An Absolute Calibration of Sub-1 keV Nuclear Recoils in Liquid Xenon Using D-D Neutron Scattering Kinematics in the LUX Detector

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Brown University

Dissertation Defense
May 10th, 2016

*** Not just Sub-1 keV: calibration over energy range spanning 0.7-74 keV**

Thanks

- Ian Dell'Antonio and Meenakshi Narain for acting as thesis committee members
- Brown Group: Rick Gaitskell, James Verbus, Samuel Chan, Dongqing Huang, Casey Rhyne, Will Taylor, and others
- Members of LUX and LZ for their ongoing collaboration

Please note

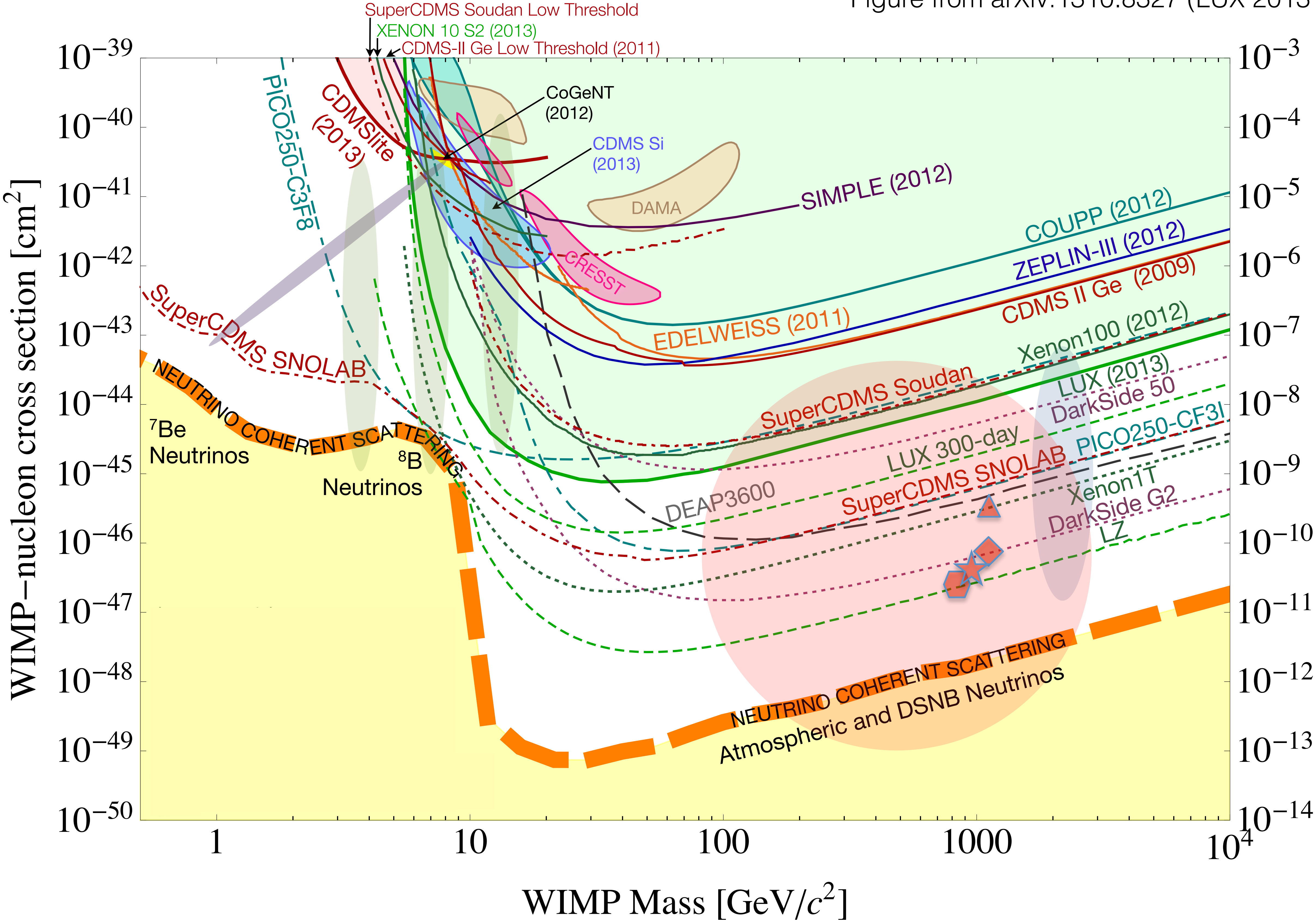
- Parts of this thesis are based directly on manuscripts in preparation for journal submission. I am the corresponding author of both articles.

[1] J. R. Verbus, C. Rhyne, D. C. Malling, M. Genecov, S. Ghosh, A. Moskowitz, S. Chan, J. J. Chapman, L. de Viveiros, C. H. Faham, S. Fiorucci, D. Q. Huang, M. Pangilinan, W. C. Taylor, and R. J. Gaitskell, "Proposed low energy absolute calibration of nuclear recoils in a dual-phase noble element TPC using D-D neutron scattering kinematics," (2016), in preperation.

[2] D. S. Akerib *et al.*, "Low-energy (0.7–74 kev) nuclear recoil calibration of the LUX dark matter experiment using D-D neutron scattering kinematics," (2016), in preperation.

The WIMP direct detection result landscape as of late 2013

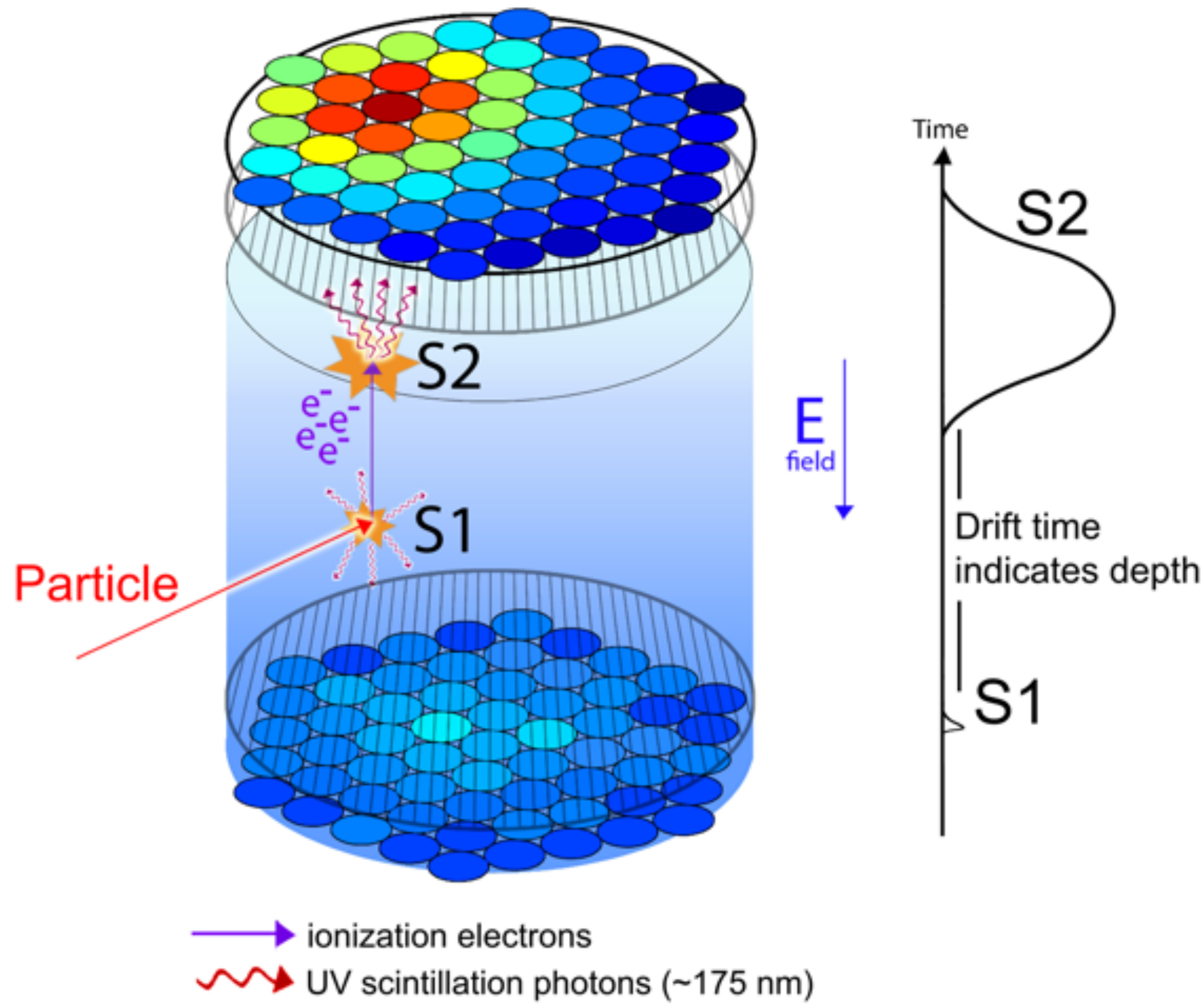
Figure from arXiv:1310.8327 (LUX 2013 added)



The LUX Detector

The LUX dark matter detector

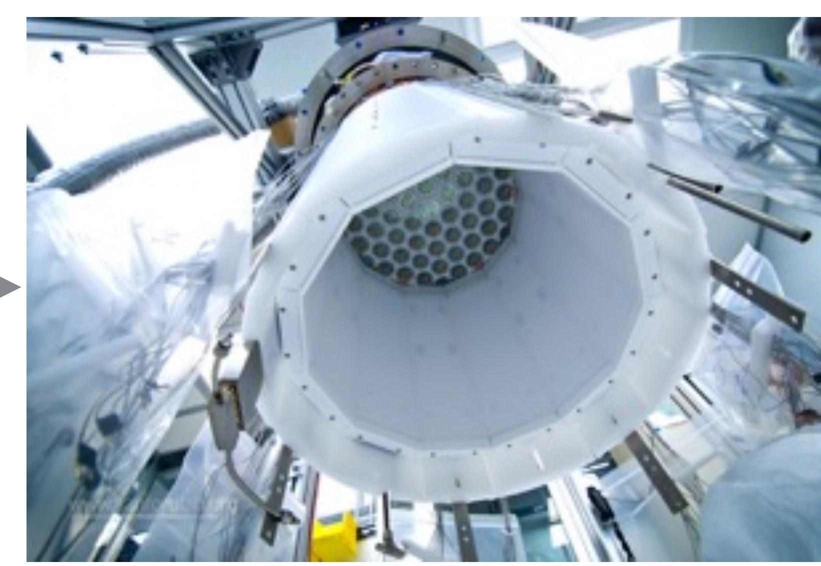
- Virtues of a dark matter detector
  - Massive, radioactively quiet, discriminatory, low threshold
- What is LUX?
  - A particle detector
  - A monolithic wall-less fiducial region within 370 kg, two-phase Xe TPC
  - Viewed by 122 Photomultiplier Tubes
  - Able to reconstruct (x, y, z) for each event
  - Exceptional self-shielding from outer xenon layer
  - Discrimination between electronic and nuclear recoils (99.6%)
- How would LUX see dark matter?
  - It detects scintillation photons and ionized electrons created by particle interactions
  - If dark matter interacted with a xenon atom, energy transferred to that atom would be visible to LUX
  - g_1=0.115 and g_2 = 11.4 are the amplification factors for each quanta during the D-D calibration period
  - n_γ and n_e are the fundamental measured quantities



LUX background reduction techniques

1492 m underground

- **4850 ft (1492 m) underground in the Black Hills of South Dakota**
  - **Reduces muon flux by $x10^{-7}$**
- Surrounded by a 8 m diameter water shield
  - External cavern neutron and gamma backgrounds are subdominant to detector components
- Central 145 kg fiducial volume used for WIMP search
  - Gamma rays from detector components reduced by $x10^{-4}$ due to xenon self shielding
- **Final result:** Reduction of gamma and neutron background to expectation of <1 signal event in 300 days of search (after discrimination)



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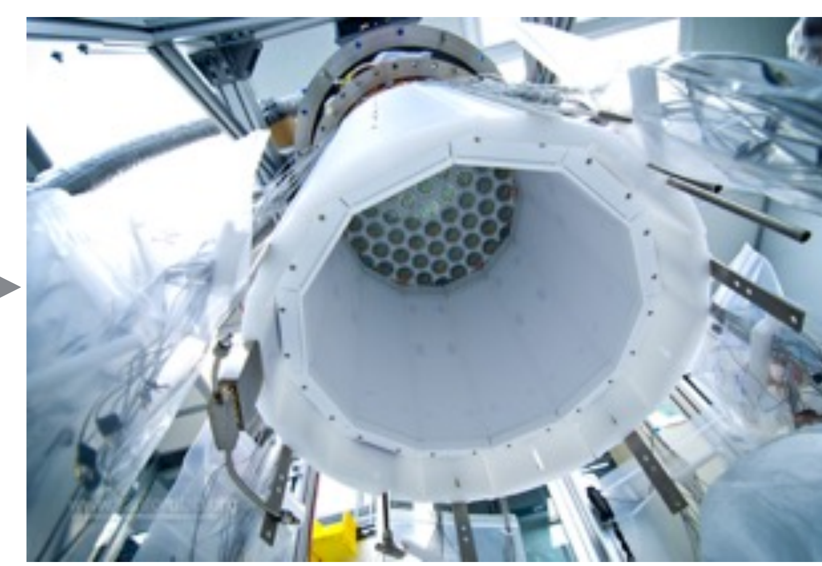
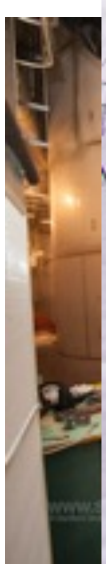
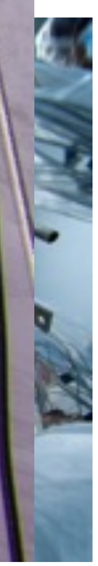


LUX background reduction techniques



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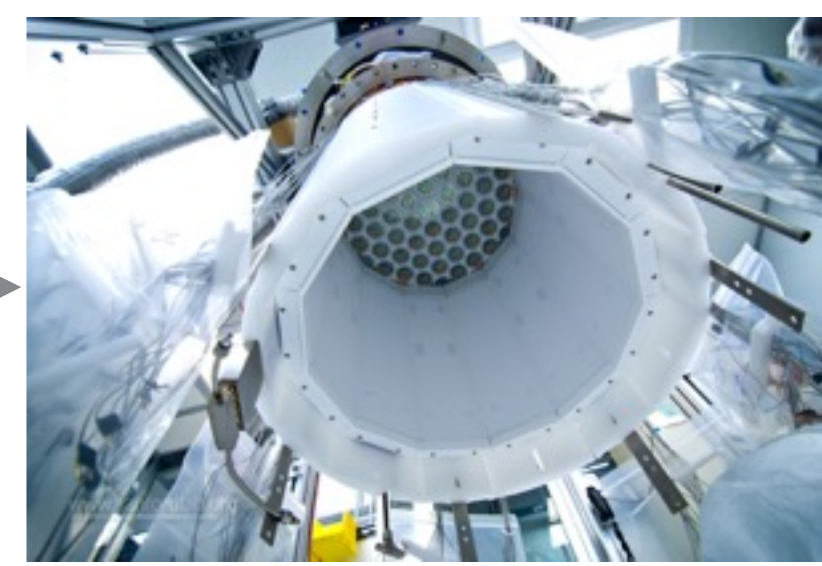
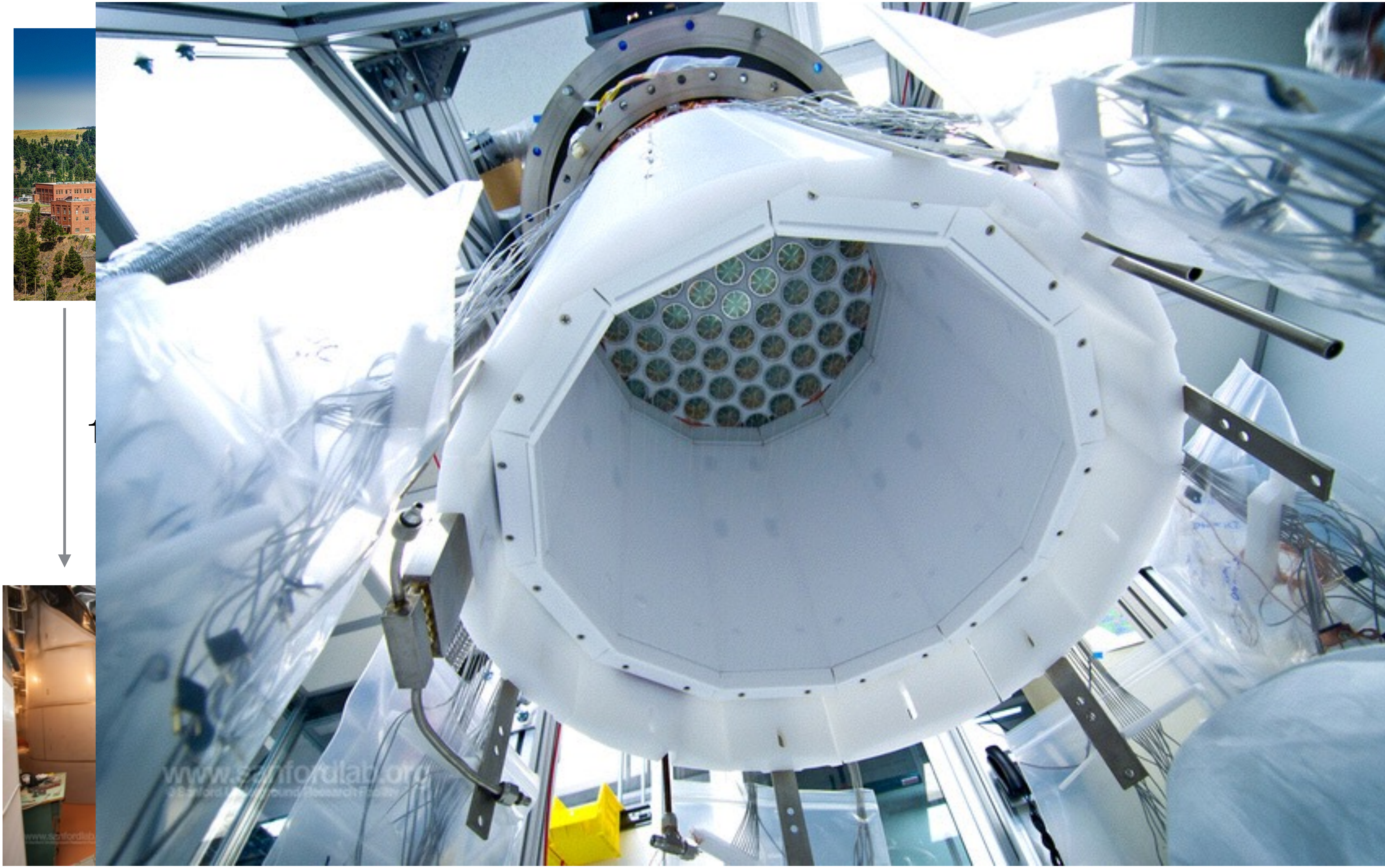


LUX background reduction techniques



LUX background reduction techniques

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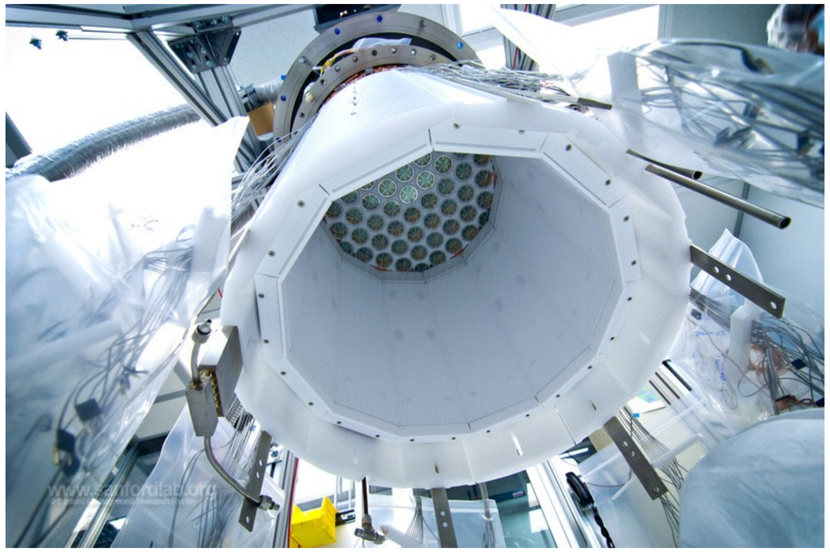


The Need for Low Energy Nuclear Recoil Calibrations

Defining detector response

Scintillation (S1) response

Signal carrier production:

- Light yield $\boldsymbol{L_y(E_{nr})}$ in units of photons / keVnr

Signal carrier detection:

- g1 = 0.115 ± 0.004 detected photons per scintillation photon at the interaction site

Ionization (S2) response

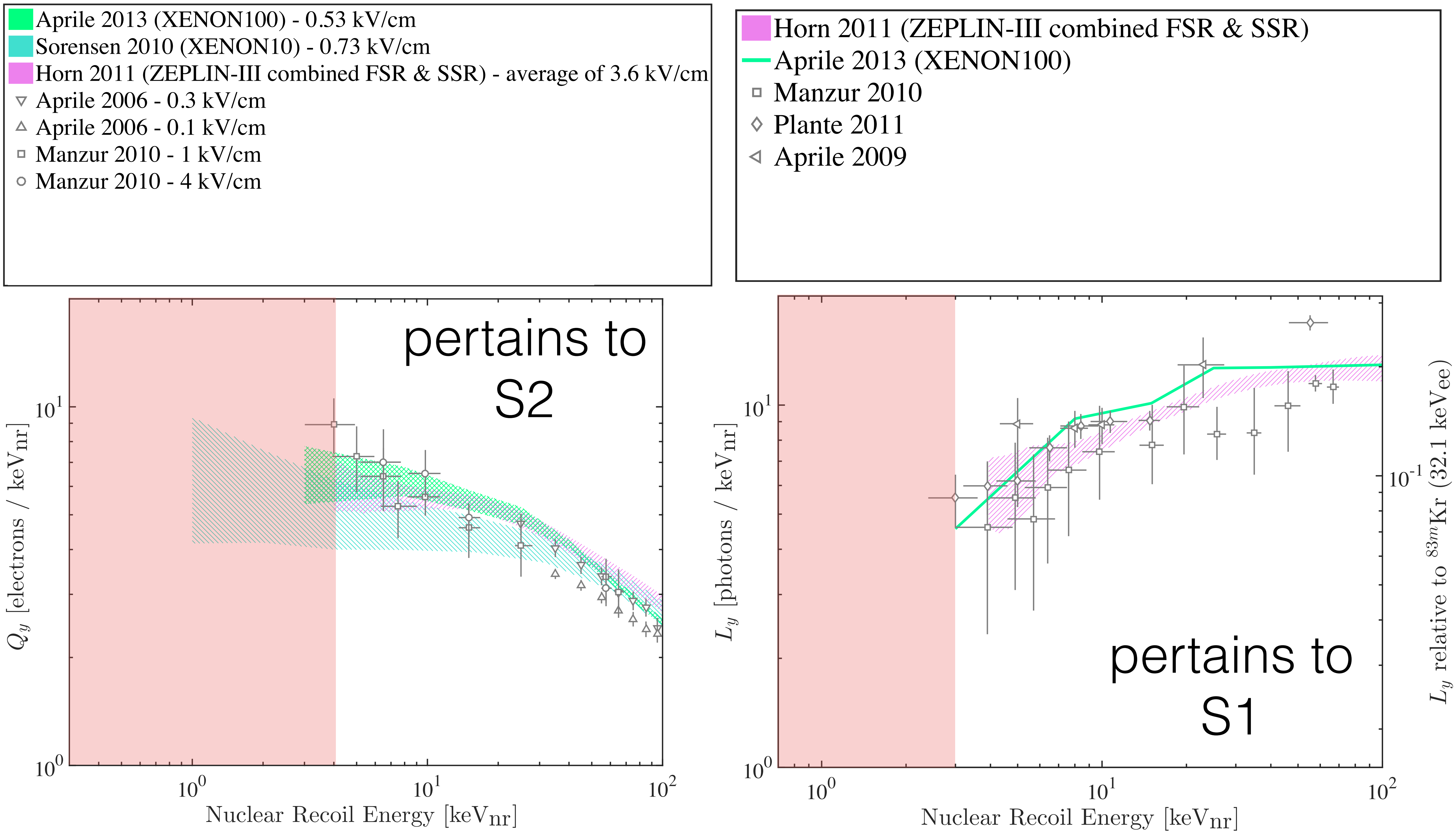
Signal carrier production:

- Ionization yield $\boldsymbol{Q_y(E_{nr})}$ in units of electrons / keVnr

Signal carrier detection:

- g2 = 11.4 detected photons per ionization electron at the interaction site
- electron extraction efficiency is 0.48 ± 0.04

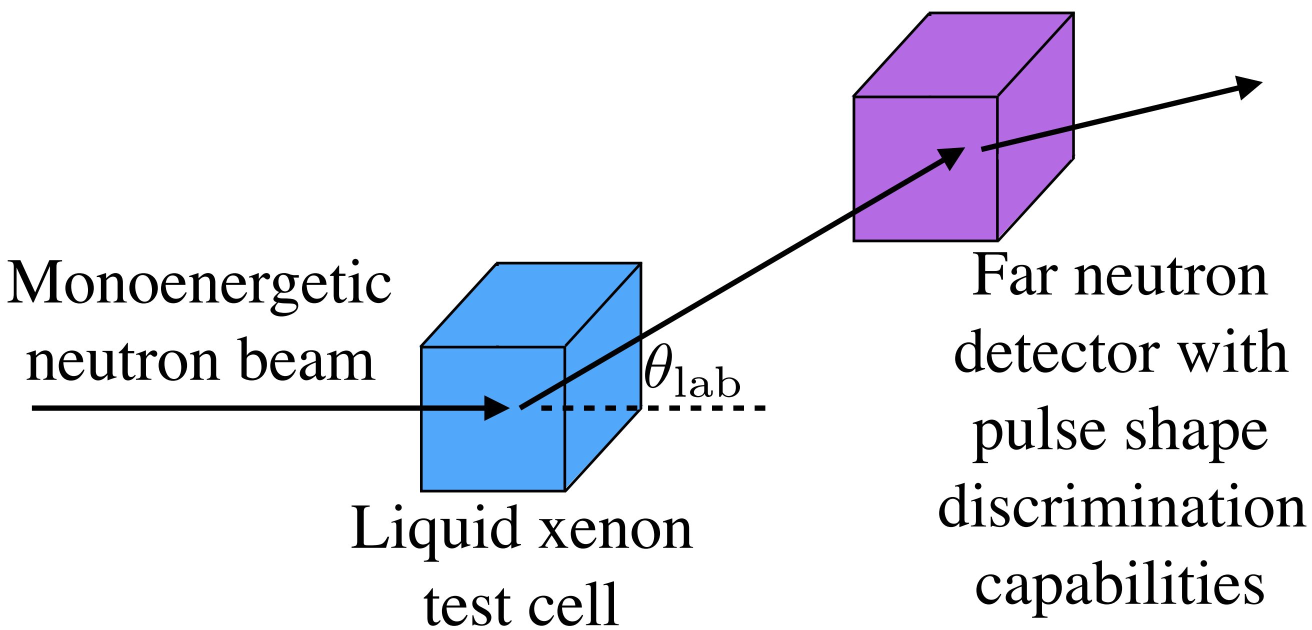
No fixed scattering angle measurements below 3 keV$_{nr}$



Existing techniques used for existing liquid xenon nuclear recoil calibrations

Neutron scattering kinematics in small test cell

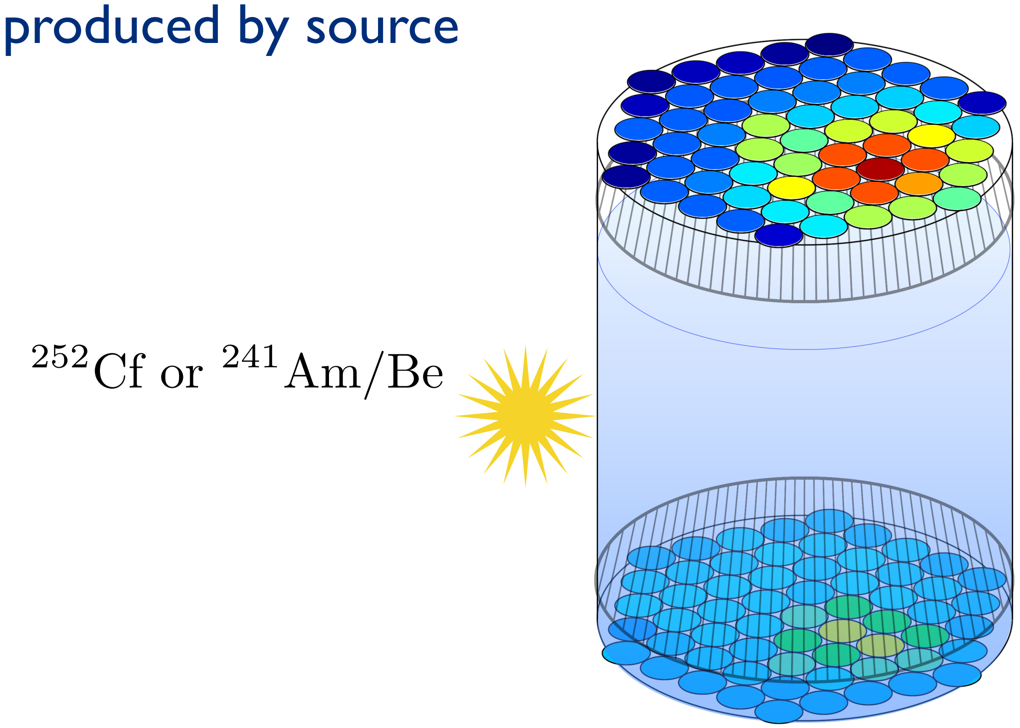
- Recoil energy defined by fixed scattering angle
- Susceptible to systematic effects due to neutron scatters in passive material
- Not *in situ* calibration of dark matter instrument



$$E_{\mathrm{nr}} \approx E_n \frac{4 m_n m_{\mathrm{Xe}}}{(m_n + m_{\mathrm{Xe}})^2} \frac{1-\cos\theta}{2}$$

Continuum neutron sources next to TPC

- *In situ* in the dark matter instrument
- Featureless, continuous neutron spectrum produced by 252Cf or 241Am/Be
  - Can also use spectrum endpoint
- Energy scale is determined by simulation best fit to observed signal spectra
- Susceptible to systematic effects due to neutron scatters in passive material
- Contamination from high-energy gamma rays produced by source

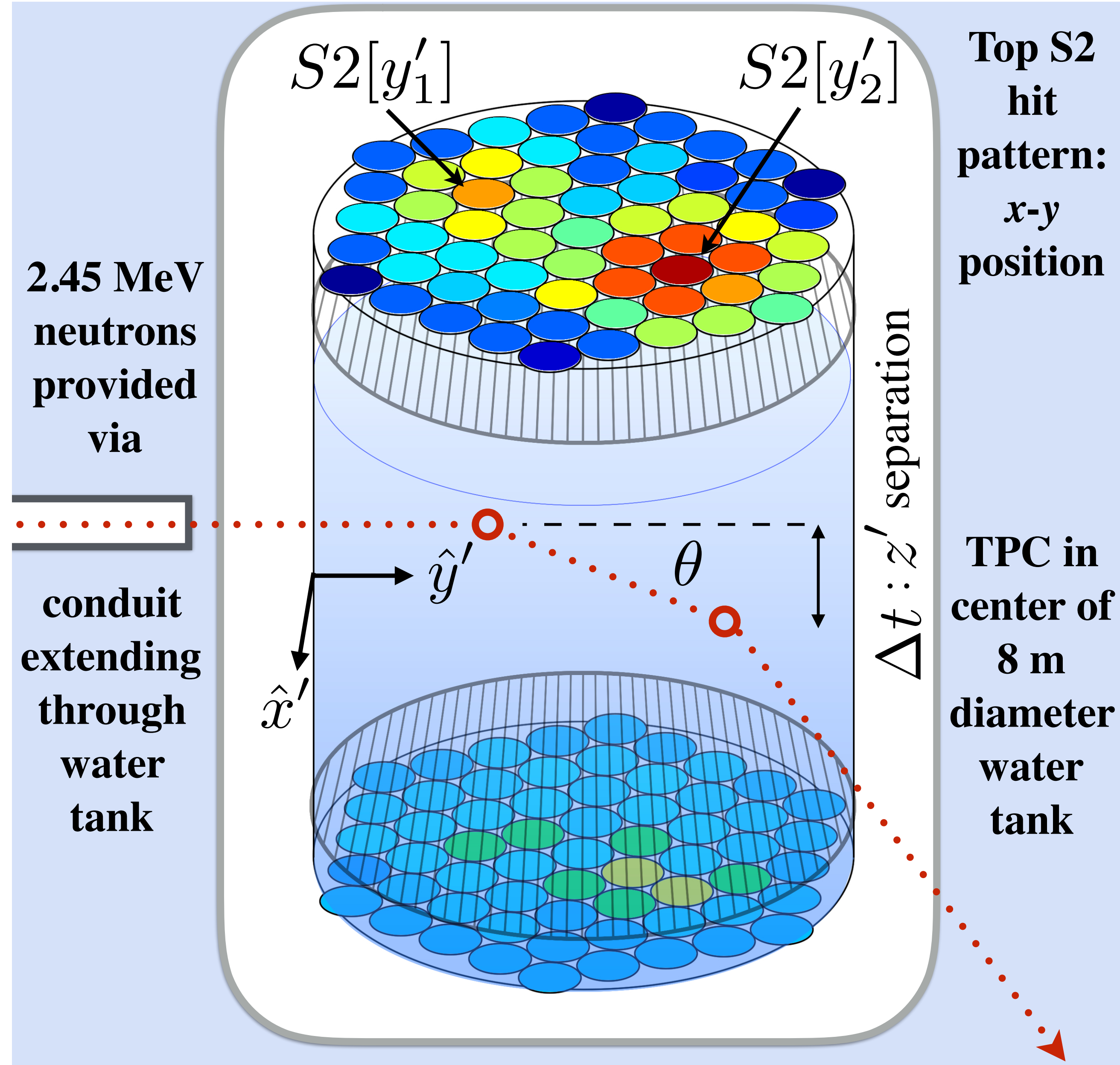


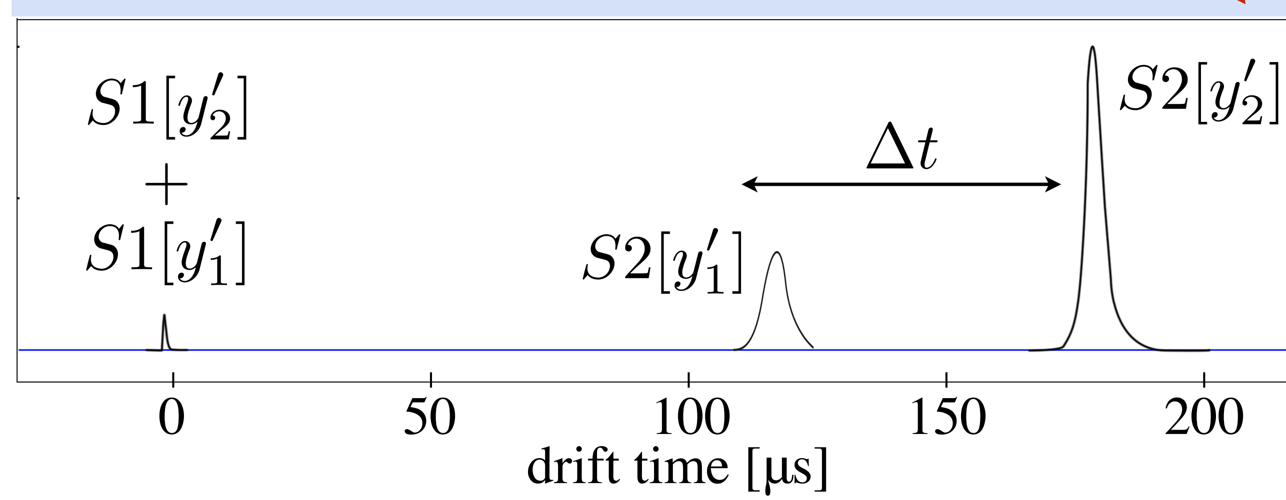
A new *in situ* calibration technique using monoenergetic D-D neutron scattering kinematics

- Use a monoenergetic neutron source to introduce a beam of collimated neutrons into LUX
- Reconstruct multi-scatter interaction positions
- Measure energy from scattering angle

$$E_{\mathrm{nr}} \approx E_n \frac{4 m_n m_{\mathrm{Xe}}}{(m_n + m_{\mathrm{Xe}})^2} \frac{1-\cos\theta}{2}$$

- Precise LUX calibration of g1 and g2 provides **absolute measurement** of quanta produced
- **Significant** reduction in systematics

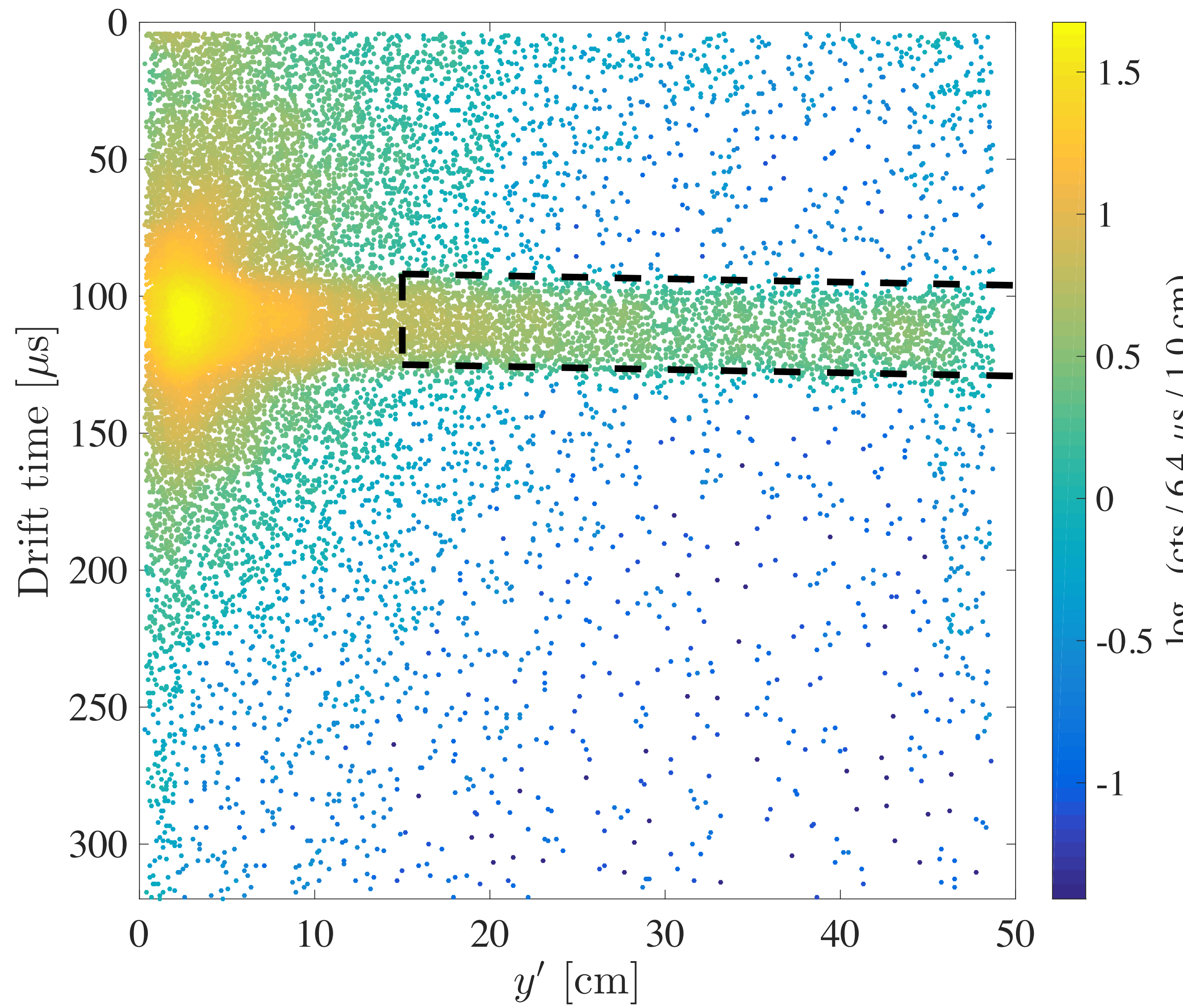




The D-D Hardware Setup at SURF

Neutron conduit installed in the LUX water tank

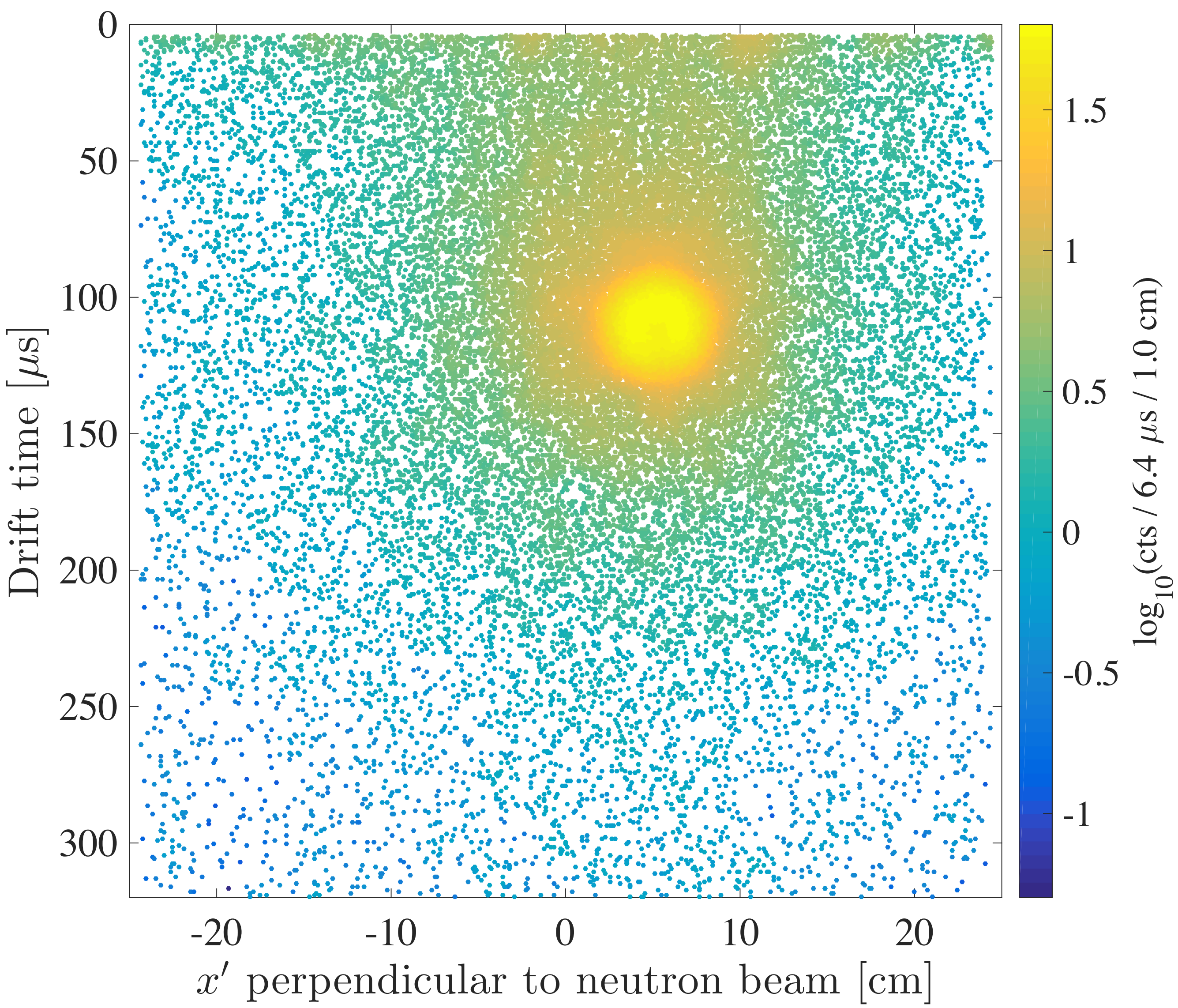
Adelphi Technology, Inc. DD108 neutron generator installed outside LUX water tank

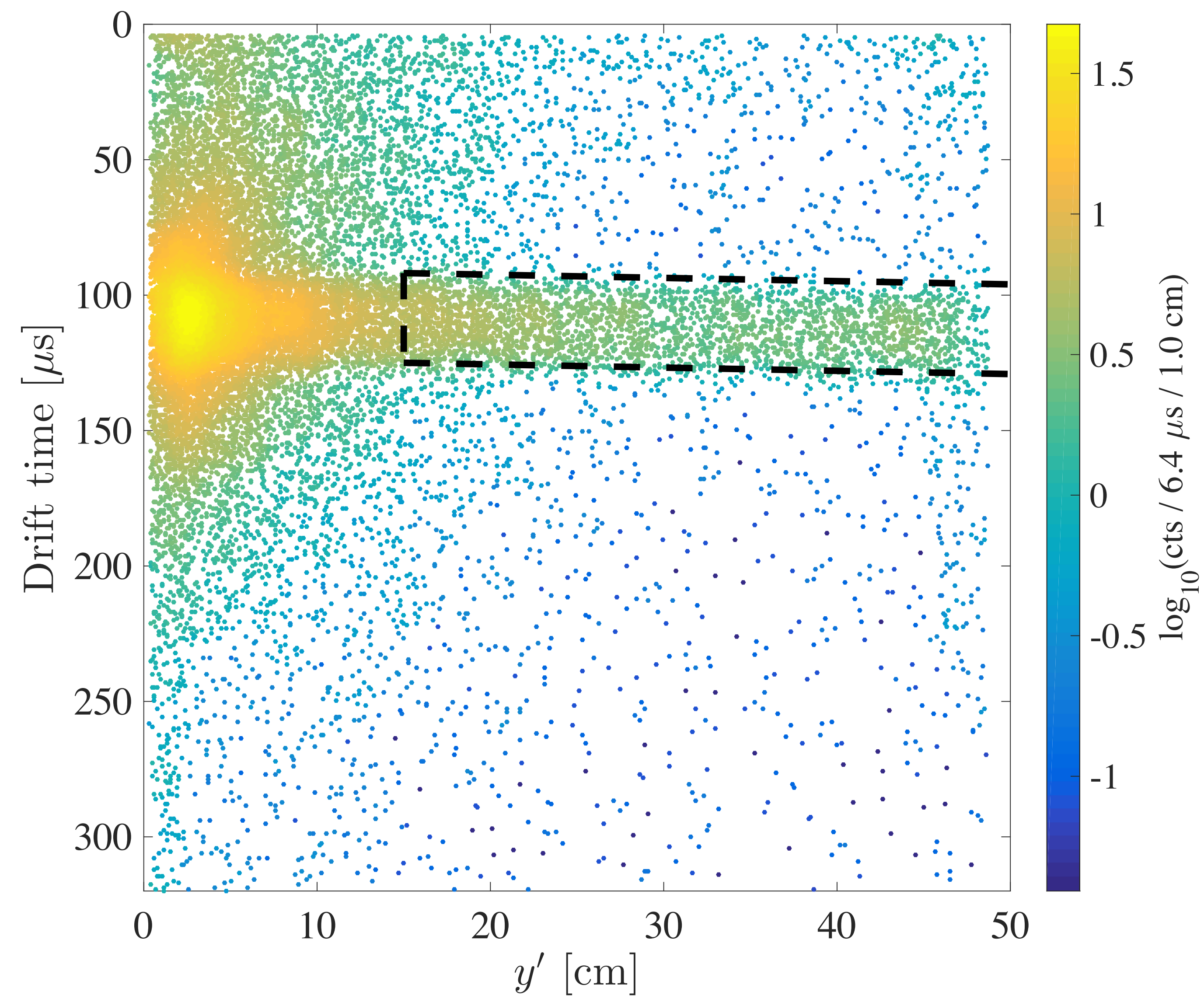


- Neutron generator/beam pipe assembly aligned 16.1 cm below liquid level in LUX active region to maximize usable single / double scatters
- Beam leveled to ~1 degree
- 107 live hours of neutron tube data used for analysis
- Neutron production rate: $(2.5 \pm 0.3) \times 10^6$ n/s

Beam projection in active region

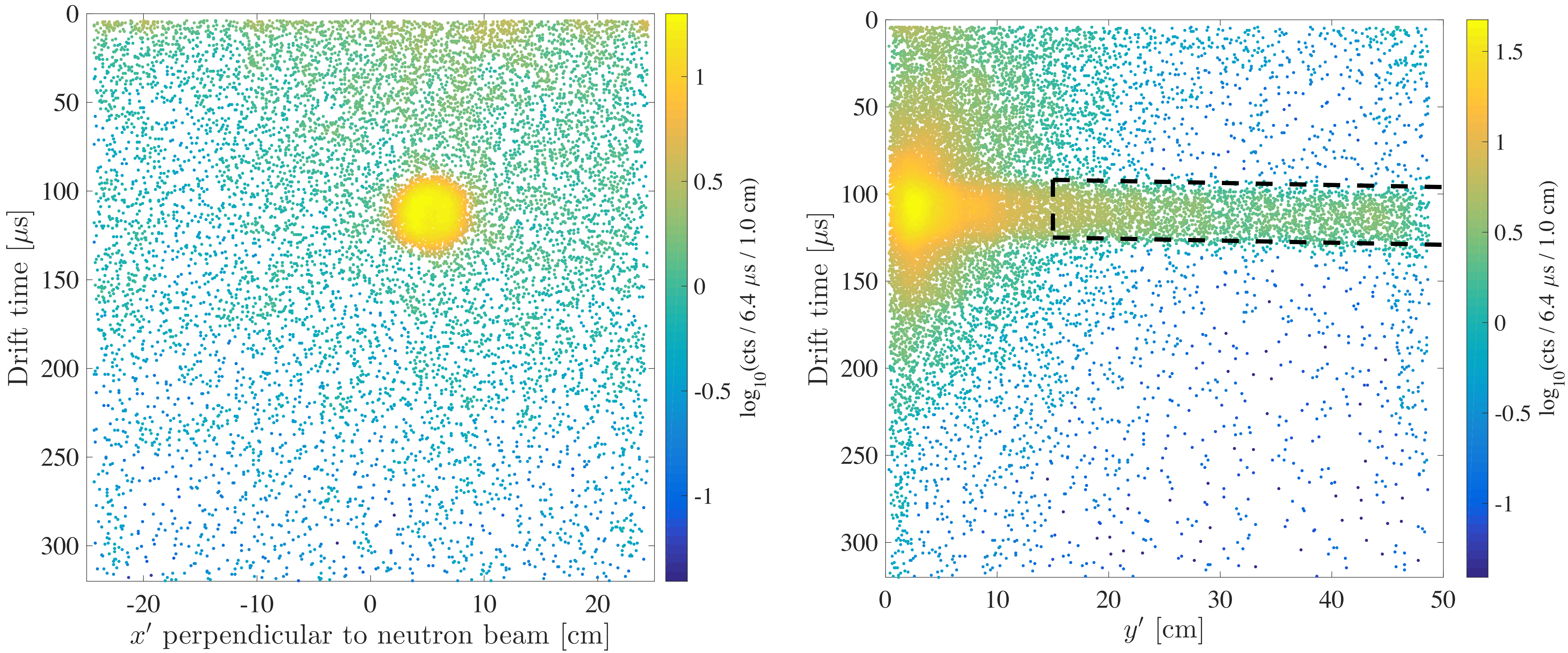
- The shine from neutron scatters in passive detector materials is visible
- Historically, nuclear recoil calibrations have significant systematics associated with neutrons scattering in passive material
  - We can fiducialize away from such backgrounds!





