Low-energy Monoenergetic Neutron Production with a DD-Neutron Source for sub-keV Nuclear Recoil Calibrations in the LUX and LZ Experiments

Will Taylor
Particle Astrophysics (Gaitskell) Lab, Brown University
On behalf of the LUX and LZ Collaborations

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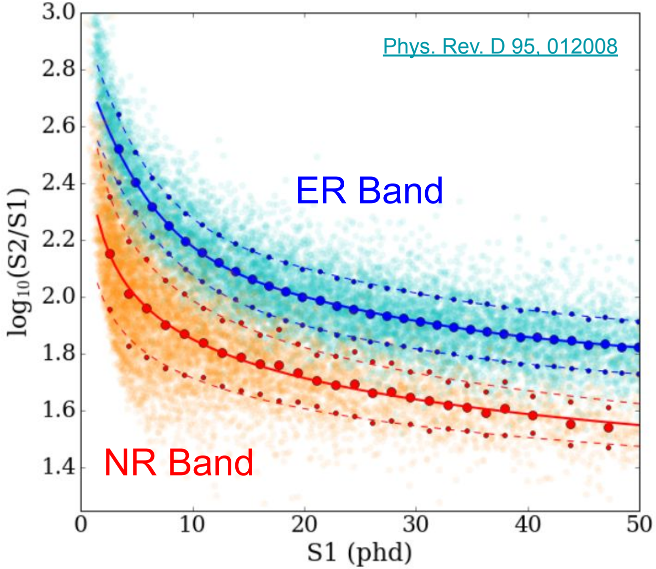
Operation of Liquid Noble Detectors

- Particle interactions produce prompt scintillation (S1) and delayed electron (S2) signals
- 3D position reconstruction via PMT hitmap (xy) and time difference between S1 and S2 (z)
- Background discrimination from S2/S1 ratio
  - 99.8% discrimination, 50% NR acceptance
- Position reconstruction also allows for resolution of multiple vertices in multi-scatter events with O(cm) resolution in xy and O(mm) in z



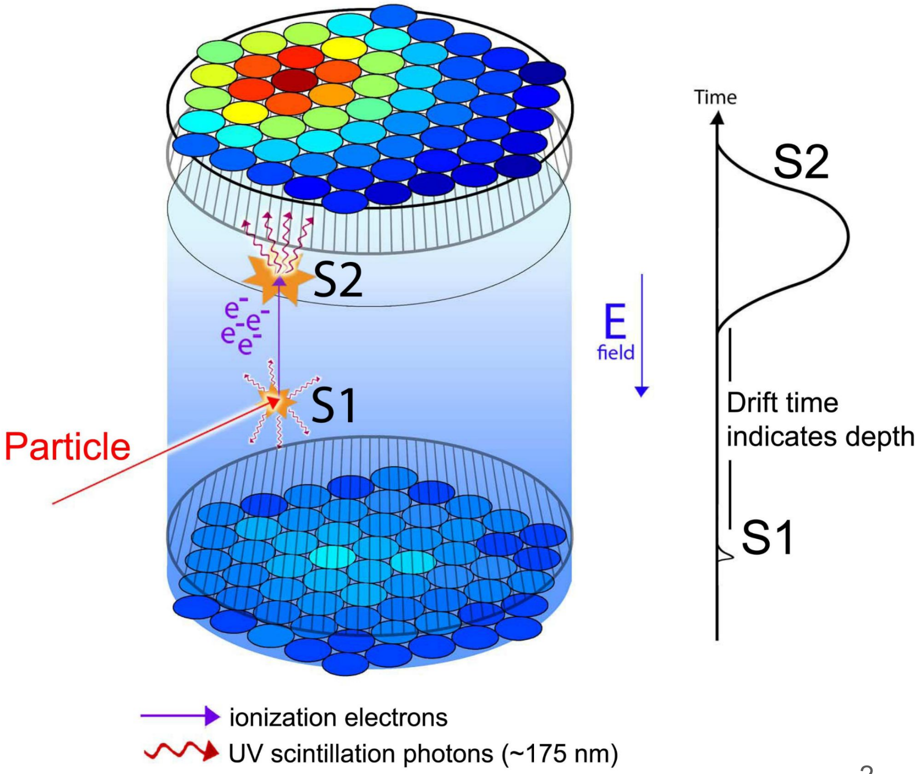


Figure from C. Faham (Brown University)

Deuterium-Deuterium (DD) Generator

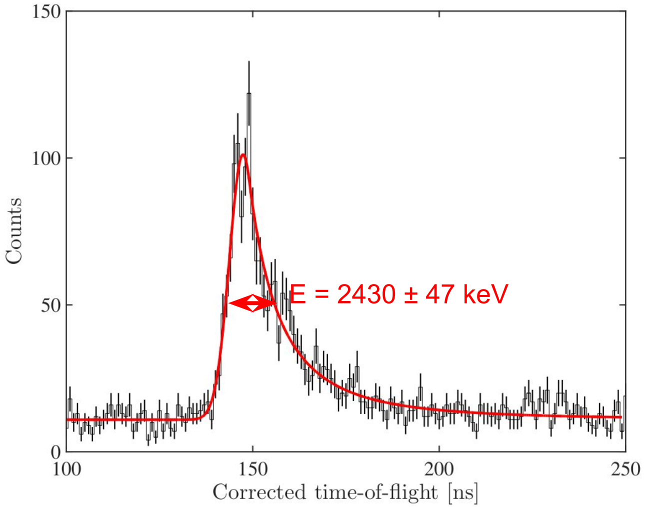
Monoenergetic 2450 keV neutrons are produced via deuterium-deuterium (DD) fusion at intensities up to 10^9 n/s

