Background model for the LUX experiment

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IOP
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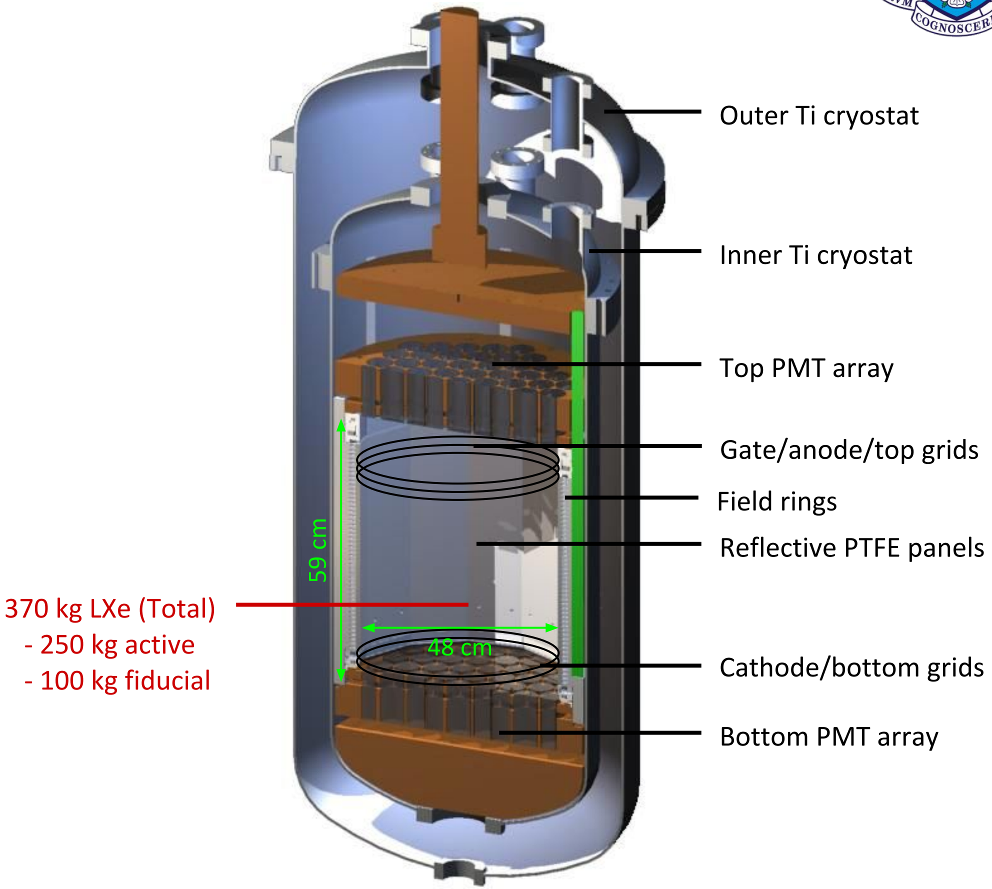
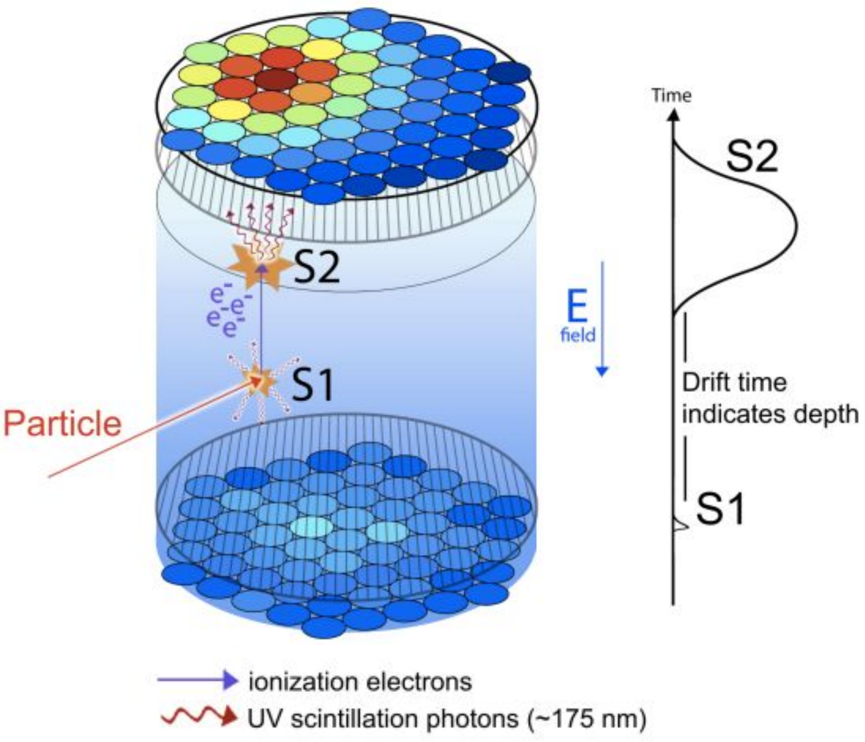
LUX detector

- Located at SURF, South Dakota, USA
  - 1478 m underground
- Dual phase xenon Time Projection Chamber (TPC)
  - A liquid xenon (LXe) volume
    - Plus a gas phase above the grids
  - A vertical electric field over the LXe volume
    - Average field strength of ~200 V/cm
  - 2 Photomultiplier tube (PMT) arrays
    - 61 PMTs per array



