Measurement of Ultra-low Energy Nuclear Recoils in the LUX Detector Using a D-D Neutron Generator

James Verbus
Brown University

2015 LOWECAL
Chicago, IL

September 23rd, 2015

BROWN

Postdoc position available

- Postdoc position available in Brown Particle Astrophysics Group
- If interested, please contact group leader Richard Gaitskell
    - Richard_Gaitskell@brown.edu

BROWN

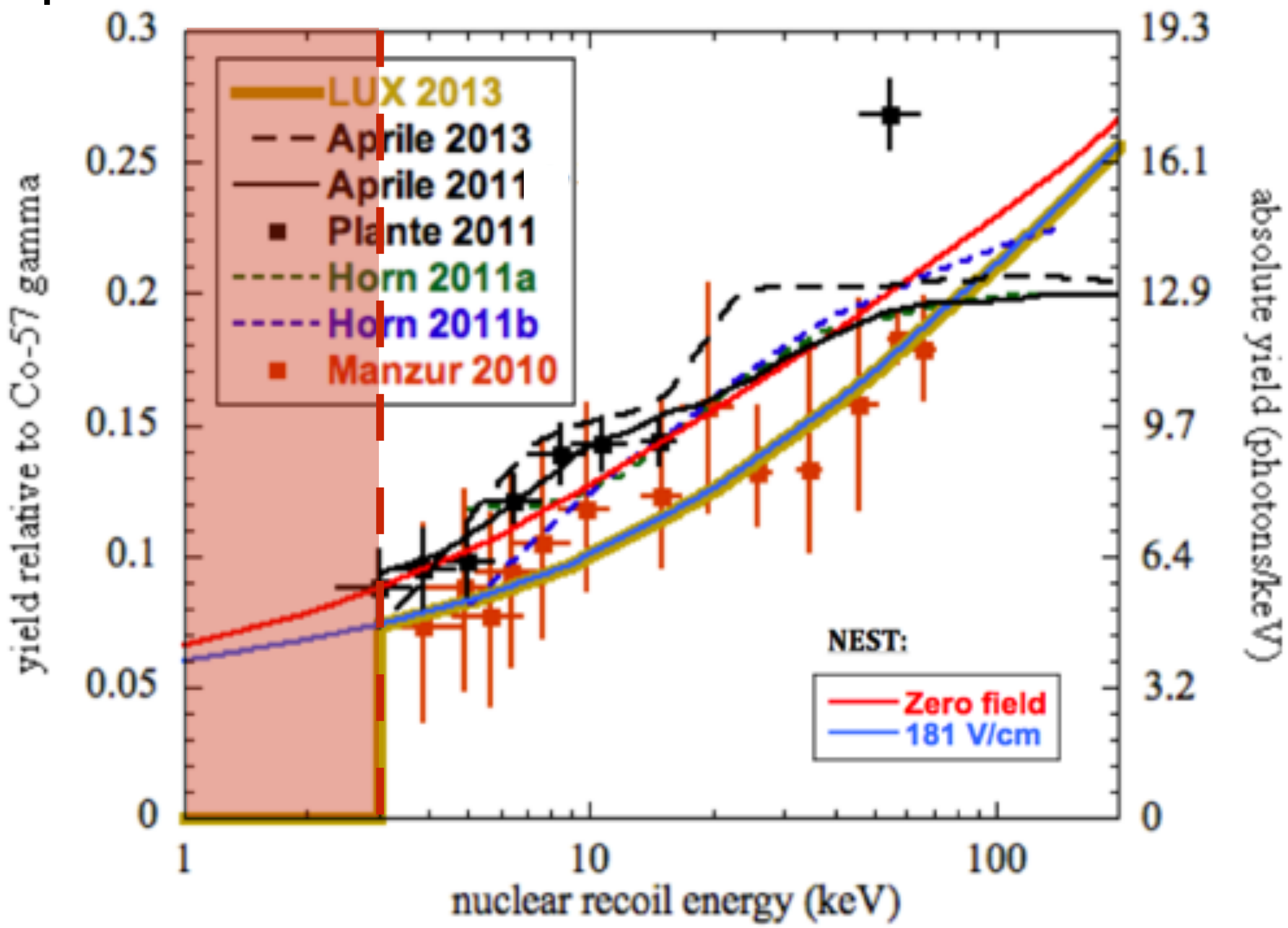
LUX in the 8m Diameter Water Tank

Conservative Nuclear Recoil Light and Charge Yields Assumed for LUX 2014 PRL

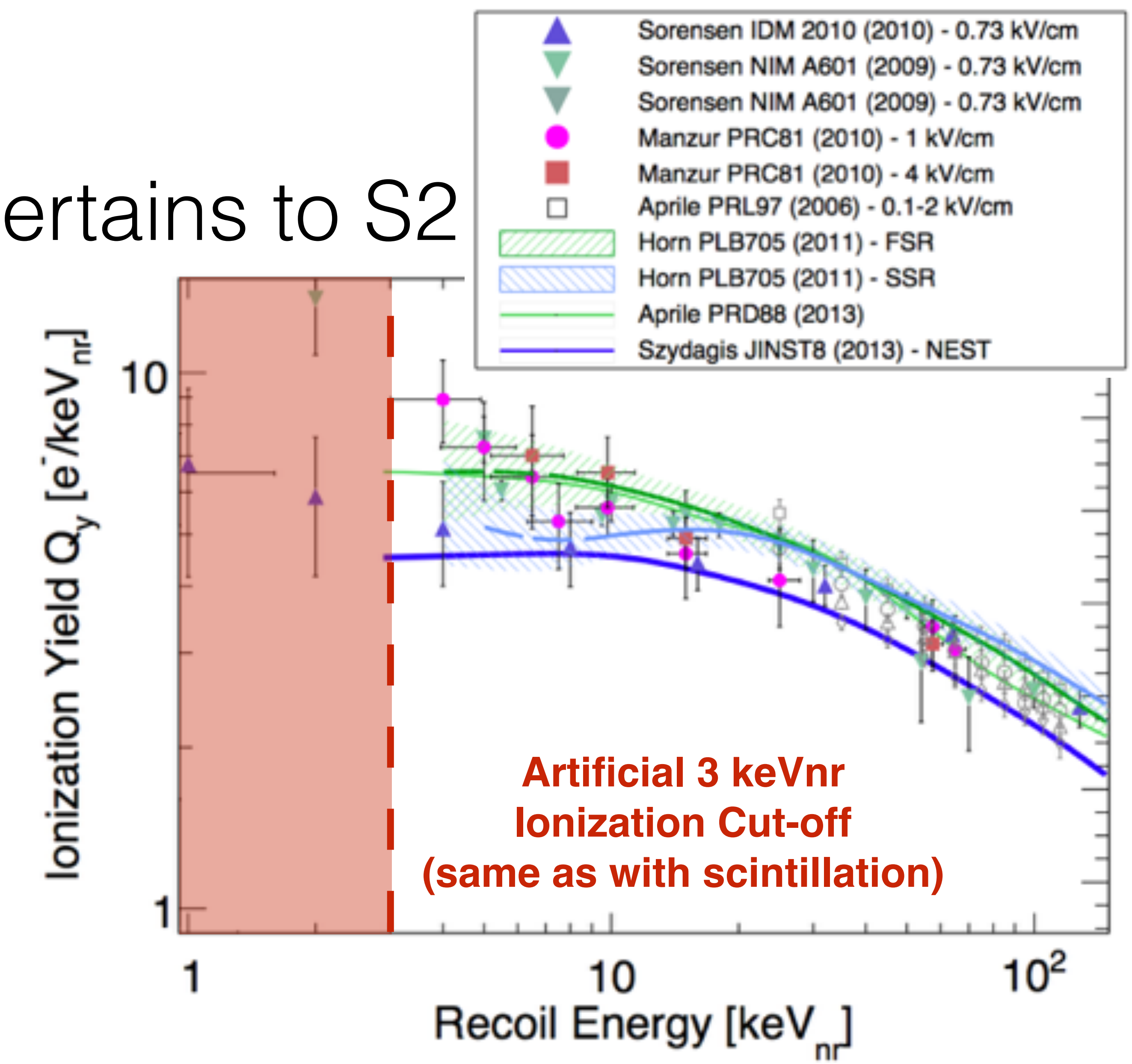
- Modeled Using Noble Element Simulation Technique (NEST)
  - Szydagis et al., arxiv:1106.1613
- NEST based on canon of existing experimental data.
- Artificial cutoff in light and charge yields assumed below 3 keVnr, to be conservative.
- Includes predicted electric field quenching of light signal, to 77-82% of the zero field light yield

- **Conservative threshold used in LUX 2014 PRL Dark Matter Result arXiv:1310.8214v2**

pertains to S1

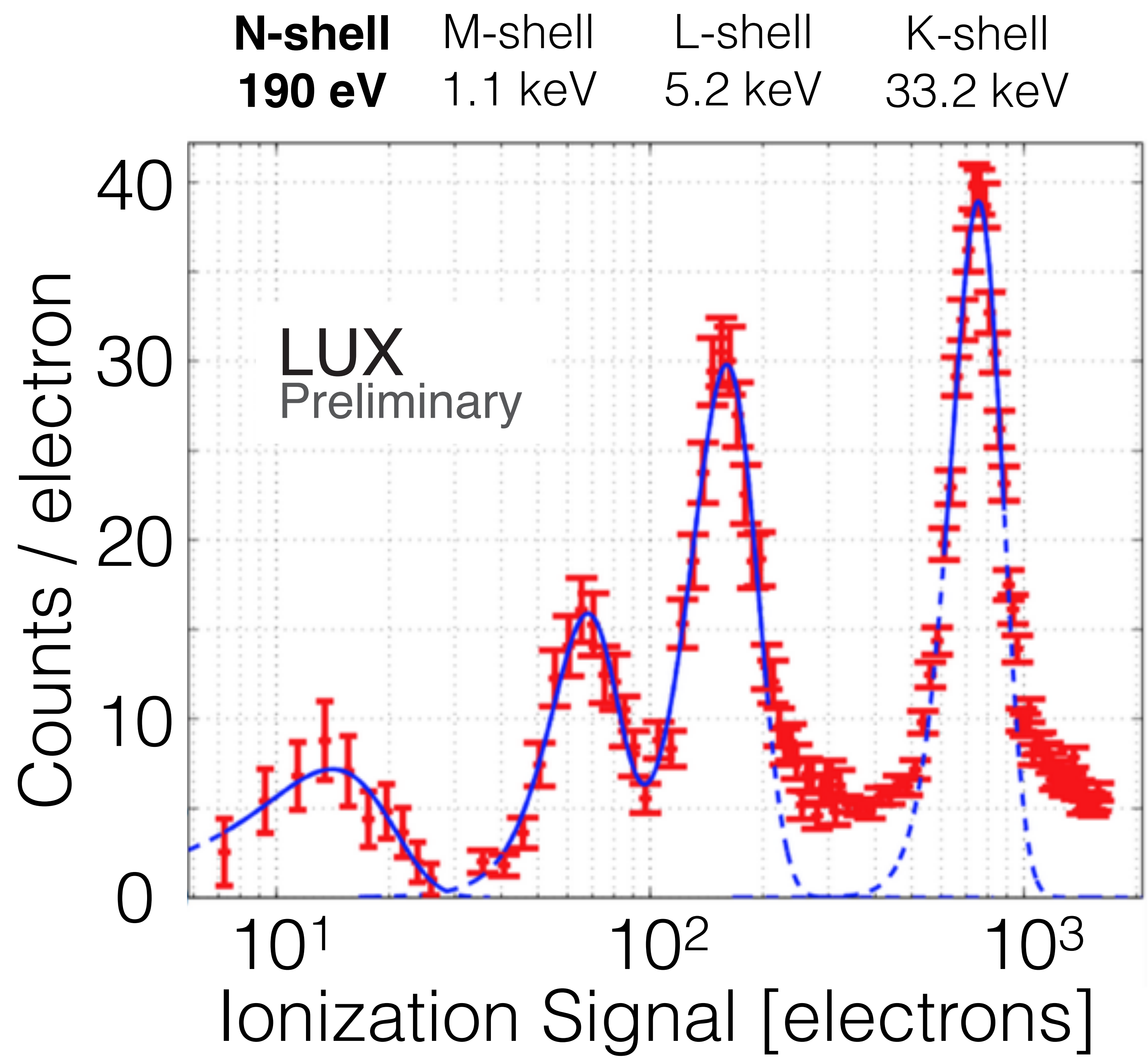


pertains to S2



By the way, LUX has in situ calibration from 190 eV x-ray

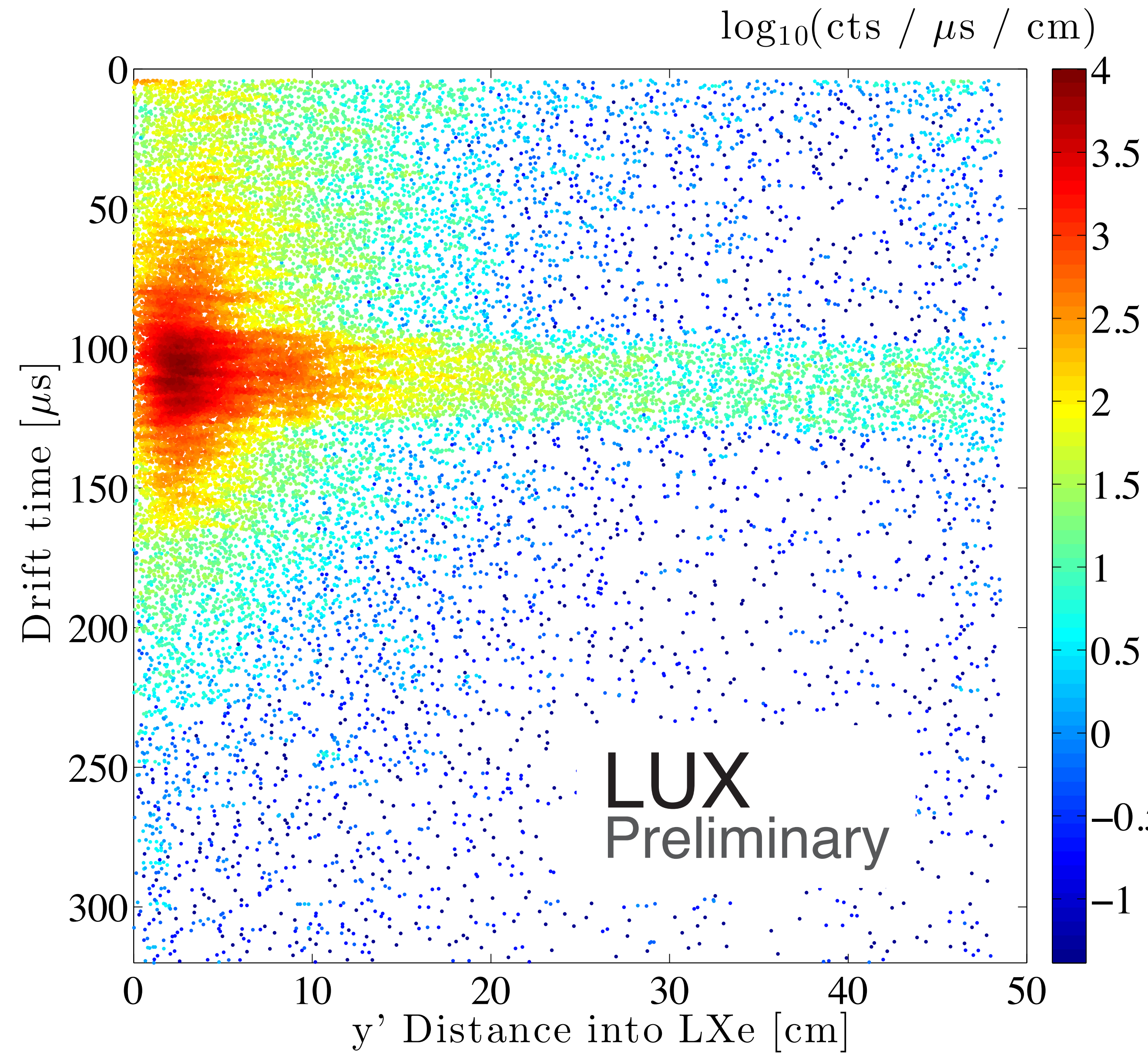
- Using x-rays from ^{127}Xe electron capture
- Events unambiguously tagged by coincident 203 keV gamma
- Provides in situ measurement of ER ionization yield to energies as low as **190 eV**



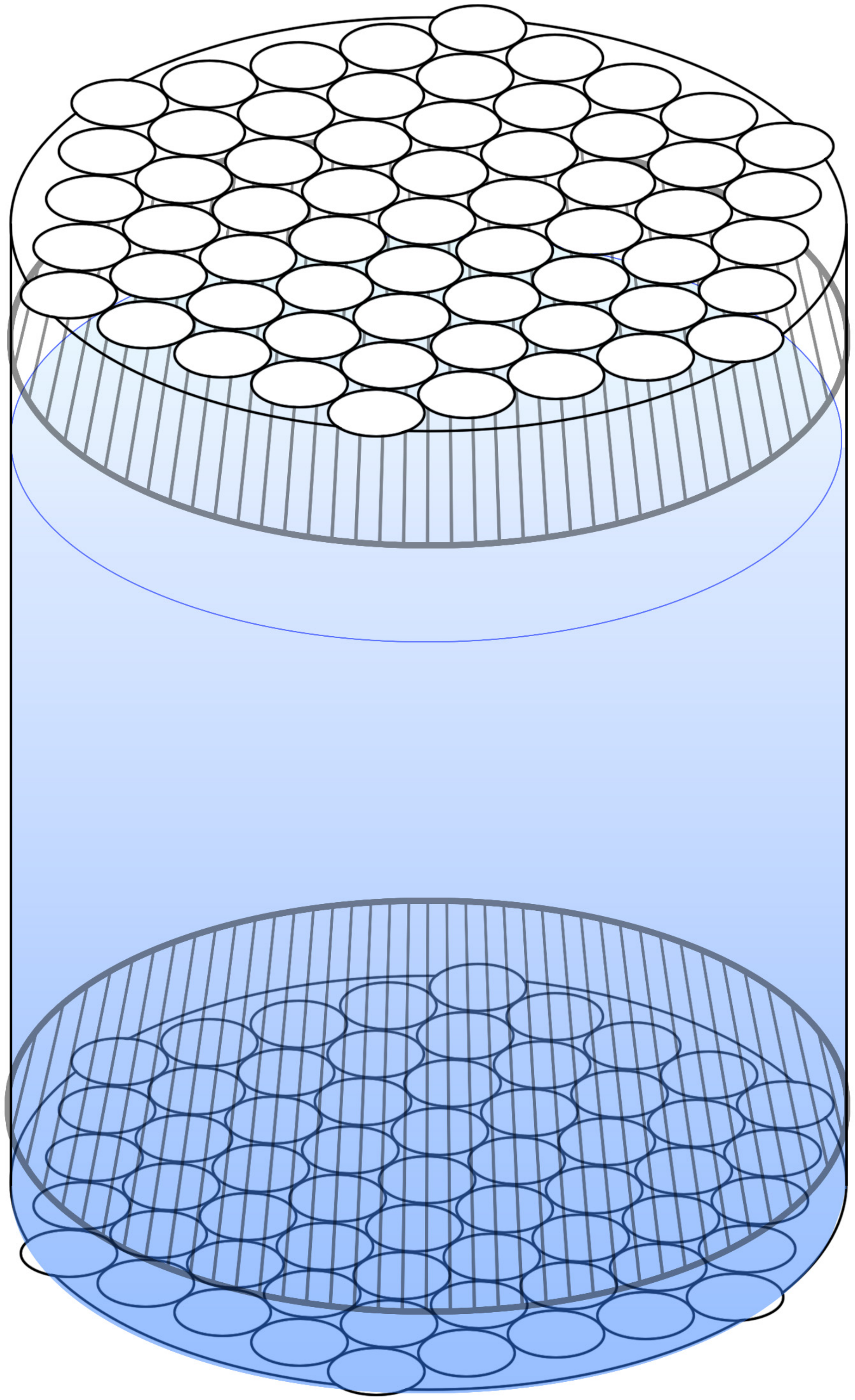
From recent ^{127}Xe work by Dongqing Huang (Brown University):
http://pa.brown.edu/talks_files/2015_dqhuang_TAUP.pdf

