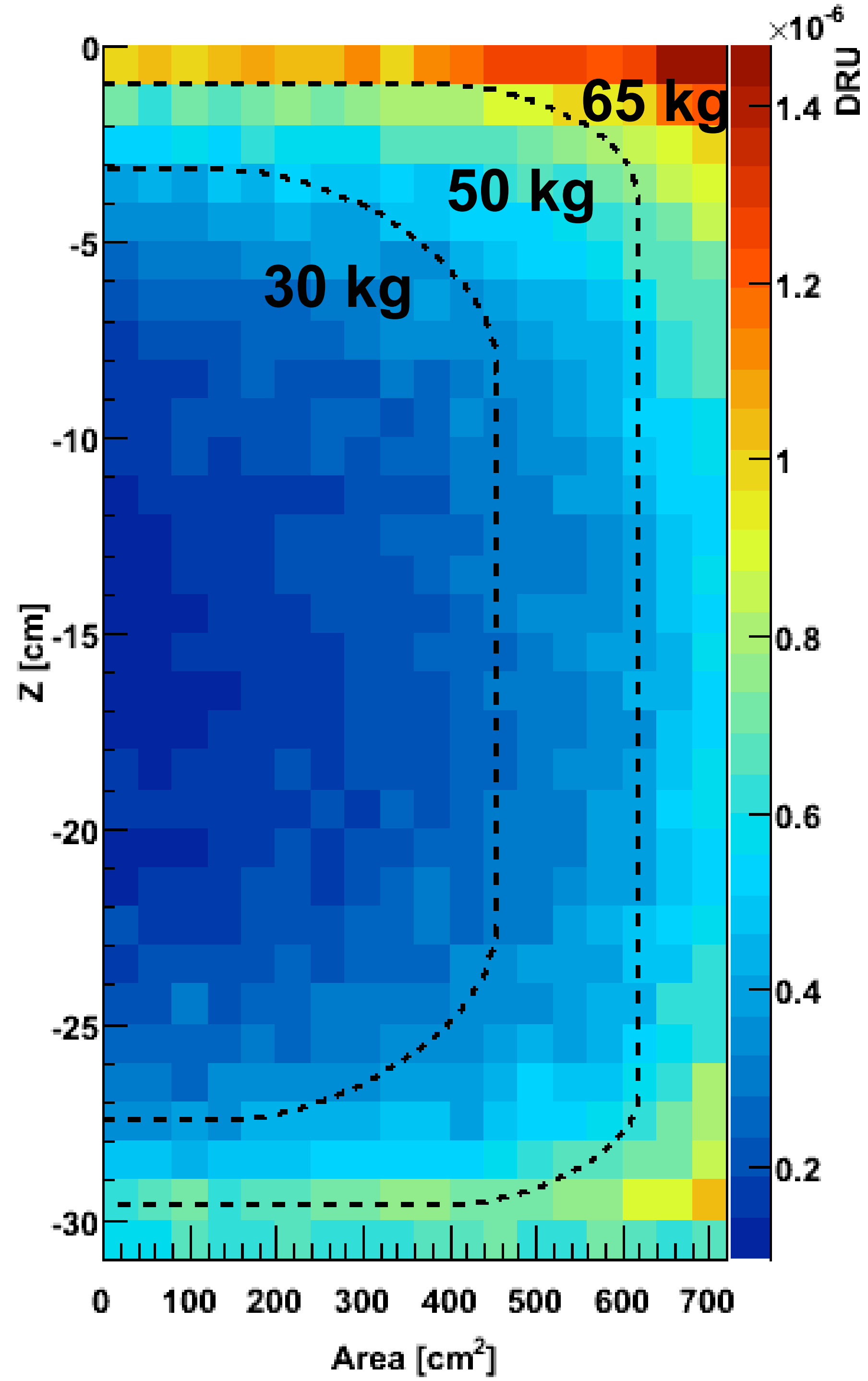
*Grids, Cables, Support bars, Resistor chain, Polyethylene shield

Background from Detector Materials, Fiducial Volume Cuts

Electron recoils:
0-100keVee, single scatters



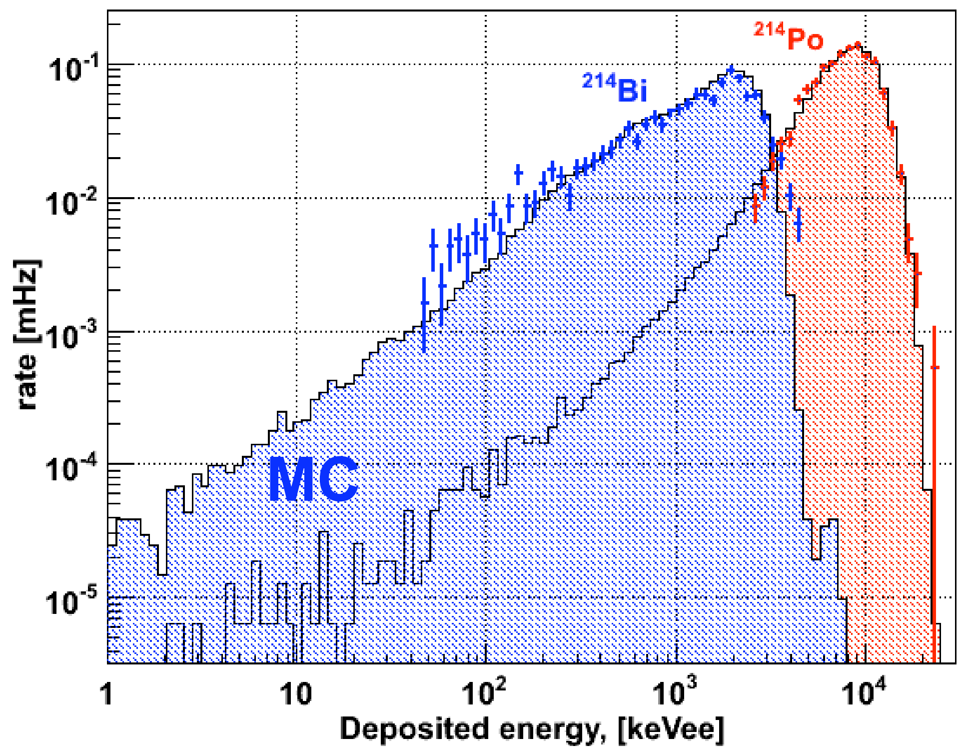
Nuclear recoils:
5-100keVnr, single scatters

