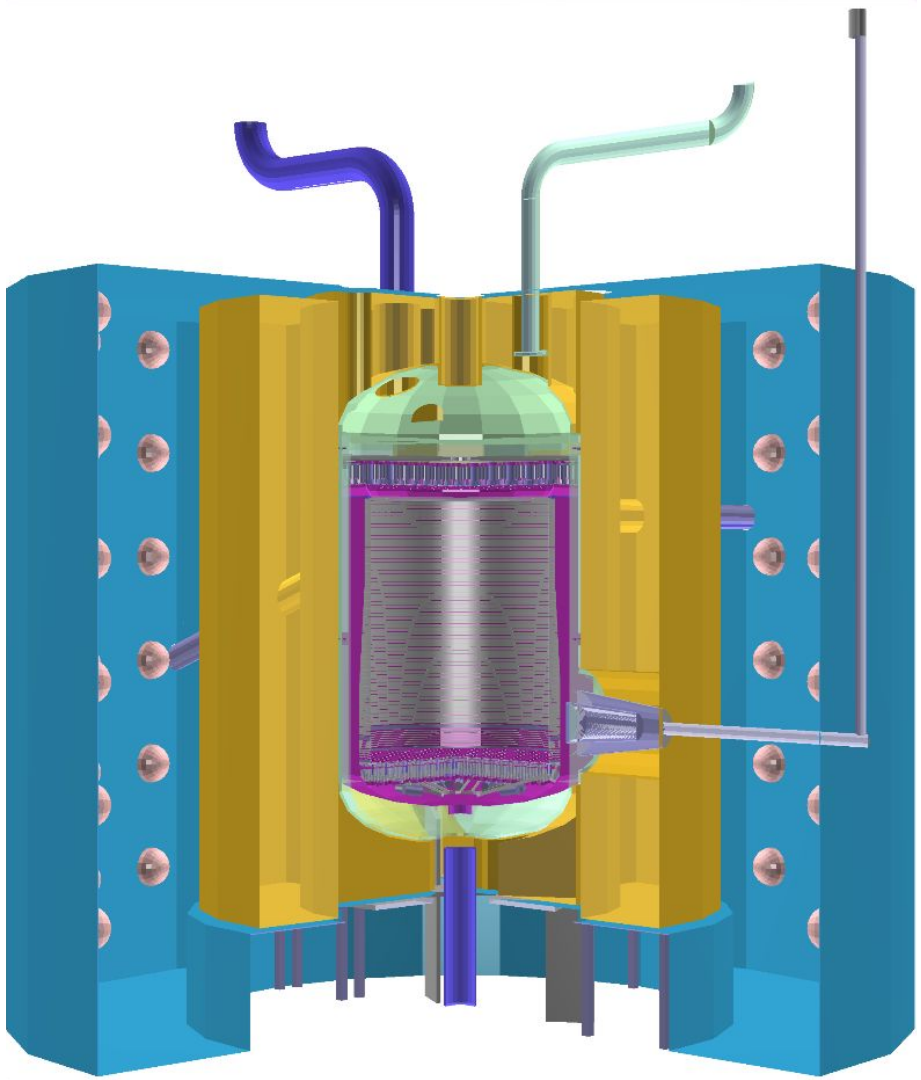
The LUX-ZEPLIN (LZ) simulation framework

Alberto Uson
DIMPPE meeting

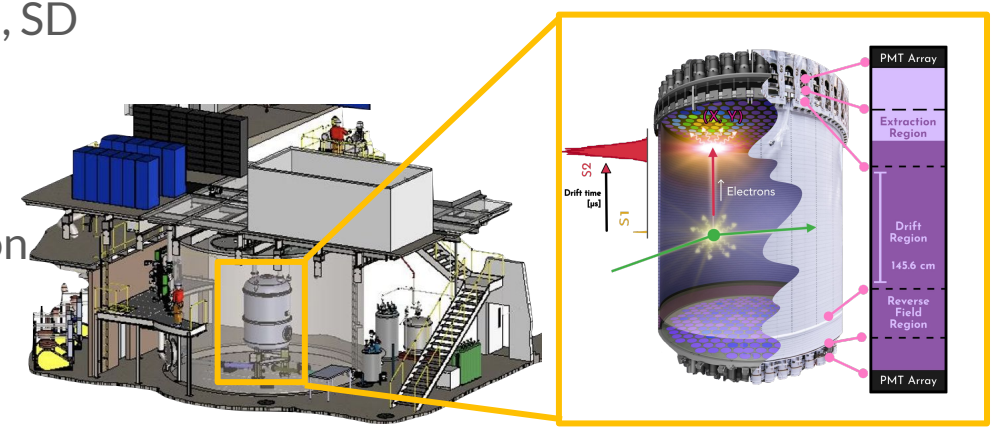
29/10/2026



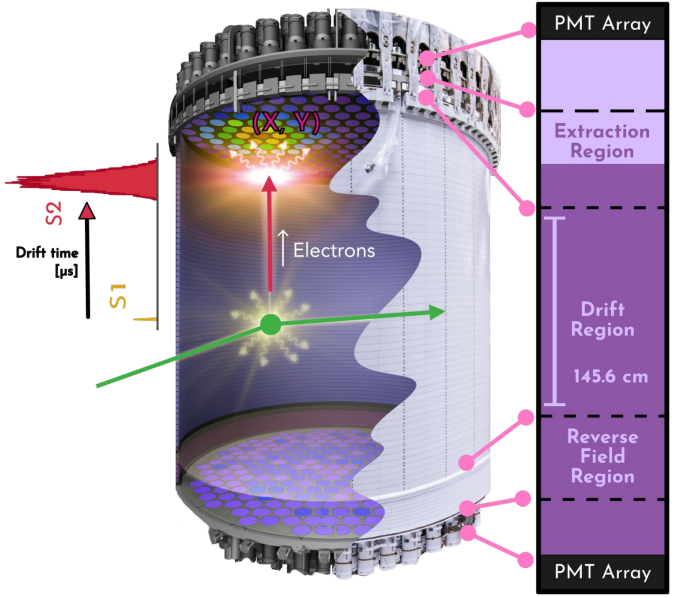
The LUX-ZEPLIN (LZ) Experiment

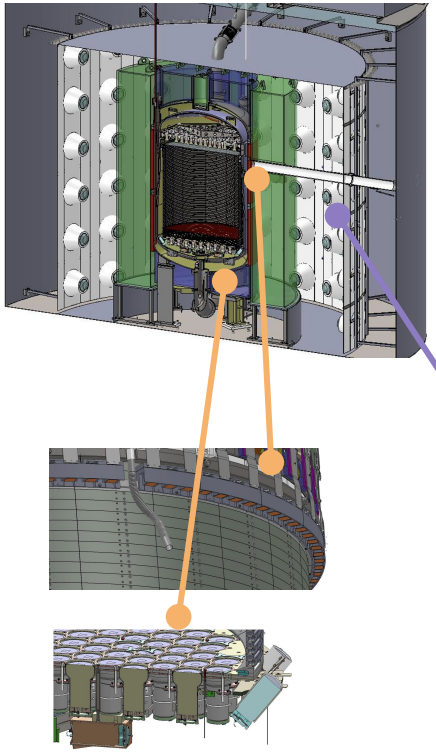
- Optimised for searching WIMPs with masses above ~5 GeV/c2
- Sensitive to additional processes, including BSM physics: 0v$\beta\beta$, axions, etc
- Located 1 mile underground at the Sanford Underground Research Facility (SURF), SD (US)
- Comprises:
  - Liquid Xenon (LXe) Time Projection Chamber (TPC)
  - Veto system



