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

Speaker: Teal Pershing (LLNL)

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Contributing authors: Daniel Naim, Brian Lenardo, Jingke Xu, James Kingston, Eli Mizrachi, Vladimir Mozin, Phillip Kerr, Sergey Pereverzev, Adam Bernstein, Mani Tripathi

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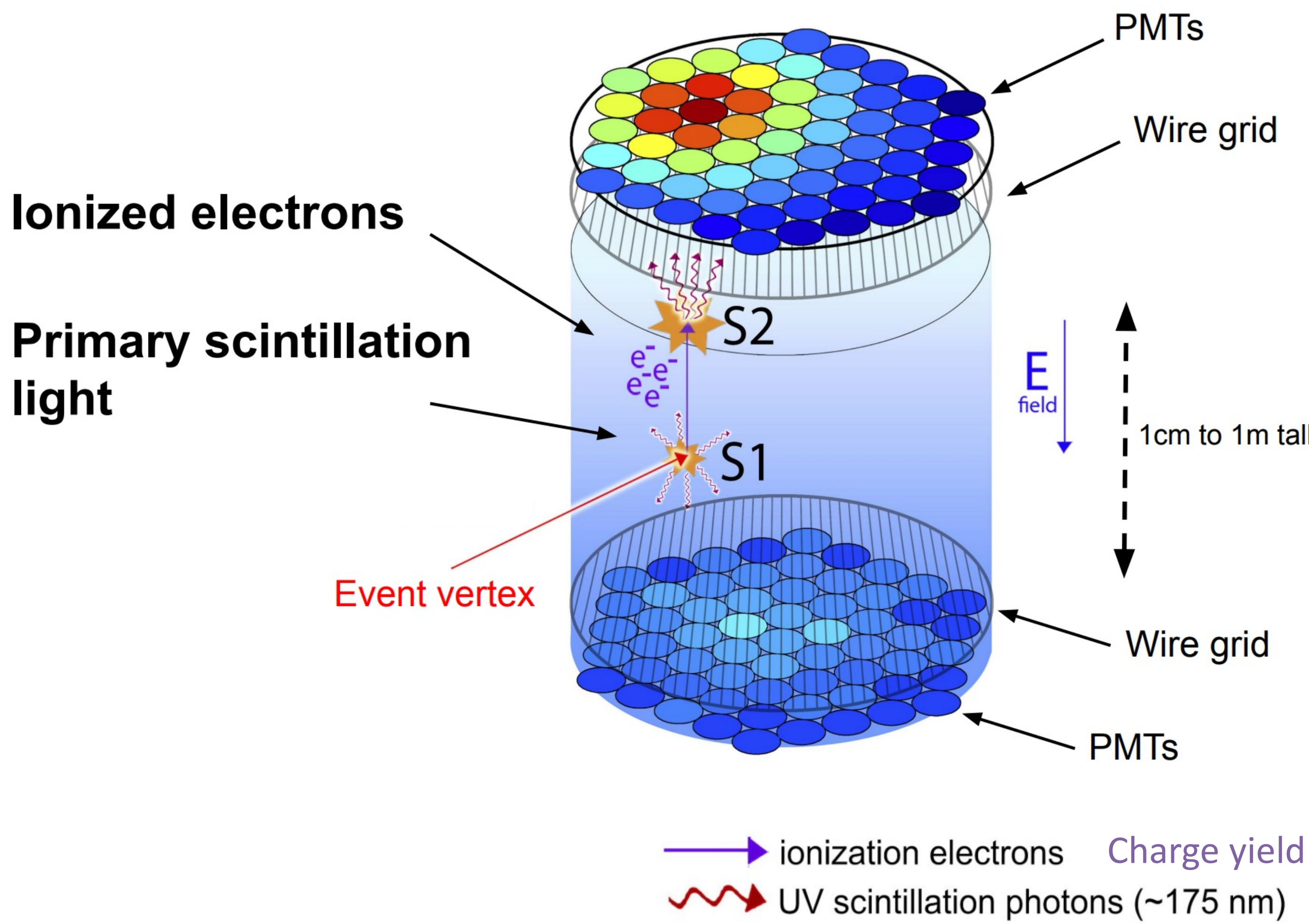
# Detecting particle interactions in Xenon TPCs

Figure by CH Faham (Brown)