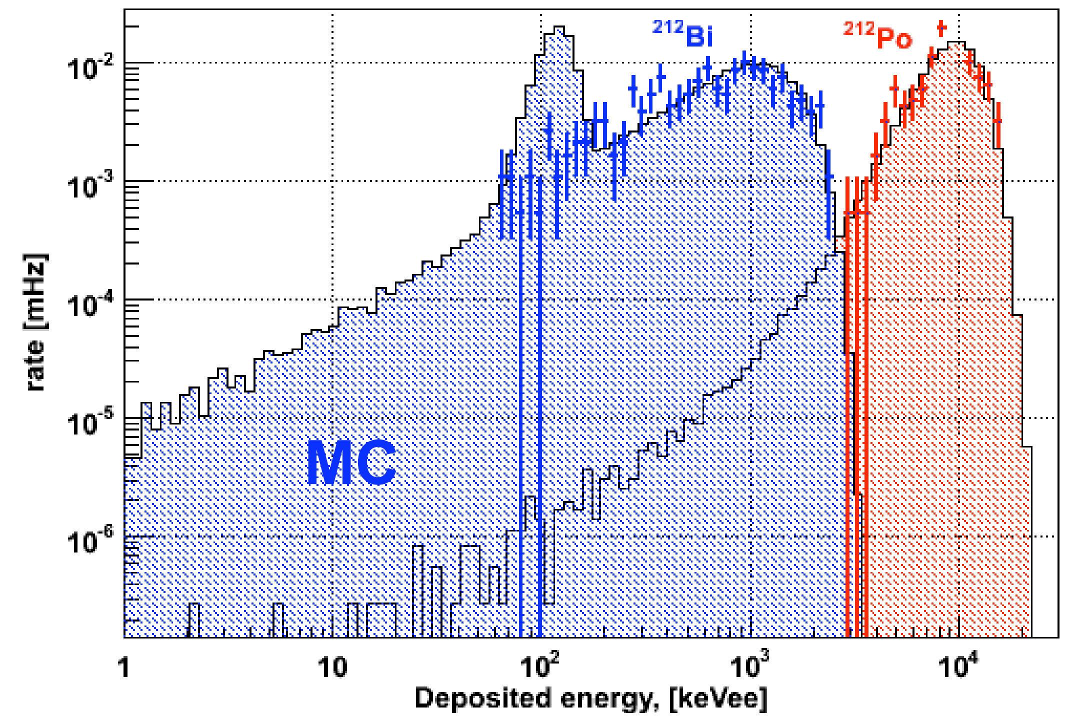


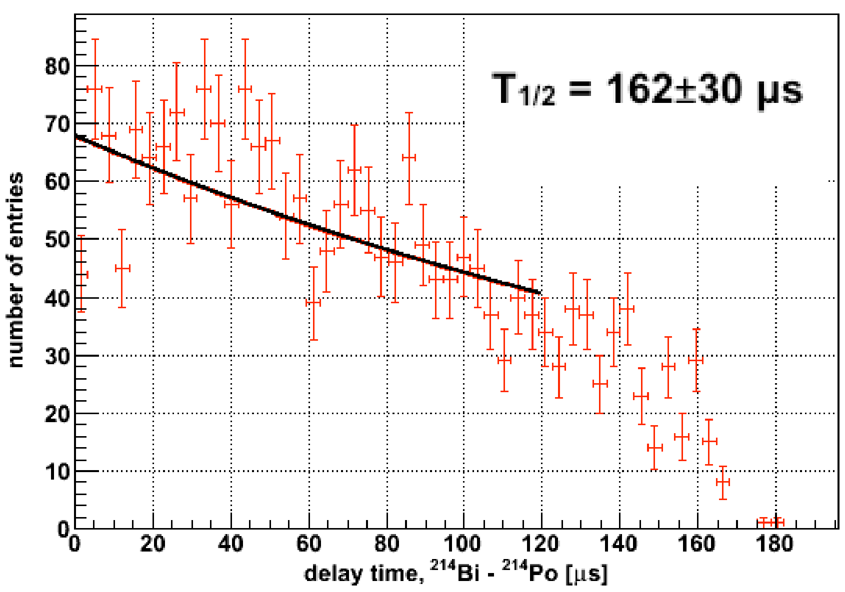
Intrinsic Contamination: Delayed Coincidence Analysis

^{238}U … ^{222}Rn ($T_{1/2}$=3.8d) … ^{214}Bi ($T_{1/2}$=19.7m) $\xrightarrow{\beta,\ E_{max}=3.27MeV}$ ^{214}Po ($T_{1/2}$=164μs) $\xrightarrow{\alpha,\ E=7.69MeV}$ ^{210}Pb

