Simulation results for a low energy NR yields measurement in LXe using the MiX detector

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Based on "*Feasibility Study to use Neutron Capture for an Ultra-low Energy Nuclear-recoil Calibration in Liquid Xenon*" - PRD 106, 032007 (2022)

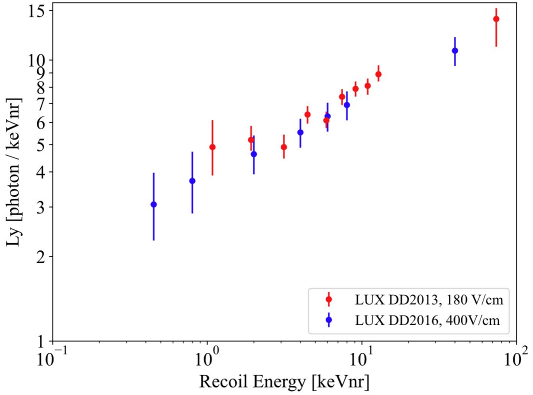
LIght Detection In Noble Elements (LIDINE)
22nd September 2022, Warsaw

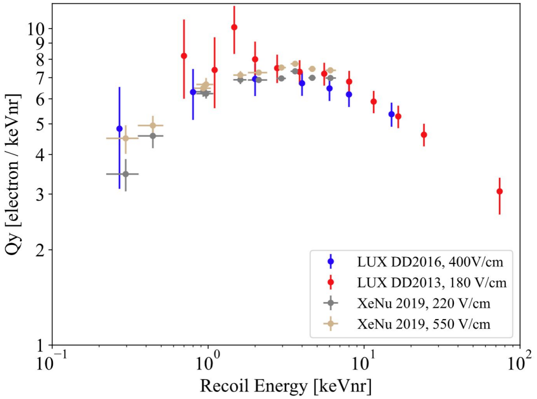
Motivation

Goal: A measurement of the NR scintillation and ionization yields in LXe below 0.3 keV_{nr}.

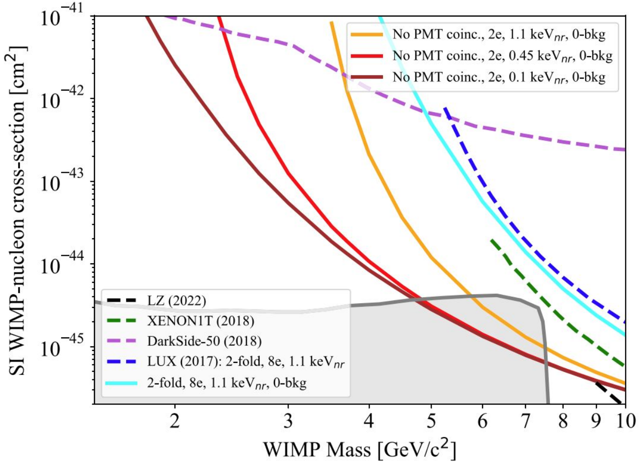
Current lowest measurements:

- Charge yield: 0.27 keV
- Light yield: 0.45 keV





Lowest energy measurements of the light and charge yields of nuclear recoils in LXe.

