Low-energy ionization background in LUX/LZ and its implications

Jingke Xu, LLNL

Nagoya Workshop on Future Noble Gas Detectors

Nagoya, Japan

February 15th, 2024

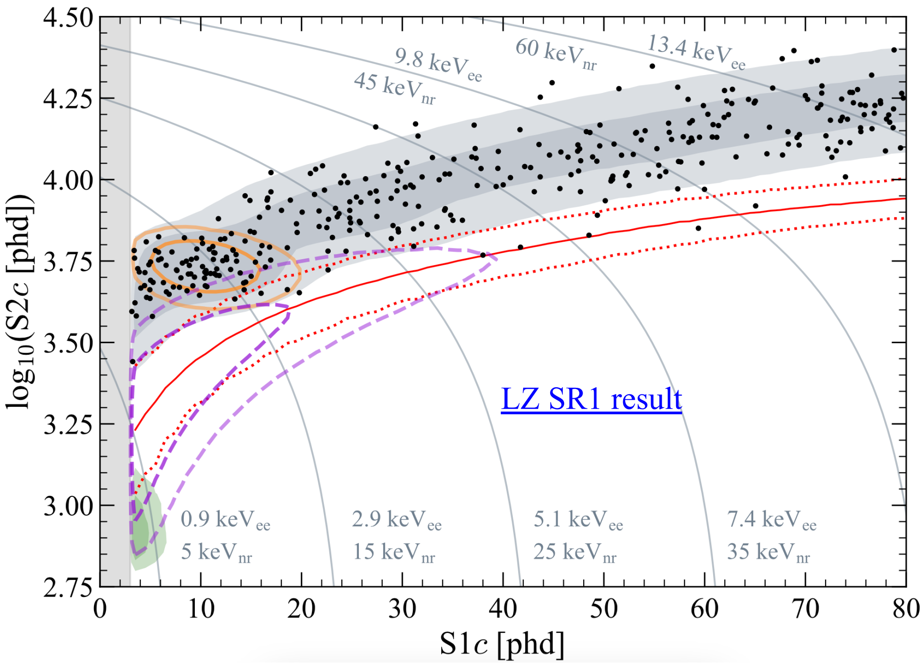
LLNL-PRES- 860115

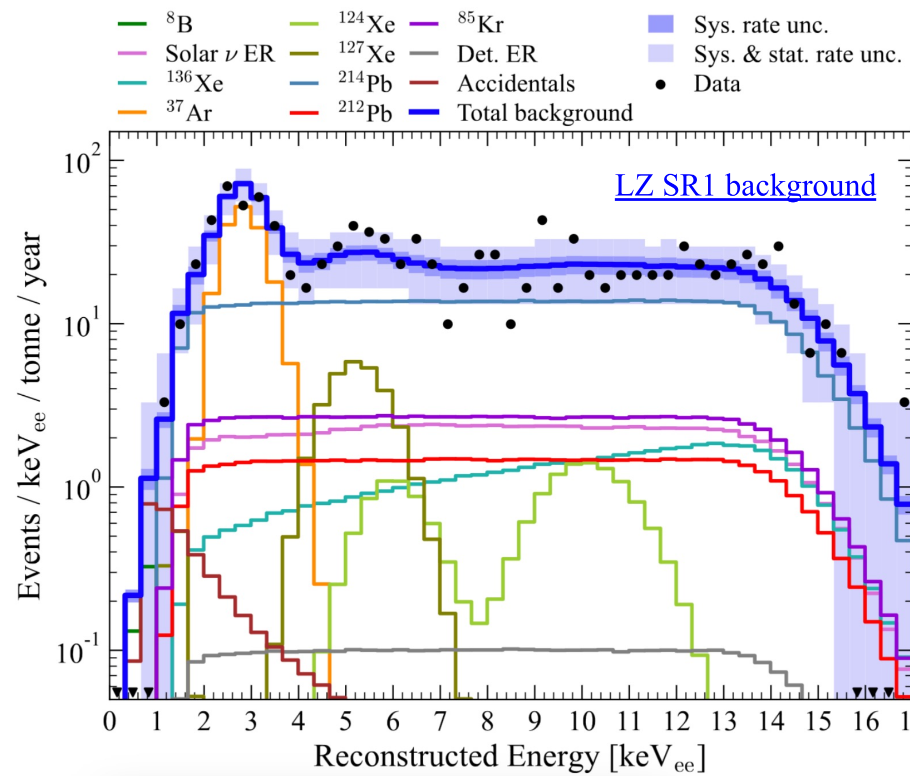
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

LXe TPCs achieved extremely low backgrounds

- LXe TPCs achieved ER background rates as low as $\mathcal{O}(10)$ events/keV/tonne/year
- NR background rates are $\mathcal{O}(100)$ times lower

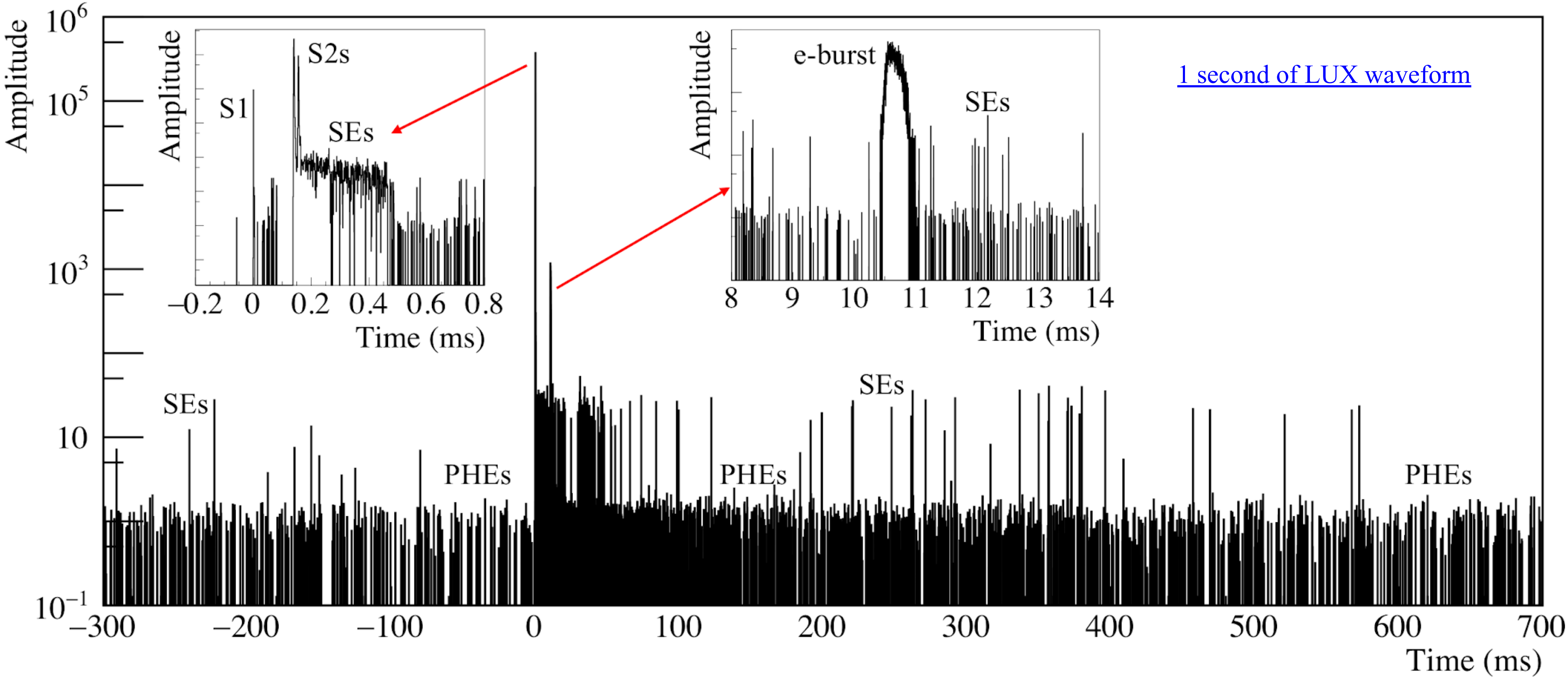




… except in the low-energy region

For the smallest signals produced in a LXe TPC, we typically have

- $\mathcal{O}$(kHz)/tonne of ionization electron backgrounds
- $\mathcal{O}$(MHz)/tonne of single photoelectron backgrounds