Neutron beam energy purity

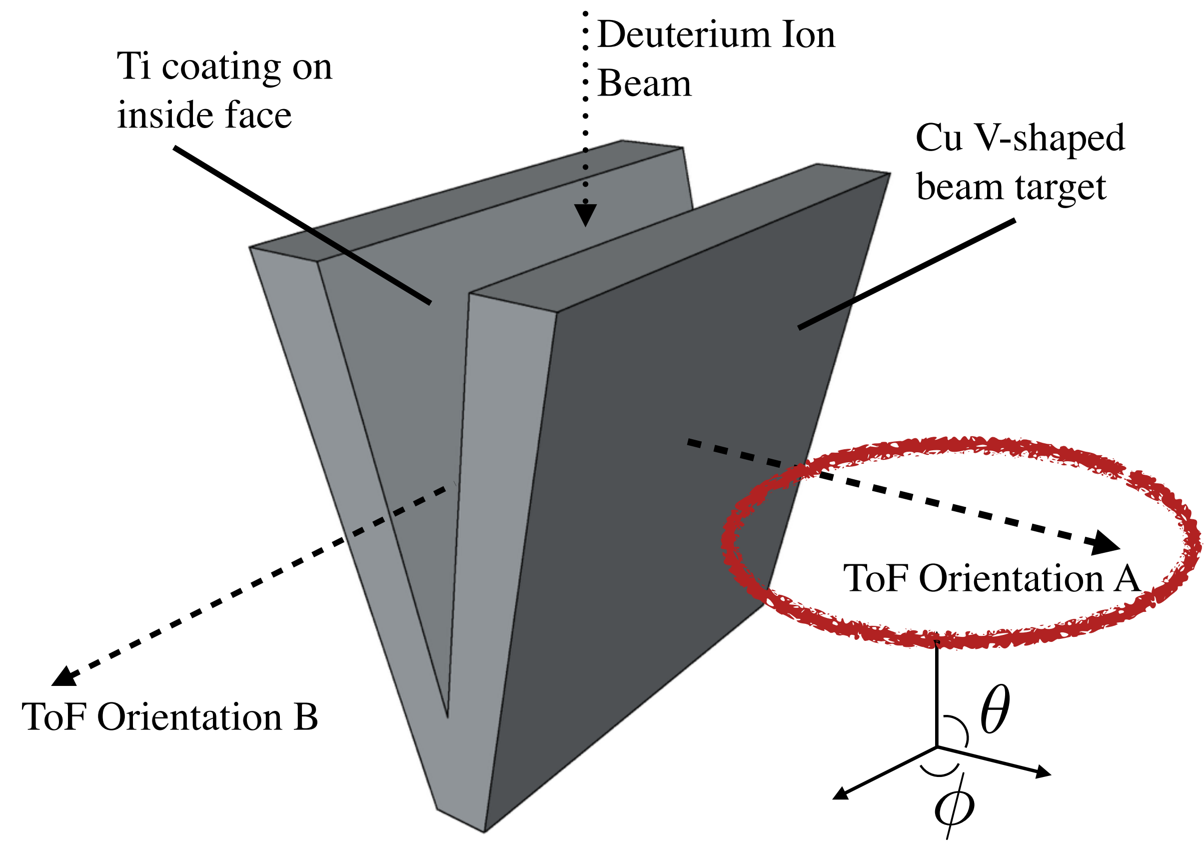
- After application of y' >15 cm beam neutron energy purity cut
- This cut eliminates neutron shine from passive materials, and ensures 95% of neutrons in beam sample have energy within 6% of 2.45 MeV
- Neutron beam edge profile demonstrates precision of the LUX detector position reconstruction

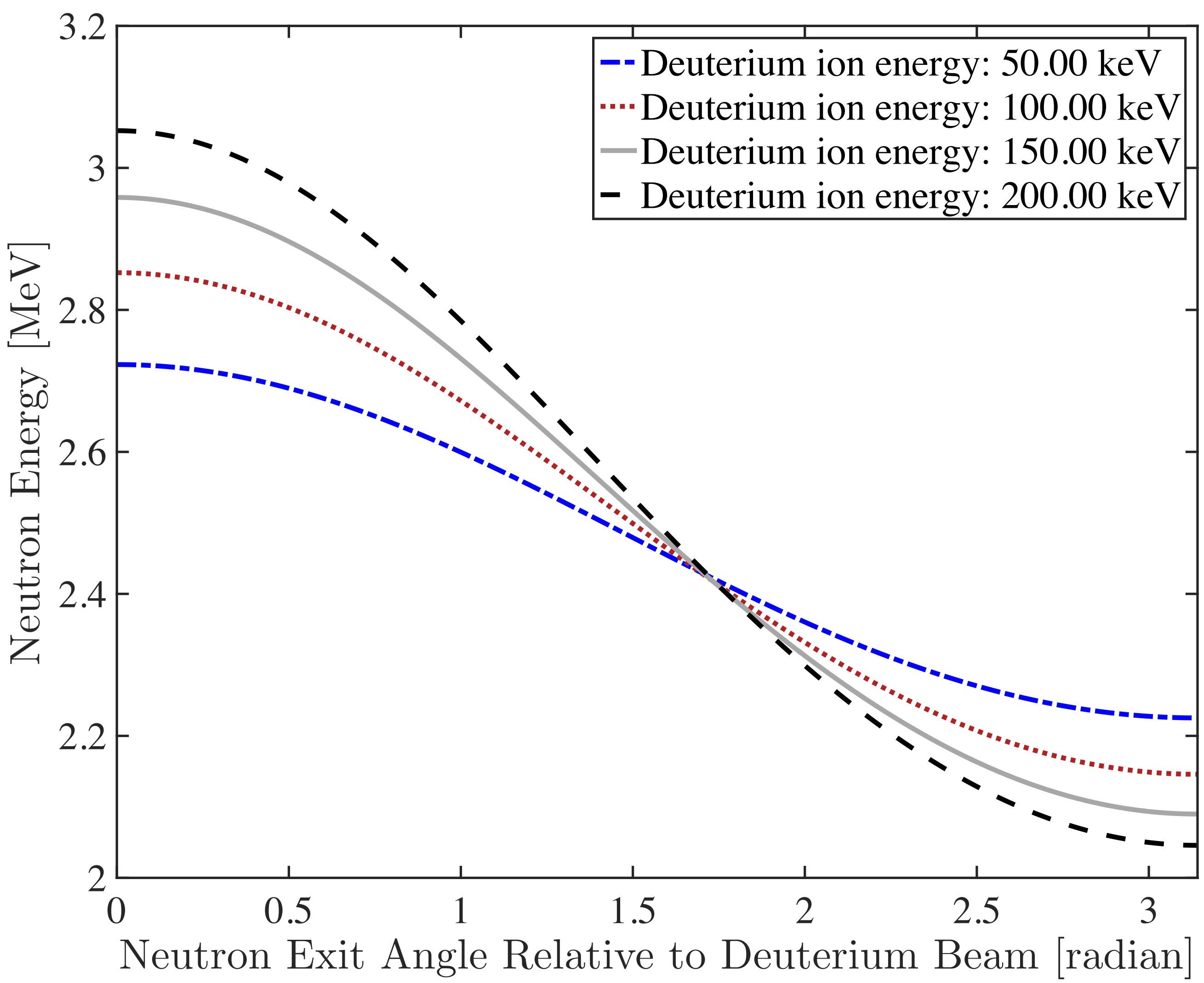


Measurement of the D-D Source Neutron Spectrum Using Time-of-Flight at Brown University

Dependence of neutron energy on D-D source orientation

- We used "Target orientation A" for the LUX nuclear recoil calibration
- DD108 was operated using 80 kV acceleration potential for LUX calibration

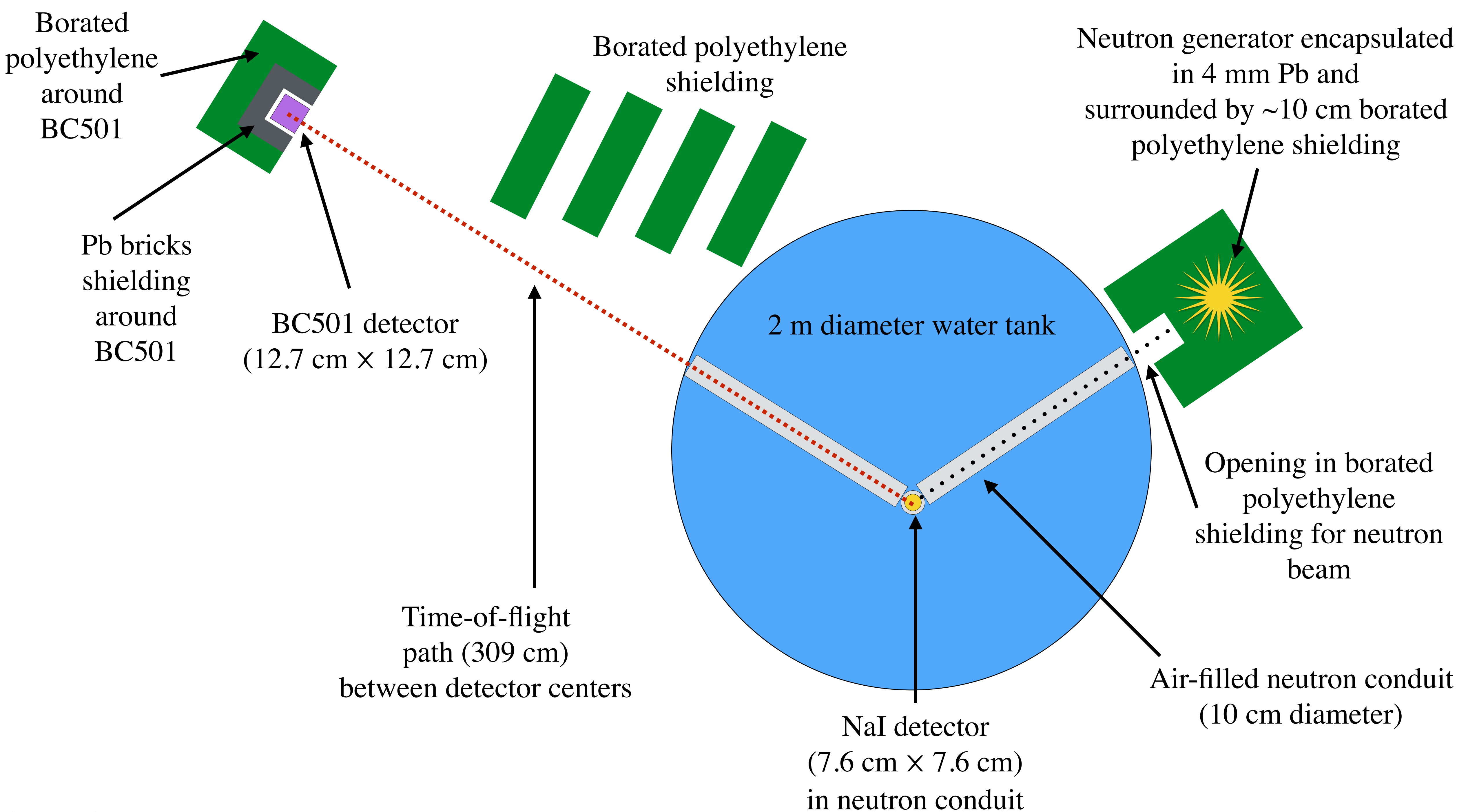




- Neutron flux also varies by a factor of two depending on ongoing neutron direction

Neutron time-of-flight experimental setup at Brown University

M. Genecov, S. Ghosh, A. Moskowitz (Brown UTRA students) collaborated on the experimental design, operation, and data analysis



$66^\circ \pm 4^\circ$ scattering angle

Neutron time-of-flight experimental setup at Brown University

M. Genecov, S. Ghosh, A. Moskowitz (Brown UTRA students) collaborated on the experimental

Borated polyethylene

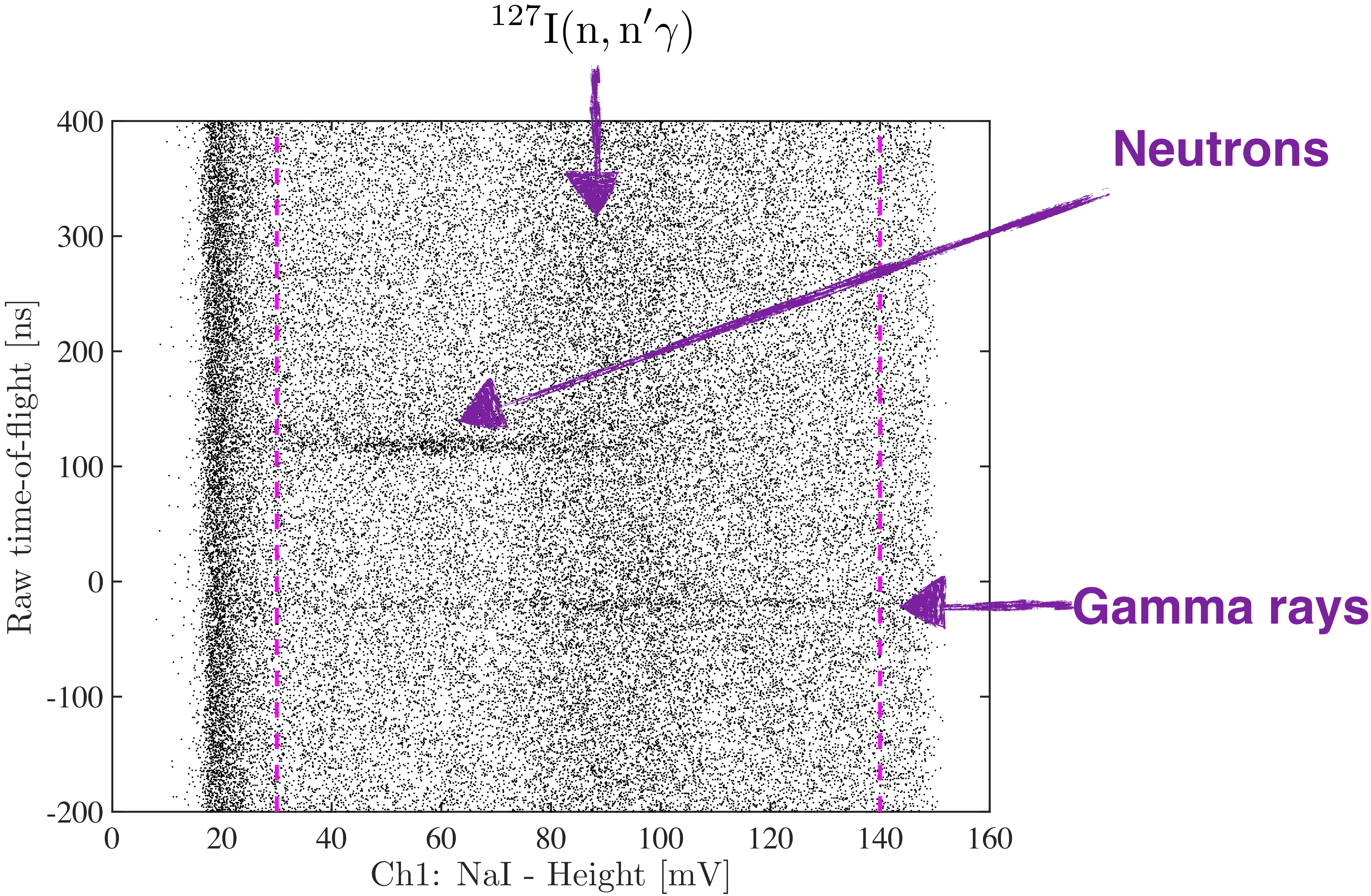
Neutron generator encapsulated
in 4 mm Pb and
rrounded by ~10 cm borated
polyethylene shielding

Time-of-fligh
path (309 cm
between detector c

in neutron conduit

$66^\circ \pm 4^\circ$ scattering angle

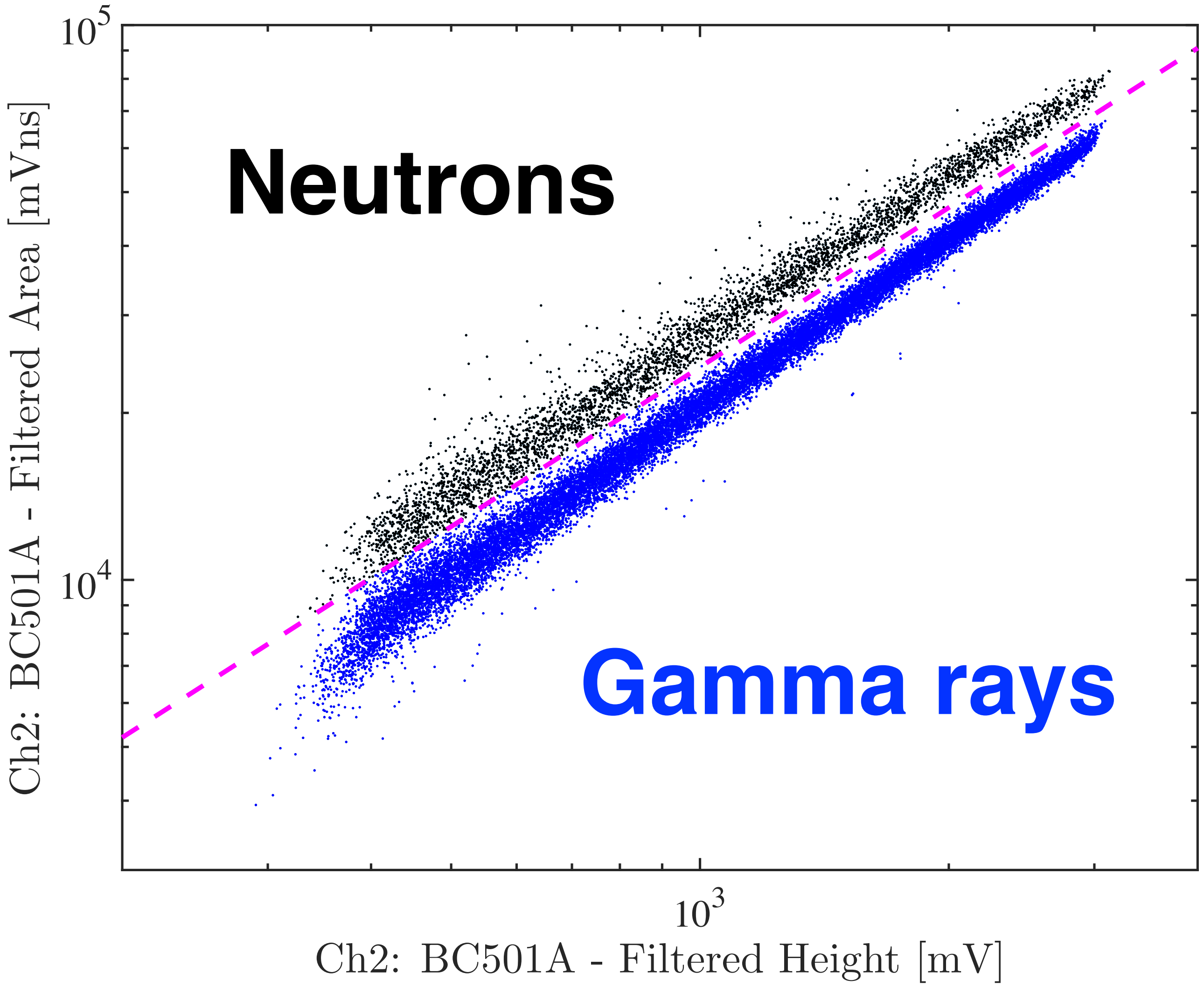
Target orientation A: time-of-flight data



