

Calibrating the scintillation and ionization responses of xenon recoils for high-energy dark matter searches

CPAD 2022
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[arXiv 2207.08326](#)
[Phys. Rev. D. 106, 052013](#)

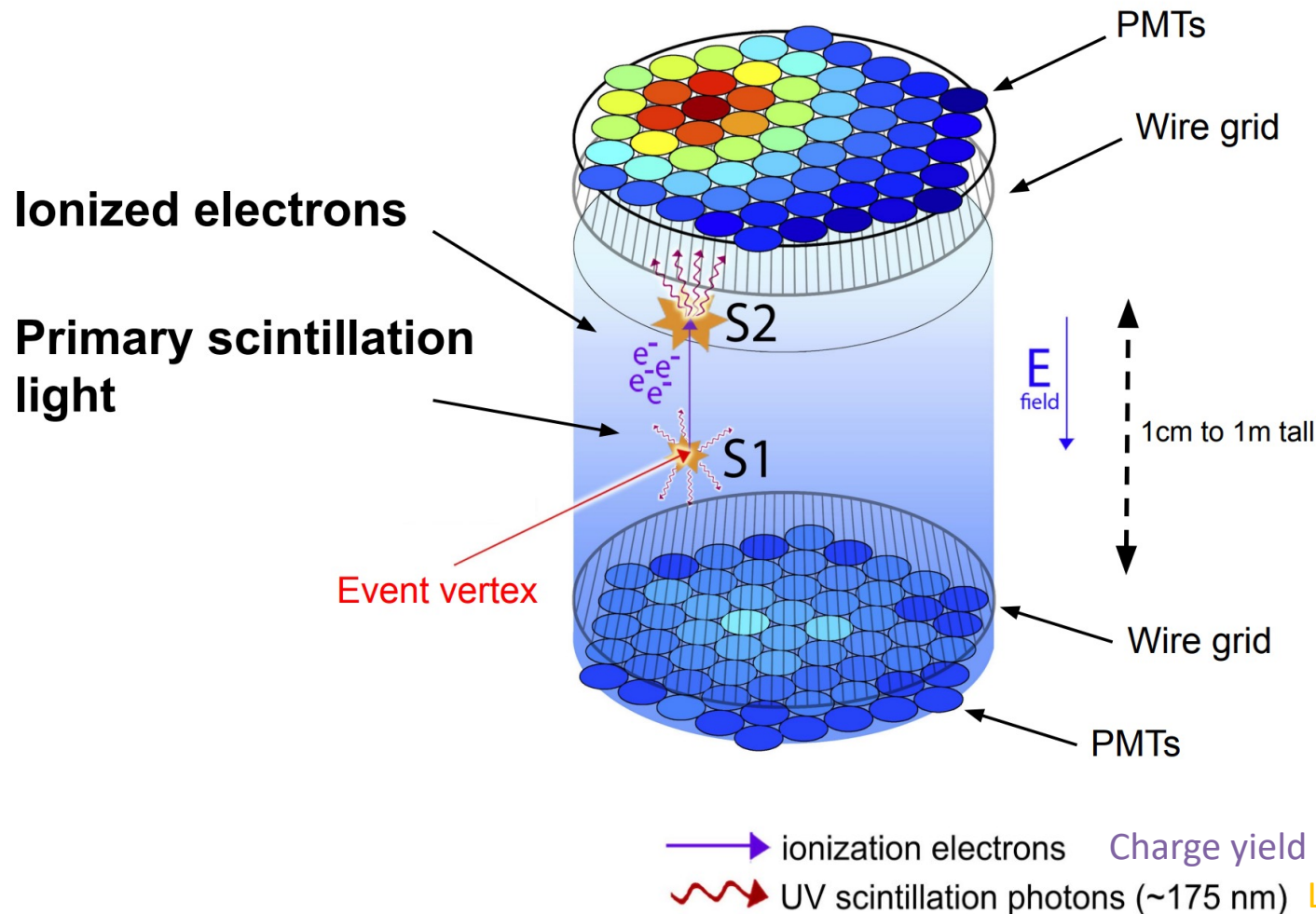
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Bernstein, Mani Tripathi



Detecting particle interactions in Xenon TPCs

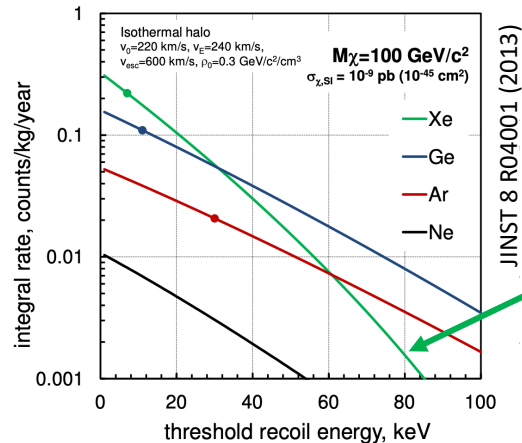
Figure by CH Faham (Brown)



Dark matter searches using Xenon TPCs

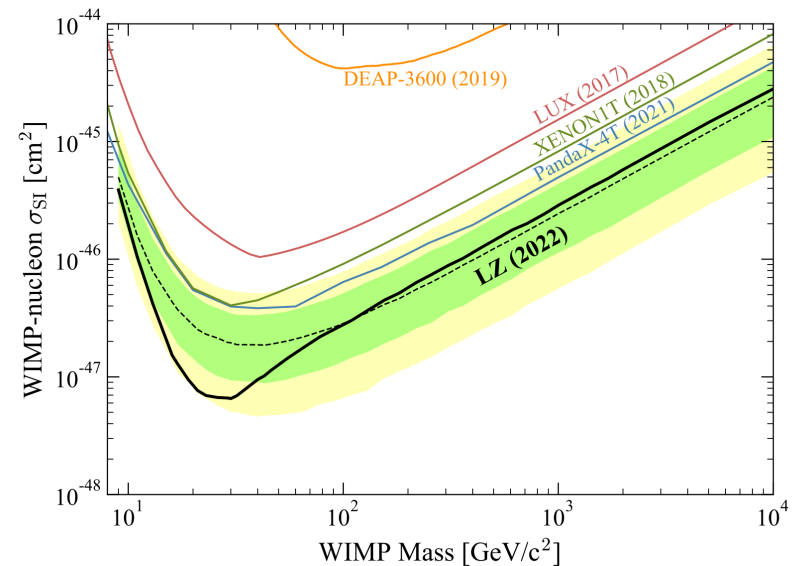
- Most WIMP dark matter searches with xenon TPCs have optimized searches on neutron recoil energy signatures predicted by canonical dark matter models (<100 keV regime)
 - So far, no detection of a WIMP signal in the commonly searched region

WIMP-Nucleon differential count rate for several elements ($\sigma = 10^{-45} \text{ cm}^2$)



