Experimental search for the Migdal Effect in a compact liquid xenon TPC

Brian Lenardo, on behalf of:
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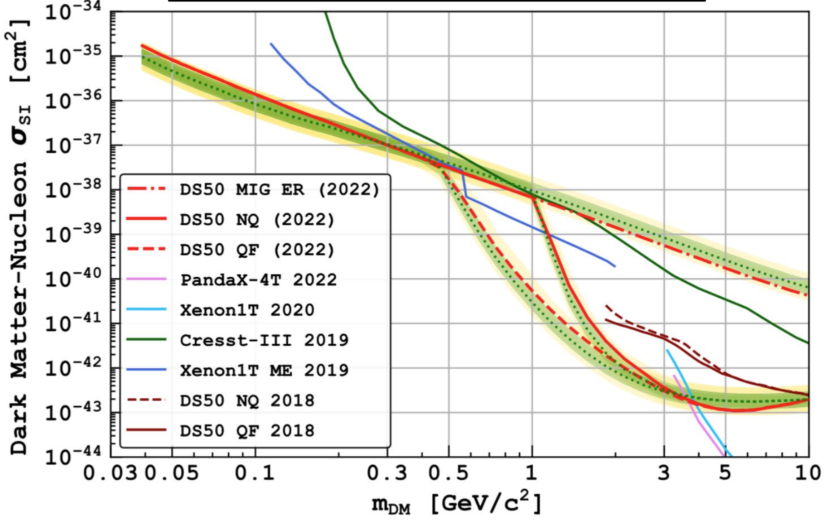
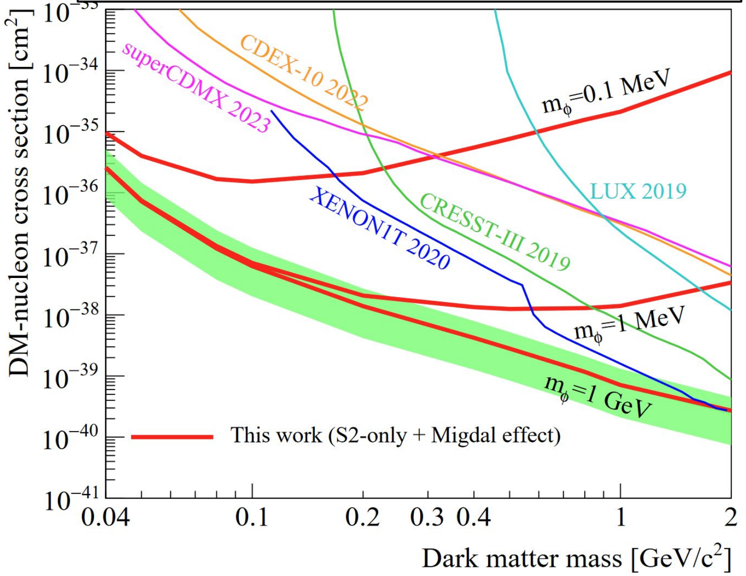
CPAD 2023
SLAC National Accelerator Lab
Menlo Park, CA

Dark matter constraints at ~few GeV and below

Darkside-50, *PRL* (2023)



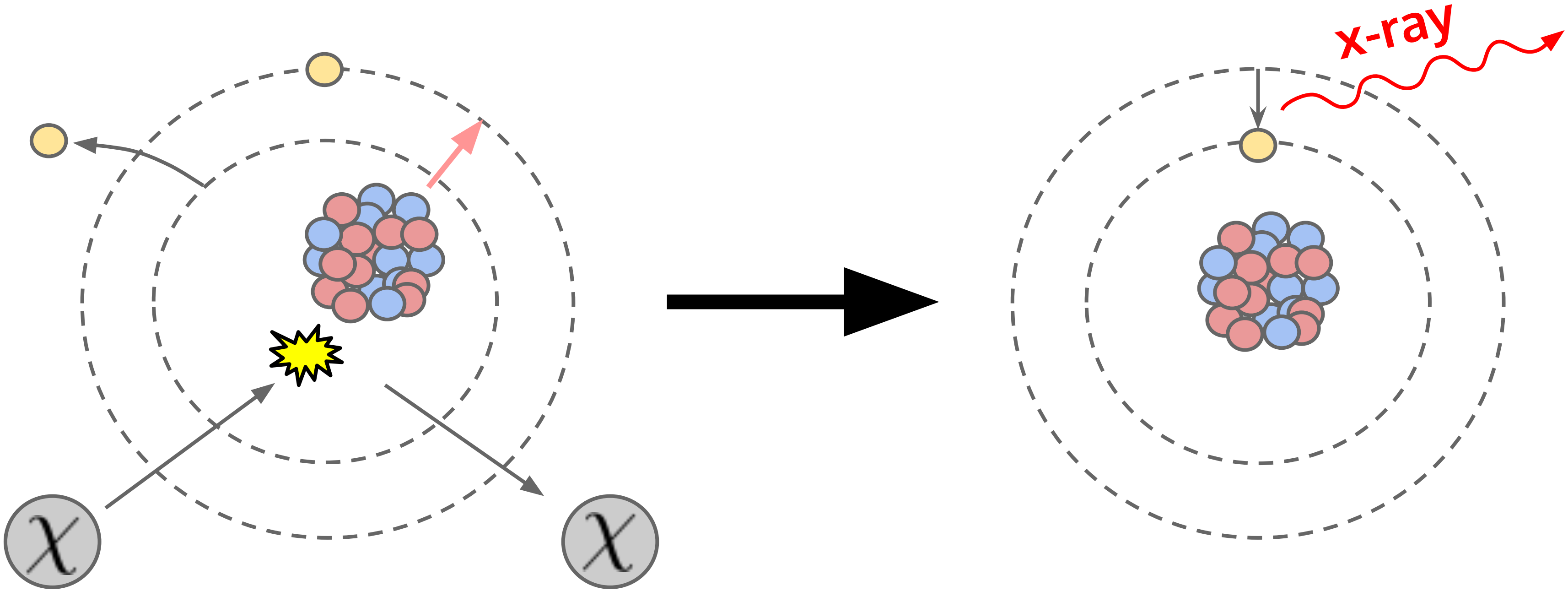
PandaX-4T, *Accepted by PRL* (2023)



The most stringent reported limits for dark matter in the 30 MeV - 3 GeV mass range come from noble liquid experiments that include the "Migdal effect" in their signal models.

What is the Migdal Effect?