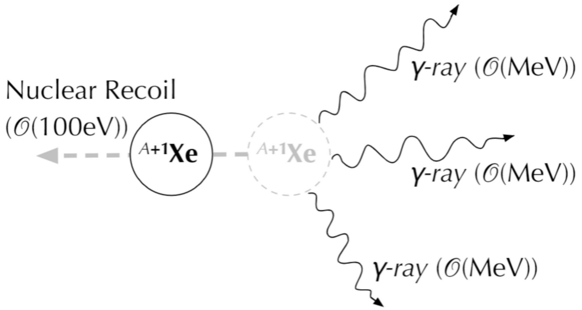


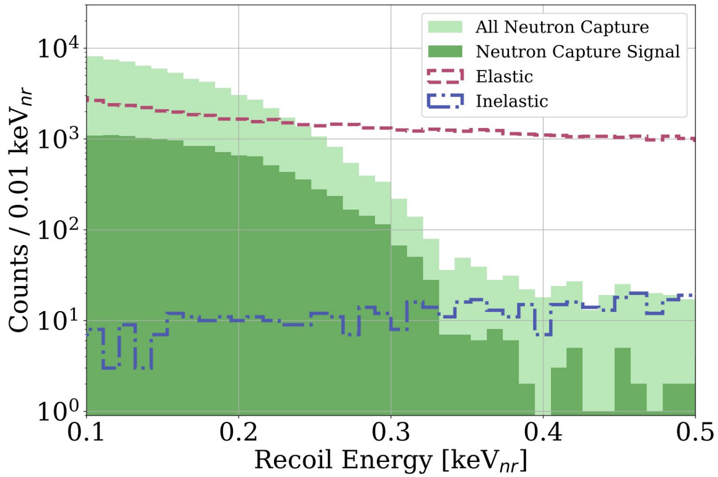
WIMP sensitivities at various energy thresholds with yields extrapolated using NEST v2.0.1

1. D.Q. Huang, Brown University PhD thesis,
2. LUX Collaboration, 1608.05381
3. B. Leonardo, et. al., 1908.00518

Neutron Capture NR

Following neutron capture on xenon, the asymmetric emission of prompt **γ** rays will cause nuclei to recoil.





Simulated recoils of neutron interactions in the MiX detector

Events where all **γ** rays escape the active volume of the detector will have pure NR signature.

MiX Detector and Simulations

MiX - Small dual-phase TPC with high signal collection:

- *g1 = 0.239 ± 0.012 PE/photon**
- *g2 = 16.1 ± 0.6 PE/electron*

S. Stephenson, et. al.
JINST **10** P10040 (2015)

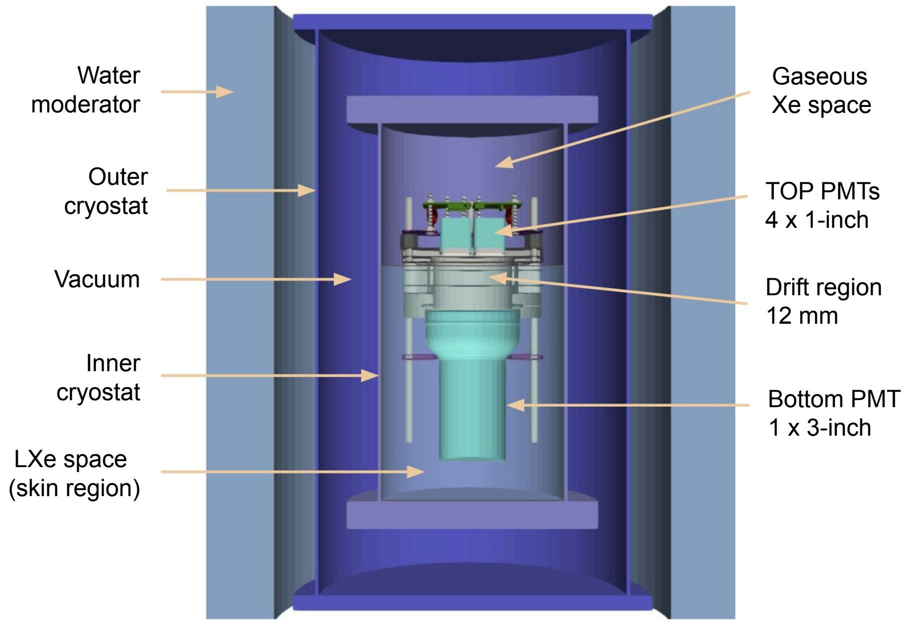
BACCARAT was used to simulate the passage and interactions of neutrons in MiX:

LUX Collaboration, NIM A **675**, 63 (2012)
LZ Collaboration, Astroparticle Physics **125**, 102480 (2021)

- 2.45 MeV D-D neutrons shot at the detector in pulses.
- A water tank surrounds the detector to moderate neutrons.

