The Feasibility of Liquid Xenon Proportional Scintillation Counter for Low-energy Physics Searches

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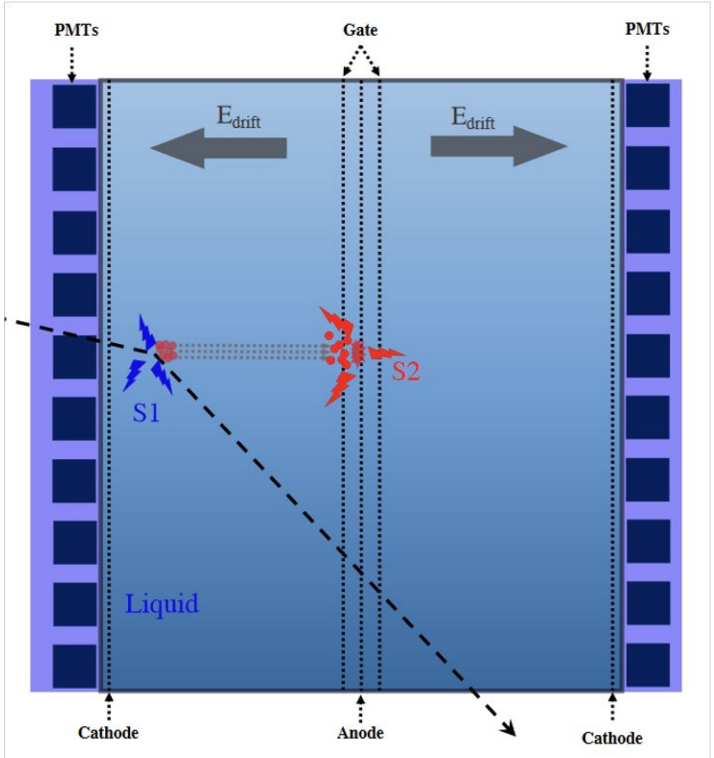
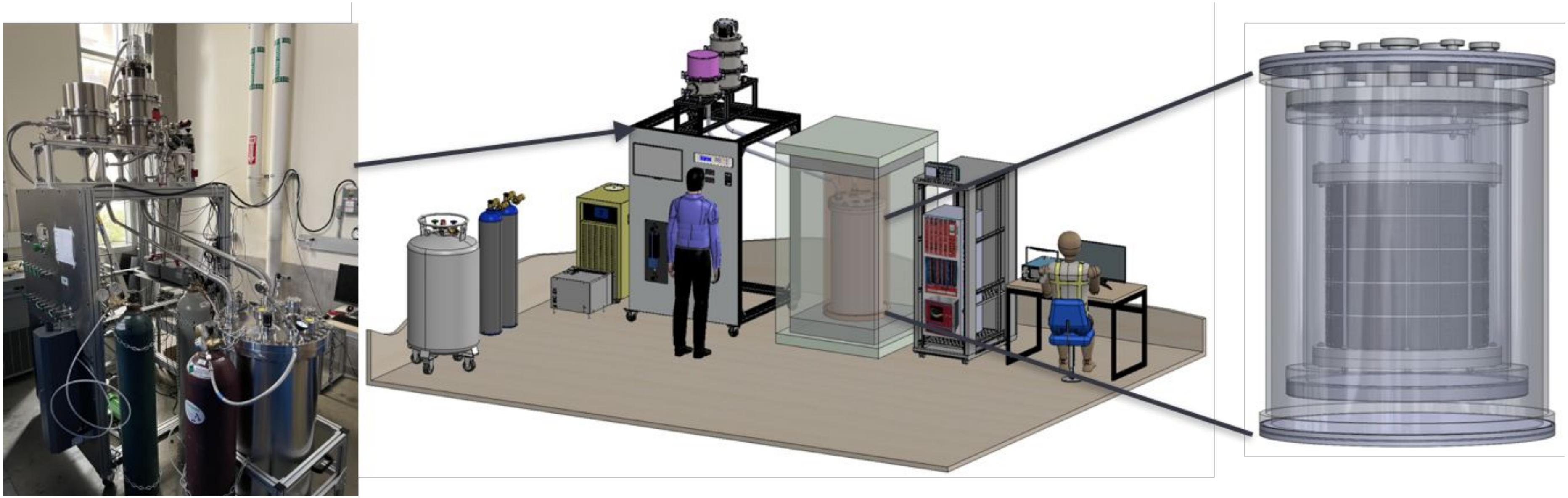
Single Phase Liquid Xenon Proportional Scintillation Counter (LXePSC)



Principle of a cylindrical Single-Phase LXe detector, first proposed by *Qing Lin*, JINST 16 P08011, 2021

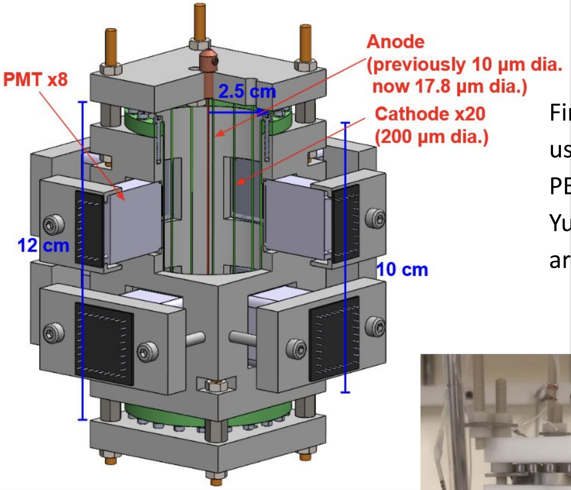
- A Proportional Scintillation Counter-like design (thin anode wire in the center) was first proposed by Qing Lin (2102.06903, JINST 2021).
  - **No liquid-gas interface: 100% electron extraction efficiency**
  - **S2 in LXe (~20 photon/e-) is typically much smaller than S2 in GXe: less unwanted S2 light, less dynamic range requirement for ADC**
  - **Weak field on the cathode: less micro discharges; anode/gate surface area is very small: less e- from metal surface**
  - **More photosensor coverage & no reflection at liquid/gas interface: higher light collection (lower S1 threshold, better sensitivity for low-mass DM)**
  - **Fast liquid-phase purification; scalability.**

NUXE - a LXePSC for Reactor Neutrino and Light DM Searches

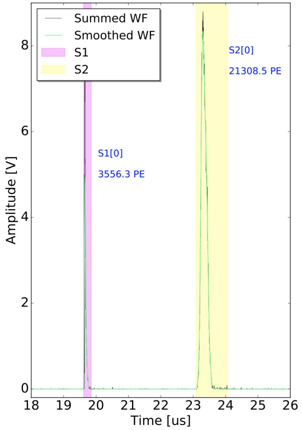


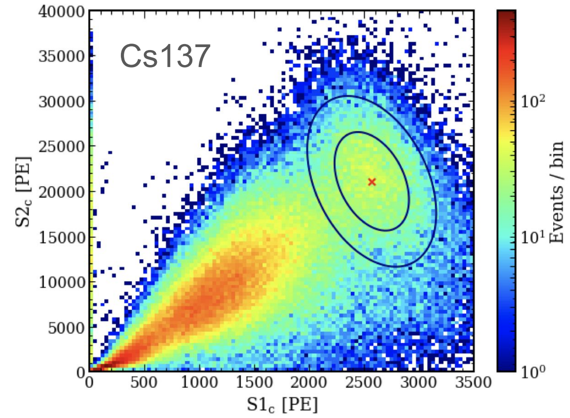
- **NUXE** is a planned reactor neutrino CEvNS experiment using ~100 kg LXe (or Xe-doped LAr) single-phase PSC
- Single-and-few e- background will need to be reduced significantly for a sensitive detection of reactor neutrinos at surface
- **The same detector system can be moved underground for light dark matter search.**

First Demonstrations of LXePSC Operation at UCSD

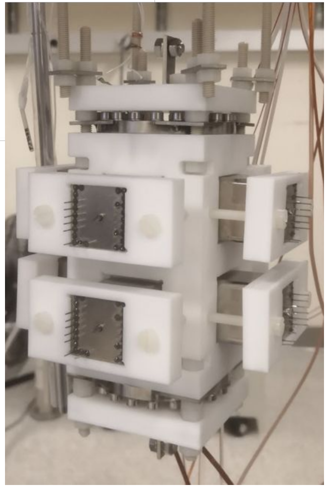


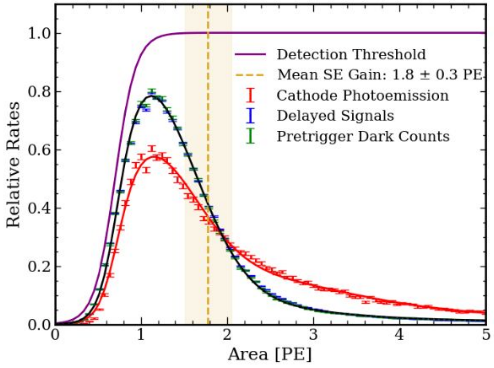
First trial: a 25-um anode is used, reached e- gain of 0.7 PE/e-.
Yuehuan Wei et al.
arXiv:2111.09112, JINST 2022

