ER/NR Discrimination in Liquid Xenon with the LUX Experiment

Vetri Velan

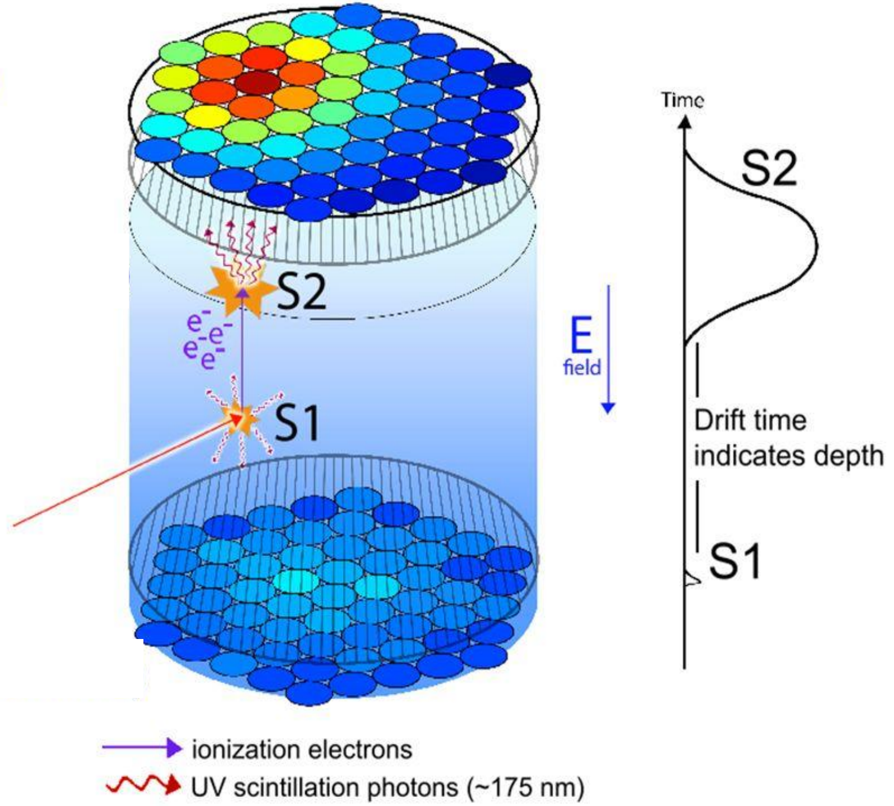
Identification of Dark Matter

July 23, 2018

Berkeley
UNIVERSITY OF CALIFORNIA

LUX

The Large Underground Xenon Experiment (LUX)



- Two-phase liquid/gas xenon time projection chamber
- 250 kg of active xenon
- Operated at Sanford Underground Research Facility in Lead, South Dakota
- Particle interactions produce two light signals:
  - Primary scintillation light (***S1***)
  - Secondary scintillation light (***S2***) from charge extracted in gas phase
- ***S1*** and ***S2*** detected by 122 photomultiplier tubes

LUX Operations

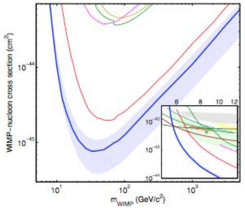
2006: LUX collaboration formed

2008: LUX funded (DOE + NSF)

July 2012: LUX moves UG

April 2013: First science run starts

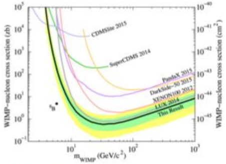
Nov 2013: First WS results reported (85.3 live-days)



PRL, 112, 091303 (2014)

Sept 2014: 332-day run start

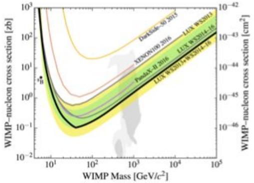
Dec 2015: Re-analysis of WS2013 published



PRL, 116, 161301 (2016)
PRL, 116, 161302 (2016)

May 2016: WS2014-16 finished

July 2016: 332-day WS result announced



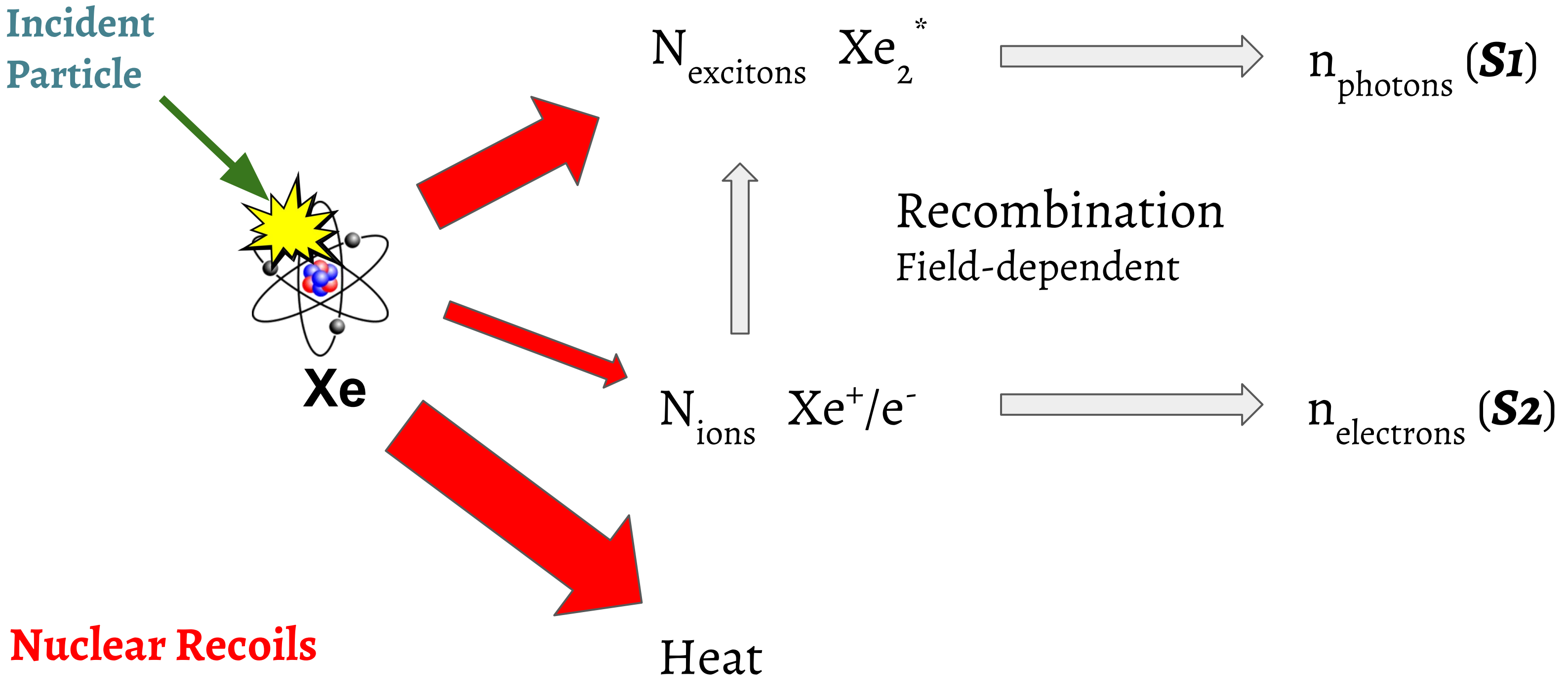
PRL, 118, 021303 (2017)

