Simulation for rare decays in LEGEND detectors

Gran Sasso Hands-on 2023

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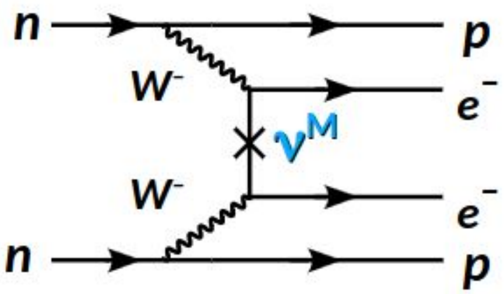
Motivation for the experiment

- **Lepton Number violation** related to leptogenesys theories
- Studying the nature of neutrino **(Majorana or Dirac particle)**
- **IO/NO** of neutrino masses



$$Q_{\beta\beta} = M_{init} - M_{final} - 2m_e$$

$$T_{1/2}^{0\nu\beta\beta} \sim \frac{Mt}{N^{0\nu\beta\beta}}$$

exposure

observed events

$$T_{1/2}^{0\nu\beta\beta} \sim \sqrt{\frac{Mt}{BI\,\Delta E}}$$

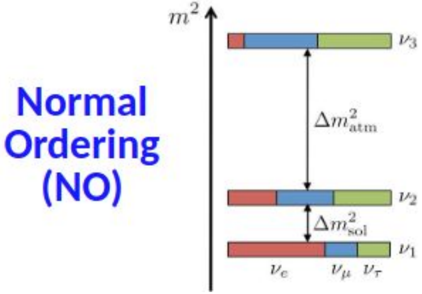
background index

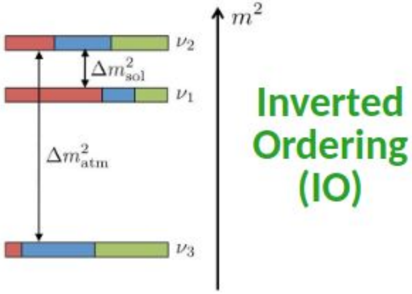
energy resolution $Q_{\beta\beta}$

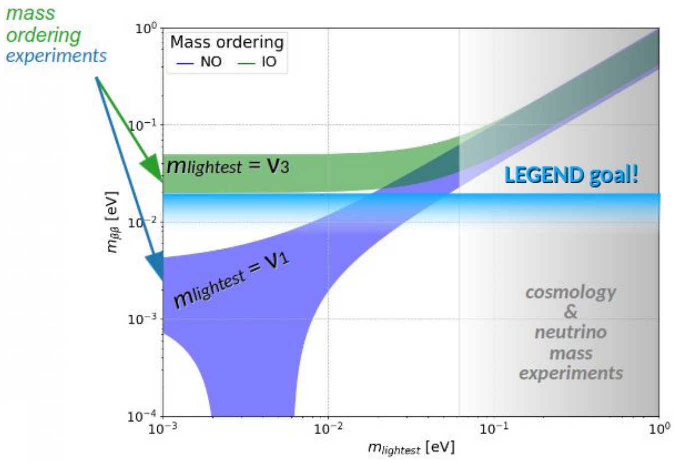
$$m_{\beta\beta}^2 = \left(\left(F^{0\nu} \right) \cdot \left| M^{0\nu} \right|^2 \cdot T_{1/2}^{0\nu\beta\beta} \right)^{-1}$$

