Modeling the low-energy accidental coincidence background in the LUX-ZEPLIN experiment

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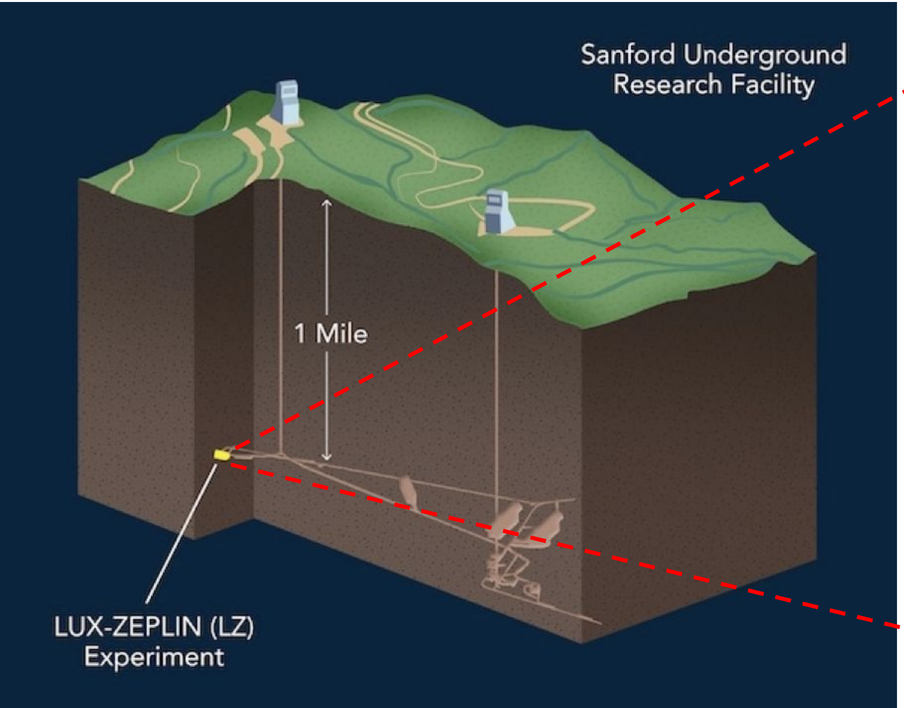
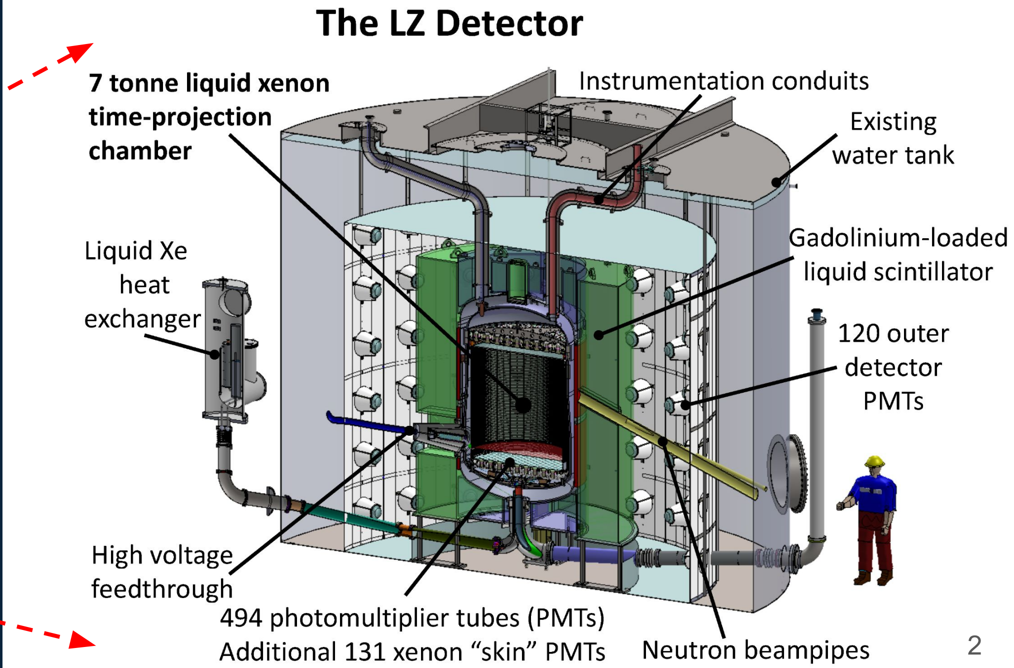
LZ Detector Design: NIM A, 953 163047 (2020)

The LUX-ZEPLIN (LZ) detector

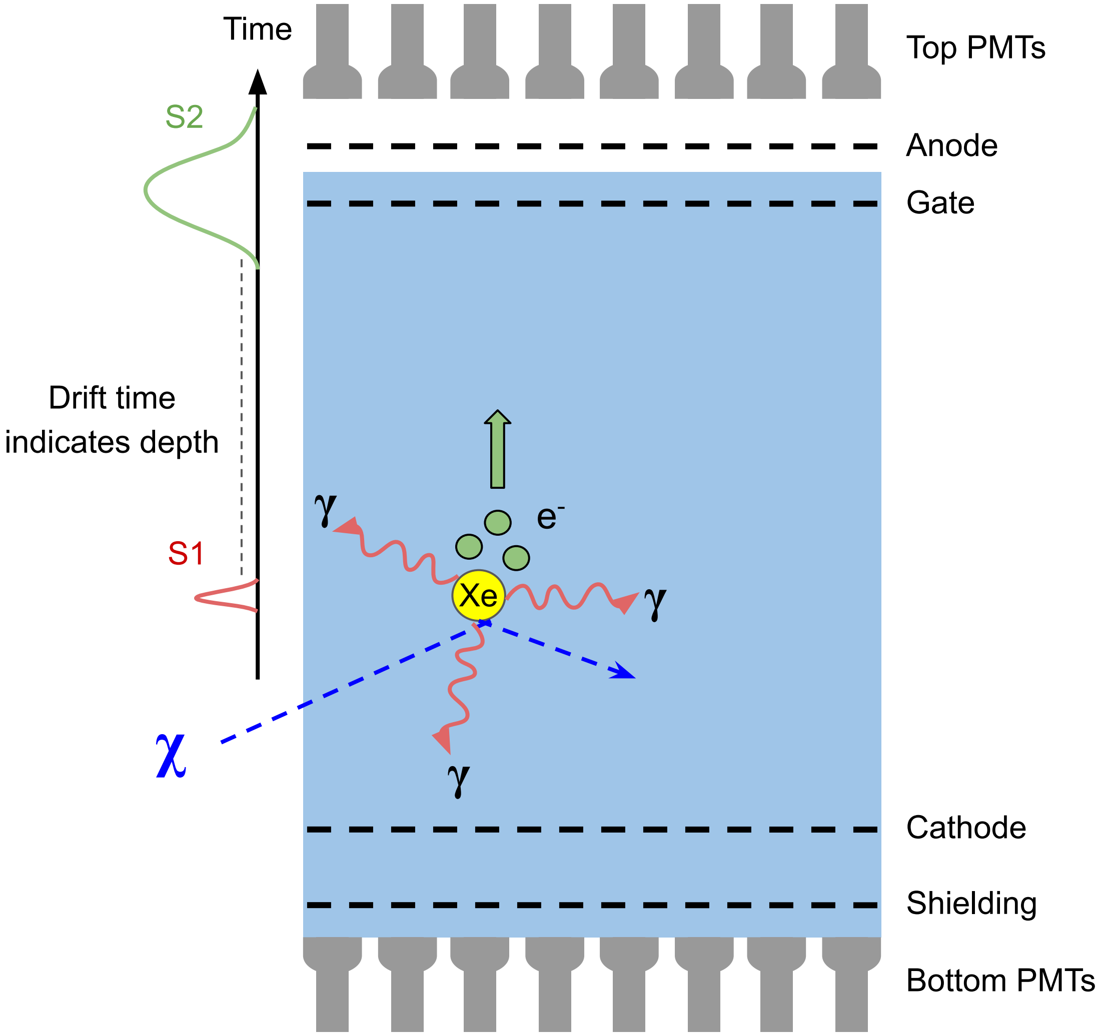
- Liquid xenon time projection chamber (LXe TPC) searching for dark matter (DM) interactions
- A mile underground at the Sanford Underground Research Facility (SURF) in South Dakota, USA