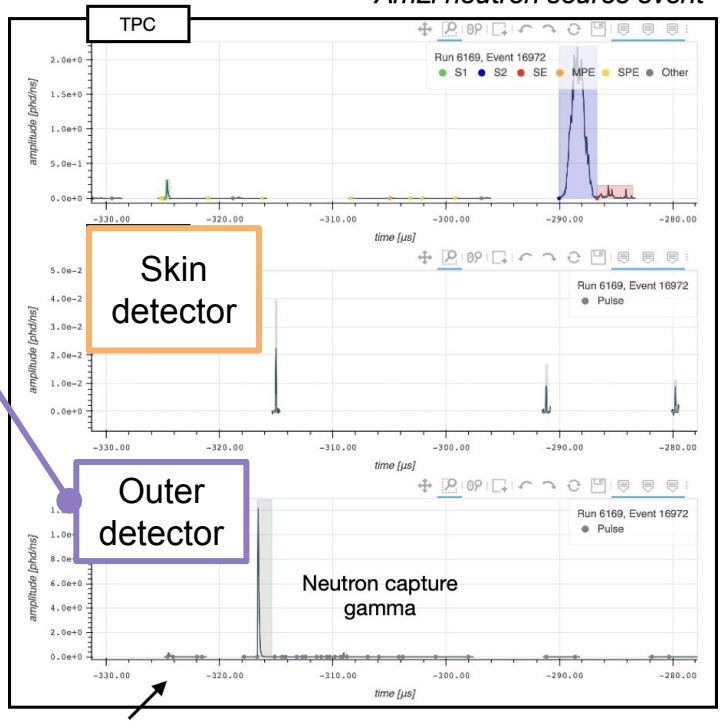


The LUX-ZEPLIN (LZ) Experiment





AmLi neutron source event



The LZ simulation framework - Overview

Been using this framework successfully since the detector started running

Publication from 2020: https://doi.org/10.1016/j.astropartphys.2020.102480

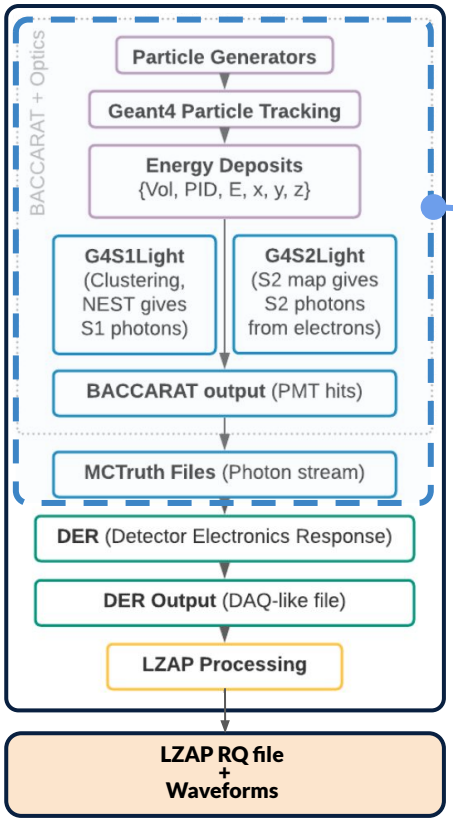
Language: C++

Comprise multiple packages → modular structure

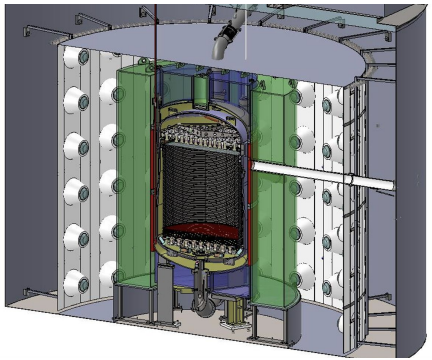
Depending on the use, we have two main simulation chains:

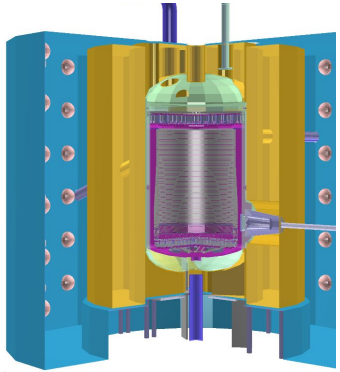
- "Full" chain: simulates most physics, and produces data-like output → computationally expensive
- "Fast" chain: parametric sim → allows higher stats

Full chain simulations

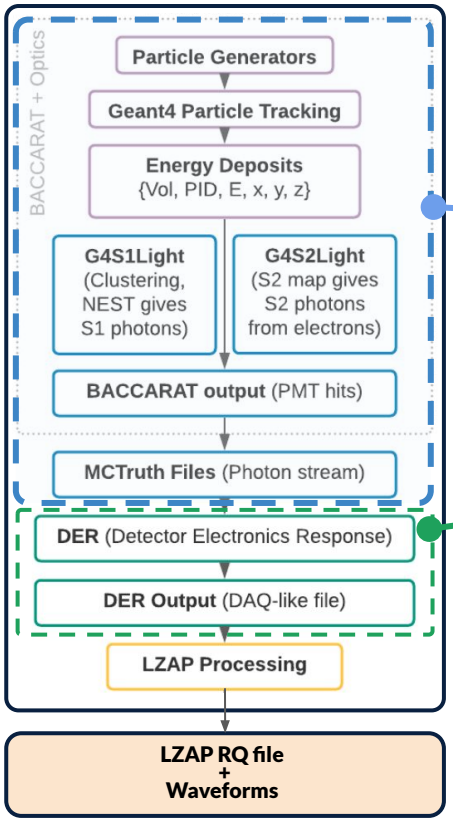


- Includes two main modules:
  - LZ's **Geant4**-based (v10.3…) package to:
    - simulate particles or radioactive decays producing energy depositions
    - Cluster deposits and convert to charge/yield through NEST* (see back up)
    - Track S1 photons
    - Model e- transport (based on electric field model from custom LZ sims), extraction region, S2 light maps



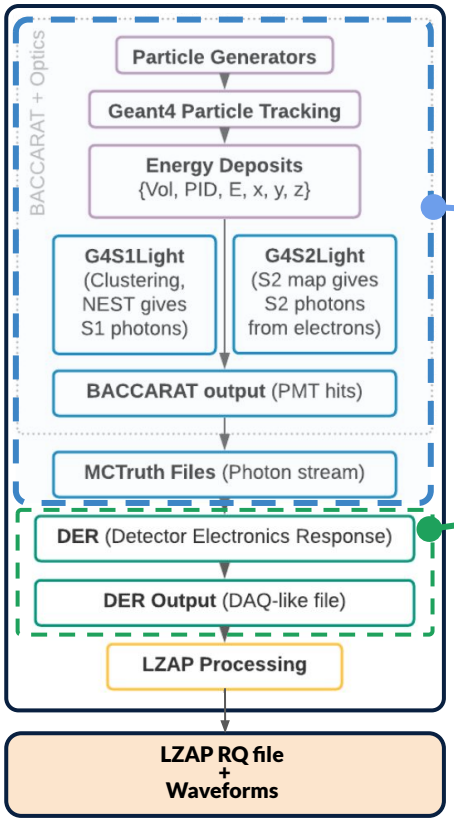


Full chain simulations



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  - Electronics response package to simulate PMT response of S1 and S2 light on PMTs. Computationally expensive

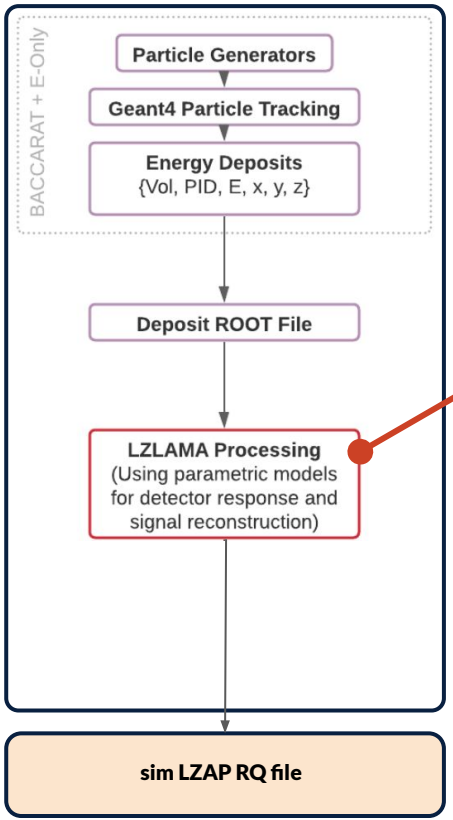
Full chain simulations



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  - Electronics response package to simulate PMT response of S1 and S2 light on PMTs. Computationally expensive

