LZ simulations

Vitaly A. Kudryavtsev
University of Sheffield, United Kingdom

for the LZ Collaboration

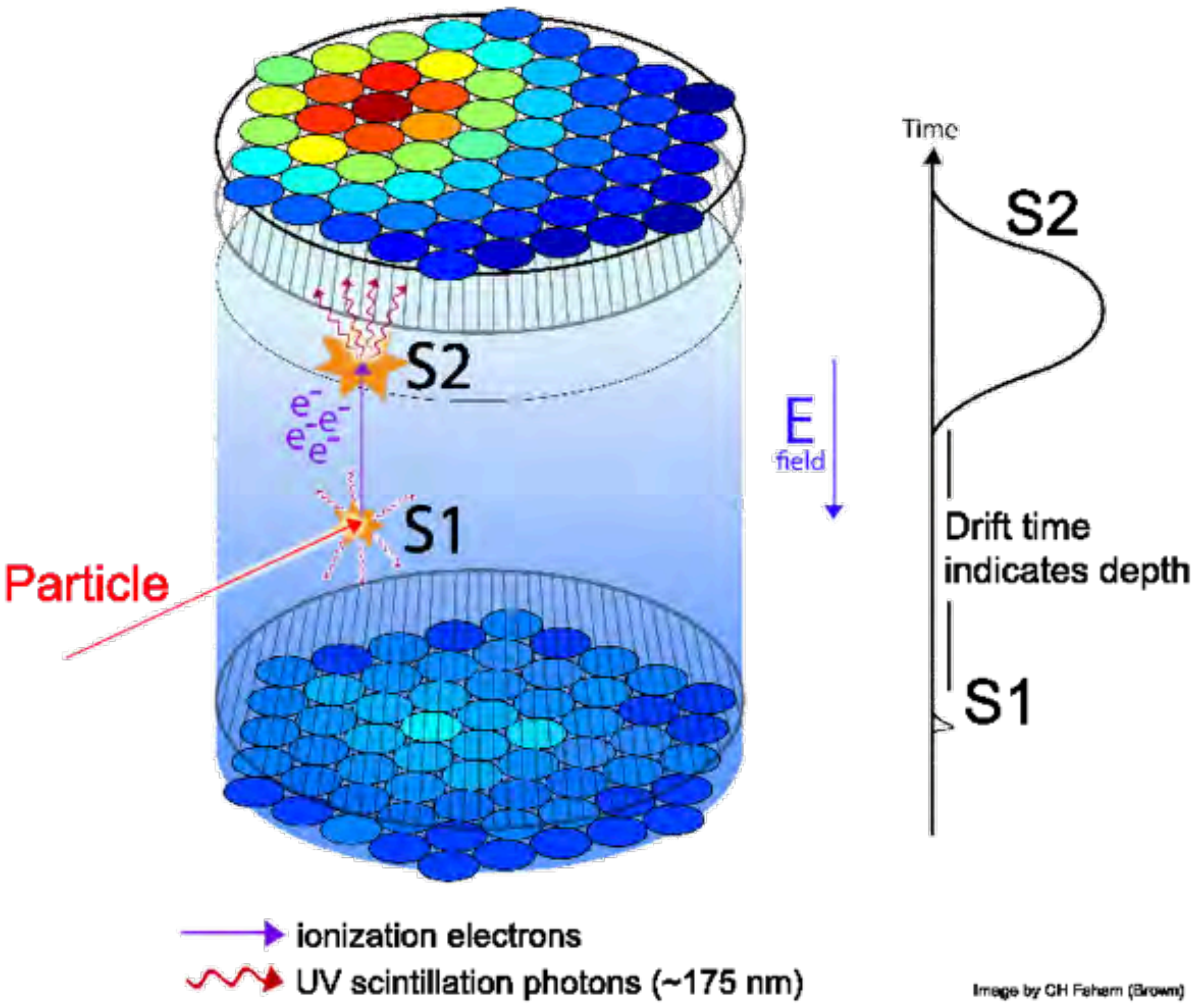
Outline

- Introduction: LZ experiment.
- LZ detector in CAD design and simulations.
- BACCARAT (and its predecessor LUXSim).
- Event generators.
- Detector response.
- Applications.
- Conclusions.

LUX-ZEPLIN (LZ) experiment

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics, Korea
- Fermi National Accelerator Laboratory
- Imperial College London
- LIP Coimbra, Portugal
- Lawrence Berkley National Laboratory
- Lawrence Livermore National Laboratory
- MEPhI-Moscow, Russia
- Northwestern University
- Pennsylvania State University
- Royal Holloway, University of London
- SLAC National Accelerator Laboratory
- South Dakota School of Mines and Technology
- South Dakota Science and Technology Authority
- STFC Rutherford Appleton Laboratory
- Texas A&M University
- University at Albany, SUNY
- University College London
- University of Alabama
- University of Bristol
- University of California, Berkeley
- University of California, Davis
- University of California, Santa Barbara
- University of Edinburgh
- University of Liverpool
- University of Maryland
- University of Michigan
- University of Massachusetts
- University of Oxford
- University of Rochester
- University of Sheffield
- University of South Dakota
- University of Wisconsin – Madison
- Washington University in St. Louis
- Yale University