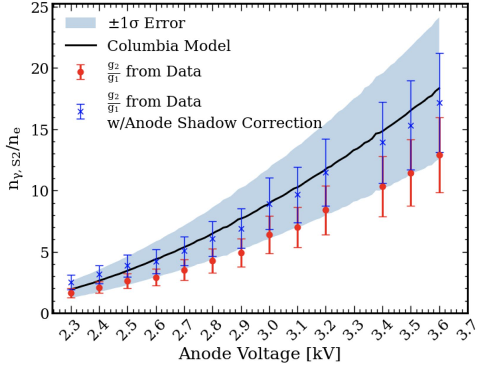




A 0.6-kg active target LXePSC

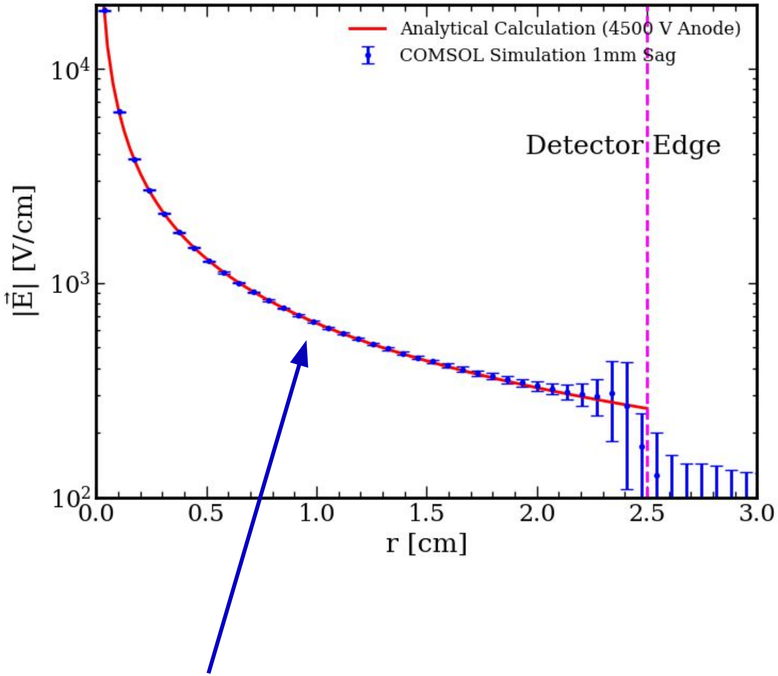






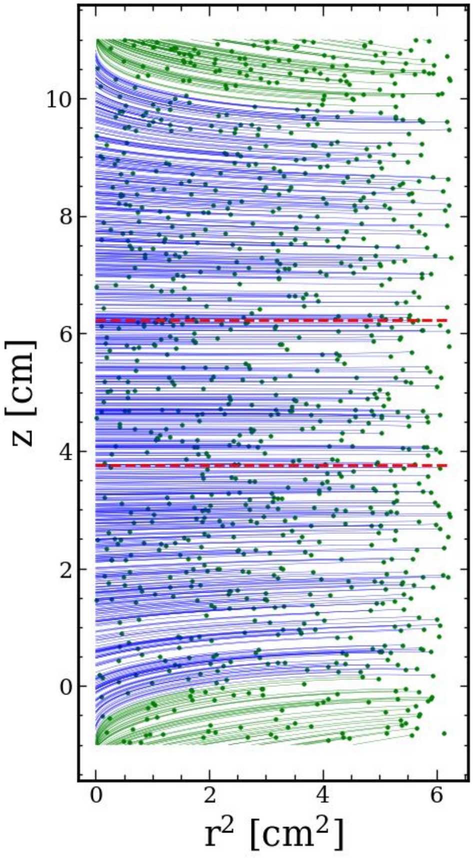
Later a 10-um anode is used. Reached 1.8 PE/e- gain.
Jianyang Qi et al. arXiv:2301.12296, JINST 2023

Electric field



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

- Simulated charge trajectories
    - Green: Charge not reaching anode
    - Blue: Charge reached the anode
    - Red: Approximate fiducial volume in z



Two main questions

Can the single-phase still discriminate between ER and NR?

Can the single-phase mitigate the single-electron background after a large S2?

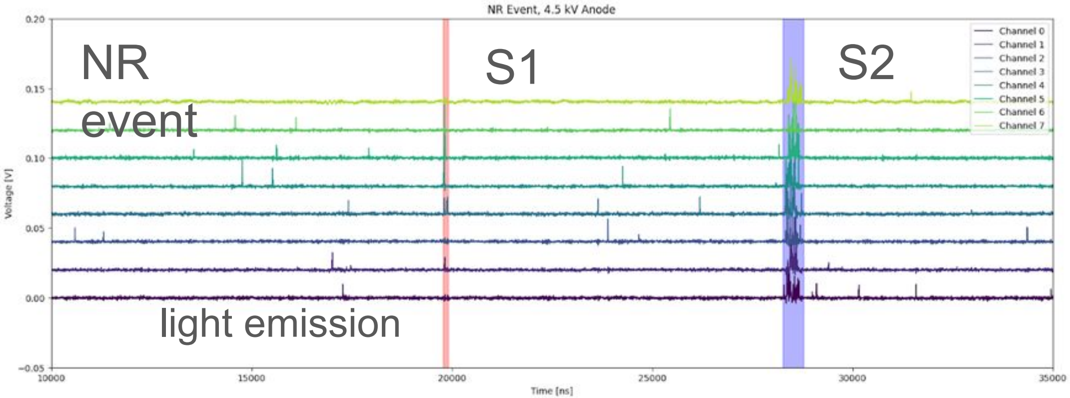
ER/NR Discrimination

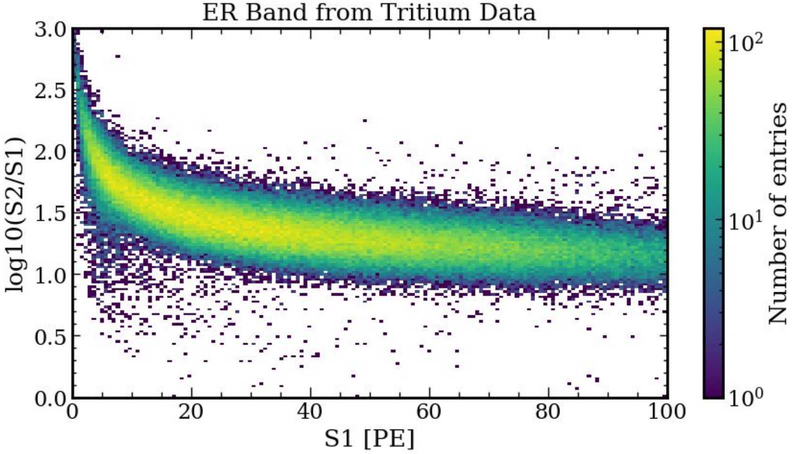
ER/NR calibration with the 18 µm anode

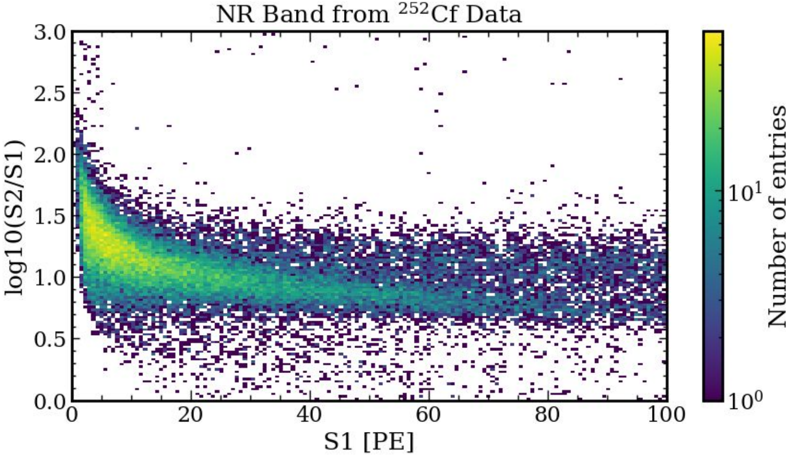
- Switched from a 10 µm to 18 µm diameter anode wire ⇒ larger gain from the same **E** field around the anode
  - Higher electric field in the bulk
  - Anode: 4.5 kV, Cathode: -0.6543 kV
- ^{252}Cf calibration:
  - ^{129m}Xe and ^{131m}Xe activated lines (236 and 164 keV gammas, respectively)
  - Nuclear recoil band
- Xe activated lines:
  - High statistics
  - Cut in drift time slices to constrain the electric field for doke plot
- Tritium:
  - Gives us a measurement of ER-leakage for small g_2

Electron and Nuclear recoil bands

- Cuts applied:
    - Z-cut
    - Diffusion cut
    - Multiple scatter
    - Noise/accidental coincidence
    - Undershoot cut