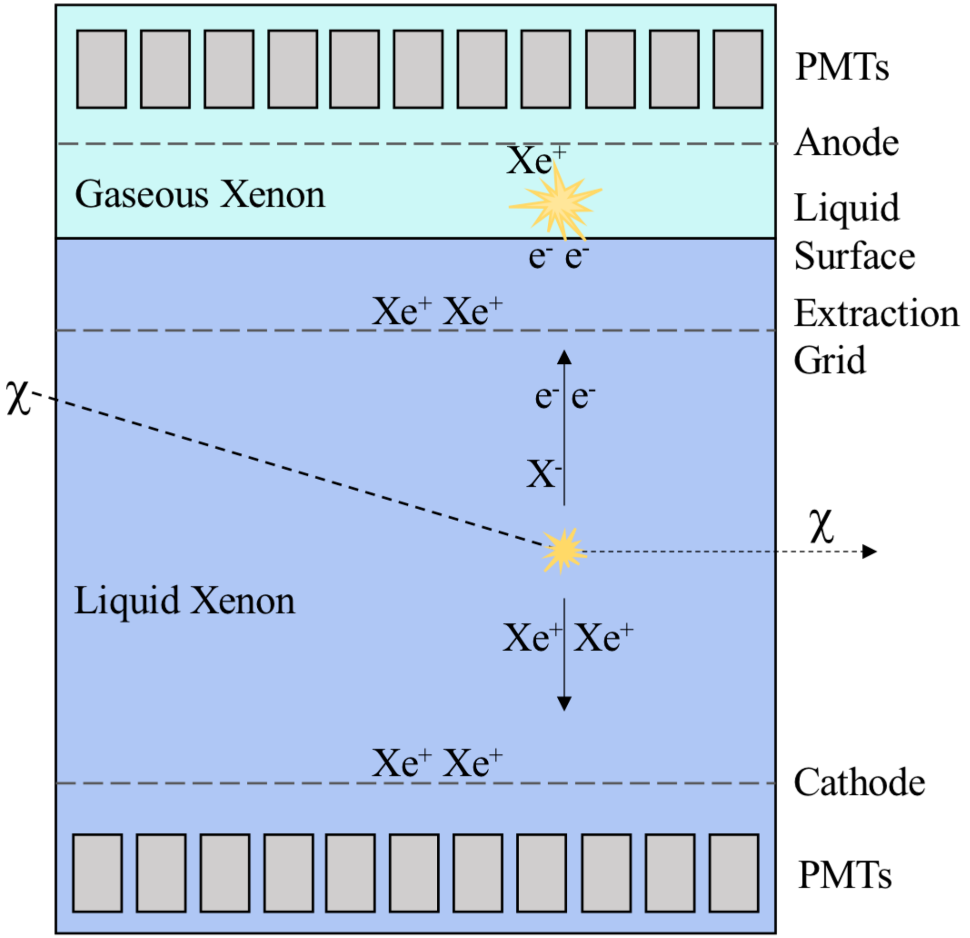
1 second of LUX waveform

Possible sources of electrons

Particle interactions

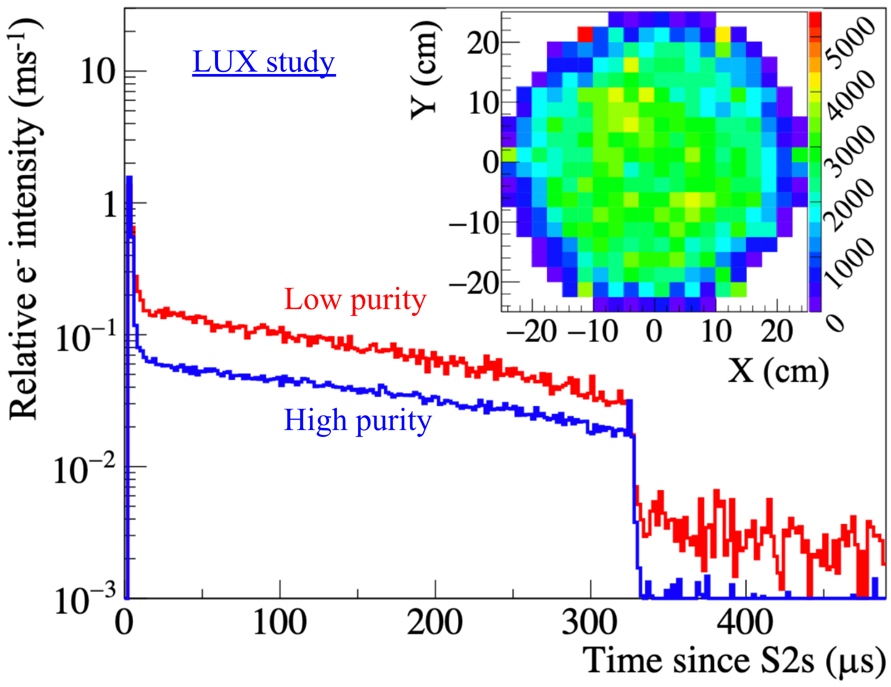
- Bulk LXe
  - Scintillation → photoionization
  - Ionization electrons
    - Captured by impurities
    - Trapped under LXe surface
    - Emit into the gas
      - Photoionization by S2
      - Ionization near anode?
  - Positive ions
    - Drift to cathode?
    - Flow with liquid?
    - Combine with anions/electrons?
- Detector surface
  - Charge loss
  - S1 suppression by high field

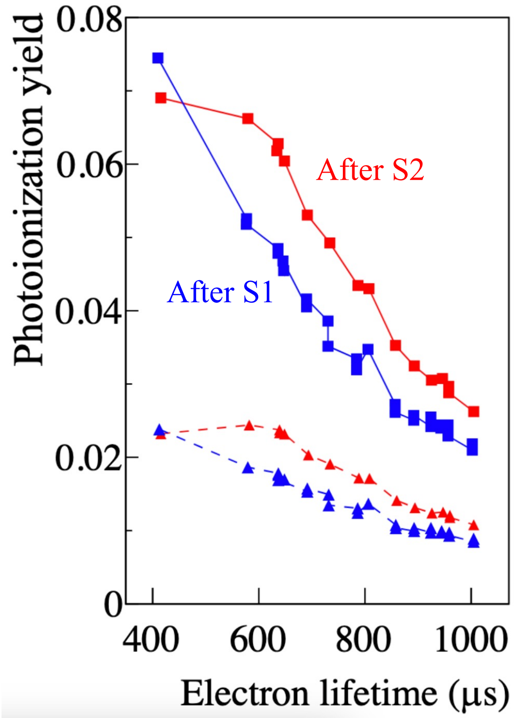
Grid emission under strong field



Photoionization is well understood

- Background electron rate substantially enhanced following S1/S2 light
- Electrons appear to be emitted from bulk liquid
- High electron yield with low liquid xenon purity → some impurity is ionized

