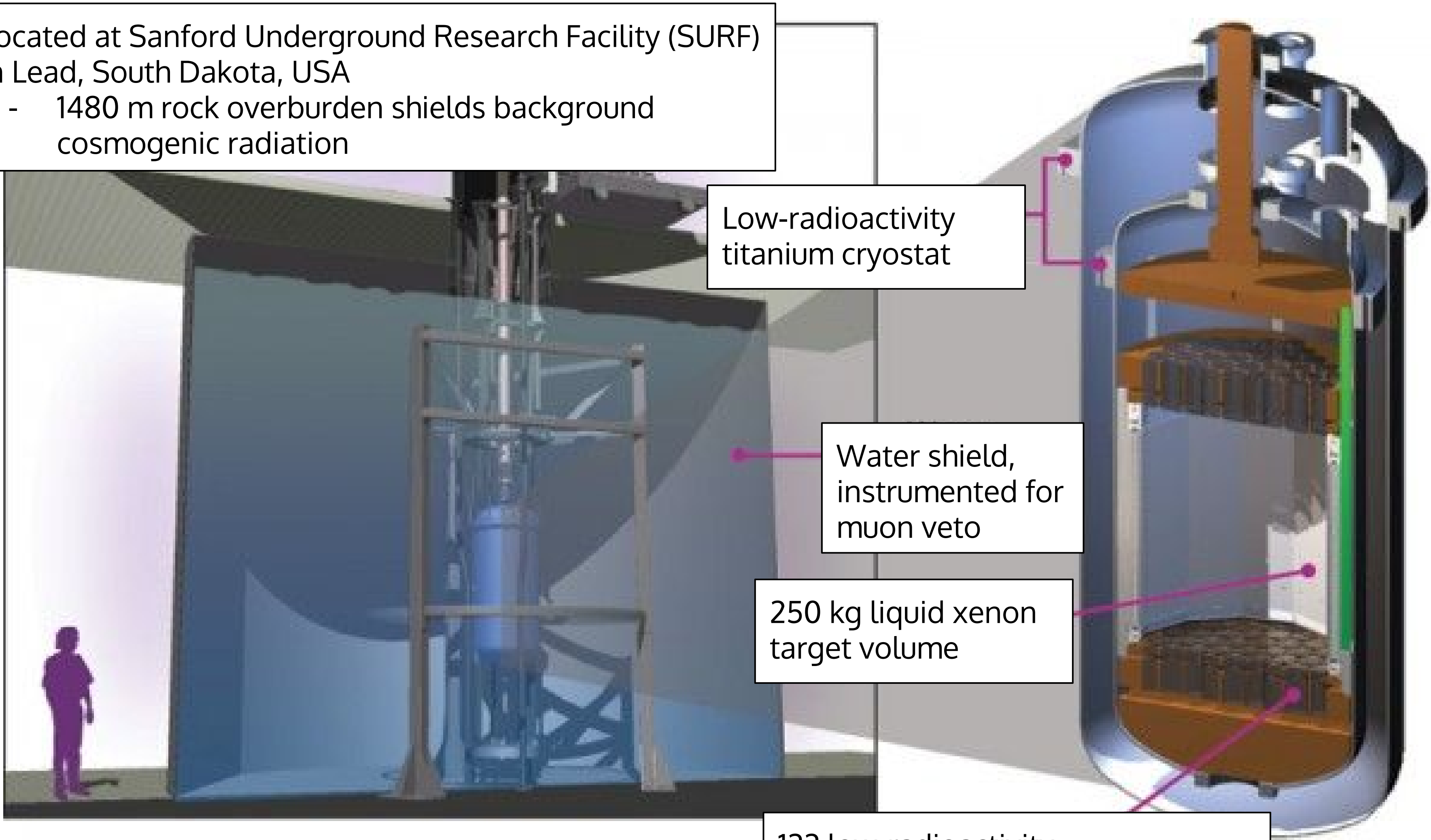
# Liquid Xenon Scintillation Measurements and Pulse Shape Discrimination in the LUX Dark Matter Detector

Brian Lenardo
UC Davis / LLNL
LIght Detection In Noble Elements
September 22, 2017

# The LUX dark matter experiment

Located at Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA

- 1480 m rock overburden shields background cosmogenic radiation



Low-radioactivity titanium cryostat

Water shield, instrumented for muon veto

250 kg liquid xenon target volume

122 low-radioactivity photomultiplier tubes for high-efficiency light collection

# Scintillation PSD analysis in LUX

Goals:

- Measure electron recoil and nuclear recoil scintillation time distributions at DM search energies
- Develop pulse shape discriminant for use in future dark matter searches with LUX

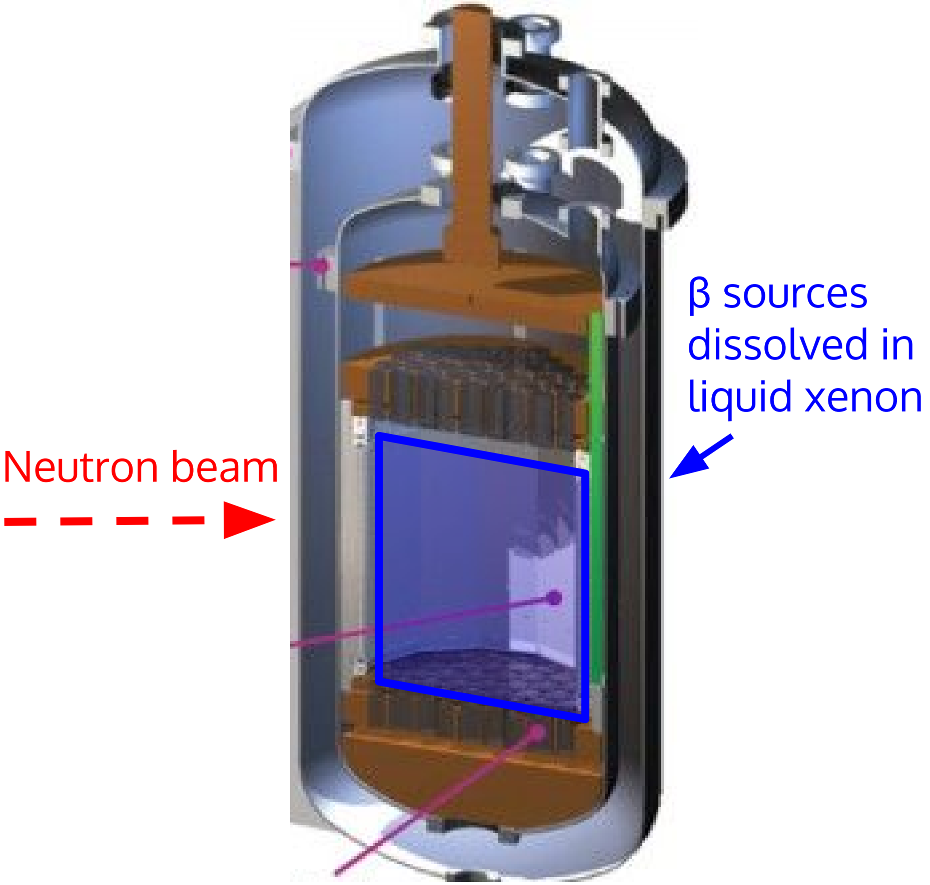
# ER/NR calibration data

**Fast neutrons from D-D generator**

- Collimated 2.45 MeV beam
- Elastic scatters → nuclear recoils 0 - 74 keV.