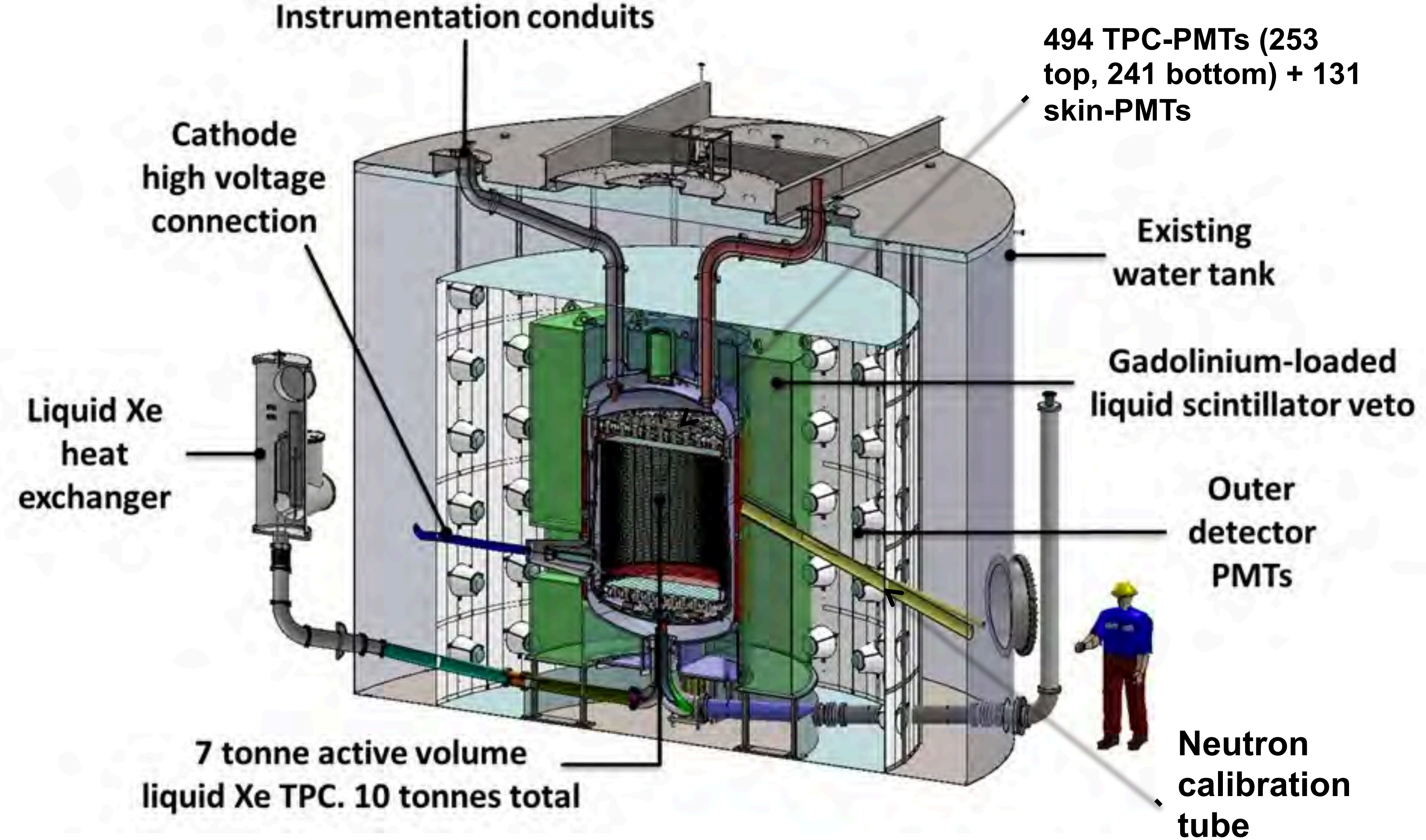
Principle of WIMP detection in LXe TPC



- Liquid xenon time projection chamber – LXe TPC.
- S1 – primary scintillation.
- S2 –secondary scintillation, proportional to ionisation.
- Position reconstruction based on the light pattern in the PMTs and delay between S2 and S1.

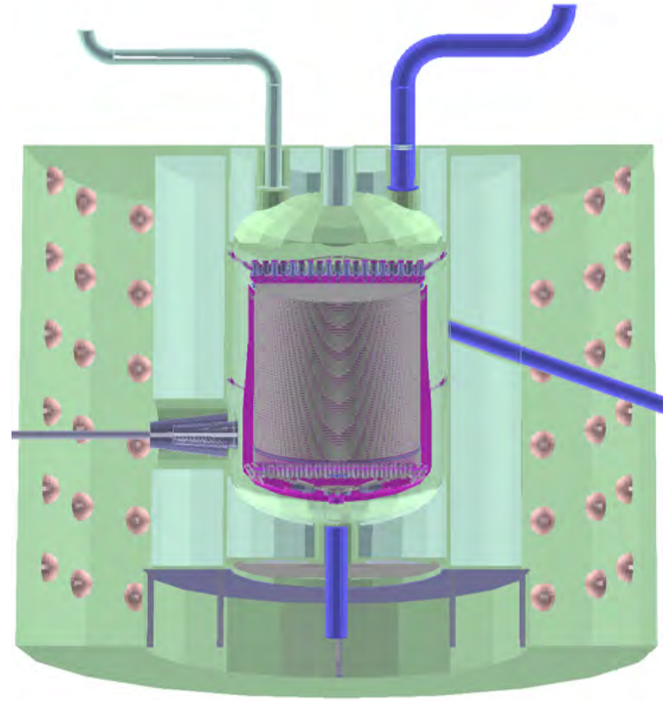
LZ detector

LZ Collaboration, arXiv:1509.02910[physics.ins-det], 1703.09144v1 [physics.ins-det]
Talk by C. Hall on Tuesday morning on the status of LZ.