- Output: data-like waveforms
- Very intensive CPU use, due to DER → **not for high stats PDFs building, but for mock data challenges, understanding detector effects and waveform studies**

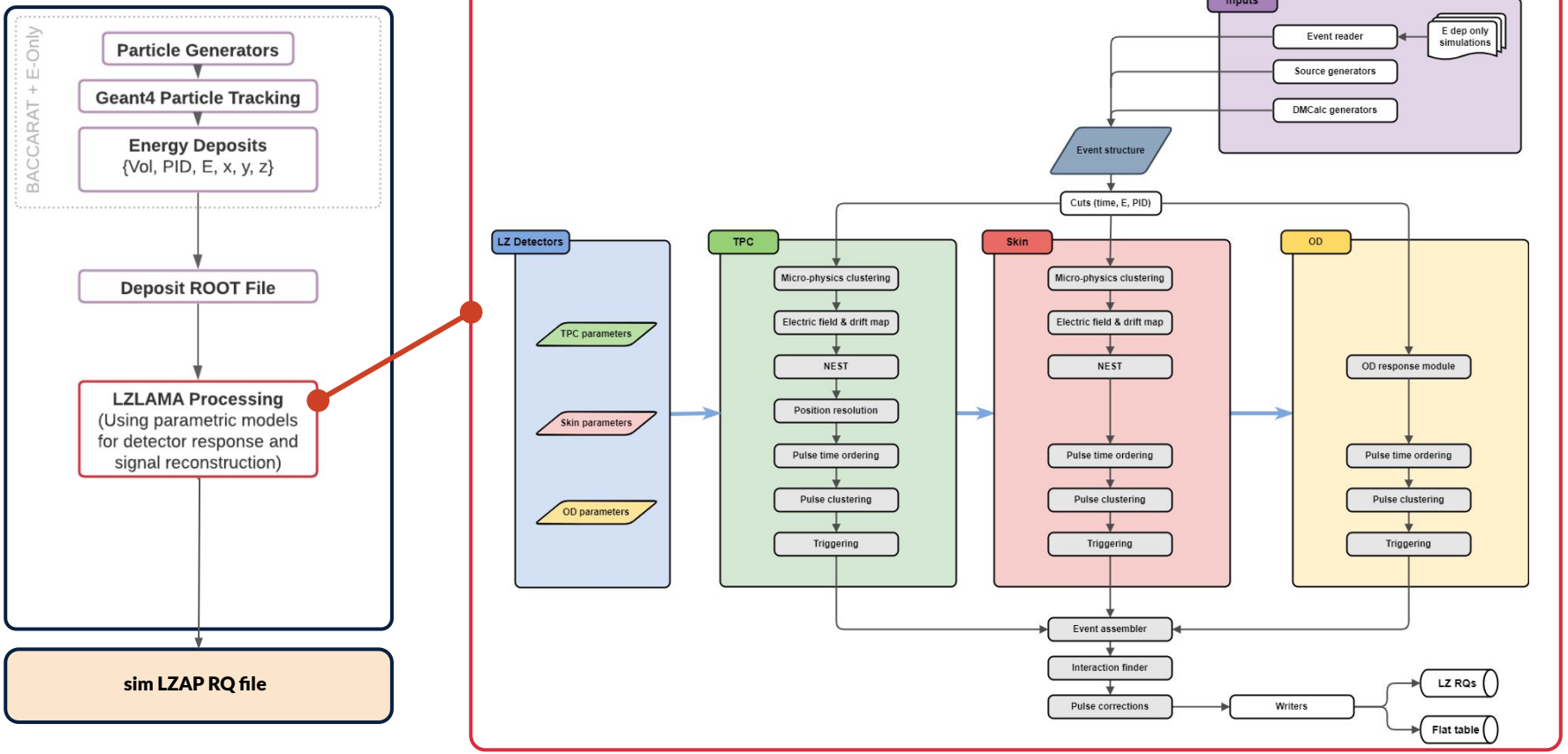
Fast chain simulations



- Much quicker framework to produce higher-stats samples for PDF building
- It starts similarly to the full chain, **until G4 energy deposits**
- Then, after clustering and calculating quanta → parametric model for particle propagation and detector response

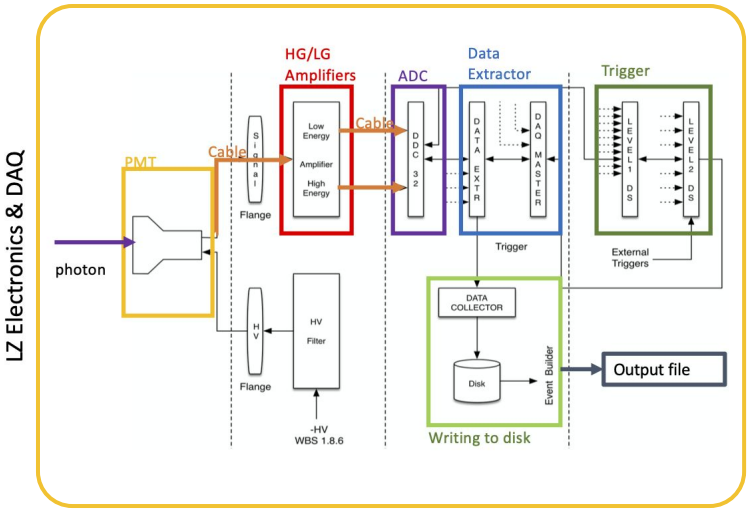
- Output: **no waveforms**; (some) reduced quantities used in high-level analysis only
- Much **faster** (x10^4) than full chain

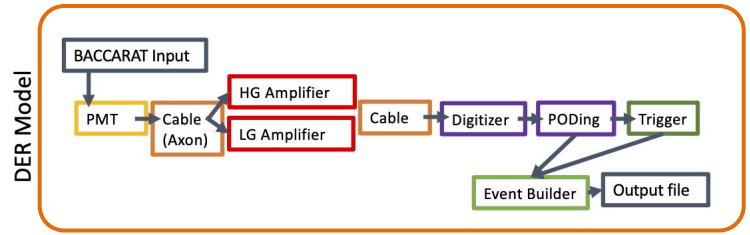
Fast chain simulations: parametric model

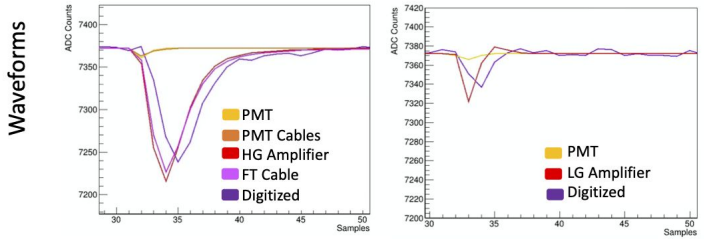


Detector Electronics Response (DER) module

- Simulates PMT signal generation and subsequent processing by LZ analogue front-end electronics and digitisers
- No open-source code… (as LZ's codes)
- Creates mock digitised waveforms