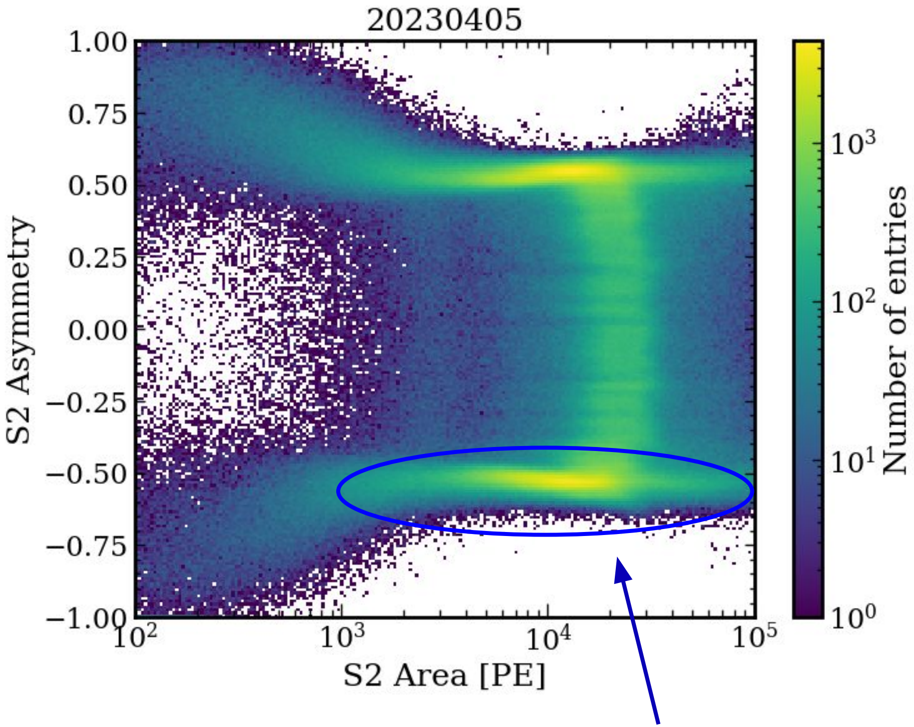




Z-selection

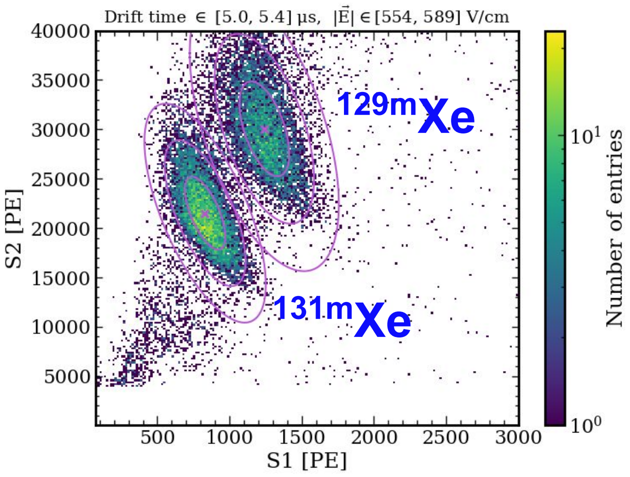
$$Asymmetry = \frac{Area_{top} - Area_{bottom}}{Area_{top} + Area_{bottom}}$$

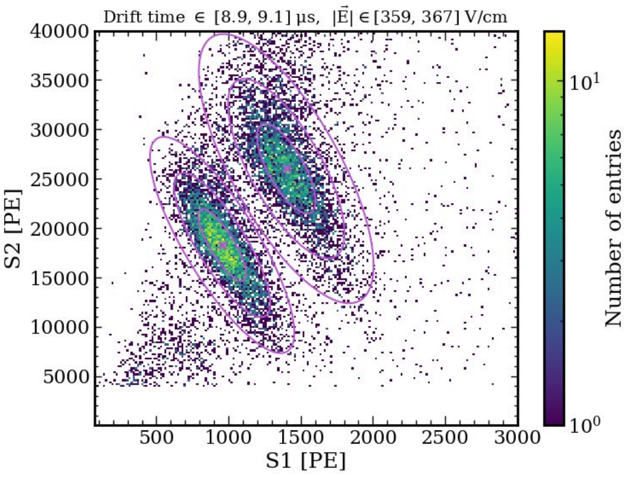
- ➢ Top (bottom) area means the sum of the light seen by the top (bottom) four PMTs
- ➢ Used to select a range in z
- ➢ Cuts against backgrounds near top and bottom plates
- ➢ S2 asymmetry is between -0.25 and 0.25 unless otherwise stated

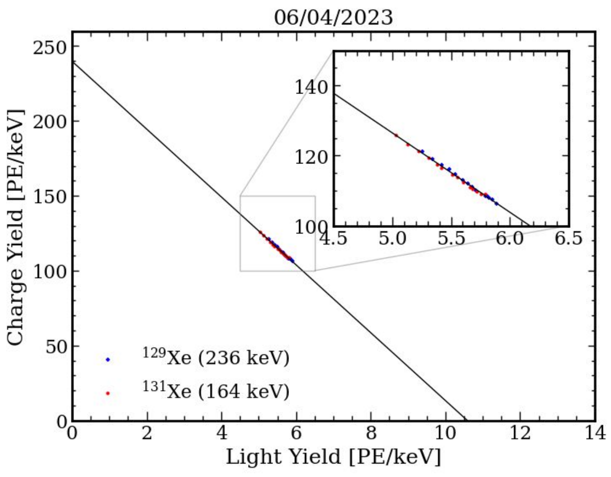


Backgrounds near top and bottom

Activated xenon lines

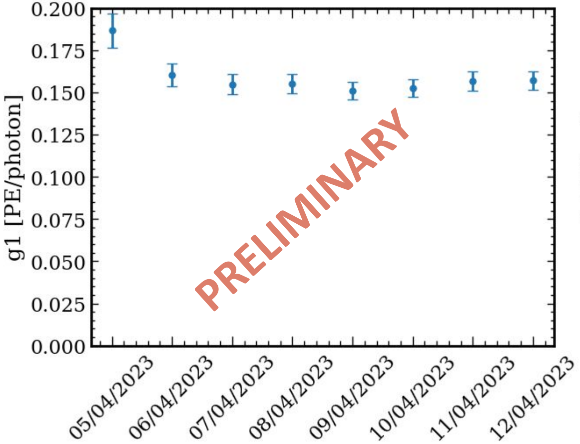


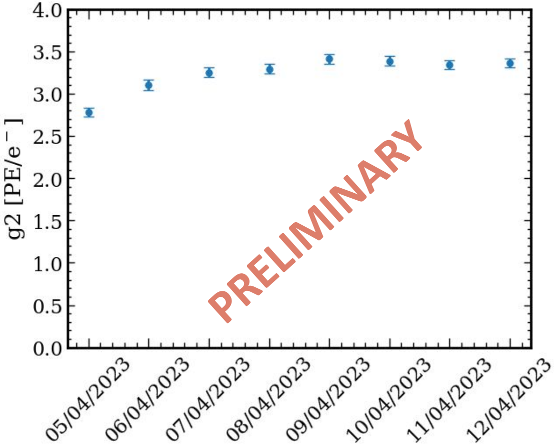


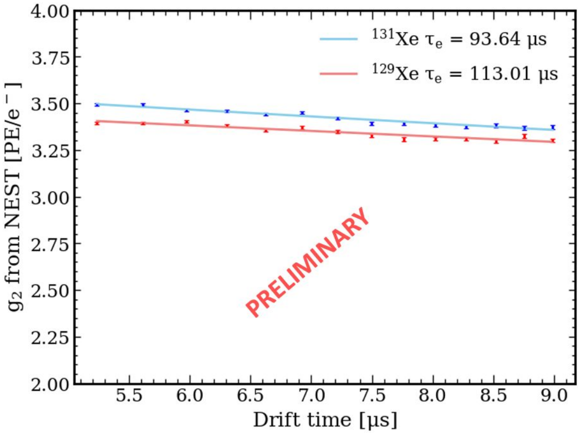


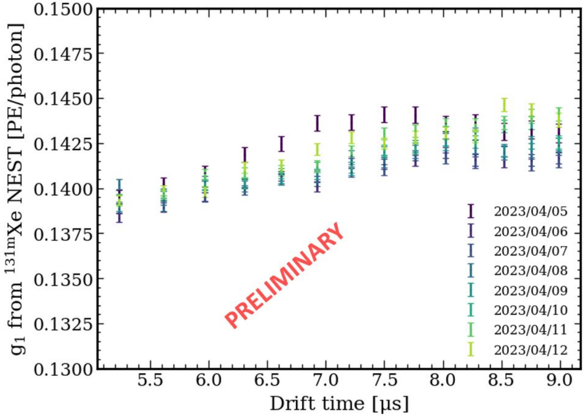
- ➢ Clear ^{131m}Xe and ^{129m}Xe lines (164 and 236 keV respectively)
- ➢ Selected with |S2 Asymmetry| < 0.25
- ➢ Sliced in drift time to constrain electric field
- ➢ g_2 measured to be ~3.3 PE/e^-
- ➢ g_1 approximately 0.15 PE/photon