Event rate drops considerably for xenon at >100 keV scatters

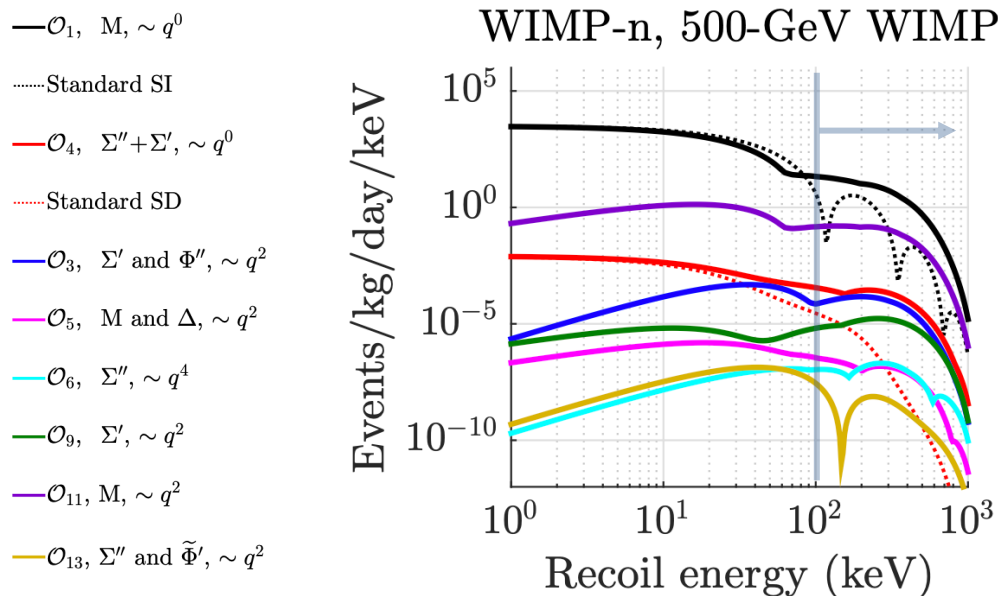
First WIMP search results from the LZ experiment



arXiv 2207.03764 (2022)

Expanding the search window for WIMP recoils

- Can test aspects of models predicting higher energy nuclear recoils
 - Some couplings in effective field theories suppressed at lower recoil energies
 - Inelastic WIMP scatters can result in higher energy signals
- Room to improve sensitivity for higher mass WIMPs in canonical models
 - Merit in searching for signatures of dark matter in less-explored ranges



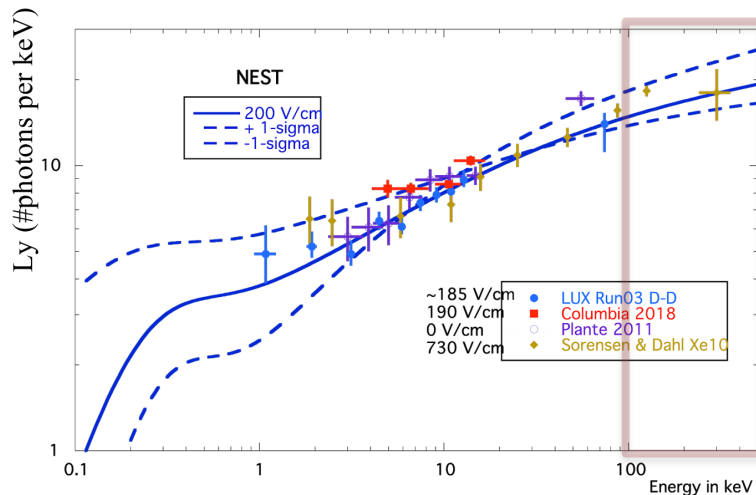
Interaction rates for couplings predicted in effective field theory framework go to higher recoil energies

arXiv:2102.06998

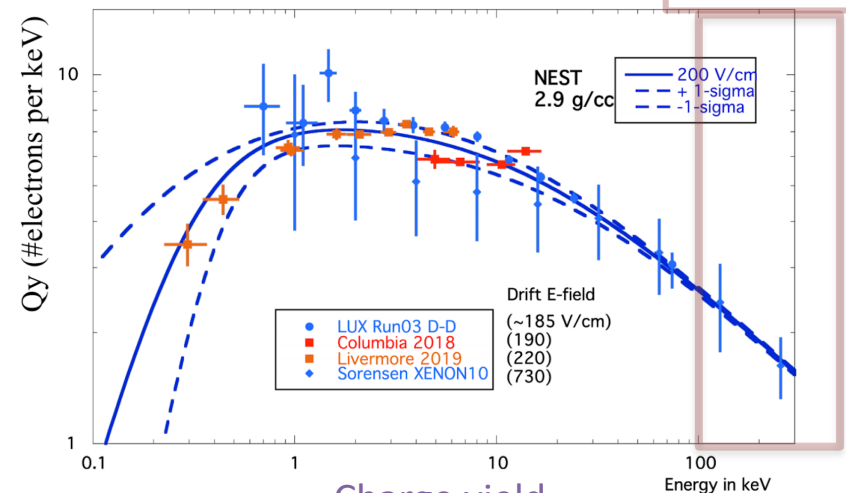
Characterizing light and charge yield of xenon recoils

- Light and charge yield calibrations inform what S1/S2 sizes are expected from nuclear recoils at different energies
- Additional higher energy calibrations (>100 keV) would help reduce uncertainties associated with event reconstruction
- Also need these yields at different drift field strengths to study field dependence

Summary of current light/charge yield measurements in xenon



Light yield

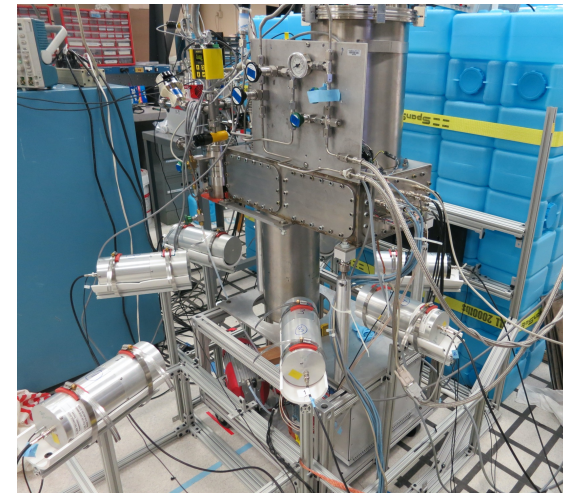
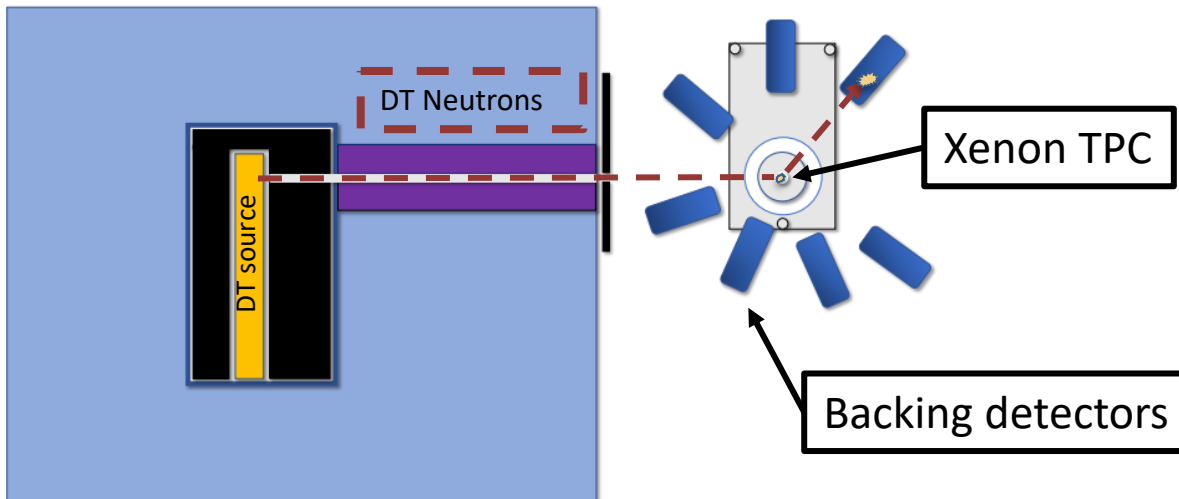


Charge yield

More data needed!