LZ detection principle

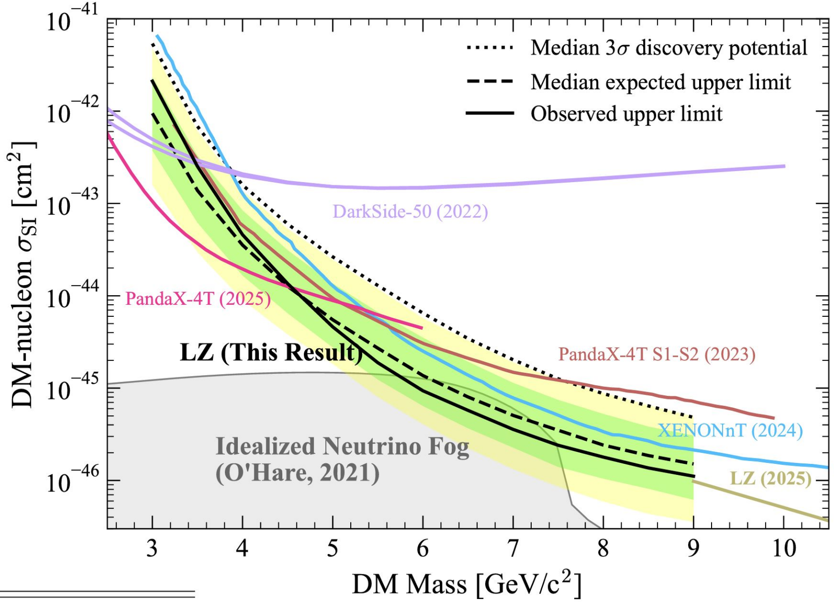
- Particle interactions produce photons and electrons
- Photons detected immediately by top and bottom photomultiplier tube (PMT) arrays → prompt scintillation (S1) signal
- Electrons drift to the liquid surface, are extracted, and produce delayed electroluminescence (S2) signal



Recent low-energy results

Refer to Alberto Uson's talk for discussion of LZ's new low-mass DM and ^{8}B results

- World-leading limits on DM-nucleon scattering cross-sections for masses from 5-9 GeV/c^2
- Strongest (4.5σ) evidence of CEνNS process in xenon from ^{8}B solar neutrinos
- Dominant background is instrumental: ***accidental coincidences (AC)*** of S1 and S2 signals
- How do we model this AC background?



WS2025 results: arXiv:2512.08065

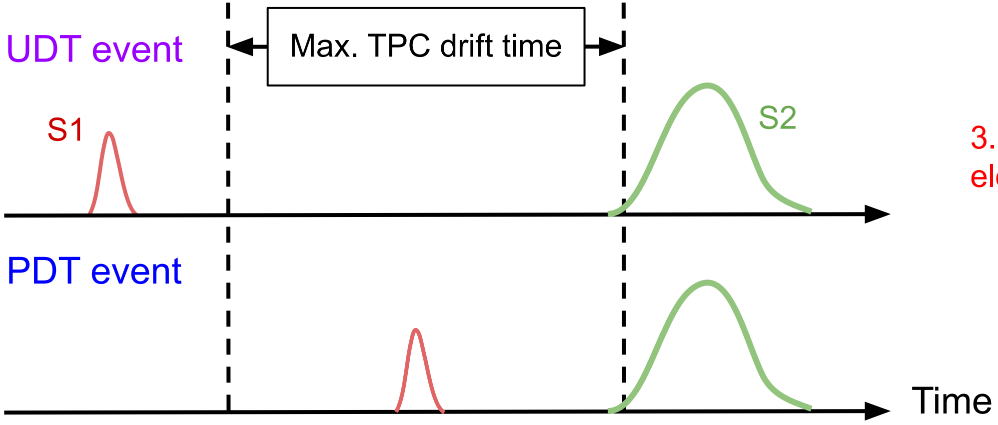
Components	Expectation	Background-Only Fit	3 GeV/c^2 Fit	9 GeV/c^2 Fit	^{8}B CEνNS Unconstrained Fit
SI DM	-	-	$0.5^{+5.1}_{-0.5}$	$0.0^{+4.1}_{-0.0}$	-
^{8}B CEνNS	$20.6^{+8.9}_{-6.8}$	$15.0^{+2.9}_{-2.5}$	$14.7^{+3.1}_{-2.7}$	$15.0^{+2.9}_{-2.5}$	$12.3^{+7.0}_{-5.4}$
Accidental coinc.	6.6 ± 0.3	6.5 ± 0.3	6.5 ± 0.3	6.5 ± 0.3	6.6 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$
Total	$27.2^{+10.1}_{-7.3}$	$21.6^{+4.7}_{-3.8}$	$21.7^{+7.1}_{-4.2}$	$21.6^{+6.2}_{-3.8}$	$18.9^{+7.0}_{-5.5}$
σ_{eff}	0 ± 1	$-0.81^{+0.59}_{-0.60}$	$-0.86^{+0.63}_{-0.69}$	$-0.81^{+0.58}_{-0.60}$	0 ± 1

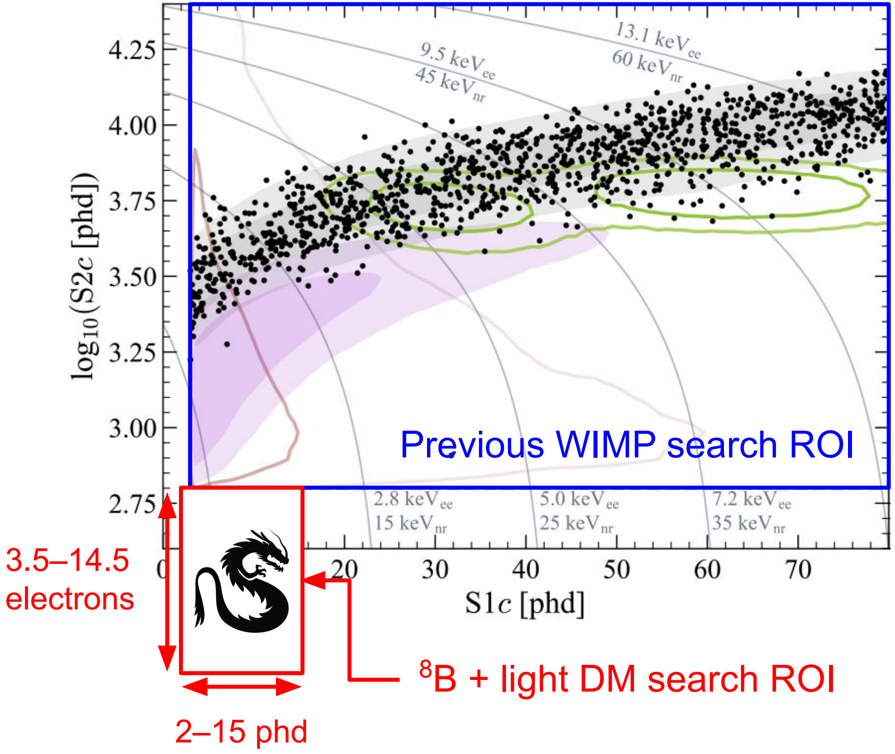
Accidental coincidences are the dominant low-energy background