g_1, g_2, and electron lifetime





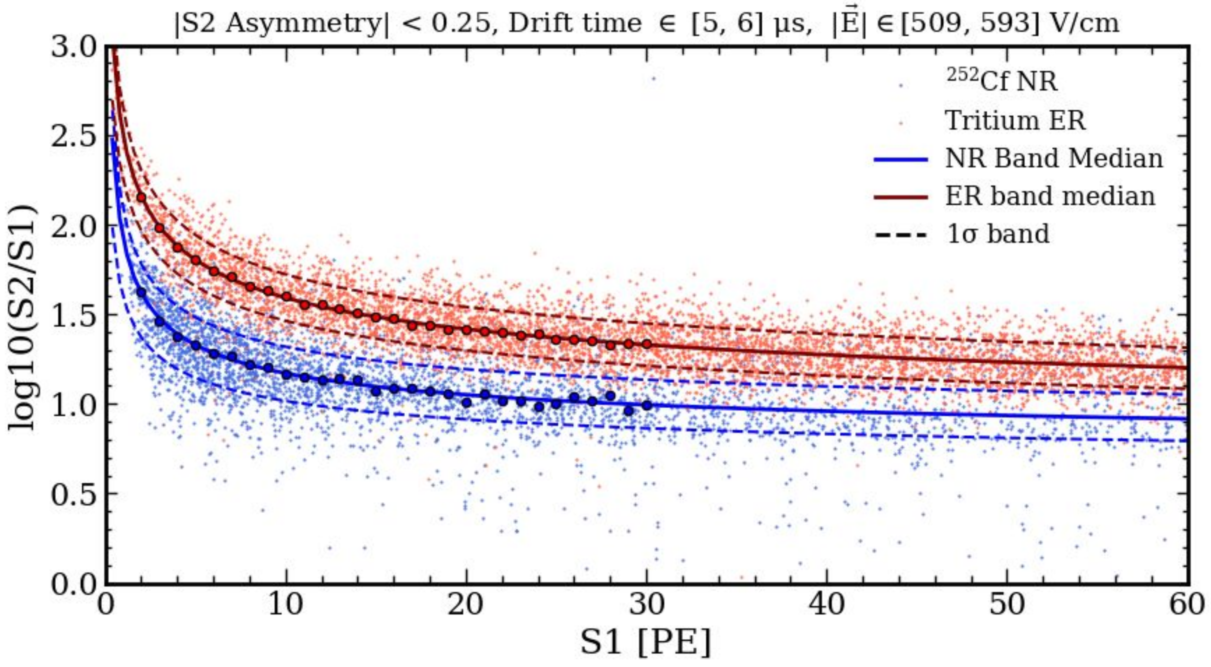




- ➢ g_1 and g_2 are consistent from data vs NEST prediction
- ➢ NEST g_1 and g_2 are obtained from $S1/n_{ph}$ and $S2/n_e$
- ➢ Electron lifetime can be estimated (with large uncertainty) using NEST

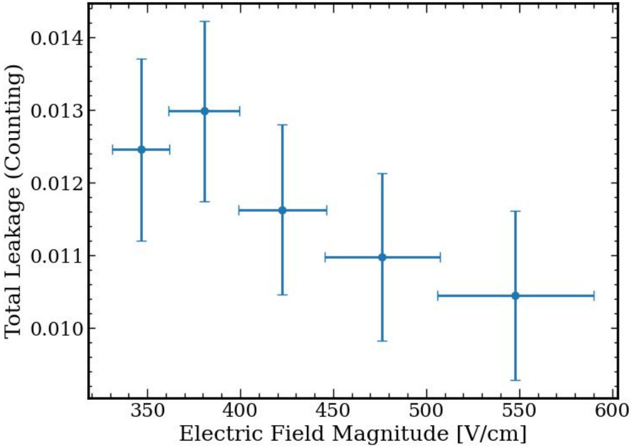
ER/NR discrimination

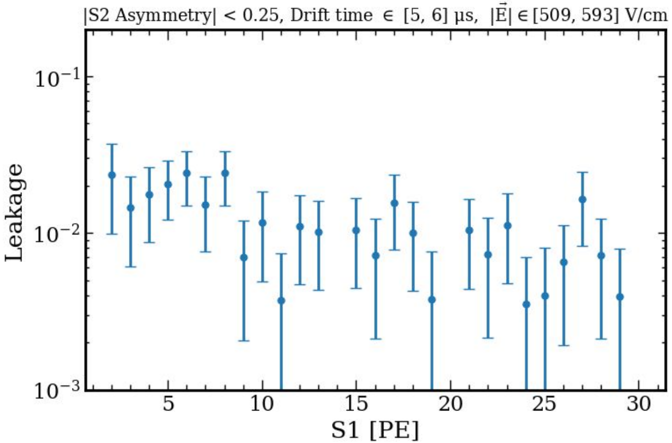
- 1σ regions are well separated
- However: a “shower” of leakage events for both ER and NR
- Likely due to partial charge loss near CIV
- Methods to calculate leakage:
  - Direct counting
  - Gaussian fitting
  - Skew gaussian fitting

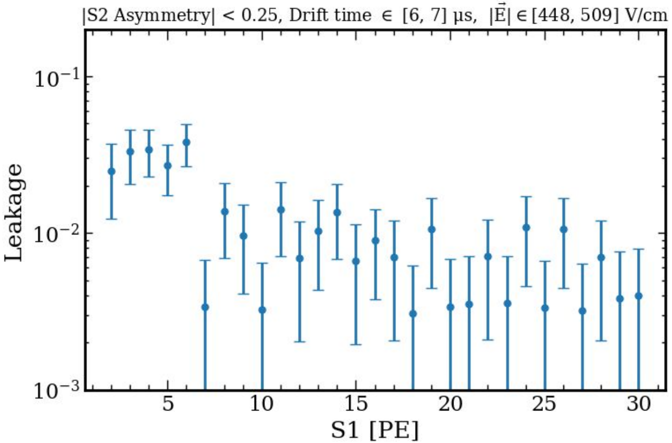


ER/NR discrimination: Leakage by counting

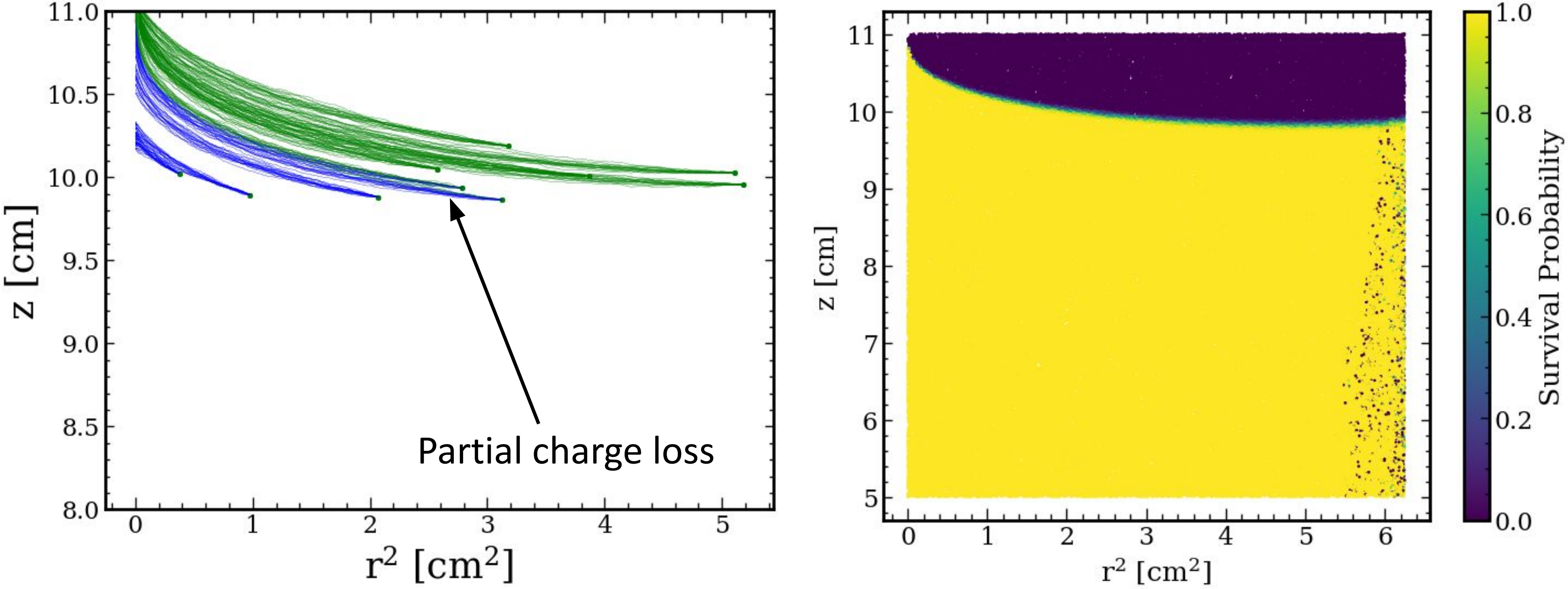
- Find NR median, count tritium events below NR median
- NR Acceptance ~ 47.5% (after data-quality cuts + NR events below median)
- Some bins have leakage < 0.01, most have leakage>0.01





