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KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

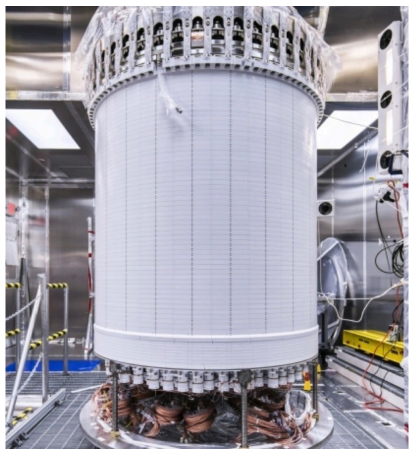
Backgrounds in the LUX-ZEPLIN (LZ) Experiment

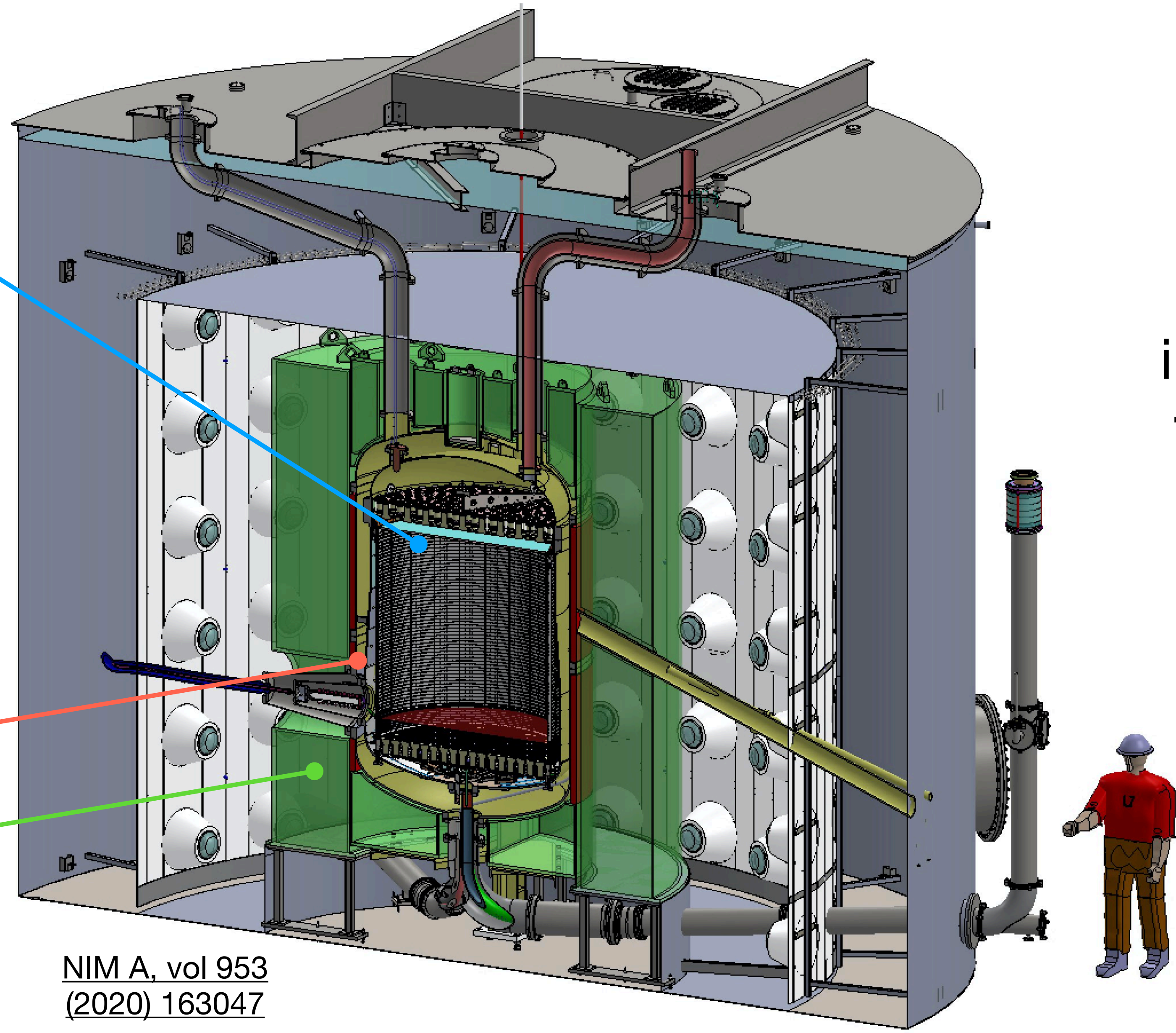
Ann Wang
Stanford/SLAC
On behalf of the LZ Collaboration