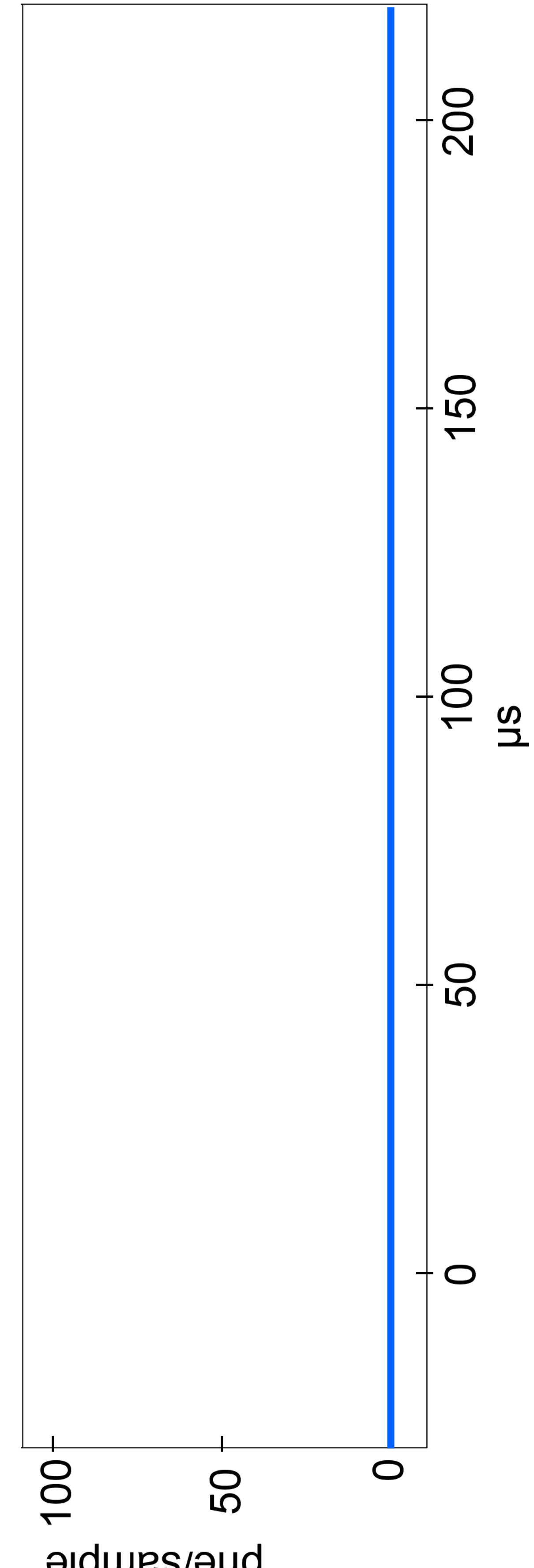
Neutron Conduit Installed in the LUX Water Tank

Adelphi Technology, Inc. DD108 Neutron Generator Installed Outside LUX Water Tank



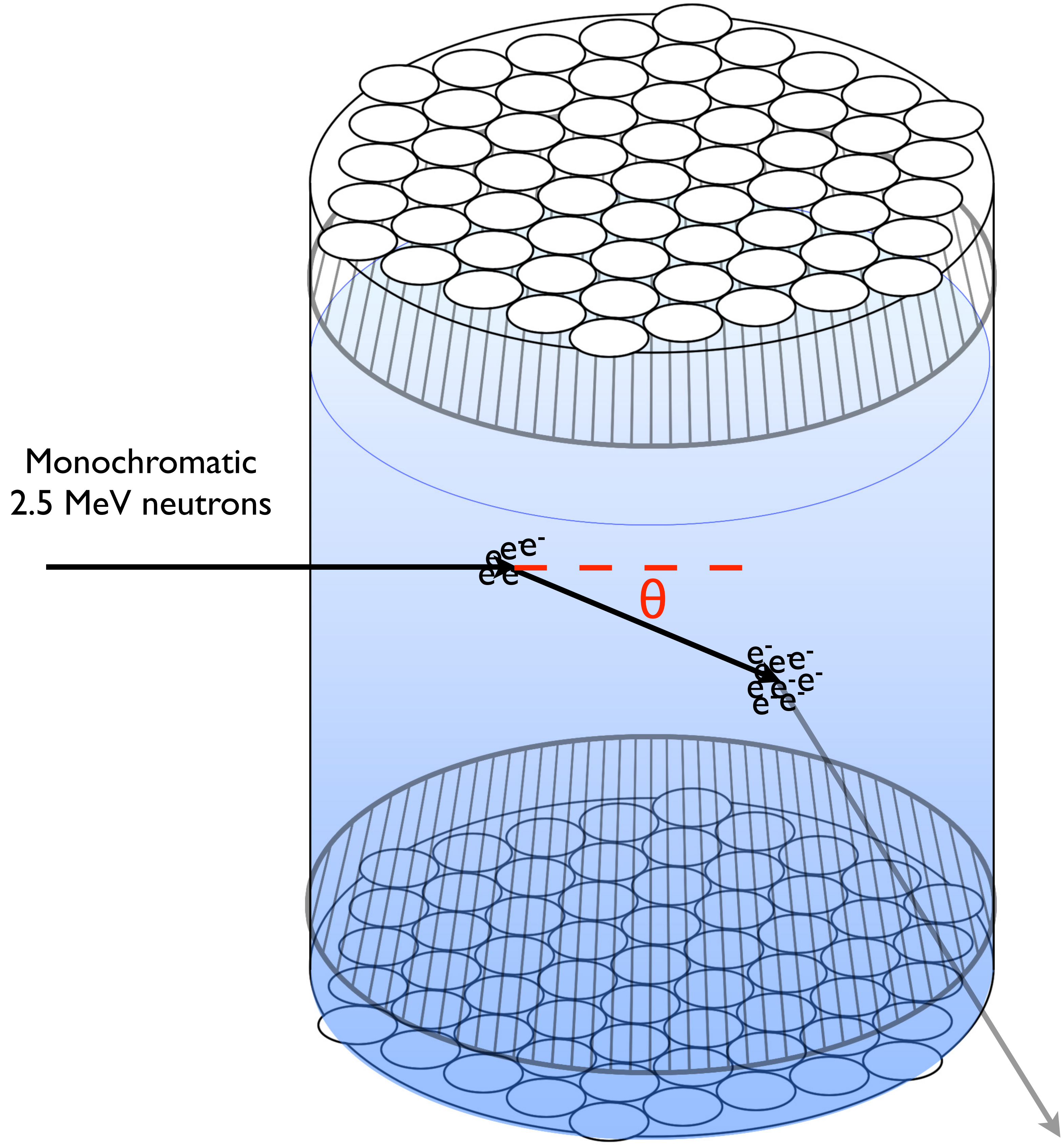
- Neutron generator/beam pipe assembly aligned 17 cm below liquid level in LUX active region to maximize usable single / double scatters
- Beam leveled to ~1 degree
- 107 live hours of neutron tube data used for analysis

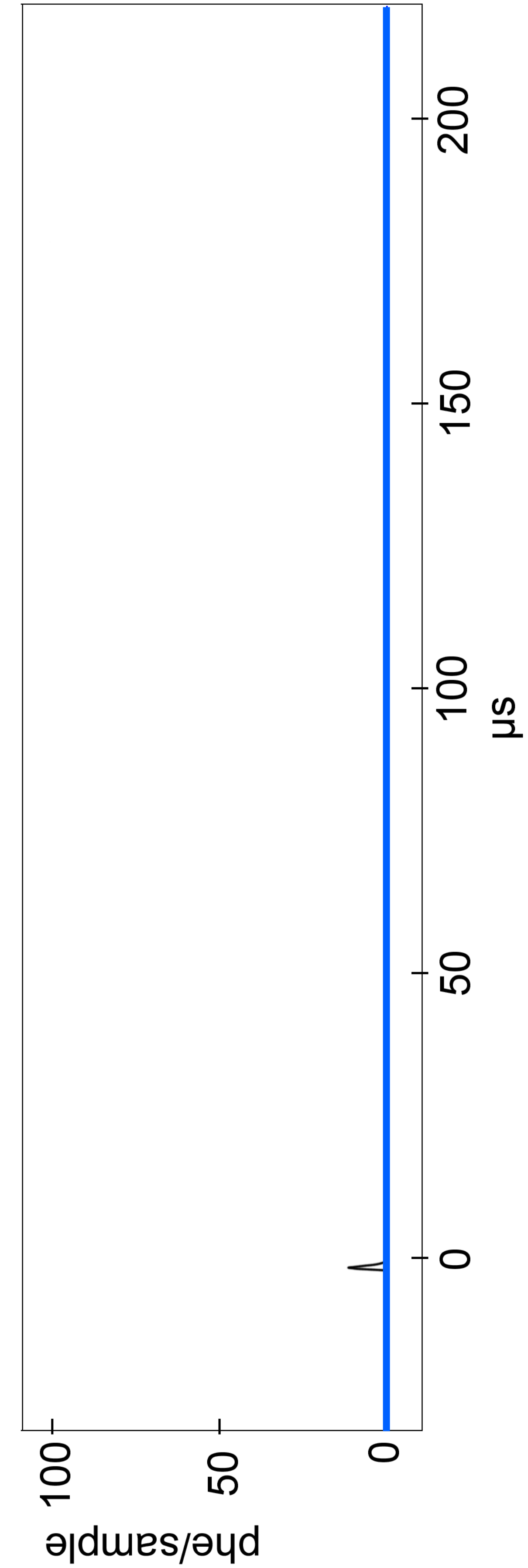




$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

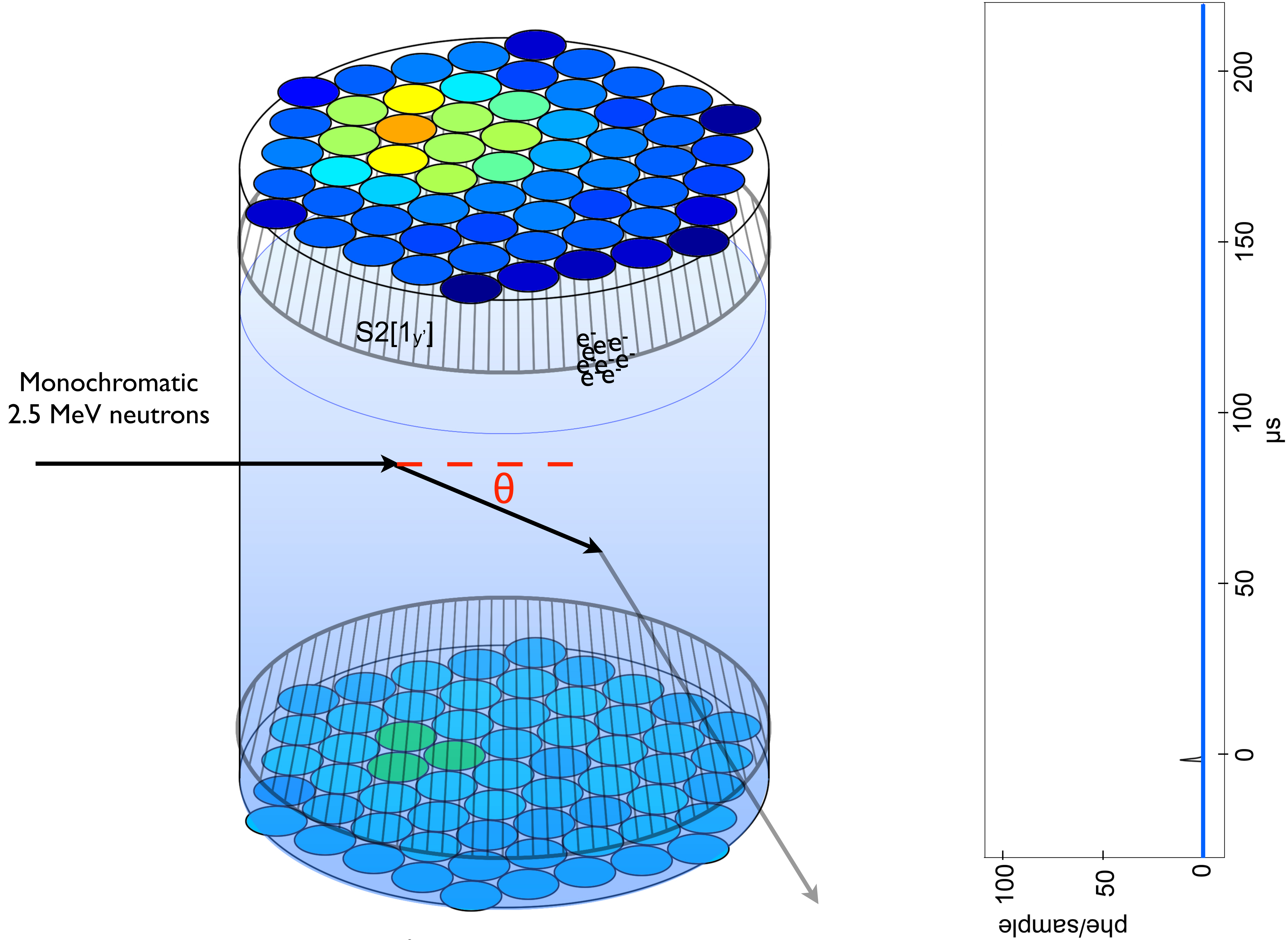
Samuel Chan, Carlos Faham for the LUX Collaboration





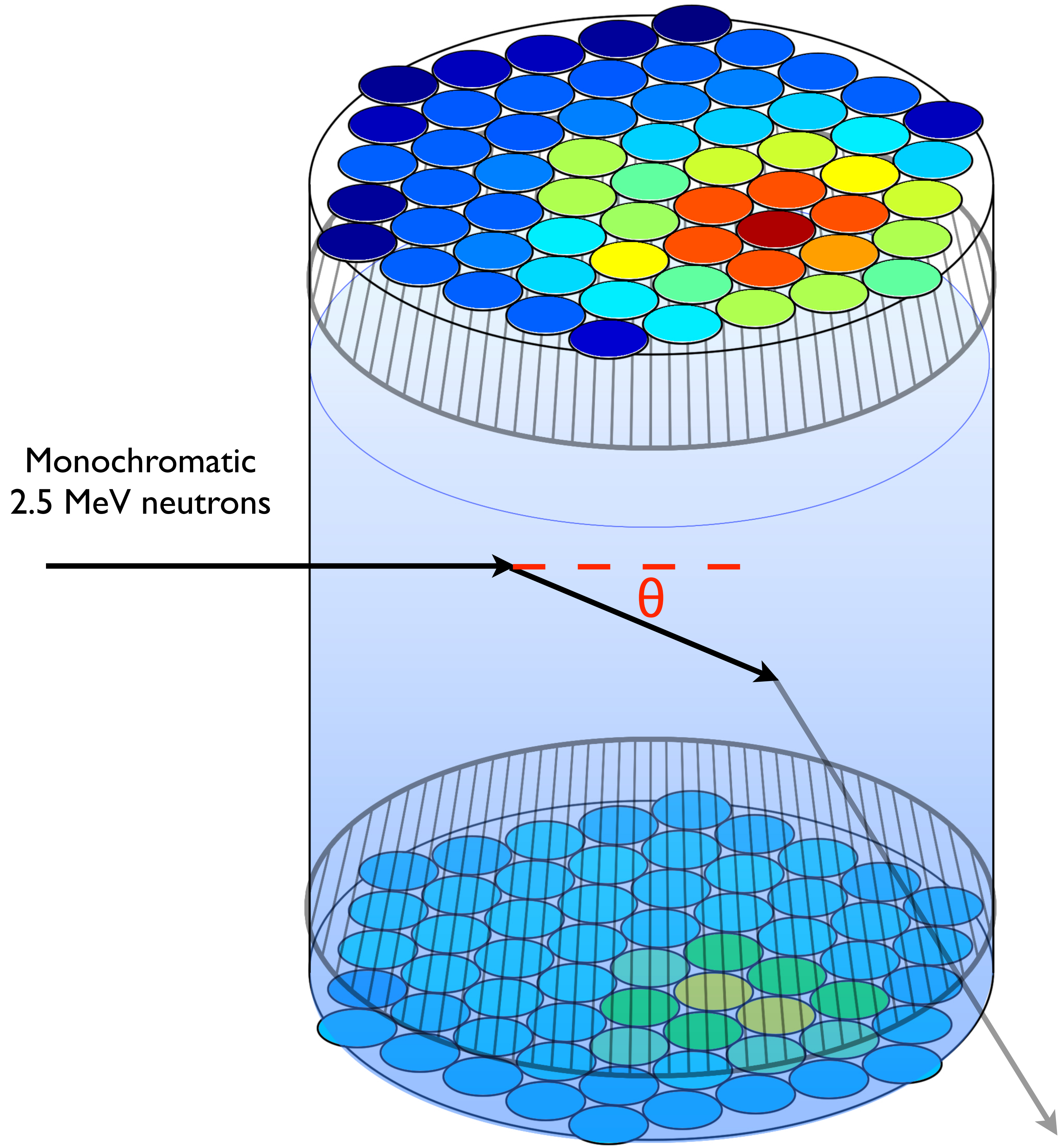
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

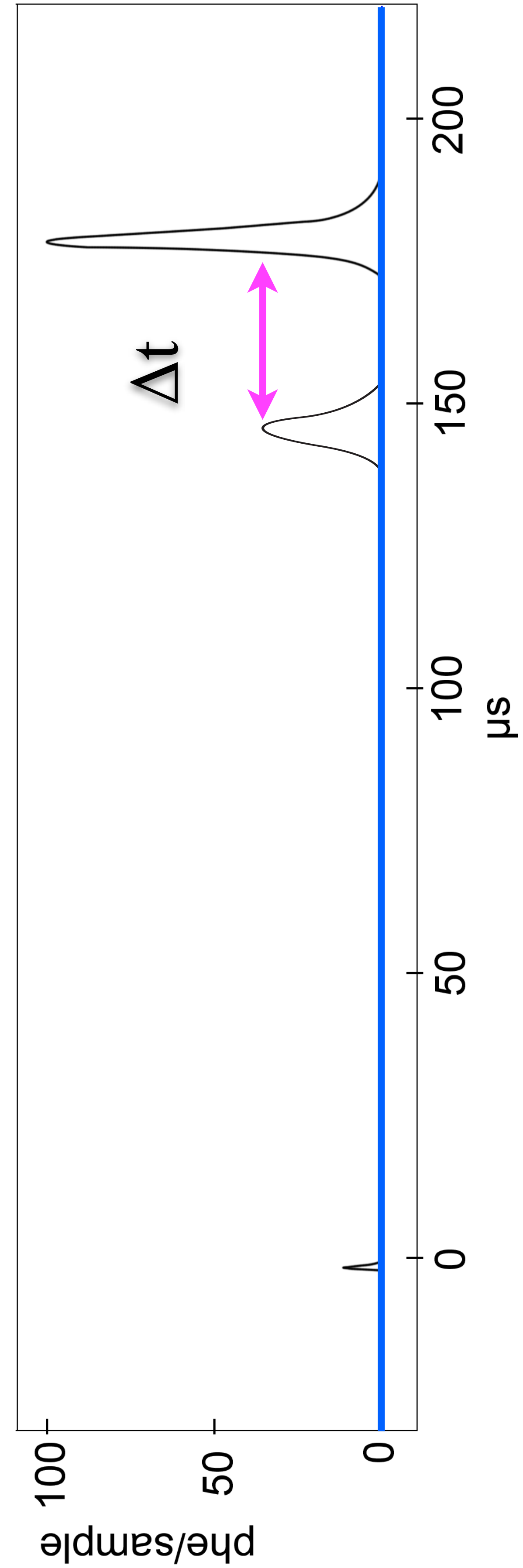
Samuel Chan, Carlos Faham for the LUX Collaboration



$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

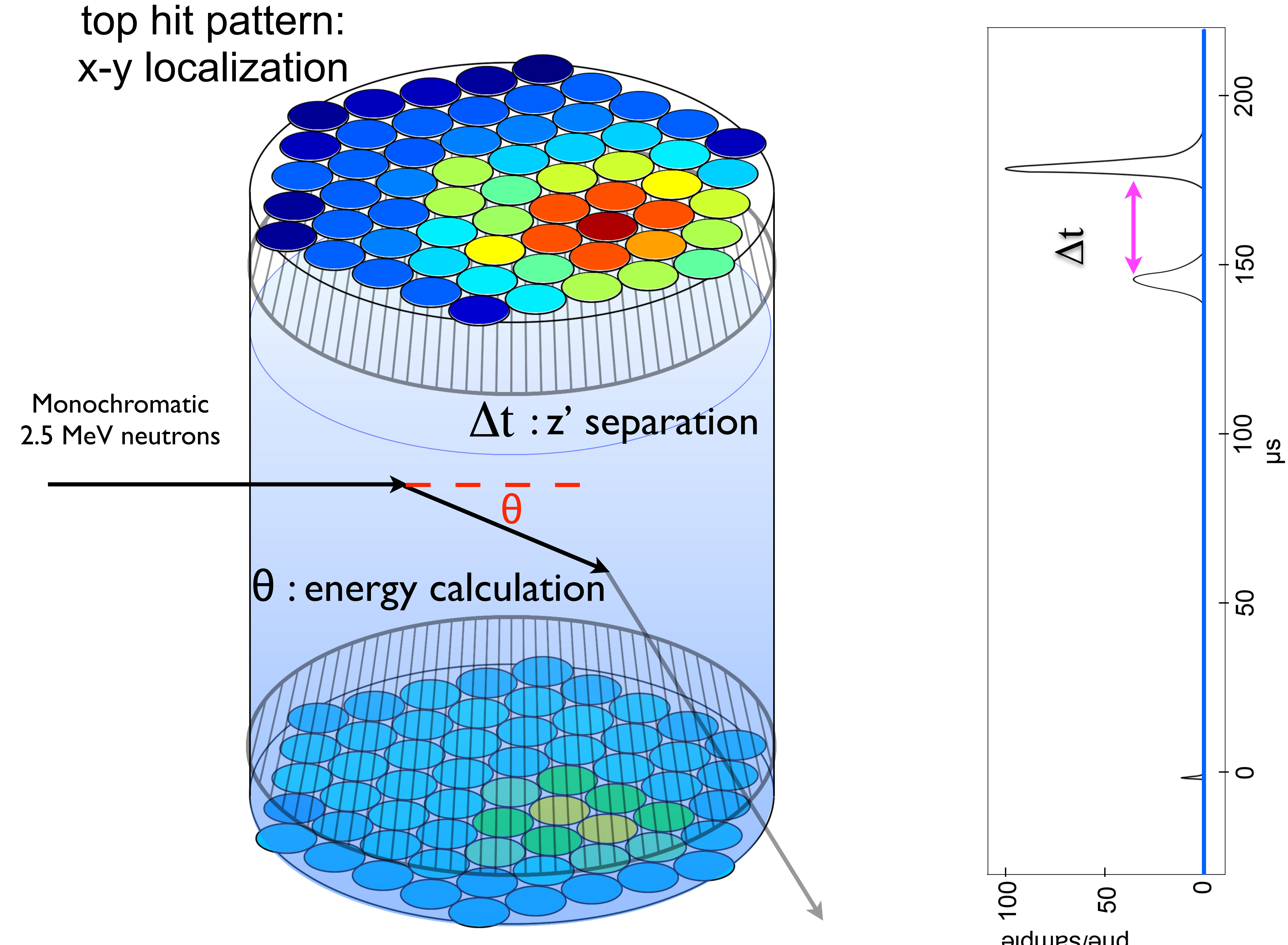
Samuel Chan, Carlos Faham for the LUX Collaboration