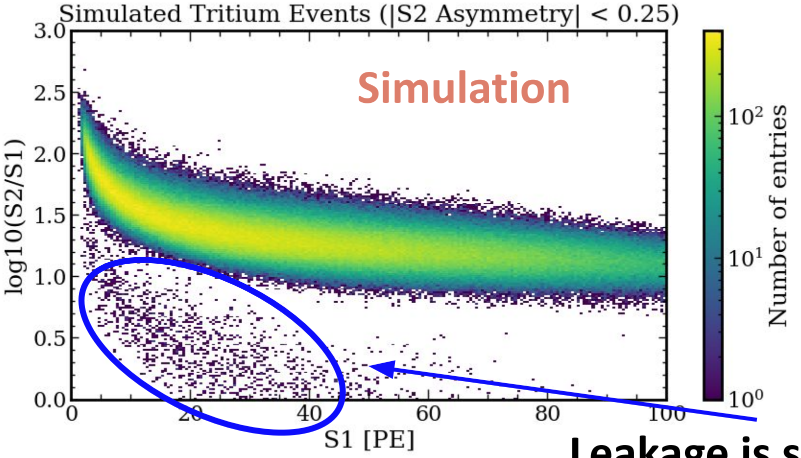


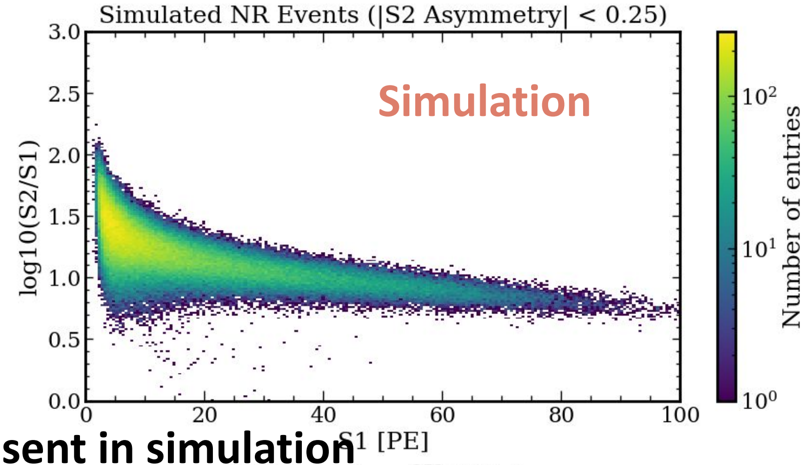
ER/NR discrimination: Charge Insensitive Volume (CIV) leakage



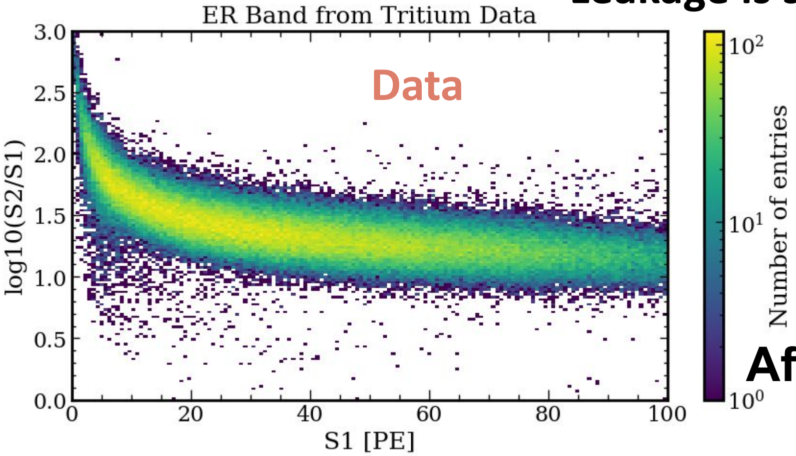
- ➢ Longitudinal diffusion coefficient from O. Njoya (2020)
- ➢ Transverse diffusion coefficient from EXO-200 (2017)

ER/NR discrimination: CIV leakage

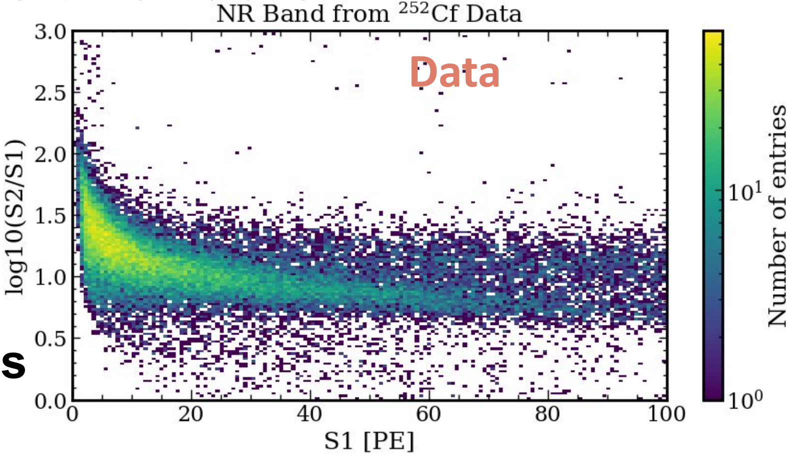

Simulated Tritium Events (|S2 Asymmetry| < 0.25)


Simulated NR Events (|S2 Asymmetry| < 0.25)

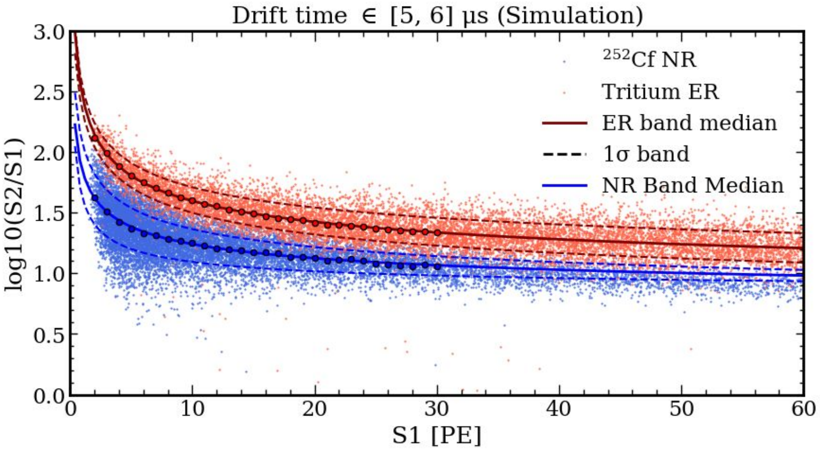
Leakage is still present in simulation


ER Band from Tritium Data

After cuts

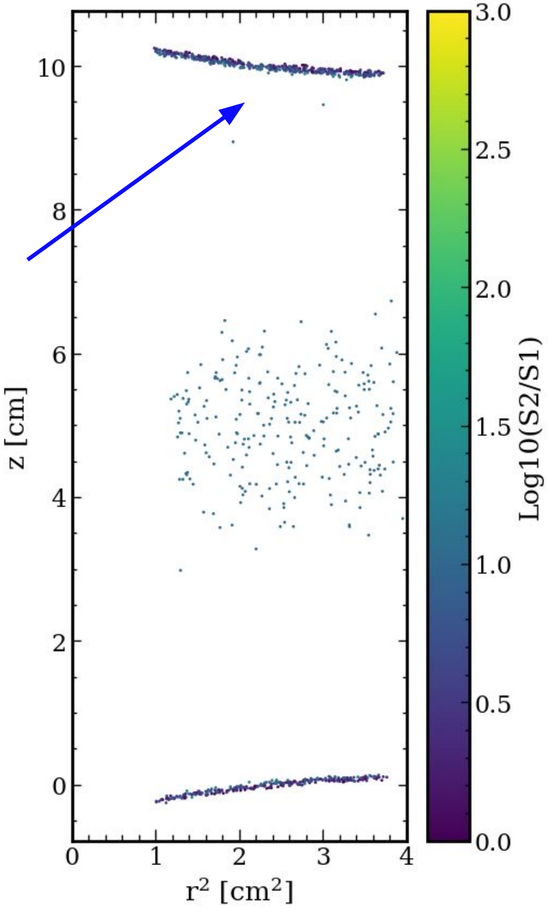

NR Band from ^{252}Cf Data

ER/NR discrimination: CIV leakage



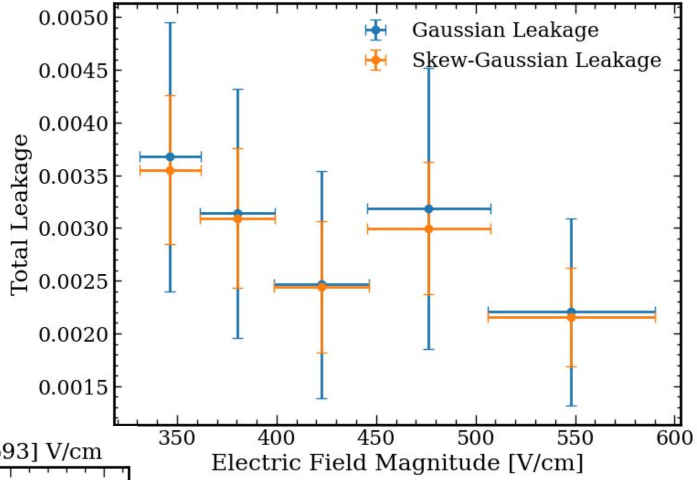
Leakage events (below NR median) concentrated near top and bottom CIV

