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

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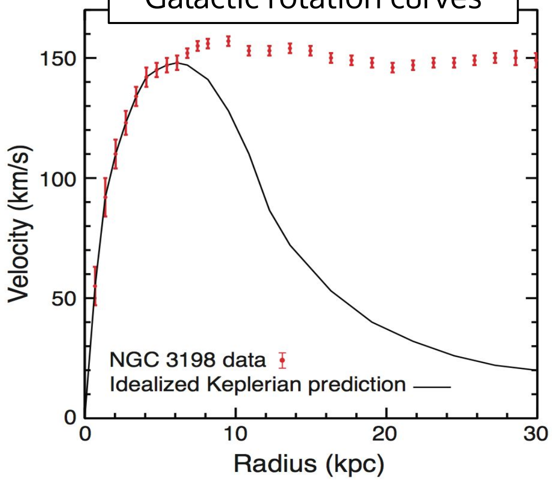
Outline

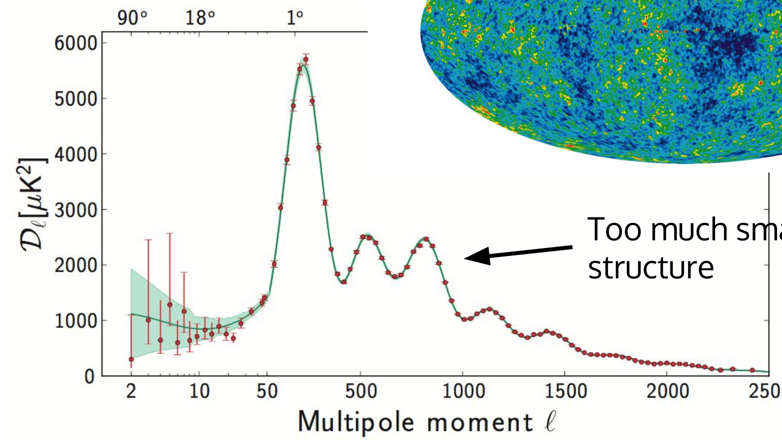
- WIMP dark matter
- The LUX experiment
- Analysis of scintillation pulse shapes
- Testing background rejection using pulse shape discrimination

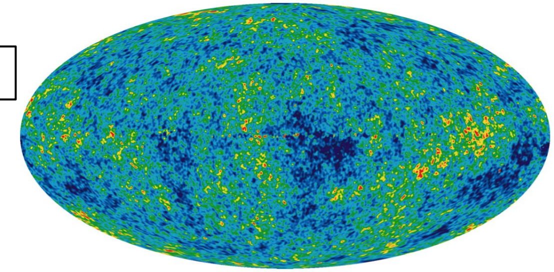
Dark matter

Galactic rotation curves



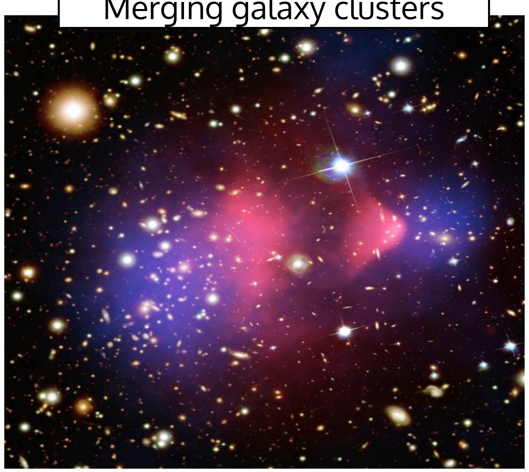
Comsic microwave background





Too much small-scale structure

Merging galaxy clusters



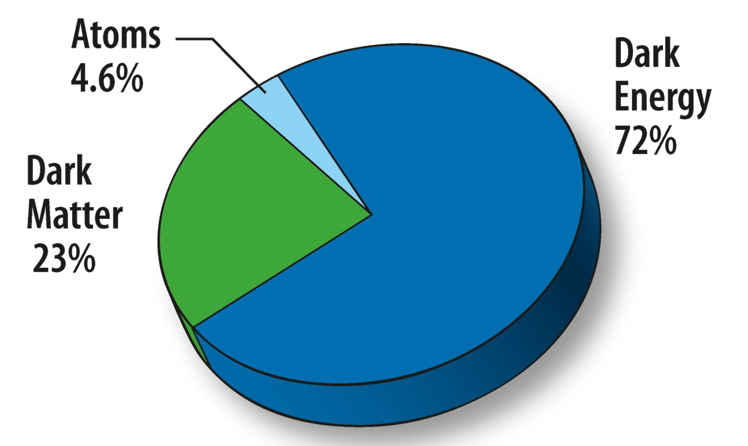
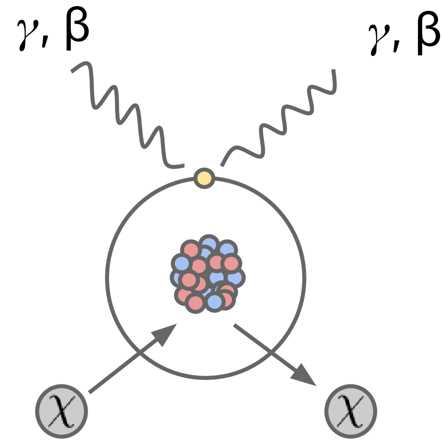


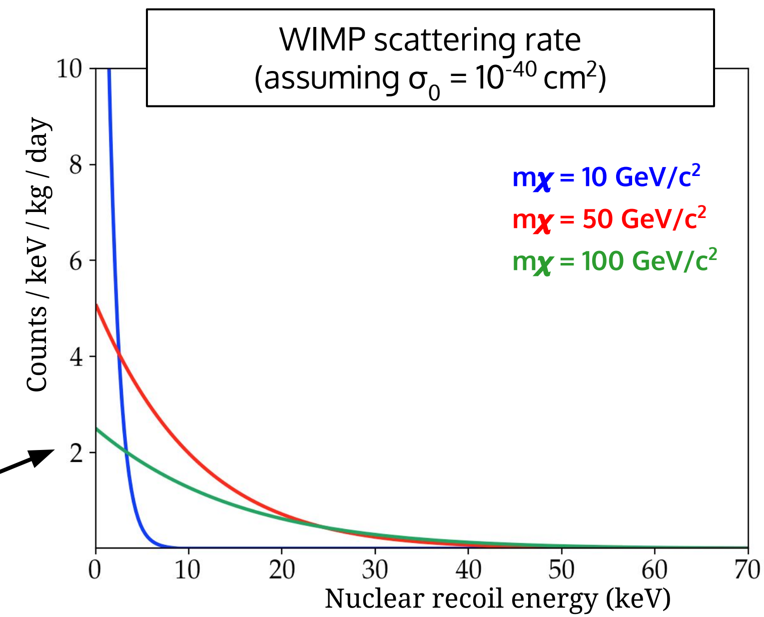
Chart from WMAP

WIMP dark matter



Weakly **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 (γ'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