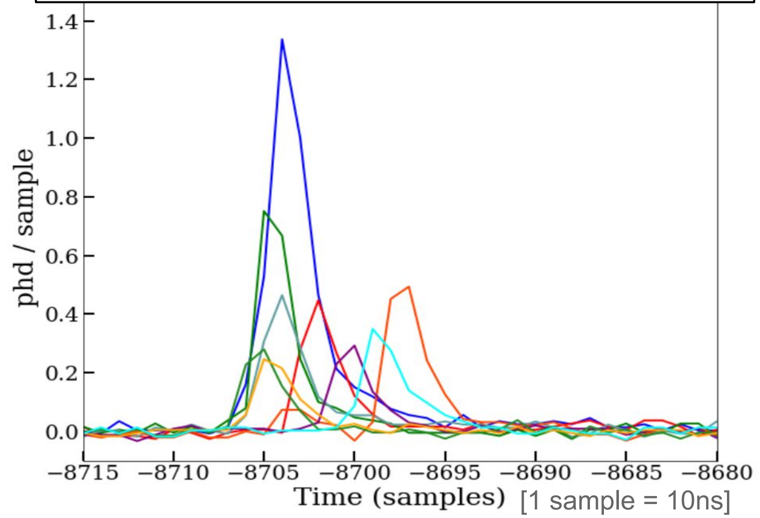
**Beta decays from $^{3}$H and $^{14}$C source**

- Methane with $^{3}$H or $^{14}$C dissolved into liquid xenon circulation system
- Source removed by standard purification system
- Populates detector uniformly with electron recoils from beta decay (0 - 150 keV)

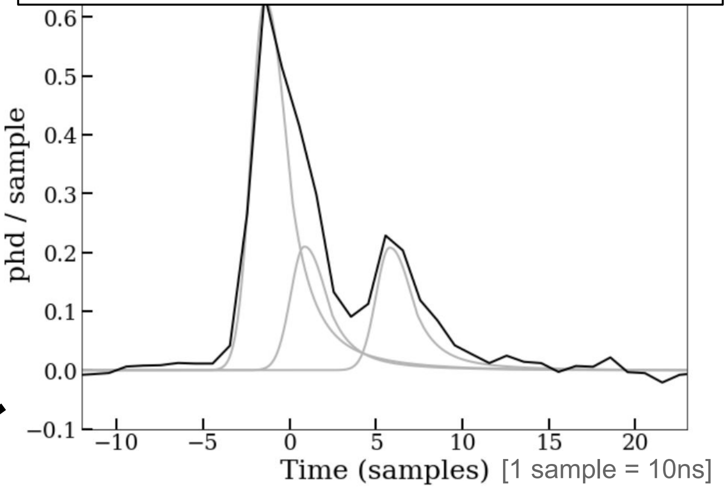


# Photon timing algorithm

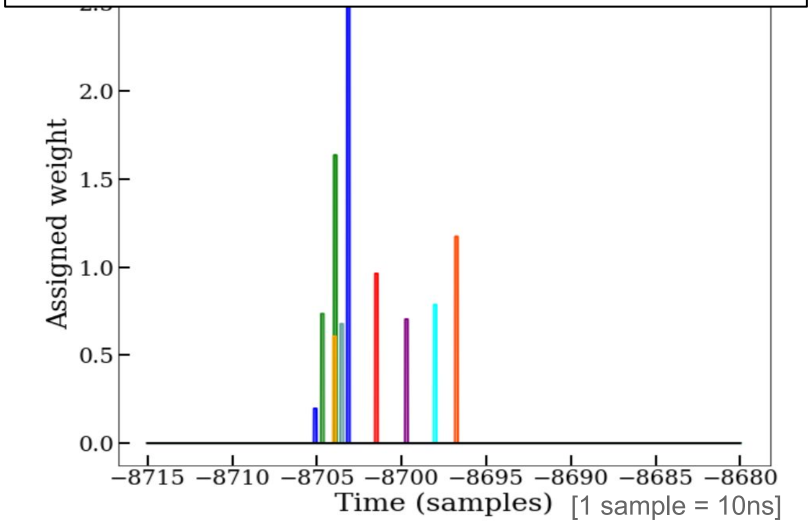
1. Raw scintillation pulse in PMTs



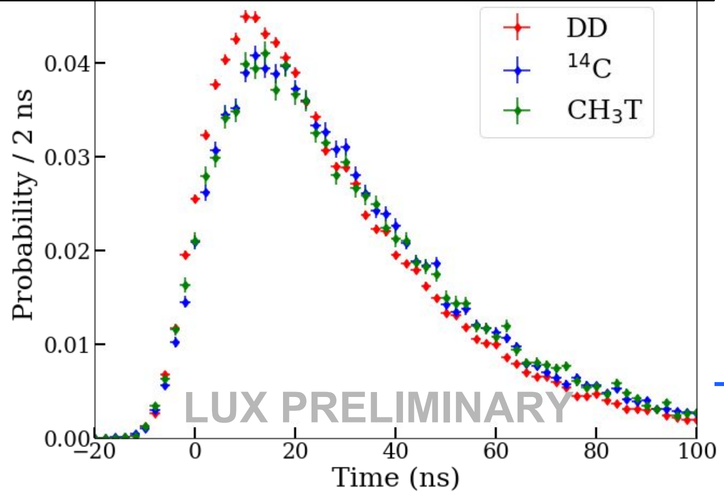
2. Single-photon templates fit to waveforms



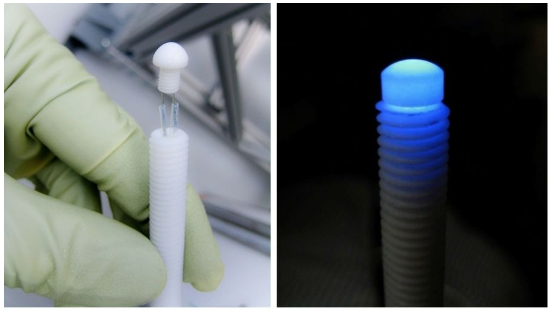
3. Times identified, corrections applied



4. Many pulses summed together to produce average histogram



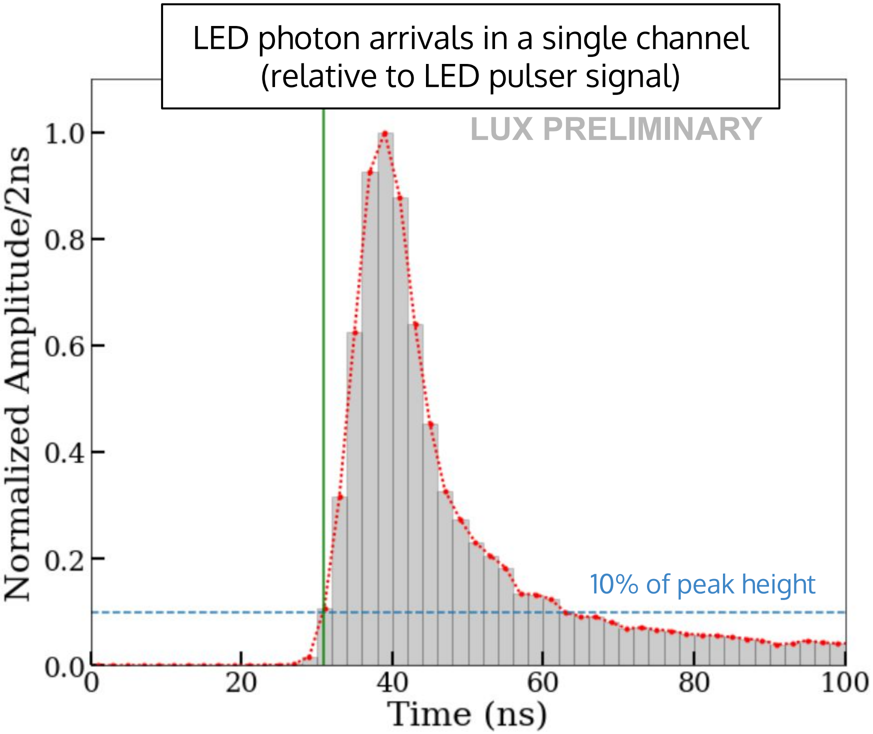
# Timing calibration using LEDs



Six blue LEDs (440nm) embedded in each PMT array at top and bottom of xenon volume.