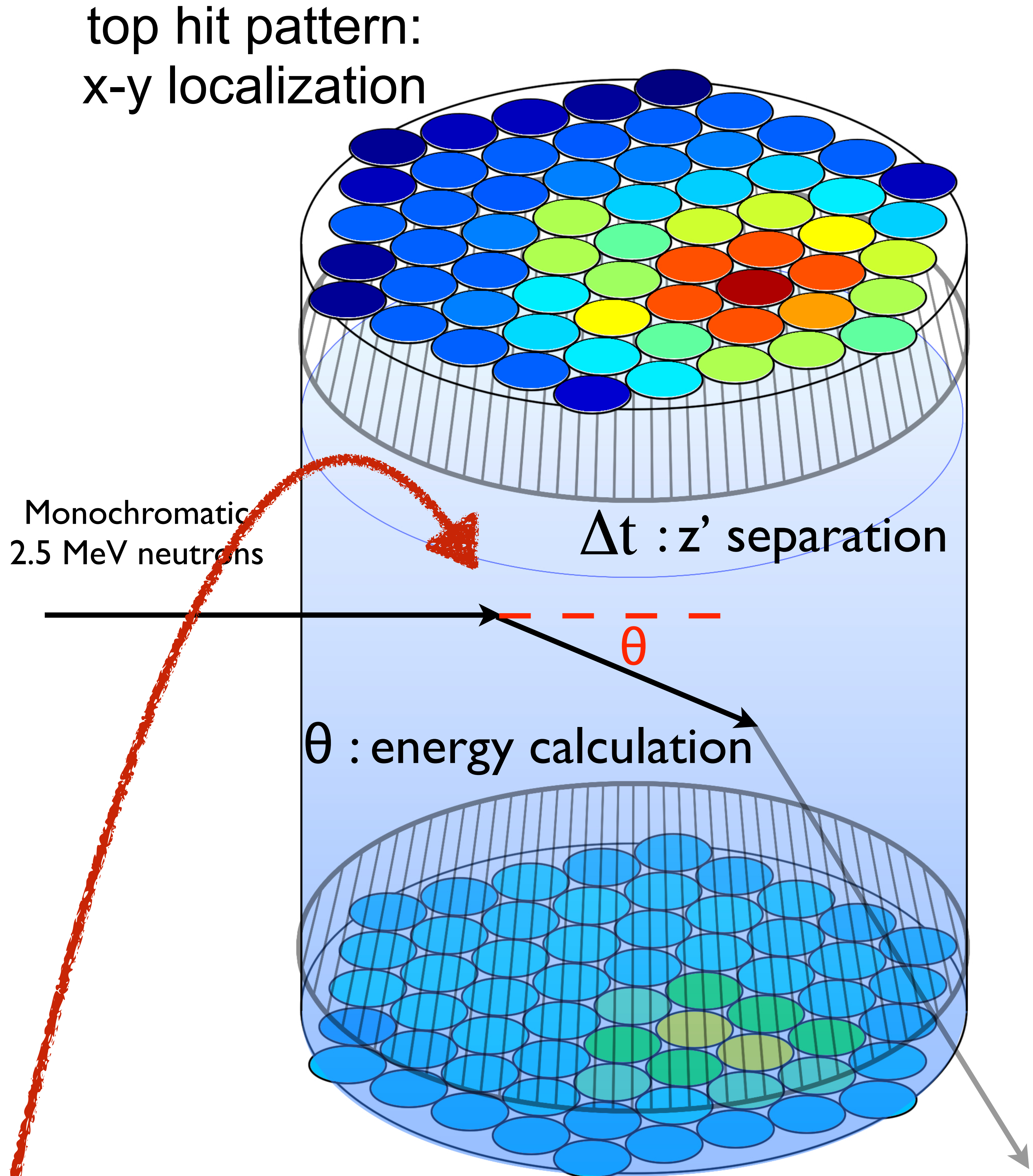
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

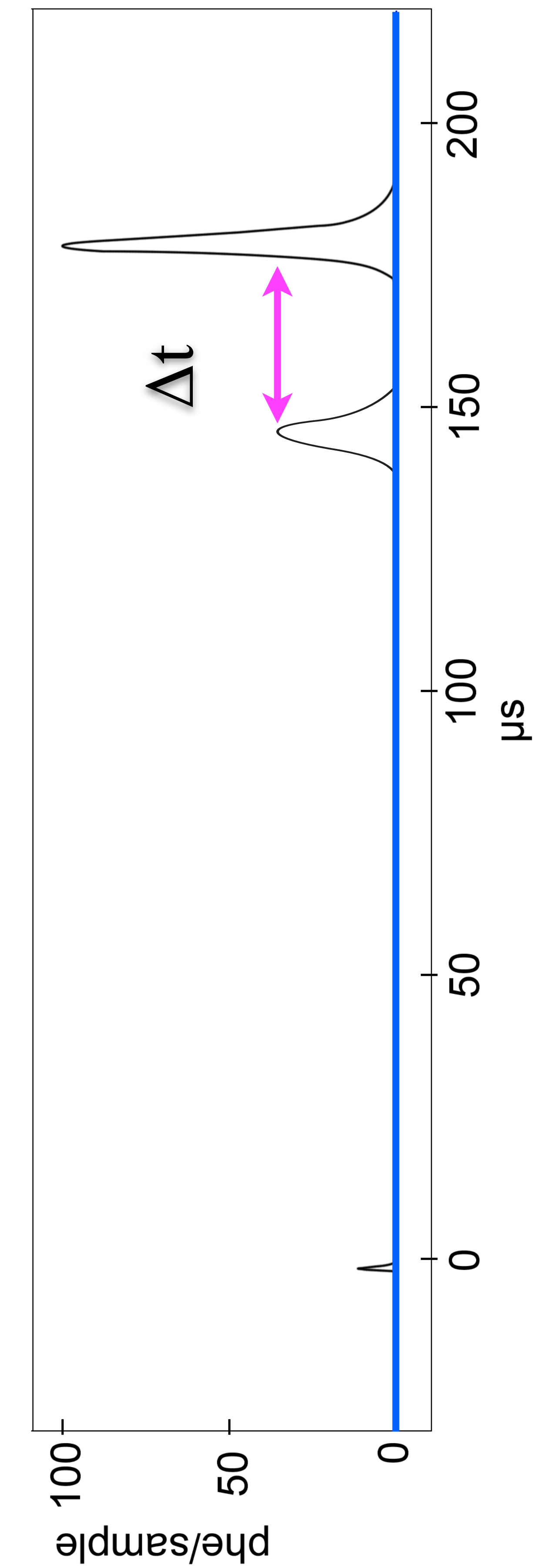
Samuel Chan, Carlos Faham for the LUX Collaboration



$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

Samuel Chan, Carlos Faham for the LUX Collaboration



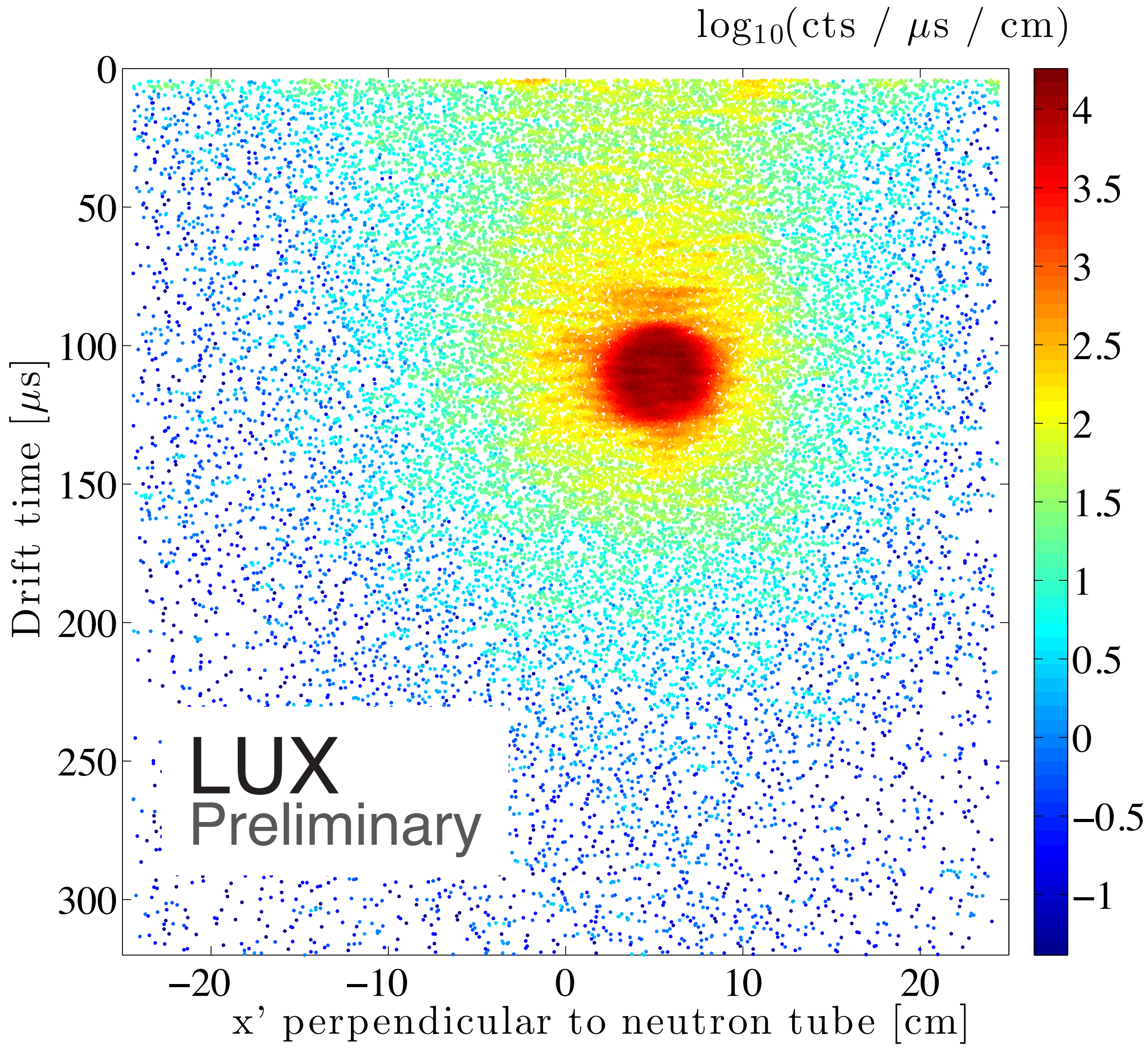


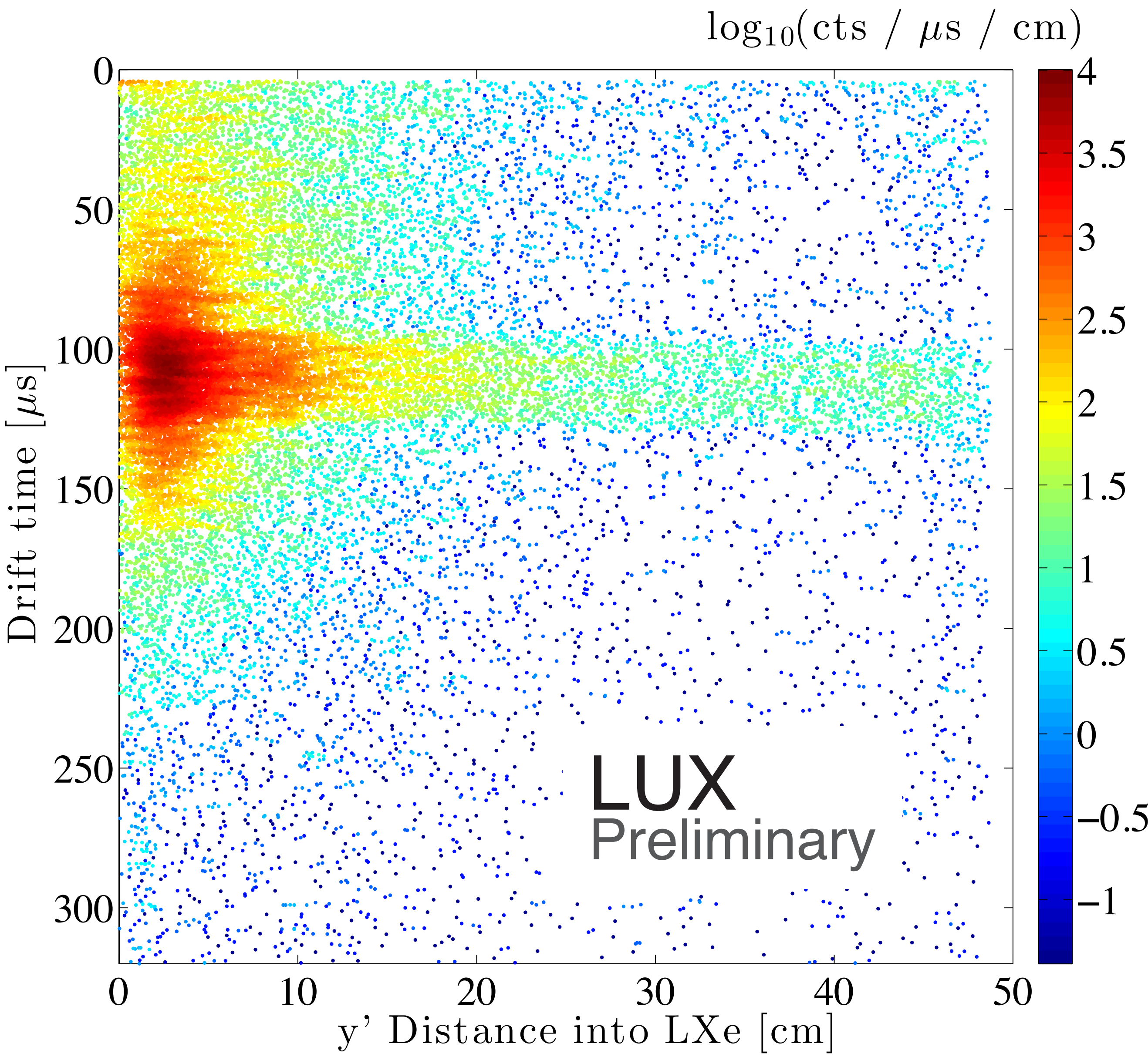
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

Samuel Chan, Carlos Faham for the LUX Collaboration

Beam Projection in Active Region

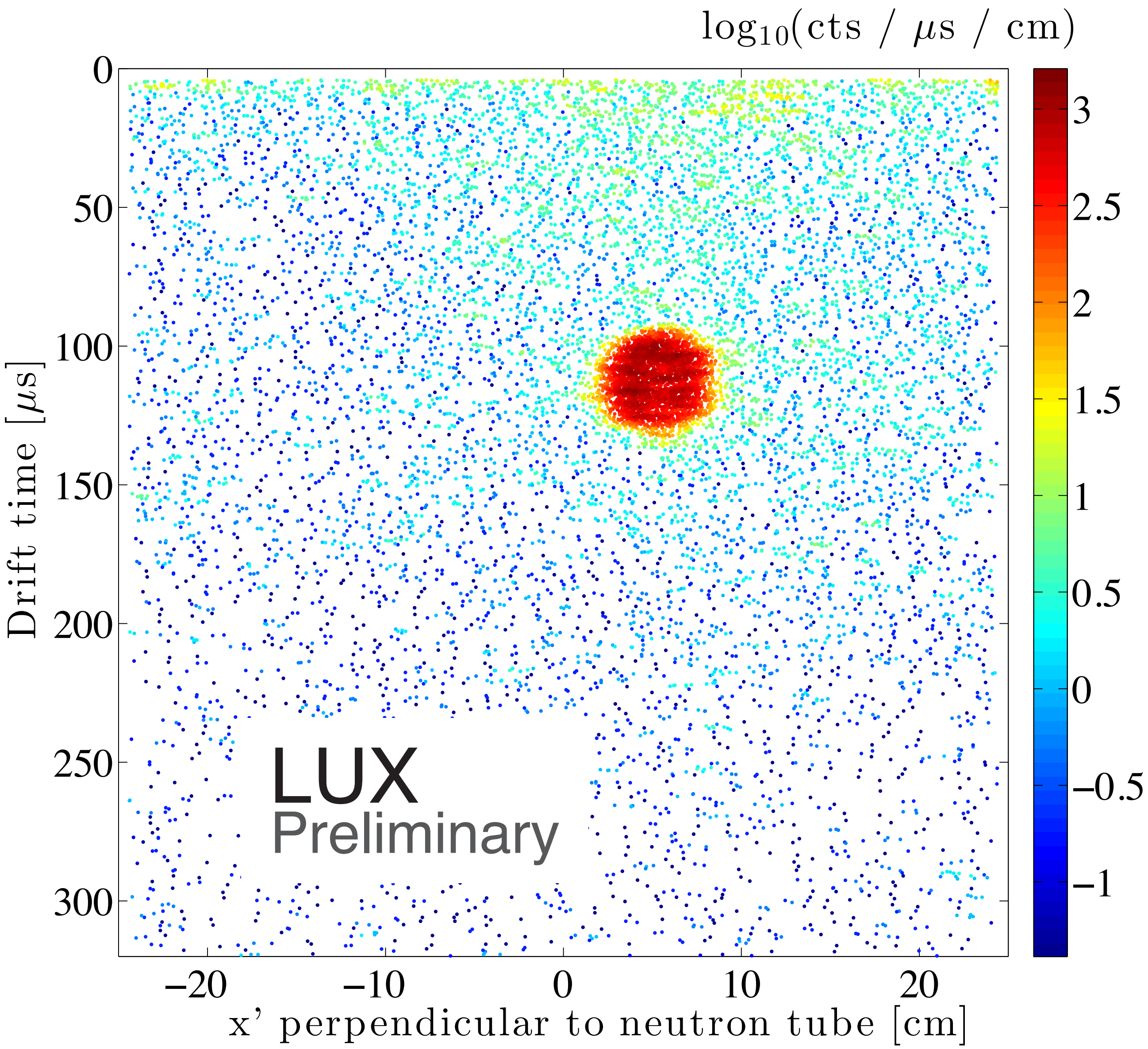
- The shine from neutron scatters in passive detector materials is visible.
- Historically, NR calibrations have significant systematics associated with neutrons scattering in passive material.
  - We can fiducialize away from such backgrounds!