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

The DD source is an extraordinarily pure neutron source with very little intrinsic gamma contamination. Bremsstrahulung X-rays from ejected electrons in the DD generator are easily shielded by Pb.
99.99% of x-rays can be blocked with 4 mm of Pb

Well-suited for nuclear recoil detection efficiency measurements - known neutron energy and intensity

Measured ToF spectrum at Brown.
Nucl. Instrum. Methods A851, 68 (2017)



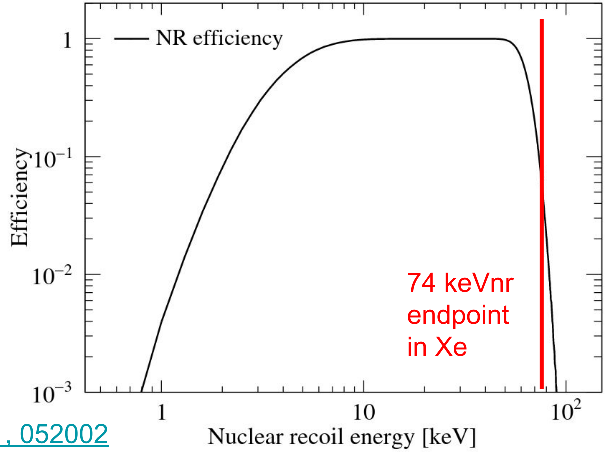
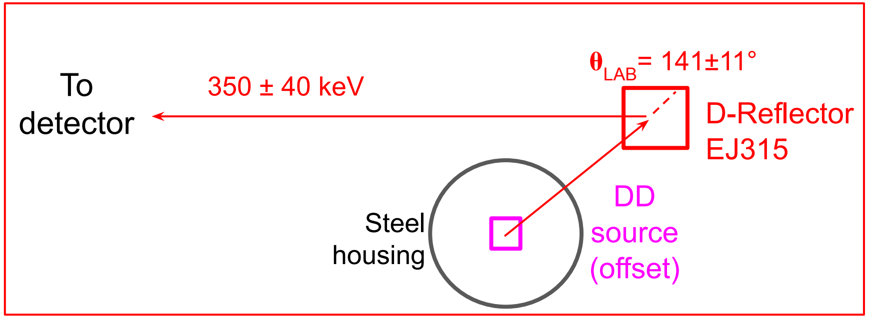
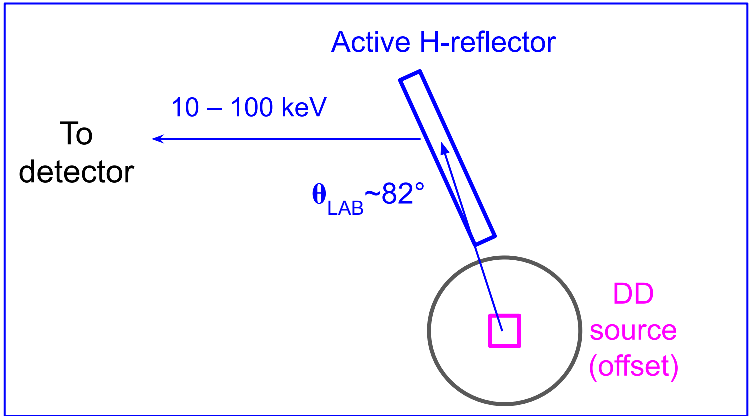


Figure from
Phys. Rev. D 101, 052002

DD Generator Calibration Techniques





Direct Neutrons

Neutrons exit DD generator and travel directly to the detector

Deuterium-Reflected Neutrons

Neutrons exit DD generator, reflect off a deuterated target, and travel to the detector.
Geometry and shielding configuration select a specific backscatter angle, retaining monoenergetic feature
Angle uncertainty is dominated by the size of the reflector target
7.62 cm diameter x 7.62 cm height in these measurements.
Smaller targets have smaller uncertainty, but provide lower reflected neutron flux.

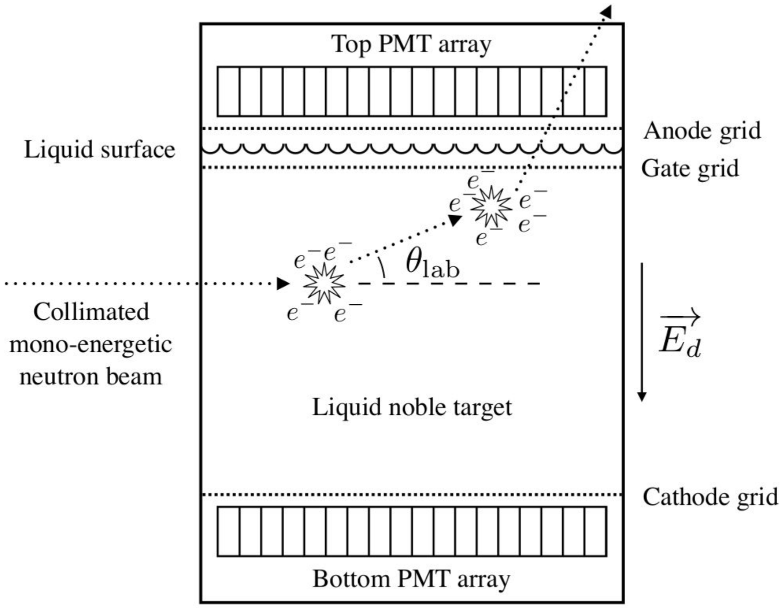
Hydrogen-Reflected Neutrons

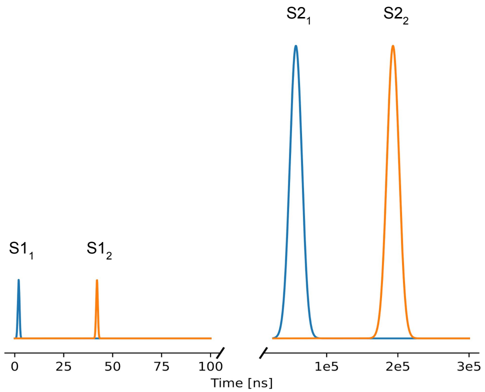
Neutrons exit DD generator, reflect off an active hydrogenated target, and travel to the detector
Hydrogen scattering kinematics are less constrained, resulting in a spectrum of low-energy neutrons, but neutron tagging in the active target permits per-neutron energy measurement via time of flight