WS2024 results: PRL 135, 011802 (2025)

The accidental coincidence background

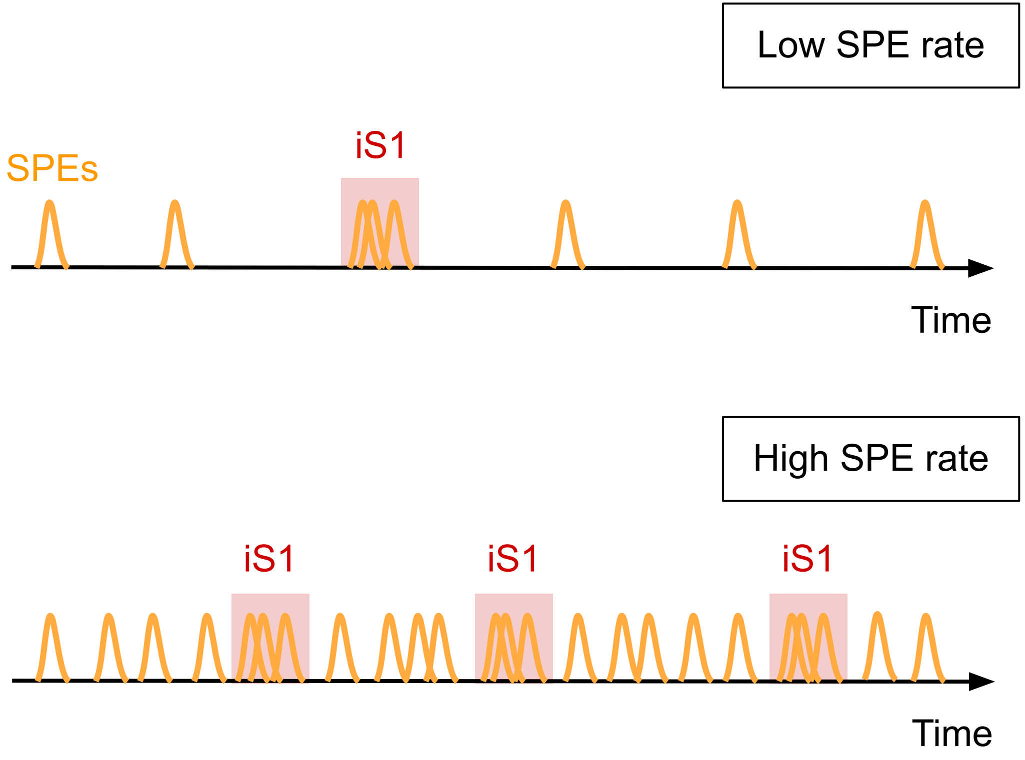
- Observe events with unphysically-long drift times (UDTs) from pileup of “isolated” S1s and S2s (iS1s and iS2s) → pure AC sideband
    - Can also mimic particle interactions with physical drift times (PDTs)
- At small S1/S2 sizes, AC rate increases drastically and is historically underpredicted





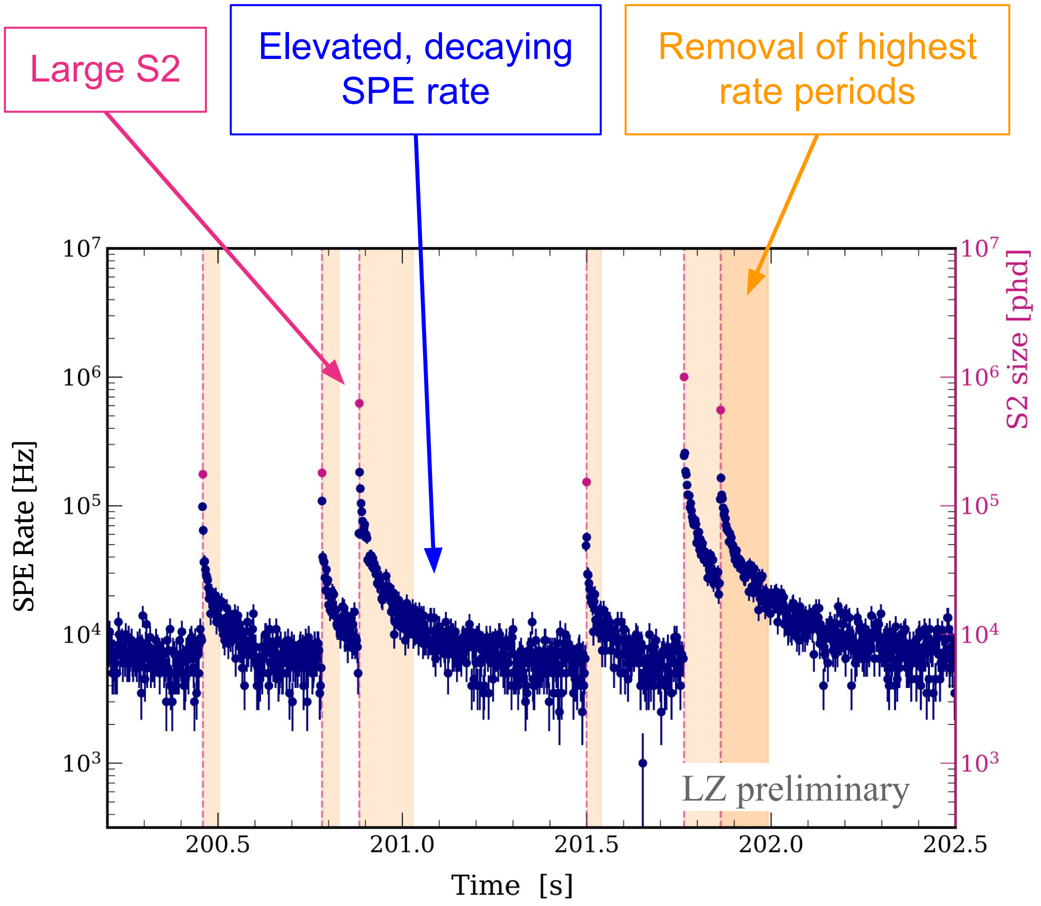
Pileup iS1s and iS2s

- Many small iS1s come from pileup of single photoelectrons (SPEs) in the detector
    - An iS1 is defined to consist of at least 3 coincident SPEs
- Small iS2s produced by pileup of coincident single electrons (SEs) and other instrumental effects



Instrumental effects

- Instrumental effects produce simultaneously-elevated SPE and SE rates
- Example: “afterglow” following large S2s, decaying over ~seconds
- Resulting iS1 and iS2 rates are ***time-varying and correlated*** → small, pileup iS1s/iS2s during high-rate periods are more likely to form AC events
    - Explains under-prediction by naive models at low S1/S2 areas
- Effect remains even after high-rate exclusion cuts