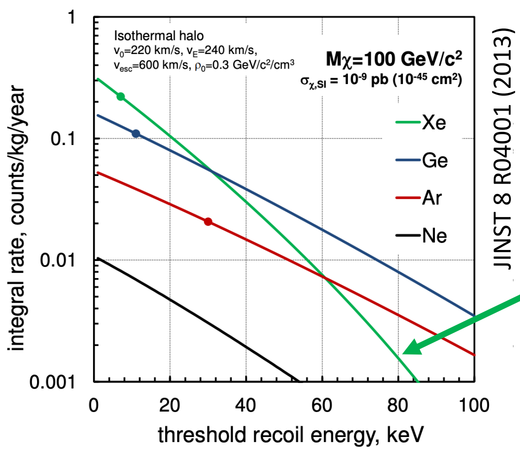

Charge yield

Light yield

# Dark matter searches using Xenon TPCs

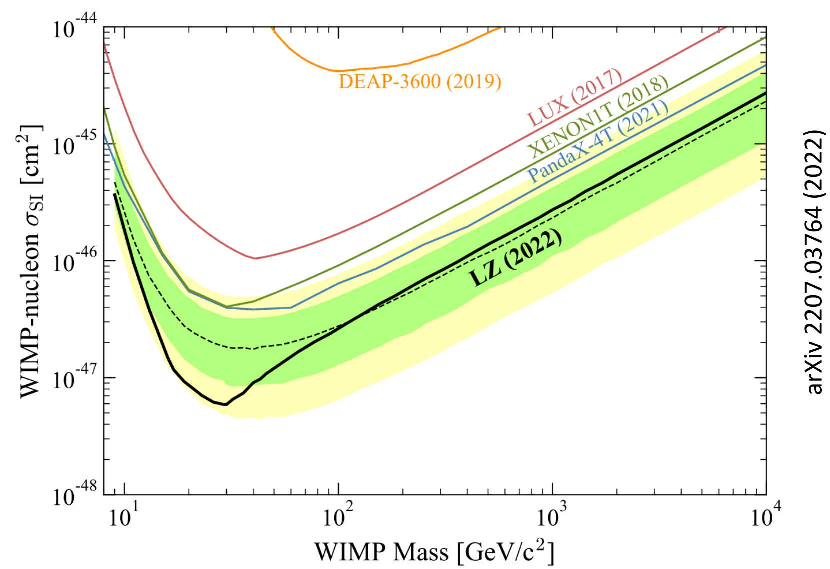
- Most WIMP dark matter searches with xenon TPCs have optimized searches on neutron recoil energy signatures predicted by canonical dark matter models (<100 keV regime)
  - So far, no detection of a WIMP signal in the commonly searched region

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



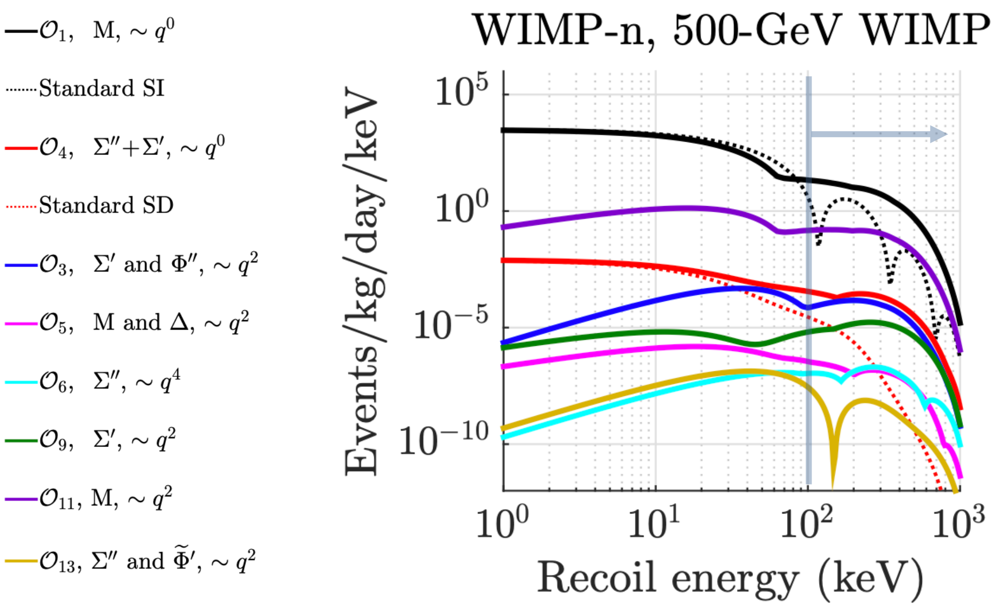

Event rate drops considerably for xenon at >100 keV scatters

First WIMP search results from the LZ experiment



# 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




arXiv:2102.06998

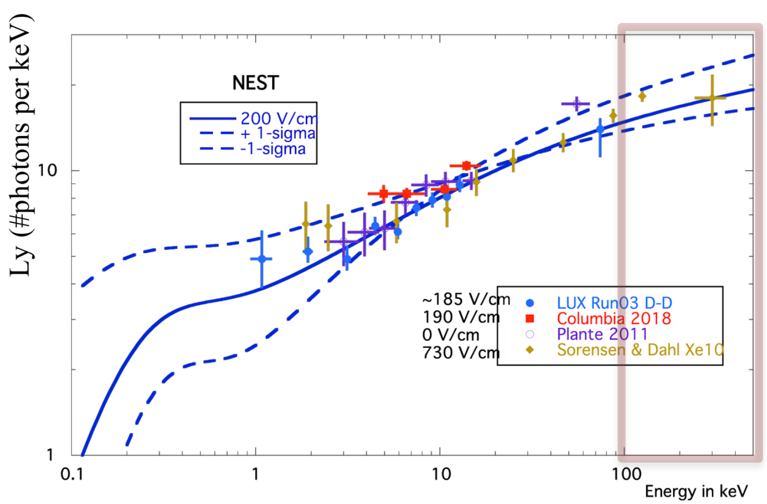
Interaction rates for couplings predicted in effective field theory framework go to higher recoil energies

# 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

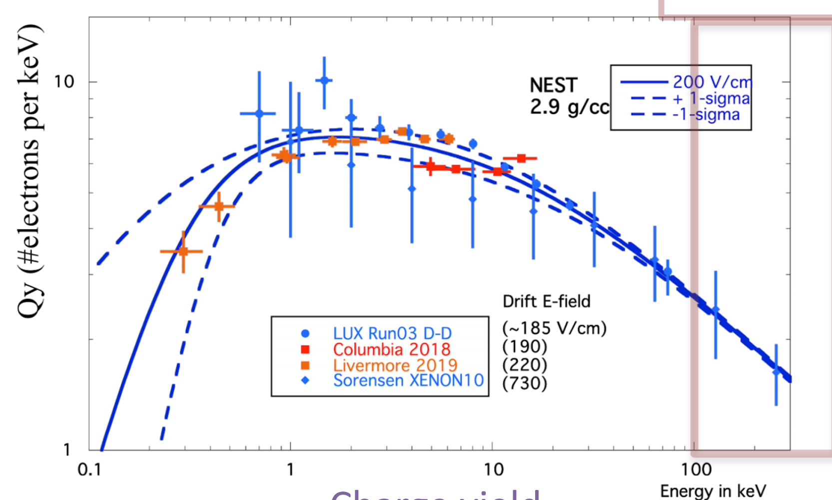
Summary of current light/charge yield measurements in xenon

More data needed!