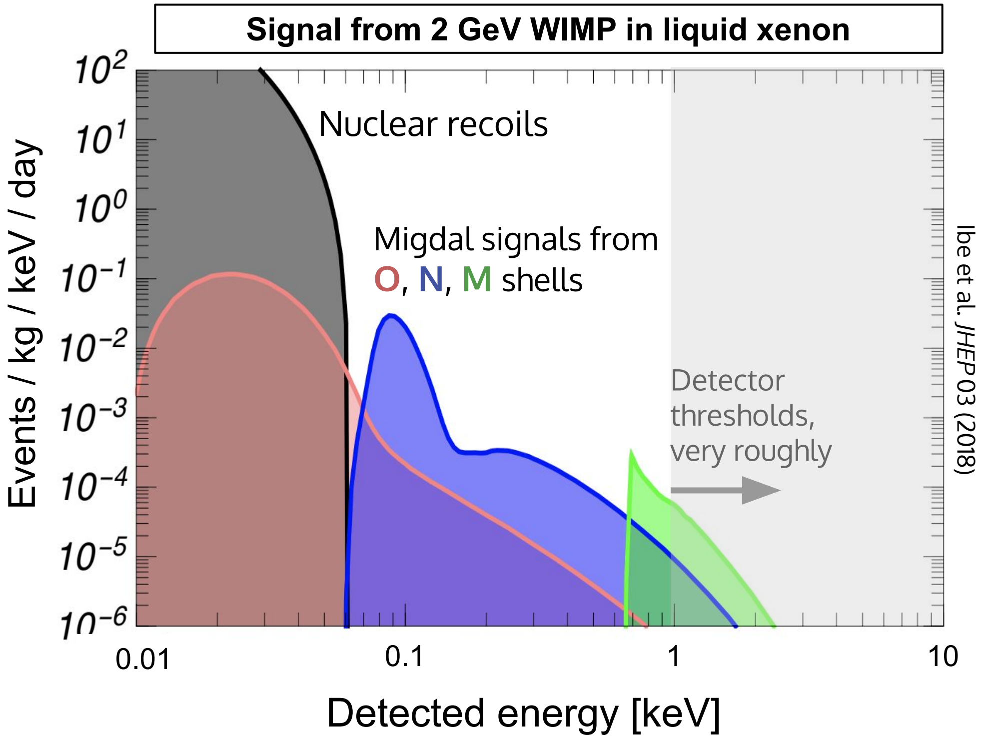
A nuclear recoil boosts the nucleus relative to the electrons, which can **excite or ionize** the atom, resulting in X-ray/Auger emission



What is the Migdal Effect?

Enables detectors to "see" ultra-low-energy nuclear scattering that would otherwise be below threshold.

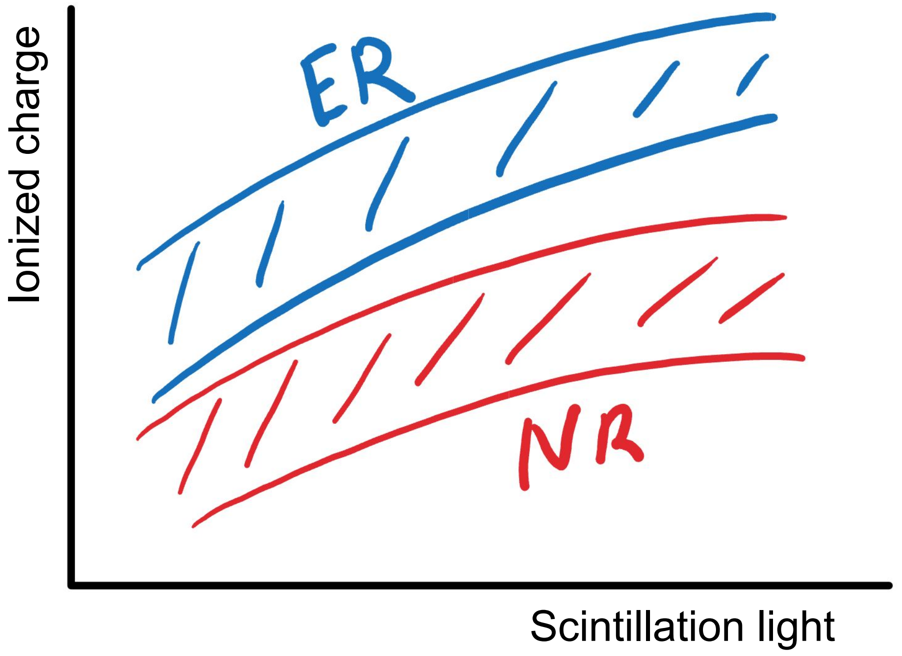
But, has never been experimentally validated!



Our goal

Measure the Migdal effect in liquid xenon with nuclear recoils induced by neutrons.

- Elastic neutron scattering creates **nuclear recoils (NR)**
- Search for small fraction of events with additional **electron recoil (ER)**



