Measurement of the nuclear recoil ionization yield in liquid xenon from 0.3 keV to 6 keV

Brian Lenardo
Stanford University

Magnificent CEvNS Workshop
November 10, 2019

Dual-phase xenon TPC detectors

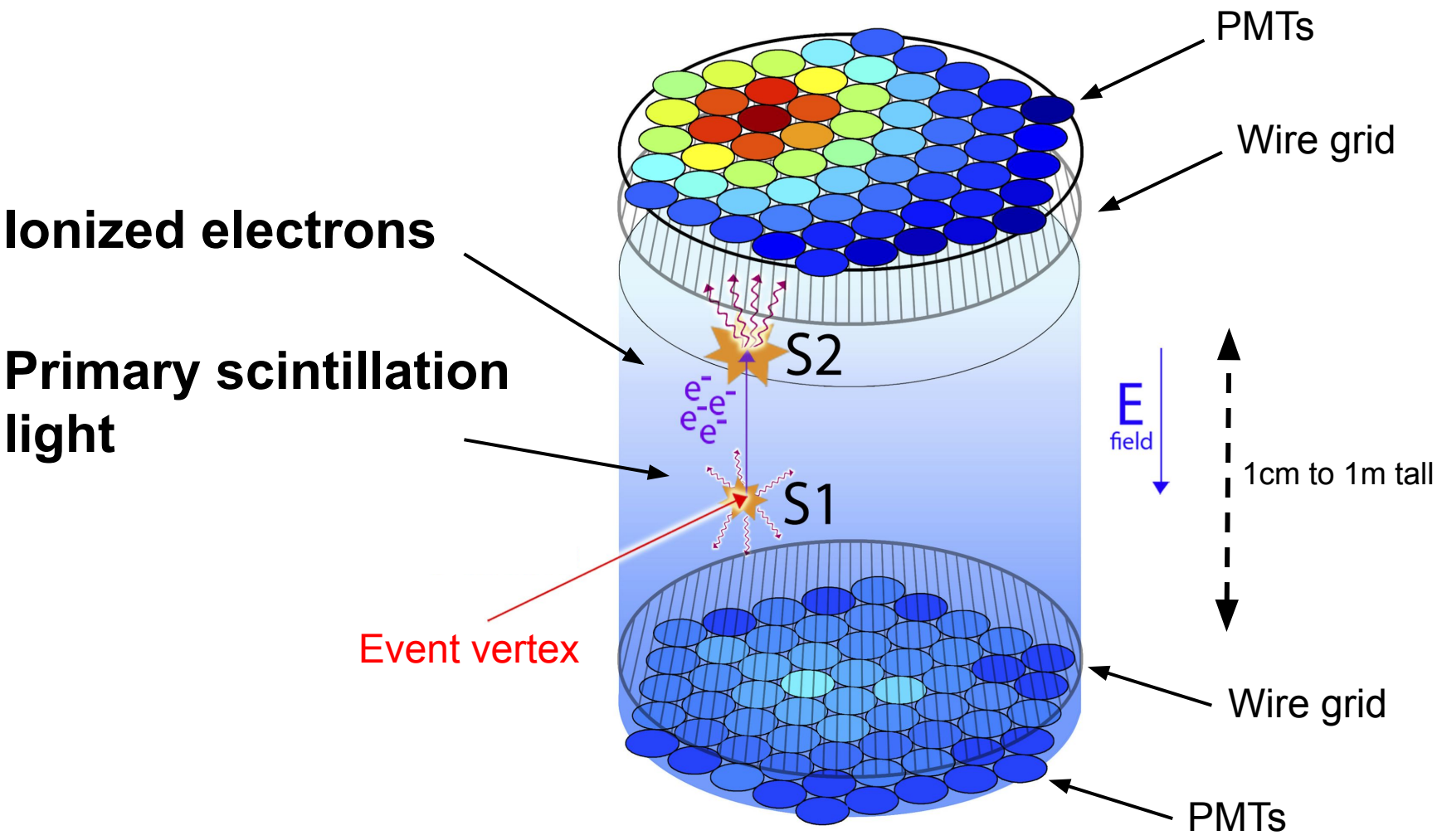
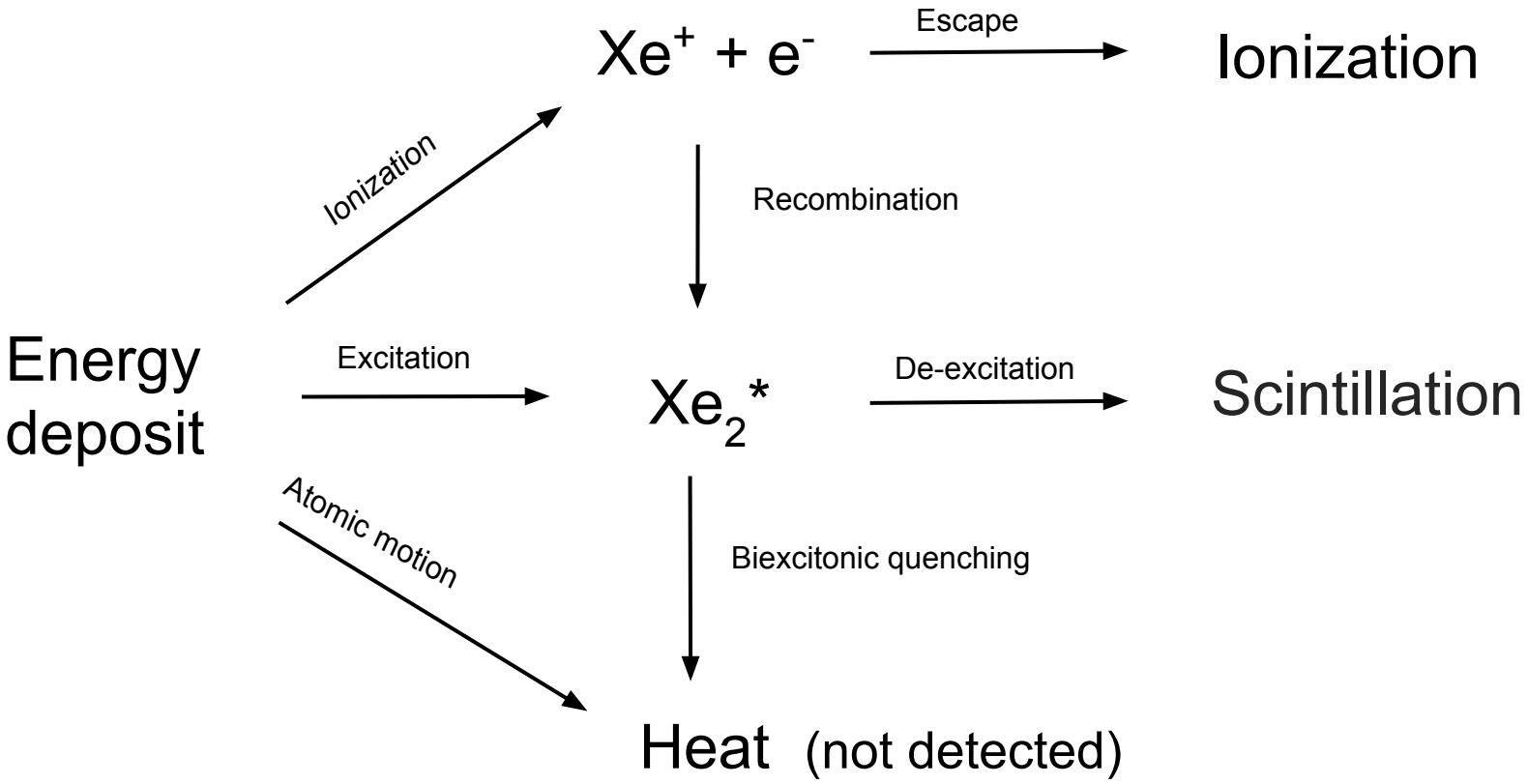
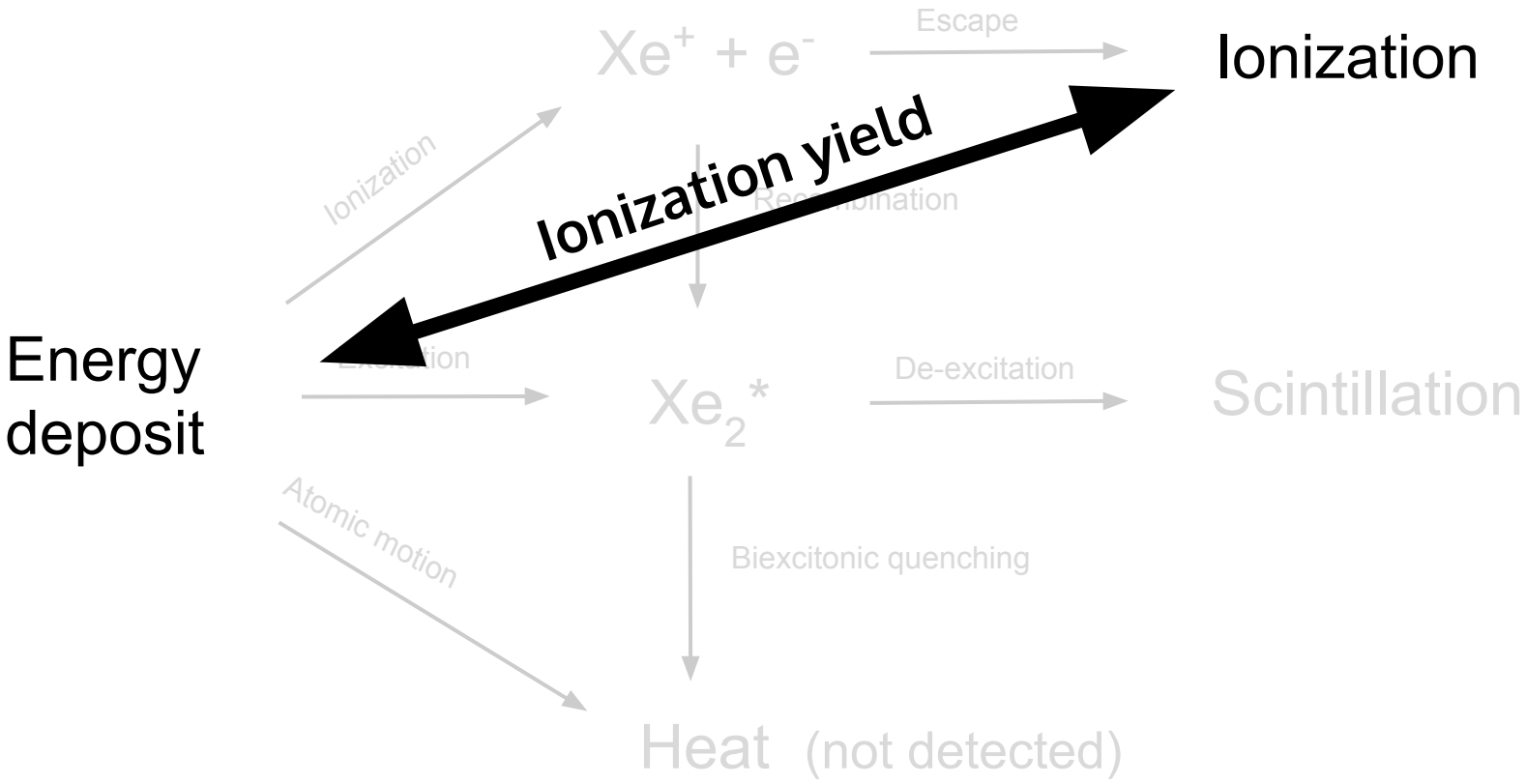


Image by CH Faham (Brown)