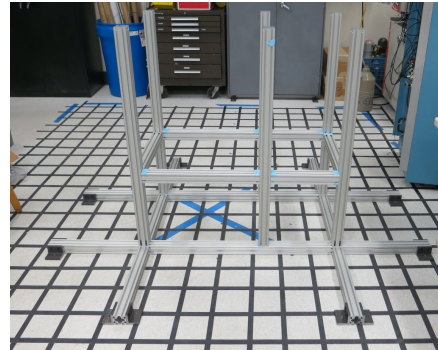
The XeNu DT measurement at LLNL

- Collimated monoenergetic (14.1 MeV) beam used to generate nuclear recoils
 - Energy endpoint for neutron elastic scatters: 430 keV
- Coincident pulse in a Backing Detector (BD) used to reconstruct scattering angle/energy
 - Seven BDs used to tag scatters associated with different recoil energies
- DT source operated at $4.7\text{E}7$ neutrons/sec for a total of 40 hours
 - Neutron recoils characterized at three different drift fields (200, 760, and 2000 V/cm)



Collimator and shielding construction

- DT source (Thermo-scientific P385) emits neutrons in all directions
 - Neutrons hitting backing detectors will result in false xenon-BD coincidence signals
 - Neutrons scattering off surrounding environment form backgrounds for neutrons directly from source
- Custom stand designed for DT source and necessary shielding
 - Lead mounted around source/collimator to reduce mean energy of off-beam neutrons
 - Borated polyethylene and water surrounding source to slow/stop gammas and neutrons
 - Borated slime used to further fill cracks within shielding structure
- Entire stand surrounded with borated water for further neutron/gamma shielding
 - 1" collimator formed using borated polyethylene



DT stand frame, anchored



DT stand frame, constructed and partially shielded



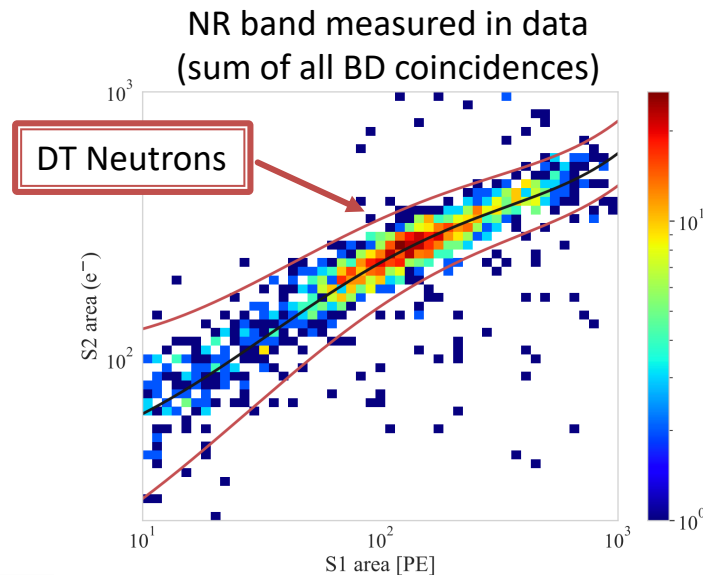
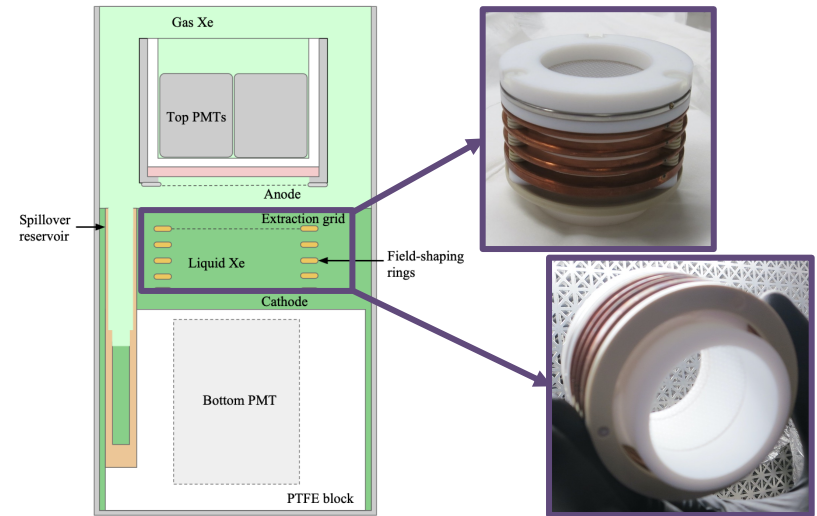
Neutron collimator



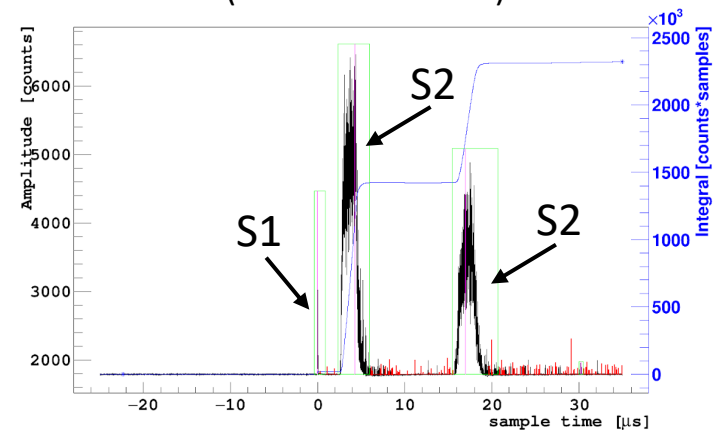
DT source cave

The XeNu Detector

- Dual-phase TPC
 - 150 g active xenon (5 cm diam., 2.5 cm. high)
 - Top: Four 1" Hamamatsu R8520-406 PMTs
 - Bottom: One 2" Hamamatsu R8778 PMT
- High reflectivity PTFE lines active volume to increase S1 light yield
 - Improves NR/ER discrimination, time-of-flight estimation, and precisely measuring the S1 light yield