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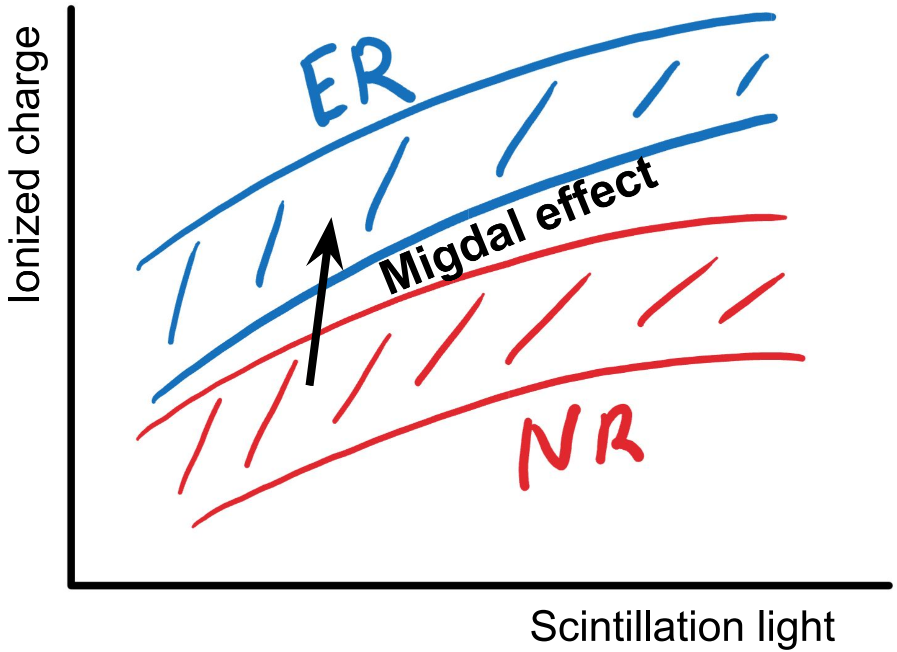
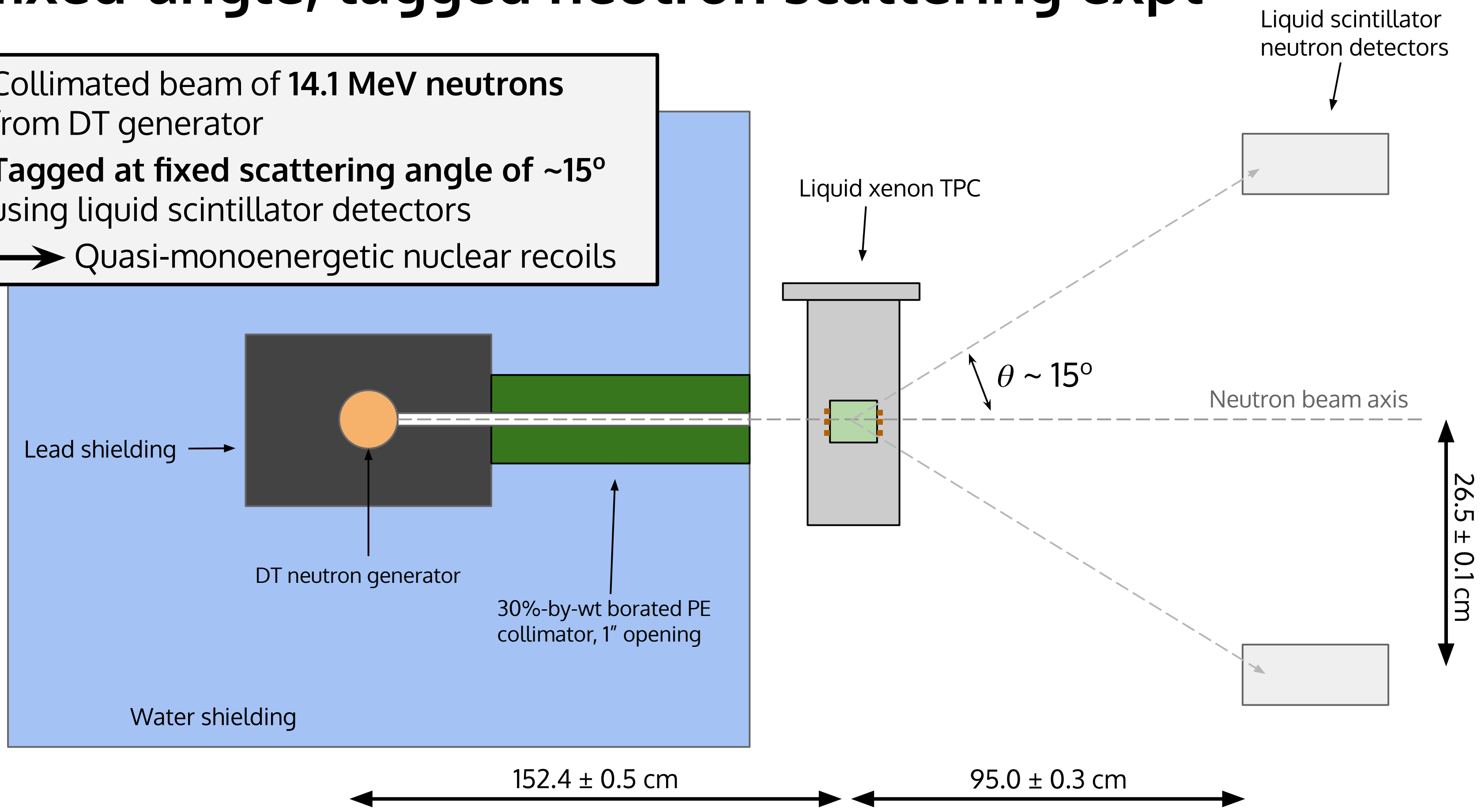


A fixed-angle, tagged neutron scattering expt

- Collimated beam of **14.1 MeV neutrons** from DT generator
- **Tagged at fixed scattering angle of ~15º** using liquid scintillator detectors

→ Quasi-monoenergetic nuclear recoils



Why fixed-angle?

Features of this approach:

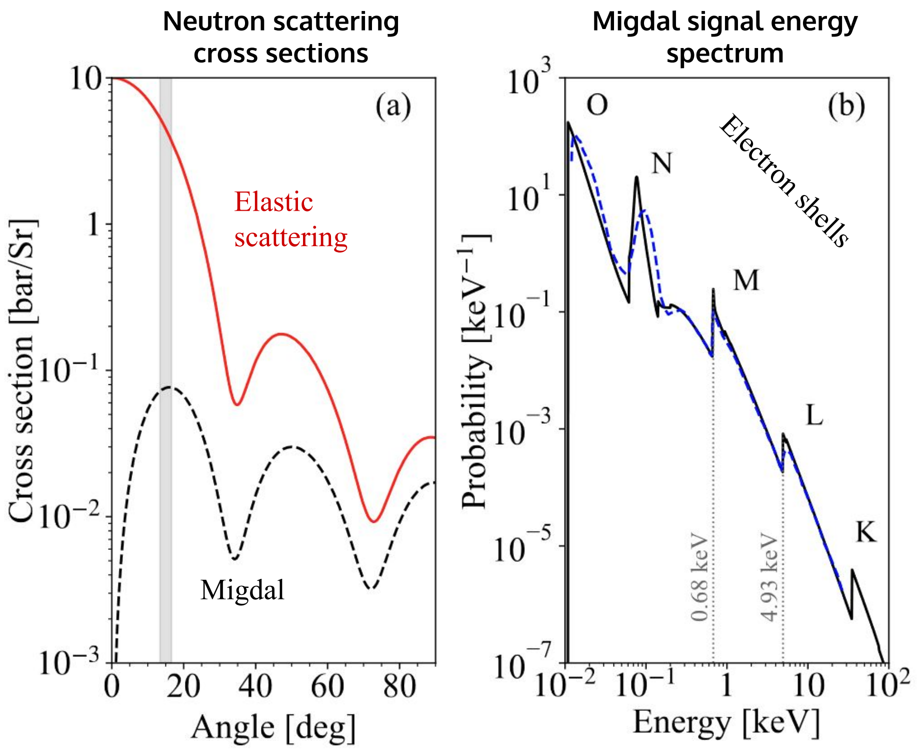
- Ratio of Migdal/elastic is well-predicted; avoid possible energy-dependent systematics in neutron cross sections
- Narrow signal region allows characterization of backgrounds in sidebands