TeVPA 2024

The LZ Experiment

Liquid Xe TPC





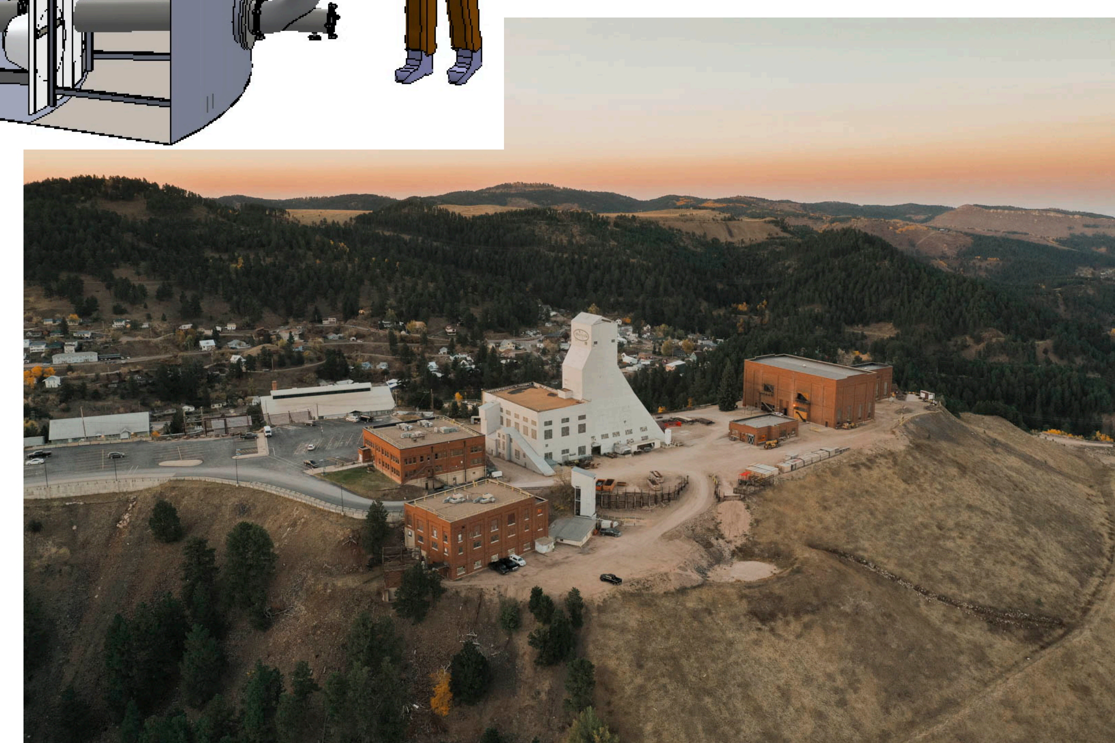
Skin Detector

Gadolinium Liquid Scintillator Outer Detector

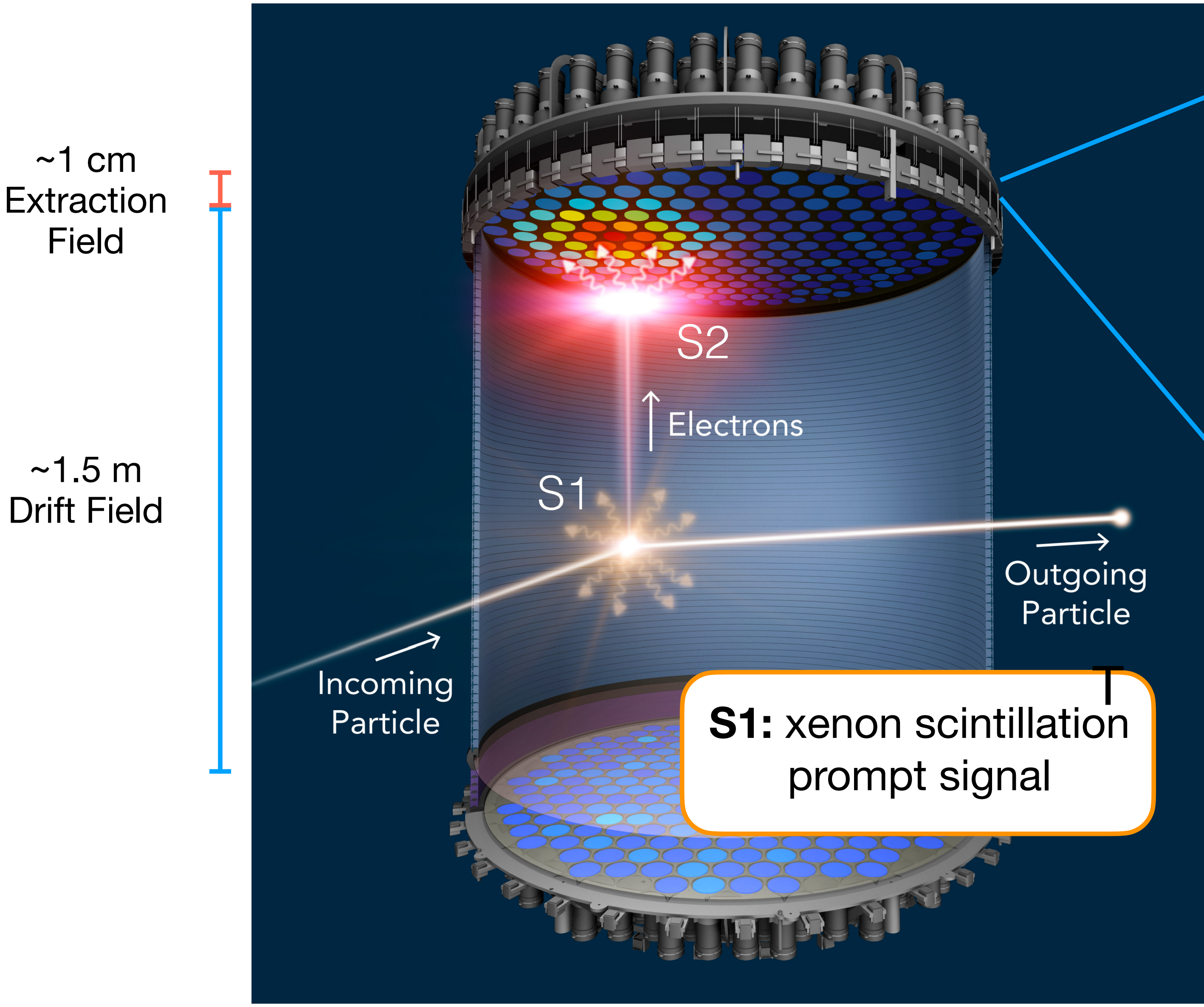
NIM A, vol 953 (2020) 163047