**Timing calibration procedure:**

1. Pulse LEDs with 20 ns FWHM pulses to produce light at known times
2. Build distribution of photon arrivals in each channel
3. Use rising edge (10% height) as reference time to correct for relative timing offsets
4. Repeat with 4 different LEDs to compute uncertainties in calibration



LED photon arrivals in a single channel (relative to LED pulser signal)

Relative offsets between channels: ~20 ns

Uncertainty in calibration: σ = 2 ns

# Modeling pulse shapes

**Detector effects:**

- Timing resolution
  - PMT transit time spread
  - Uncertainties in timing calibrations
  - Uncertainties from template fitting

$$P_r = \frac{1}{\sqrt{2\sigma^2}} e^{-x^2/(2\sigma^2)}$$

- Optical transport
  - Modeled using optical simulations in Geant4
  - Empirical analytic model fit to simulation

$$P_o(t) = A\,\delta(t) + (1 - A)\left[\frac{B_a}{\tau_a}\, e^{-t/\tau_a} + \frac{B_b}{\tau_b}\, e^{-t/\tau_b}\right]$$

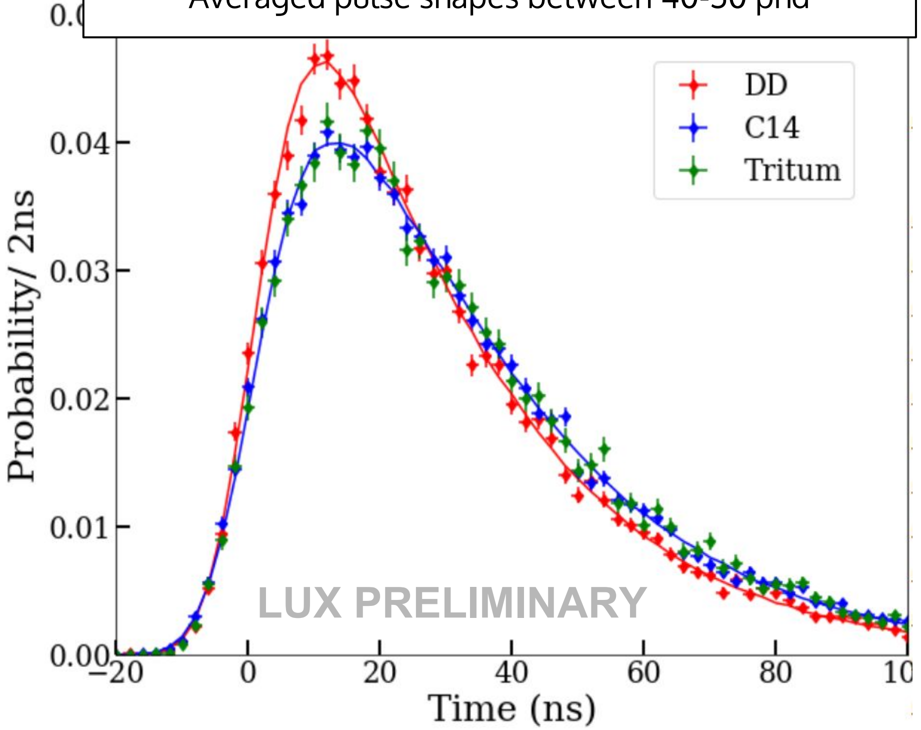
**Liquid xenon physics:**

- Ratio and time constants of singlet and triplet states

$$P(t) = C_1\, e^{-t/\tau_1} + C_3\, e^{-t/\tau_3}$$

# Fitting to calibration data

Averaged pulse shapes between 40-50 phd



Fully convolved pulse shape model

$$P(t) = \sum_{i=1,3}\sum_{j=a,b} \frac{C_i\,A}{2}\, e^{\frac{\sigma^2}{2\tau_i^2}-\frac{t}{\tau_i}}\left[1+\mathrm{erf}\left(\frac{t-\frac{\sigma^2}{\tau_i}}{\sigma\sqrt{2}}\right)\right] + \frac{C_i\,(1-A)\,B_j}{2(\frac{\tau_j}{\tau_i}-1)}\, e^{\frac{\sigma^2}{2\tau_j^2}-\frac{t}{\tau_j}}\left[1+\mathrm{erf}\left(\frac{t-\frac{\sigma^2}{\tau_j}}{\sigma\sqrt{2}}\right)\right] - \frac{C_i\,(1-A)\,B_j}{2(\frac{\tau_j}{\tau_i}-1)}\, e^{\frac{\sigma^2}{2\tau_i^2}-\frac{t}{\tau_i}}\left[1+\mathrm{erf}\left(\frac{t-\frac{\sigma^2}{\tau_i}}{\sigma\sqrt{2}}\right)\right]$$

| Free Parameter | Expected |
|---|---|
| $(C_1\boldsymbol{\tau}_1) / (C_3\boldsymbol{\tau}_3)$ for ER | ~0.1 |
| $(C_1\boldsymbol{\tau}_1) / (C_3\boldsymbol{\tau}_3)$ for NR | ~1.52 (at ~100 MeV) |
| $\boldsymbol{\tau}_1$ | 2.2 - 4.3 ns * |
| $\boldsymbol{\tau}_3$ for ER | 21 - 27 ns * |
| $\boldsymbol{\tau}_3$ for NR | 21 - 27 ns * |
| σ | ≥ 3.1 ns |

* Range of measured values from Kubota (1978 & 1979), and Hitachi (1983)

# Fit results

Model is fitted to all histograms for ER and NR at all energies simultaneously

- Allows us to vary parameters common among different energy / particle type bins (i.e. σ, $\tau_1$, etc. )