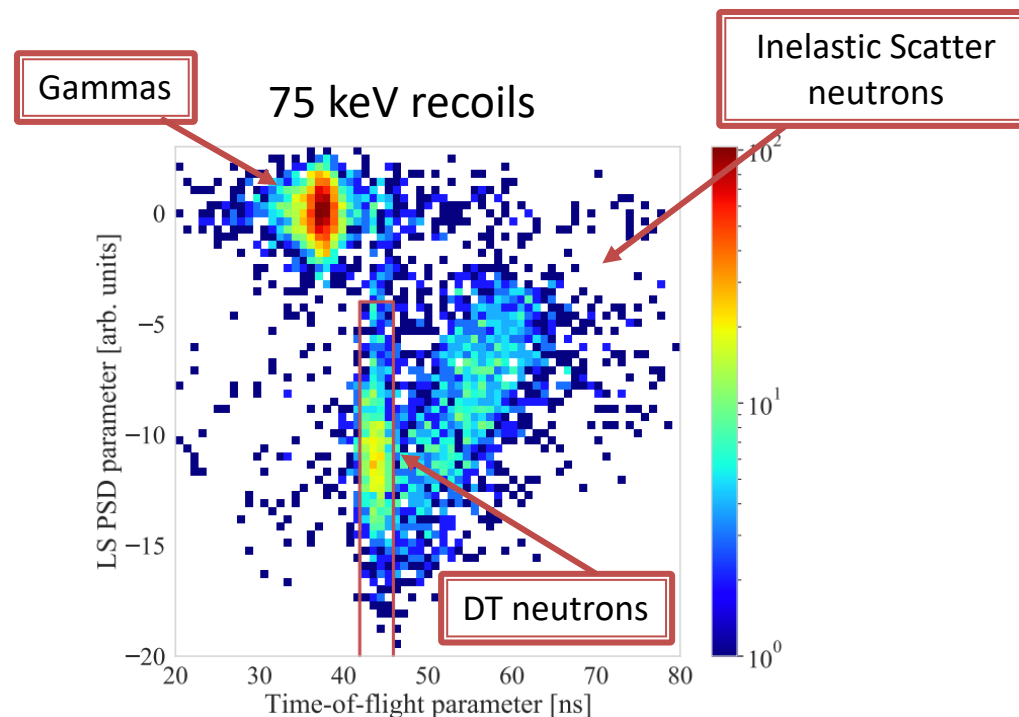
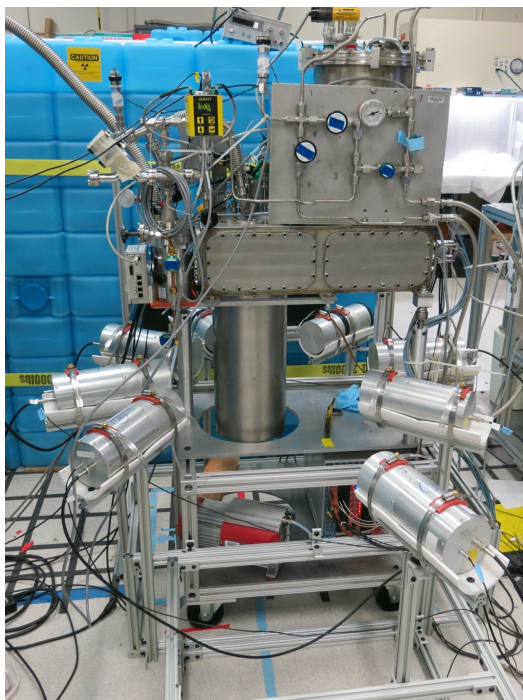


Multi-scatter event in XeNu
(60-Co calibration)



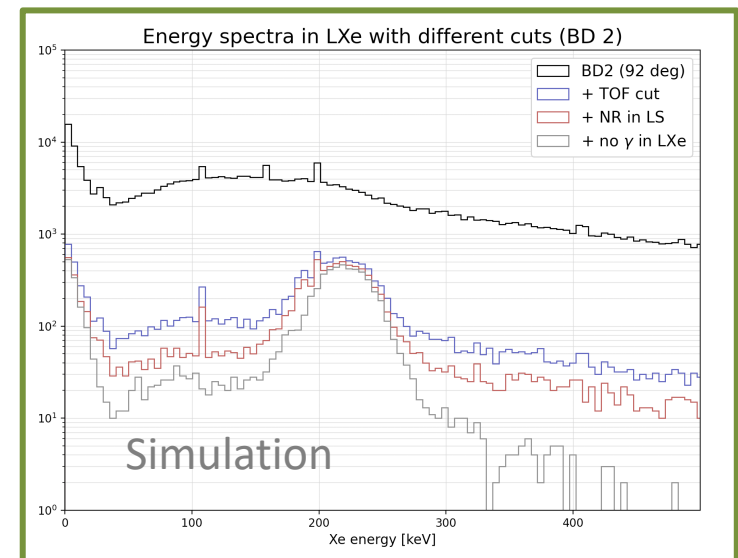
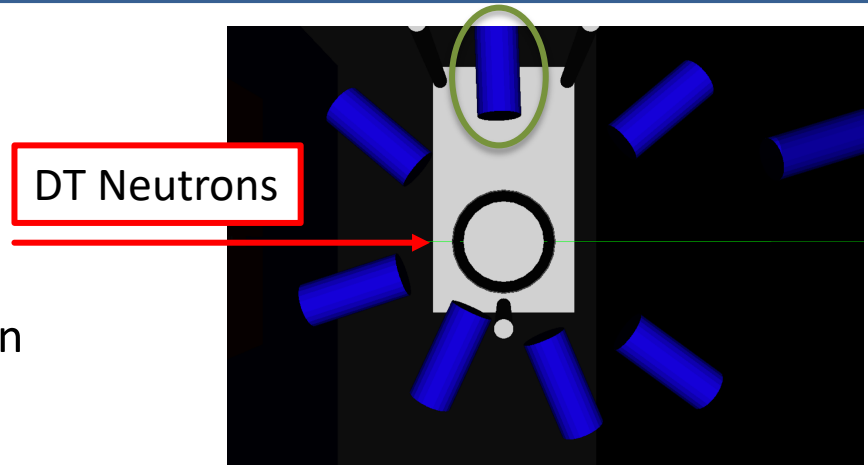
Backing detectors

- 4" diameter backing detectors composed of a single PMT coupled to either EJ-301 or EJ-309 liquid scintillator from Eljen
 - Prompt-to-total ratio used on pulses in BDs to discriminate neutrons and gammas
 - Time-of-flight parameter (S1 and LS pulse time difference) provides further discrimination
- Combination of LS and TPC neutron selection cuts provide a nearly gamma-free neutron elastic scatter dataset



