Simulations of gamma-ray background from rock for dark matter experiments

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WIMP detection

- The constituents of dark matter still remain a mystery.
- Both LZ (LUX-ZEPLIN) and its predecessor LUX were designed to search for promising candidates for dark matter, Weakly Interacting Massive Particles (WIMPs).
- The experiments look for nuclear recoil events from dark matter elastic scattering off nuclei, illustrated in Figure 1, within a two-phase xenon time projection chamber (TPC).
- Figure 2 displays the particle signal observed in the LUX and LZ detector TPCs. After the initial S1 signal, produced by scintillation light, ionisation electrons drift from the liquid to the gas region of the TPC due to the high electric field. At this point electroluminescence occurs due to the passage of the high-energy electrons through the gas, generating the S2 signal.

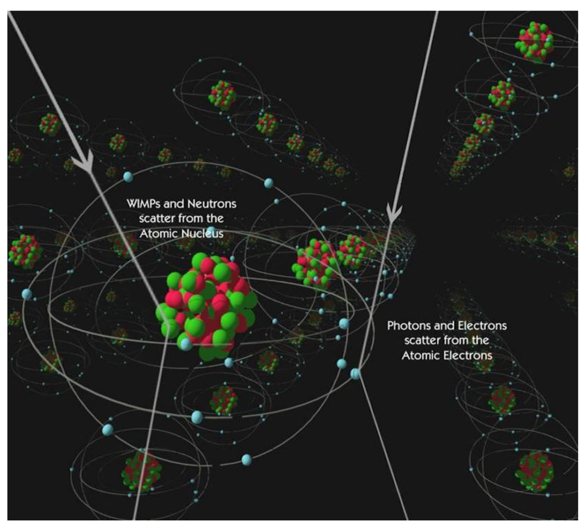

Figure 1: Illustration of particle scattering interactions with an atom. Courtesy of M. Attisha taken from `http://cdms.berkeley.edu/Education/DMpages/science/directDetection.shtml`

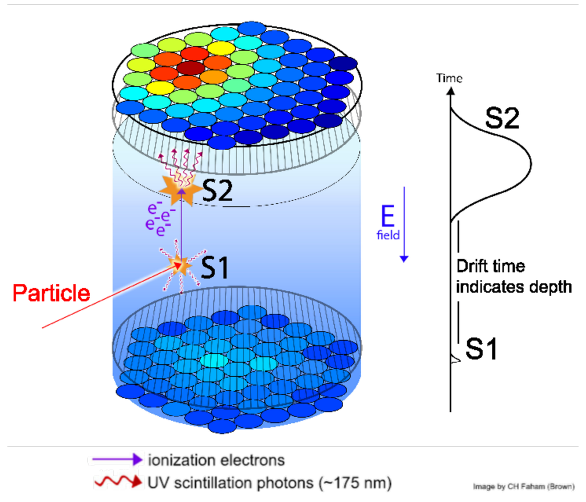

Figure 2: Illustration of signal generation from the two-phase TPC in LUX and LZ detectors.

LUX and LZ detectors [1, 2]

- Located 4850 ft underground at Sanford Underground Research Facility, South Dakota, USA.
- Both detectors are two-phase xenon TPCs. LUX has 250 kg active mass of liquid xenon (LXe) (∼100 kg fiducial mass) and LZ has 7 tonne active mass of LXe (∼5.6 tonne fiducial mass).
- Gamma-ray and neutron fluxes from the cavern rock are significantly attenuated by the large water tank ($h \times d$ = 592.8 cm × 762 cm) shown in both Figures 3 and 4. Steel plates are placed in an "inverted-pyramid" formation underneath the water tank to increase shielding against gamma rays.
- LZ will also employ an outer detector system to reduce background events. Comprised of a liquid scintillator (green tank in Figure 4) and a LXe "skin" inside the inner cryostat, the outer detector will operate as a veto system.
- LUX detector was decommissioned in late 2016.
- LZ detector is planning to run for 1000 days of live time. It is currently under construction and expecting to take data from 2020.