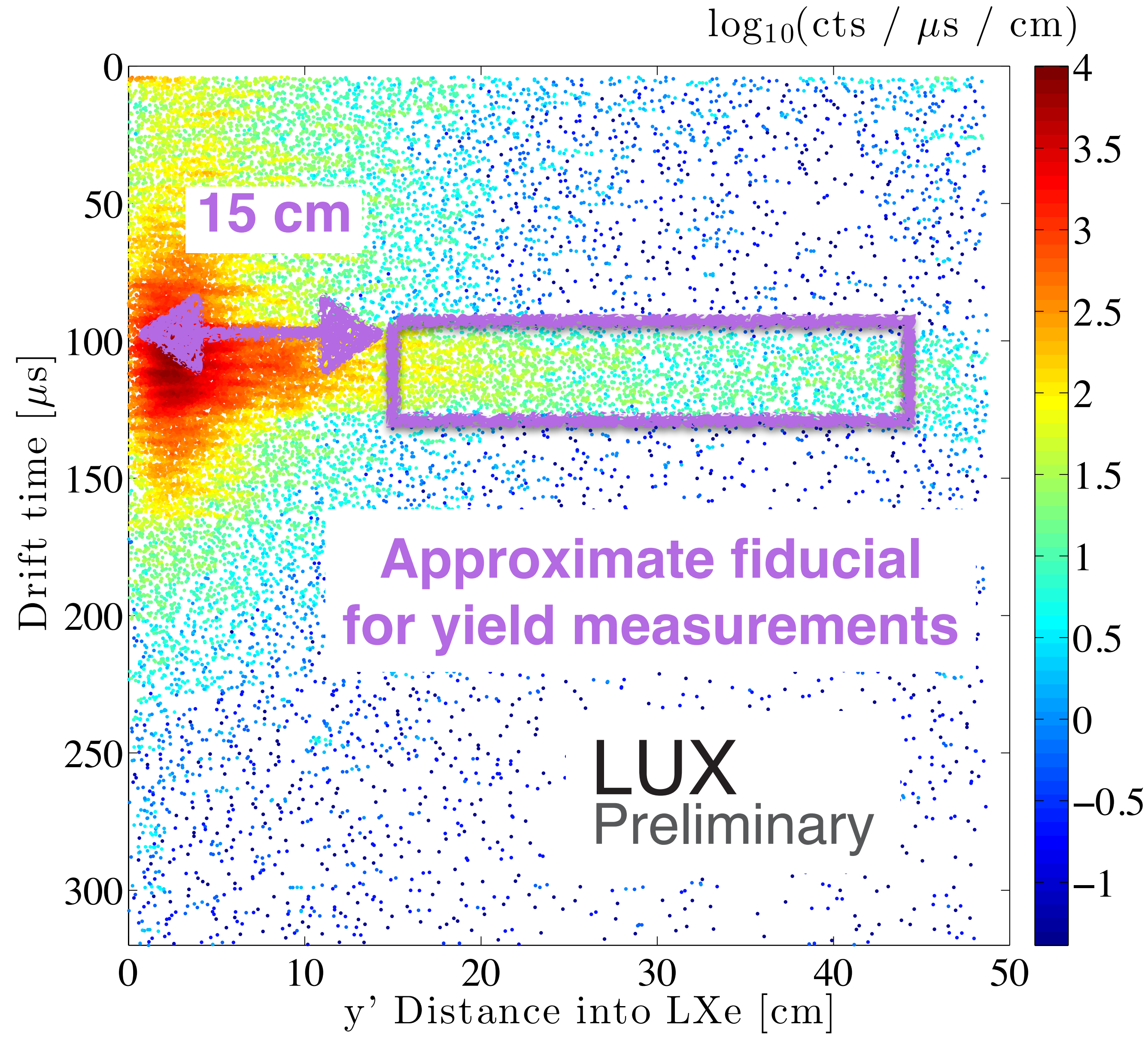




Neutron Beam Energy Purity

- After application of 15 cm depth-into-LXe beam purity cut
- This cut eliminates shine from passive materials and ensures 95% of neutrons in beam sample have energy within 4% of 2.45 MeV.
- Cut based on simulation, but we are showing REAL DATA



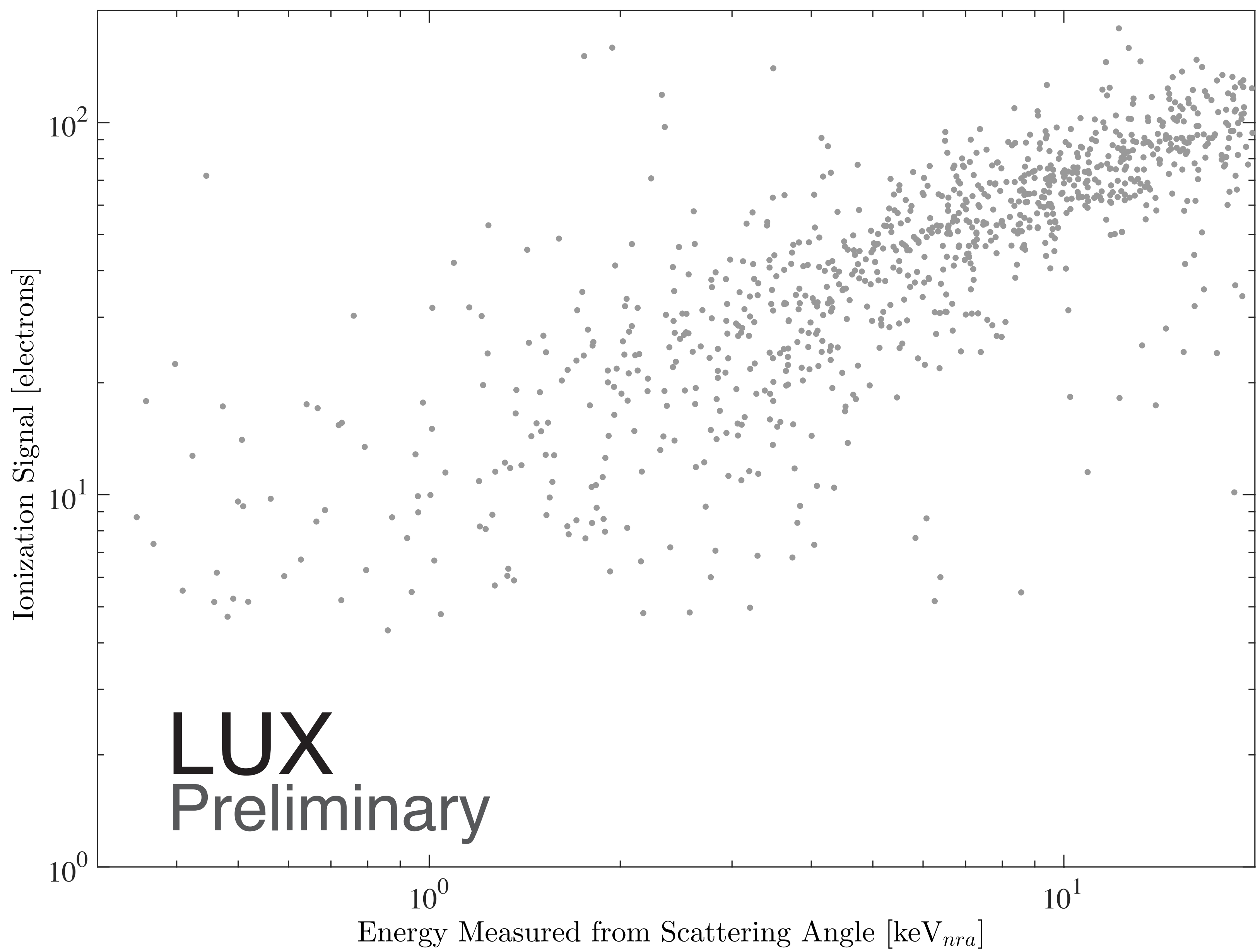


Observed Ionization Signal

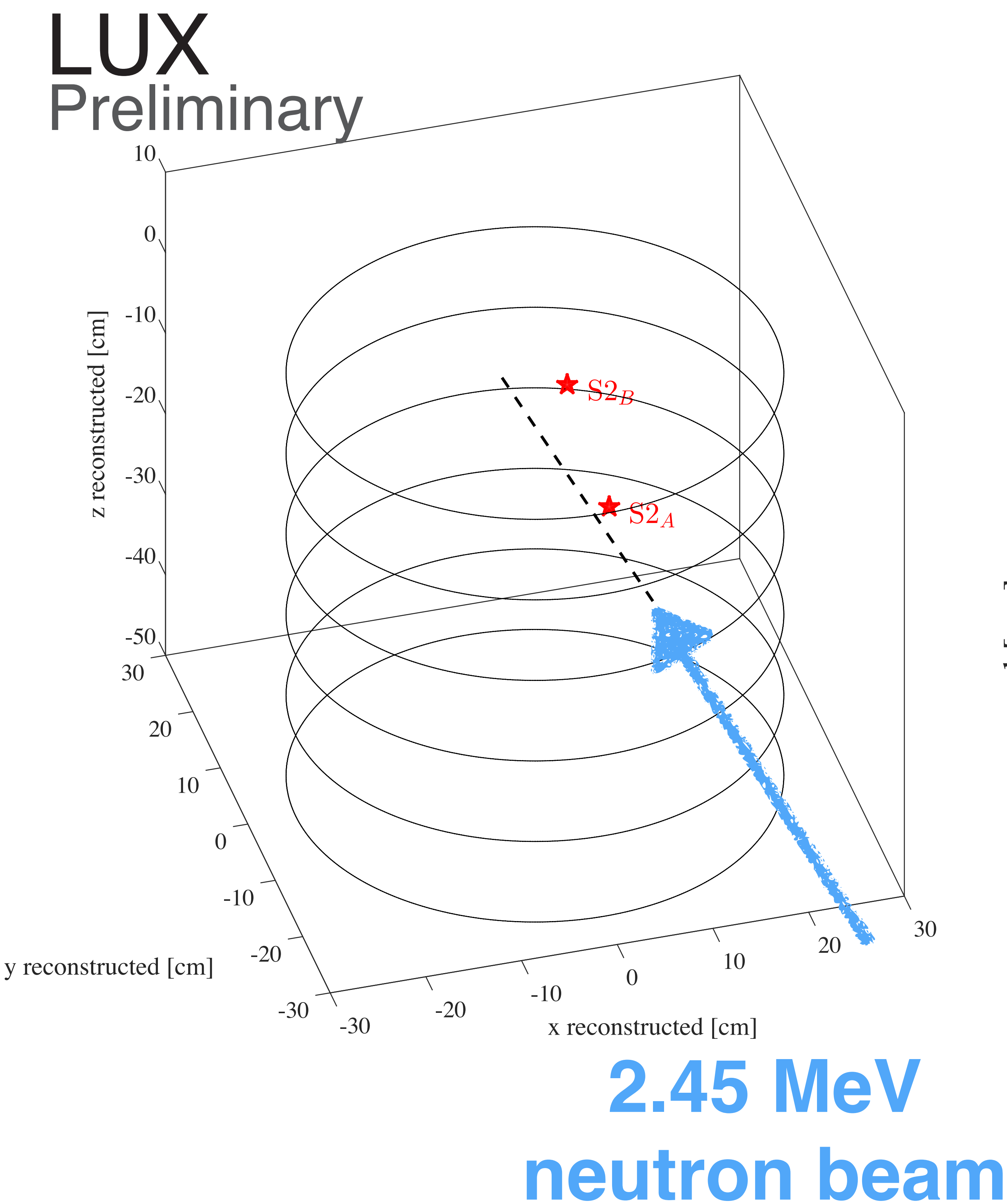
- Event Selection Cuts
  - Event Identification
    - Select double scatters
    - Determine vertex ordering via scattering geometry only
  - Neutron Beam Energy Purity
    - Enforced via position of scatters along beam line / depth into active LXe
    - After geometry cut, 95% of neutrons have energy within 4% of 2.45 MeV
  - Data Quality
    - Ensure quiet detector conditions
    - Ensure properly reconstructed events
- Cuts are flat for S2[1_y] (first scatter along beam direction) in energy region of interest

Grey Points - Individual double scatter events

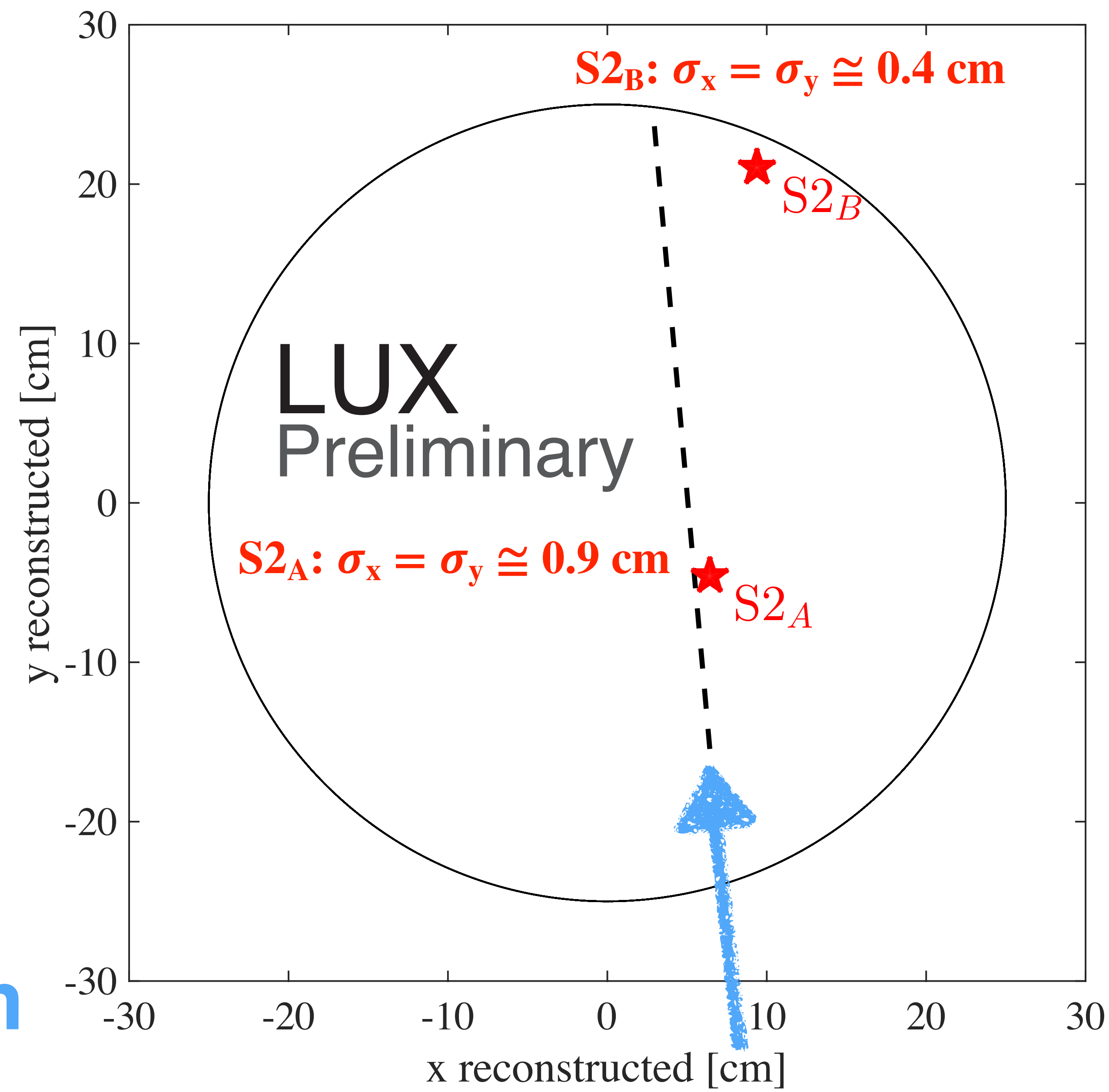
Double Scatter (S1, 2xS2s > 50 phe)

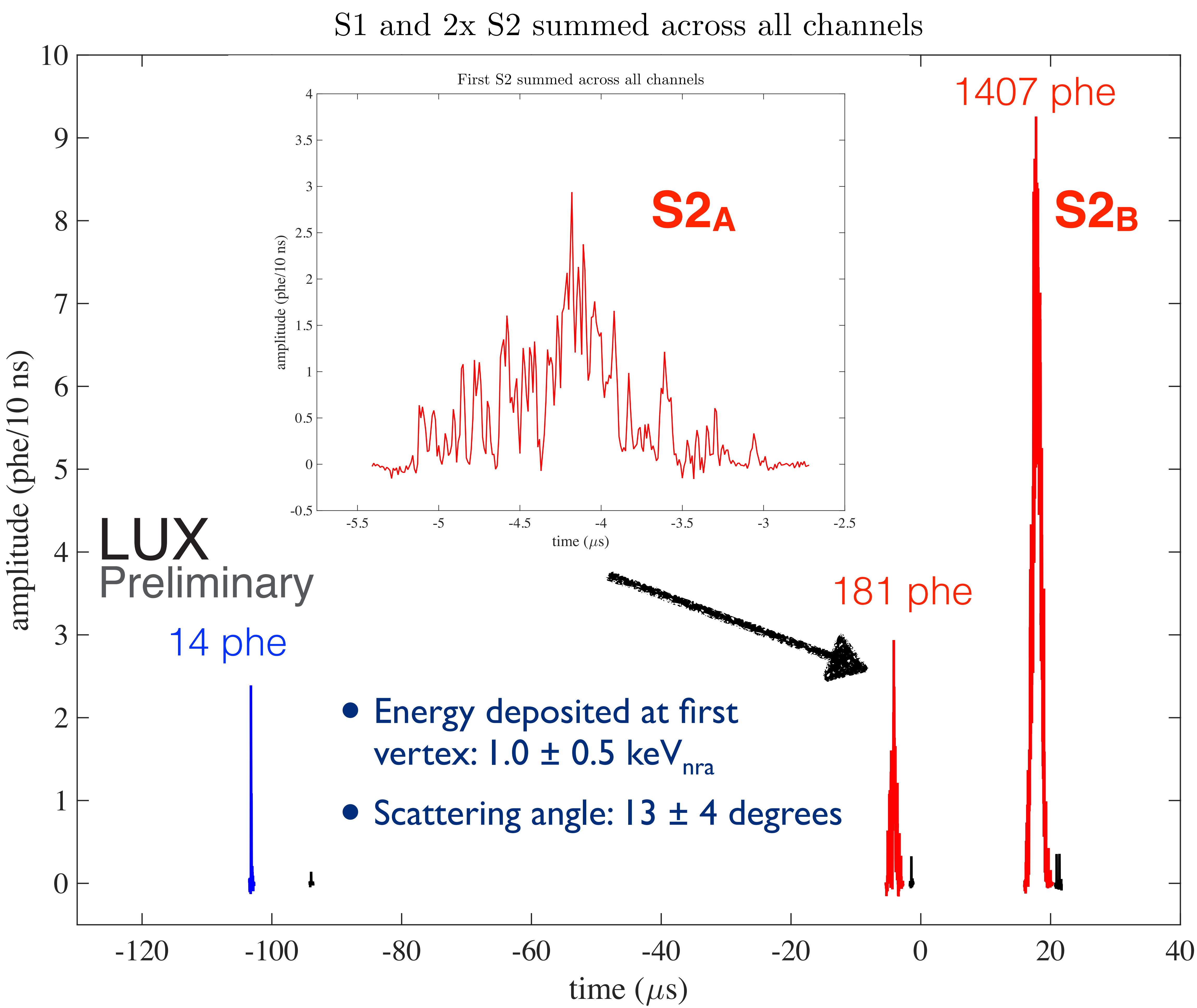


What does a 1 keV$_{nra}$ double scatter look like?



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





S1 and 2x S2 summed across all channels
First S2 summed across all channels
amplitude (phe/10 ns)
time (μs)
S2A
S2B
1407 phe
181 phe
14 phe
LUX
Preliminary
Energy deposited at first vertex: 1.0 ± 0.5 keVnra
Scattering angle: 13 ± 4 degrees
amplitude (phe/10 ns)
time (μs)

Ionization Signal Absolutely Measured below 1 keV_{nra} in LUX

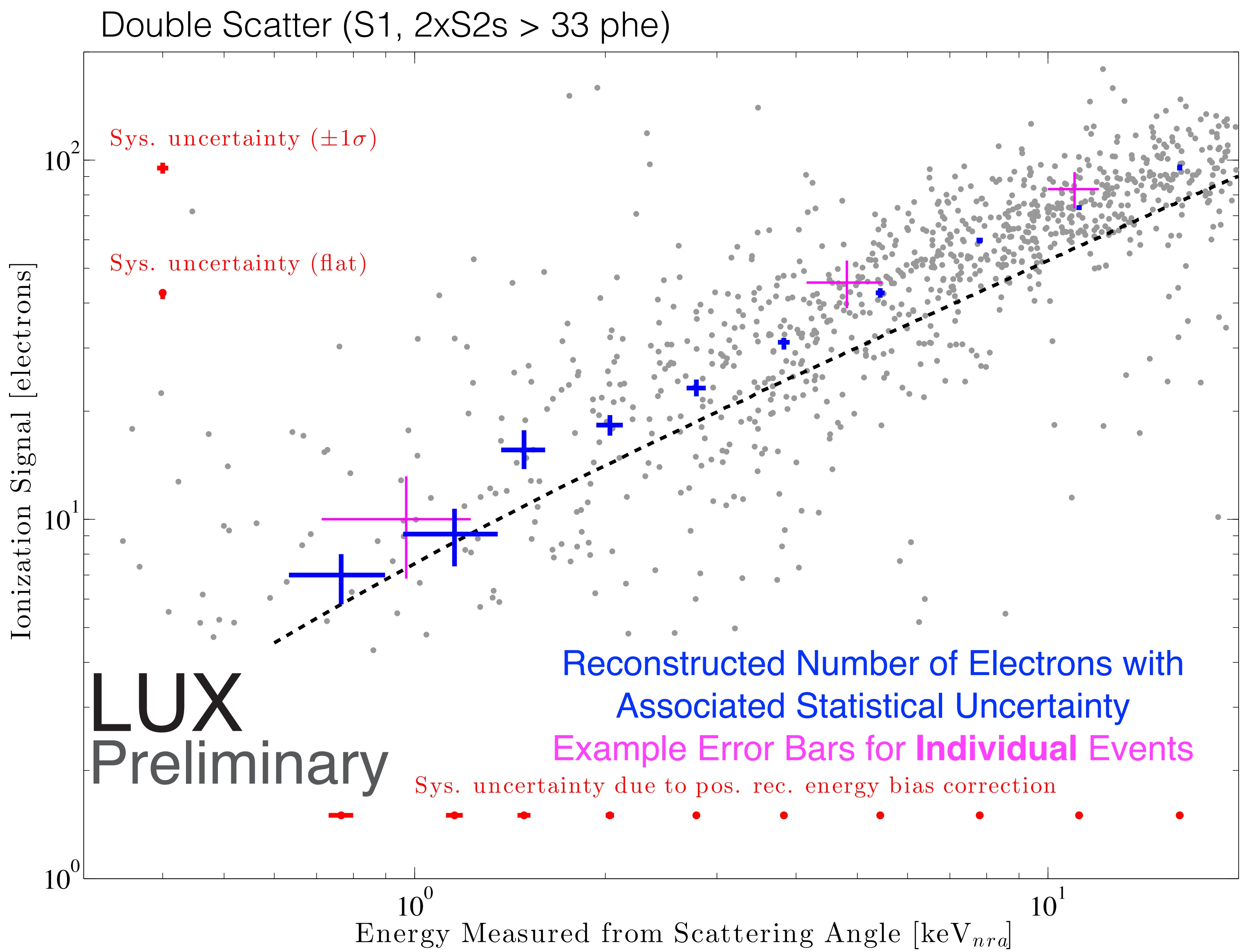
- Reconstruct number of electrons at interaction site by matching ionization signal model with observed event distribution using extended maximum-likelihood
- Red systematic error bar shows common scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency
- Lowest event energy included for analysis is 0.3 keV_{nra}

Grey Points - Individual double scatter events

Magenta Crosses - Error bars for individual event from best 10% from each bin

Blue Crosses - Reconstructed number of electrons at interaction site accounting for threshold, resolution, and Eddington bias effects in signal analysis

Black Dashed Line - Szydagis et al. (NEST v1.0) Predicted Ionization Signal at 180 V/cm