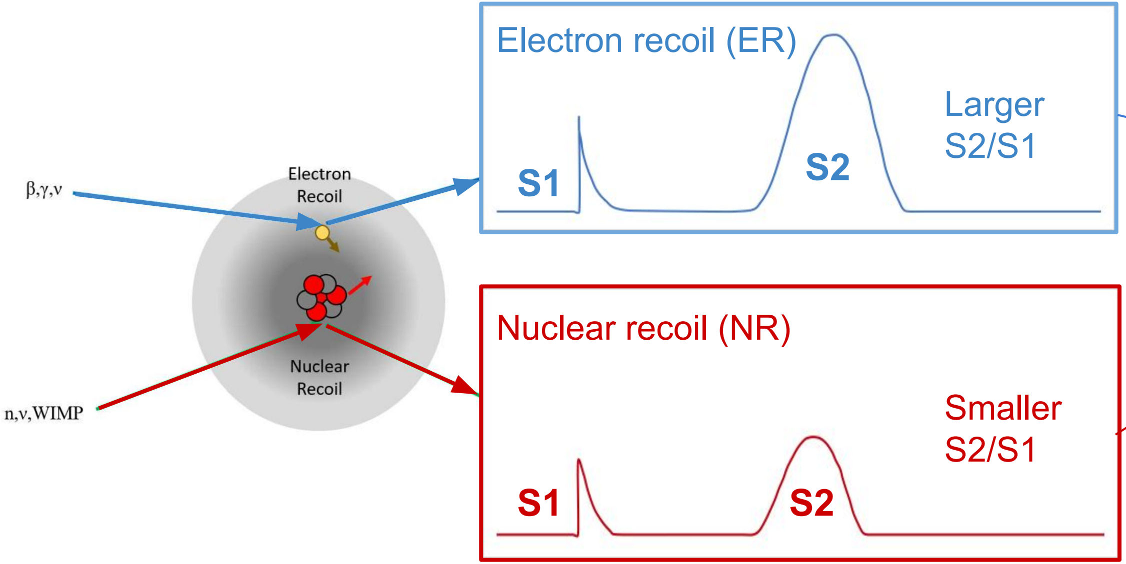
Detection principle



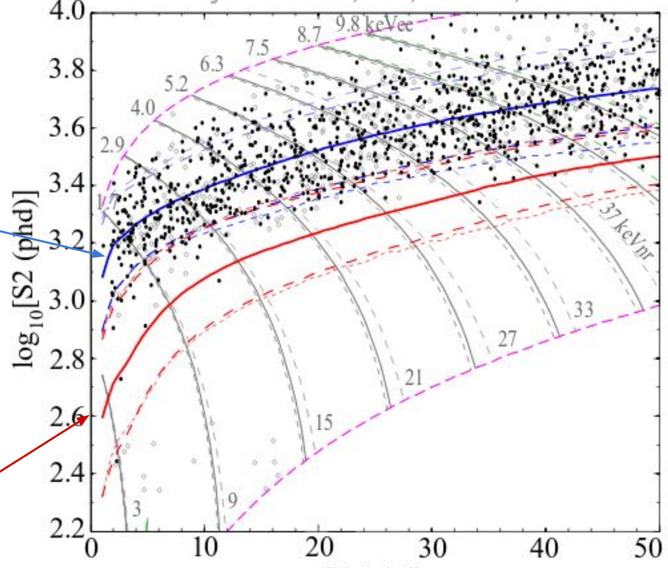
- LUX is sensitive to interacting particles via two channels
  - Scintillation
  - Ionisation
- An expected signal consists of two flashes of light (S1 & S2)
  - S1 - Prompt scintillation photons which are immediately detected by PMTs
  - S2 - Electrons which drift towards the gas phase are extracted. A high electric field accelerates them in the gas creating a delayed electroluminescence signal

Electron recoils vs. nuclear recoils

- LUX's standard WIMP search is tuned to look for a WIMP-nucleus scatter
    - 100% of detected electron recoils are considered background for WIMP search
- Background discrimination
    - $(S2/S1)_{NR} < (S2/S1)_{ER}$



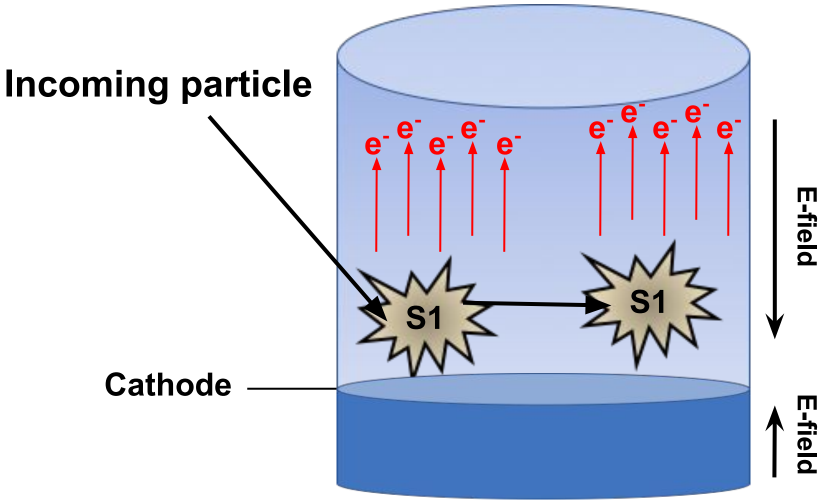
Phys Rev Lett, 118, 021303, 2017



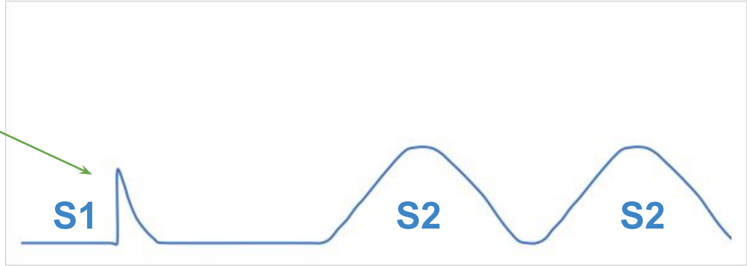
LUX run 4 data (332 days)

Multiple scatters

- 100% of multiple scatters (MS) are background to WIMP search
- MS S1 signals are indistinguishable
  - A detector resolution limitation for all dual phase TPCs
- Multiple S2 pulses signify a multiple scatter event
- Separate S2 signals can be spatially distinguished
  - cm accuracy in XY
  - mm accuracy in Z