phase space factor

nuclear matrix element



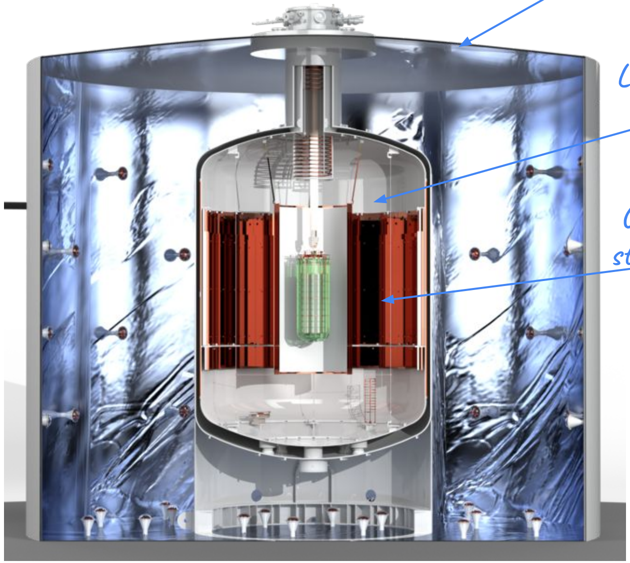




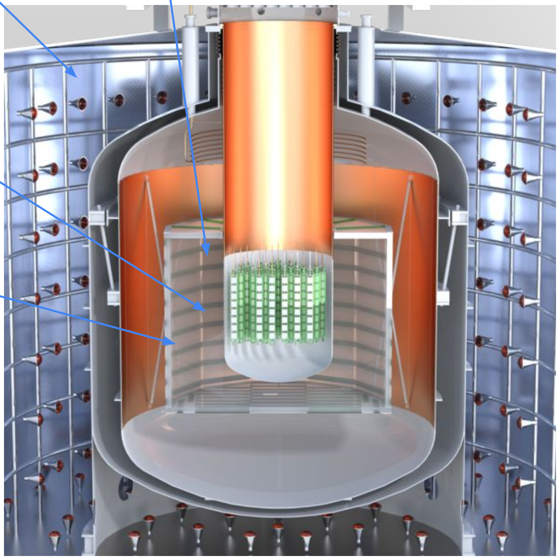
LEGEND detector

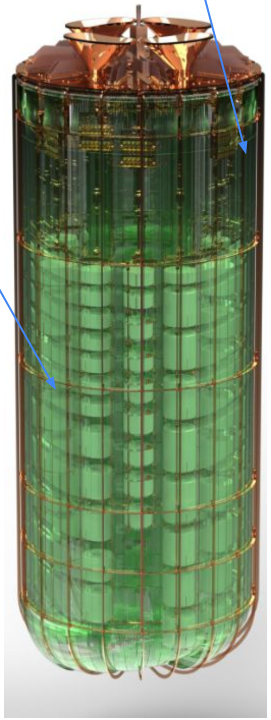
$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^{-}\ [+ 2\bar{\nu}_e]$