Ionization Signal Absolutely Measured below 1 keV_{nra} in LUX

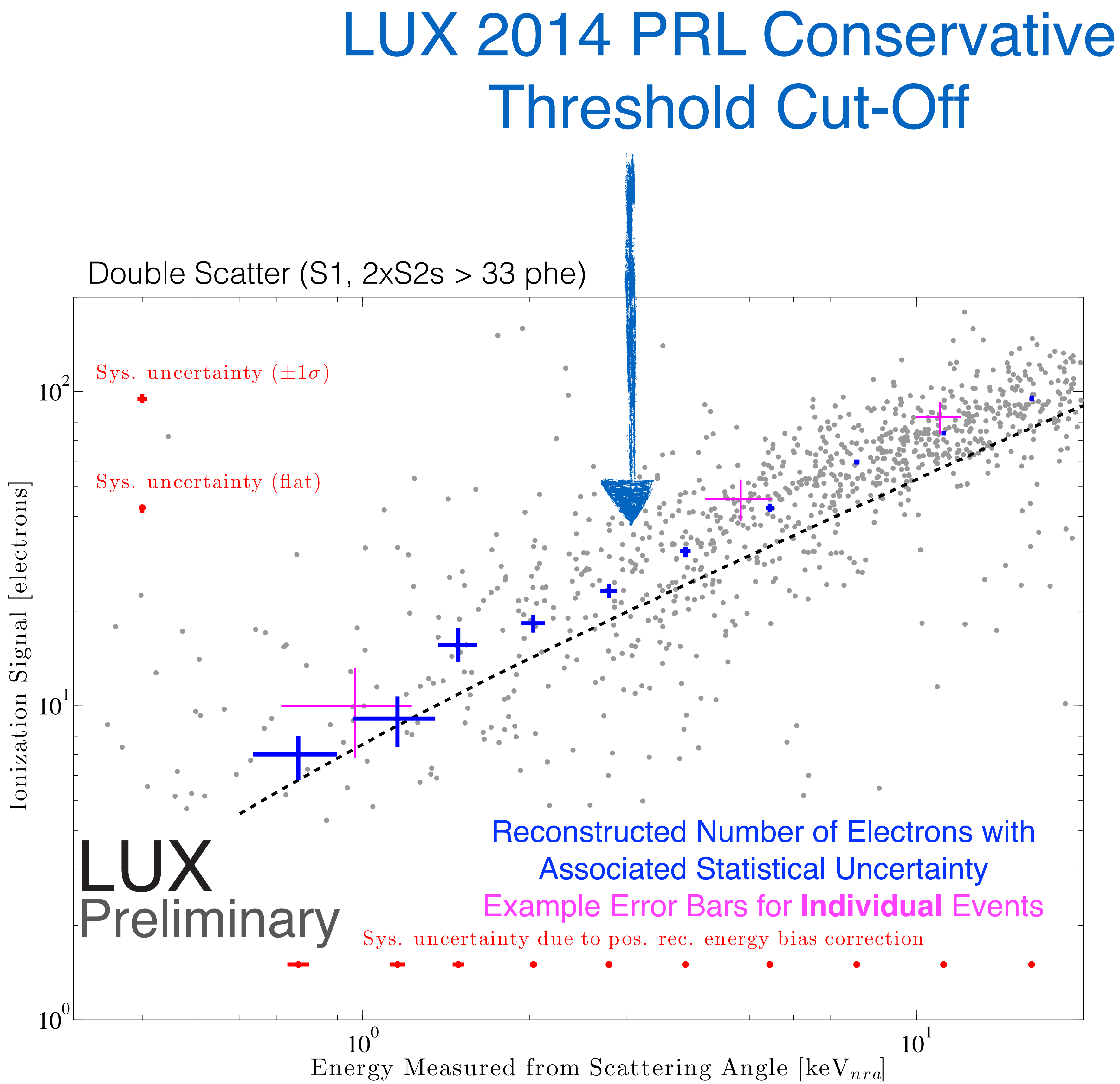
- Reconstruct number of electrons at interaction site by matching ionization signal model with observed event distribution using extended maximum-likelihood
- Red systematic error bar shows common scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency
- Lowest event energy included for analysis is 0.3 keV_{nra}

Grey Points - Individual double scatter events

Magenta Crosses - Error bars for individual event from best 10% from each bin

Blue Crosses - Reconstructed number of electrons at interaction site accounting for threshold, resolution, and Eddington bias effects in signal analysis

Black Dashed Line - Szydagis et al. (NEST v1.0) Predicted Ionization Signal at 180 V/cm



Ionization Yield Absolutely Measured below 1 keV_{nra} in LUX

- Red error bars show systematic uncertainties
  - (1σ) bar dominated by uncertainty in electron extraction efficiency
  - (flat) bar accounts for detector parameter uncertainties
  - Pos. Rec. bias correction error bars compensate for modest Eddington bias due to pos. rec. uncertainties
- Updated analyses in upcoming LUX Run03 papers have revised g1 and g2 values using data driven S1 vs. S2 anti-correlation
  - Provides strong determination of absolute normalization of yields
  - Shifts measured Qy lower by ~10%

Blue Crosses - LUX Measured Qy; 180 V/cm (absolute energy scale)

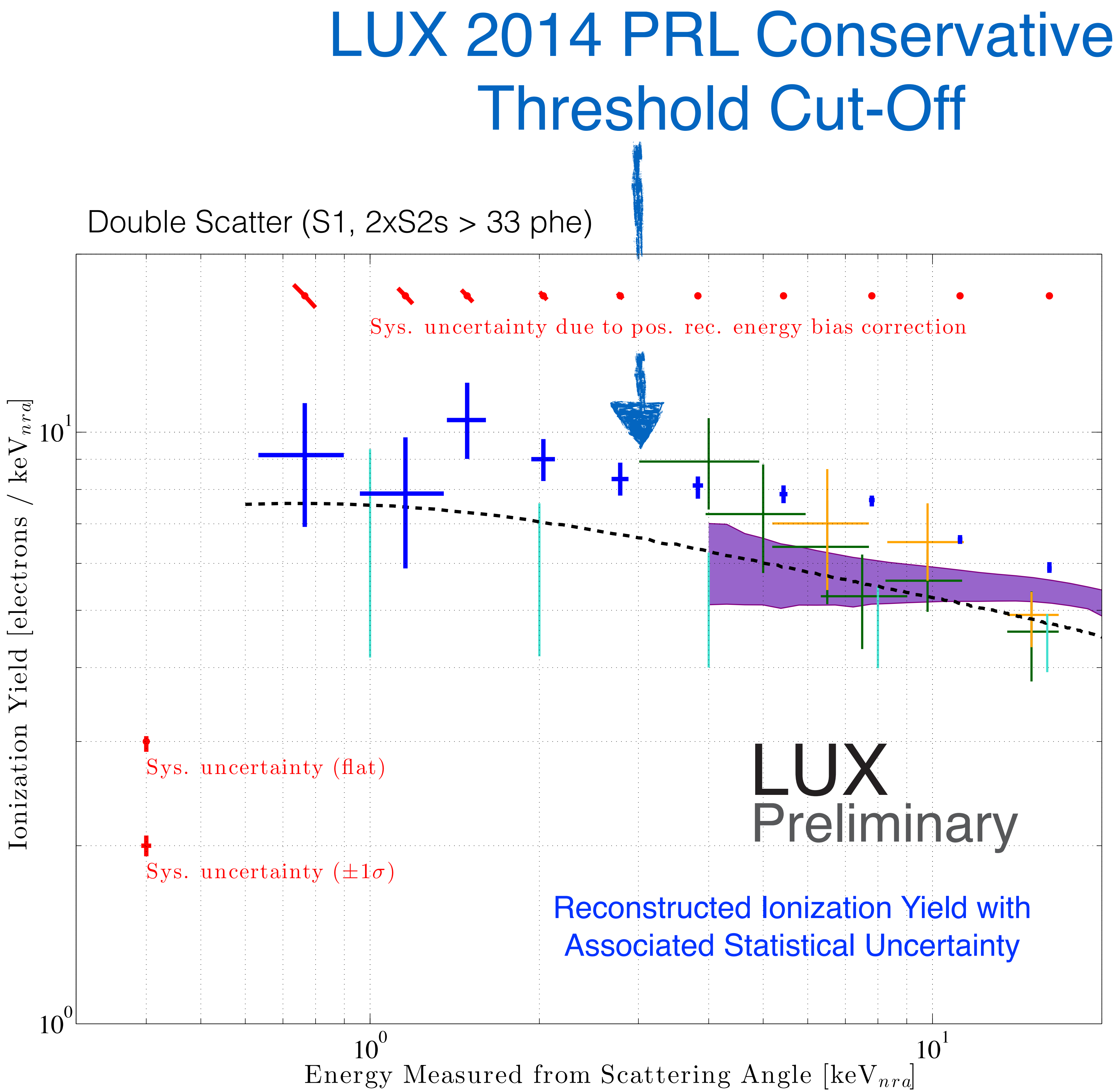
Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)

Orange Crosses - Manzur 2010; 4 kV/cm (absolute energy scale)

Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)

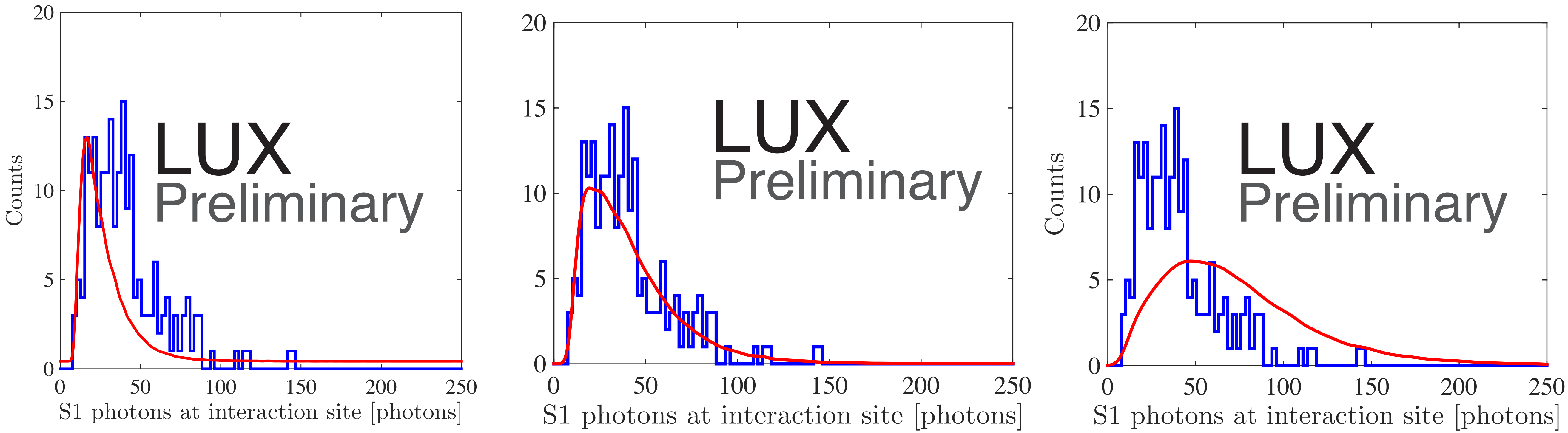
Teal Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)

Black Dashed Line - Szydagis et al. (NEST v1.0) Predicted Ionization Yield at 180 V/cm



Example: $S1_c$ Spectrum from 400-500 $S2_{sc}$

- Use absolutely calibrated S2 yield to set energy scale for extraction of L_y from D-D neutron single scatter event population
- Measure number of S1 photons produced at interaction site for fixed slice in $S2_{sc}$ (absolutely calibrated by LUX D-D Q_y)
- For each fixed $S2_{sc}$ bin, determine L_y via unbinned maximum likelihood optimization comparing simulated reconstructed S1 spectra to data
  - Both absolute number of events and spectrum shape incorporated into optimization



L_{eff} Measured in LUX Using Absolute Energy Scale

- LUX L_y values reported at 180 V/cm
- X error bars representative of error on mean of population in bin
- Energy scale defined using LUX measured Qy
- Method can be extended below existing 1.2 keV_{nrS2} point
- ^{32m}Kr light yield at 32.1 keV measured to be 45.7 ± 3.13 photons/keV using same D-D beam fiducial

Blue Crosses - LUX Measured L_y; reported at 180 V/cm (absolute energy scale)

Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)

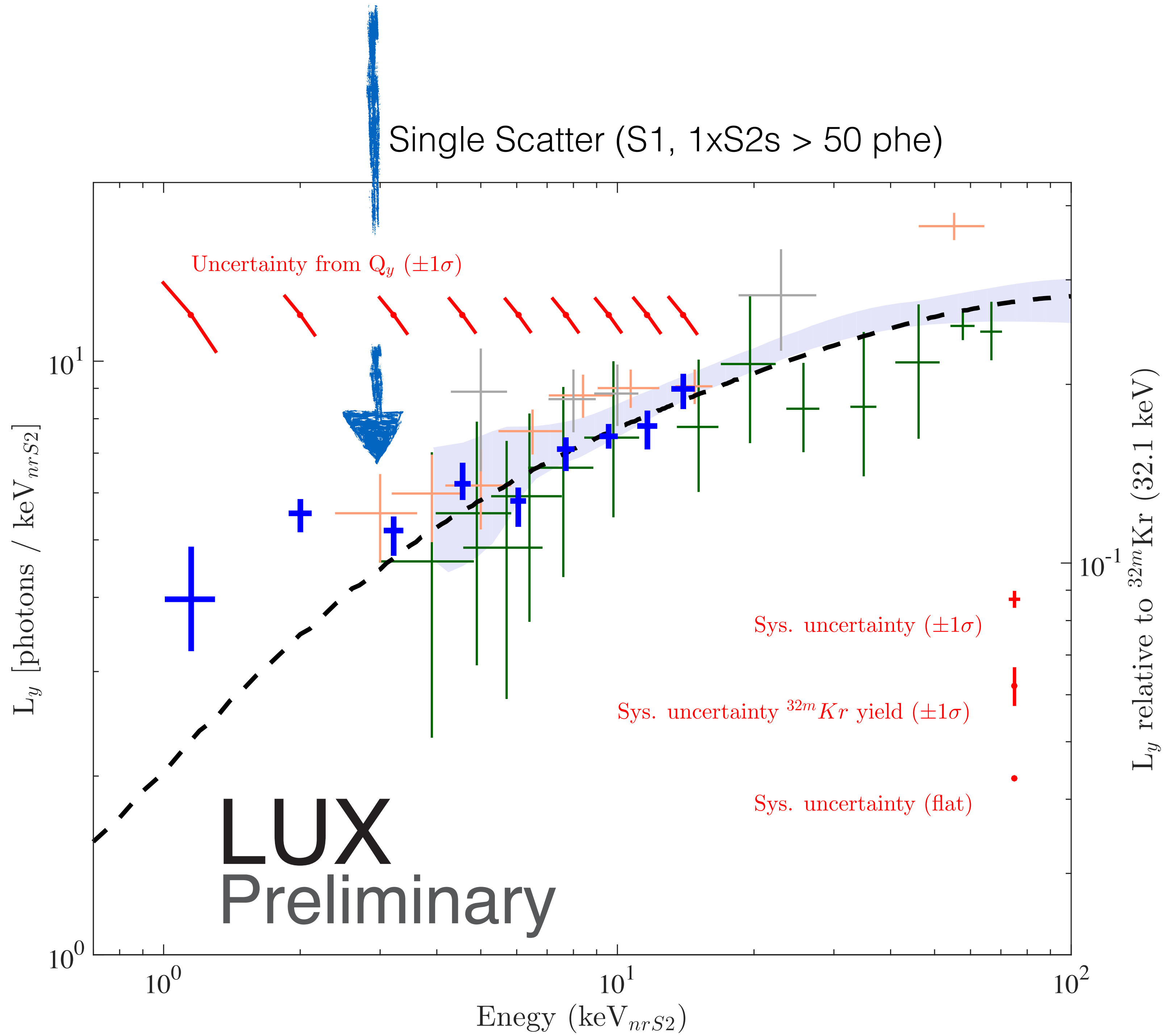
Purple Band - Horn Combined Zeplin III FSR/SSR; 3.6 kV/cm, rescaled to 0 V/cm (energy scale from best fit MC)

Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)

Grey Crosses - Aprile 2009 (absolute energy scale)

Black Dashed Line - Szydagis et al. (NEST v1.0) Predicted Scintillation Yield at 181 V/cm

LUX 2014 PRL Conservative Threshold Cut-Off



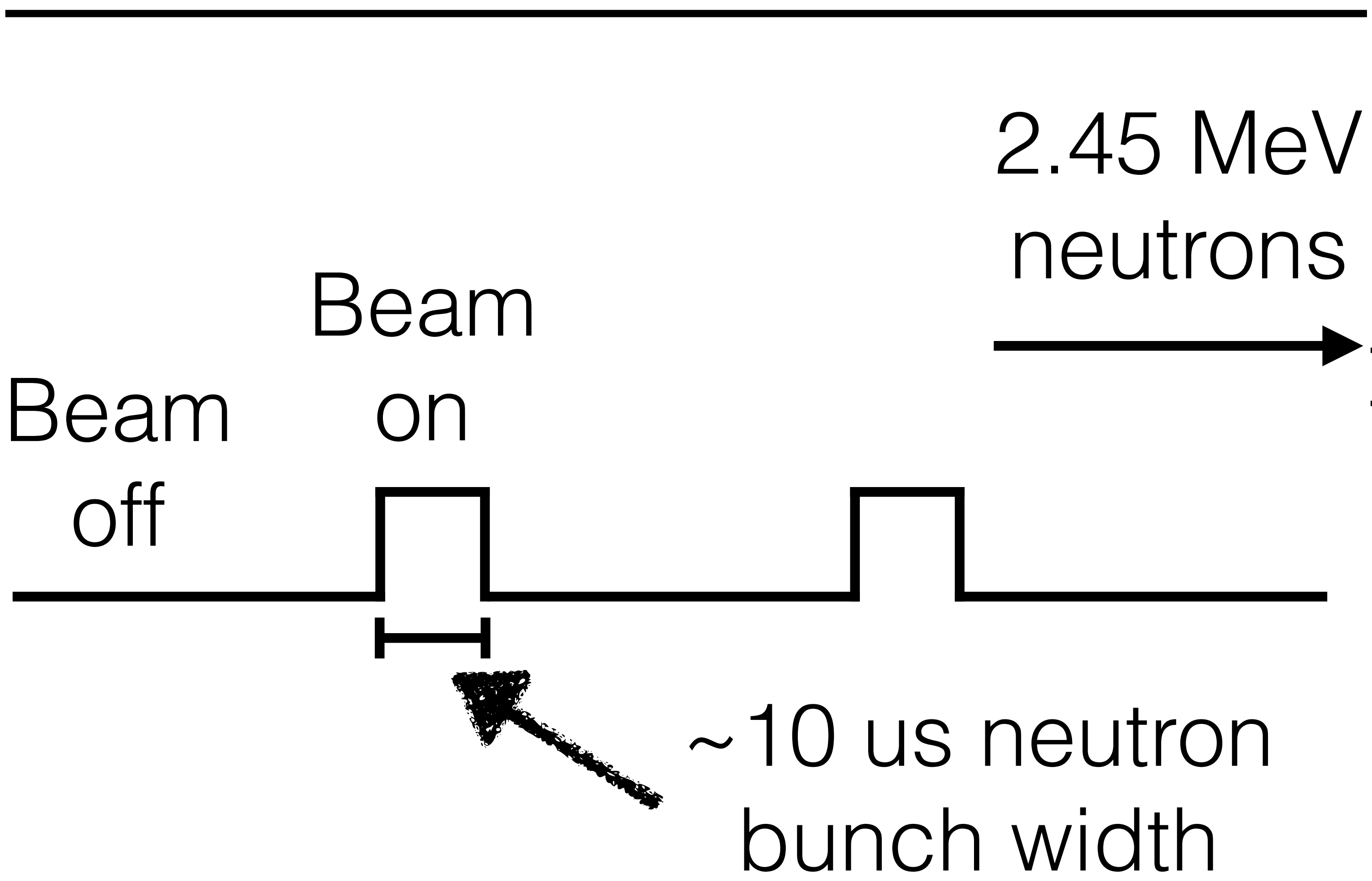
Summary of LUX D-D results

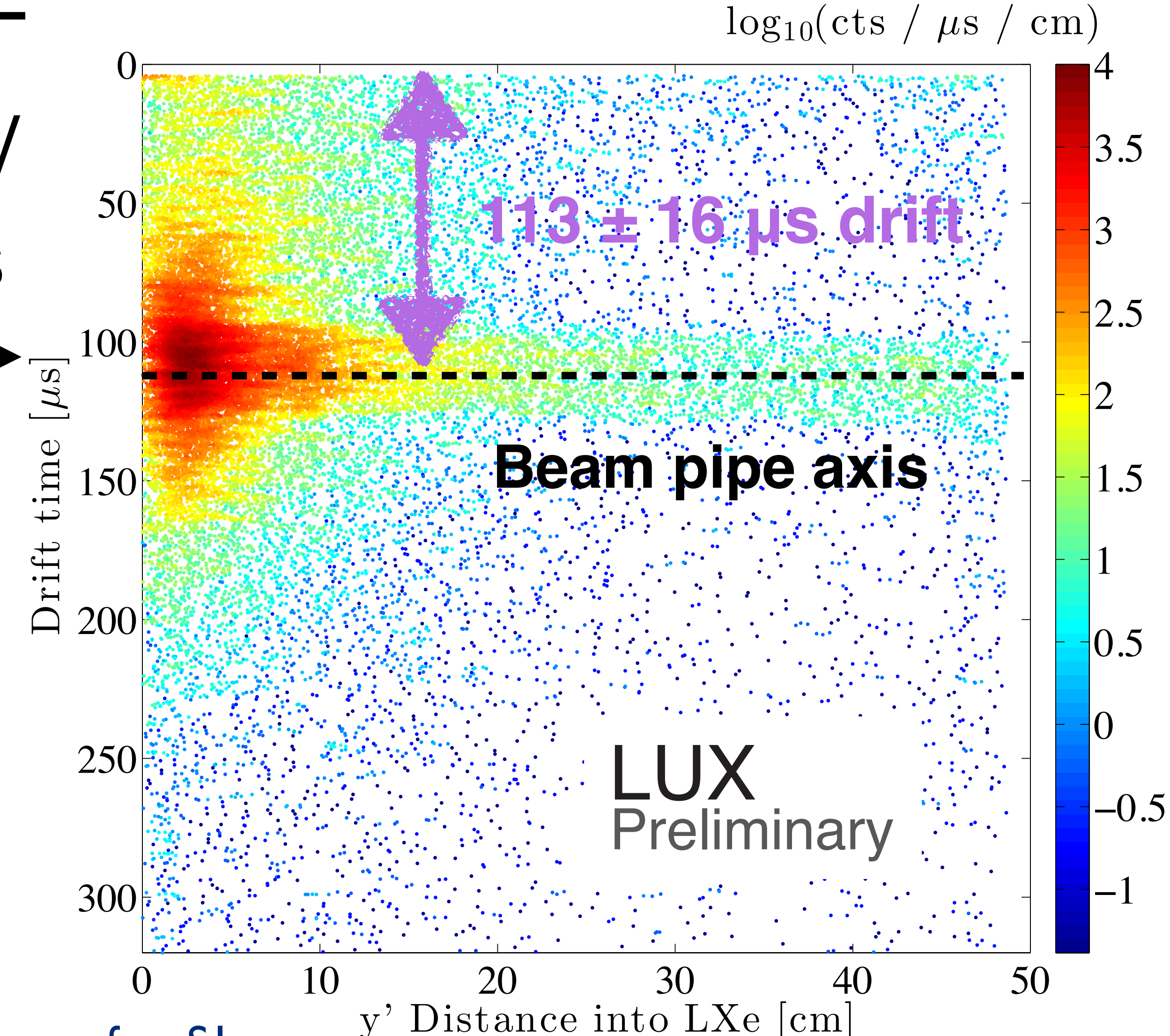
- LUX absolute nuclear recoil calibration performed using mono-energetic D-D neutrons in-situ
  - Clear confirmation of the response used in the first LUX WIMP search analysis with an order of magnitude improvement in calibration uncertainties
  - The 2014 PRL WIMP analysis only assumed a detector response at and above 3 keVnr
  - D-D neutron calibration technique allows us to calibrate detector response in region well below this, and provides a significant improvement in LUX sensitivity to low mass WIMPs using existing 2014 PRL WIMP search dataset
- Coming soon
  - LUX paper on D-D results
  - NEST fit to D-D light and charge yields
  - Updated WIMP search limit from reanalysis of 2014 PRL dataset
- But that isn't all…