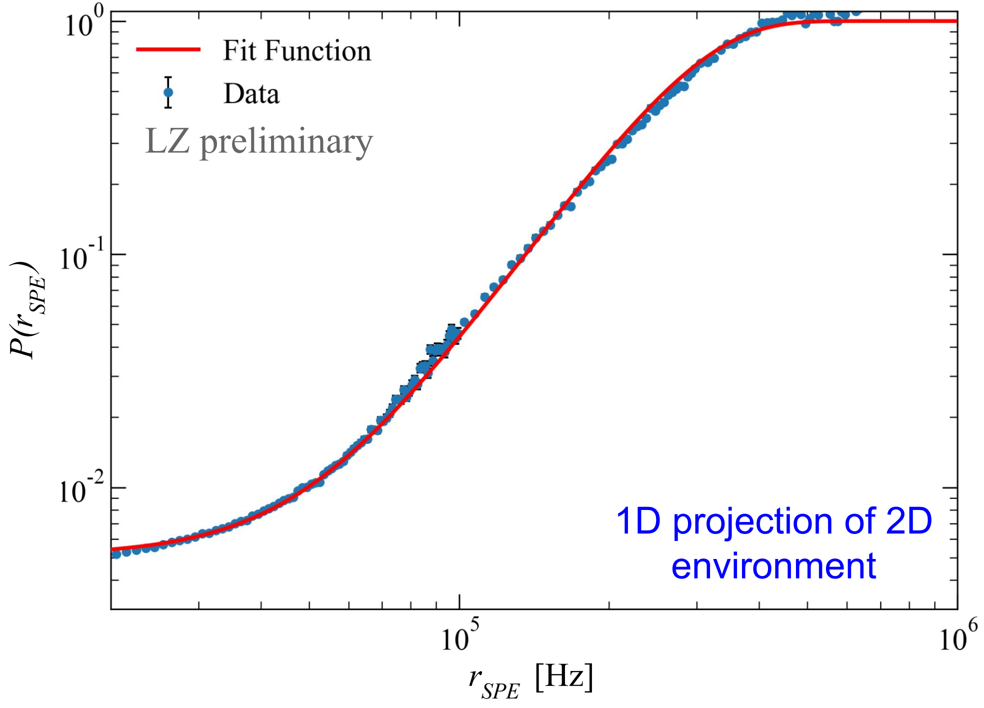


SE rate also elevated + decaying (not pictured)

Quantifying AC event probability

- Probability ***P*** for an iS2 to form an AC event is determined by the current iS1 rate
- iS1 rate depends on SPE and SE rates, or detector ***environment*** $\boldsymbol{(r_{SPE}, r_{SE})}$
- Calculate $P(r_{SPE}, r_{SE})$ by sampling random windows throughout the dataset
  - P = 0.4% during "normal" conditions and ~100% at sufficiently high rates

Probability for an iS2 to form an AC event



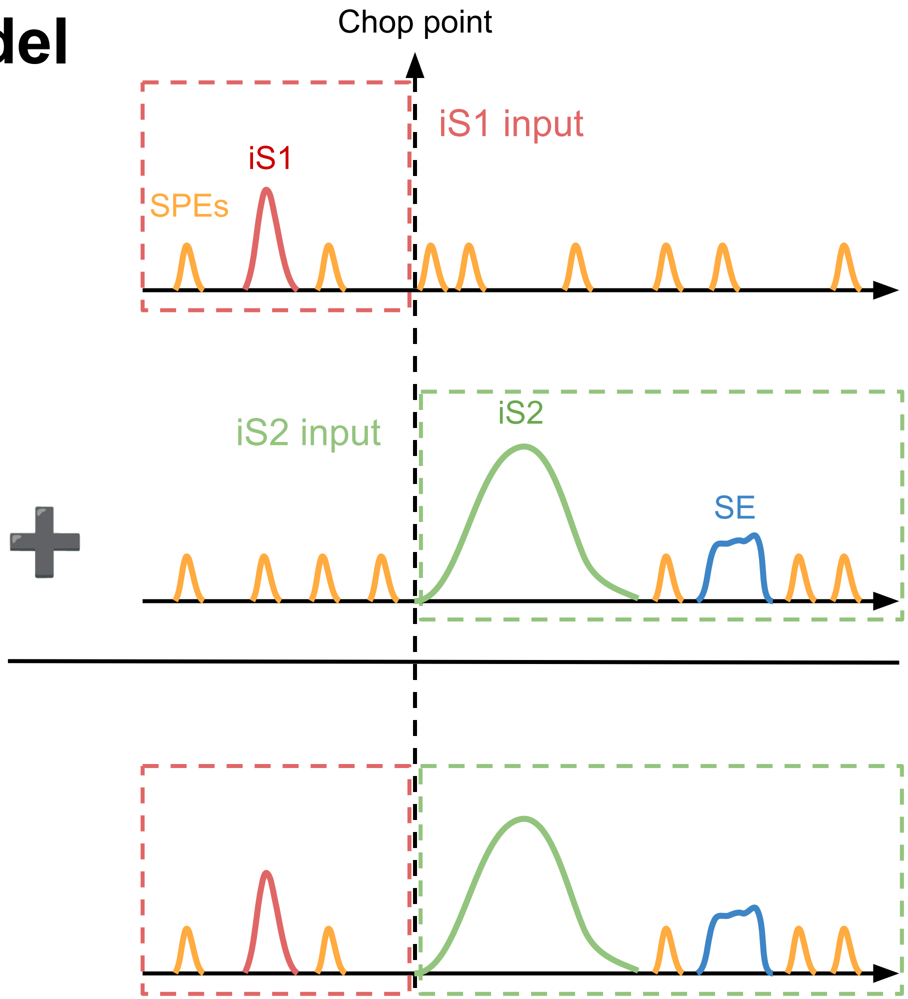
1D projection of 2D environment

Building a low-energy AC model

High-statistics, data-driven model using real iS1s and iS2s in LZ:

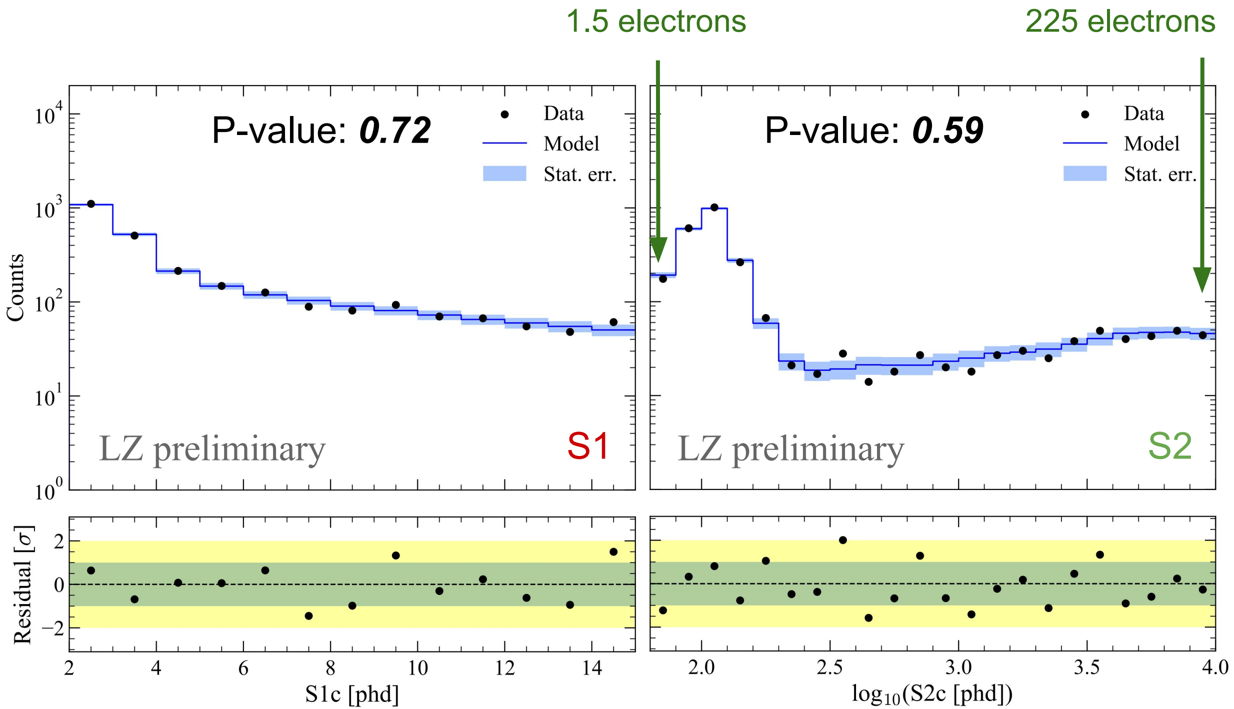
1. Select input events containing iS1s or iS2s and compute their SPE and SE rates
2. Perform weighted pairing of events* according to their probability *P* of forming an AC event: "***environment-matched pairing***"
3. For each pair, "chop" both events at the onset of the iS2 and "stitch" the waveforms together to create millions of synthetic AC events