LEGEND-200



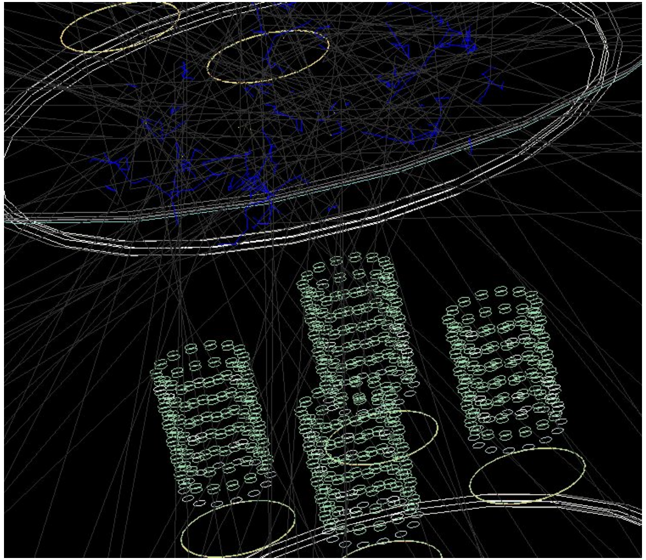
LEGEND-1000

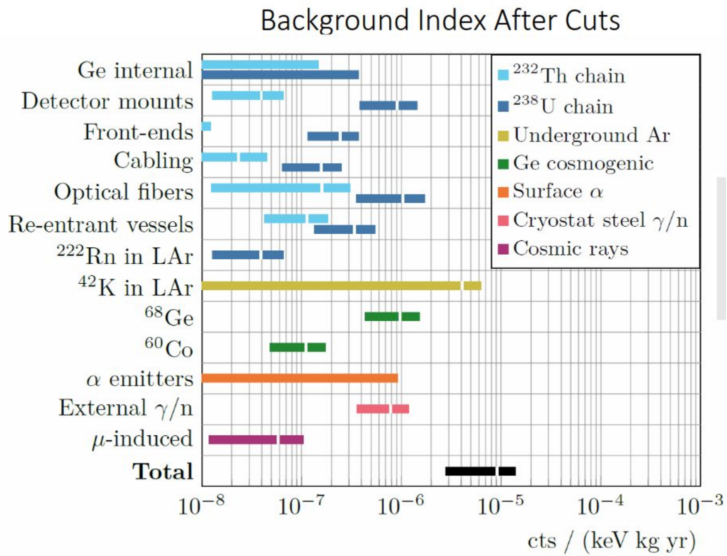




Detector simulation by GEANT4

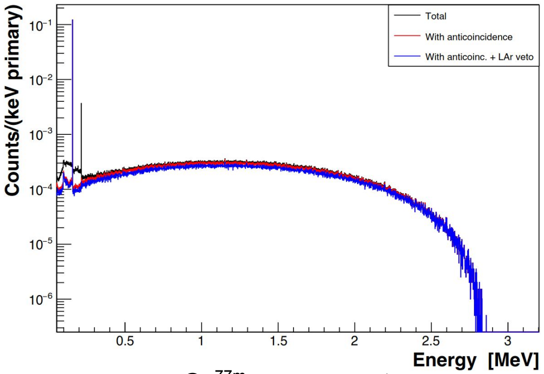
- For simulation the *warwick-legend* package is used
- The μ-induced events are simulated (2.5e6 simulations with muons as input particles)
- the neutron moderator (PMMA tube) used for reducing high-energy neutrons, produced in cosmic ray showers initiated by muons in mountain and detector materials



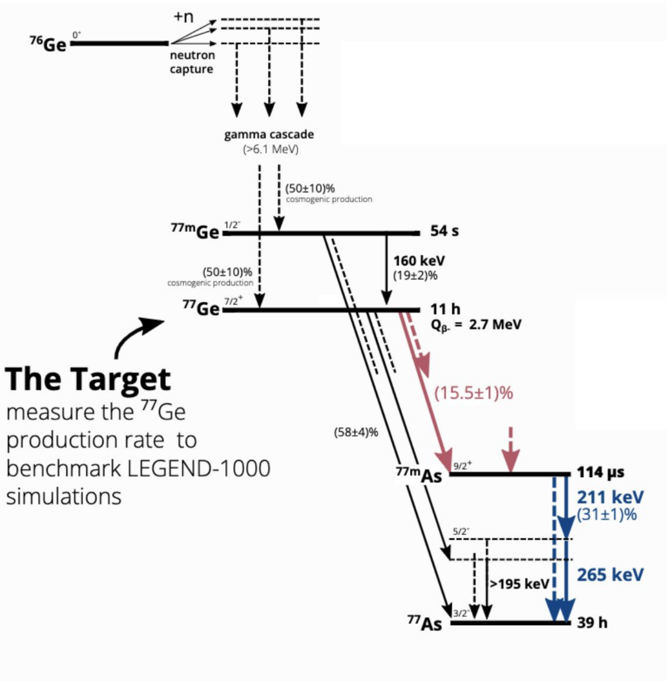


Ge^{77} / Ge^{77m} decay

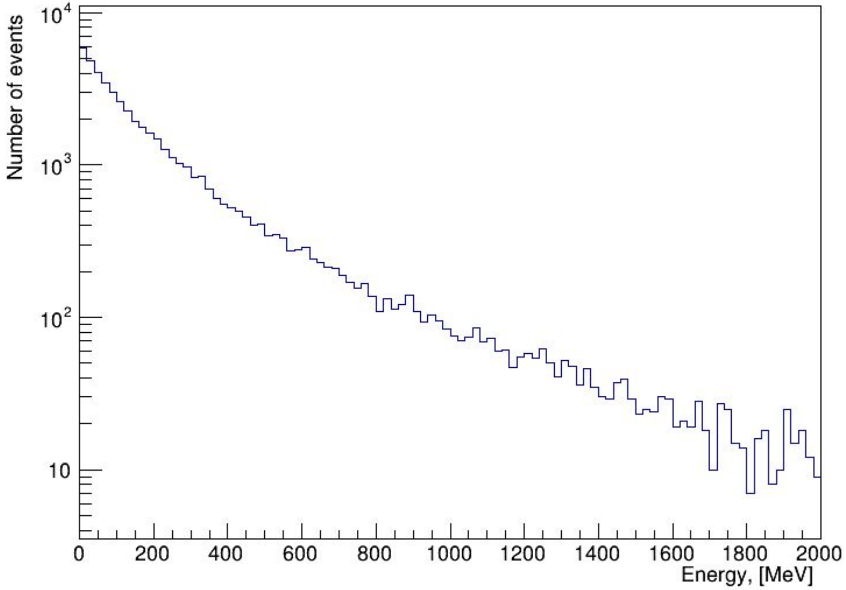
- The one of the main aim of LEGEND experiment – searching the 0νββ decay of Ge^{76}
- $Ge^{76}+n \rightarrow Ge^{77}+...$
- The Ge^{77} decay is the main background for process under study
- The decays Ge^{77} and Ge^{77m} were simulated
- The Ge^{77m} decay is pure β-decay with Q-value > 2039 keV (ROI for 0νββ decay Ge^{76})



