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

## James Verbus
## Brown University

Dissertation Defense
May 10th, 2016

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

# Thanks
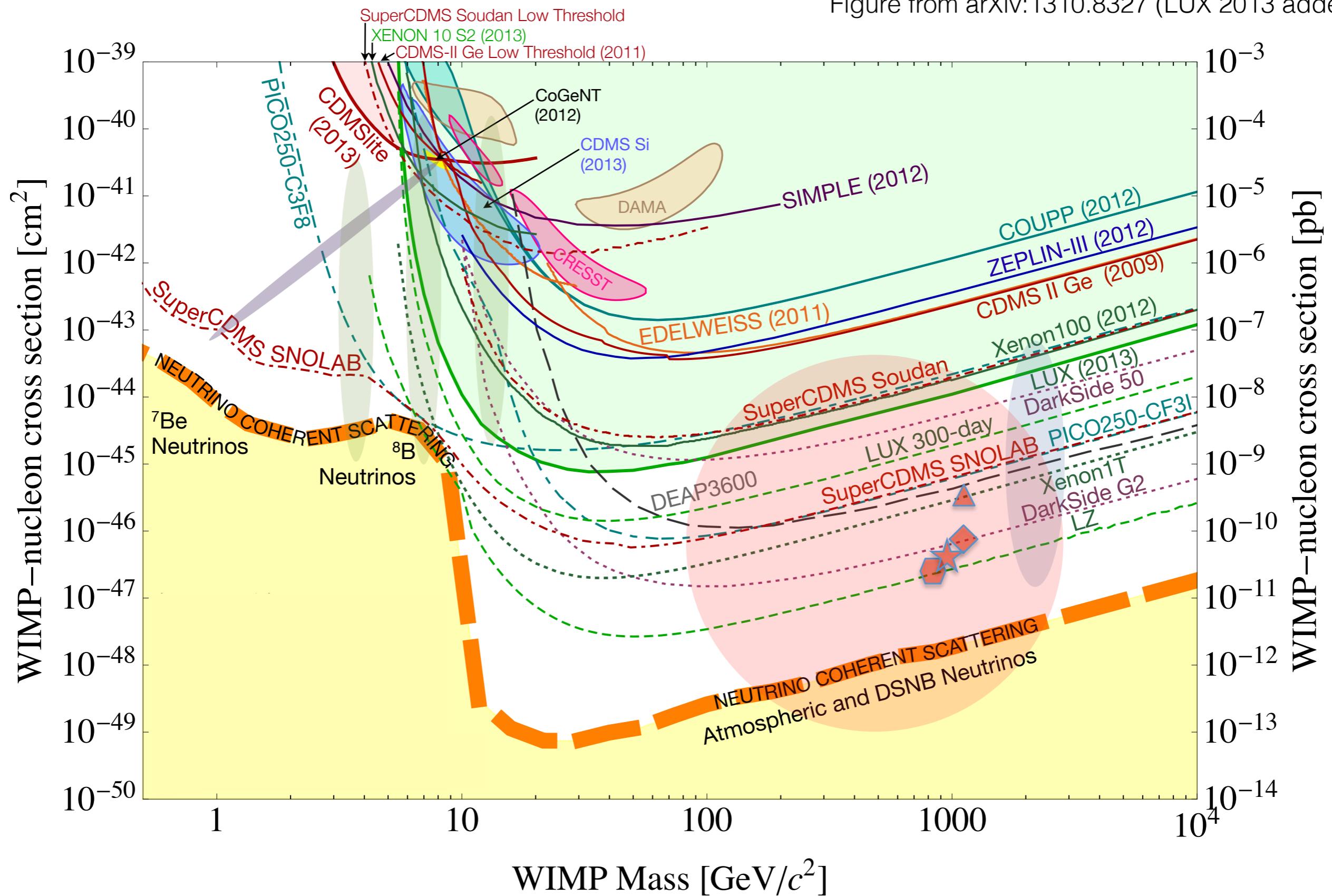
- Ian Dell'Antonio and Meenakshi Narain for acting as thesis committee members

- 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.
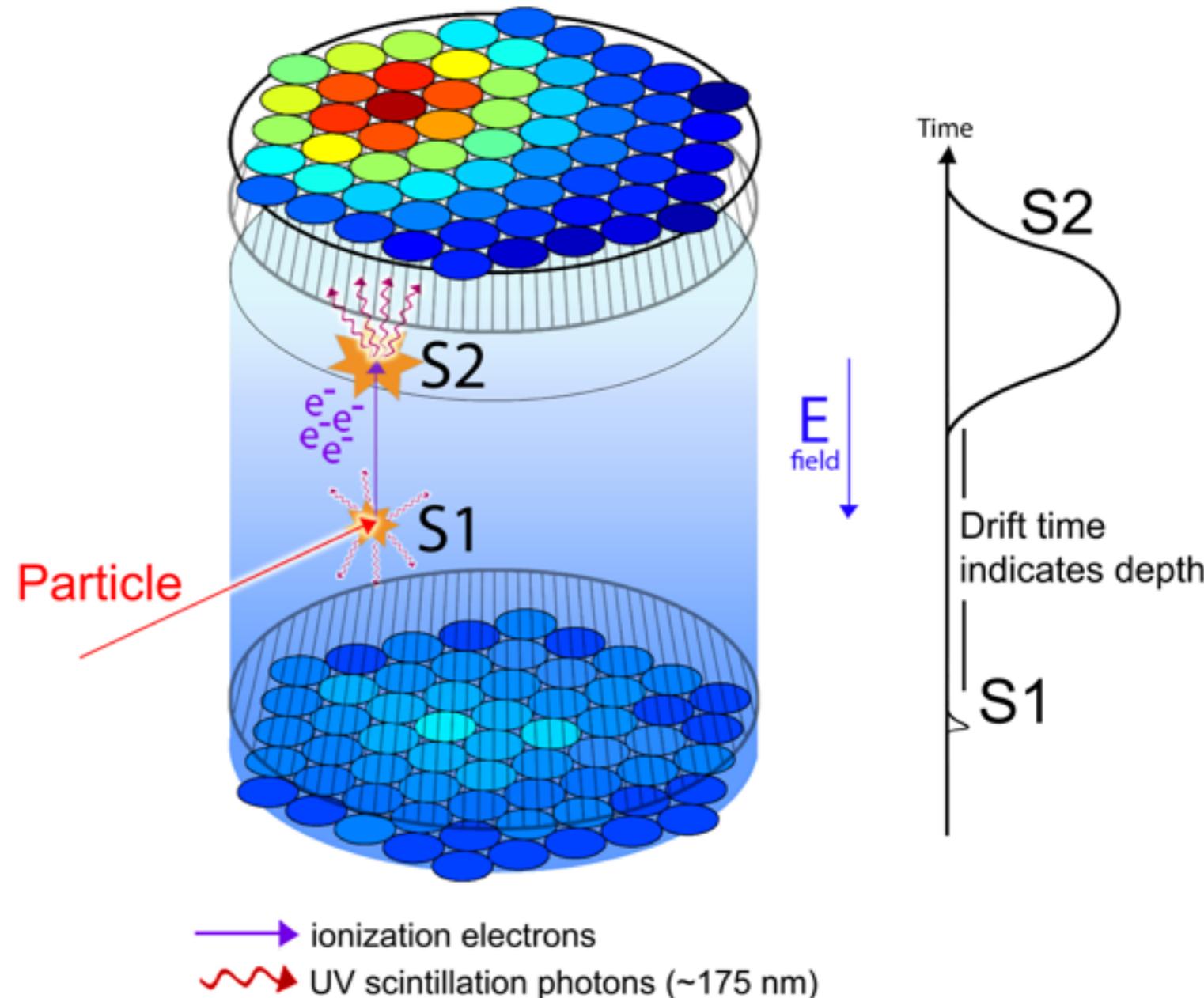
# The WIMP direct detection result landscape as of late 2013



Figure from arXiv:1310.8327 (LUX 2013 added)
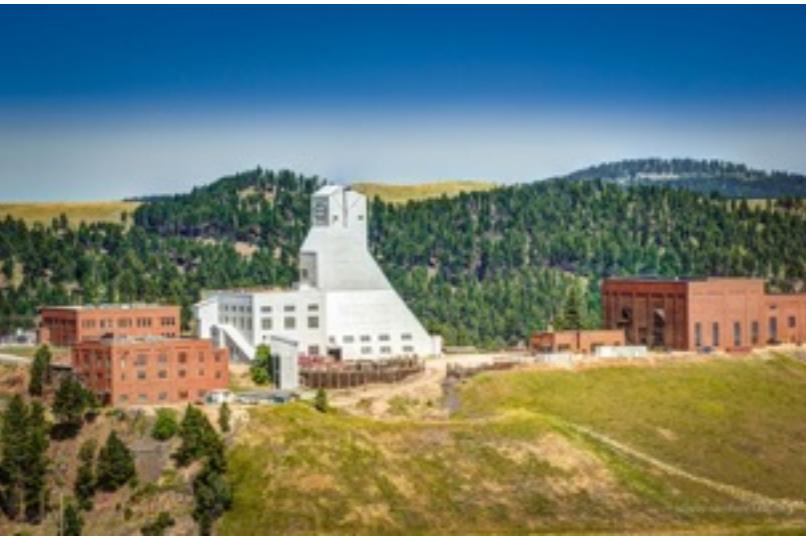
# The LUX Detector

# 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

  - $g1 = 0.115$ and $g2 = 11.4$ are the amplification factors for each quanta during the D-D calibration period

  - $n_\gamma$ and $n_e$ are the fundamental measured quantities



ionization electrons

UV scintillation photons (~175 nm)

# LUX background reduction techniques



**1492 m underground**



- **4850 ft (1492 m) underground in the Black Hills of South Dakota**

  - **Reduces muon flux by $\times 10^{-7}$**

- 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 $\times 10^{-4}$ 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)

- **4850 ft (1492 m) underground in the Black Hills of South**



$0^{-4}$ due

to

# LUX background reduction techniques
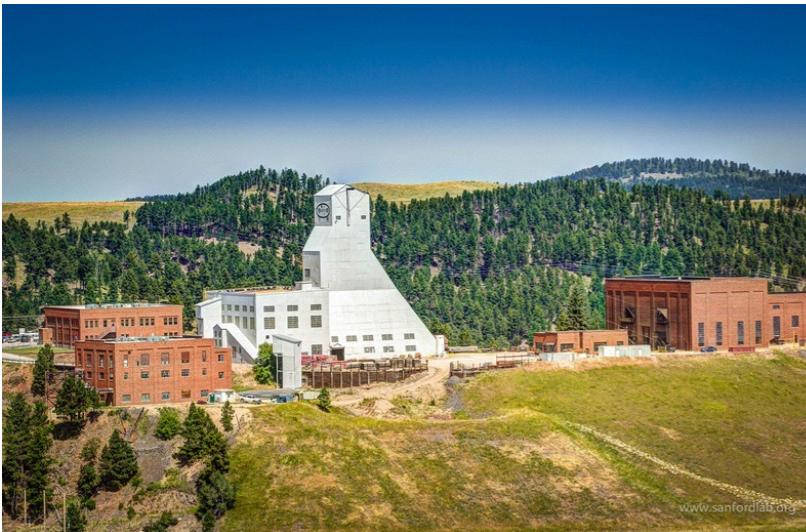


1492 m underground

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1492 m underground

# The Need for Low Energy Nuclear Recoil Calibrations

# Defining detector response

| Scintillation (S1) response | Ionization (S2) response |
|---|---|

**Signal carrier production:**

- Light yield $L_y(E_{nr})$ in units of photons / keVnr
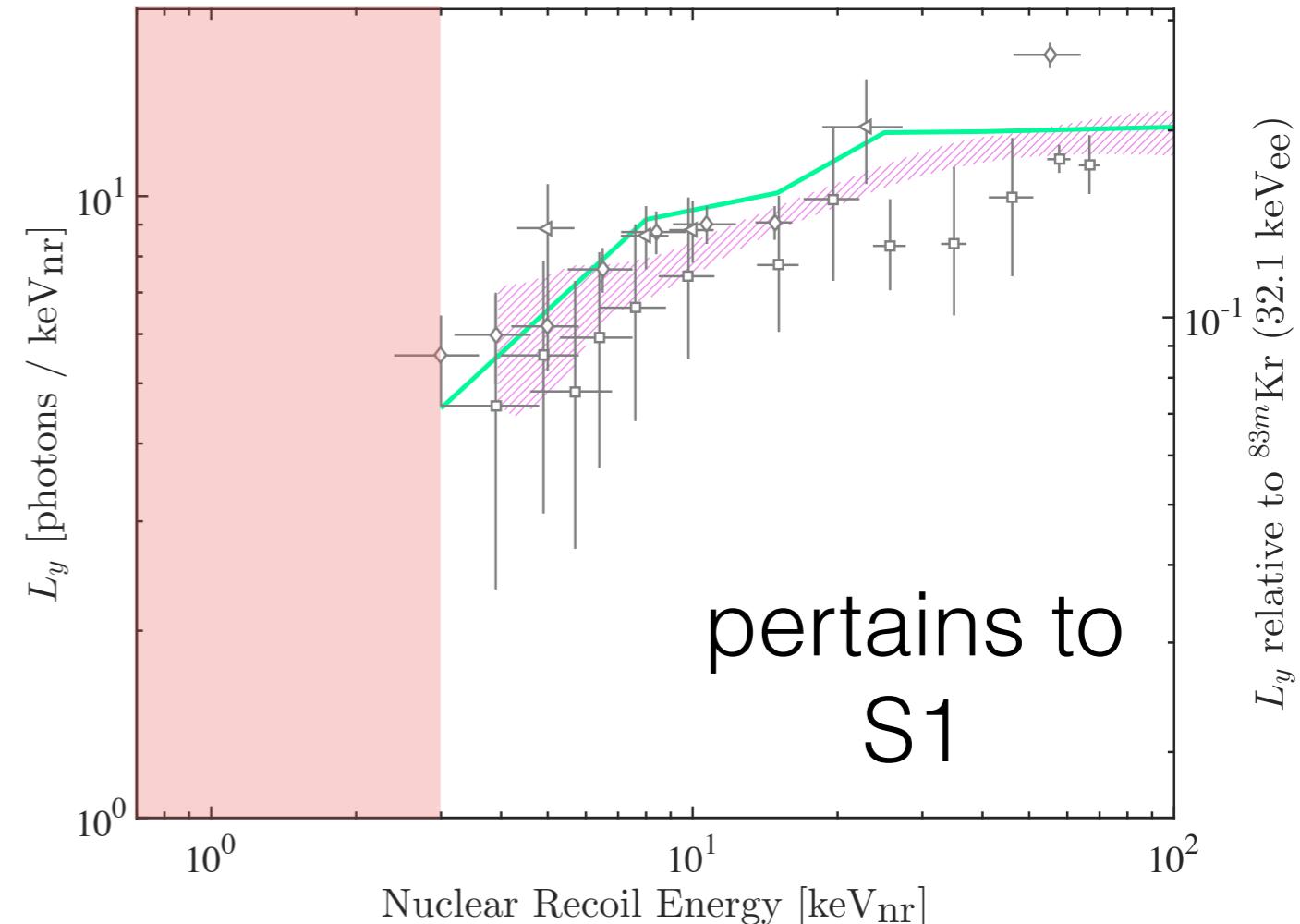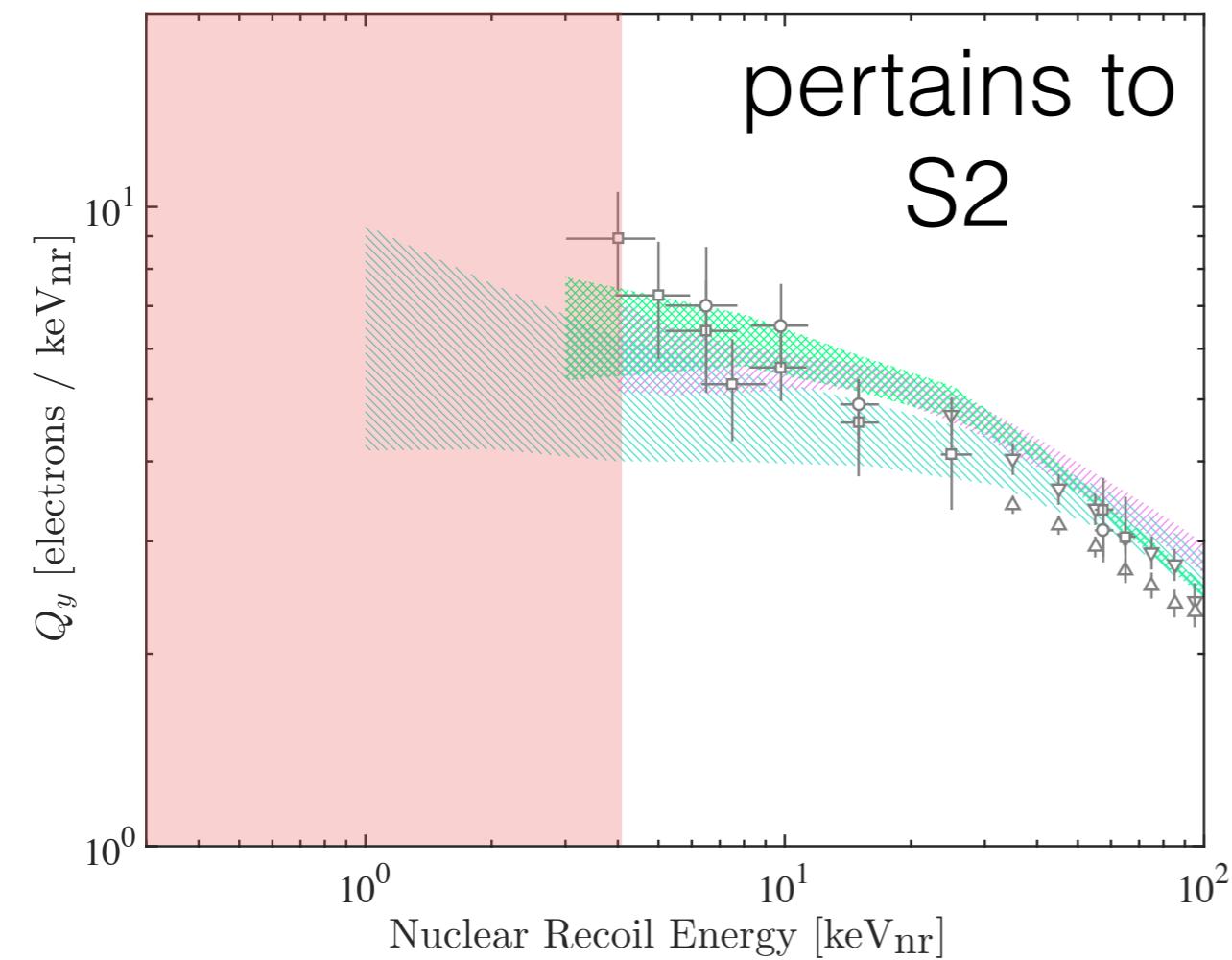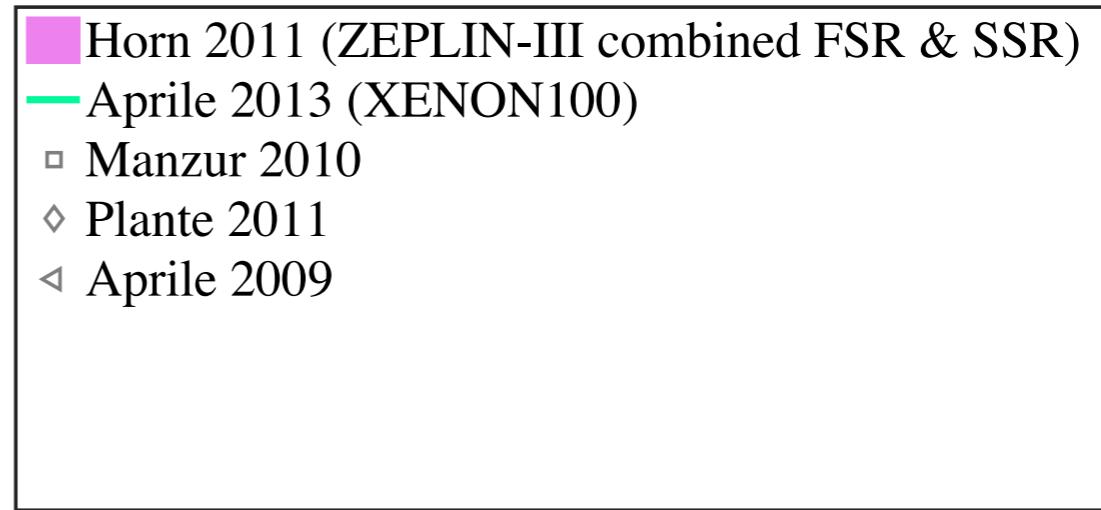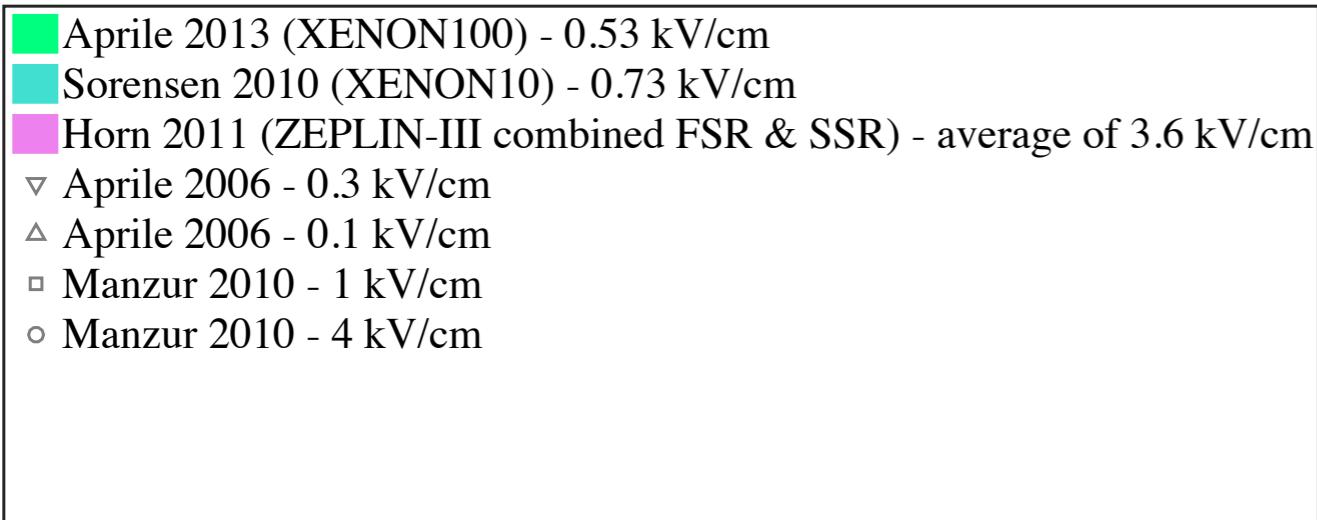
**Signal carrier production:**

