# Low-energy Event Detection in a Liquid Xenon Proportional Scintillation Counter

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CPAD Workshop

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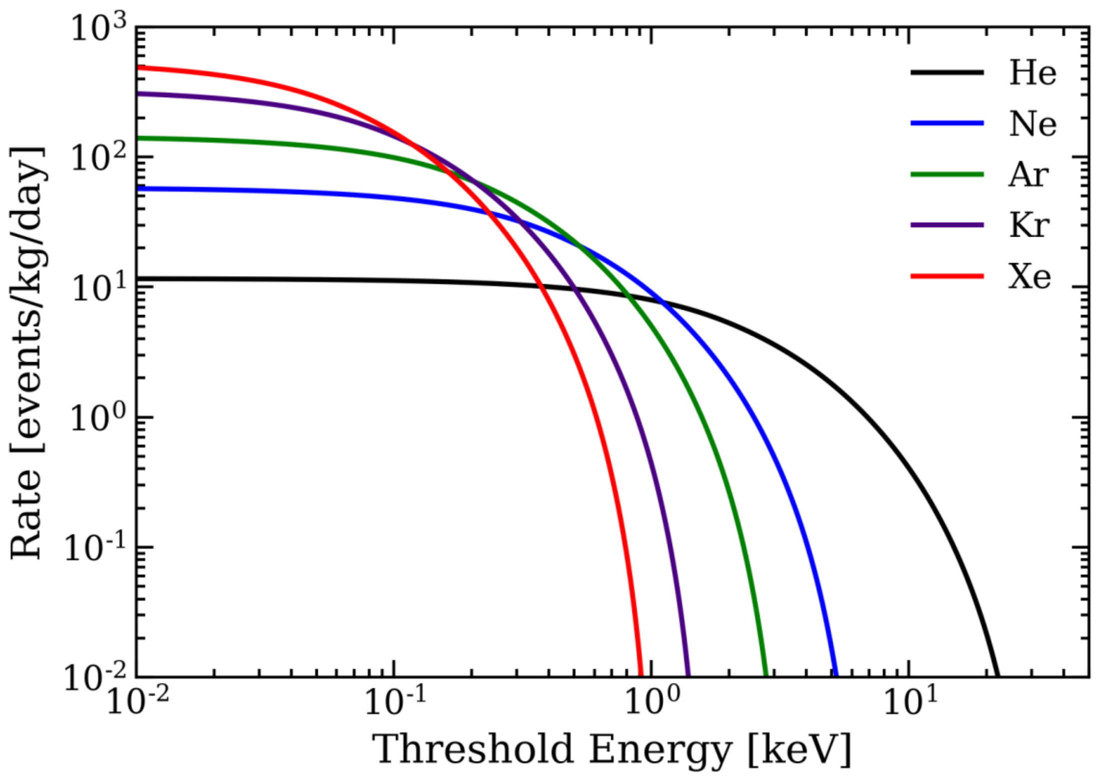
# LBECA

An R&D Program towards a **L**ow **B**ackground **E**lectron **C**ounting **A**pparatus

- R&D program supported by DOE (2018-2020)
  - Investigate single-and-few e- background in liquid xenon detectors
  - Dedicated setups to test various ideas to mitigate the electron background
  - Accurate calculations and modeling of expected low energy signals
- Following the R&D program, propose/build a liquid xenon detector with much reduced single e- background for Light DM Search

# Motivation

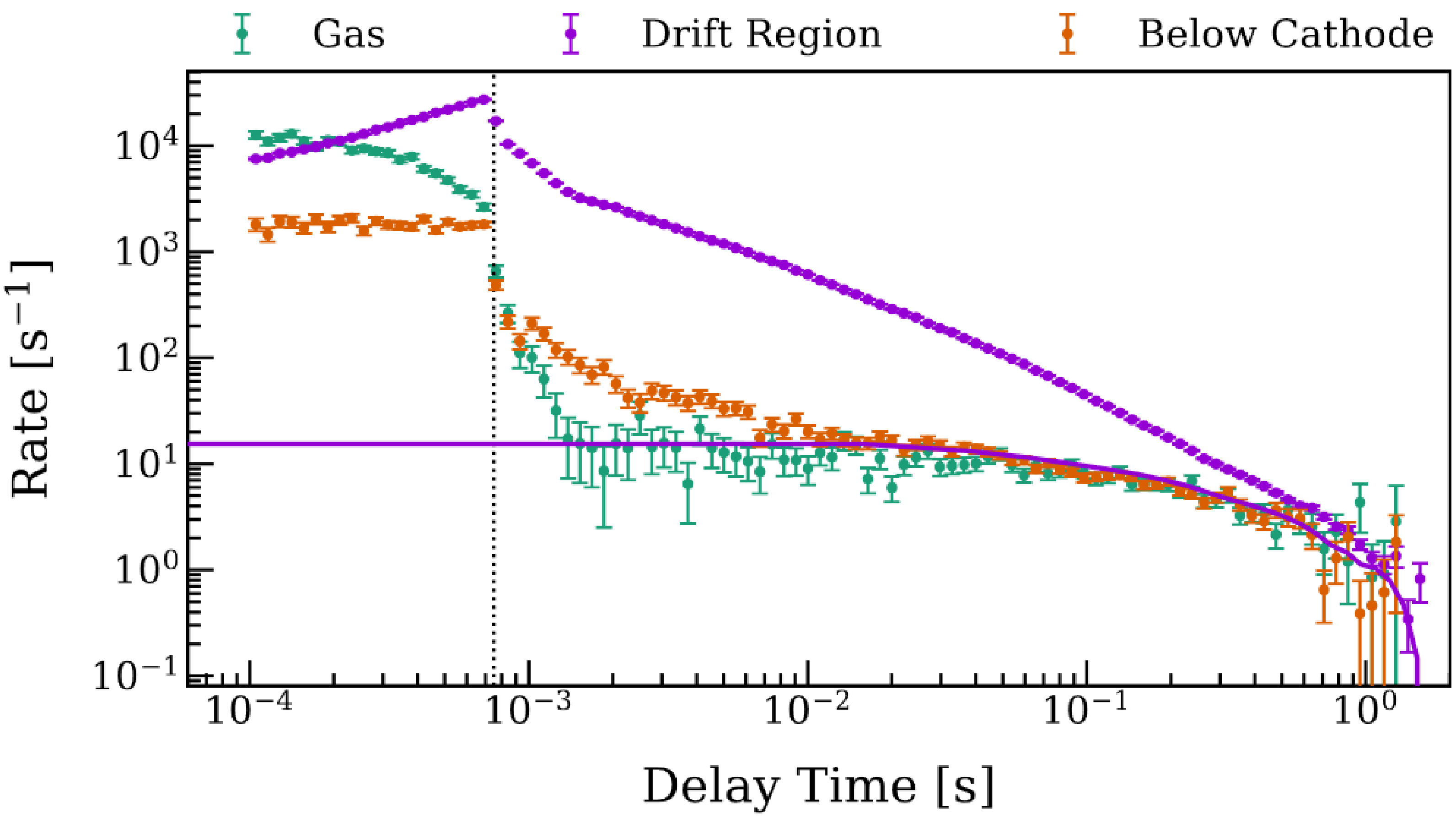



Integrated reactor CEvNS rate on different noble elements *(K. Ni et. Al. universe7030054)*

- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) at a nuclear reactor
  - High flux
  - Sub-keV nuclear recoils in Xe (mostly S2-only events)
- Next generation of LXe dark matter searches for:
  - WIMPs (if ER/NR discrimination is comparable)
  - Light dark matter (if S2 only background can be reduced)

