Application of a DD-Neutron Source for Low-Energy Nuclear Recoil Calibrations in the LZ Experiment

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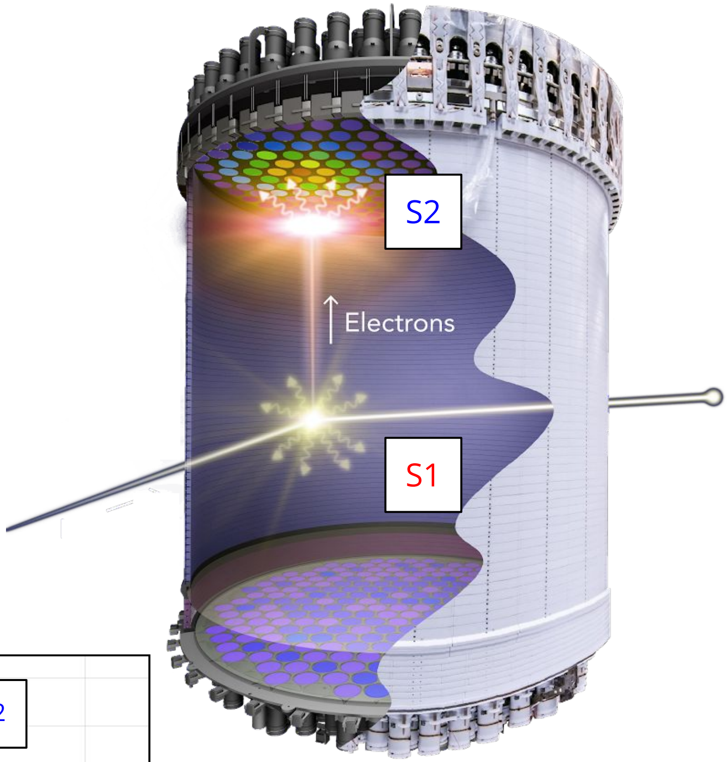
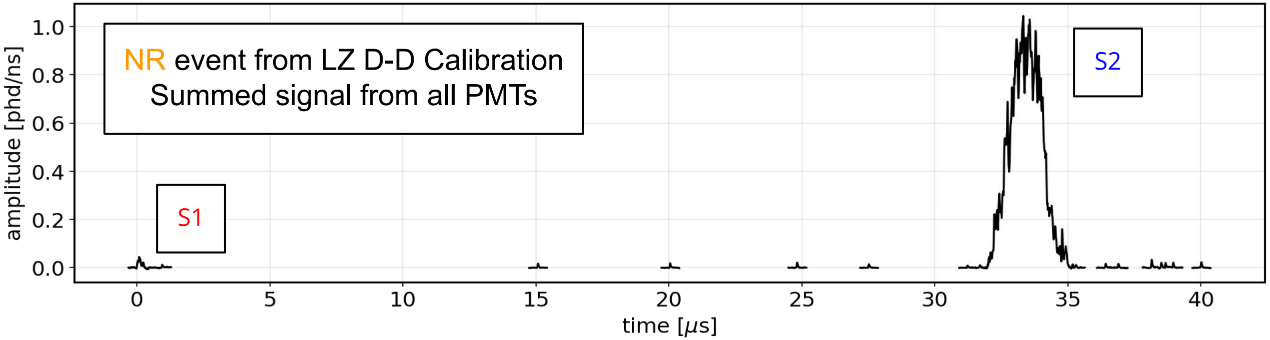
On behalf of the LZ Experiment
CPAD Workshop 2022

The LZ Experiment

- The LUX-ZEPLIN (LZ) experiment uses a liquid-gas dual-phase xenon time projection chamber (TPC)
- Ratio of scintillation (S1) to electroluminescence (S2) allow classification of particle interactions
- Calibrate expected signal response of electron recoils (ER) and nuclear recoils (NR) using sources of known energy:
  - ER → gammas, betas
  - NR → neutrons



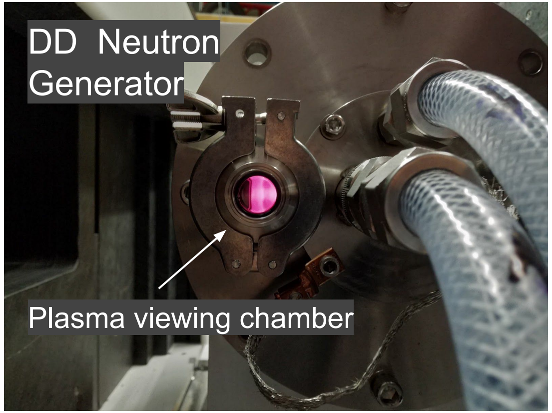


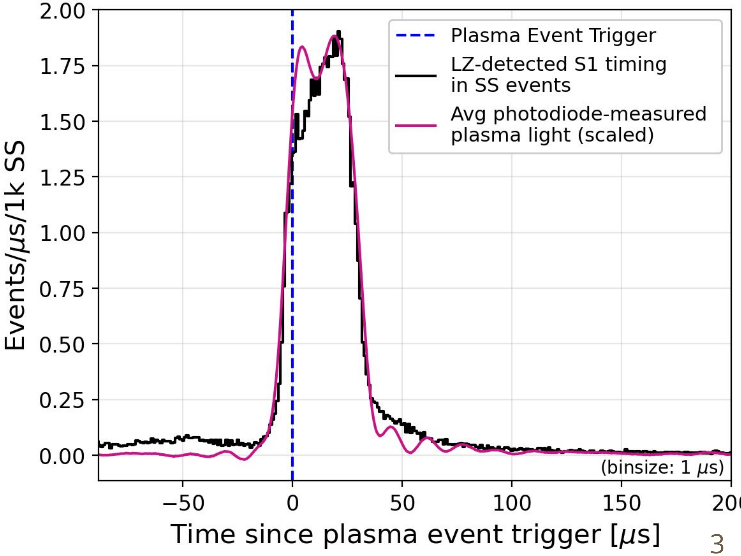
The Neutron Source: Adelphi DD109

- Generates neutrons via deuterium-deuterium fusion
  - Monoenergetic 2.45 MeV neutrons
  - Neutron intensities up to 10^9 n/sec