Our analysis looks for Migdal effect with the **M-shell** and the **L-shell:**

~7 keV nuclear recoils

+

~1 or ~5 keV electron recoils



The team

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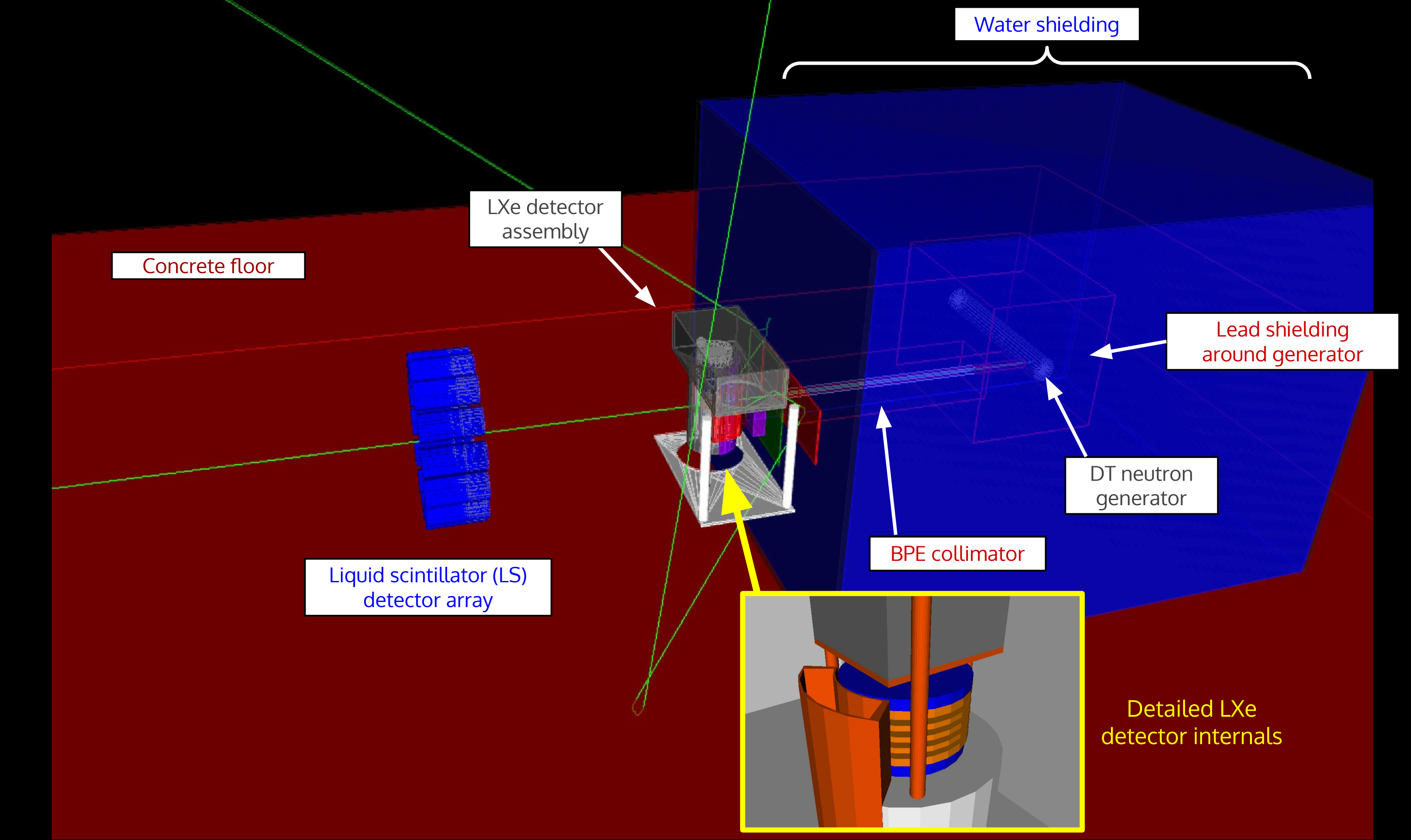
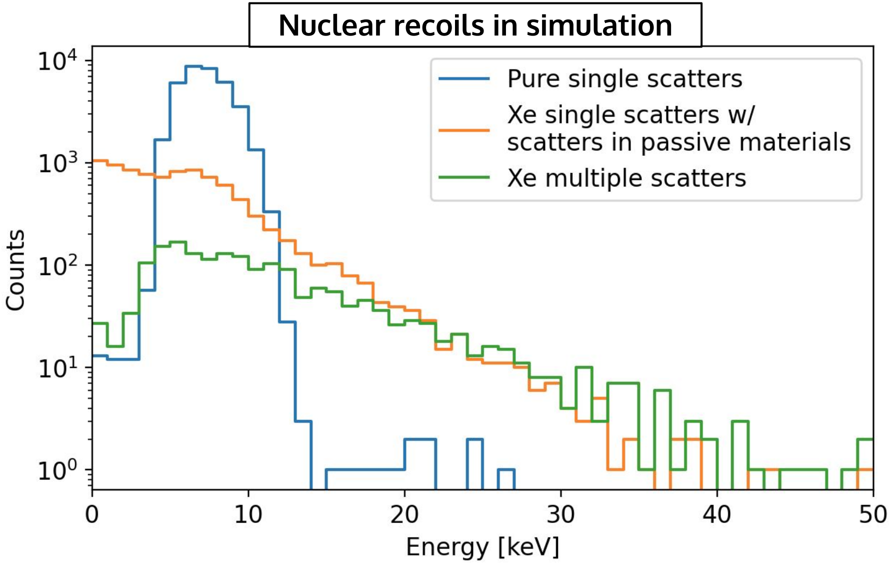
Geant4 geometry



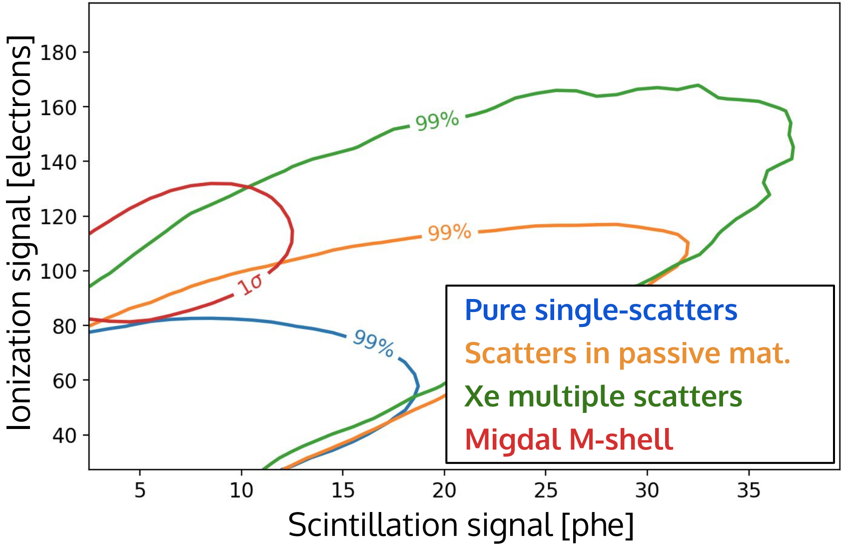

LXe TPC (hidden)
internals
5cm diameter
CAUTION
RADIATION AREA

Simulation



- Nuclear recoil peak at 7.0 +/- 1.6 keV
- **NR backgrounds** from scattering in **passive materials** and **multiple-scattering in Xe**
- **Very low ER backgrounds** (not shown) from inelastic-induced γ-rays