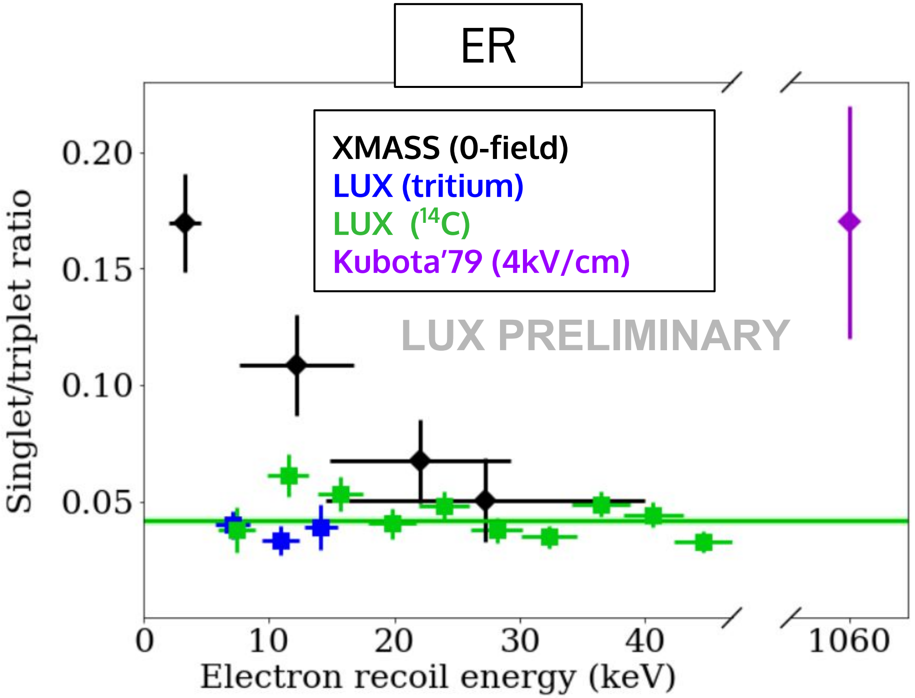
LUX PRELIMINARY

| Parameter | Expected | Best fit ± stat. | Fit sys. err. | Optical sys. err. |
|---|---|---|---|---|
| $(C_1\tau_1) / (C_3\tau_3)$ for ER | ~0.1 | 0.042 ± 0.006 | ± 3.1% | +75% / -66% |
| $(C_1\tau_1) / (C_3\tau_3)$ for NR | 1.52 (at ~100 MeV) | 0.269 ± 0.034 | ± 3.1% | +20% / -10% |
| $\tau_1$ | 2.2 - 4.3 ns * | 3.27 ± 0.66 ns | ± 1% | +11% / -70% |
| $\tau_3$ for ER | 21 - 27 ns * | 25.89 ± 0.06 ns | ± 1.9% | +0.5% / -0.6% |
| $\tau_3$ for NR | 21 - 27 ns * | 23.97 ± 0.17 ns | ± 1.9% | +0.1% / - 1.1% |
| σ | ≥ 3.1 ns | 3.59 ± 0.09 ns | ± 1.1% | ± 1.2% |

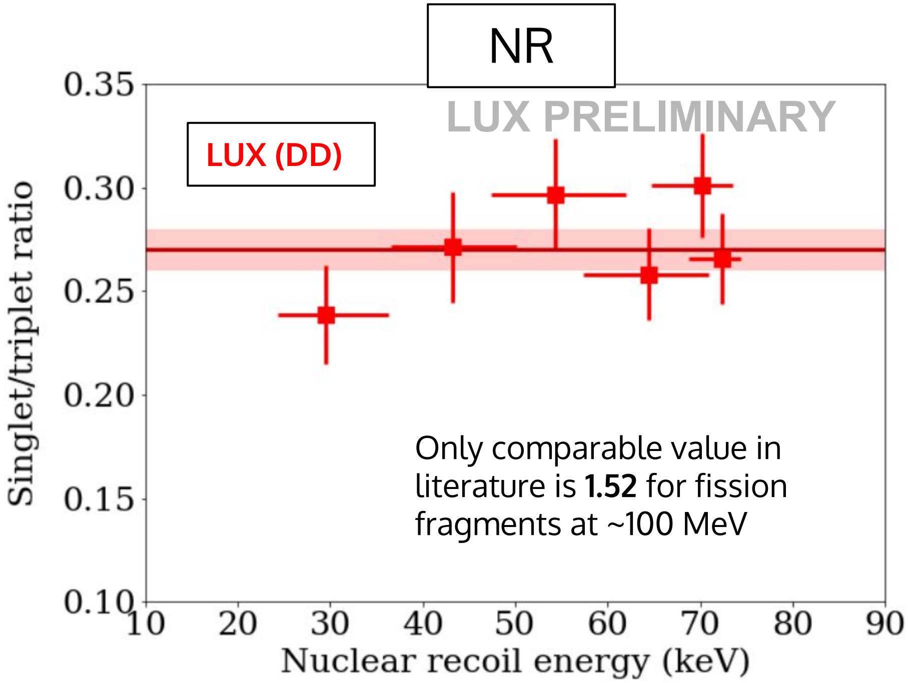
* Range of measured values from Kubota (1978 & 1979), and Hitachi (1983)

# Singlet/triplet ratio energy dependence

ER



NR



Only comparable value in literature is **1.52** for fission fragments at ~100 MeV

---

**Three important results**:

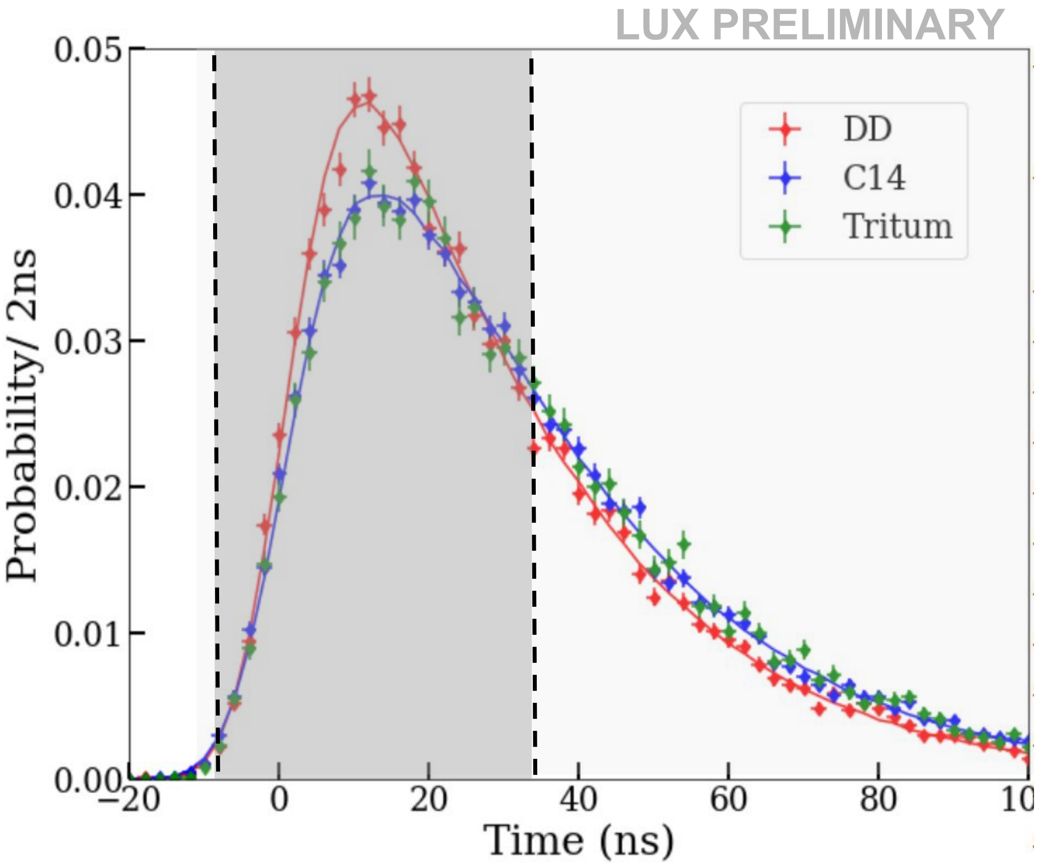
- **NR ratio is much smaller at low energies than published measurements made at high energies**
- **ER ratio has no significant energy dependence under applied field**
- **NR may show energy dependence? Not prominent in our data**