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

**Signal carrier detection:**

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

**Signal carrier detection:**

- g2 = 11.4 detected photons per ionization electron at the interaction site

- electron extraction efficiency is 0.48 ± 0.04
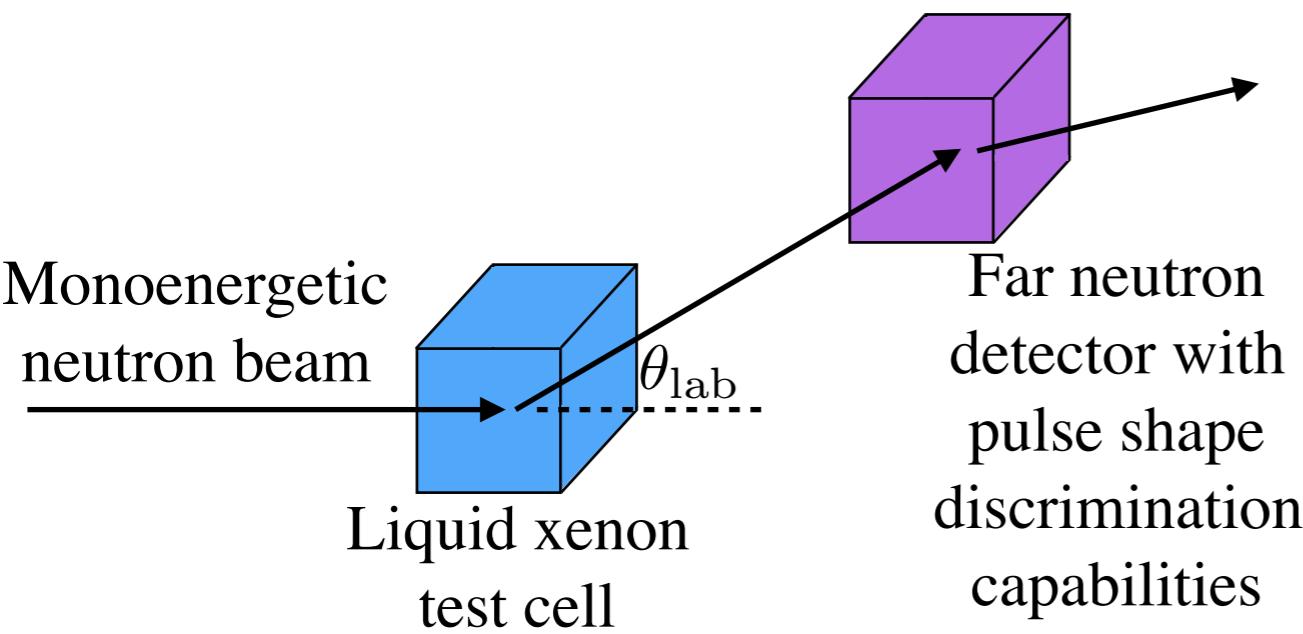
# No fixed scattering angle measurements below 3 keV$_{nr}$

Aprile 2013 (XENON100) - 0.53 kV/cm
Sorensen 2010 (XENON10) - 0.73 kV/cm
Horn 2011 (ZEPLIN-III combined FSR & SSR) - average of 3.6 kV/cm
▽ Aprile 2006 - 0.3 kV/cm
△ Aprile 2006 - 0.1 kV/cm
□ Manzur 2010 - 1 kV/cm
○ Manzur 2010 - 4 kV/cm

Horn 2011 (ZEPLIN-III combined FSR & SSR)
Aprile 2013 (XENON100)
□ Manzur 2010
◇ Plante 2011
◁ Aprile 2009

pertains to S2

pertains to S1

# Existing techniques used for existing liquid xenon nuclear recoil calibrations

## Neutron scattering kinematics in small test cell
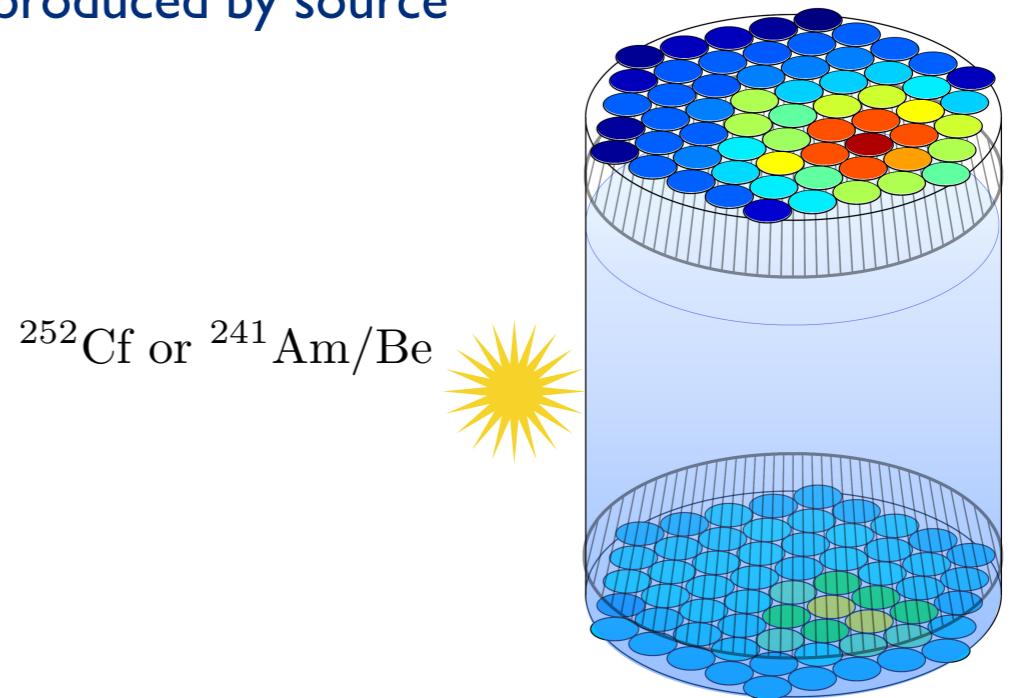
- Recoil energy defined by fixed scattering angle

- Susceptible to systematic effects due to neutron scatters in passive material

- Not *in situ* calibration of dark matter instrument

Monoenergetic neutron beam

$\theta_{\text{lab}}$

Liquid xenon test cell

Far neutron detector with pulse shape discrimination capabilities

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

## 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
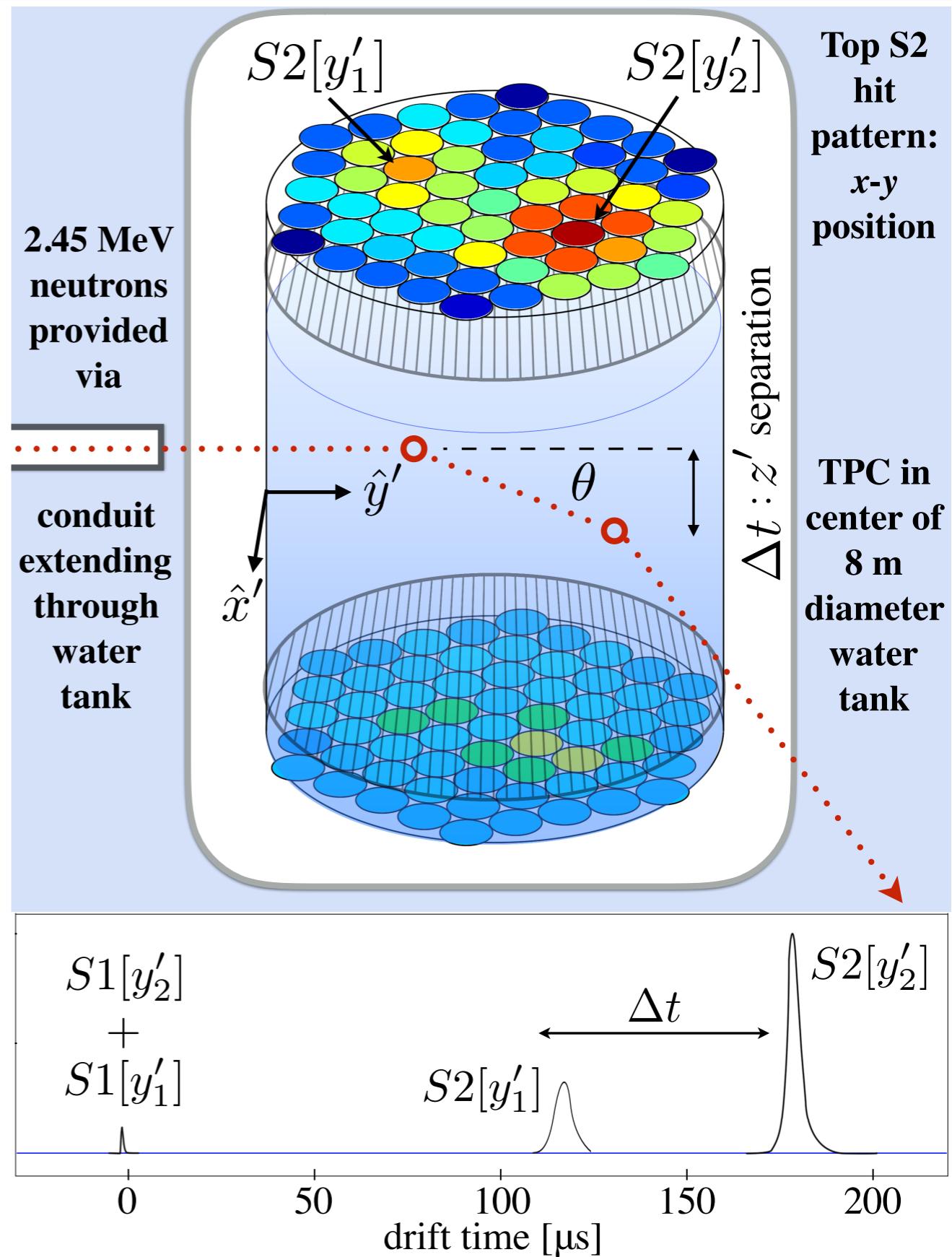
$^{252}$Cf or $^{241}$Am/Be

- 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



$S2[y'_1]$  $S2[y'_2]$  **Top S2 hit pattern: *x-y* position**

**2.45 MeV neutrons provided via**

$\hat{y}'$  $\theta$  $\Delta t : z'$ separation

**TPC in center of 8 m diameter water tank**

$\hat{x}'$

**conduit extending through water tank**

$S1[y'_2]$
$+$
$S1[y'_1]$     $S2[y'_1]$     $\Delta t$     $S2[y'_2]$

drift time [μs]
0    50    100    150    200
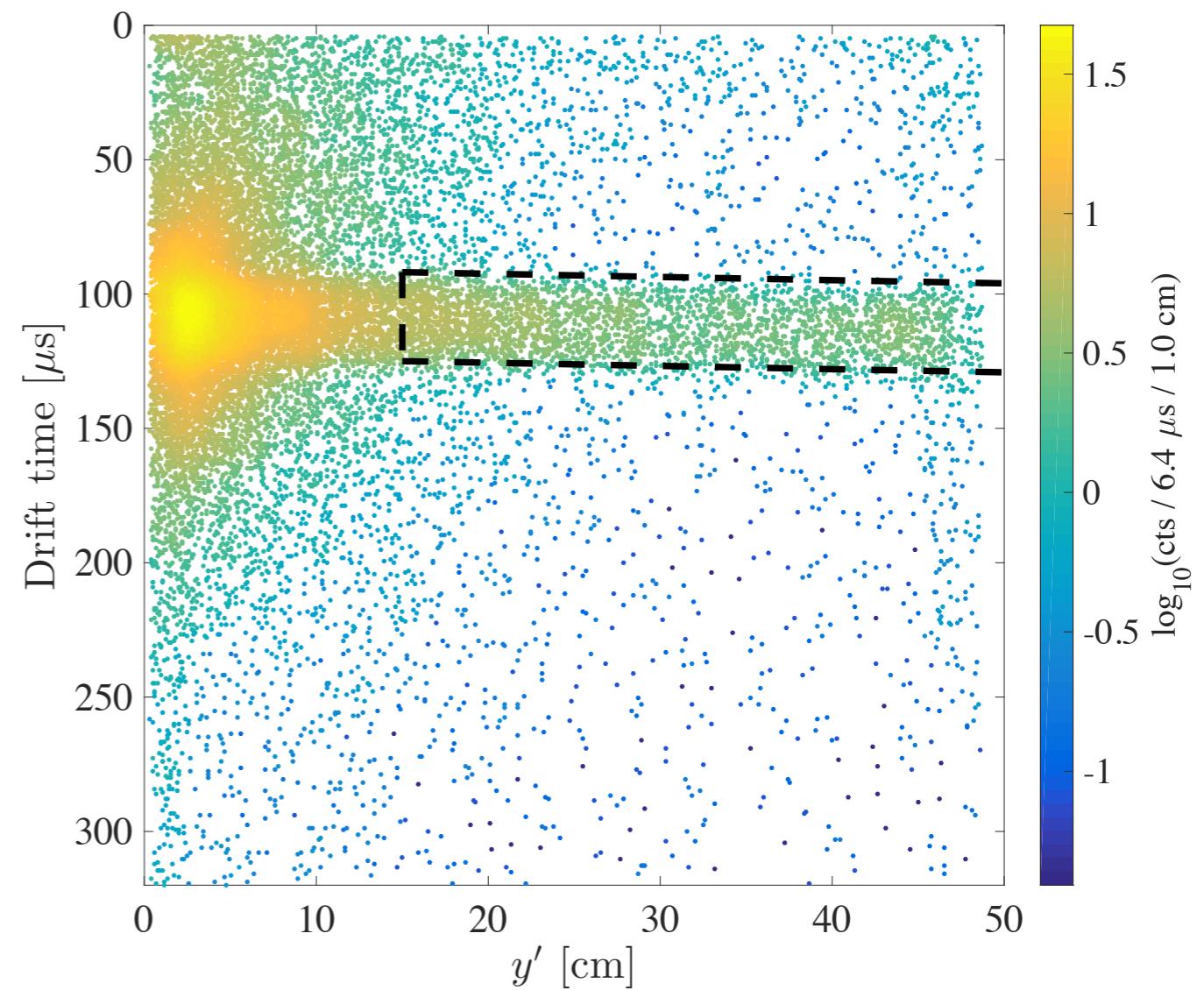
# The D-D Hardware Setup at SURF
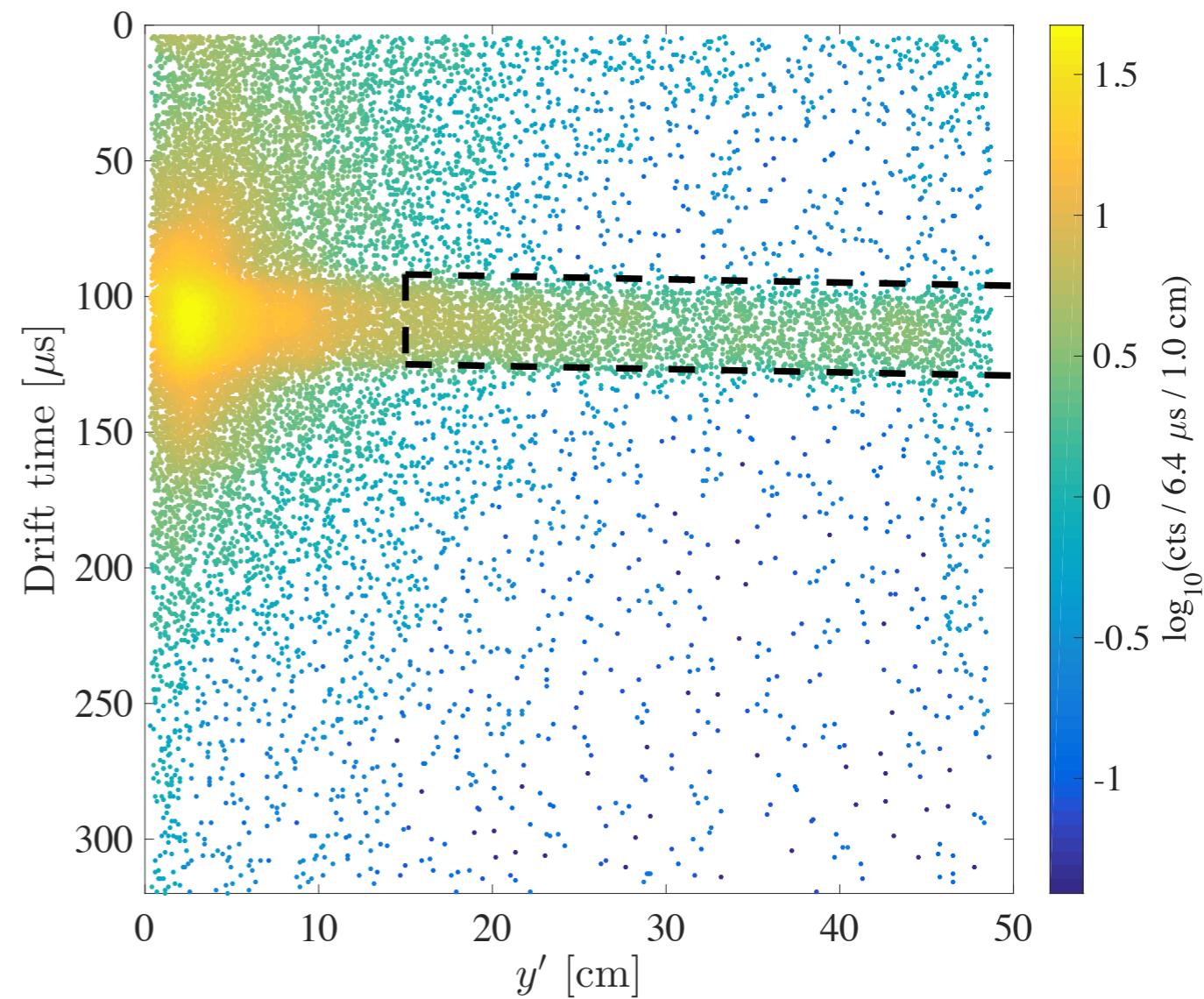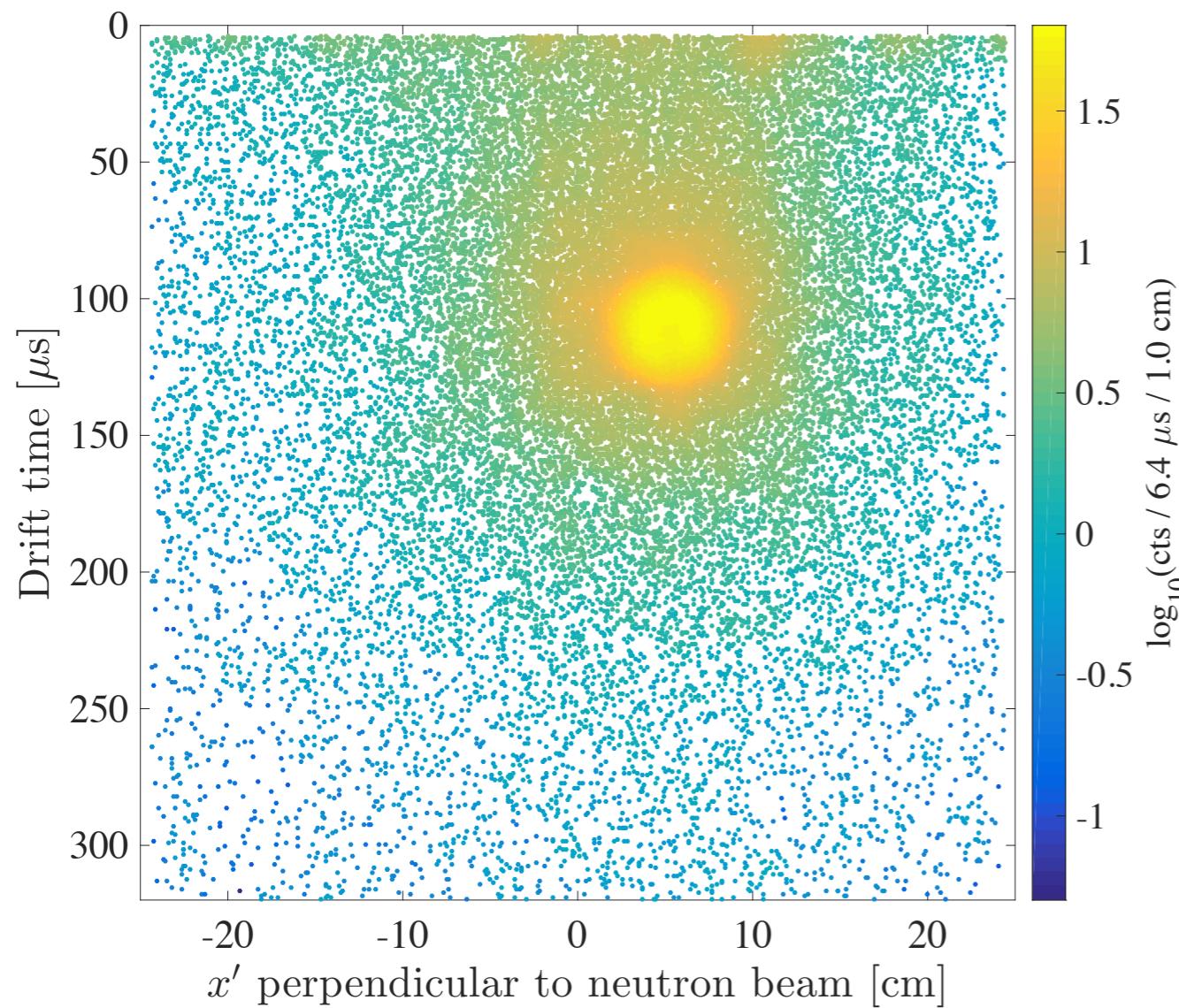
**377 cm**

- 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: $(2.5 \pm 0.3) \times 10^6 \text{ n/s}$
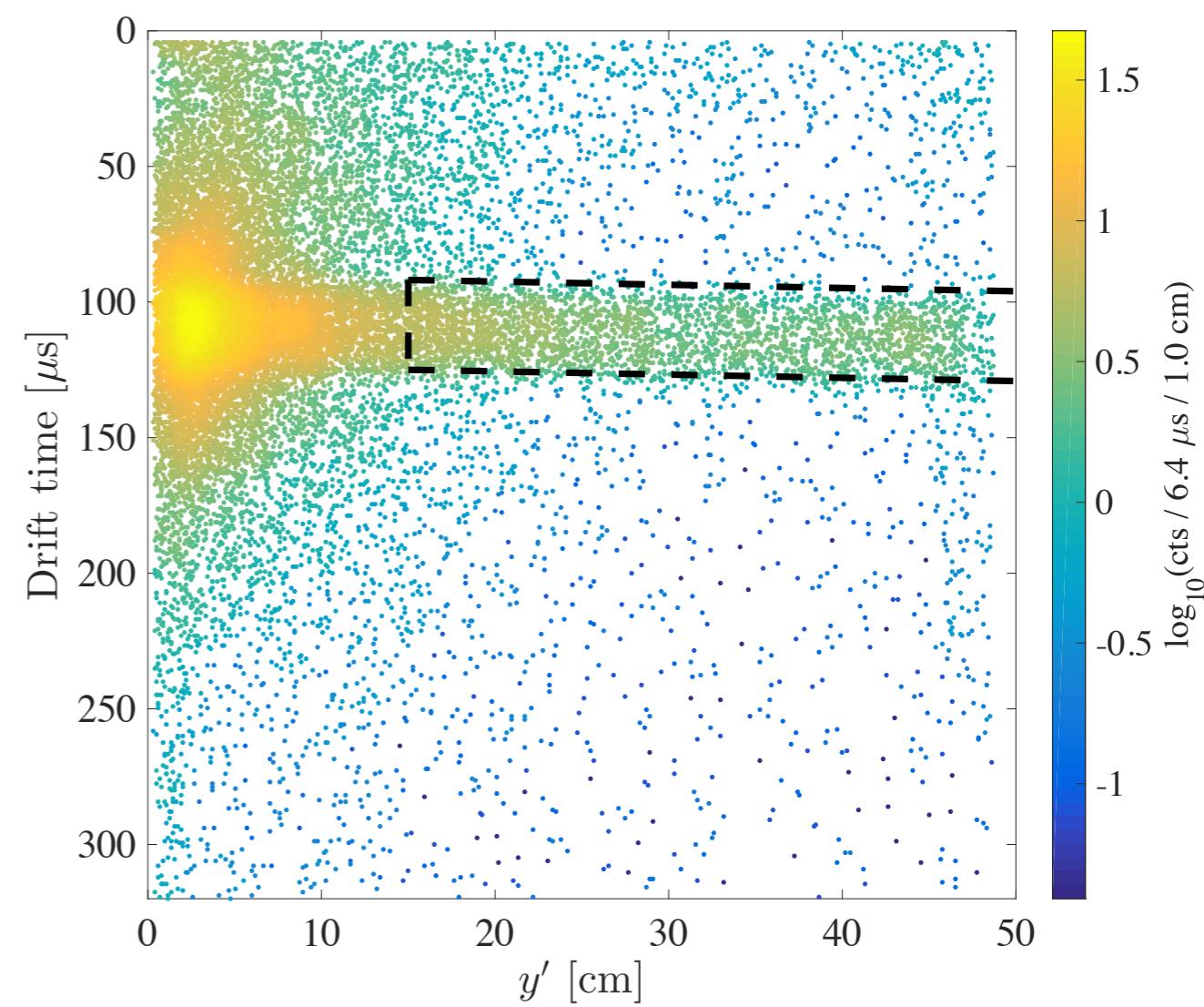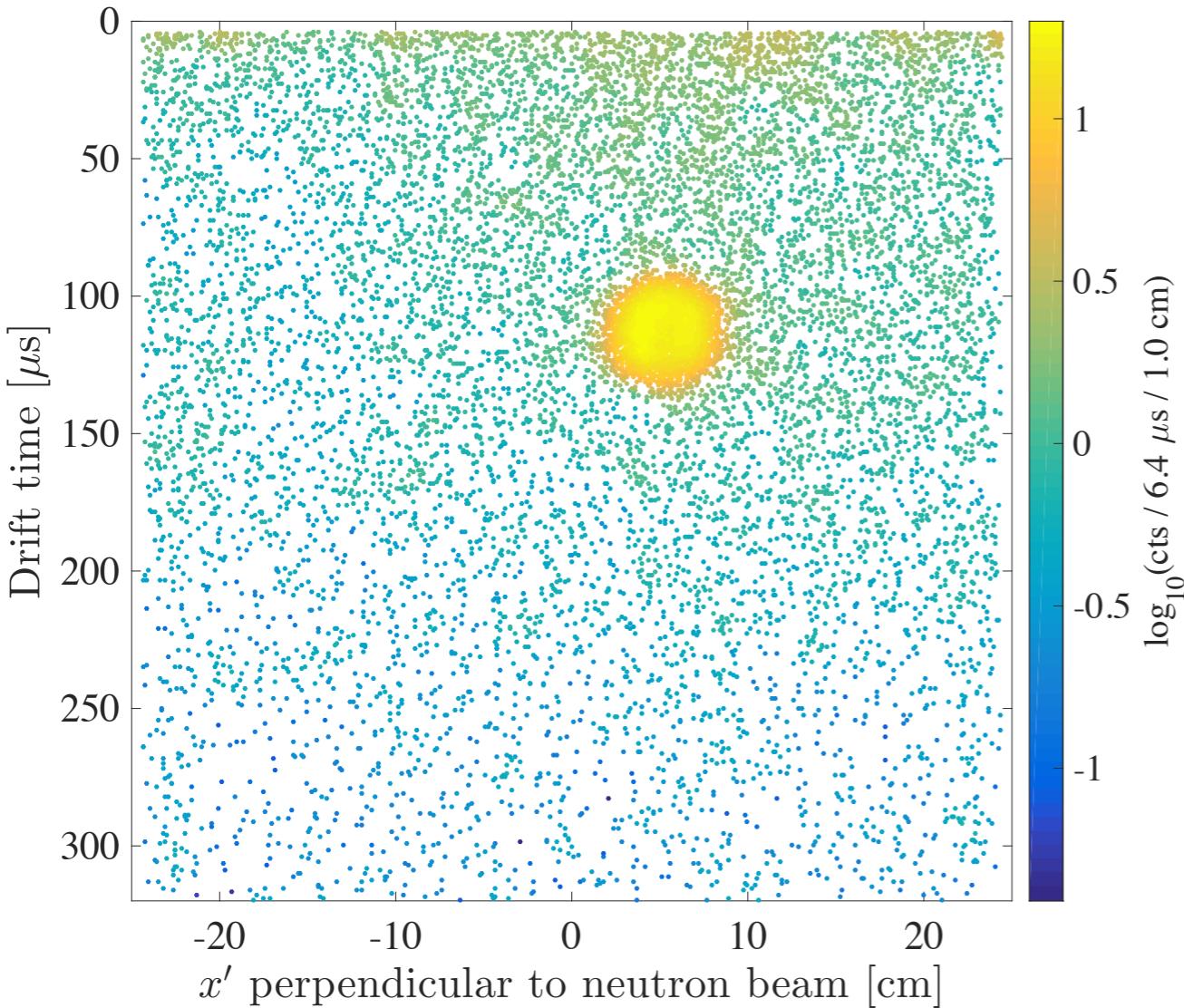
# Beam projection in active region

