Electronic vs. nuclear recoil discrimination and single electron emission in PIXeY

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Technology and Instrumentation in Particle Physics (TIPP)

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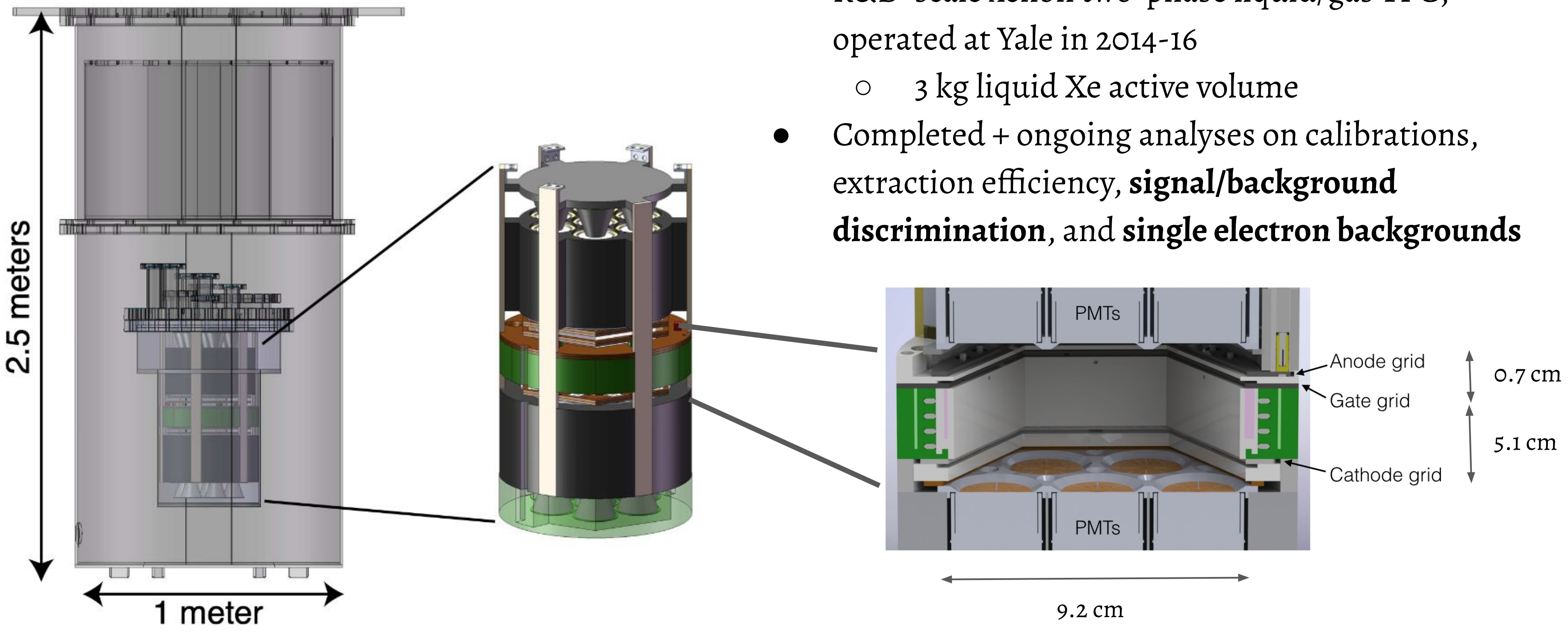
PIXeY: Particle Identification in Xenon at Yale

- R&D-scale xenon two-phase liquid/gas TPC, operated at Yale in 2014-16
  - 3 kg liquid Xe active volume
- Completed + ongoing analyses on calibrations, extraction efficiency, **signal/background discrimination**, and **single electron backgrounds**