Fusion Reaction	Branching Ratio
$^2D + ^2D \rightarrow {}^3He + n$ (2.45 MeV)	0.50
$^2D + ^2D \rightarrow {}^4He + \gamma$ (23.84 MeV)	5×10^{-8}

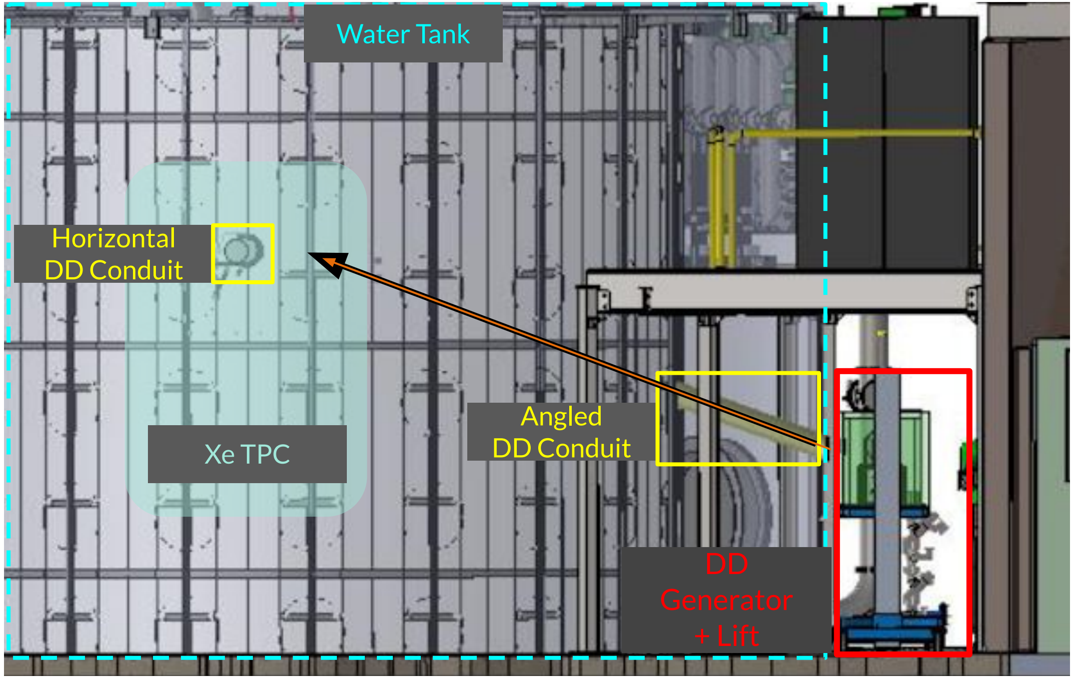
  - **DD is a pure neutron source with very little intrinsic gamma contamination**
- Neutron pulses with frequency down to 100 Hz, and pulse width as narrow as 25 us
  - The ignition of plasma inside the generator head is an immediate indication of neutron production
  - Measuring the light intensity of plasma, we know when a set of neutrons are produced and thus when to record an event