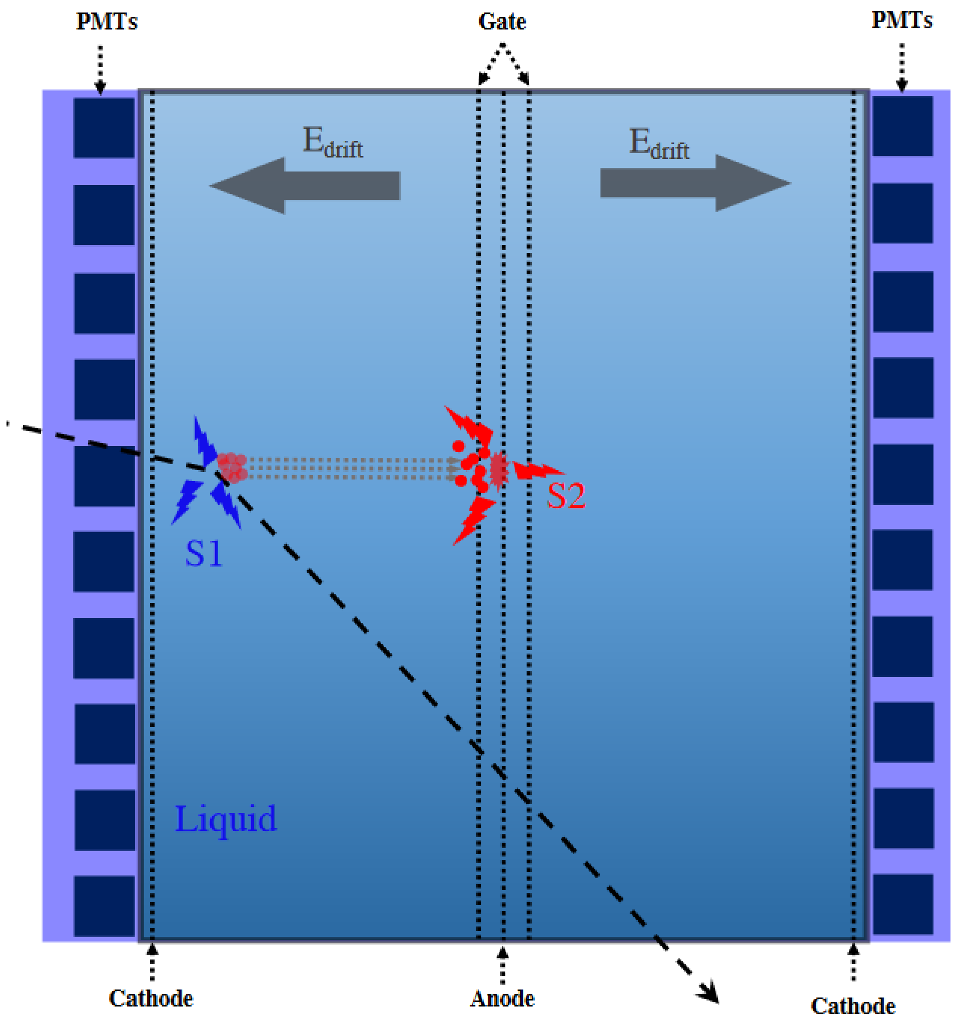
# Single-electron Background in Dual Phase LXe TPCs

- Single-electrons up to 1 second after a large S2 pulse
- Seen in dual-phase LXe TPCs (LUX, XENON1T)
- Major background for low-energy ionization-only searches
- Origins are unclear:
  - Could be related to the liquid-gas interface
  - Could be related to impurities
  - Or a mix of both




XENON1T, arXiv:2112.12116 (PRD 2022)

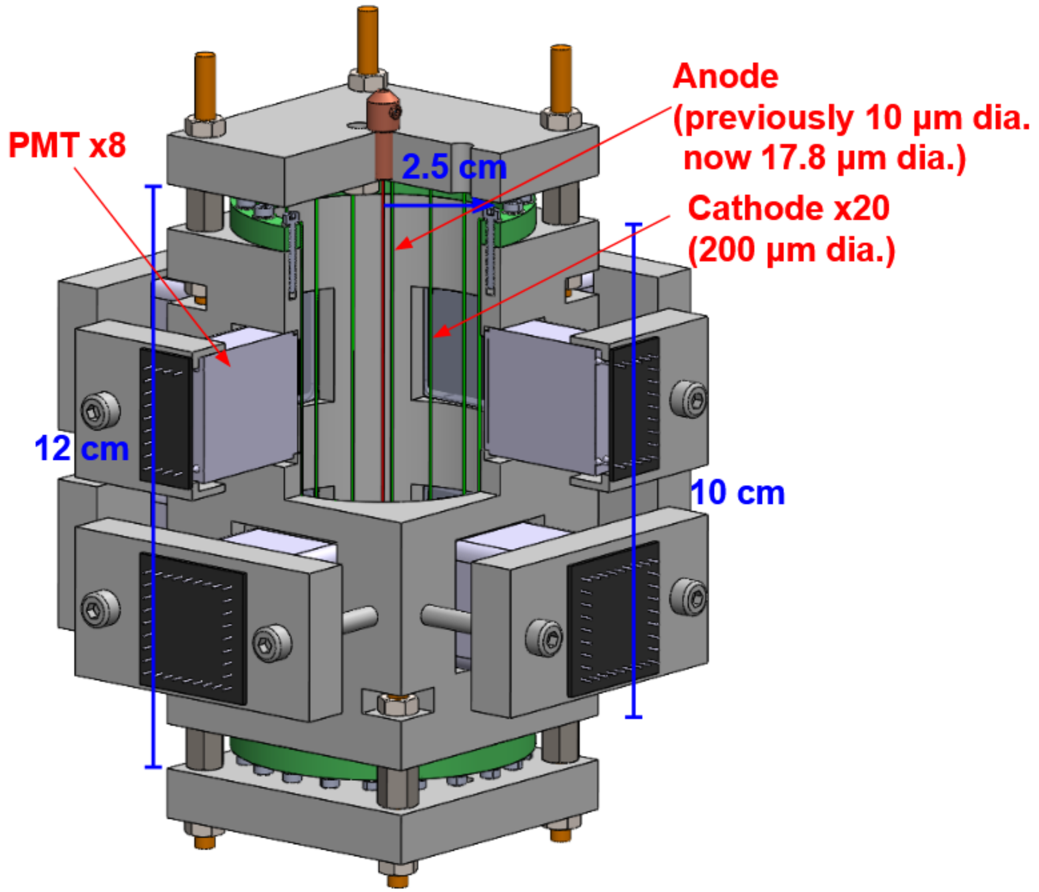
# Liquid Xenon Proportional Scintillation Counter (LXePSC)




Principle of a single phase liquid Xenon (LXe) detector (Qing Lin *JINST* **16** P08011)

- Produces S2 directly in liquid:
  - 100% extraction efficiency
  - Simplifies detector design (no need to maintain a gas-gap)
  - Potential to investigate the origin of the single-electron background after a large S2
- Needs > 425 kV/cm to produce S2s in LXe (E. Aprile et. al.: JINST 9 P11012 (2014))