Sept 2016: decommissioning start

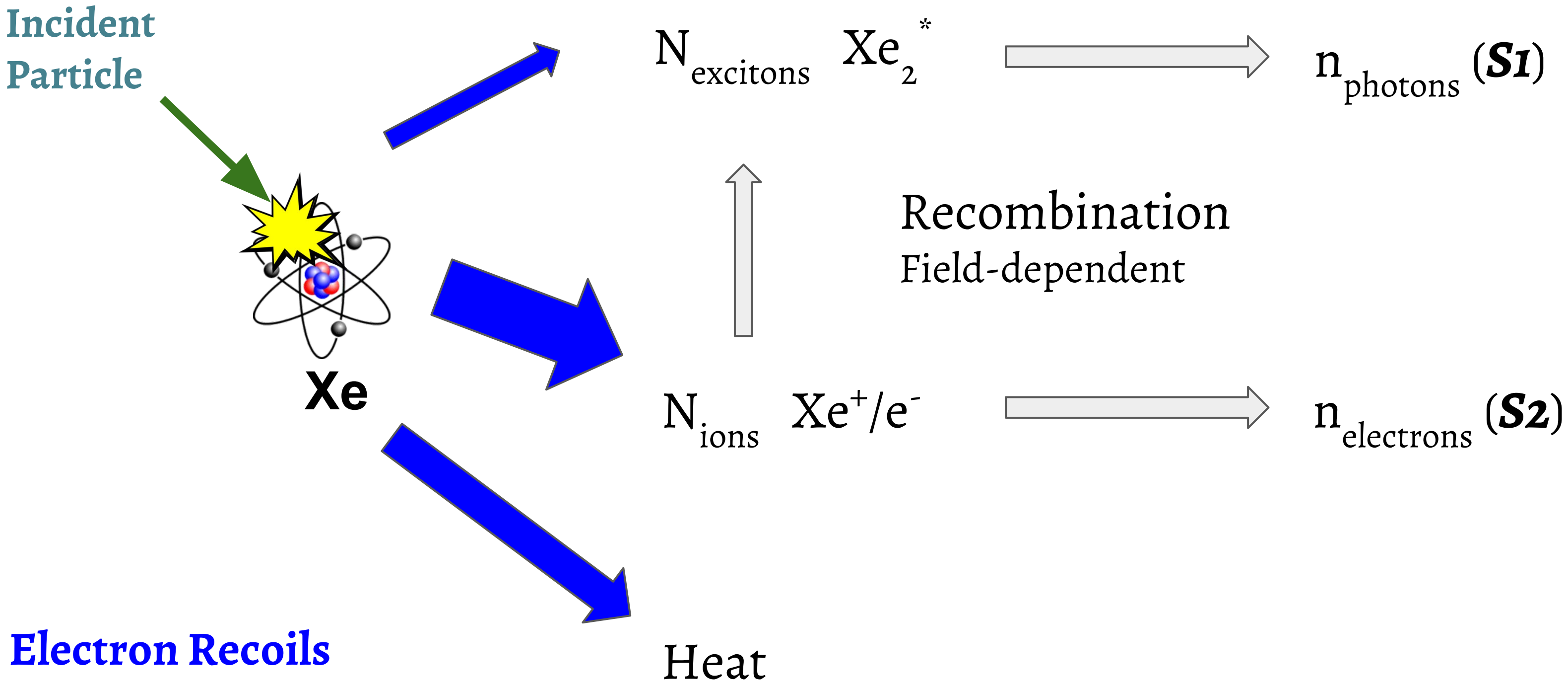
June 2017: LUX installed in a museum

Analysis still ongoing

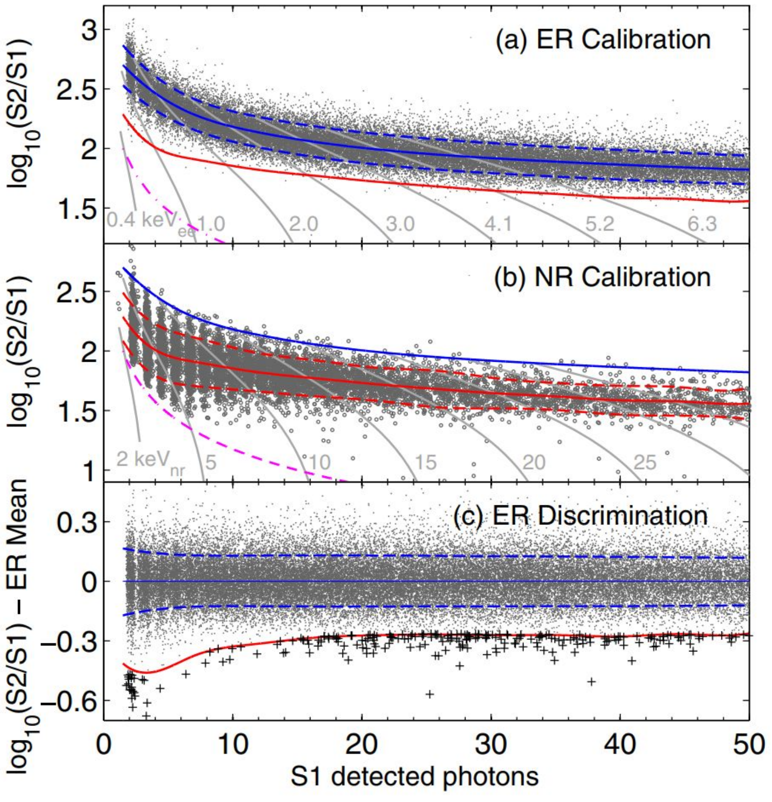
Energy Partitioning in Liquid Xenon



Energy Partitioning in Liquid Xenon



Electron and Nuclear Recoils (ER/NR)