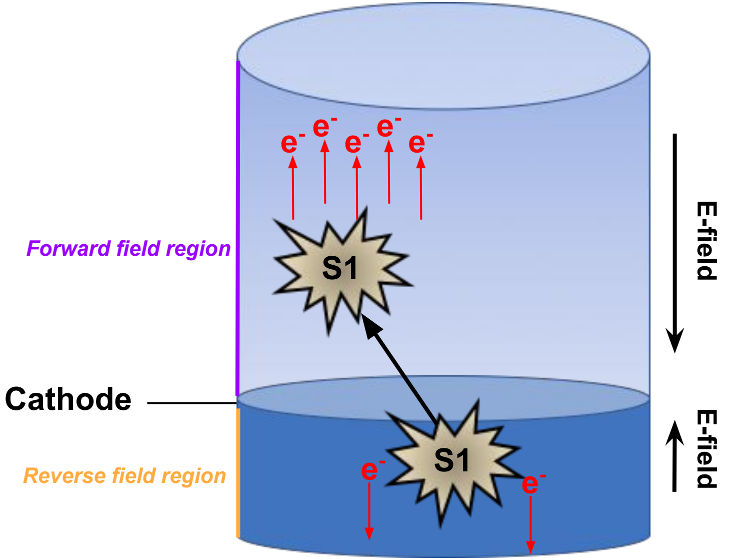


Two S1 signals merge



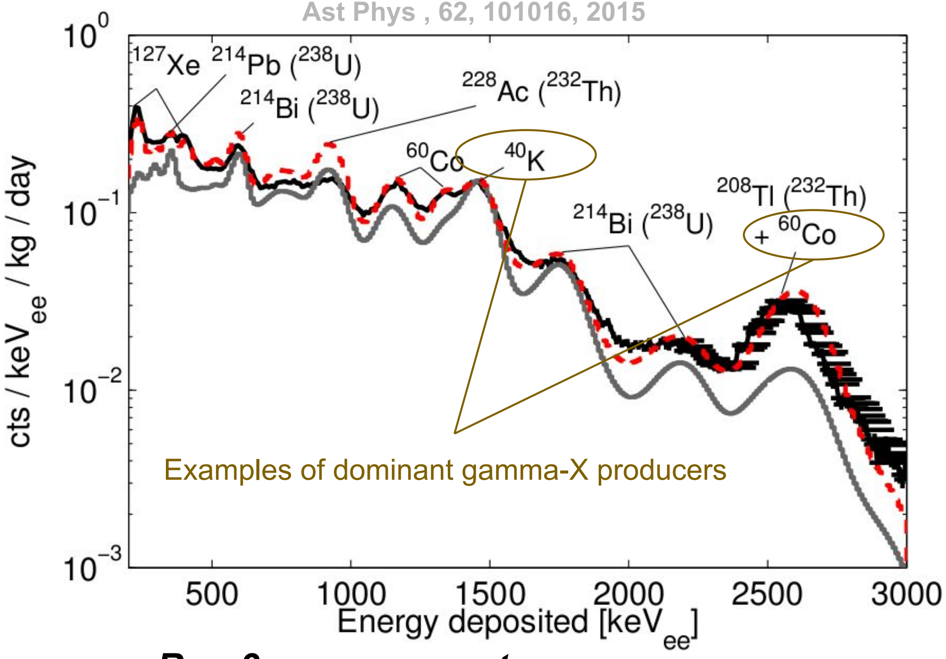
Gamma-X events (fake WIMPs)

- Gamma-X - A multiple scatter, with an energy deposition above the cathode and one below the cathode
- An enhanced S1 signal relative to the S2 signal will be observed
    - Since only the S2 signal from the scatter above the cathode is seen
- The reduced S2/S1 ratio can push events out of the ER band into the NR band



Where are these high energy γ's coming from?

Ast Phys , 62, 101016, 2015



Run 3 gamma spectrum

Black - Measured LUX run 3 data (85.3 days)

Red - Fitted simulation spectrum

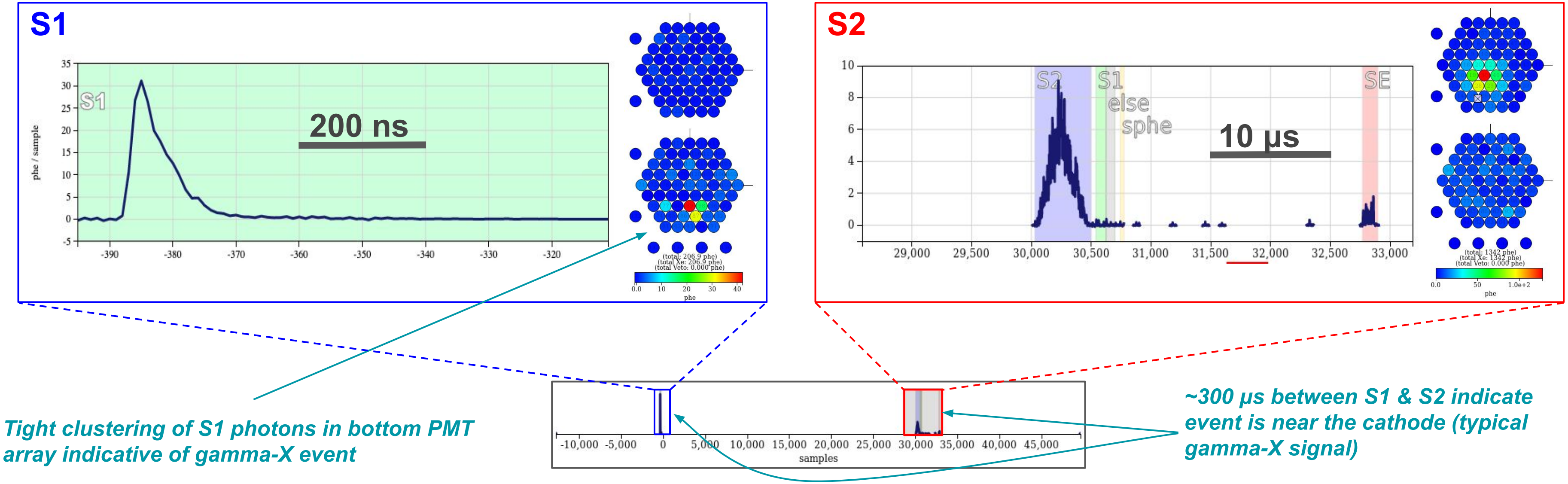
Gray - Simulation spectrum (pre-fit)

- Dominant contribution to gamma-X events:
  - ^{60}Co, ^{232}Th, ^{40}K, ^{238}U
  - These are present in the bottom PMT array
- Other sources are capable of producing gamma-X events under the right circumstances
  - Expected to produce a subdominant contribution