DD Neutron Calibrations

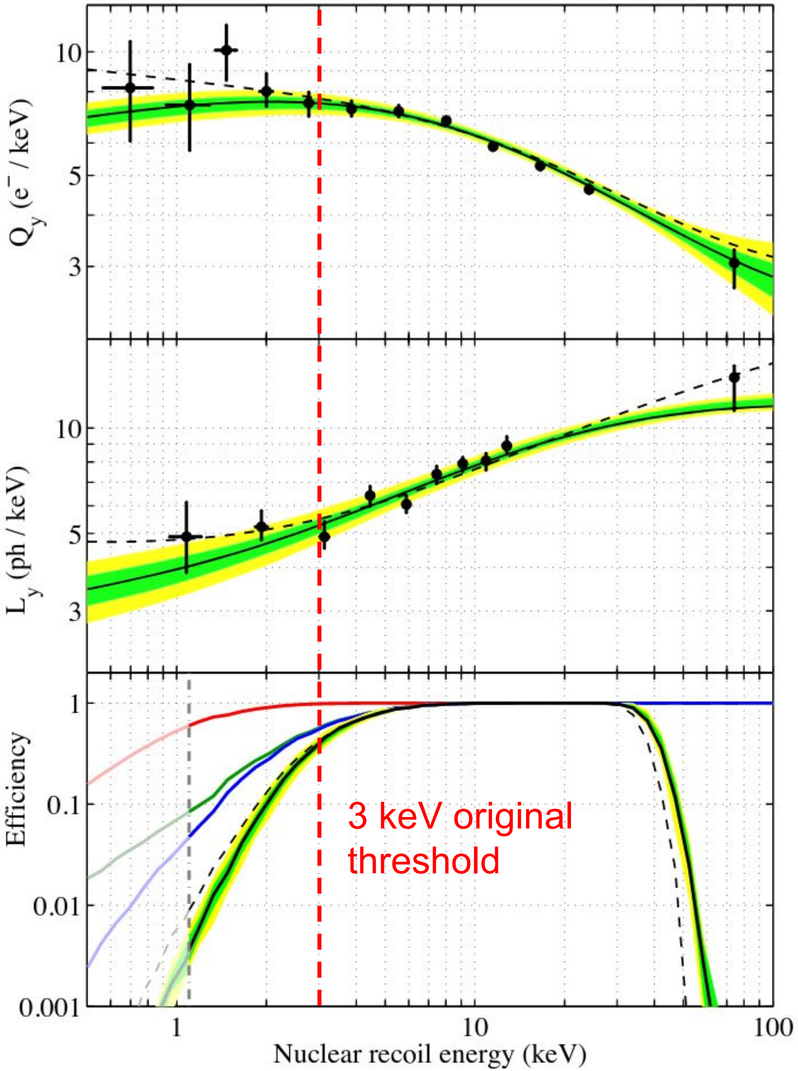
$$E_{\mathrm{nr},A} = \zeta E_n \qquad \zeta = \frac{4 m_n m_A}{(m_n + m_A)^2} \frac{(1 - \cos\theta_{\mathrm{CM}})}{2}$$

- Recoil energy absolutely determined by scattering angle thanks to monoenergetic neutron energy
- DD-Direct
  - Use multi-scatter events to measure recoil energy
  - Measure S2 from first scatter to get charge yield
  - Use single scatter events with S2 now as a proxy for energy to get light yield
- D-Reflector / H-Reflector
  - Slower neutrons allow S1 separation by selecting events with >32 cm scatter separation.
  - S1-separable multiscatter events provide per-neutron independent L_y and Q_y calibrations



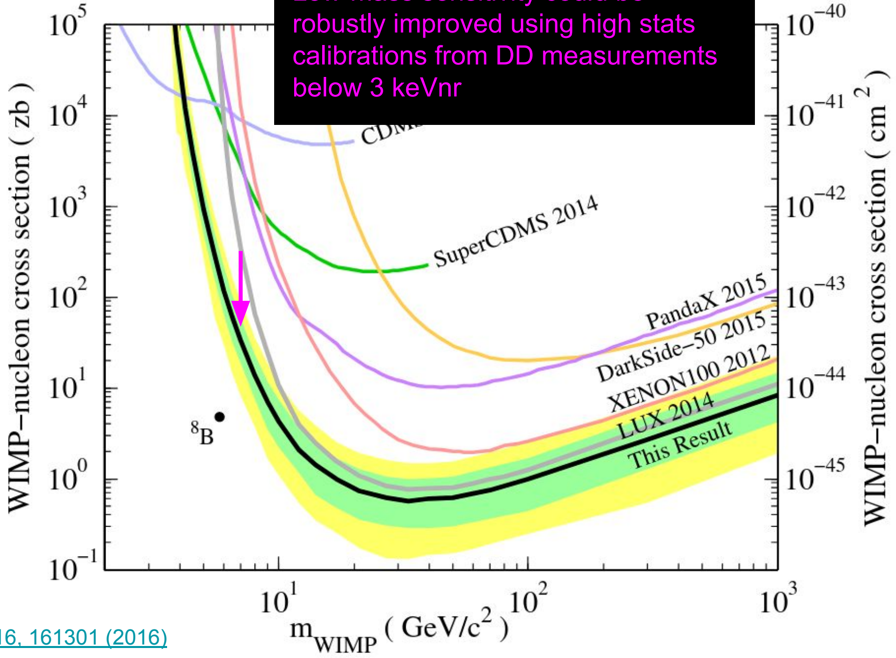


LUX DD Calibration Results



- Direct (2.45 MeV) DD neutron calibrations were successfully deployed in LUX
- Demonstrated observable signal at 1.1 keVnr (Ly) and 0.7 keVnr (Qy)
- Lightest detectable WIMP: M_{WIMP}(GeV)≈(1/4)√(E_{thresh}(keV) x A)
  - Lower demonstrated threshold →lighter detectable WIMPs
- 7x improvement in sensitivity at a WIMP mass of 7 GeV