Developing a model for experimental data

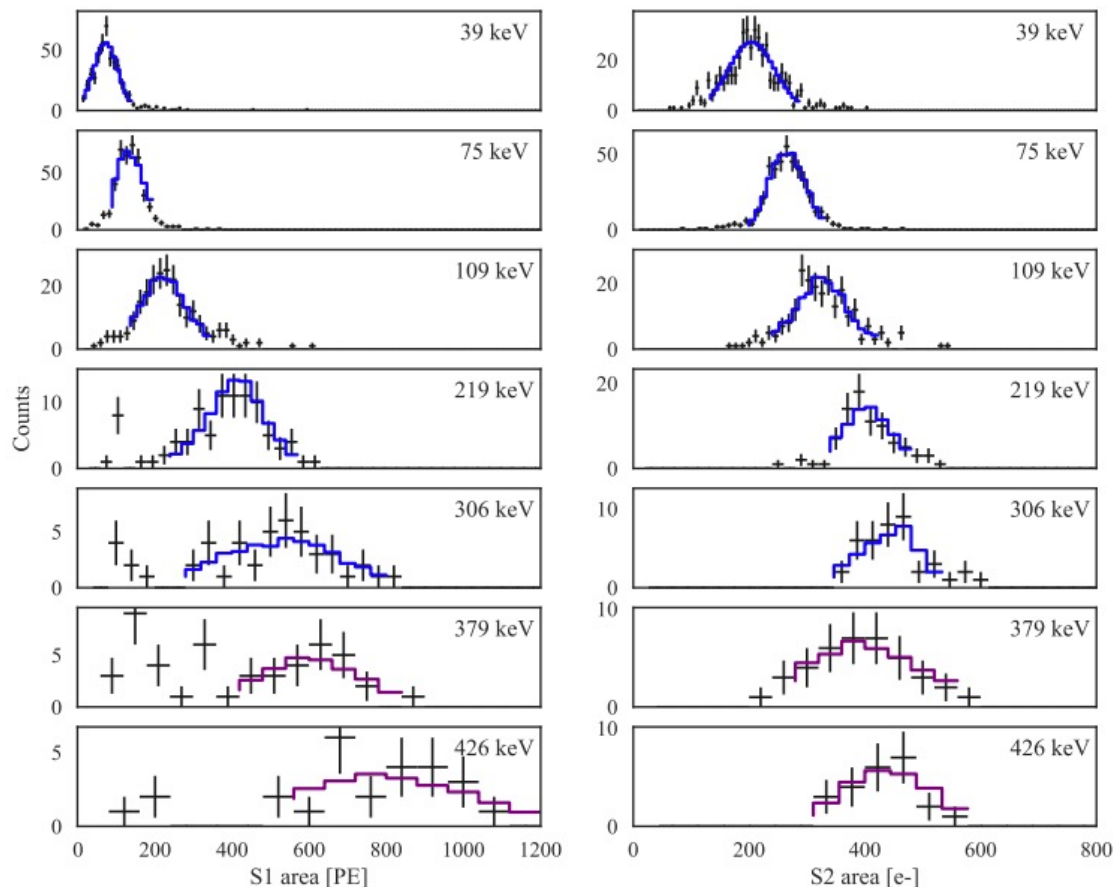
- Full GEANT4-based simulation of detectors, DT source, and shielding
- Preliminary cuts equivalent to those applied in data also applied in simulation
 - Time-of-flight
 - Neutron scatter in backing detector
 - No gamma scatter in xenon TPC
- Detector effects and corrections quantified with calibration data, then applied to simulation using MC techniques to convert to PE/e- counts
 - Light collection efficiency
 - Electron extraction efficiency
 - S1 and S2 drift time dependence corrections



Fits to S1/S2 distributions in data

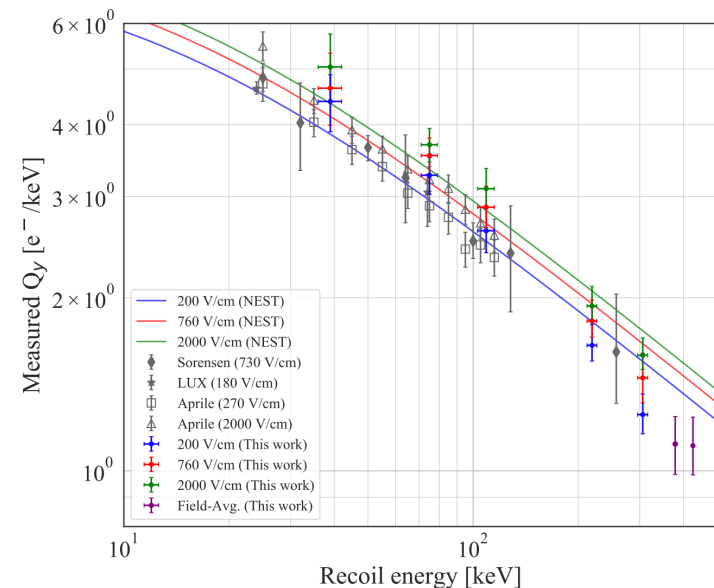
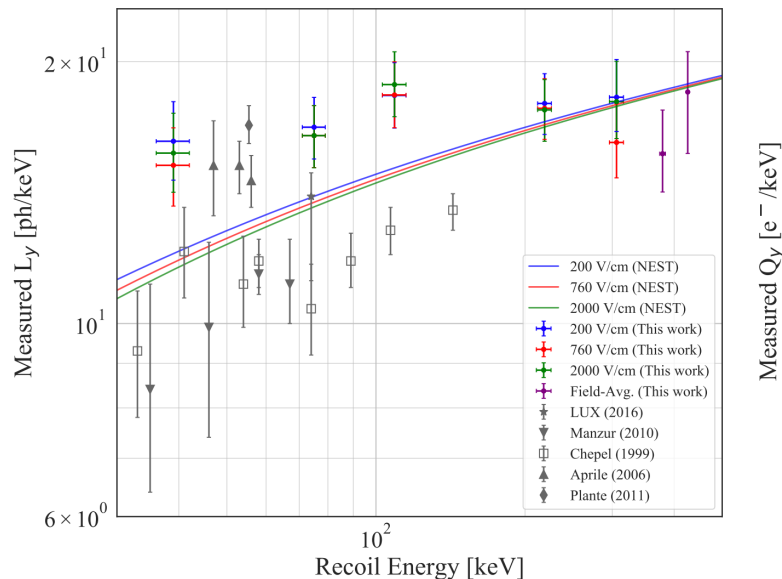
- Model to perform fits to data developed with GEANT4-based simulation of detectors, DT source, and shielding
 - Detector effects and necessary corrections applied to simulated energy distribution to model photon/electron counts
- Light/charge yield values providing the best fit to data estimated using MCMC-based Metropolis-Hastings algorithm
 - Light/charge yield are assumed to locally be a Power law shape near the recoil energy peak
- For higher energies, much lower statistics in peak than expected/predicted by Geant4
 - Due to low statistics, field-averaged values are estimated for the largest recoil energy datasets

Best fits for 2000 V/cm drift field dataset



Preliminary light/charge yield estimates

- Measured charge and light yields shown in comparison to past measurements and predictions from NESTpy v2.3.6
 - Higher values than NEST at <200 keV recoil energies, lower than NEST above 200 keV
- Field dependence of data generally in agreement with predictions in NEST
 - Inconclusive field dependence for light yield due to uncertainties on measurement
 - Charge yield increases as the drift field strength increases



Conclusions

- Nucleon recoil calibrations are needed for Xenon at energies >100 keV to help improve sensitivity to larger energy scattering signatures in dark matter
- A measurement of light/charge yields for nuclear recoils up to 426 keV in energy has been completed
 - Field-dependent yields measured up to 306 keV
 - Field-averaged yields reported at 379 keV and 426 keV due to lower-than-anticipated statistics
- Light/charge yield measurements will be incorporated into NEST following final publication of results



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Back-up slides



Neutron elastic scatter event selection

- Several preliminary cuts applied to select neutron elastic scatters
 - Time of flight, LS pulse shape discrimination, Xenon TPC S1/S2 discrimination
- Cuts aggressively remove majority of background gammas and accidentals, providing a pure sample of neutron elastic scatters