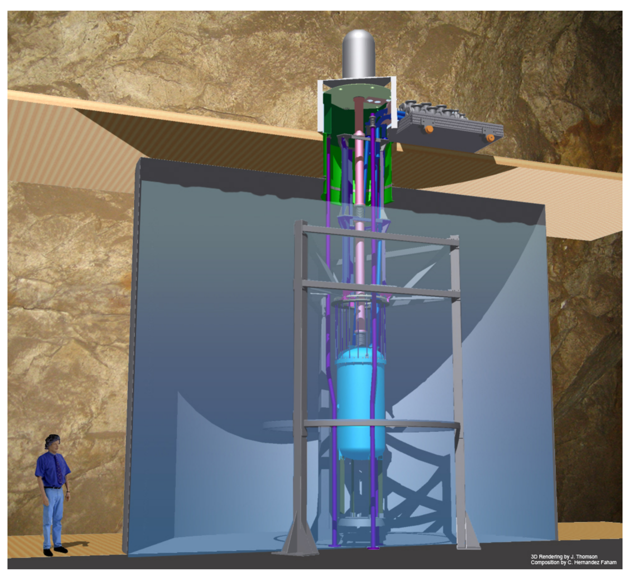

Figure 3: 3D rendering of LUX in water tank [3].

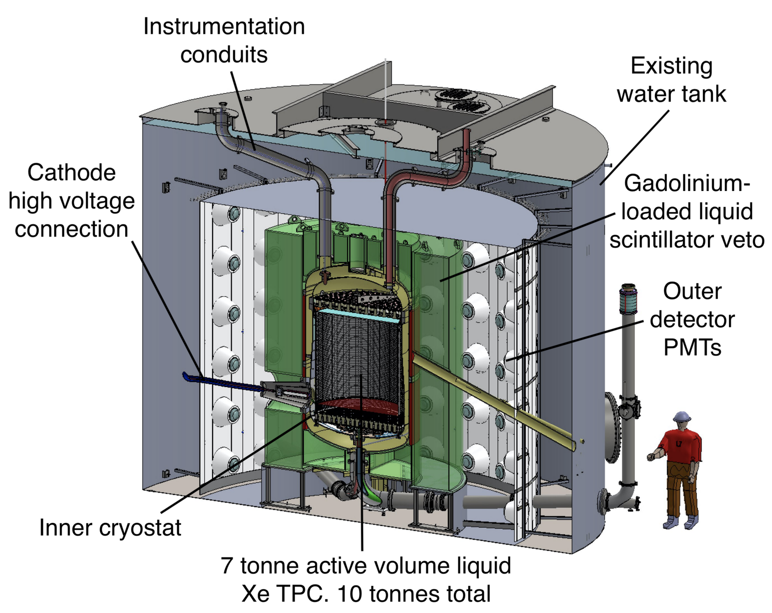

Figure 4: 3D rendering of a cutaway of the LZ detector [4].

Motivation and method

The aim of this work is to simulate gamma rays from the cavern rock. The goals are listed below.

- Identify the contribution of gamma rays from the cavern rock to the background for WIMP searches in LUX and LZ.
- Identify the background from gamma rays from the cavern rock to other physics studies (such as neutrinoless double beta decay).
- Understand the gamma-ray rate in the outer detector for the LZ experiment.

Method:

- Simulate ^{232}Th, ^{238}U and ^{40}K decays with LUXSim and BACCARAT (simulation software based on GEANT4, developed for LUX and LZ respectively [5, 2, 6]) as they are sources of background gamma rays from the cavern rock for the LUX and LZ detectors. Full decay chains for all isotopes were simulated assuming secular equilibrium.
- Separate the simulation into stages as these simulations require a significant number ($\sim 10^{16}$) of decays. At stage boundaries gamma rays are saved and then re-propagated 100 times, as illustrated in Figure 5. This event biasing method allows us to increase statistics with smaller CPU time.
- To define the stage boundaries the LUX simulations used an innovative approach employing parallel worlds, a feature within GEANT4 which allows the user to generate overlapping volumes. Currently results via this approach are only available for LUX but LZ simulations are in progress.