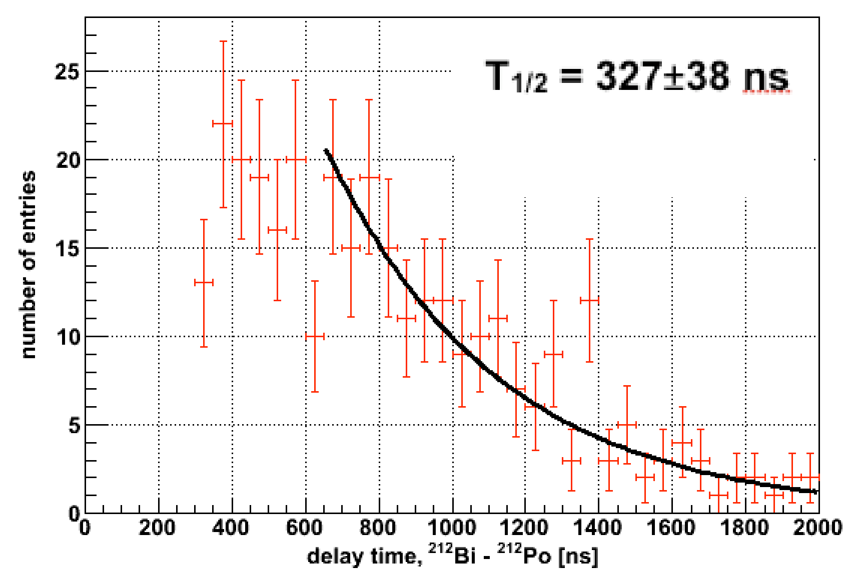
^{232}Th … ^{220}Rn ($T_{1/2}$=55.6s) … ^{212}Bi ($T_{1/2}$=19.7m) $\xrightarrow{\beta,\ E_{max}=2.25MeV}$ ^{212}Po ($T_{1/2}$=299ns) $\xrightarrow{\alpha,\ E=8.79MeV}$ ^{208}Pb