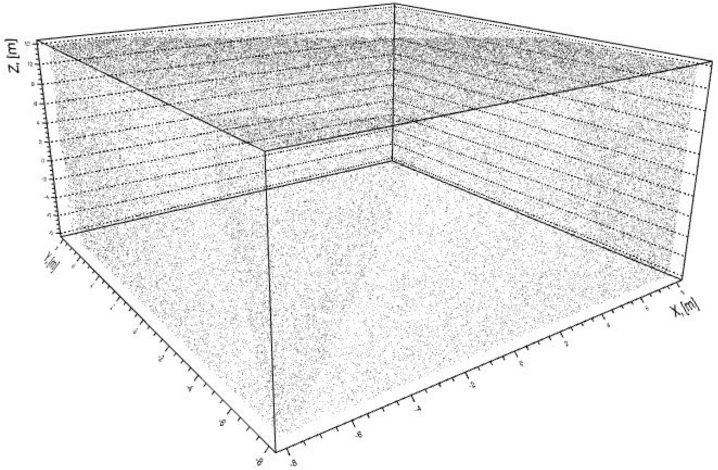
Ge^{77m} energy spectrum



Muon background events

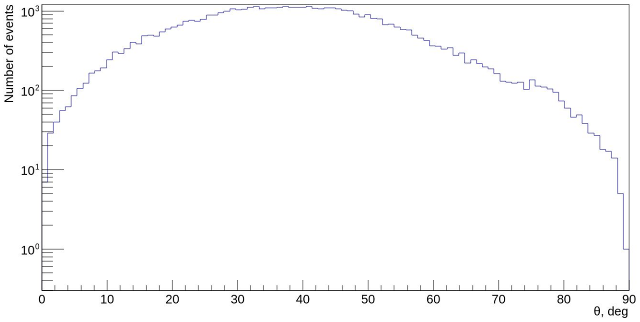


Primary muons spectrum

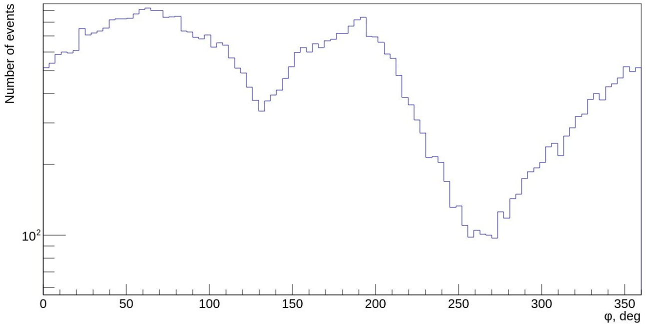


3D visualization of primary muons coordinates

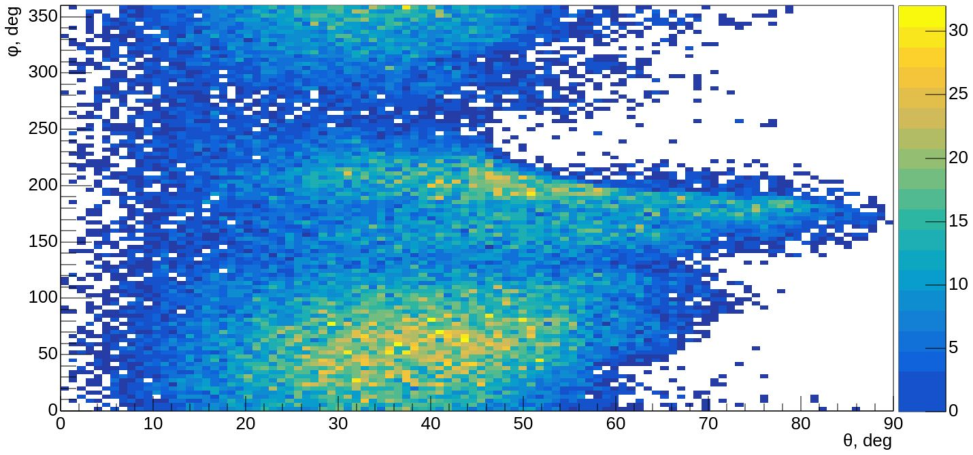