# LXePSC at UCSD: SanDiX

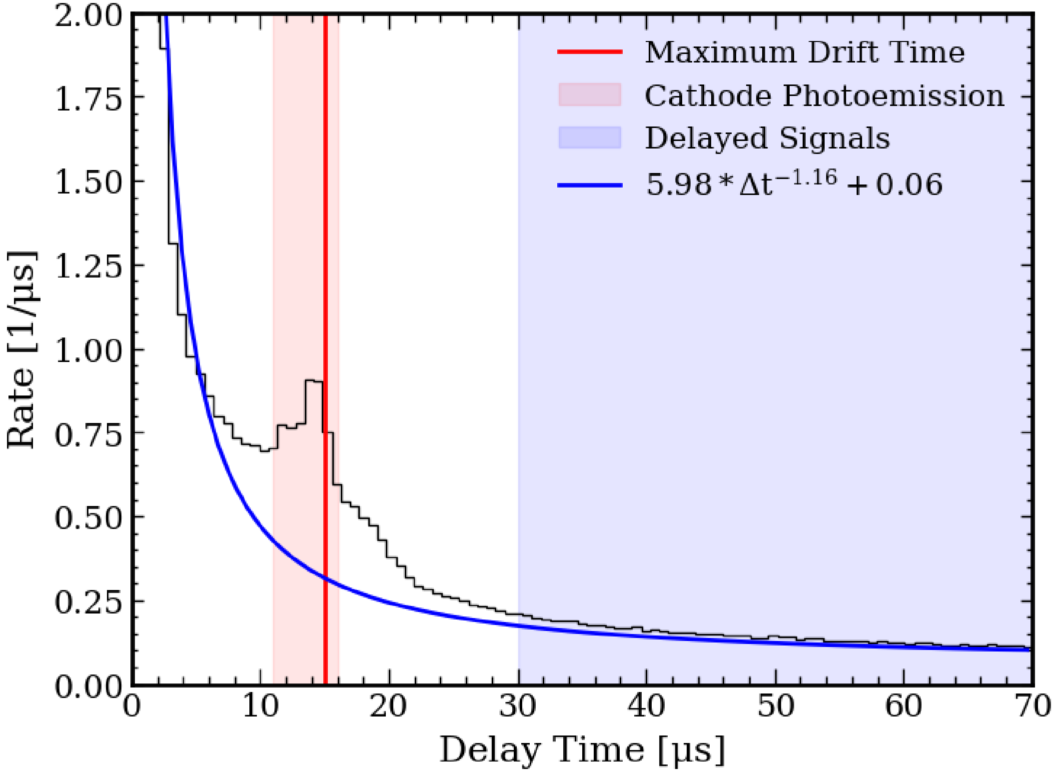


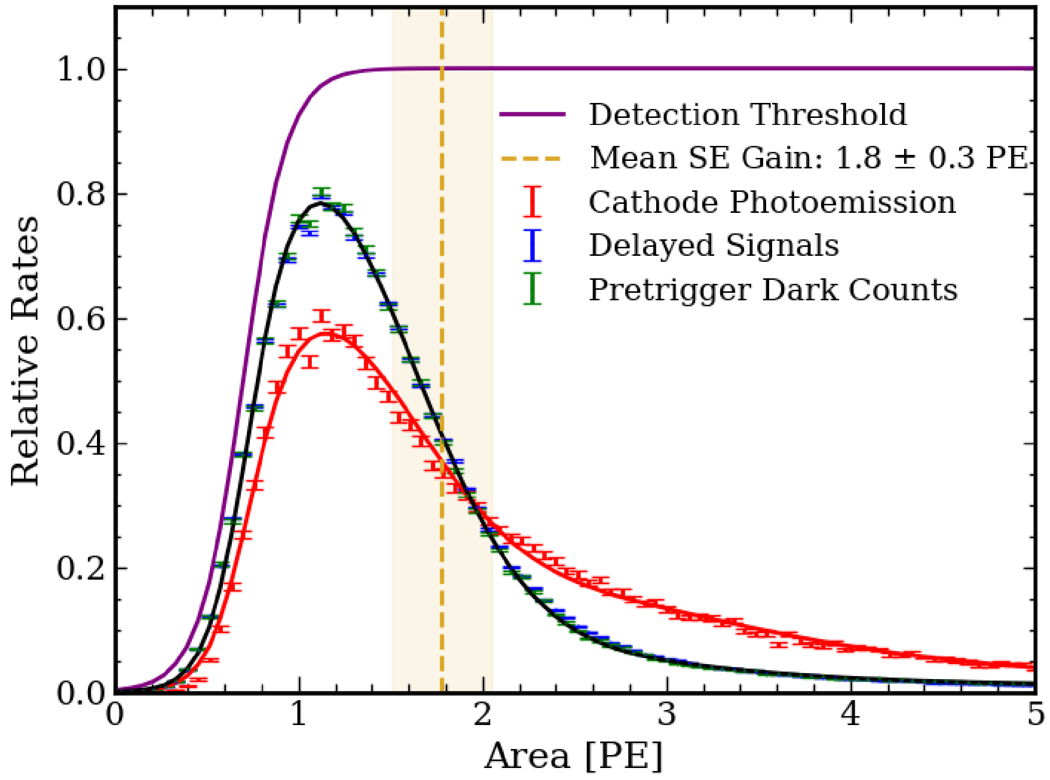

Modified from a design by Dr. Yuehuan Wei

- Previous results:
  - 25 µm anode wire, arXiv:2111.09112 (LIDINE 2021, JINST 2021)
  - 10 µm anode wire, arXiv:2301.12296 (JINST 2023)

- Recently changed wire to 18 µm
  - Smaller maximum field
  - Larger electroluminescence region

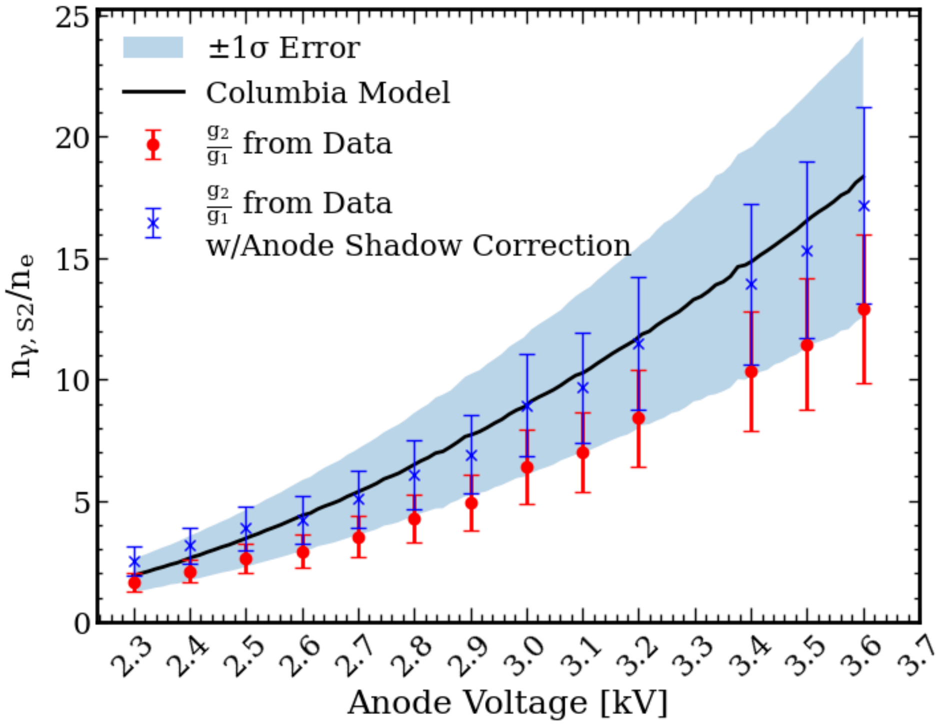
# Previous Results: 10 µm Anode

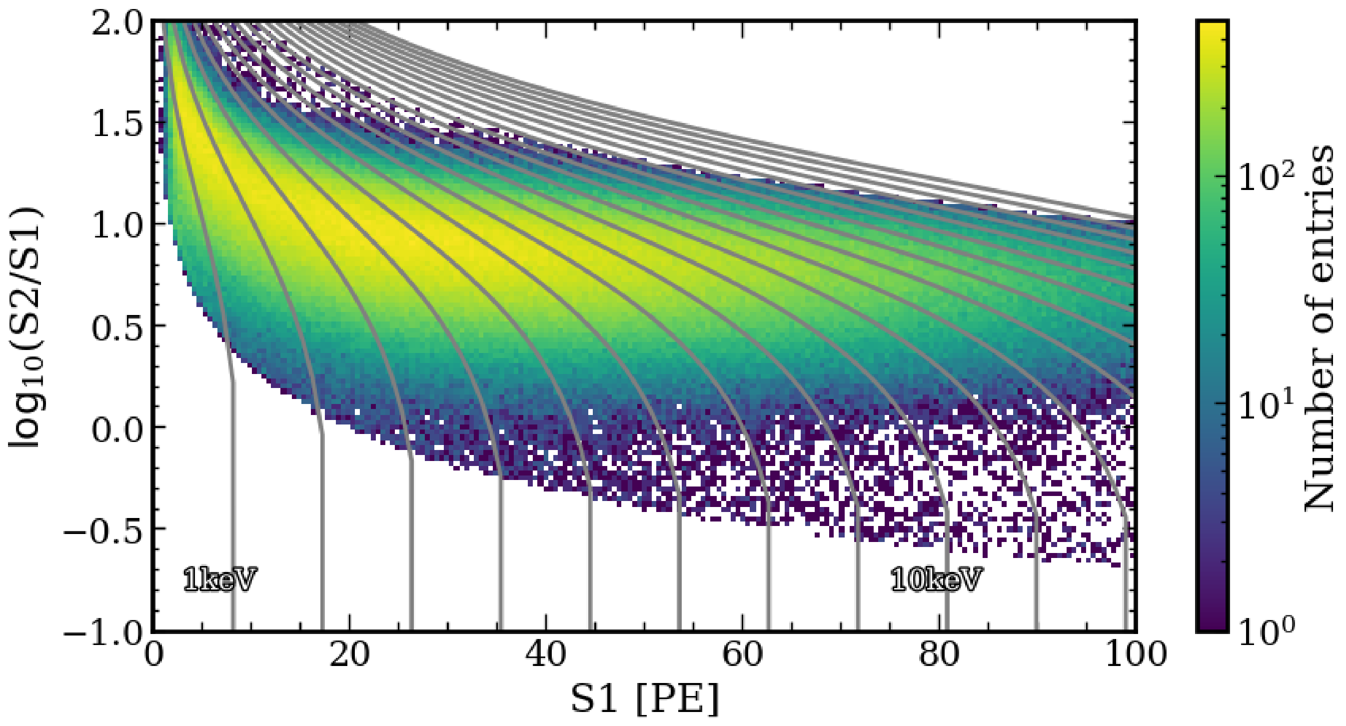



- Evidence of S2 pulse induced single electron emission from cathode wires
- Measured g2 of 1.8±0.3 PE/e-
- More details at arXiv:2301.12296