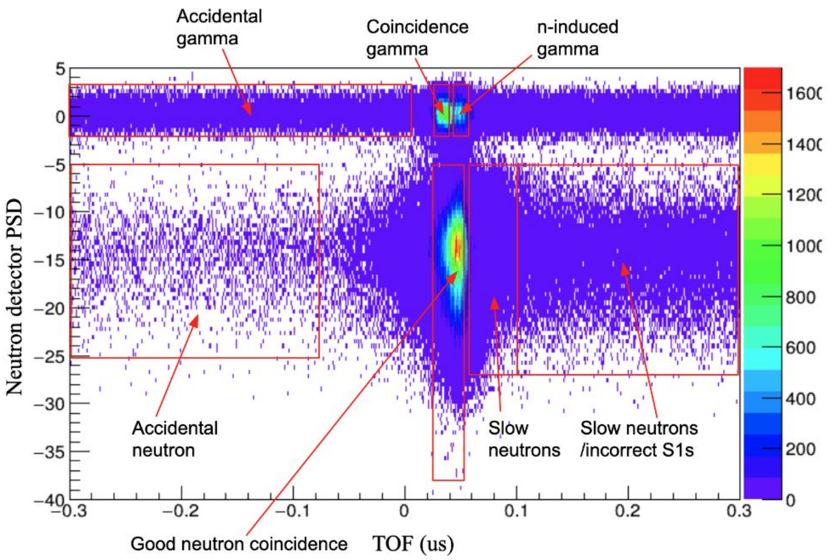
- **Migdal effect M-shell signals** contain ER + NR, giving **peaked signal region** in scintillation vs. ionization phase space.
- **Backgrounds** can be constrained in sidebands



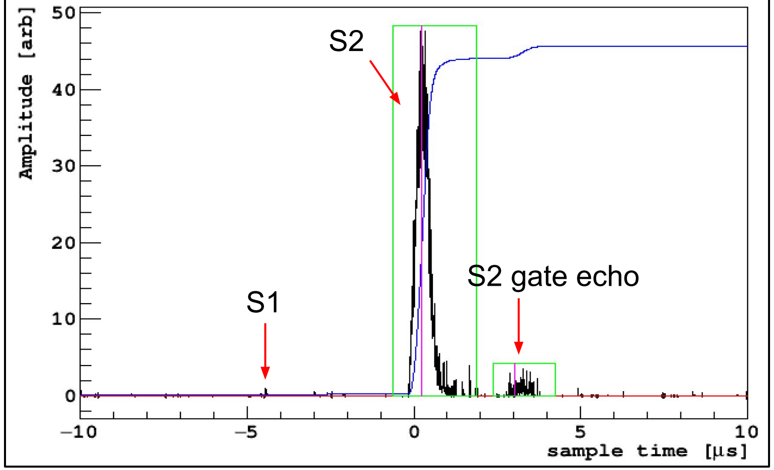
Data analysis

Step 1: use LS tagging detectors

- Tag neutrons using **pulse shape discrimination**, removing most gamma bkgs
- Use **time-of-flight** between LXe and LS to remove accidentals, off-beam neutrons, etc.



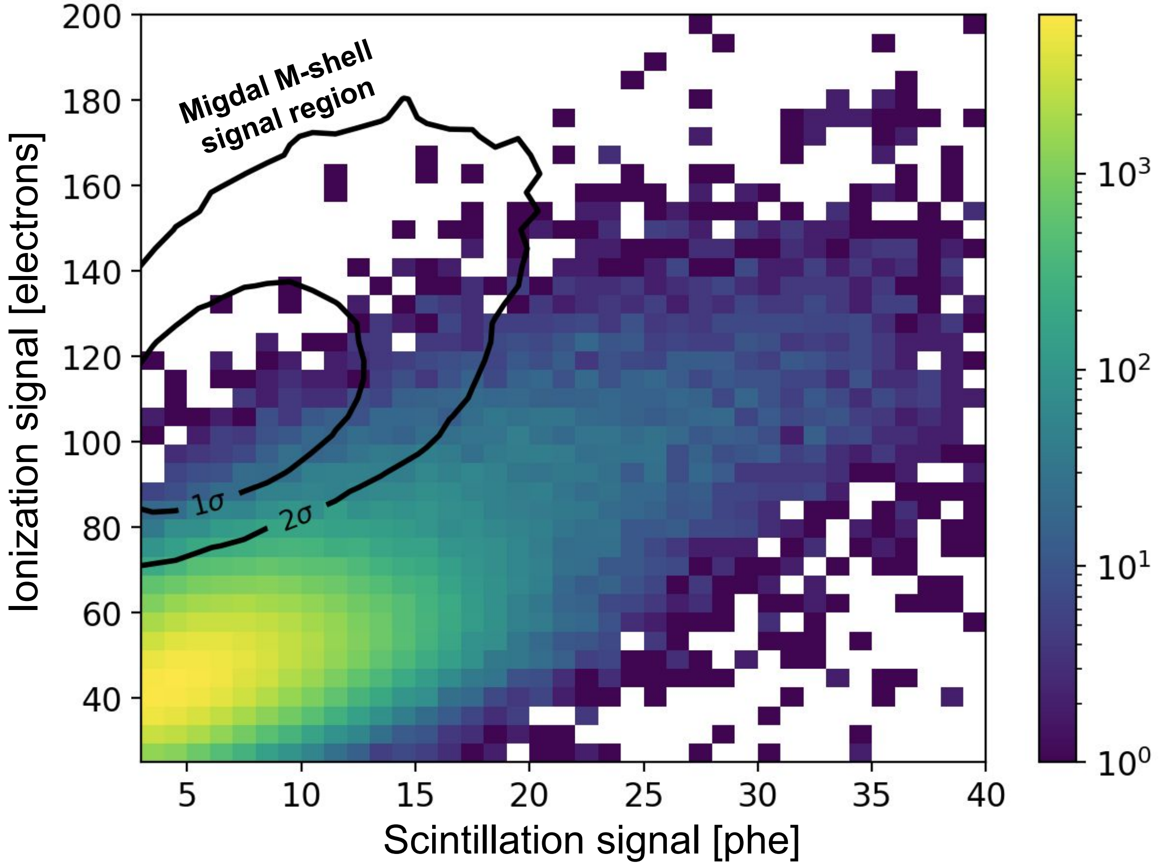
Example single-scatter event



Step 2: select good events in LXe TPC

- **Single-scatter candidates identified** as events with a single charge signal (S2)
- **Further unresolved multi-scatter rejection** based on S2 quality (mainly width and shape)