BACCARAT

- Based on LUXSim: D. S. Akerib et al., Nucl. Instrum. Meth. A 675, 63 (2012) – the simulation framework for LUX.
- BACCARAT: BASICALLY, A COMPONENT-CENTRIC ANALOG RESPONSE TO ANYTHING.
- Described in: V. Gehman, K. Kazkaz, and M. Szydagis, LBNE Far Detector Simulation and Reconstruction Meeting, 01/31-02/01, 2014.
- Based on GEANT4: S. Agostinelli et al., Nucl. Instrum. Meth. A506, 250 (2003).
- Used as a simulation tool to predict the LZ sensitivity: D. S. Akerib et al. (LZ Collaboration), arXiv:1802.06039 [astro-ph.IM].



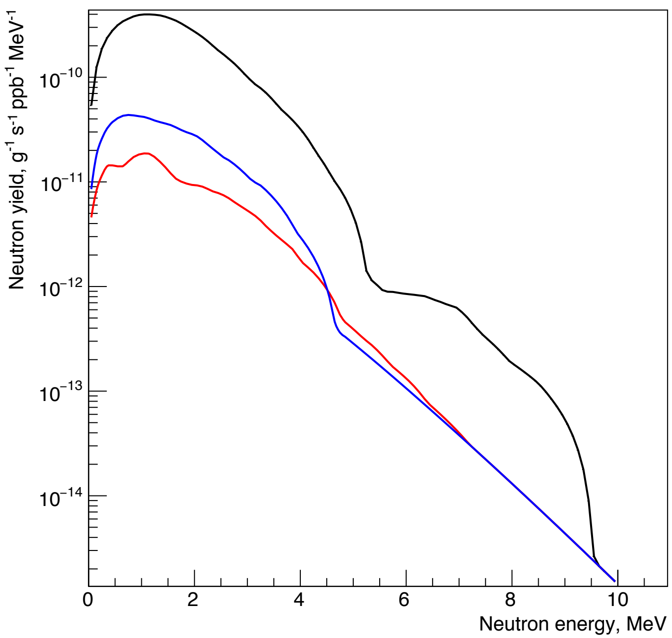
Talk by M. E. Monzani on Tuesday morning on projected LZ sensitivity.

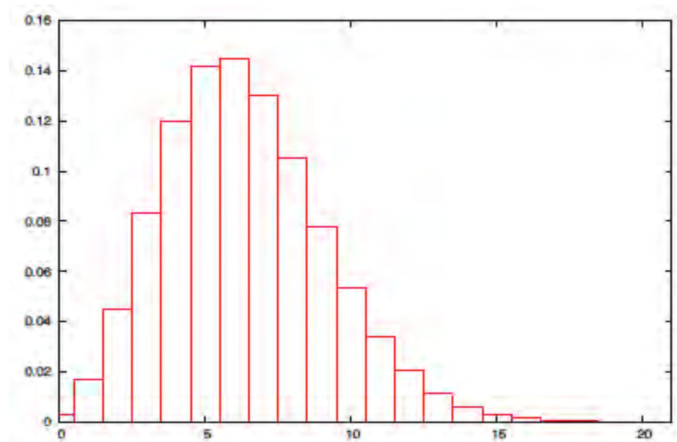
Event generators: gamma-rays and betas

- Based on GEANT4 radioactive decay.
- Ions are decaying and all particles are transported:
  - Gamma-rays are of critical importance here.
  - Alphas are not important unless produced in LXe target or on a surface in contact with LXe target; neutrons from (alpha,n) reactions are simulated separately.
  - Betas usually are quickly absorbed but can also produce a bremsstrahlung photon so need to be included; also betas inside LXe target – radon.
- Two main generators for decay chains:
  - Decay chain is simulated in equilibrium; can be split by individual isotopes or sub-chains during further analysis.
  - An 'age' of a 'source' and its initial activity are used as an input to calculate the probability of decays of all isotopes in a chain (daughters of a parent isotope).

Neutrons

- Neutron generator is based on extended SOURCES4A: W. B. Wilson et al., Technical Report LA-13639-MS, Los Alamos (1999), V. Tomasello, V. A. Kudryavtsev & M. Robinson, Nucl. Instrum. & Meth. in Phys. Res. A 595, 431 (2008).
- Spontaneous fission (SF) is tagged by recording coincident gammas and neutrons: on average 6 gammas and 2.01 neutrons from ^{238}U: https://nuclear.llnl.gov/simulations/fission_v1.9/fission.pdf; J. M. Verbeke et al. Comp. Phys. Comm. 191 (2015) 178.
- Neutrons from SF from components close to LXe (PTFE cage, cryostat, PMTs) are rejected with efficiency ~99% or better; Akerib et al. (LZ Collaboration), arXiv:1802.06039.
- Now working on coincident gammas from (α,n) reactions (transitions to excited states).