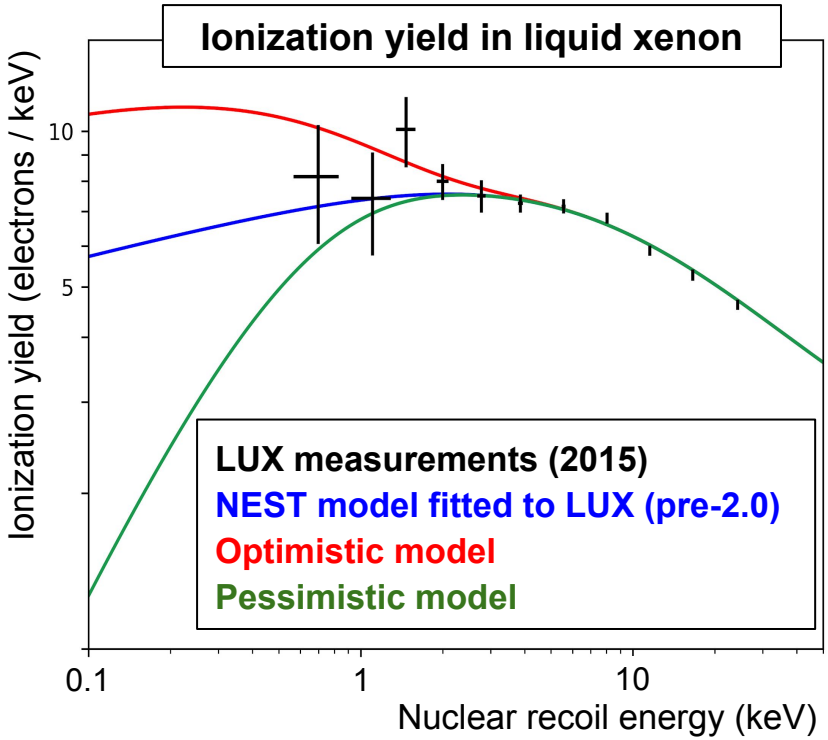
Signal production in xenon



Signal production in xenon



Systematic uncertainty for reactor CENNS



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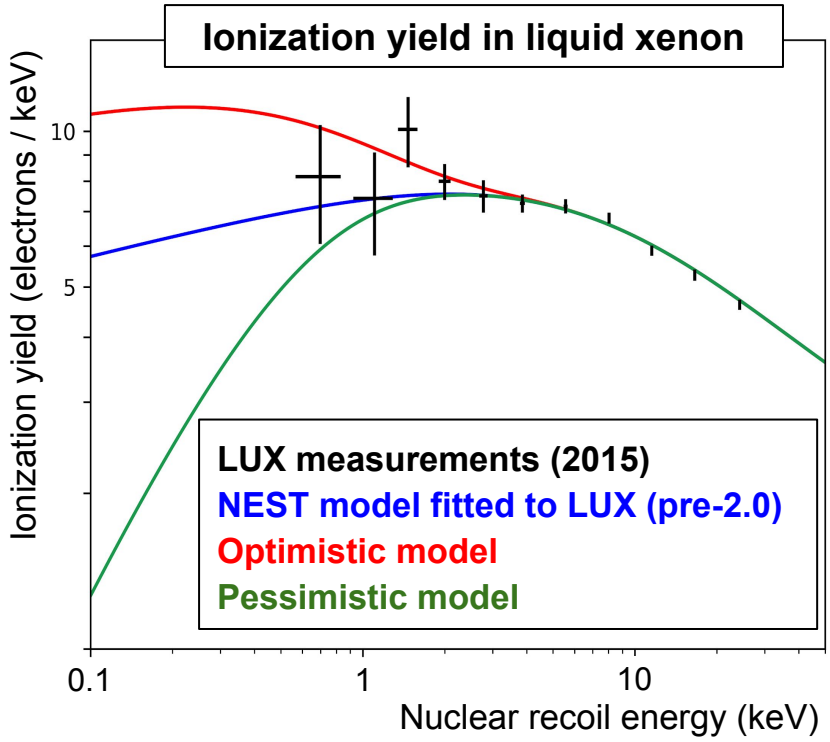
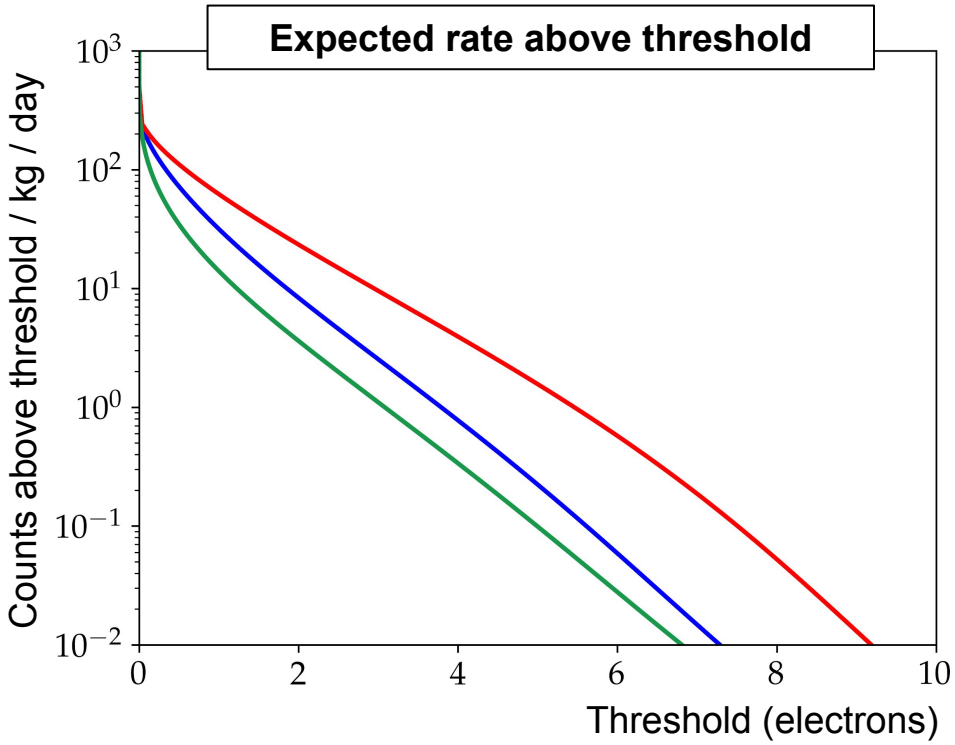
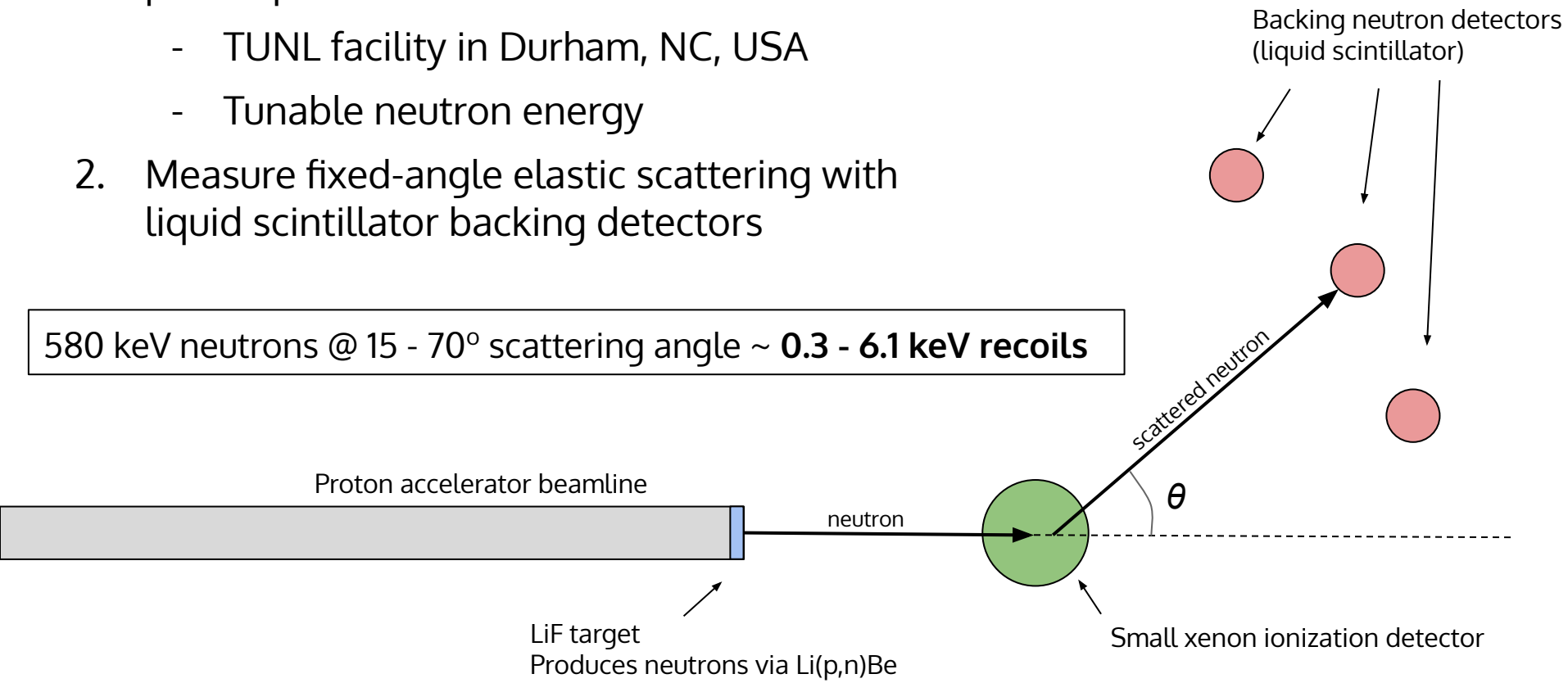




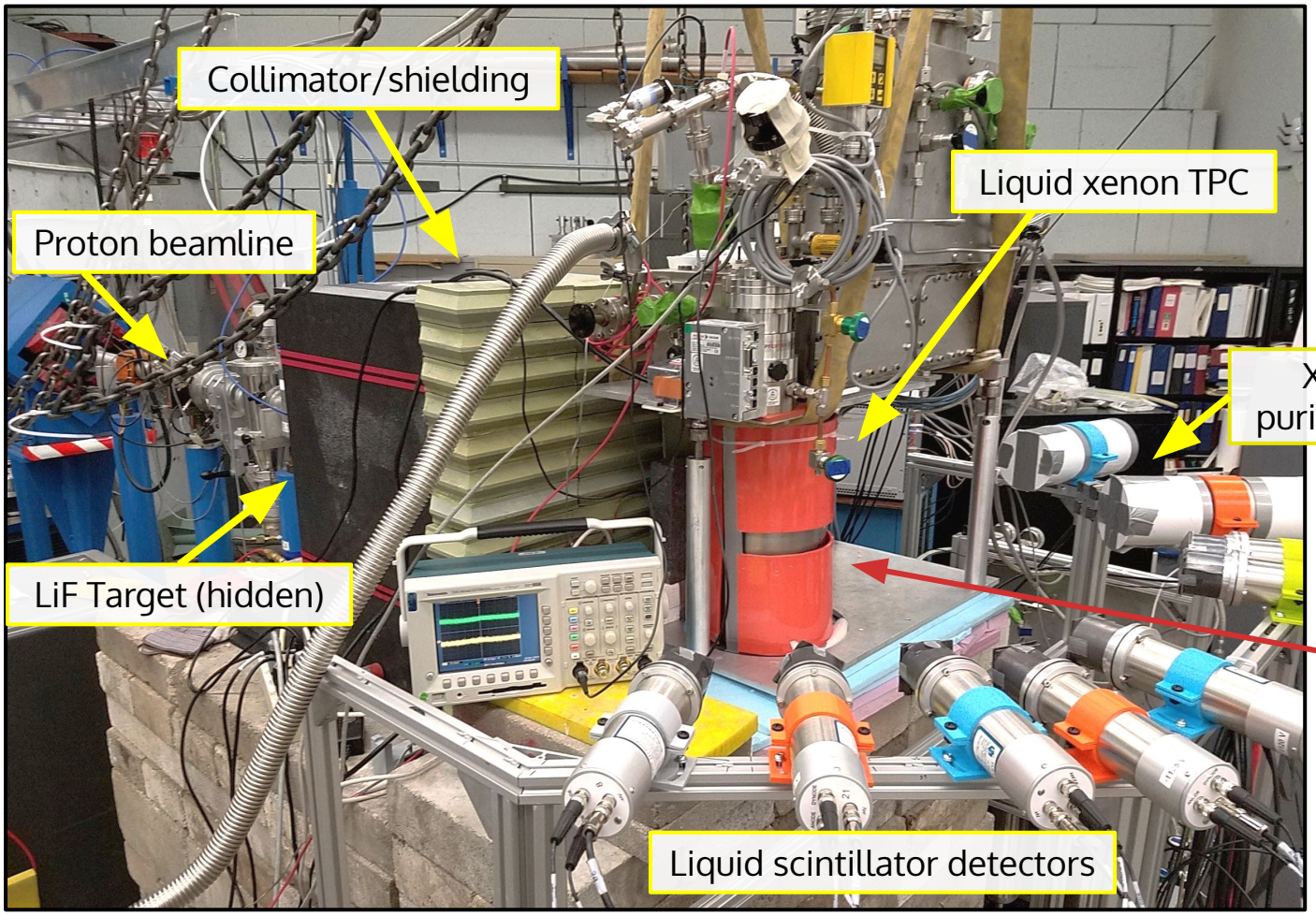
The XeNeu experiment at TUNL

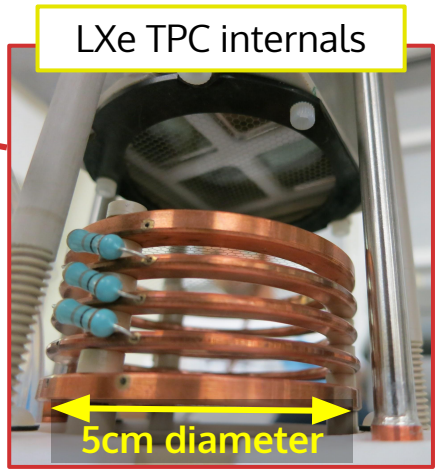
1. Monoenergetic neutrons produced by pulsed proton accelerator
   - TUNL facility in Durham, NC, USA
   - Tunable neutron energy
2. Measure fixed-angle elastic scattering with liquid scintillator backing detectors