DD Generator Deployment in LZ

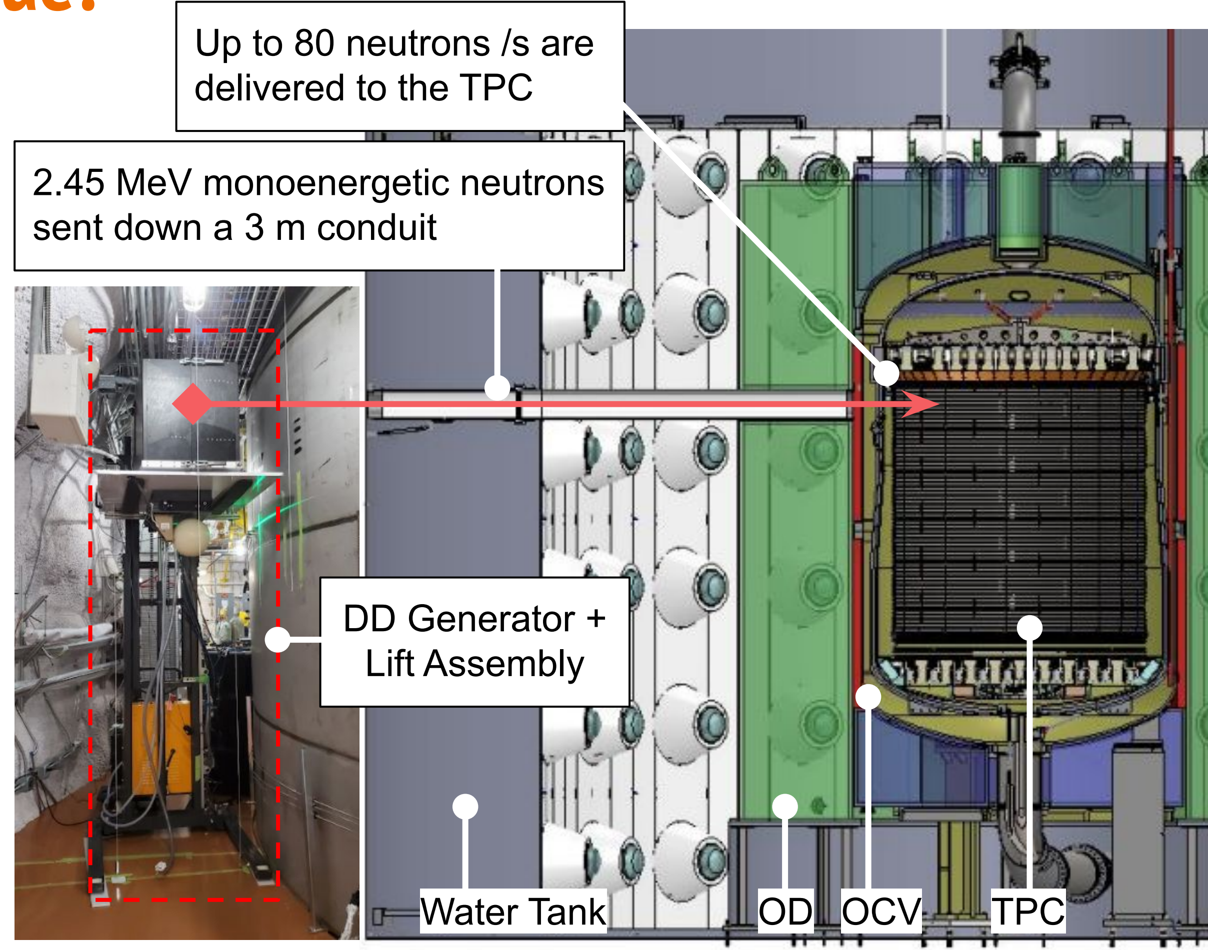
- Two conduits allow passage through water tank
  - one angled
  - one horizontal
- DD generator sits outside water tank and fires down conduits
  - Generator is on a lift that provides X,Y,Z translation for positioning
  - Borated poly (BPE) shielding provides 100x reduction in isotropic neutron flux
  - Shielding has a window aimed toward conduit
  - Conduits localize NR events within TPC
- Operated in three modes:
  - **Direct**
  - **D-reflector**
  - **H-reflector**



Davis Campus, Sanford Underground Research Facility (SURF)

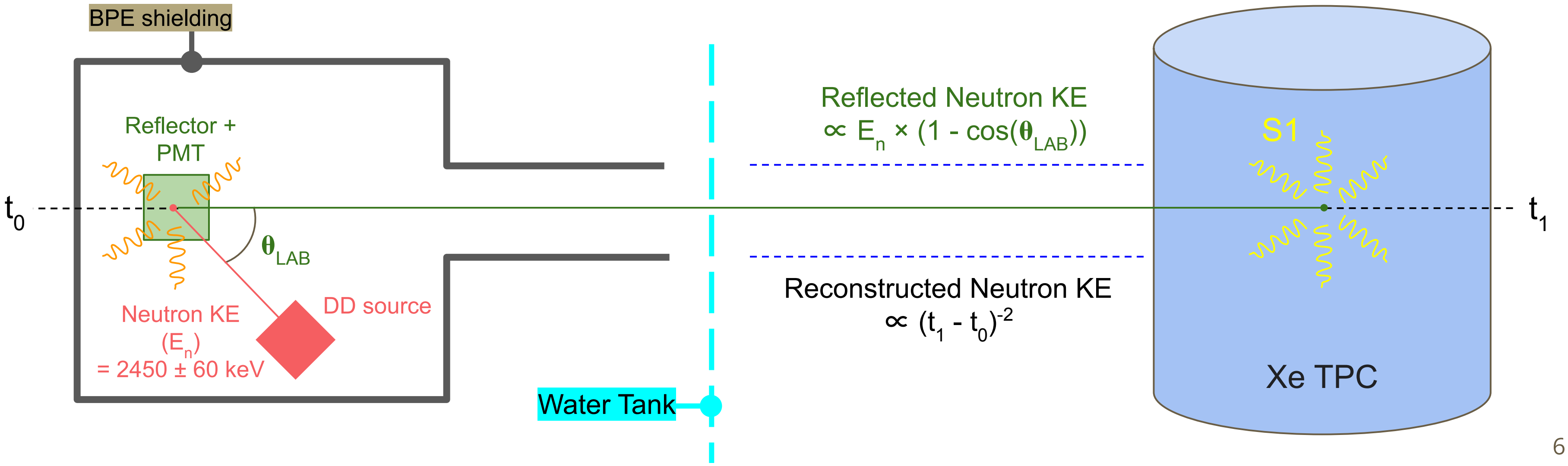
DD Calibration Technique: Direct Mode

- 2.45 MeV neutron targeted directly at the Xe TPC
- A cutout of BPE shielding determines the direction of neutron beam
- The conduit is drained during operation to make a collimated neutron beam into TPC
- Events are triggered on neutron arrival time (determined from pulsed plasma timing)