Gamma-X identification

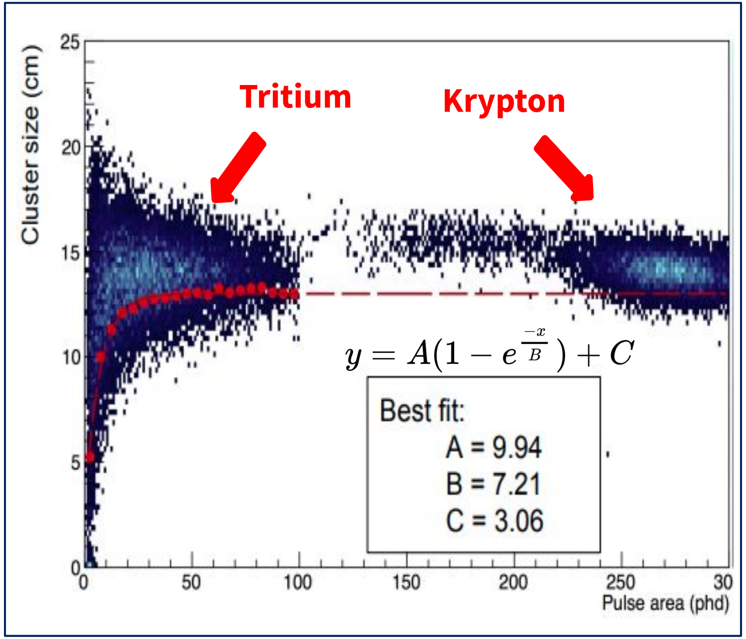
- Gamma-X events tend to appear deep in the LXe (near the cathode typically)
- Gamma-X events tend have a particular S1 topology in the bottom PMT array
  - Tightly clustered photon pattern in bottom PMT array
- These features can be used to define a cut parameter

Example of a suspected gamma-X event



Gamma-X cut development

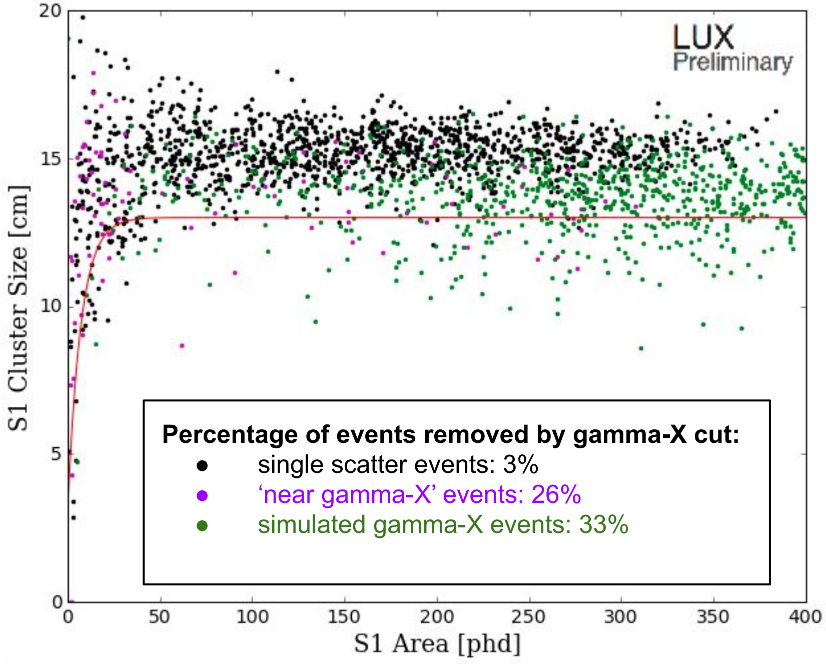
- Cut parameter: S1 cluster size
    - Area weighted mean radius for the S1 light collected in the bottom PMTs
- Cut based on tritium calibration data
    - 80% event acceptance selected
    - Acceptance points fitted to an empirical curve
    - Events below this curve were removed
- Thus, events with the tightest clustering were removed
    - Theoretically removing more gamma-X events than single scatter



Run 4: 2014/09-2016/05, 332 live days

Gamma-X cut validation

- Single scatter events:
  - Run 4 data selection
  - Events with 1 S1 and 1 S2
  - All run 4 WIMP search cuts applied
  - Acceptance is better than 80% due to other data analysis cuts
- ‘Near gamma-X’ events:
  - Run 4 data selection
  - Events with 1 S1 and 2 S2s signals
  - One energy deposition within 2 cm of cathode
  - Fiducial cut extended to cathode
  - All other run 4 WIMP search cuts applied
- Simulated gamma-X events:
  - Selection placed on simulated background from bottom PMT array
  - Events required to deposit energy once above the cathode and below
- Cut removes more simulated gamma-X events and ‘near gamma-X’ events than single scatters



Black - run 4 single scatter events (WIMP search cuts)
Purple - run 4 multiple scatter events within 2 cm of cathode
Green - simulated gamma-X events
Red - run 4 gamma-X cut

Gamma-X simulation background

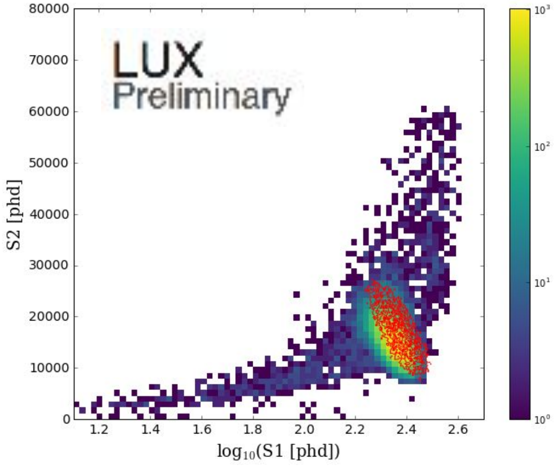
- Backgrounds from bottom PMT array should dominate gamma-X production
- Decay rate based on post decommissioning radio-assay
- Gamma-X selection made at MC Truth level
- For 332 simulated live days:
    - **6637 gamma-X events identified (before cuts)**

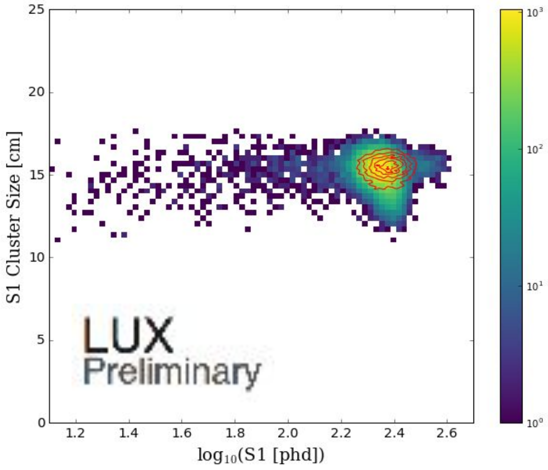
LUX Preliminary

Source	Decay rate (Bq)	Simulated decays (332 days)	Single scatter production in fiducial region before cuts (Evt/kg/day/keV)	Gamma-X Production in fiducial region before cuts (Evt/kg/day/keV)
^{232}Th	0.17	4.88×10^{6}	2.1×10^{-2}	1.1×10^{-2}
^{238}U	0.64	1.92×10^{7}	7.8×10^{-3}	4.6×10^{-2}
^{60}Co	0.16	4.59×10^{6}	1.9×10^{-3}	6.3×10^{-2}
^{40}K	4.1	1.18×10^{8}	4.9×10^{-2}	8.0×10^{-2}