Dual-phase xenon TPC detectors

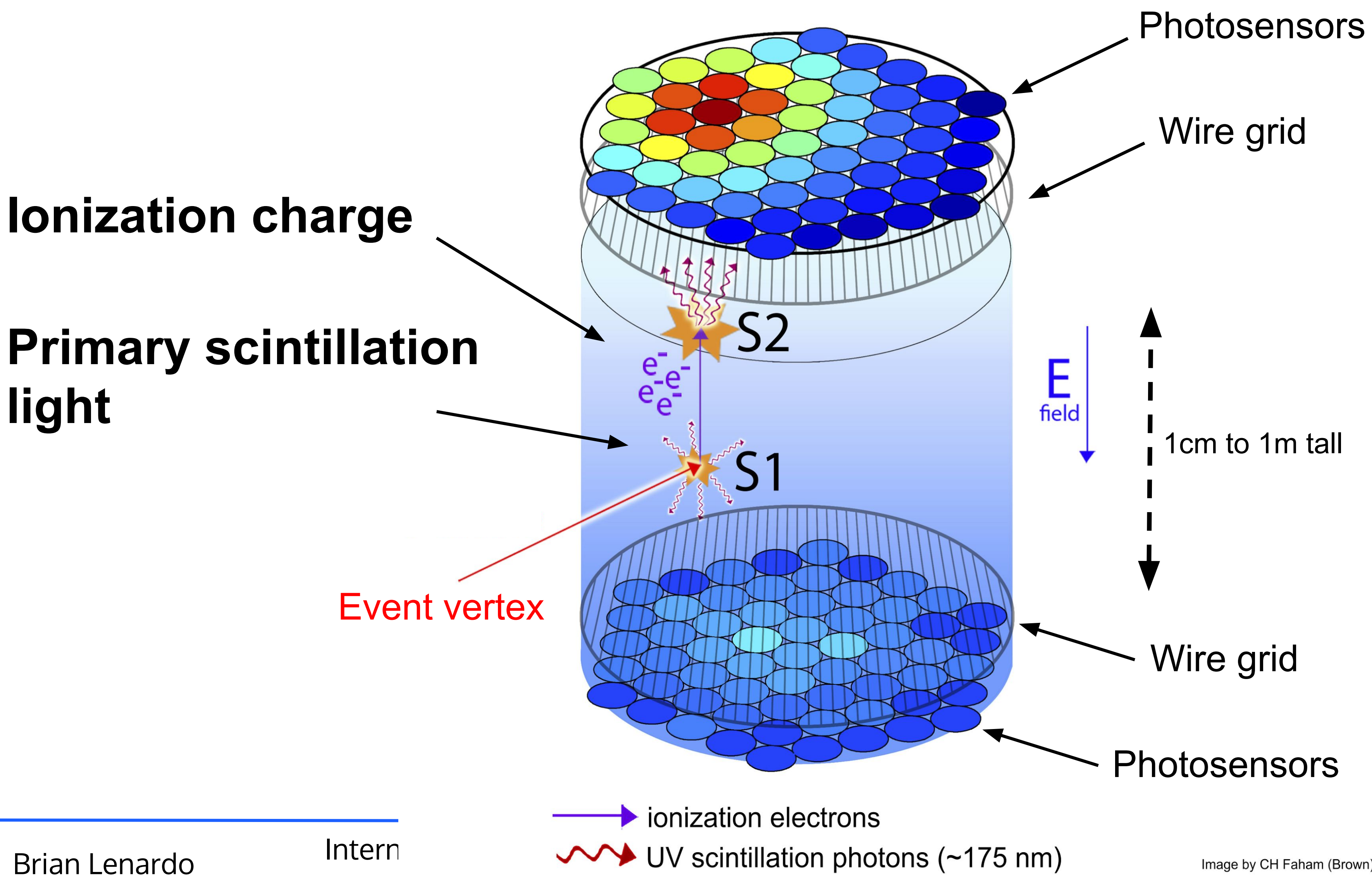
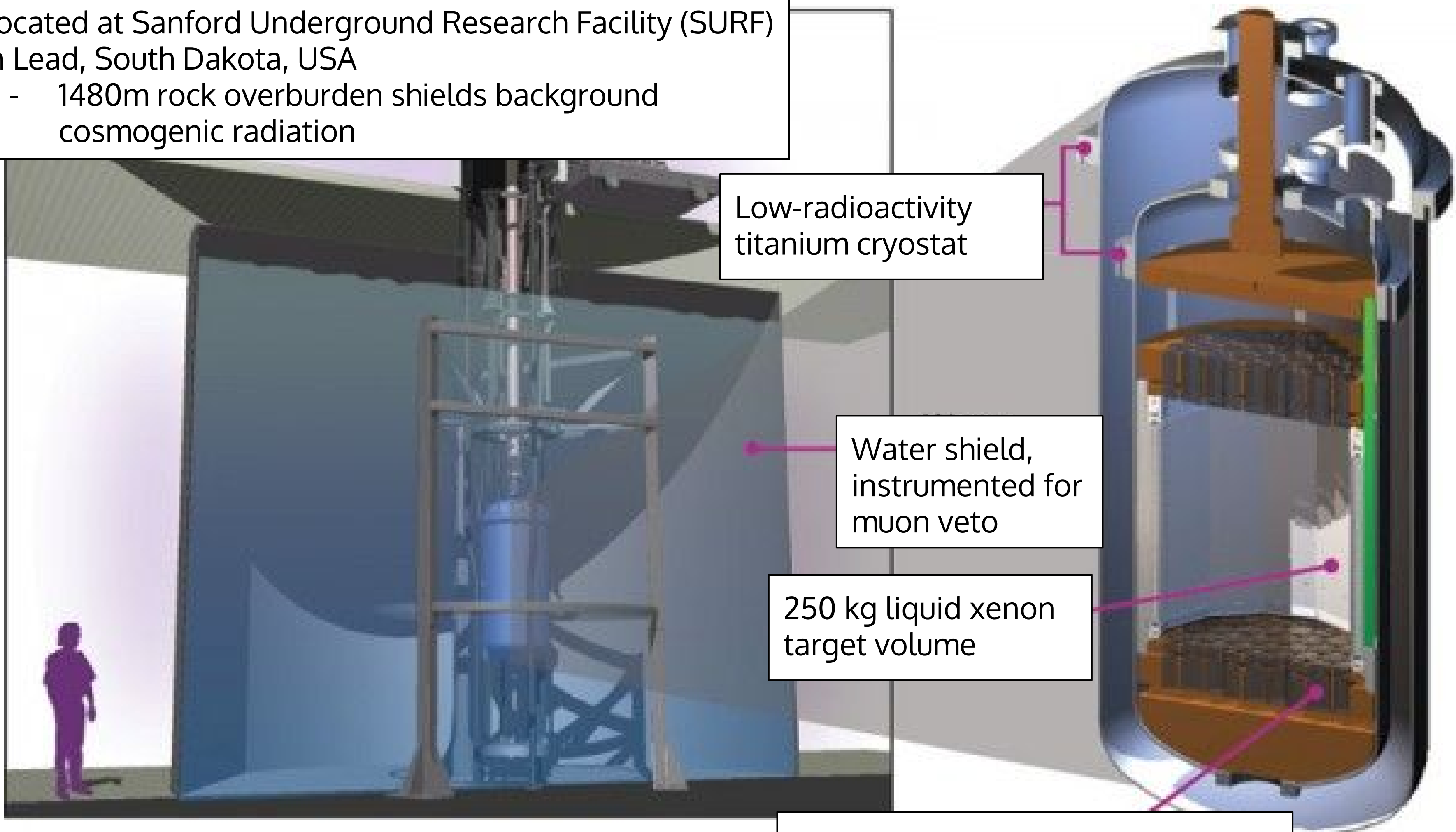


Image by CH Faham (Brown)