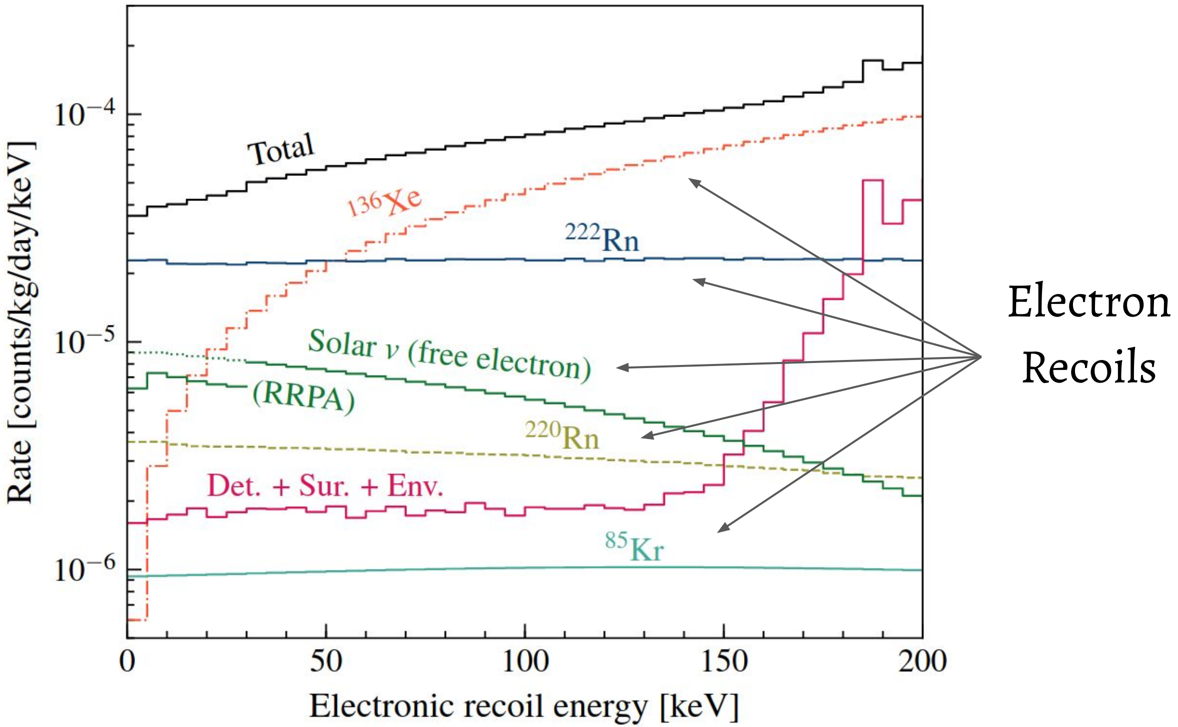


Backgrounds for Nuclear Recoil Searches

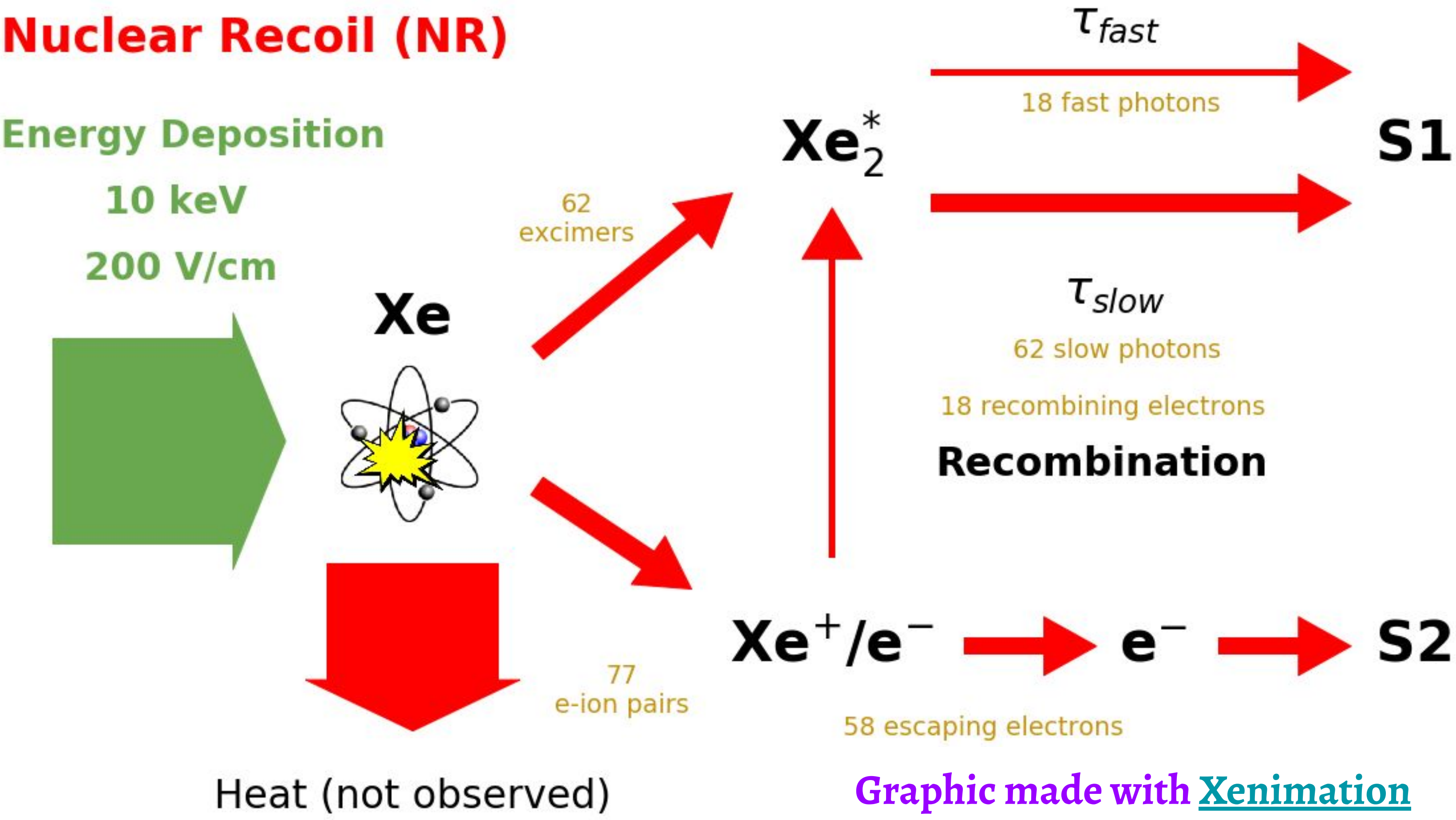
Dominant backgrounds for WIMP dark matter nuclear recoil (NR) searches are electron recoils (ER). Upcoming experiments will face challenging backgrounds that cannot be eliminated by shielding and fiducialization.

LUX-ZEPLIN Projections

Phys. Rev. D 101, 052002

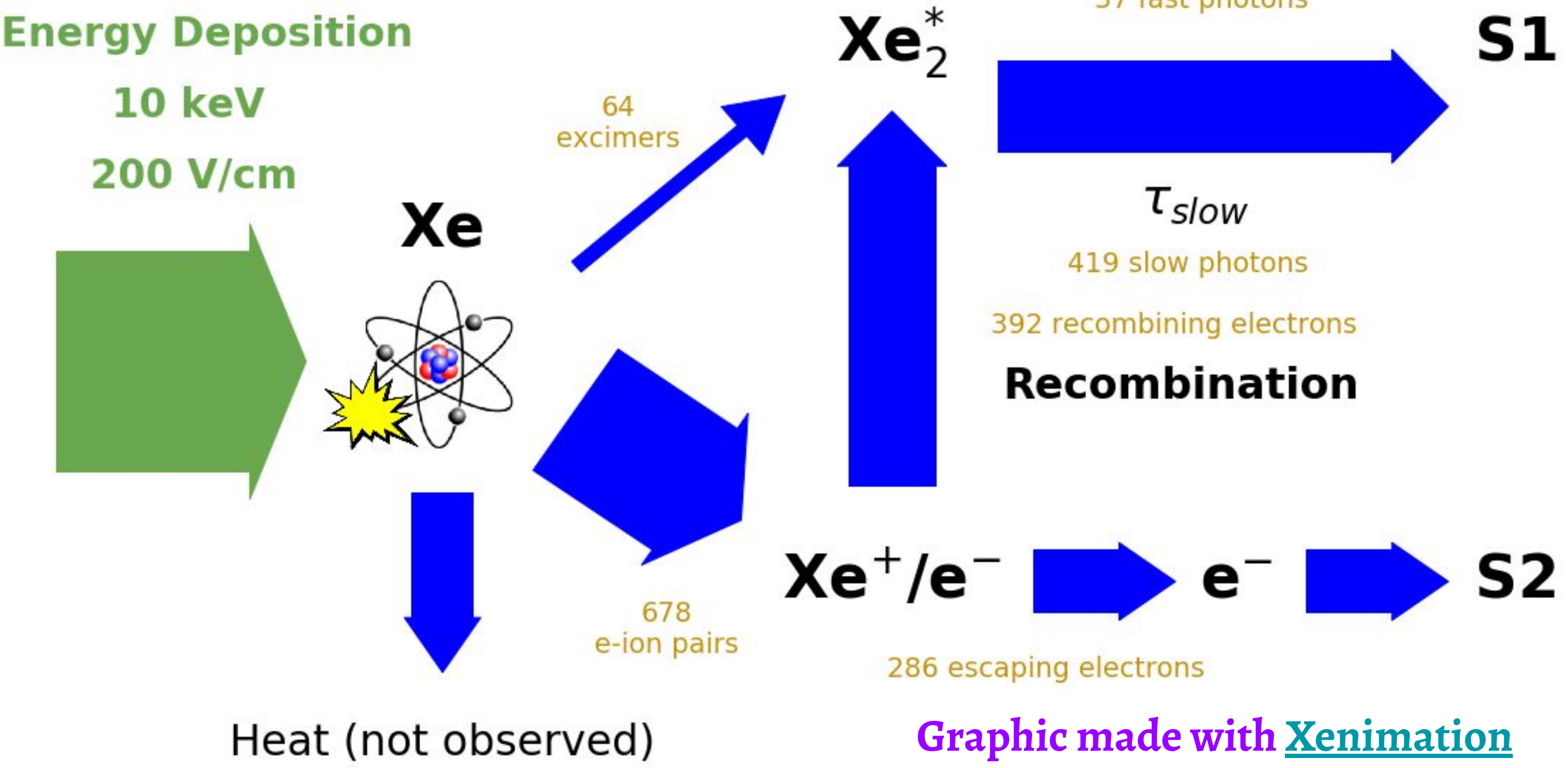


Nuclear Recoil (NR)