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

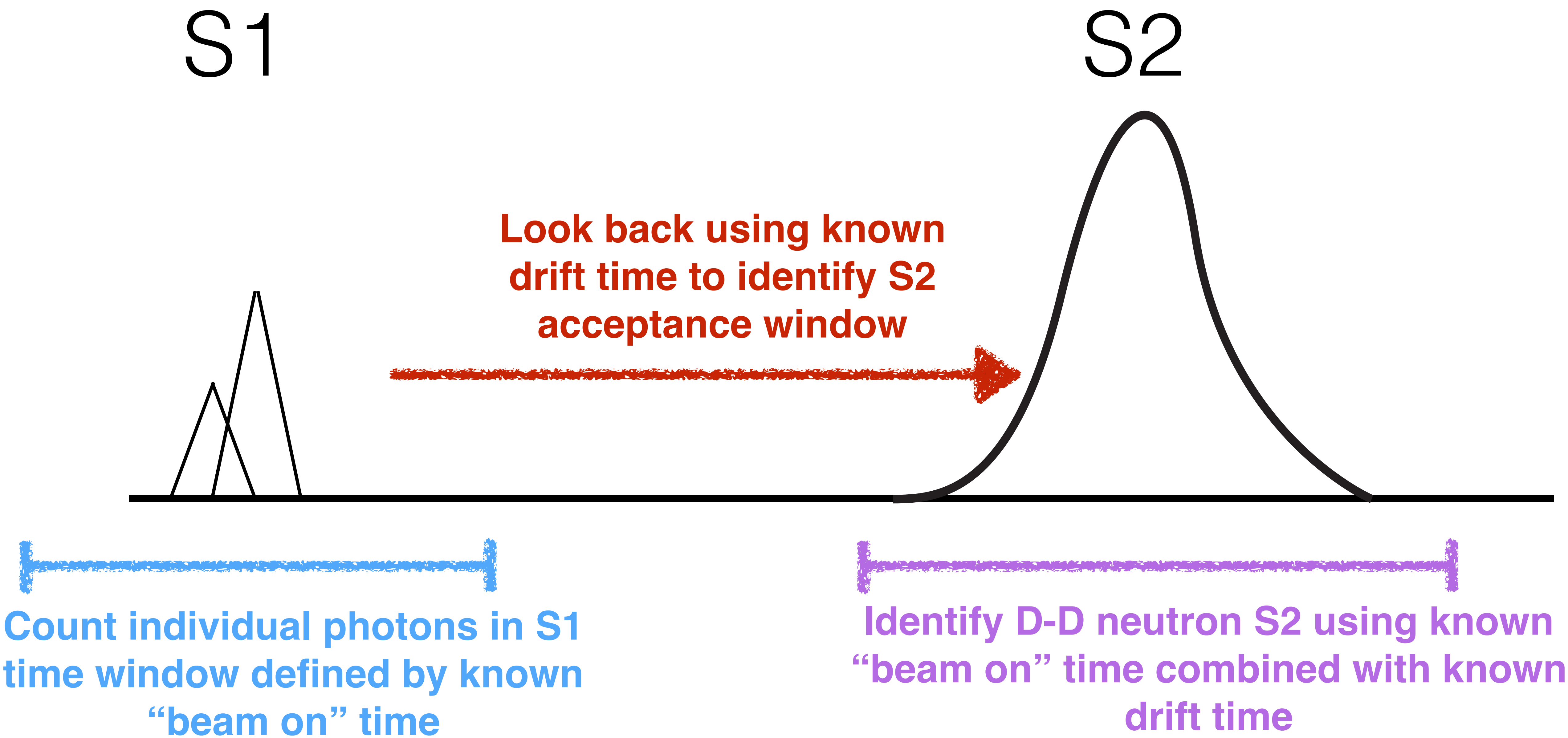
Reduction of D-D neutron bunch width time structure



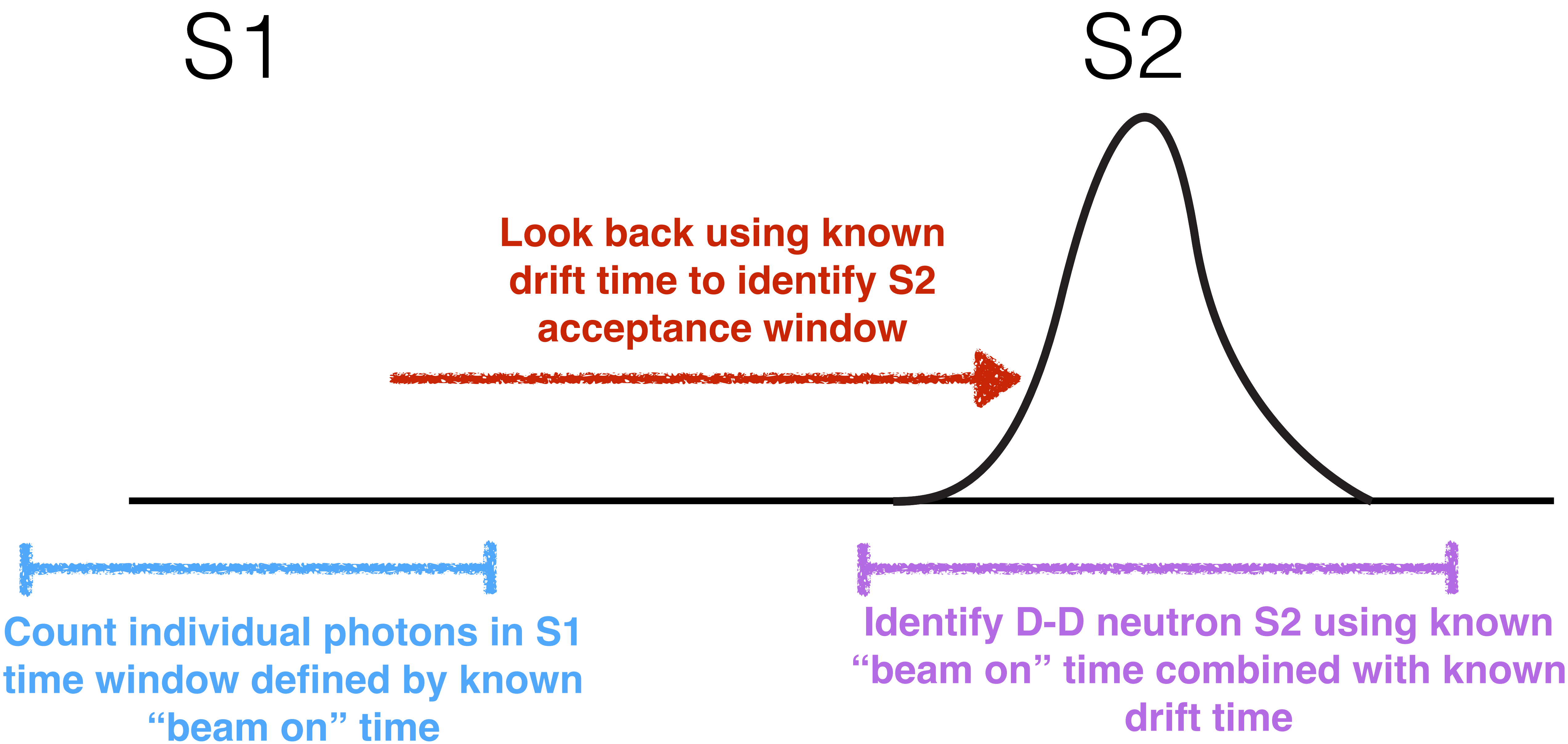


- DD beam-on time functions as a proxy for the t_0 even in the absence of an S1
  - Removes dependence upon S1 production/detection for S2 only double scatter Q_y measurement
- For reference, without an S1 we can fiducialize in Z (given 1.5 mm/us) with a precision:
  - 100 us (current generator spec) neutron pulse => 15 cm Z fiducialization precision
  - 10 us neutron pulse =>1.5 cm Z fiducialization precision
    - Z fiduciallization precision equal to that from x, y reconstruction (and < diameter of neutron tube)
  - 1 us neutron pulse => 0.15 cm Z fiducialization precision
    - Z fiduciallization precision equal to standard (1 S1, 1 S2) technique (and << diameter of neutron tube)

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



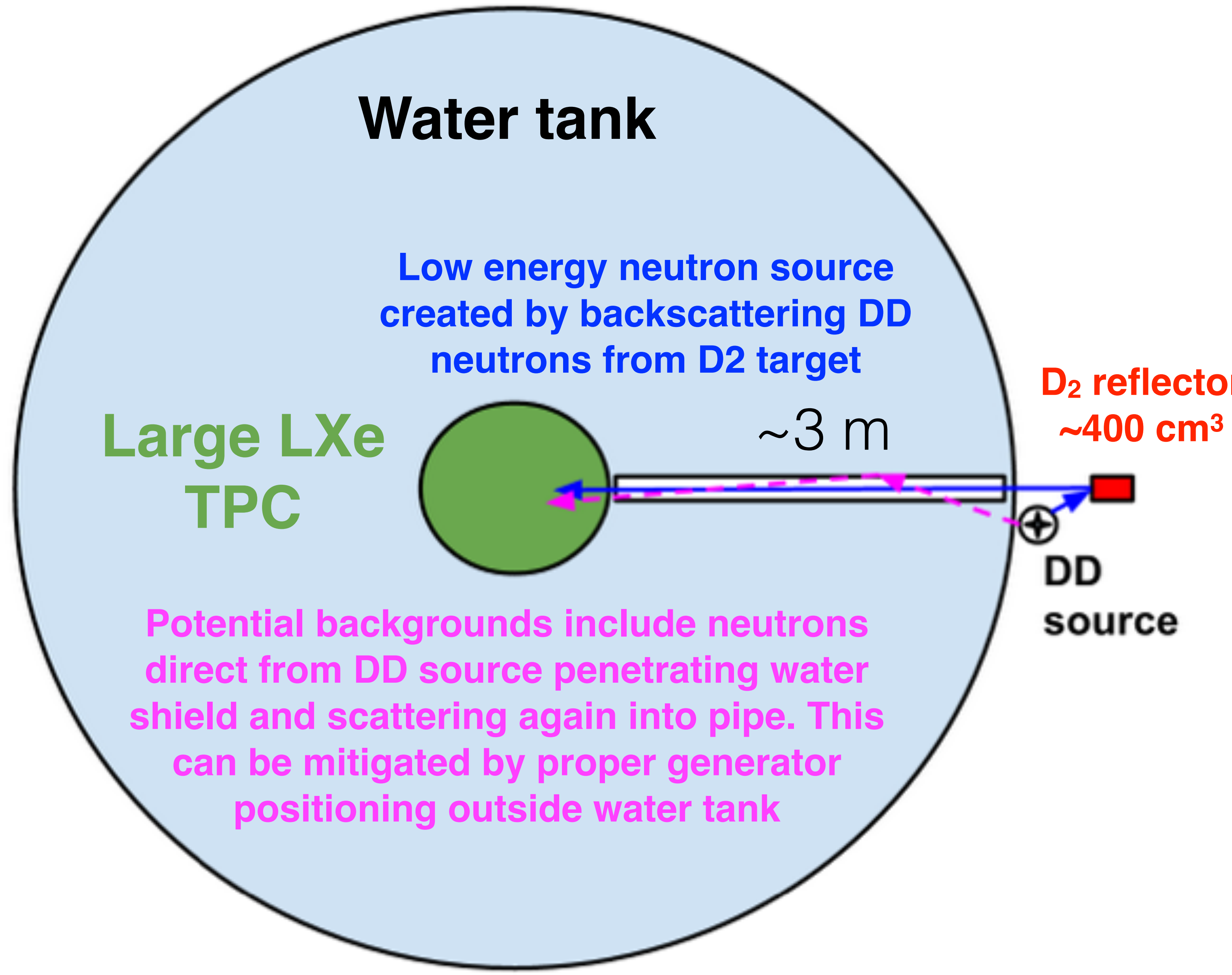
- Can identify small S2 events from D-D scatters and look at the statistics of the associated S1 signal. For given S2 size, can measure ***0***, 1, 2, … photon events
- In addition to advanced no-S1 studies, narrow trigger pulse allows for powerful reduction and understanding of calibration backgrounds



- 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

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

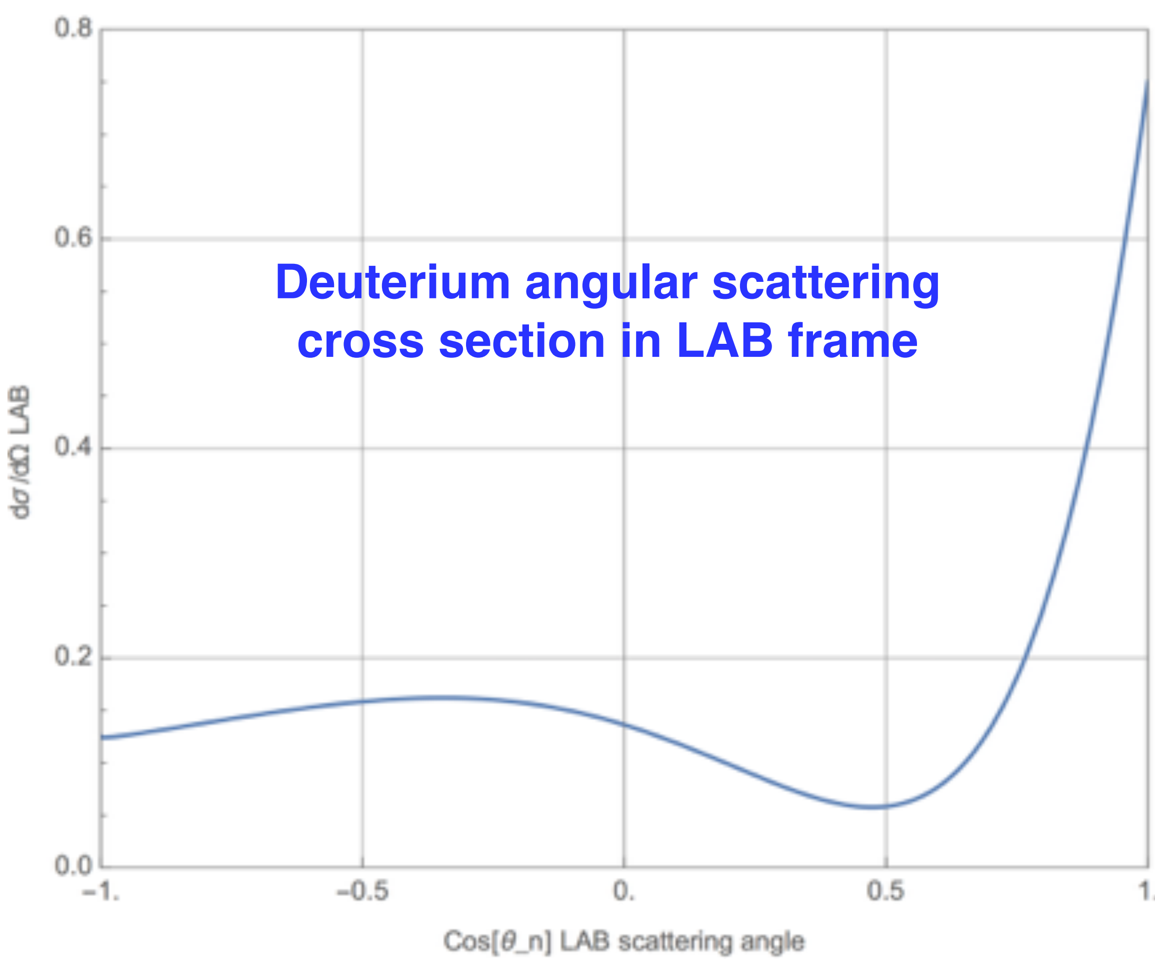
- D-D generator source out of line with the neutron conduit to suppress direct 2.45 MeV neutrons
- 700 bar D_2 gas cylinder in-line with the neutron conduit to function as a D-D neutron reflector



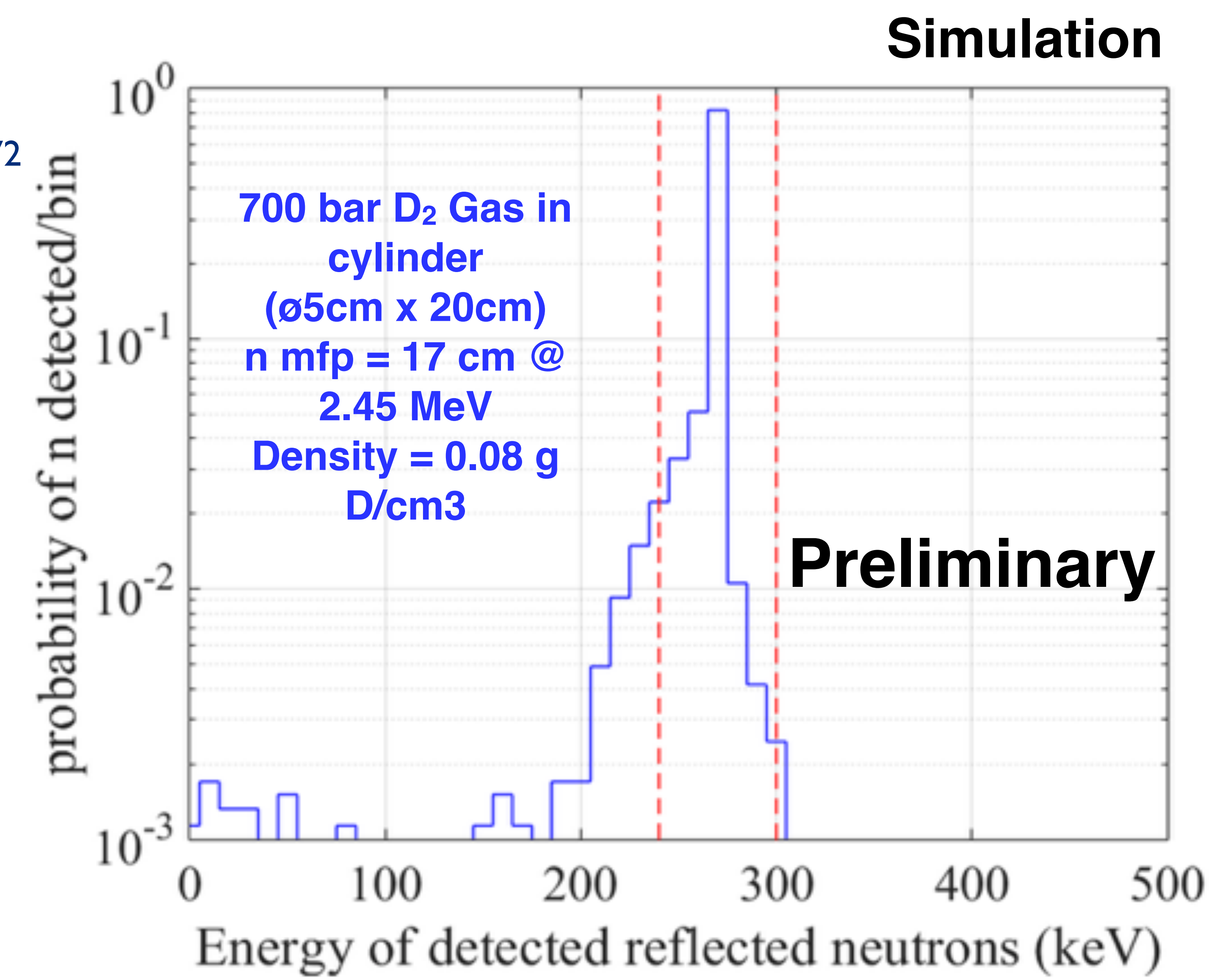
- Small solid angle presented by 5 cm diameter neutron conduit ensures only neutrons that backscatter at near 180° (272 keV) are incident upon the large LXe TPC

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

- Neutron beam energy purity
  - For 700 bar D_2 target, 94% of reflected neutrons are within +/-10% of central peak value of 272 keV
- Observed event rate
  - Useful reflected flux incident on the detector is 1/375x the flux of a direct line of sight D-D source with same intensity
  - Expect to achieve useful event rates enhanced above (7.5x) standard line-of-sight 2.45 MeV D-D calibrations in the range 1-4 keV_{nr}
    - Increase in neutron generator flux, differential spectrum enhancement, and no inelastic losses for 272 keV neutrons



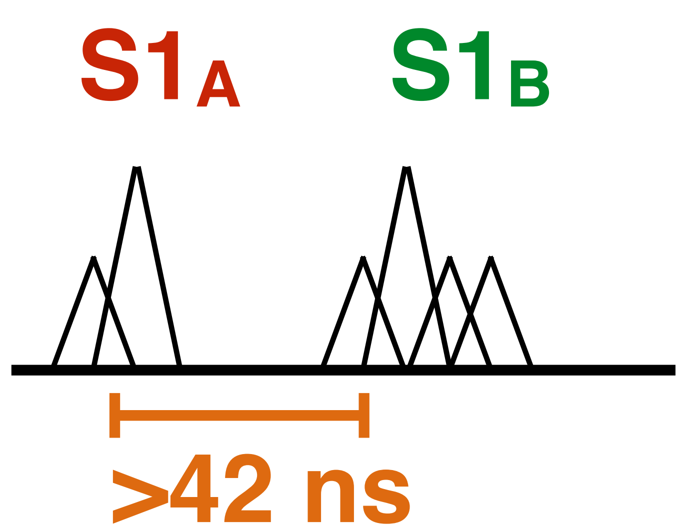
- The same 13° scatter waveform shown earlier, identified in existing D-D data, would be a **110 eV** nuclear recoil using 272 keV incident neutrons
  - Can study Q_y in lowest ever regime where expectation for signal is ~1-2 ionization electrons!