- 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
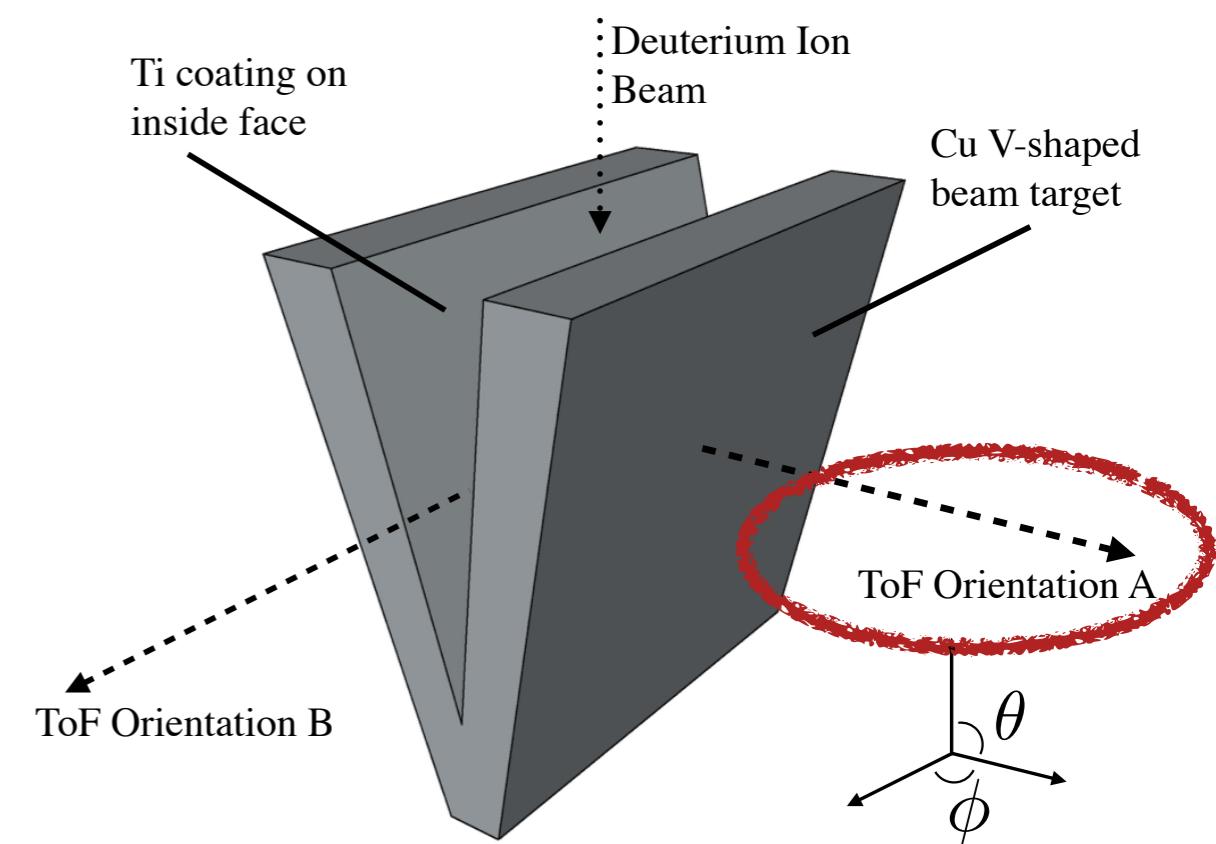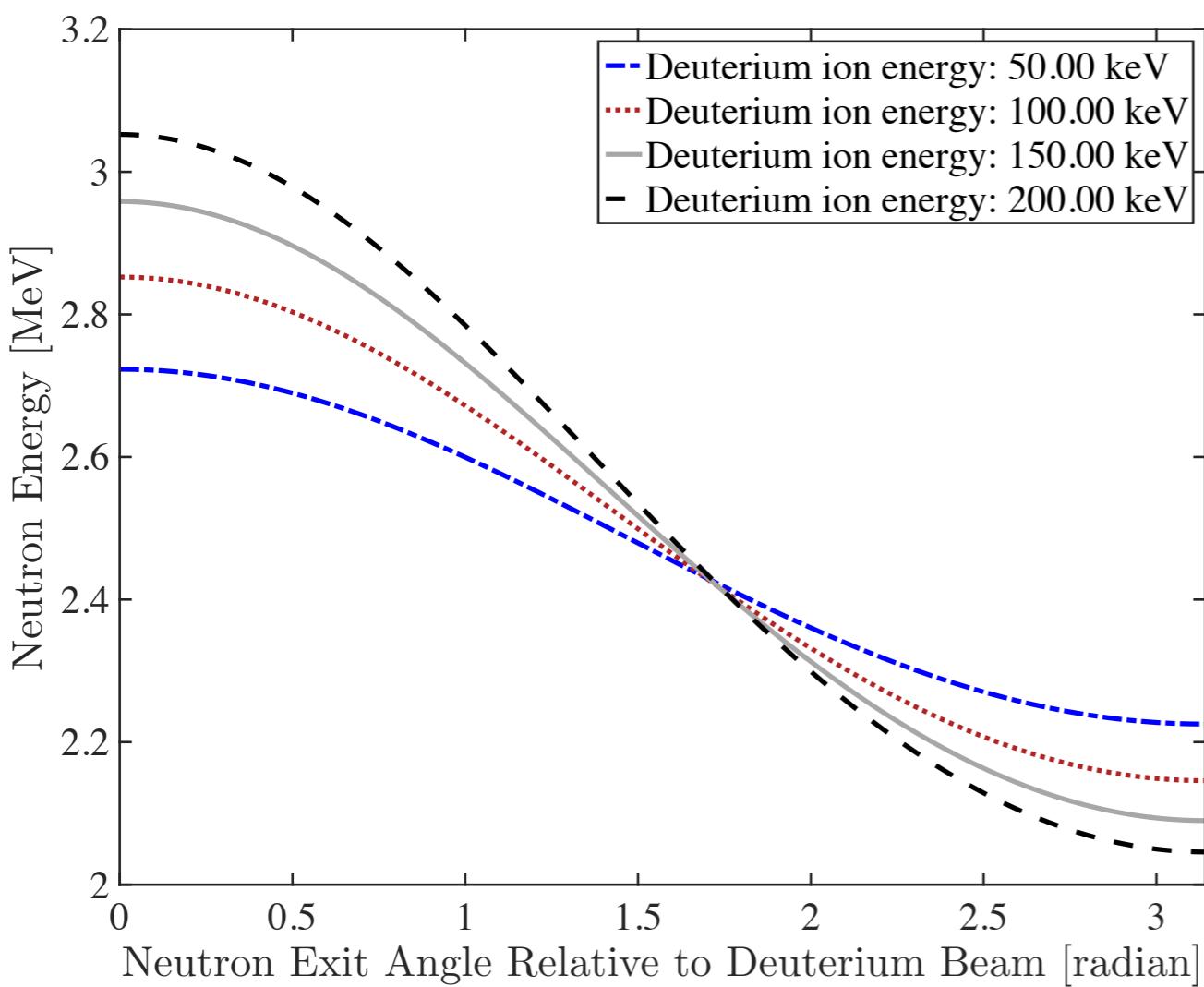
- After application of y' >15 cm beam neutron energy purity cut

- 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
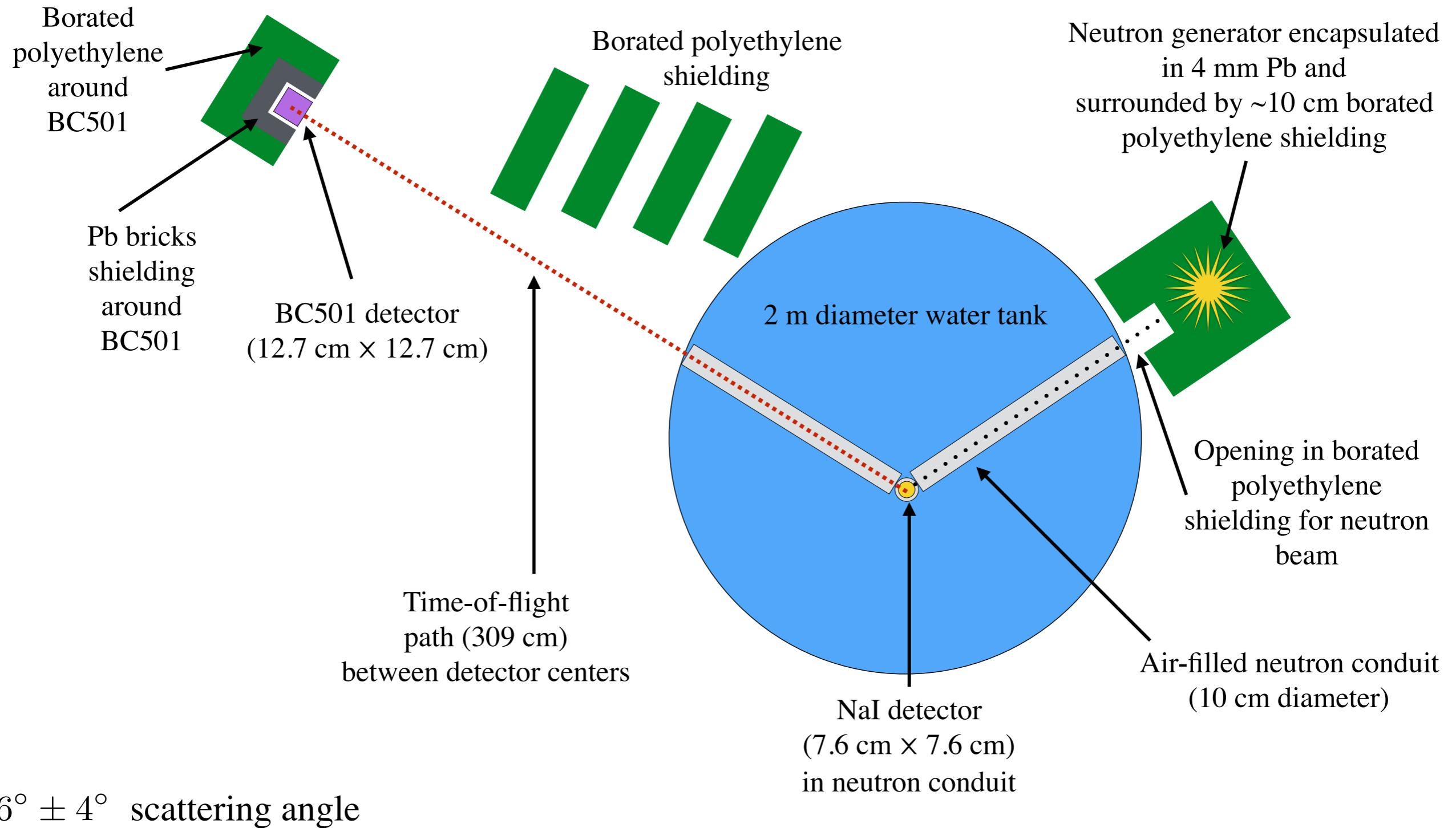
- We used "Target orientation A" for the LUX nuclear recoil calibration

- 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

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



Borated polyethylene around BC501

Pb bricks shielding around BC501

BC501 detector (12.7 cm × 12.7 cm)

Borated polyethylene shielding

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

2 m diameter water tank

Opening in borated polyethylene shielding for neutron beam

Time-of-flight path (309 cm) between detector centers

NaI detector (7.6 cm × 7.6 cm) in neutron conduit

Air-filled neutron conduit (10 cm diameter)

$66° \pm 4°$ scattering angle

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



Borated polyethylene

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

(12.7 cm x 12.7 cm)

Time-of-flight path (309 cm) between detector

in neutron conduit
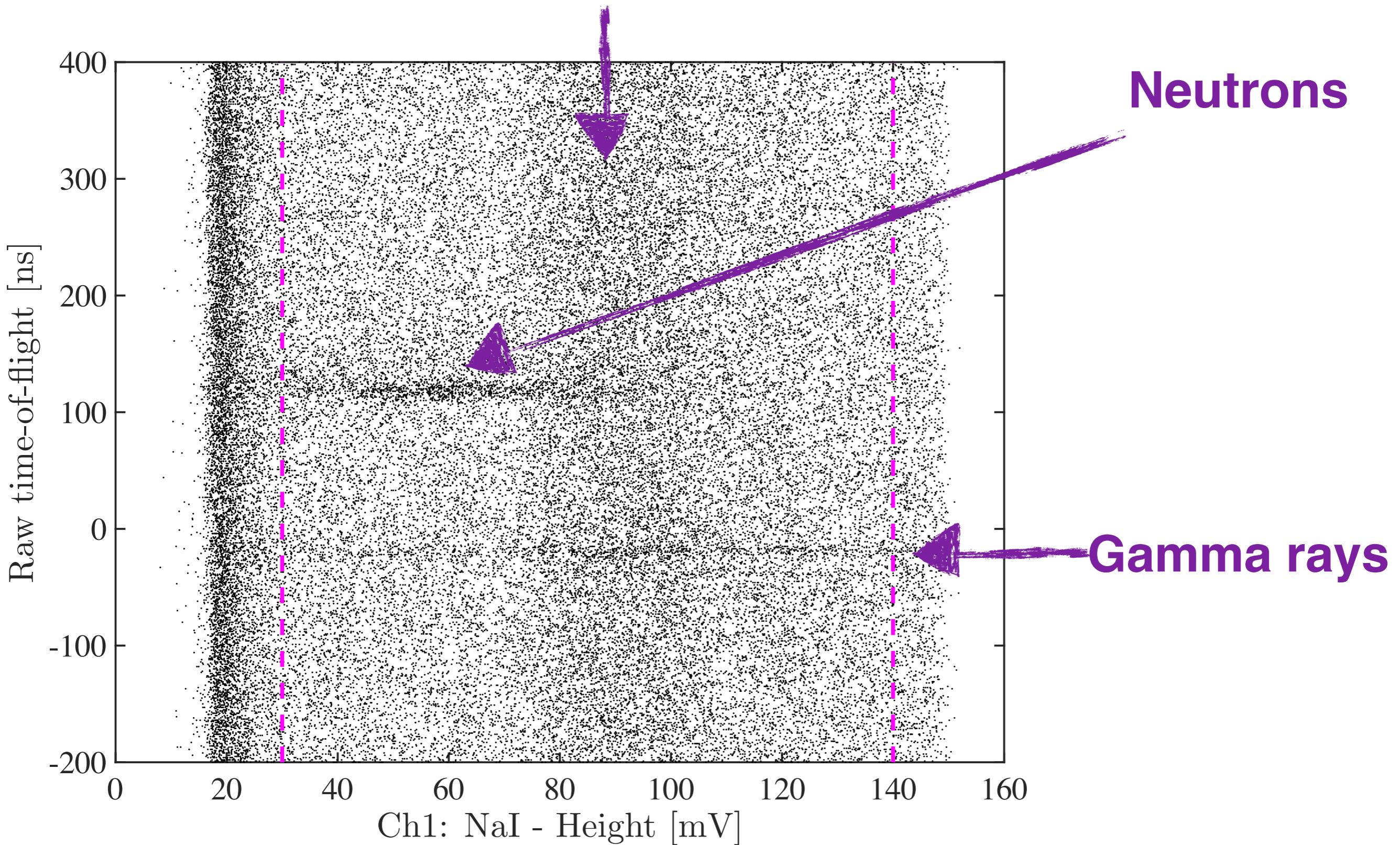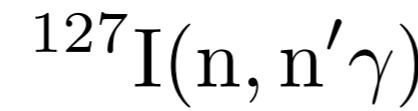
$66° \pm 4°$ scattering angle