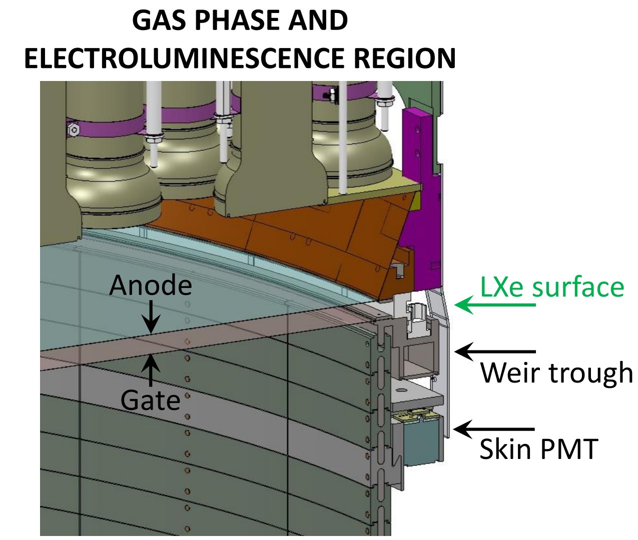
Designed to look for dark matter interactions with **7 tonnes of xenon**

Located ~ a mile underground at the Sanford Underground Research Facility (SURF) in South Dakota