580 keV neutrons @ 15 - 70° scattering angle ~ **0.3 - 6.1 keV recoils**



Experimental setup on beam



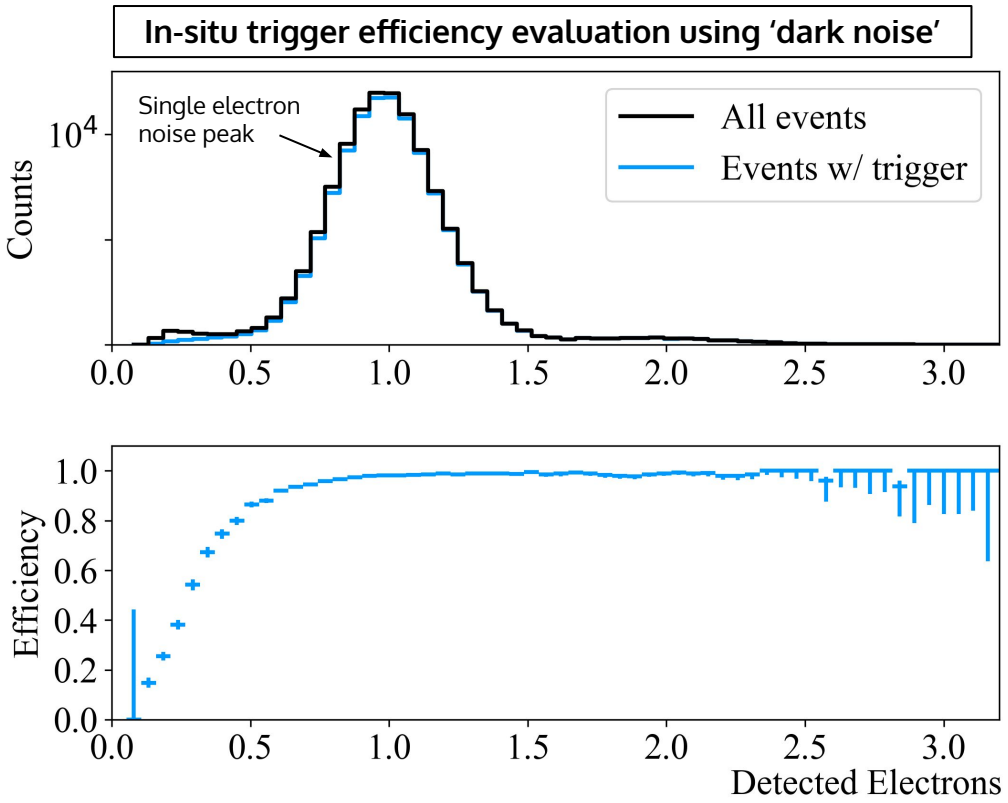


Triggering efficiencies

DAQ triggered on coincidence between Xe-TPC and any liquid scintillator detector

S2 trigger efficiency measured in-situ (see right)

- Dedicated data taken while digitizing the trigger logic signal
- Measure coincidences between trigger logic and the S2-signals that DO NOT provide the event trigger
- **>97% efficiency for single extracted electrons**



Measurement campaign

Completed over the course of two weeks, November 2018

Three electric field settings in TPC

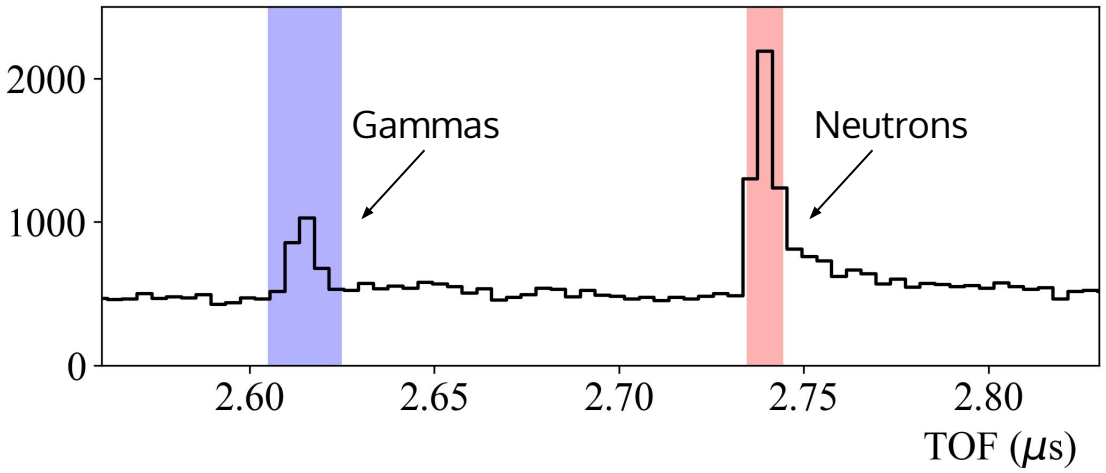
- 220V/cm, 550V/cm, 2.2kV/cm
- ~2 days of data at each field
- Fourth field obtained using data from above extraction grid (6.2 kV/cm)

Detector operation stable throughout

- Liquid & gas temperatures stable within 0.2K (~0.1%)
- Gas pressure stable within 0.02bar (~1%)

Data analysis & results

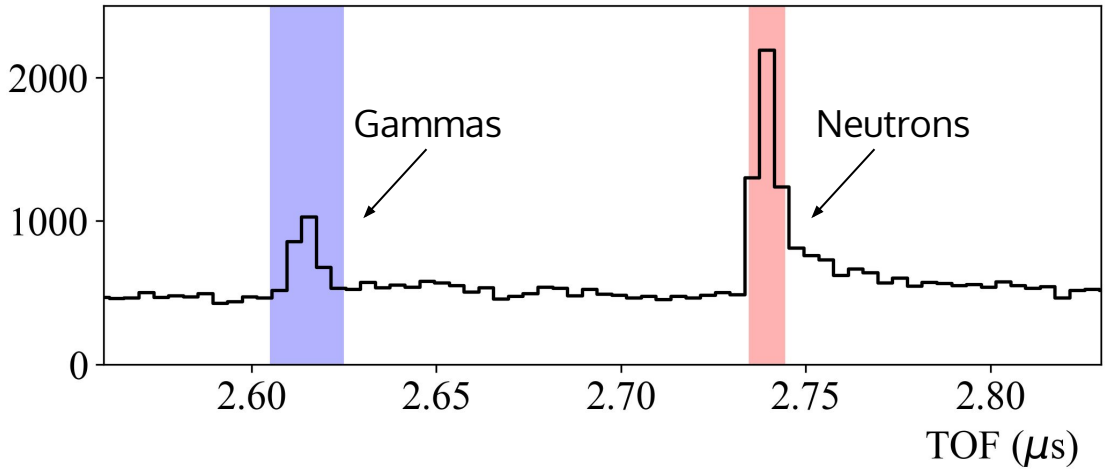
Background reduction using tagging detectors



Time-of-flight (TOF):

Time between beam pulse and liquid scintillator signal

Background reduction using tagging detectors



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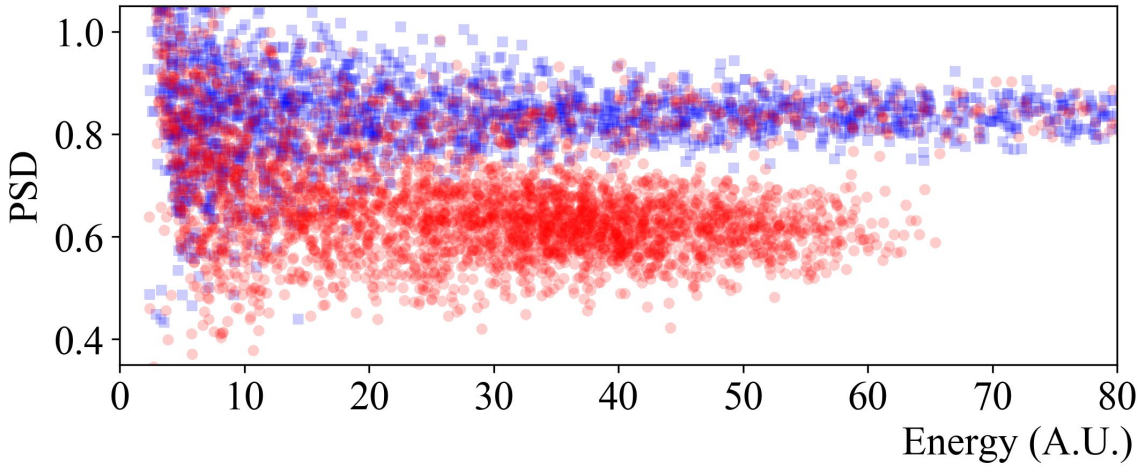
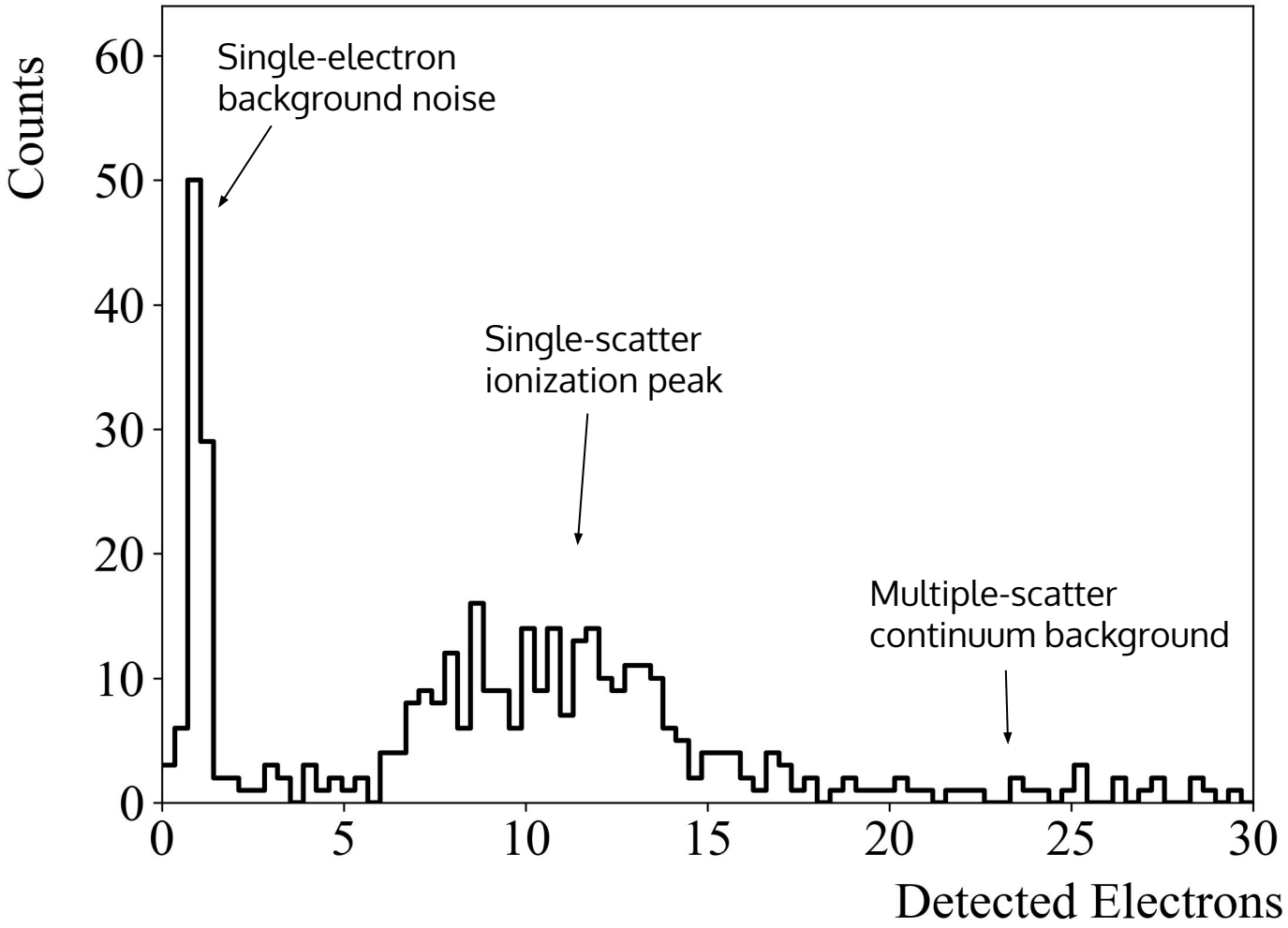


Pulse shape discrimination:

Liquid scintillator allows neutron/gamma separation via pulse shape

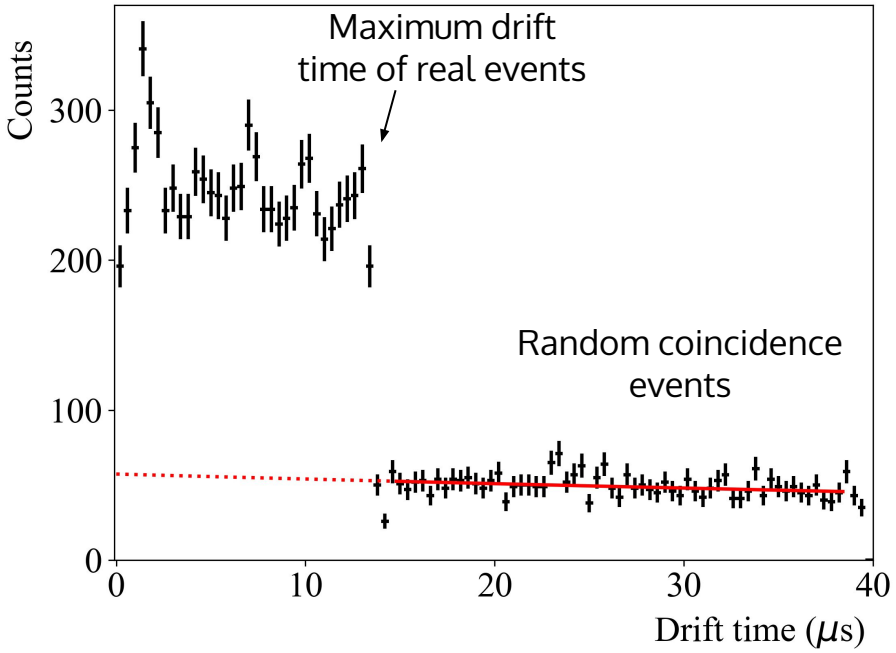
Example spectrum in XeTPC (1.6 keV recoils)



Background subtraction

Random coincidence backgrounds can be subtracted off

- Measure contribution using drift time information
- Extrapolate expected contribution to region of interest



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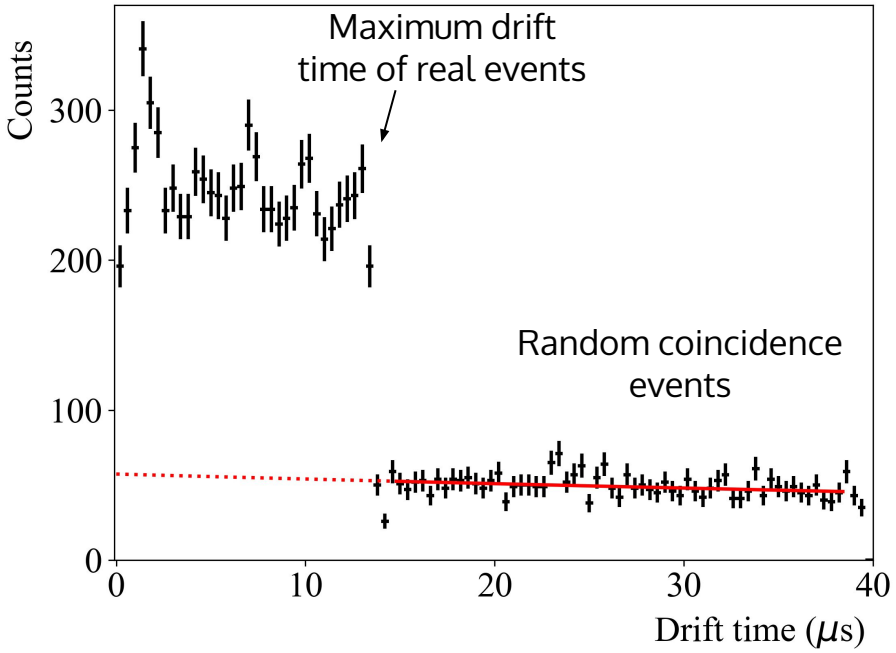
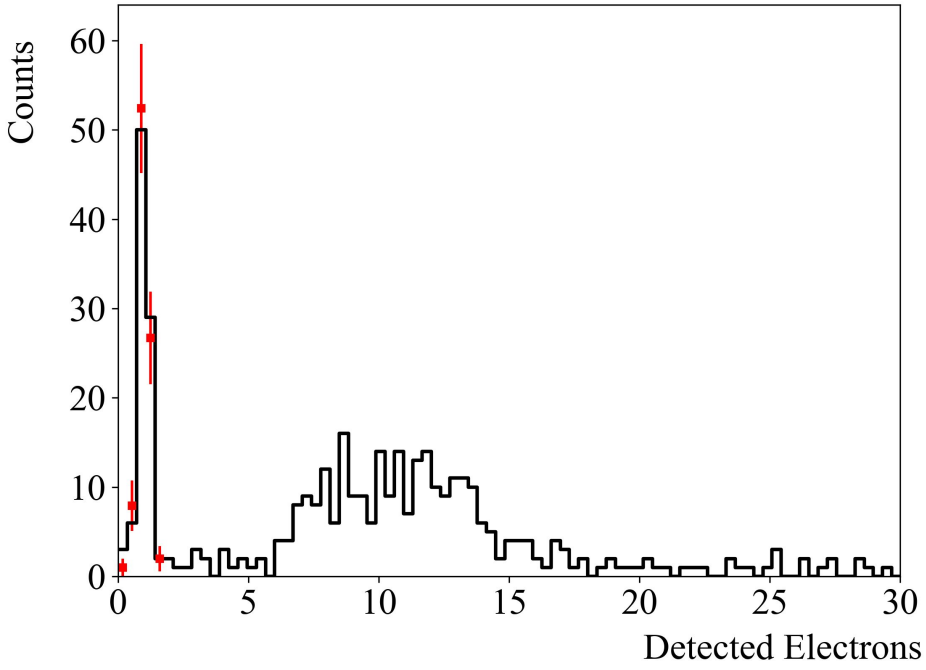




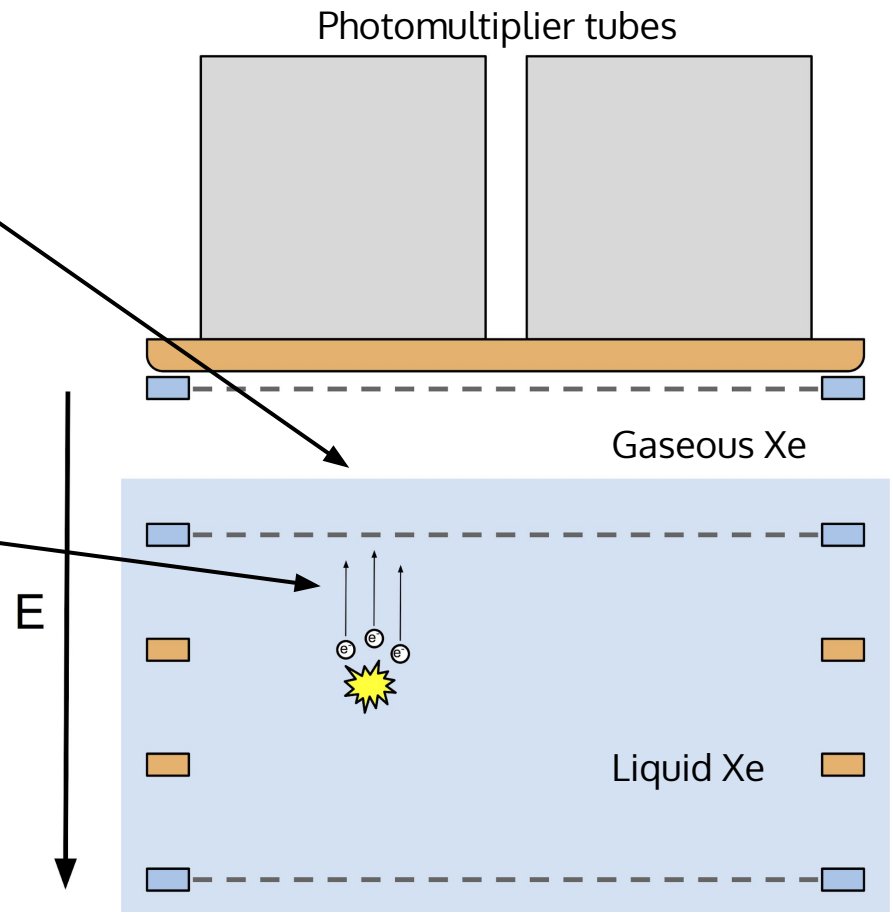
Calibrating charge loss mechanisms

Electron extraction efficiency

Electrons left behind at the liquid/gas barrier

Electron lifetime

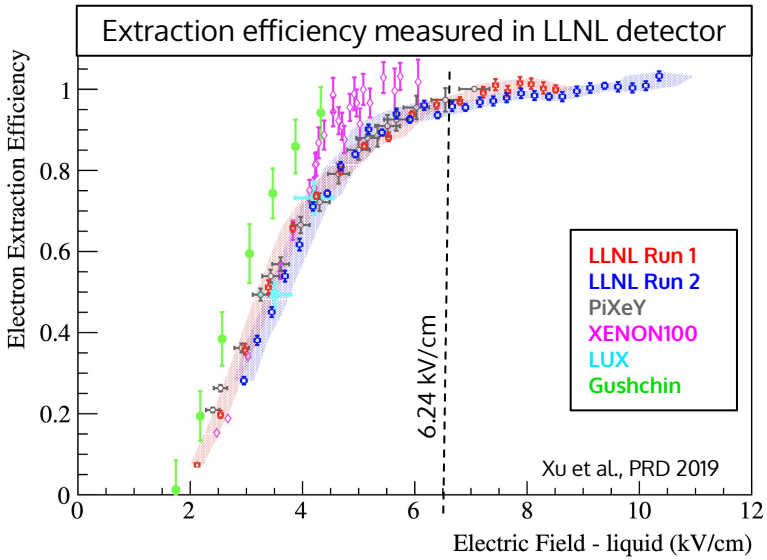
Electrons trapped by electronegative impurities in the liquid



Calibrating charge loss mechanisms

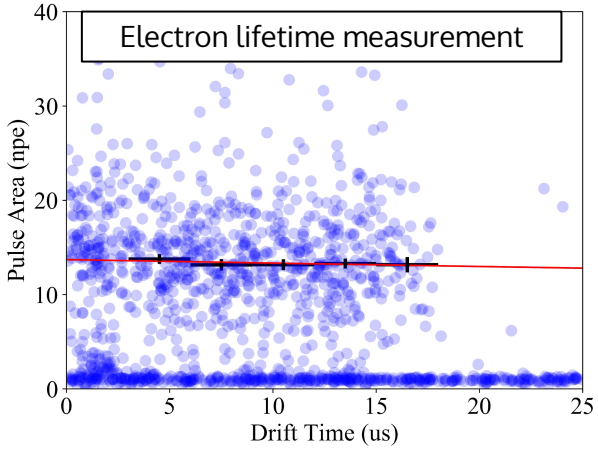
Electron extraction efficiency

- Calibrated in previous work PhysRevD.99.103024 (2018)
- Estimated to be 95.5% during this measurement

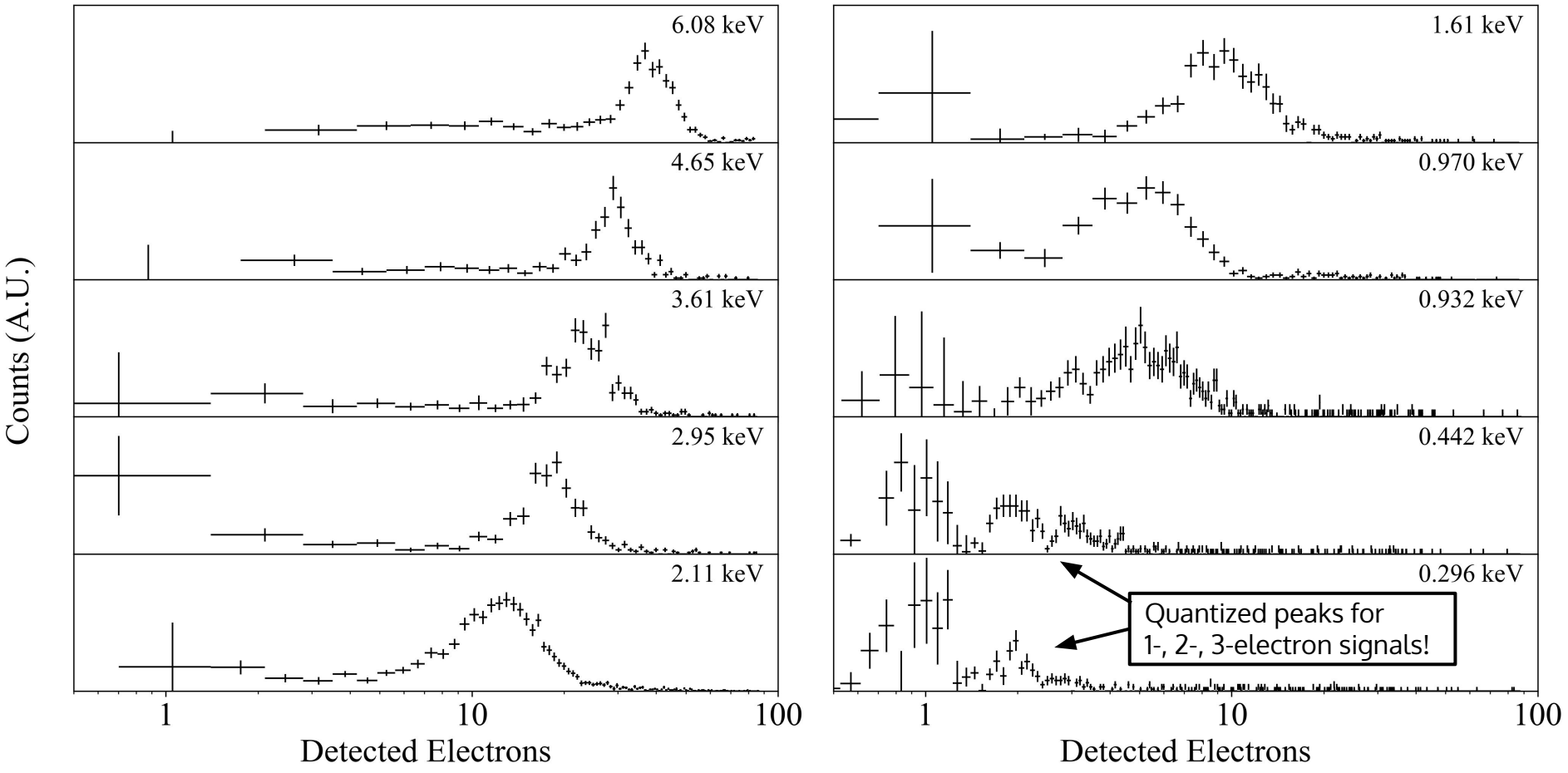


Electron lifetime

- Measured using 2 keV nuclear recoil peak
- $\tau = 232\ ^{+294}_{-84}$ μs
- No significant changes over time during entire measurement campaign