Muon background events



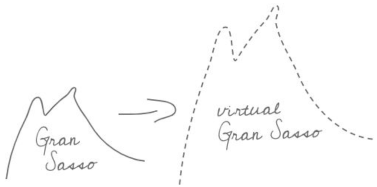
Distribution of theta angle of pulse



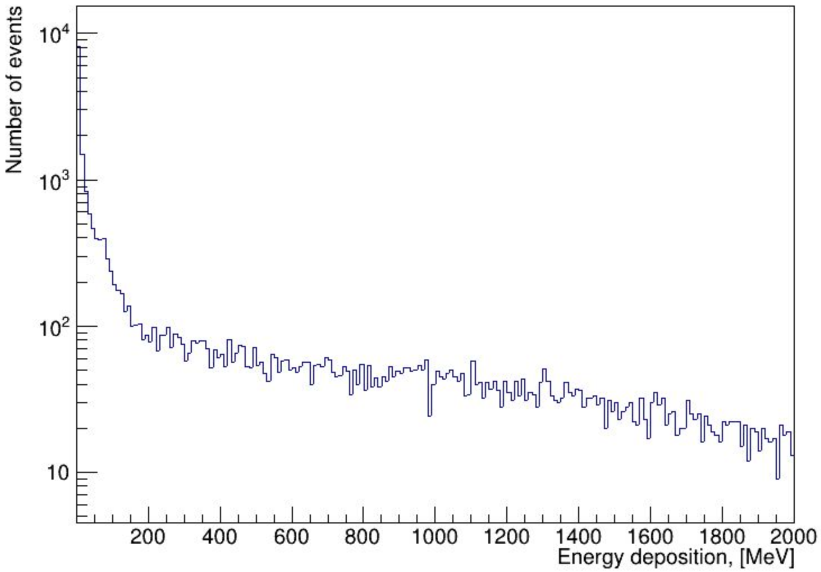
Distribution of phi angle of pulse



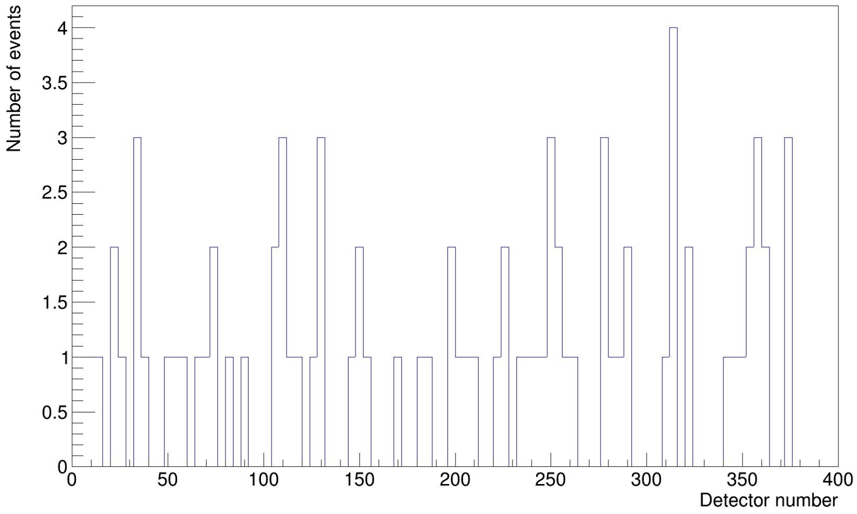
Distribution of phi and theta angles of pulse