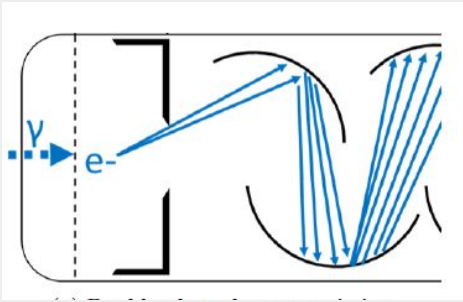


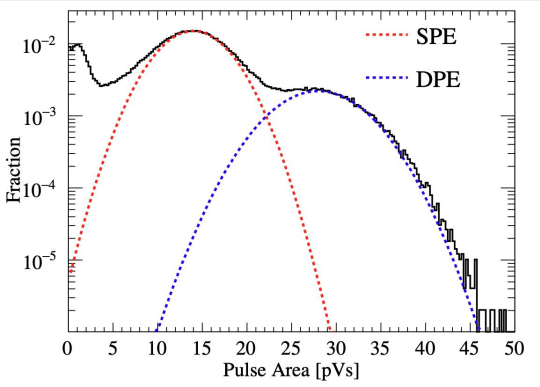


DER: PMT Model

- Consider each photon hit and decides whether is detected, via QE (considered uniform across photocathode)
- Single photon response varies with gain and time of flight
- Several responses include in model:
  - Double Photoelectric (DPE) Effect - two phe from one energetic photon
  - First dynode conversion (one multiplication stage missed)
  - Inelastic scatter at first dynode (delayed undersized response)
  - Second dynode collection
  - Afterpulsing
  - Dark counts

Probability of each effect depend on individual PMTs and photon wavelength

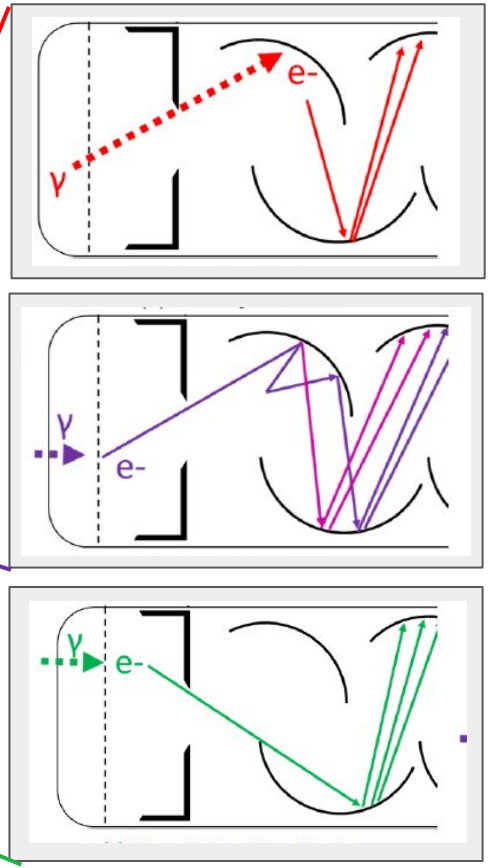




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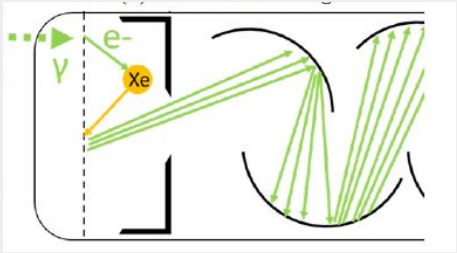
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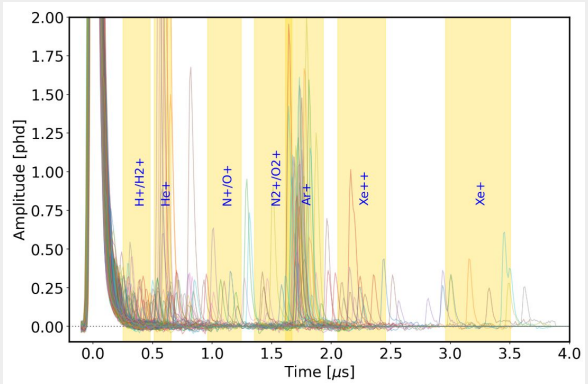


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Values from PMT LED calibration

DER: PMT Model

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- Number of dark counts on a channel decided using Poisson distribution
- Timing added randomly

Probability of each effect depend on individual PMTs and photon wavelength

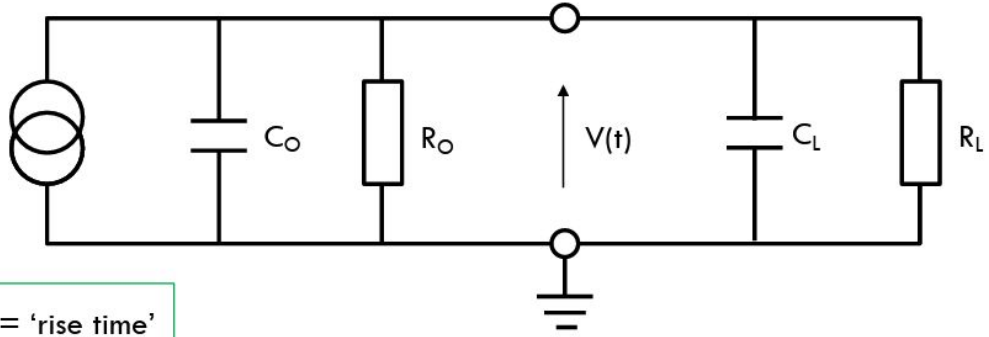
DER: PMT Model

N = number of photoelectrons

G = photomultiplier gain

$e = -1.6\times10^{-19}$ C

$$I_A(t) = \frac{Q_A}{\tau_i} e^{-t/\tau_i}$$



$Q = NGe$

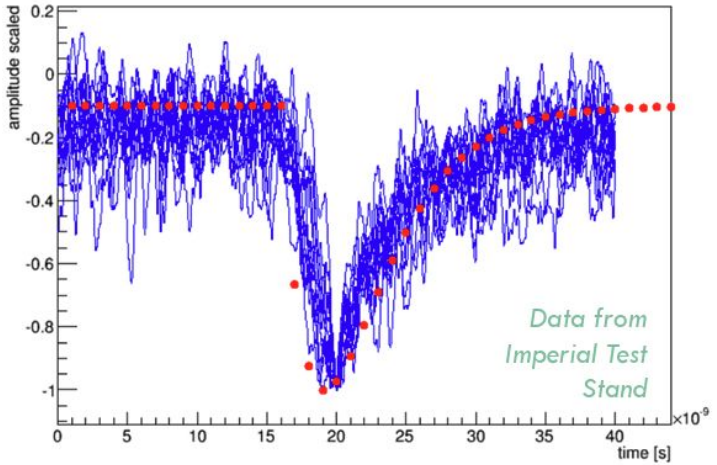
$R = \frac{R_O R_L}{R_O + R_L}$

$\tau = RC$ = 'rise time'

$C = C_O + C_L$

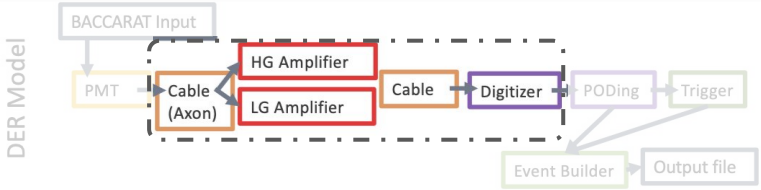
τ_i = 'fall time'

$$V(t) = \frac{Q_A R}{\tau_i - \tau}\left(e^{-t/\tau_i} - e^{-t/\tau}\right)$$



- Time constants τ_i, τ extracted from per-channel
- Presently used for all PMTs in the analytic chain