Target orientation A: verification of D-D source neutron energy spectrum

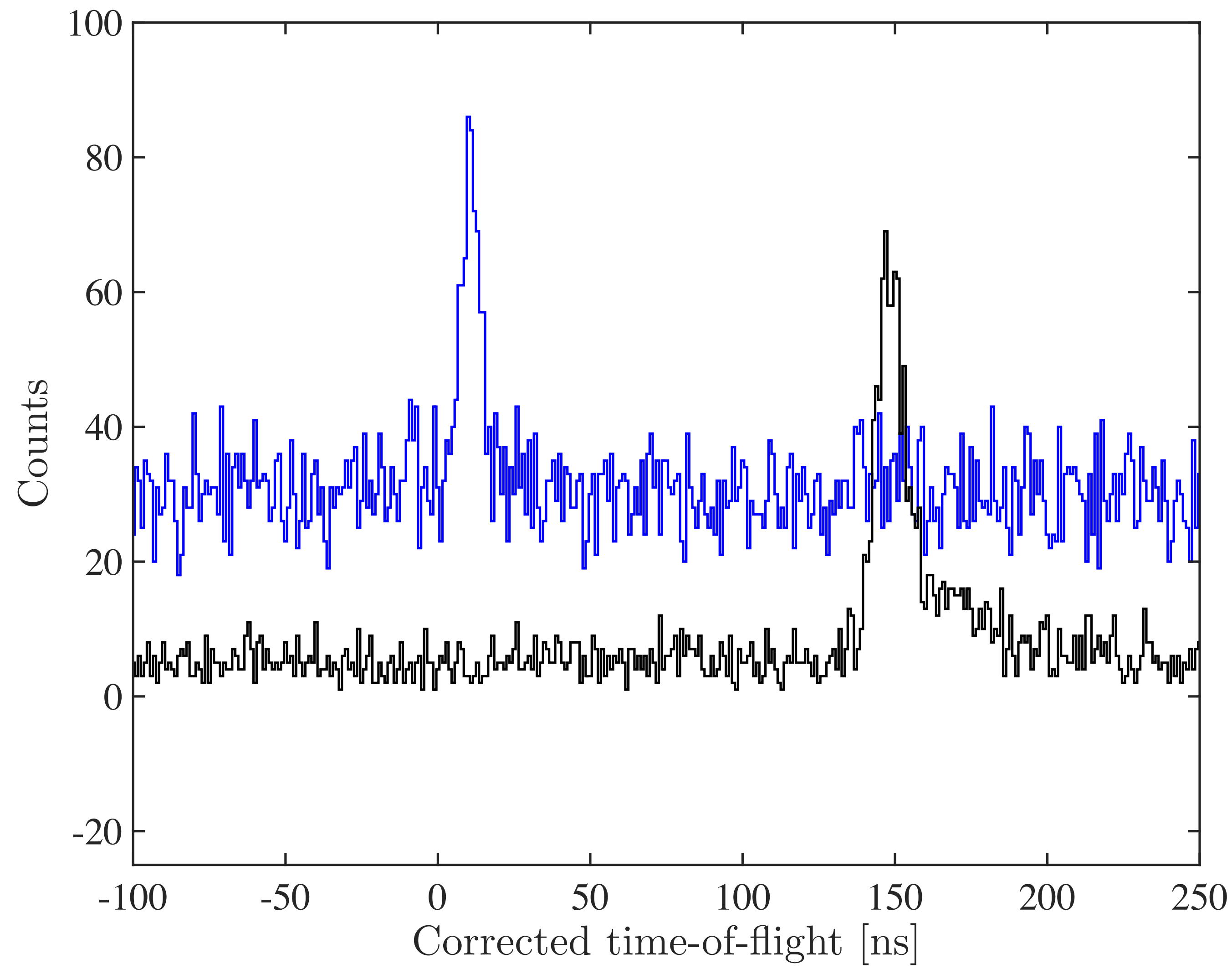
- Mean neutron energy is in agreement with theoretical value of 2.45 MeV

$$2.401 \pm 0.012\,(\text{stat}) \pm 0.060\,(\text{sys})\ \text{MeV}$$

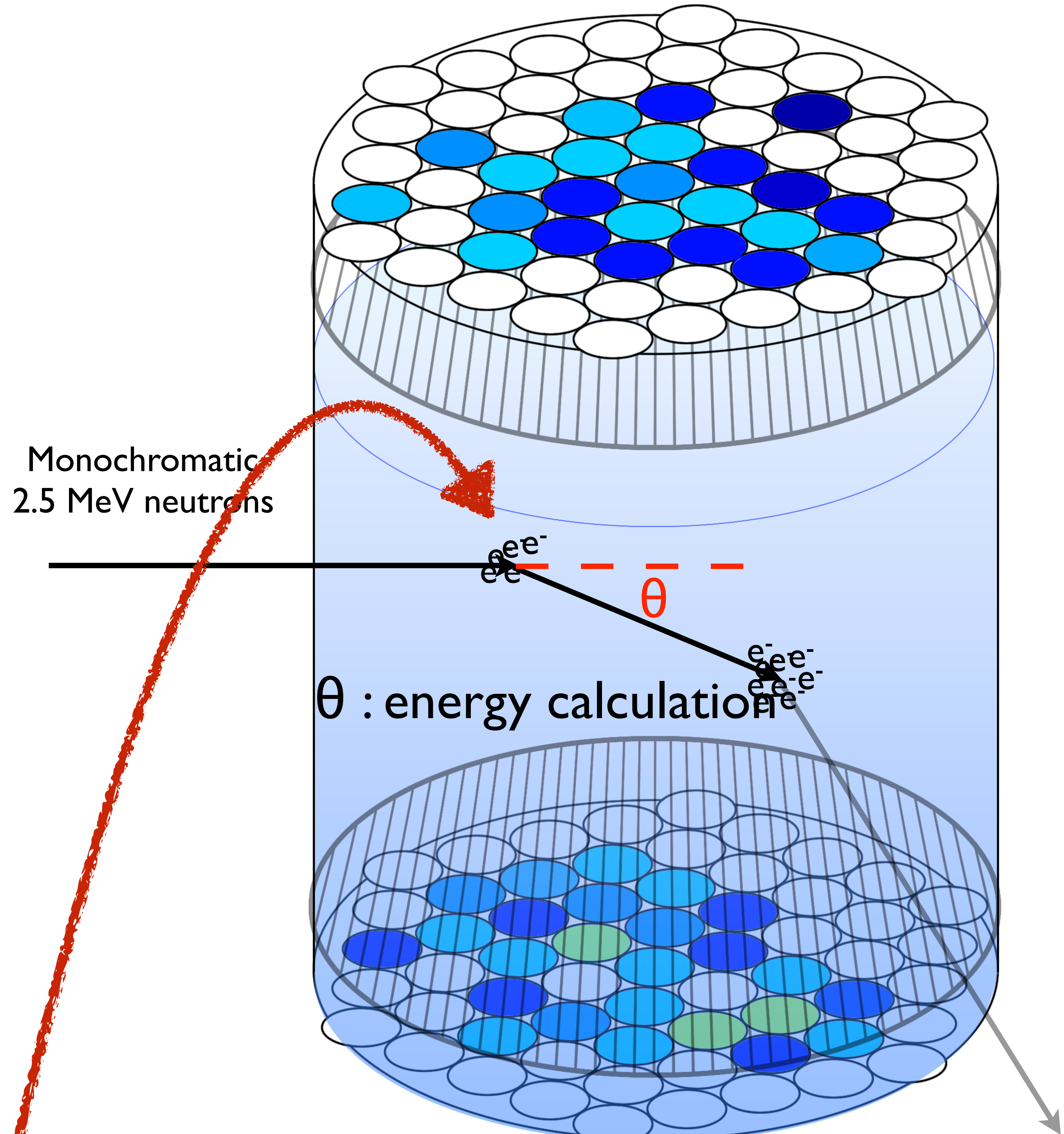


- Outgoing neutron energy distribution width:

$$\frac{\sigma}{\mu} = 4.4\% \pm 0.6\%\,(\text{stat}) \pm 0.8\%\,(\text{sys})$$



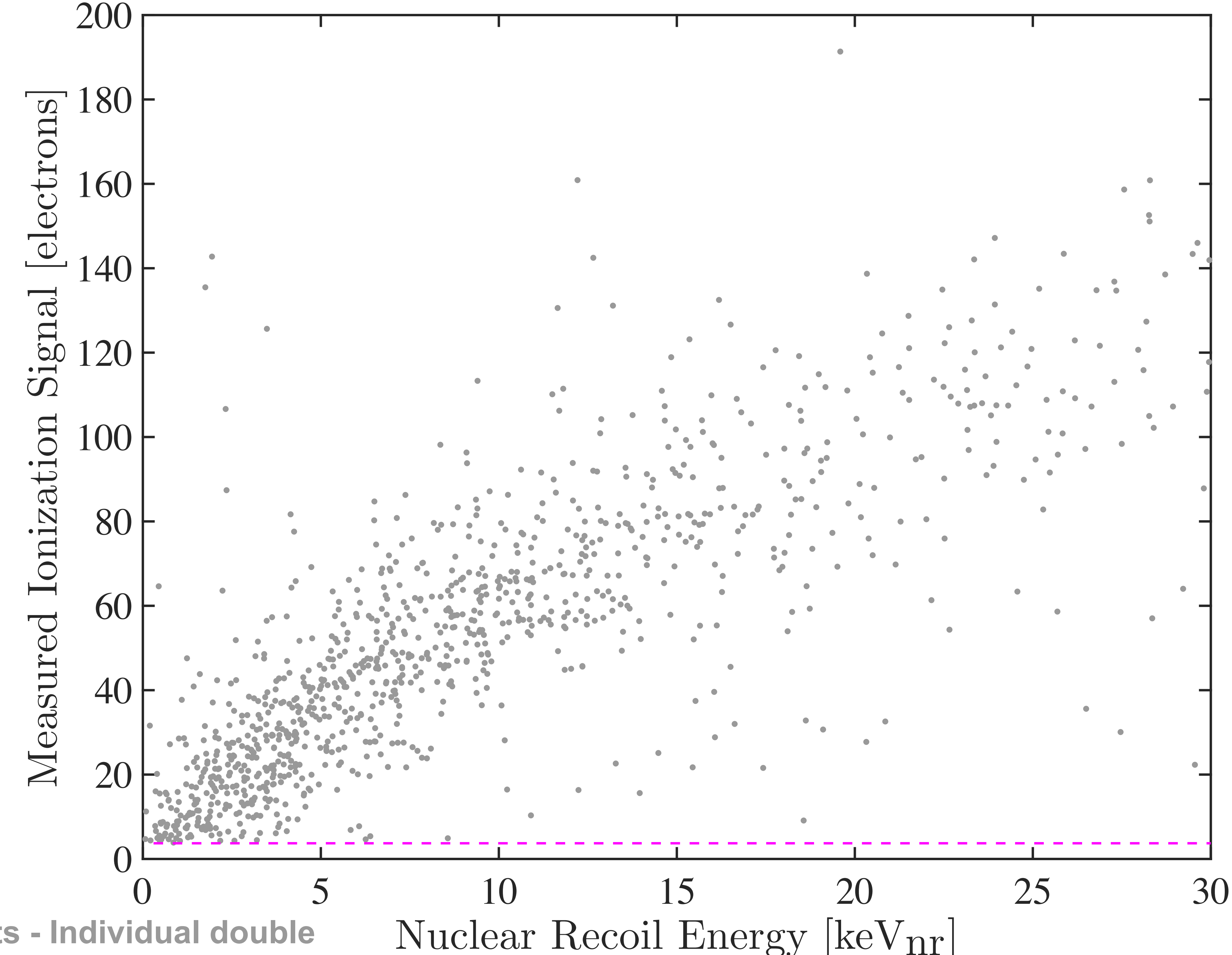
D-D Low-Energy *Qy* Measurement



$$E_{\mathrm{nr}} \approx E_n \frac{4 m_n m_{\mathrm{Xe}}}{(m_n + m_{\mathrm{Xe}})^2} \frac{1 - \cos\theta}{2}$$

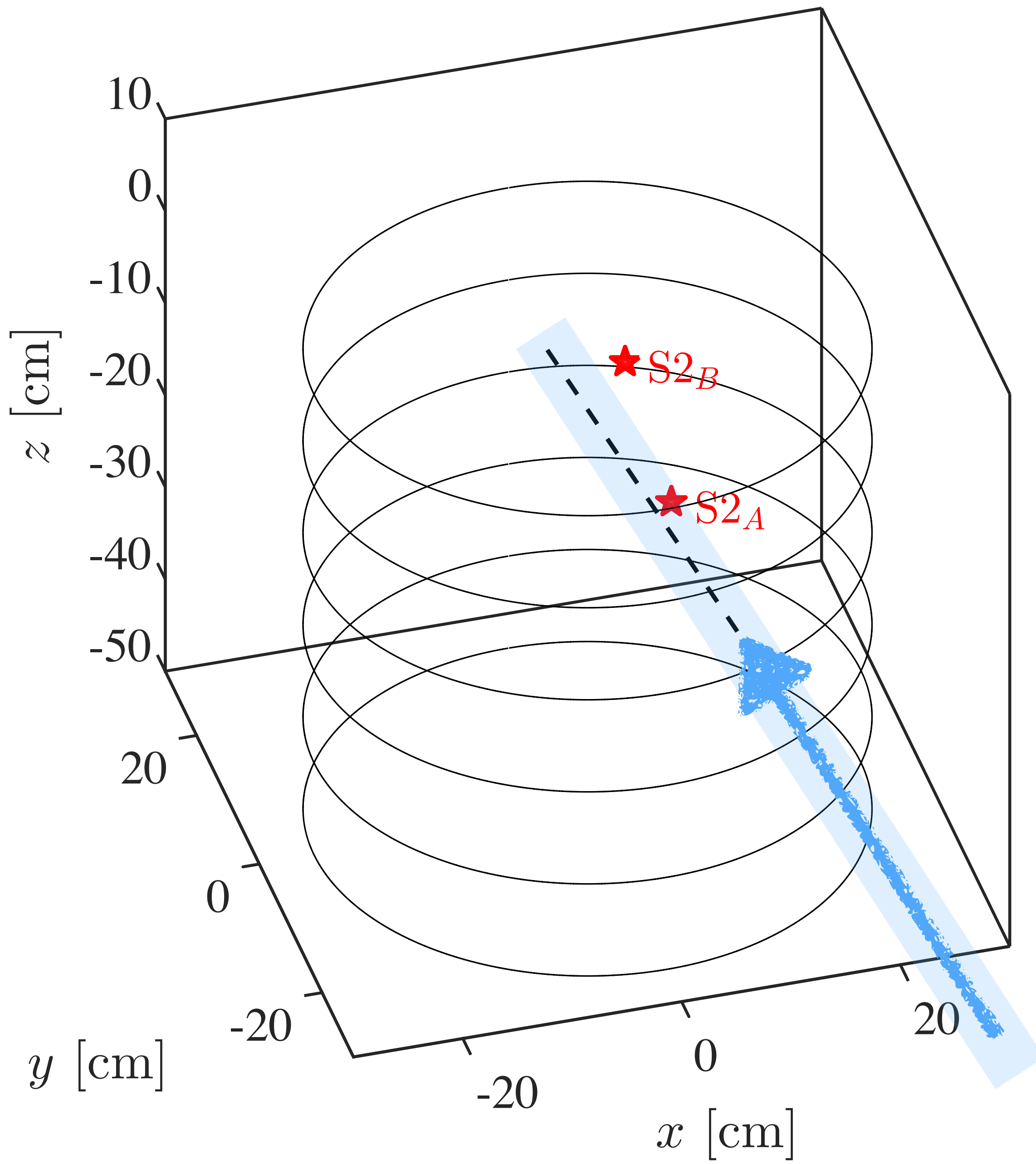
Samuel Chan, Carlos Faham for the LUX Collaboration

Observed ionization signal



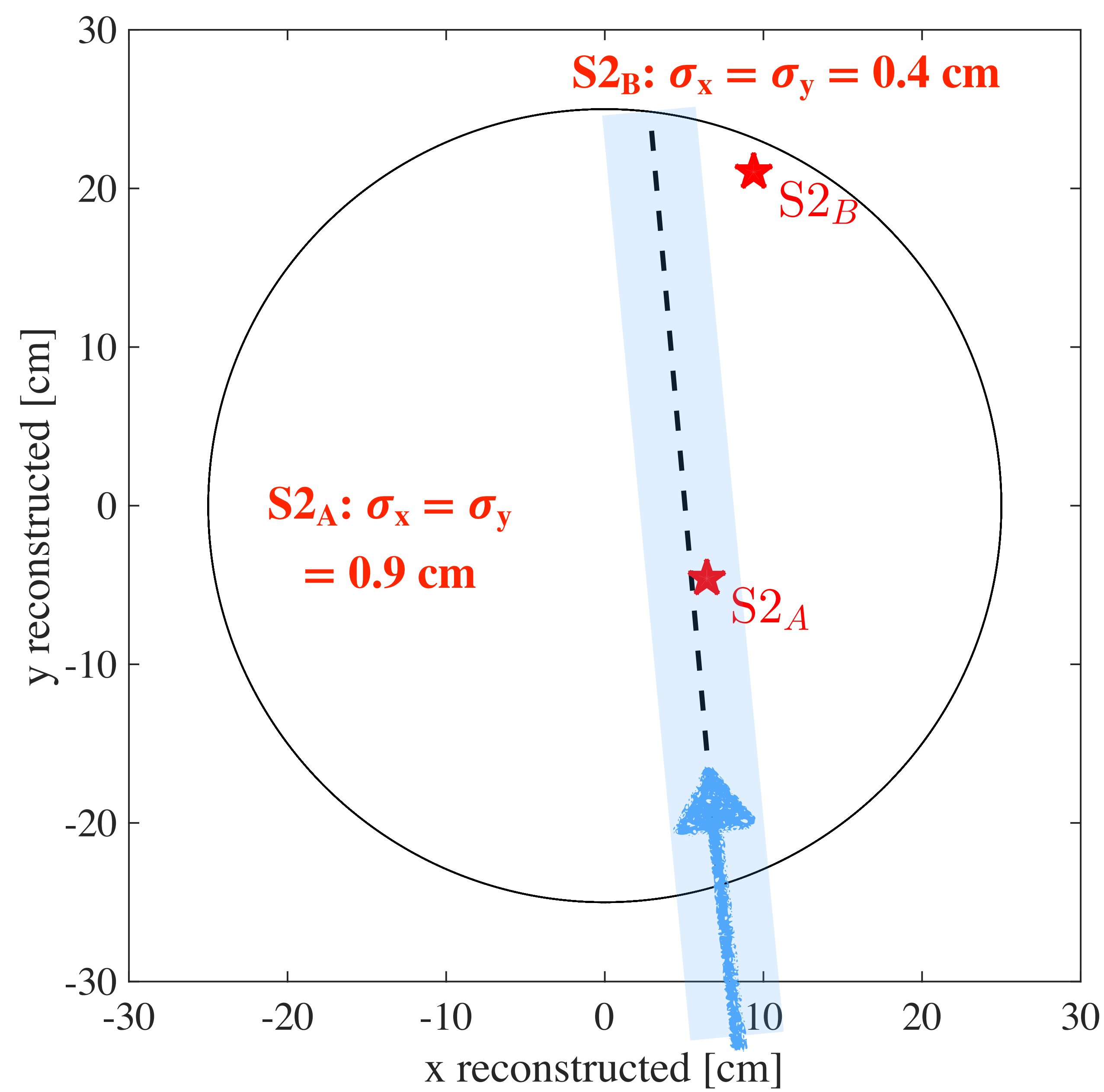
Grey Points - Individual double scatter events

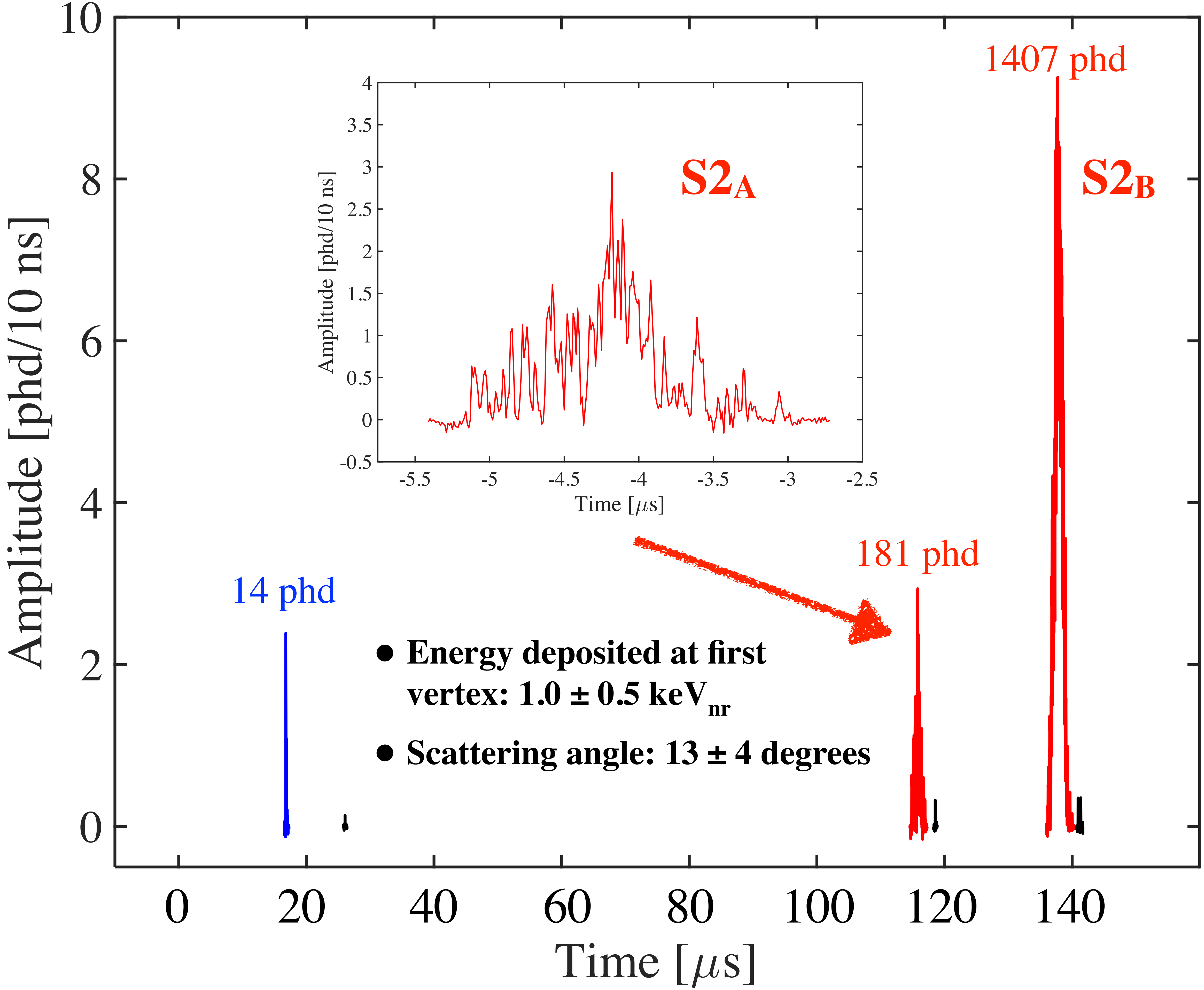
What does a 1 keV$_{nr}$ double scatter look like?



2.45 MeV neutron beam

- *x*, *y*, *z* position of both S2 vertices from a 1 keV$_{nr}$ double-scatter in REAL DATA





1407 phd
S2A
S2B
Amplitude [phd/10 ns]
Time [μs]
181 phd
14 phd
Energy deposited at first vertex: 1.0 ± 0.5 keVnr
Scattering angle: 13 ± 4 degrees