The LUX Experiment

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

- 1480m rock overburden shields background cosmogenic radiation



The LUX collaboration

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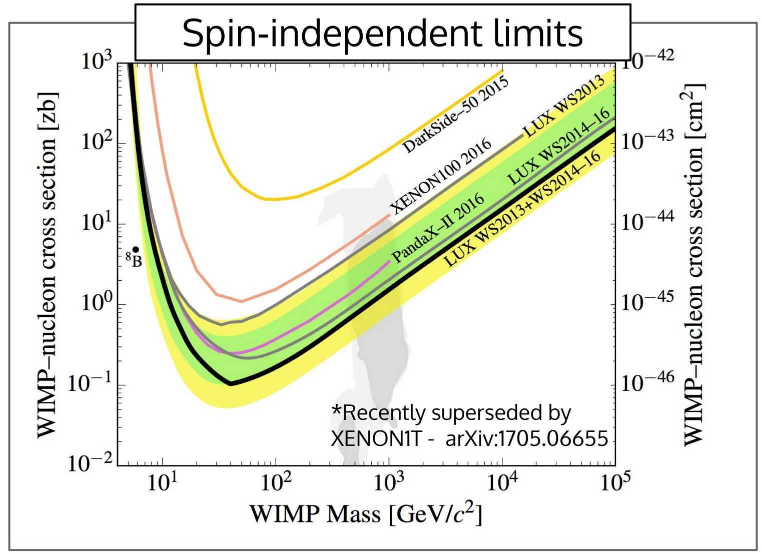
Dark matter results from LUX

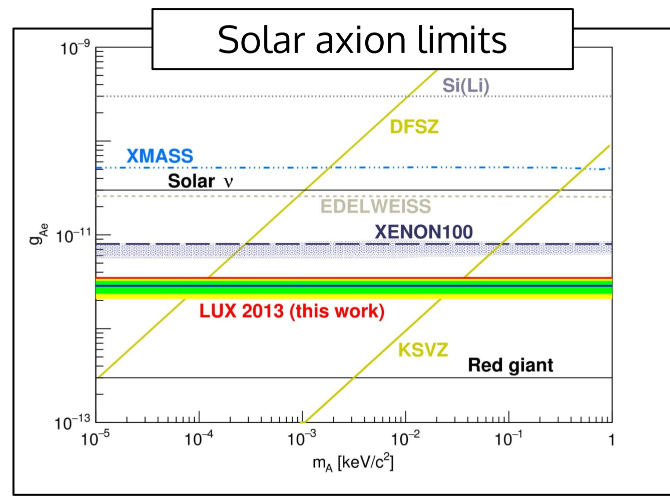
World-leading upper limits on dark matter interactions!

- Spin-independent WIMP scattering
  - *PRL **118**, 021303 (2017)*
- Spin-dependent WIMP scattering
  - *Accepted by PRL (2017)*
- Axions and axion-like-particles
  - *Accepted by PRL (2017)*



Pioneering in-situ calibration techniques

- Dissolved radioactive sources for in-situ detector stability and background response calibrations
  - *PRD **93**, 072009 (2016)*
- High-precision nuclear recoil calibration using DD neutrons
  - *arXiv:1608.05381, submitted to PRC*

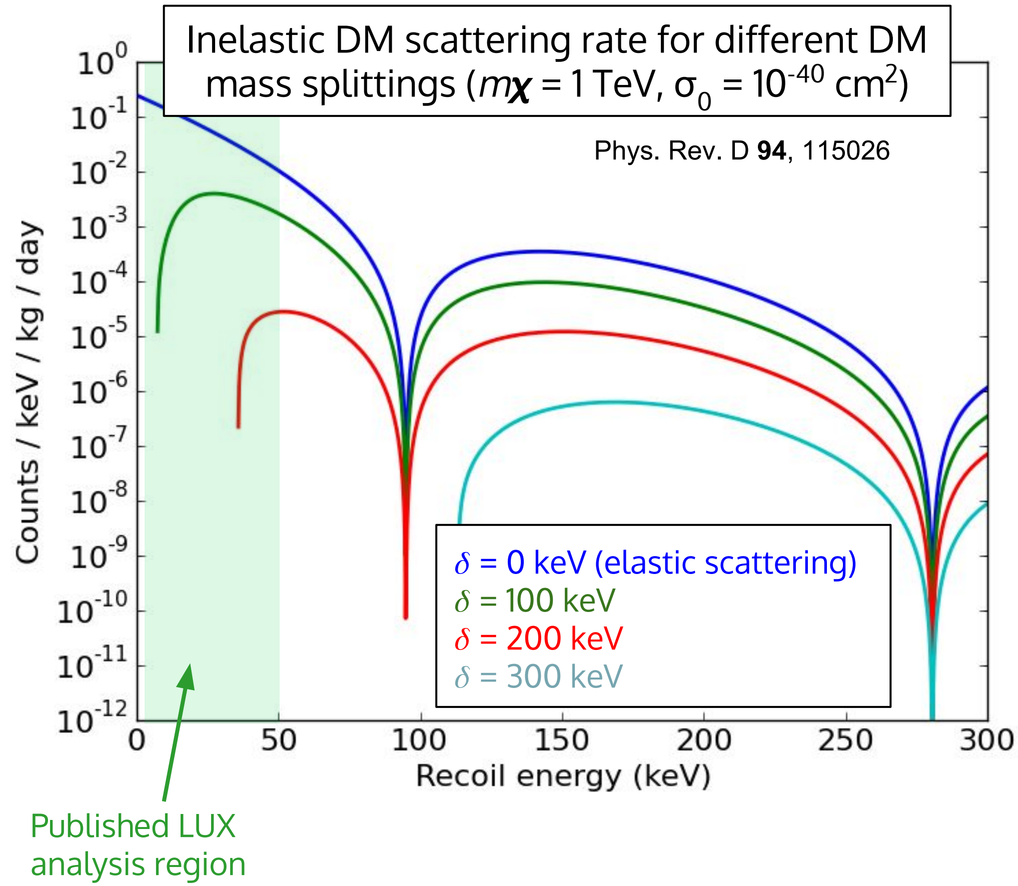


Possible future searches with higher energy nuclear recoils

Dark matter inelastic scattering:

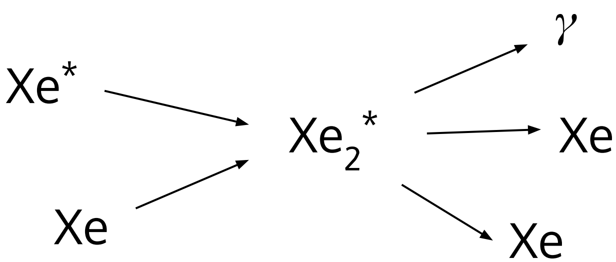
- $\chi + N \rightarrow \chi^* + N$
- Kinematically suppresses low-energy recoils

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



Scintillation pulse shape discrimination

S1 scintillation pulse shape discrimination



Xenon scintillates via dimer de-excitation from two excited states:

- Singlet state (~3ns)
- Triplet state (~24ns)

Relative amount of each state is different depending on recoil type, allowing for pulse shape ER/NR discrimination.