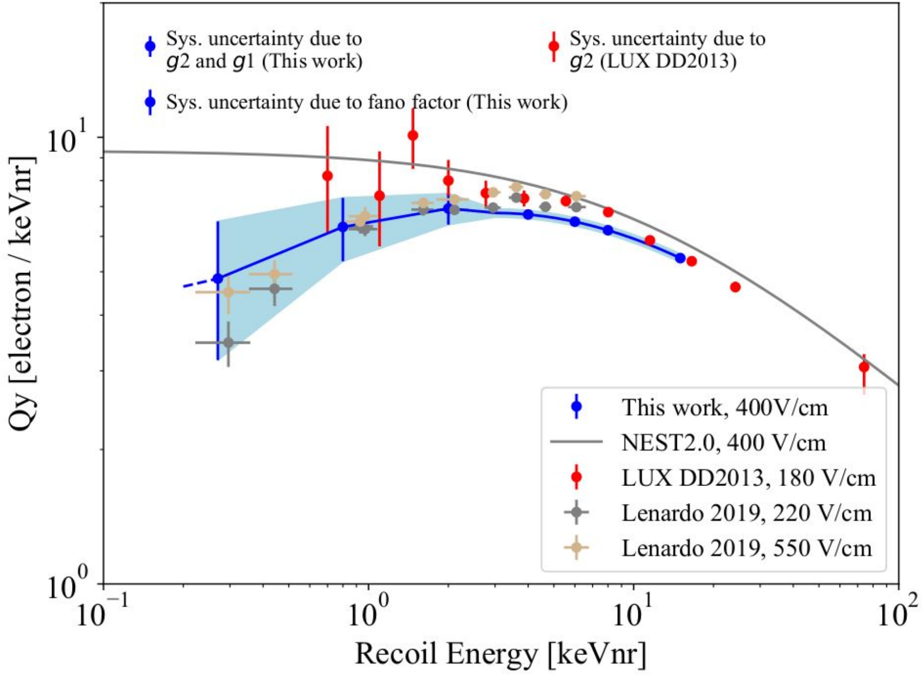
Low-mass sensitivity could be robustly improved using high stats calibrations from DD measurements below 3 keVnr

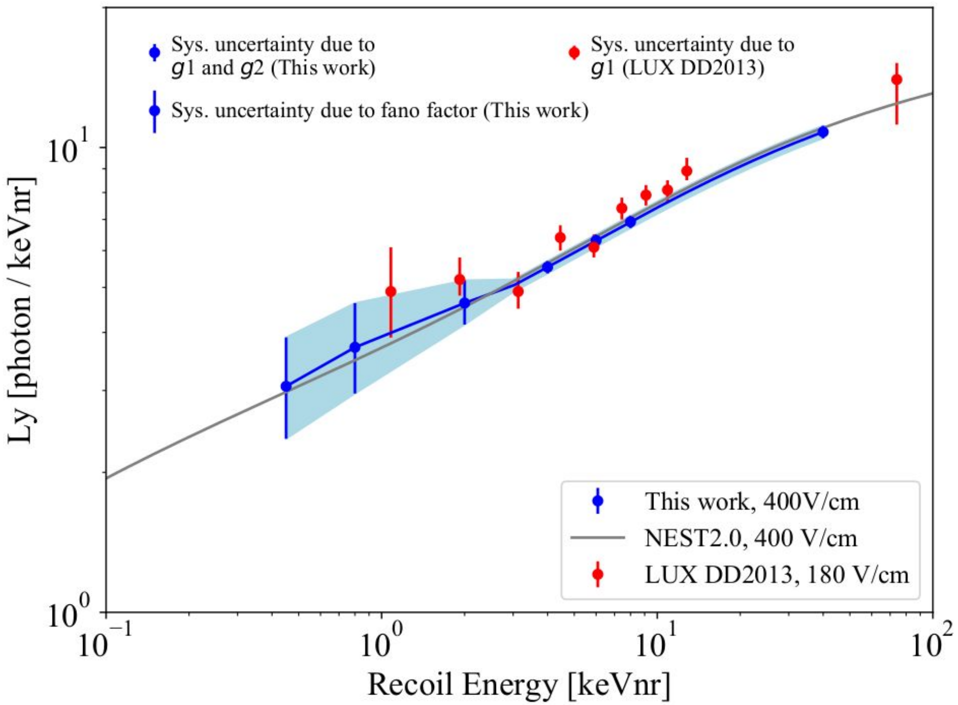


Figures from
[Phys. Rev. Lett. 116, 161301 (2016)]

LUX DD Calibration Results

- New results from LUX2016 DD data push Qy and Ly measurements even lower in energy
- 0.27 keVnr - Qy
- 0.45 keVnr - Ly