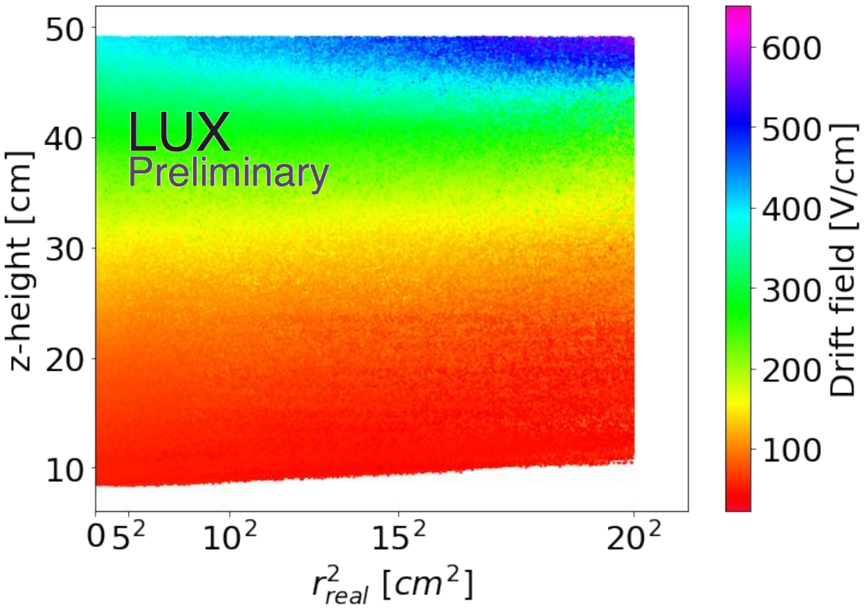
Phys. Rev. D 97, 102008 (2018)

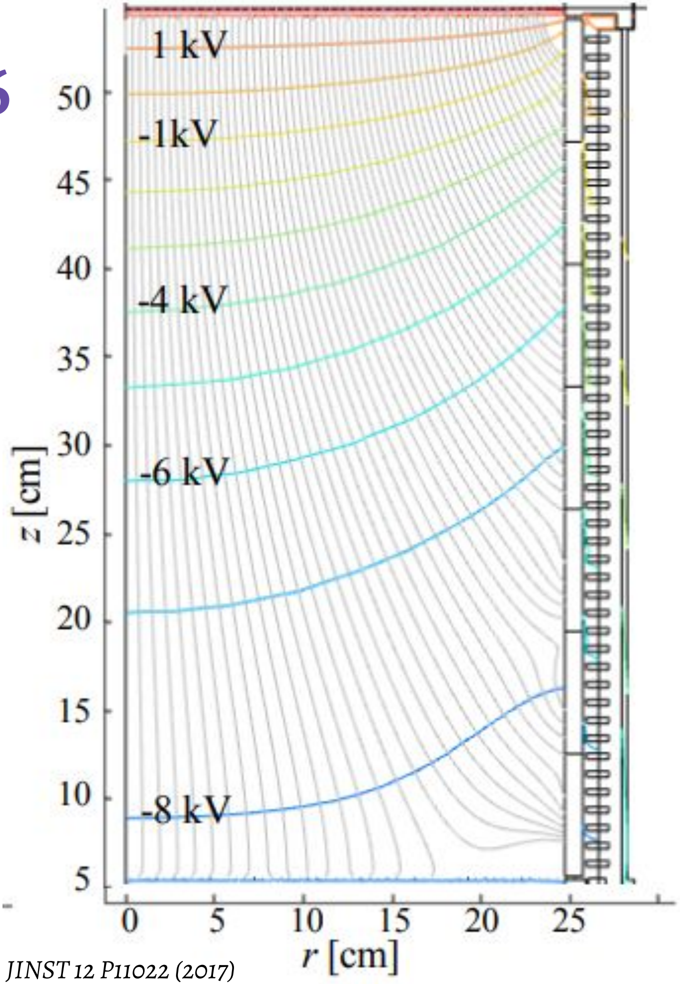
- Our signal is NR: spin-independent nuclear scattering
- Our backgrounds are dominantly ER: e.g. β, γ, ν (for ton-scale experiments)
- ERs deposit more energy into charge than NRs → discrimination variable is charge-to-light ratio ***log_{10}(S2/S1)***
- E.g. for 2013 run, LUX saw an average ER leakage of 0.2% at 50% NR acceptance over the range 0 < (***S1***/phd) < 50
  "phd" = "photons detected"

Electric Field Variation in WS2014-16

- Field lines are not parallel; field magnitude is not uniform
- We constructed a model of the LUX electric field, represented by "maps" of position → E-field value

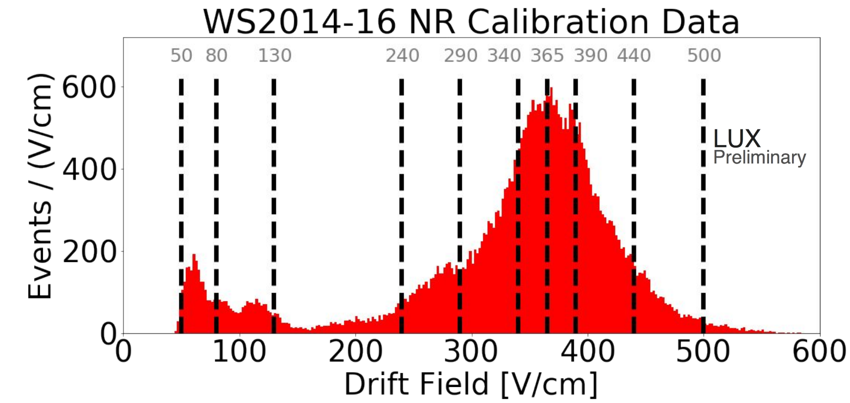
^{83m}Kr data, Oct 2015 - May 2016

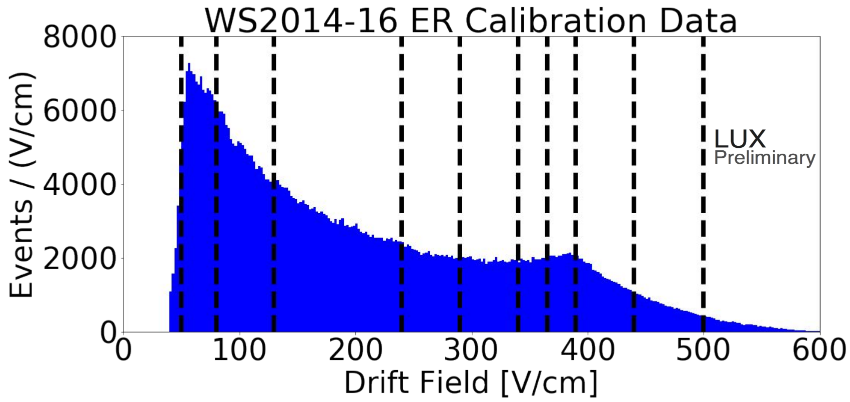




JINST 12 P11022 (2017)