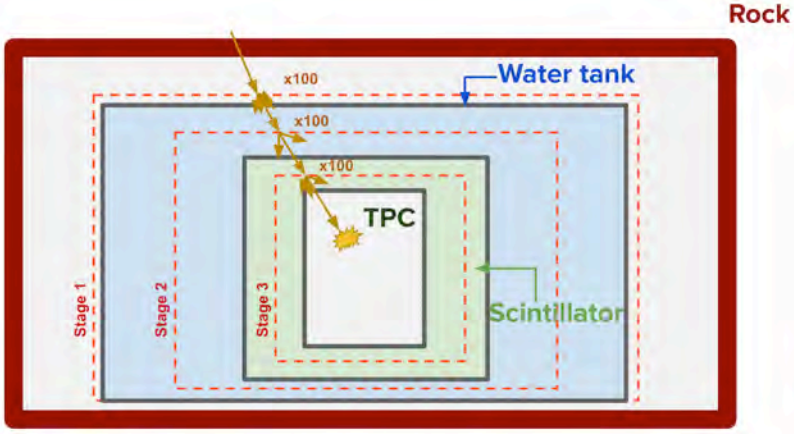


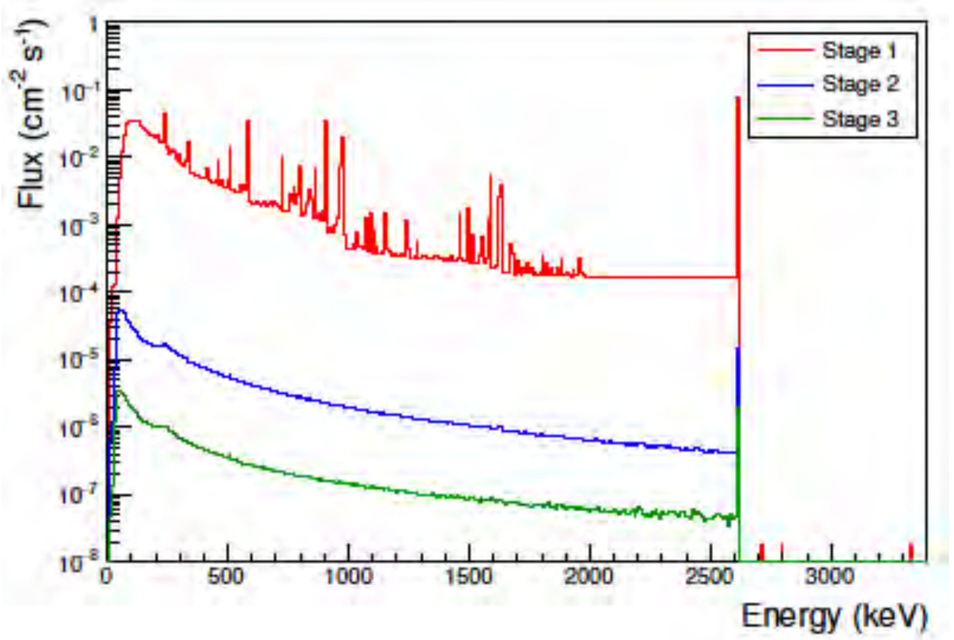


Gamma multiplicity

Gammas from rock

- Difficult to model in one stage: about 10^{15} decays are needed to simulate a year of data.
- Several steps: gammas are recorded at different boundaries, the number is increased by 100 and they are propagated further.
- Neutrons from rock are suppressed by a large thickness of water and scintillator (>90 cm).
- First results in LZ TDR: arXiv: 1703.09144v1 [physics.ins-det]
- New measurements of gammas from rock: Talk by L. Korley, Friday afternoon.