Discrimination improves with energy, due to photon statistics

Successfully used by XENON10 in a search for inelastic dark matter out to 74 keV

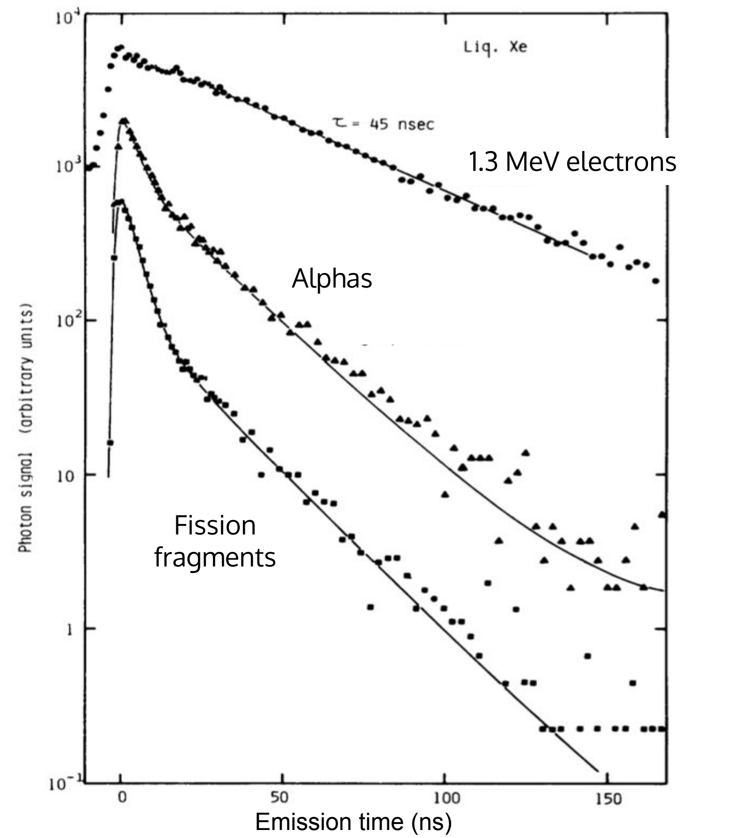


FIG. 4. Decay curves obtained for the luminescence from liquid xenon excited by electrons (●), α particles (▲), and fission fragments (■).

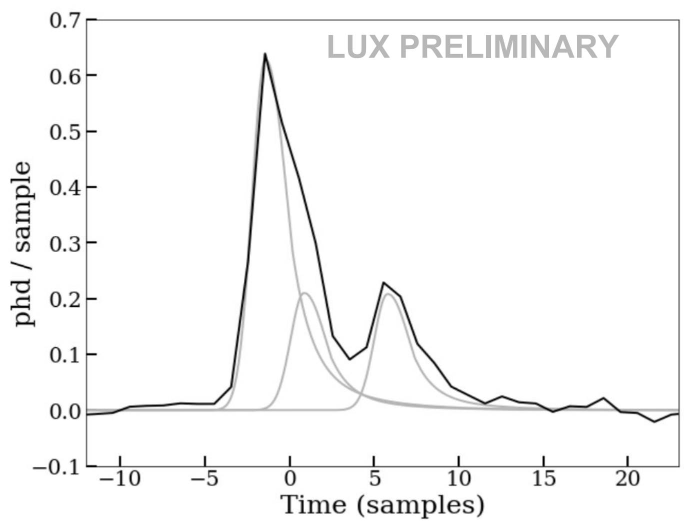
Hitachi 1983

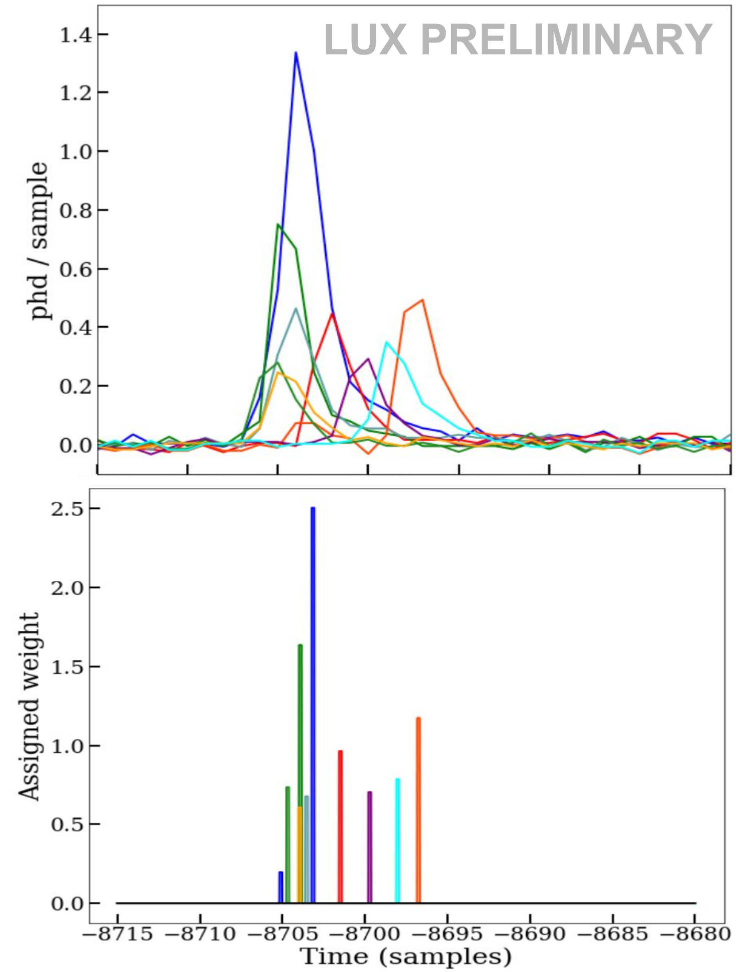
Scintillation PSD analysis in LUX

We aim to:

- **Develop an algorithm for precision timing** of individual photons
- **Build a model of photon arrival times** that decouples xenon scintillation physics from detector effects
- **Fit that model to data** to better understand xenon scintillation physics at energies relevant to dark matter searches
- **Implement a prompt-fraction PSD technique** to reduce backgrounds in future dark matter search analyses

Photon timing algorithm

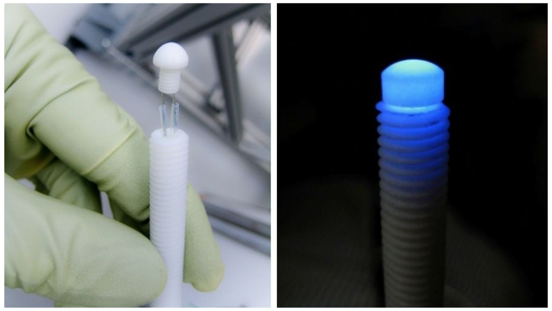




Template-fitting algorithm reconstructs arrival times

- Bayesian model selection algorithm used to resolve pile-up
  - 1.6ns precision for photons separated by >10ns (1 sample)
  - Pile-up resolved down to separations of 10ns (1 sample)
- Fitted area of templates used to correct for unresolved pile-up

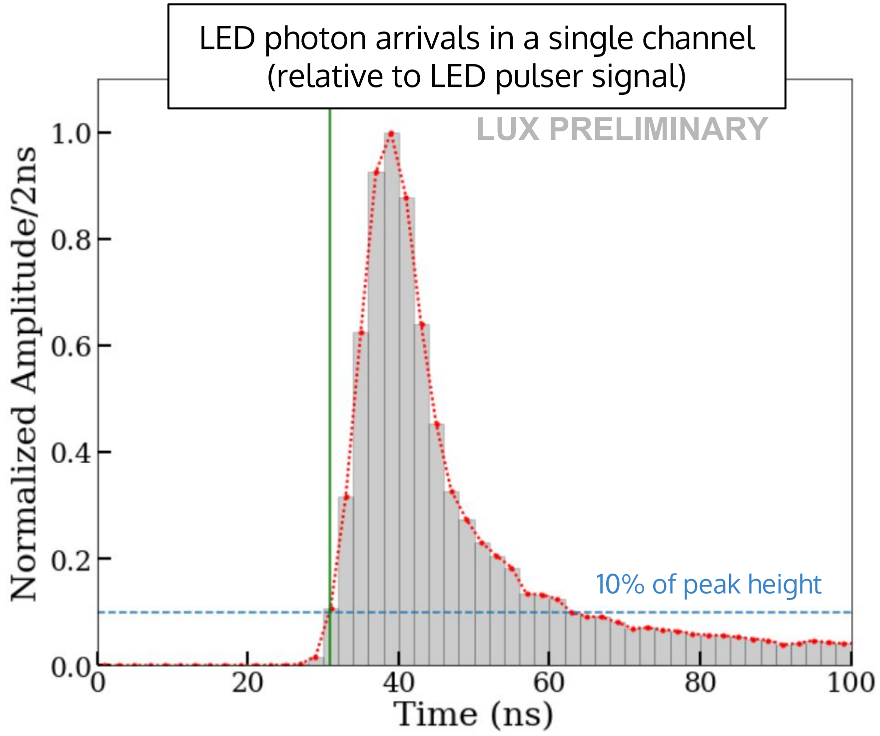
Timing calibration using LEDs



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

Timing calibration procedure:

1. Pulse LEDs with 20ns 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



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
- Optical transport

LXe physics:

- Time constants of singlet and triplet states
- Ratio of singlet/triplet states
- Recombination time?