# Prompt fraction discriminator

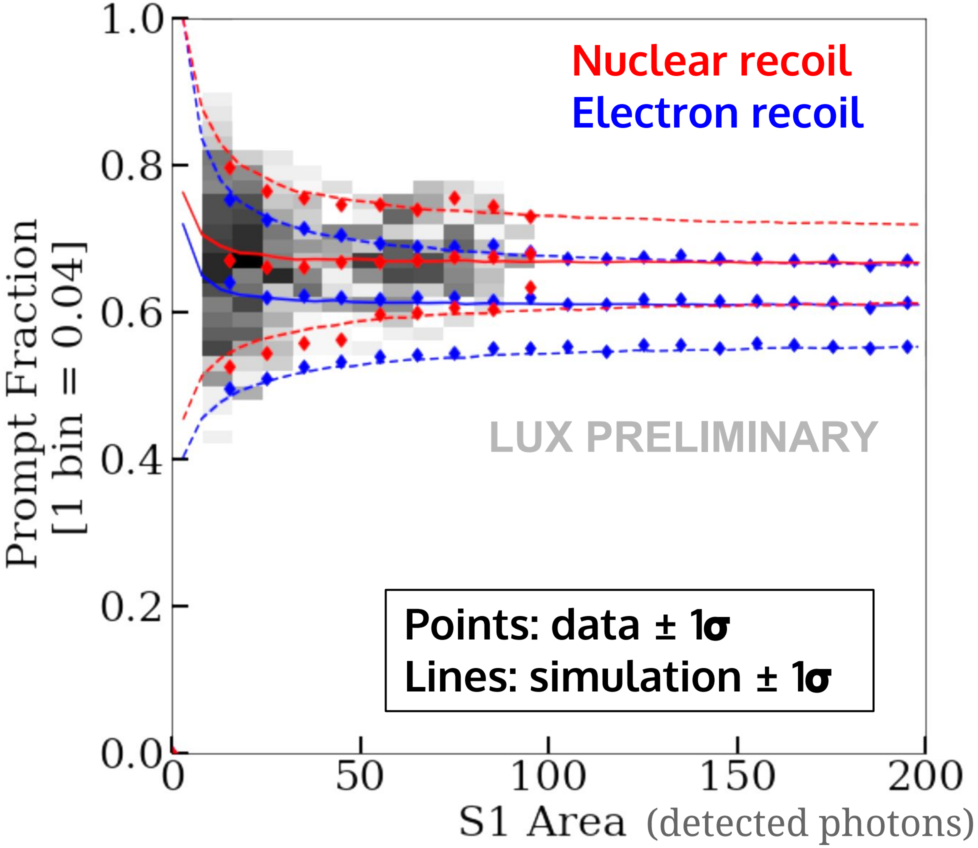
PSD accomplished through optimized prompt fraction

Also, **built a toy MC** that draws photon times from best-fit timing distribution and

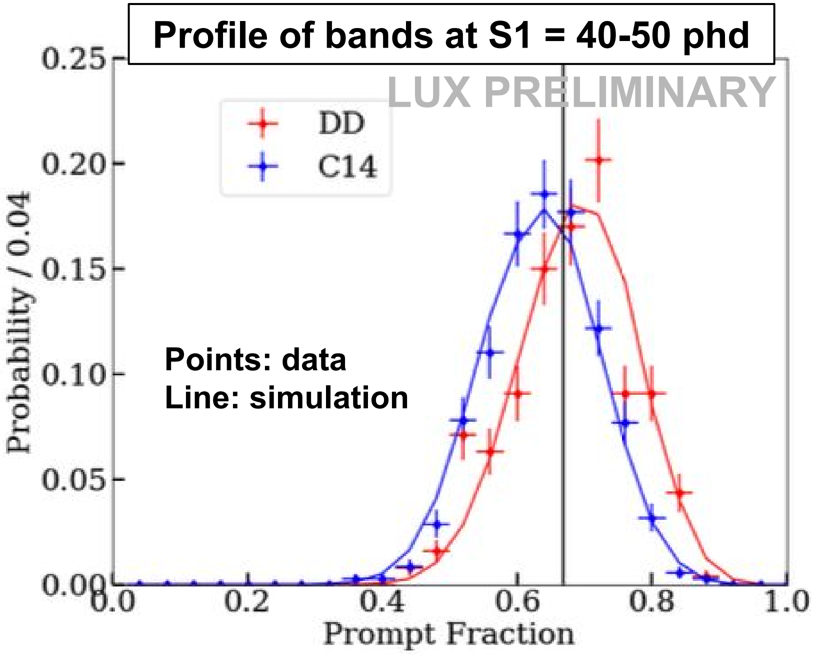
- Adds fluctuations in PMT signal size
- Adds fluctuations in 5% area time from digitization
- Computes prompt fraction discrimination



# Prompt fraction discrimination



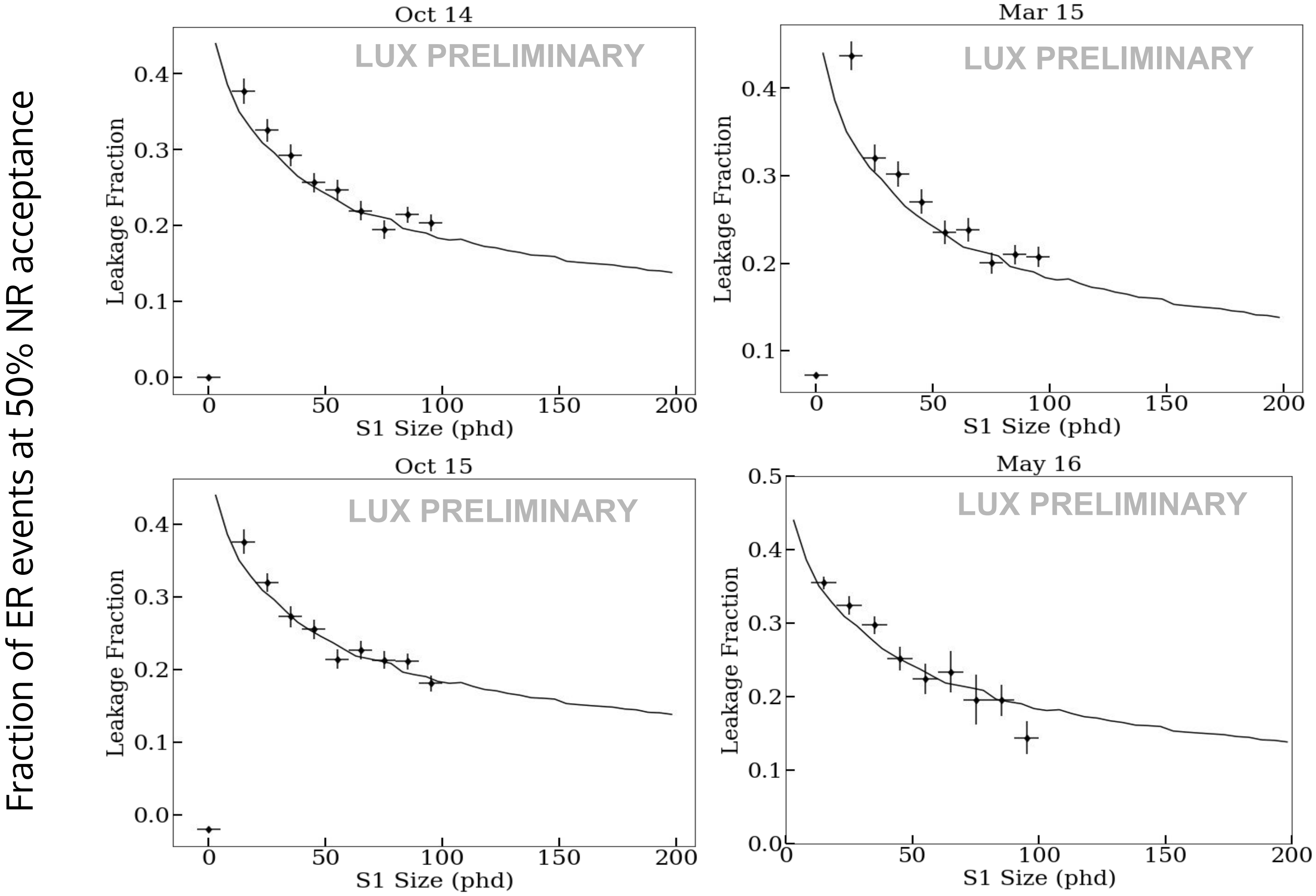
Points: data ± 1σ
Lines: simulation ± 1σ



**Profile of bands at S1 = 40-50 phd**

**Points: data**
**Line: simulation**

# ER leakage into NR 50% acceptance region



# Summary

- We are studying pulse shape discrimination for background rejection in dark matter analyses with LUX
- Built a framework for timing photon arrivals
- Used an analytic model to reconstruct singlet/triplet ratios at low energies (NR for the first time)
- Demonstrated prompt fraction discrimination with LUX calibration data
- Constructed a Monte Carlo model that reproduces ER/NR distributions, can be used in LUX simulations and analysis