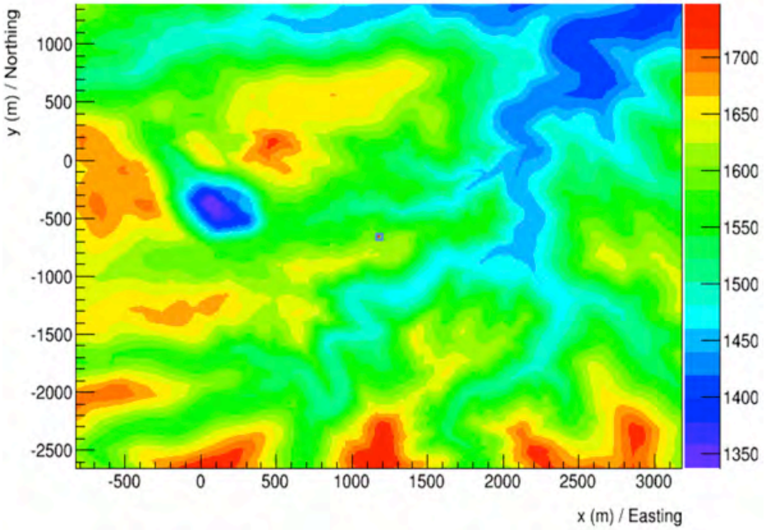


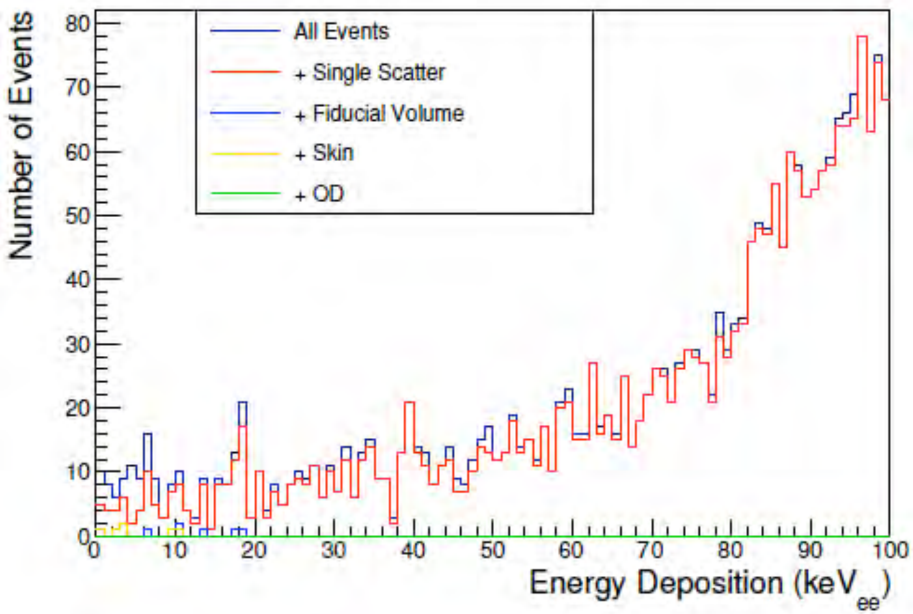


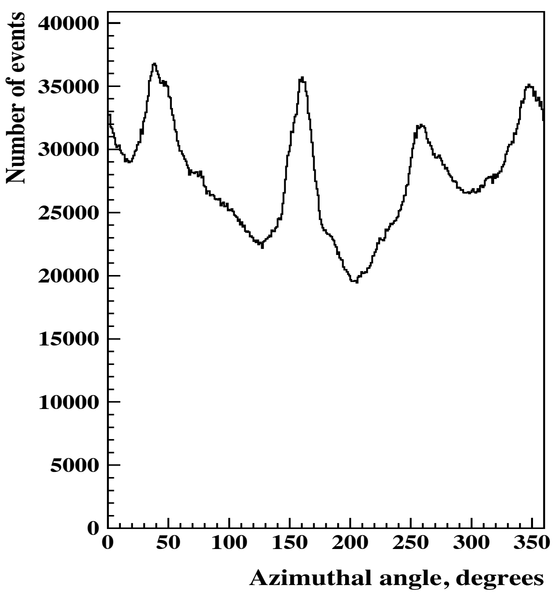
D. Woodward. PhD Thesis, University of Sheffield (2018)

Muon-induced neutrons

- Muon model based on surface profile and muon transport through rock (MUSIC and MUSUN): Kudryavtsev, CPC, 180, 339 (2009), arXiv:0810.4635.
- Supported by measurements: MAJORANA Demonstrator veto and Davis' experiment veto systems.