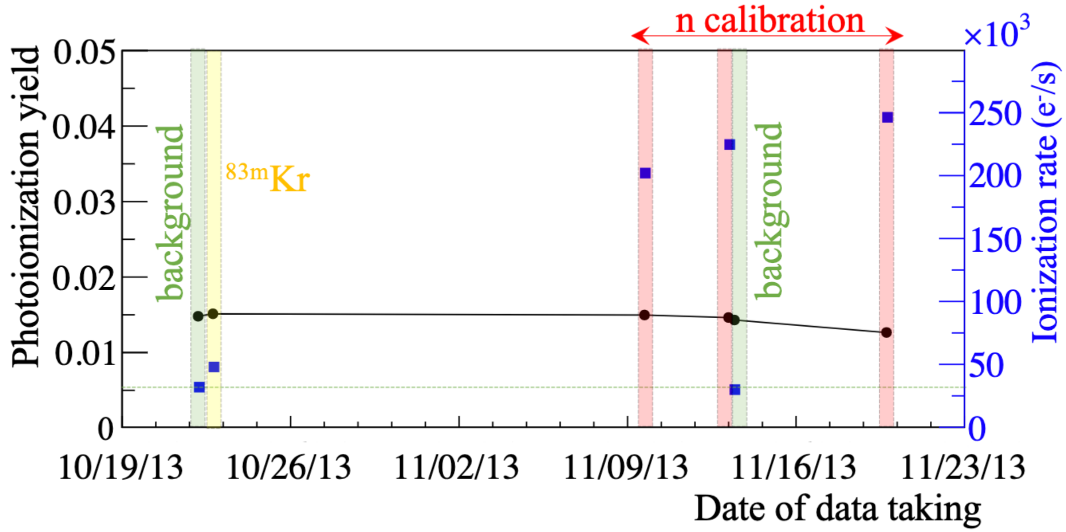


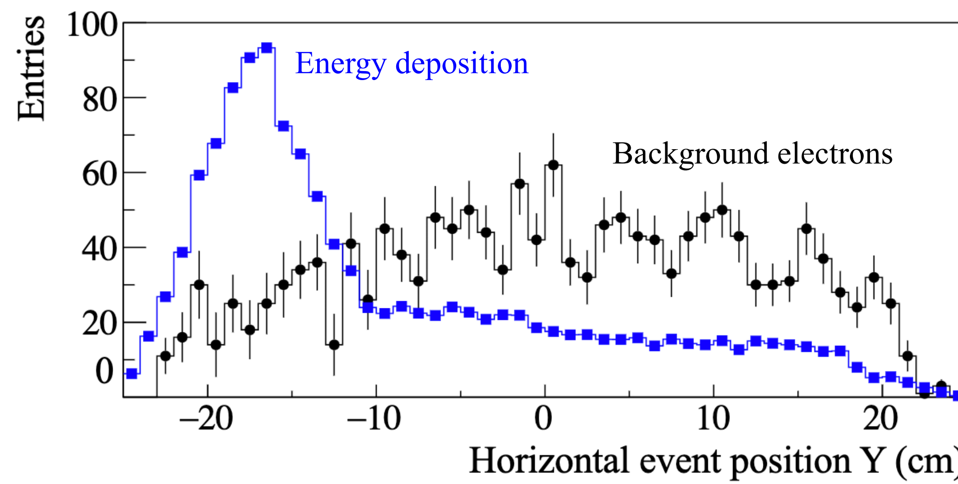


… except for what is ionized

It was suggested that O_2^- may be what is ionized – if this is true:

- High energy dump in detector → high O_2^- concentration → high photoionization rate
- LUX study did not see this correlation either in time or in space
- O_2^- concentration should be higher near the top of the TPC
- LUX optical studies suggest that the ionization center may be uniformly distributed

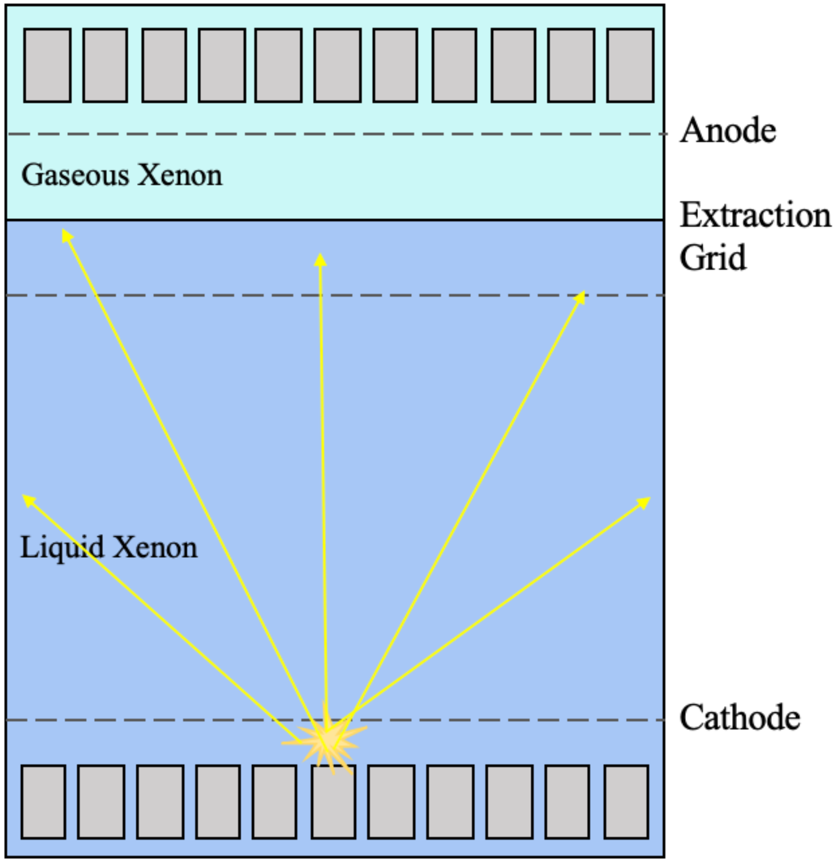




Can it contribute to Accidental backgrounds?

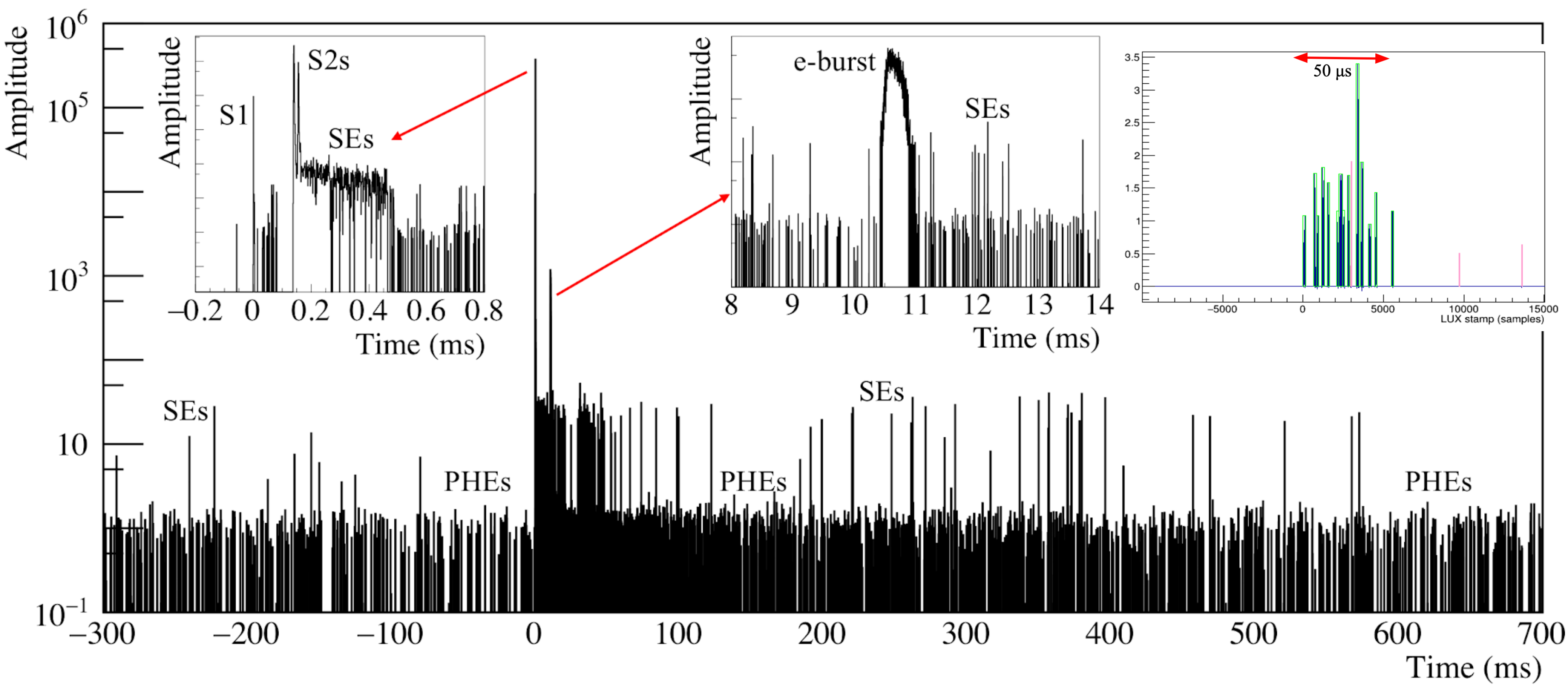
Not really

- High light intensity is needed to produce significant photoionization S2s, so triggering light would be detected
- Photoionization in bulk mostly leads to single electron emission (maybe pileups)
- Photoelectrons from grids may be sizeable but with fixed time delay (out of fiducial)