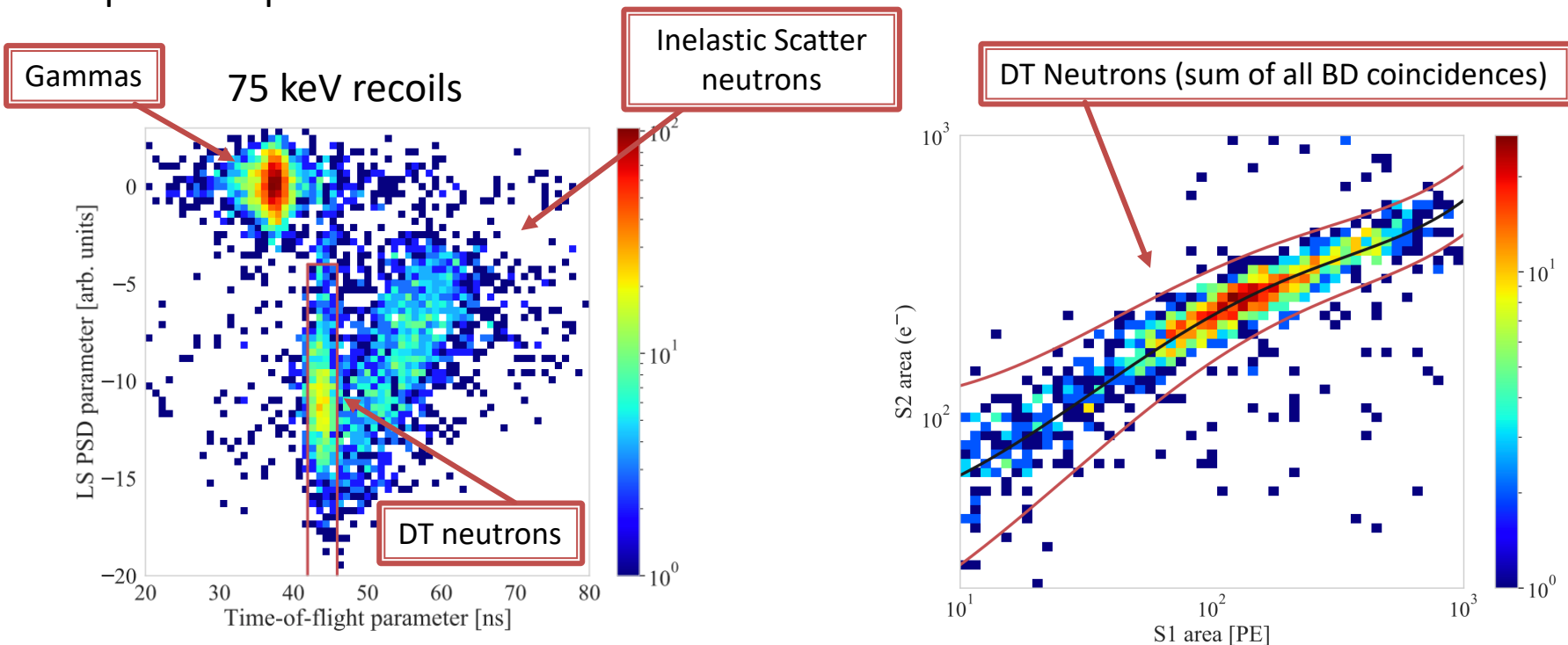


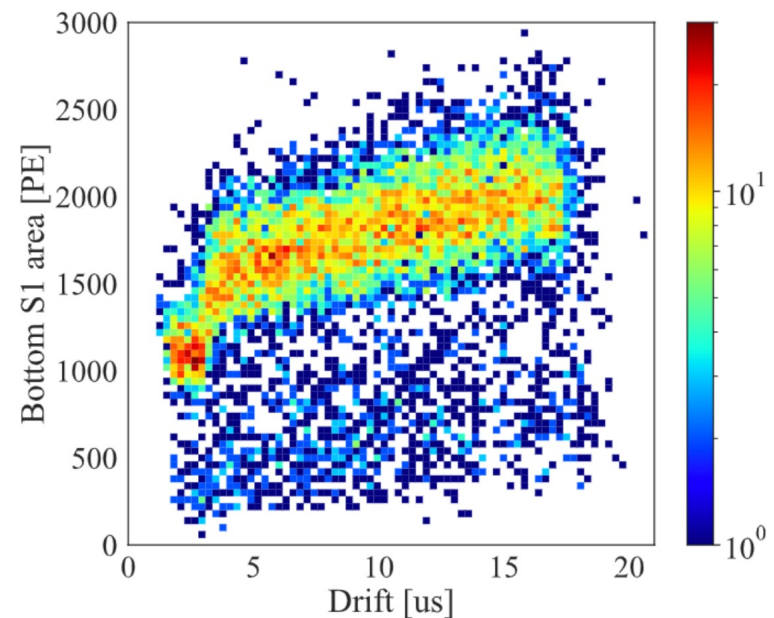
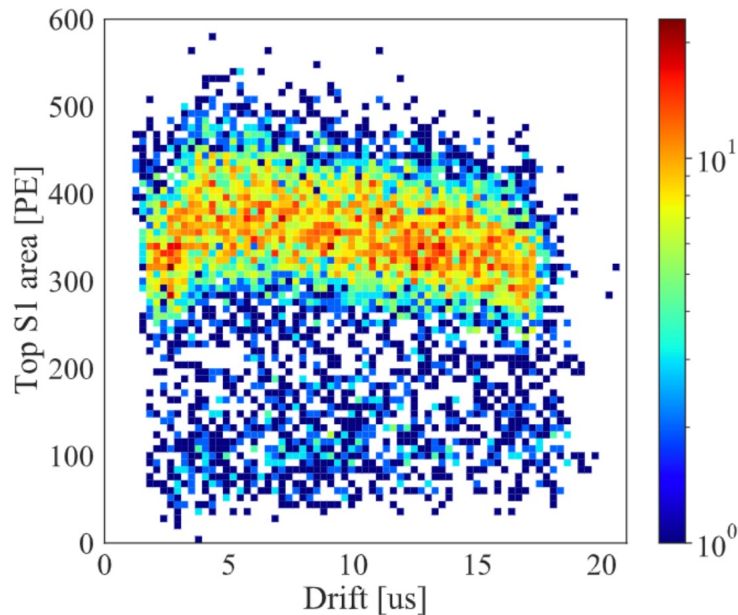
Table of measured values in experiment

- TOF systematic quantifies uncertainty due to (n,2n) contamination of primary DT neutron peak
 - Re-evaluate fits using TOF windows on both sides of the primary DT neutron peak ([-2,0] ns and [0,+2] ns around TOF mean)
- LCE systematic quantified via uncertainty on g1 fit extracted from Doke plot
- EEE systematic uncertainty evaluated for XeNu in previous measurement