**iS1 and iS2 inputs are drawn from similar rate environments to mimic real AC events*



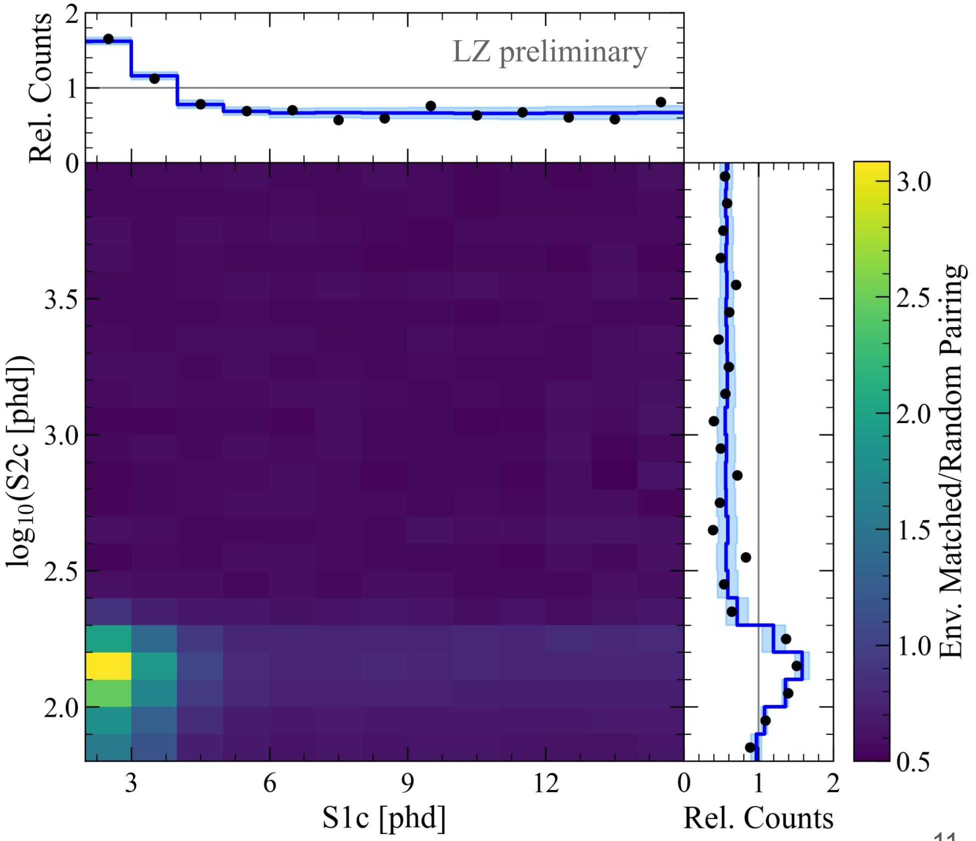
Validation with UDT data

- Normalize model to rate of UDTs
- Observe ***statistical agreement*** in S1 and S2 spectra down to 1.5-electron S2s
- Incur $\boxed{\frac{1}{\sqrt{\#\ \mathrm{UDTs}}} = 1.9\%}$ uncertainty in extrapolation to PDT AC rate



Impact of environment-matched pairing

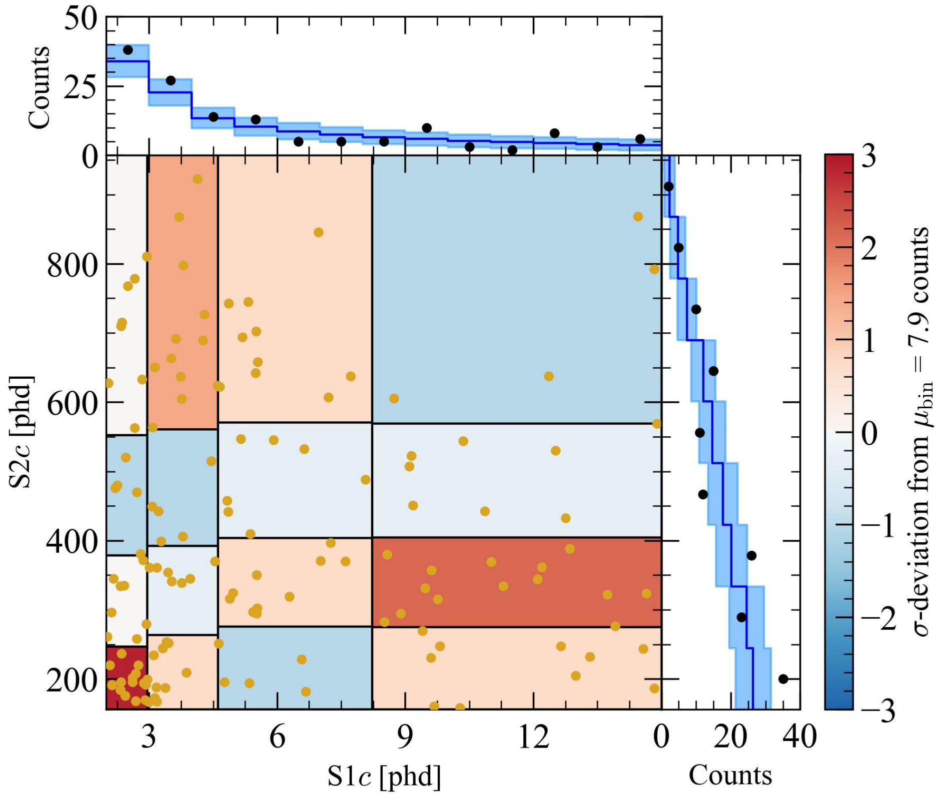
- Compare environment-matched AC rate prediction with purely random pairing
- Env-matched production has:
  - More AC events with small S1s/S2s overall
  - Preferential pairing of small iS1s with small iS2s rather than larger pulses
- Comparison with UDT data shows necessity of env-matched modeling technique



Model prediction in ^{8}B / light DM ROI

- Apply ^{8}B / light DM ROI selection: S1 2–15 photons detected*, S2 3.5–14.5 electrons
- Model predicts ***130.6* ± *1.4 (sys.)*** UDT events
  - Binomial acceptance error from ROI selection
- ***139 events*** observed; consistent with model accounting for poisson fluctuations
- After extrapolating to PDTs and applying final event selection (95% AC rejection efficiency), we expect ***6.6* ± *0.3 (sys.)*** AC events in LZ's ^{8}B / light DM search

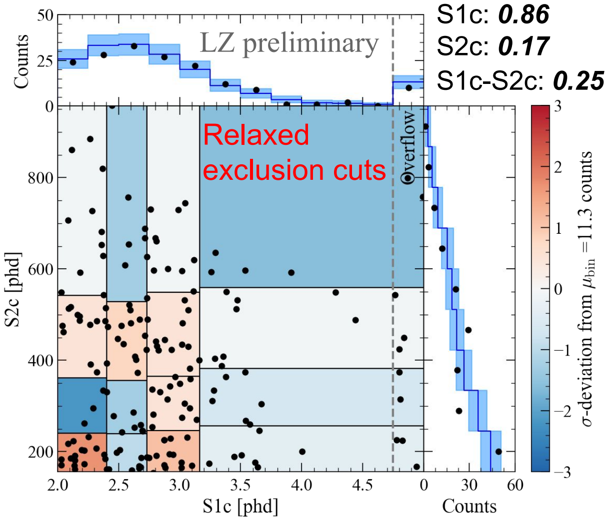
**Detector SPE response varies. A 3-PE S1 may be equivalent in size to 2 "average" SPEs*