Simulation parameter validation

- Cut parameters can be validated by comparison of simulated ^{83m}Kr calibration source against run 4 data
- Simulations are close to matching data
    - Improvements to simulations are in progress





run 4 data, including Kr83m calibration source
Red - Contour of simulated run 4 Kr83m

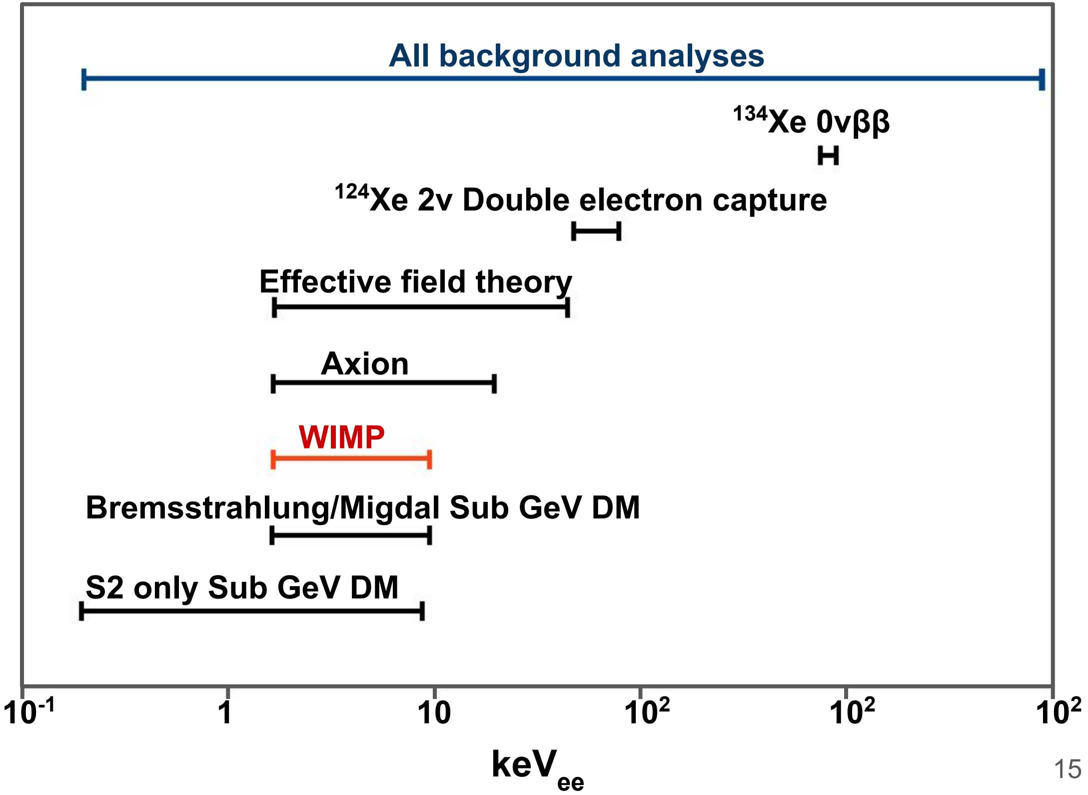
Alternative cut

- An alternative cut is being developed using a Boosted Decision Tree (BDT)
  - Trained on simulated gamma-X events
- BDT cut is early in development, and current does not use many parameters
- BDT cut already better with false negatives
  - Lower number of data events are removed, the vast majority of which are not gamma-X events
- Also removes a much higher proportion of simulated gamma-X events
- **BDT cut will improve as more parameters are included**

LUX Preliminary	**Proportion of events removed**		
Cut Type	**Data: SS**	**Data: Near GX**	**Sim GX**
Proposed BDT cut	1.8%	19.1%	71.5%
Existing GX cut	3.2%	26.0%	33.4%

LUX Energy Range

- LUX's WIMP search is only one of several analysis taking place
- Gamma-X events were not a problem for LUX's run 4 WIMP search
- Understanding this background is still essential:
    - At higher energies, such as LUX's EFT search
    - G3 WIMP searches, such as LZ