# Previous Results: 10 μm Anode



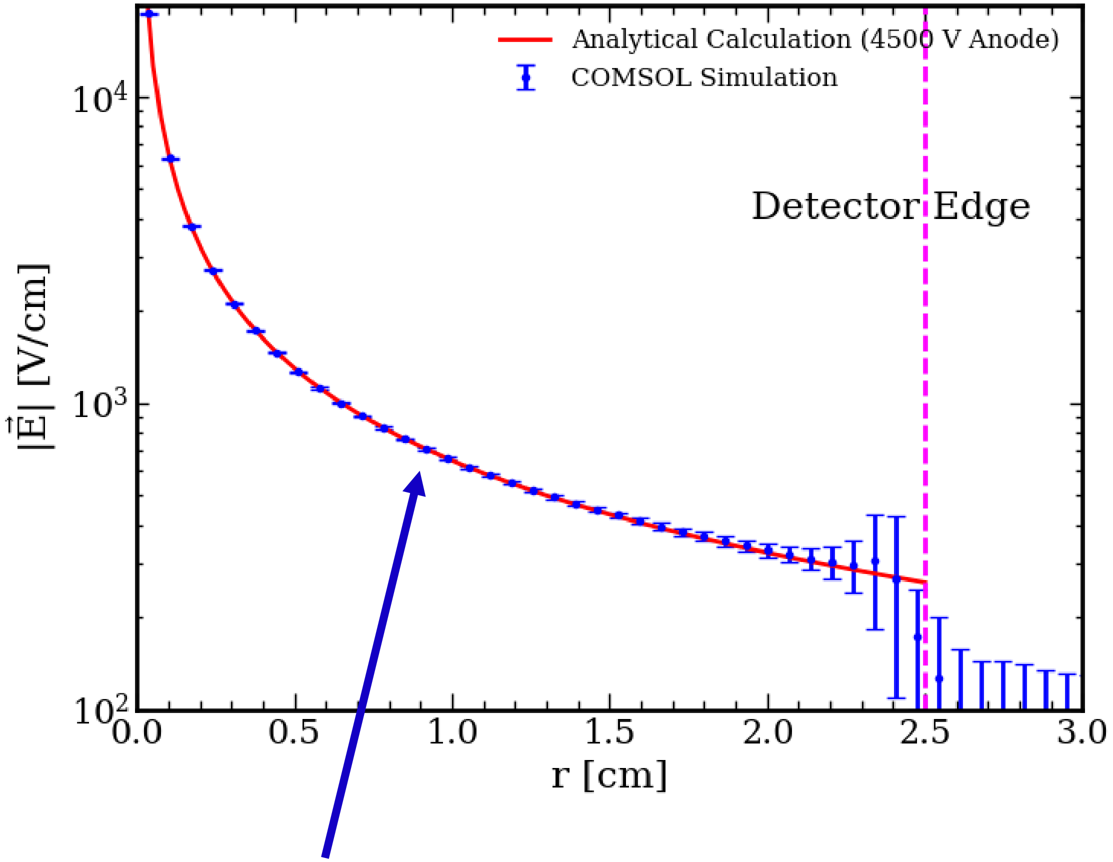




- EL gain consistent with Aprile et al. (JINST 9 P11012 (2014)) after correcting for the wire shadow effect
- Low Energy ER from tritium decays observed
- More details at arXiv:2301.12296

# Current Results: 18 μm Anode Test

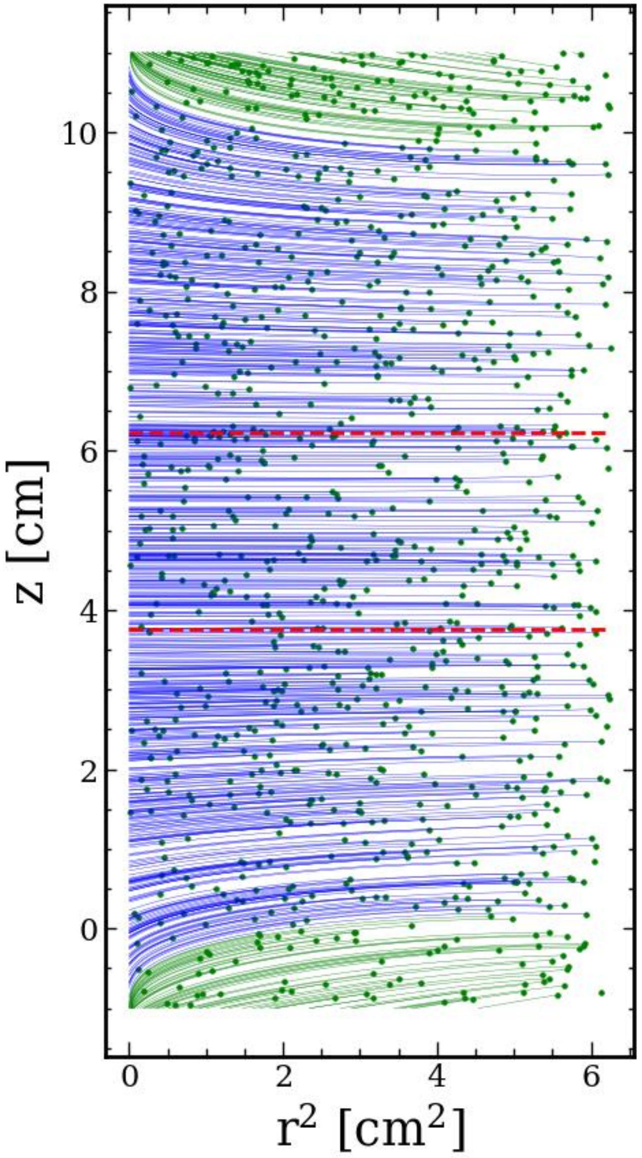
- Larger anode diameter (18 μm) ⇒ larger electroluminescence region
  - Higher electric field in the bulk
  - Anode: 4.5 kV, Cathode: -650 V
- $^{252}$Cf calibration:
  - $^{129m}$Xe and $^{131m}$Xe activated lines (236 keV and 164 keV gammas, respectively)
  - Nuclear recoil band
- Xe activated lines:
  - High statistics (made possible with new triggerless digitizers!)
  - Cuts in drift time (i.e. electric field) for Doke-plot
- Tritium:
  - Gives us a measurement of ER-leakage for small $g_2$

# Electric Field

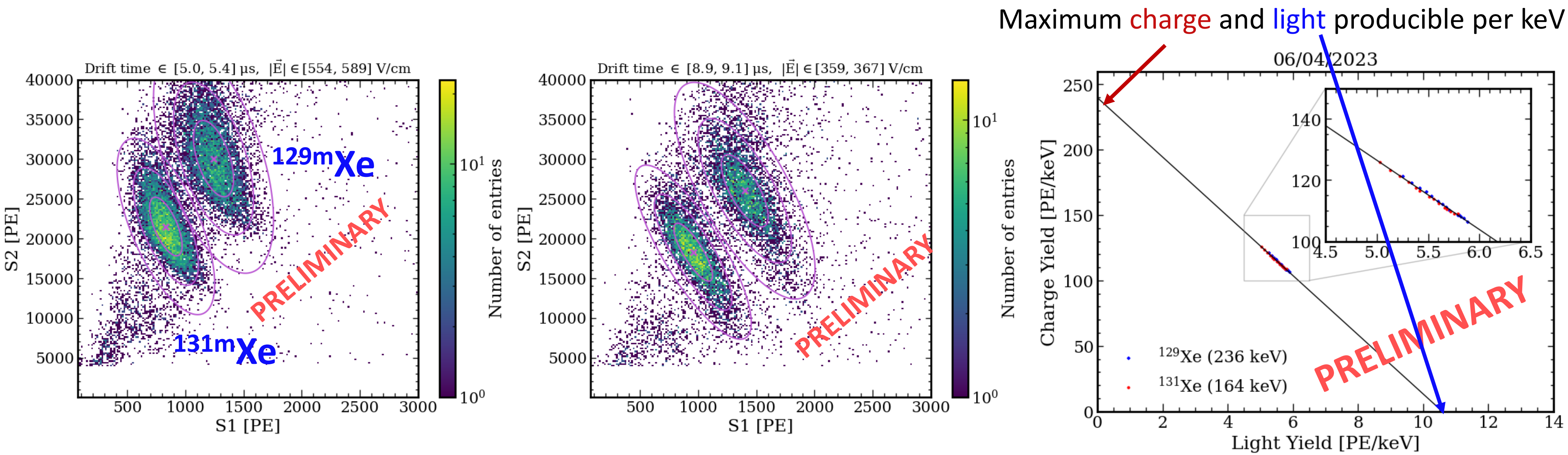



Field simulation is consistent with analytic field (near the center in z and r)

- Charge insensitive volumes (CIV) near the top and bottom
  - Next iteration will have field shaping rings
  - Current experiment has ~17% CIV
- CIV may cause charge loss (i.e. smaller S2s)