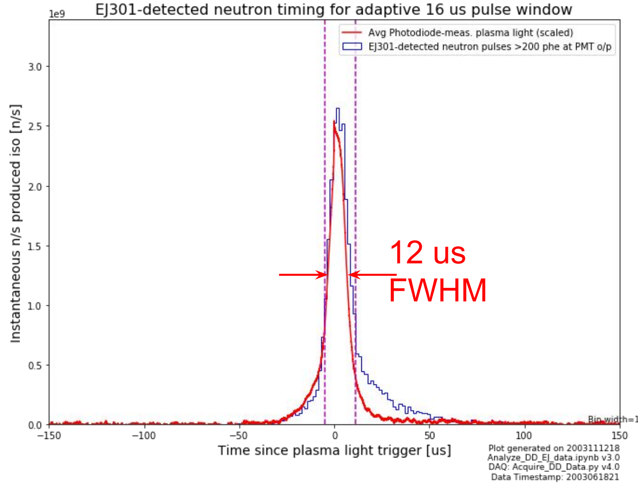
- New results obtained through the combination of a comprehensive signal model, NEST predictions, and less restrictive geometric cuts to improve event statistics in combination with a pulsed DD neutron source
- See [CPAD 2018 talk] for additional information

Figures from [Donging Huang's PhD thesis]
Publication forthcoming

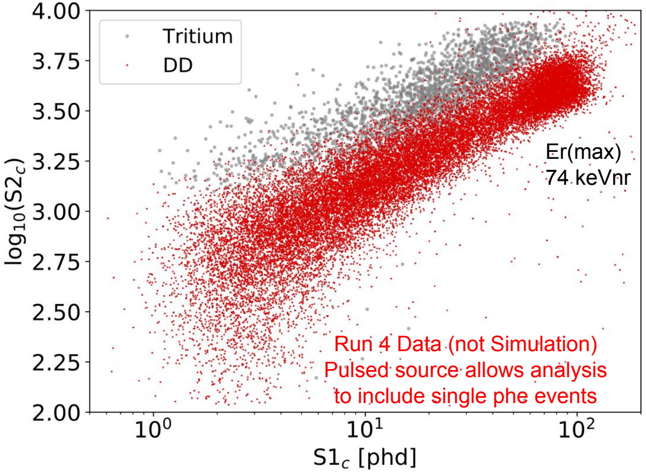
Improvements in Adelphi Technologies DD Generator

- The Gaitskell group at Brown worked with Adelphi to improve the instantaneous intensity (neutrons per second) and reduce pulse width
    - Commercial development guided by dark matter research interests
- Pulsed source allows very clear background estimation of small S1, S2 which is critical for low energy and (S2-only) event rate signal vs background analyses
    - Dongqing Huang's LUX analysis makes use of 20 us wide pulsing structure → pushed down to single phe events
    - Demonstrated 12 us FWHM with upgrades
- Signal-to-noise ratio is inversely proportional to the neutron pulse duty cycle
    - Reduce duty cycle to improve signal
- Intensity increased by factor of 10
    - Offsets drops in duty cycle

Direct Measurement of Neutron Pulse Intensity (2.5×10^9 n/s) and Width (σ=5.0 us) from Adelphi DD Generator following magnetron upgrade

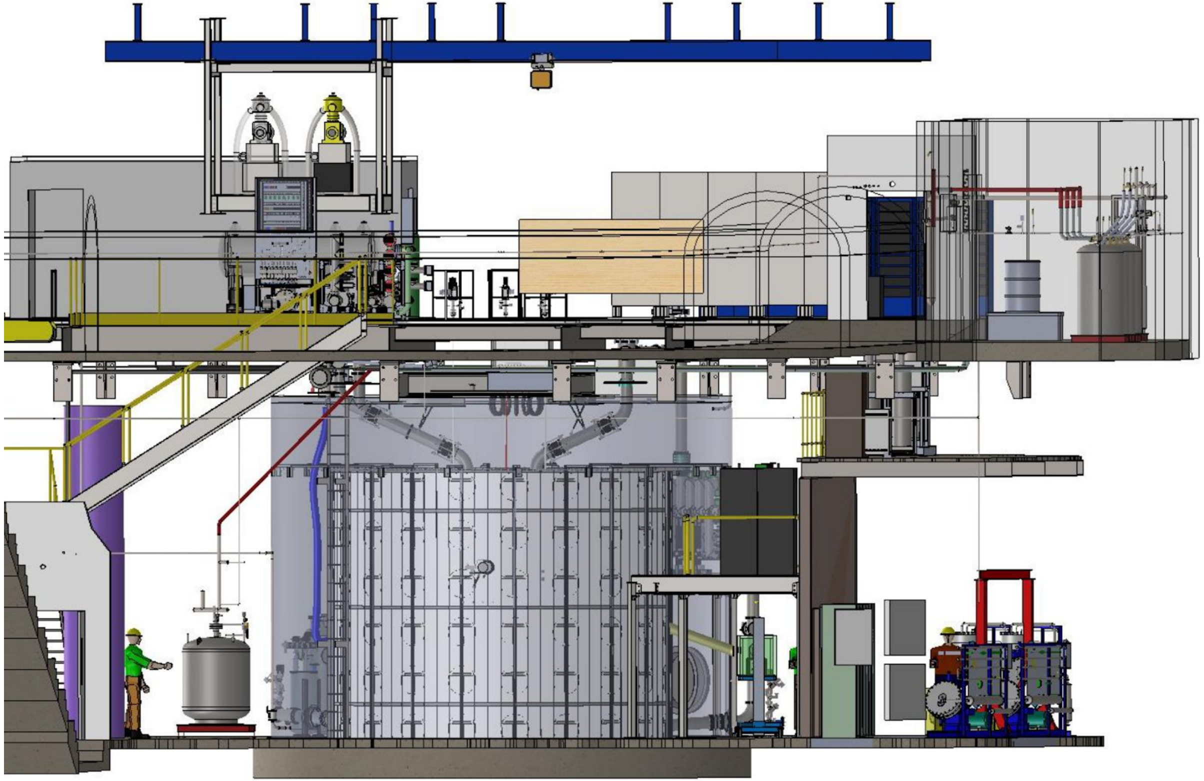


LUX Run 4 DD NR Band Direct Measurement
And comparison with 3H ER Measurement Dongqing Huang