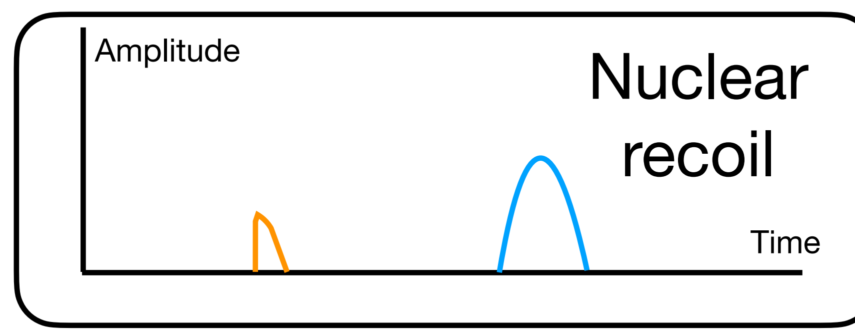


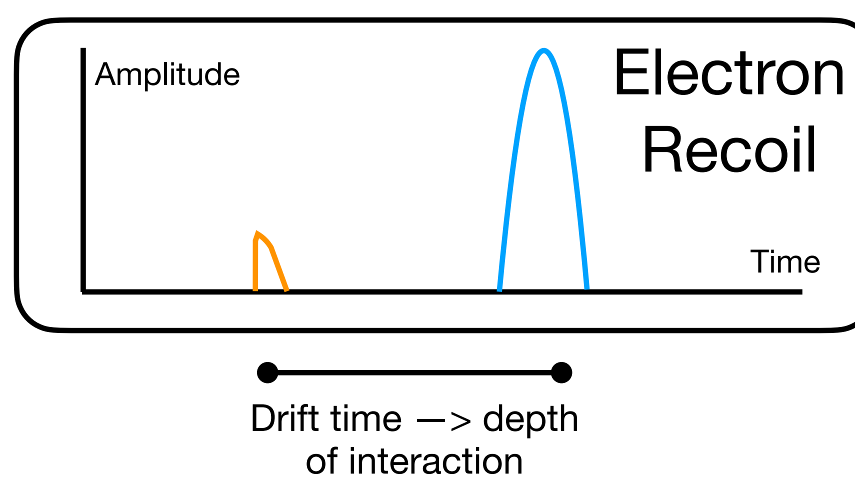
Detection Concept





S2: electrons drift to higher field region —> produce electroluminescence light





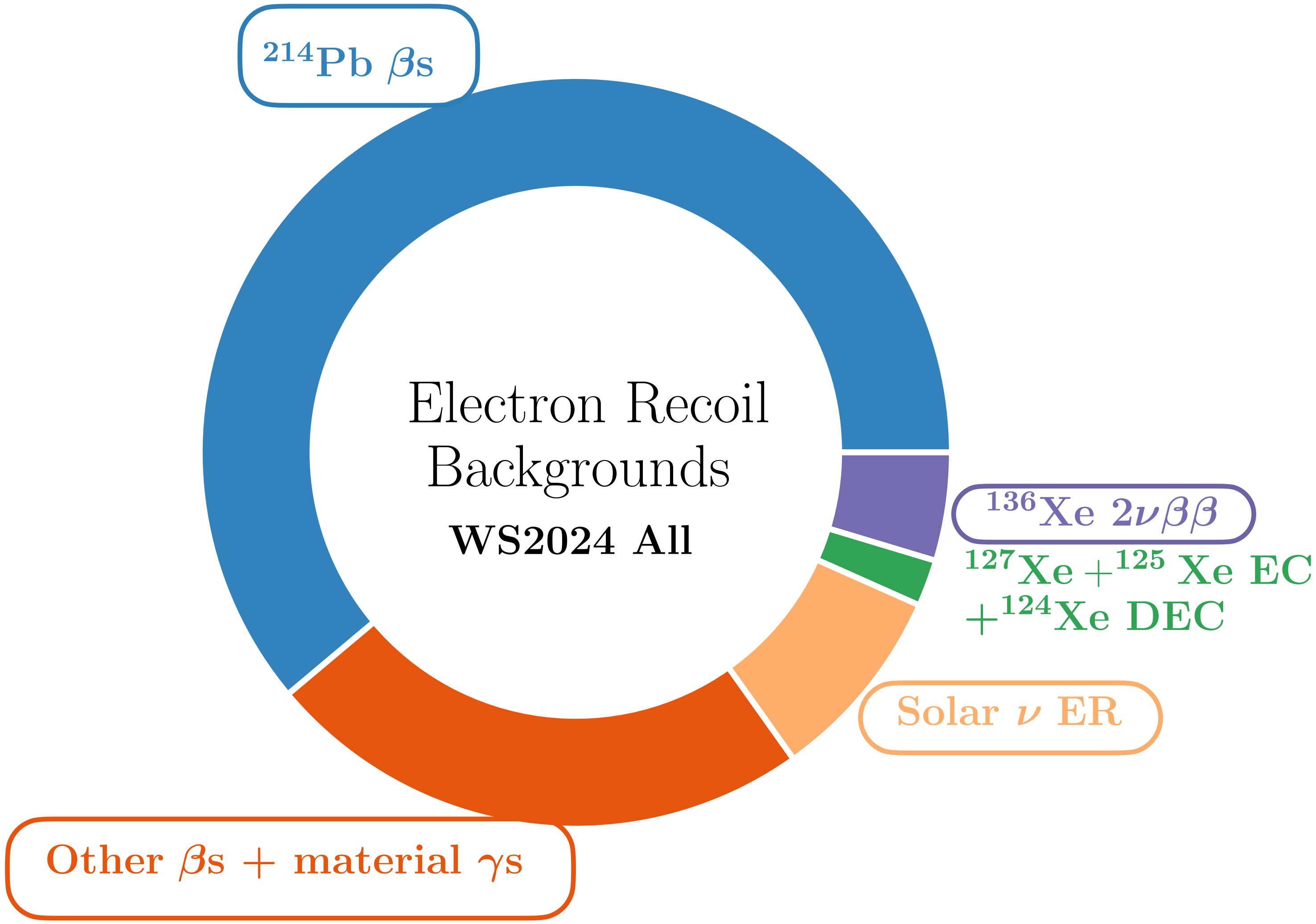
- Two signals: **S1 and S2**
- Ratio of S1 to S2 signal probes interaction type: *electron vs nuclear recoil discrimination*

Backgrounds

- Rare event search: ~10 dark matter events/yr
- WIMP interactions —> nuclear recoil signal
- **Important to control & quantify backgrounds!**

Background composition:

- **Electron recoil** backgrounds, including:
  - Betas & gammas including Rn chain decays
  - Solar neutrino interactions and Xe-136 double beta decay