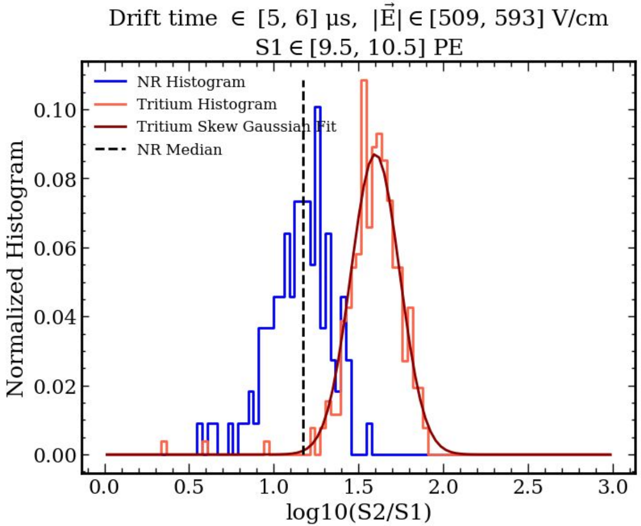
- ➢ MC truth positions
- ➢ Asymmetry cut applied

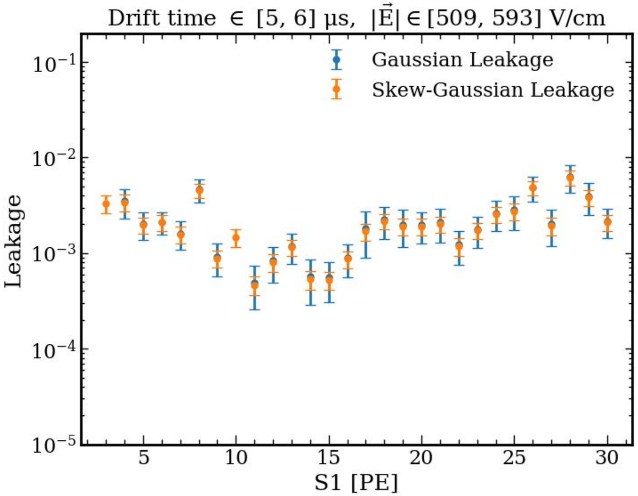


ER/NR discrimination: Leakage by fitting

- 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 and skew gaussian
- Find fitted proportion below the NR median





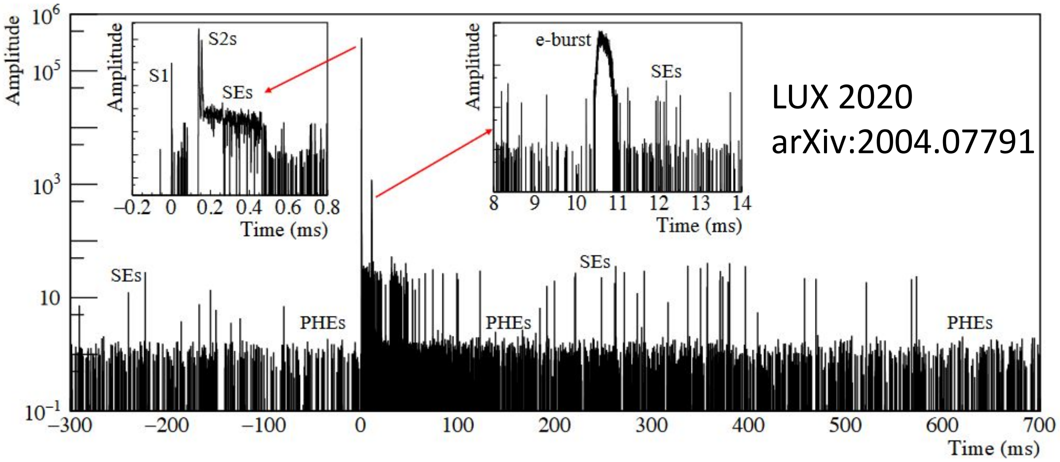


ER/NR discrimination: Conclusion

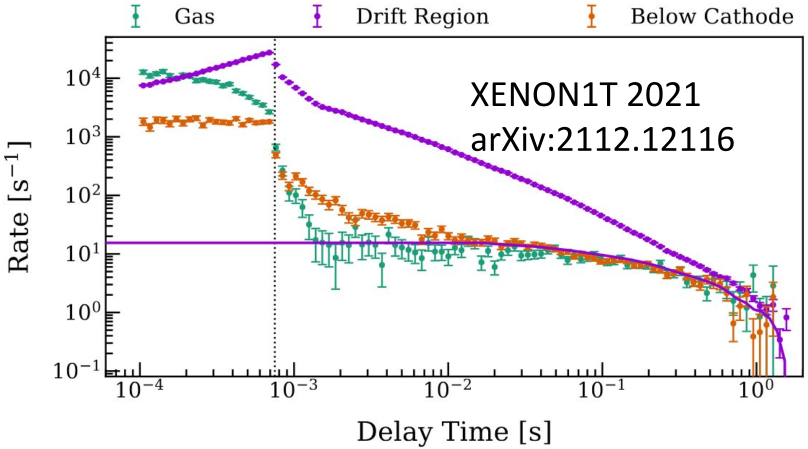
- Counting shows leakage of order 10^{-2}~10^{-3}
- Gaussian/skew-gaussian fittings show leakage of order 10^{-3}
- Simulation shows a significant portion of leakage events is due to CIV
  - If we design the detector, e.g. using shaping rings, to minimize CIV then we may see a reduction in the leakage from direct counting
- Single phase LXe TPC detectors using proportional scintillation are likely able to retain good ER/NR discrimination despite a low g_2