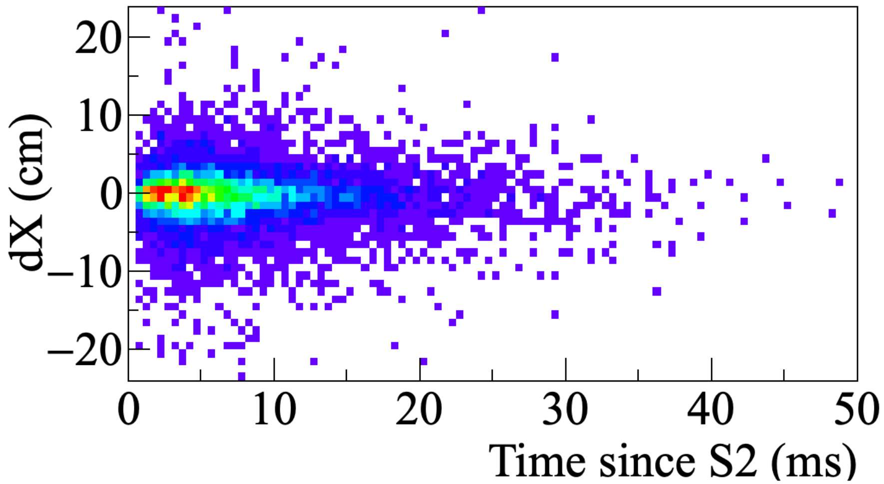
E-bursts were observed in XENON10 and LUX

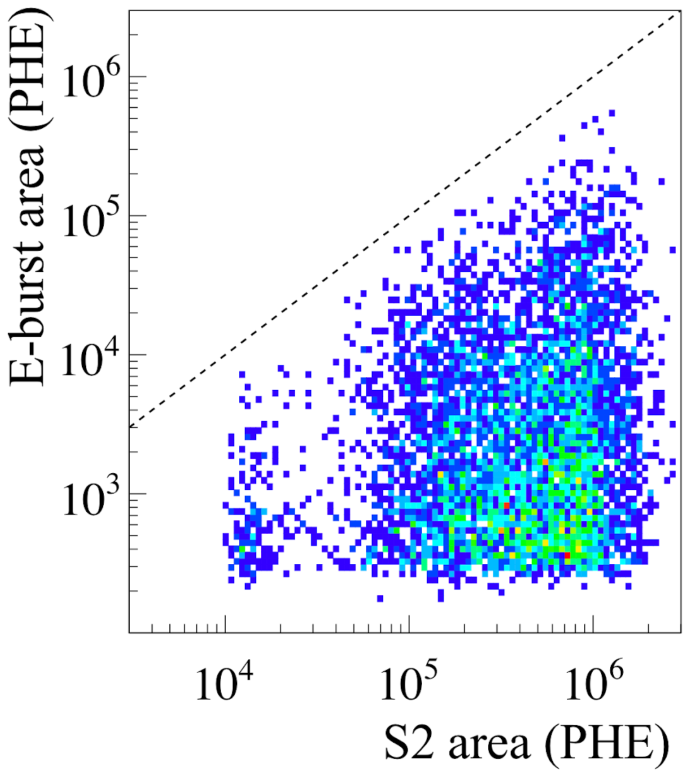
- Both XENON10 and LUX observed large electron clusters that last for $\mathcal{O}$(10μs) to $\mathcal{O}$(ms)
- Perhaps the most prominent electron background pathology

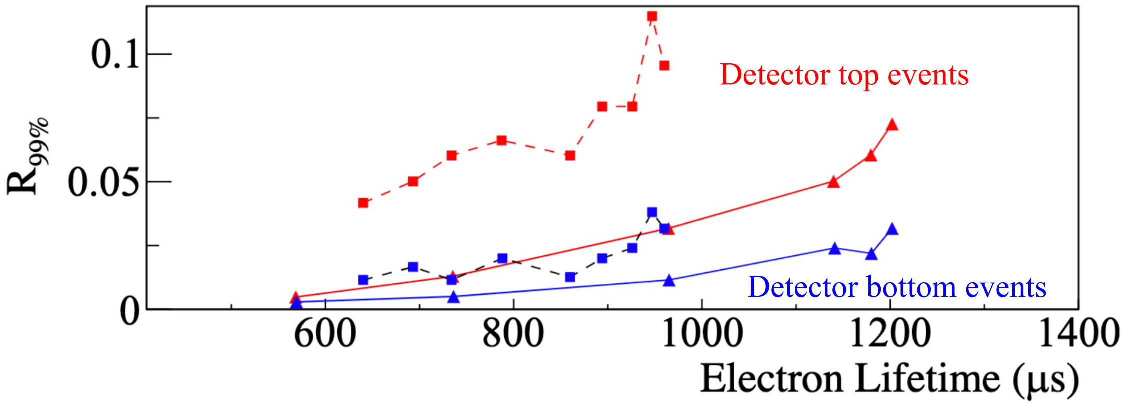


Are e-bursts from unextracted electrons?

- Positions of majority electrons coincide with progenitor S2
- Upper size limit traces progenitor S2 size
- More emission with high purity and less drift



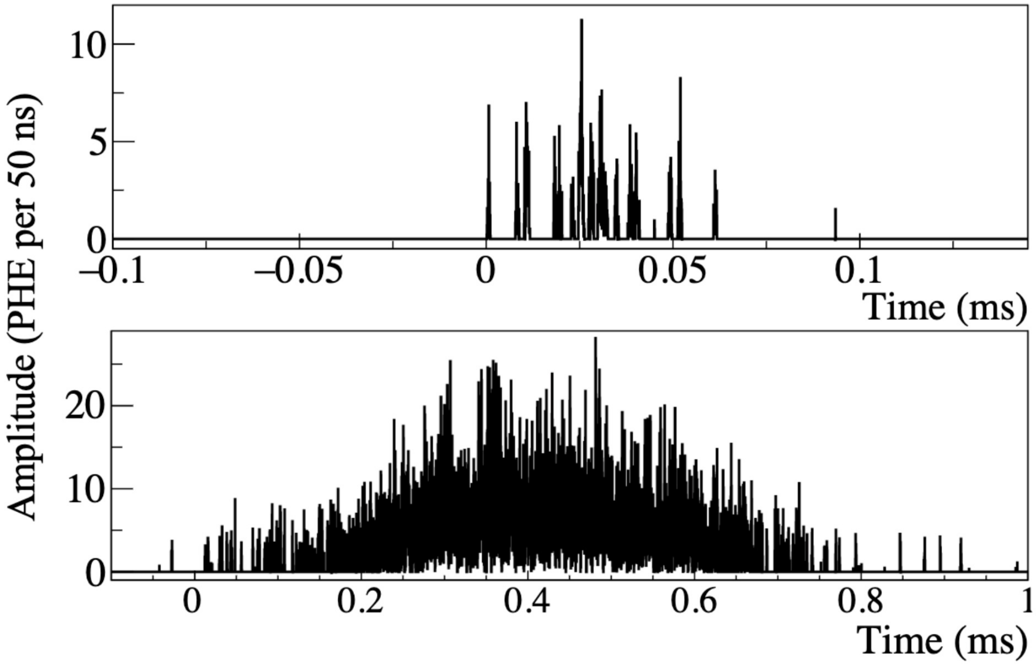




Can it contribute to Accidental backgrounds?