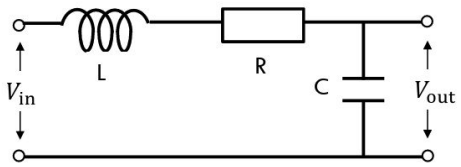
DER: Analogue Electronics



Response of cables, amplifiers, and digitisers simulated

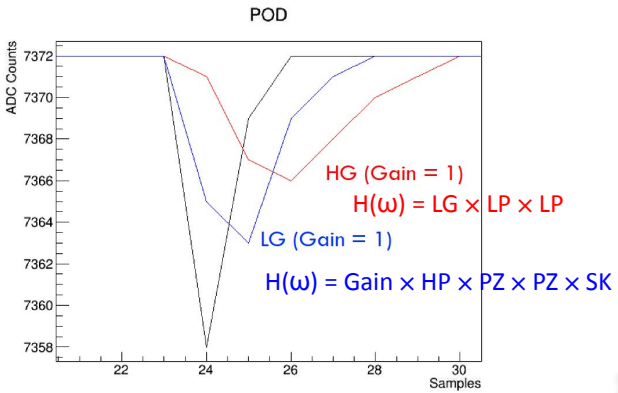
- **Filter Response Model**: low-pass (LP), high-pass (HP), pole-zero (PZ), sallen-key (SL)
- **Cables**: transmission line model approximated with series of PZ filters. Two cable types modelled:
  - PMT to amplifier (axon)
  - Amplifier to digitiser (LMR100)
- **Amplifiers**: HG and LG amplifiers with transfer functions derived from circuitry of amplifiers in our DAQ setup
- **Digitiser** samples every 10 ns. Adjustable baseline noise. ADC saturation simulated

Transmission line model



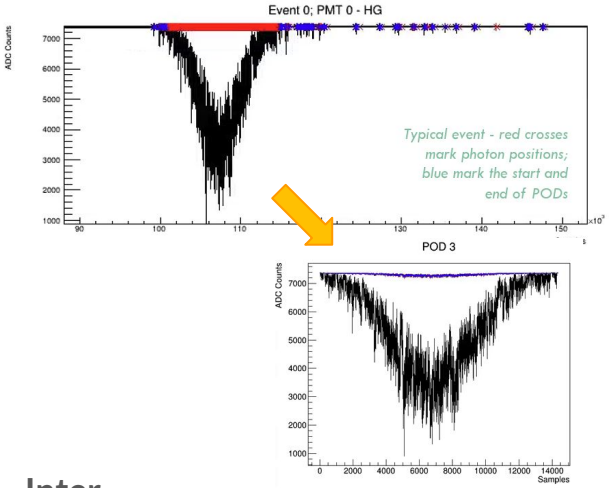
Skin Effect | Dielectric

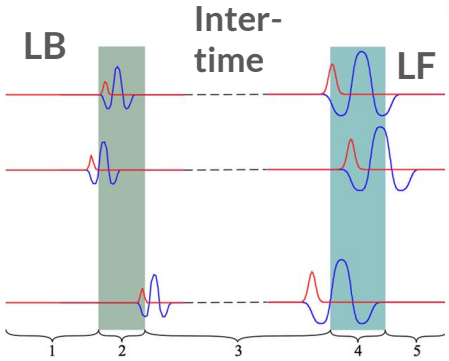
$$H(\omega) = e^{-\alpha l} \quad \text{with} \quad \alpha = \frac{1}{2WZ_0}\sqrt{\frac{\omega\mu}{2\sigma}} + \frac{\omega \tan\theta\sqrt{\varepsilon_r}}{2c}$$



DER: data sparsification and event building

- **Pulse-Only Digitization**: Save only samples around identified pulses; look for X consecutive samples above/below threshold to mark start/end
- **Trigger** algorithm: S1 and S2 triggers implemented (as in data)
  - Convolve the waveforms with a trigger filter (≡integrator)
  - Checked whether convolved WF passes threshold
  - Repeated for n channels (n = PMT coincidence requirement) → trigger points
- **Event building**: for each trigger point:
  - Look-back (LB) and look-forward (LF) times set
  - Further trigger point recorded if inter-time > LB+LF





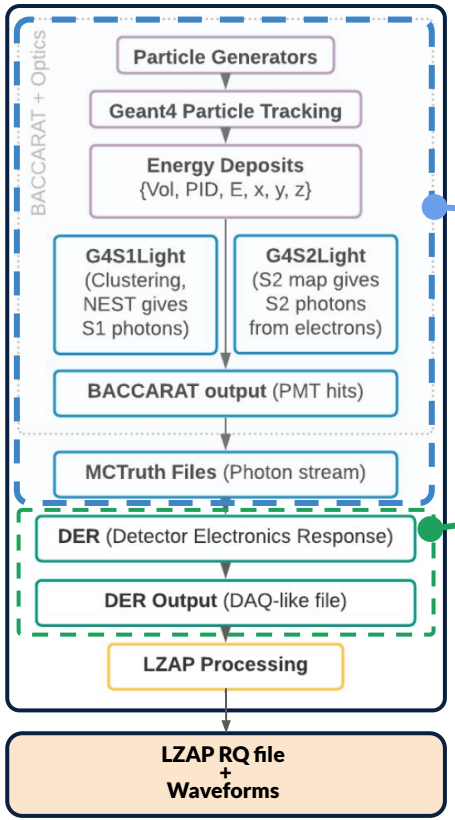
[Nucl. Instrum. Methods Phys. Res. A. **818** 57-67 (2016)]

Conclusions

- Monte-Carlo simulations used to generate signal (WIMPs), background, and calibration sources and their effect in the LZ detector; essential for searches
- Good agreement with real data
- Different modes to run our simulations, depending on the level of detail and the computation time/effort required
    - **Full** chain to produce data-like waveforms, with electronic effects → computationally expensive
    - **Parametric** chain → less detail but very quick
- Both use in **Geant-4**, with a suite of event generators and physics models integrated
- More and more WF-based analyses within the experiment, need for:
    - Fast (parametric) waveform simulation
    - Speed up full chain