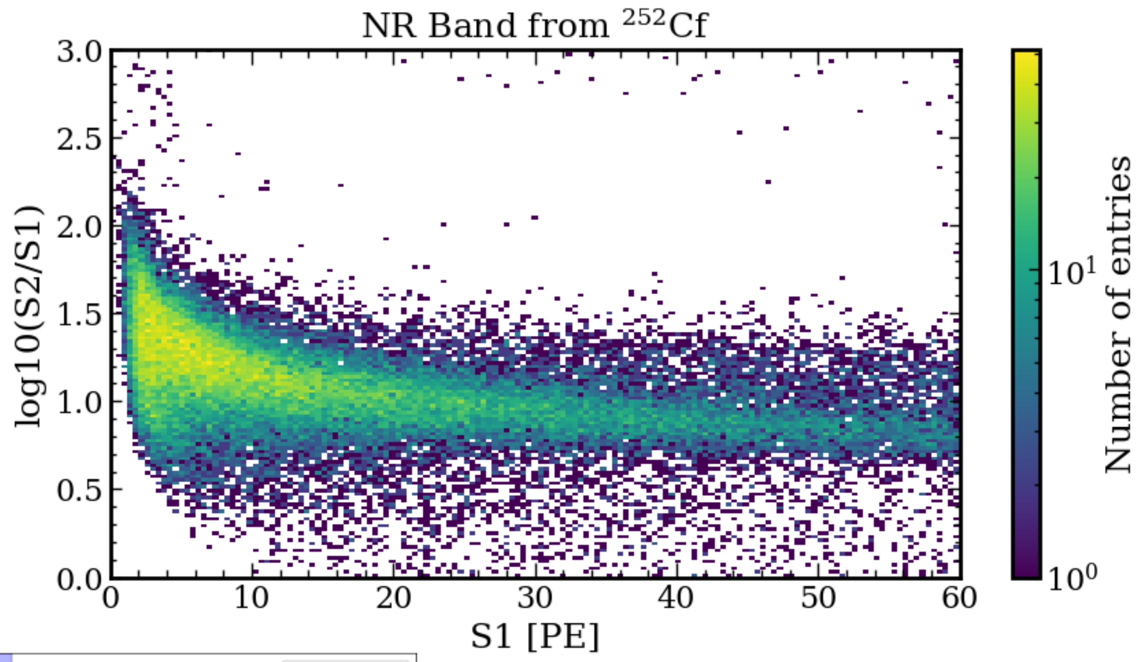
# Activated Xenon Lines

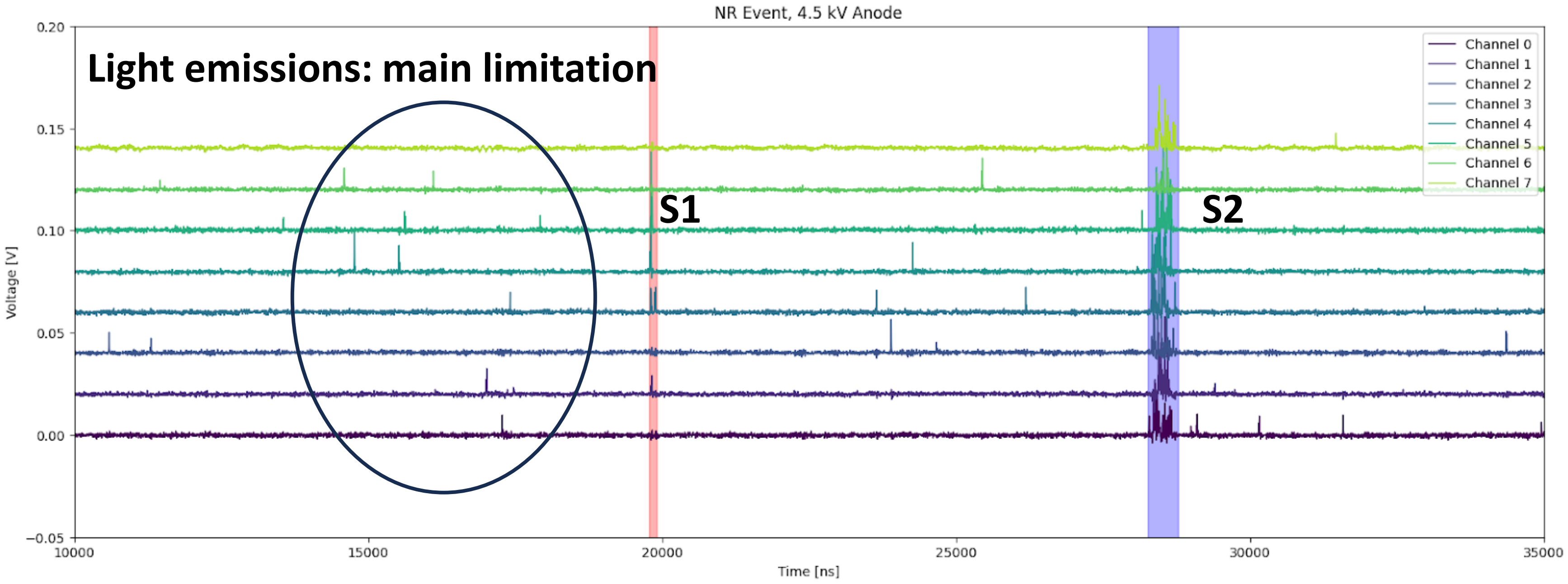



- Clear $^{131m}$Xe and $^{129m}$Xe lines (164 and 236 keV respectively)
- Larger drift times → larger event radius → smaller electric field
- Drift time slices correspond to electric field slices
- Single-electron gain is the same regardless of drift time slice
- $g_2$ measured to be ~3.5 PE/e$^-$ (before electron lifetime effects)
- $g_1 \approx 0.14$ PE/photon (photosensor coverage: 29%)

# Nuclear Recoils

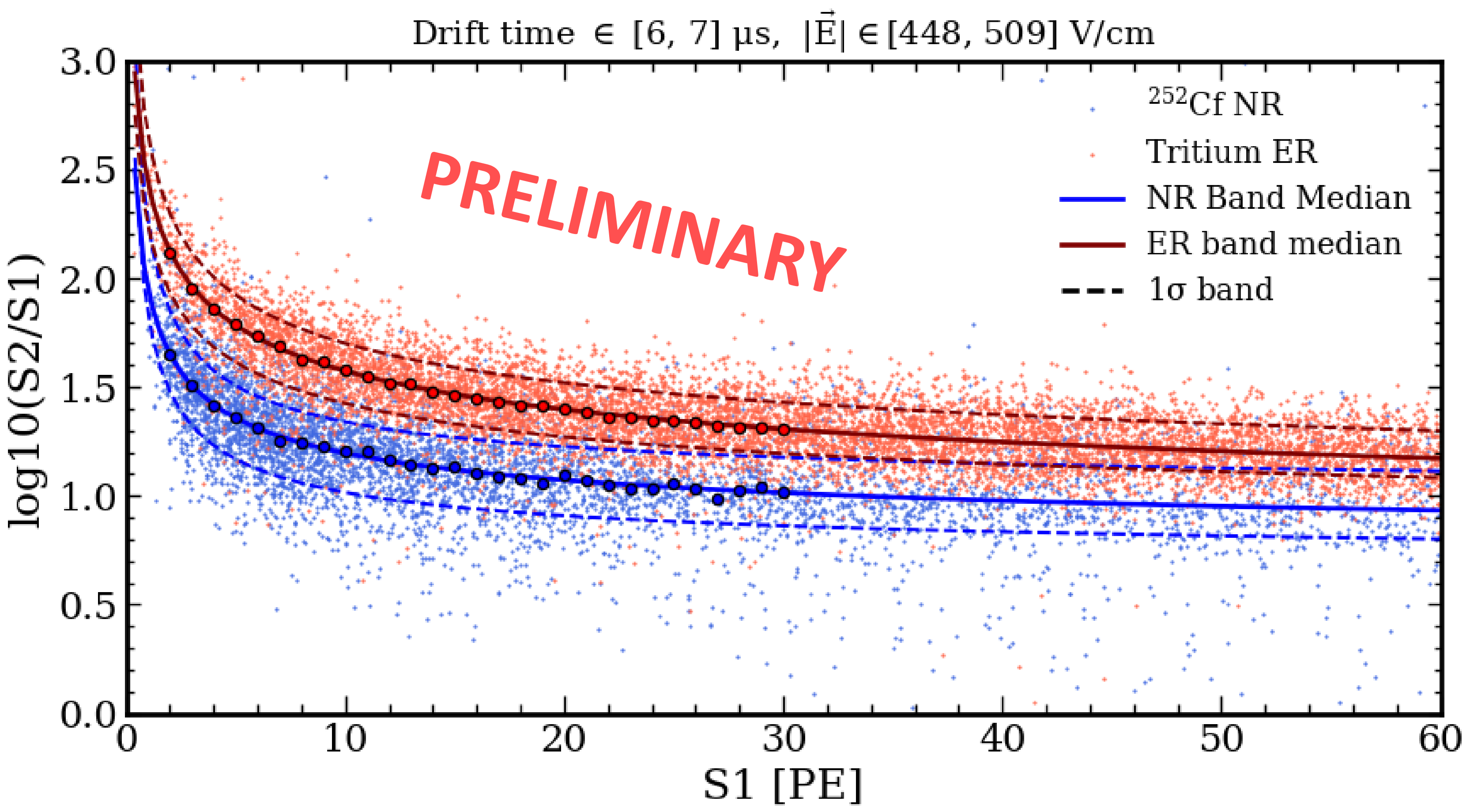
- Cuts applied:
  - z-cut
  - Diffusion cut (drift time vs S2 width)
  - Multiple scatter
  - Noise cuts