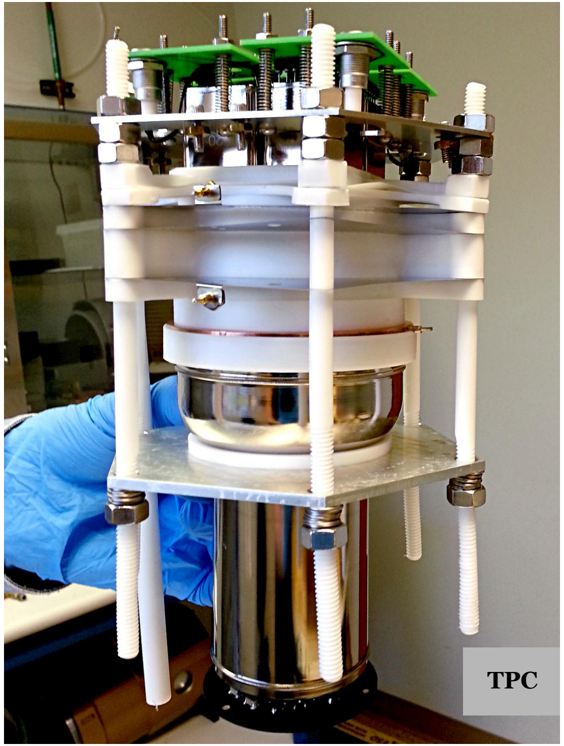
Pulse width, frequency, and moderator thickness were optimized using simulations.

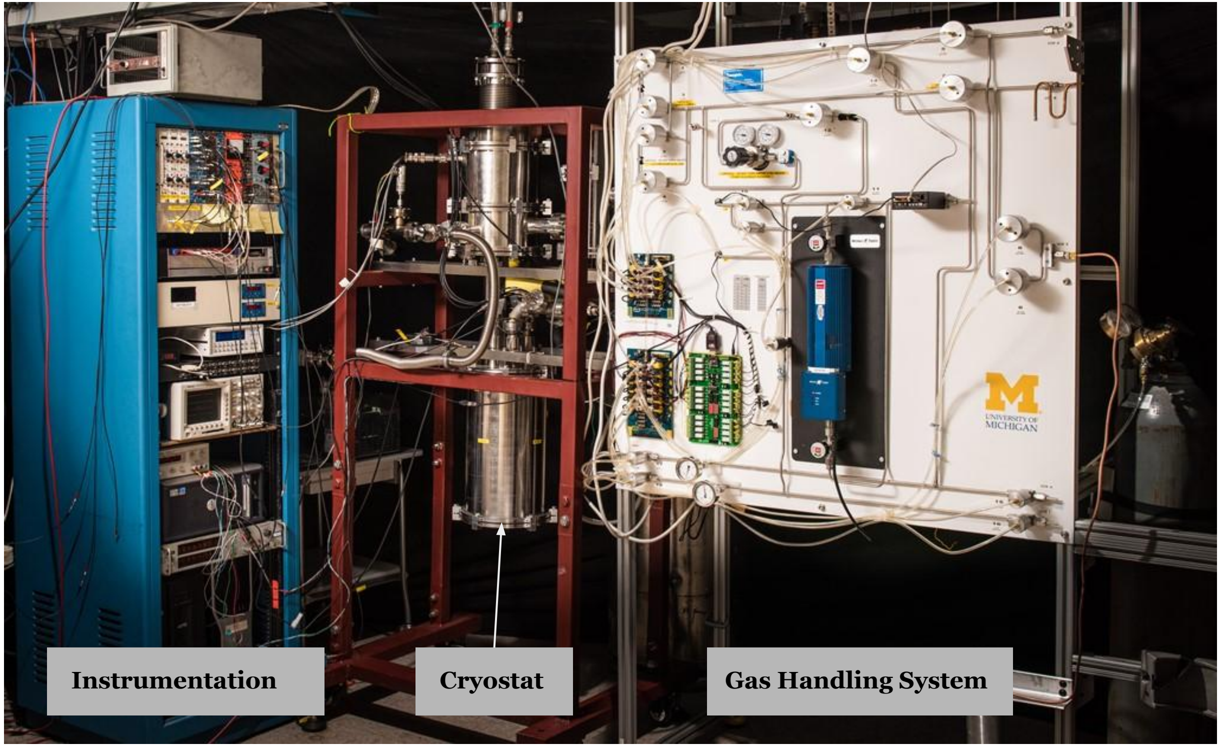
* Large TPCs in dark matter searches have g1 ~ 0.1 PE/photon.