# Target orientation A: time-of-flight data
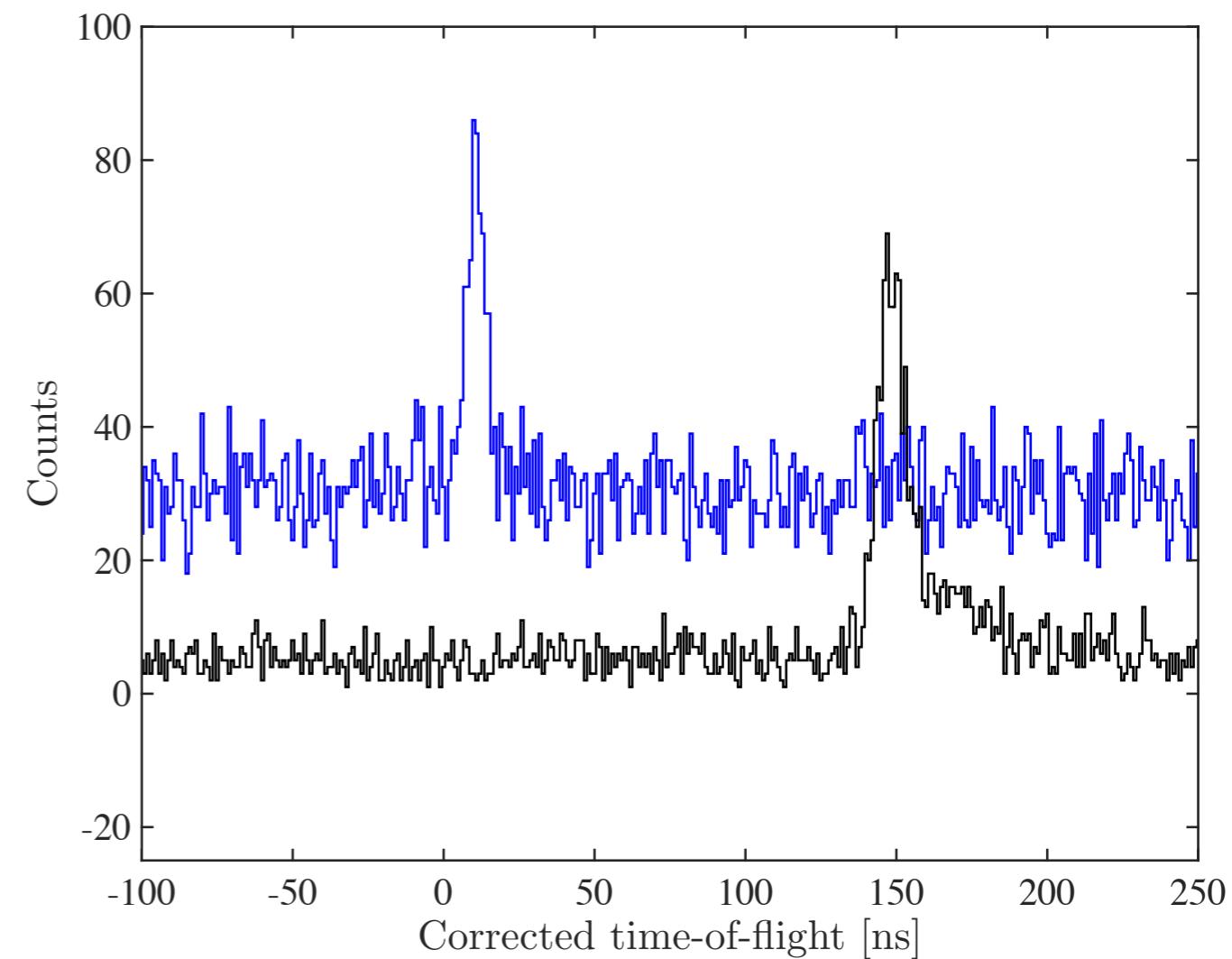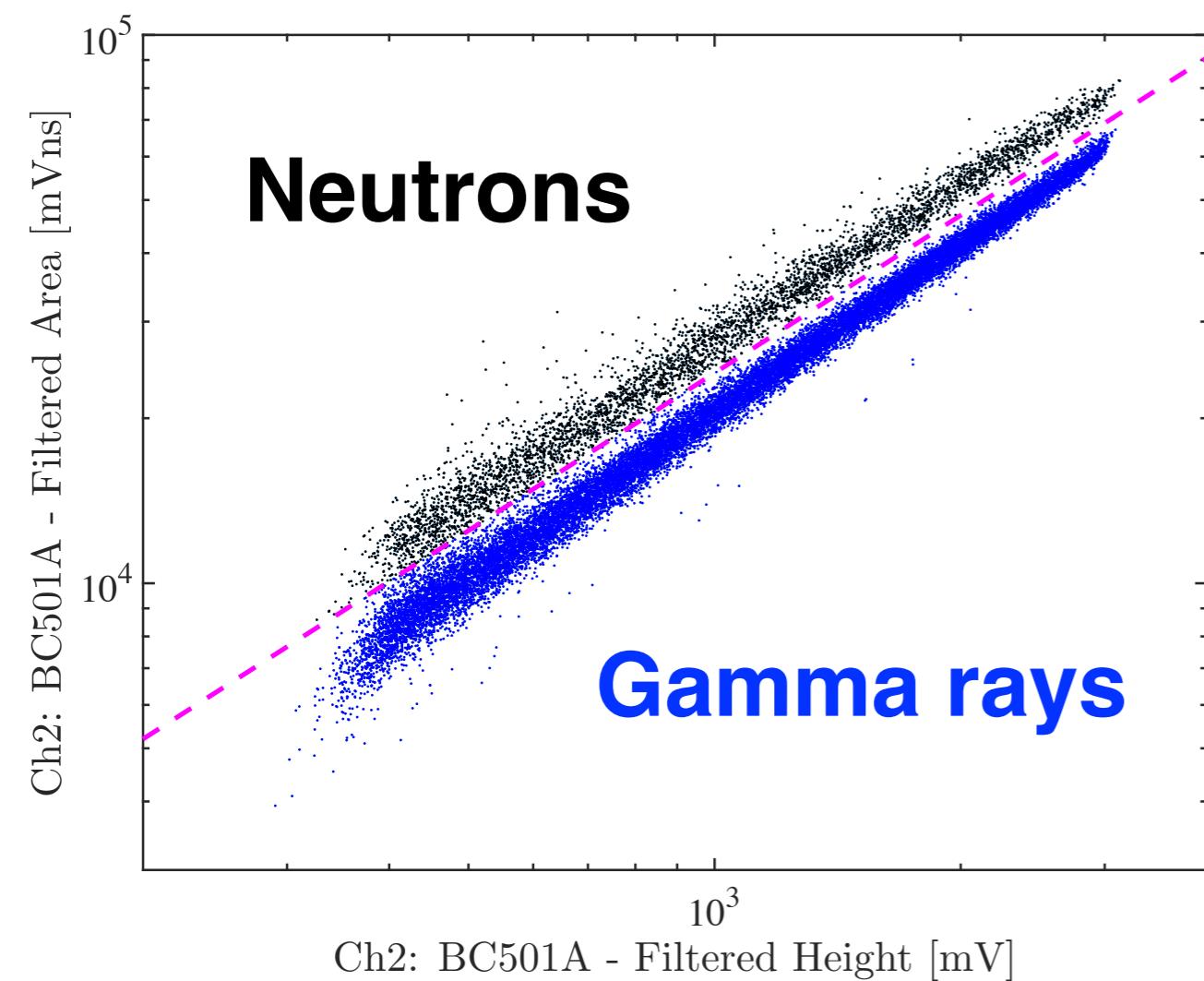
- **Mean neutron energy is in agreement with theoretical value of 2.45 MeV**
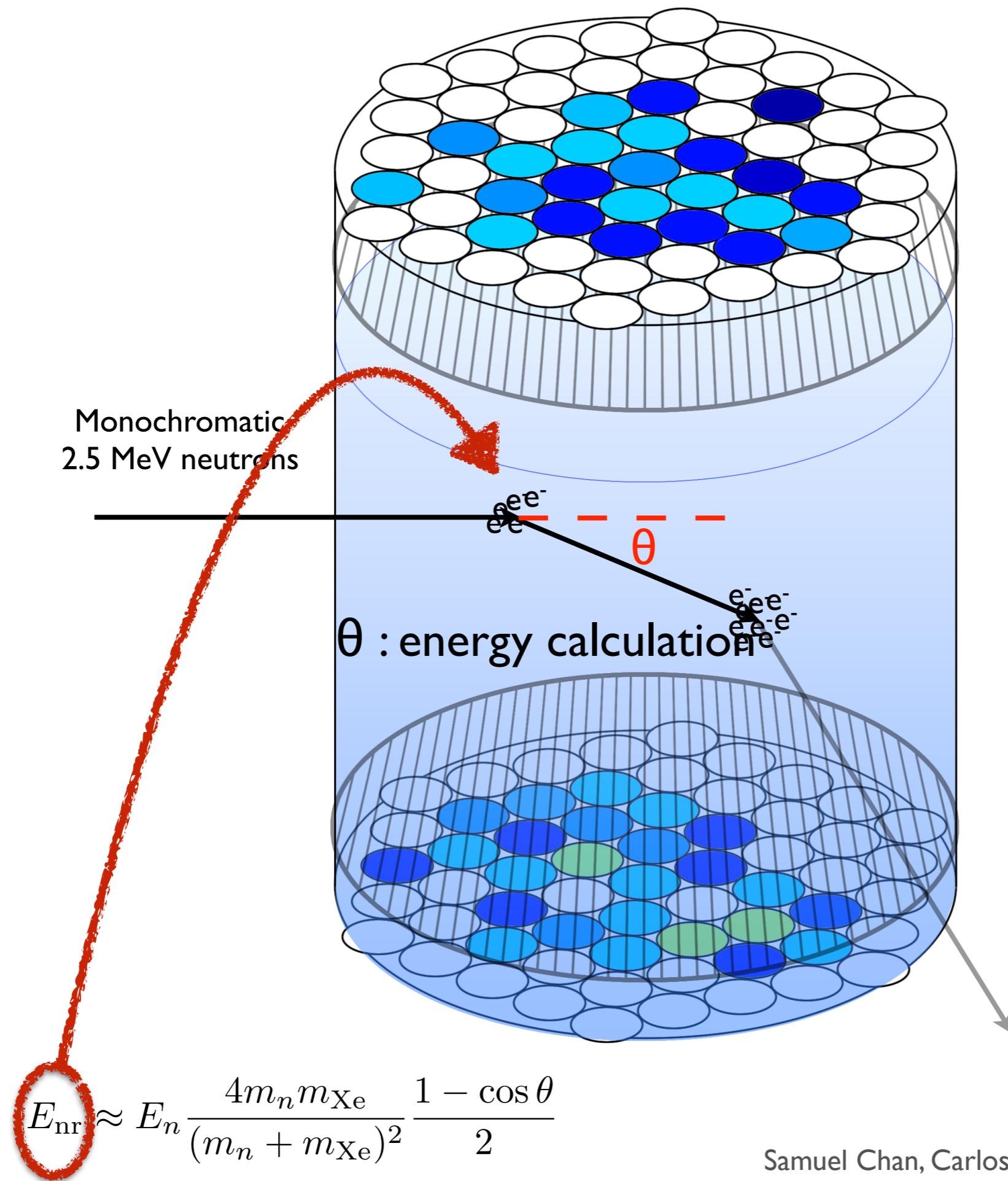
$$2.401 \pm 0.012 \, (\text{stat}) \pm 0.060 \, (\text{sys}) \, \text{MeV}$$

- **Outgoing neutron energy distribution width:**
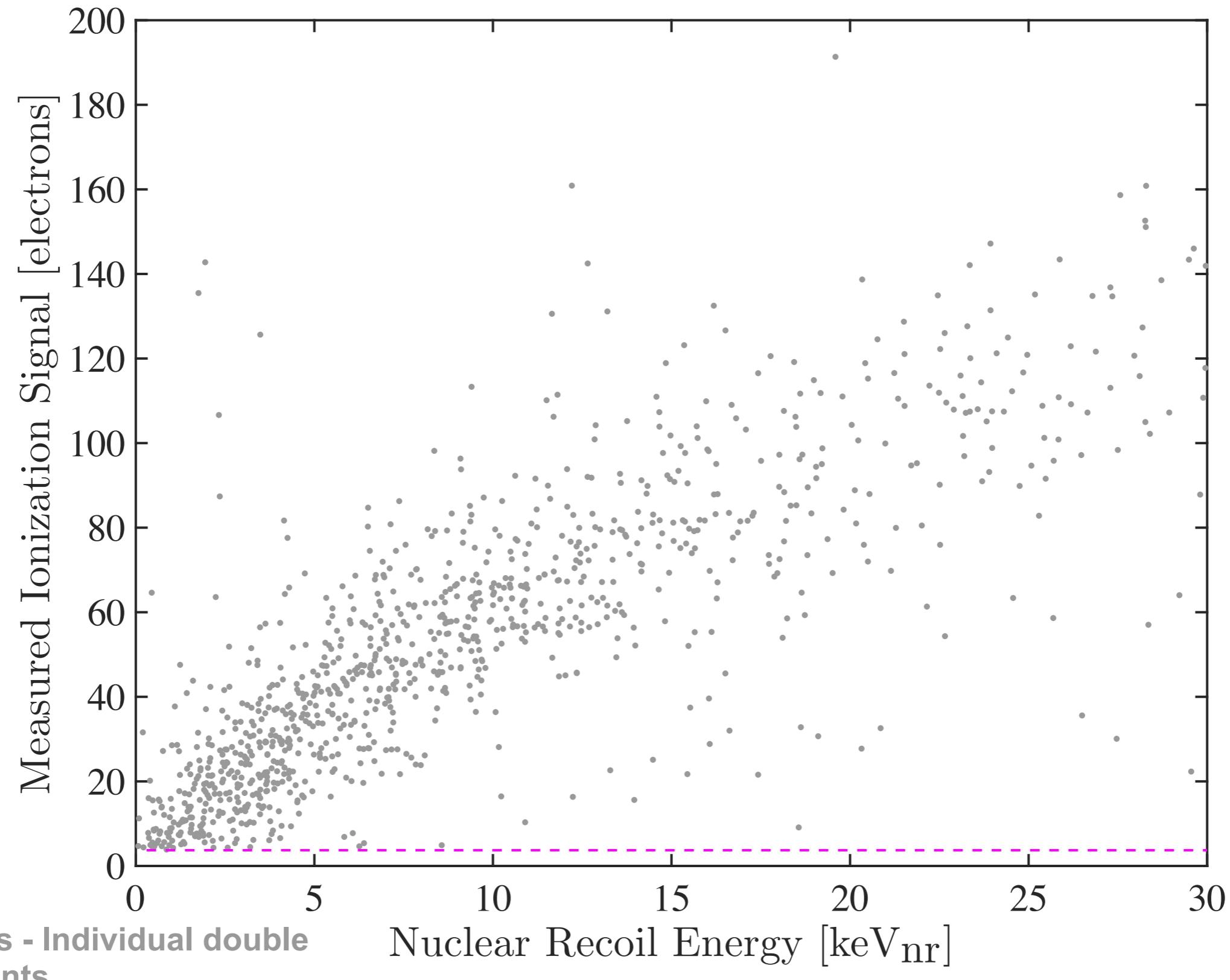
$$\frac{\sigma}{\mu} = 4.4\% \pm 0.6\% \, (\text{stat}) \pm 0.8\% \, (\text{sys})$$
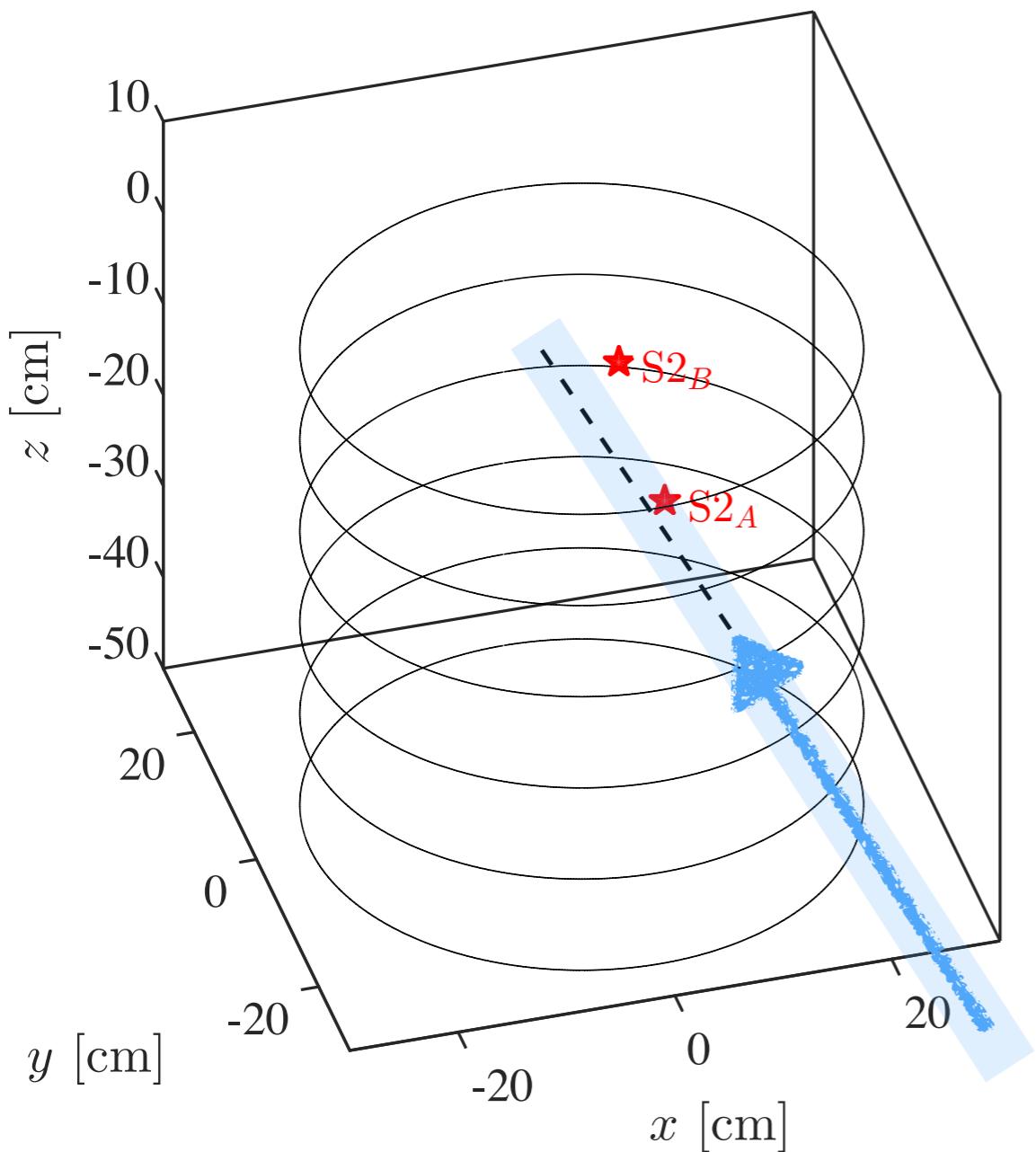
# D-D Low-Energy *Qy* Measurement

Monochromatic
2.5 MeV neutrons

e⁻ e⁻
e⁻ e⁻

$\theta$

$\theta$ : energy calculation

e⁻ e⁻
e⁻ e⁻ e⁻
e⁻ e⁻

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

Samuel Chan, Carlos Faham for the LUX Collaboration

# Observed ionization signal



Grey Points - Individual double scatter events
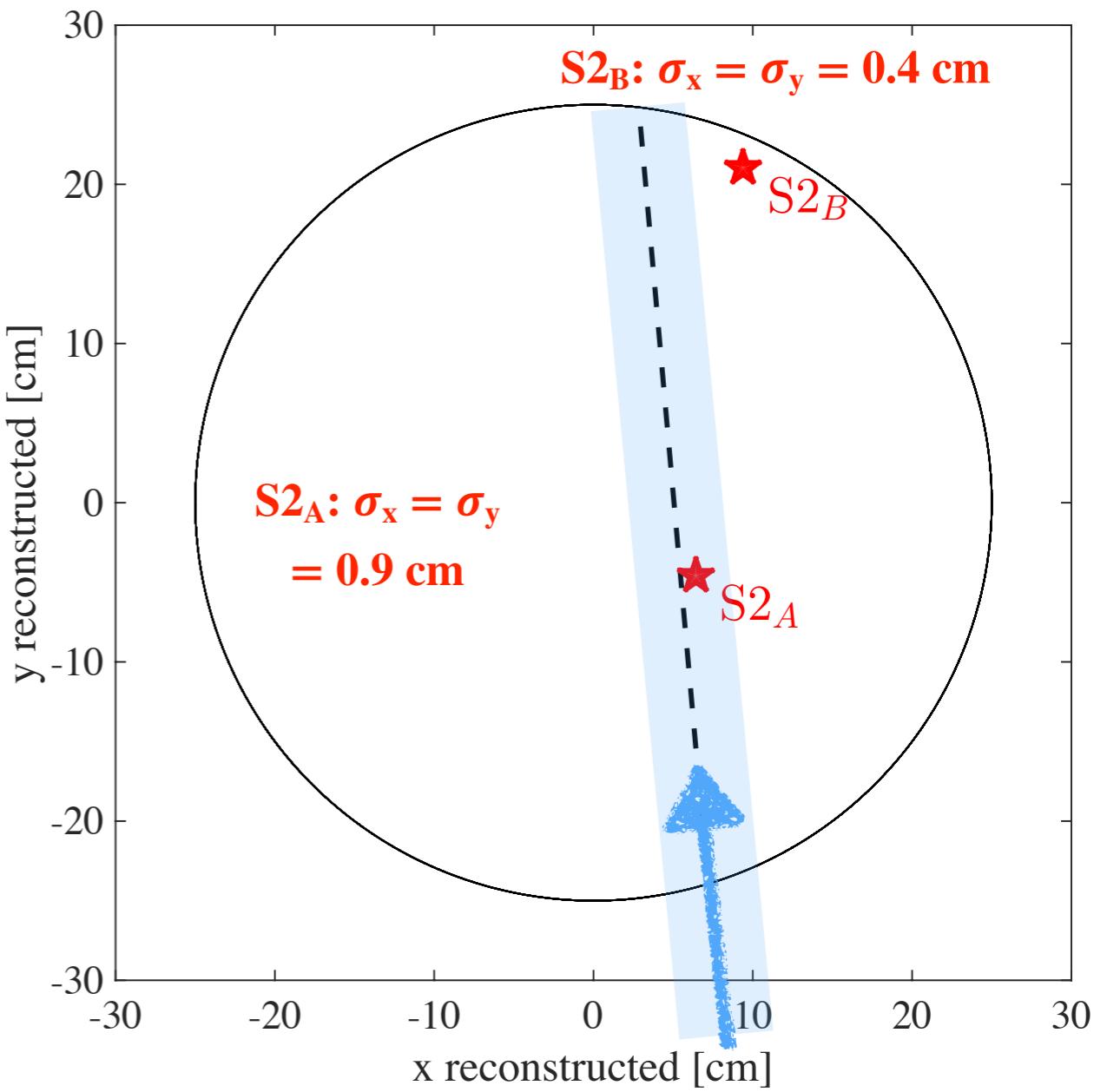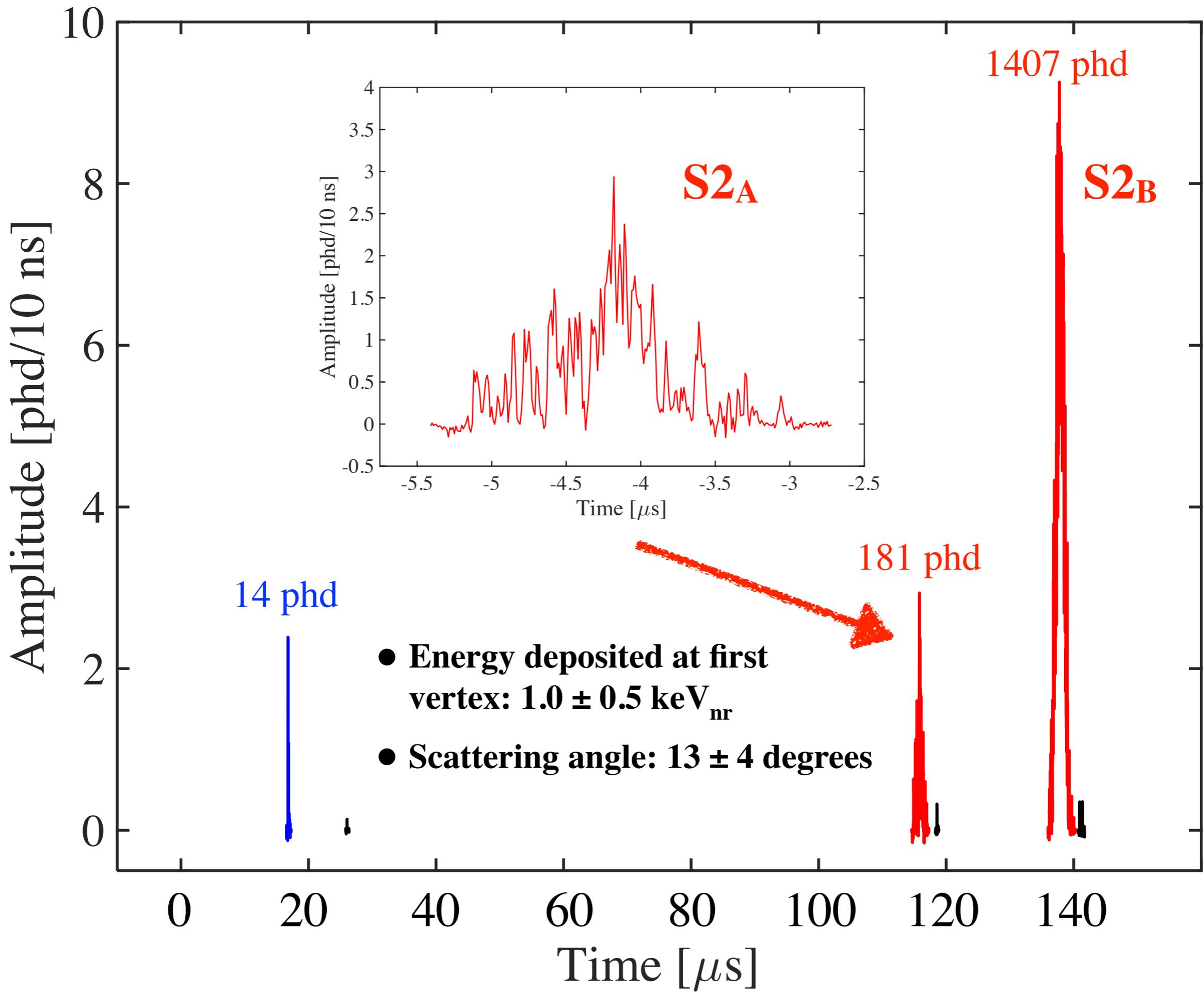
# What does a 1 keV$_{nr}$ double scatter look like?