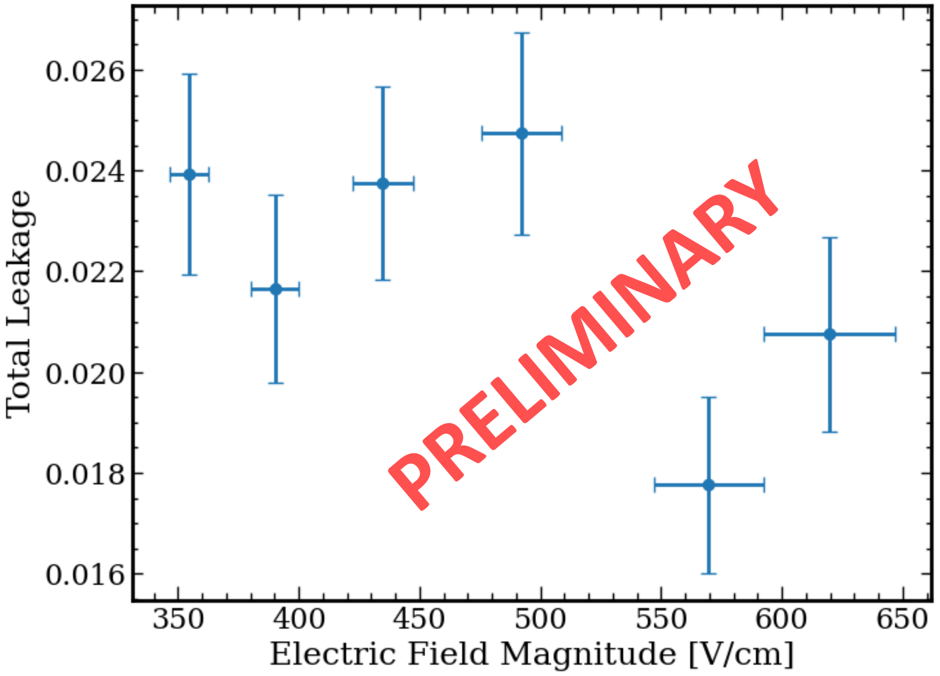
# ER (Tritium)/NR Discrimination

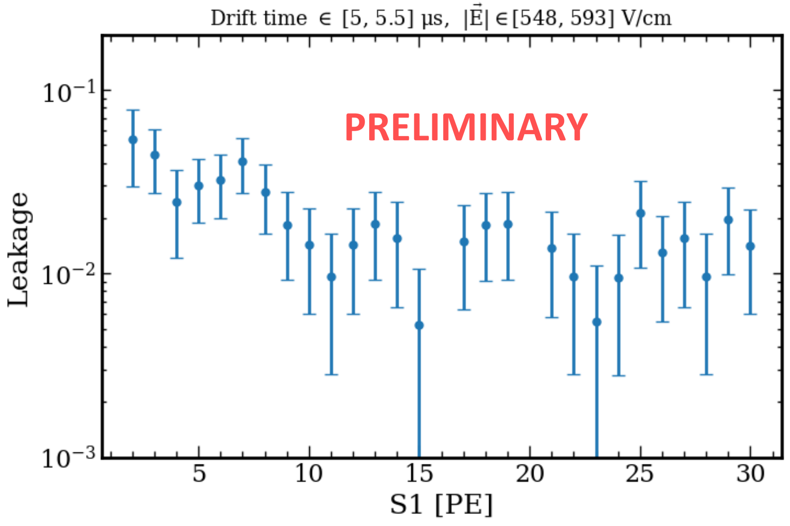
- 1σ regions seem well separated
- However: a "shower" of leakage events for both ER and NR
  - Could be due to imperfect charge collection (charge insensitive volume)
- Two methods to calculate leakage:
  - Counting
  - Gaussian fitting

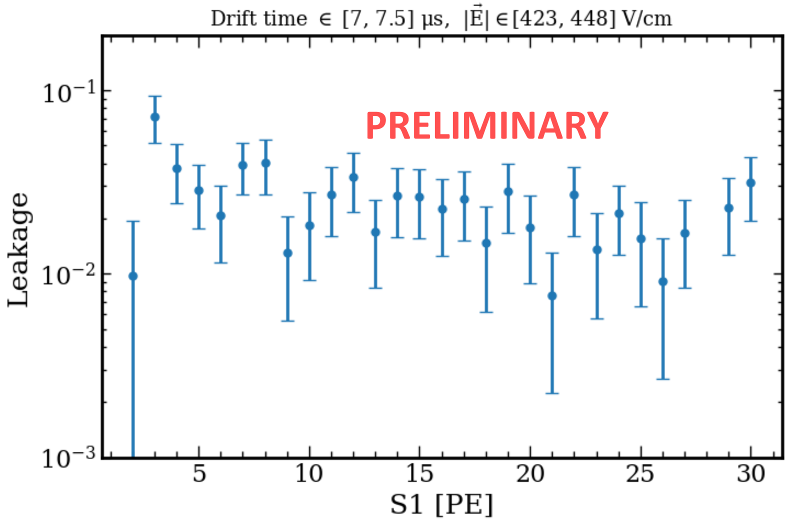


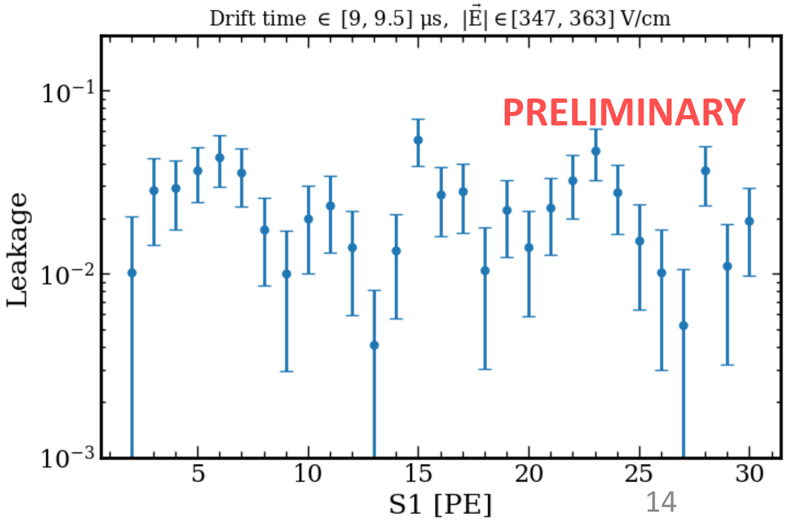
# ER (Tritium)/NR Discrimination: Leakage by counting

- Find NR median, count tritium events below NR median
- NR Acceptance ~47.5% (after data-quality cuts + NR events below median)
- Some bins have leakage < 0.01, but most have leakage > 0.01
- Investigation of leakage events is still ongoing