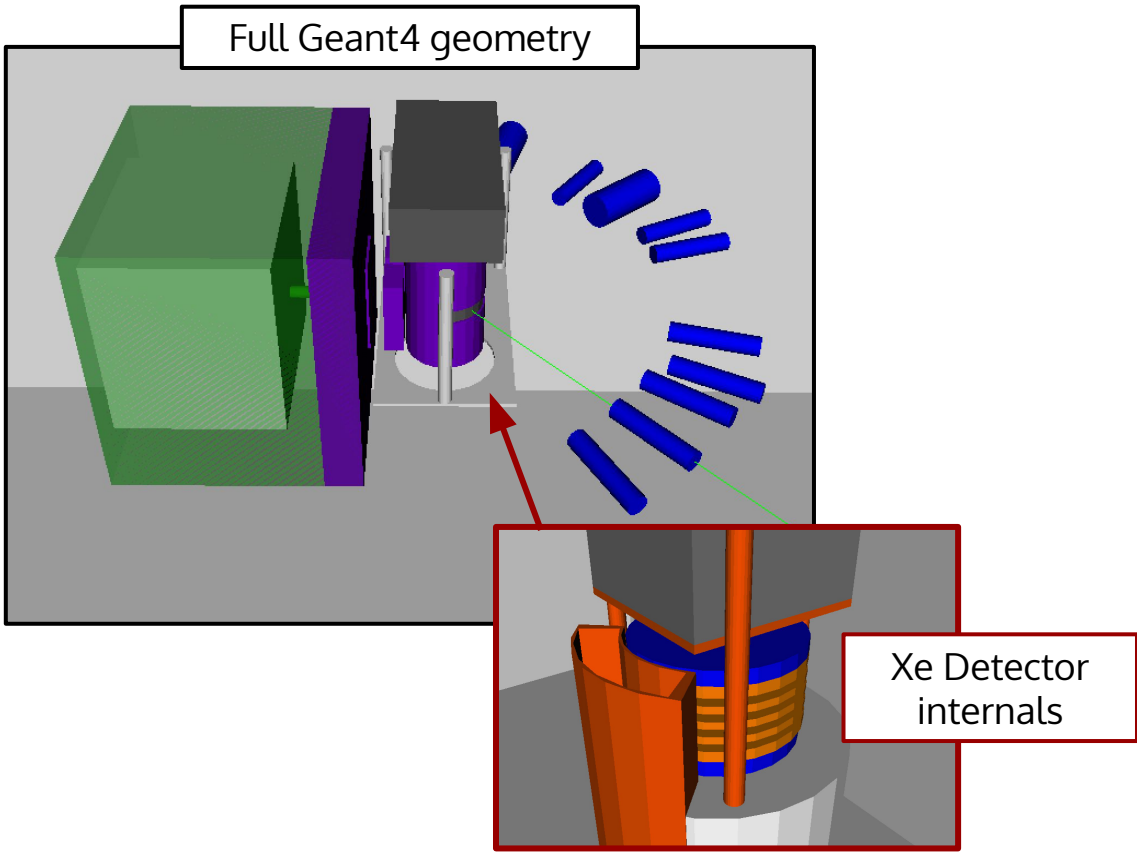
BG-subtracted, efficiency-corrected spectra



Simulations

Neutron propagation simulated with Geant4

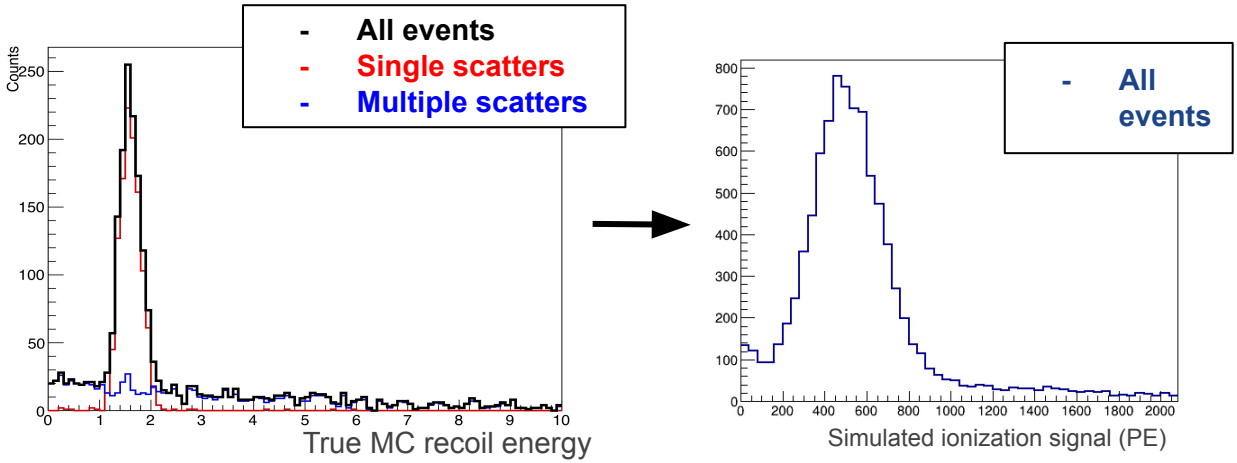
- Full detail of xenon detector internals
- Collimator + shielding surrounding detector made of polyethlyene, borated poly, lead
- Provides scattering volumes and energy deposited



Fitting with simulated spectra

Simulated spectra are smeared in four steps:

1. **Ionization production (variable charge yield)**
   a. Modeled using Gaussian distribution (Poisson distribution for lowest energies)
2. **Electron lifetime sampling**
   a. Binomial sampling
3. **Electron extraction sampling**
   a. Binomial sampling
4. **Single-electron electroluminescence statistics**
   a. Gaussian, ~20% width

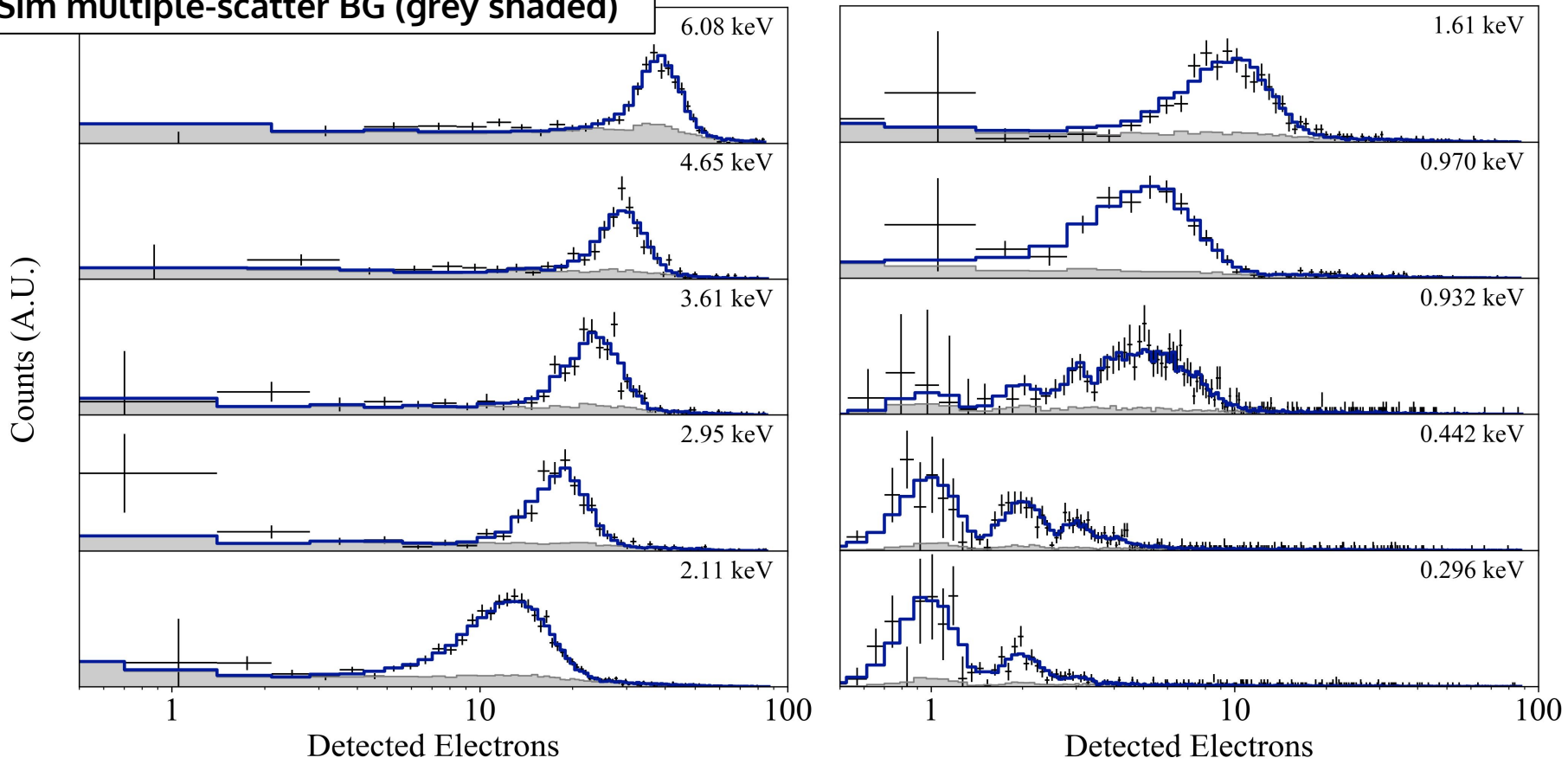


Three fit parameters:

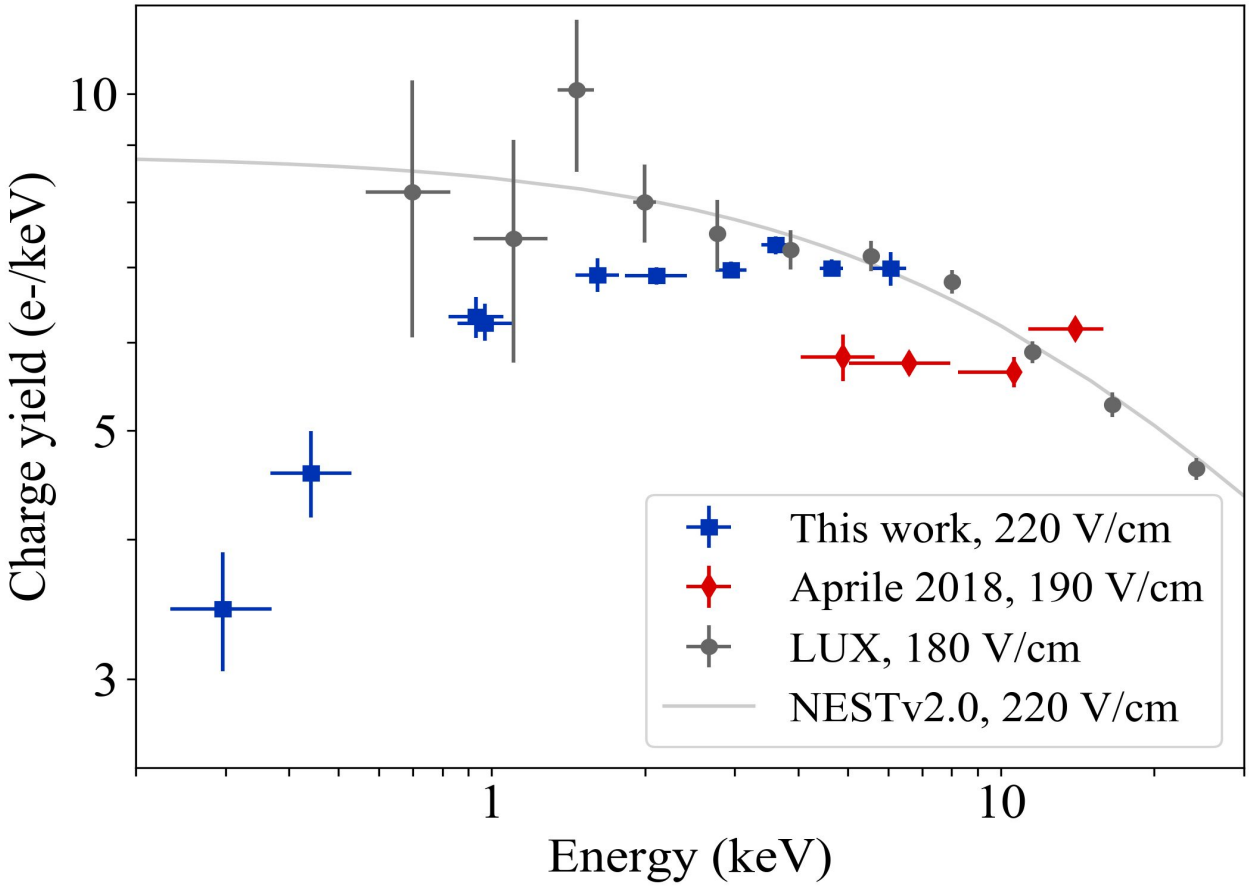
- Distribution mean (Q_y / charge yield)
- Distribution width (if gaussian)
- Overall normalization

Fitted ionization spectra from 6.1 to 0.3 keV

Data (black points)
Full simulated distributions (blue lines)
Sim multiple-scatter BG (grey shaded)



Ionization yield measurement



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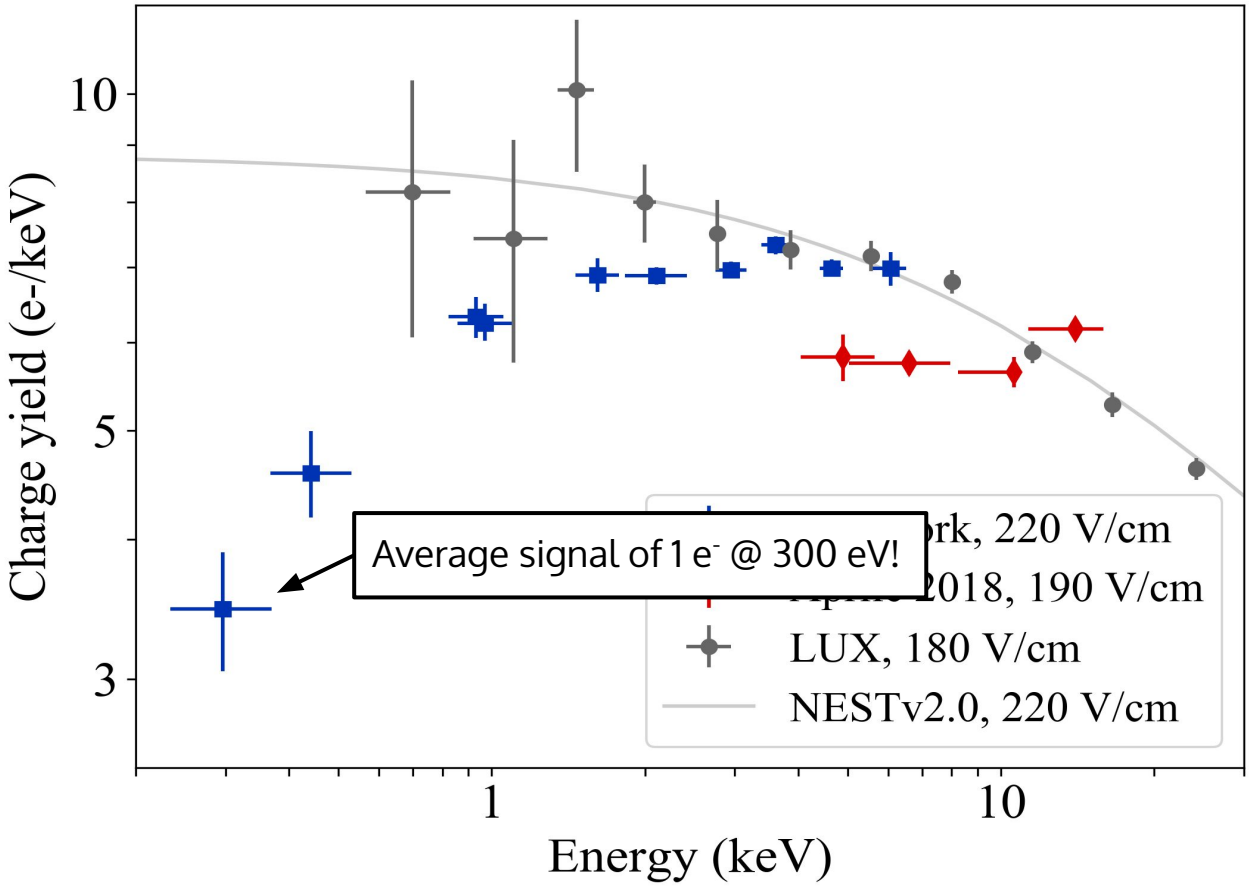
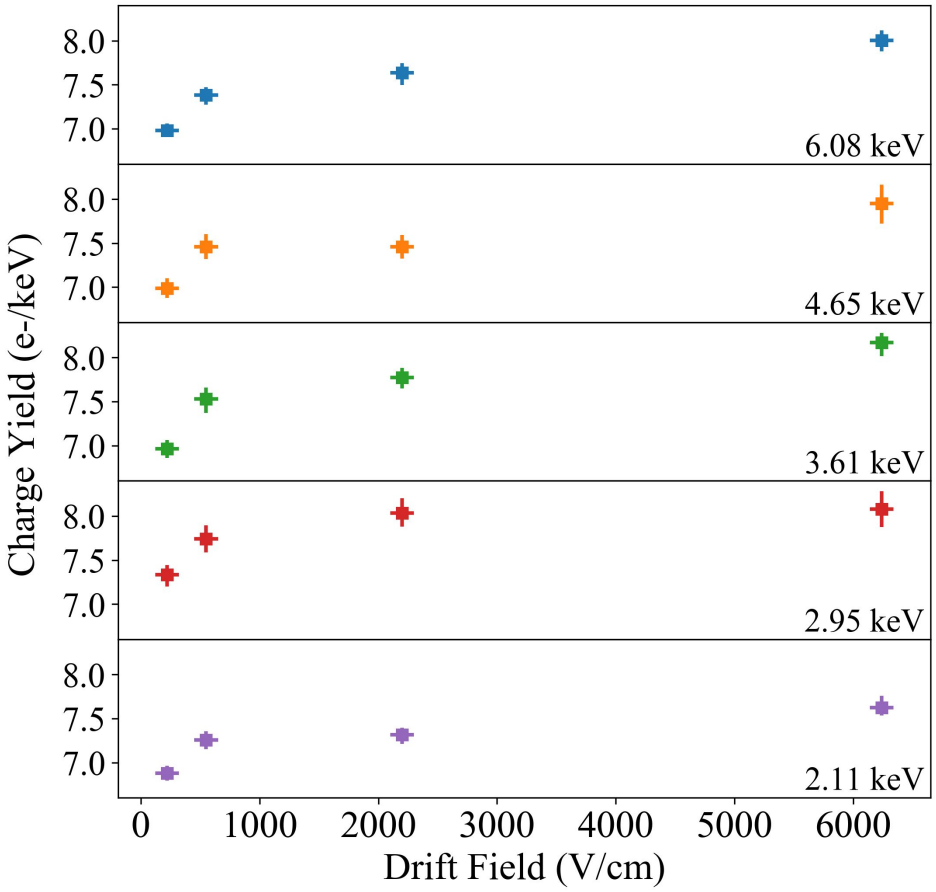
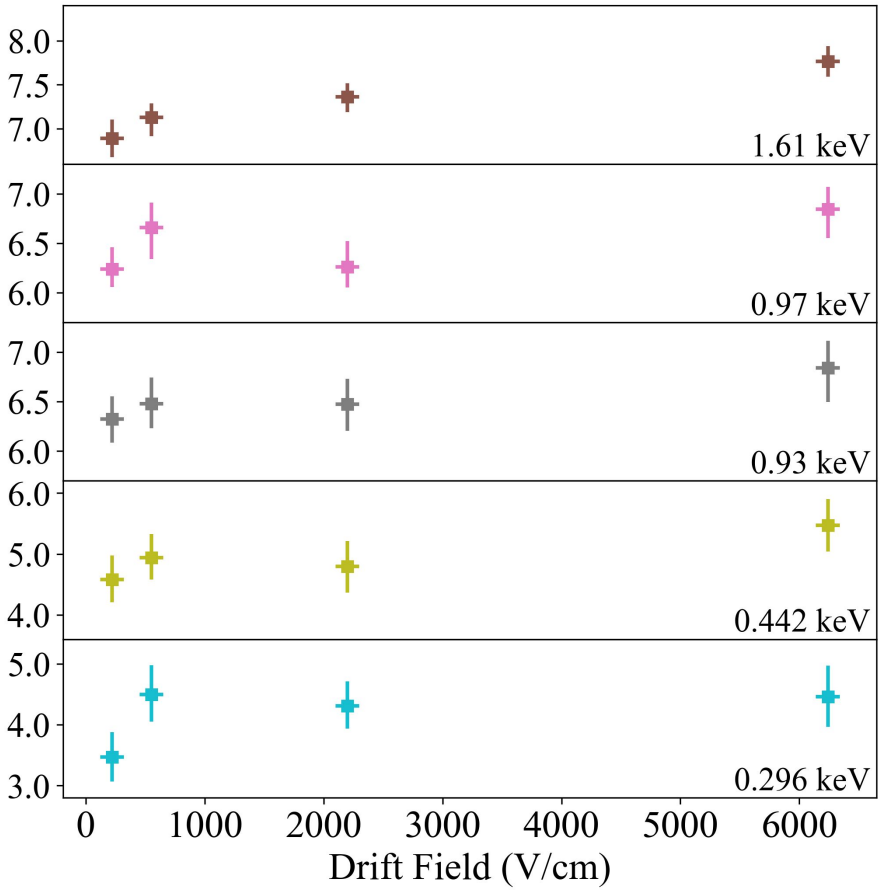
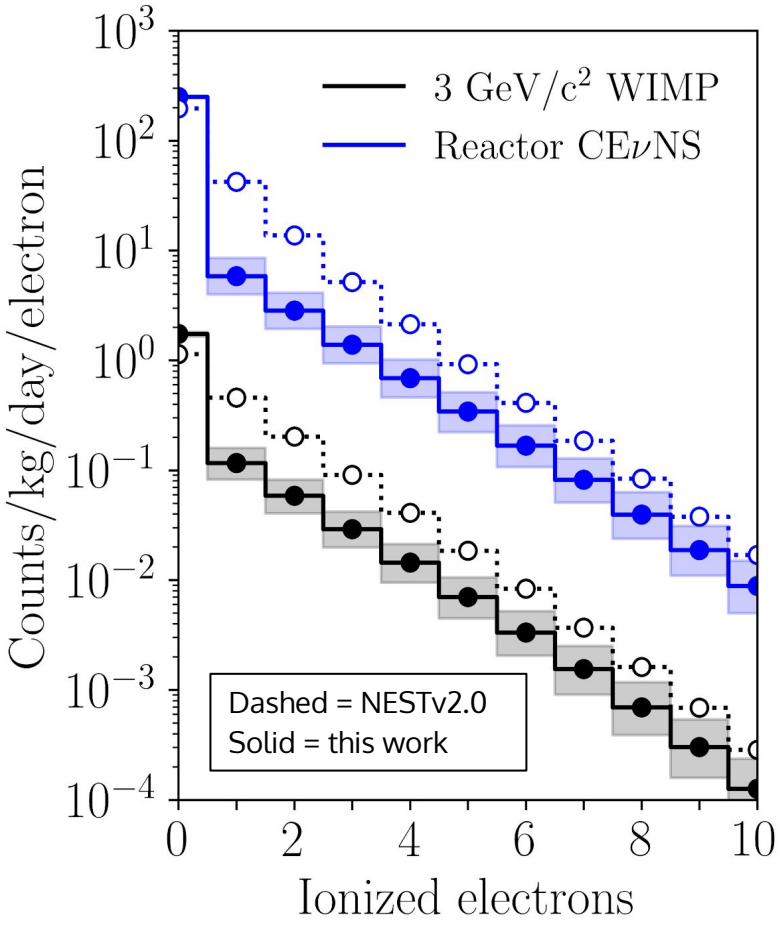