Strategy for Studying Discrimination





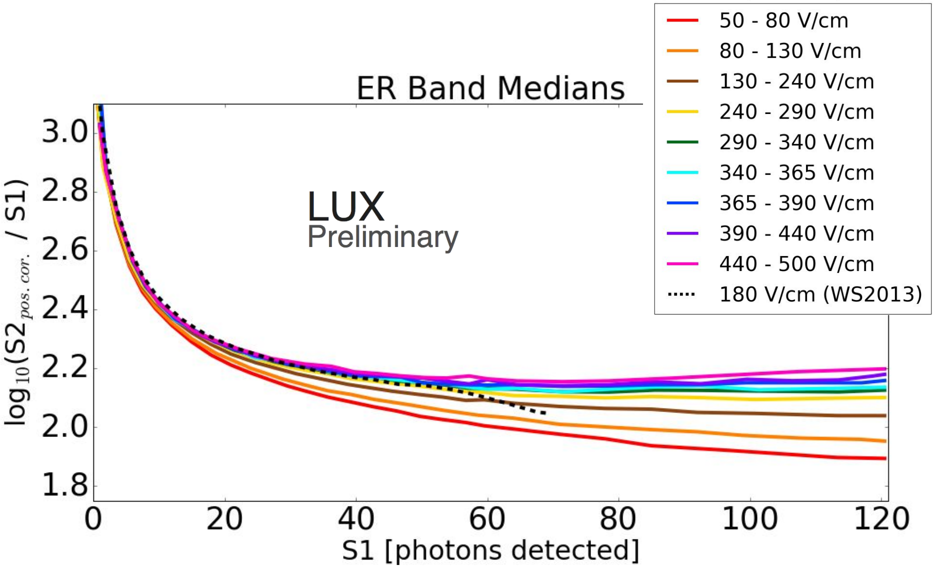
- Goal: Understand discrimination as a function of electric field
- ER calibration data: ^{3}H, ^{14}C
  NR calibration data: DD neutrons
  (2.45 MeV, mono-energetic)
- Strategy: split WS2014-16 data into nine bins based on the electric field at the recoil site (bin boundaries shown at left)
- Do discrimination analysis within each bin

Electron Recoil Band

- Calculate the ER band: split data into ***S1*** bins, do a Gaussian fit of ***log_{10}(S2/S1)*** distribution in each ***S1*** bin to get the median and width

- ER band is calibrated with ^{3}H and ^{14}C data (only ^{3}H for WS2013), but weights are applied to simulate a flat-energy ER spectrum

- Data is corrected for varying light collection efficiency (known as g_1) in detector; ***S1*** signals are normalized to g_1 = 0.087 at top of detector
  - See details in backup

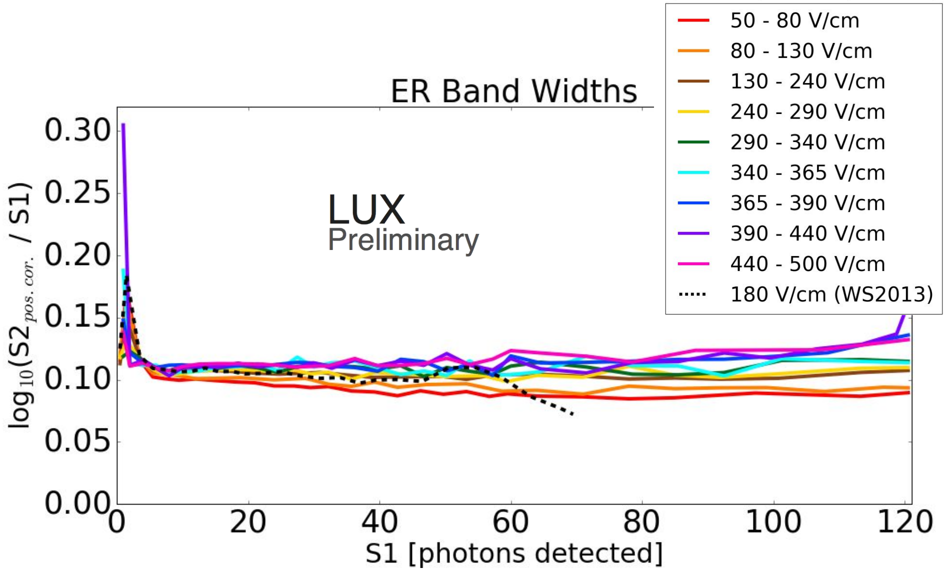


Electron Recoil Band

- Calculate the ER band: split data into ***S1*** bins, do a Gaussian fit of ***log_{10}(S2/S1)*** distribution in each ***S1*** bin to get the median and width

- ER band is calibrated with ^3H and ^{14}C data (only ^3H for WS2013), but weights are applied to simulate a flat-energy ER spectrum

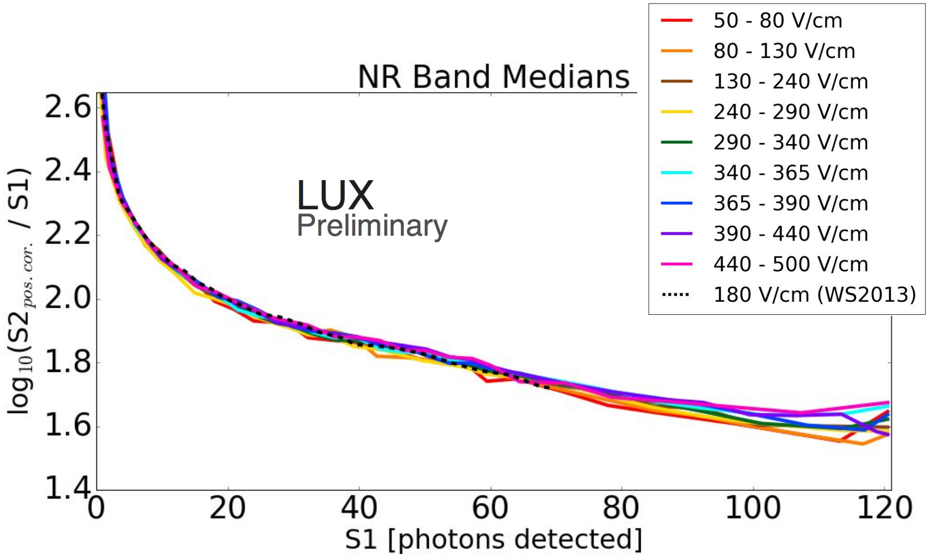
- Data is corrected for varying light collection efficiency (known as g_1) in detector; ***S1*** signals are normalized to $g_1 = 0.087$ at top of detector
  - See details in backup