Back-up

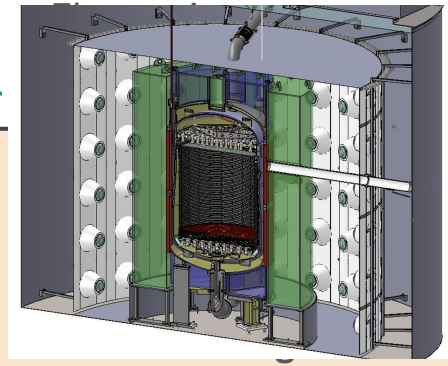
Full chain simulations

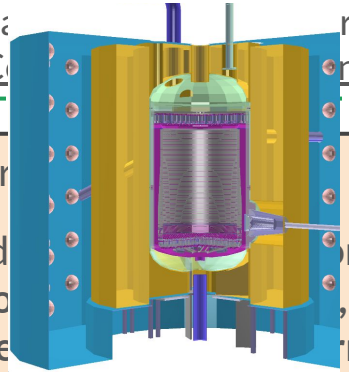


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response of

nsive



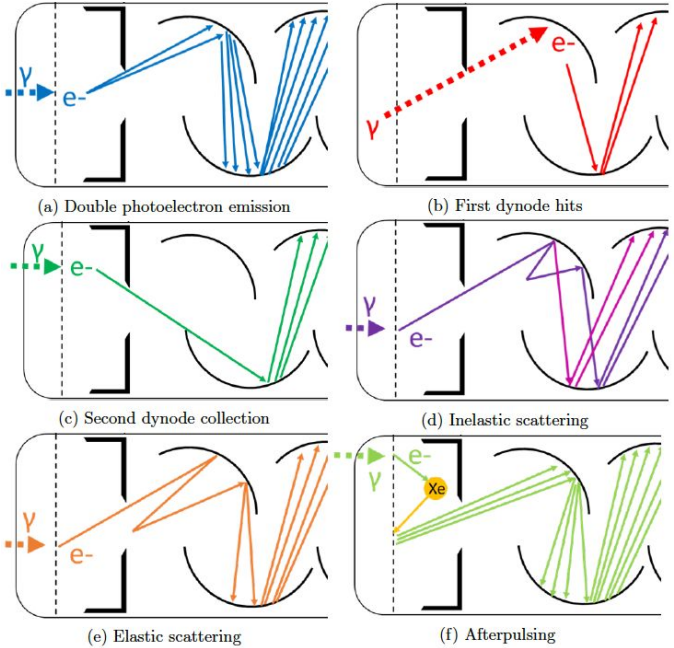


r high stats

rm studies

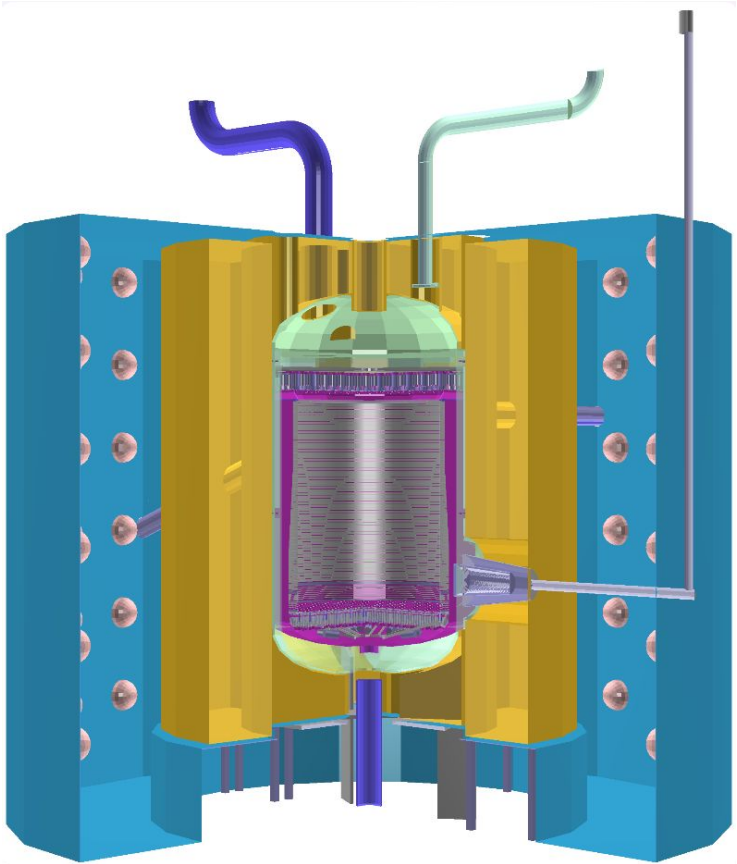
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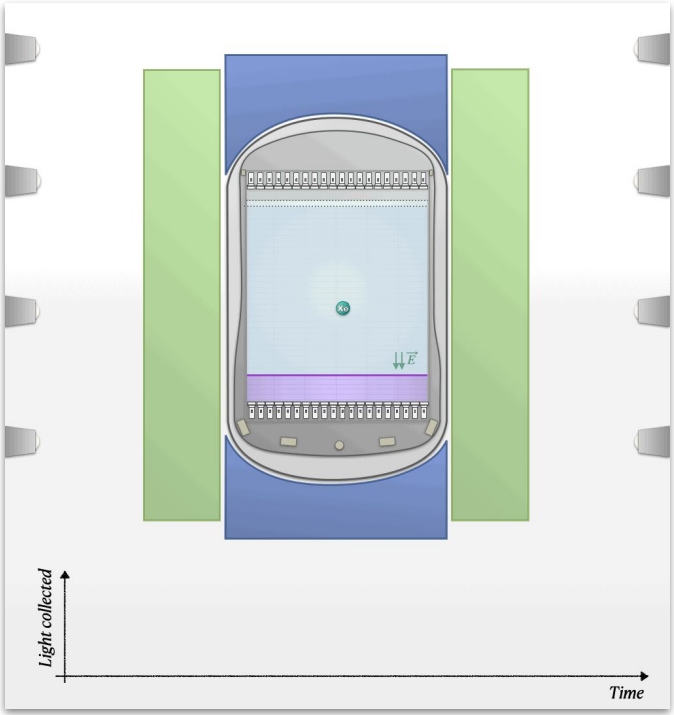
Probability of each effect depend on individual PMTs and photon wavelength