J. Balajthy, CPAD 2019

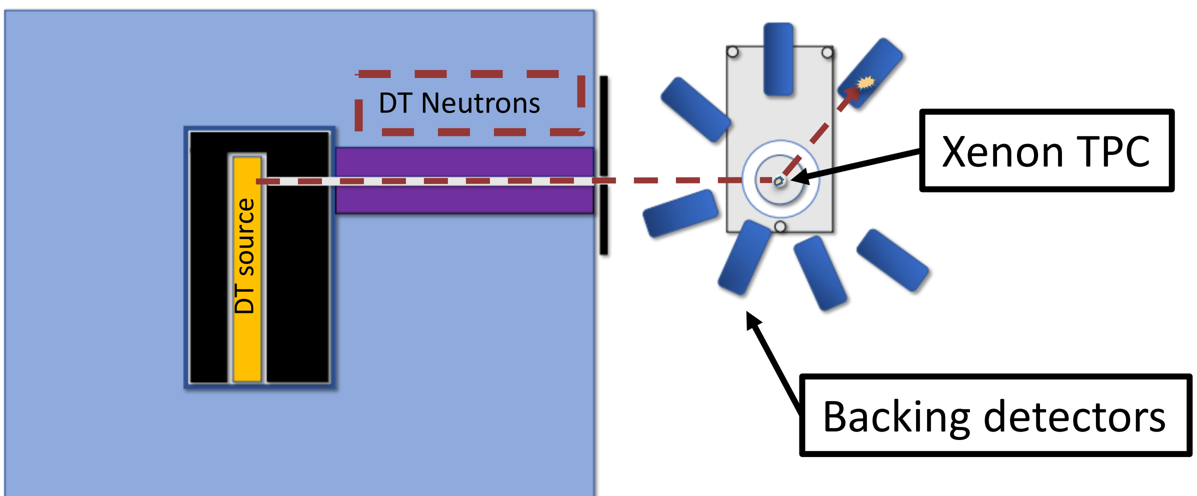
Light yield

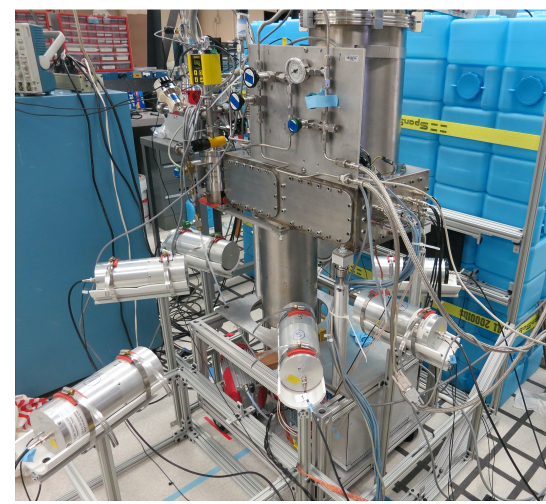



Charge yield

# The XeNu DT measurement at LLNL

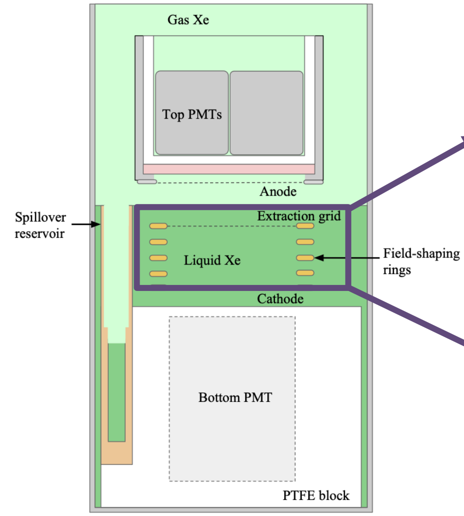
- Collimated monoenergetic (14.1 MeV) beam used to generate nuclear recoils
  - Energy endpoint for neutron elastic scatters: 430 keV
- Coincident pulse in a Backing Detector (BD) used to reconstruct scattering angle/energy
  - Seven BDs used to tag scatters associated with different recoil energies
- DT source operated at 4.7E7 neutrons/sec for a total of 40 hours
  - Neutron recoils characterized at three different drift fields

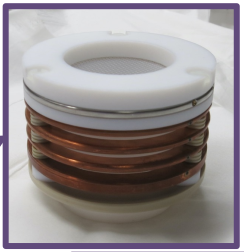


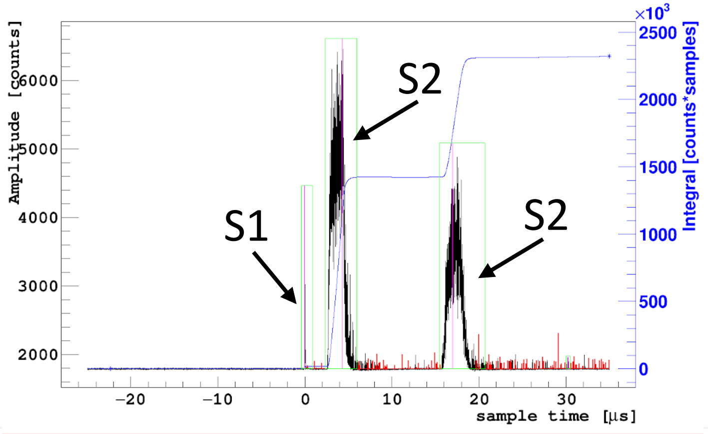
# The XeNu Detector

- 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 yield
- Field in electron drift and extraction fields are independently tunable
  - Data collected at three drift fields to characterize field dependence of yields
    - 200 V/cm
    - 760 V/cm
    - 2000 V/cm