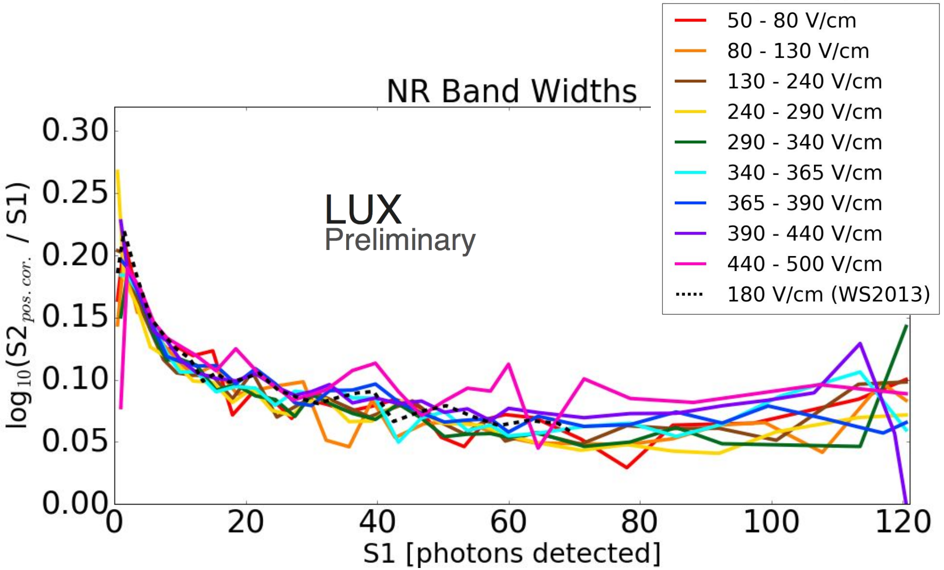


Nuclear Recoil Band

- NR band is calculated in the same way as ER, but without flattening the energy spectrum: the DD energy spectrum roughly mimics a 50 GeV/c^2 WIMP
- Also shift the NR median vertically based on the different $g_2 = S2 / n_{electrons}$ in each run

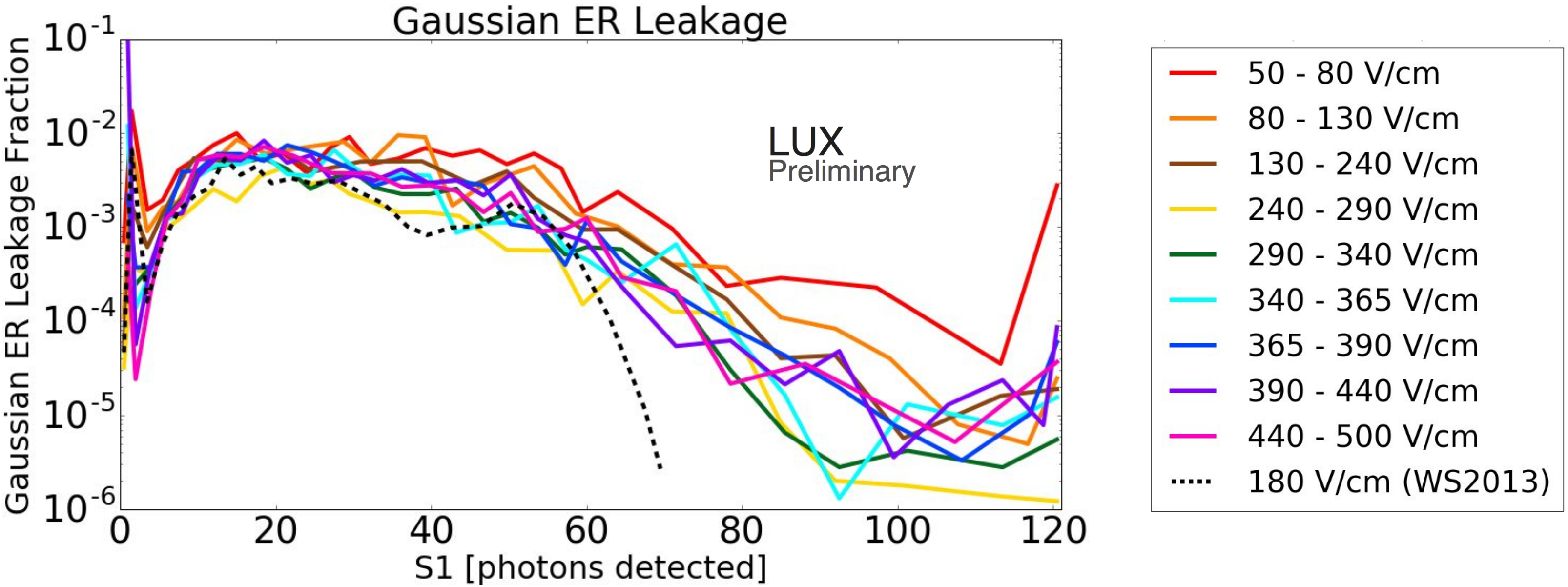
$g_2^{2013} = 12.1$ $g_2^{2014\text{-}16} = 19.09$