Ionization signal absolutely measured below 1 keV_{nra} in LUX

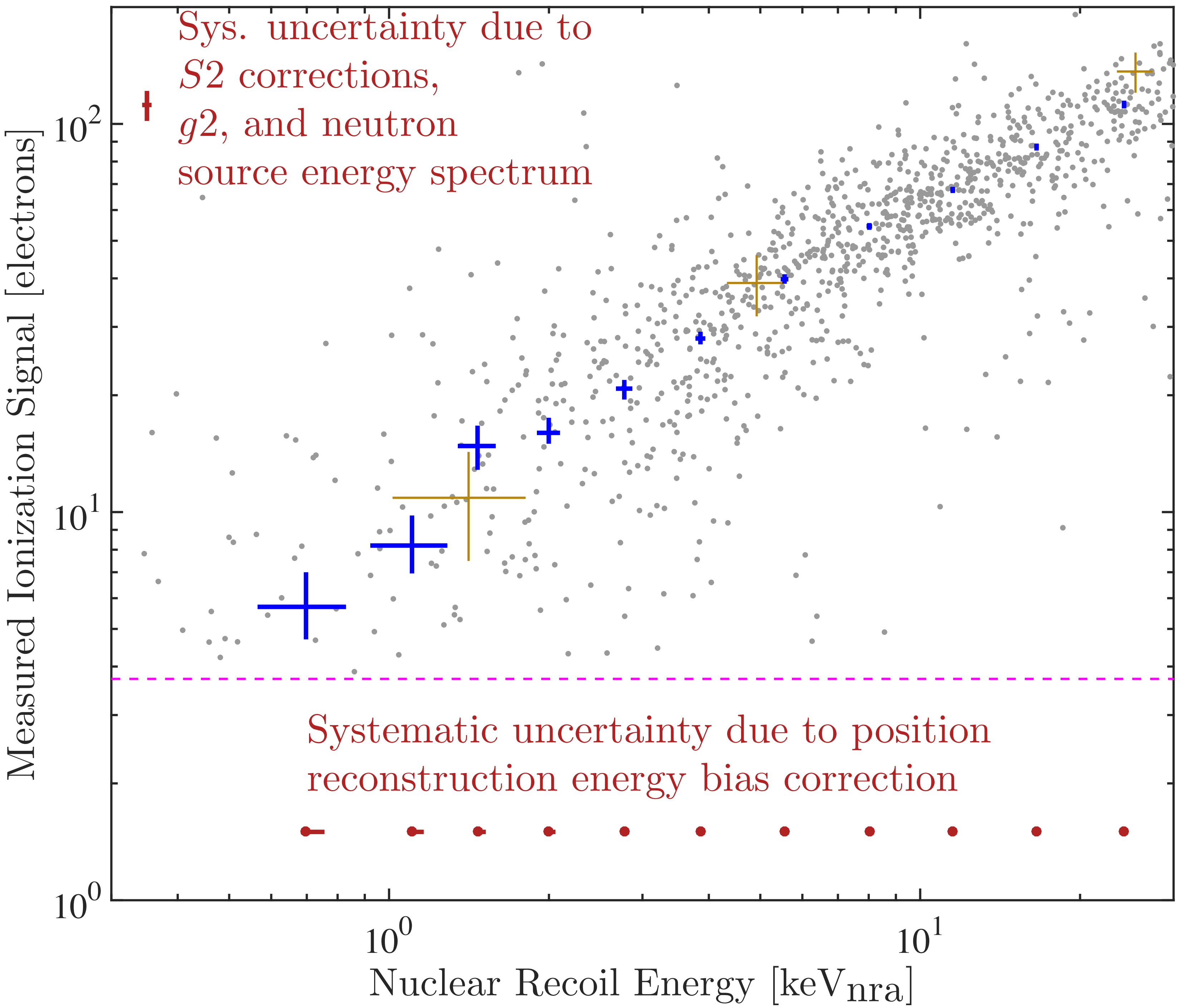
Individual double scatter events

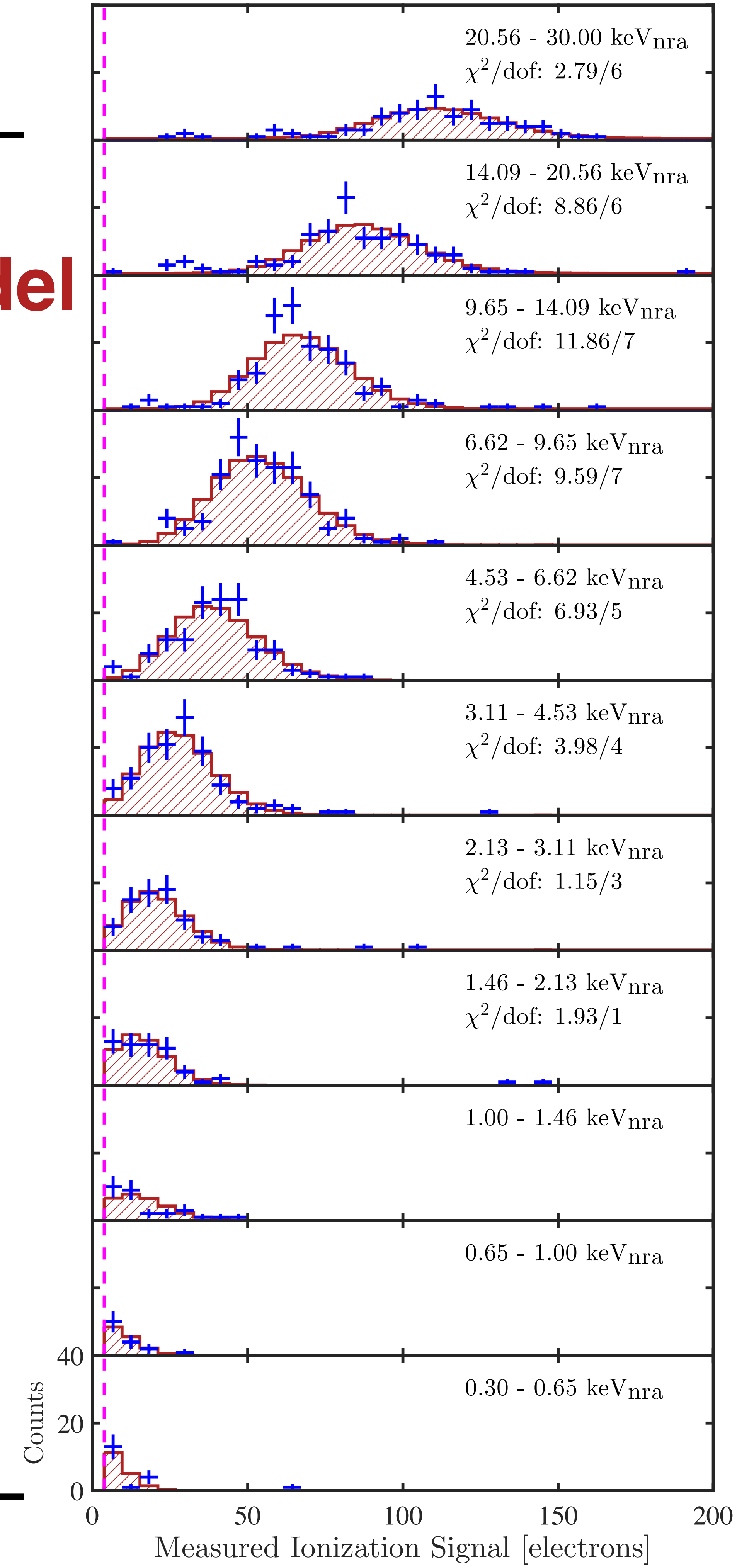
Reconstructed number of electrons with associated statistical uncertainty

Example error bars for individual events

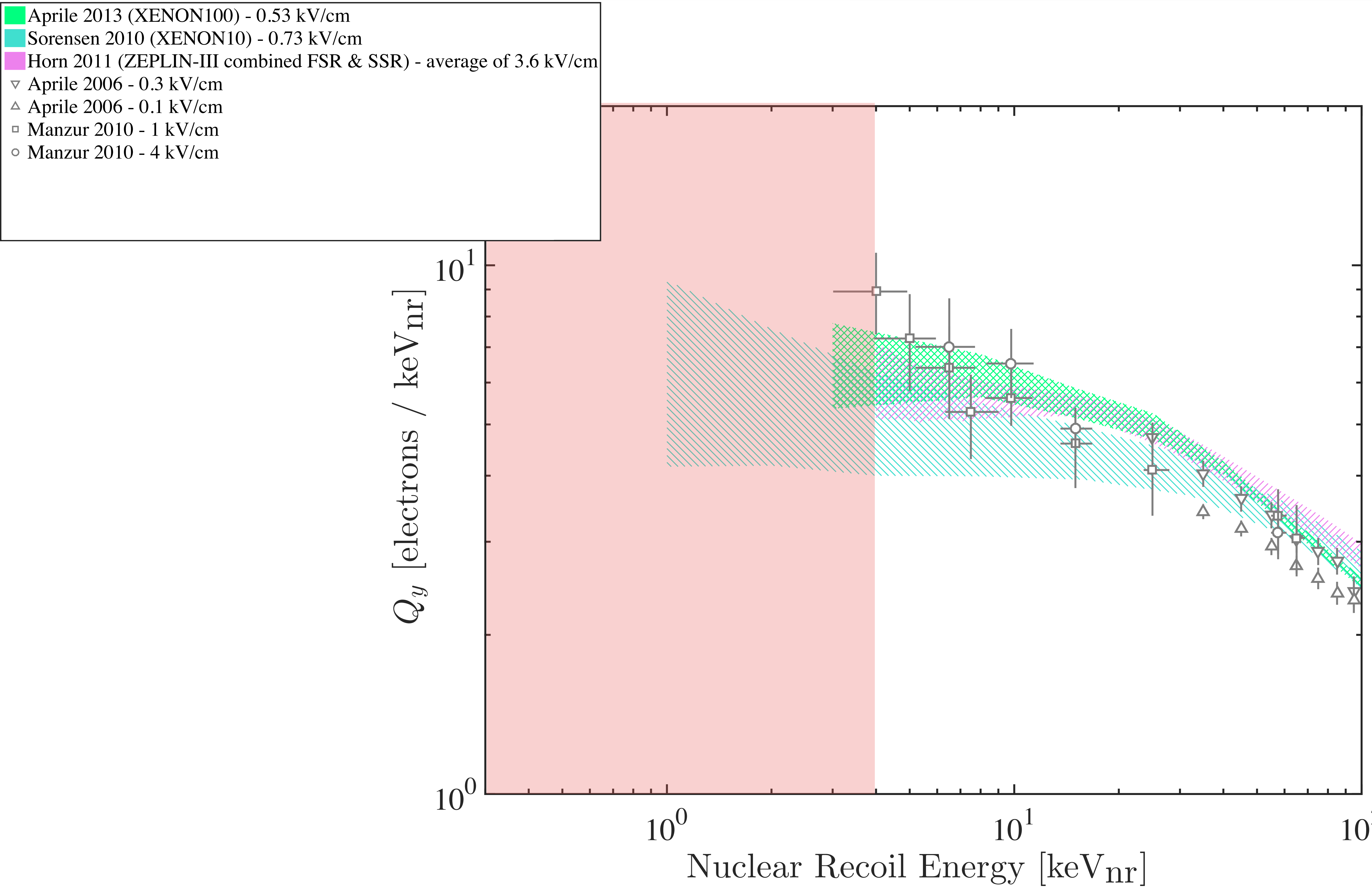
Data

Best-fit model





Ionization yield absolutely measured below 1 keVnr in LUX



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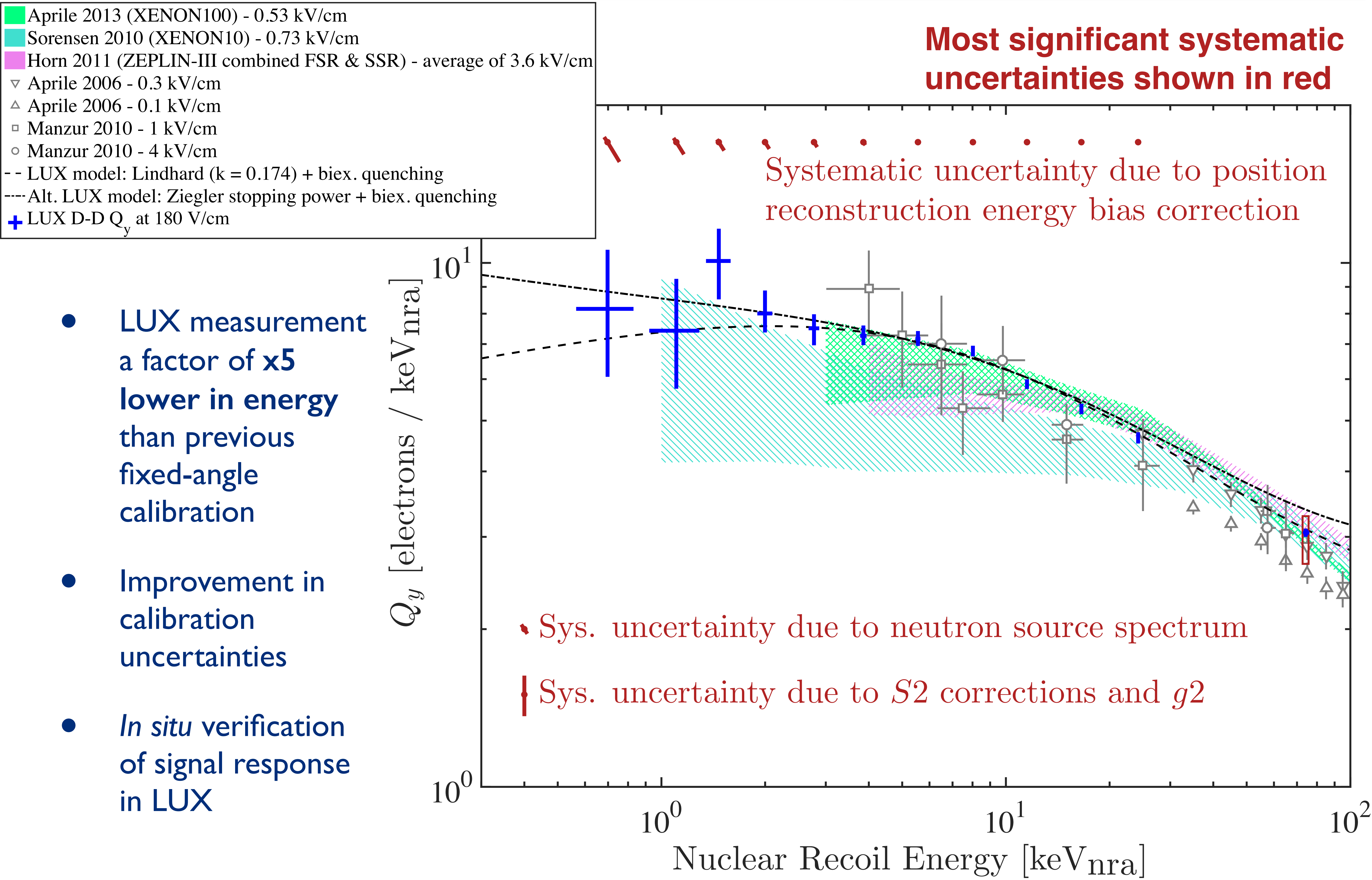
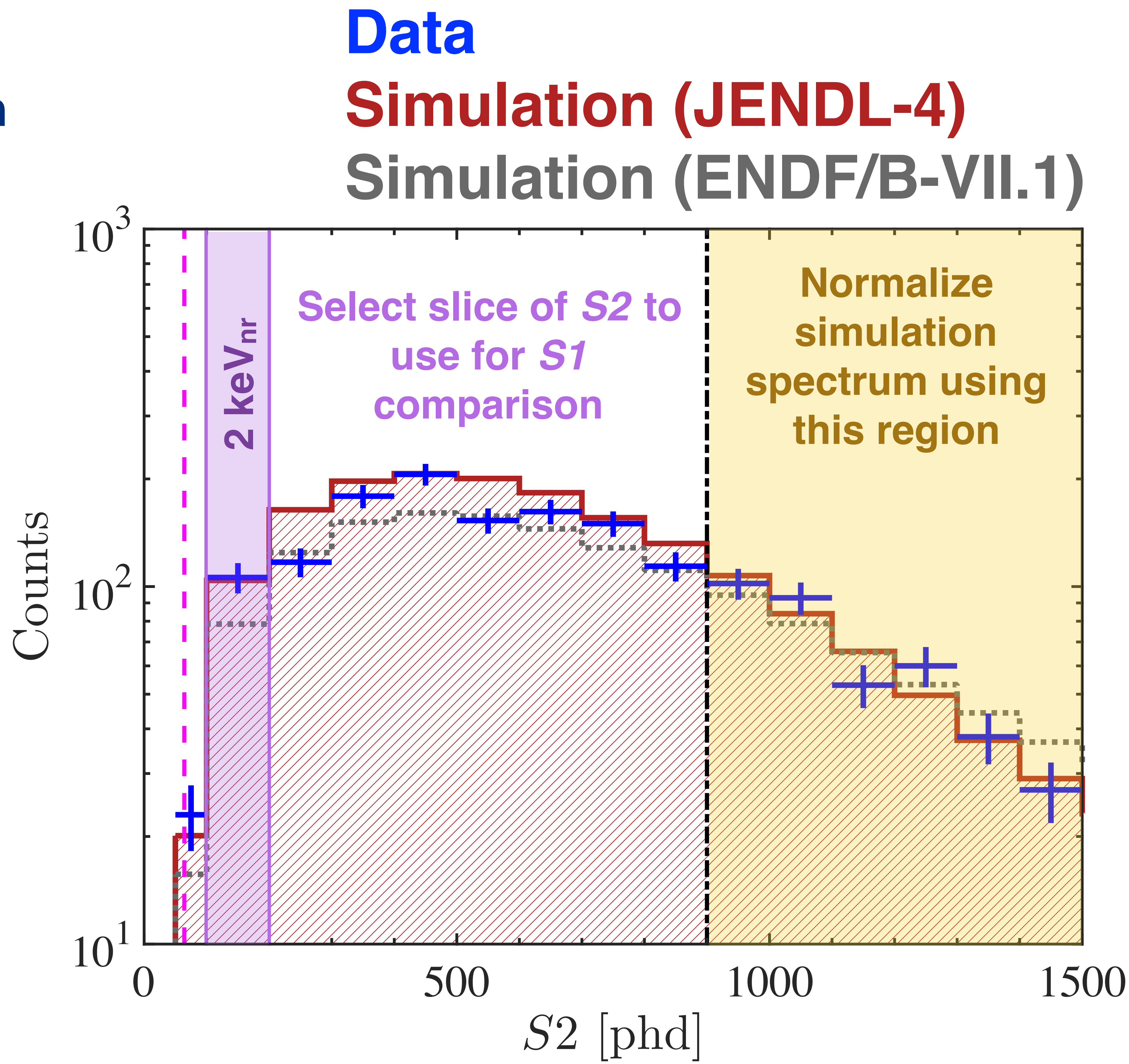


- LUX measurement a factor of **x5 lower in energy** than previous fixed-angle calibration
- Improvement in calibration uncertainties
- *In situ* verification of signal response in LUX

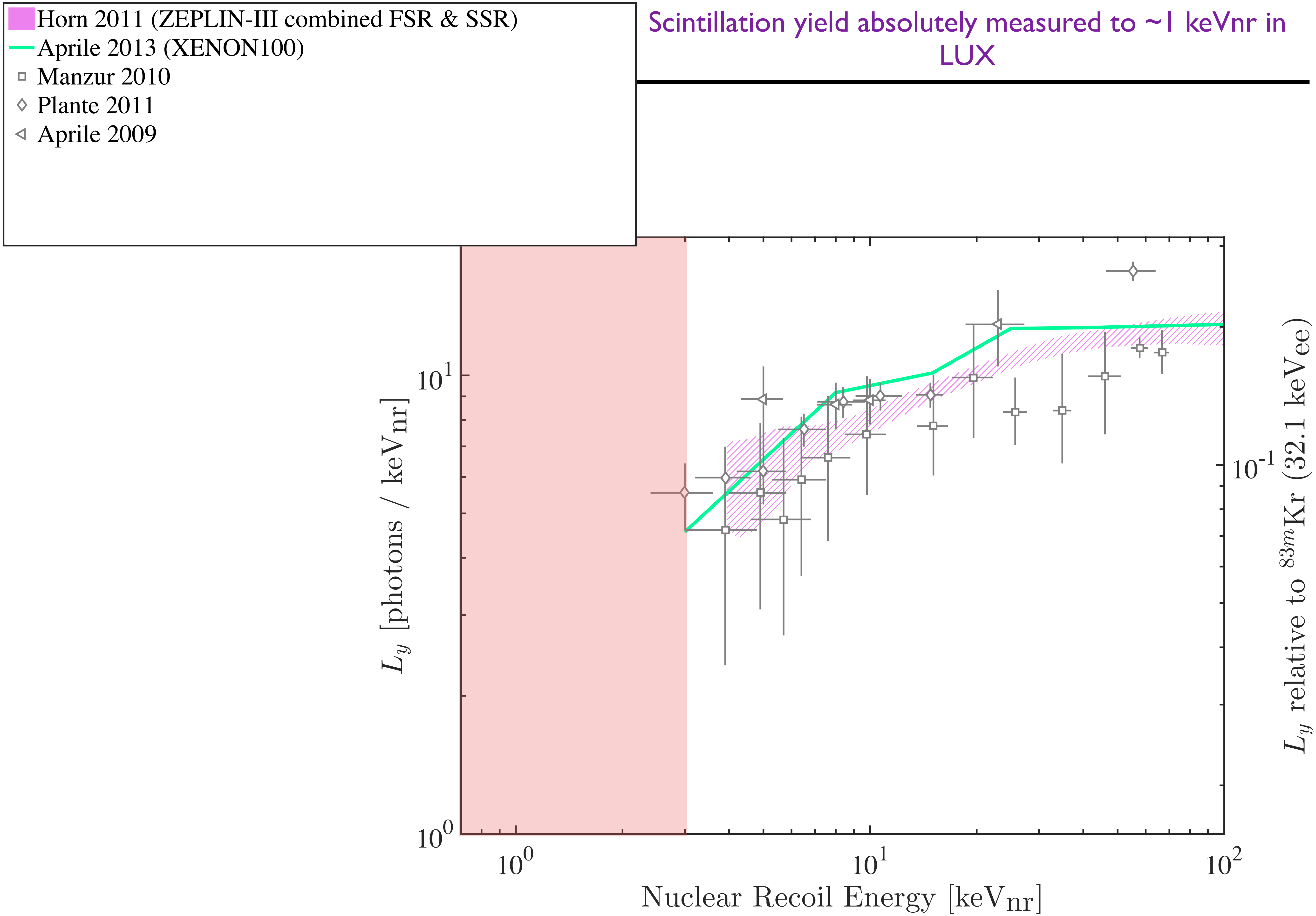
D-D Low-Energy *Ly* Measurement

Measuring the scintillation yield

- Use **single scatters** inside neutron beam projection with y' > 15 cm
- L_y measurement range is 50-900 phd $S2$
- Simulation event distribution is normalized outside of L_y measurement range using 900 < $S2$ < 1500 phd

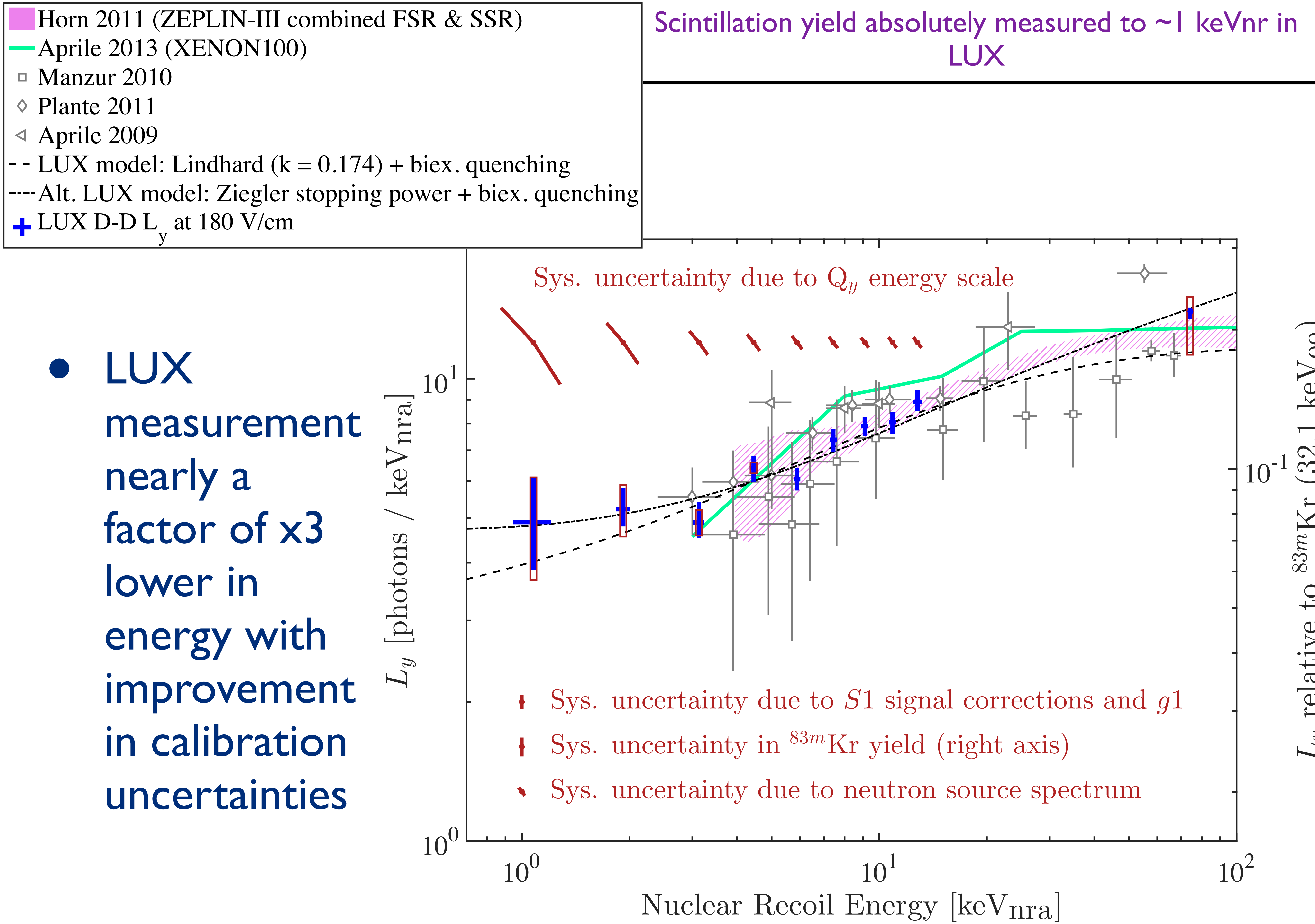


Scintillation yield absolutely measured to ~1 keVnr in LUX



Scintillation yield absolutely measured to ~1 keVnr in LUX

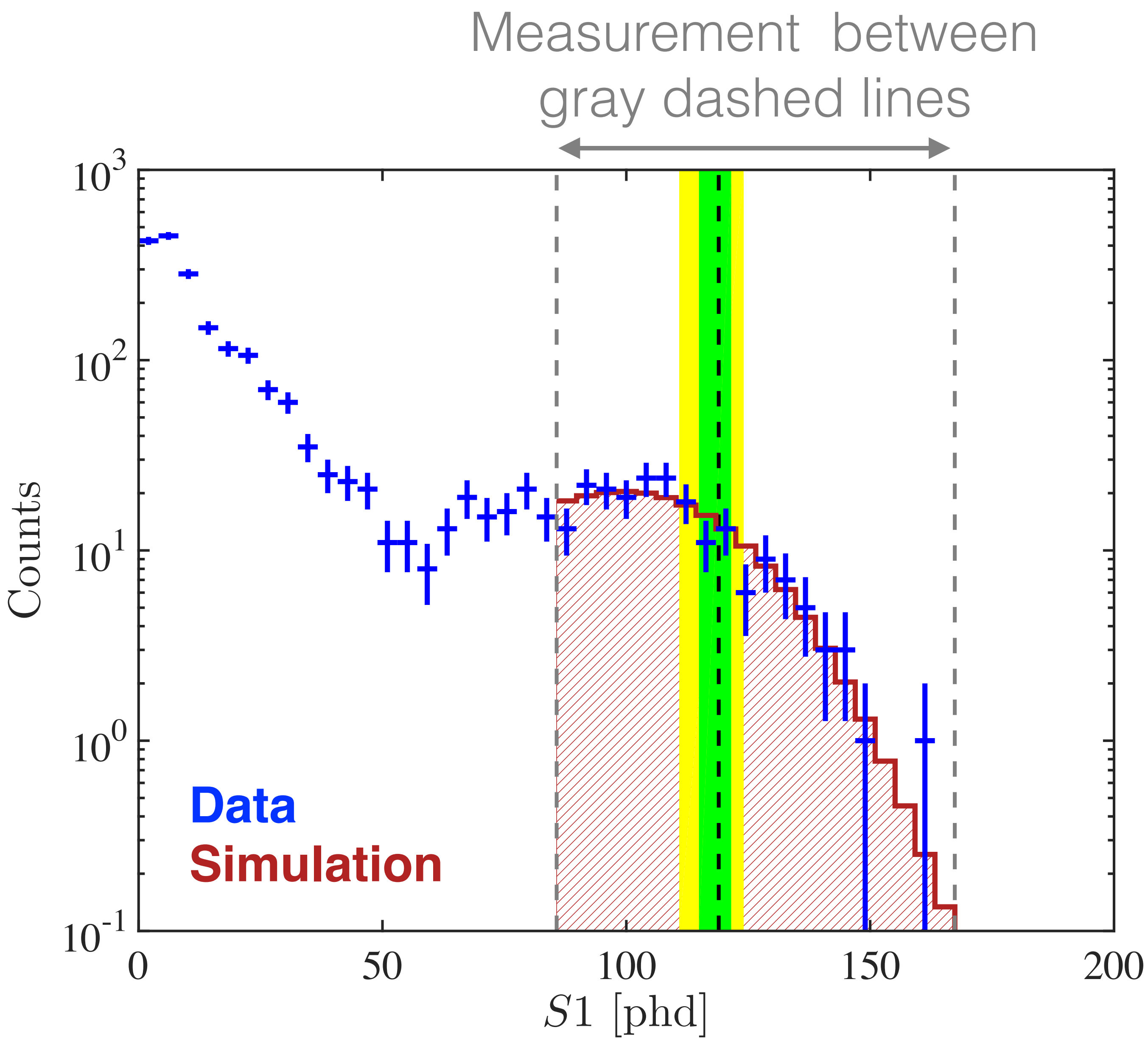
- LUX measurement nearly a factor of x3 lower in energy with improvement in calibration uncertainties