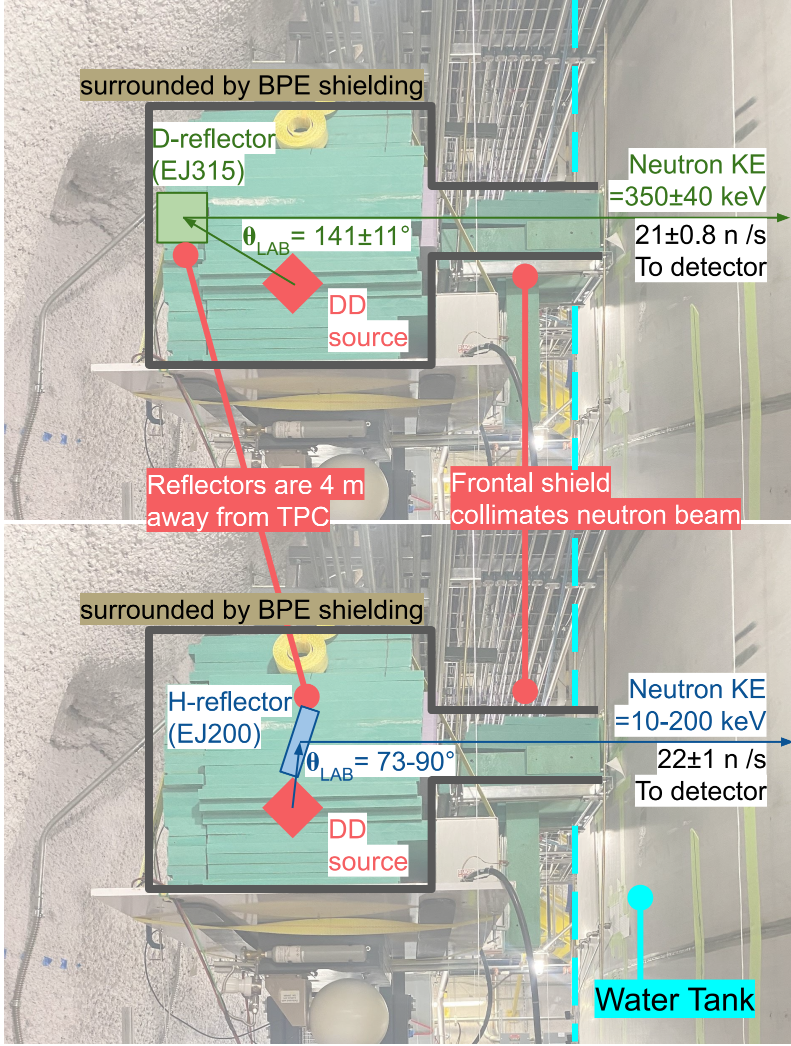
DD Calibration Technique: D-/H-Reflector Mode

- Reduce kinetic energy by reflecting 2.45 MeV DD neutrons off deuterium-loaded or hydrogen-loaded target
- Measure neutron time of flight (ToF: $t_1 - t_0$) between reflectors and TPC for per-neutron energy reconstruction
  - t_0: Scintillation light from recoiling neutrons observed with PMTs attached to the reflector
  - t_1: Primary photon signal (S1) from neutron recoil in TPC
- Reflector placement and shielding configuration determines neutron scattering angle
  - The optimal configuration of reflector position and shielding was tested and verified at Brown.
- End result is a clean, low energy, neutron source with per event KE-tagging.



DD Calibration Technique: D-/H-Reflector Mode

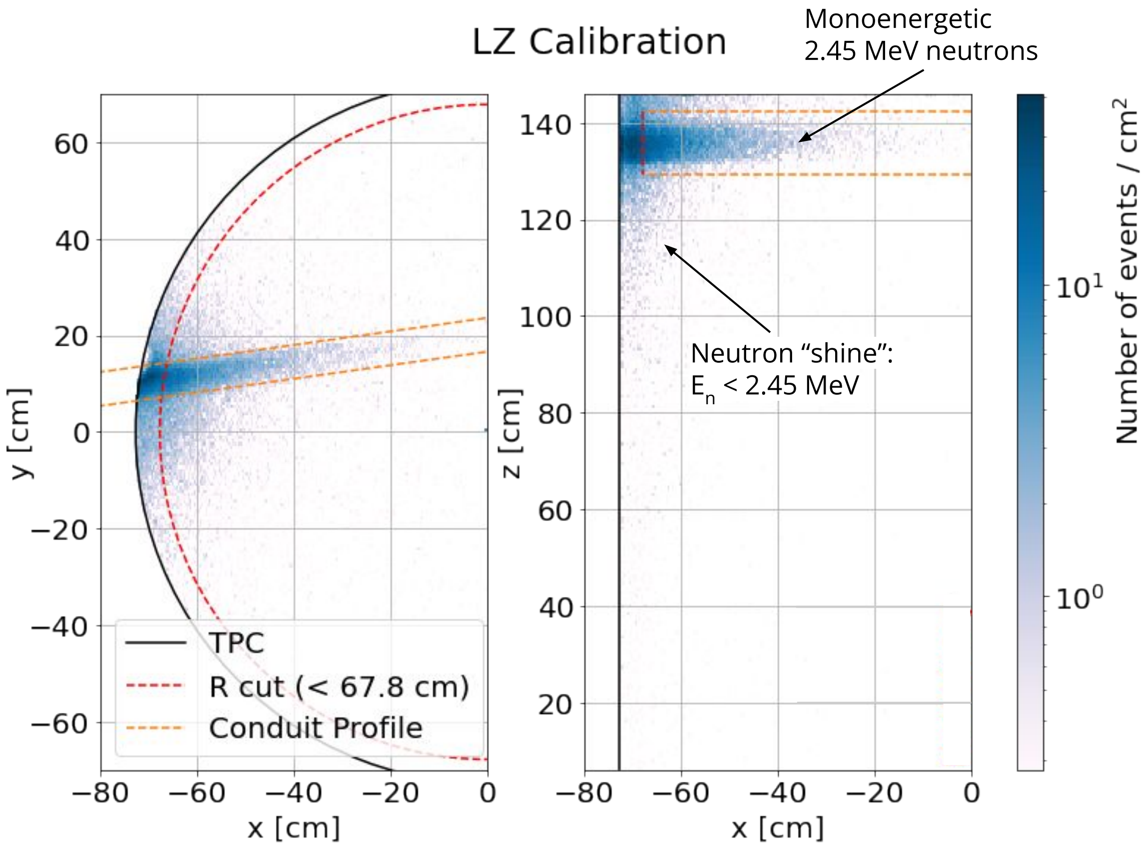
- D-reflector:
  - Neutrons reflected off a deuterium-loaded target scattered by 141±11° resulting in dominantly 350±40 keV monoenergetic neutron beam.
  - Active EJ315 scintillator gives per-event info:
    - Pulse size → Neutron energy
    - PSD → Neutron/gamma discrimination
    - Fast (10 ns) timing resolution on scatter
- H-reflector:
  - Forward scattering 73-90° with H resulting in dominantly lower kinetic energy between 10-200 keV.
  - Kinetic energy is not constrained as well as D-reflector, but can be measured from ToF.