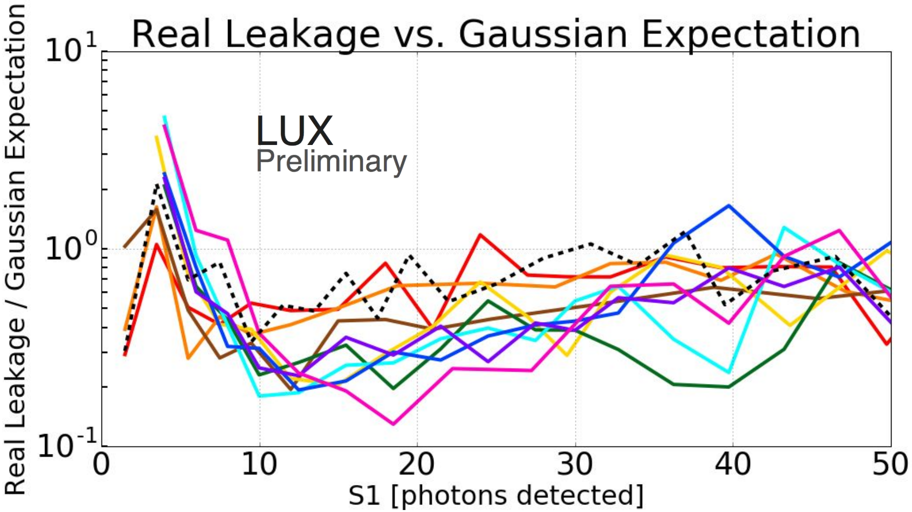
Gaussian Leakage

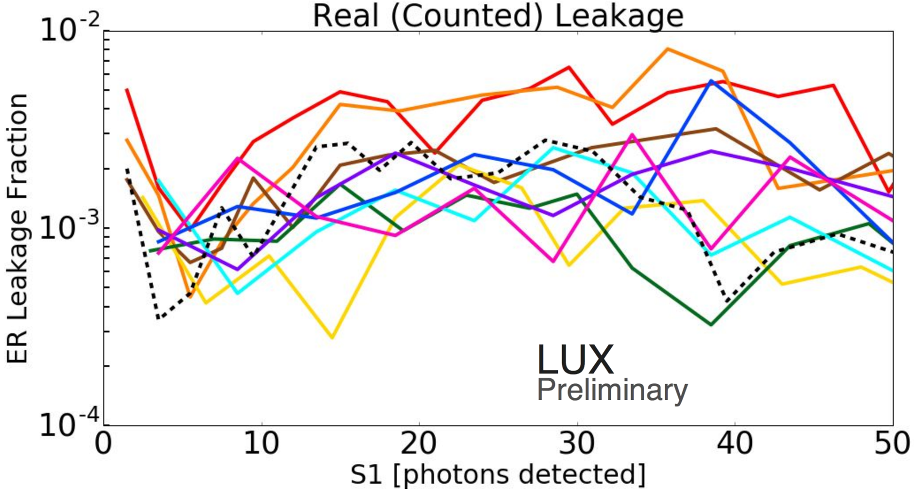
- If the ER band is perfectly Gaussian in ***log_{10}(S2/S1)***, estimate the leakage fraction by using ER/NR band median and ER width
  - Report ER leakage at 50% NR acceptance

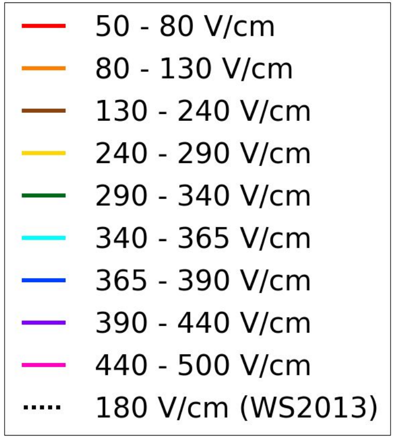


Real Leakage

- Alternative method to measure leakage: count the number of ER events falling below the NR band
- Loss of statistics above ~50-60 phd; i.e. 0% of ER events are below the NR band



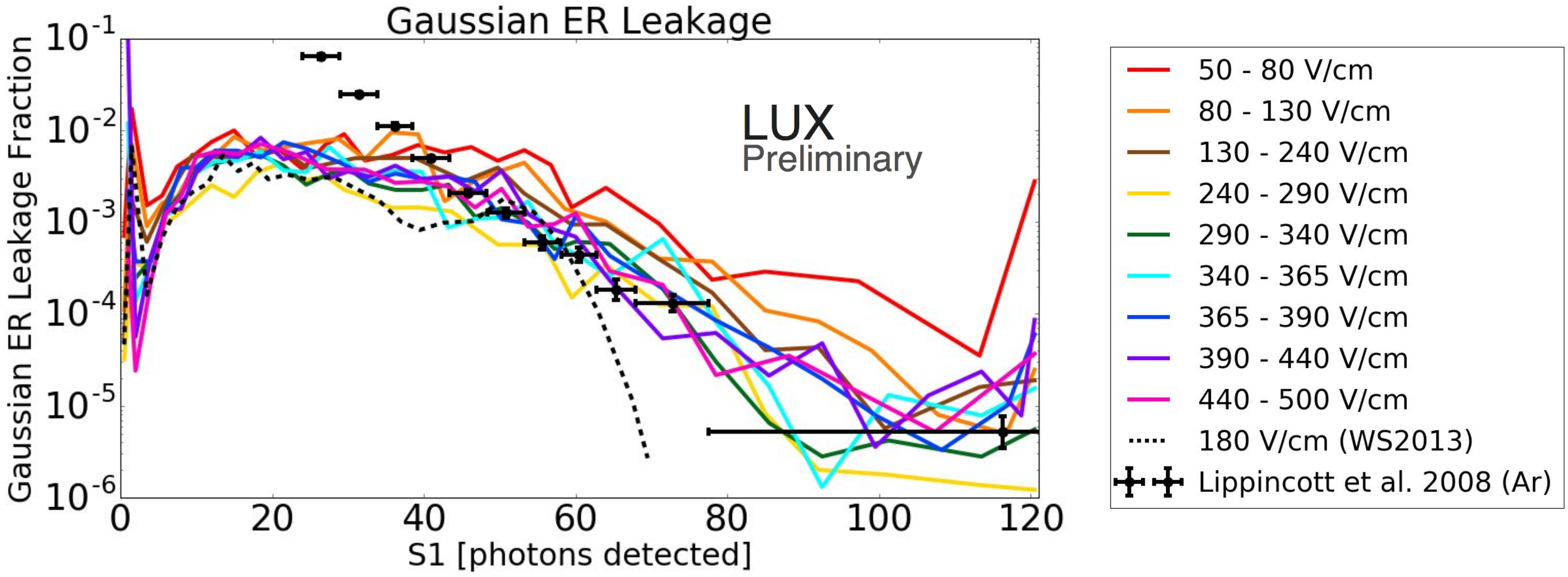




Note: see backup slides for comparisons of Gaussian and real leakage for each field bin

Gaussian Leakage: Comparison to Argon

- Compare our results in LXe to measurements of pulse-shape discrimination in LAr (zero-field) by Lippincott et al. 2008



Phys. Rev. C 78, 035801 (2008)

Summary and Conclusions

- Discrimination in LXe is a crucial topic to study for the future of direct detection
- Mild dependence on drift field observed, most evident below 200 V/cm
- Strong dependence on energy observed; leakage fraction decreases rapidly with energy
- Ramifications for future LXe DM experiments
  - Evidence of strong background rejection for high-energy NR physics searches (e.g. EFT, inelastic dark matter)
  - Promising for WIMP searches; potential to overcome backgrounds from Rn daughters, ^{85}Kr beta decay, and *pp* ν's by increasing energy threshold