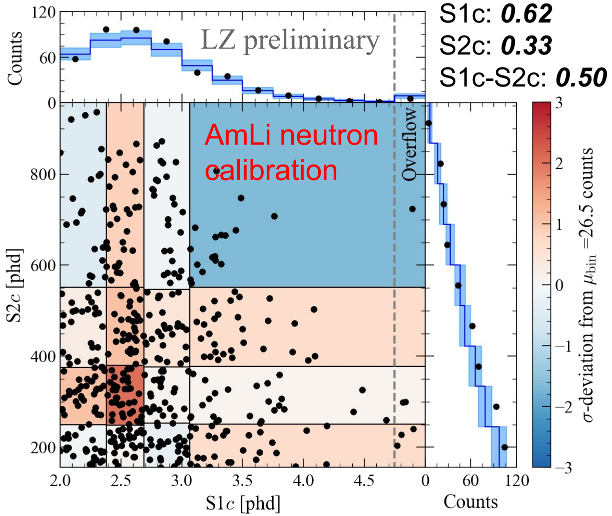


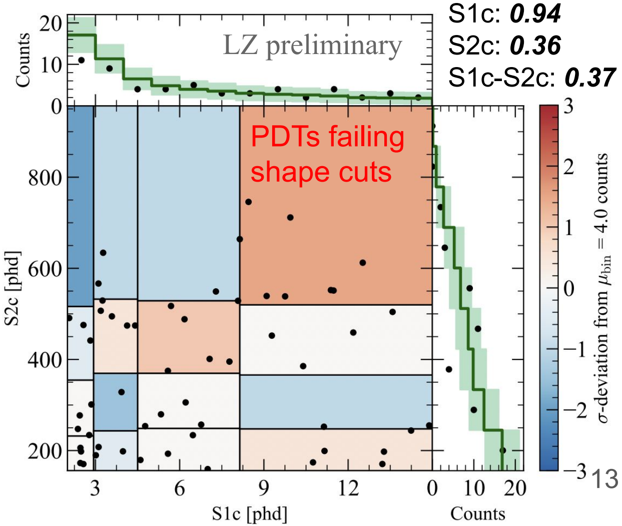
S1, S2, and 2-dimensional {S1, S2} p-values are ***0.38***, ***0.48***, and ***0.28***

Additional model validations

- Statistically distinct regions to “stress test” the model:
  - Relaxed exclusion cuts → average SPE rate ***6x*** higher, SE rate ***3x*** higher
  - During AmLi neutron calibration → high rate of iS2s
  - Events in PDTs failing final event selections
- Statistical agreement in S1 and S2 spectra for ***all*** model validations performed



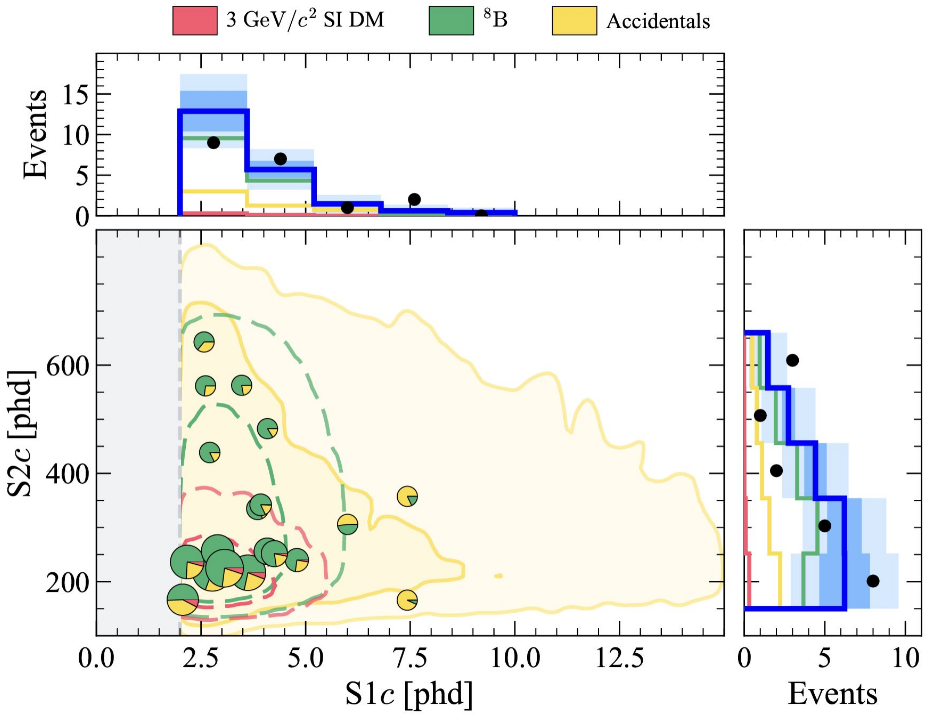




Summary

- Successfully developed a model for AC events that are composed of instrumental iS1s and iS2s
- Demonstrated agreement between our model and real AC events
- Validated the model with additional statistically distinct sidebands

This model allowed us to accurately predict the ***rate*** and ***shape*** of the AC background in the low-S1/S2 regime, which enhanced the sensitivity of LZ's recent ^{8}B / light DM search.



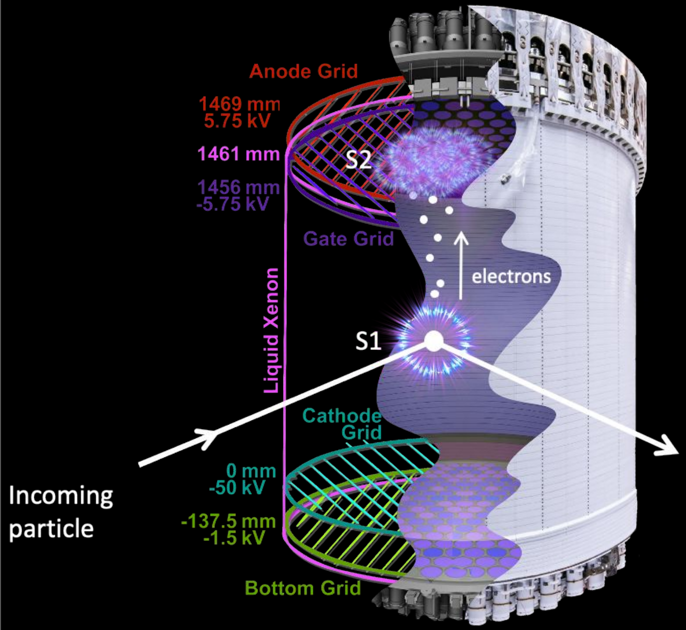


Image by Nicolas A. (Imperial College London)

Thank you!