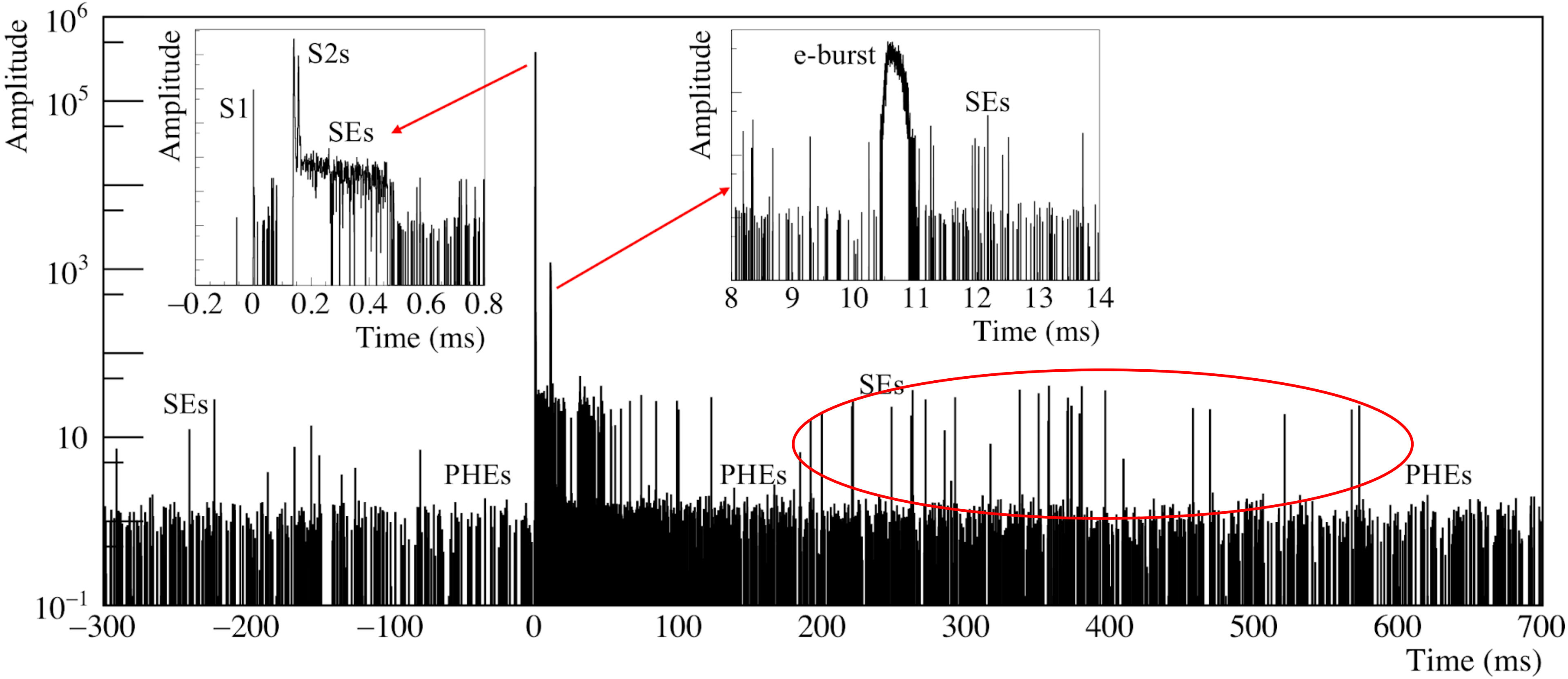
Possibly but not likely

- LZ doesn't observe e-bursts (XENON100/1T/nT haven't reported such clusters)
- Majority of e-bursts are easy to cut out due to size and duration
- Low intensity ones could appear like a sizeable lone S2 (to be mis-paired with a random S1)



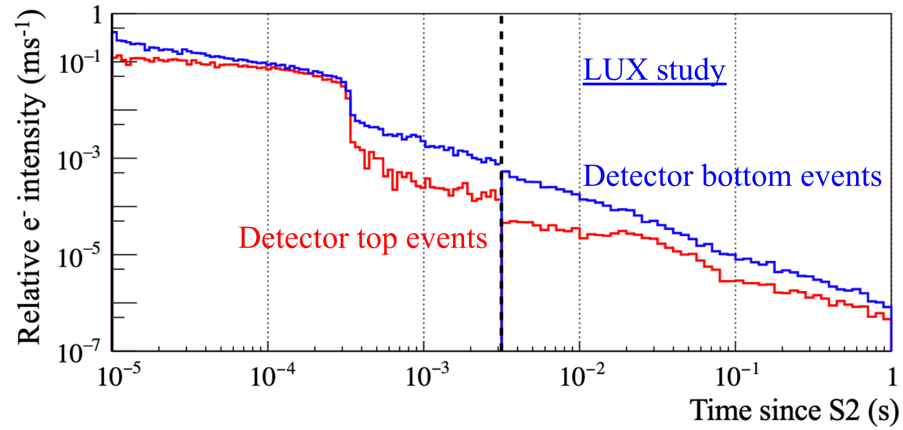
The slow bubbling of electrons

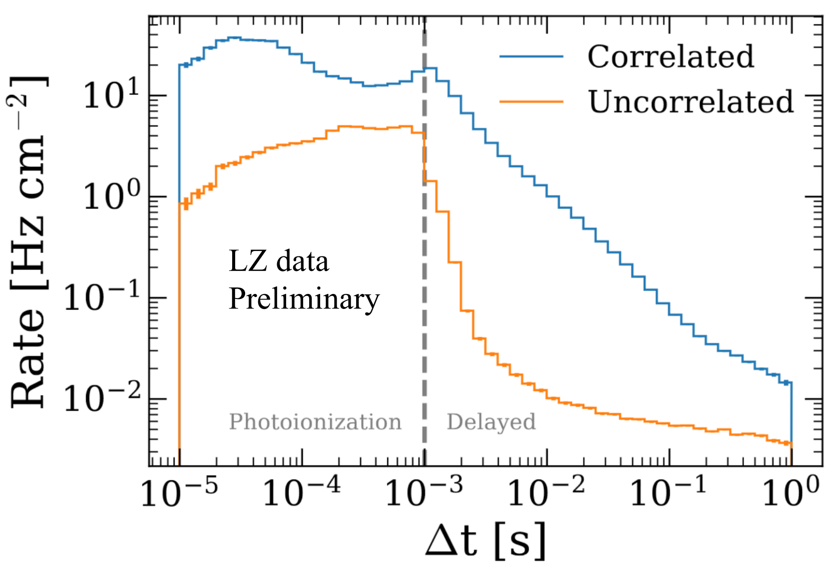
- Continued emission of electrons is observed up to >1s after a progenitor S2
- Most slow-release electrons also have the same position as the progenitor S2

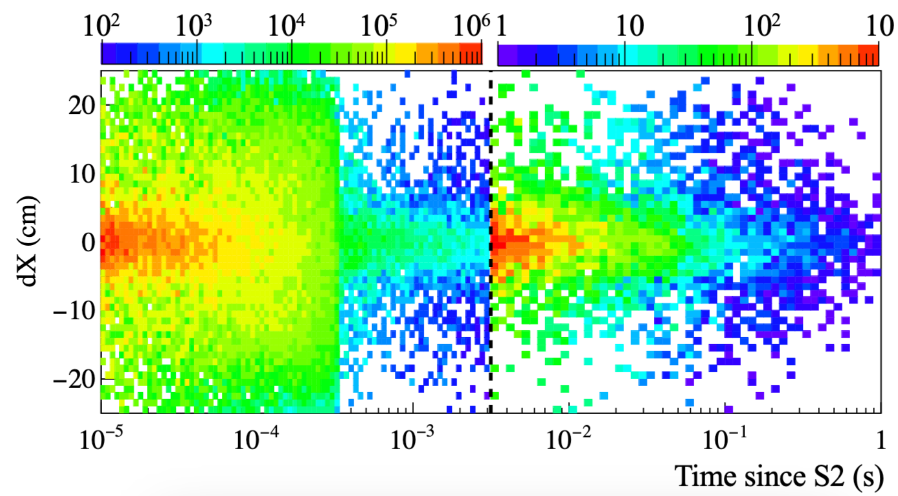


Its confusing power-law time dependence

- Electron rate exhibits unusual power-law-like time dependence
- Observed in LUX and LZ, confirmed by XENON1T, AsteriX (and single phase TPC)
- Very few physics processes follow power-law distributions (even more difficult to explain non-integer exponent)