Modeling pulse shapes

Detector effects:

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

  Add all of these in quadrature, treat as normally distributed smearing with total width σ
- Optical transport

LXe physics:

- Time constants of singlet and triplet states
- Ratio of singlet/triplet states
- Recombination time for ER?

Modeling pulse shapes

Detector effects:

- Timing resolution
  - PMT transit time spread
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- Optical transport

LXe physics:

- Time constants of singlet and triplet states
- Ratio of singlet/triplet states
- Recombination time for ER?

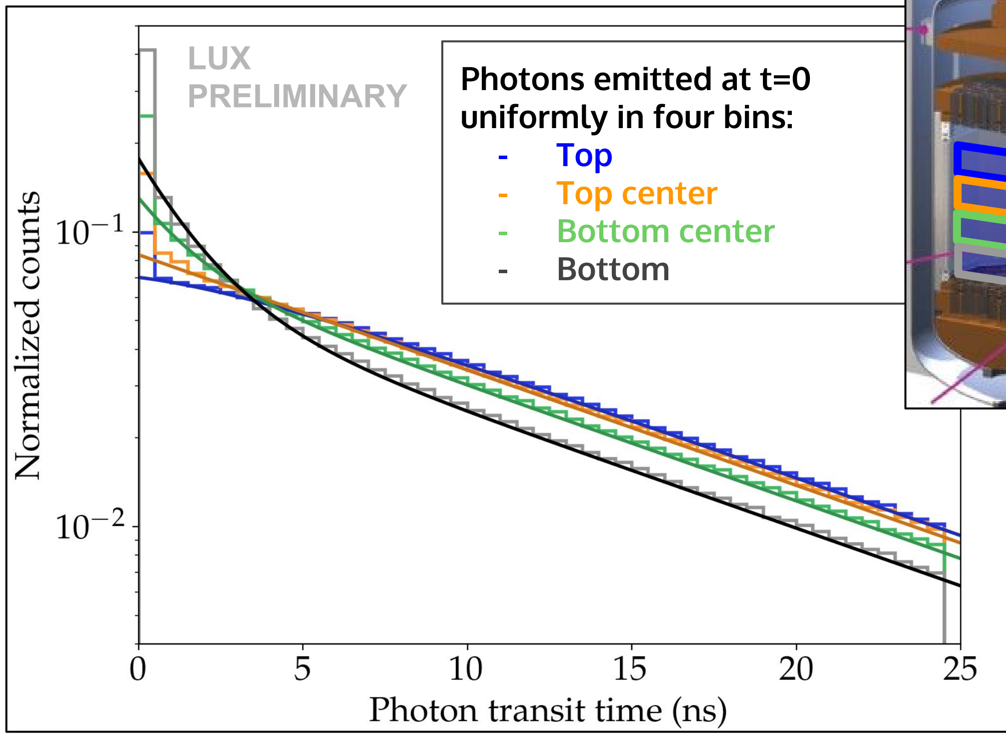
Optical transport

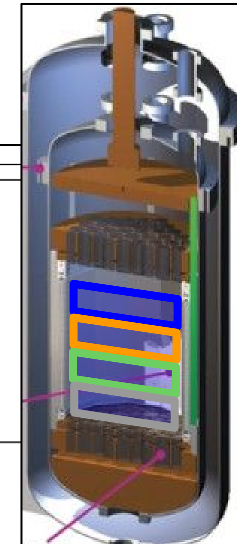
Photons in LUX typically scatter before arriving in PMTs.

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

$B_b = (1 - B_a)$

τ_a = long-time constant (11.2 ns)

τ_b = short-time constant (varies to fit short-time behavior)

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

Modeling pulse shapes

Detector effects:

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

LXe physics:

- Time constants of singlet and triplet states
- Ratio of singlet/triplet states
- Recombination time for ER?

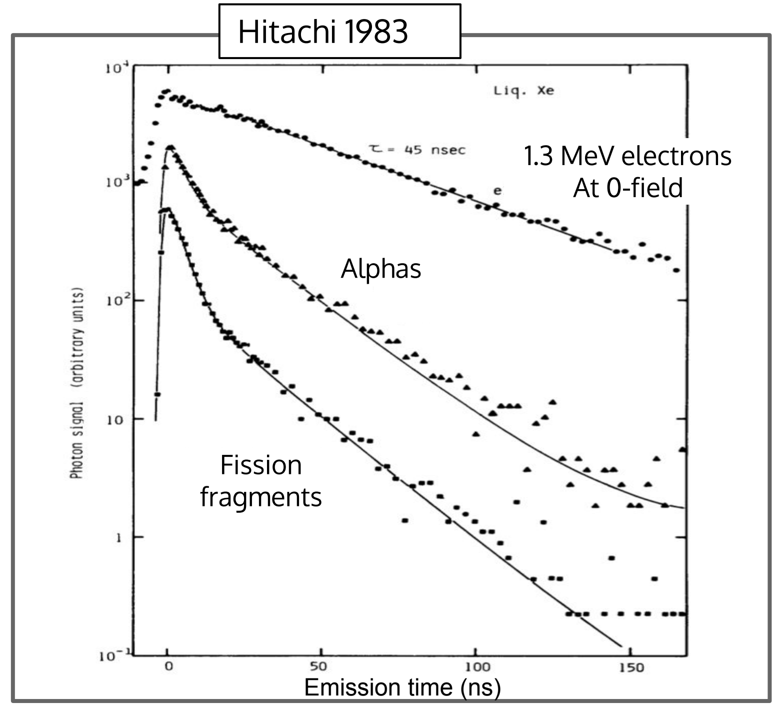
LXe physics

Emission can be modeled as:

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

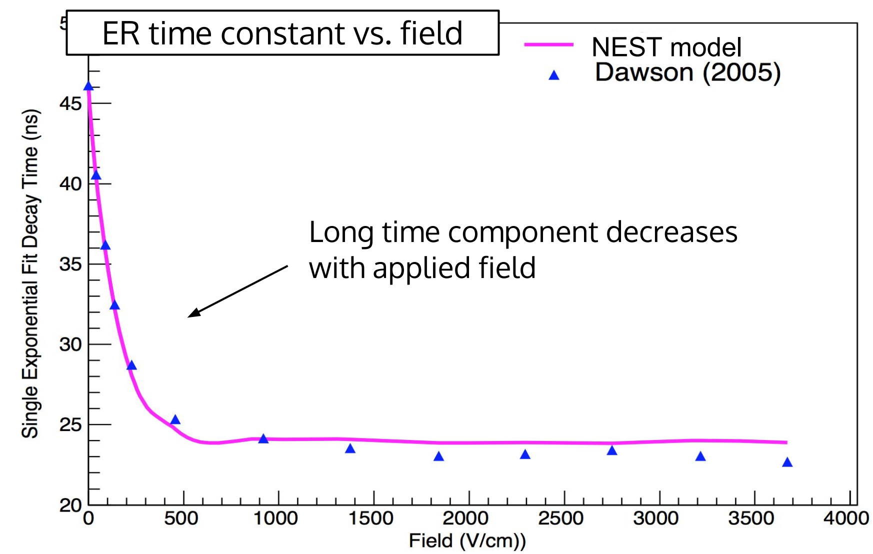
with three free parameters:

- 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



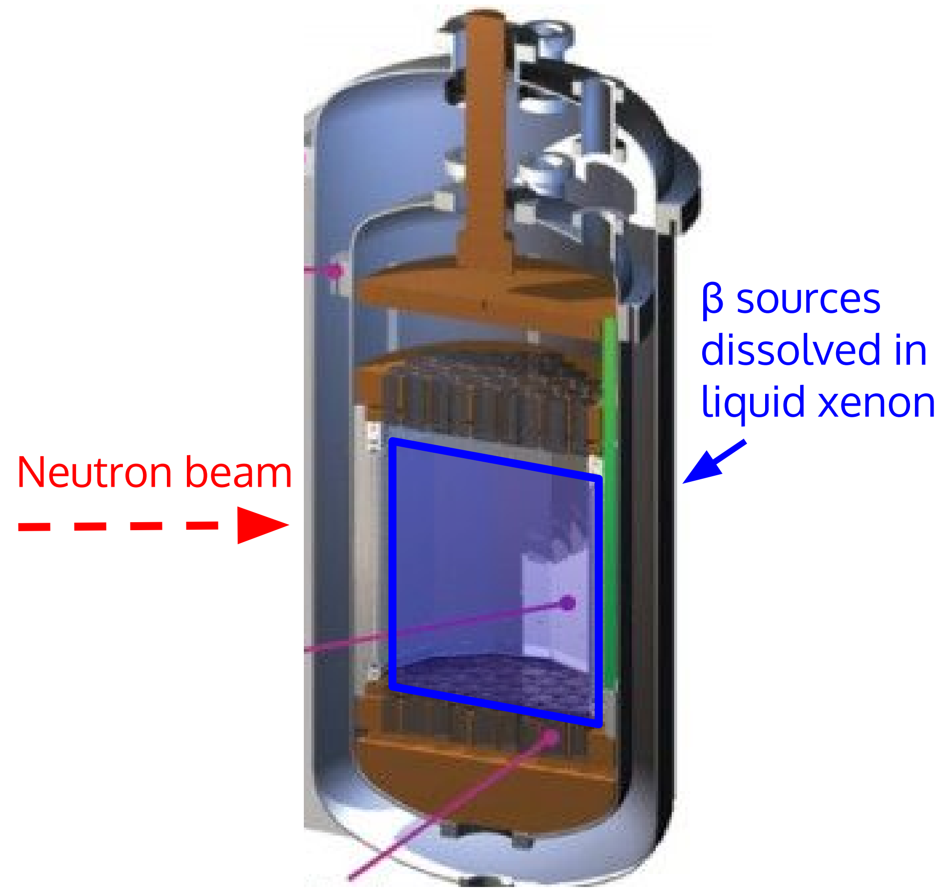
Fitting to ER/NR calibration data

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

- Tritiated / carbonated methane dissolved into liquid xenon circulation system
- Source removed by standard purification system
- Populates detector uniformly with electron recoils from beta decay (0 - 150 keV)



Fitting to calibration data

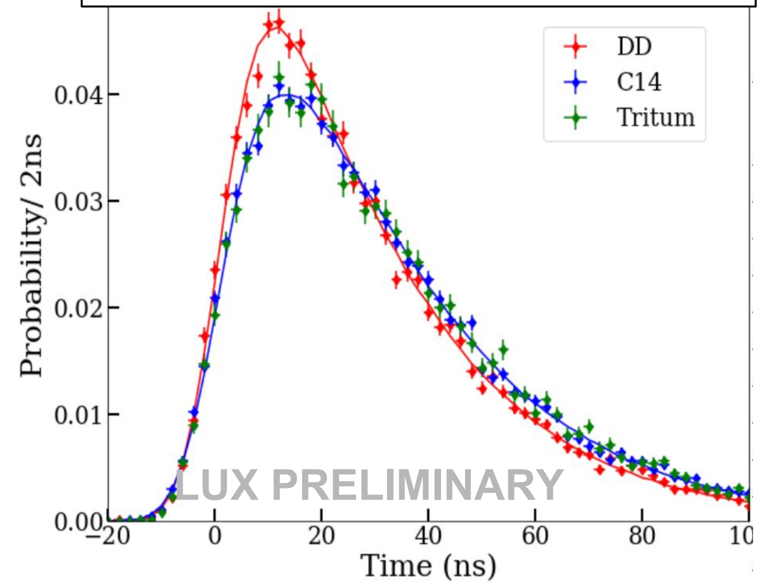
Create average S1 pulse shapes by histogramming arrival times from many calibration pulses

- Pulses lined up by 5% area time of summed waveform
- Bin pulses by size to create different histograms for different energies

Parameter	Expected
$(C_1\tau_1) / (C_3\tau_3)$ for ER	~0.1
$(C_1\tau_1) / (C_3\tau_3)$ for NR	~1.52 (at ~100 MeV)
τ_1	2.2 - 4.3 ns *
τ_3 for ER	21 - 27 ns *
τ_3 for NR	21 - 27 ns *
σ	≥ 3.1 ns

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

Averaged pulse shapes between 40-50 phd



Fully convolved pulse shape model

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

Fit results

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

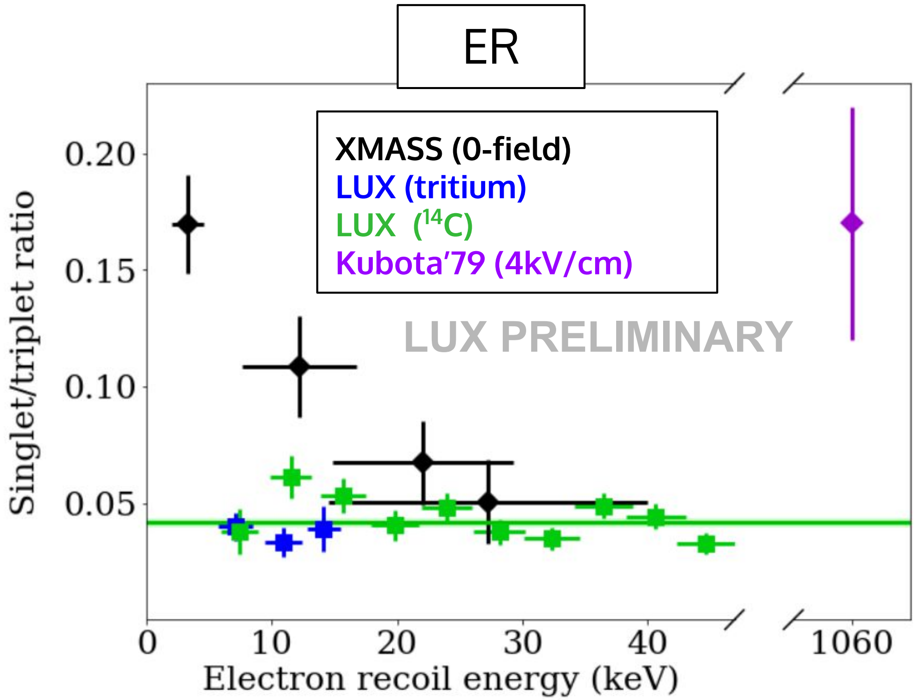
- Allows us to vary parameters common among different energy / particle type bins (i.e. σ, τ_1, etc.)