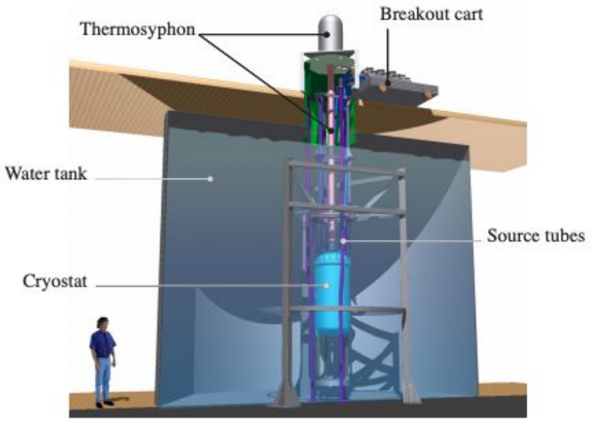
Summary

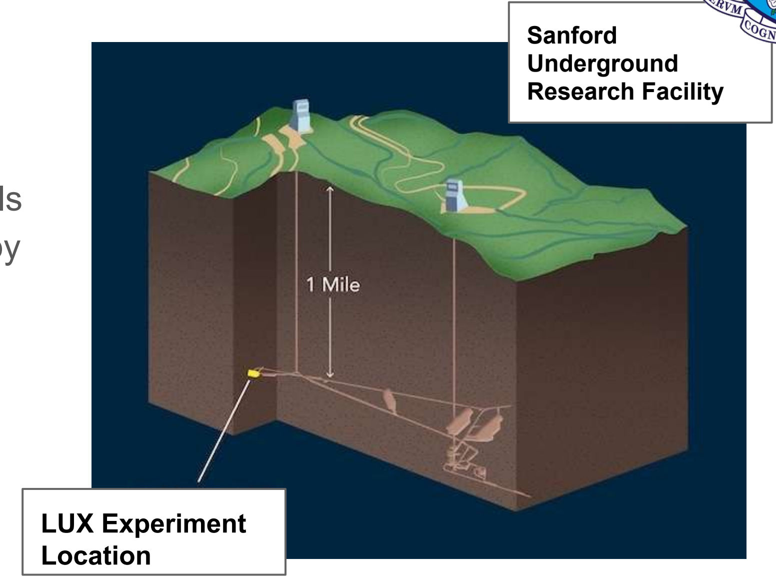
- Gamma-X simulations, cut and validation are developing positively
    - Work on simulations continues but continue to show positive improvements
    - Cut currently removes ~30% of gamma-X events with little loss to single scatter data
    - Work is in progress on an improved cut using a BDT
- Gamma-X events could be a background for future studies
    - Or for searches at higher energy ranges
    - Cuts can be developed based on precise simulations and particular selections of multiple scatter events

Backup Slides

External background reduction

- Several precautions exists to ensure external backgrounds are subdominant
  - Depth at detectors location limits cosmogenic signals
  - Gammas produced in cavern rock further reduced by 300 tonne water shield (2.5 m.w.e)
    - Water tank outfitted with PMTs for muon tagging

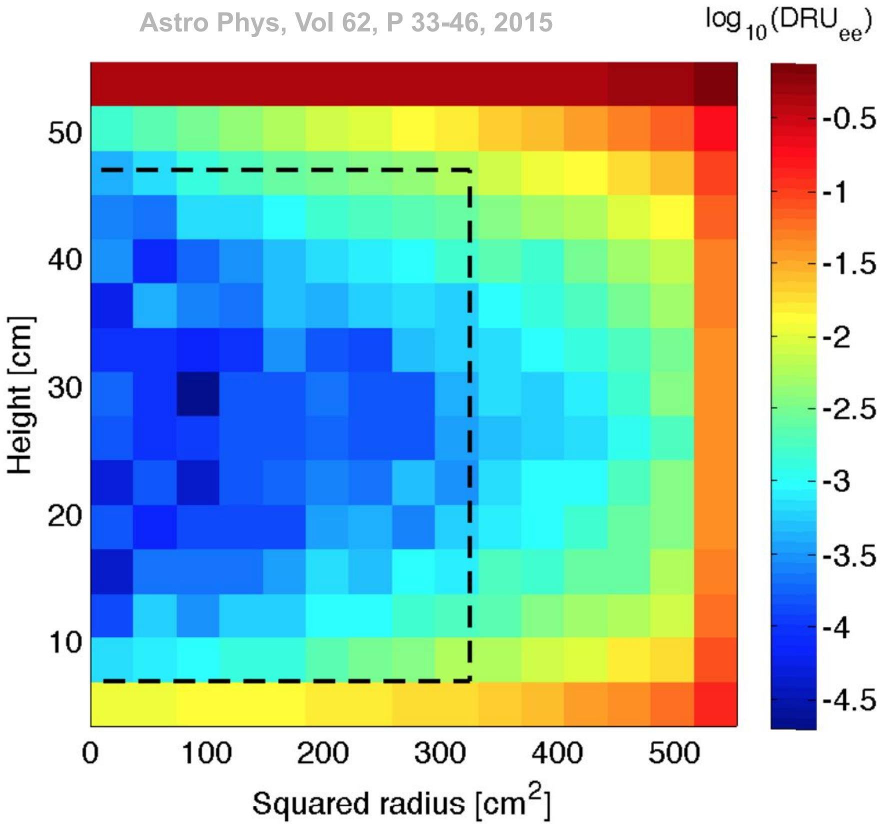




- Thus the dominant background signal is from low-energy electron recoils (ER)
  - Originating from detector components, surfaces, and Xe contamination
  - Generated through electromagnetic interactions from photons or electrons

Fiducialization

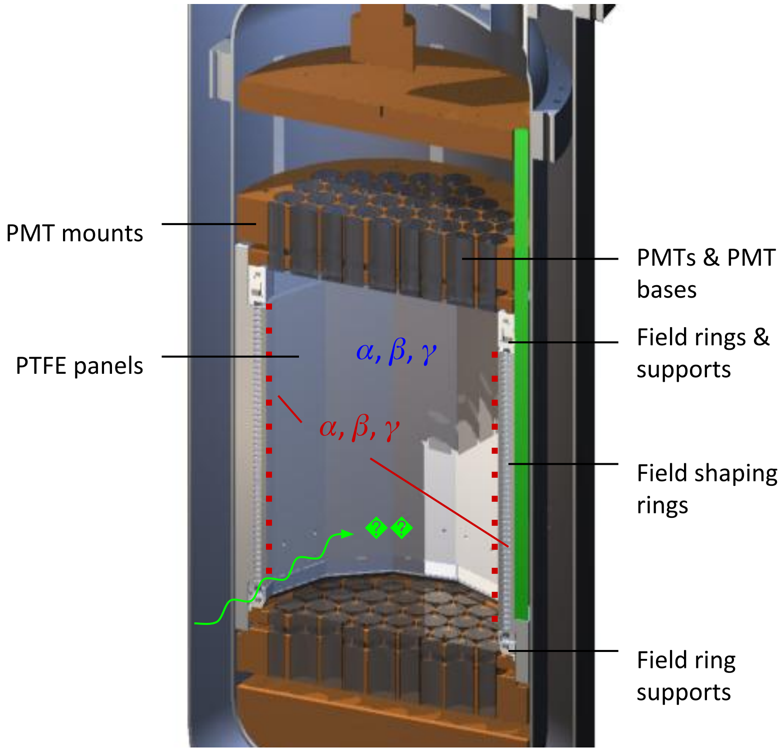
Astro Phys, Vol 62, P 33-46, 2015



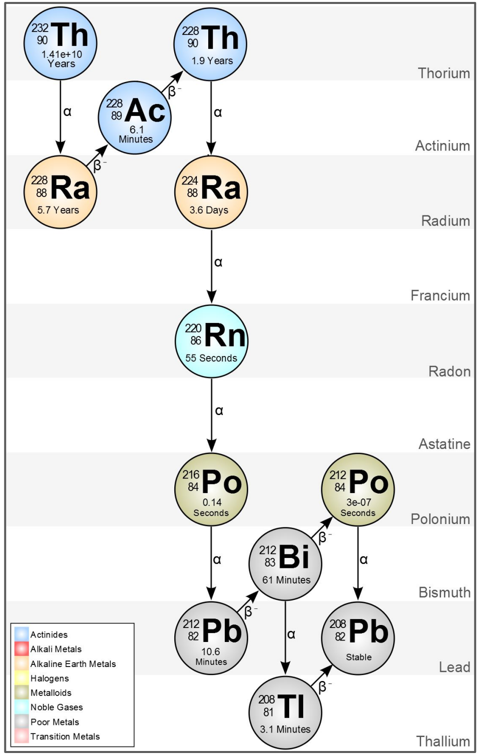
- Fiducialization - The exclusion of signals in LXe near the walls, cathode, and gas phase
- Allows for background reduction from detector components and surfaces
- Density of LXe target (2.9 g cm^{-3}) attenuates γ ray signals to the outer edge of the active region
  - mean free path on the order of several cm
-