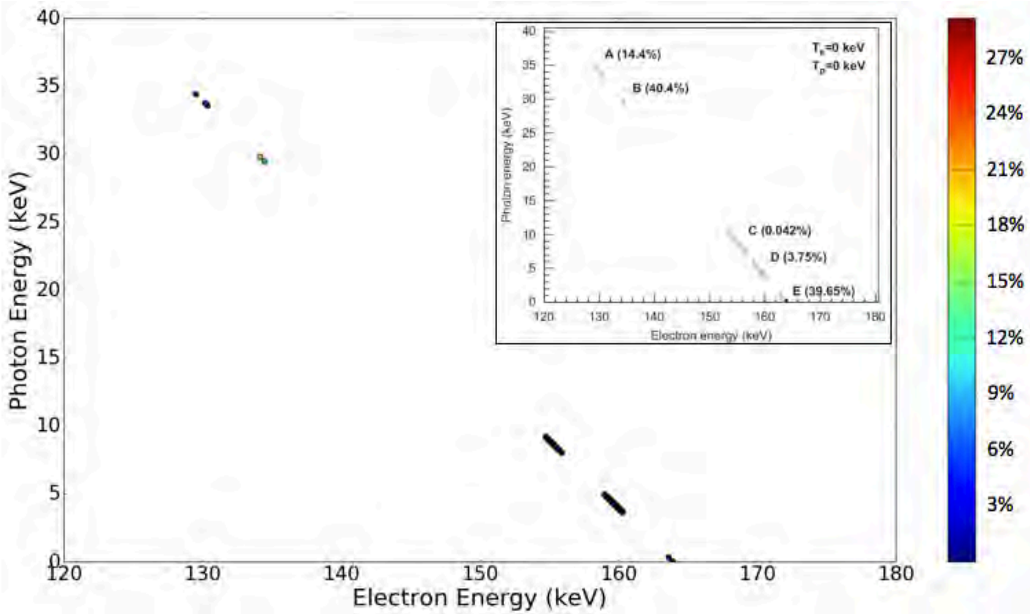


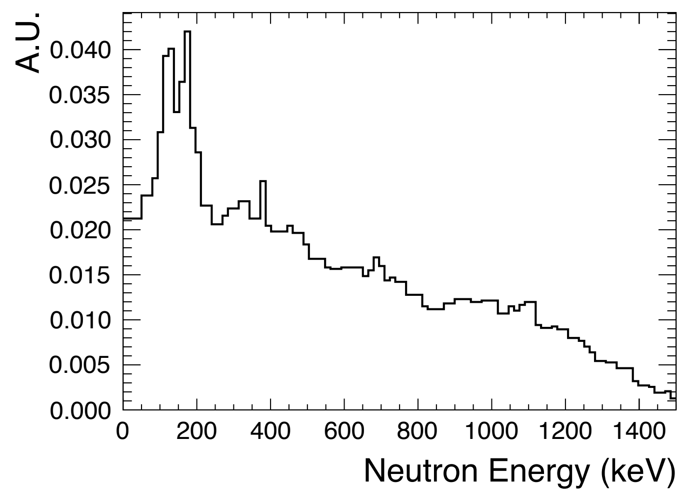




D. Woodward. PhD Thesis, University of Sheffield (2018)

Calibration sources

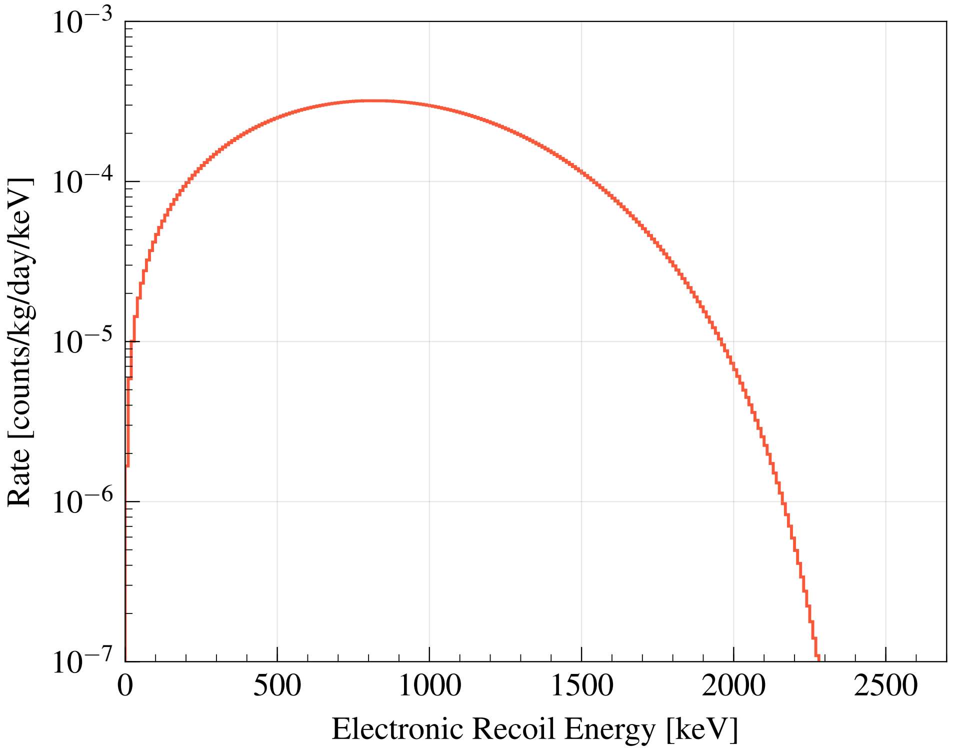




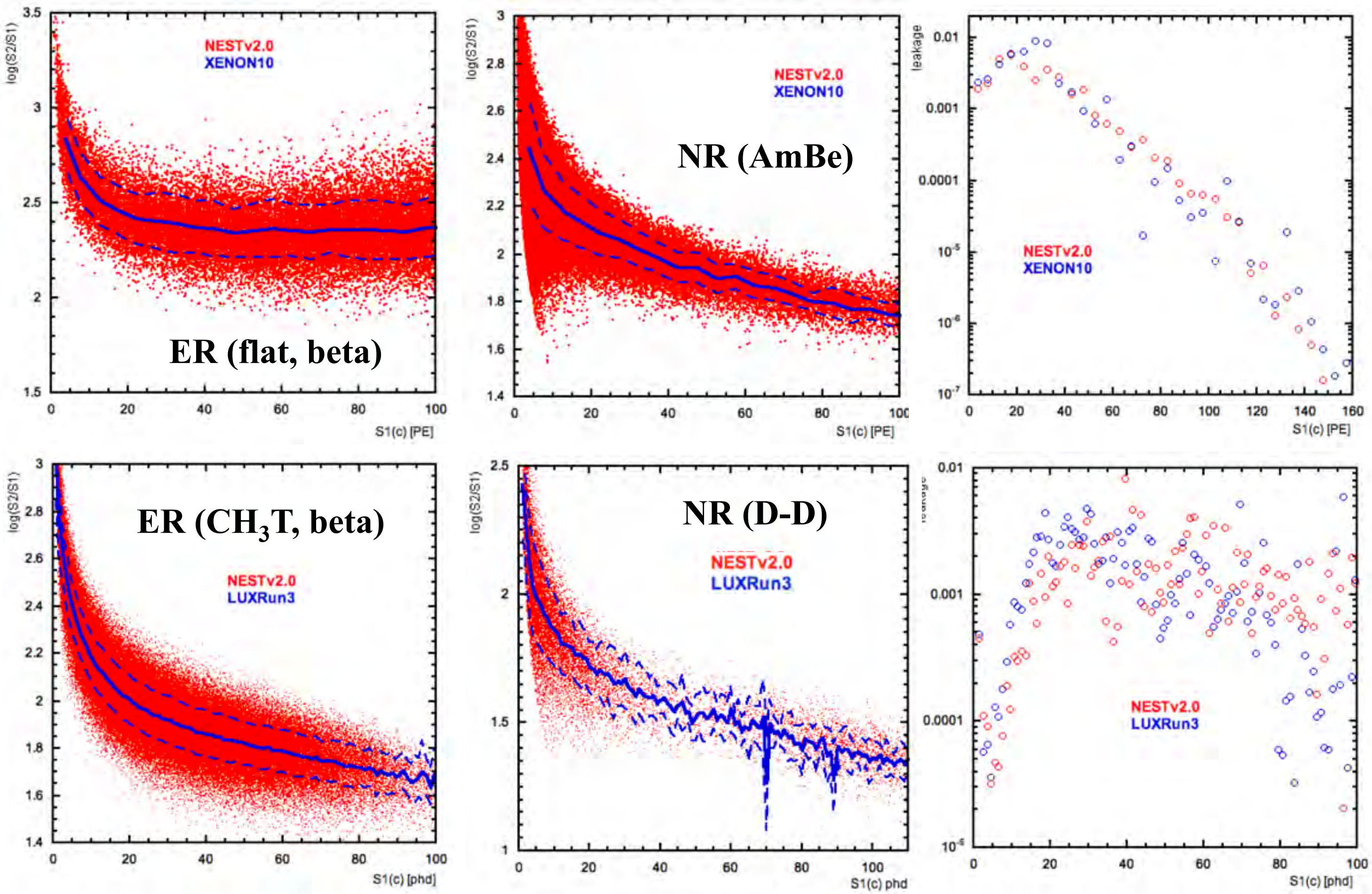
- ^{131m}Xe uniformly distributed through the xenon volume, half life 11.8 days.
- Based on the calculation of atomic de-excitations from A. Ringbom, Applied Radiation and Isotopes 70, 1499 (2012).
- Left plot: Photon energy vs electron energy; the sum gives 163.9 keV isomeric state energy.
- Example: Am-Li for neutron calibration. Right: spectrum to generate neutrons.
- Also DD, ^{83m}Kr, CH_3T, ^{22}Na etc.