DD Generator Deployment in LZ

- Two conduits connected to the OCV and the water tank wall
  - one angled
  - one horizontal
- DD generator sits outside water tank and fires down conduits
  - Generator is on a lift that provides x/y as well as z translation for positioning
  - Borated poly shielding provides 100x reduction in isotropic neutron flux
  - Shielding has a window aimed toward conduit



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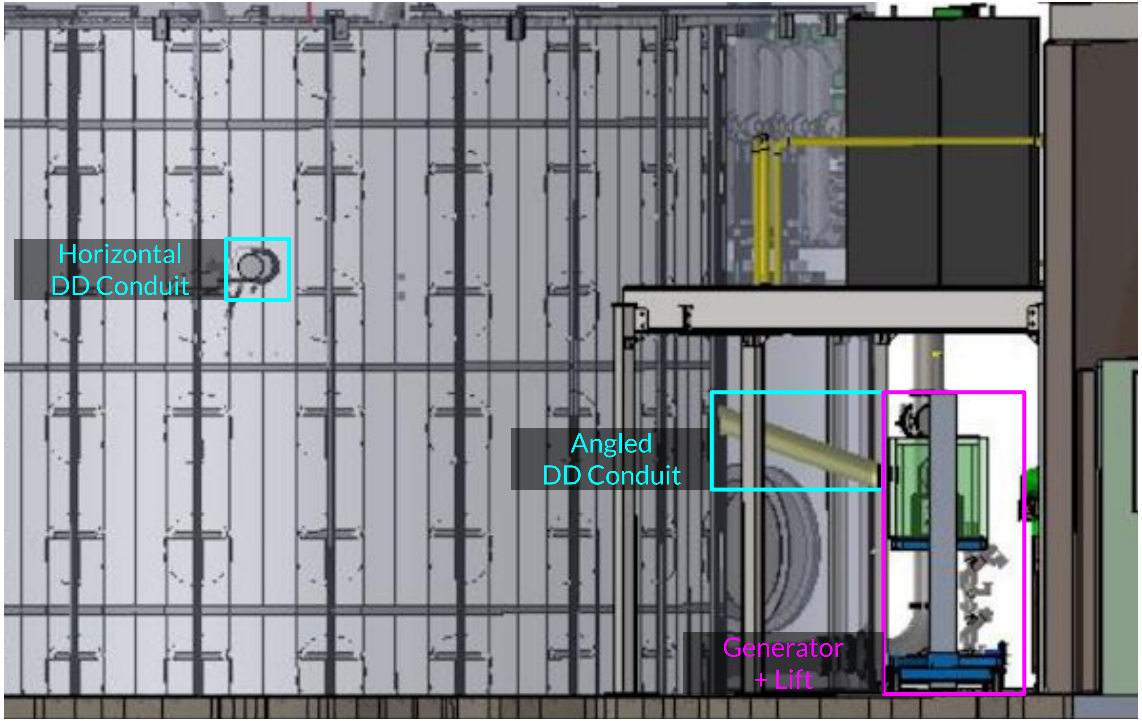
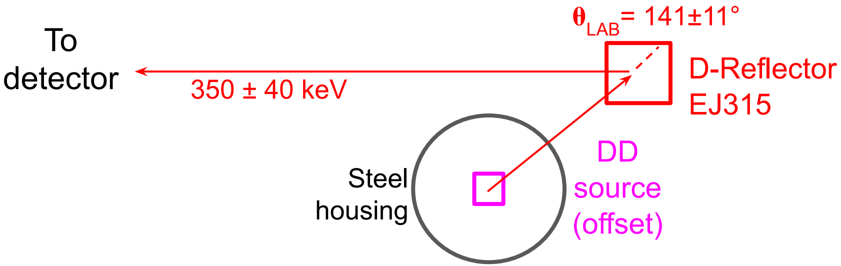
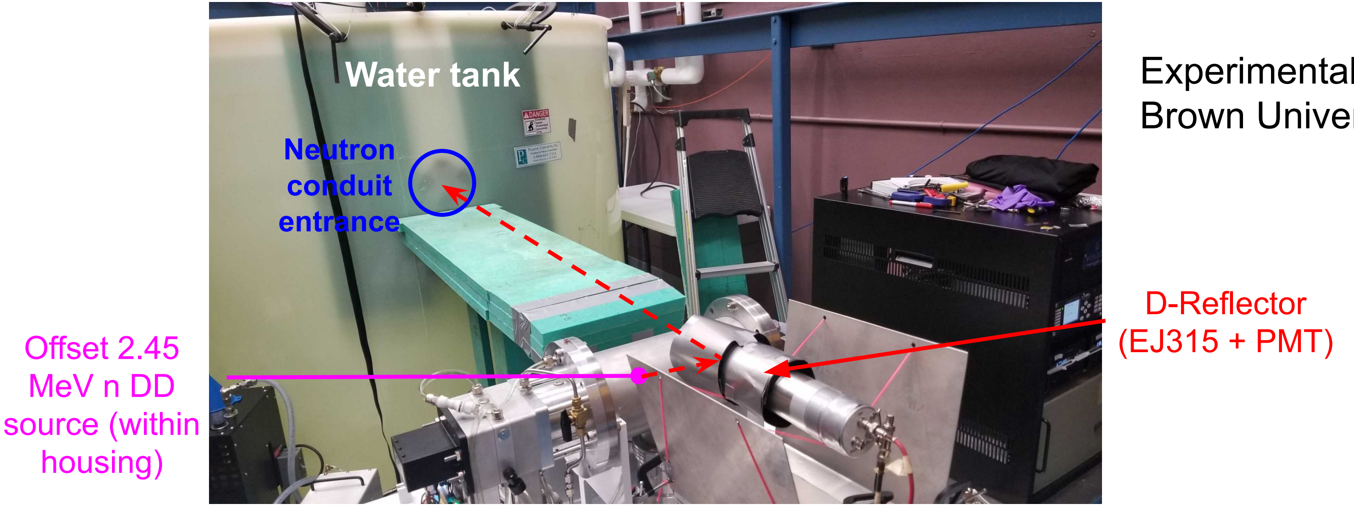