Data after selection cuts applied



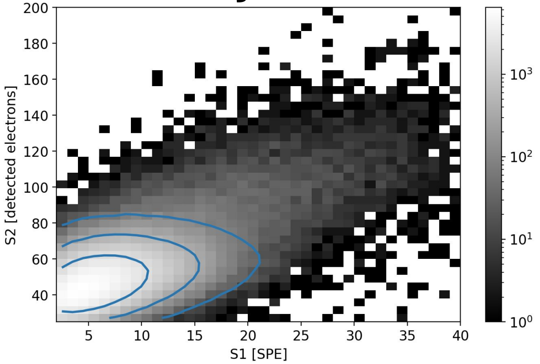
We end up with 300,000 neutron scattering events passing our cuts

Predict ~200 M-shell Migdal events in this event sample

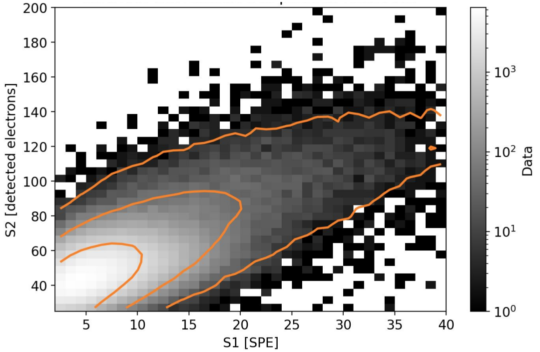
2-D PDFs for backgrounds and signals, overlaid on data

Backgrounds

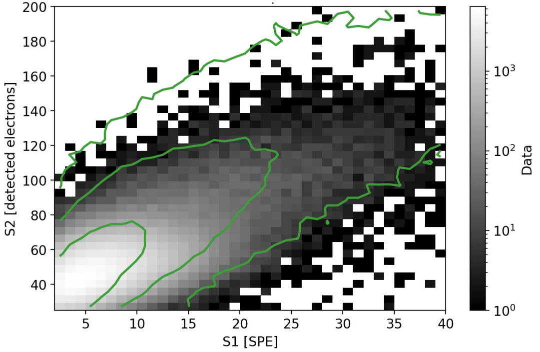
Pure single-scatters



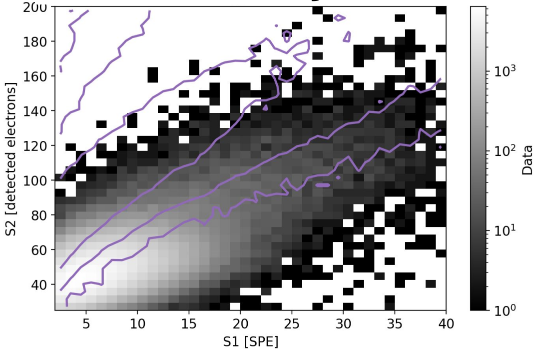
Scatters in passive materials



Unresolved Xe multiple-scatters

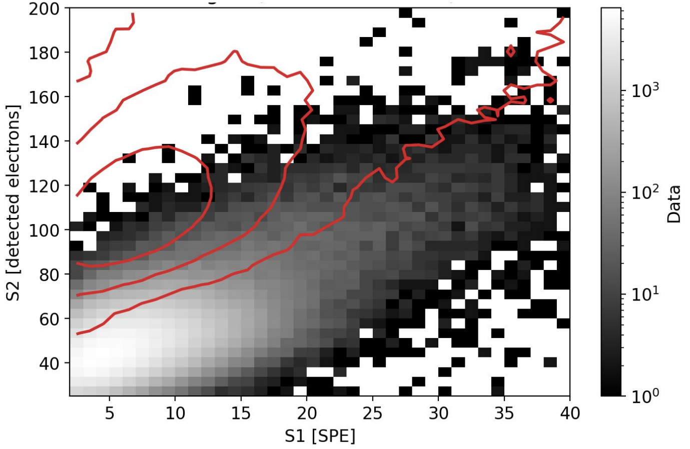


Uniform ER background



Signal

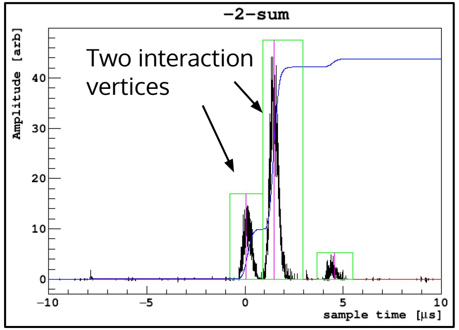
Migdal M-shell signals



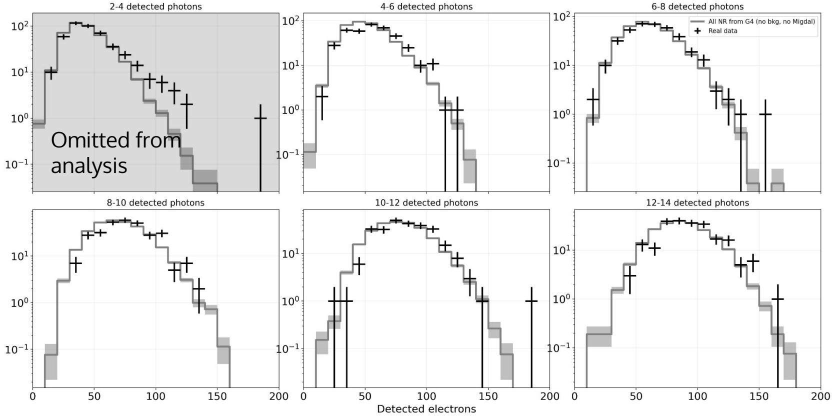
Background model shape validations

Neutron multi-scattering model validated using *resolved* multi-scatters

Example event with two S2's

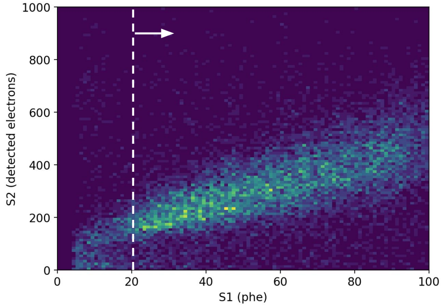


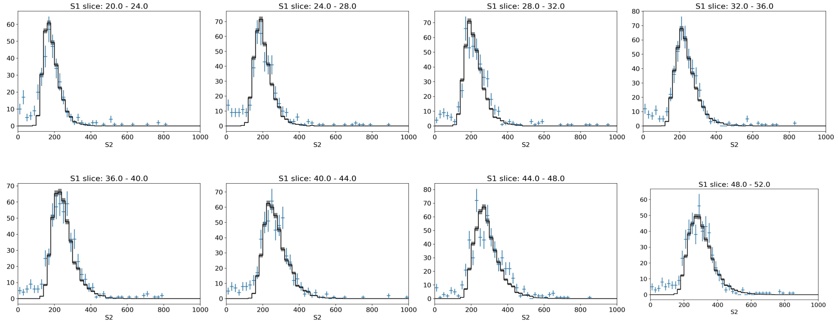
Plots of S2 (charge), in bins of S1 (scintillation)