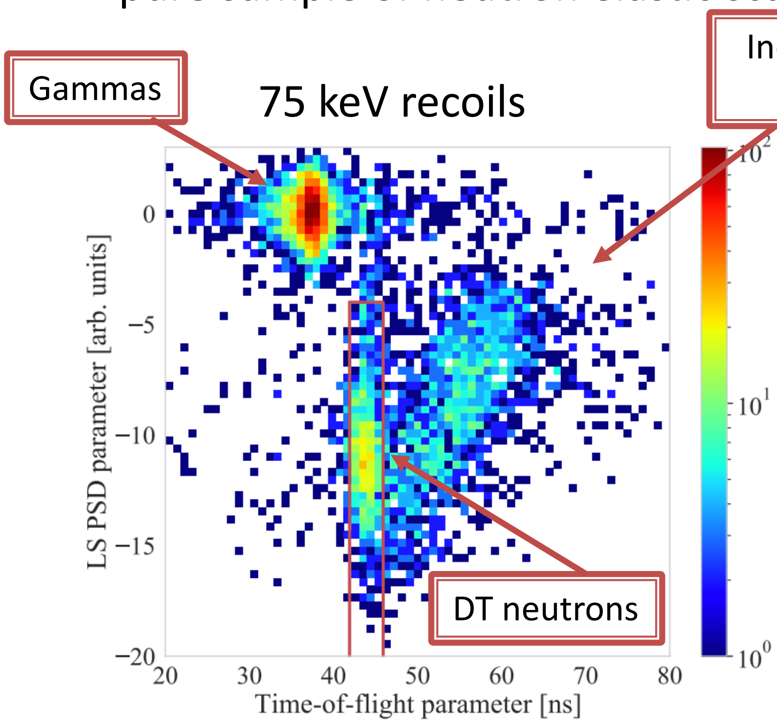



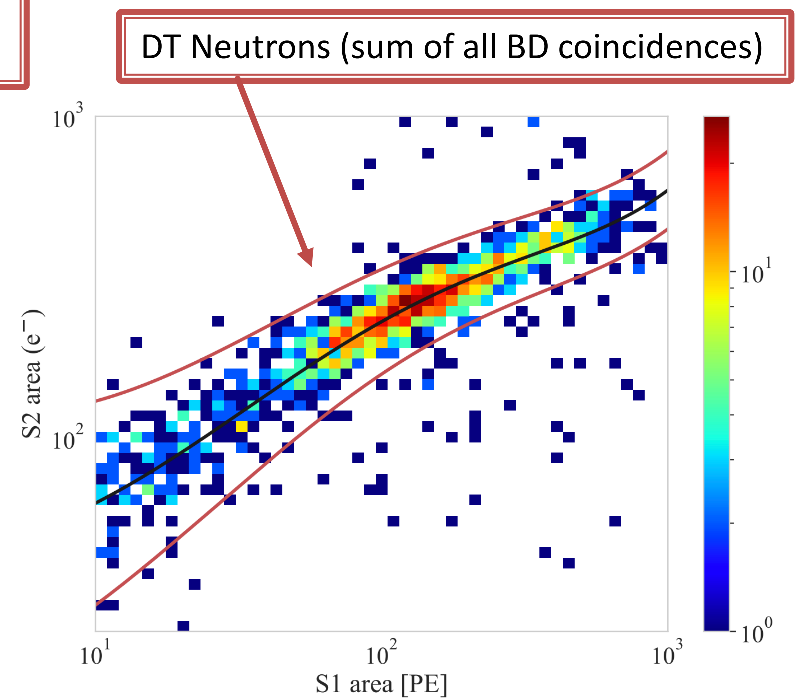
Multi-scatter event in XeNeu
(60-Co calibration)