D-Reflector Kinematics

- Converts 2.45 MeV neutrons into a tagged monoenergetic 350+/-40 keV (HWHM) source via reflection off a deuterated scintillator behind the DD source (right)
- Passive design component:
  - Deuterium reflector material gives maximum energy reduction that retains a narrow, monoenergetic reflected neutron peak.

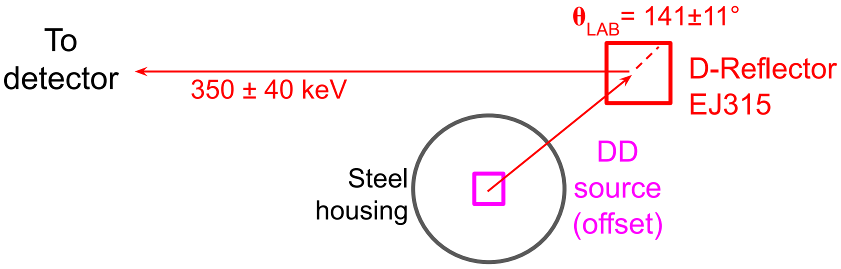


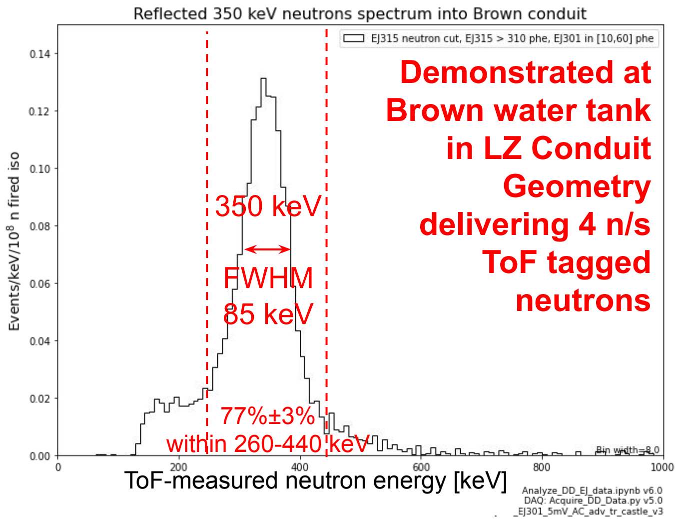


Experimental setup at Brown University

D-Reflector Active Tagging

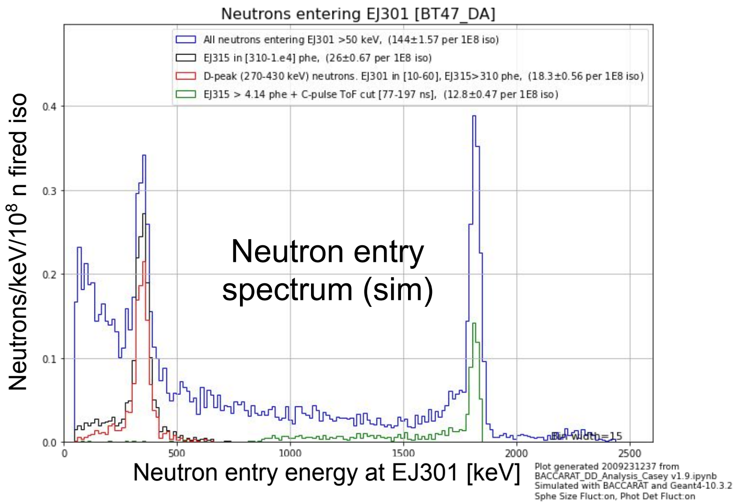
- Active EJ315 scintillator Deuterium Loaded "D-Reflector":
  - Neutron energy info via pulse size
  - Neutron/gamma discrimination via PSD
  - Fast (4 ns) timing resolution on scatter
- Signal + PSD cuts further isolate clean, monoenergetic 350 keV neutrons down the conduit.
- Time of flight measurements permit per-neutron energy reconstruction





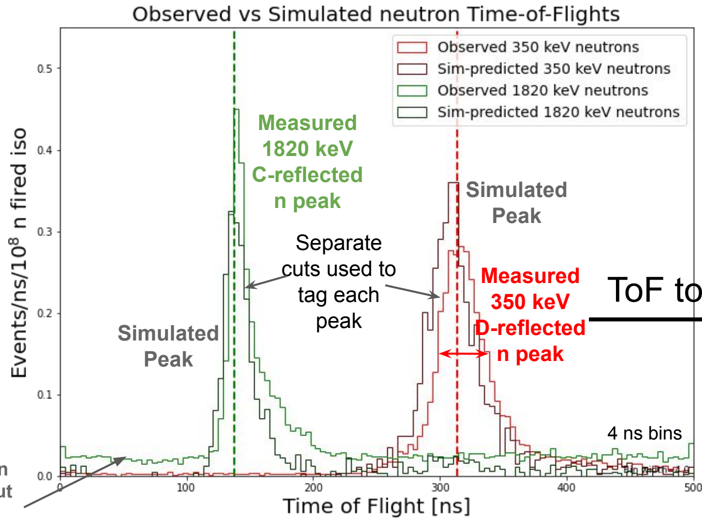
Optimized Demonstration at Brown

- Time of flight test at Brown setup has demonstrated efficient D-reflector operation.
  - 350 keV (red) and 1820 keV (green) ToF peaks shown below measure[d] reflection off deuterium and carbon, consistent with sims
  - 50:1 D-peak signal to random coincidence within the peak ToF window
- D-Reflector has been well characterized