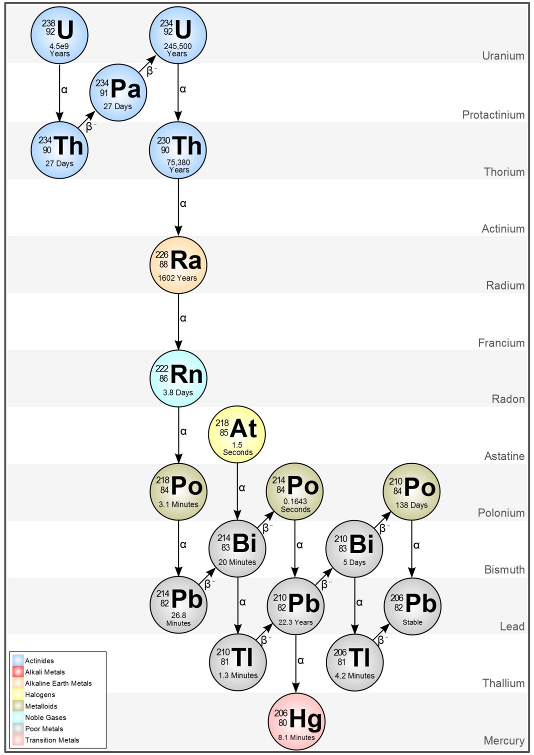
Internal α, β, and γ sources

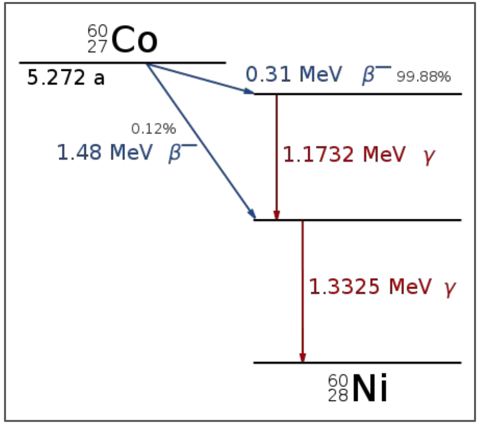
1. γ's from radioactive contamination in the detector components
   a. Intrinsic: ^{238}U, ^{232}Th, and ^{40}K
   b. Activation of the Ti and Cu: ^{46}Sc and ^{60}Co
2. α, β, and γ's from radioactive contamination in the Xe
   a. Xe activation: ^{127}Xe, ^{125}I, ^{133}Xe, ^{131m}Xe, ^{129m}Xe, ^{125}Xe
   b. ^{222,220}Rn progeny
   c. Contamination: ^{85}Kr and ^{39}Ar
3. α, β, and γ's radioactivity on the detector surfaces
   a. Plate-out of ^{222}Rn daughters: ^{210}Pb, ^{210}Bi, ^{210}Po

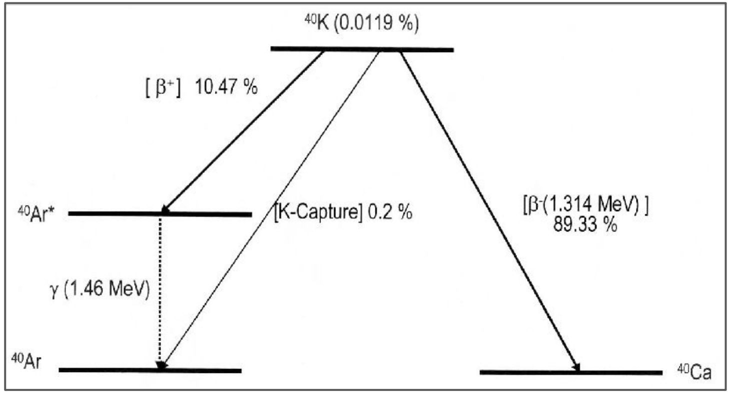


Background decay modes









Low energy background rates

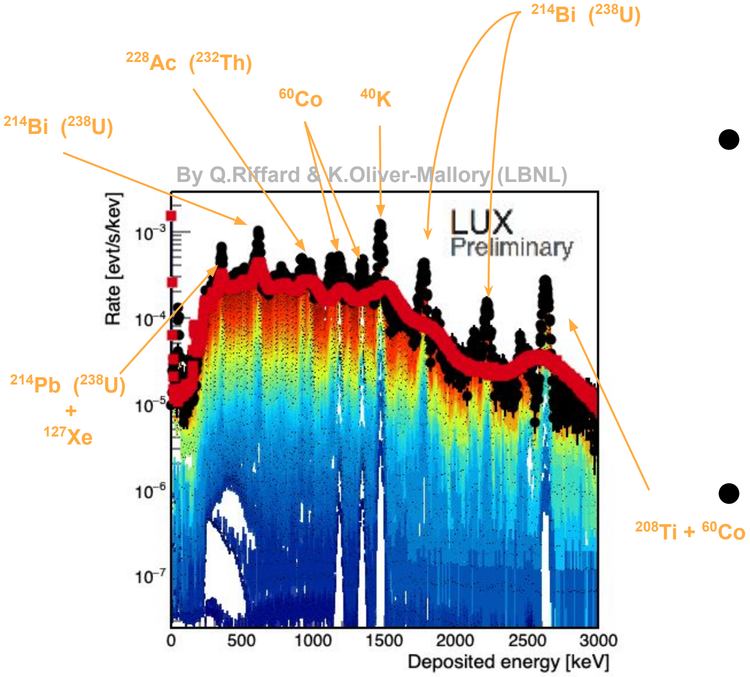
- Rates in 100 kg fiducial
- ER rates averaged over 0.9-5.3 keV_{ee} ROI
- NR rates averaged over 3.4-25 keV_{nr} ROI
- Rates taken from second half of run 3
- ^{127}Xe given in brackets (not expected to contribute to run 4)