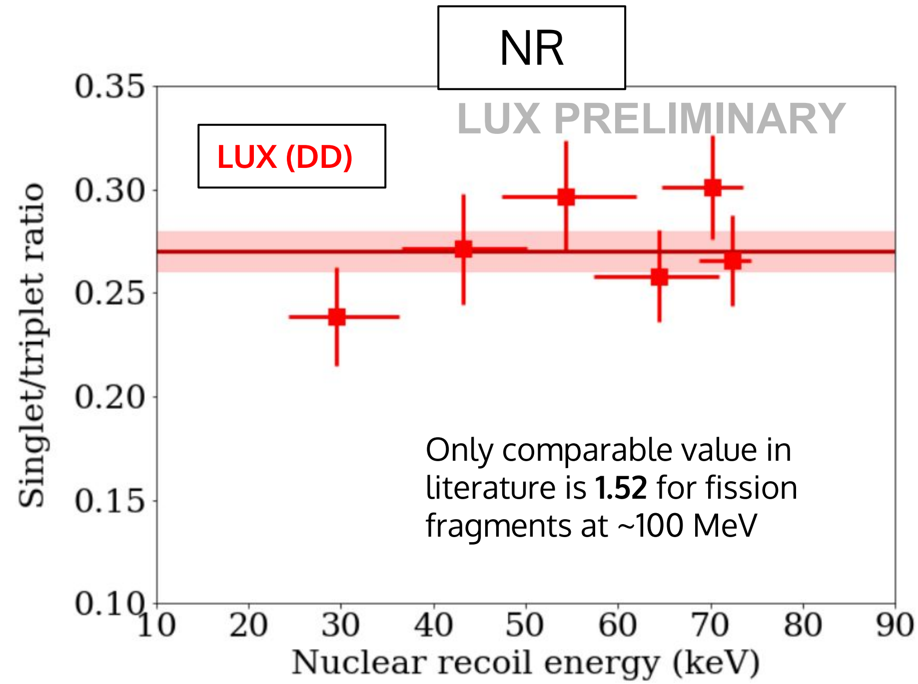
LUX PRELIMINARY

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%	In progress
$(C_1\tau_1) / (C_3\tau_3)$ for NR	~1.52 (at ~100 MeV)	0.269 +/- 0.034	+/-3.1%	---
τ_1	2.2 - 4.3 ns *	3.27 +/- 0.66 ns	+/-1%	---
τ_3 for ER	21 - 27 ns *	25.89 +/- 0.06 ns	+/-1.9%	---
τ_3 for NR	21 - 27 ns *	23.97 +/- 0.17 ns	+/-1.9%	---
σ	≥ 3.1 ns	3.59 +/- 0.09 ns	+/-1.1%	---

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

Singlet/triplet ratio energy dependence





Systematic errors still being evaluated. However, **three important preliminary results**:

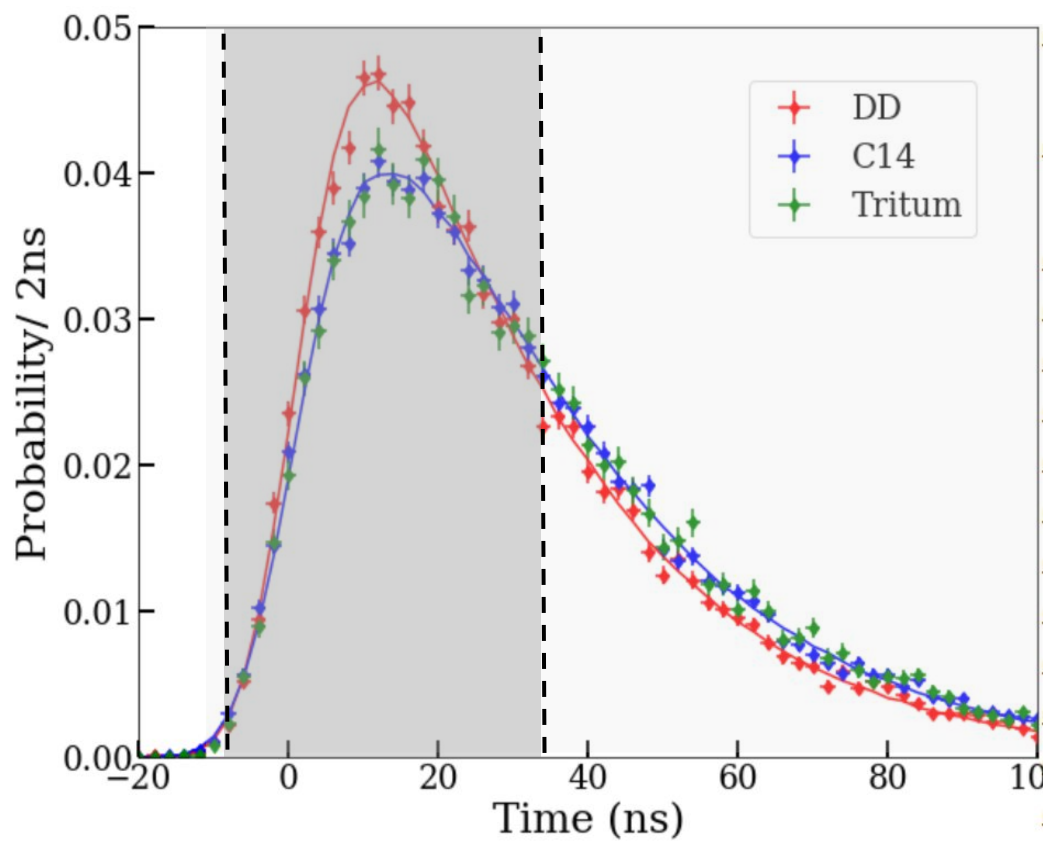
- **NR ratio is much smaller at low energies than published measurements made at high energies**
- **ER ratio has no significant energy dependence under applied field**
- **NR may show energy dependence?**

Prompt fraction discriminator

Prompt fraction discrimination windows:

- Prompt = -10 through 34 ns
- Total = -14 through 130 ns

Optimize the prompt window to maximize discrimination across all energies in our calibration data (0-74keV nuclear recoils)



Building a Monte Carlo

Need simulation code to generate arbitrary signal/background distributions for LUX dark matter searches.