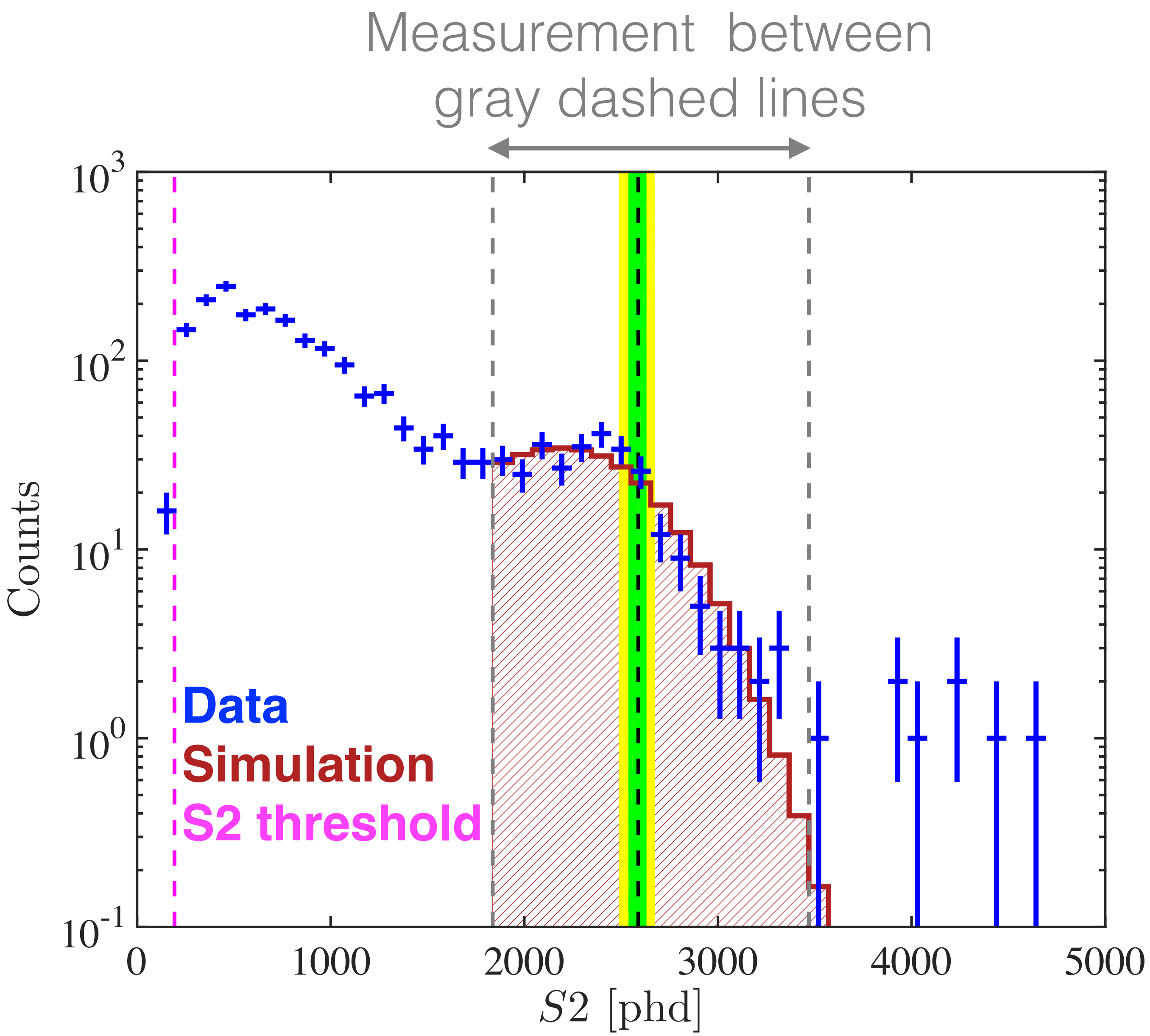


Signal Yields at the D-D Nuclear Recoil Spectrum Endpoint

Signal yields at the D-D spectrum endpoint

- The light and charge yields measured at 74 keV_{nr} using nuclear recoil spectrum endpoint
- Best fit signal yield shown by **black dashed line** with 1- and 2-$\boldsymbol{\sigma}$ statistical uncertainties given by green and yellow bands, respectively





Impact of the Calibration on LUX and Other Liquid Xenon Dark Matter Experiments

Lindhard-based best fit model and total quanta

- NEST model (arXiv:1412.4417) fit simultaneously to LUX D-D *Ly*, *Qy*, and NR
- Extract quenching factor (fraction of energy given to detectable electronic excitation)

$$E_{\rm nr} = \frac{W}{\mathcal{L}(E_{\rm nr})}\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

$$W = 13.7\ \text{eV}$$

- Lindhard-based model is consistent with LUX data over two orders of magnitude (as low as 1.1 keV_{nr})

$$\epsilon = 11.5\left(\frac{E_{\rm nr}}{\text{keV}_{\rm nr}}\right)Z^{-7/3}$$

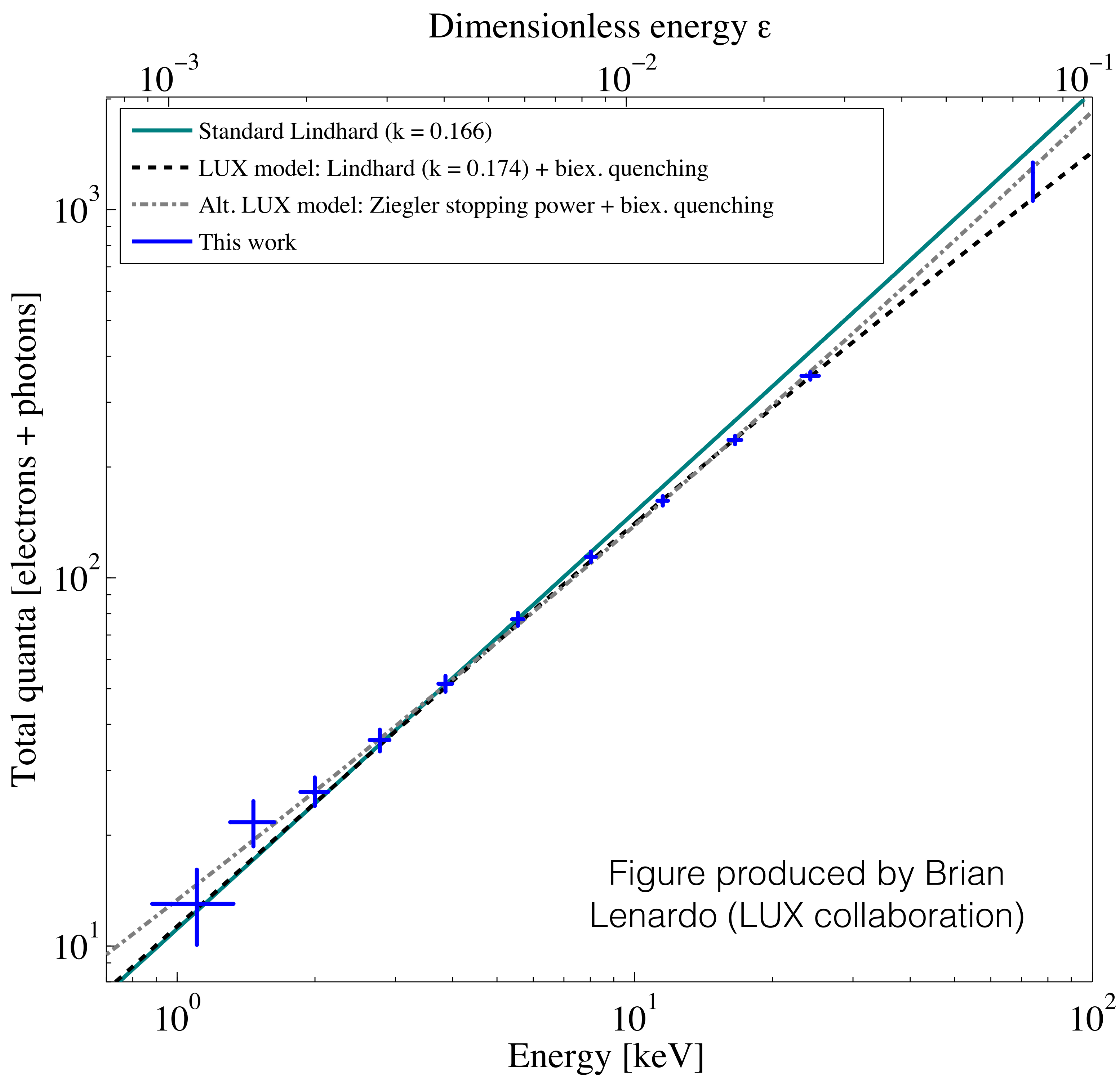
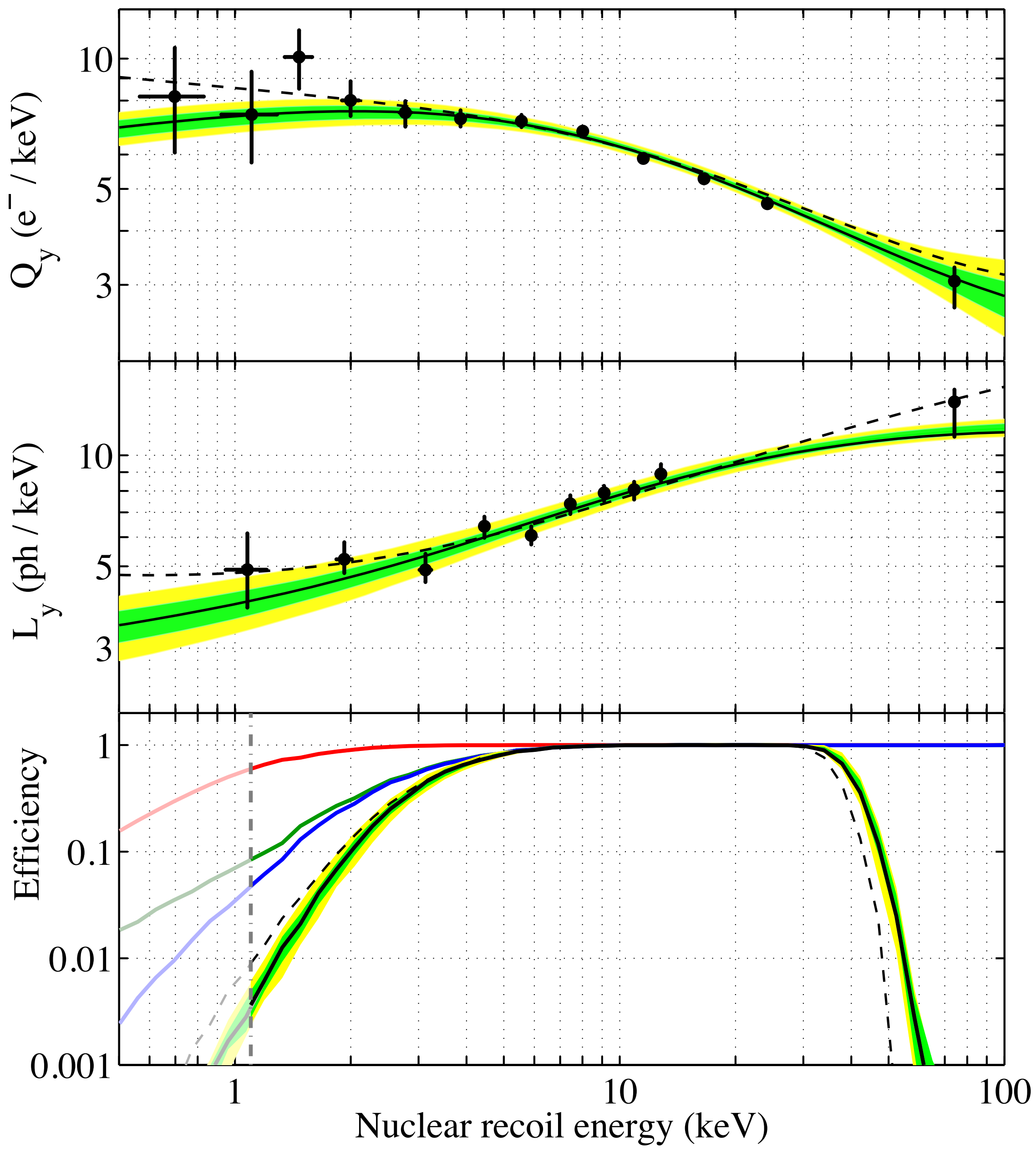
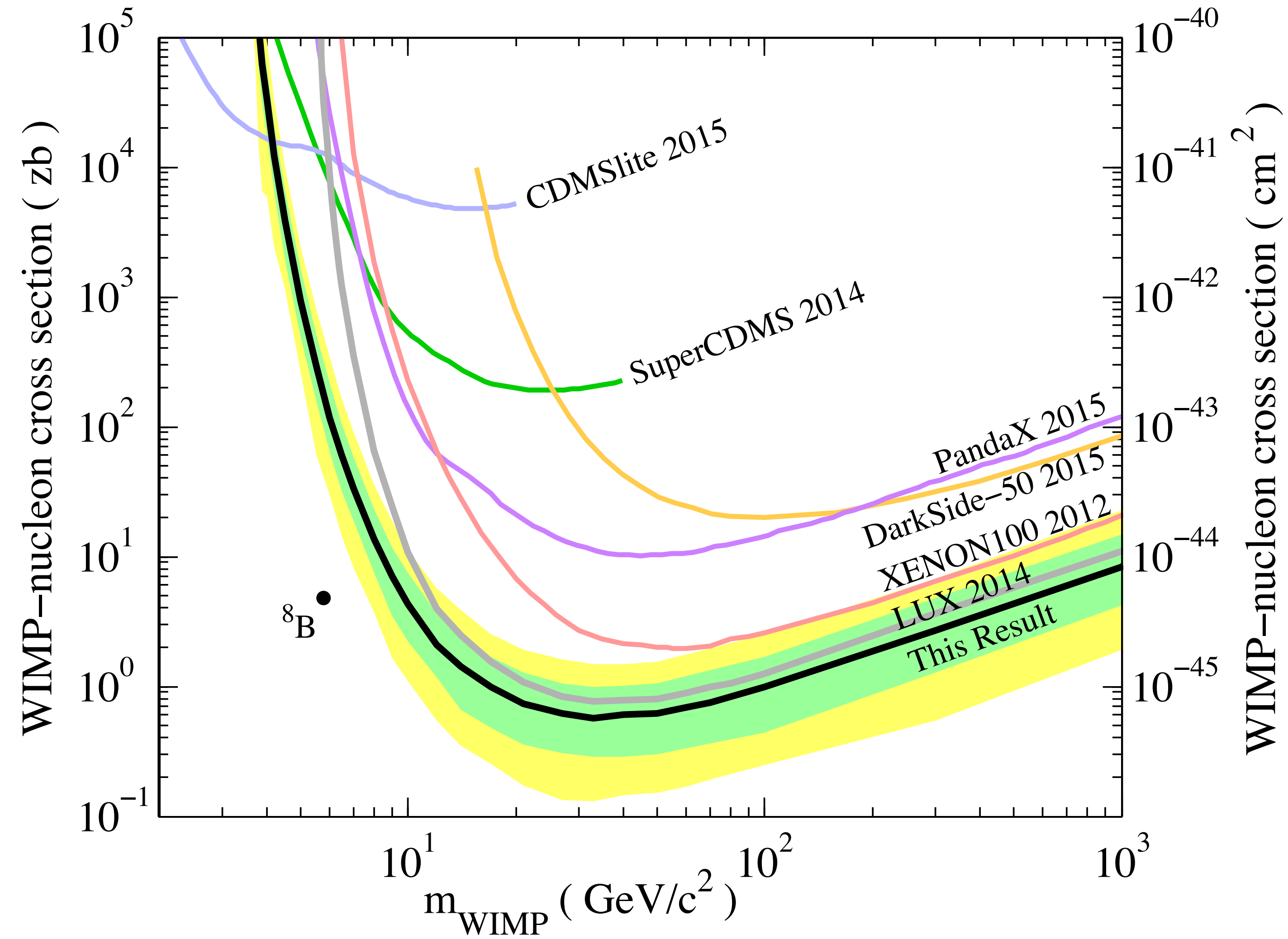


Figure produced by Brian Lenardo (LUX collaboration)

LUX Run03 WIMP search

- LUX measured nuclear recoil signal yields span entire WIMP search energy range





- WIMP search sensitivity improved x7 for 7 GeV/c^2 mass WIMP
- Lowest kinematically accessible WIMP mass reduced from 5.2 to 3.3 GeV/c^2
- Strong disagreement with low-mass WIMP interpretation of anomalous signals in other dark matter experiments

Coherent elastic neutrino-nucleus scattering (CENNS)

- LUX measurement of nuclear recoil signal response **down to 1.1 keV$_{nr}$** allows precise calculation of expectation for observed CENNS rate in liquid xenon
- LUX Run03 reanalysis (arXiv:1512.03506)
  - Expect **0.10 to 0.16 observed events**
- Next generation LZ detector (calculations by A. Dobi)
  - For baseline LZ detector performance, expect **7 CENNS ^{8}B observed events**
  - For optimistic LZ detector performance, (g1=12%, 2 PMT coincidence) expect **55 CENNS ^{8}B observed events**

$$^8\mathrm{B} \rightarrow ^7\mathrm{Be}^* + e^+ + \nu_e$$

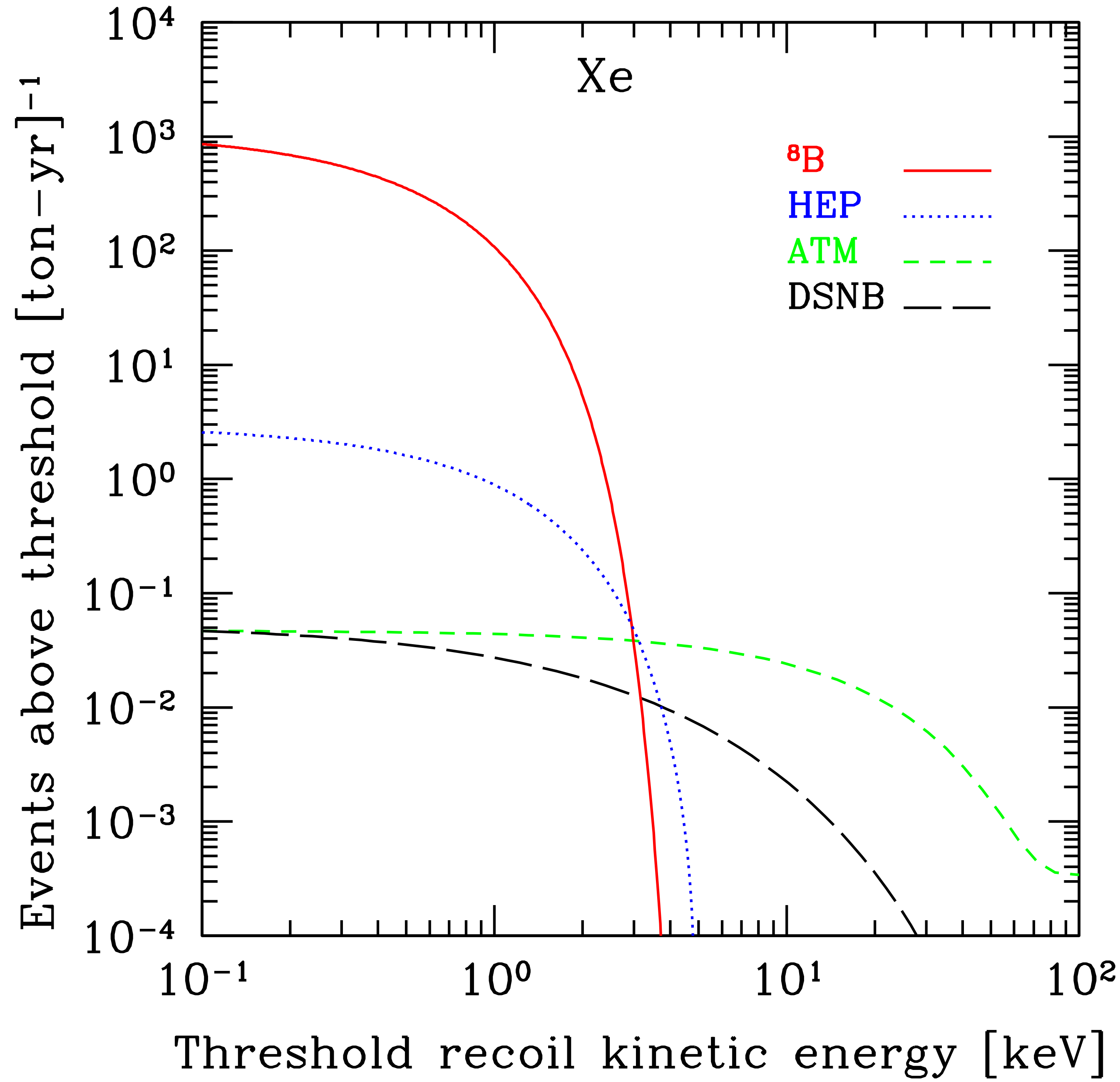


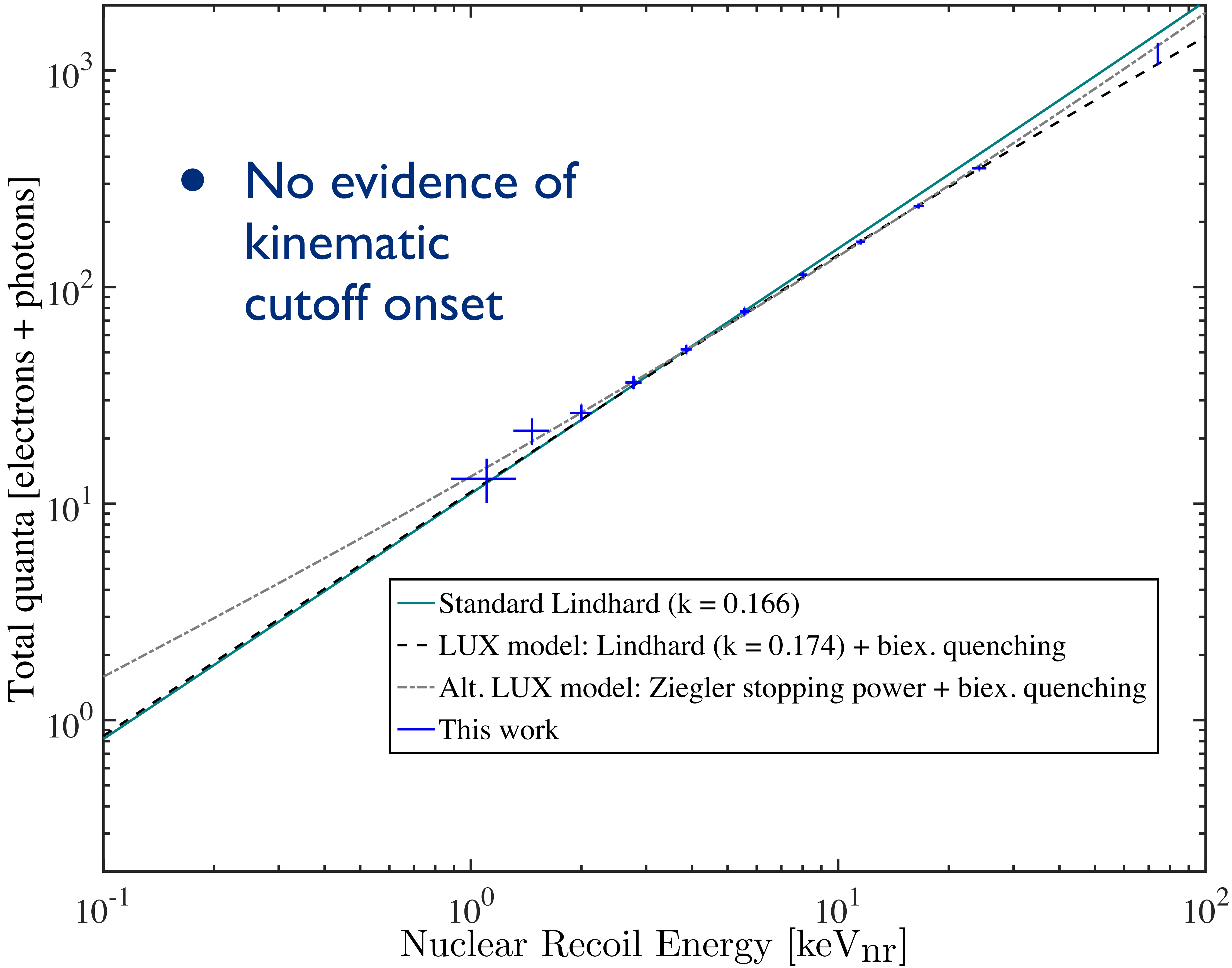
Figure from Strigary 2009 (arXiv:0903.3630)

How low (in energy) can this technique go?