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

**2.45 MeV neutron beam**

S2$_B$: $\sigma_x = \sigma_y = 0.4$ cm

S2$_A$: $\sigma_x = \sigma_y = 0.9$ cm

14 phd

1407 phd

S2$_A$

S2$_B$

181 phd

- Energy deposited at first vertex: 1.0 ± 0.5 keV$_{nr}$
- Scattering angle: 13 ± 4 degrees
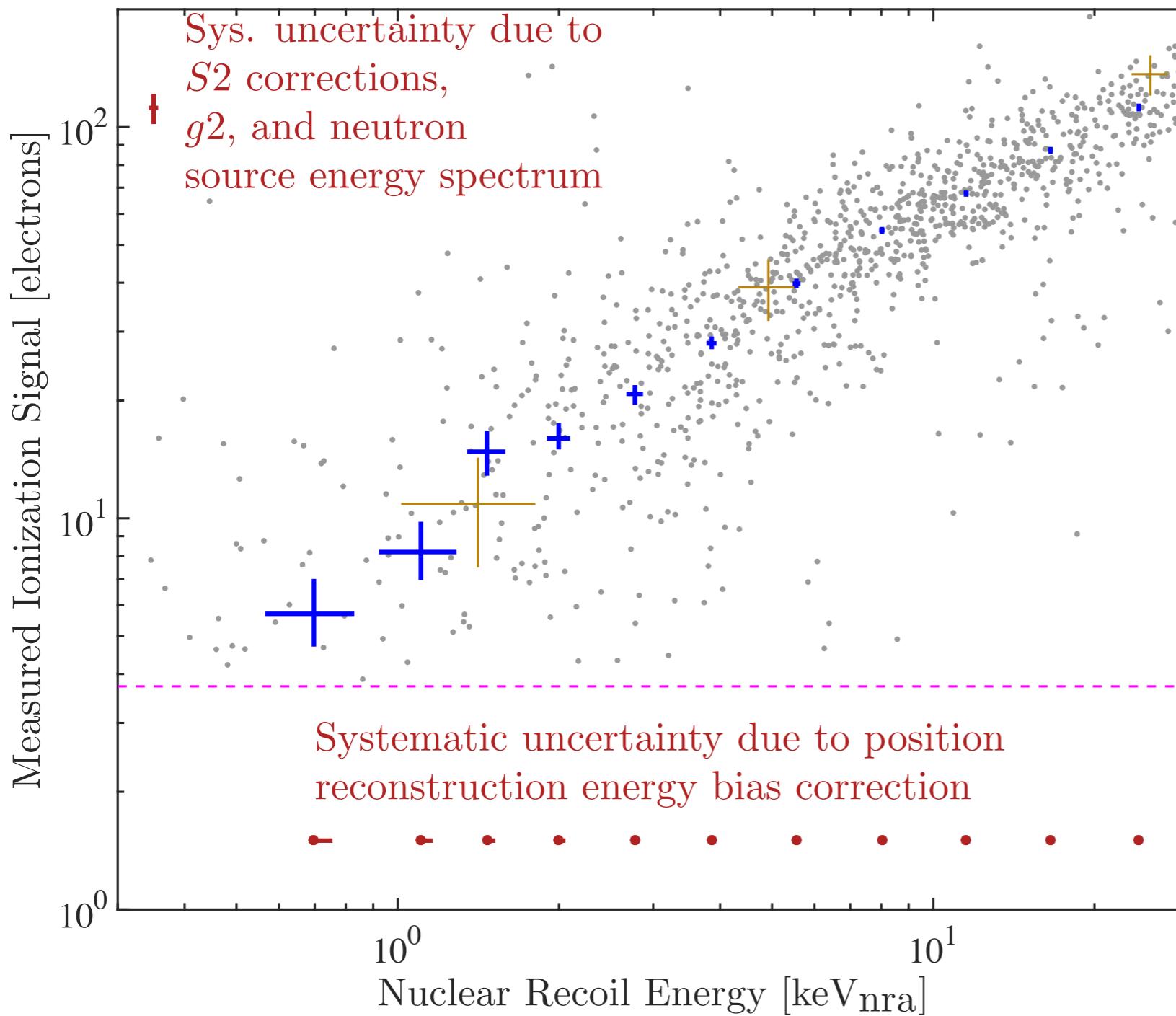
# Ionization signal absolutely measured below 1 keV$_{nra}$ in LUX
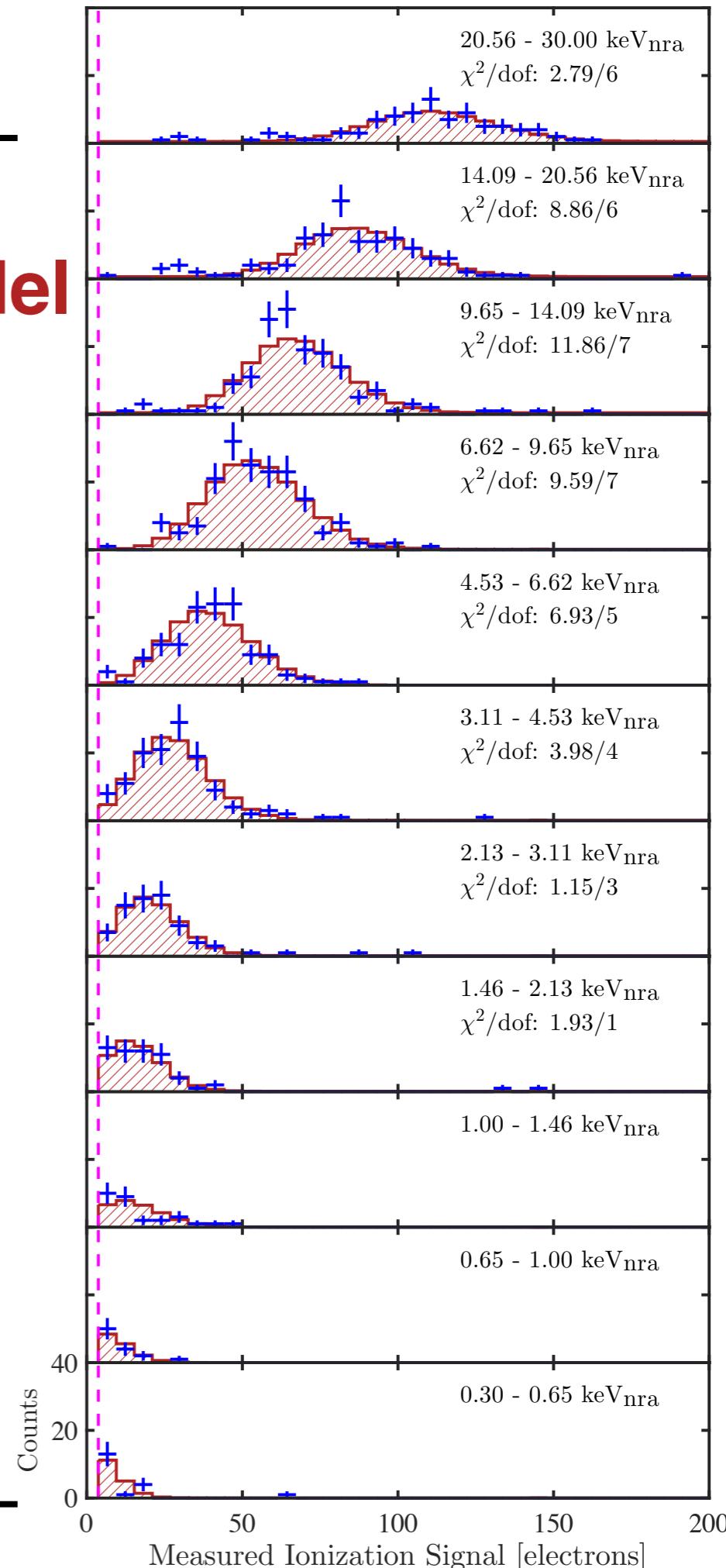
Individual double scatter events

**Data**

Reconstructed number of electrons with associated statistical uncertainty
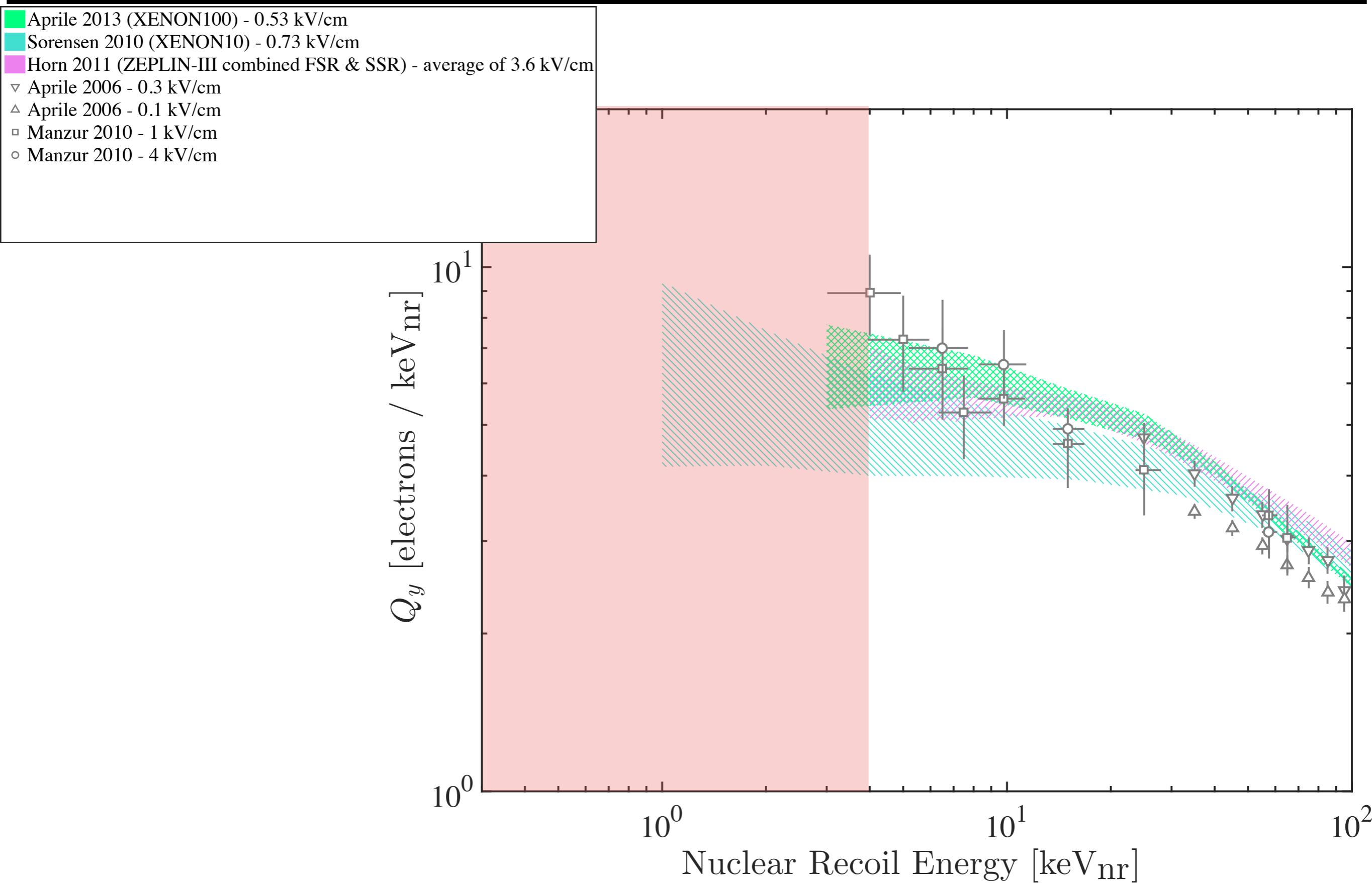
**Best-fit model**

Example error bars for individual events

Sys. uncertainty due to $S2$ corrections, $g2$, and neutron source energy spectrum

Systematic uncertainty due to position reconstruction energy bias correction

Measured Ionization Signal [electrons]

Nuclear Recoil Energy [keV$_{nra}$]

20.56 - 30.00 keV$_{nra}$
$\chi^2$/dof: 2.79/6

14.09 - 20.56 keV$_{nra}$
$\chi^2$/dof: 8.86/6

9.65 - 14.09 keV$_{nra}$
$\chi^2$/dof: 11.86/7

6.62 - 9.65 keV$_{nra}$
$\chi^2$/dof: 9.59/7

4.53 - 6.62 keV$_{nra}$
$\chi^2$/dof: 6.93/5

3.11 - 4.53 keV$_{nra}$
$\chi^2$/dof: 3.98/4

2.13 - 3.11 keV$_{nra}$
$\chi^2$/dof: 1.15/3

1.46 - 2.13 keV$_{nra}$
$\chi^2$/dof: 1.93/1

1.00 - 1.46 keV$_{nra}$

0.65 - 1.00 keV$_{nra}$

0.30 - 0.65 keV$_{nra}$

Counts

Measured Ionization Signal [electrons]

# Ionization yield absolutely measured below 1 keVnr in LUX



Legend:
- Aprile 2013 (XENON100) - 0.53 kV/cm
- Sorensen 2010 (XENON10) - 0.73 kV/cm
- Horn 2011 (ZEPLIN-III combined FSR & SSR) - average of 3.6 kV/cm
- ▽ Aprile 2006 - 0.3 kV/cm
- △ Aprile 2006 - 0.1 kV/cm
- ▢ Manzur 2010 - 1 kV/cm
- ○ Manzur 2010 - 4 kV/cm

$Q_y$ [electrons / keV$_\text{nr}$]

Nuclear Recoil Energy [keV$_\text{nr}$]

**Most significant systematic uncertainties shown in red**

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Sorensen 2010 (XENON10) - 0.73 kV/cm
Horn 2011 (ZEPLIN-III combined FSR & SSR) - average of 3.6 kV/cm
▽ Aprile 2006 - 0.3 kV/cm
△ Aprile 2006 - 0.1 kV/cm
▢ Manzur 2010 - 1 kV/cm
◯ Manzur 2010 - 4 kV/cm
- - LUX model: Lindhard (k = 0.174) + biex. quenching
---- Alt. LUX model: Ziegler stopping power + biex. quenching
+ LUX D-D $Q_y$ at 180 V/cm

Systematic uncertainty due to position reconstruction energy bias correction

- 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

Sys. uncertainty due to neutron source spectrum

Sys. uncertainty due to $S2$ corrections and $g2$

$Q_y$ [electrons / keV$_{\text{nra}}$]

Nuclear Recoil Energy [keV$_{\text{nra}}$]

# D-D Low-Energy *Ly* Measurement
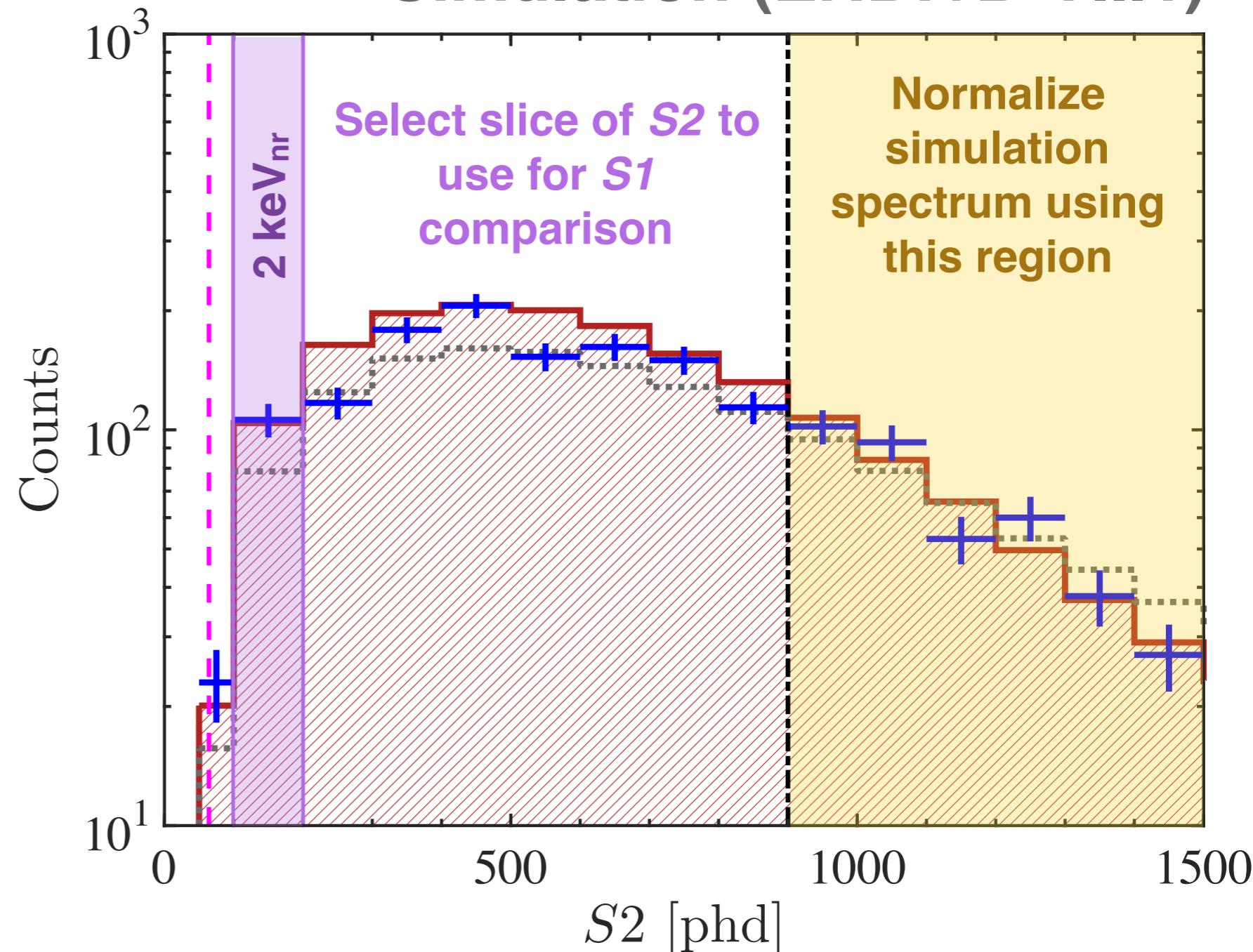
# Measuring the scintillation yield
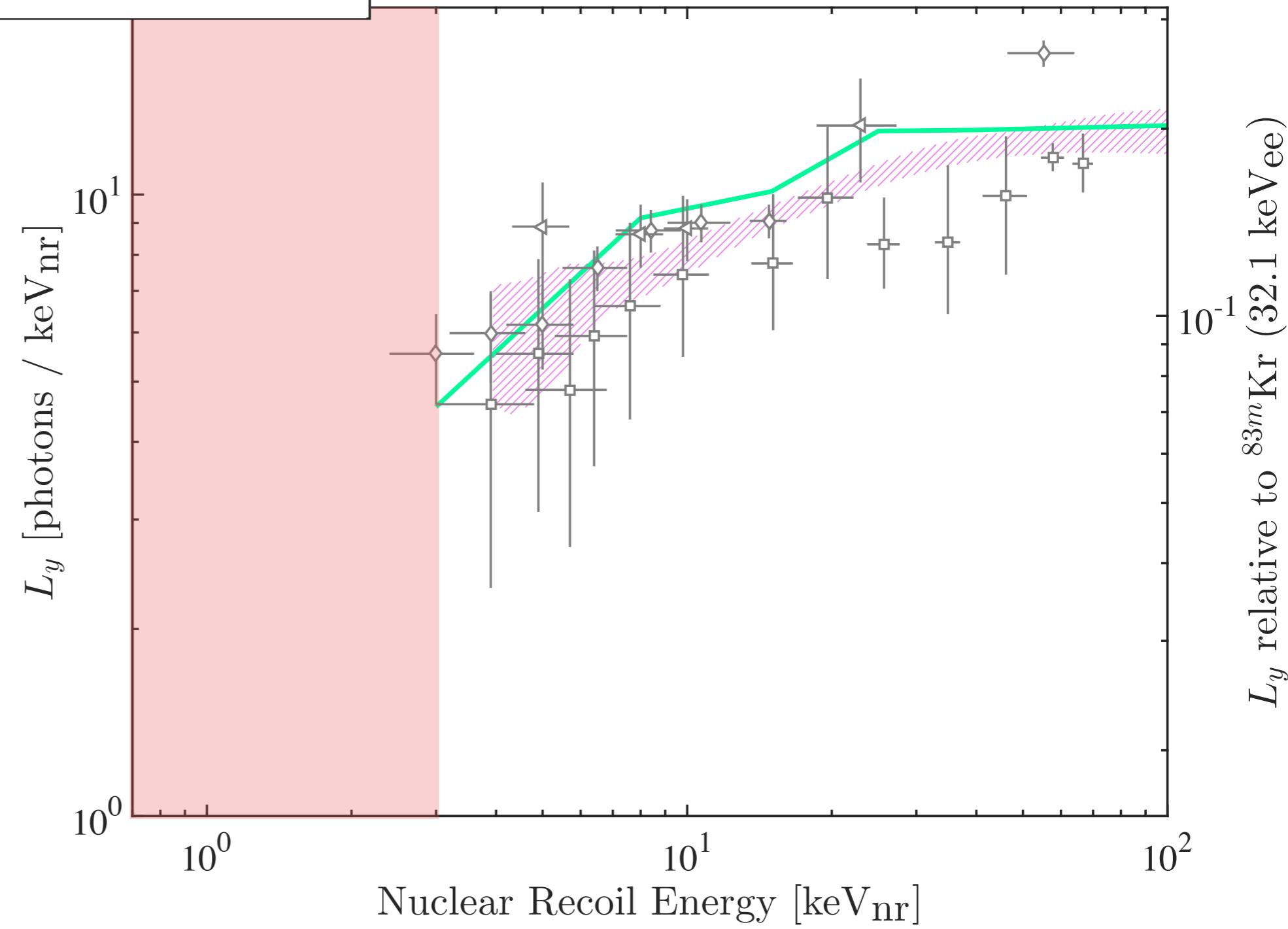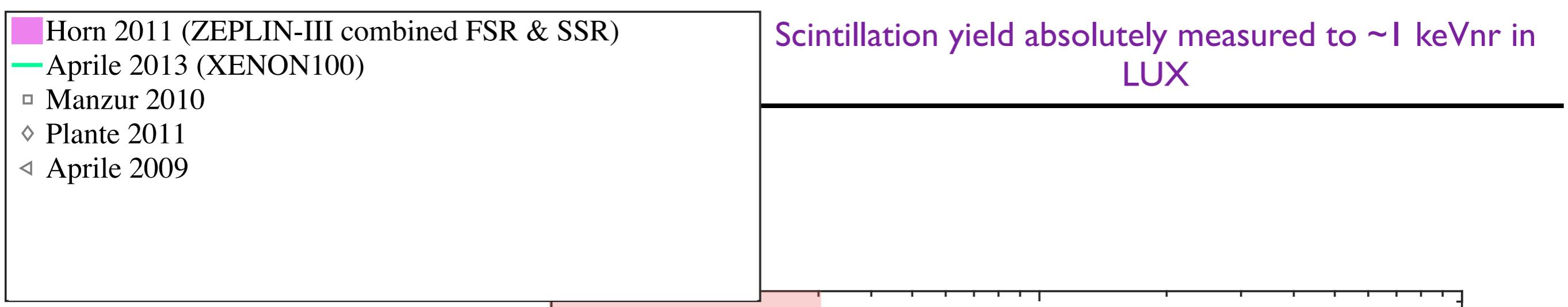
- Use **single scatters** inside neutron beam projection with y' > 15 cm

- $L_y$ measurement range is 50-900 phd $S2$

- Simulation event distribution is normalized outside of $L_y$ measurement range using $900 < S2 < 1500$ phd

**Data**
**Simulation (JENDL-4)**
**Simulation (ENDF/B-VII.1)**
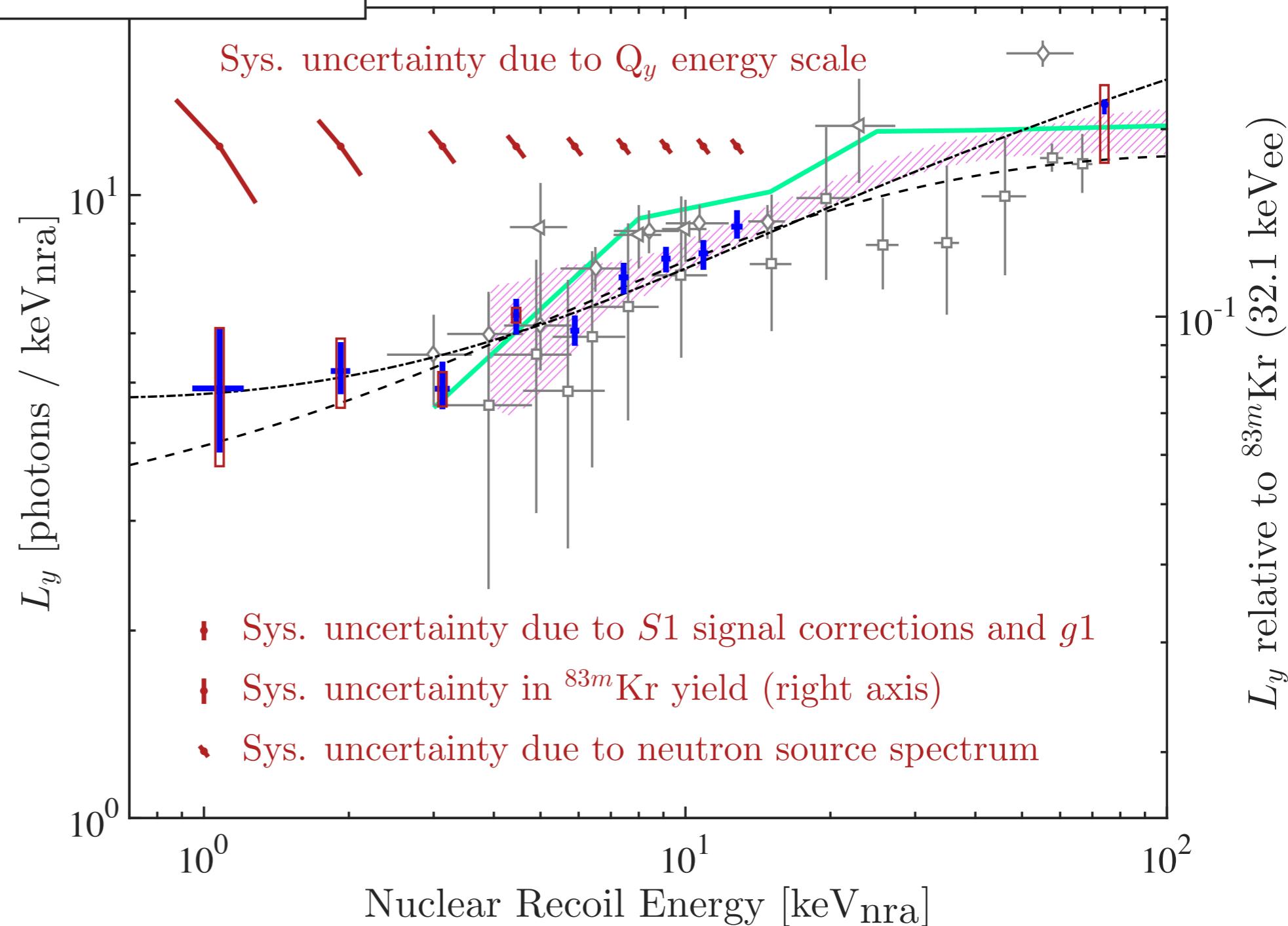
Select slice of *S2* to use for *S1* comparison