Results of
LZ Calibration

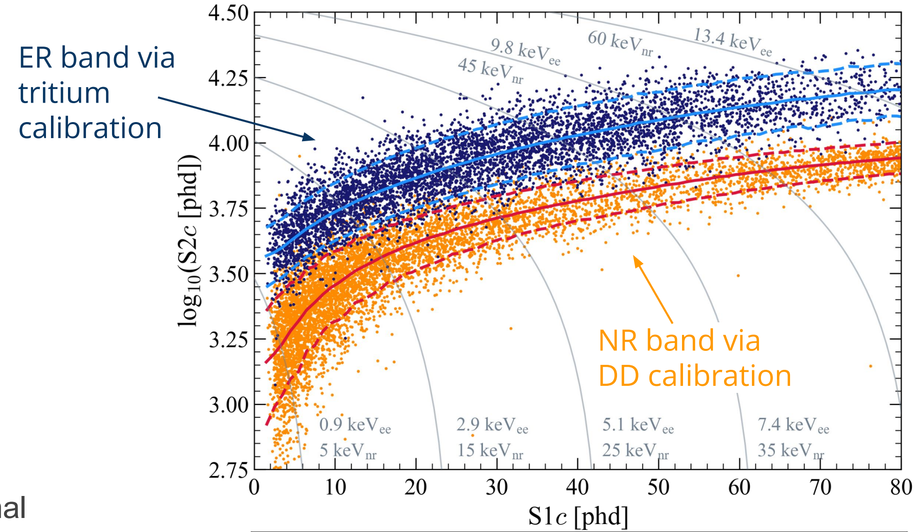
Direct Mode (2.45 MeV): Conduit Profile Cut

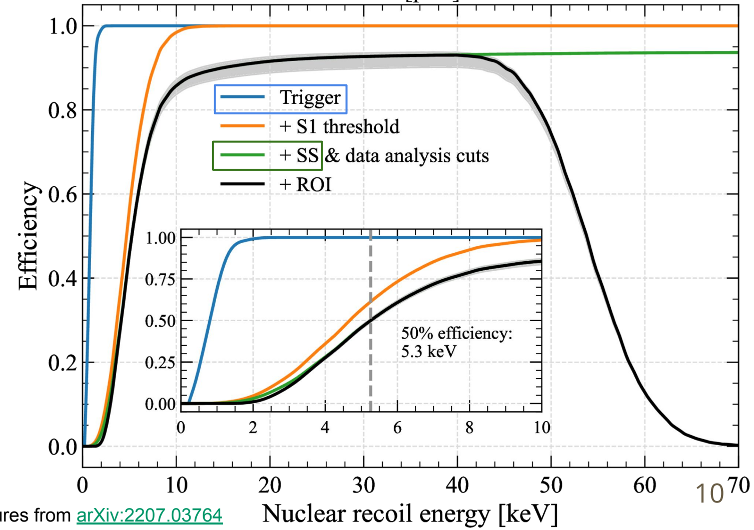
- Observe clear boundary of conduit from XYZ position reconstruction
- Conduit profile cuts are used to select pure 2.45 MeV neutrons
  - 90 +/- 2 % of neutrons do not interact with other material before entering LXe
- Narrow conduit cross-section (5 cm ID) constrains Z position and reduces systematic uncertainties in event reconstruction



Direct Mode (2.45 MeV): NR Band and Signal Efficiencies

- Select neutron events with three simple criteria:
  - Single scatters
  - Neutron position within conduit profile
  - S1 time within plasma pulse timing window
- Observed a clean NR band from direct DD data
  - Very low gamma emission from DD source → minimal electron recoil (ER) event rate
  - NR band means and widths agree with simulated band from NEST to better than 1% and 4% in log10S2c, respectively
- Data-driven signal efficiencies for the trigger and reconstruction use DD data (bottom right)
  - **DAQ trigger efficiency** → compare the external trigger of the generator against the TPC S2 trigger logic
  - **Reconstruction efficiency** → compare the reconstruction results of low-energy NR events against a large set of events manually identified as single scatters (SS)