Graphic made with Xenimation

Electronic Recoil (ER)



Graphic made with [Xenimation]

ER/NR Discrimination

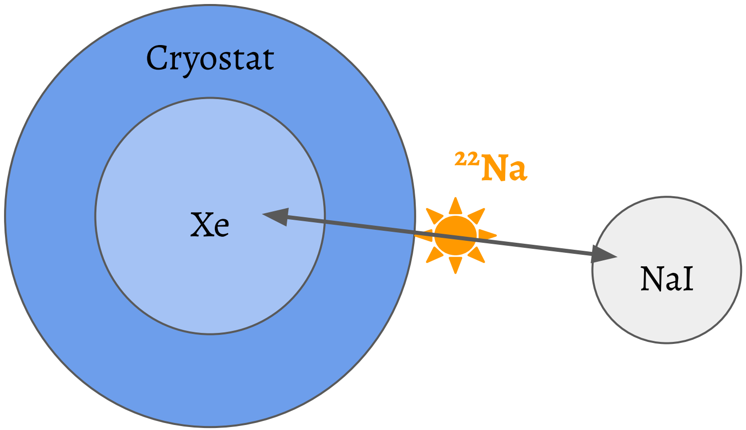
- Discriminate ER from NR by using the ratio of charge-to-light produced by the recoil
  - In practice, discrimination variable is: $\mathbf{\log_{10}(S2 / S1)}$
- PIXeY calibrations for ER and NR allow us to study discrimination as a function of parameters like drift field and energy
- Detector parameters and data parameters for this analysis:
  - Data collected with single-scatter recoils isolated: one S1 pulse, followed by one S2 pulse
  - Additional cuts applied for quality and fiducial volume selection
  - Extraction gas field: **8.0 kV/cm**
  - Drift fields: **117 V/cm** and **213 V/cm**
  - **g1 = 0.110** phe / photon created
  - **g2 = 30.2** phe / escaped electron

PIXeY Calibrations

Electronic Recoils: ^{22}**Na**

Gamma source

Tag recoils with an external NaI detector



Nuclear Recoils: **D-D**

2.5 MeV monoenergetic neutrons generated from deuterium fusion

Recoil spectrum ~ 60 GeV WIMP

Detector Effects Calibration: ^{83m}**Kr**

Two-step decay, depositing 32.1 and 9.4 keV conversion electrons

Dissolved in liquid xenon; recoil events uniformly fill the detector

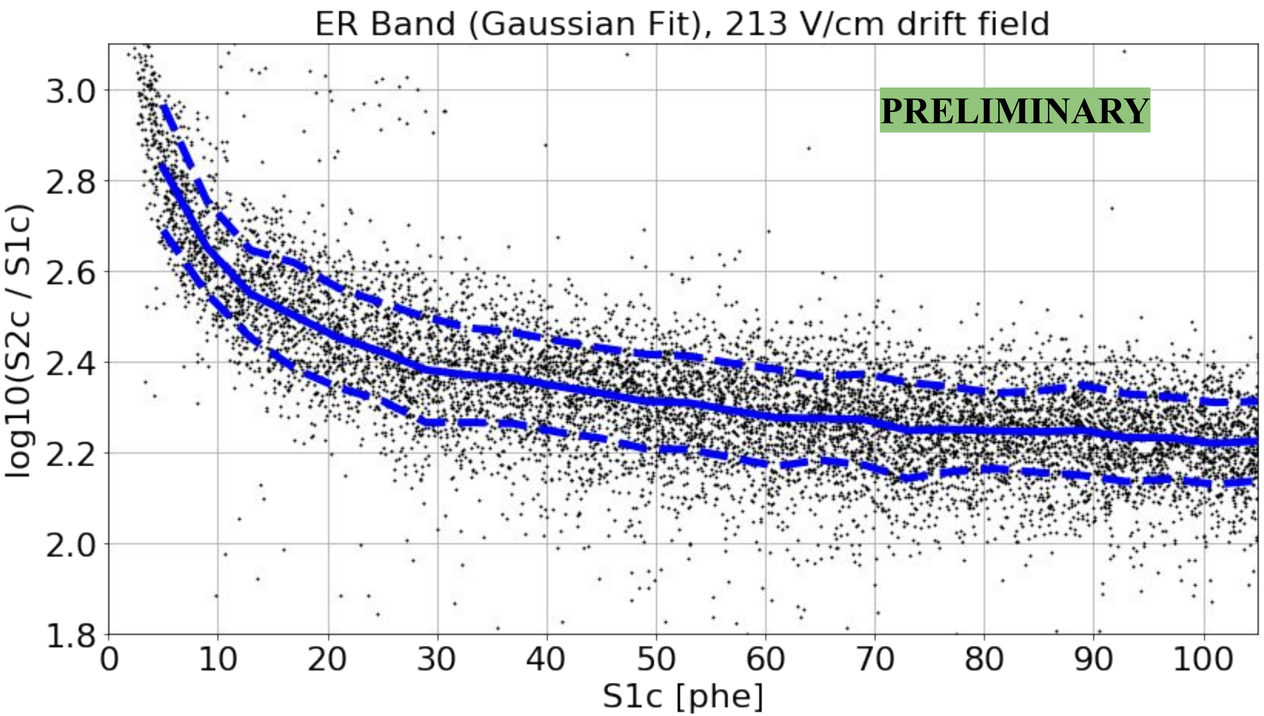
Allows us to identify clean mono-energetic signals and characterize position-dependent and field-dependent phenomena

Electronic Recoil Band

Events are split into bins of S1c → the distribution of log10(S2c/S1c) is fit to a Gaussian

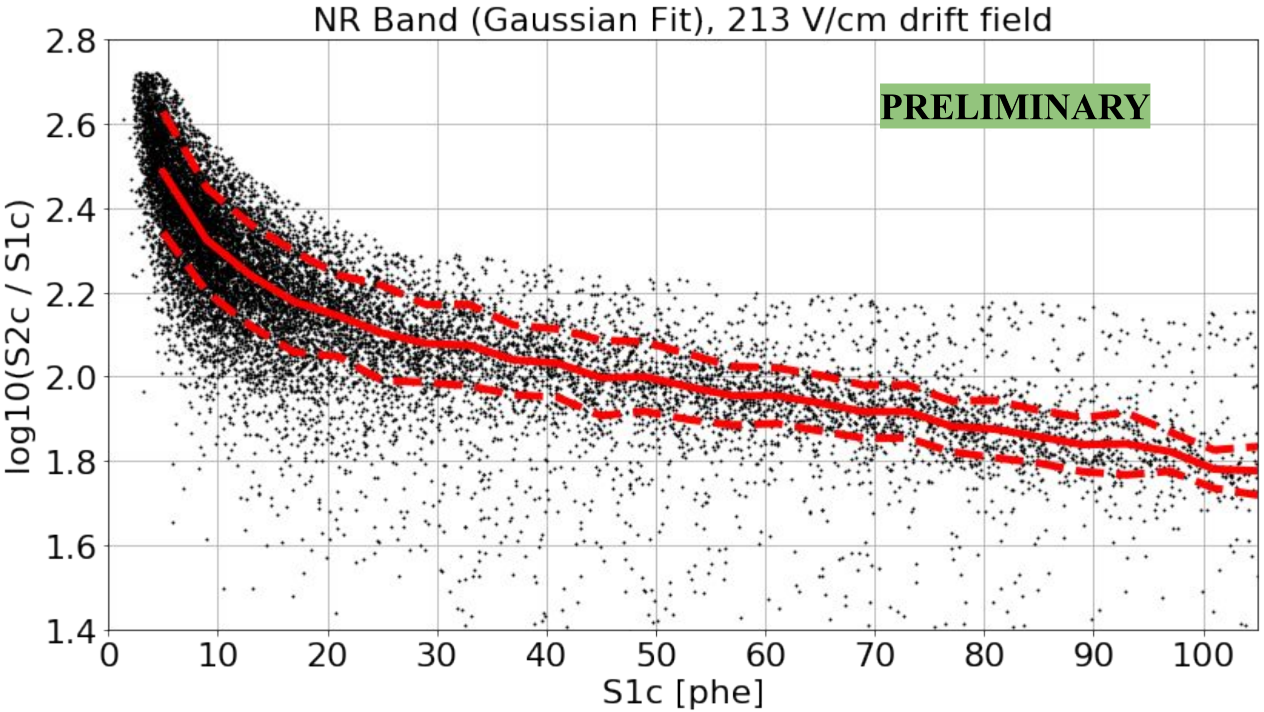
The ER band median and width (1σ) are extracted