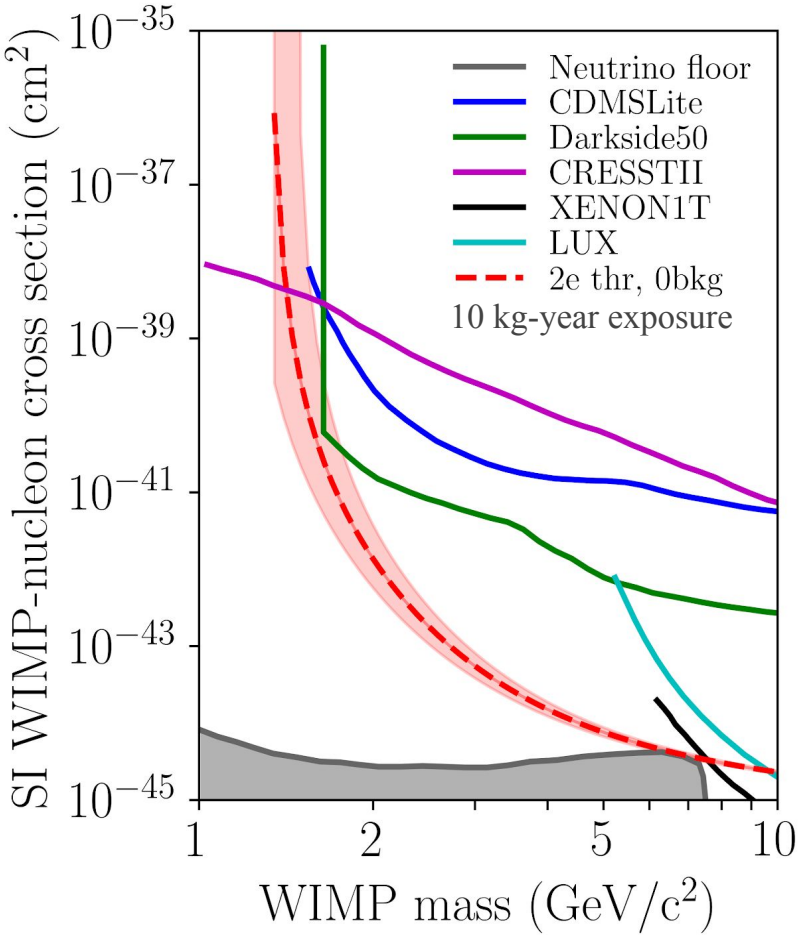
Dependence on applied electric field





Improved projections for CENNS and DM





Conclusions

- **Successful measurement of liquid xenon charge production from 0.3 - 6 keV**
  - Both energy and field-dependence
- **First measurement of nuclear recoils producing single-electron ionization signals in liquid xenon**
  - Average charge signal at 0.3 keV is ~1 electron
  - Approaching the “quantum limit” of liquid xenon detectors
- **Enables precise predictions of signal rates for low-energy CENNS signals (and low-mass WIMPs) in dual-phase xenon detectors**

The Team

Lawrence Livermore National Lab:

- Jingke Xu
- Sergey Pereverzev
- Adam Bernstein
- Kareem Kazkaz
- Tomi Akindele

UC Davis:

- Daniel Naim
- Mani Tripathi

Duke/TUNL:

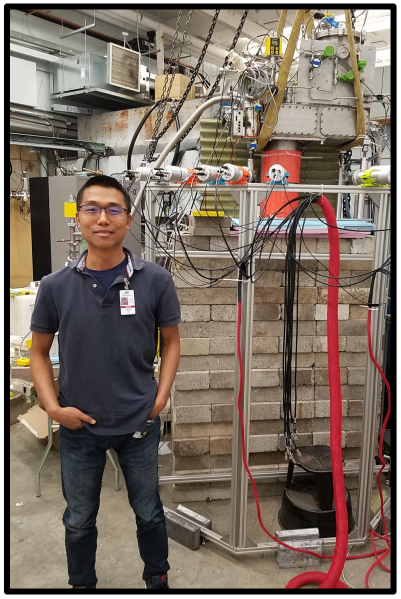
- Connor Awe
- Long Li
- Sam Hedges
- Jay Runge
- Peibo An
- Phil Barbeau

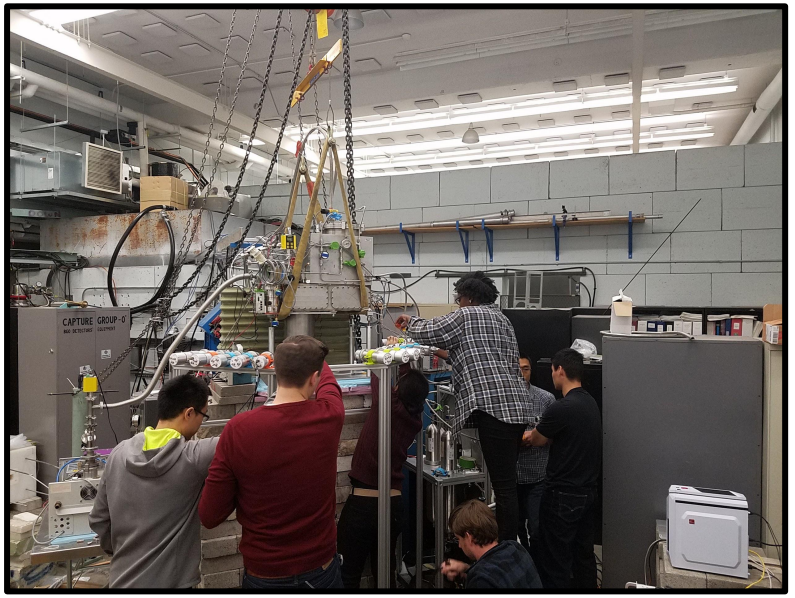
Stanford:

- Brian Lenardo

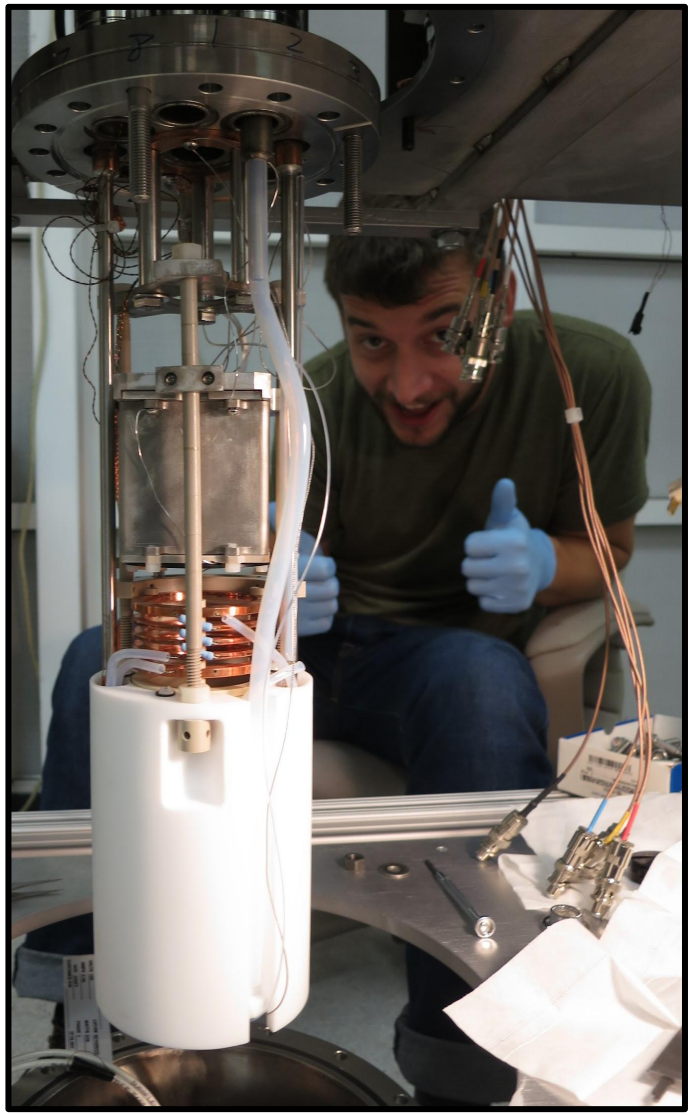
Now at UChicago:

- Jimmy Kingston

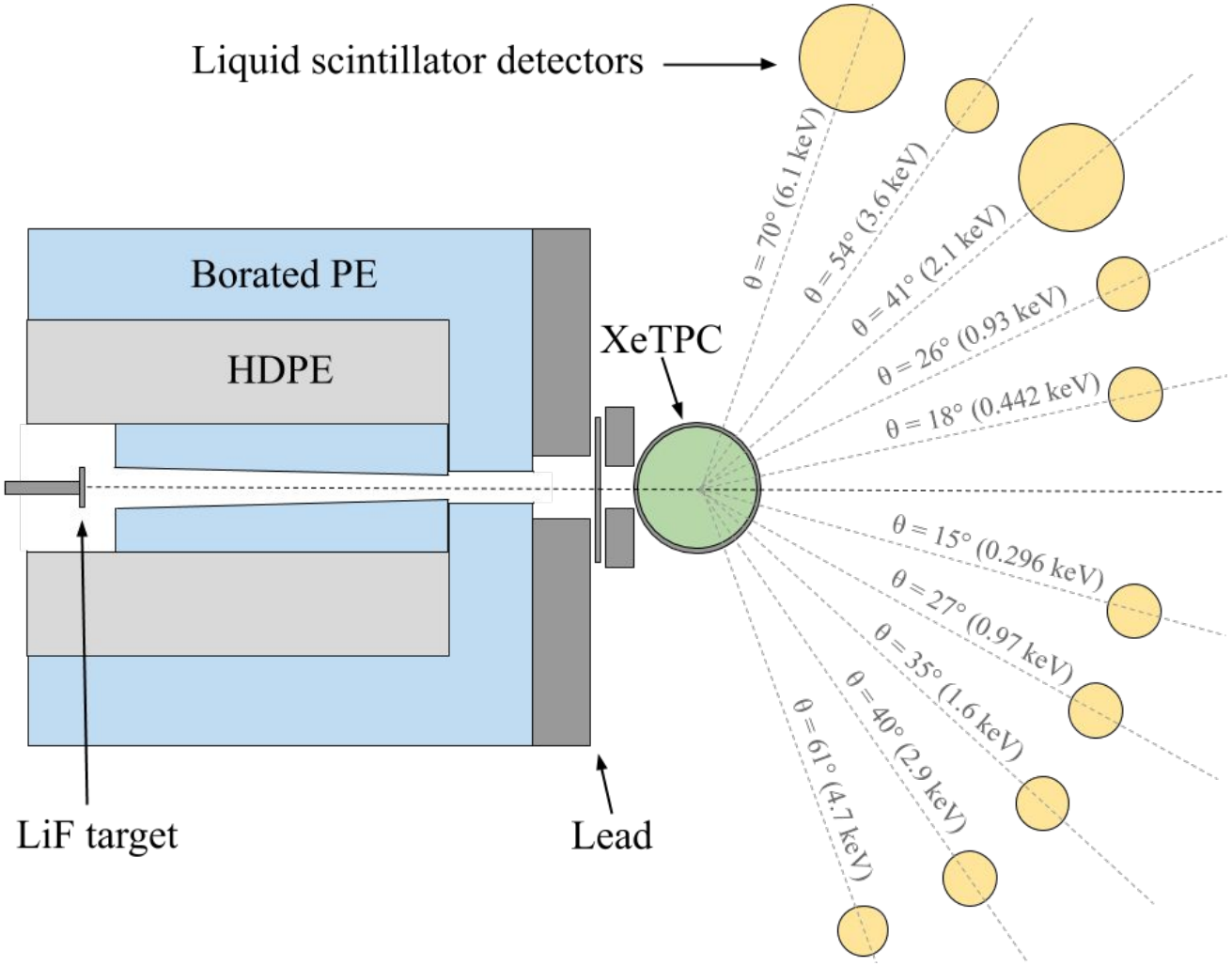




Thank you!