Electron recoil modeling benchmarked with ^{60}Co γ-ray Compton scatters

2D plot of ^{60}Co γ-ray data



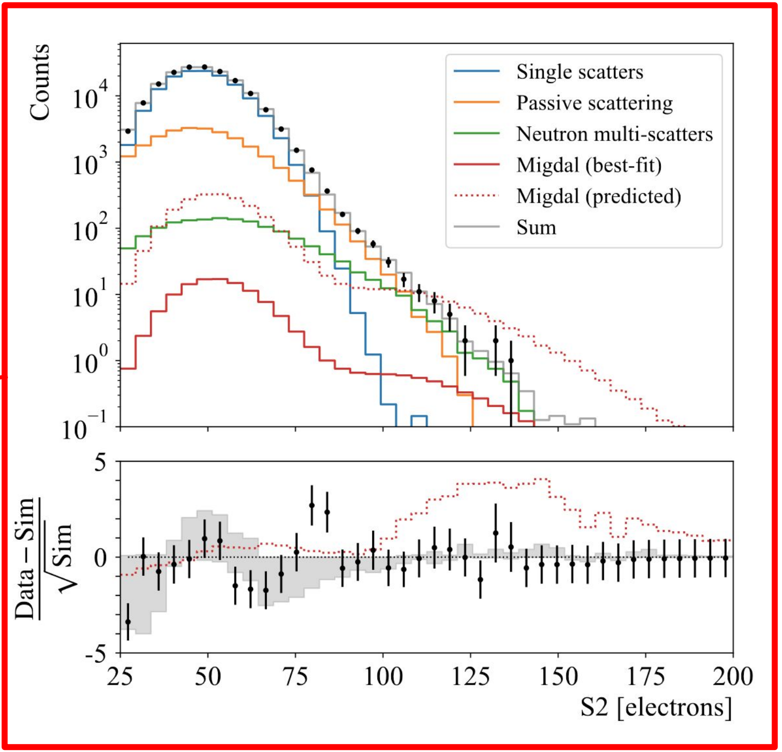


M-shell analysis (7 keV NR + ~1 keV ER)

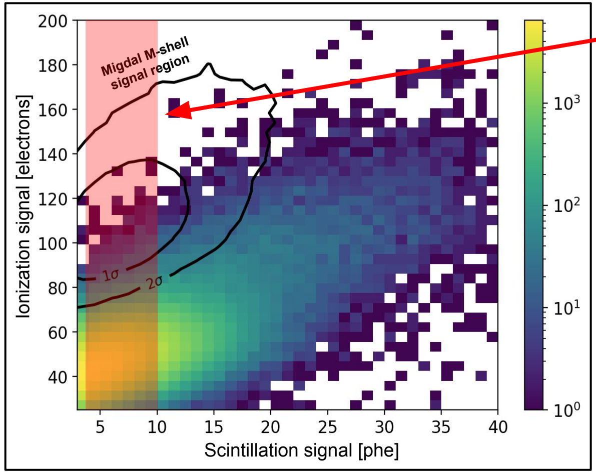
Full 2D profile likelihood analysis was performed using the signal/bkg PDFs

Our data are consistent with our predicted backgrounds, and **disfavor the presence of Migdal events in our expected signal region**

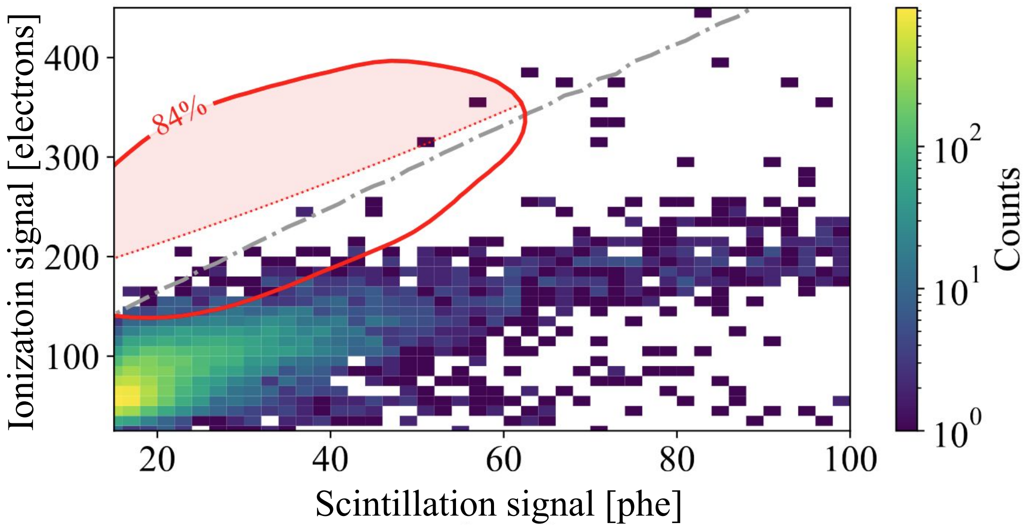
Projection of S2 distribution for S1 = 4-10 phe



1D projection just for visualization



L-shell analysis (7 keV NR + 5 keV ER)



Higher-energy range

Slight changes to scint. signal cuts:

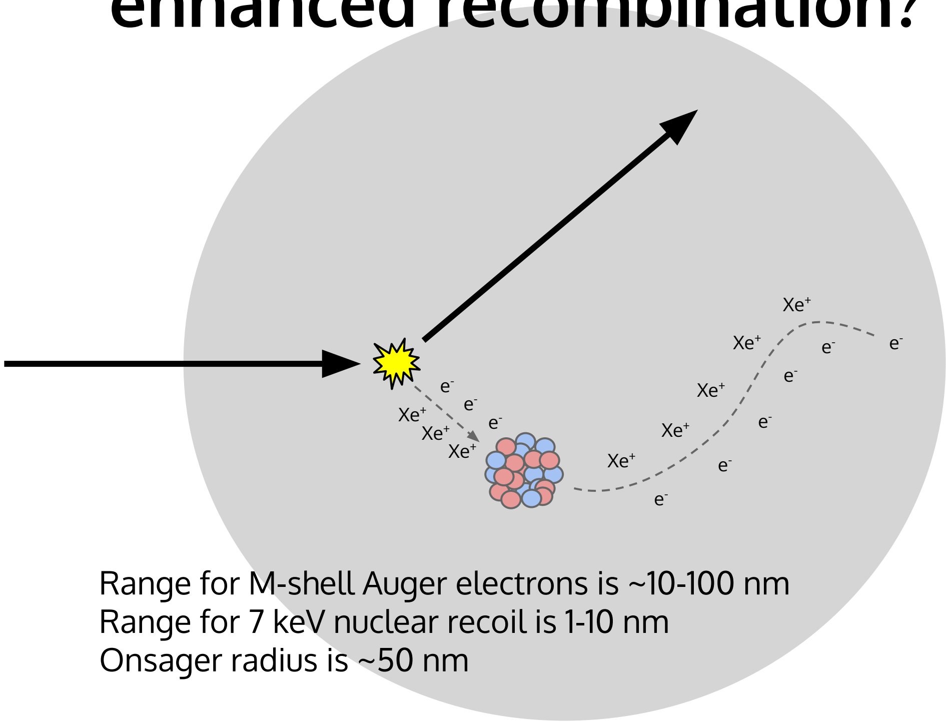
- Relaxed quality cuts (no longer near threshold):
  - Boosts stats by ~30%
- Tighter time-of-flight cut (better precision with larger signals)

Simple cut-and-count analysis in the **shaded red** region:

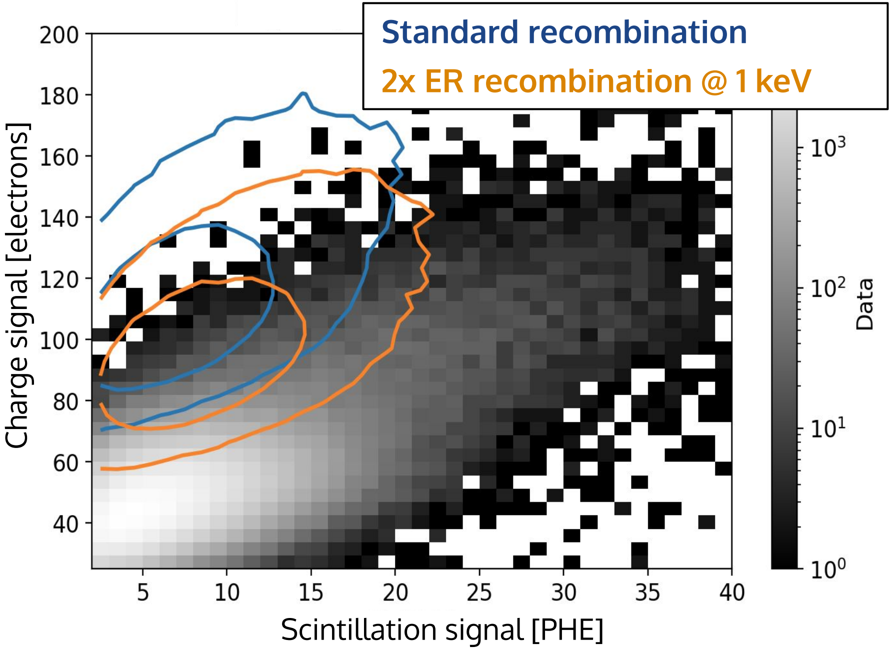
Expected bkg	2.1 ± 0.9
Expected signal	5.6 ± 1.2
Observed counts	**2**

So, where is the Migdal effect?

A possible hypothesis: enhanced recombination?



Range for M-shell Auger electrons is ~10-100 nm
Range for 7 keV nuclear recoil is 1-10 nm
Onsager radius is ~50 nm



Could the electrons from the ER component be recombining with the ions from the NR component?

→ **Would shift Migdal events towards the region with high NR backgrounds**

Summary

Performed a high-statistics, fixed-angle neutron scattering experiment in an attempt to characterize the Migdal effect in liquid xenon (arXiv:2307.12952)

Successfully achieved **ultra-low backgrounds** in the predicted signal region and **sufficient NR statistics** for a high expected signal rate

We **do not see any signal consistent with the predicted Migdal effect.**

- One possibility is enhanced electron-ion recombination for the localized energy deposits – **does not affect below-threshold DM searches, but could hide the signal in experiments like this one.**
- Follow-up experiments and analyses under consideration to explore this:
  - ➔ Higher drift field
  - ➔ Lower nuclear recoil energy
  - ➔ Targeting L-shell Migdal effect

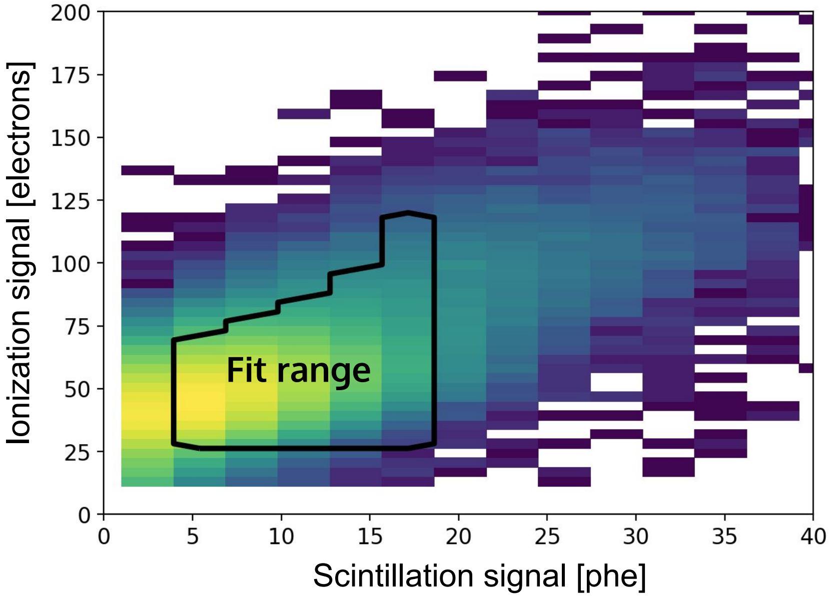
Thank you!

Back up

Liquid xenon response modeling

Fit NEST nuclear recoil model to high-stats single-scatter peak

- Explore a range of model parameters which vary **charge + light yields** and distribution **width**



NEST model space used in fits