Ast Phys , 62, 101016, 2015

Source	Background Rate
γ rays	$(1.0 \pm 0.1_{\text{stat}} \pm 0.1_{\text{sys}})$ mDRU_{ee}
^{214}Pb	0.2 mDRU_{ee}
^{85}Kr	$(0.17 \pm 0.10_{\text{sys}})$ mDRU_{ee}
Int. neutrons	170 nDRU_{nr}
Ext. neutrons	180 nDRU_{nr}
Total predicted	1.4 ± 0.2 mDRU_{ee} + 350 nDRU_{nr}
Total observed	1.7 ± 0.3 mDRU_{ee} $(0.14 \pm 0.03$ ^{127}Xe)

Preliminary LUX gamma spectrum (run 4)

- Fiducial cut
  - r < 230 mm
  - 70 mm < z < 500 mm
- Normalisation of simulations to be based on radio-assay measurements
  - No fit to measured spectrum yet



Red - LUX run 4 data (332 days)
Black - Combined simulation spectrum (pre-fit)

- Resolution model simulation spectrum still under development
  - Resolution model designed to fix peak widths
- Model fit will provide tighter constraint on background

Gamma-X cut parameter

- Area weighted mean radius for the S1 light collected in the bottom PMTs

$x_i,\ y_i\ =\ x\ and\ y\ location\ of\ each\ PMT\ in\ the\ bottom\ array$

$a_i\ =\ uncorrected\ quantity\ of\ light\ (phd)\ seen\ in\ each\ PMT$

$$A = \sum_i^{bottom\ PMTs} a_i$$

$$\bar{x} = \frac{\sum_i^{bottom\ PMTs} (a_i \cdot x_i)}{A}$$

$$\bar{y} = \frac{\sum_i^{bottom\ PMTs} (a_i \cdot y_i)}{A}$$

$$cluster\_size\_gx = \frac{\sum_i^{bottom\ PMTs} a_i \sqrt{\left((x_i - \bar{x})^2 + (y_i - \bar{y})^2\right)}}{A}$$

Simulated gamma-X events

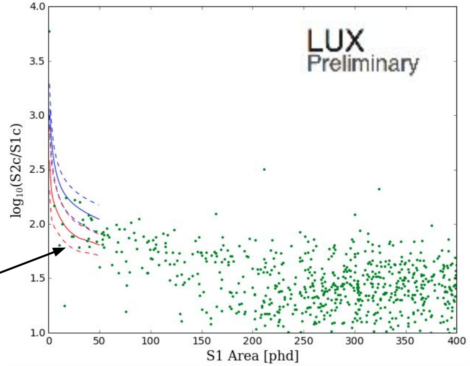
- 3 data analysis cuts significantly affect gamma-X rate
  - Fiducial cut
  - S1 cut
  - Isolated S1 cut
- Several data analysis cuts used in the WIMP search were highly effective at removing GX events
  - Even before applying a specific GX cut

LUX Preliminary

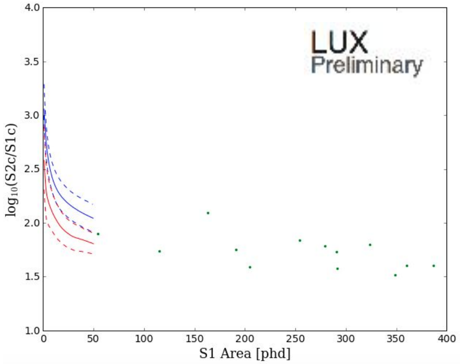
Cut applied	No cut	Fiducial cut	Fid+S1 cut	Fid+S1+ other quality cuts
Number of GX events	6637	1278	525	15
Events in WIMP ROI	34	6	6	0

Published NR and ER bands from run 4 WIMP search

Phys Rev Lett, 118, 021303, 2017



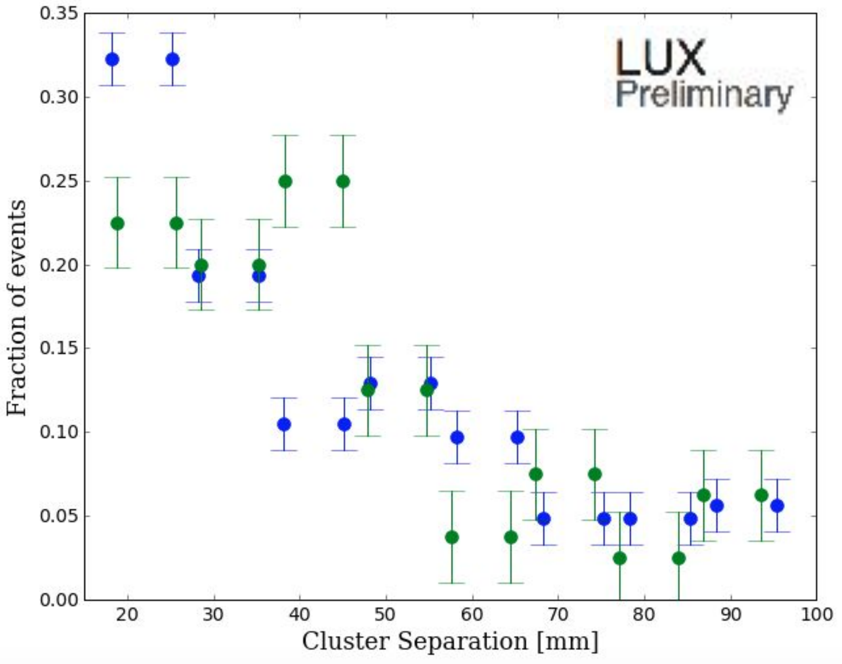
*Simulated gamma-X events **before** cuts*



*Simulated gamma-X events **after** cuts*

Cluster separation validation status

- A further validation is to apply the 'near gamma-X' cut to the simulations and compare the distance between the two S2 clusters
- Analysis is statistically limited
  - n_Events from data = 96
  - n_Events from sims = 124
- Result may suggest further development to simulations



Blue - simulated 'near gamma-X' events
Green - run 4 'near gamma-X' events