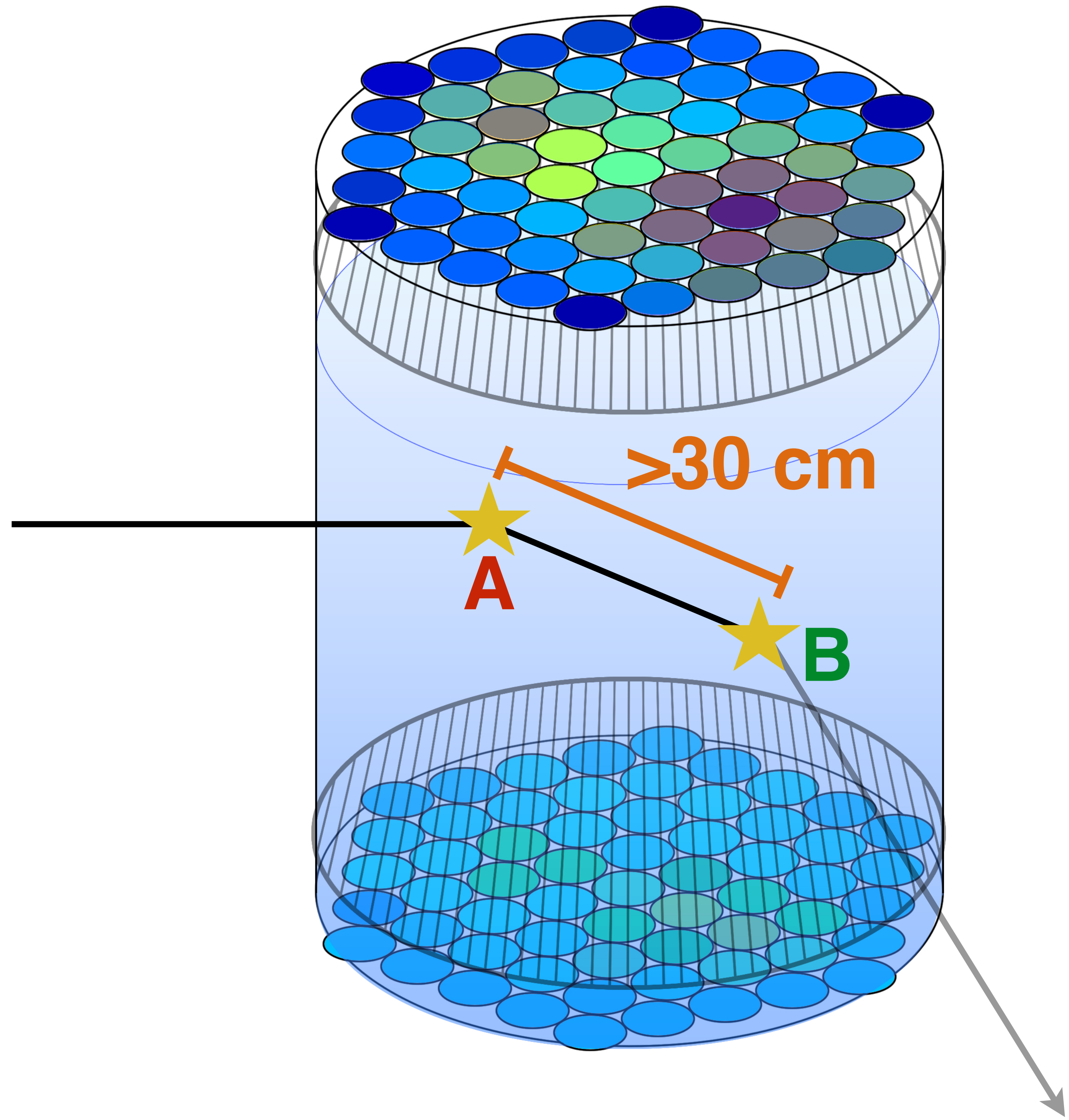


Simulations work by Casey Rhyne (Brown University)

Direct, absolute measurement of L_y using neutron scattering kinematics

- But 272 keV neutrons are also 3x slower than direct 2.45 MeV D-D neutrons…
- Double scatter events with 30 cm vertex separation => 42 ns ToF for 272 keV neutrons between vertices
  - We expect an experiment could observe 100s of such events given reasonable calibration runtimes (weeks) in a large LXe TPC
  - If able to achieve even longer path lengths (>50 cm), then >70 ns separation between vertices is possible
- Can distinguish photons in $S1_A$ from those in $S1_B$
- As in current Q_y measurement, can use angle to absolutely reconstruct the deposited energy for vertex A
  - Can now use direct angle based energy measurement for L_y determination using $S1_A$ photon count





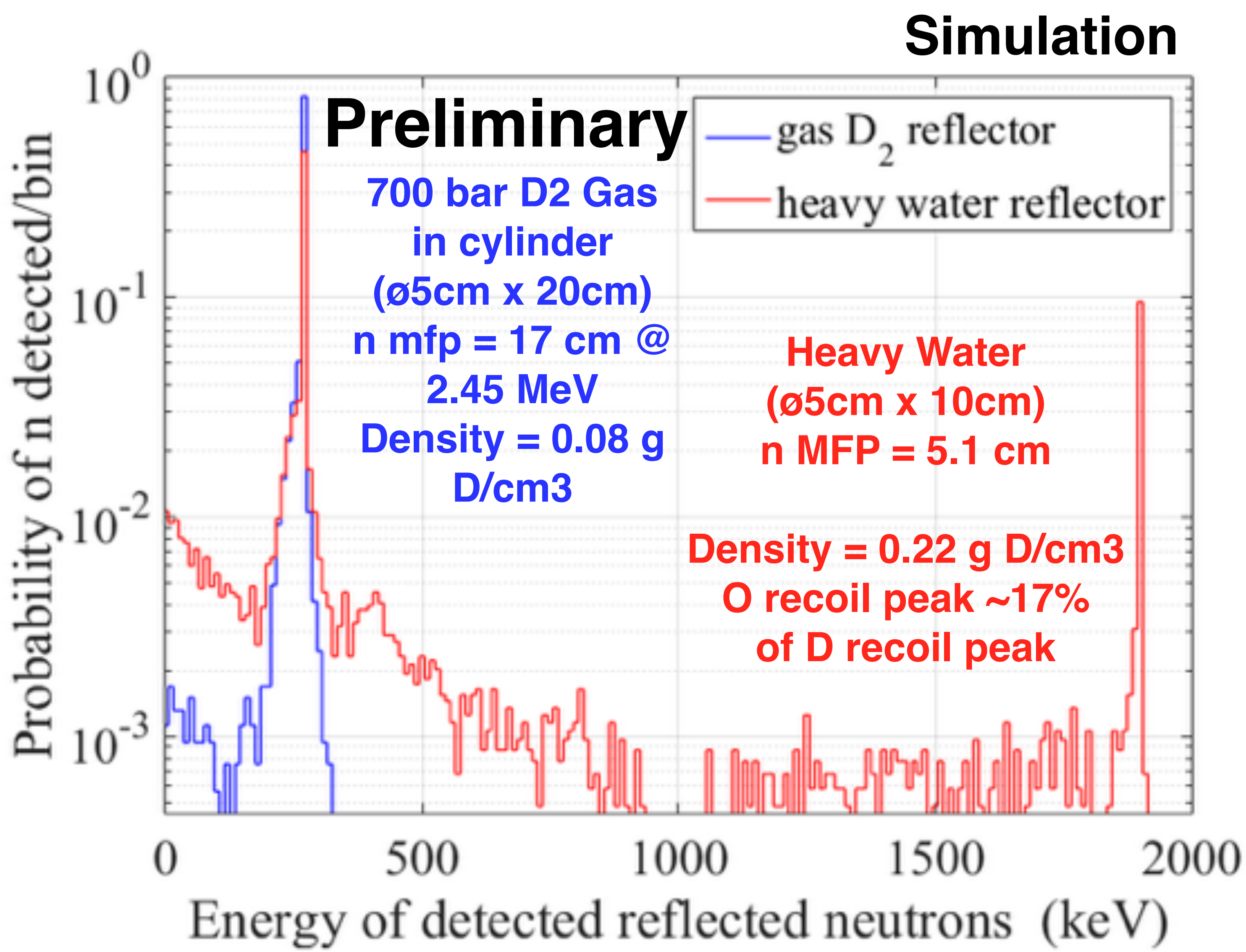
Postdoc position available

- Postdoc position available in Brown Particle Astrophysics Group
- If interested, please contact group leader Richard Gaitskell
  - Richard_Gaitskell@brown.edu

Additional Slides

Consider D_2O for D-D neutron backscatter target

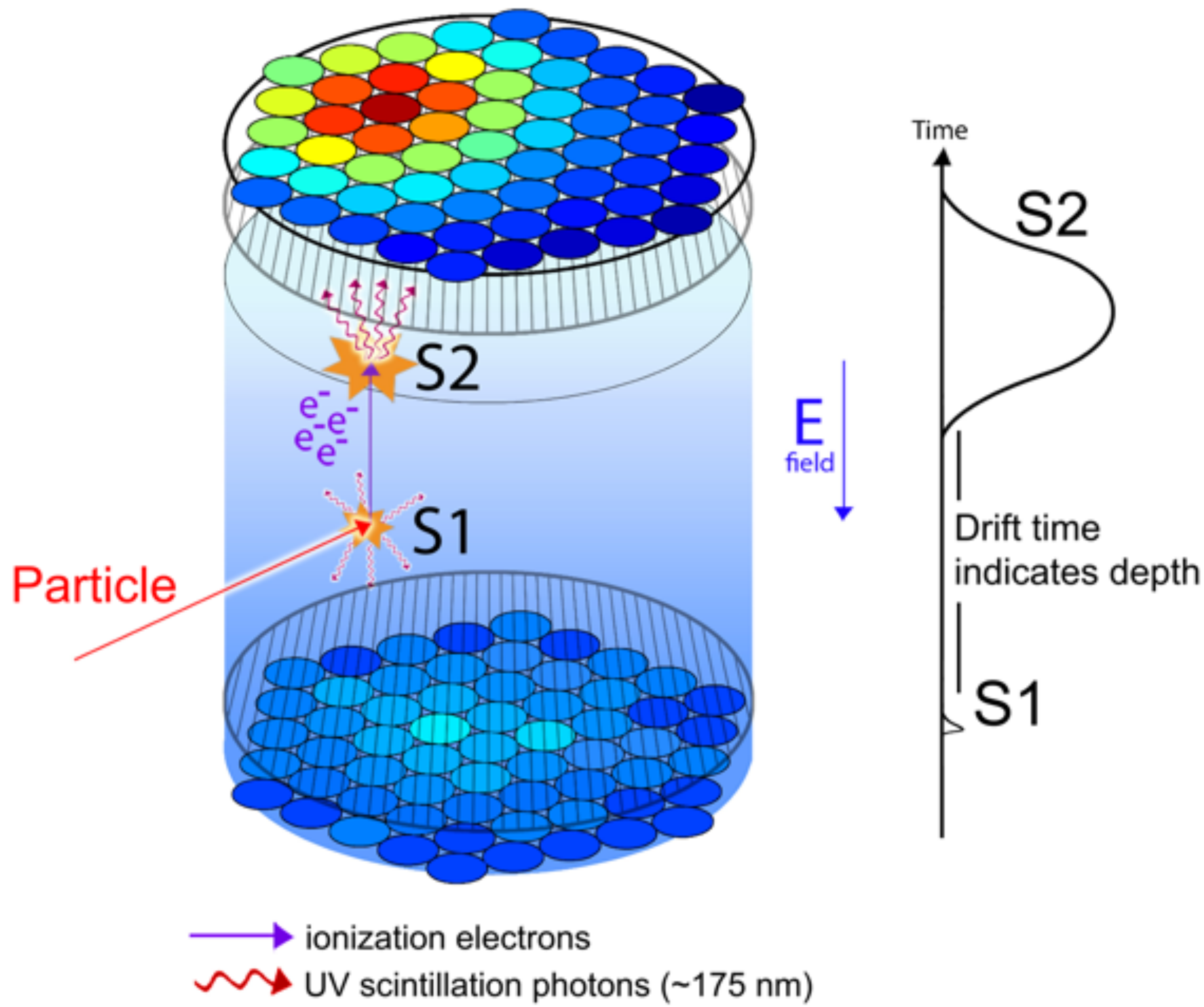
- Alternate D-loaded backscatter target: heavy water
- For heavy water, 56% of reflected neutrons are within +/-10% of central peak value of 272 keV



Simulations work by Casey Rhyne (Brown University)

The LUX Dark Matter Detector

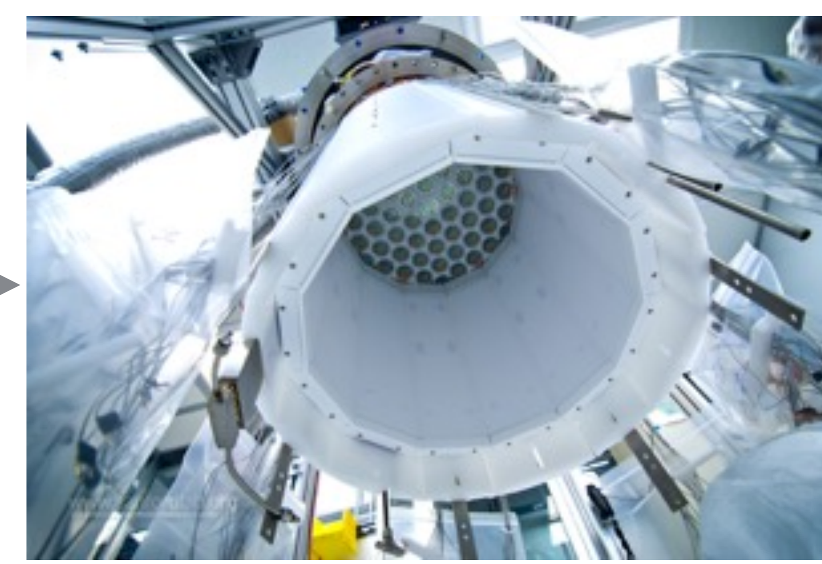
- What is LUX?
  - a particle detector
  - a monolithic wallless fiducial region within 370 kg, two-phase Xe TPC
  - viewed by 122 Photomultiplier Tubes
  - able to reconstruct (x,y,z) for each event
  - exceptional self-shielding from outer xenon layer
  - discrimination between electronic and nuclear 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
  - $g_1 \sim O(0.10)$ and $g_2 \sim O(10)$ are the amplification factors for each quanta
  - n_γ and n_e are the fundamental measured quantities



LUX has extremely low background

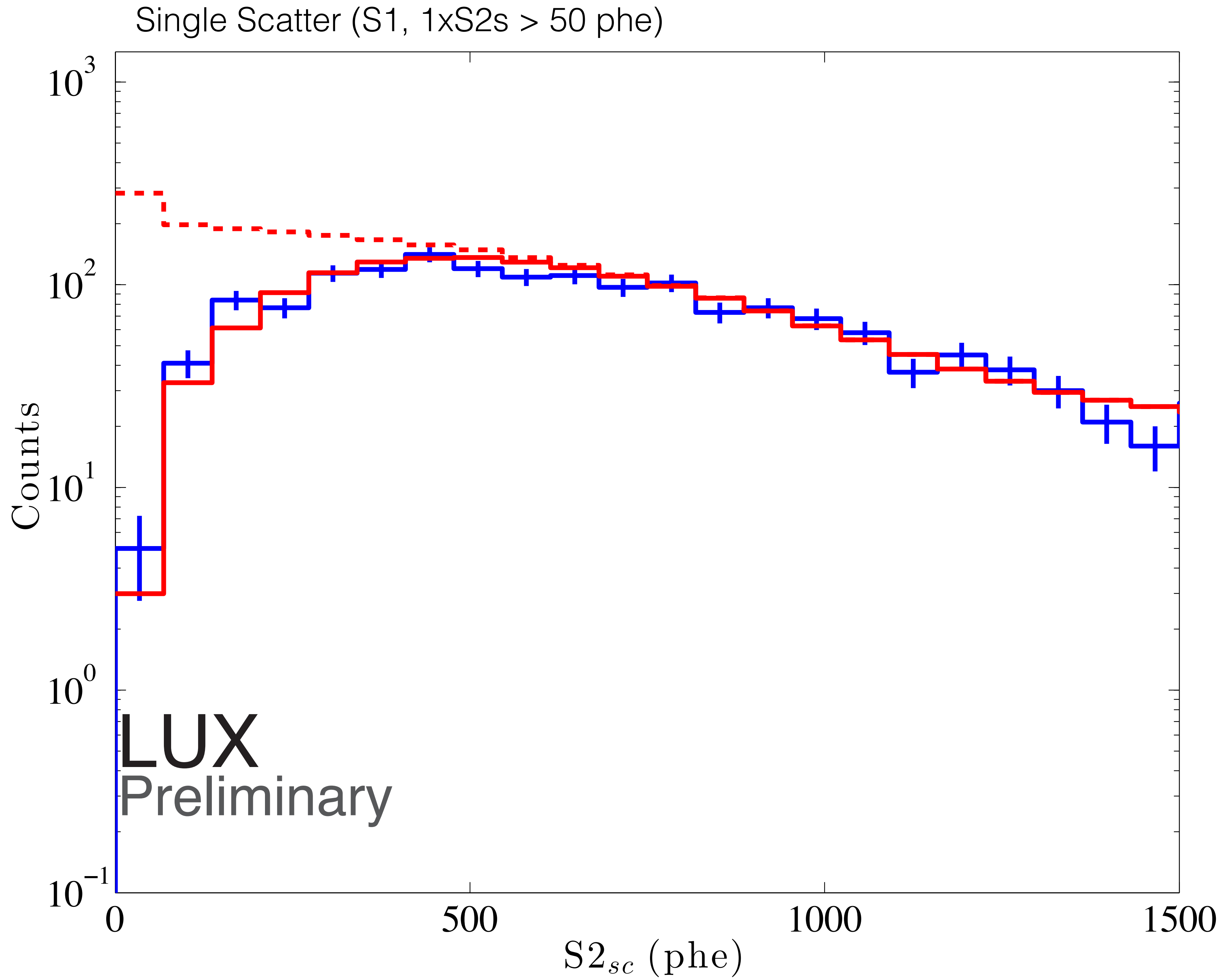
1492 m underground

- 4850 ft (1492 m) underground in the black hills of South Dakota (4300 meters water equiv.) ... reduces muon flux to <1 muon per day
- surrounded by a 7.6 m diameter water shield ... reduces gamma and neutron backgrounds to <1 projected event in 300 days of searching
- limiting factor is detector construction materials ... this limit is <2 background events per DAY in the central 118 kg target in the energy window of interest… and is **decreasing**