Electron Trains in Single-phase LXe

What are trains…



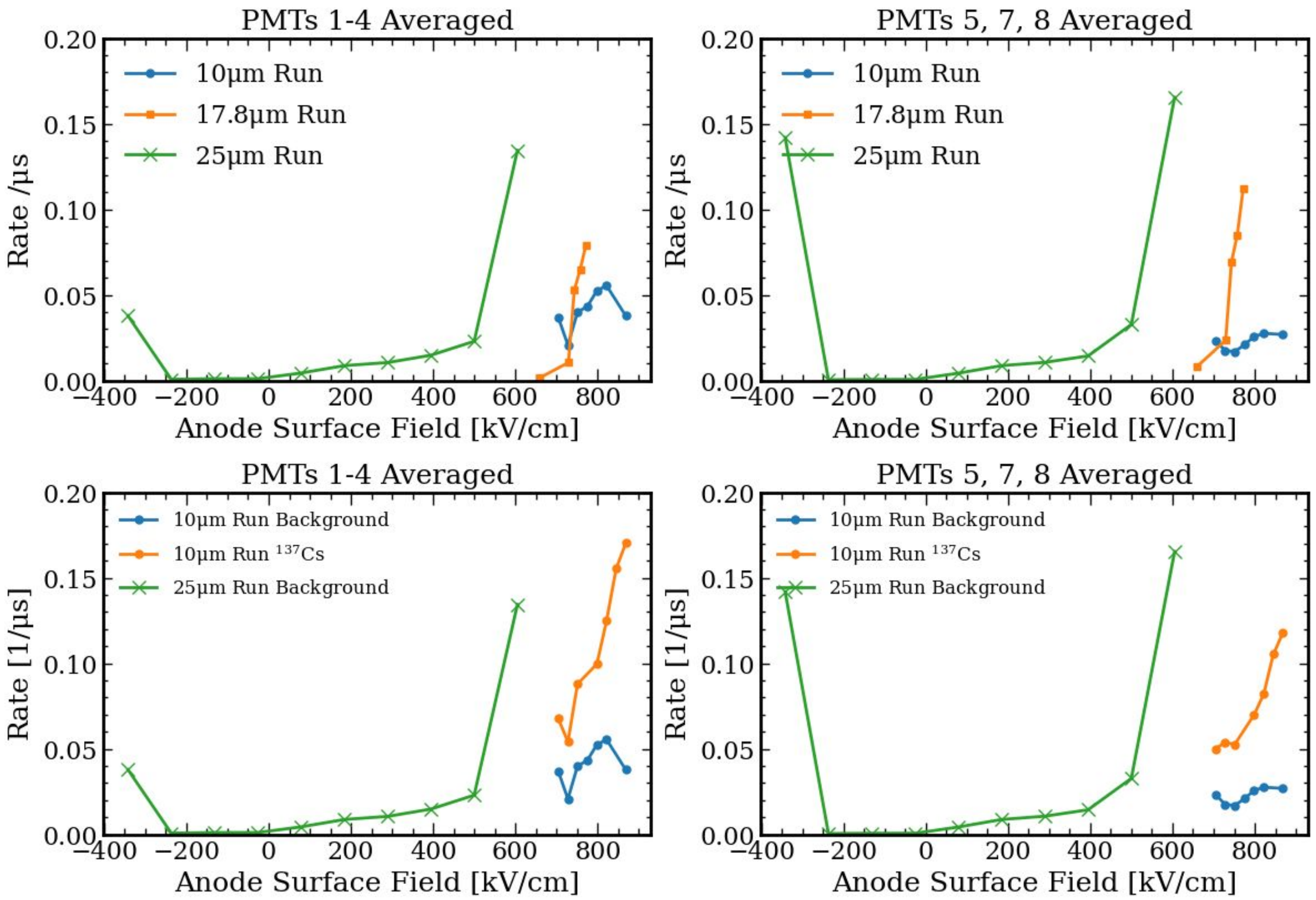
LUX 2020
arXiv:2004.07791



XENON1T 2021
arXiv:2112.12116

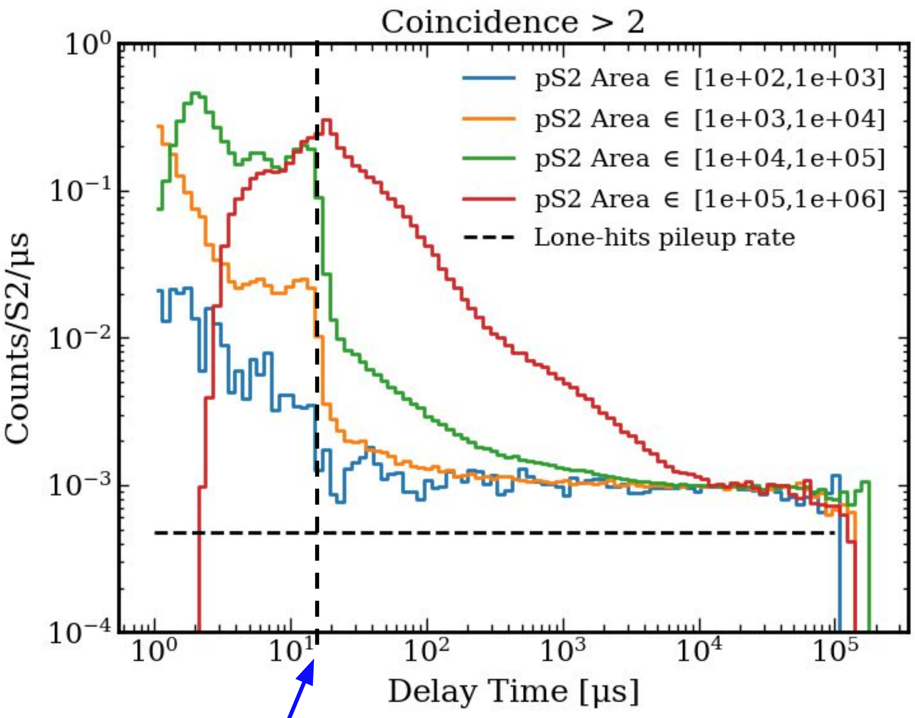
- ➢ Single electrons up to 1 second after a large S2 pulse (primary S2)
- ➢ Seen in dual-phase LXe TPCs (LUX, XENON1T)
- ➢ Major background for low-energy ionization-only searches
- ➢ More at tomorrow’s talks for two-phase detectors

Light emission throughout our runs



- ➢ Main limiting factor for the single-phase detector
- ➢ Seems to be correlated with anode surface area as well as electric field
- ➢ Correlated with event rate as well (see Cs-137 curve)

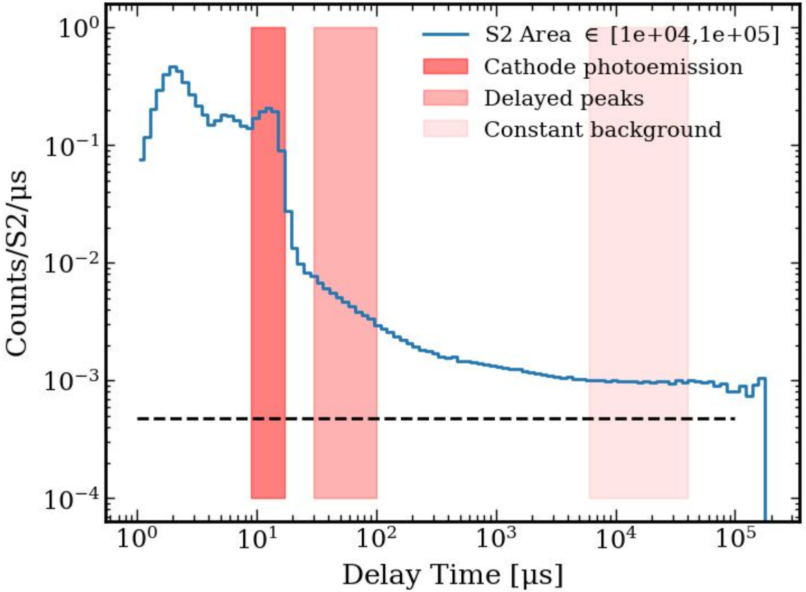
Trains in our single-phase LXe detector (18 µm anode run, g2~3.3 PE/e-)

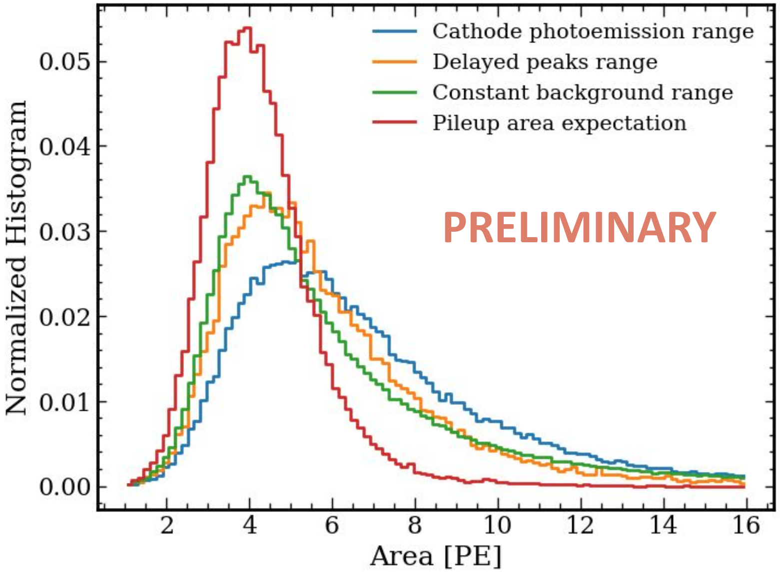


Maximum drift time

- ➢ Rates are calculated for peaks with 3-fold coincidence
- ➢ Delay time is time after the S2
- ➢ Clear photoemission population around 1 max drift time
- ➢ All rates decay to the same level regardless of primary S2 area
- ➢ Pileup rate calculated from PMT lone hits rate before an S1

Are these rates from electrons?