LZ detector in our simulations

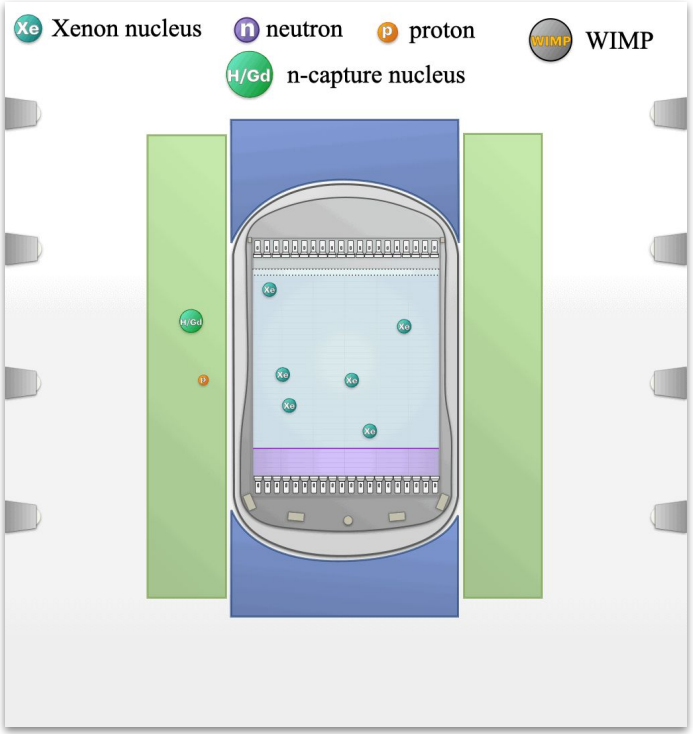


TPC 101

WIMP-like event

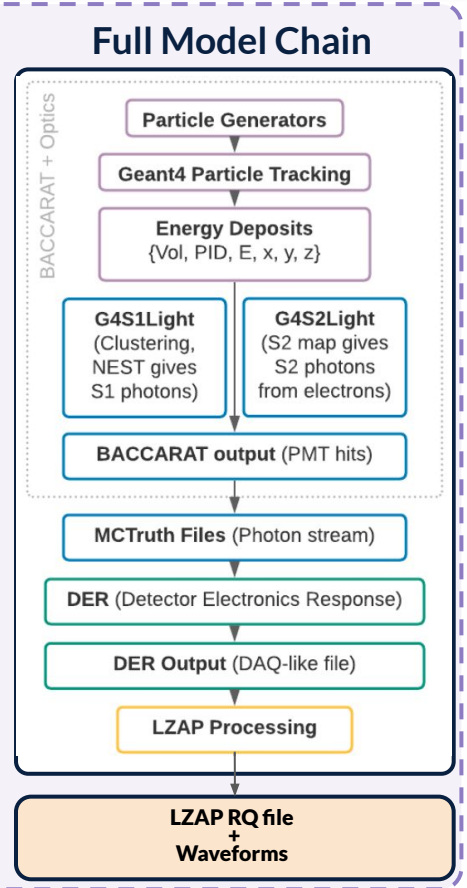


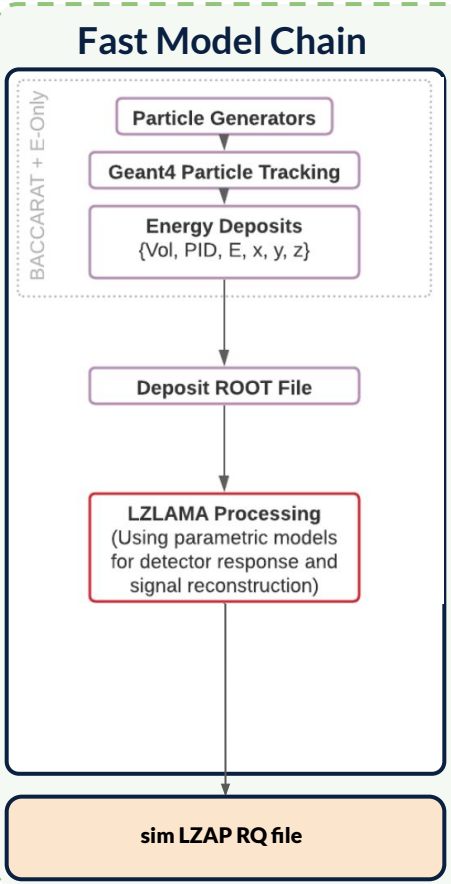
neutron-like event

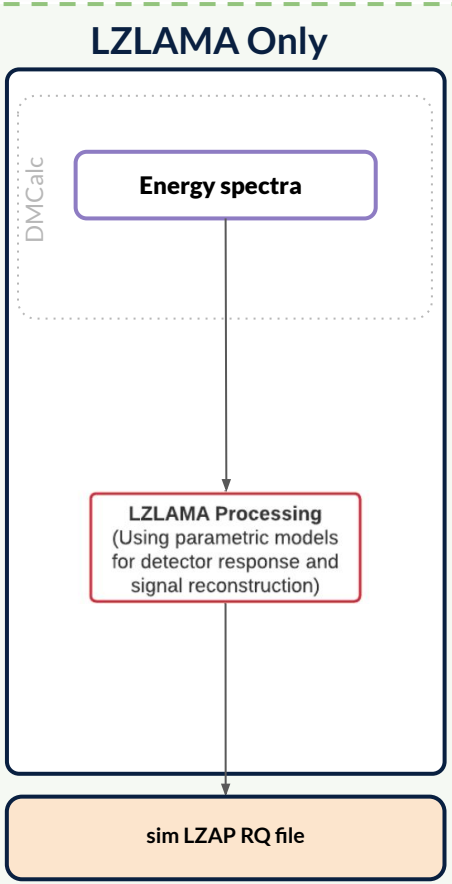


The LZ simulation framework - Overview

For waveform and selection efficiencies studies







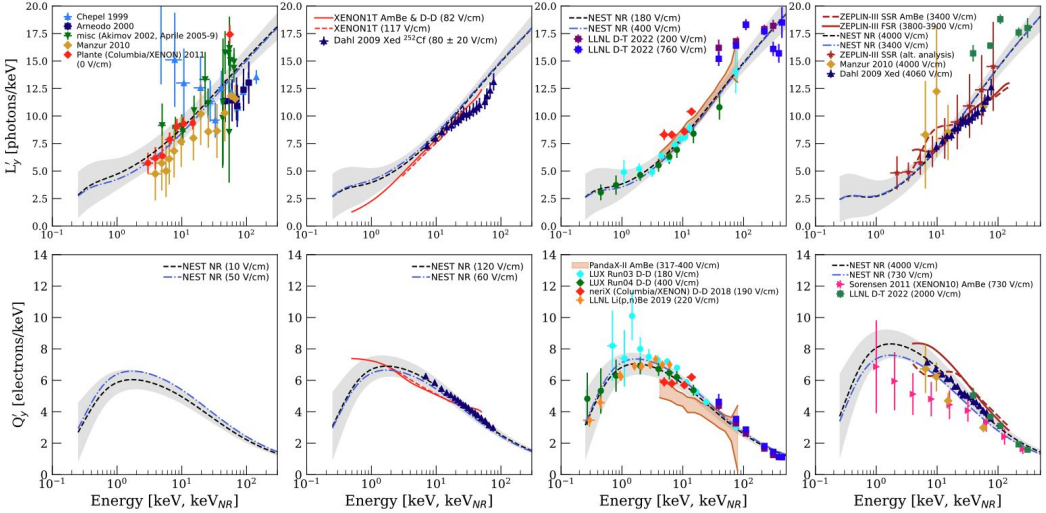
For PDF building

NEST (Noble Element Simulation Techniques)

LZ-independent semi-empirical toolkit to model light and charge production as a function of the particle type, energy, and electric field in noble elements

Latest reference: https://doi.org/10.3389/fdest.2024.1480975

Light (top) and charge (bottom) yields for nuclear recoils for different electric field intensities (increasing from left to right)



LZ (LUX-ZEPLIN) collaboration

- 38 institutions
- 250 scientists, engineers, and technical staff

Thanks to our sponsors and participating institutions!

Science and Technology Facilities Council

Fundação para a Ciência e a Tecnologia

SANFORD UNDERGROUND RESEARCH FACILITY

Swiss National Science Foundation

Institute for Basic Science

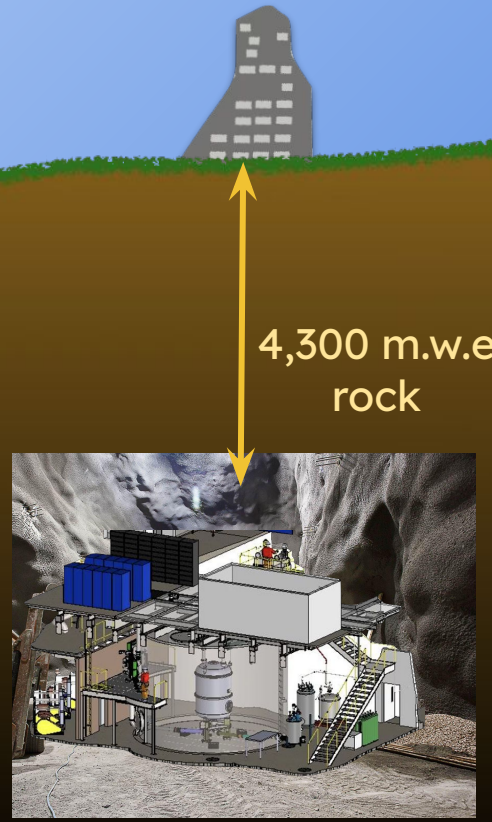


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Imperial College London
King's College London
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Lawrence Livermore National Lab.
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SLAC National Accelerator Lab.
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South Dakota Science & Technology Authority
STFC Rutherford Appleton Lab.
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US Europe Asia Oceania

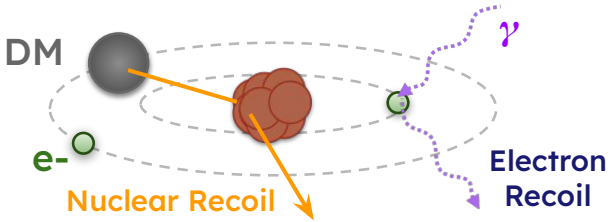
The LUX-ZEPLIN detector

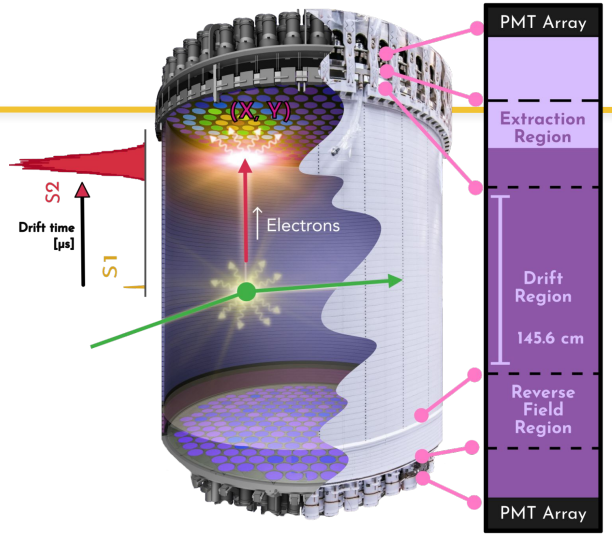
- Optimised for searching WIMPs with masses above ~3 GeV/c^2
- Sensitive to additional processes, including BSM physics: $0\nu\beta\beta$, axions, etc
- Located 1 mile underground at the Sanford Underground Research Facility (SURF), SD (US)
- Comprises:
  - Liquid Xenon (LXe) Time Projection Chamber (TPC)
  - Veto system