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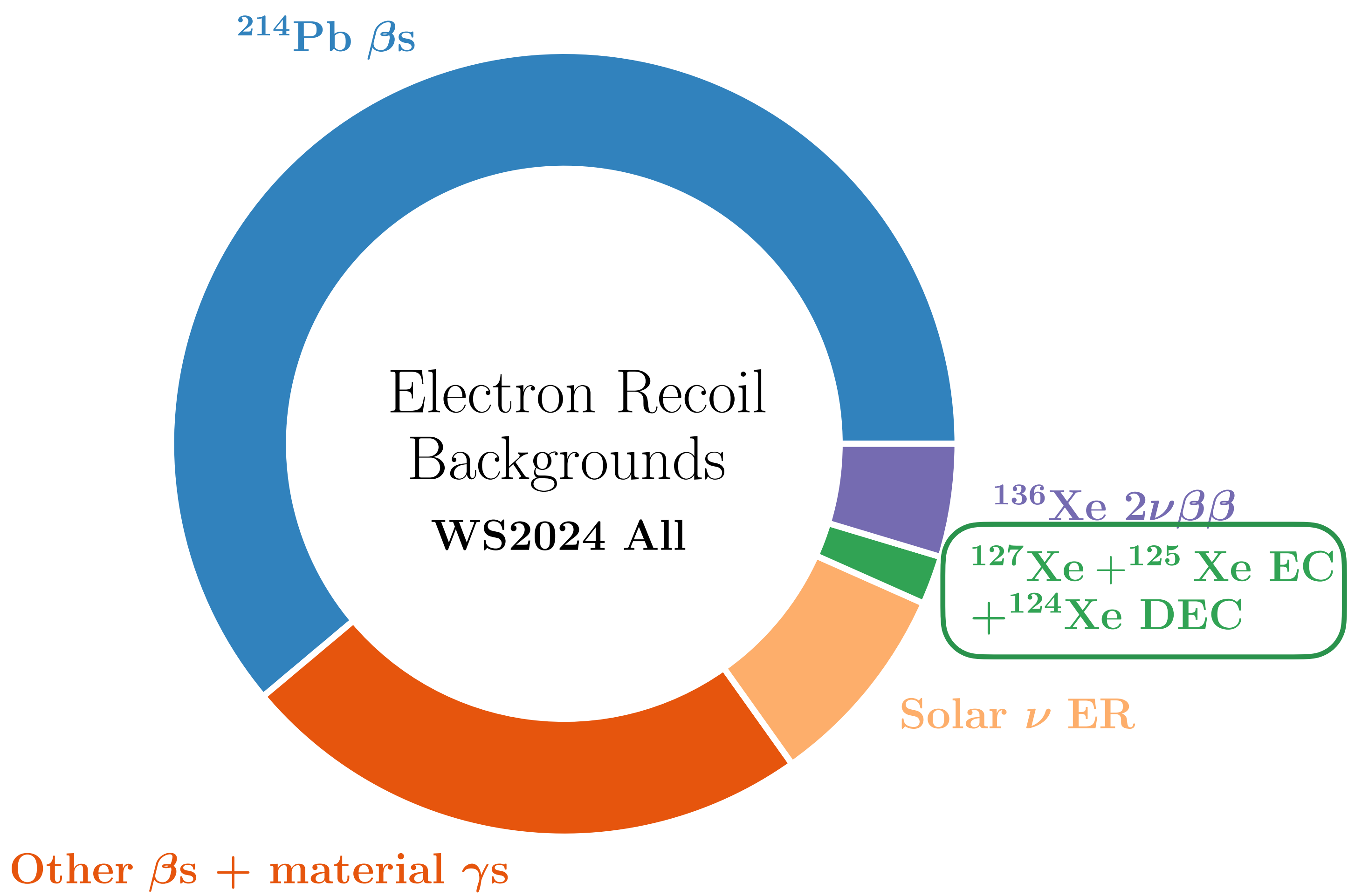
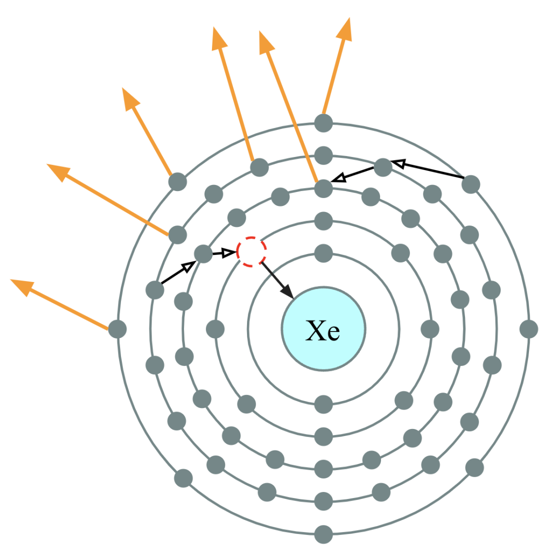
    - Xe-127 and Xe-125 EC
    - Xe-124 *double* EC: **half-life of 1.1×10^{22} years!**