# Acknowledgements

**The LUX collaboration**

**Sanford Underground Research Facility (SURF)**

**LUX PSD subgroup**

- Dev Ashish Khaitan (U of Rochester)
- Mongkol Moongweluwan (U of Rochester)
- Daniel Hogan (UC Berkeley)
- Prof. Matthew Szydagis (U Albany, SUNY)
- Dr. Kareem Kazkaz (LLNL)

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

# The LUX collaboration

## Berkeley Lab / UC Berkeley

| | |
|---|---|
| Bob Jacobsen | PI, Professor |
| Murdock Gilcrease | Senior Scientist |
| Kevin Lesko | Senior Scientist |
| Michael Witherell | Lab Director |
| Peter Sorensen | Divisional Fellow |
| Simon Fiorucci | Project Scientist |
| Evan Pease | Postdoc |
| Daniel Hogan | Graduate Student |
| Kelsey Oliver-Mallory | Graduate Student |
| Kate Kamdin | Graduate Student |

## Brown University

| | |
|---|---|
| Richard Gaitskell | PI, Professor |
| Junhui Liao | Postdoc |
| Samuel Chan | Graduate Student |
| Dongqing Huang | Graduate Student |
| Casey Rhyne | Graduate Student |
| Will Taylor | Graduate Student |
| James Verbus | Ex-Postdoc |

## University of Edinburgh

| | |
|---|---|
| Alexander Murphy | PI, Professor |
| Paolo Beltrame | Ex-Research Fellow |
| Maria F. Marzioni | Graduate Student |
| Tom Davison | Graduate Student |

## Lawrence Livermore National Laboratory

| | |
|---|---|
| Adam Bernstein | PI, RED group leader |
| Kareem Kazkaz | Physicist |
| Jingke Xu | Postdoc |
| Brian Lenardo | Graduate Student |

## Stanislaus State

| | |
|---|---|
| Wing To | PI, Assistant Professor |

## Imperial College London

| | |
|---|---|
| Henrique Araujo | PI, Professor |
| Tim Sumner | Professor |
| Alastair Currie | Ex-Postdoc |
| Adam Bailey | Ex-Graduate Student |
| Khadeeja Yazdani | Ex-Graduate Student |
| Nellie Marangou | Graduate Student |

## SLAC NATIONAL ACCELERATOR LABORATORY

| | |
|---|---|
| Dan Akerib | PI, Professor |
| Thomas Shutt | PI, Professor |
| Tomasz Biesiadzinski | Research Associate |
| Christina Ignarra | Research Associate |
| Alden Fan | Research Associate |
| Wei Ji | Graduate Student |
| TJ Whitis | Graduate Student |

## LIP Coimbra

| | |
|---|---|
| Isabel Lopes | PI, Professor |
| José Pinto de Cunha | Assistant Professor |
| Vladimir Solovov | Senior Researcher |
| Alexandre Lindote | Postdoc |
| Francisco Neves | Auxiliary Researcher |
| Claudio Silva | Research Fellow |
| Paulo Bras | Graduate Student |

## PennState

| | |
|---|---|
| Carmen Carmona | PI, Assistant Professor |
| Emily Grace | Postdoc |

## SD Mines

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

| | |
|---|---|
| Xinhua Bai | PI, Professor |
| Douglas Tiedt | Graduate Student |

## SDSTA / Sanford Lab

| | |
|---|---|
| David Taylor | Senior Engineer |
| Markus Horn | Research Scientist |

## UNIVERSITY AT ALBANY

State University of New York

| | |
|---|---|
| Matthew Szydagis | PI, Assistant Professor |
| Cecilia Levy | Postdoc |
| Jack Genovesi | Research Assistant |

## TEXAS A&M UNIVERSITY

| | |
|---|---|
| Robert Webb | PI, Professor |
| Paul Terman | Graduate Student |

## Berkeley

| | |
|---|---|
| Daniel Mckinsey | PI, Professor |
| Ethan Bernard | Project Scientist |
| Elizabeth Boulton | Graduate Student |
| Junsong Lin | Postdoc |
| Brian Tennyson | Graduate Student |
| Lucie Tvrznikova | Graduate Student |
| Vetri Velan | Graduate Student |

## UCDAVIS

UNIVERSITY OF CALIFORNIA

| | |
|---|---|
| Mani Tripathi | PI, Professor |
| Aaron Manalaysay | Project Scientist |
| James Morad | Ex-Graduate Student |
| Sergey Uvarov | Ex-Graduate Student |
| Jacob Cutter | Graduate Student |
| Dave Hemer | Senior Machinist |

## WISCONSIN

UNIVERSITY OF WISCONSIN–MADISON

| | |
|---|---|
| Kimberly Palladino | PI, Assistant Professor |
| Shaun Alsum | Graduate Student |
| Rachel Mannino | Postdoc |

## UC SANTA BARBARA

| | |
|---|---|
| Harry Nelson | PI, Professor |
| Sally Shaw | Postdoc |
| Scott Haselschwardt | Graduate Student |
| Curt Nehrkorn | Graduate Student |
| Melih Solmaz | Graduate Student |
| Dean White | Engineer |
| Susanne Kyre | Engineer |

## UCL University College London

| | |
|---|---|
| Chamkaur Ghag | PI, Professor |
| Jim Dobson | Postdoc |
| Umit Utku | Graduate Student |

## UNIVERSITY OF MARYLAND

| | |
|---|---|
| Carter Hall | PI, Professor |
| Jon Balajthy | Graduate Student |

| | |
|---|---|
| Scott Hertel | PI, Assistant Professor |
| Christopher Nedlik | Graduate Student |

## UNIVERSITY of ROCHESTER

| | |
|---|---|
| Frank Wolfs | PI, Professor |
| Wojtek Skulski | Senior Scientist |
| Eryk Druszkiewicz | Electrical Engineer |
| Dev Aashish Khaitan | Graduate Student |
| Mongkol Moongweluwan | Graduate Student |

## University of Sheffield

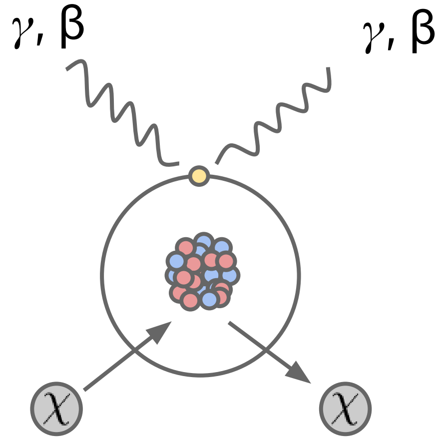
| | |
|---|---|
| Vitaly Kudryavtsev | Reader, Particle Physics |
| Elena Korolkova | Research Associate |
| David Woodward | Research Associate |
| Peter Rossiter | Graduate Student |

## UNIVERSITY OF SOUTH DAKOTA

| | |
|---|---|
| Dongming Mei | PI, Professor |

# Back up

# WIMP dark matter



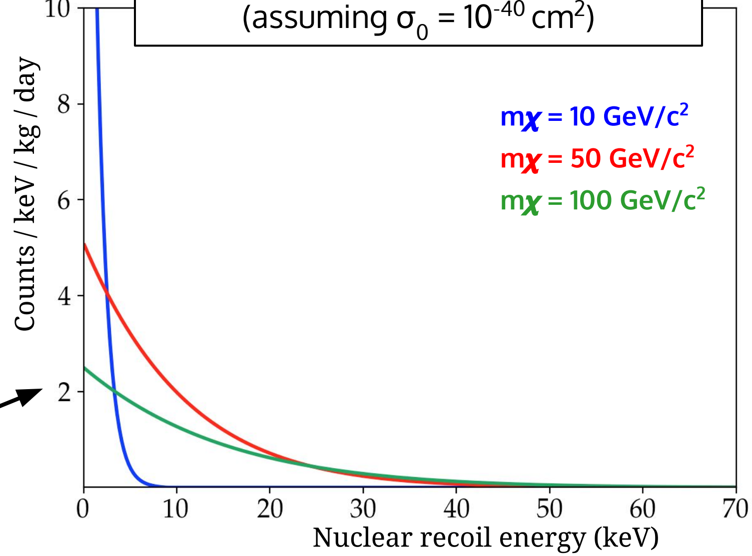
## **W**eakly **I**nteracting **M**assive **P**articles