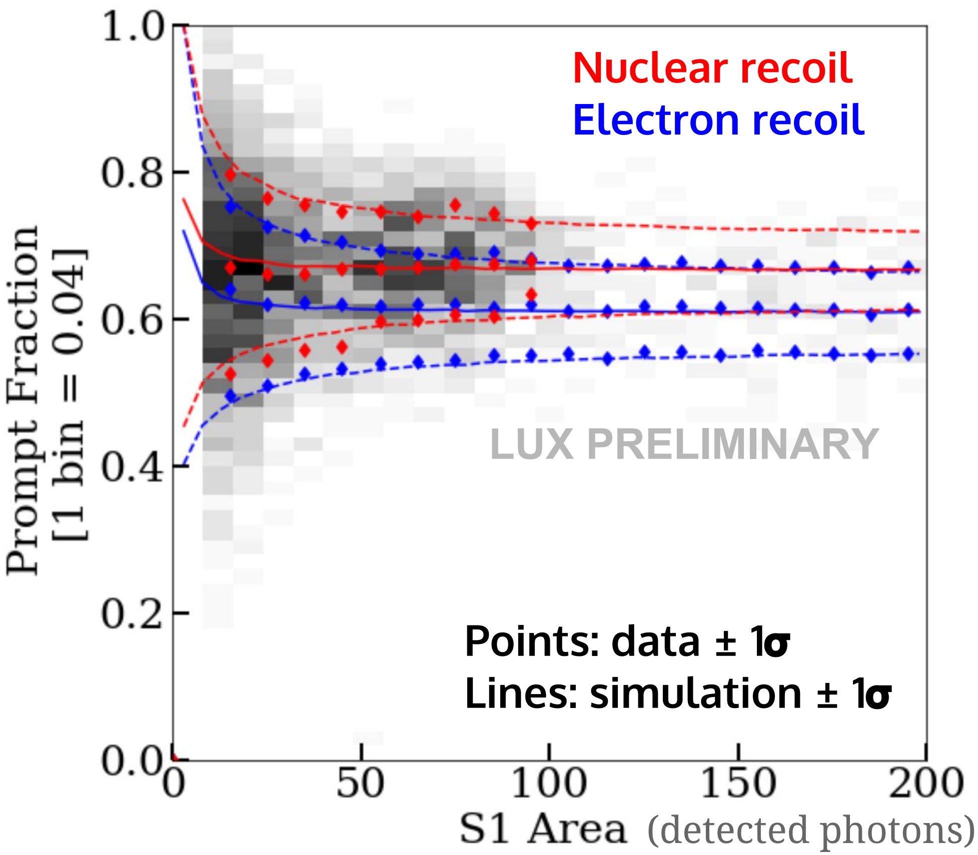
- Used to generate fake datasets in profile-likelihood statistical analysis

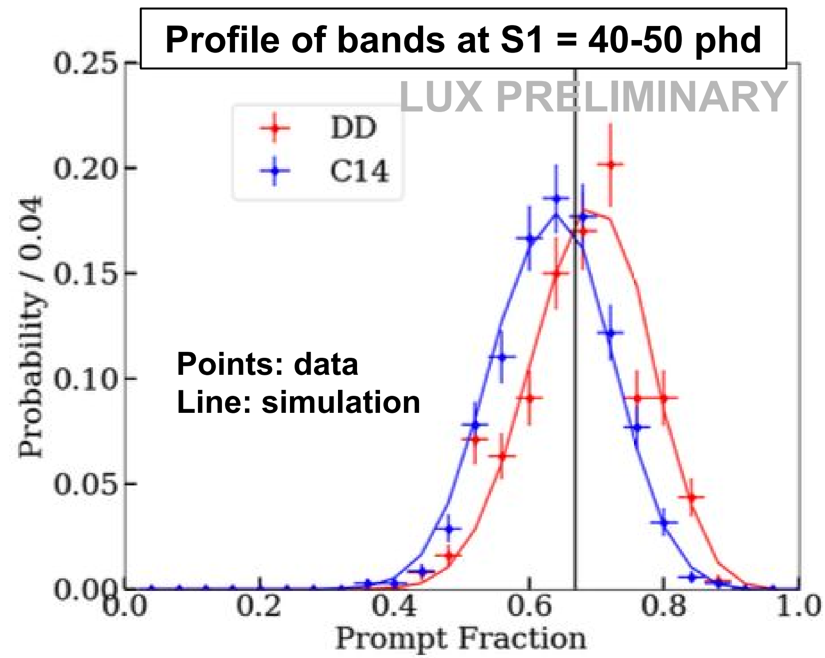
We built a toy MC that draws photon times from the best-fit timing distribution, also:

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

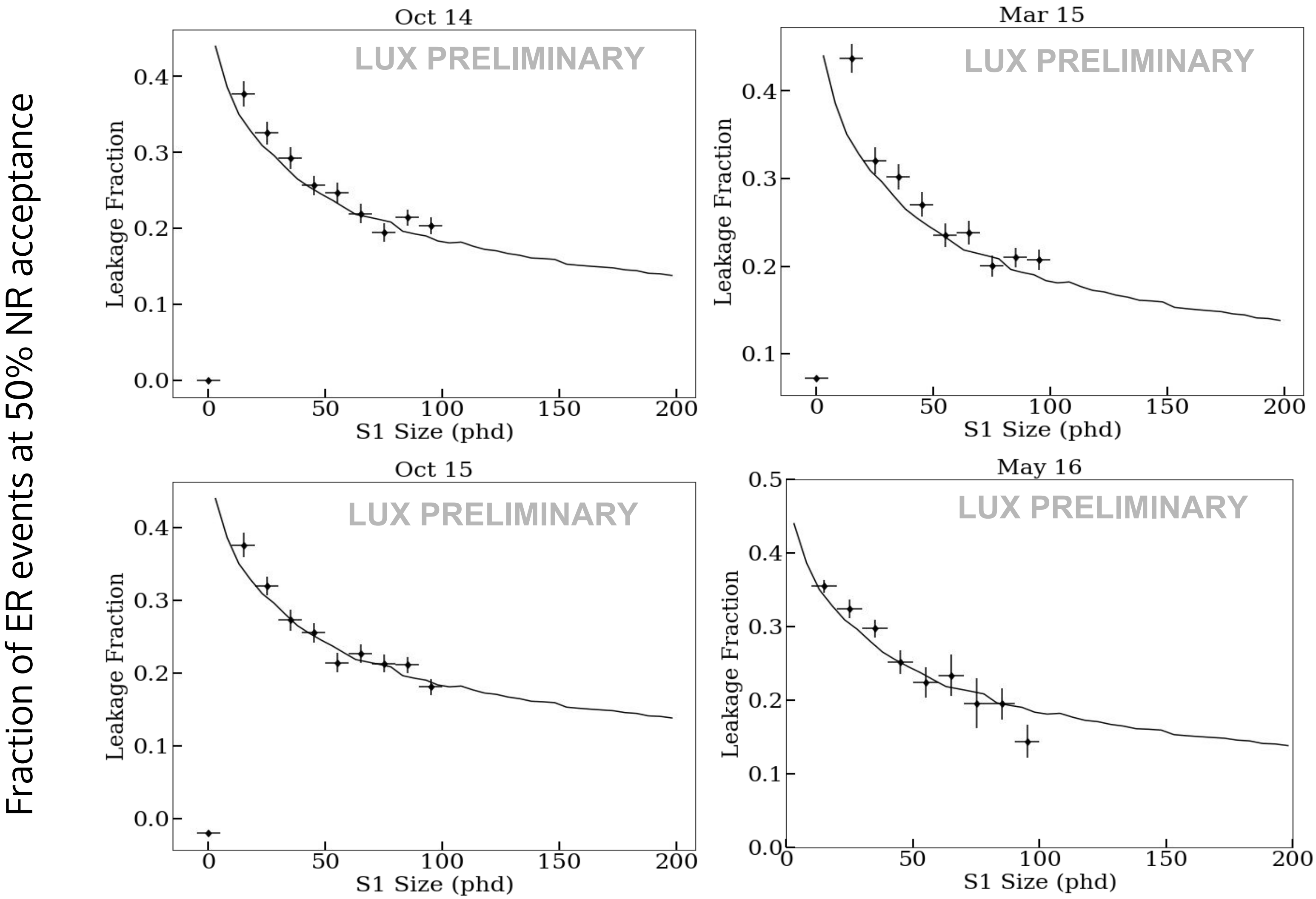
The simulation right now assumes a **constant in energy** singlet/triplet ratio for both ER and NR

Prompt fraction discrimination





ER leakage into NR 50% acceptance region



Summary

- We are interested in pulse shape discrimination for background rejection in high-energy 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)

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Back up

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???