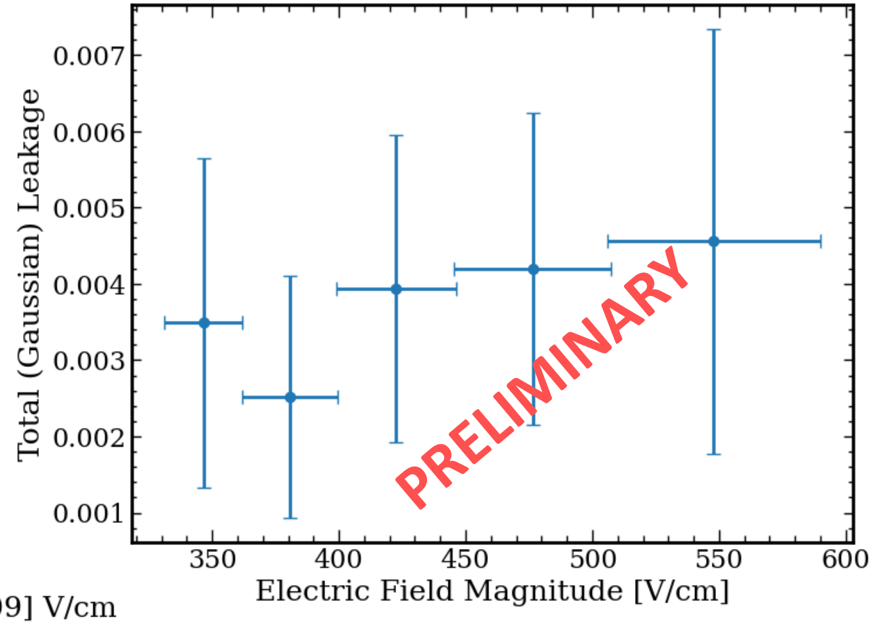



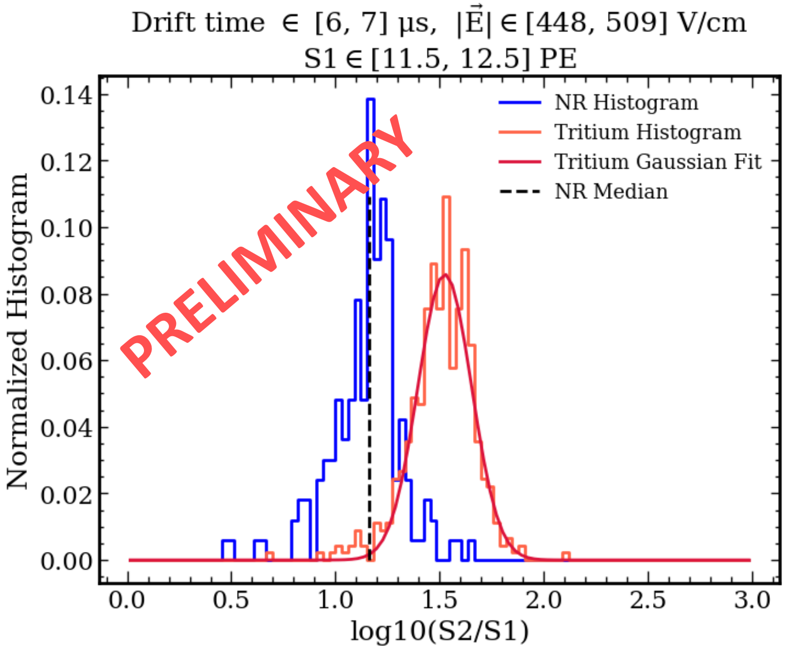



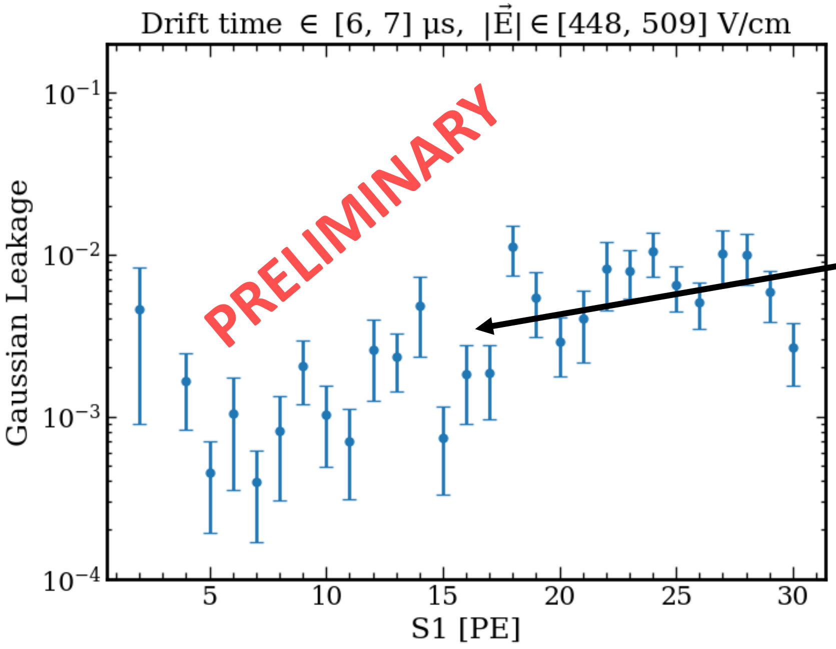



# ER (Tritium)/NR Discrimination: Leakage by fitting

- Motivation: To estimate the ideal-case leakage
  - Ideal case: no CIV, no reconstruction effects, only tritium events
- Fit tritium events' Log10(S2/S1) in each S1 slice with gaussian
- Find fitted proportion below the NR median