Skewness ignored for now



Nuclear Recoil Band

The NR band median and width are extracted the same way



Leakage and Discrimination

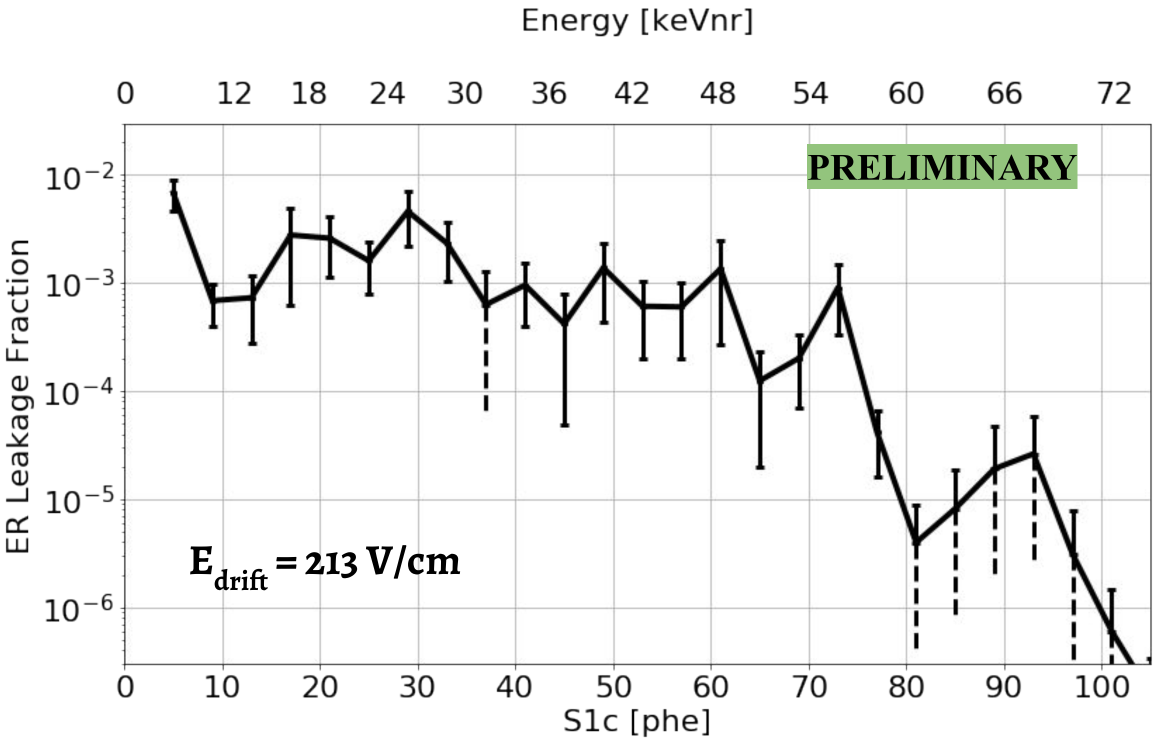
Extrapolate the ER band Gaussian fit below the NR band to calculate leakage fraction

Leakage improves dramatically with energy, as seen by others (e.g. LUX)

$\leq 10^{-6}$ leakage at S1 = 100 phe

Leakage over the WIMP search range (0-80 phd) is 2×10^{-3}, substantially better than the LZ requirement of 5×10^{-3}

(LZ requirement in arxiv:1509.02910)