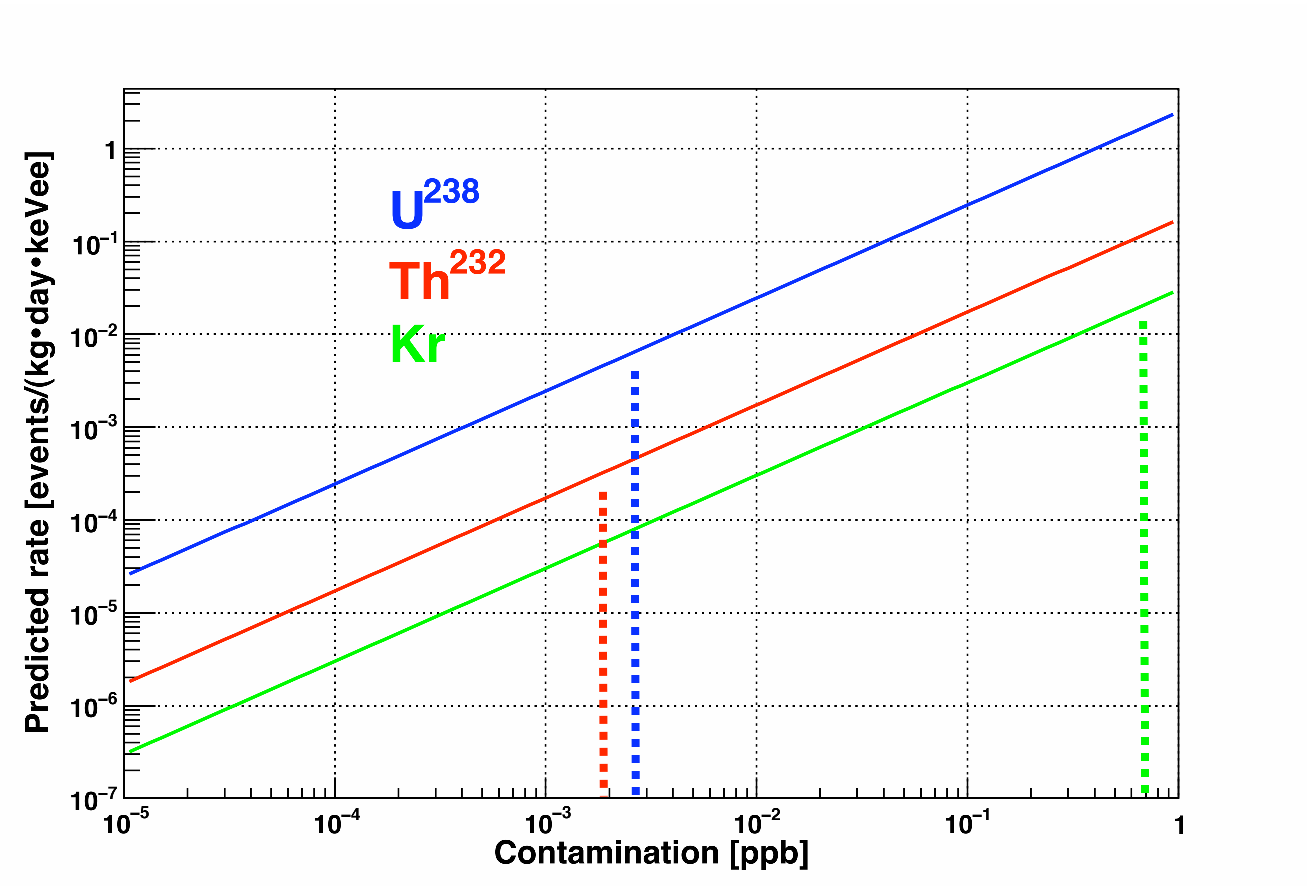
detection efficiency 35%



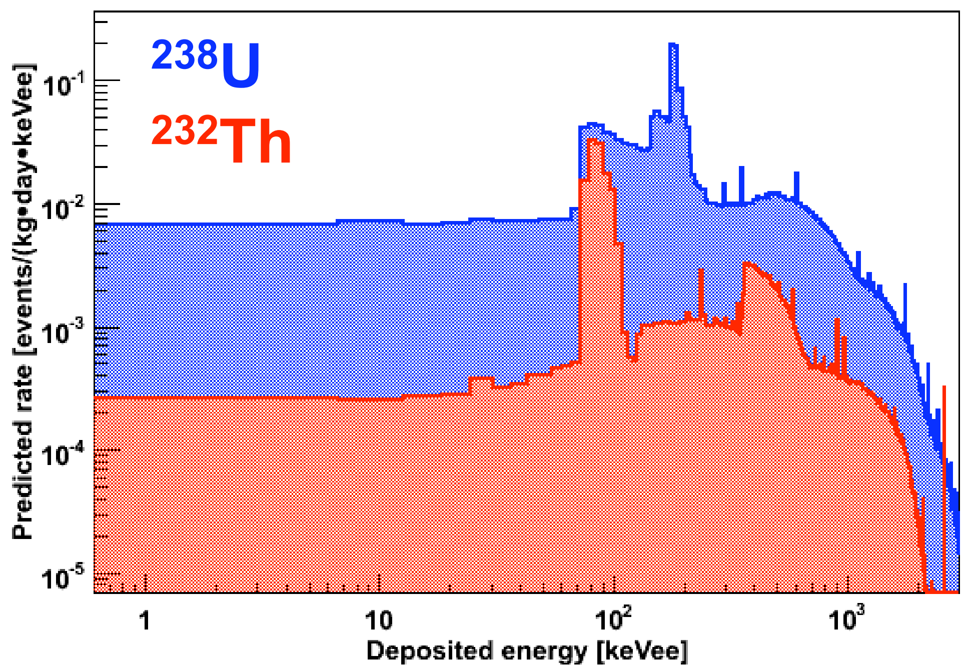
detection efficiency 12%

Contamination in LXe: ^{238}**U < 2.90 ppt,** ^{232}**Th < 1.95 ppt.**

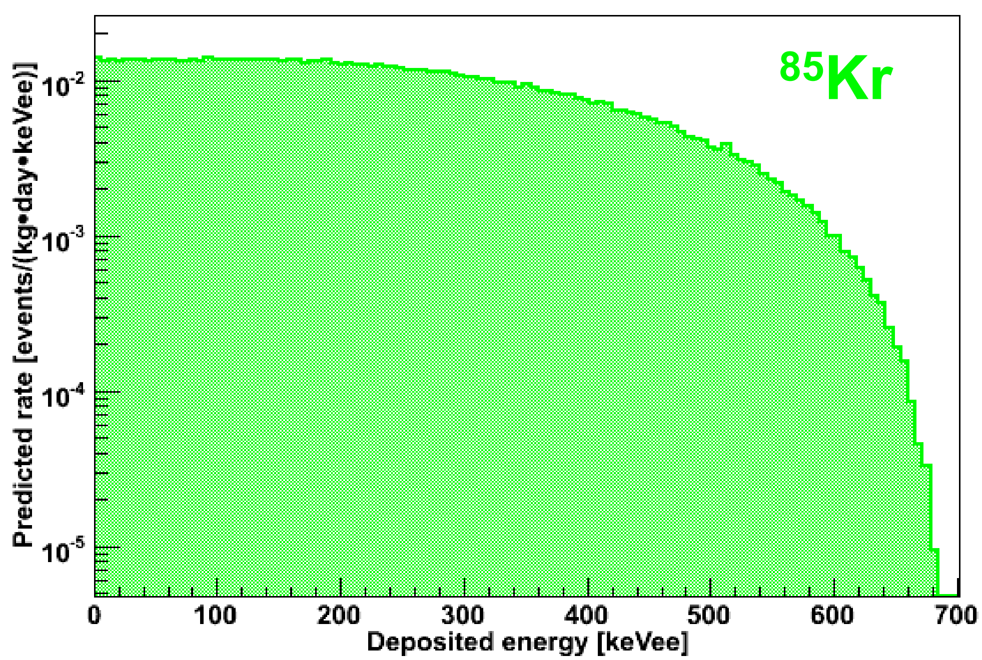
Background from Radioactive Contamination in LXe