Normalize simulation spectrum using this region

2 keV$_{nr}$

Counts

$S2$ [phd]

Horn 2011 (ZEPLIN-III combined FSR & SSR)
Aprile 2013 (XENON100)
Manzur 2010
Plante 2011
Aprile 2009

Scintillation yield absolutely measured to ~1 keVnr in LUX

$L_y$ [photons / keV$_{nr}$]

$L_y$ relative to $^{83m}$Kr (32.1 keV$_{ee}$)

Nuclear Recoil Energy [keV$_{nr}$]

Scintillation yield absolutely measured to ~1 keVnr in LUX

Legend:
- Horn 2011 (ZEPLIN-III combined FSR & SSR)
- Aprile 2013 (XENON100)
- Manzur 2010
- Plante 2011
- Aprile 2009
- LUX model: Lindhard (k = 0.174) + biex. quenching
- Alt. LUX model: Ziegler stopping power + biex. quenching
- LUX D-D $L_y$ at 180 V/cm
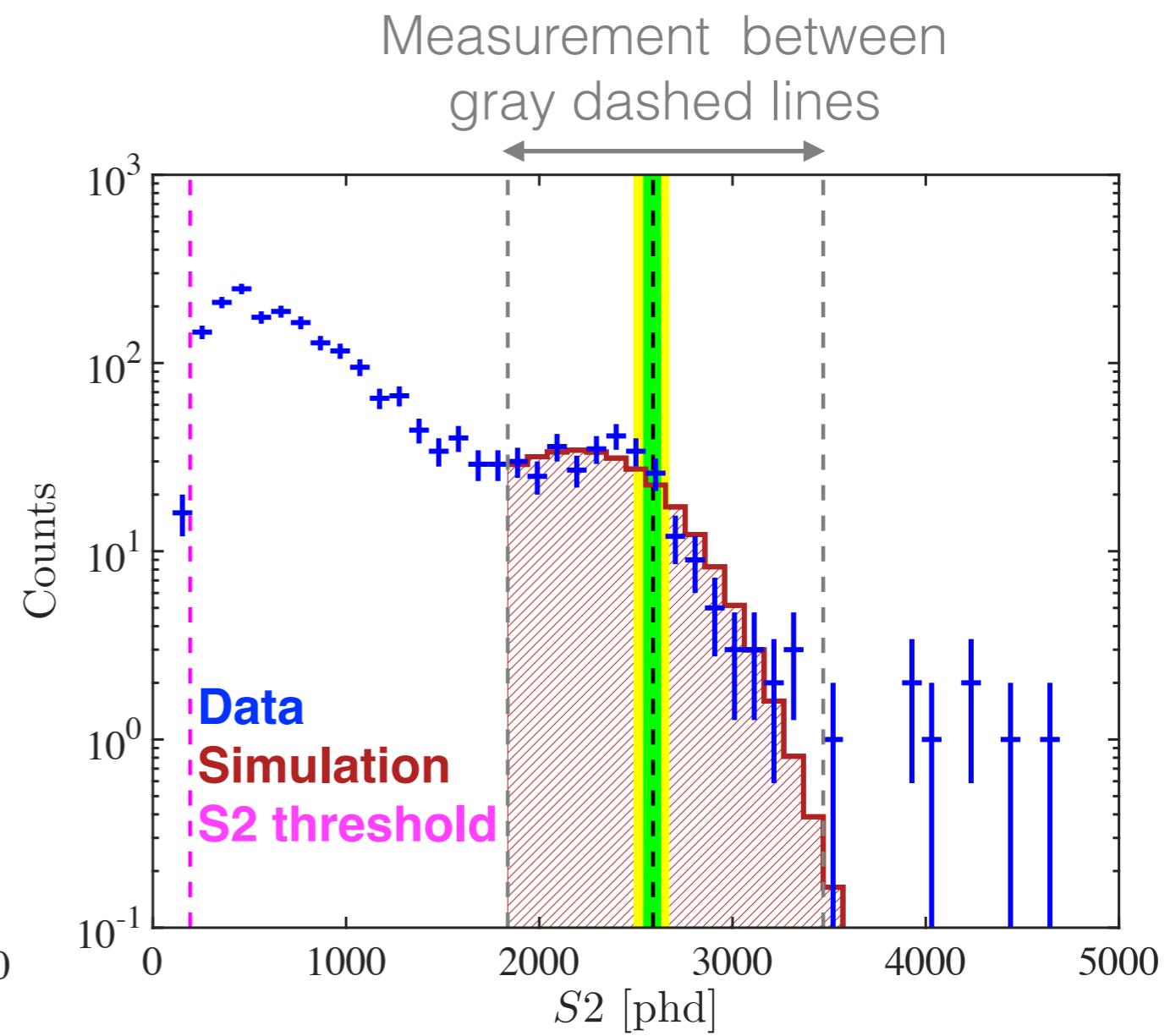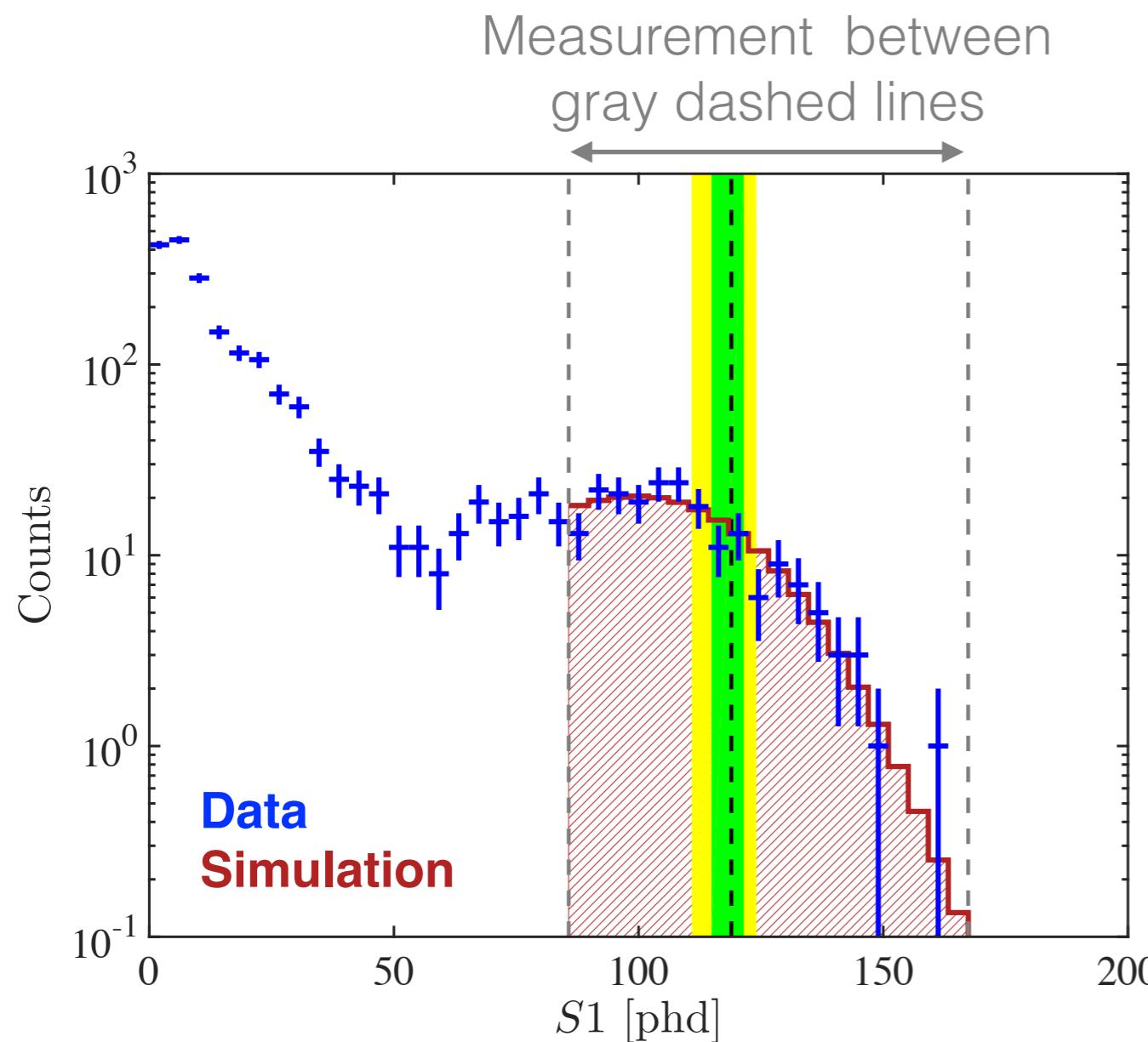
- LUX measurement nearly a factor of x3 lower in energy with improvement in calibration uncertainties

Sys. uncertainty due to $Q_y$ energy scale

Sys. uncertainty due to $S1$ signal corrections and $g1$

Sys. uncertainty in $^{83m}$Kr yield (right axis)

Sys. uncertainty due to neutron source spectrum

$L_y$ [photons / keV$_{nra}$]

$L_y$ relative to $^{83m}$Kr (32.1 keV$_{ee}$)

Nuclear Recoil Energy [keV$_{nra}$]

# Signal Yields at the D-D Nuclear Recoil 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-$\sigma$ statistical uncertainties given by green and yellow bands, respectively



Measurement between gray dashed lines

Measurement between gray dashed lines

# Impact of the Calibration on LUX and Other Liquid Xenon Dark Matter Experiments
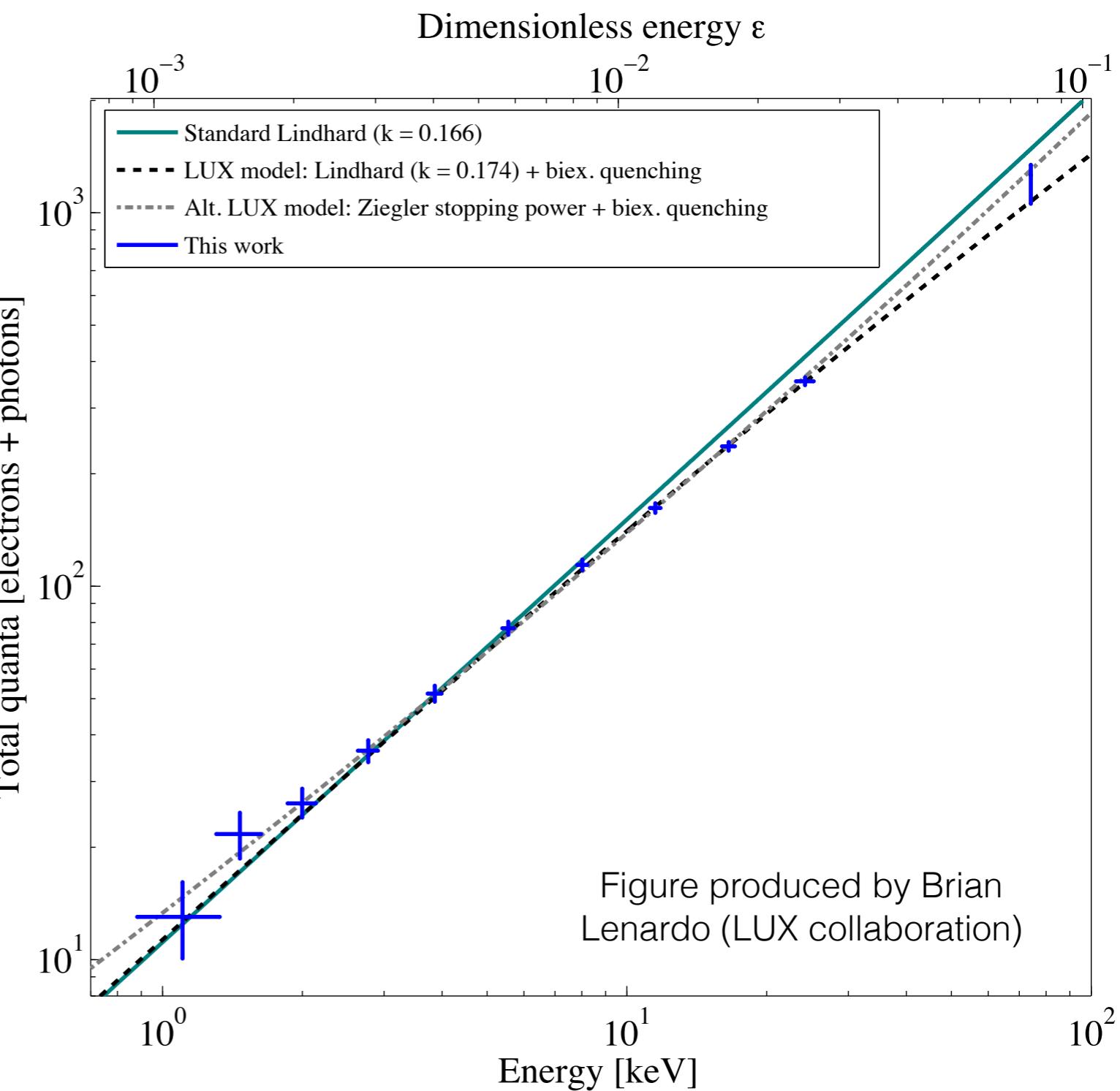
- NEST model (arXiv:1412.4417) fit simultaneously to LUX D-D *Ly*, *Qy*, and NR

- Extract quenching factor (fraction of energy given to detectable electronic excitation)

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

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

$$W = 13.7 \text{ eV}$$
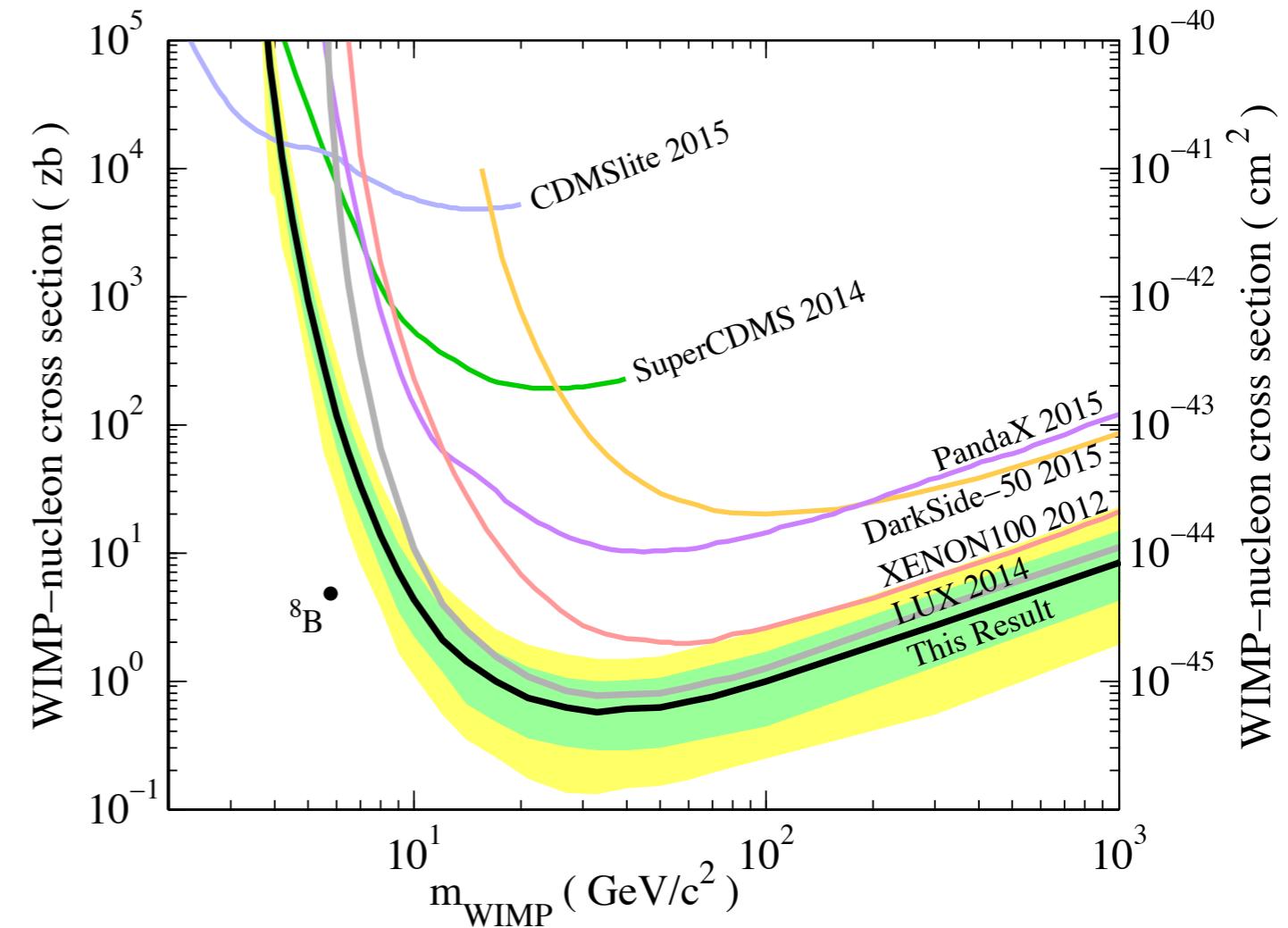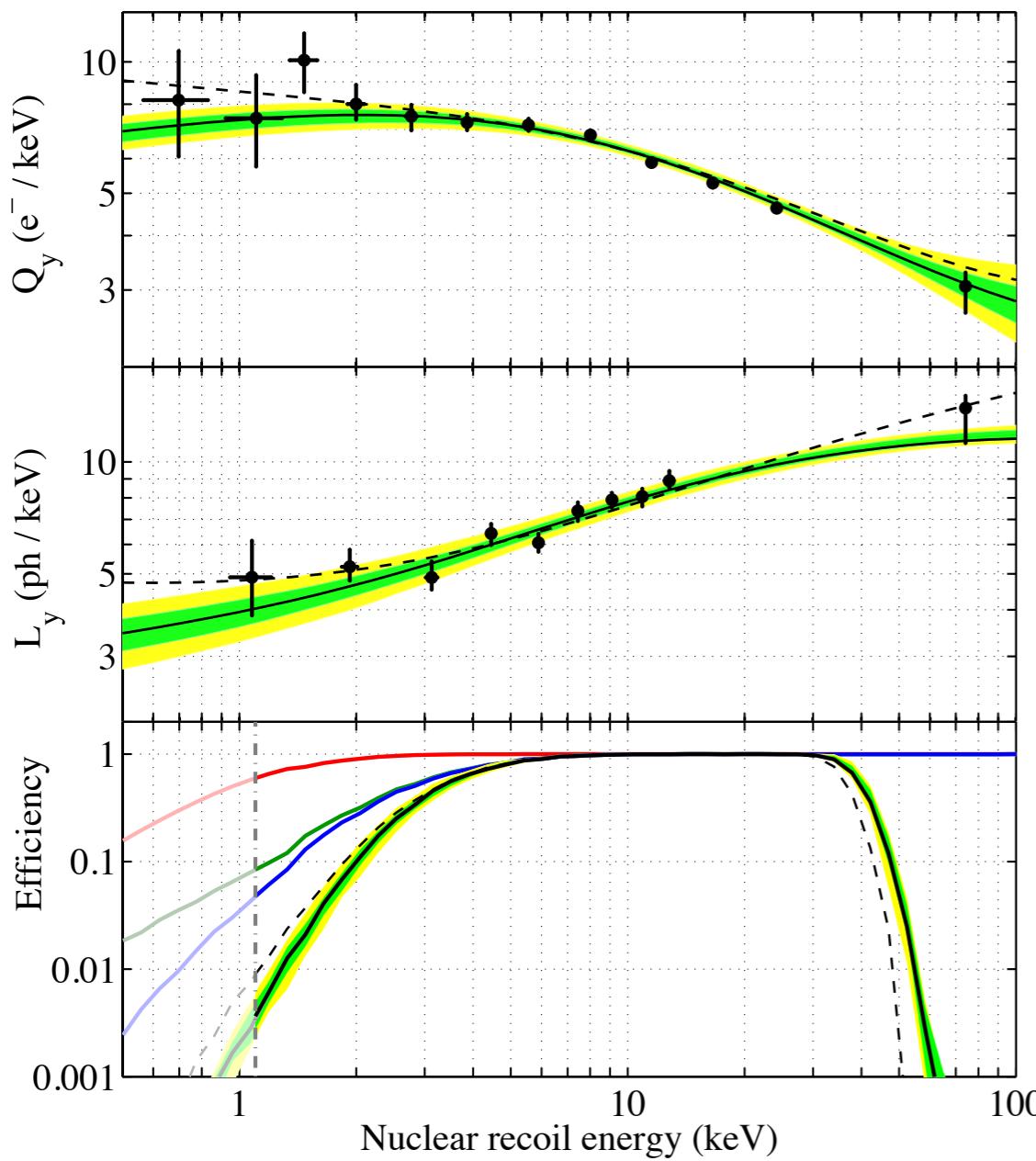
- Lindhard-based model is consistent with LUX data over two orders of magnitude (as low as 1.1 keV$_{\mathrm{nr}}$)



Dimensionless energy ε

Standard Lindhard (k = 0.166)
LUX model: Lindhard (k = 0.174) + biex. quenching
Alt. LUX model: Ziegler stopping power + biex. quenching
This work

Total quanta [electrons + photons]

Energy [keV]

Figure produced by Brian Lenardo (LUX collaboration)