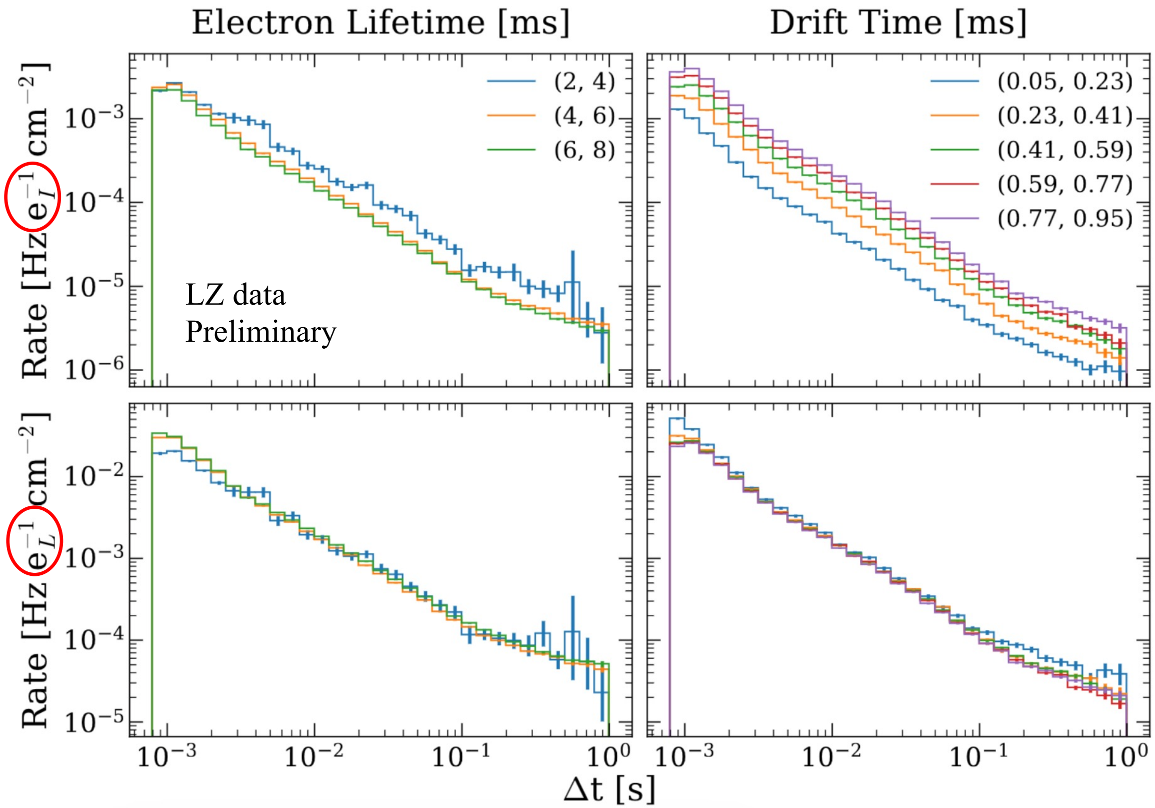
We know where these electrons are from

Top plots normalize electron rate to initial progenitor size

- High electron rate at low LXe purity
- High electron rate at long progenitor S2 drift time

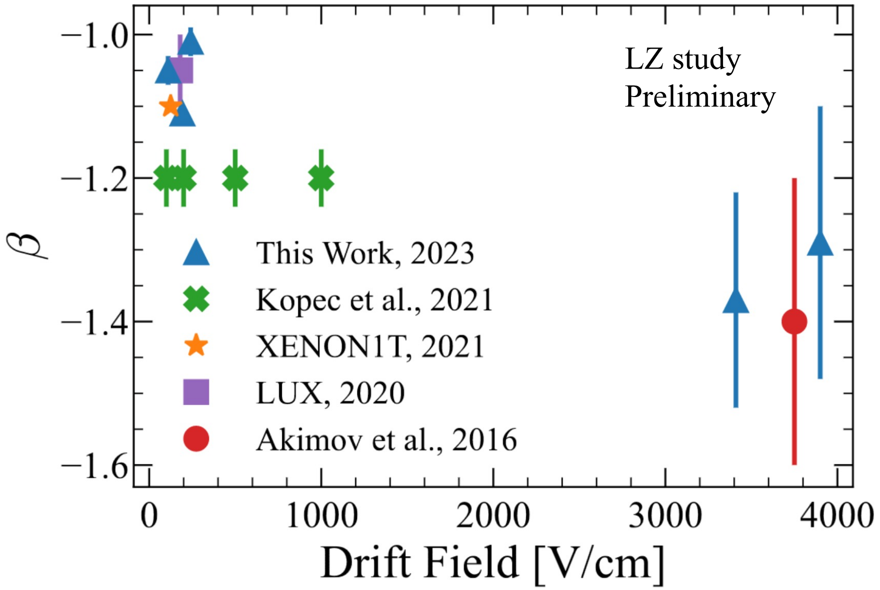
Bottom plots normalize electron rate to drift electron loss

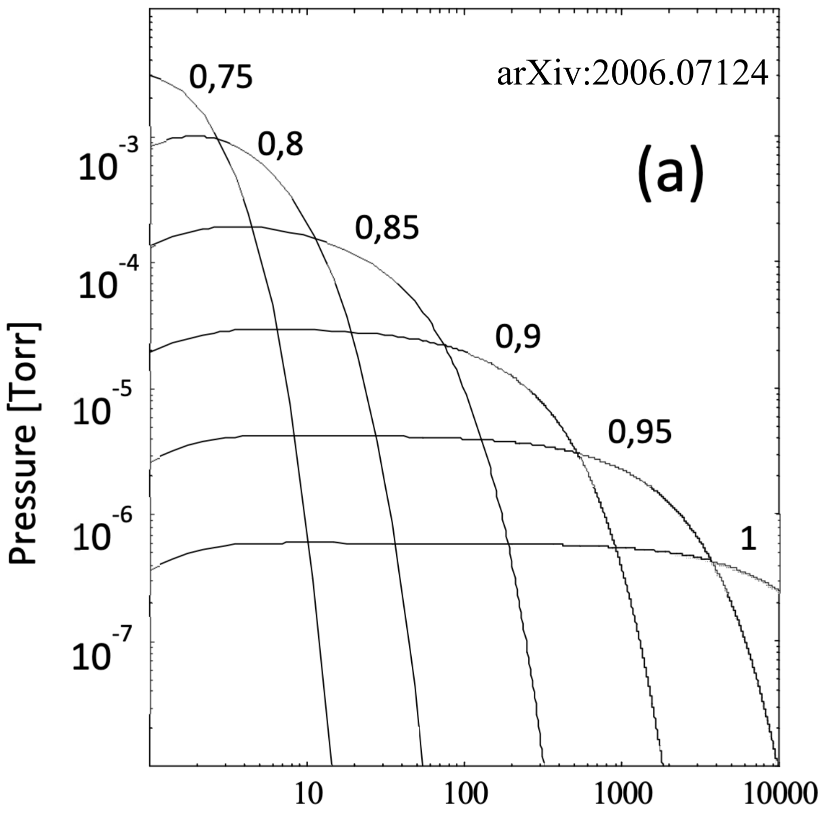
- Rate dependence on LXe purity and drift time is removed
- Emission rate mostly depends on progenitor electrons lost to impurities during drift



… but how do they come out?