- **New neutral particle, beyond the standard model**
- **Weak-scale interaction cross-section** gives us the right amount of dark matter
- Predicted to produce **NUCLEAR RECOILS** (no EM interactions)
- Most backgrounds ($\gamma$'s and β's from radioactive decay) produce **ELECTRON RECOILS**

**Assumptions**

- Weak scale scattering cross section with nuclei
- Mass density ~ 0.3 GeV/$c^2$/$cm^3$
- Maxwellian velocity distribution with $v_0$ = 220 km/s
- Velocity distribution truncated at galactic escape velocity

WIMP scattering rate
(assuming $\sigma_0 = 10^{-40}$ $cm^2$)



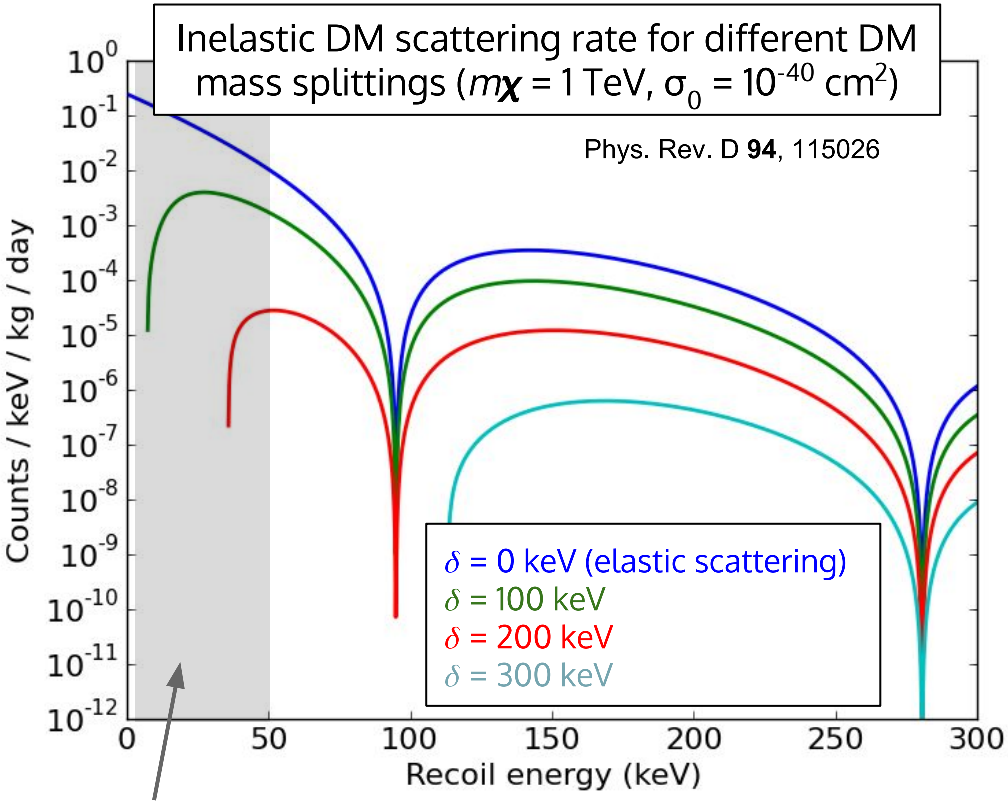
# Possible future searches with higher energy nuclear recoils

**Dark matter inelastic scattering:**

- $\chi + N \rightarrow \chi^* + N$
- Kinematically suppresses low-energy recoils

These searches would require us to extend our acceptance at higher energies

Larger window could introduce new/more backgrounds


Inelastic DM scattering rate for different DM mass splittings ($m_\chi$ = 1 TeV, $\sigma_0 = 10^{-40}$ cm$^2$)

Phys. Rev. D **94**, 115026

Published LUX analysis region

# Liquid xenon TPC advantages

**Low threshold**

  - Can detect events that produce 10’s of scintillation photons and 1’s of ionization electrons

**Low background**

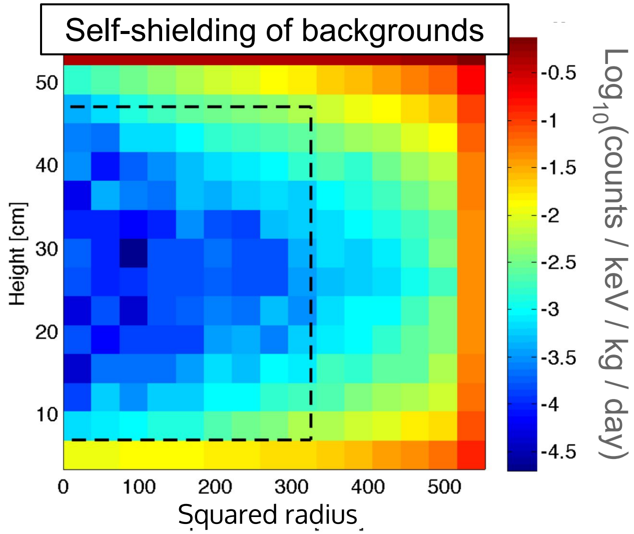
  - No long-lived radioactive xenon isotopes
  - High-Z and high density provides self-shielding in large detectors

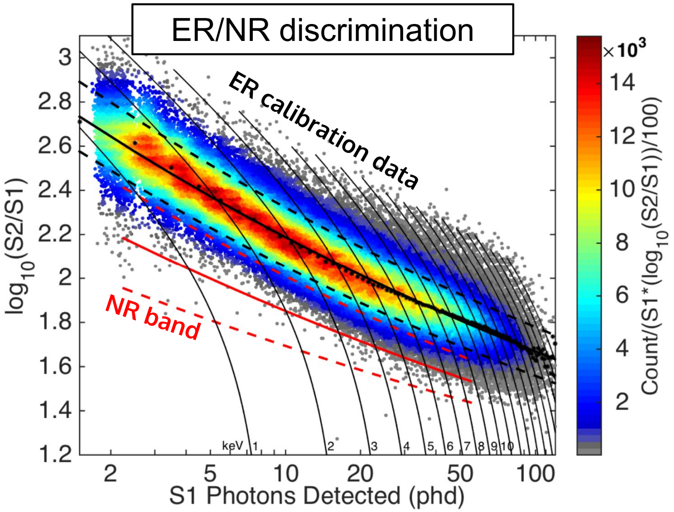
**Scalable technology**

  - ~20 years development experience
  - Ton-scale detectors are in operation

**Particle ID (ER/NR) capabilities**

  - Charge/light ratio (~99.9% rejection)
  - PSD???