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LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

https://lz.lbl.gov/

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
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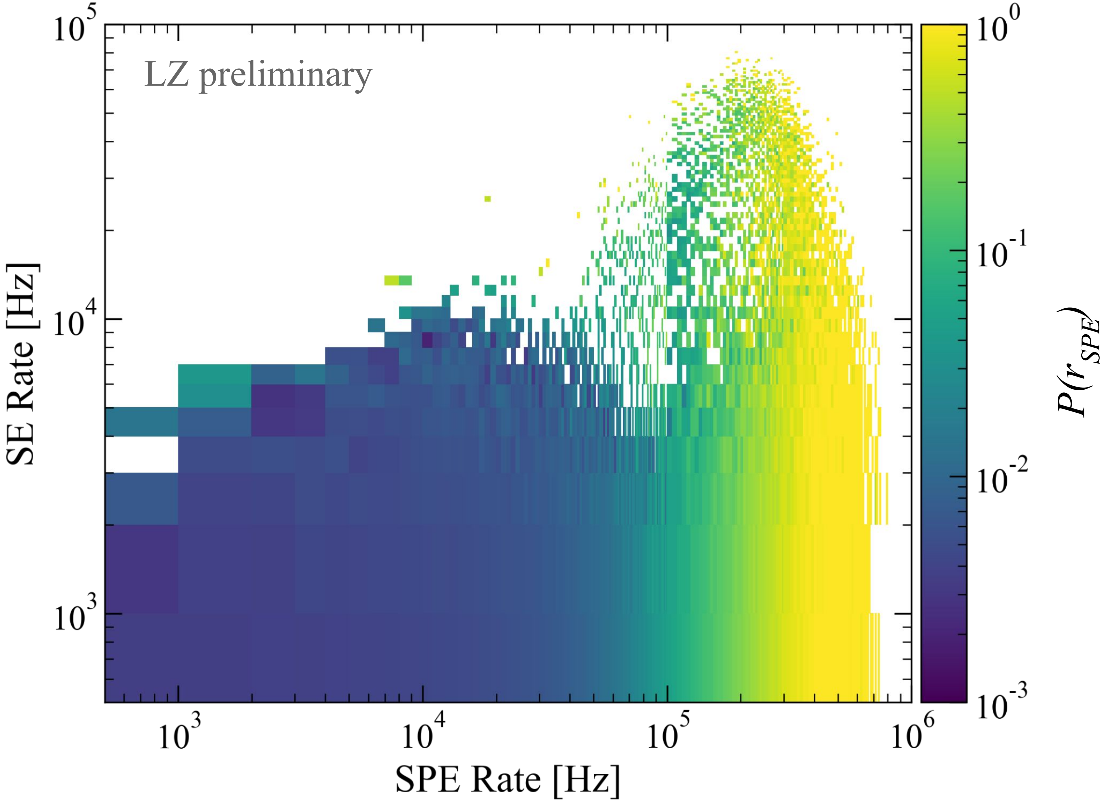
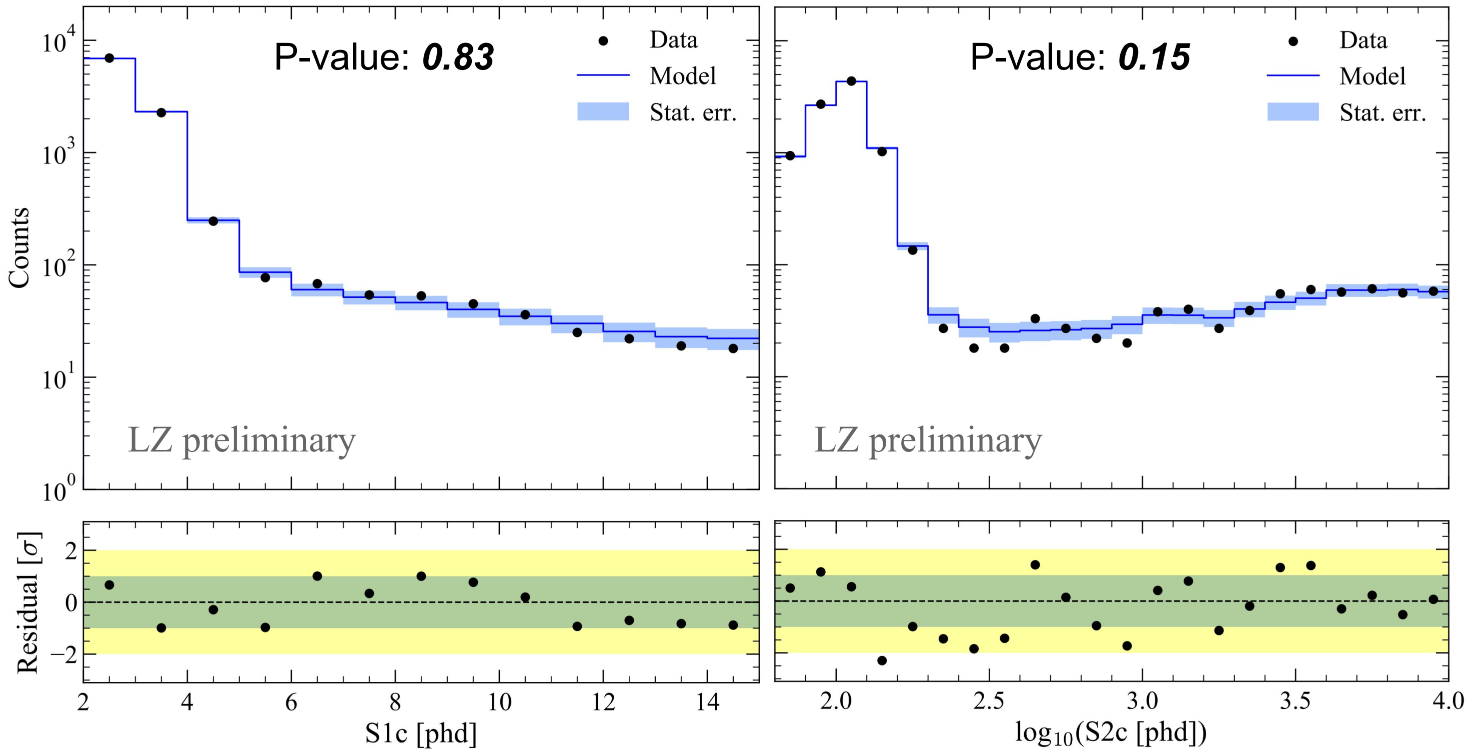
Backup