Acknowledgments

<u>LUX Talks at IDM 2018</u>

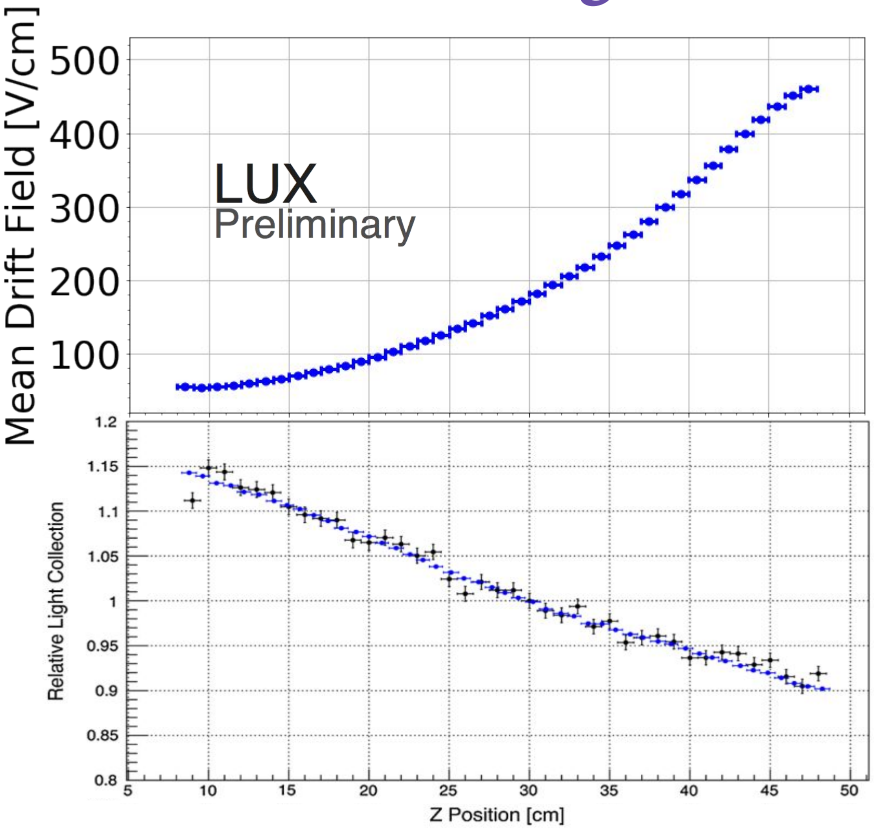
"Results on sub-GeV dark matter direct detection with LUX Run 3 data by using Bremsstrahlung and Migdal-effect signal"
Junsong Lin, July 24 at 14:00

"Recent Analysis Efforts of the LUX Collaboration"
Kelsey Oliver-Mallory, July 25 at 09:15

LUX Collaboration
Sanford Underground Research Facility
Lead, South Dakota
September 2016

Backup Slides

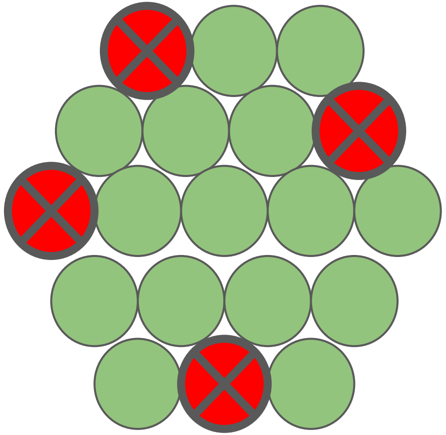
Correction for Light Collection Efficiency

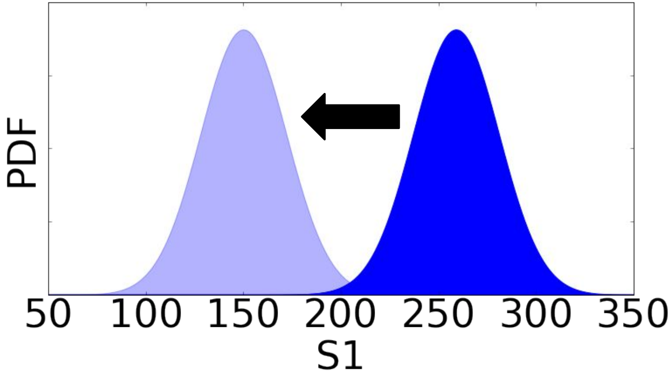


Phys. Rev. D 97, 102008 (2018)

- Important parameter for a LXe TPC is the light collection efficiency, $g_1 = S1 / n_{photons}$
- Higher g_1 → dampens fluctuations in **S1** signal → lower leakage
- In LUX WS2013, average $g_1 = 0.117$
  In LUX WS2014-16, average $g_1 = 0.099$
- Geometric dependence of g_1 in LUX; **S1** light collected mostly in the bottom PMTs due to total internal reflection at liquid surface
- Need to disentangle position-dependent electric field from position-dependent g_1