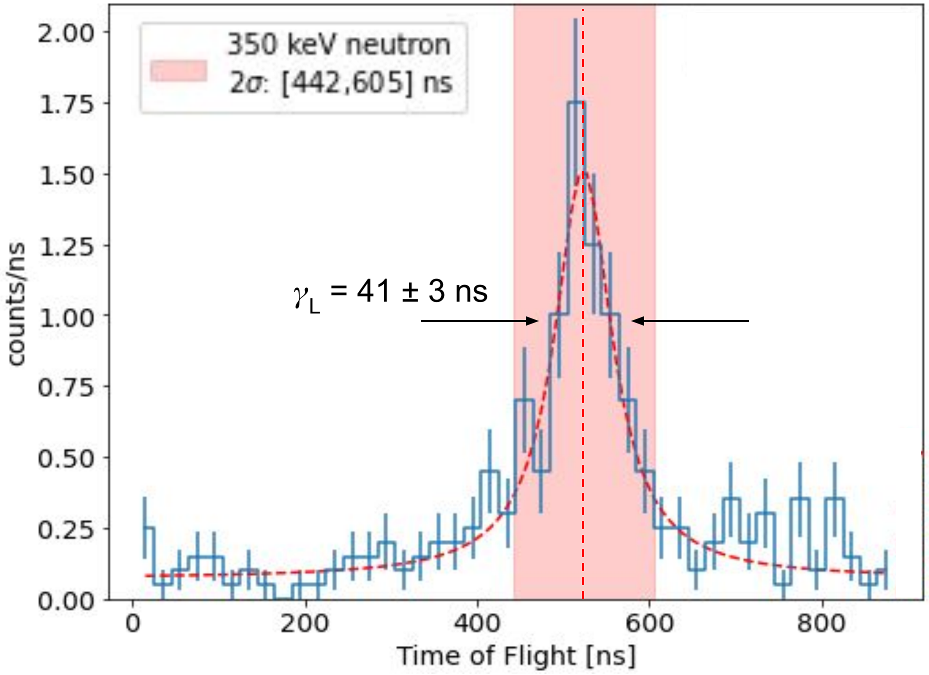




Figures from arXiv:2207.03764

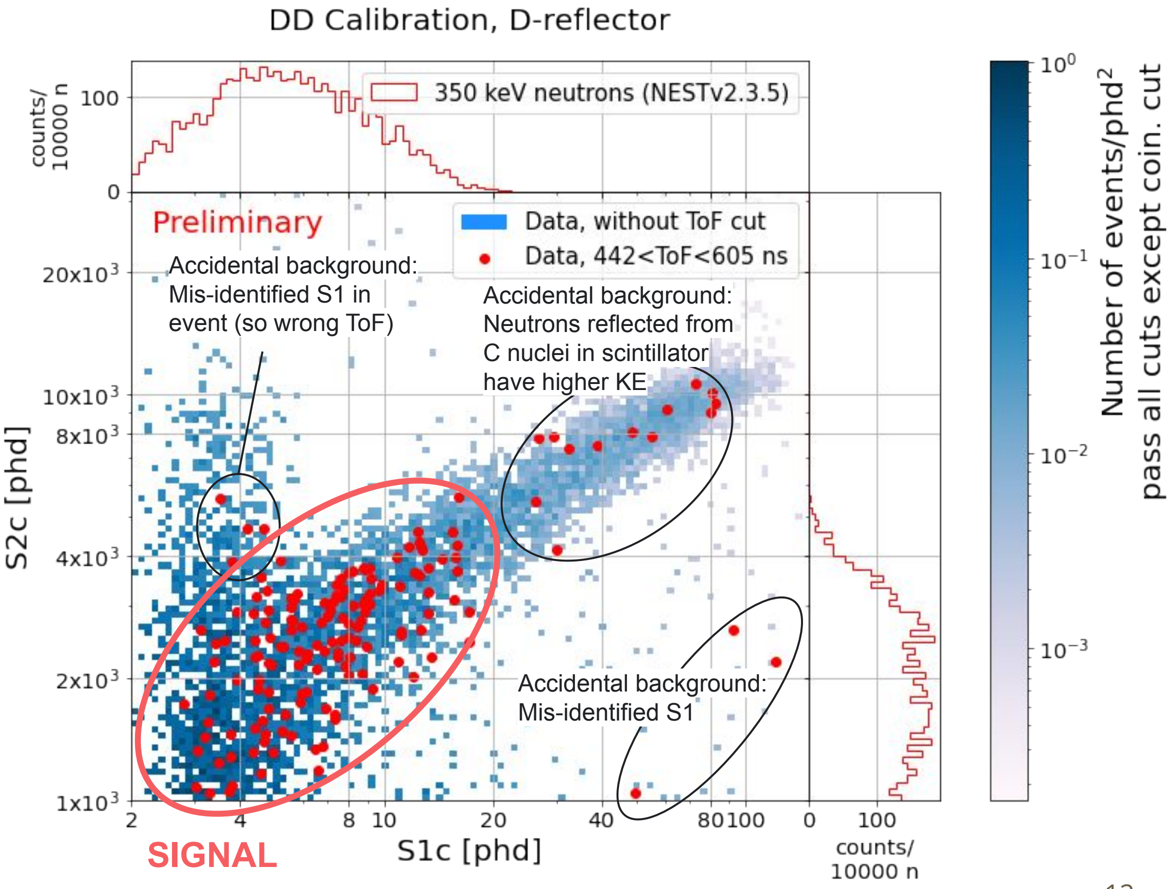
D-Reflector (350 keV): Neutron Tagging and Time of Flight

- A distinct peak in ToF of 11σ above the accidental backgrounds
  - Only single scatters are analyzed
  - Observed a peak at 523 ± 34 ns, with a Lorentzian width of 41 ± 3 ns
  - Time for a 350 keV neutron to fly 4.1 m is 502 ns
- Per-neutron information from D-reflector:
  - **Pulse area** → how much kinetic energy a neutron lost at the reflector
  - **Pulse shape discrimination** → neutrons have larger tail area than gammas
  - **Coincidence with S1** → presence of reflector pulse 0-1 us ahead of S1 time at the detector
- Select monoenergetic neutrons through ToF cut for events within ±2σ of the peak