# 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

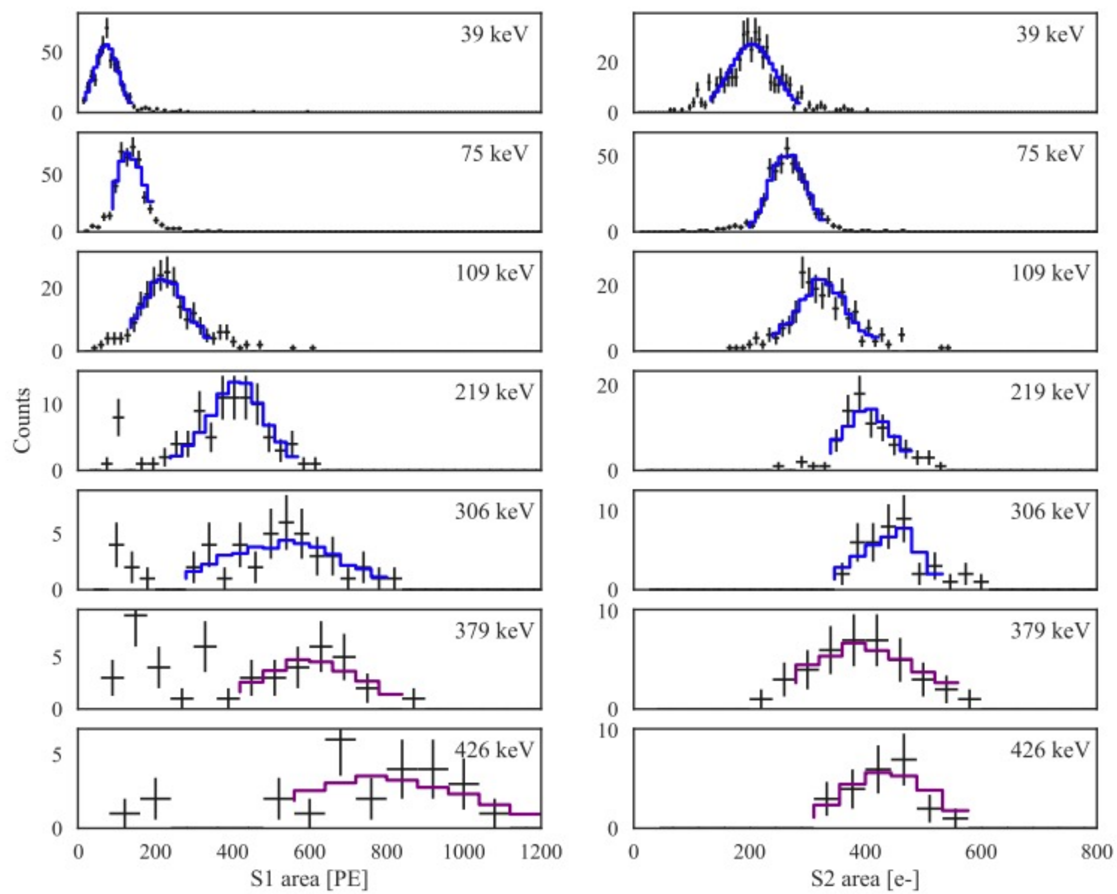


# Fits to S1/S2 distributions in data

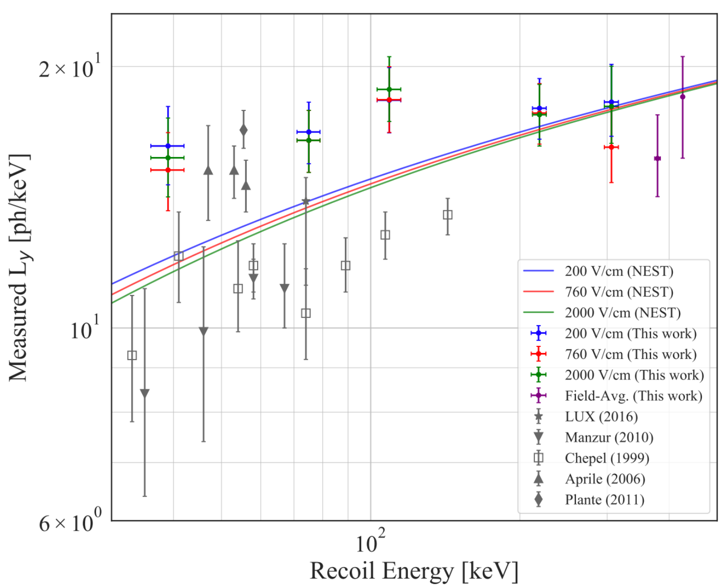
- Model to perform fits to data developed with GEANT4-based simulation of detectors, DT source, and shielding
  - Detector effects and necessary corrections applied to simulated energy distribution to model photon/electron counts
- Light/charge yield values providing the best fit to data estimated using 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

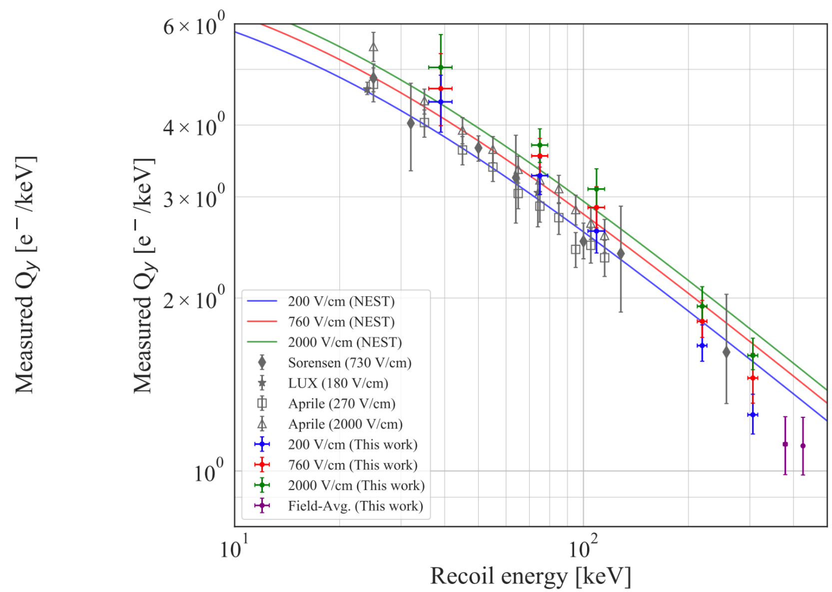
Best fits for 2000 V/cm drift field dataset



# 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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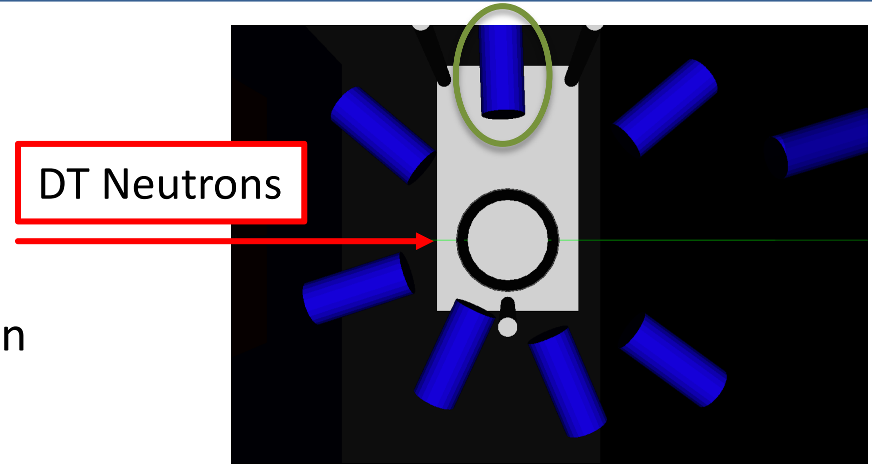
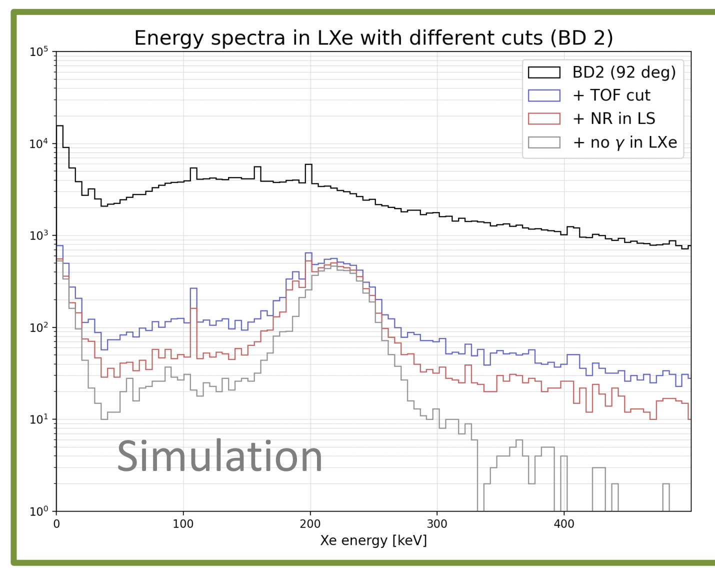
# Back-up slides