Scaled to 2.90ppt of ^{238}U
1.95ppt of ^{232}Th

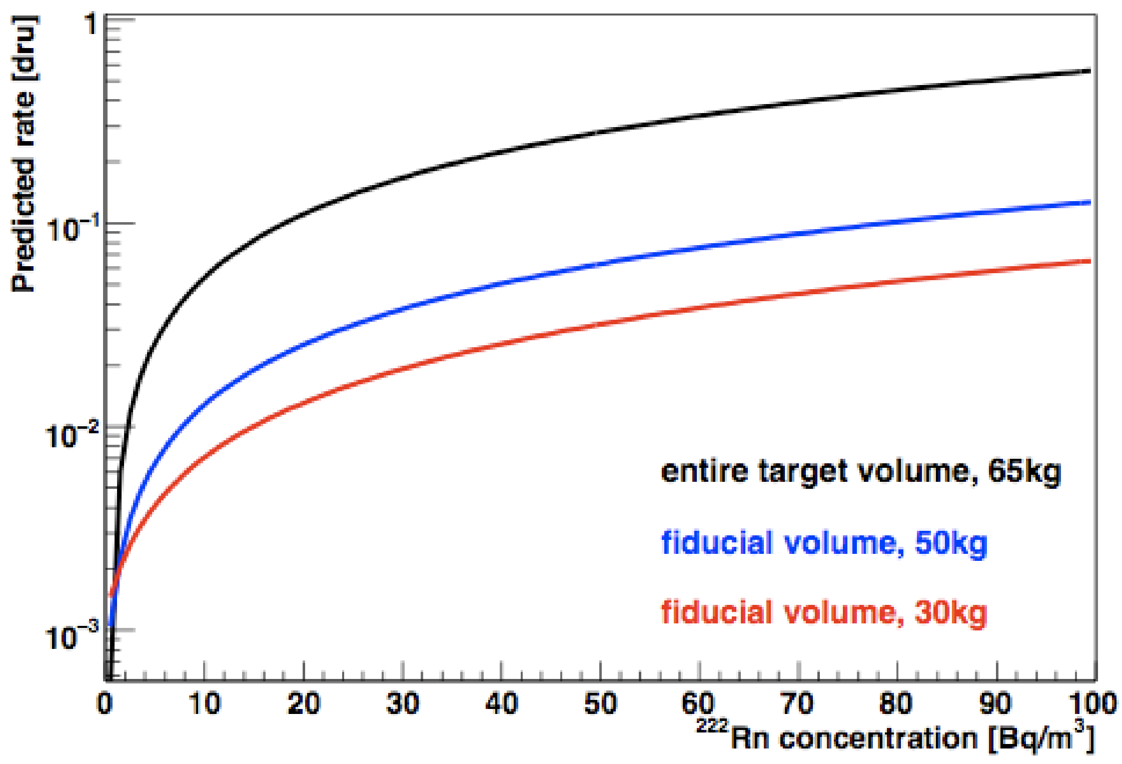


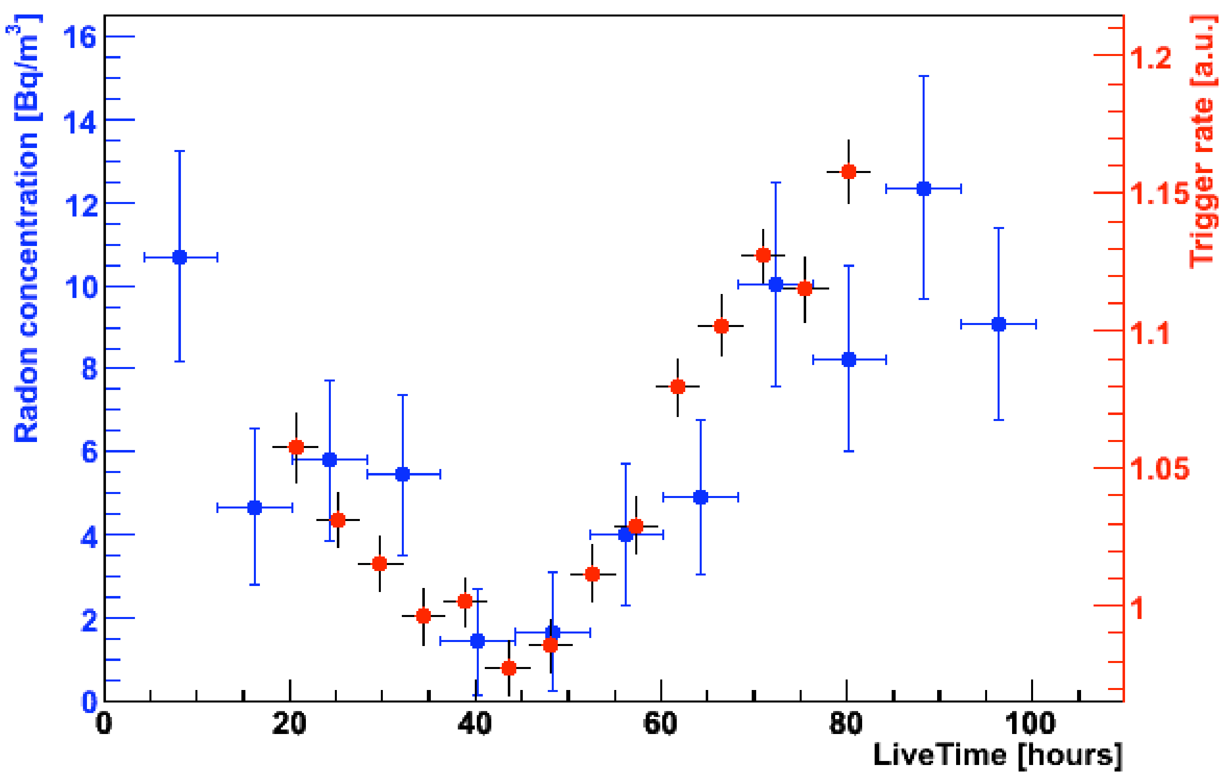
Scaled to 0.7ppb of Kr

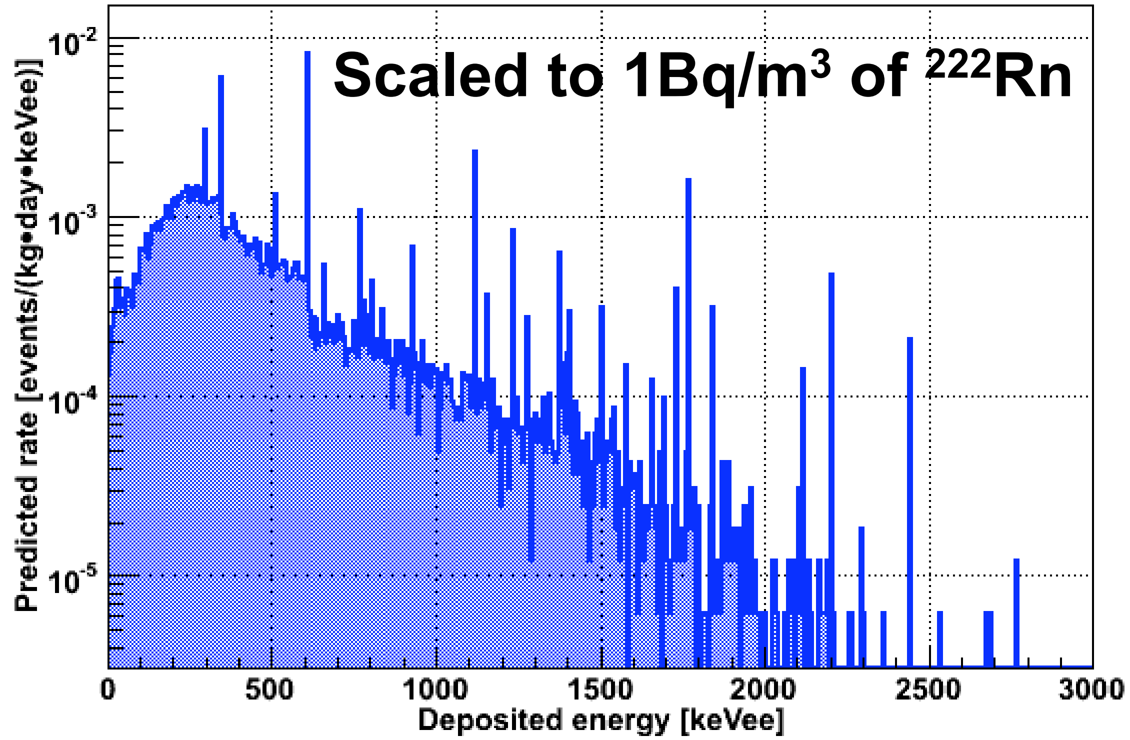


- **Kr contamination of Xe is measured with the delayed coincidence analysis as 0.7 ppb (before processing with distillation column)**
- **Collecting statistics for delayed coincidence analysis after Kr purification**