See back-up & Scott Haselschwardt's talk for more details

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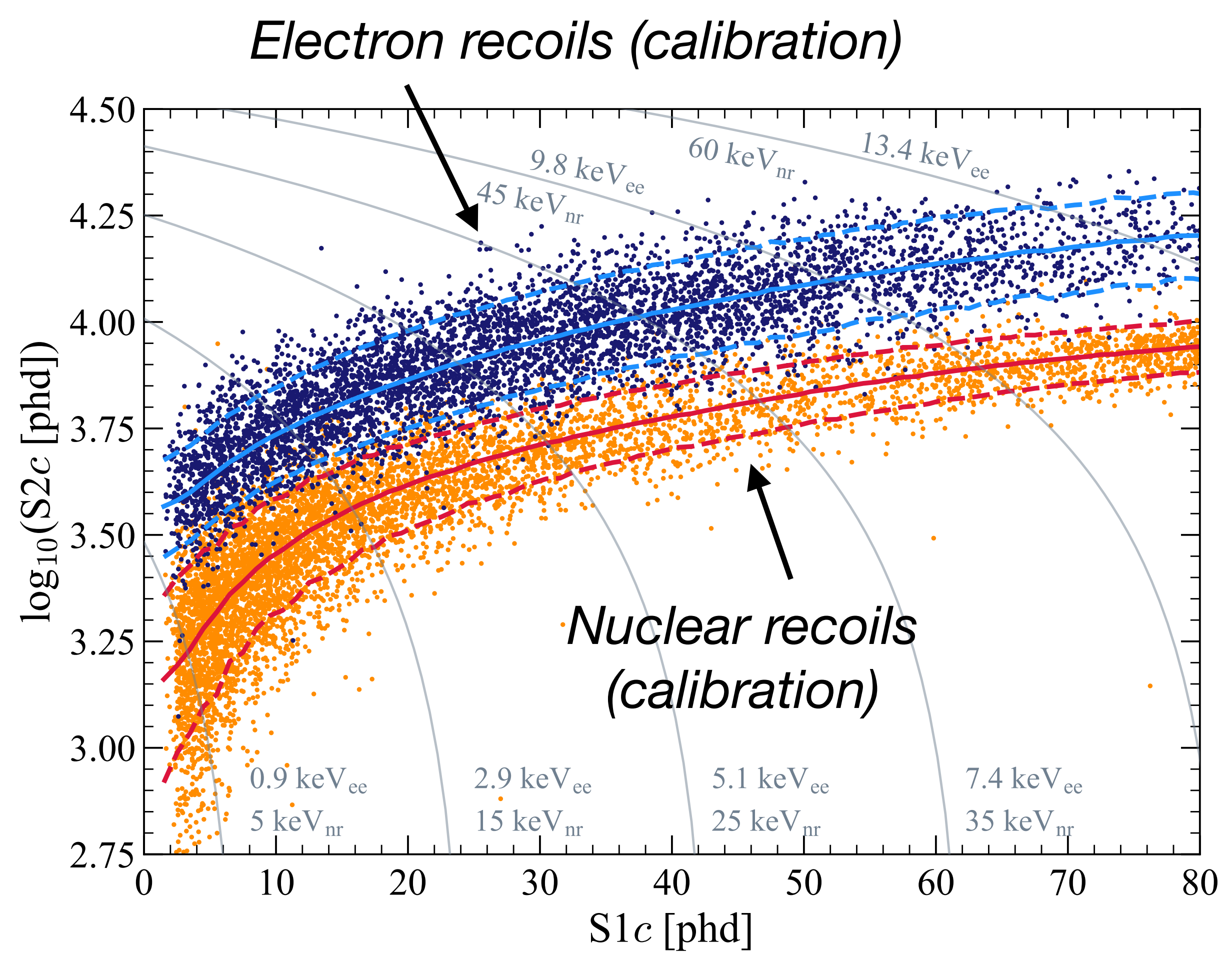

LZ First DM Results
PRL 131, 041002 (2023)

- **Nuclear recoil** backgrounds, including:
  - Neutrons, neutrinos
- Spurious instrumental effects forming **accidental backgrounds**