Model of the MiX detector with a water tank around it

Experimental Setup





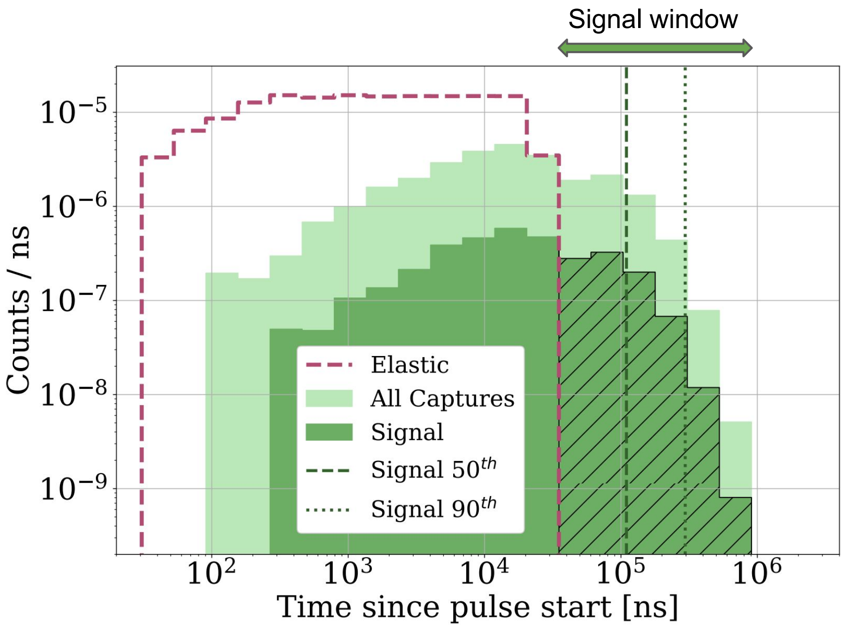
Signal Event Isolation Using Timing

In each neutron pulse...

- The water tank partially moderates neutrons and filters them by speed.
- Since the capture cross section scales inversely with neutron speed, capture events occur much later than scatters.
- There is a signal window where the only NRs are due to neutron capture.

Optimal parameters for pulsed neutron generator:

- *Pulse width = 30 μs*
- *Pulse frequency = 60 Hz*



Simulated time (from the start of the pulse) at which neutron interactions occurred in the MiX TPC.

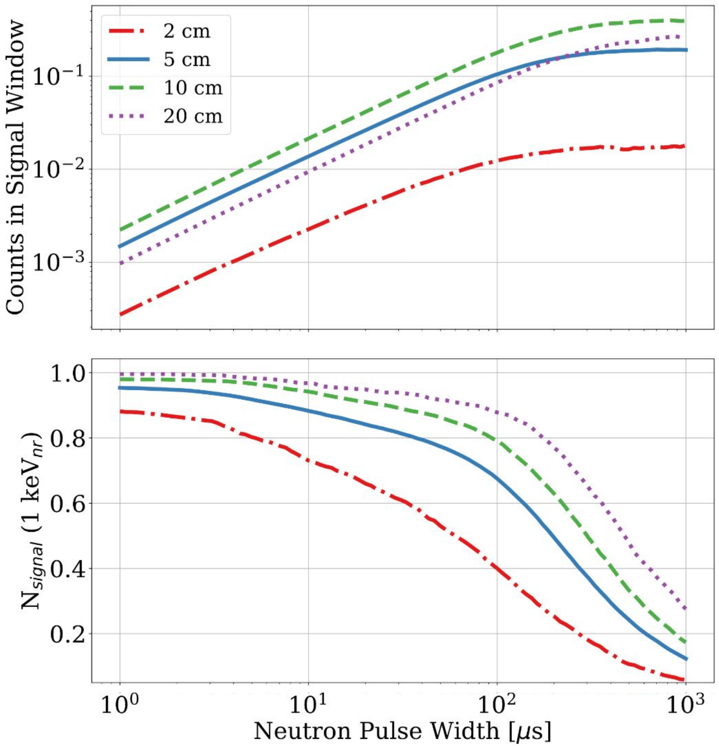
Signal Optimization - Neutron Pulse Width

Neutron pulse width affects the timing of neutron scatters more than neutron captures.