- 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**

$$^8\text{B} \rightarrow\, ^7\text{Be}^* + e^+ + \nu_e$$
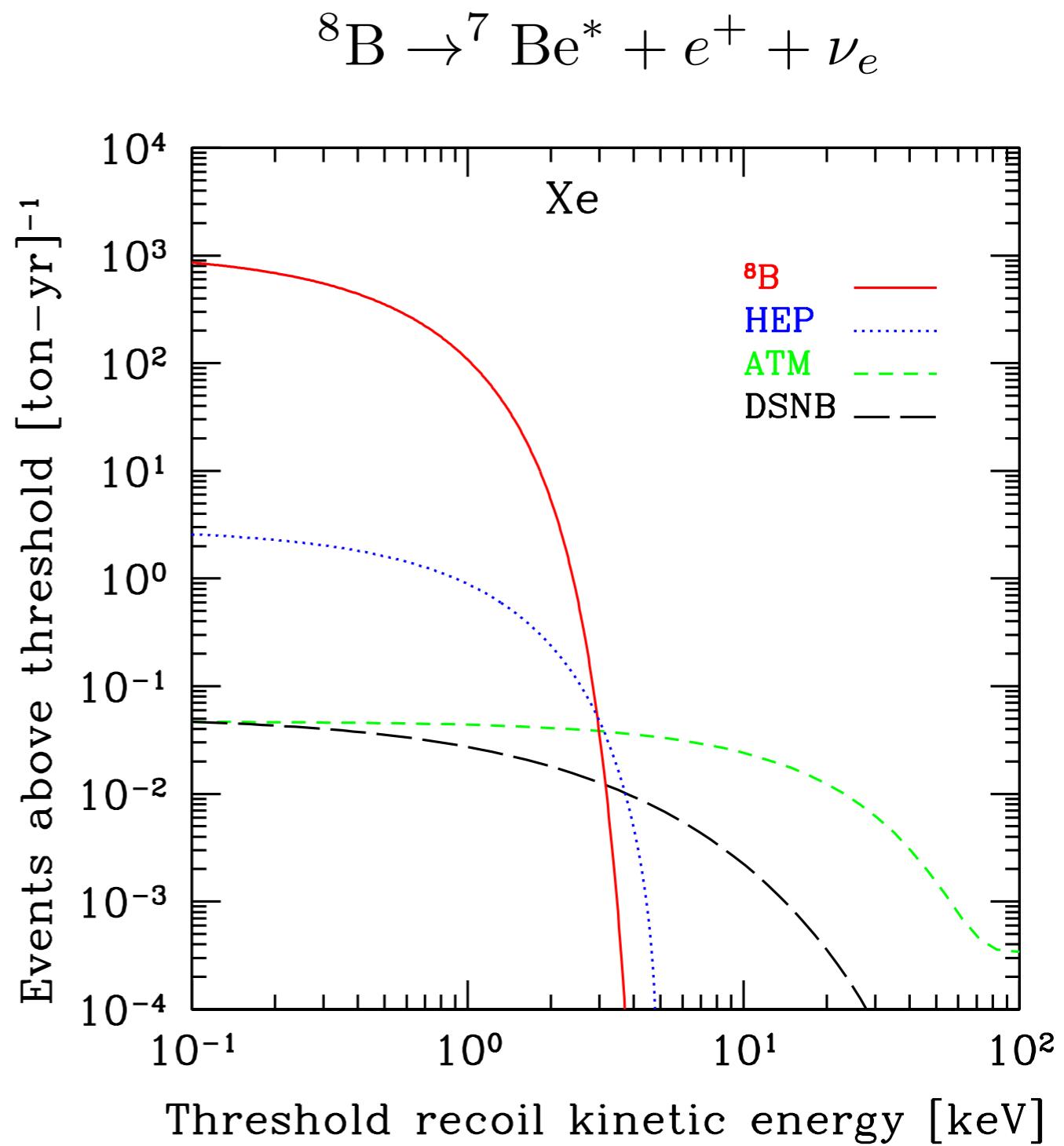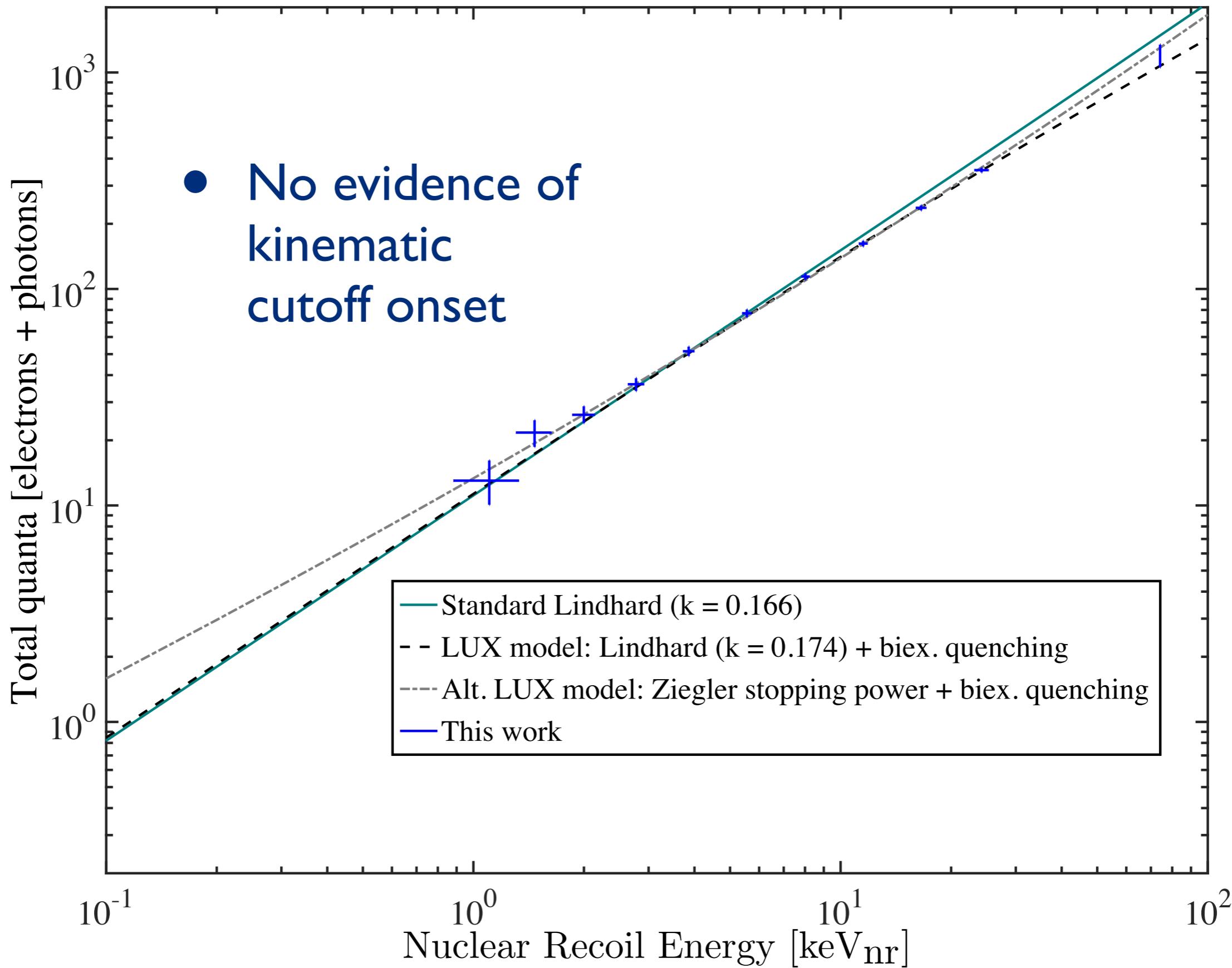
Figure from Strigary 2009 (arXiv:0903.3630)

# 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**

- No evidence of kinematic cutoff onset

Legend:
- Standard Lindhard (k = 0.166)
- LUX model: Lindhard (k = 0.174) + biex. quenching
- Alt. LUX model: Ziegler stopping power + biex. quenching
- This work

Y-axis: Total quanta [electrons + photons]
X-axis: Nuclear Recoil Energy [keV$_{nr}$]

# Detector performance limitations
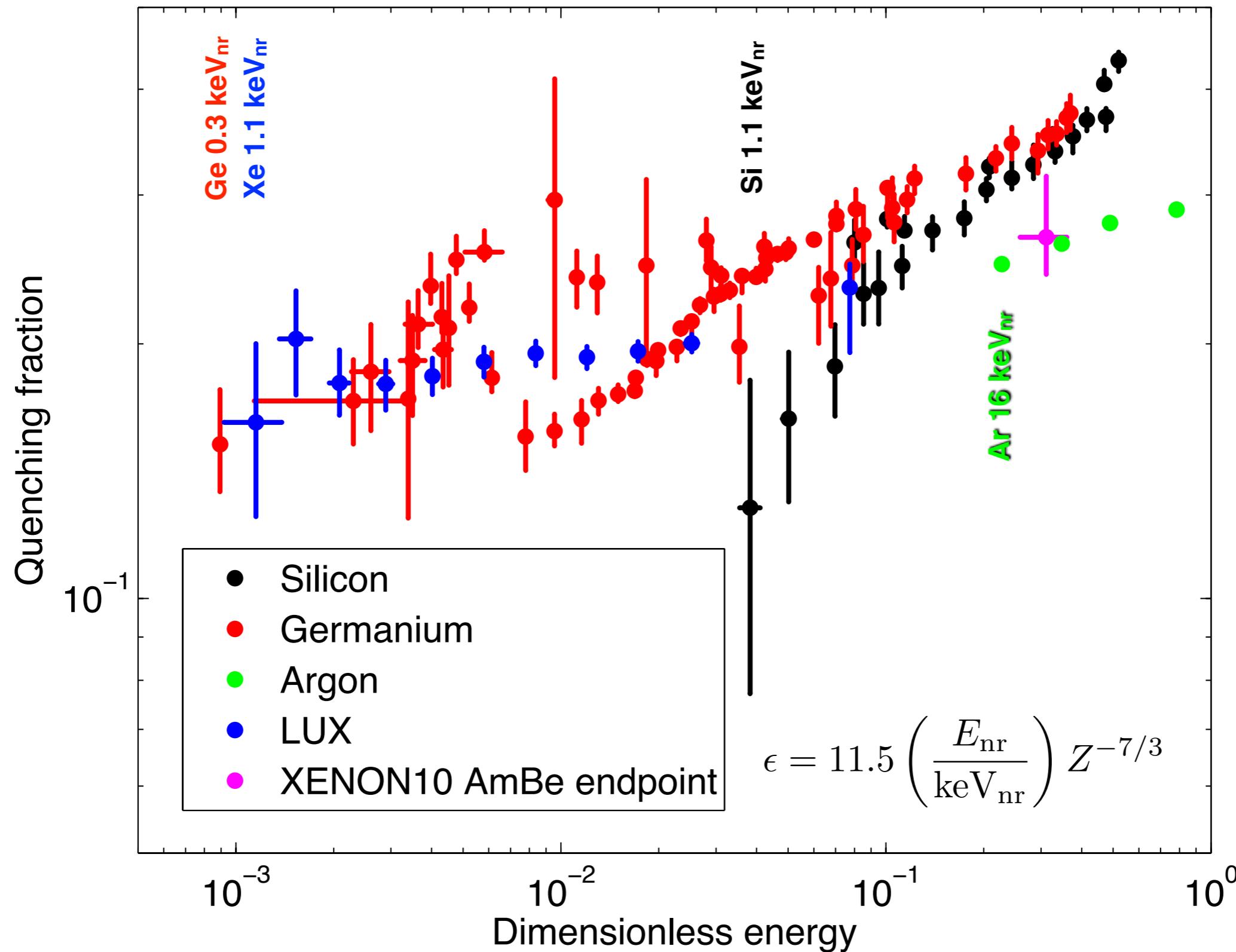
- Expectation values for number of signal carriers (produced and observed)

| 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)

$$\epsilon = 11.5 \left( \frac{E_{\mathrm{nr}}}{\mathrm{keV_{nr}}} \right) Z^{-7/3}$$

Legend:
- Silicon (black)
- Germanium (red)
- Argon (green)
- LUX (blue)
- XENON10 AmBe endpoint (magenta)

Axis labels: Quenching fraction (y), Dimensionless energy (x)

Annotations: Ge 0.3 keV$_\mathrm{nr}$, Xe 1.1 keV$_\mathrm{nr}$, Si 1.1 keV$_\mathrm{nr}$, Ar 16 keV$_\mathrm{nr}$
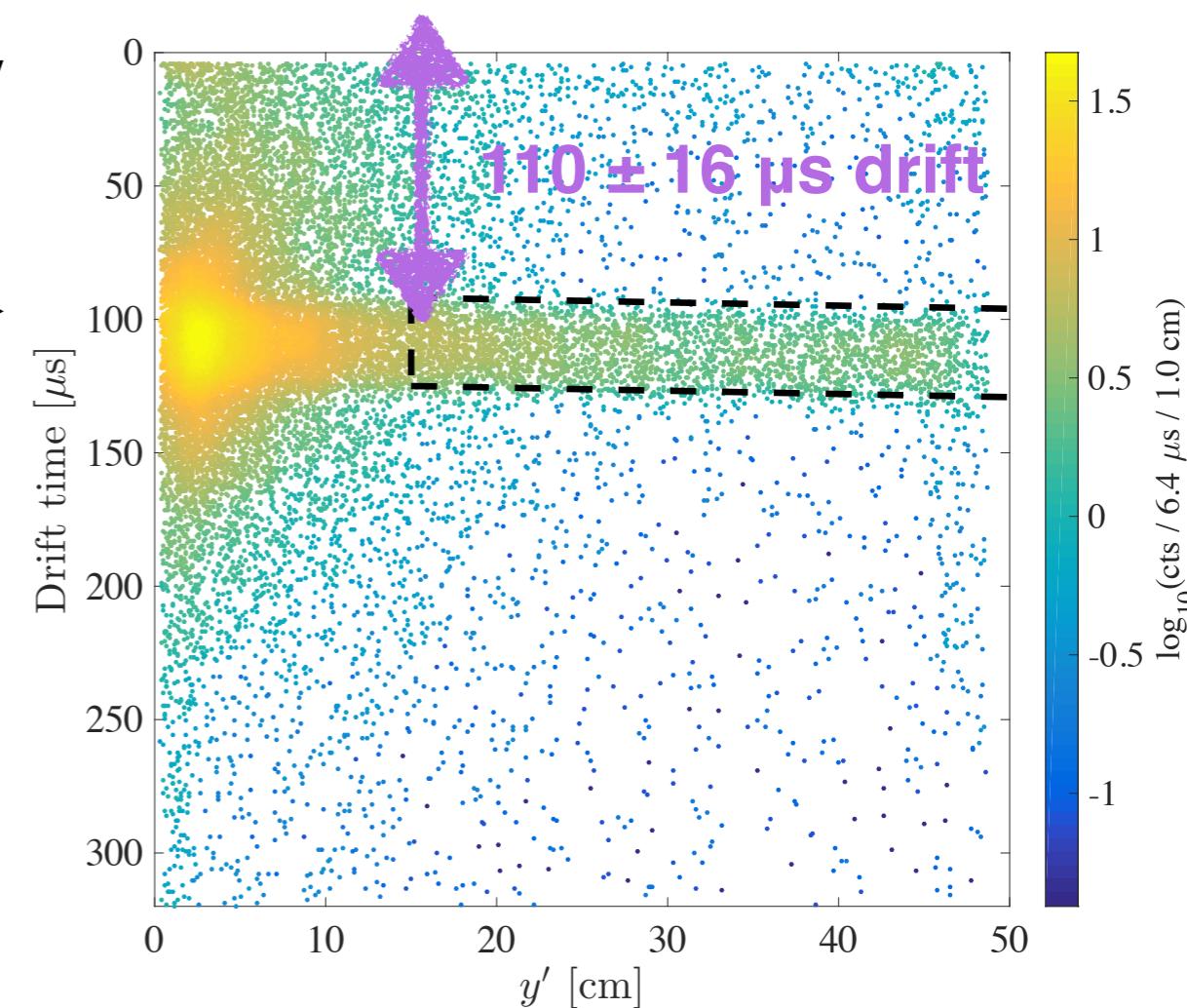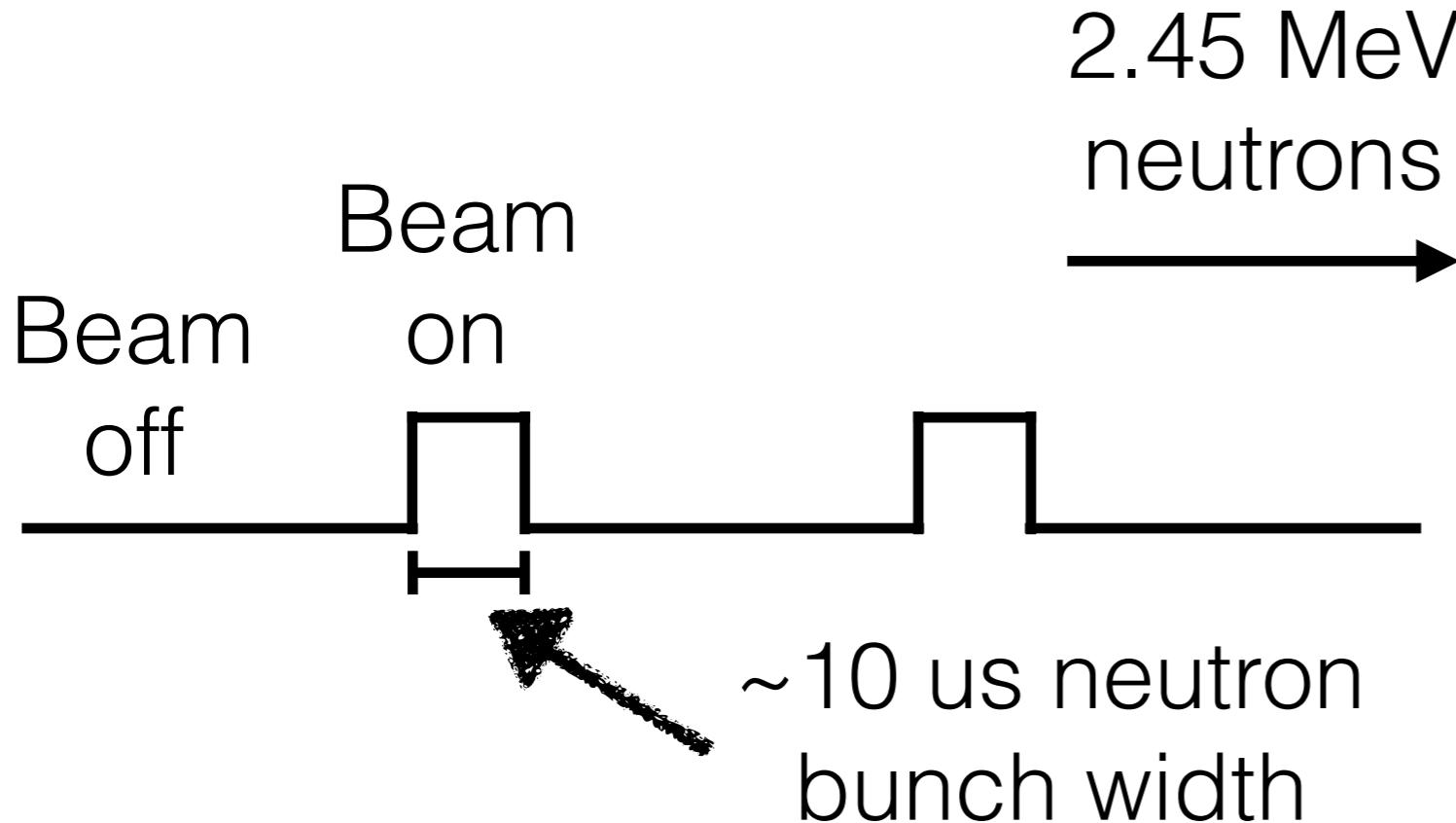
# Improvements to the Calibration Technique

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.
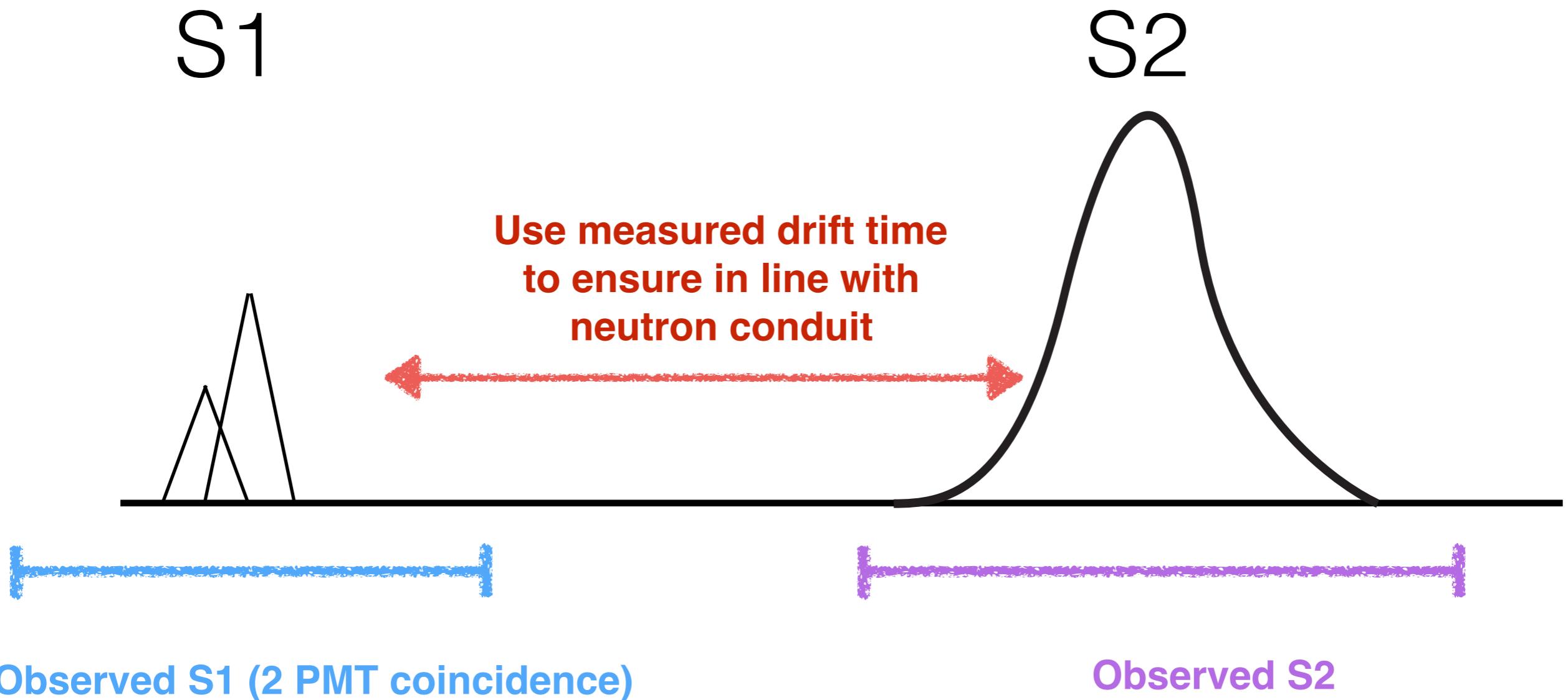
1.  Reduction of D-D neutron bunch width time structure

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

Beam off

Beam on

2.45 MeV neutrons

~10 us neutron bunch width

110 ± 16 µs drift

Drift time [µs]

$y'$ [cm]

$\log_{10}(\text{cts} / 6.4\ \mu s / 1.0\ cm)$
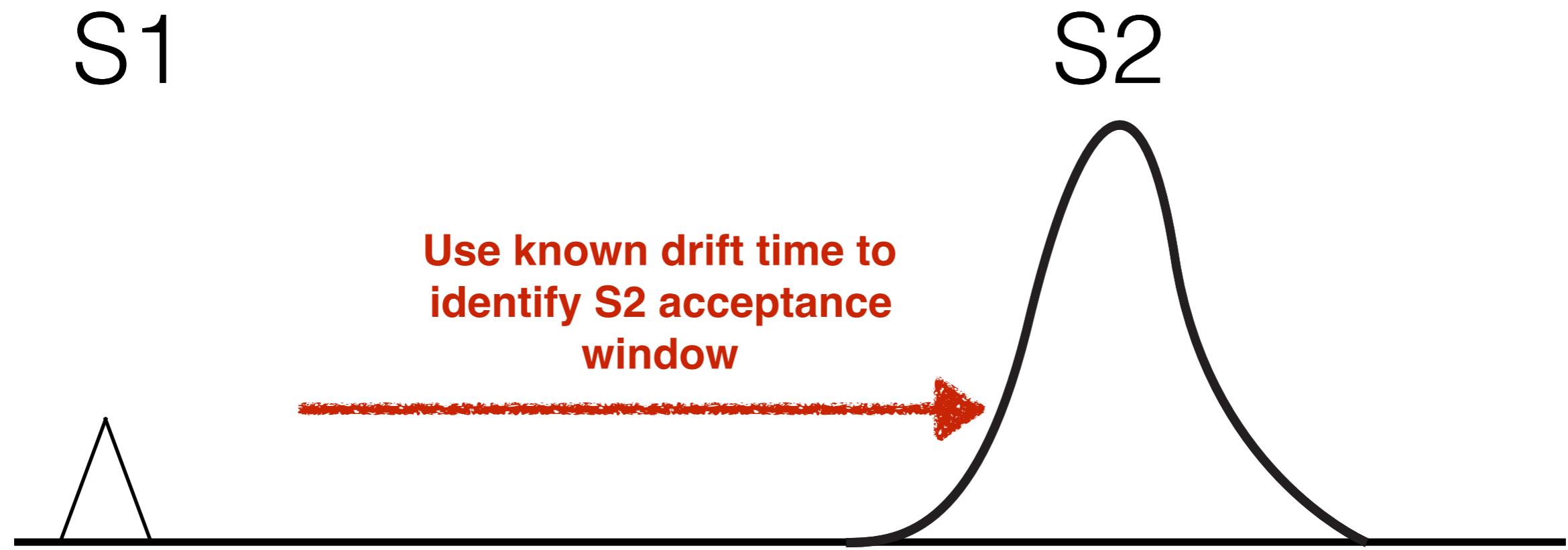
- DD beam-on time functions as a proxy for the $t_0$ even in the absence of an S1