Self-shielding of backgrounds


ER/NR discrimination

# LXe scintillation physics

**Emission** can be modeled as:

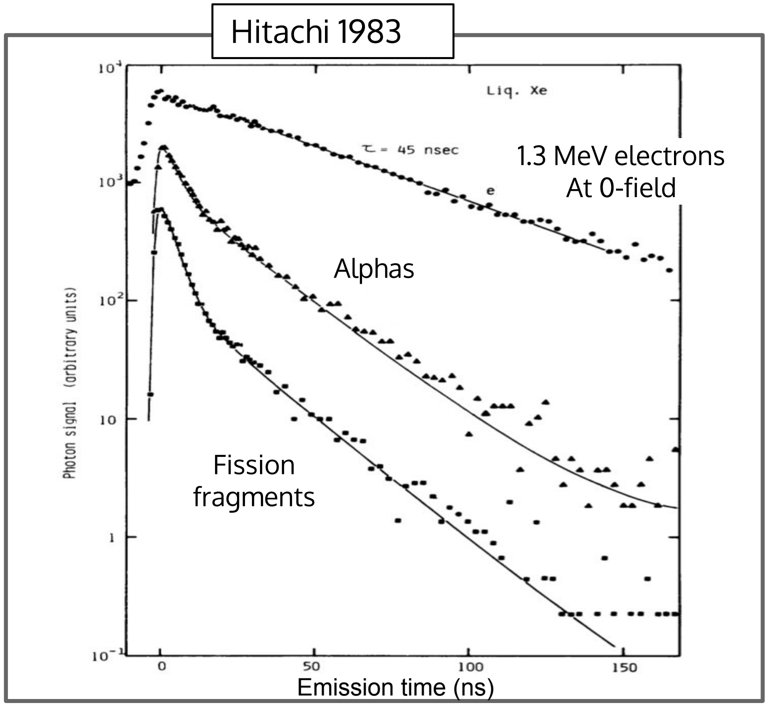
$$P(t) = C_1\, e^{-t/\tau_1} + C_3\, e^{-t/\tau_3}$$

with three free parameters:

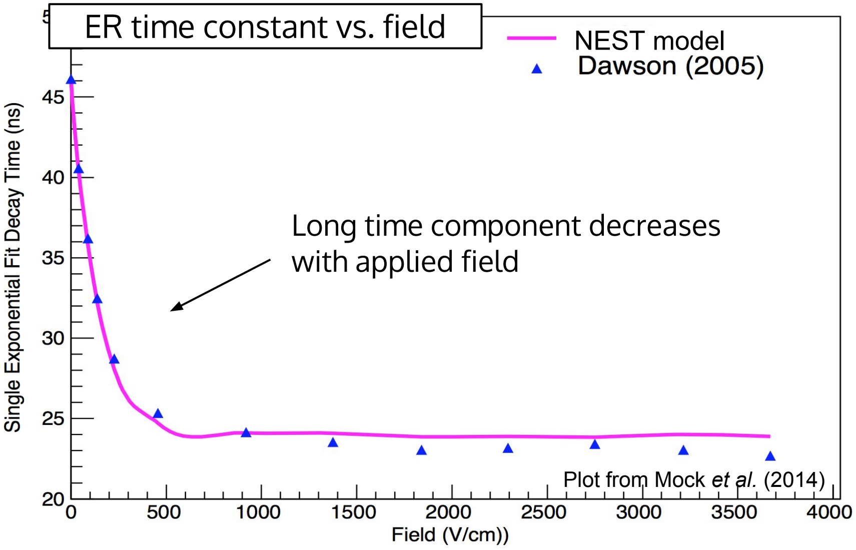
- Singlet time $\boldsymbol{\tau}_1$
- Triplet time $\boldsymbol{\tau}_3$
- Singlet/triplet ratio $(C_1\boldsymbol{\tau}_1)/(C_3\boldsymbol{\tau}_3)$

**Recombination** of electrons and ions can contribute to timing

- Only observed in electron recoils (ER)
- Suppressed by applied electric field and high LET at low energies
    - NEST model (Mock et al.) predicts ~1ns effect in LUX data
- We treat it as a different $\boldsymbol{\tau}_3$ for ER and NR



Plot from Hitachi (1983)



Long time component decreases with applied field

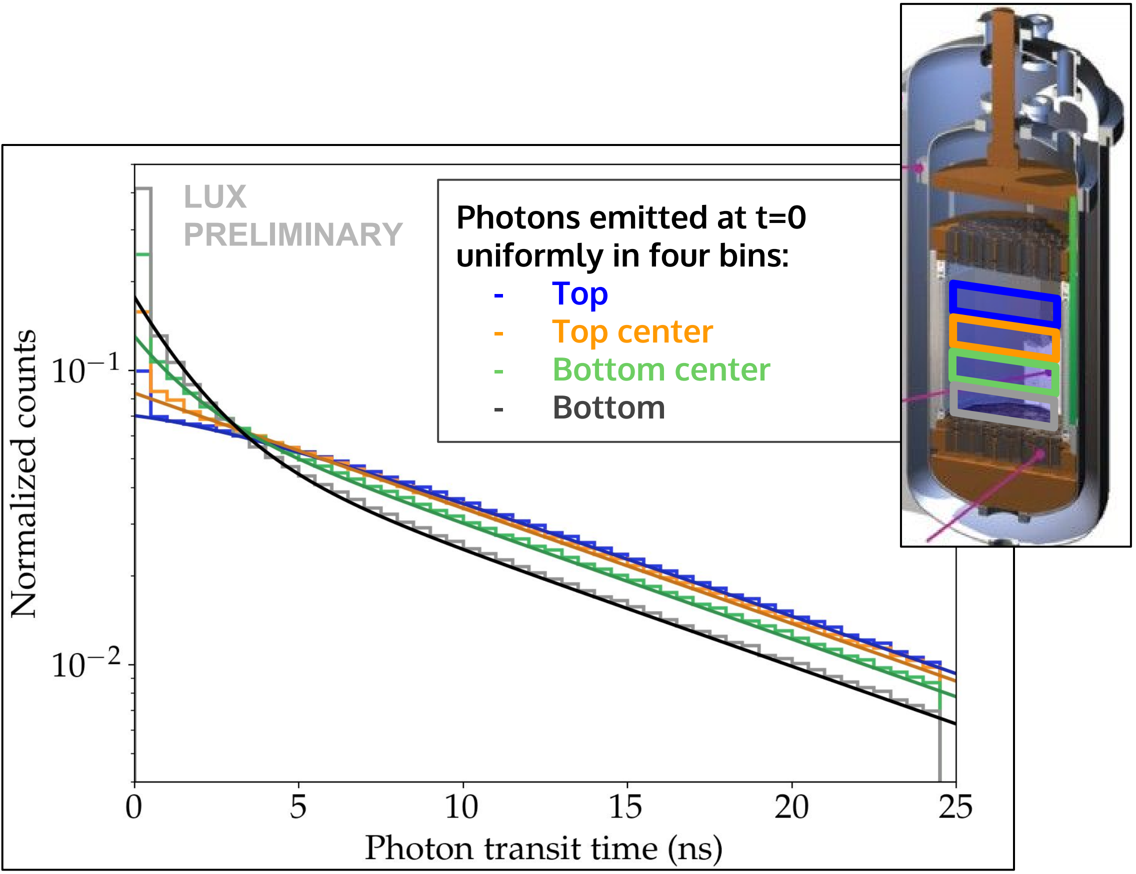
Plot from Mock *et al.* (2014)

# Optical transport

Photons in LUX typically scatter before arriving in PMTs.

Studied using ray-tracing simulations in LUXSim (LUX Geant4 simulation package)

- Direct-path transit time subtracted
- Short-time behavior driven by geometric efficiency of bottom PMTs



Sims are fit to an analytic model for easy convolution and simulation.

$A$ = direct-hit fraction

$B_a$ = weights exponential terms

$B_b$ = ( 1 - $B_a$ )

$\tau_a$ = long-time constant ( 11.2 ns )

$\tau_b$ = short-time constant (varies to fit short-time behavior)

$$P_o(t) = A\,\delta(t) + (1-A)\left[\frac{B_a}{\tau_a}\,e^{-t/\tau_a} + \frac{B_b}{\tau_b}\,e^{-t/\tau_b}\right]$$