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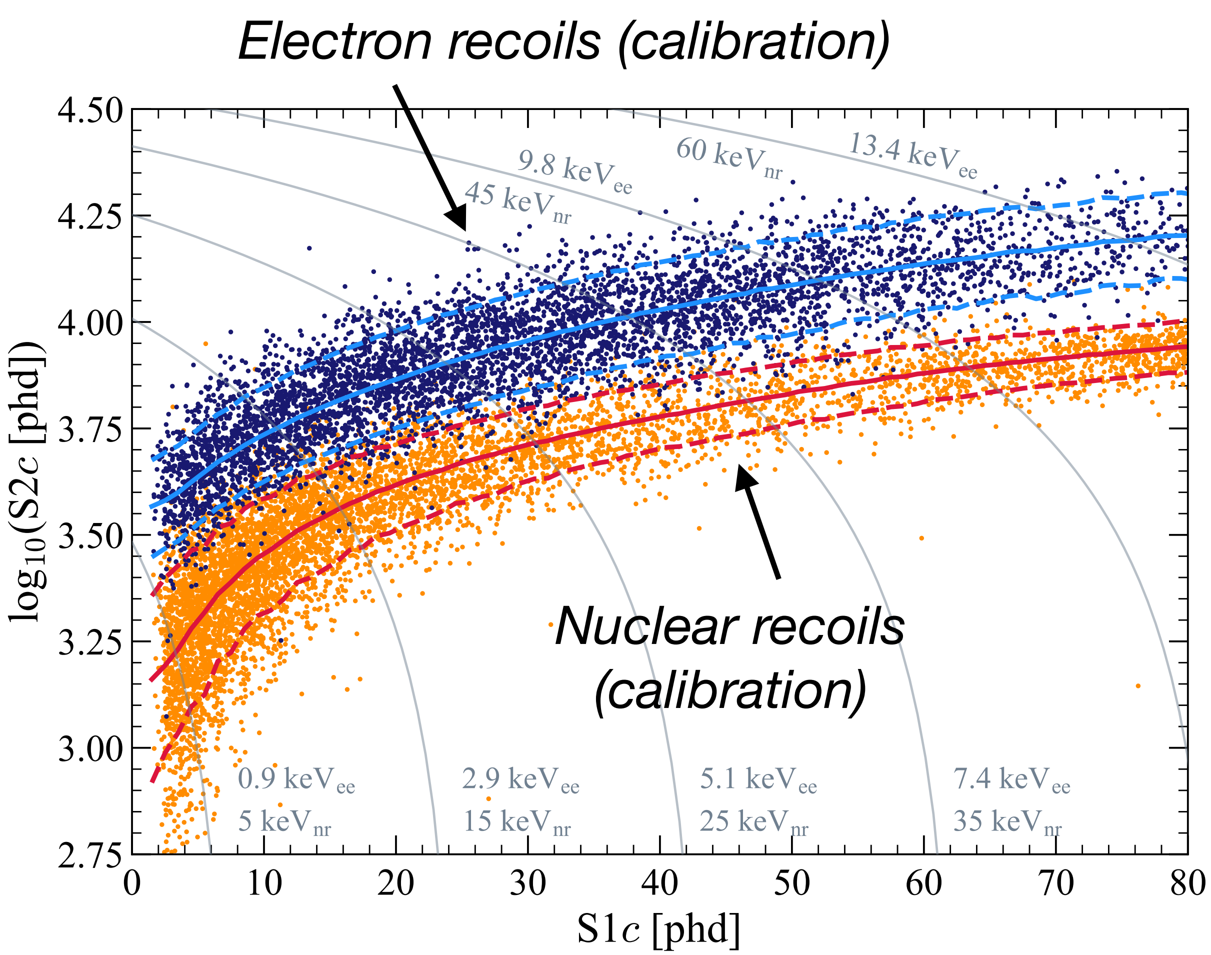
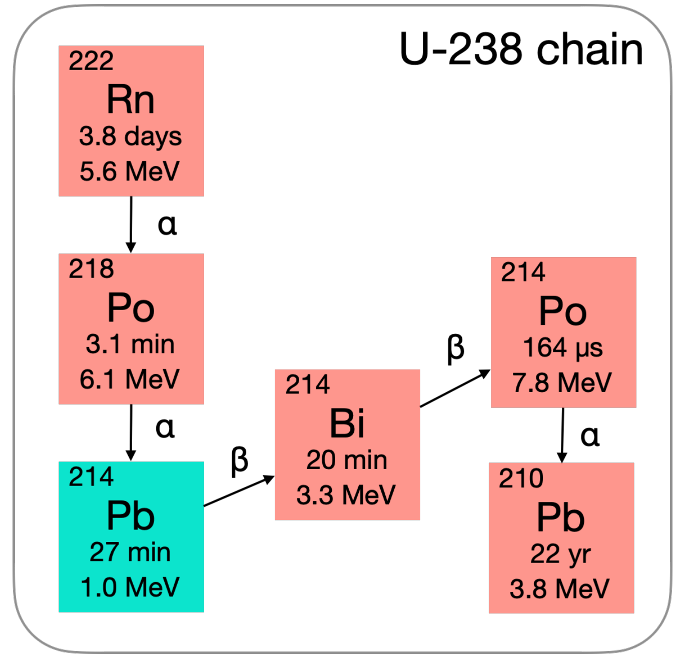