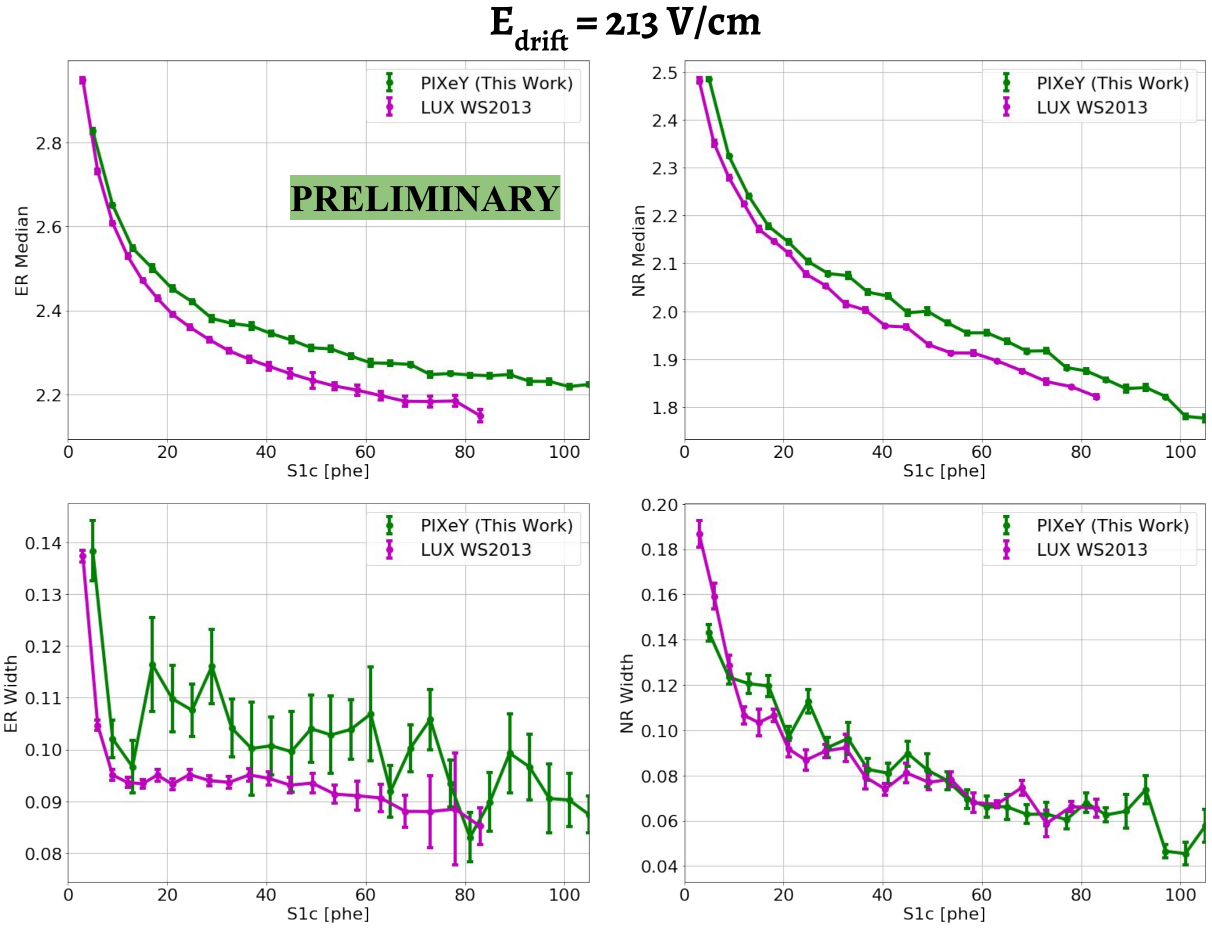
LUX Comparison

PIXeY: g1 = 0.110,
drift field = 213 V/cm
LUX 2013: g1 = 0.117,
drift field = 180 V/cm

Lower band median and width in LUX make sense, because of higher g1 and lower field

LUX “ER width” is σ_-, the width of the downwards fluctuations. By definition: $\sigma_- < \sigma$. Thus using σ_- with skewness will give better leakage.

(LUX data from Phys. Rev. D 102, 112002 (2020))

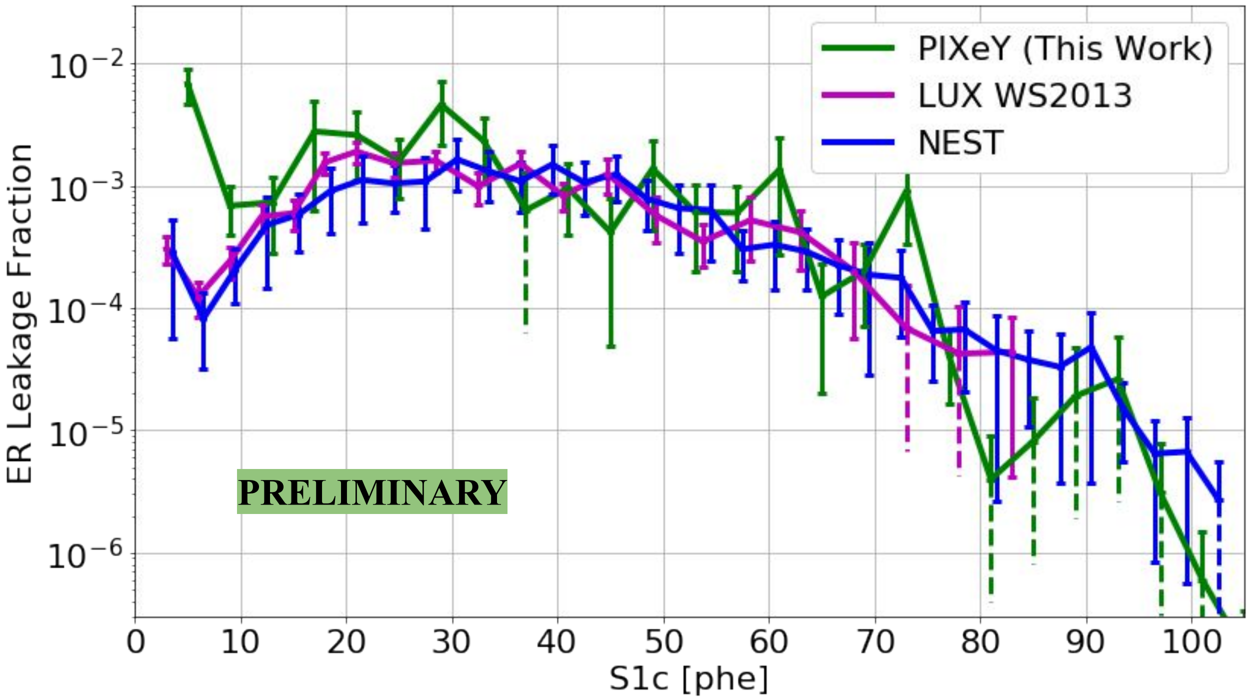


Comparison to LUX Data and NEST Simulation

Simulated PIXeY with NEST, using correct detector parameters for g1, g2, drift and extraction fields, etc.

PIXeY leakage matches LUX and NEST remarkably well!

Slightly better leakage in LUX at low energies explained by their use of a skew-Gaussian extrapolation. E.g., LUX leakage is 0.1% (vs 0.2% in PIXeY) in WIMP ROI.

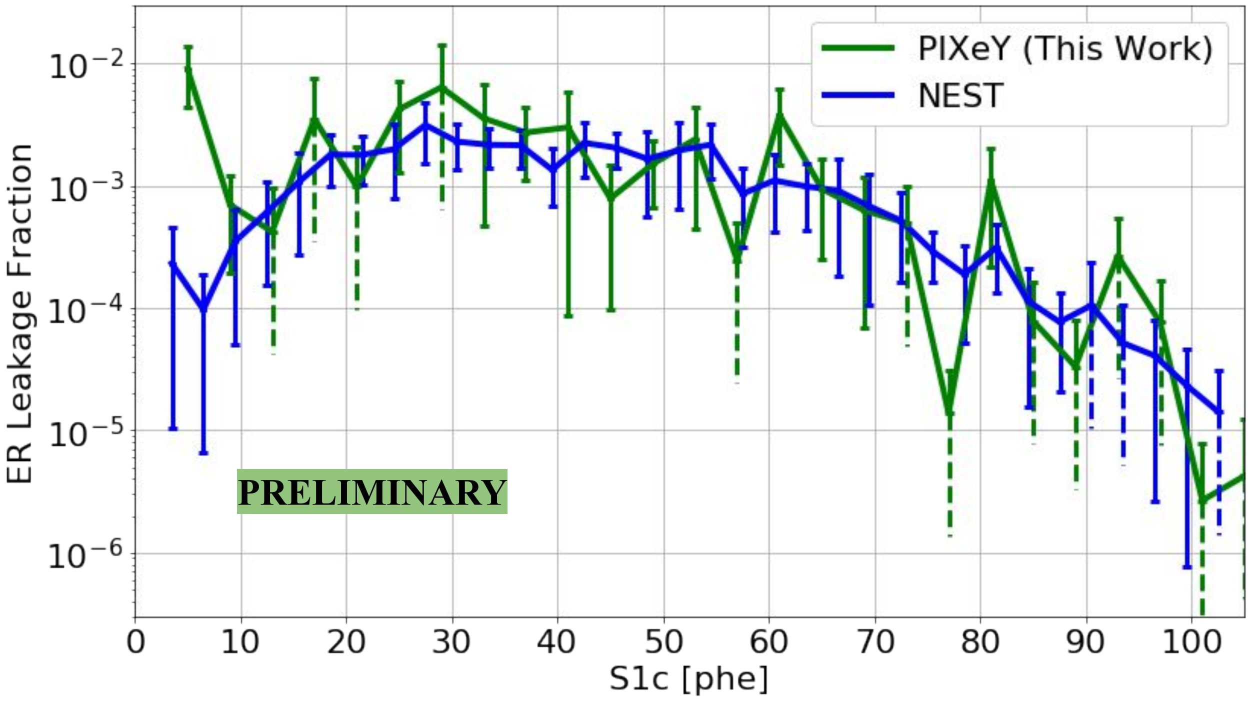


Varying Drift Electric Field

Analysis repeated with a drift field of 117 V/cm

Leakage similar to 213 V/cm, but slightly worse → consistent with LUX findings of minimum leakage at 300 V/cm

Matches NEST again, except at S1 < 10 phe; discrepancy most likely due to threshold effects, currently under study.