Gamma Background from ^{222}Rn in the Shield Cavity



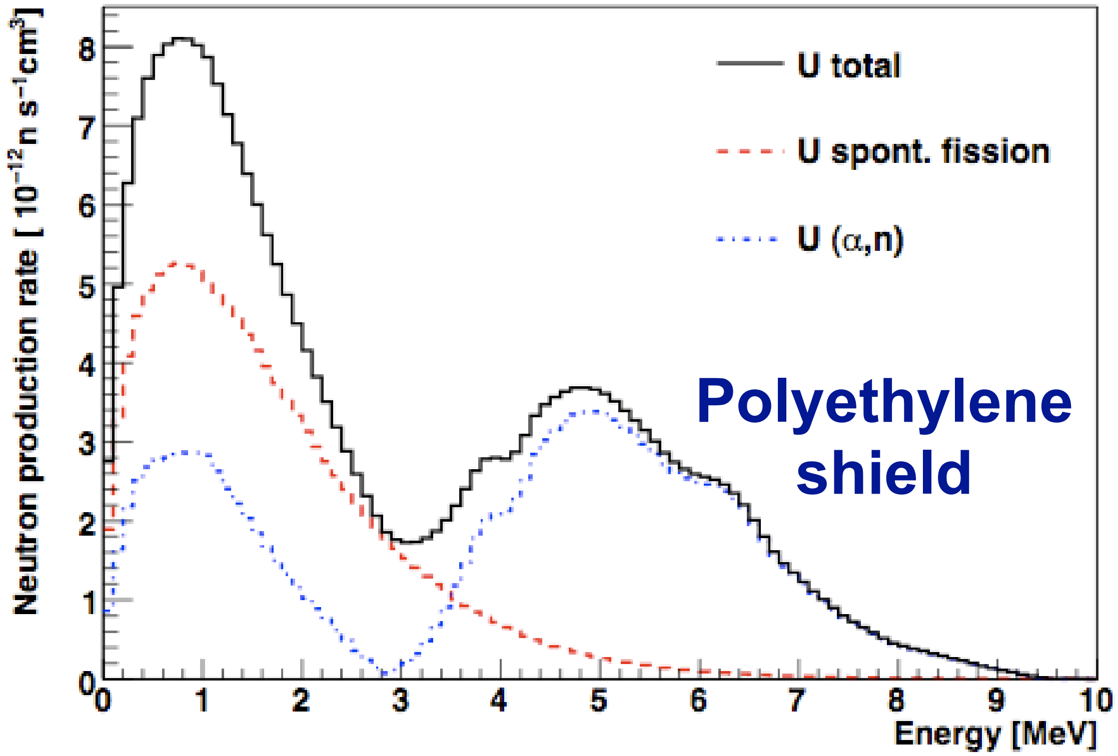


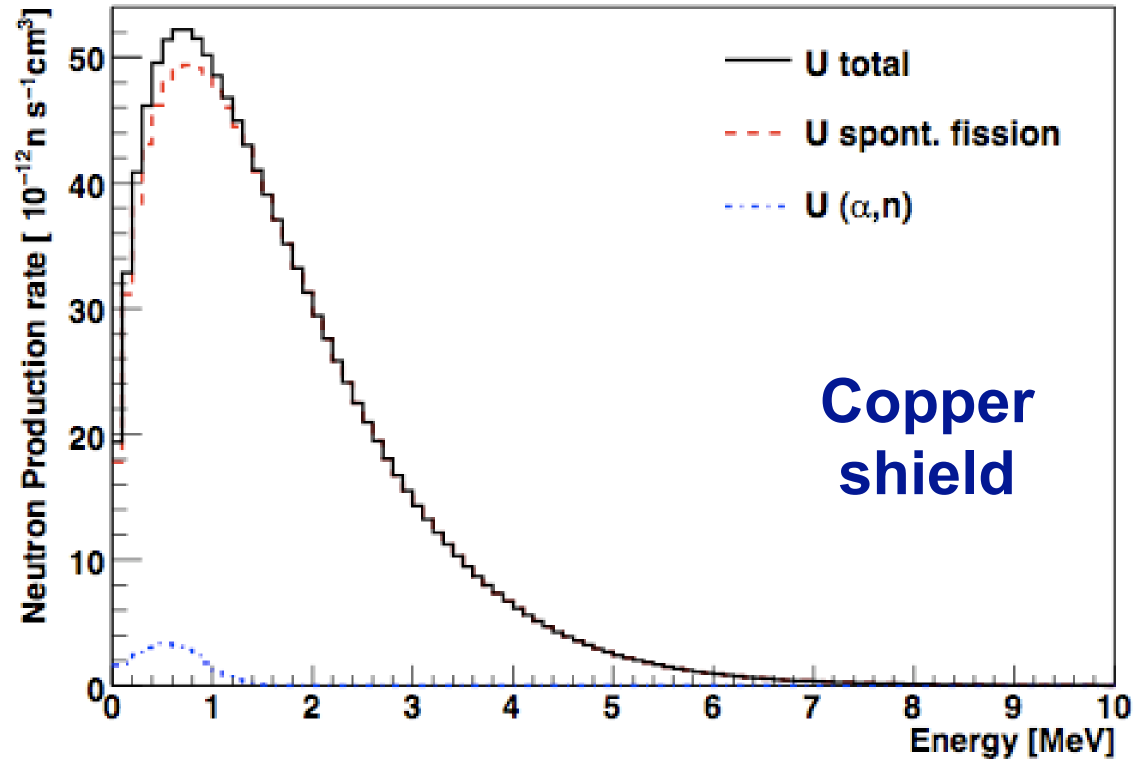


- The measured activity of radon in the tunnel is > 100 Bq/m^3
- With the closed shield door and constant flushing with nitrogen (6 SLPM) the concentration of Rn in the shield cavity is 1-2 Bq/m^3, which is predicted to contribute a few mDRU in the low energy part of the spectra (1-60 keV_{ee})