scattering angle (deg.)	recoil energy (keV)	Qy					Ly				
		0.2 kV/cm	0.76 kV/cm	2.0 kV/cm	Field avg.	TOF sys.	0.2 kV/cm	0.76 kV/cm	2.0 kV/cm	Field avg.	TOF sys.
36 ± 1	39 ± 3	4.39 ^{+0.23} _{-0.33}	4.63 ^{+0.52} _{-0.50}	5.04 ^{+0.50} _{-0.48}	-	+5.3% -2.7%	16.2 ^{+0.8} _{-0.7}	15.2 ^{+0.5} _{-0.8}	15.7 ^{+0.8} _{-0.7}	-	+5.5% -2.3%
50 ± 1	75 ± 4	3.26 ^{+0.16} _{-0.16}	3.54 ^{+0.17} _{-0.17}	3.69 ^{+0.14} _{-0.14}	-	+1.6% -1.4%	16.8 ^{+0.2} _{-0.2}	16.4 ^{+0.2} _{-0.2}	16.4 ^{+0.3} _{-0.3}	-	+1.9% -1.3%
67 ± 2	109 ± 6	2.62 ^{+0.16} _{-0.16}	2.87 ^{+0.15} _{-0.15}	3.10 ^{+0.15} _{-0.15}	-	+4.3% -2.3%	18.3 ^{+0.5} _{-0.4}	18.3 ^{+0.5} _{-0.5}	18.8 ^{+0.5} _{-0.4}	-	+3.5% -0.5%
92 ± 2	219 ± 7	1.66 ^{+0.08} _{-0.08}	1.82 ^{+0.09} _{-0.10}	1.93 ^{+0.08} _{-0.08}	-	+6.4% -1.8%	17.9 ^{+0.4} _{-0.4}	17.7 ^{+0.3} _{-0.4}	17.6 ^{+0.5} _{-0.4}	-	+2.2% -0.1%
115 ± 3	306 ± 10	1.25 ^{+0.08} _{-0.08}	1.45 ^{+0.13} _{-0.12}	1.59 ^{+0.07} _{-0.07}	-	+2.0% -1.2%	18.2 ^{+0.6} _{-0.5}	16.1 ^{+0.7} _{-0.6}	18.0 ^{+1.0} _{-0.8}	-	+6.4% -3.0%
140 ± 2	379 ± 5	-	-	-	1.12 ^{+0.14} _{-0.14}	+3.1% -2.0%	-	-	-	15.7 ^{+0.9} _{-0.8}	+8.0% -3.1%
162 ± 2	426 ± 2	-	-	-	1.11 ^{+0.14} _{-0.13}	+4.6% -1.2%	-	-	-	18.5 ^{+1.3} _{-1.5}	+4.9% -10.0%
LCE systematic unc.		-					±7.4%				
EEE systematic unc.		±3.0%					-				

Drift time correction applied to S1 data

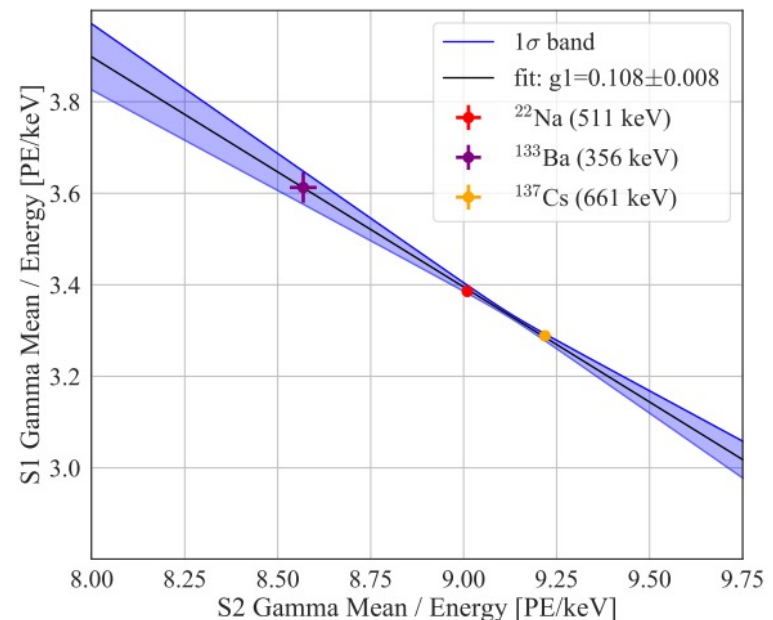
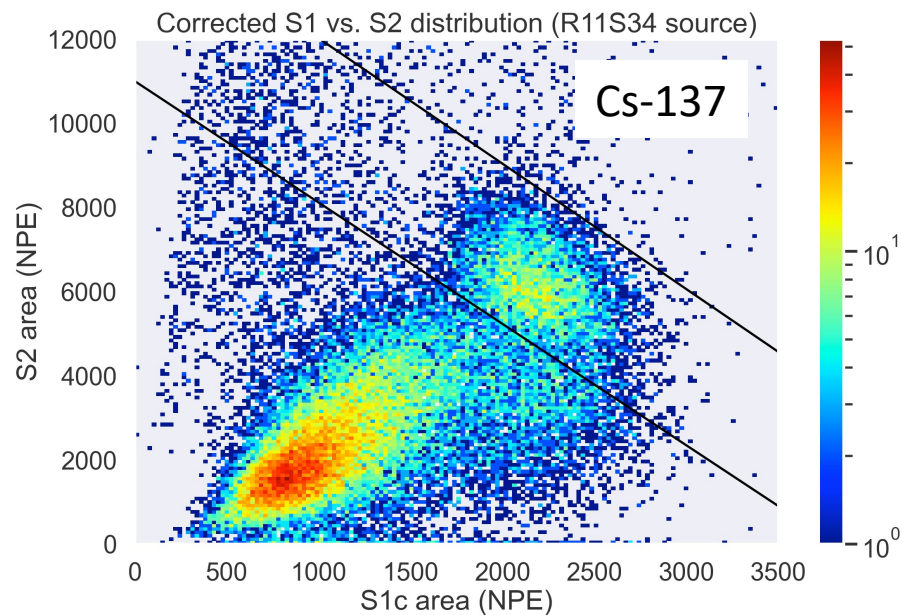
- Collection efficiency of S1 light for top/bottom PMTs is interaction depth-dependent
- Correction applied to top/bottom PMTs to correct S1 area relative to center of TPC



Light Collection Efficiency Measurement

- Fit a 2D Gaussian to the endpoint of several calibration sources
- Then, fit a line on the S1/energy vs. S2/energy space and extract light yield with a line fit

$$E = W(n_{\text{ph}} + n_e) = W_{e/\gamma} \left(\frac{S1}{g1} + \frac{S2}{g2} \right)$$



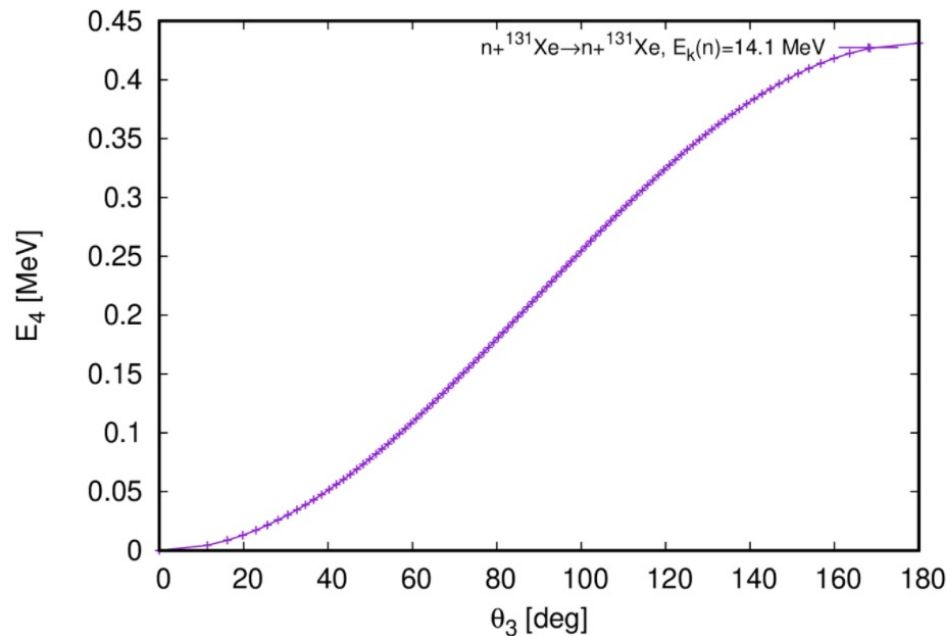
Neutron-Xenon elastic scattering spectrum