Increase in neutron pulse width causes number of signals to increase, until the elastic scatters overlap with captures (decreasing signal window length).

$$\mathrm{N}_{\mathrm{signal}}(E_{\downarrow}, w_n) = \frac{\text{Number of capture signals after the last scatter}}{\text{Total number of capture signals}}$$

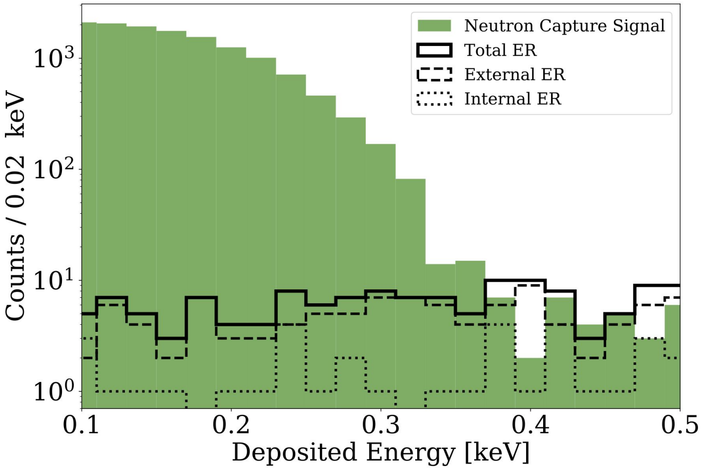
First hint of constraints of the neutron pulse width.



Signal counts per pulse and fraction of signals in the acquisition window as a function of neutron pulse width

Low Energy ER and Single Electron Backgrounds

Estimate of the low energy ER background shows it not to be a concern.



Simulated low energy deposits from ERs, along with the neutron capture signal deposits

Single electron backgrounds typically follow large energy depositions in LXe, and are obstacles for the ionization measurement.

- SE emission time scales can be O(10 ms)

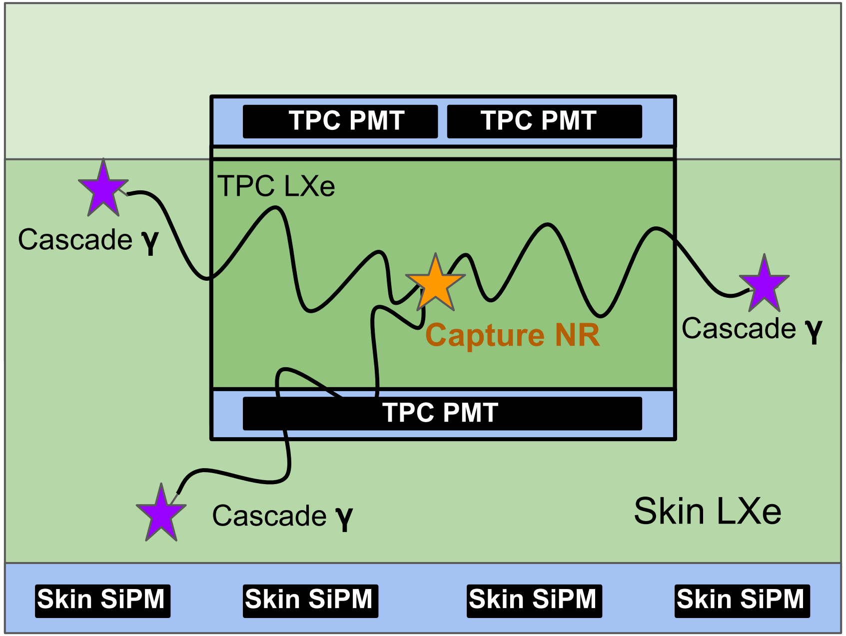
  LUX Collaboration, Phys. Rev. D **102**, 092004 (2020)

- Longer than acquisition windows, constraining the neutron pulsing frequency:
  - *f = 60 Hz*
  - *Require SE rates to decay following large deposits from previous pulses.*
- SE background would have to be subtracted from events recorded in each pulse.
- However, with the region outside the MiX TPC (skin) instrumented, signal events can be positively identified in time.

Mitigating SE Background

In addition to neutron pulsing, the SE BG rate can also be further suppressed.

- Tagging TPC capture NR signals with coinciding cascade γ rays that escape the TPC but deposit energy in the skin.
- Simulations show that 70% of neutron capture signal events can be tagged.