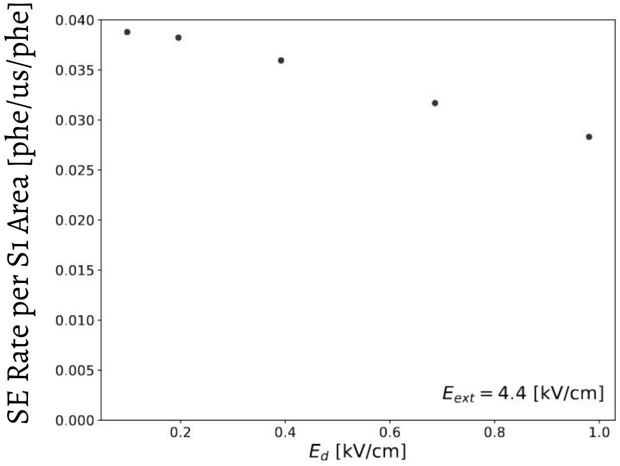
Backgrounds for Low-Energy Searches

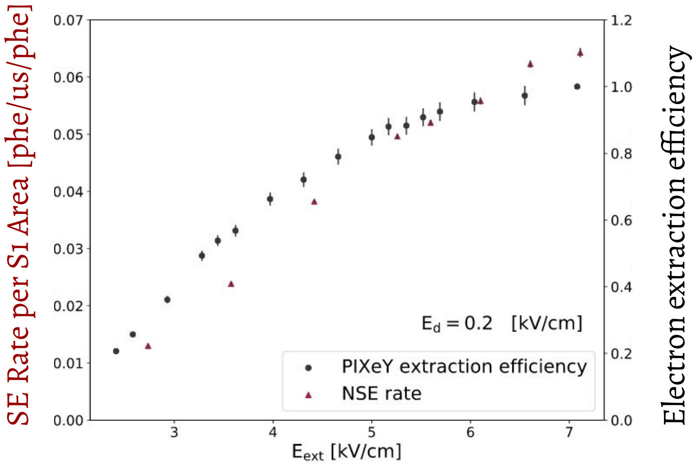
- Single electron (SE) backgrounds in xenon TPCs are a hindrance
  - Can be incorrectly classified as S2 pulses associated with an S1
  - Worsens energy resolution
  - Increases DAQ/trigger dead time
  - **Dangerous background for low-mass dark matter searches!**
    - In particular, "S2-only" searches (without an S1), looking for DM at ~few GeV
- Conducted an analysis of electron backgrounds using PIXeY ^{83m}Kr data (arXiv:2101.03686)
- Single electron backgrounds studied as a function of:
  - Drift and extraction fields
  - Timing (i.e. before the S1, between the S1 and S2, after the S2)

Photoionization from the S1 Light

Identify single electrons between the S1's and S2

Rate increases with extraction field → suggests the source of the SE's is photoionization of impurities by S1 photons





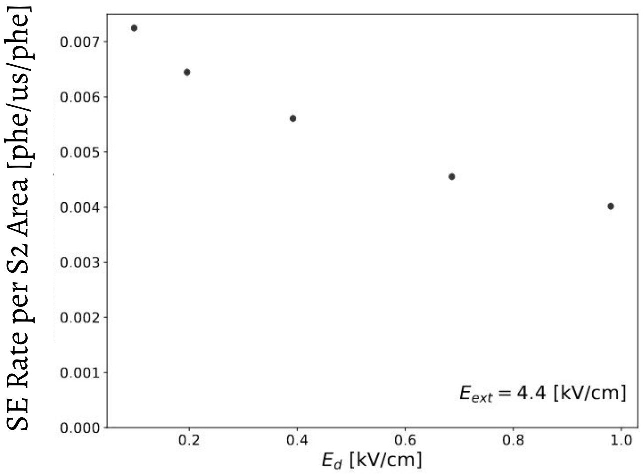
Rate decreases with drift field. Few potential causes:

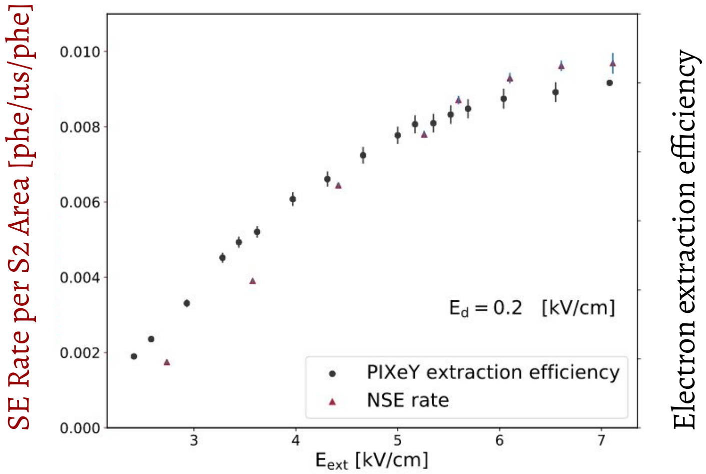
- Increased drift velocity → decreased interaction time between e-'s and impurities → lower density of anions
- Electron capture cross-section varies with field
- Charged impurities are drifted out of the detector more quickly