# 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



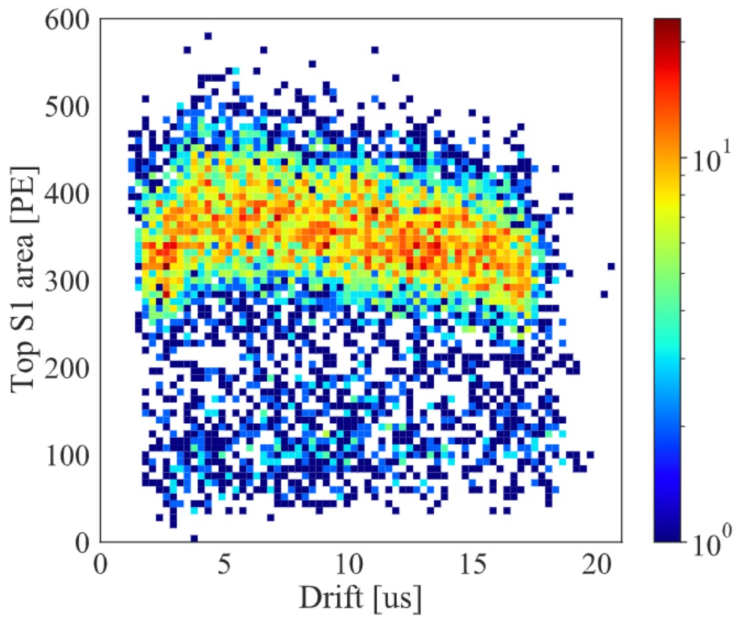
# Table of measured values in experiment

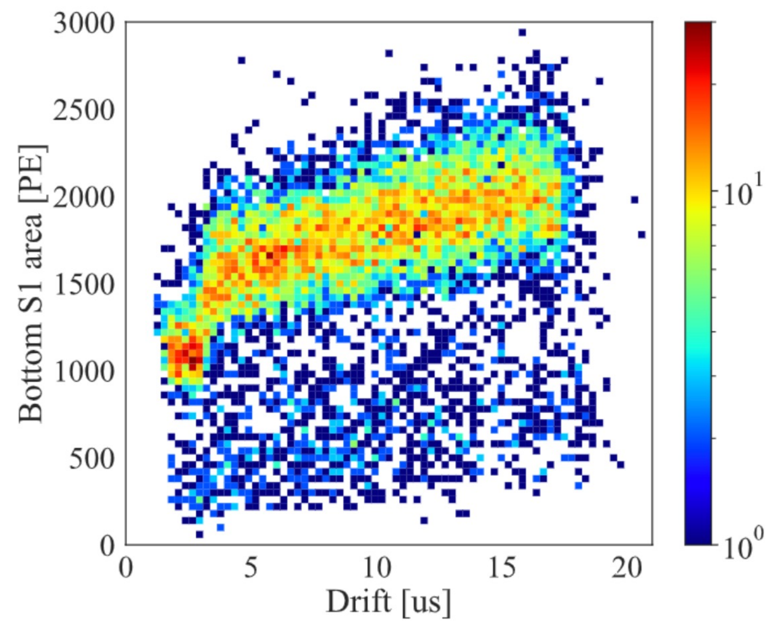
- TOF systematic quantifies uncertainty due to (n,2n) contamination of primary DT neutron peak
  - Re-evaluate fits using TOF windows on both sides of the primary DT neutron peak ([-2,0] ns and [0,+2] ns around TOF mean)
- LCE systematic quantified via uncertainty on g1 fit extracted from Doke plot
- 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. |
| $36 \pm 1$ | $39 \pm 3$ | $4.39^{+0.23}_{-0.33}$ | $4.63^{+0.52}_{-0.50}$ | $5.04^{+0.50}_{-0.48}$ | - | $^{+5.3\%}_{-2.7\%}$ | $16.2^{+0.8}_{-0.7}$ | $15.2^{+0.5}_{-0.8}$ | $15.7^{+0.8}_{-0.7}$ | - | $^{+5.5\%}_{-2.3\%}$ |
| $50 \pm 1$ | $75 \pm 4$ | $3.26^{+0.16}_{-0.16}$ | $3.54^{+0.17}_{-0.17}$ | $3.69^{+0.14}_{-0.14}$ | - | $^{+1.6\%}_{-1.4\%}$ | $16.8^{+0.2}_{-0.2}$ | $16.4^{+0.2}_{-0.2}$ | $16.4^{+0.3}_{-0.3}$ | - | $^{+1.9\%}_{-1.3\%}$ |
| $67 \pm 2$ | $109 \pm 6$ | $2.62^{+0.16}_{-0.16}$ | $2.87^{+0.15}_{-0.15}$ | $3.10^{+0.15}_{-0.15}$ | - | $^{+4.3\%}_{-2.3\%}$ | $18.3^{+0.5}_{-0.4}$ | $18.3^{+0.5}_{-0.5}$ | $18.8^{+0.5}_{-0.4}$ | - | $^{+3.5\%}_{-0.5\%}$ |
| $92 \pm 2$ | $219 \pm 7$ | $1.66^{+0.08}_{-0.08}$ | $1.82^{+0.09}_{-0.10}$ | $1.93^{+0.08}_{-0.08}$ | - | $^{+6.4\%}_{-1.8\%}$ | $17.9^{+0.4}_{-0.4}$ | $17.7^{+0.3}_{-0.4}$ | $17.6^{+0.5}_{-0.4}$ | - | $^{+2.2\%}_{-0.1\%}$ |
| $115 \pm 3$ | $306 \pm 10$ | $1.25^{+0.08}_{-0.08}$ | $1.45^{+0.13}_{-0.12}$ | $1.59^{+0.07}_{-0.07}$ | - | $^{+2.0\%}_{-1.2\%}$ | $18.2^{+0.6}_{-0.5}$ | $16.1^{+0.7}_{-0.6}$ | $18.0^{+1.0}_{-0.8}$ | - | $^{+6.4\%}_{-3.0\%}$ |
| $140 \pm 2$ | $379 \pm 5$ | - | - | - | $1.12^{+0.14}_{-0.14}$ | $^{+3.1\%}_{-2.0\%}$ | - | - | - | $15.7^{+0.9}_{-0.8}$ | $^{+8.0\%}_{-3.1\%}$ |
| $162 \pm 2$ | $426 \pm 2$ | - | - | - | $1.11^{+0.14}_{-0.13}$ | $^{+4.6\%}_{-1.2\%}$ | - | - | - | $18.5^{+1.3}_{-1.5}$ | $^{+4.9\%}_{-10.0\%}$ |
| 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