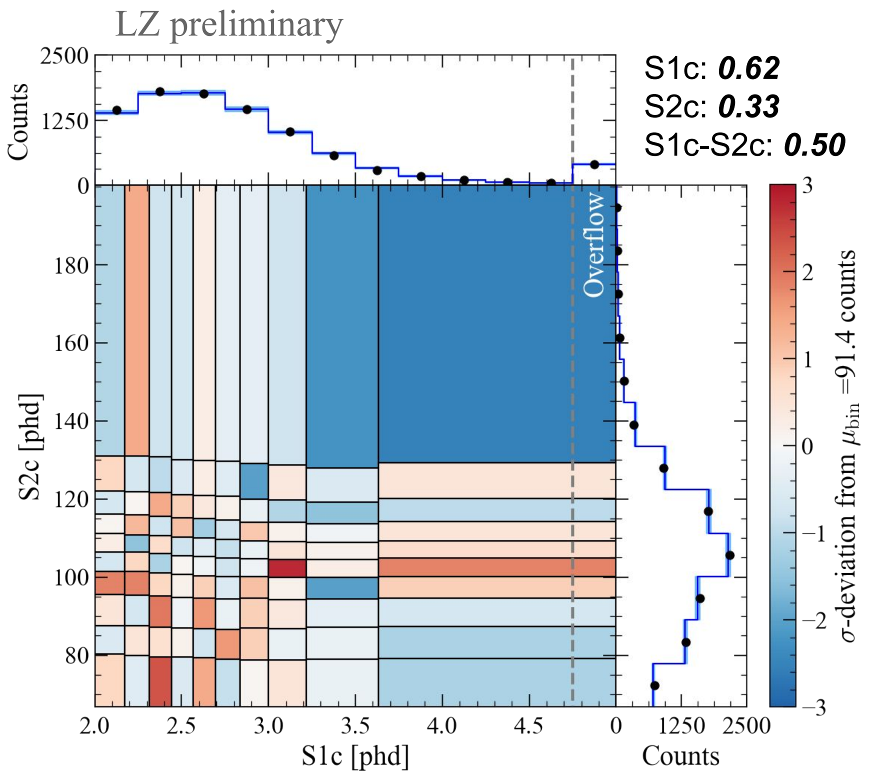
2D pairing weights



High-rate region normalization plots



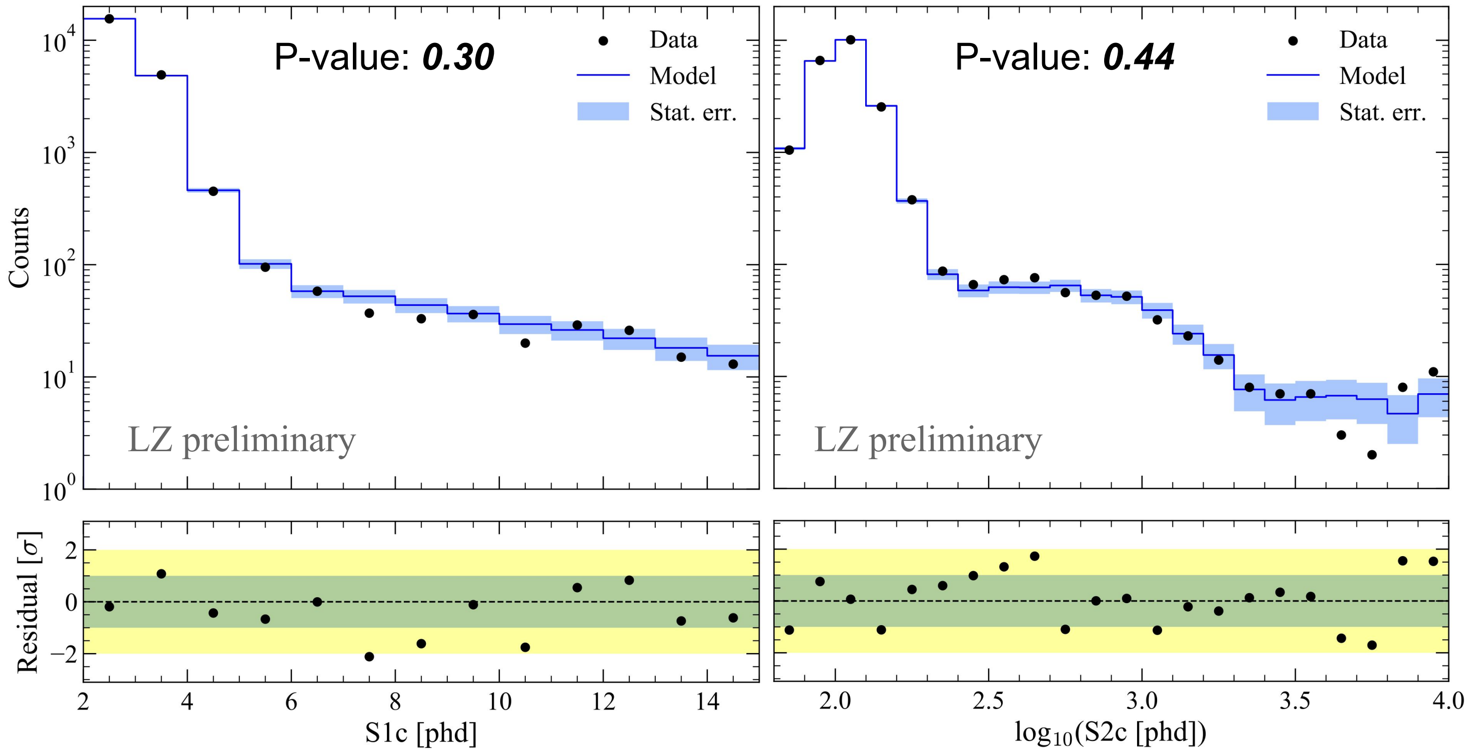
High-rate region below the ROI



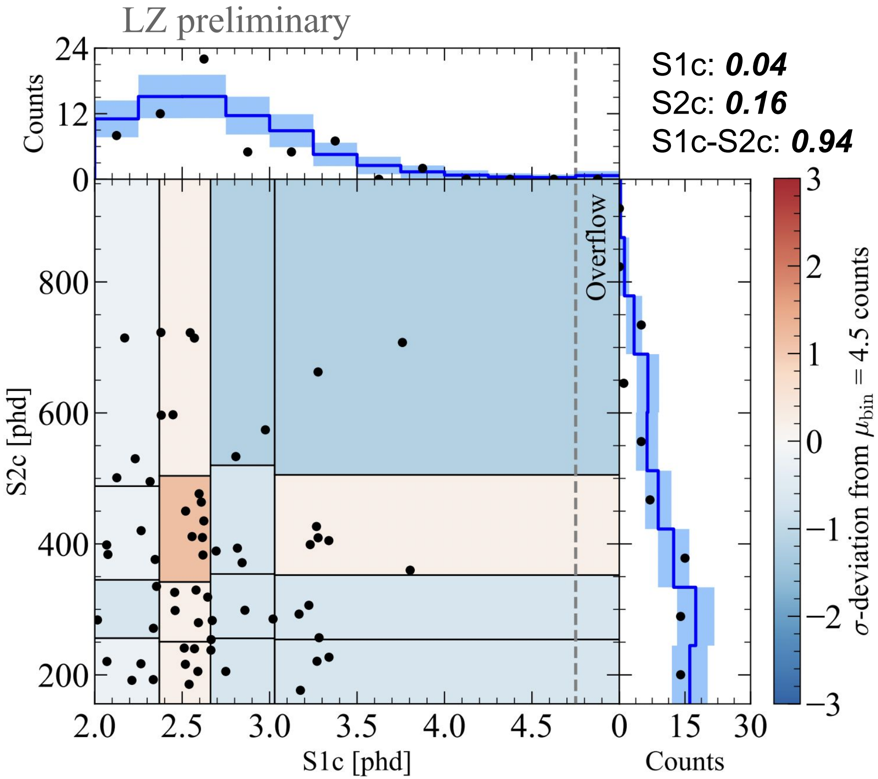
S1c: ***0.62***
S2c: ***0.33***
S1c-S2c: ***0.50***

Not indicative of S2-only search sensitivity due to different data selection / exclusion cuts

AmLi calibration normalization plots



AmLi calibration after final event selection



S1c: ***0.04***
S2c: ***0.16***
S1c-S2c: ***0.94***

Expected vs. observed counts in all validation regions

Validation	Data quality cut stage	Observed	Expected	Difference (σ)
High-rate	ROI (3.5–14.5 e^-) prior	169	180.6 ± 13.3 (stat.) ± 3.8 (sys.)	-0.84
	Below ROI ($< 3.5\ e^-$) prior	9152	$9139.6 \pm 26.0 \pm 13.0$	$+0.43$
	ROI post	8	$11.6 \pm 3.4 \pm 0.8$	-1.03
	Below ROI post	2270	$2189.9 \pm 41.3 \pm 14.2$	$+1.83$
AmLi	ROI prior	449	$423.5 \pm 20.4 \pm 9.9$	$+1.12$
	Below ROI prior	20646	$20660.0 \pm 23.9 \pm 18.3$	-0.47
	ROI post	61	$72.5 \pm 8.5 \pm 3.6$	-1.24
	Below ROI post	2795	$2761.0 \pm 49.0 \pm 10.9$	$+0.68$
WS2025	PDTs in ROI & FV post	56	$64.0 \pm 7.7\ ^{+1.6}_{-1.3}$	-1.04
	ROI prior	139	$130.6 \pm 11.1 \pm 1.4$	$+0.74$
	Below ROI prior	2107	$2105.7 \pm 21.0 \pm 3.1$	$+0.06$
	ROI post	9	$6.8 \pm 2.6 \pm 0.3$	$+0.86$
	Below ROI post	427	$437.6 \pm 19.1 \pm 7.9$	-0.51