- LZ studies the power-law exponent at different LXe electric fields
- A possible increase at high electric field
- Result may reconcile past measurements
- We may explain the power-law in analogy with outgassing rate in vacuum systems



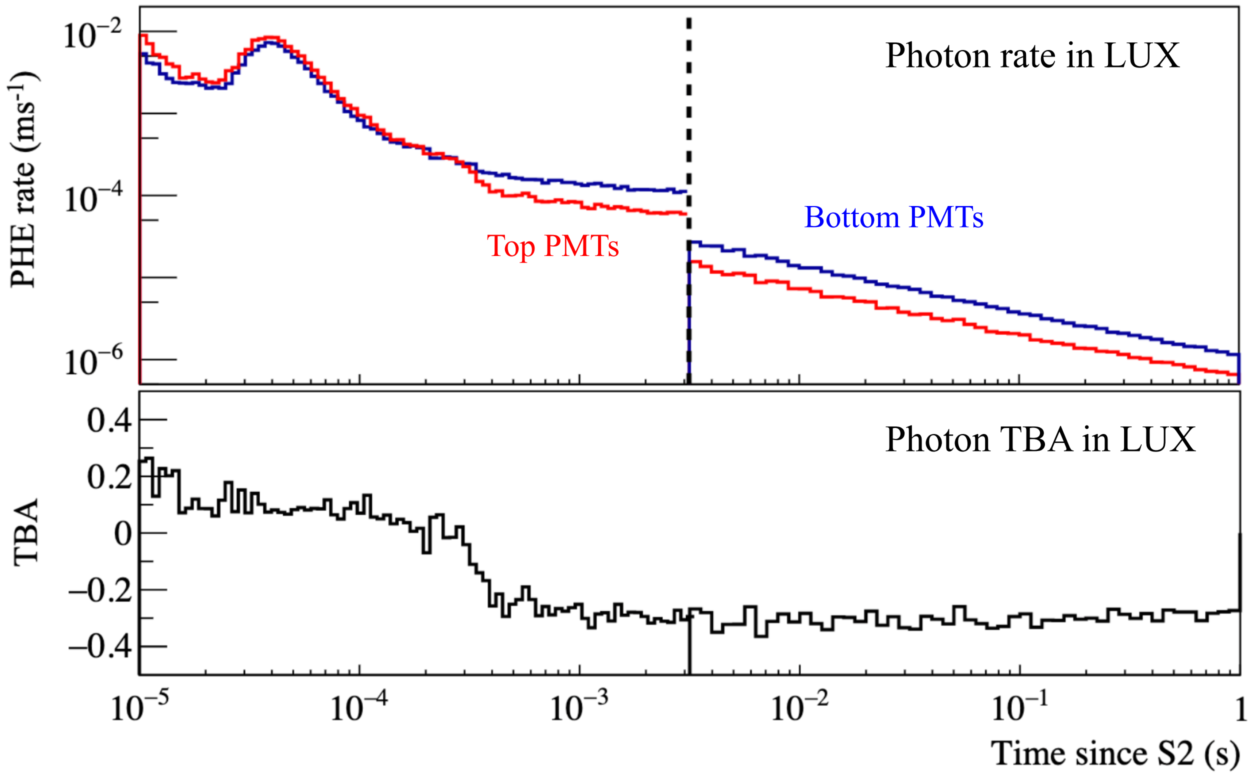


Outgassing in a vacuum chamber follows a power-law time dependence if there are multiple surface adsorption energy levels in the system

Can it contribute to Accidental backgrounds?

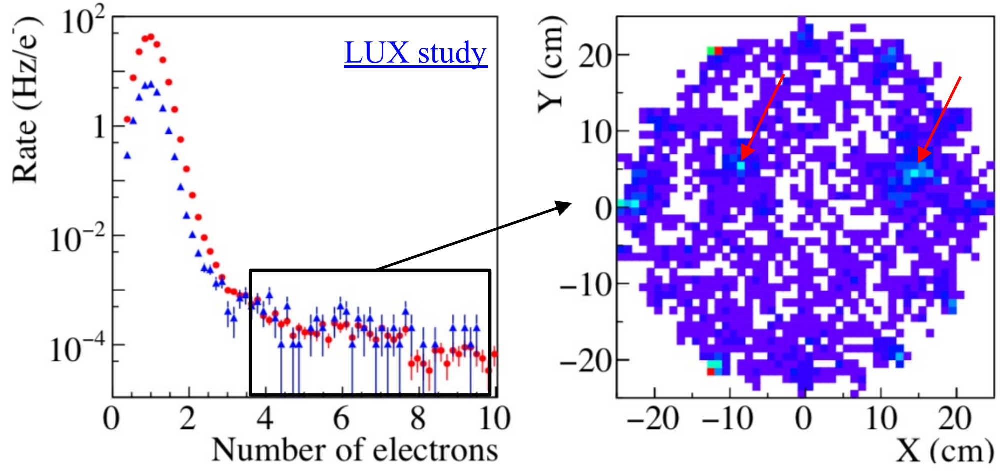
Yes and no

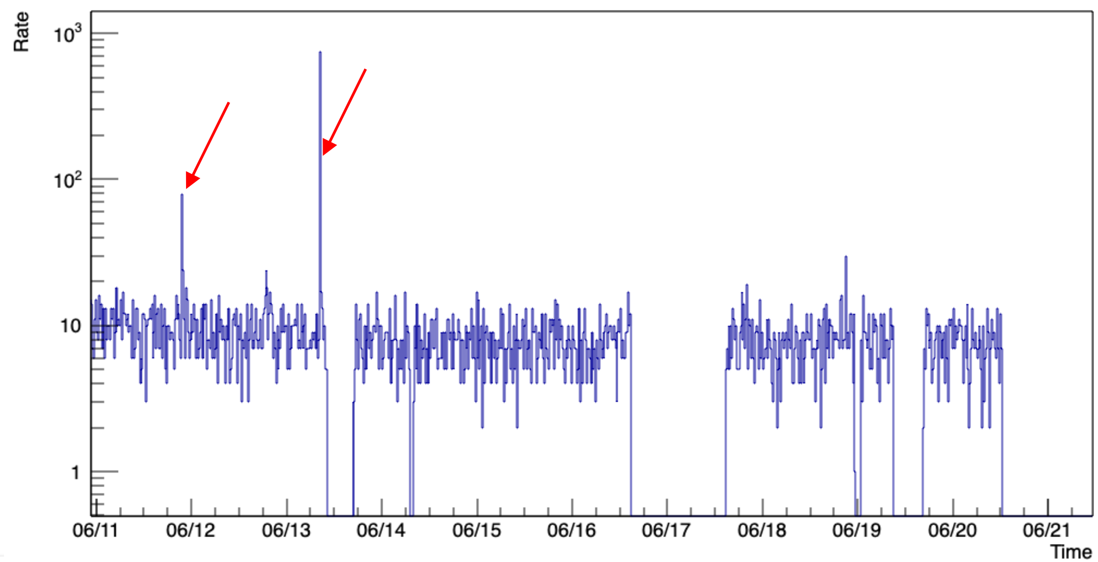
- Delay emission electrons are primarily single electrons (pileup in high-rate region)
- Veto after large progenitor S2s is effective
- However, delayed photon emission follows a similar power-law form (not a constant rate)
- Pile-up S1s are more likely to be a problem



The scary phenomenon that shall not be named

- Electric grids may emit electrons and contribute to high voltage instability
- Even during “stable” high voltage operation periods transient electron emissions can occur
- Significant contamination of multi-electron pulses from weak grid emission