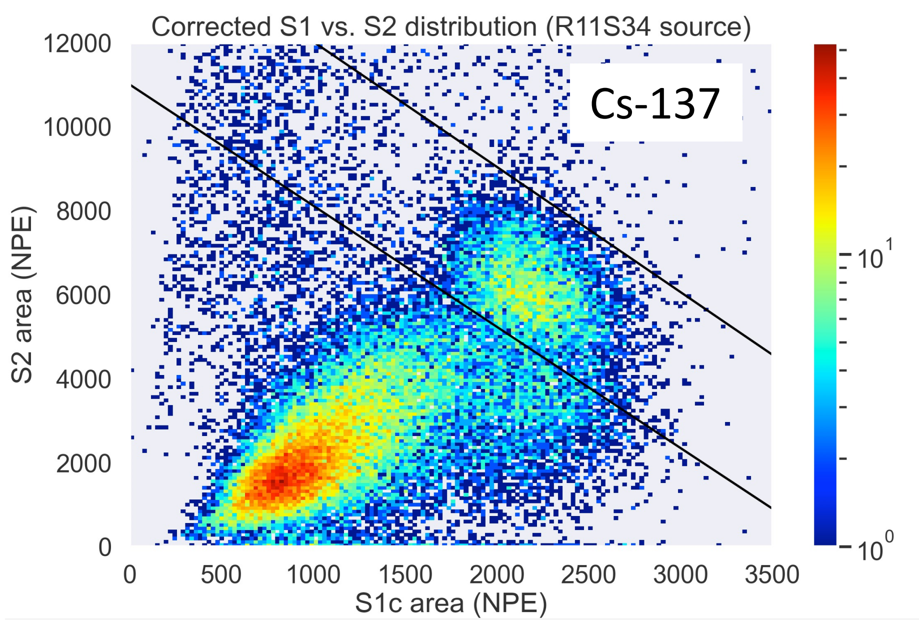


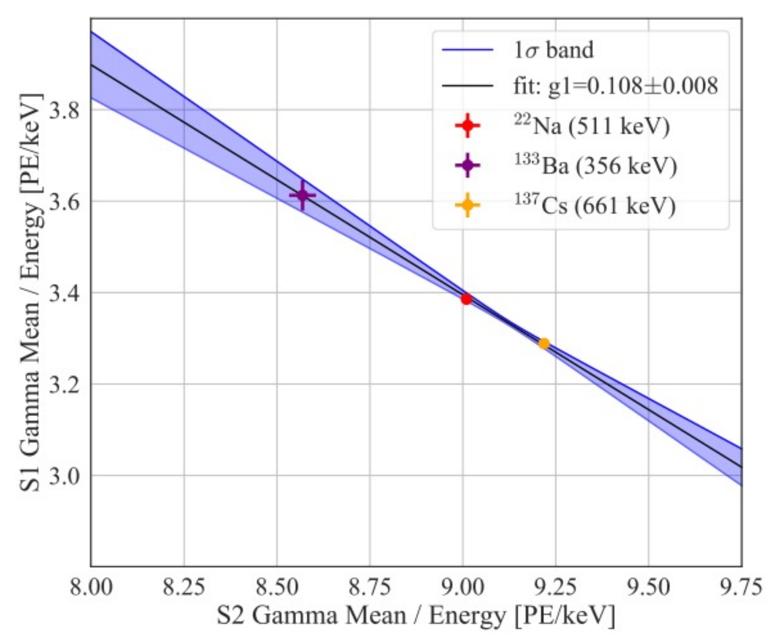



# Light Collection Efficiency Measurement

- 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

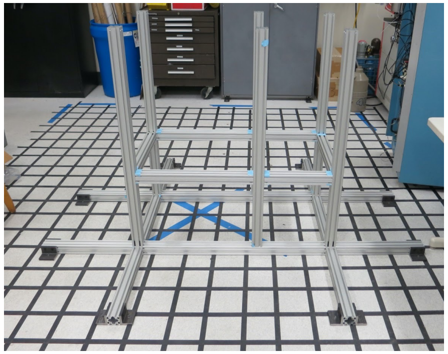
$$E = W(n_{\mathrm{ph}} + n_e) = W_{e/\gamma}\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$



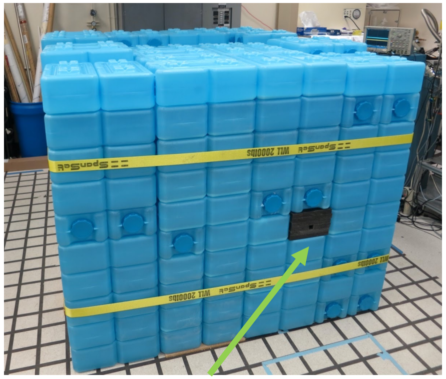
# Collimator and shielding construction

- DT source 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
- Stand designed for LLNL DT source
  - 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
- 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