Double-beta decay of ^{136}Xe

- From DECAY0 generator: O. A. Ponkratenko, V. I. Tretyak, and Yu. G. Zdesenko, Phys. At. Nucl. 63 (2000) 1282-1287, arXiv:nucl-ex/0104018 [nucl-ex].
- Spectrum of energy depositions in LXe from these simulations.
- Solar neutrinos, see D. S. Akerib et al. (LZ Collaboration), arXiv:1802.06039 [astro-ph.IM].



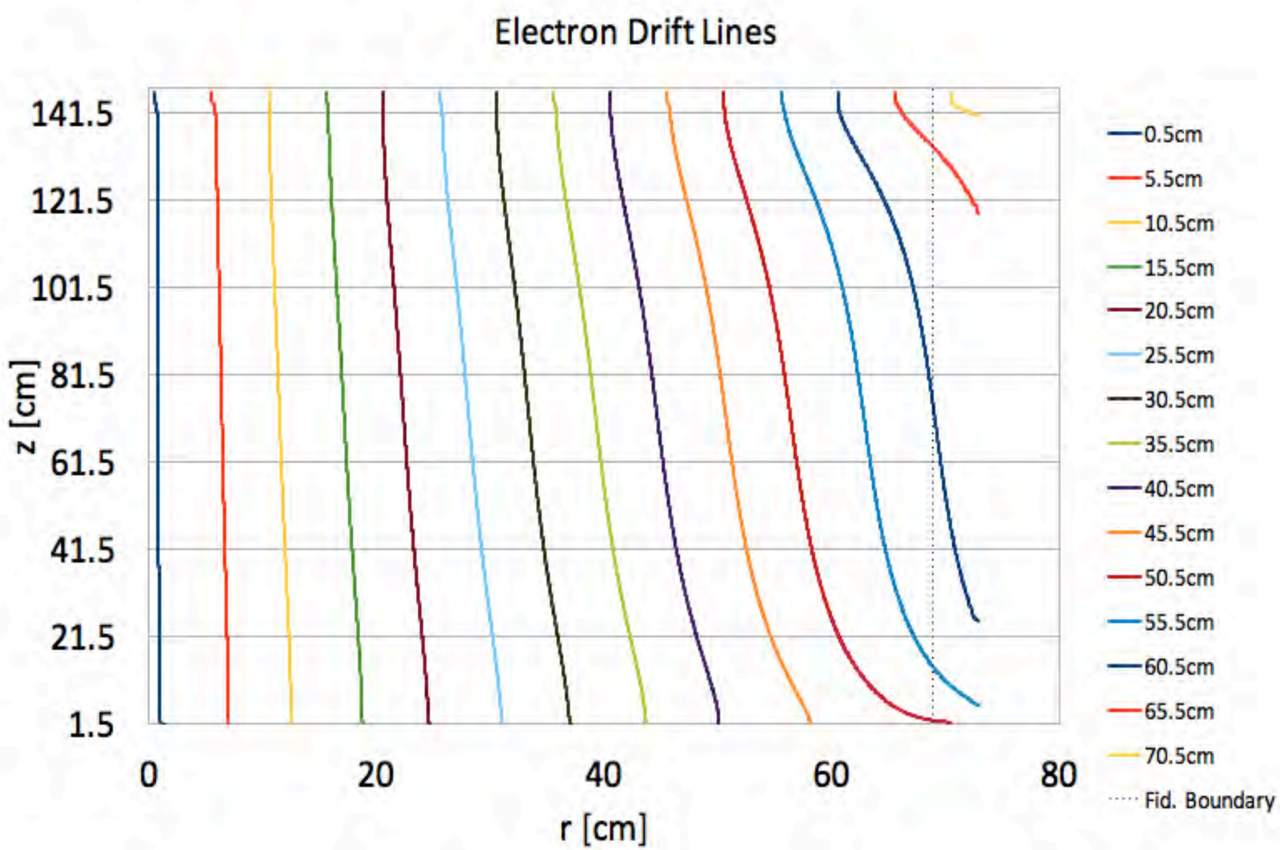
Detector response



NEST vs XENON10 and LUX data. Right: fraction of ERs leaking below the mean of NR band.

- NEST v2.0: B. Lenardo, K. Kazkaz, A. Manalaysay, J. Mock, M. Szydagis, and M. Tripathi, IEEE Trans. Nucl. Sci. 62, 3387 (2015), arXiv:1412.4417 [astroph.IM].

Electron drift, optical tracking and electronics

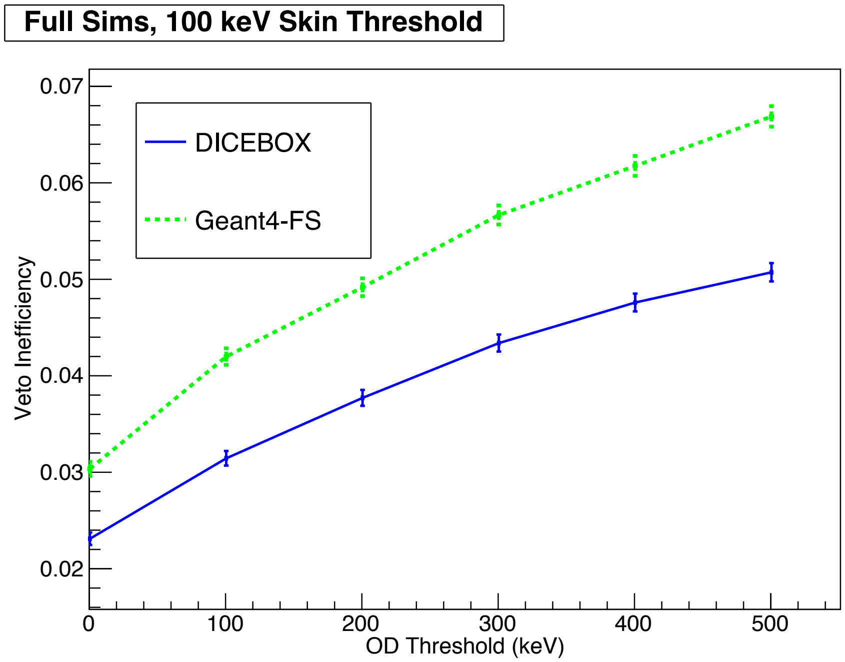


- Accurate electric field simulation.
- Optical tracking: full Geant4 tracking or 'fast' NEST for S1;
- Lookup tables for S2.
- Detector electronics response: full chain from PMTs to waveform digitisation (paper in preparation).

Background from single electrons following an S2 signal (electron trains) is modelled based on measurements.

Outer detector

- Modified optical properties of the scintillator (LAB) within GEANT4.
- Modified Birk's law based on measurements with the 'screener' (paper in preparation).
- Modified treatment of neutron capture on Gd – accurate cascade modelling based on DICEBOX: F. Becvar, Nucl. Instrum. Meth. A417, 434 (1998).



The LZ OD neutron inefficiency vs energy threshold.
The baseline threshold for the outer detector is 200 keV to avoid false vetos from the decays of ^{14}C, ^{152}Gd, and ^{147}Sm in the Gd-loaded scintillator.

Applications

- Background model and sensitivity studies; latest version in D. S. Akerib et al. (LZ Collaboration), arXiv:1802.06039 [astro-ph.IM].
  - Simulations of all (or almost all) sources of background events.
  - Event selection and cuts similar to future analysis cuts but at high level parameters (position, S1, S2, number of scatters).
  - Reasonable assumptions about resolutions and position sensitivity.
  - Baseline detector parameters.
  - Output: background table and sensitivity predictions.
- Mock data challenges (MDCs).
  - Full detector response included.
  - MDC1 – summer 2017.
  - MDC2 – 2018.
  - Main goal: full MC production, event reconstruction and analysis.

Conclusions

- The LZ experiment will be operational in 2020 with 7 tonnes of liquid xenon as a target material (inside the TPC).
- The LZ experiment is expected to reach the sensitivity of 1.6×10^{-48} cm^2 to spin-independent WIMP-nucleon cross-section and 2.7×10^{-43} cm^2 to spin-dependent WIMP-neutron cross-section at 40 GeV/c^2 WIMP mass.
- Other physics topics include search for axions and ALPs, extending WIMP search to masses below 5 GeV and search for neutrinoless double-beta decay.
- Intensive simulation campaigns have been running at the US and UK Data Centres (NERSC, LBL and GridPP-UK, respectively) to construct background model, evaluate projected sensitivities and model the whole chain of real event processing and reconstruction.
- Generators, some of which have been described here, form the basis for these simulations.