Photoionization from the S2 Light

Identify single electrons after the S2

Same behavior → suggests the same cause



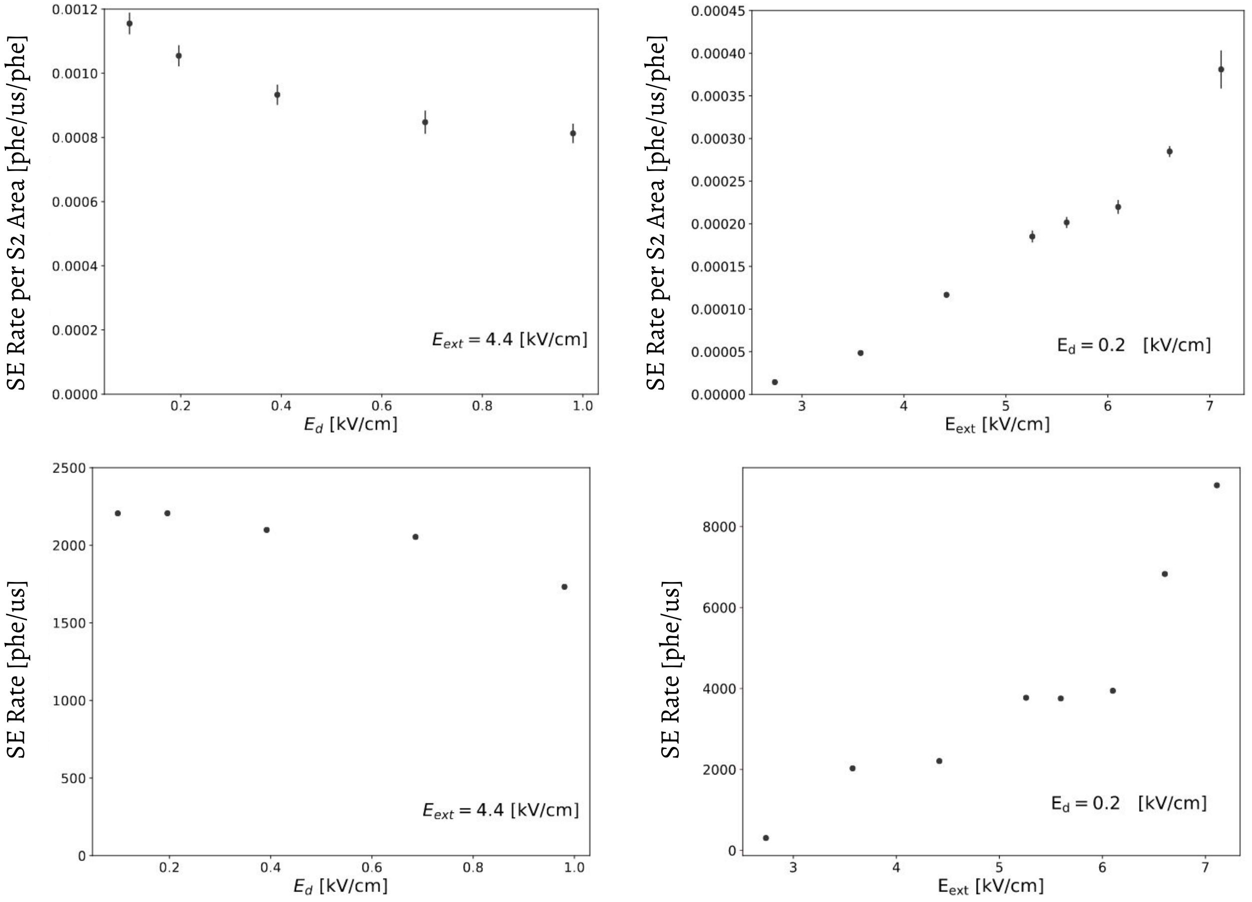


SE Background Uncorrelated with S1 and S2

Identify single electrons long after the S2 (top) or before the S1 (bottom)

Same behavior as previous, but understood to be from:

- Field emission from the gate grid
- Delayed release of electrons from impurities



Field Emission

- Fowler-Nordheim theory offers a guide to a better understanding of field emission
    - Electric field on gate grids → metallic conduction band electrons tunnel into LXe
    - Electron emission dependent on applied field, material, and grid surface roughness
- PIXeY measurements are consistent with the predicted electron emission rate

Summary and Conclusions

- Demonstrated robust ER/NR discrimination at high energies, achieving a factor of ~10^6 ER rejection at S1 = 100 phe (E = 70 keVnr)
- Future discrimination work will focus on ER skewness and variation of drift field

- Better of understanding of single electron backgrounds: their dependence on field, timing, and their sources
- Full details of single electron analysis located at arXiv:2101.03686; includes more details about SE timing

Thank you!

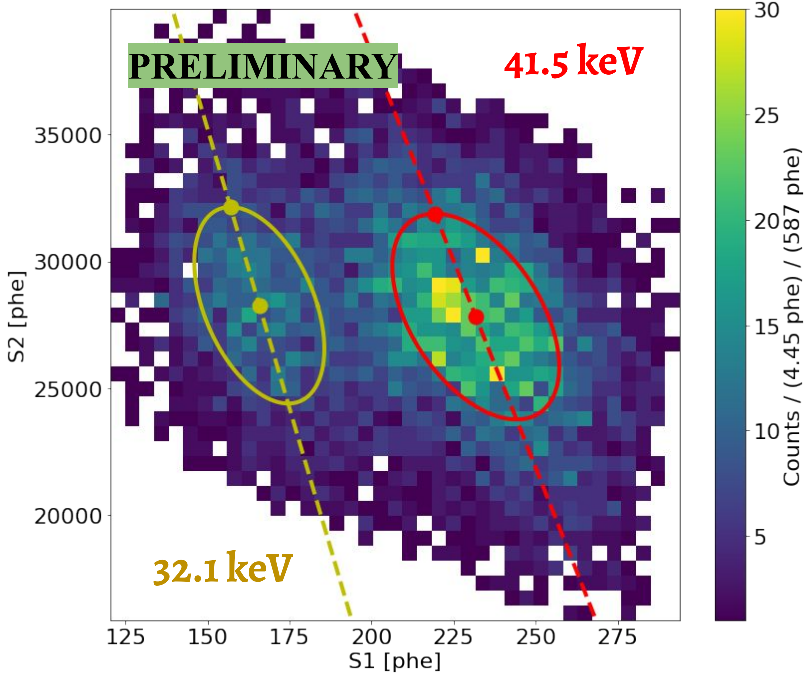
Any questions?

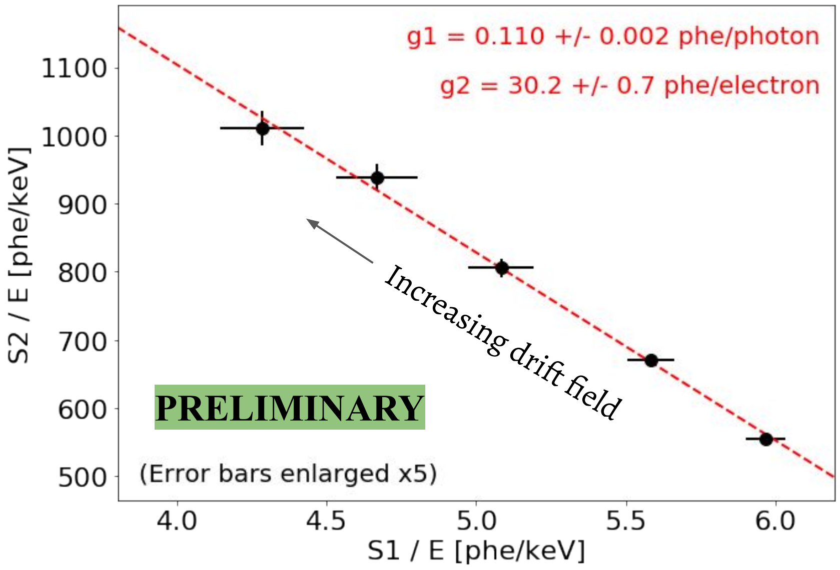
Backup

PIXeY Detector Parameters

Calculate g1 and g2 using the “Doke” technique

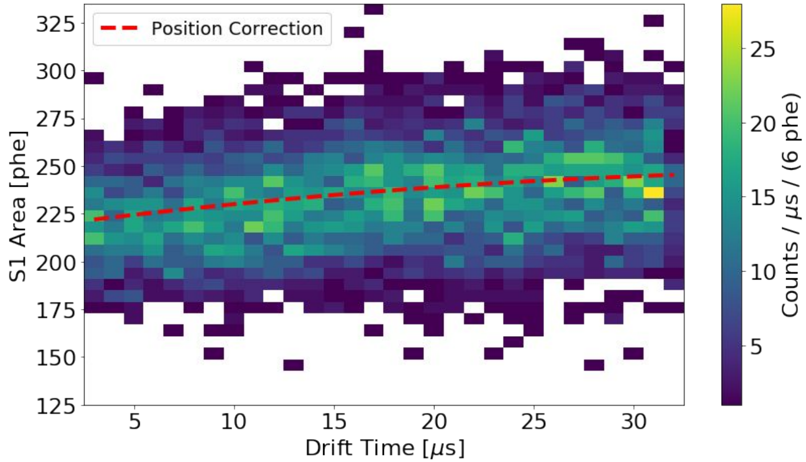
- These represent the average signal size for each photon and electron leaving the recoil site