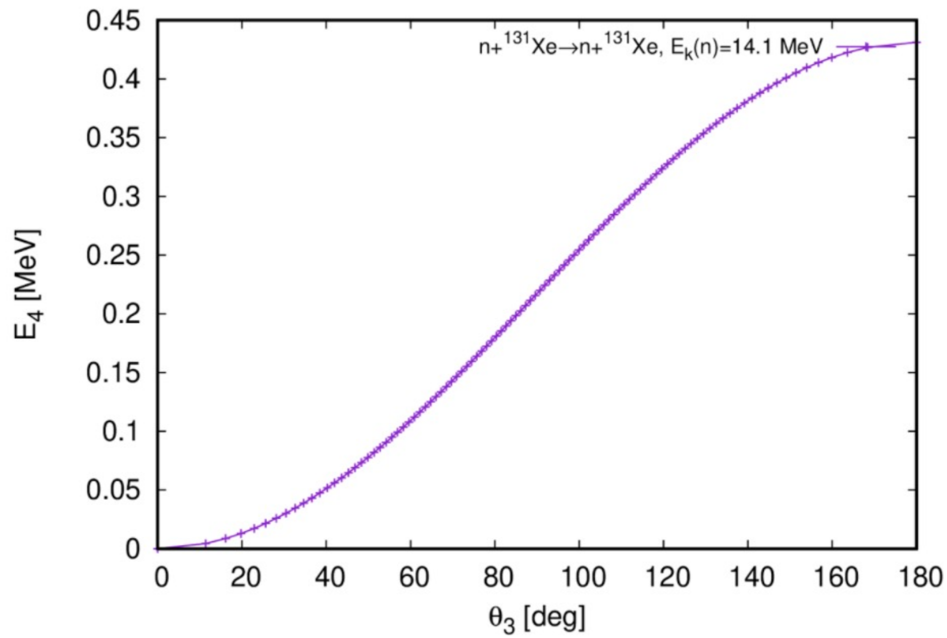
# Neutron-Xenon elastic scattering spectrum

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

**Reaction summary for n+$^{131}$Xe→n+$^{131}$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.

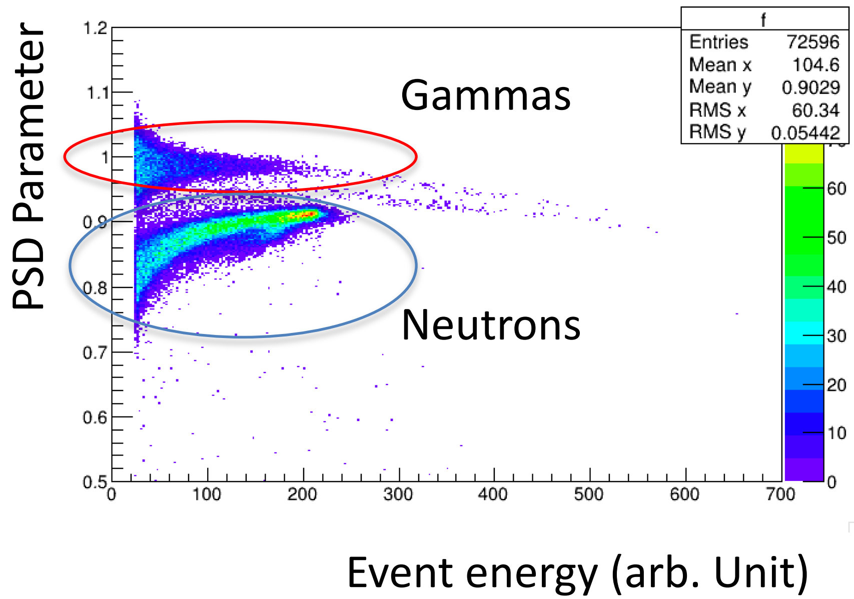
$KE_4$ as a function of $\theta_3$:



# 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

Neutron/gamma discrimination in backing detectors (commissioning data)



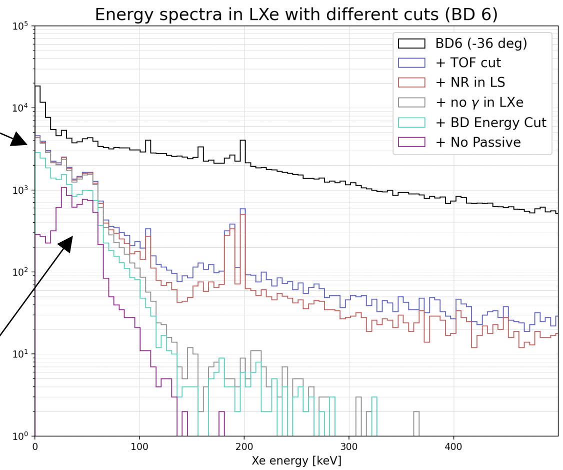
# Uncertainties in lowest recoil energy

- 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

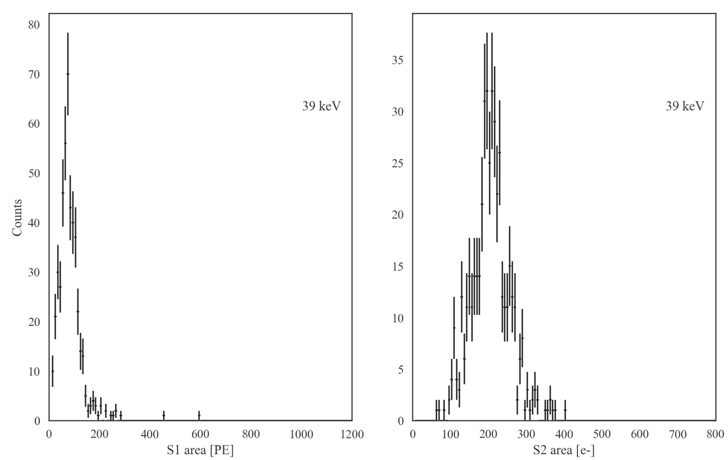
Simulated energy distribution, lowest angle LS coincidence scatters

Excess in low-energy scatters from passive materials

Dip in predicted ES cross-section results in two-hump feature




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