Neutrons from (α,n) reactions and Spontaneous Fission

- Neutron energy spectra and and rates from the (α,n) reactions and spontaneous fission are produced with SOURCES4A code





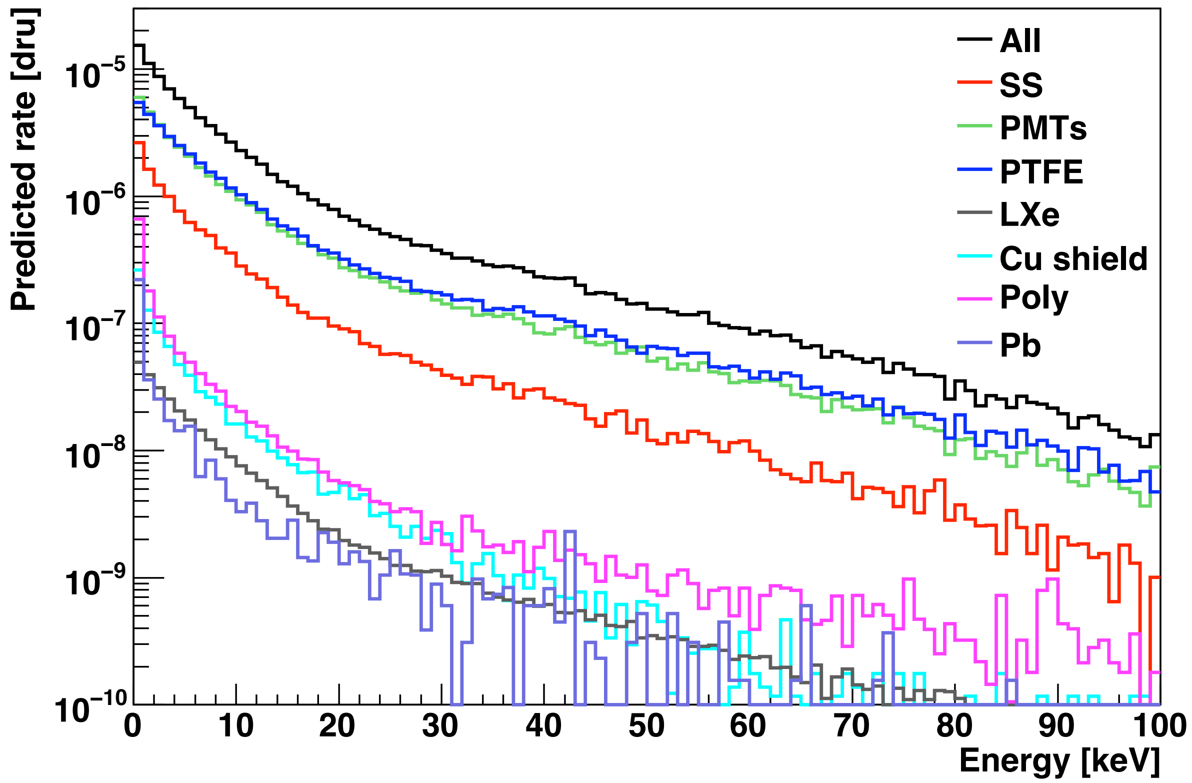
Material	n/year from U+Th (for measured activity and mass)
Steel	< 12.5
PTFE	< 14.1
PMTs[1]	< 21.8
LXe[2]	< 0.1
Polyethylene	< 39.7
Copper shield	< 2.0
Lead	< 1483.4

Material	U activity [ppb]	Th activity [ppb]	Total rate [$n{\cdot}y^{-1}{\cdot}g^{-1}$]
Rock	6800 ± 670	2167 ± 74	7.1
Concrete	1380 ± 240	1230 ± 250	2.5

* The cross-section for an (α,n) reaction decreases with *Z* of the target

Neutrons from (α,n) reactions and Spontaneous Fission

- **Neutron propagation with GEANT4 and prediction of the background rates**



- **Predicted BG from detector materials**

Material	Single scatter nuclear recoils per year in 50 kg FV	Single scatter nuclear recoils per year in 30 kg FV
Steel	< 0.088	< 0.039
PTFE	< 0.299	< 0.126
PMTs	0.277 ± 0.06	0.110 ± 0.02
LXe	< 0.003	0.001
Polyethylene	< 0.006	< 0.003
Copper shield	< 0.005	< 0.002
Lead	< 0.001	< 0.001
Total	**0.68**	**0.28**

- **Predicted BG from rock and concrete**

shield configuration	Single nuclear recoils per year in 50 kg FV	Single nuclear recoils per year in 30 kg FV
w/o water shield	4.78 ± 1.48	1.96 ± 0.94
with water shield	0.48 ± 0.15	0.20 ± 0.09

- **In order to moderate neutrons from the rock and concrete, tanks filled with water are placed around the shield box**

Muon-Induced Neutron Background

SIMULATION OF THE MUON-INDUCED NEUTRONS:

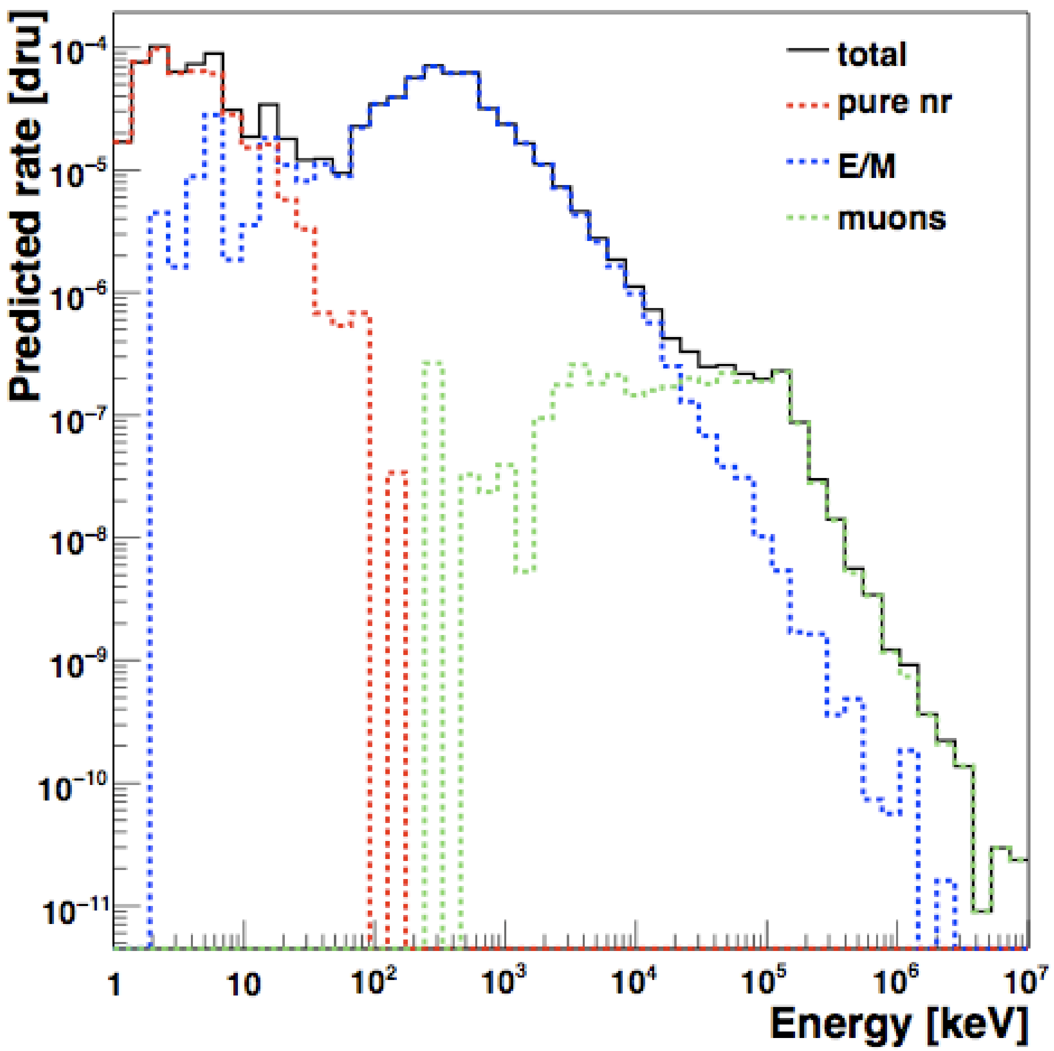
- **Transportation of muons from the Earth's surface down to the underground laboratory is simulated with MUSIC code (neutron yield strongly depends on the depth of the experimental hall and the mountain profile).** Used data for LNGS from:
  P. Antonioli et al., Astrop. Phys. 7 357 (1997),
  V.A.Kudryavtsev et al., Phys. Lett. B471 251 (1999).

- **Calculation of the angular distribution and the energy spectra at the experimental site is carried out with MUSUN code (sampling single atmospheric muons at the Gran Sasso laboratory, taking into account the slant depth distribution).**

- **Muon propagation with GEANT4 using QGSP-BIC-HP physics list.**

Physical Process	% of produced neutrons	% for a target with high Z	low Z
Hadronic	77	60	92
Electromagnetic	18	39	7
Muon spallation	4	1	1
μ^- capture	1	ignored	ignored

Muon-Induced Neutron Background



- **Contribution to the muon-induced background**

Material	Contribution to the total recoils rate [%]
Rock	0.04
Concrete	0.11
Polyethylene	1.8
Copper	37.6
Pb	4.6
Stainless steel	6.6
LXe	38.8
PTFE and PMTs	10.5

- **Predicted BG rate from muon-induced neutrons (EM component excluded)**

Type	Target mass	Nuclear recoils per year
Pure single+multiple scatters	entire target volume (65 kg)	36.3 ± 1.6
Pure single scatters	50 kg FV	0.27 ± 0.13
Pure single scatters	30 kg FV	< 0.07

Summary and Outlook

- The detailed model of the detector is developed within GEANT4 framework
- Results obtained with the optical simulations agree with the data (in the target volume)
- Veto efficiency measurements are performed (~100 positions). Data is being compared with MC model
- Electron and nuclear backgrounds from various sources are predicted. Detailed paper is in preparation

Electron recoils

(before S2/S1 discrimination)

Source of BG	events/(kg·day·keVee) 50 kg FV	events/(kg·day·keVee) 30 kg FV
Detector and shield materials	< 21.01	< 7.73
^{238}U and ^{232}Th in LXe	<5.57	<3.24
^{85}Kr in LXe	< 11.85	< 7.05
^{222}Rn in the cavity	< 2.56	< 1.24
All sources	< 40.99	< 19.26

Nuclear recoils

Neutron source	Single nuclear recoils per year in 50 kg FV	Single nuclear recoils per year in 30 kg FV
Detector and shield materials	< 0.68	< 0.28
Cavern	0.48 ± 0.15	0.20 ± 0.09
Cosmic ray muons	0.27 ± 0.13	< 0.07
All sources	< 1.43	< 0.55

Thank you.

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