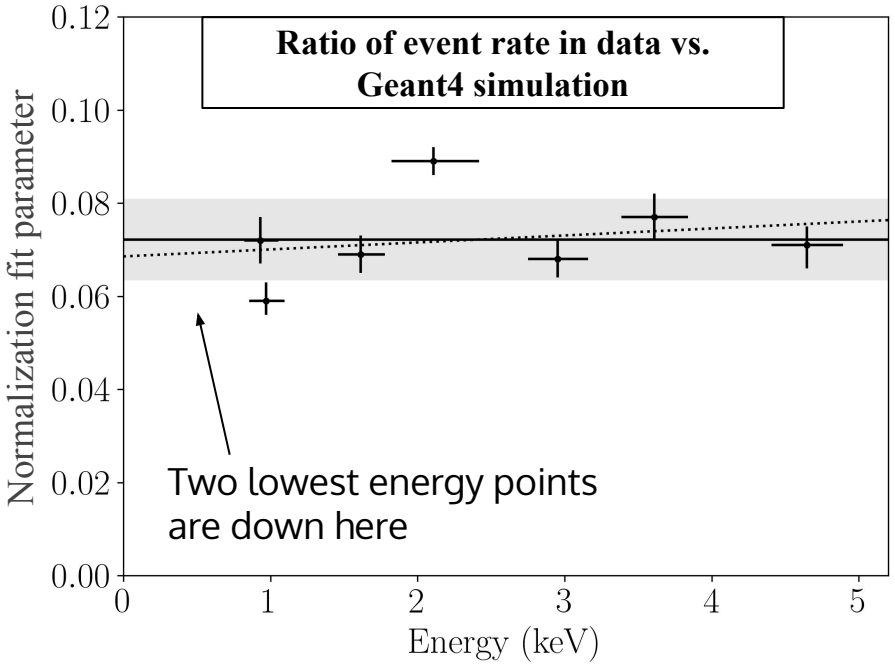
Experiment schematic



Scaling the two lowest-energy spectra

Normalization parameter needs to be extrapolated using normalizations at higher energies

- Essentially, assumes angular cross section built into Geant4 is accurate
- We allow for two different sources of systematic uncertainty (below)



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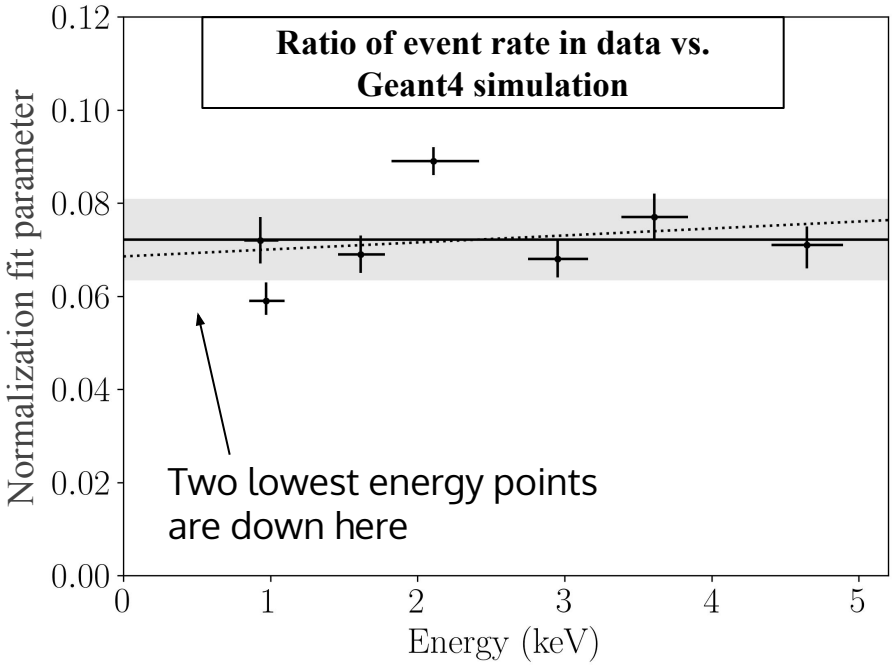
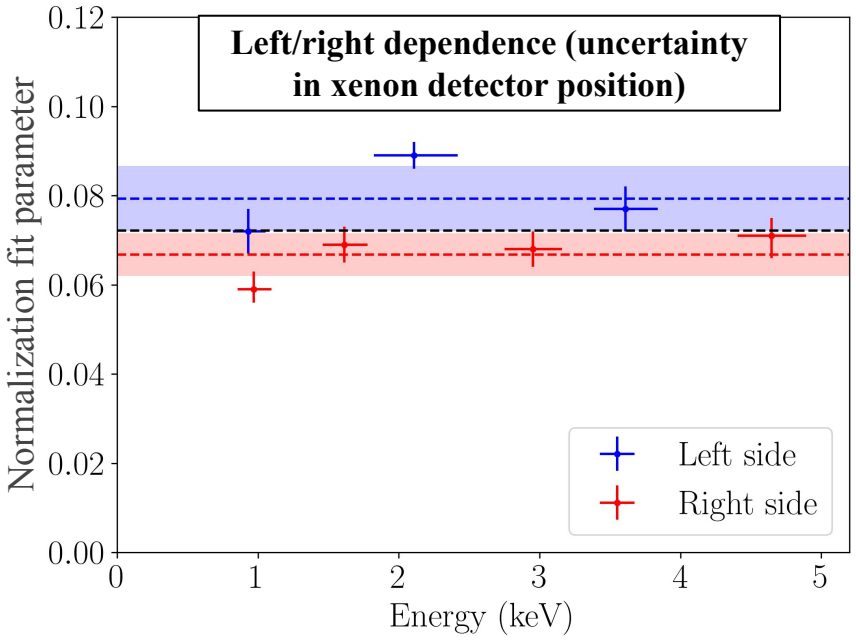
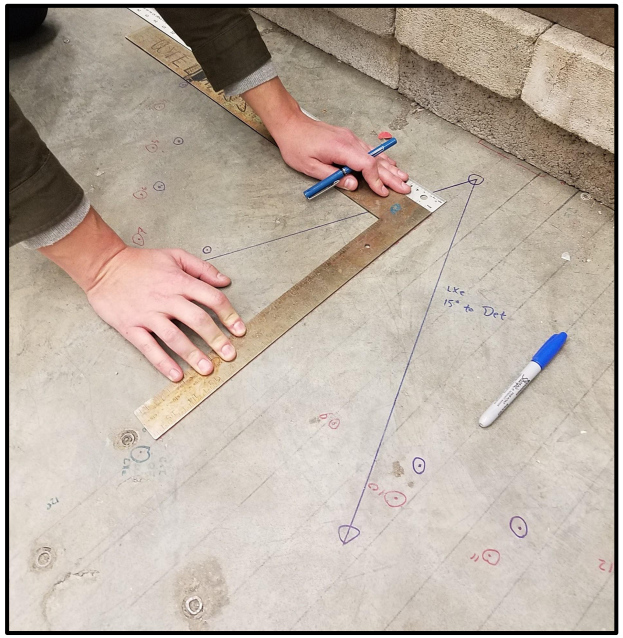




Energy uncertainties: Neutron energy & detector positions

1. **Incident neutron energy measured via time-of-flight**
   a. 579 +/- 3 keV (10 keV width)
   b. Constant in time
2. **Liquid scintillator detector positions measured via plumb bob**
   a. Estimated <5mm uncertainty in position
      i. ~1 -- 3 % uncertainty in recoil energy

$$E_{\mathrm{nr}} = E_n \frac{4 m_n m_{\mathrm{Xe}}}{\left(m_n + m_{\mathrm{Xe}}\right)^2} \frac{1 - \cos\left(\theta_{\mathrm{CM}}\right)}{2}$$

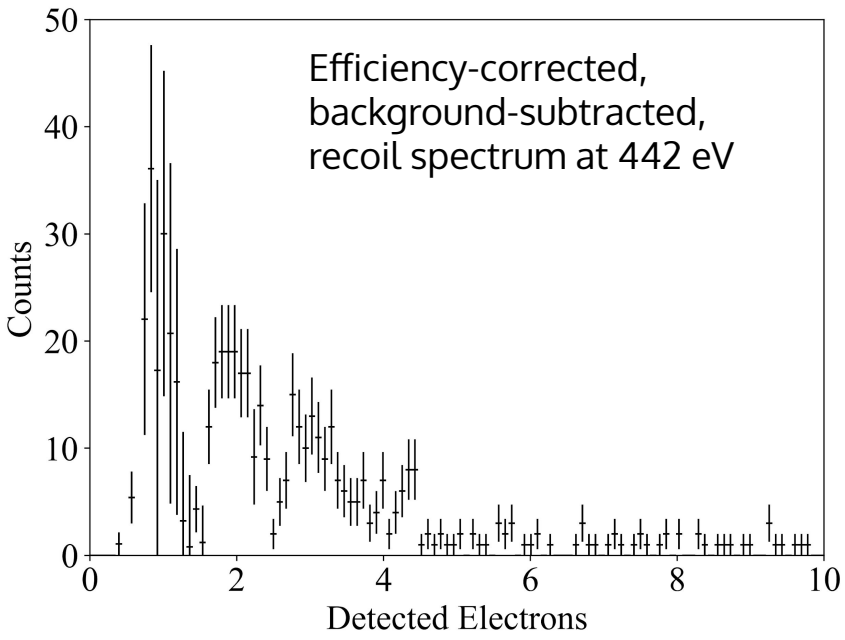


Fitting the two lowest-energy spectra

Low-energy distributions truncated at single electrons (no 0-electron events)

To get ionization yield:

- **Fix normalization to Geant4 prediction**
- **Assume Poisson distribution for ionization fluctuations**
  - Consistent with model-independent estimation (counting events in each peak)



Total uncertainty budget

TABLE I: Charge yield as a function of energy, measured at four different applied electric fields. The energies and their error bars are the mean and central 68-percentile of the simulated recoil energy distribution for single-scatter events in each BD channel. Uncertainties in the energy (denoted ΔE) are divided into two parts: uncorrelated and correlated (explained in the text). The yields are given with the statistical uncertainties from the fit; systematic uncertainties in the yield are shown in separate columns/rows and are described in Section IV D.

BD	E (keV)	ΔE		Q_y				Scaling syst.	Modeling syst.
		Uncorr.	Corr.	220V/cm	550V/cm	2.2kV/cm	6.3kV/cm		
1	$6.08^{+0.42}_{-0.52}$	±3.3%	$^{+0.04}_{-0.04}$	$6.98^{+0.08}_{-0.08}$	$7.382^{+0.09}_{-0.11}$	$7.63^{+0.11}_{-0.14}$	$8.00^{+0.12}_{-0.13}$	-	-
2	$4.65^{+0.25}_{-0.24}$	±0.8%	$^{+0.04}_{-0.04}$	$6.99^{+0.12}_{-0.11}$	$7.46^{+0.14}_{-0.14}$	$7.46^{+0.14}_{-0.14}$	$7.95^{+0.21}_{-0.23}$	-	-
3	$3.61^{+0.23}_{-0.22}$	±0.9%	$^{+0.04}_{-0.03}$	$7.33^{+0.11}_{-0.13}$	$7.74^{+0.15}_{-0.15}$	$8.03^{+0.17}_{-0.15}$	$8.08^{+0.20}_{-0.20}$	-	-
4	$2.95^{+0.21}_{-0.20}$	±1.1%	$^{+0.04}_{-0.03}$	$6.96^{+0.10}_{-0.10}$	$7.53^{+0.13}_{-0.16}$	$7.77^{+0.11}_{-0.12}$	$8.17^{+0.11}_{-0.15}$	-	-
5	$2.11^{+0.31}_{-0.28}$	±1.3%	$^{+0.03}_{-0.03}$	$6.88^{+0.09}_{-0.09}$	$7.26^{+0.10}_{-0.10}$	$7.31^{+0.08}_{-0.10}$	$7.63^{+0.14}_{-0.09}$	-	-
6	$1.61^{+0.16}_{-0.15}$	±1.5%	$^{+0.03}_{-0.03}$	$6.89^{+0.21}_{-0.22}$	$7.13^{+0.16}_{-0.21}$	$7.36^{+0.15}_{-0.18}$	$7.764^{+0.18}_{-0.17}$	-	-
7	$0.97^{+0.13}_{-0.11}$	±2.0%	$^{+0.03}_{-0.03}$	$6.23^{+0.22}_{-0.18}$	$6.66^{+0.25}_{-0.32}$	$6.26^{+0.26}_{-0.21}$	$6.84^{+0.23}_{-0.29}$	-	-
8	$0.93^{+0.12}_{-0.11}$	±2.0%	$^{+0.03}_{-0.03}$	$6.32^{+0.23}_{-0.24}$	$6.48^{+0.27}_{-0.25}$	$6.47^{+0.26}_{-0.30}$	$6.84^{+0.27}_{-0.35}$	-	-
9	$0.442^{+0.088}_{-0.074}$	±3.0%	$^{+0.016}_{-0.018}$	$4.58^{+0.39}_{-0.38}$	$4.94^{+0.38}_{-0.36}$	$4.80^{+0.41}_{-0.43}$	$5.47^{+0.43}_{-0.43}$	-5.9%	5.5%
10	$0.296^{+0.074}_{-0.062}$	±3.6%	$^{+0.018}_{-0.014}$	$3.47^{+0.41}_{-0.40}$	$4.50^{+0.48}_{-0.45}$	$4.31^{+0.40}_{-0.37}$	$4.46^{+0.50}_{-0.50}$	+6.4%	11.0%
Electron lifetime systematic				±2.9%	±2.5%	±2.1%	-		
Extraction efficiency systematic				+2.0% / −1.5%					