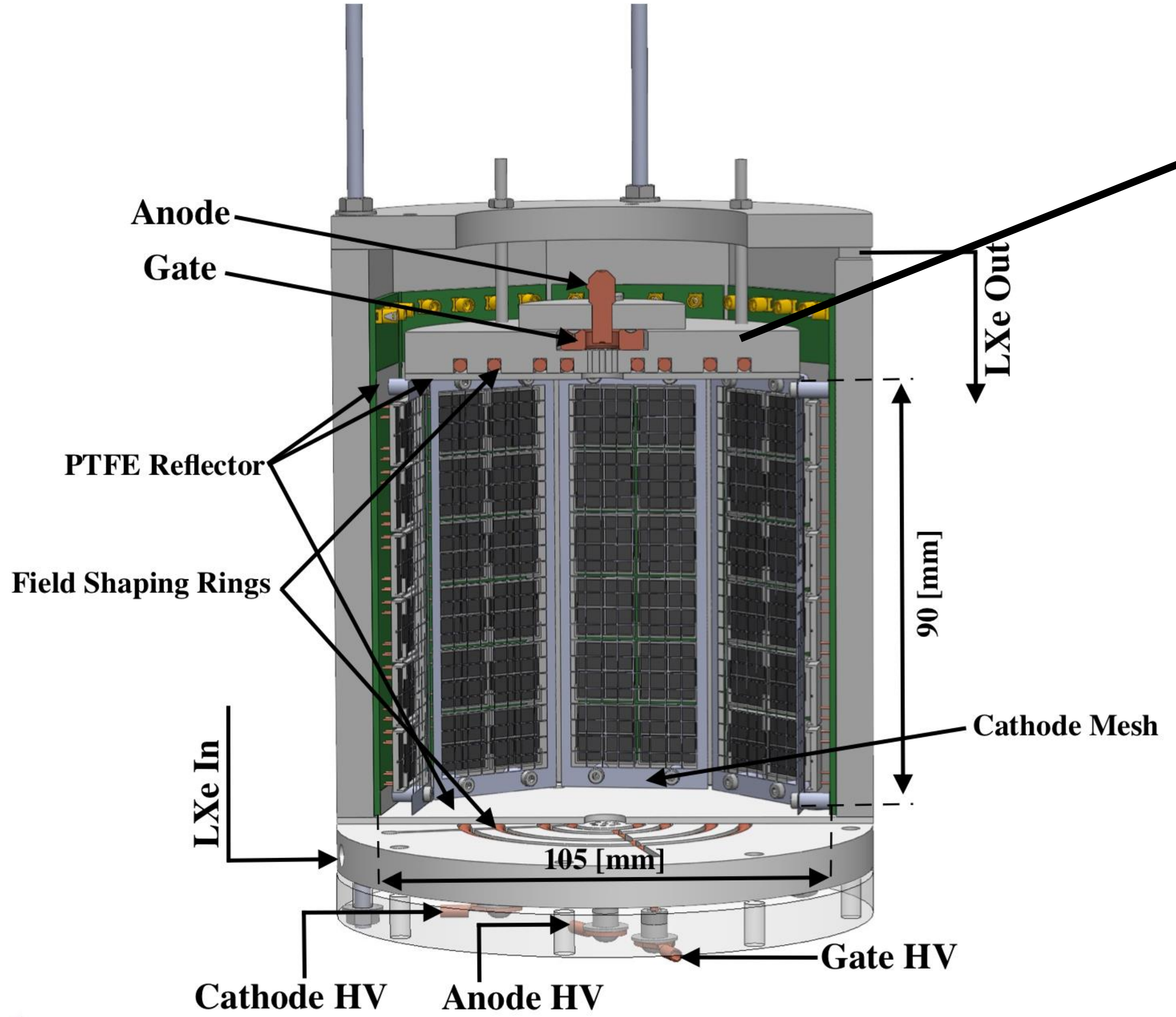


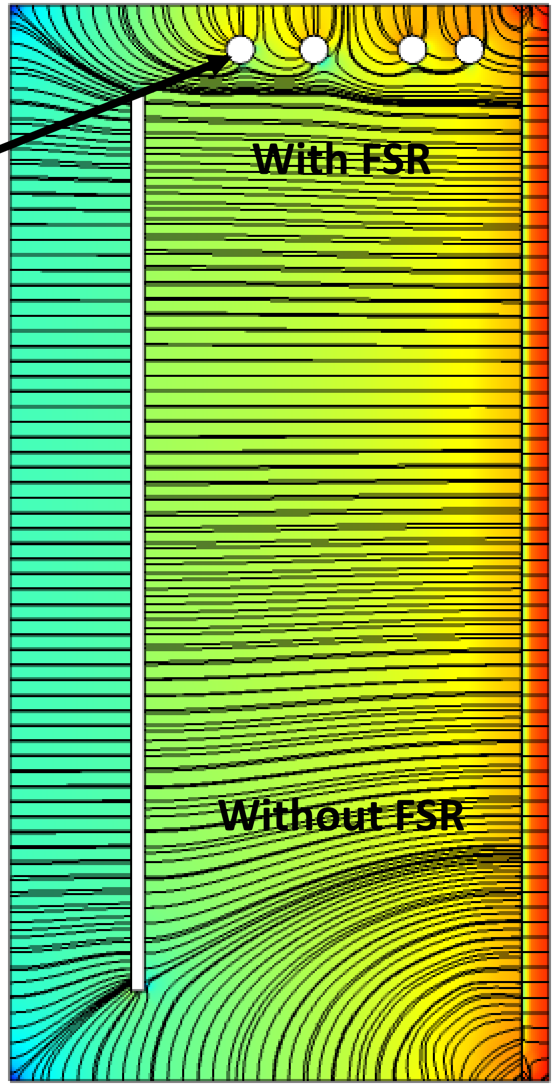



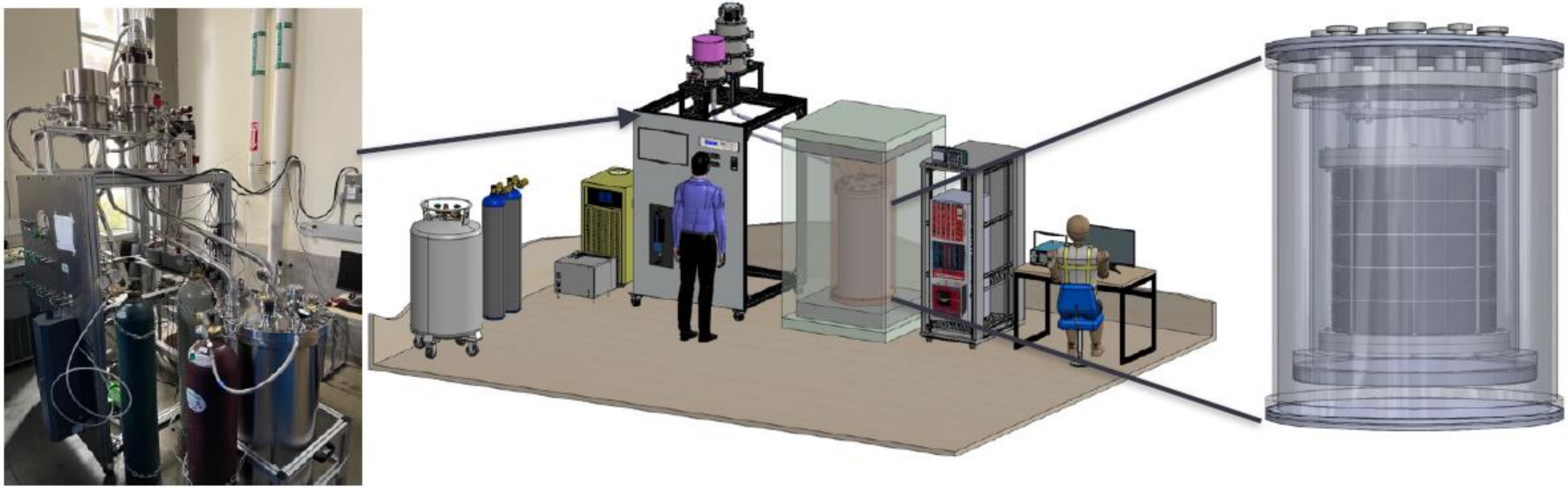
# Future Steps

- NUXE-3: A 3 kg prototype
- Gate to separate drift region from electroluminescence region
- Dense SiPM array on the outside for more coverage
- Field shaping rings for a more uniform field and lower charge insensitive volume



# Further into the future: NUXE-100 as LBECA



**If LXePSC is successful in reducing single electron background: Scale up!**

- **NUXE** is a planned reactor neutrino CEvNS experiment using ~100 kg LXe (or Xe-doped LAr) single-phase PSC
- The same detector system can be moved underground for light dark matter search after demonstrating the detection of reactor neutrinos.

# Further into the future: Extraction-less TPC

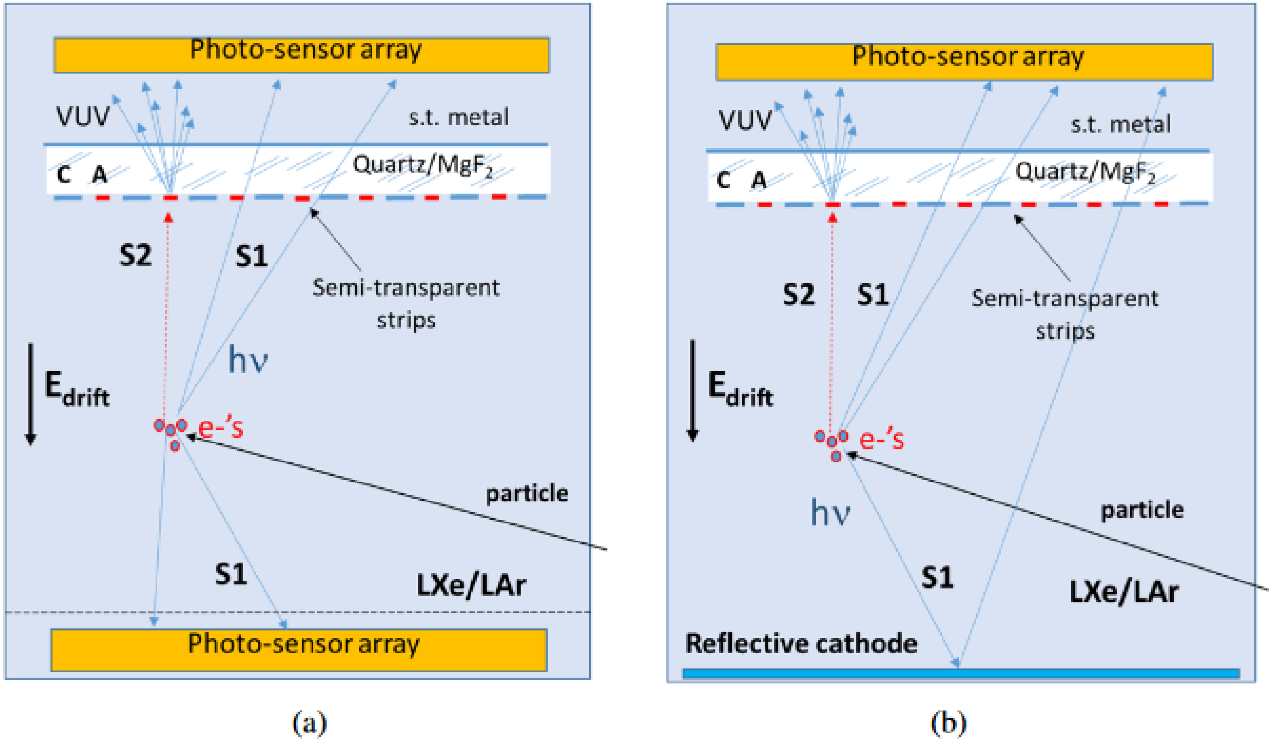



Figure from A. Breskin 2022 JINST 17 P08002

**Regardless, results of this talk suggest ER/NR discrimination can still be maintained in the single-phase**

- Strip-coated electrodes on a quartz window
- No need to maintain liquid level and worry about extraction efficiency

# Summary

- Obtained a $g_2$ of 3.5 PE/$e^-$ while maintaining sensitivity to low-energy (O(1keV)) events
- Obtained an energy calibration (doke plot) by slicing the data in radial slices
- First observation of nuclear-recoil events in a single-phase liquid Xenon detector using both light and proportional scintillation signals
- First estimation of ER-leakage for such a detector
- **Main limitation:** Higher rates of spurious light emission, low $g_2$ (might not be an issue for higher-energy NR)