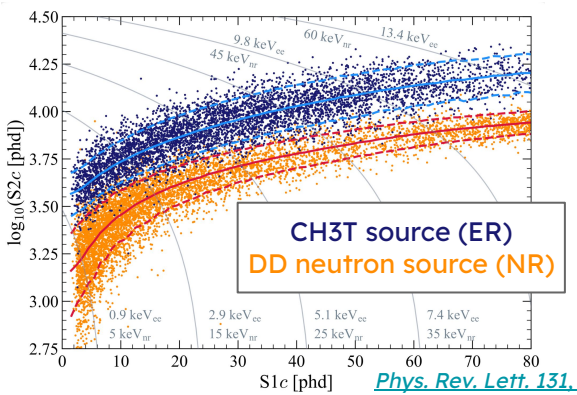


The LUX-ZEPLIN TPC

- 7t active mass dual-phase xenon TPC
- Events reconstructed combining scintillation (S1) and ionisation (S2)
- Light measured by 494 PMTs arranged in two arrays at top and bottom
- Excellent 3D position reconstruction (~mm)
- Single Scatter (SS) vs Multiple Scatter (MS) interactions discrimination
- S2/S1 signal size ratio allows nuclear (NR) vs electron (ER) recoil discrimination







Phys. Rev. Lett. 131, 041002 (2023)

Veto system

Two subsystems:

Outer detector

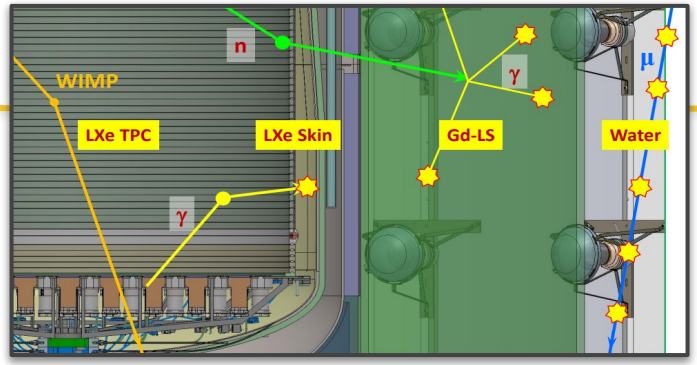
Purpose:

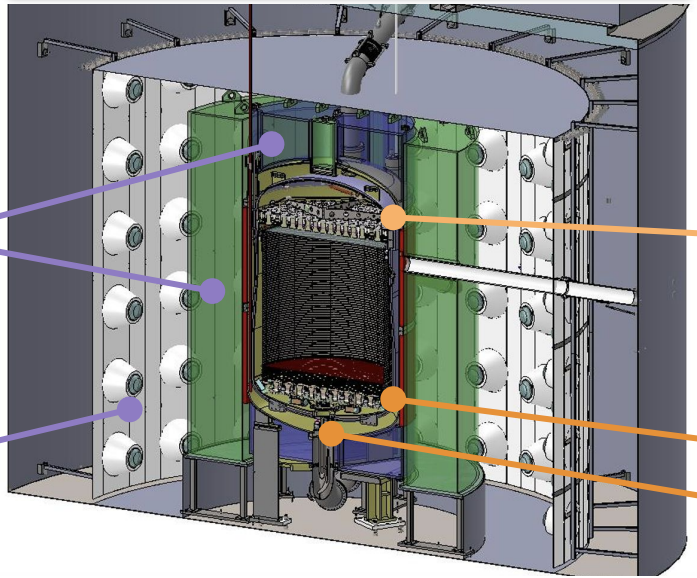
- <u>active</u> muon and internal neutrons veto
- <u>passive</u> external neutron /γ veto

See E. Bishop talk this afternoon

Comprises:

1. 10 UV-transparent acrylic tanks with 17t of Gd-loaded (0.1% by mass) liquid scintillator
2. 238t ultra-pure water tank with 120 8-inch PMTs



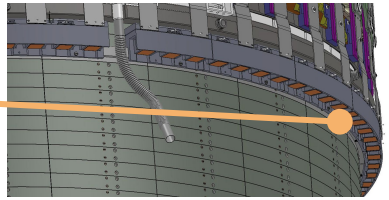


LXe *Skin* detector

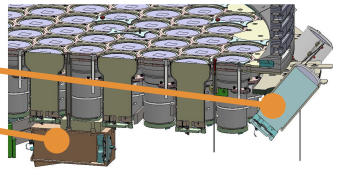
Purpose: veto Compton recoils from ~MeV radiogenic γ-rays

2t-LXe region between TPC outer walls and inner cryostat vessel instrumented with:

- 93 PMTs at the top



- 38 PMTs at the bottom



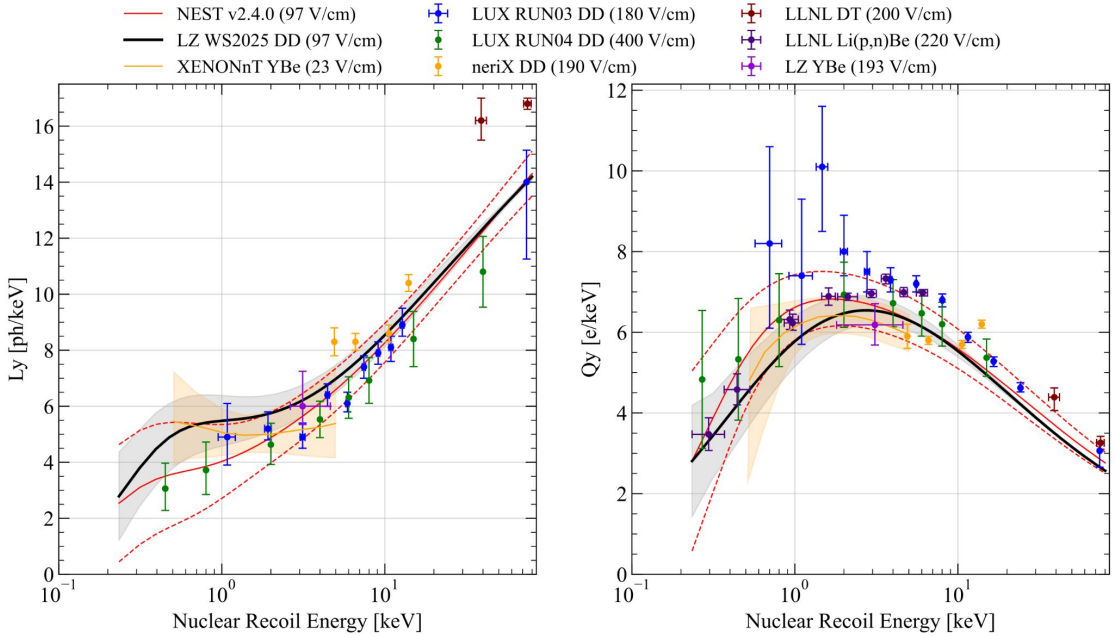
NR light/charge modelling

In LZ, NEST (Noble Element Simulation Technique) is used to model ER and NR responses

Such low ROI never explored in the experiment:

- Well calibrated low-energy NR response model with systematic uncertainties required
- DD 2.45 MeV monoenergetic neutron data exploited to model NR up to 74 keV:

→ Markov Chain Monte Carlo used to refine NEST model to match DD response



Why Liquid Xenon (LXe)?

- Noble elements excellent media for building large, homogeneous compact and self-shielding detectors.
- LXe & LAr excellent scintillators and good ionisers
- Liquid targets: high level of radiopurity / scalability
- Coherent scalar WIMP-nucleus scattering ($\sigma \propto A^2$)
- And more effective self-shielding
- In xenon: easy to remove Kr-85, but more difficult to remove Rn (comparable Z)
- Argon is spin=0, no option to perform spin-dependent searches
- Argon from atmosphere highly contaminated by Ar-39 -> U-Ar (difficult to extract and distillate large amounts)
- Xenon vs argon boiling point