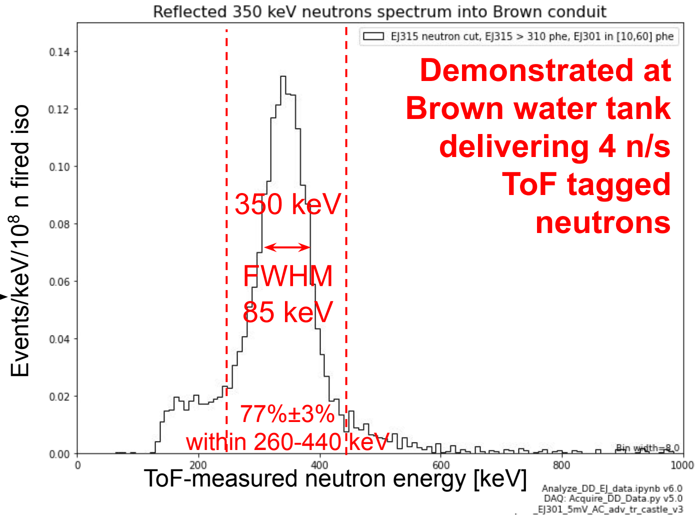
Simulation to Data

Lab measured neutron ToFs



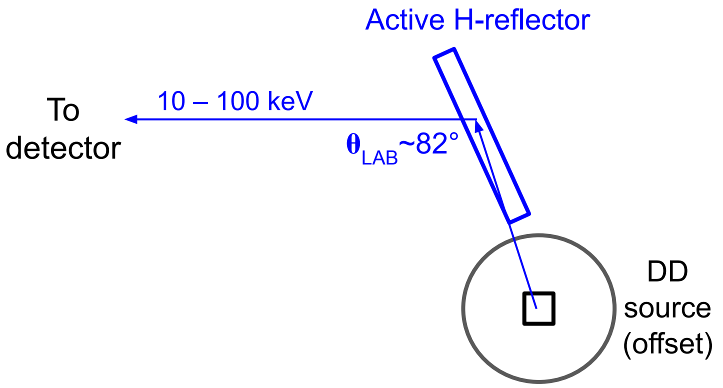
Random Coincidences in simulation not shown, but agree with observation

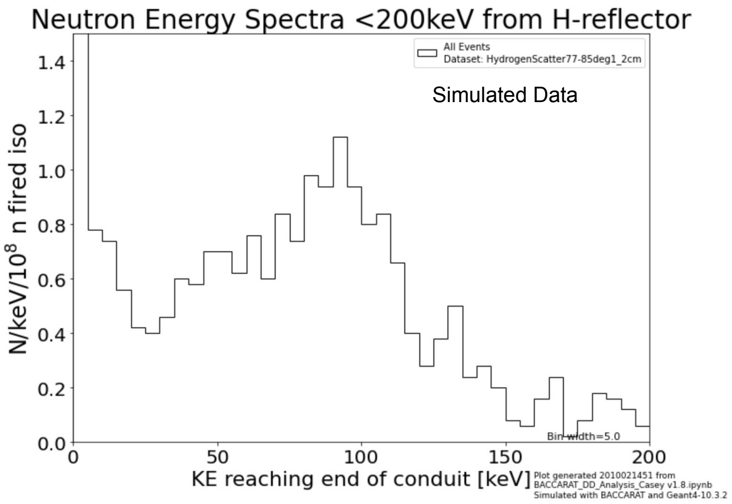
ToF to keV



H-Reflector

- Forward-scattering from hydrogen-dominated scintillator near 90 degrees in lab frame produces tagged neutrons below 100 keV
- ToF from H-Reflector to detector determines n KE for each event
  - All H-reflected low energy neutrons generate clear signals with full neutron/gamma discrimination → all neutrons <100 keV are fully tagged.
- Known neutron energy allows observation of time separation (>40 ns) of S1 vertices in a multiple scatter event for independent L_y determination:
  - n KE 100 keV / 0.42 cm/ns → 17 cm sep. req. (27% in LXe)
  - n KE 10 keV / 0.13 cm/ns → 5 cm sep req. (61% in LXe)
- H-Reflector Yield Tests being performed at Brown currently





Plot+ simulation from Eamon Hartigan-O’Connor, Casey Rhyne @ Brown Universtiy

Conclusions

- DD Generators provide an excellent neutron source for nuclear recoil calibrations in liquid noble TPCs and other dark matter detectors

- Direct 2.45 MeV neutron calibrations have provided charge and light yield measurements down to 0.27 keVnr and 0.45 keVnr in the LUX detector, respectively

- We have also been able to reduce the neutron energies by 1-3 orders of magnitude in both monoenergetic and ToF calibration modes in order to provide additional calibration opportunities at lower nuclear recoil energies

- Deuterium-reflected neutrons can be geometrically constrained to deliver a 350 keV (40 keV HWHM) with both passive and scintillating deuterium targets
    - The active scintillator target provides per-neutron time-of-flight and energy measurement

- Hydrogen-reflected neutrons can be ToF tagged with a scintillator to produce 10-100 keV neutrons for direct calibration of dark matter detectors at <~keV recoil energies
    - Currently studying beam optimization at Brown University

Thank You!

Special thanks to the U.S. Department of Energy for their support on LZ

Thanks also to the Sanford Underground Research Facility (SURF) for their support in hosting LUX and LZ