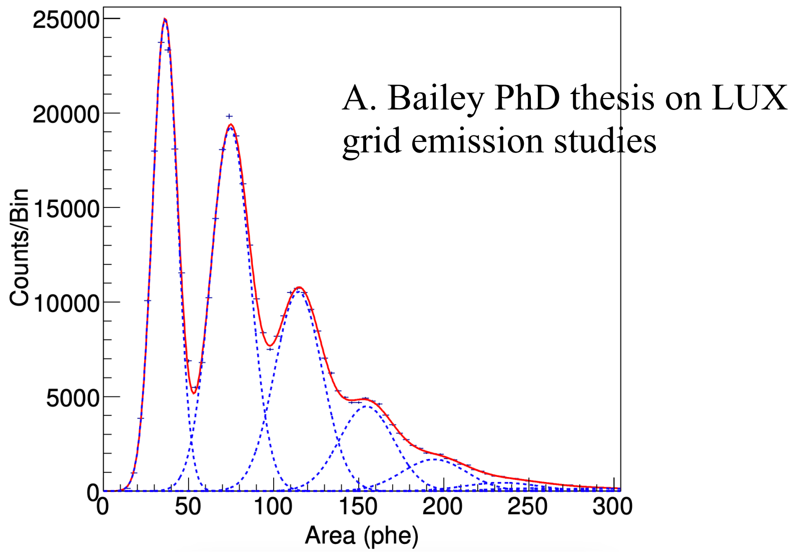


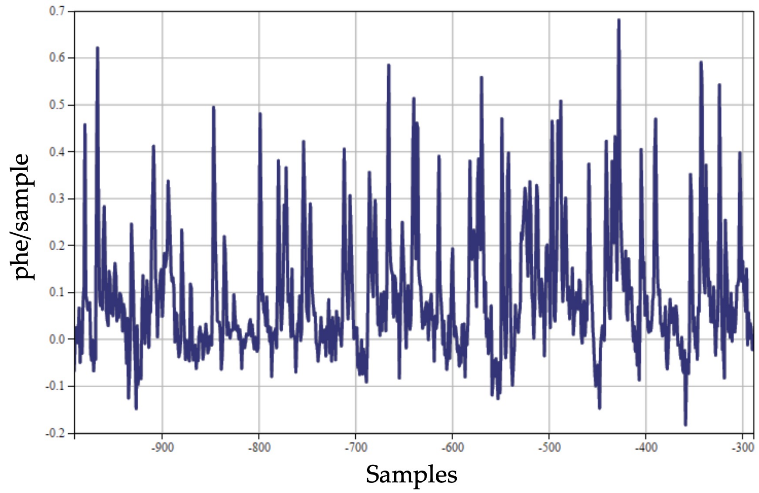


Can it contribute to Accidental backgrounds?

Likely yes

- HV instability often leads to both photon and electron emissions
- Multiple photons or electrons may be observed
- Enhance photon and electron rates during emission periods produce a higher accidental rate than a simple random pairing model
- Photon and electron correlation needs to be taken into consideration

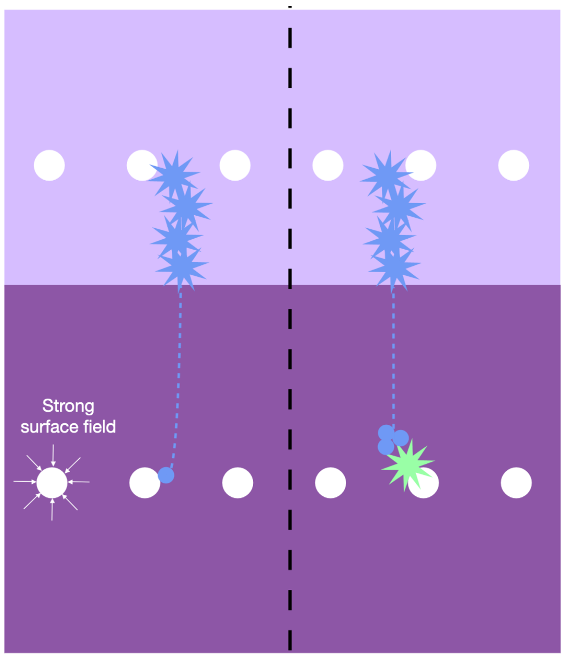


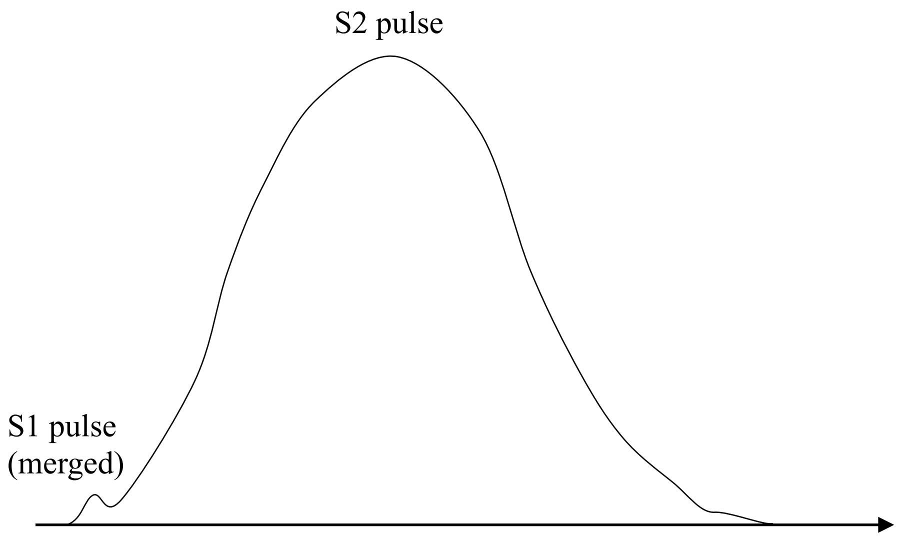


Radiogenic backgrounds deserve a spot

Radiogenic events usually produce both S1s and S2s in LXe, but

- Events in high field regions may have highly suppressed S1s
- Events in low field regions may have undetectable S2s
- Events near the liquid surface may have S1s and S2s merged together (apparent S2-only)

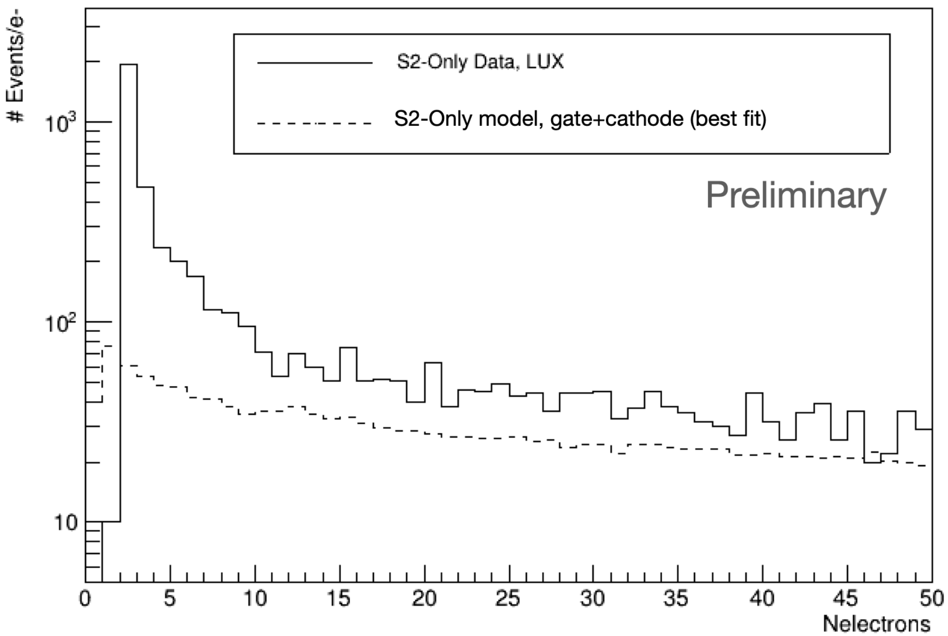




Can it contribute to Accidental backgrounds?

Yes and no

- Radiogenic backgrounds are effective in producing large "S2-only" pulses
- Same for large "S1-only" pulses
- Random pairing of such S2-only pulses with random S1s can be a significant background in WIMP searches
- These S2s often have skewed pulse shape that may be used to reject them (for relatively large S2s)



Simulated grid radiogenic background in LUX (credit to R. Linehan)

Summary

- LXe TPCs produce a wide range of pathological pulses both at low energies and high energies
- Random pairing of S1-only and S2-only events (some may be related) produces accidental backgrounds
- We have some handles to suppress S2-only backgrounds
- S1-only backgrounds are less studied (random pileup of single photon signals is hard to avoid if we want low S1 multiplicity)
- Pathological radiogenic background shall not be overlooked

Lawrence Livermore National Laboratory