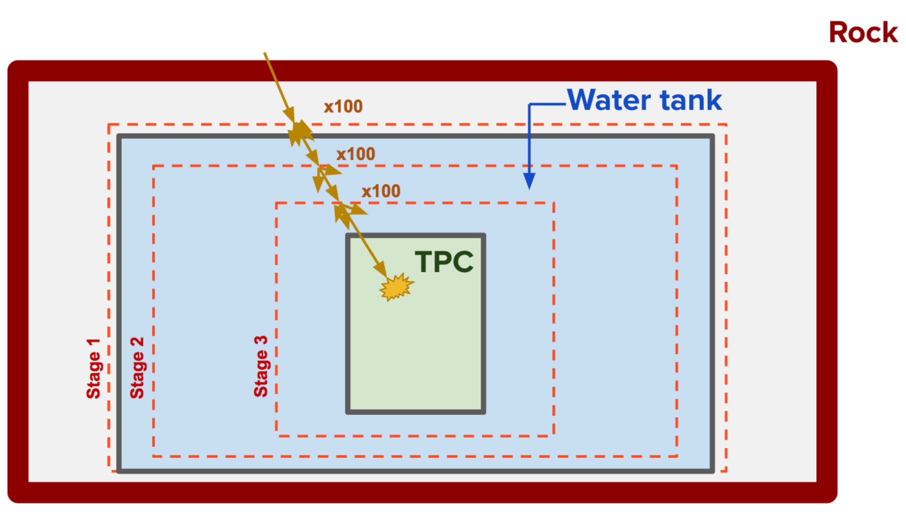

Figure 5: Illustration of event biasing method implemented. Figure provided by David Woodward.

Analysis for LUX

- After completion of the simulation, the LUX data analysis cuts shown below are applied, leaving WIMP-like candidates.
  - Keep events above the cathode inside the TPC.
  - Total energy depositions < 100 keV.
  - Single scatters ($\Delta Z < 0.65$ cm).
  - Reconstructed position inside fiducial region.
  - S1 size is > 0 detected photons.
  - S2 size is > 100 detected photons.
- The following normalisation is applied to determine the equivalent run time corresponding to the number of simulated decays:

$$t = \frac{N_{decay}}{M_s[\text{kg}] \cdot A_s[\text{Bq/kg}] \cdot 86400} \quad (1)$$

where t is run time (days), N_{decay} is the number of simulated decays, A_s is activity (A_{Th}=13.6 Bq/kg, A_{U}=24.8 Bq/kg, A_{K}=381 Bq/kg [7]) and M_s is mass of component where the gamma-ray sources are located (30 cm shell of rock = 1.16×10^6 kg).

Results

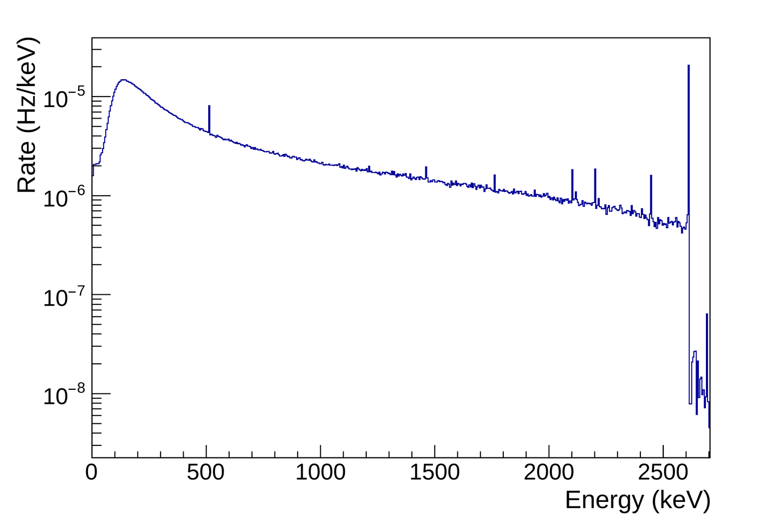

Figure 6: Energy spectra of all events above the cathode inside the LUX TPC before LUX data analysis cuts applied.