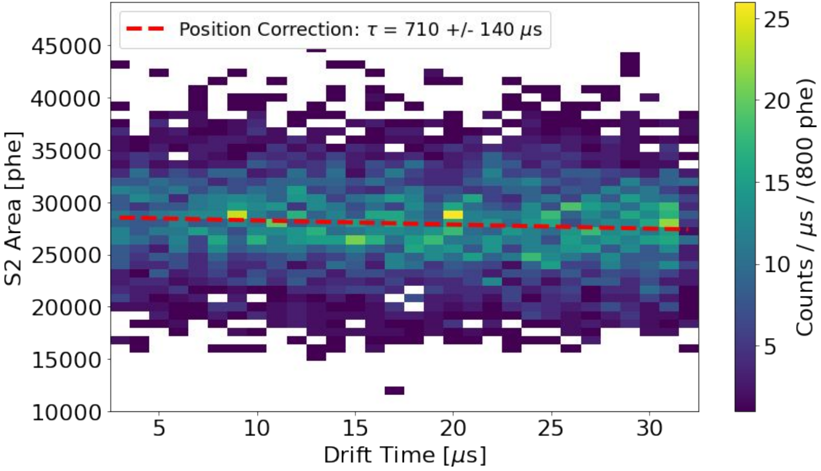




Position Corrections

- Pulse areas are dependent on the z-position of the event; S1 sizes grow with drift time, while S2 sizes fall with drift time
- S1 sizes grow with drift time (i.e. shrink with height) due to total internal reflection at the liquid-gas interface
- S2 sizes shrink with drift time (i.e. grow with height) due to ionized electrons capturing on electronegative impurities



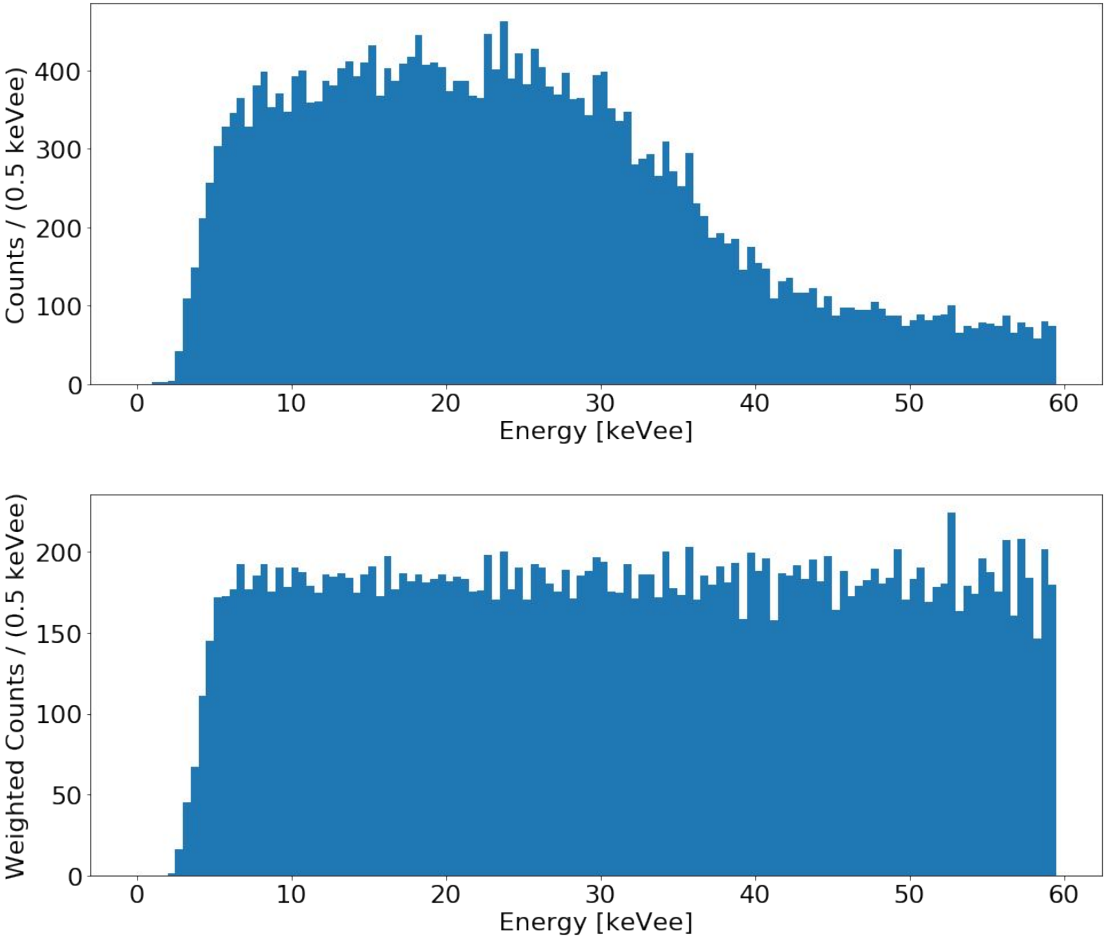


Energy Weighting

Electronic recoil events are weighted to mimic a flat spectrum in combined energy

Dark matter ER backgrounds from ^{136}Xe double beta decay, Rn/Kr internal contaminants, and solar neutrinos are roughly flat in energy

$$E = W\,(S1c / g1 + S2c / g2)$$



Noble Element Simulation Technique (NEST)

- Inter-collaboration collaboration of liquid xenon and argon physicists who construct models of energy deposition in a noble detector, as well as code to implement simulations
    - Members from LUX, LZ, XENON, (n)EXO, RED100, COHERENT, DUNE, ICARUS, MicroBooNE, SBN
- Models are based on physical principles and world averages of existing data
- PIXeY simulation:
    - Template detector file, which represents LUX WS2013
    - Detector parameters like g1, g2, drift field, extraction efficiency were adjusted to their correct values
    - Simulated a flat ER energy distribution and DD neutrons → calculated ER + NR bands and leakage fraction
- Code and more information:
    - http://nest.physics.ucdavis.edu/
    - https://github.com/NESTCollaboration

NEST Simulation

Used NEST to simulate the PIXeY experiment, with proper g1, g2, drift field, and other detector parameters

Matches pretty well, although there are some discrepancies

NEST matches LUX 2013 very well, although the detector parameters are slightly different

E_{drift} = 213 V/cm