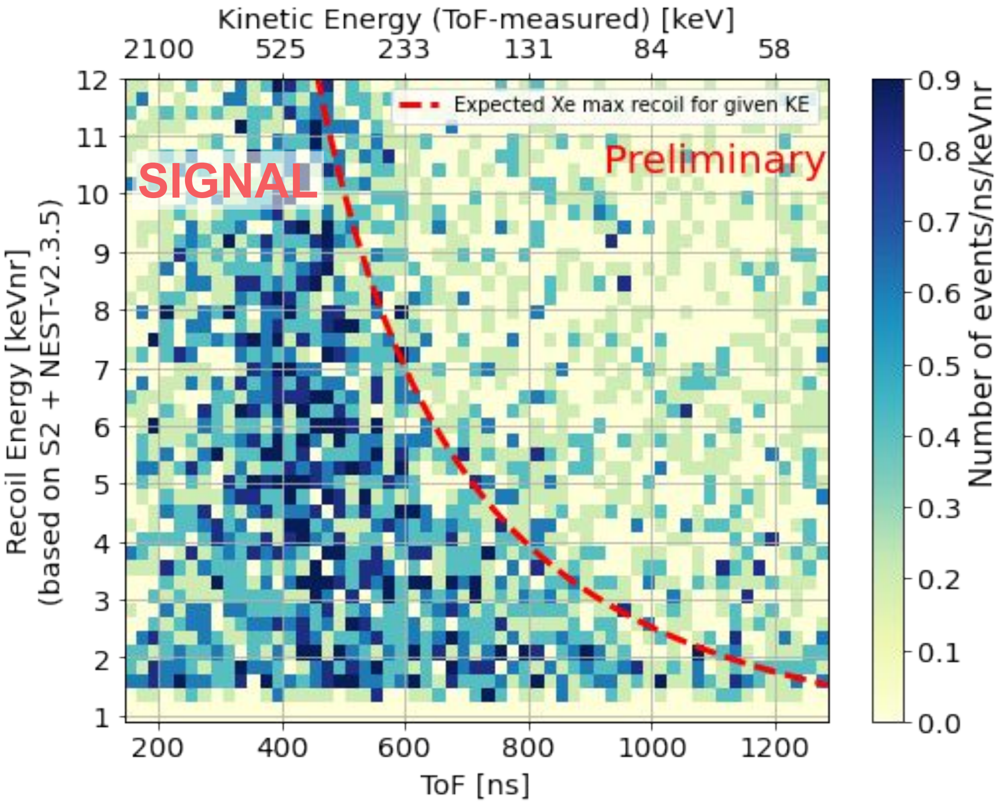
D-Reflector (350 keV): Tagged Neutrons in NR Band

- Apply ToF cut: 442<ToF<605 ns
- ToF cut selects 350±40 keV neutrons
  - Blue histogram: without ToF cut
  - Red dots: with ToF cut
- Majority are within NR band, and agree with simulated S1 and S2 distribution (top and right panels)
- Expect 25 accidentals among 170 events from 6 live hours of data.
- Expect maximum recoil energy in Xe of 10.6 ± 1.2 keVnr.
- Note, the detector condition during reflector operation was different from that of DD direct mode and WIMP search mode.



H-Reflector (10-200 keV): LZ Xe NR Event Energy vs KE from ToF

- Kinetic energy (KE) of a tagged neutron is determined by ToF between reflector and LXe TPC
- For a given neutron KE the recoil energy deposited in LXe ranges from 0 to 4/A × KE
    - The upper limit of reconstructed energy for a given ToF is indicated by red dashed line
- Enables active KE tagging of low energy single scatter NR events
    - **S1(3 ph hits) + S2(600 phd) events down to 1 keVnr in LZ Xe TPC**



Summary

- The DD generator provides a high statistics, pure source of neutrons for calibrating Xe TPCs used for dark matter detection
    - 2.45 MeV monoenergetic pulsed neutrons, as short as pulse width of 25 us
- The DD has been already been used for successful NR calibrations for LZ’s first science run
- A new calibration technique with very low neutron energies using D- and H-reflectors is demonstrated with LZ detector
    - [“D-Reflector”] EJ315 D-loaded Scintillator Reflector + DD Generator
        - Portable source of dominantly **350±40 keV** tagged neutrons
        - Observed a clear peak in ToF space that corresponds to 350 keV neutron KE.
        - Confirmed that ToF selected neutrons are in LXe NR band and have expected deposited energy
    - [“H-Reflector”] EJ200 H-loaded Scintillator Reflector + DD Generator
        - Portable source of dominantly **10-200 keV** tagged neutrons
        - LZ events show expected relationship between n ToF and S2 reconstructed energy
    - Reflectors provide low energy neutrons with known kinetic energies → will be used to further improve detector calibration

LZ (LUX-ZEPLIN) Collaboration

@lzdarkmatter

https://lz.lbl.gov/

35 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
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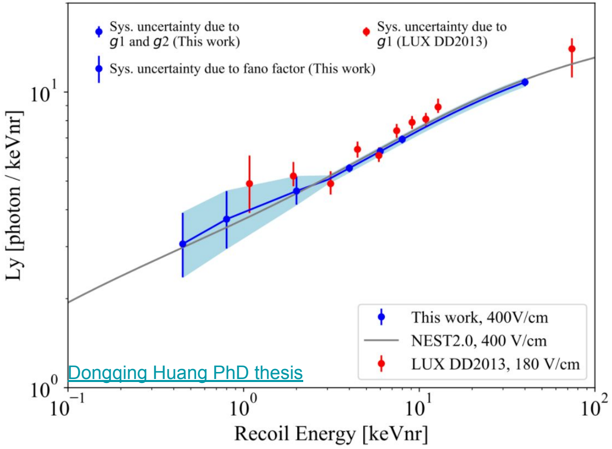
Backup