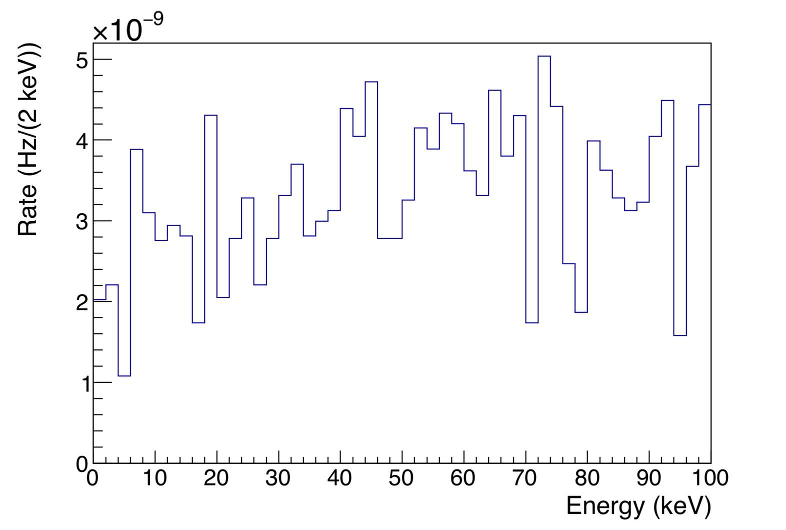

Figure 7: Energy spectra of events within the WIMP-search region of interest (< 100 keV) after LUX data analysis cuts applied.

Table 1: Results from rock gamma-ray event biasing simulations for the LUX detector, where DRU is given in units of events/kg/day/keV. * In the DRU calculation a flat background up to 100 keV has been assumed with a 105.4 kg fiducial volume.

Isotope	Simulated run time (days)	WIMP-like events	Background events in 300 days after cuts	μDRU*
^{232}Th	7.34×10^4	853	3.49 ± 0.12	1.10 ± 0.04
^{238}U	4.02×10^4	97	0.72 ± 0.07	0.23 ± 0.02
^{40}K	2.62×10^4	6	0.07 ± 0.03	0.022 ± 0.009
Total			**4.28 ± 0.14**	**1.35 ± 0.05**

- The total observed background rate for LUX of (3.6±0.4) mDRU [8] is much higher than the total rate displayed in Table 1 which shows that the gamma rays from the cavern rock are a sub-dominant background.

Table 2: A comparison between the LUX rock gamma-ray simulations and comparable simulations performed for LZ with a similar biasing technique but without parallel worlds. Conservative estimates for the activities were used in the LZ normalisation (A_{Th}=26.1 Bq/kg, A_{U}=73.4 Bq/kg, A_{K}=716 Bq/kg [2]). * In the last column the same activities have been used as for LUX normalisation.

Isotope	LUX μDRU	LZ μDRU	LZ* μDRU
^{232}Th	1.10 ± 0.04	0.093 ± 0.017	0.049 ± 0.009
^{238}U	0.23 ± 0.02	0.035 ± 0.018	0.012 ± 0.006
^{40}K	0.022 ± 0.009	0.034 ± 0.017	0.018 ± 0.009
Total	**1.35 ± 0.05**	**0.163 ± 0.030**	**0.079 ± 0.014**

Conclusions

- A novel method has been successfully deployed for simulating gamma-ray transport through large thickness of shielding, showing that the gamma rays from the cavern rock are a sub-dominant background.
- Improvements with the LZ detector design have resulted in lower background event rates from cavern rock gamma rays compared to LUX.
- LZ simulations of cavern rock gamma rays with the new stage boundaries approach are currently in progress.

References

[1] D. S. Akerib, X. Bai, S. Bedikian, E. Bernard, et al., *Nucl. Instr. Meth. Phys. Res. A.* **704**, 111 (2013).

[2] B. J. Mount, S. Hans, R. Rosero, M. Yeh, et al., (2017) LUX-ZEPLIN (LZ) Technical Design Report; LBNL-1007256, FERMILAB-TM-2653-AE-E-PPD, arXiv:1703.09144 [physics.ins-det].

[3] The LUX Collaboration, LUX detector images, (`http://luxdarkmatter.org/`).

[4] D. S. Akerib, C. W. Akerlof, S. K. Alsum, H. M. Araújo, et al., (2018) Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment; FERMILAB-PUB-18-054-AE-PPD, arXiv:1802.06039 [astro-ph.IM].

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