The main limitations on the extension of the low-energy reach of this type of nuclear recoil calibration fall into three categories:

1. **Calibration strategy limitations**
2. **Detector performance limitations**
3. **Fundamental physics limitations**

Fundamental physics limitations



- No evidence of kinematic cutoff onset

Detector performance limitations

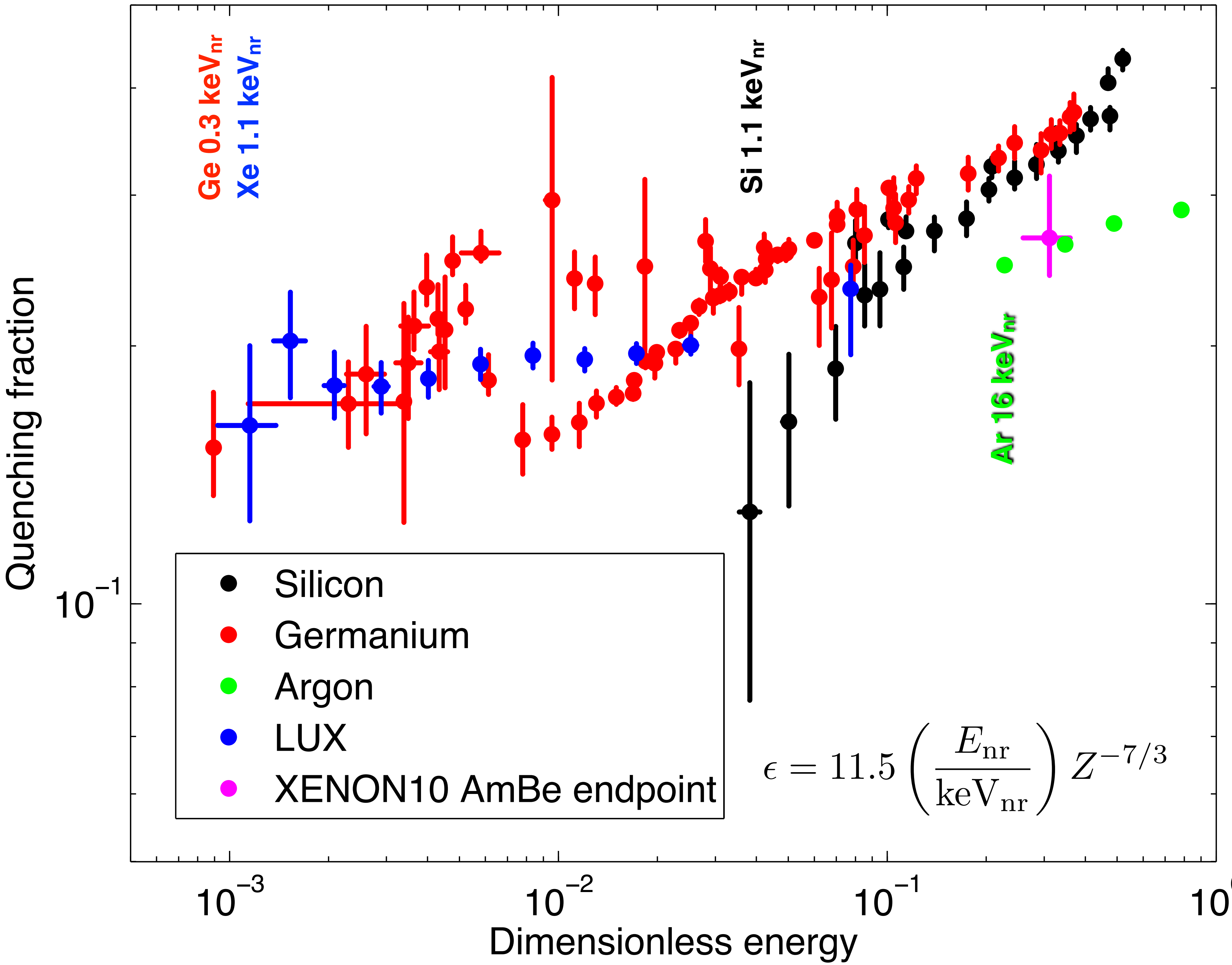
- Expectation values for number of signal carriers (produced and observed)

Recoil Energy [keV_{nr}]		n_p [photons]	$S1$ [phd]	n_e [electrons]	extracted electrons
0.1		0.29	0.03	0.56	0.23
0.4		1.4	0.16	2.7	1.1
0.7	LUX *Qy*	2.6	0.30	5.0	2.0
1.0		4.0	0.46	7.3	3.0
1.1	LUX *Ly*	4.5	0.52	8.1	3.3
10		78.1	9.0	62.5	25.5
100		1150	132	283	116

- For **100 eV** nuclear recoils (assuming electron detection efficiency of ~100%)
  - 43% of nuclear recoils will have ≥1 detected electron
  - 11% of events will have ≥2 detected electrons

Quenching fraction vs. dimensionless energy

Figure produced by Brian Lenardo (LUX collaboration)

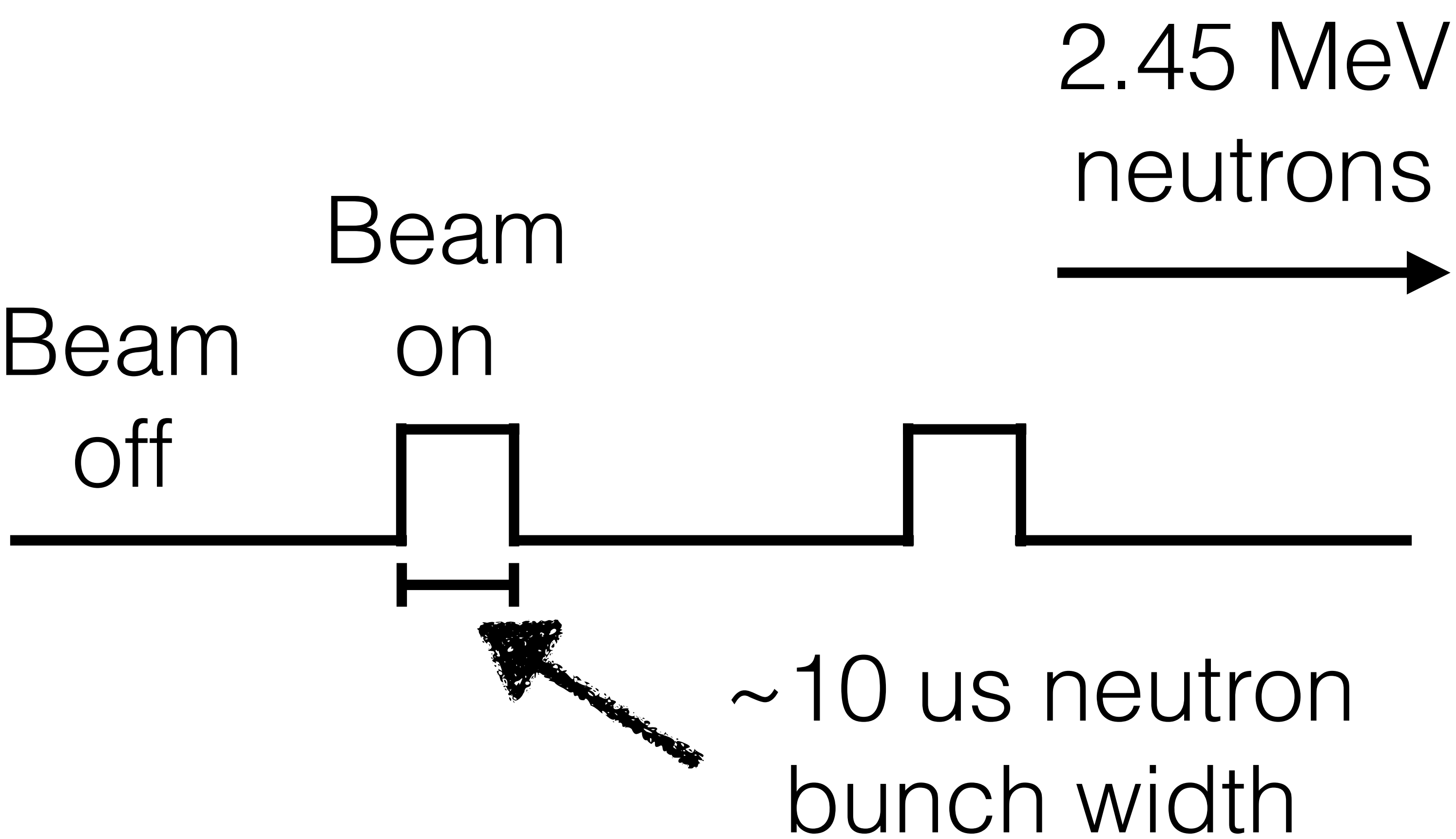


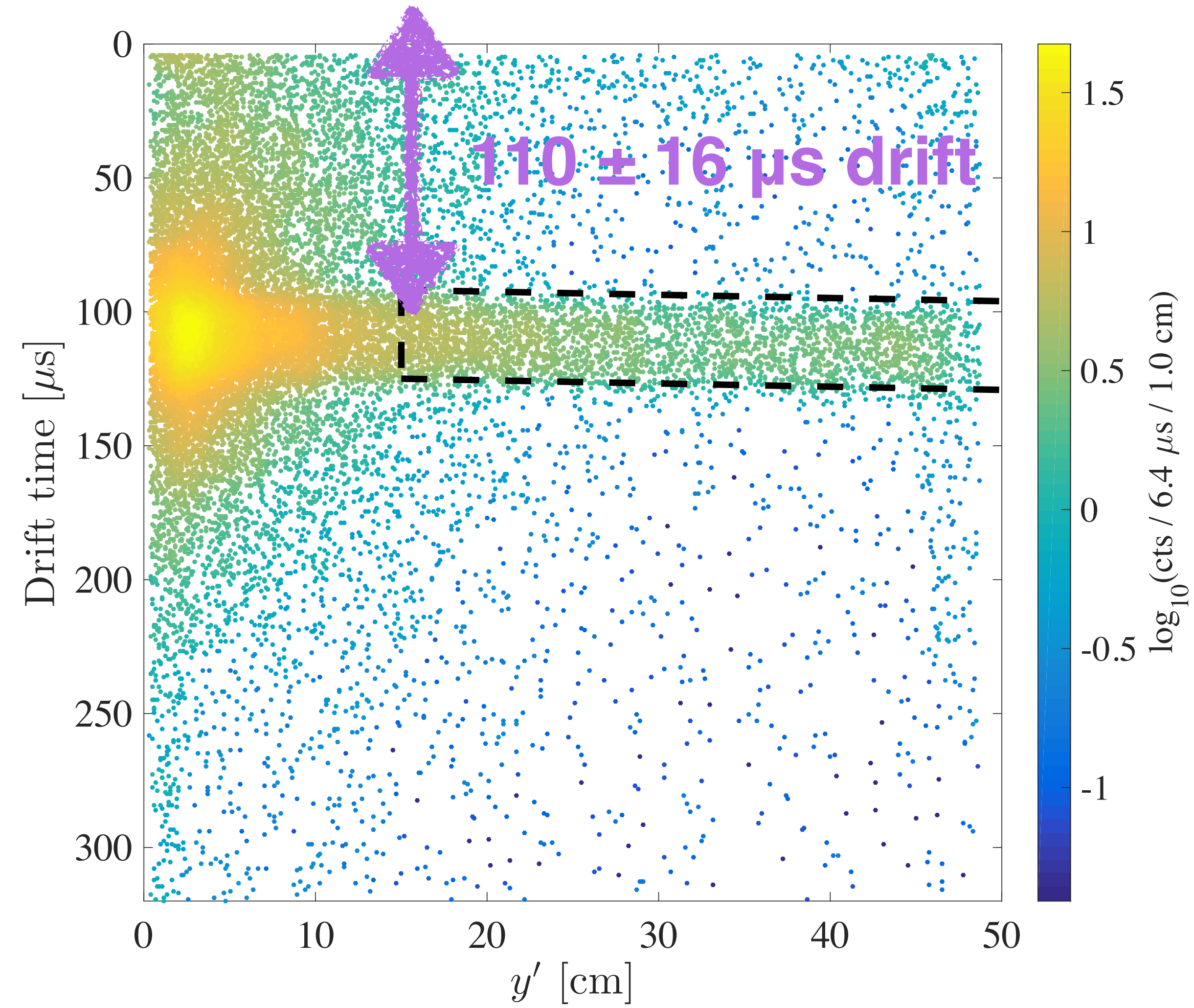
Improvements to the Calibration Technique

We're pursuing several strategies to extend the *in situ* D-D NR calibration even lower in energy with smaller uncertainties for the general calibration of TPCs.

1. Reduction of D-D neutron bunch width time structure
2. Creation of a mono-energetic 272 keV neutron source
3. Direct, absolute measurement of L_y using neutron scattering kinematics

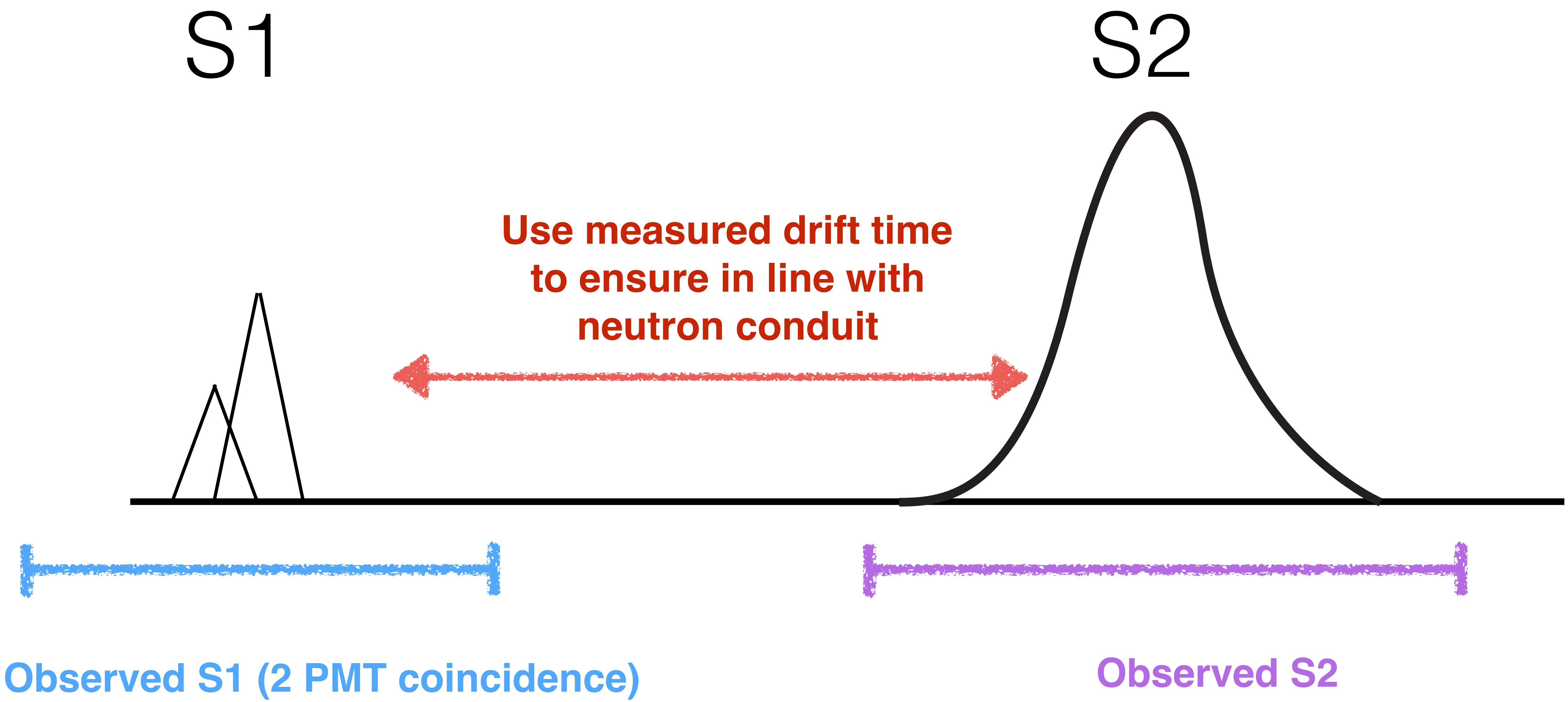
Reduction of D-D neutron bunch width time structure



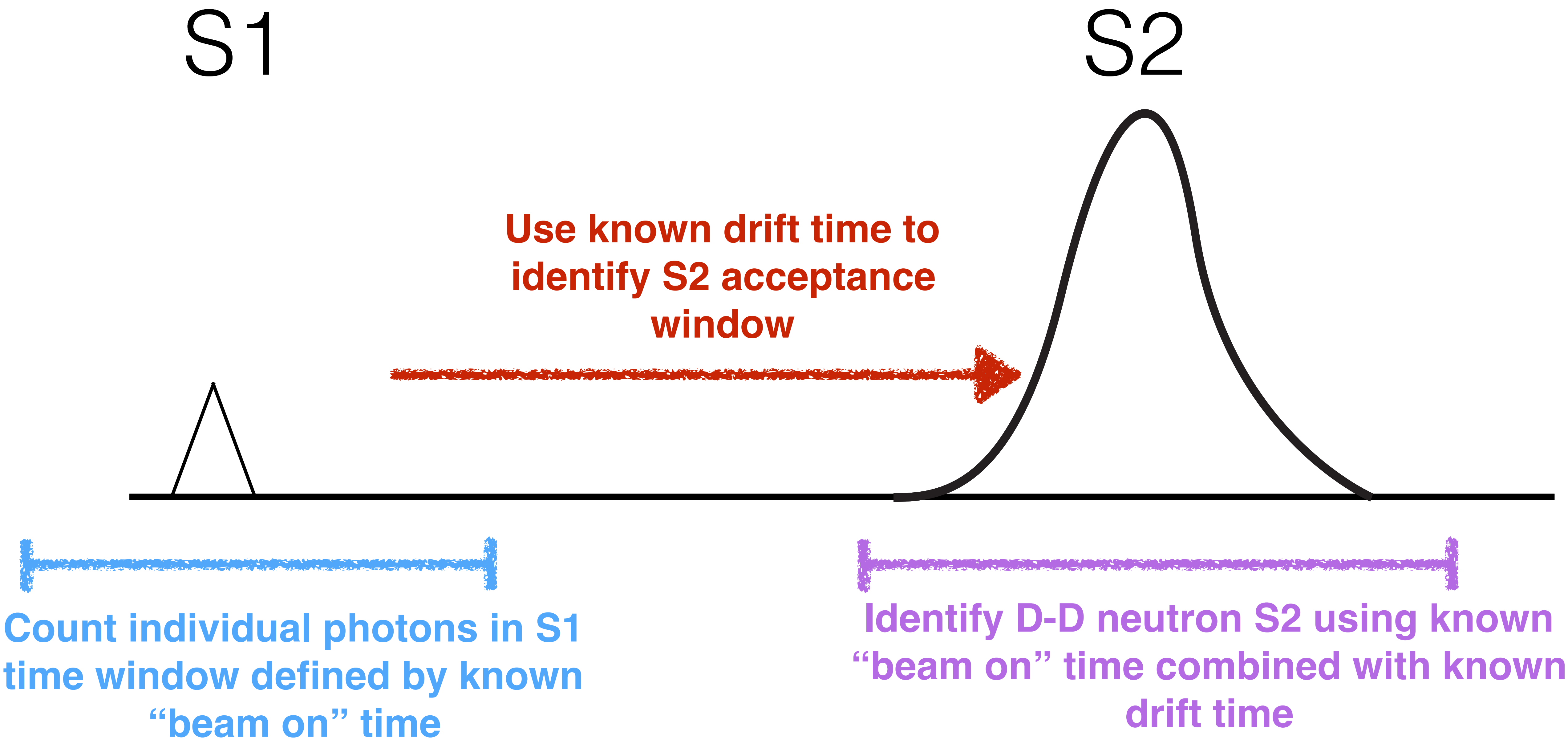


- DD beam-on time functions as a proxy for the t_0 even in the absence of an S1
  - Removes calibration dependence on S1 production/detection
- For reference, without an S1 we can fiducialize in Z (given 1.5 mm/us) with a precision:
  - 100 us (current generator spec) neutron pulse => 15 cm Z fiducialization precision
  - 10 us neutron pulse =>1.5 cm Z fiducialization precision
  - 1 us neutron pulse => 0.15 cm Z fiducialization precision