NR Calibrations in LUX

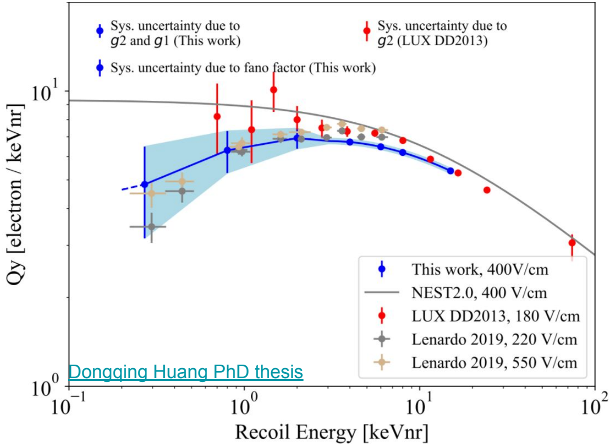
- The Adelphi deuterium-deuterium (DD)108 Neutron Generator was used in LUX (a previous generation dark matter experiment) to investigate the nuclear recoil (NR) response of the detector.
  - Absolute Light and Charge Yields were measured for NR energies of **0.45-74 keVnr** and **0.27-74 keVnr**, respectively.
  - Used to define a relationship between scintillation (S1) and ionization (S2) signal
    - Commonly referred to as NR band, this defines the expected S1-S2 parameter space for WIMP-nucleon interactions in LXe

Light Yield (LUX Experiment)



Dongqing Huang PhD thesis

Charge Yield (LUX Experiment)



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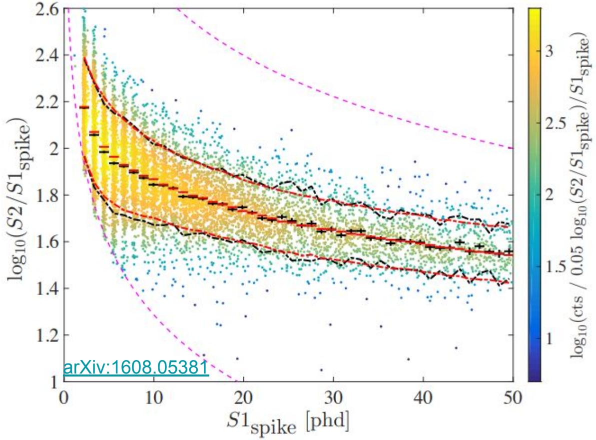
NR Band (LUX Experiment)



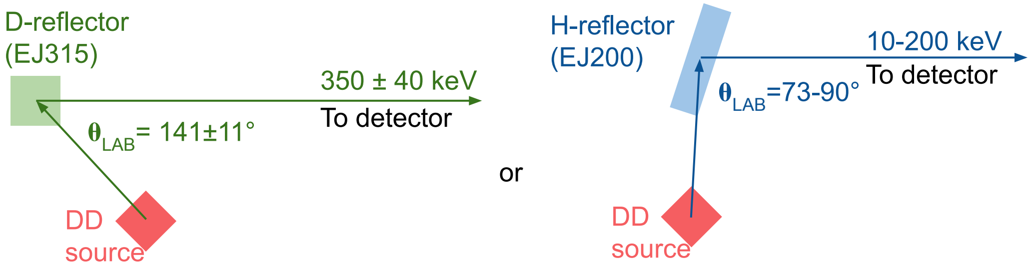
arXiv:1608.05381

DD Calibration Technique

DD Direct Mode

- ➔ 2.45 MeV neutron targeted directly at the Xe TPC
- ➔ A cutout of BPE shielding determines the direction of neutron beam
- ➔ The conduit is drained during operation to make a collimated neutron beam into TPC
- ➔ Events are triggered on neutron arrival time (determined from pulsed plasma timing)

Reflector Modes: D-reflector and H-reflector



- ➔ Reduce kinetic energy by reflecting 2.45 MeV DD neutrons off deuterium-loaded or hydrogen-loaded target
- ➔ Measure neutron time of flight (ToF: t1 - t0) between reflectors and TPC for per-neutron energy reconstruction
  - ◆ t0: Scintillation light from recoiling neutrons observed with PMTs attached to the reflector
  - ◆ t1: Primary photon signal (S1) from neutron recoil in TPC
- ➔ The kinetic energy of the neutron is determined from time of flight (ToF).
- ➔ With ToF-technique, the generator becomes a **mono-energetic low energy neutron source**
- ➔ Slow neutrons allow for identifying separated S1s for a double scatter, hence improve independent light and charge yield measurement.

H-Reflector (10-200 keV): LZ Xe NR Event Energy vs KE from ToF

- Kinetic energy (KE) of a tagged neutron is determined by ToF between reflector and LXe TPC
- For a given neutron KE the recoil energy deposited in LXe ranges from 0 to 4/A × KE
  - The upper limit of reconstructed energy is indicated by red dashed line on the right plot.
  - The expected distribution of low energy single scatter S1(3 ph hits)+S2(600 phd) events down to 1 keVnr in LZ Xe TPC are seen in lower left region of plot