- ➢ Pileup area distribution calculated by randomly sampling PMT lone-hit (light emission) rates and areas
- ➢ All shaded regions are clearly different from the light emission pileup area spectrum, indicating there might be electron train component

Model of electron train

$$R(\Delta t) = A_0 c \Delta t^p + \sum_{i=1}^{N_{prev}} A_i c (t_i + \Delta t)^p + R_{bkg}$$

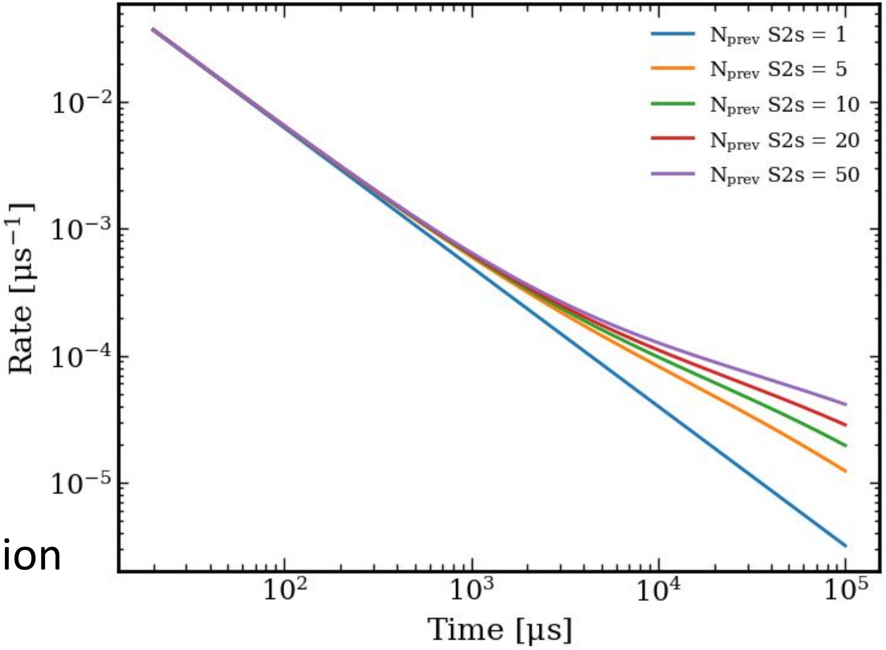
Current S2 area

Previous S2 contributions

Average over previous S2 areas and time to previous S2s

Erlang distribution

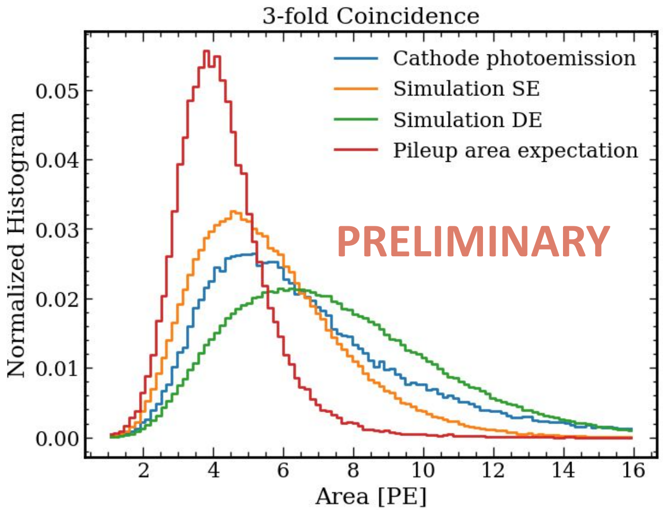
$$\langle R(\Delta t)\rangle = \langle A\rangle c\left(\Delta t^p + \sum_{i=1}^{N_{prev}} \int_0^\infty (t_i + \Delta t)^p P(t_i) dt_i\right) + R_{bkg}$$

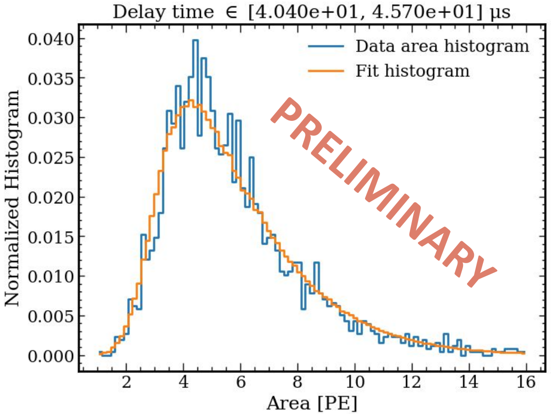


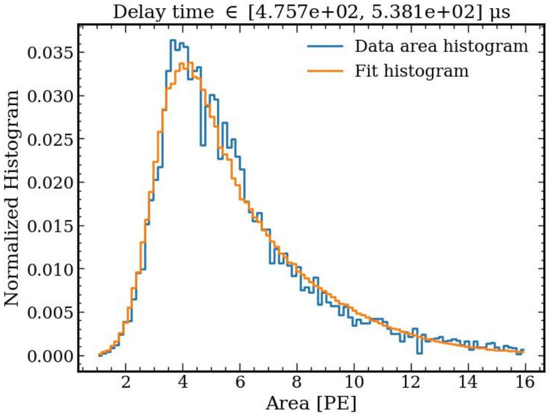
Extracting the electron portion of the trains

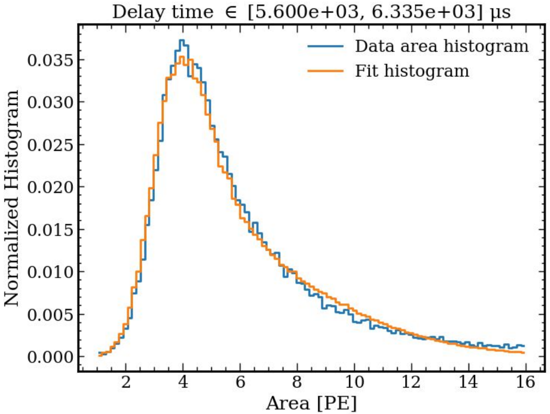
- Peak area distribution in each delay time bin can be fit with a linear combination of the expected pileup, single electron, and double electron distribution
  - SE and DE area spectrum from simulation

$$H(A) = \left(1 - \sum_{i=1}^{N_e} r_i\right) p_{pileup}(A) + \sum_{i=1}^{N_e} r_i p_{i,e}(A)$$

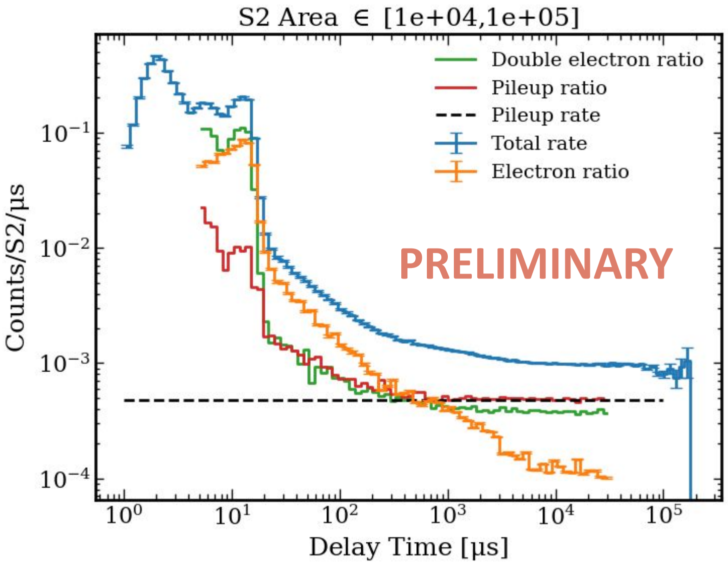


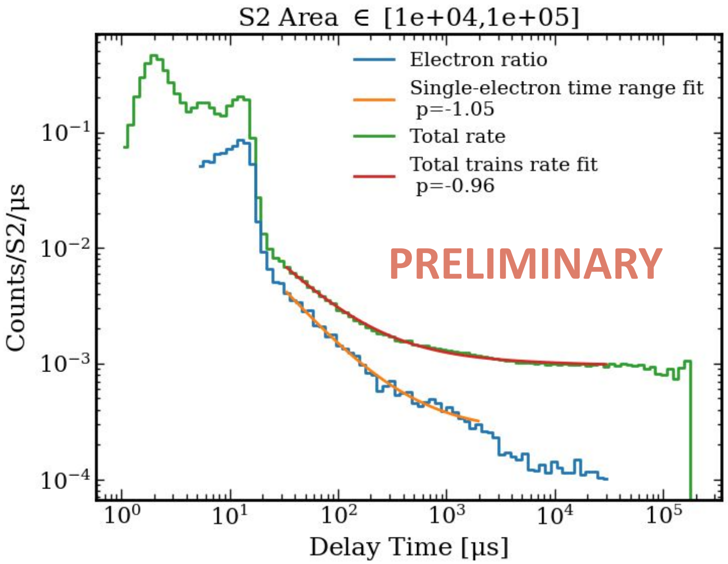






Fitting the trains: Conclusion





- Pileup rate converges to the expected value after the fitting
- Power-law decay of approximately -1 is present **even in the single phase**
    - Similar to dual phase xenon TPCs
    - Suggests that the origin of this background is likely in the bulk

Two main questions: Summary

Can the single-phase still discriminate between ER and NR?

- Yes, even with low g_2 the discrimination ability is still retained
- Better field cage design that minimizes the charge insensitive volume will help

Can the single-phase mitigate the single-electron background after a large S2?

- Likely no, the single-electron train with a power law of ~-1 is still present
- If due to impurities, purification technique needs to be developed (same for two-phase)

Backup Slides

Time-dependent correction to ER and NR bands

- g_2 tends to drift in time
- Electron lifetime (in principle) also drifts
- All S2s are correction to what they would be on April 12th (g_2 = 3.5 PE/e^-, lots of activated xenon)
- NR Correction:
  - From 40 keV ^{129}Xe neutron inelastic
- ER Correction:
  - Ratio of the ^{131m}Xe S2 size from April 12th to tritium calibration
- Electron lifetime:
  - Small difference. If $\tau_e \in [90,160]$ µs, RMS difference of S2 sizes is 2%