Reduction of D-D neutron bunch width time structure: S1 photon statistics

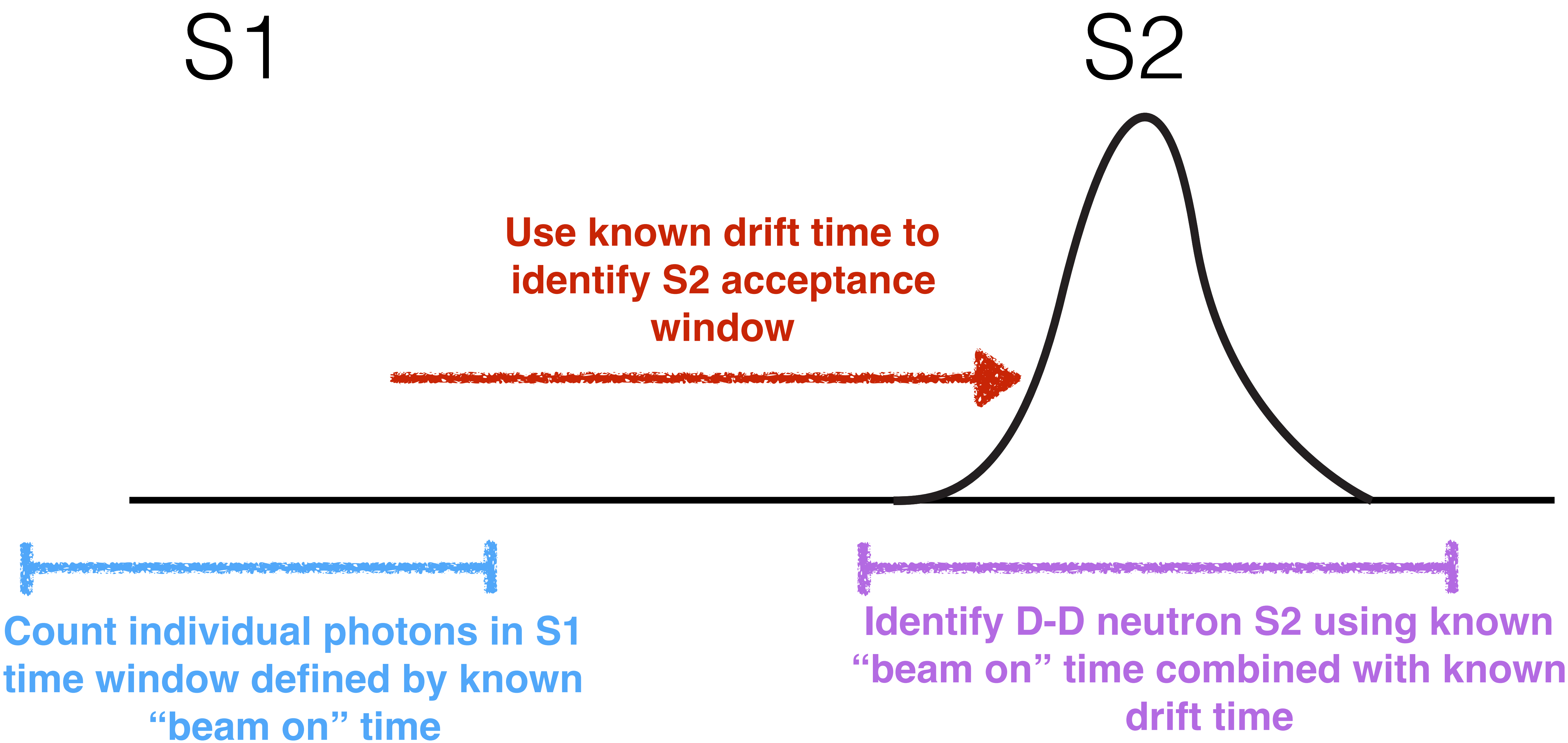


Reduction of D-D neutron bunch width time structure: S1 photon statistics



- Can identify small S2 events from D-D scatters and look at the statistics of the associated S1 signal. For given S2 size, can measure ***0***, 1, 2, … photon events
- In addition to advanced no-S1 studies, narrow trigger pulse allows for powerful reduction and understanding of calibration backgrounds

Reduction of D-D neutron bunch width time structure: S1 photon statistics



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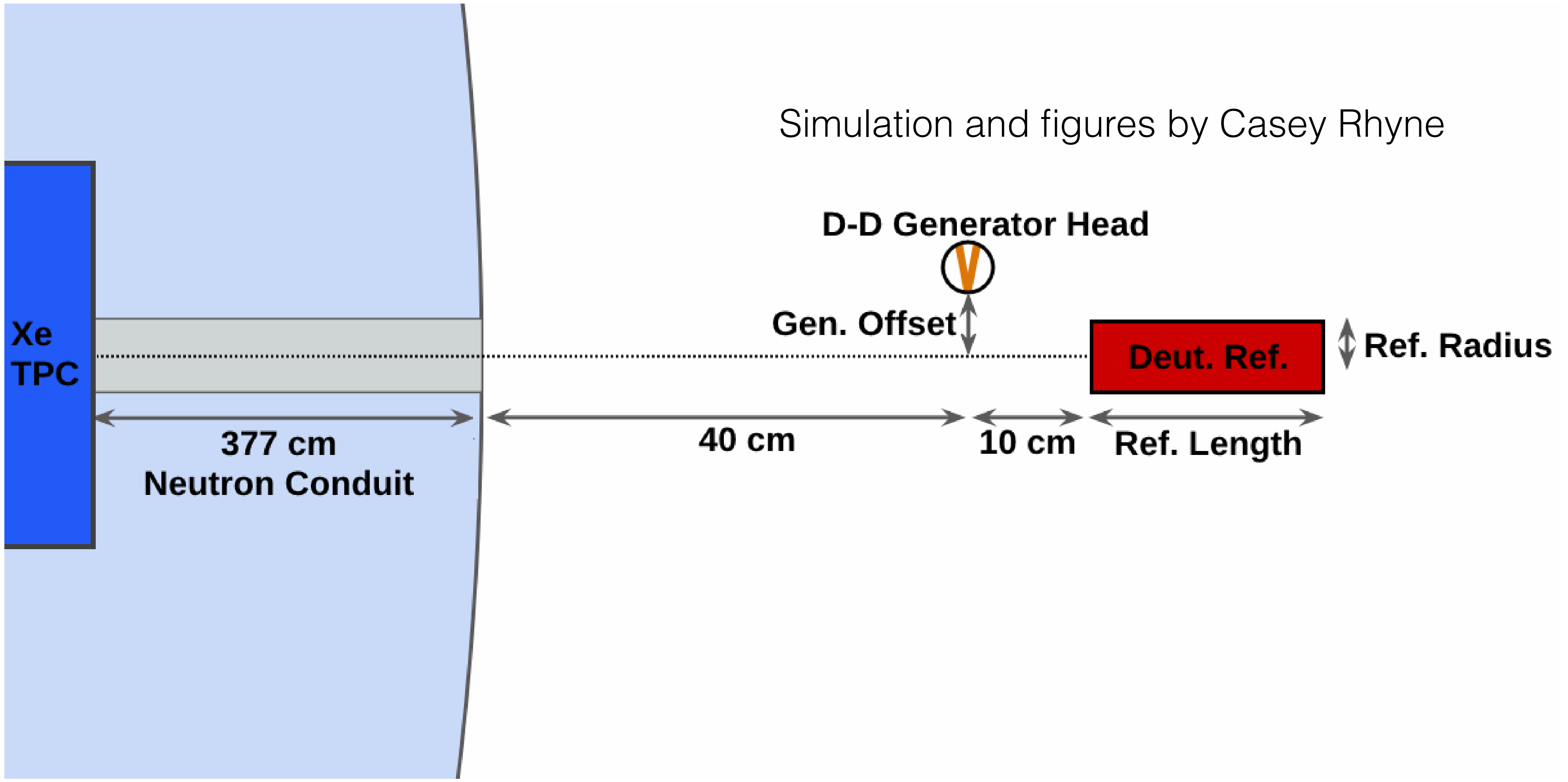
Creation of a collimated, mono-energetic 272 keV neutron source

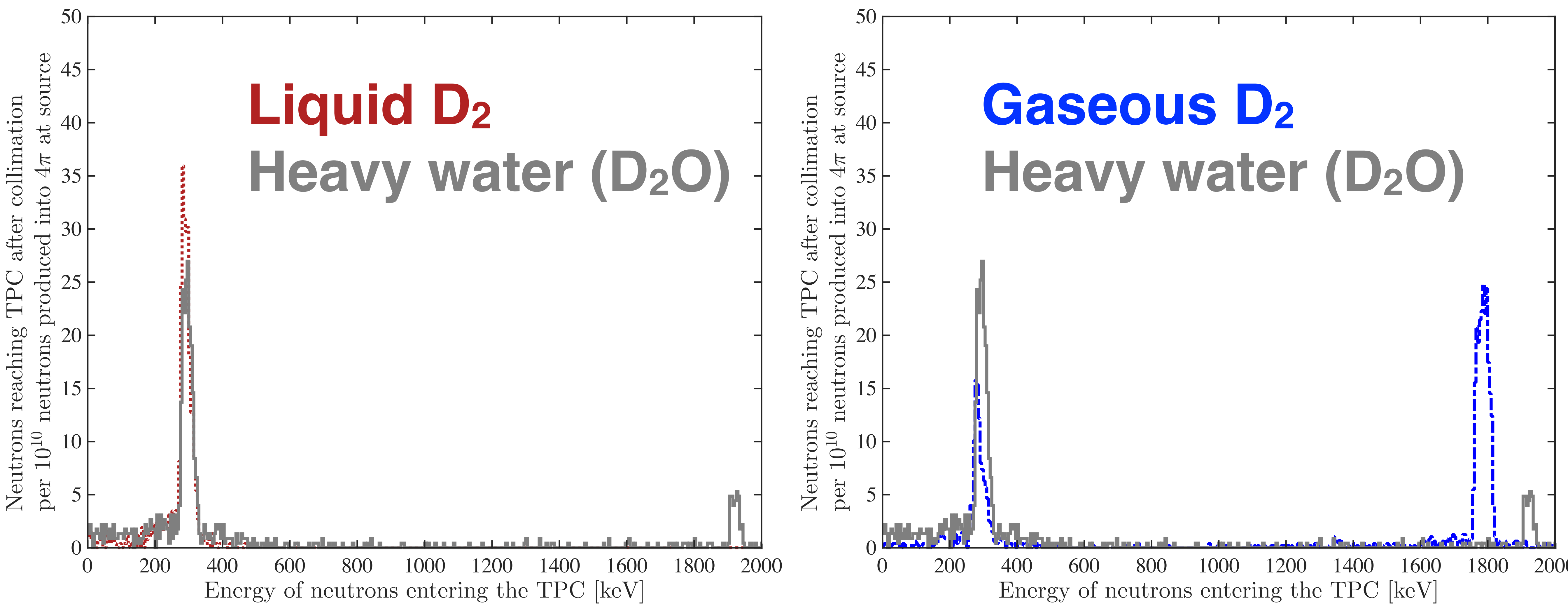


- D-loaded reflector positioned in line with neutron conduit
- Small solid angle presented by 5 cm diameter neutron conduit ensures only neutrons that backscatter at near 180° (272 keV) are incident upon the large LXe TPC

Creation of a collimated, mono-energetic 272 keV neutron source

Simulation and figures by Casey Rhyne

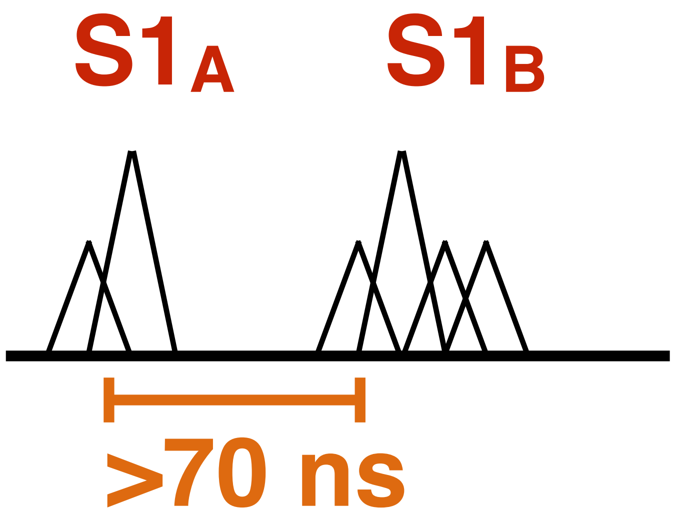
- Heavy water provides performance similar to an ideal reflector (liquid D_2)
  - 60% energy purity, but x2.3 increase in neutron flux
- Reflected intensity is x1/450 direct D-D source intensity
- 97% of events in the energy region of interest are direct from the D-reflector (not H_2O)



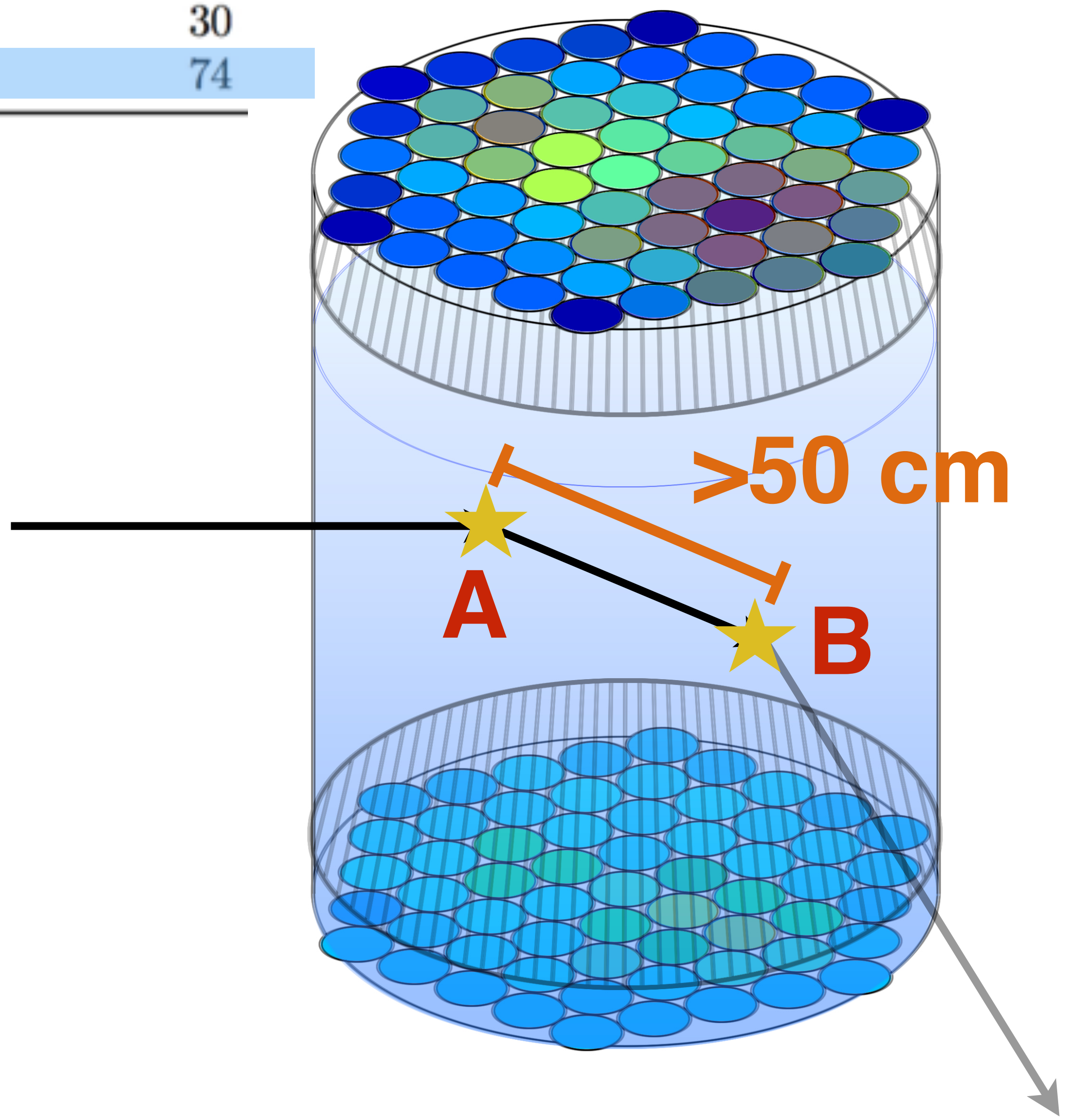
Direct, absolute measurement of L_y using neutron scattering kinematics

Table 1.2: The time-of-flight (ToF) dependence upon neutron energy. The corresponding nuclear recoil spectrum endpoint energy in argon and xenon is given in columns three and four, respectively.

E_n [keV]	ToF [ns/m]	Maximum Recoil [keV$_{nr}$]	
		Ar	Xe
1	2286	0.1	0.03
10	723	1	0.3
100	229	10	3
272	139	26	8
1000	72	96	30
2450	46	235	74



- Double scatter events with 50 cm vertex separation => 70 ns ToF for 272 keV neutrons between vertices
- Typically 30 ns characteristic time constant for S1 scintillation pulse shape
- Can distinguish photons in $S1_A$ from those in $S1_B$
- As in current Q_y measurement, use angle to reconstruct the deposited energy for vertex A

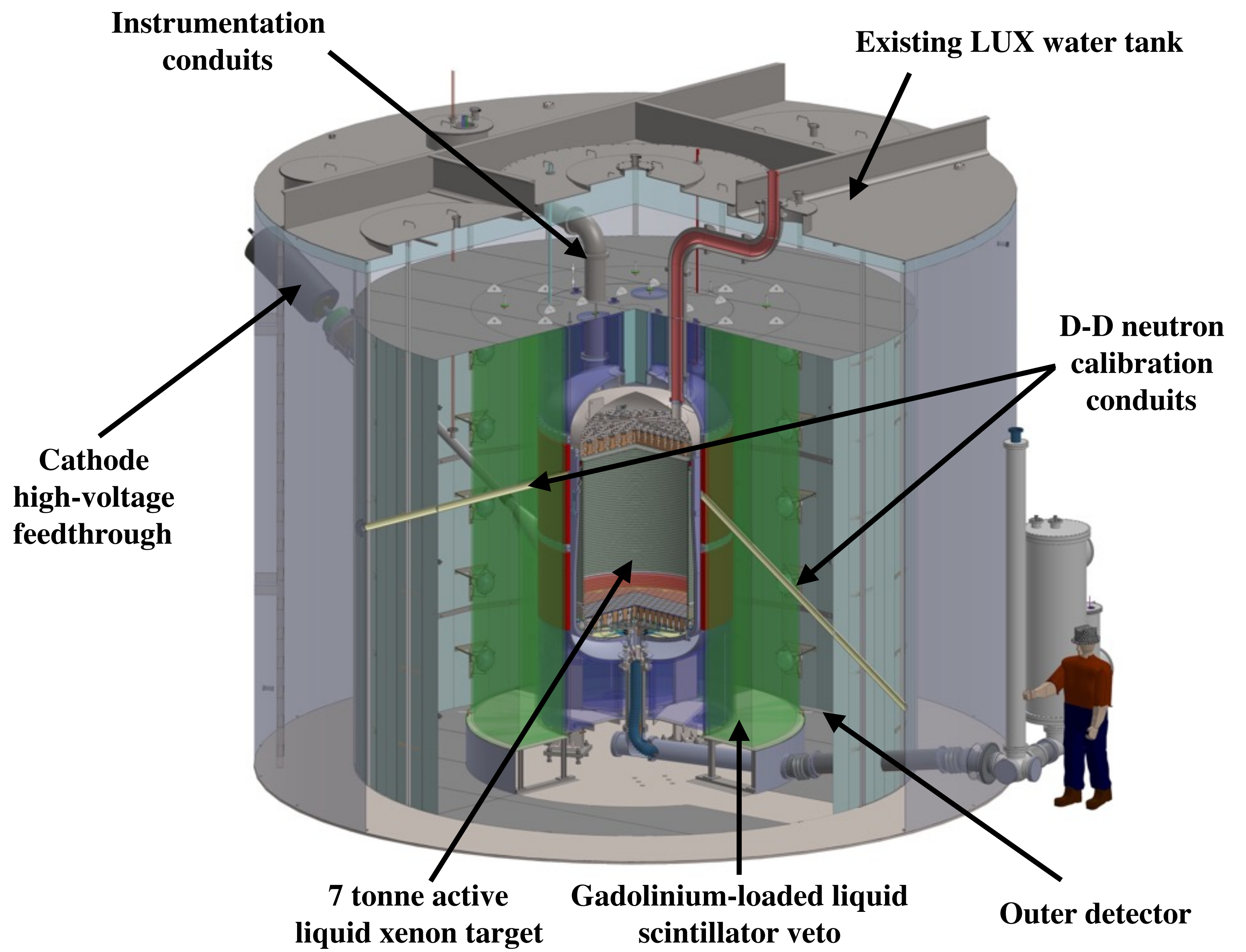


The LZ Dark Matter Experiment

The LZ dark matter experiment

Original solid model snapshot from Matt Hoff (LZ collaboration).

- Due to the success of the LUX D-D program, D-D is a core component of the LZ calibration strategy
- Two neutron conduits
- Baseline plan to include
  - Short neutron bunch width operation
  - D-reflector neutron source



- 10 tonne liquid xenon detector (7 tonne active)

Projected LZ sensitivity (1000 live days)

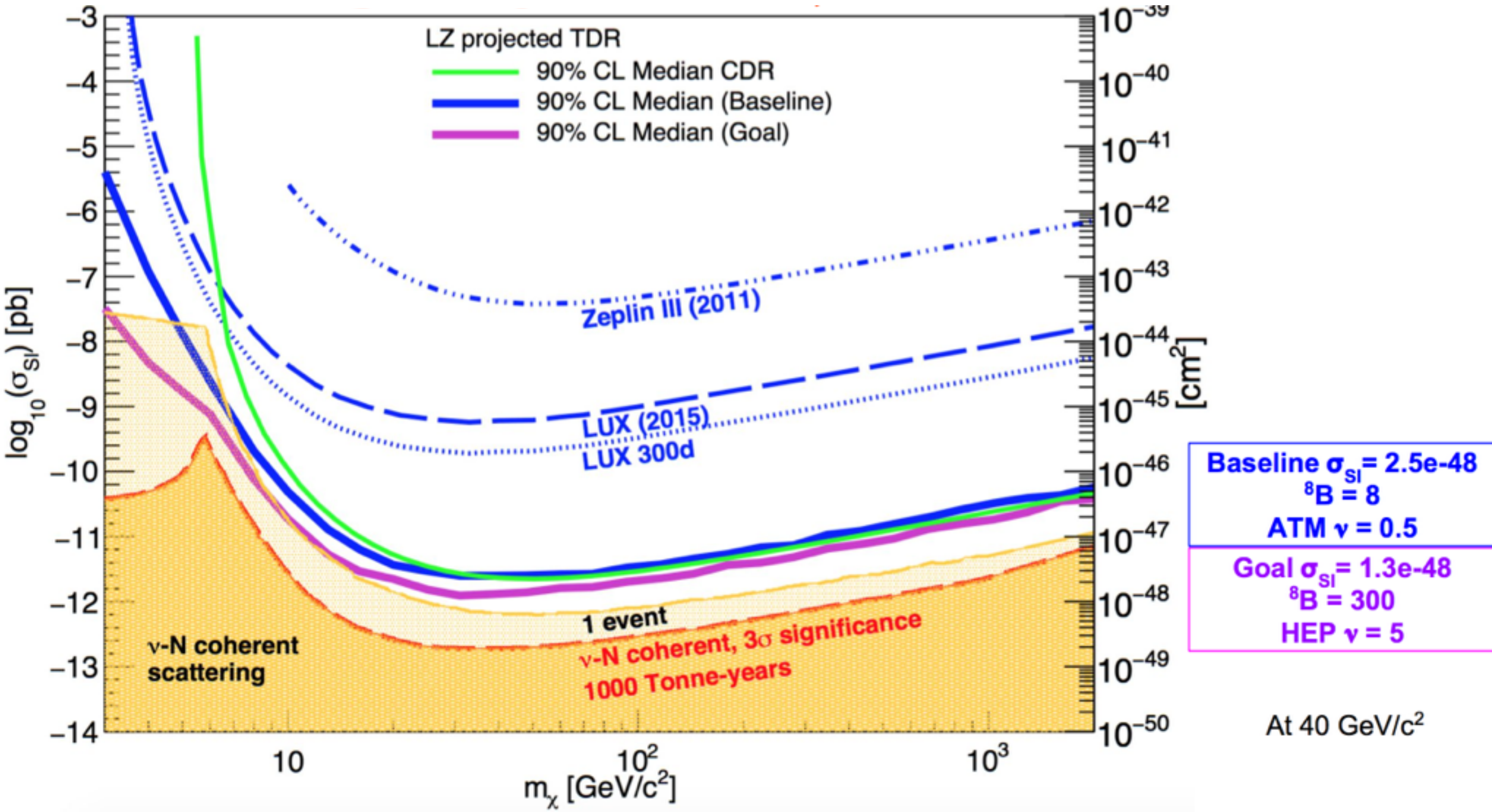


Figure from Attila Dobi (LZ Collaboration)

Conclusions

- New nuclear recoil calibration technique demonstrated in the LUX detector
  - Measured ionization and scintillation signal yields from **nuclear recoils as low as 0.7 keV$_{nr}$ and 1.1 keV$_{nr}$**, respectively
  - Measured **ionization (scintillation) a factor of x5 (x3) lower in energy** than previous experiments with reduction in calibration uncertainties
  - Measurement is **consistent with Lindhard theory** over two orders of magnitude in energy, and in **tension with a kinematic cutoff onset above 1 keV$_{nr}$**
- The measured yields significantly improve sensitivity of liquid xenon TPCs to low mass WIMPs
  - Already **world-leading** LUX Run03 limit **improved by x7 at 7 GeV c^{-2}**
  - **Strong disagreement** with low-mass WIMP interpretation of anomalous signals in several other dark matter experiments
- Provides **foundation for precise calculations** of the expected CENNS signal from ^{8}B in large liquid xenon TPCs
- This calibration technique is now a **core component** of the next generation LZ dark matter detector calibration program