Muon background events

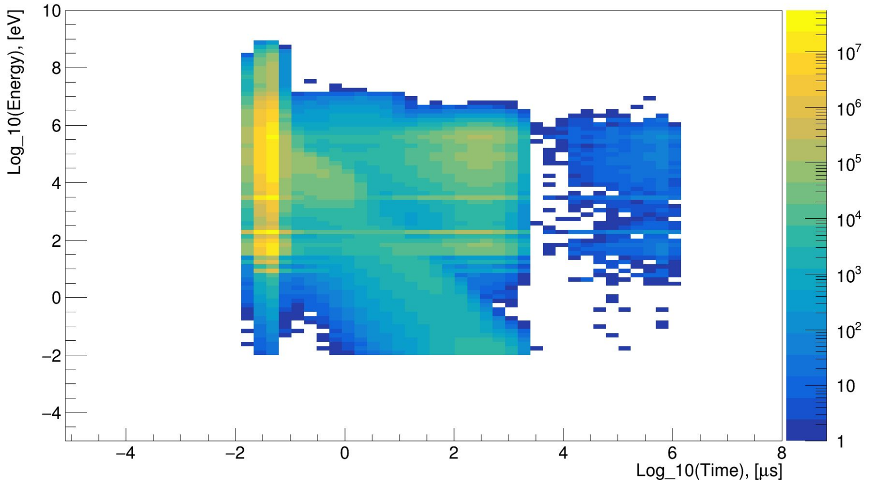


Muon-induced particles energy spectrum in germanium

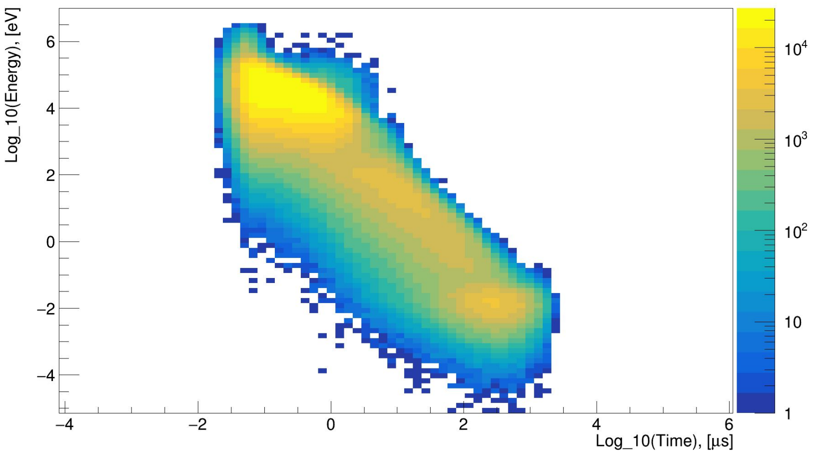


Distribution of captured neutrons in detectors

Results of simulation of neutrons

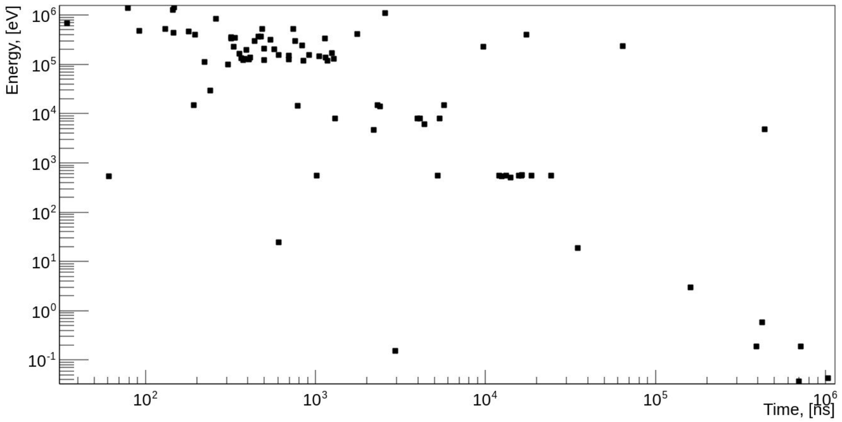


Energy distribution of muon-induces particles
as a function of time

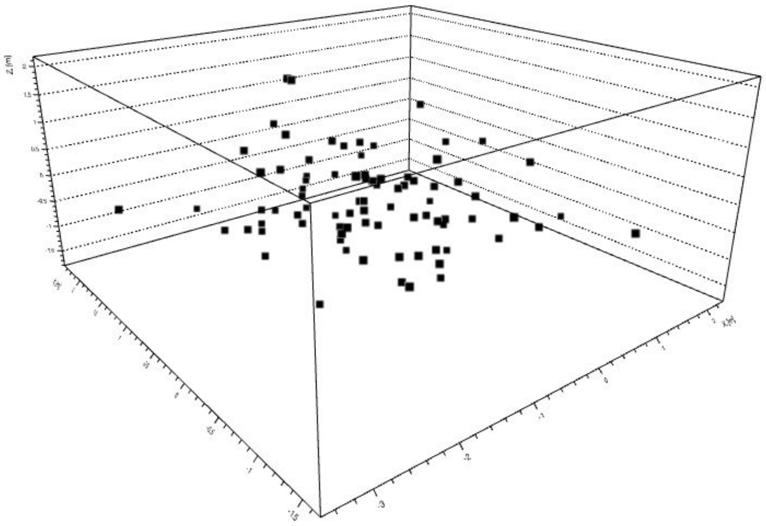


Energy distribution of produced neutrons
as a function of time

Results of simulation of neutrons



Dependence of the energy of captured neutrons on time



3D visualization of neutrons captured in the detector

Simulation results

- N_{Ge77} without neutron moderator using ≃ 0.31 events /(kg · year)
- Number of generated Ge^{77} isotopes is $\mathbf{N_{Ge77events}}$ = 84 events

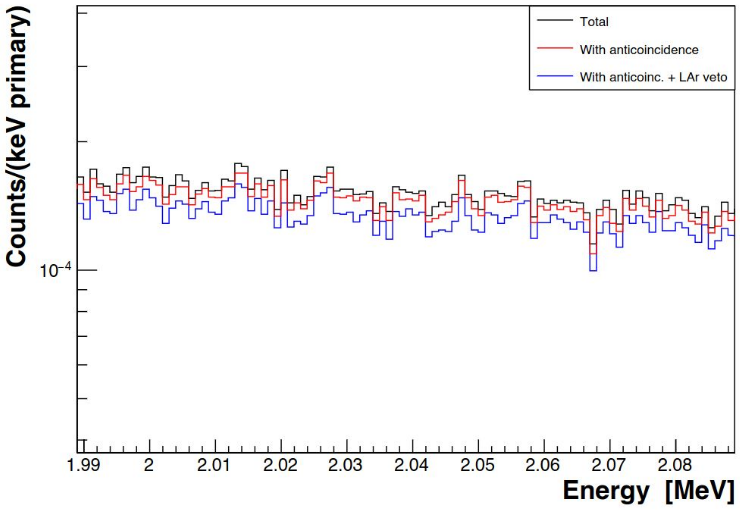
$\mathbf{N_\mu}$ = 504 events/h, $\mathbf{N_{events}}$=2450000 events, **M** = 1026.86 kg – fidusial volume

- Number of bg_events/keV/N_{Ge77} = 7e-5 cts/(keV primary) (value from plot)
- Bg index from muon induces Ge77/Ge77m isotopes = 0.15*7e-5 = 10e-6 cts/(keV · kg · year)

The use of a neutron moderator in the detector model allows to reduce the background by a factor of 2.

$$N_{Ge^{77}} = \frac{N_{Ge^{77}events} \cdot N_\mu \cdot 24 \cdot 365.25}{N_{events} \cdot M} \approx 0.15$$

number of produced isotopes/(kg · year)



Ge^{77m} decay spectrum

Conclusion

- The simulation performed allow to estimate the effect of reduction of the number of $Ge^{(m)77}$ nuclei produced
- from our results a value for the background index from this background component is

10e-6 cts/(keV kg yr)

- this value is a factor **x2 smaller** than the configuration without moderator
- in LEGEND-1000 this background requires to be further suppressed. There are different strategis under study that allow a further reduction of a factor ~10 (delayed coincidence between muon veto and Ge detectors + identification of the low-energy gamma associated with the decay).

Thank you!

Backup

LEGEND detector

Backup

	LEGEND-200	LEGEND-1000
Mass	200 kg	1000 kg
Exposure	1000 kg · year	10 000 kg · year
Bkg index	$2 \cdot 10^{-4}$ cts/(keV · kg · year)	$2 \cdot 10^{-5}$ cts/(keV · kg · year)
Resolution	2.5 keV	2.5 keV