Correction for Light Collection Efficiency

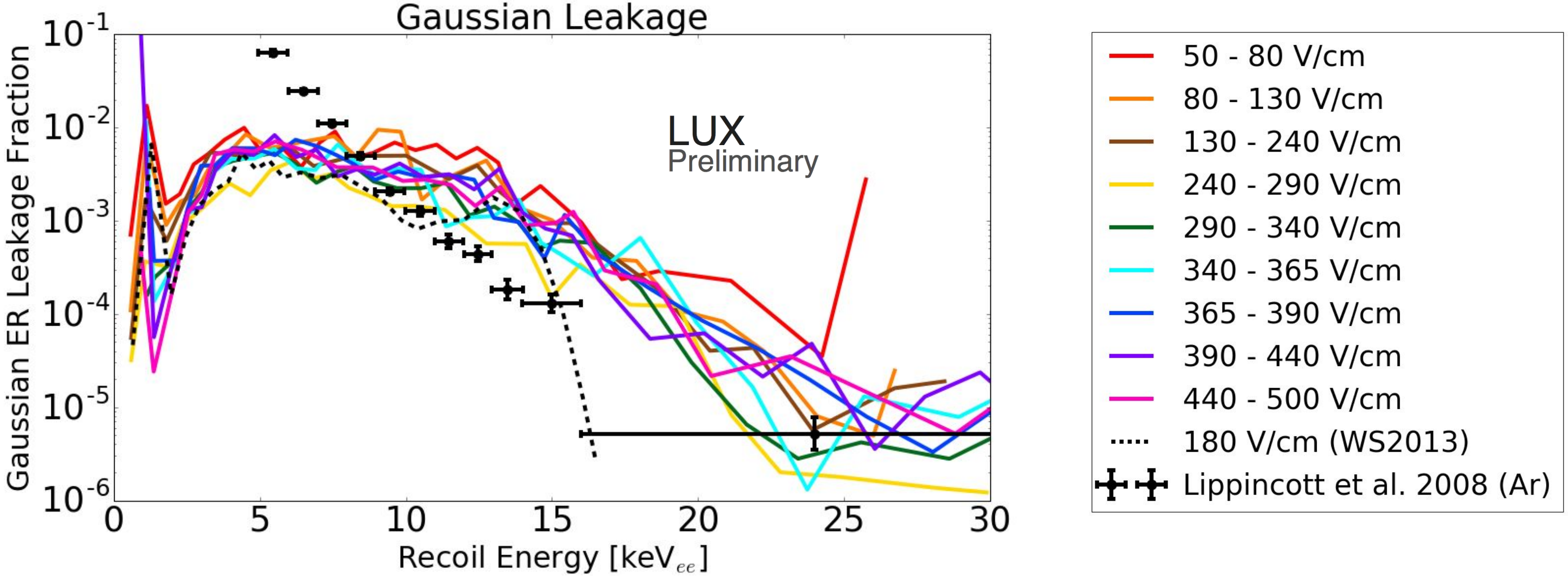




- Solution: artificially remove PMTs from analysis to decrease effective g_1
- ***S1*** signals in each field bin (and WS2013 "bin") are normalized to $g_1 = 0.087$ at the top of the WS2014-16 detector
- Use WS2013 ^{83m}Kr calibration data to determine the relationship between PMT patterns and g_1

Gaussian Leakage as a Function of Energy

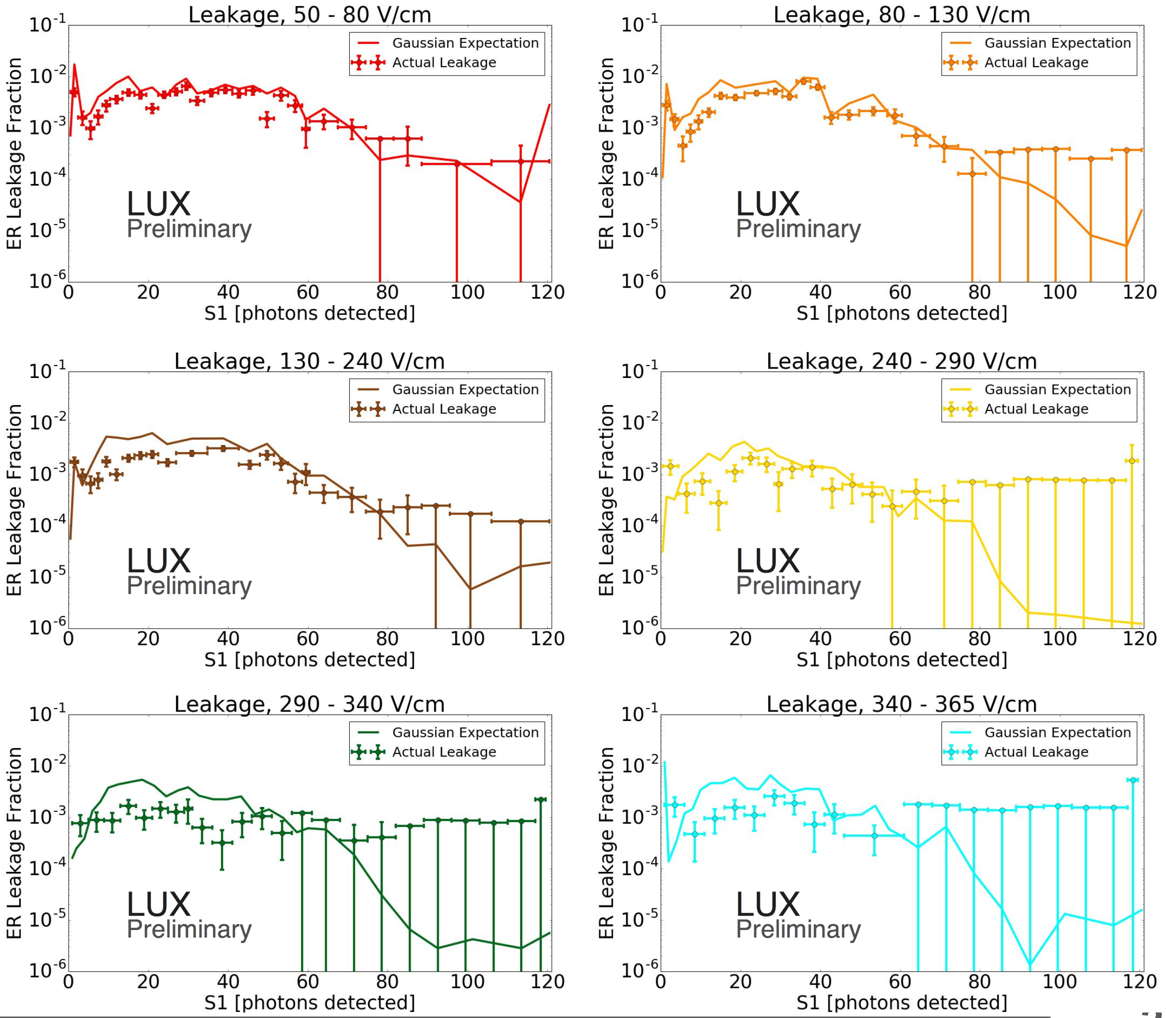
- Convert S1 to energy; shift Gaussian leakage on Slide 14 to new variable
    - LAr: Linear transformation
    - LXe: Linear sum of ***S1*** and ***S2*** signals



Phys. Rev. C 78, 035801 (2008) *JINST 9 P06013 (2014)*

Real Leakage

- Count the number of $^{14}C/^{3}H$ events falling below the NR band to get "actual" leakage
- Compare to Gaussian expectations
- Note: for high ***S1***, we often don't have any ER events fall below the NR band. We set a 90% confidence limit on leakage, using the Feldman-Cousins approach
- Estimate that if we see zero leak events, the real number of leaking events is < 2.3



Real Leakage

- Count the number of $^{14}C/^{3}H$ events falling below the NR band to get “actual” leakage
- Compare to Gaussian expectations
- Note: for high ***S1***, we often don’t have any ER events fall below the NR band. We set a 90% confidence limit on leakage, using the Feldman-Cousins approach
- Estimate that if we see zero leak events, the real number of leaking events is < 2.3