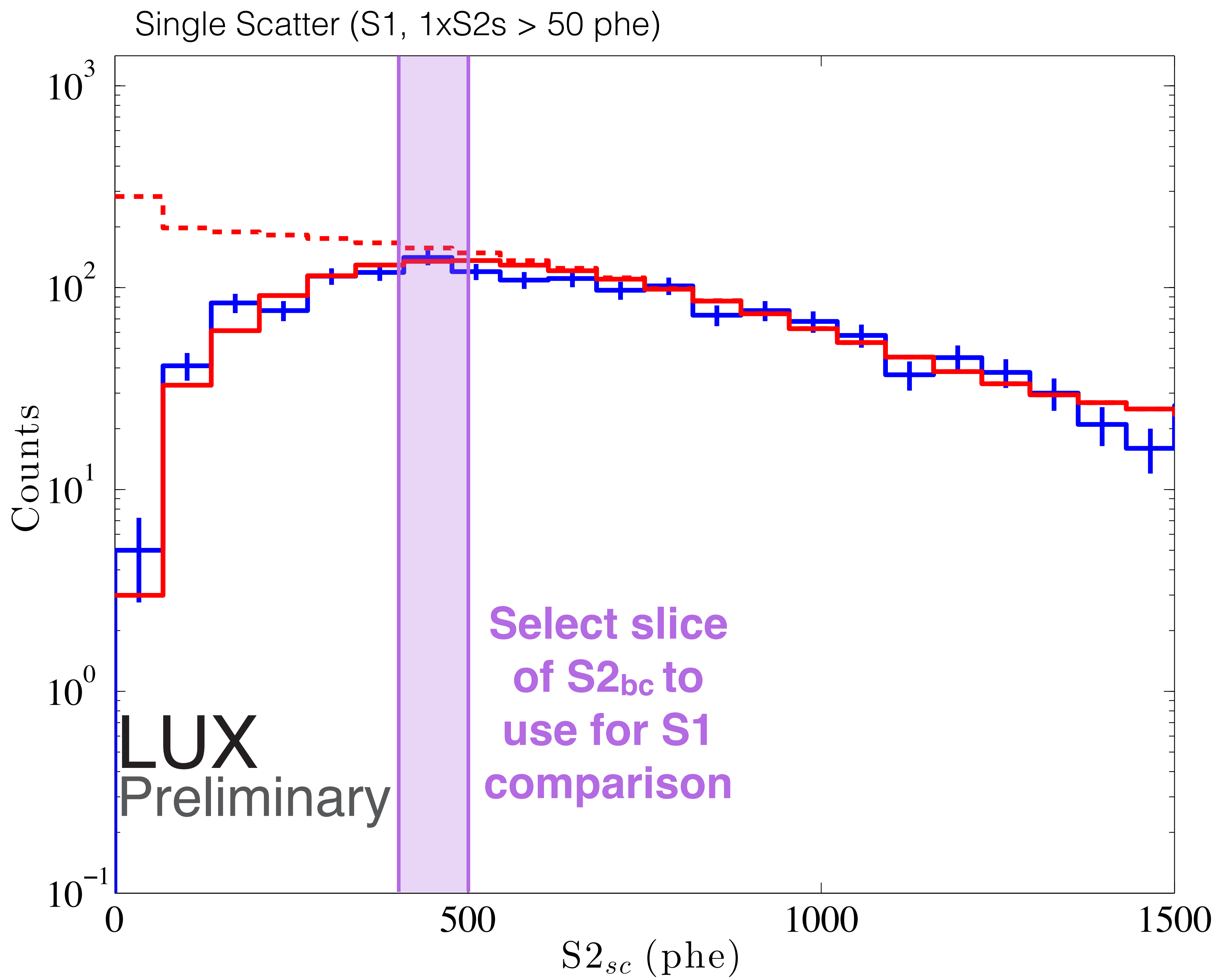
Measuring the Scintillation Yield

- Use **single scatters** with suitable selection criteria
- MC using measured LUX D-D charge yield to simulate expected single scatter energy spectrum with LUX threshold, purity, electron extraction, energy resolution effects applied
- Simulation uses JENDL-4.0 angular scattering cross-sections with isotope selection determined based upon natural abundance and total elastic cross-sections
- L_y measurement range is 0-900 phe $S2_{sc}$ using bins of 100 phe
    - Simulation event distribution is normalized outside of L_y measurement range using 900 < $S2_{sc}$ < 1500 phe



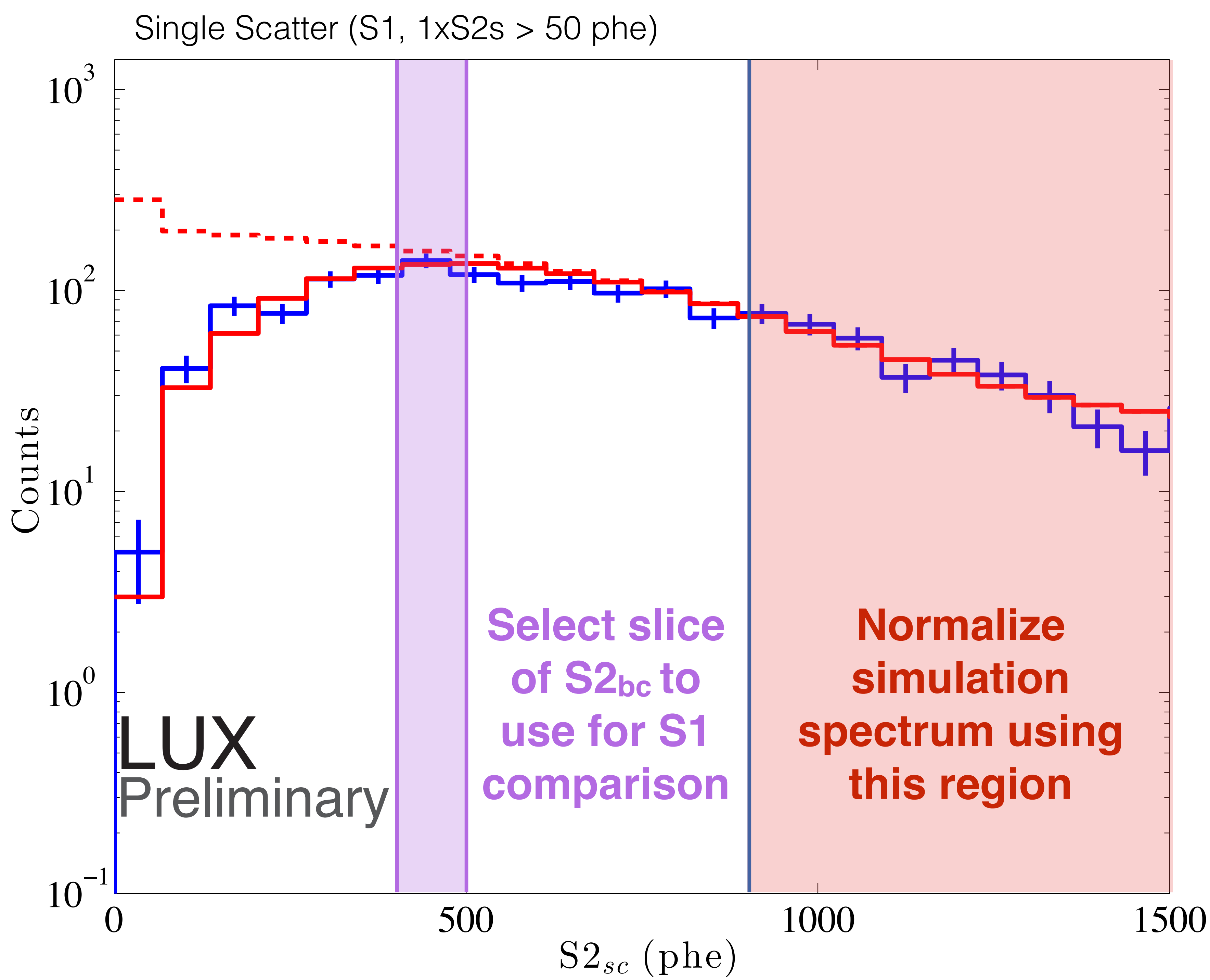
Measuring the Scintillation Yield

- Use **single scatters** with suitable selection criteria
- MC using measured LUX D-D charge yield to simulate expected single scatter energy spectrum with LUX threshold, purity, electron extraction, energy resolution effects applied
- Simulation uses JENDL-4.0 angular scattering cross-sections with isotope selection determined based upon natural abundance and total elastic cross-sections
- L_y measurement range is 0-900 phe $S2_{sc}$ using bins of 100 phe
    - Simulation event distribution is normalized outside of L_y measurement range using 900 < $S2_{sc}$ < 1500 phe

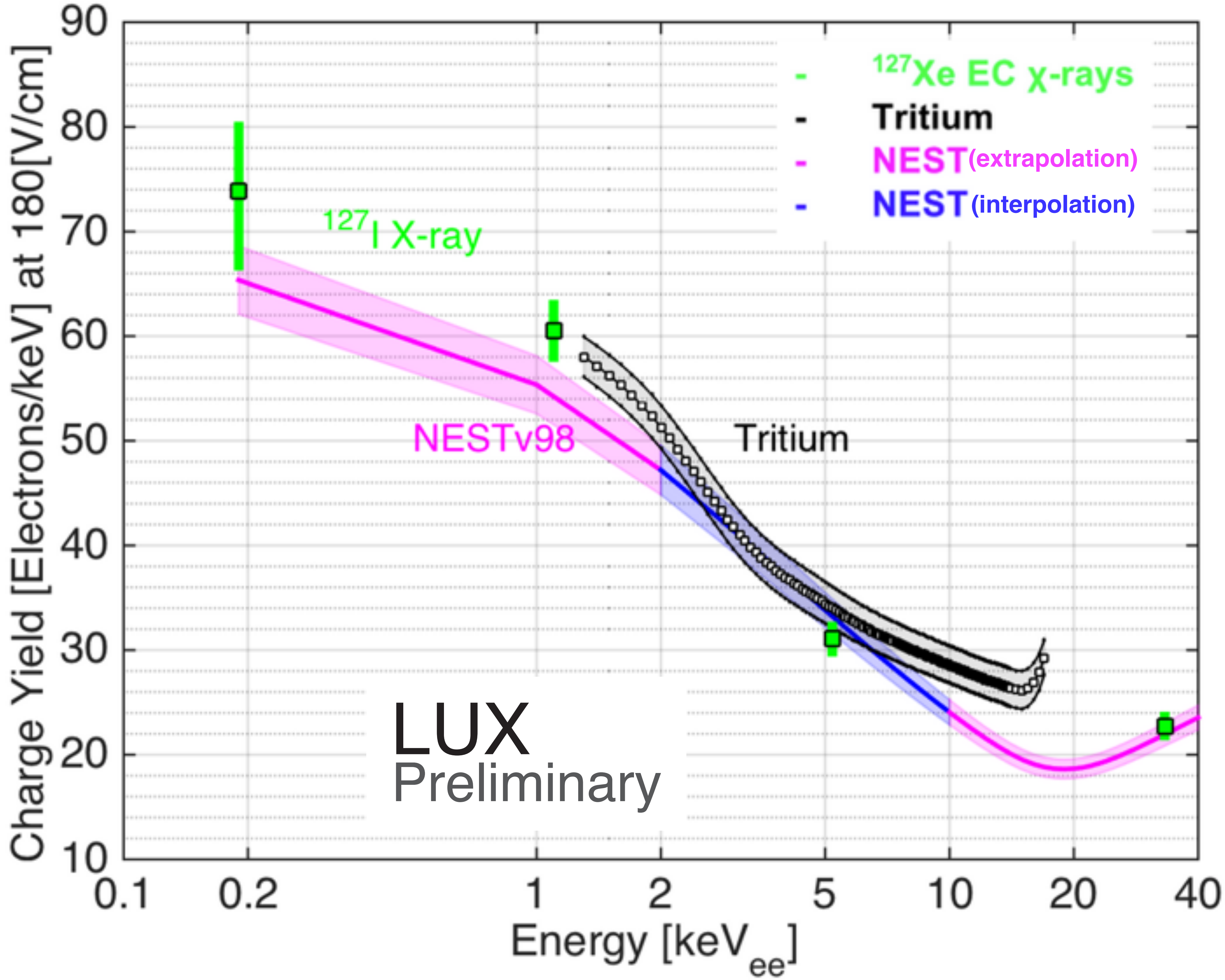


Measuring the Scintillation Yield

- Use **single scatters** with suitable selection criteria
- MC using measured LUX D-D charge yield to simulate expected single scatter energy spectrum with LUX threshold, purity, electron extraction, energy resolution effects applied
- Simulation uses JENDL-4.0 angular scattering cross-sections with isotope selection determined based upon natural abundance and total elastic cross-sections
- L_y measurement range is 0-900 phe $S2_{sc}$ using bins of 100 phe
  - Simulation event distribution is normalized outside of L_y measurement range using 900 < $S2_{sc}$ < 1500 phe



Electron Recoil Qy Comparison with Tritium[3] and NEST[1][2]



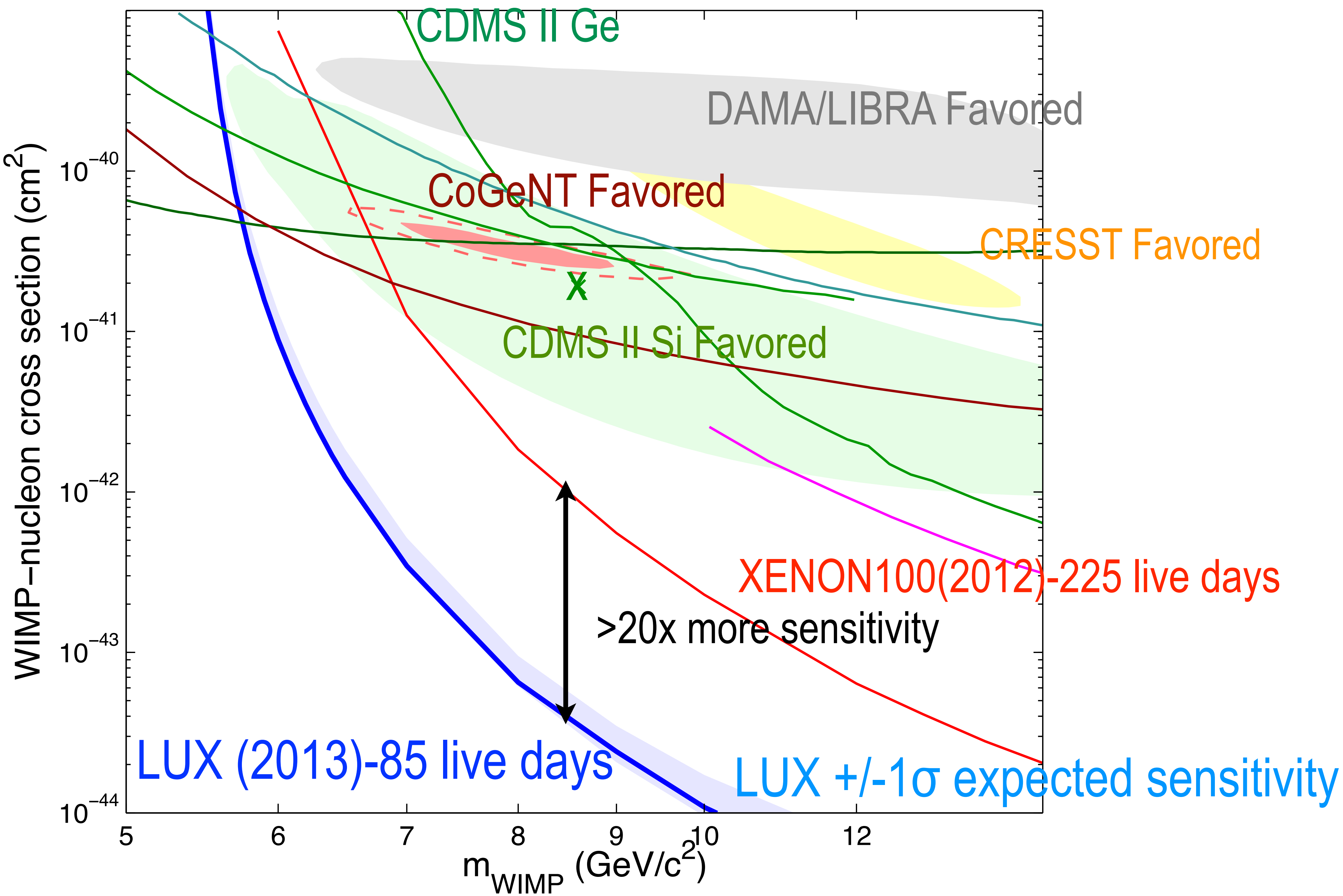
^{127}Xe work by Dongqing Huang (Brown University): http://pa.brown.edu/talks_files/2015_dqhuang_TAUP.pdf

[1] Matthew Szydagis, Adalyn Fyhrie, Daniel Thorngren, and Mani Tripathi. Enhancement of NEST Capabilities for Simulating Low-Energy Recoils in Liquid Xenon. JINST, 8:C10003, 2013. doi: 10.1088/1748-0221/8/10/C10003.

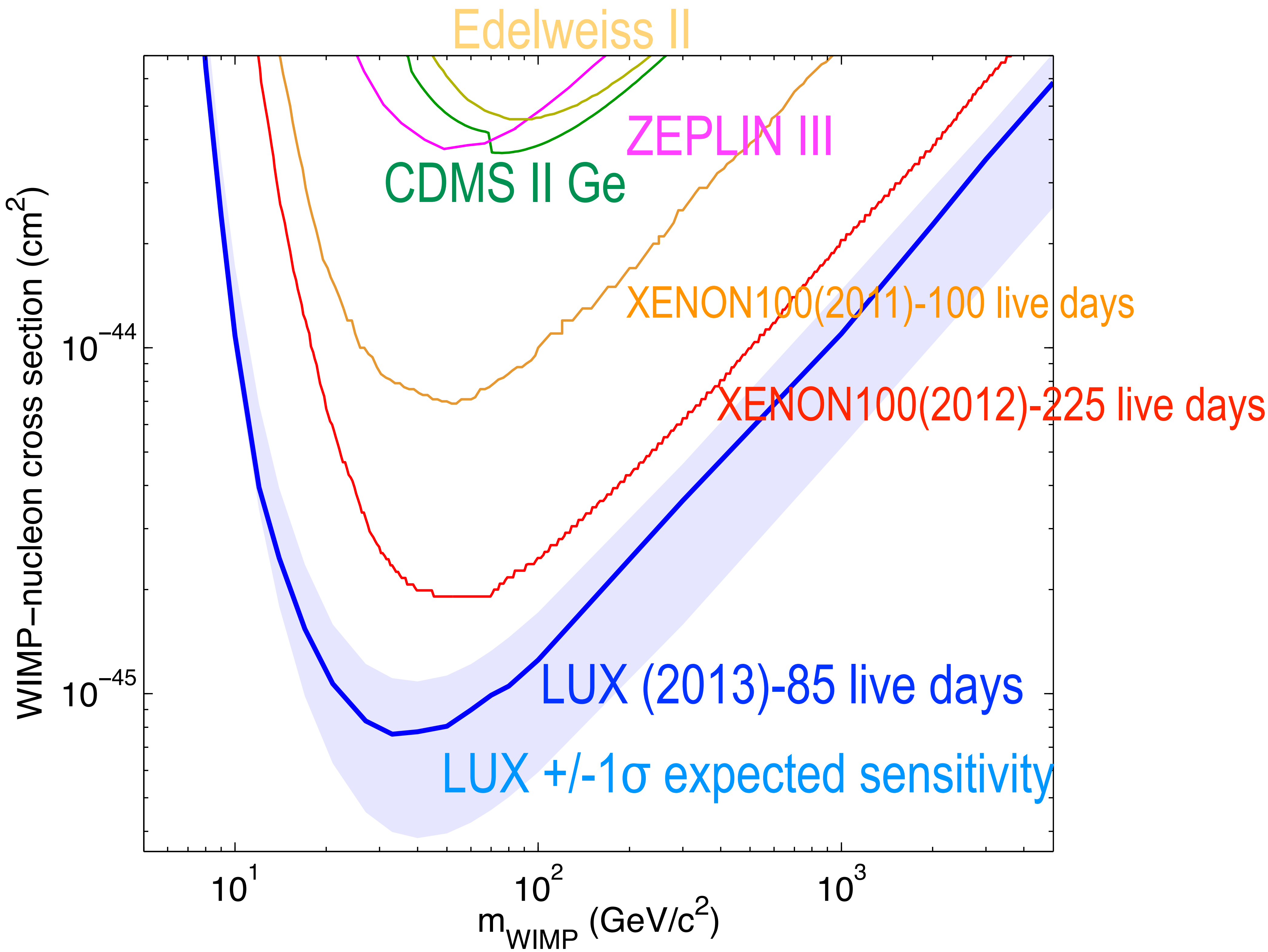
[2] Brian Lenardo, Kareem Kazkaz, Aaron Manalaysay, Matthew Szydagis, Mani Tripathi. A Global Analysis of Light and Charge Yields in Liquid Xenon. arXiv: 1412.4417 [astro-ph.IM]

[3] Attila Dobi. Measurement of ER Fluctuations in Liquid Xenon with the LUX Detector Using a Tritium Calibration Source. LIDINE 2015

Low Mass WIMPs - Fully Excluded by LUX



Spin-Independent Sensitivity



Projected LUX 300 day WIMP Search Run

- LUX 300 day run is underway
  - Extending sensitivity by another factor 5
  - Even though LUX sees no WIMP-like events in the current run, it is still quite possible to discover a signal when extending the reach
  - LUX does not exclude LUX
- WIMPs remain our favored quarry
- LZ 20x increase in target mass