  - 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

S1

S2

**Use measured drift time to ensure in line with neutron conduit**

**Observed S1 (2 PMT coincidence)**

**Observed S2**

S1

S2

**Use known drift time to identify S2 acceptance window**

**Count individual photons in S1 time window defined by known "beam on" time**

**Identify D-D neutron S2 using known "beam on" time combined with known drift time**

- 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

S1

S2

**Use known drift time to identify S2 acceptance window**
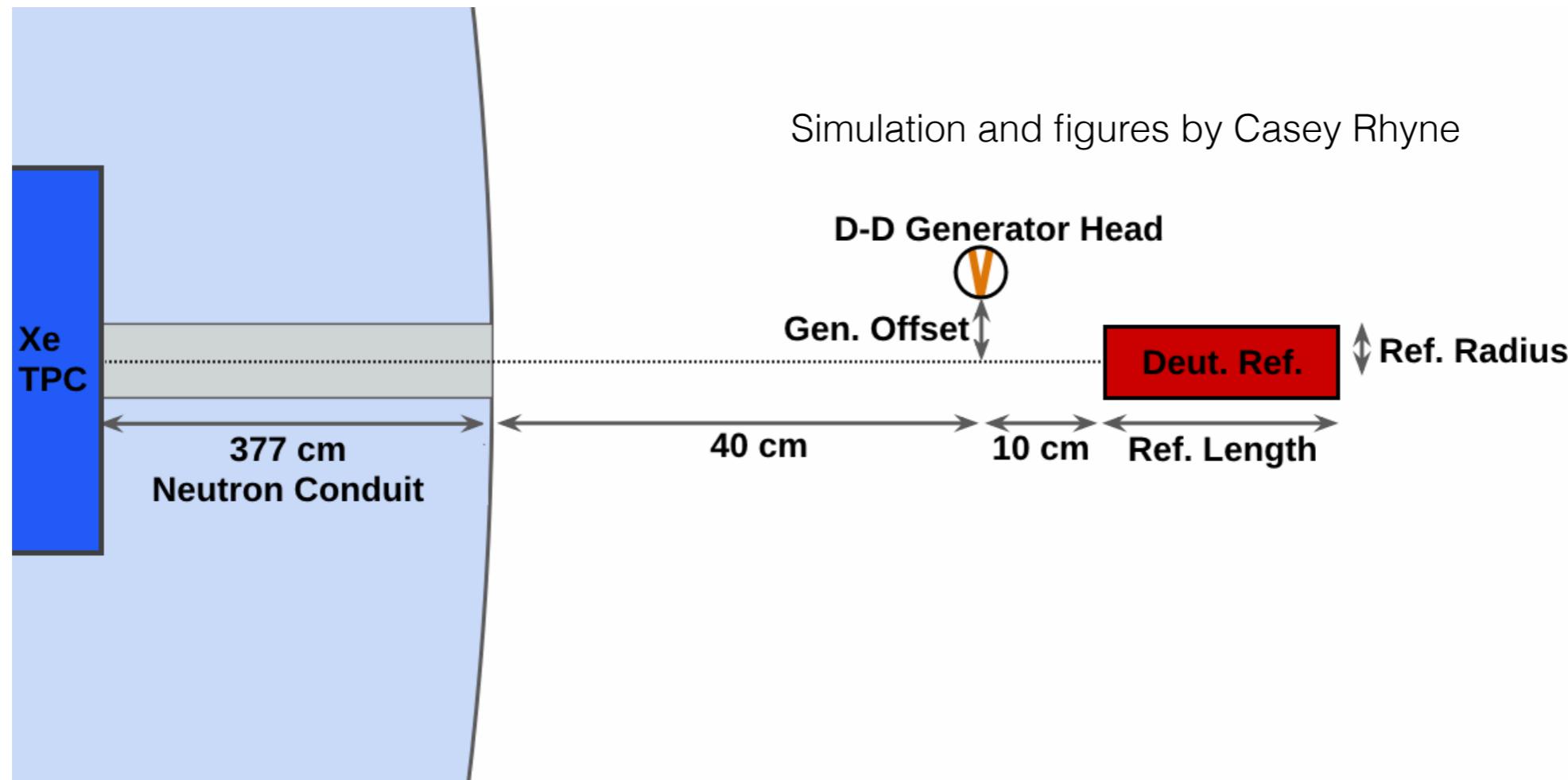
**Count individual photons in S1 time window defined by known "beam on" time**

**Identify D-D neutron S2 using known "beam on" time combined with known drift time**

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- In addition to advanced no-S1 studies, narrow trigger pulse allows for powerful reduction and understanding of calibration backgrounds

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



Simulation and figures by Casey Rhyne
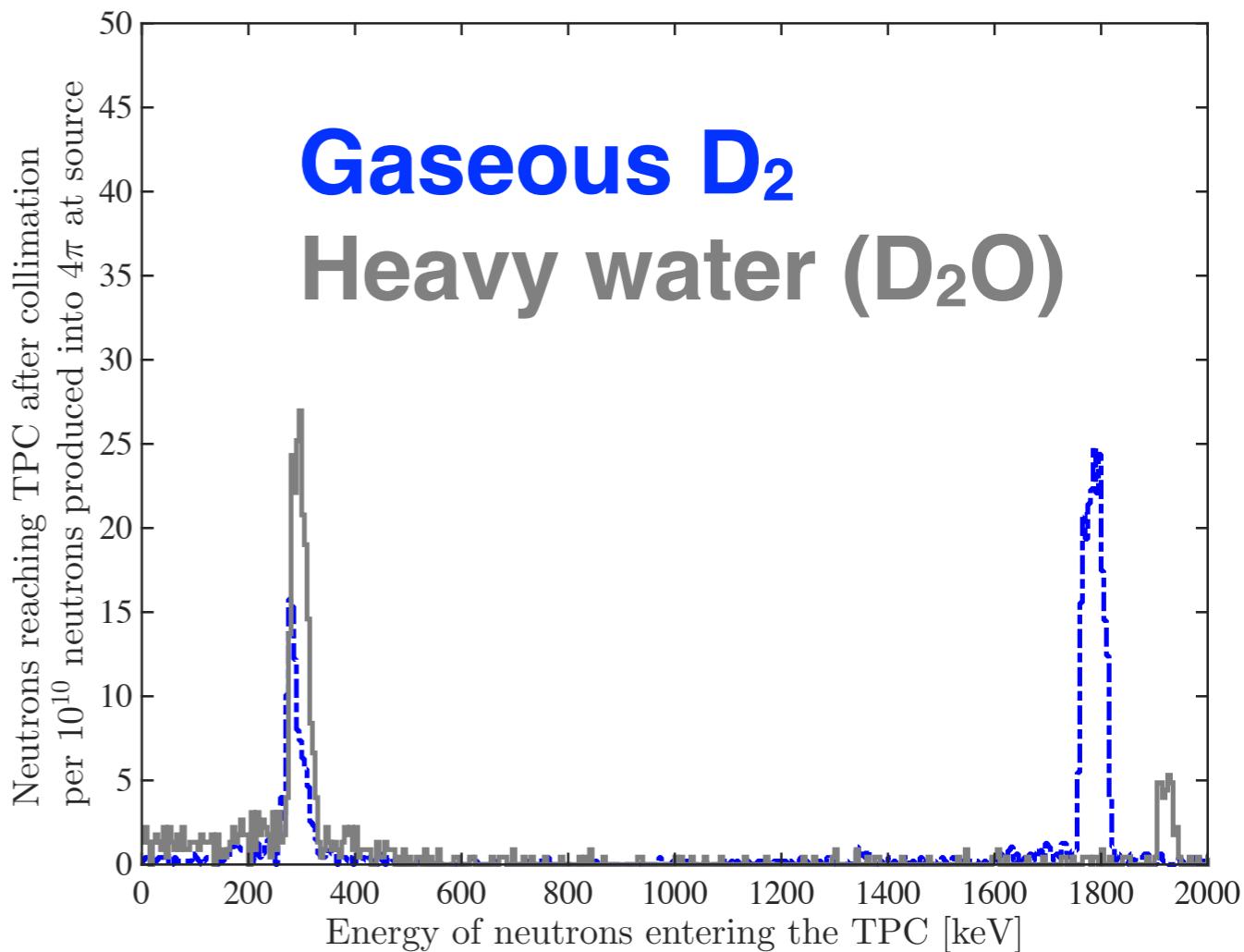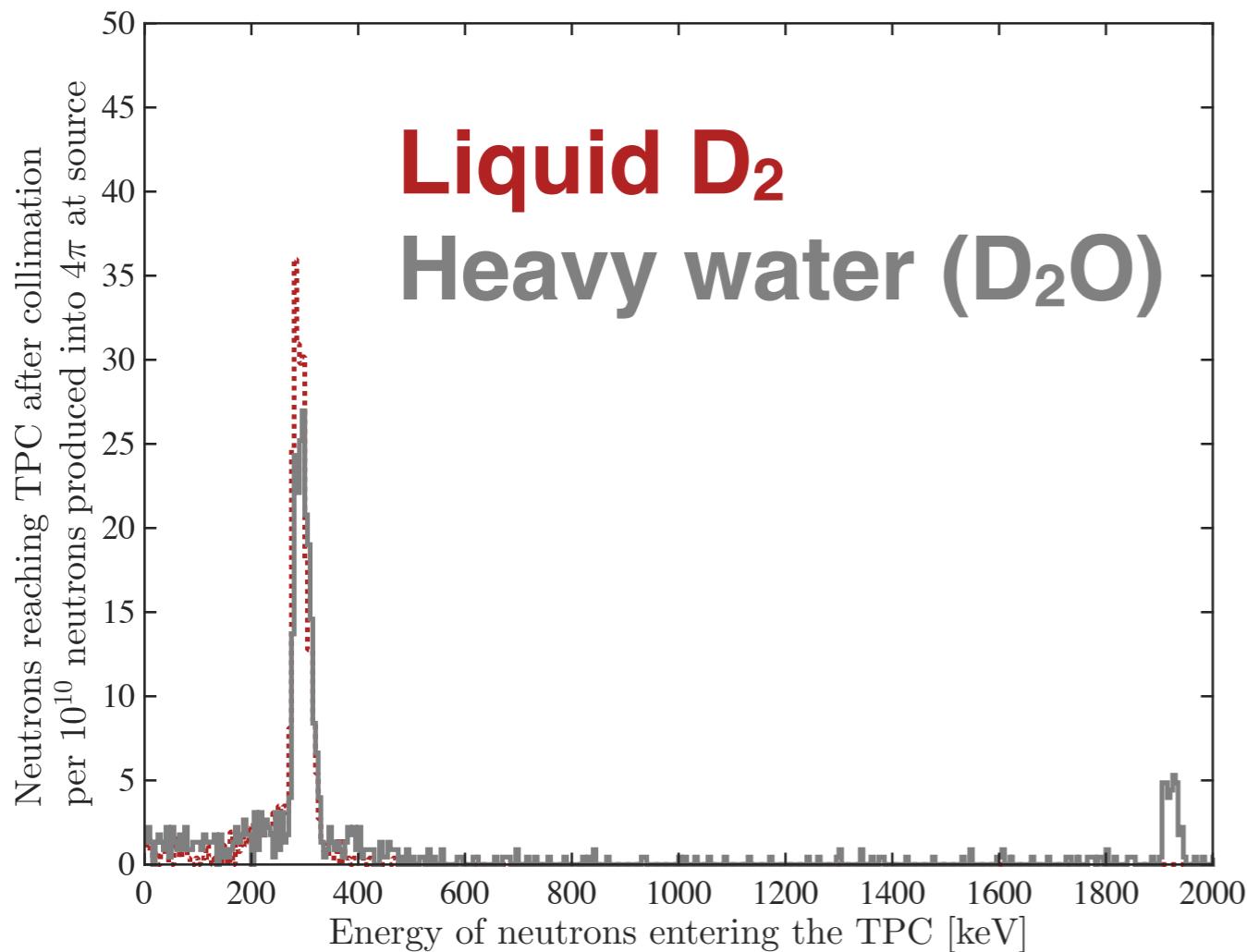
- **D-loaded reflector positioned in line with neutron conduit**

- **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 $H_2O$)
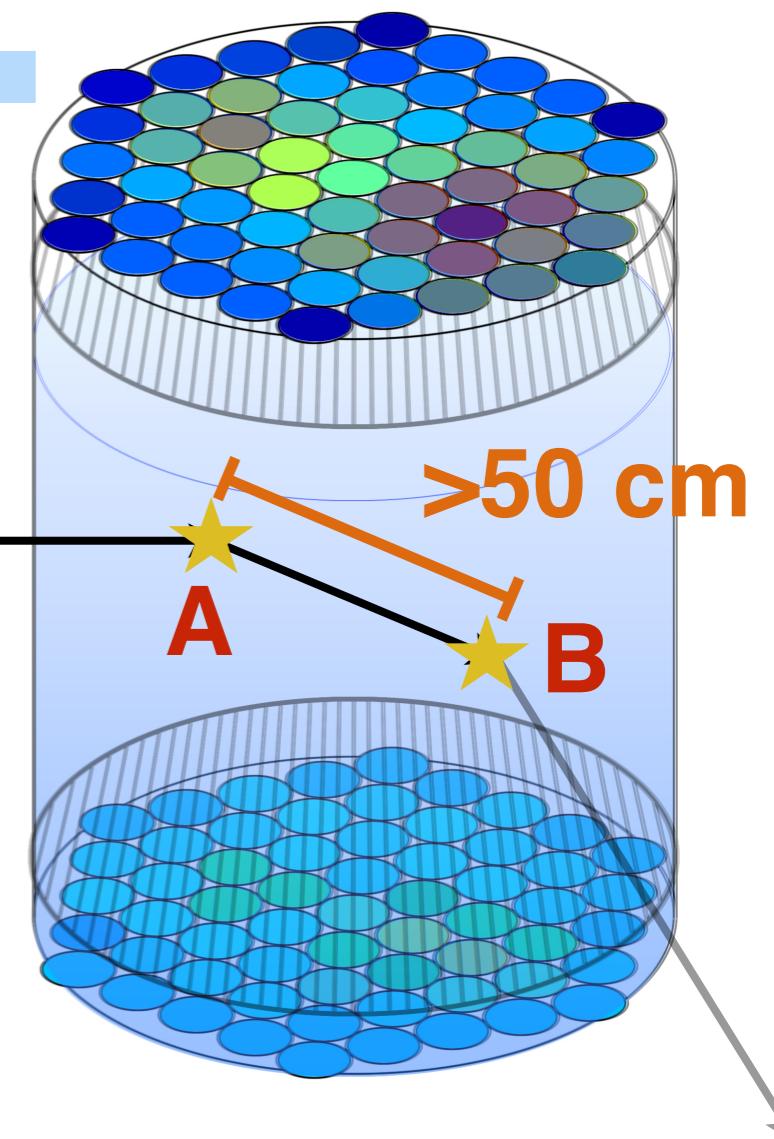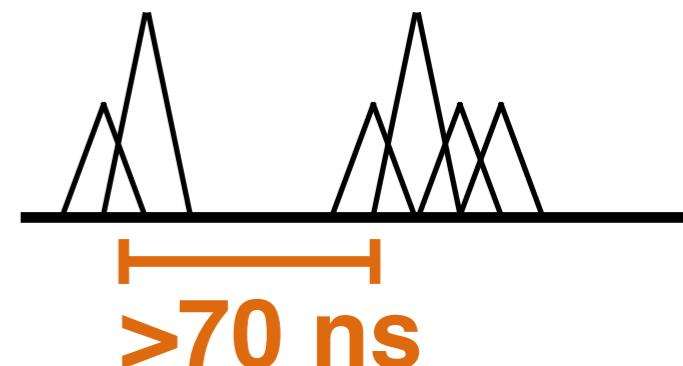
# Direct, absolute measurement of $L_y$ using neutron scattering kinematics

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 |

**S1$_A$**   **S1$_B$**

**>70 ns**

**>50 cm**

**A**   **B**
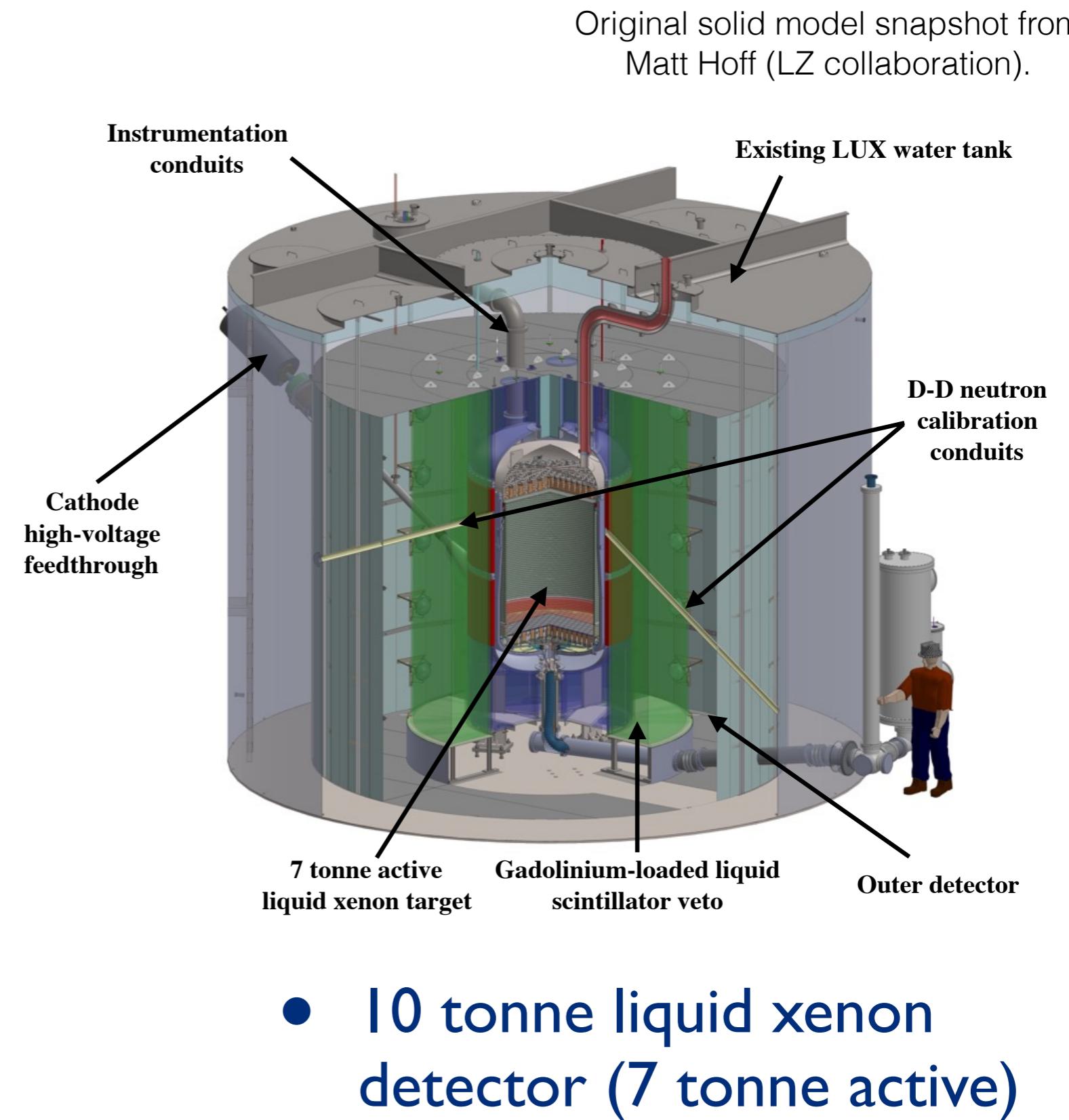
- Double scatter events with 50 cm vertex separation => 70 ns ToF for 272 keV neutrons between vertices

- 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).
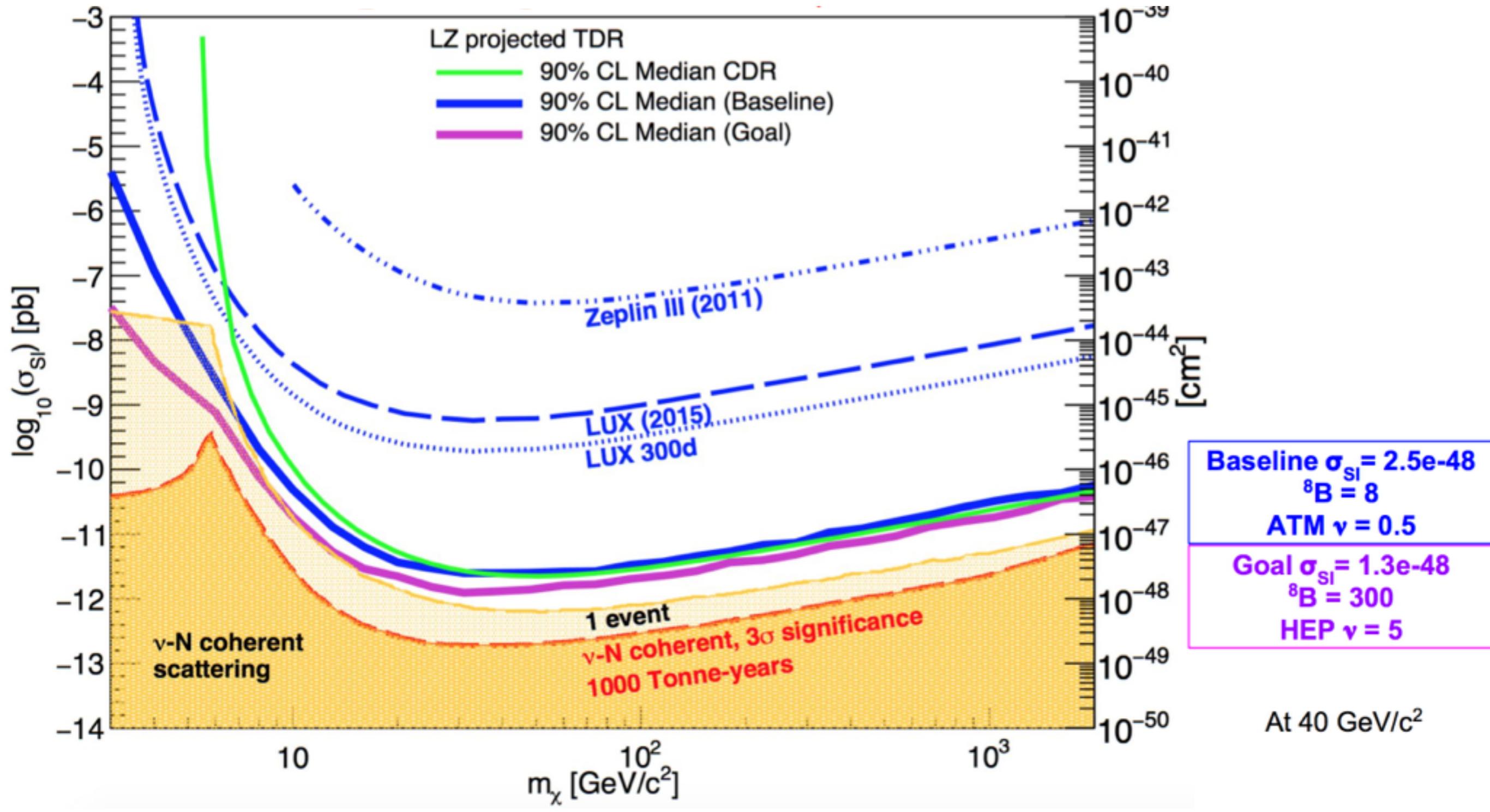
- Due to the success of the LUX D-D program, D-D is a core component of the LZ calibration strategy

- Two neutron conduits

- Baseline plan to include

  - Short neutron bunch width operation

  - D-reflector neutron source

Instrumentation conduits

Existing LUX water tank

D-D neutron calibration conduits

Cathode high-voltage feedthrough

7 tonne active liquid xenon target

Gadolinium-loaded liquid scintillator veto

Outer detector

- 10 tonne liquid xenon detector (7 tonne active)

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 w**orld-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