- Expected xenon recoil energies as a function of scattering angle
 - Energy endpoint at approximately 425 keV

Reaction summary for $n+^{131}\text{Xe}\rightarrow n+^{131}\text{Xe}$, $E_k(n)=14.1$ MeV

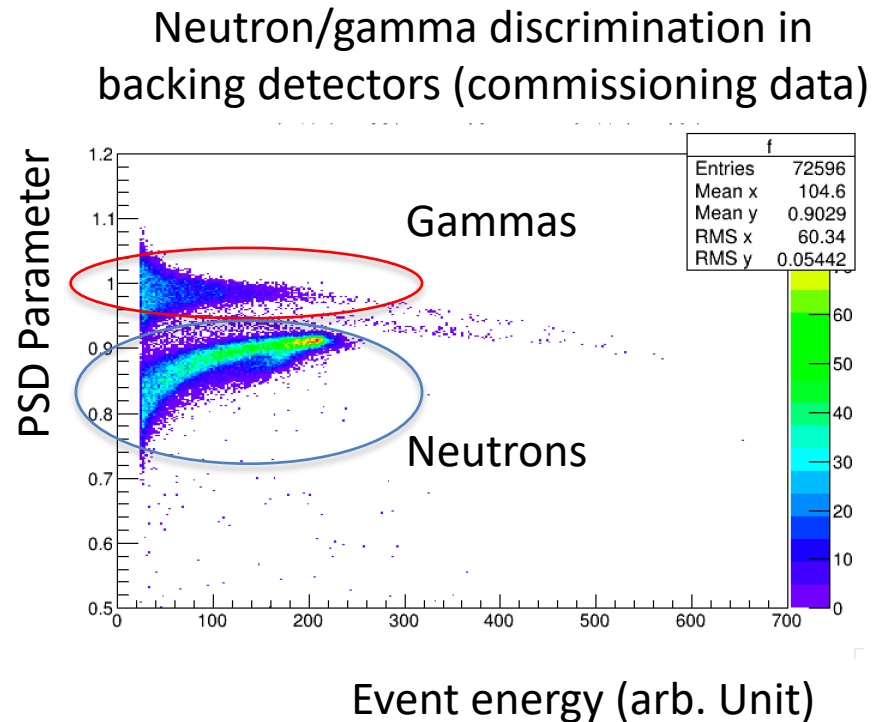
- The maximum n energy is 14.1 MeV. The minimum n energy is 13.669 MeV.
- The maximum ^{131}Xe energy is 0.431 MeV. The minimum ^{131}Xe energy is 0 MeV. The maximum ^{131}Xe angle is 90 degrees.

KE_4 as a function of θ_3 :



Selecting neutron candidate events

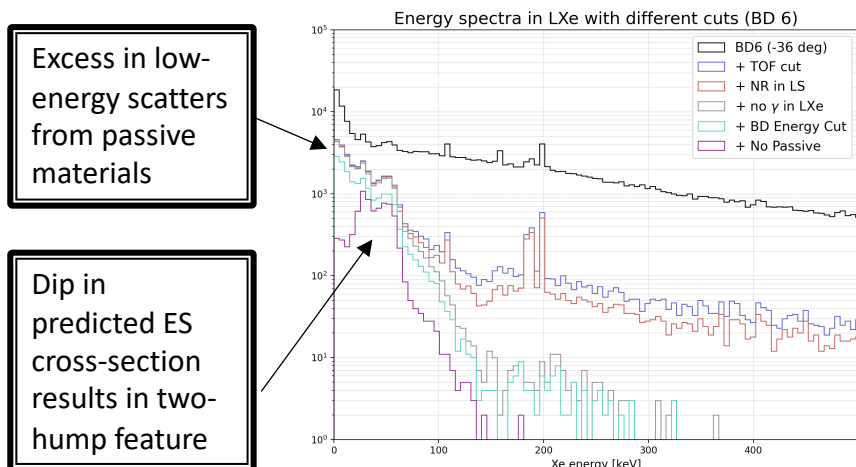
- Several handles for discriminating DT neutron events from backgrounds
 - S1/S2 ratio in Xenon TPC
 - Pulse discrimination in S1/S2 pulses
 - Pulse discrimination in backing detectors
 - Time-of-flight from Xenon TPC to backing detector
- Clear neutron/gamma separation apparent with PSD in backing detectors
- S1/S2 separation power with new reflector will be quantified prior to full data-taking run



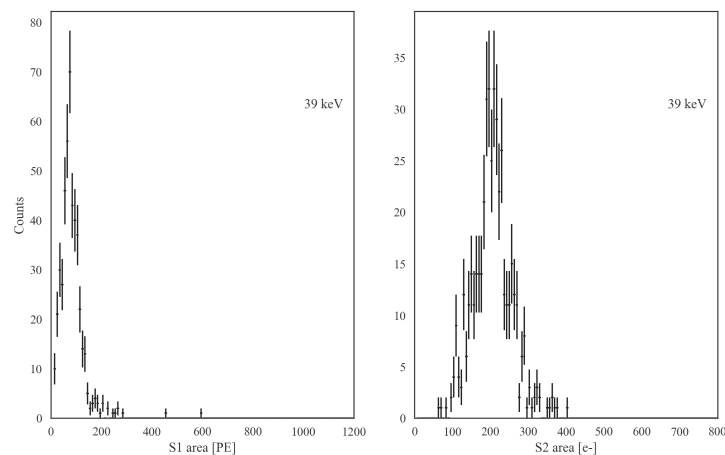
Uncertainties in lowest recoil energy

- Lowest recoil energy's Geant4-based model generally did not produce good fits to the detector data
 - Detector was placed at a peak in the inelastic scattering cross-section as predicted by Geant4
 - This corresponds to a trough in the elastic scattering cross-section, producing two-peak shape in simulation
 - Highly variable cross-section region, and current prediction in ENDF is calculated (not informed by DT data)
- Light/charge yield reported in paper instead evaluated assuming a Gaussian shape, with light/charge yield calculated directly
 - Difference in light/charge yield fits propagated as a systematic uncertainty in final results reported in table

Simulated energy distribution, lowest angle LS coincidence scatters



S1/S2 distributions, 2000 V/cm data, lowest angle LS coincidence scatters



Excess in low-energy scatters in simulation

- Larger counts in low-energy scatters observed in simulation but not in data
- Excess appears associated with neutrons which undergo scatters in passive detector materials prior to scatter in xenon
 - Majority of scatters occur on PTFE or field rings
- Several possibilities for excess in simulation relative to data
 - Uncertainties in cross-section for DT neutrons on PTFE and copper in field ring