Cartoon of how capture-induced NRs might be tagged using an instrumented skin

High Energy ER Contamination

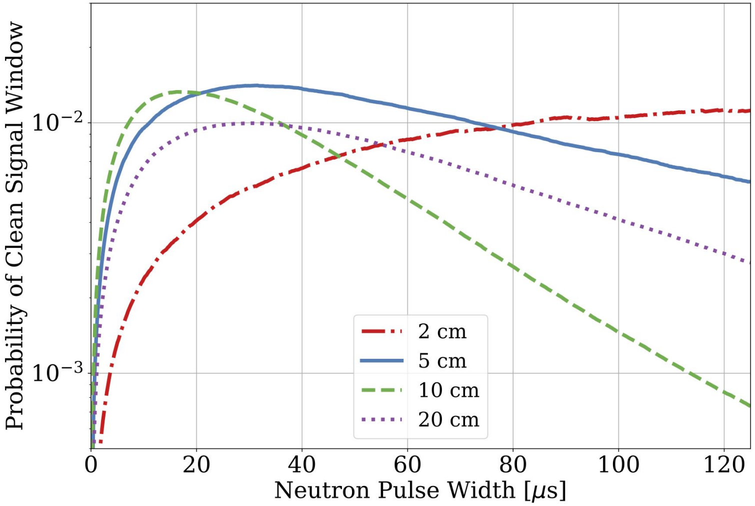
Large ERs from γ rays due to captures on nuclei outside the TPC often contaminate the capture-NRs in the signal window.

There is a tradeoff between number of neutron capture signals, and mitigating ER contamination.

For example, in larger water tanks

- More neutron thermalization and captures in the TPC.
- But, also more captures on nuclei outside TPC, whose γ rays interact in the TPC.

Optimal water tank thickness is 5 cm, and neutron pulse width is 30 μs.



Probability of obtaining a signal window with no ER deposits, as a function of pulse width

NR Spectrum Uncertainty

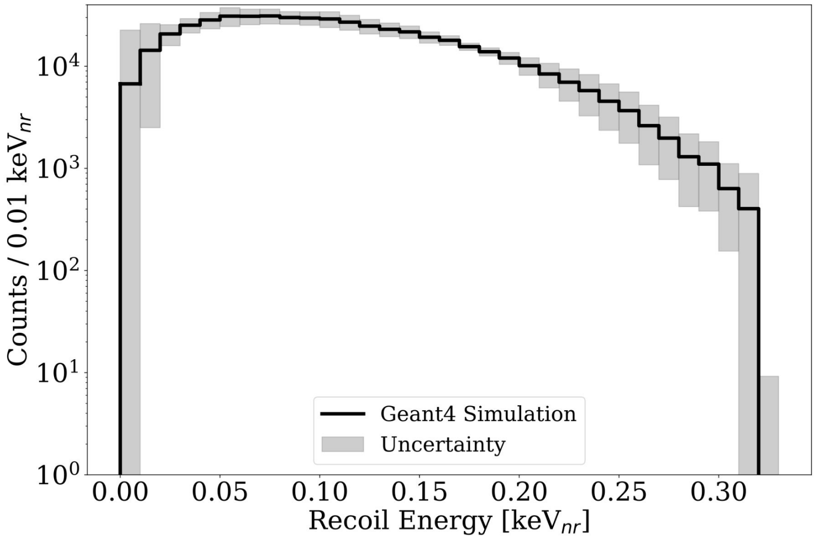
Measurement of NR yields is obtained by comparing data with energy deposition model.

Since this is a **model-dependent** measurement, we have calculated the uncertainty of the NR spectrum.

Sources of uncertainty:

- Imperfect knowledge of **γ** spectra per isotope:
  - Deviations among two databases (GEANT4 and EGAF) were used.
- No knowledge of multiplicity distributions from data:
  - Used the difference between broad and narrow distributions.

*Random emission directions of **γ** rays make the NR spectrum robust to these sources of error.*



Recoil spectrum due to thermal neutron capture produced by a custom model, with the uncertainty band calculated using deviations in existing cascade data (GEANT4 & EGAF) and our ignorance of **γ** multiplicities

1. ENSDF - Online database
2. IAEA, *Prompt gamma-ray neutron activation analysis* - Online database
3. Firestone, et. al., AIP Conference Proceedings, Vol 769 (2005)

Summary

Simulations were used to optimize the production rate of low energy recoils (below 0.3 keV_{nr}) produced by neutron capture in liquid xenon.

- A small TPC, pulsed neutron source, and a moderator allow these events to be isolated using timing information.

ER contamination and small electron backgrounds are the primary challenges to the experiment.

A **model-dependent** measurement of NR yields can be carried out by fitting a yield model to measurements, assuming the NR energy spectrum is correct.

- Several uncertainties, primarily the deviations in measured **γ** cascades of xenon, contributing to the NR spectrum are identified and combined.