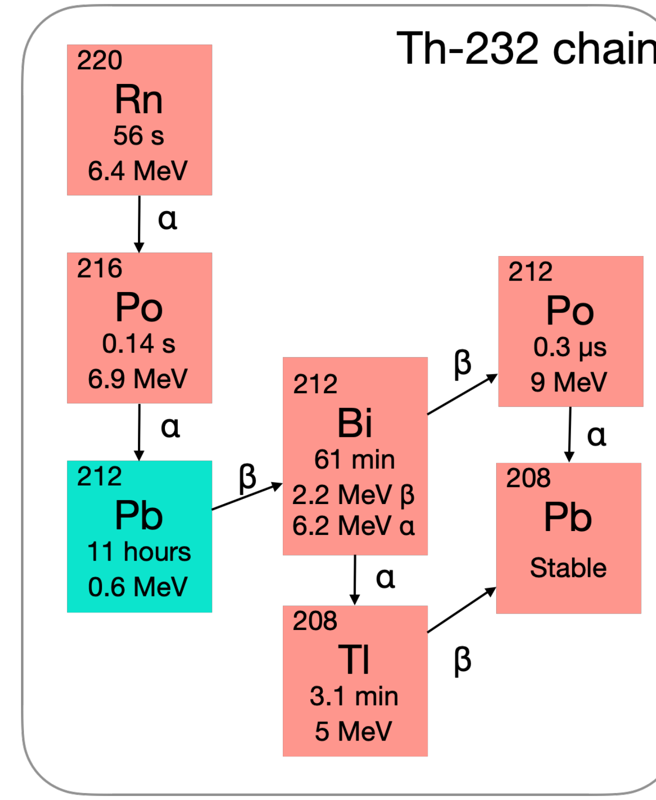
LZ First DM Results
PRL 131, 041002 (2023)

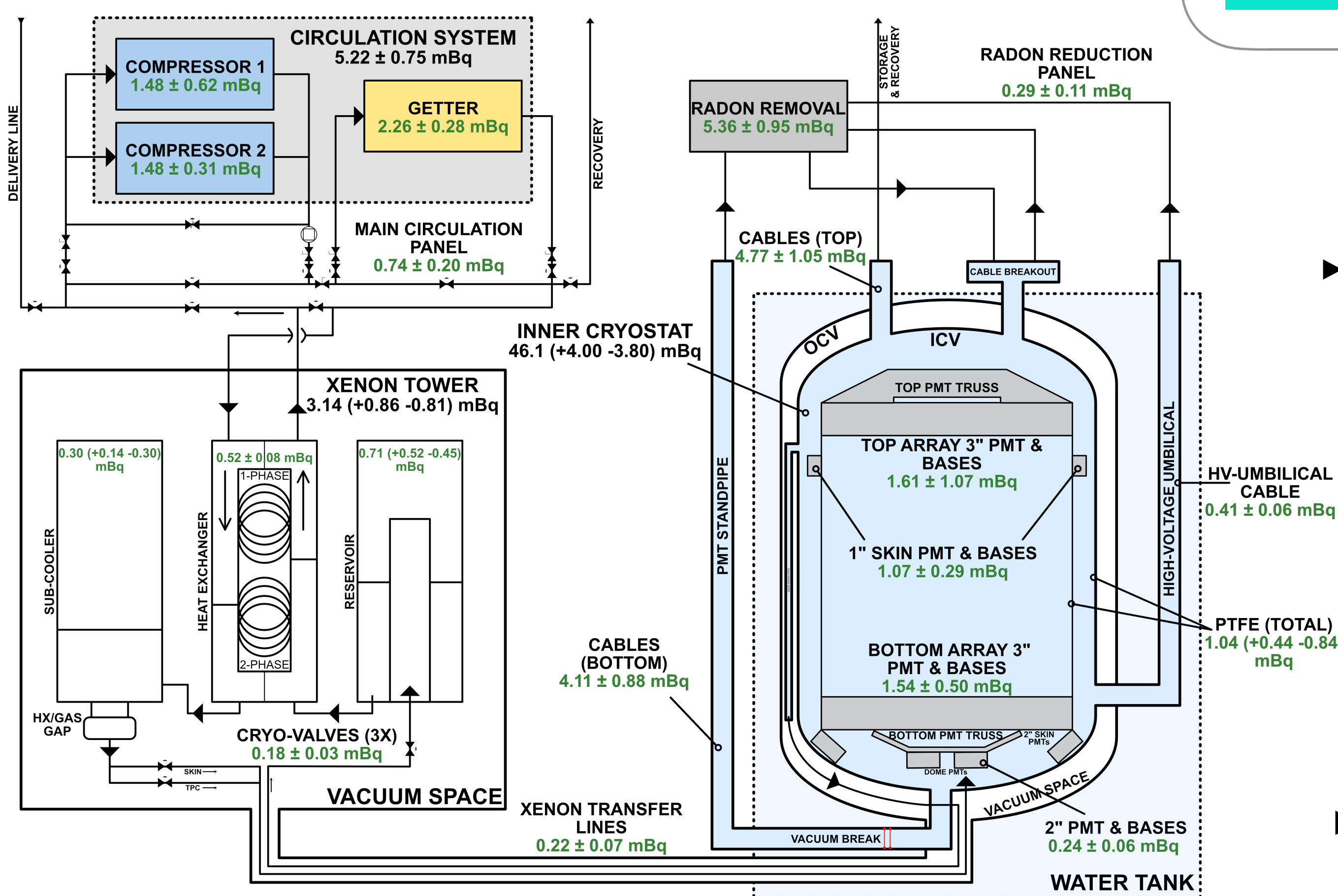
I'll focus on a few key backgrounds

Radon background

- **Major background:** beta decays from U-238 (Rn-222) and Th-232 (Rn-220) chains
- Largest contribution: **Pb-214 naked betas**
  - Rn-222 diffuses further than Rn-220



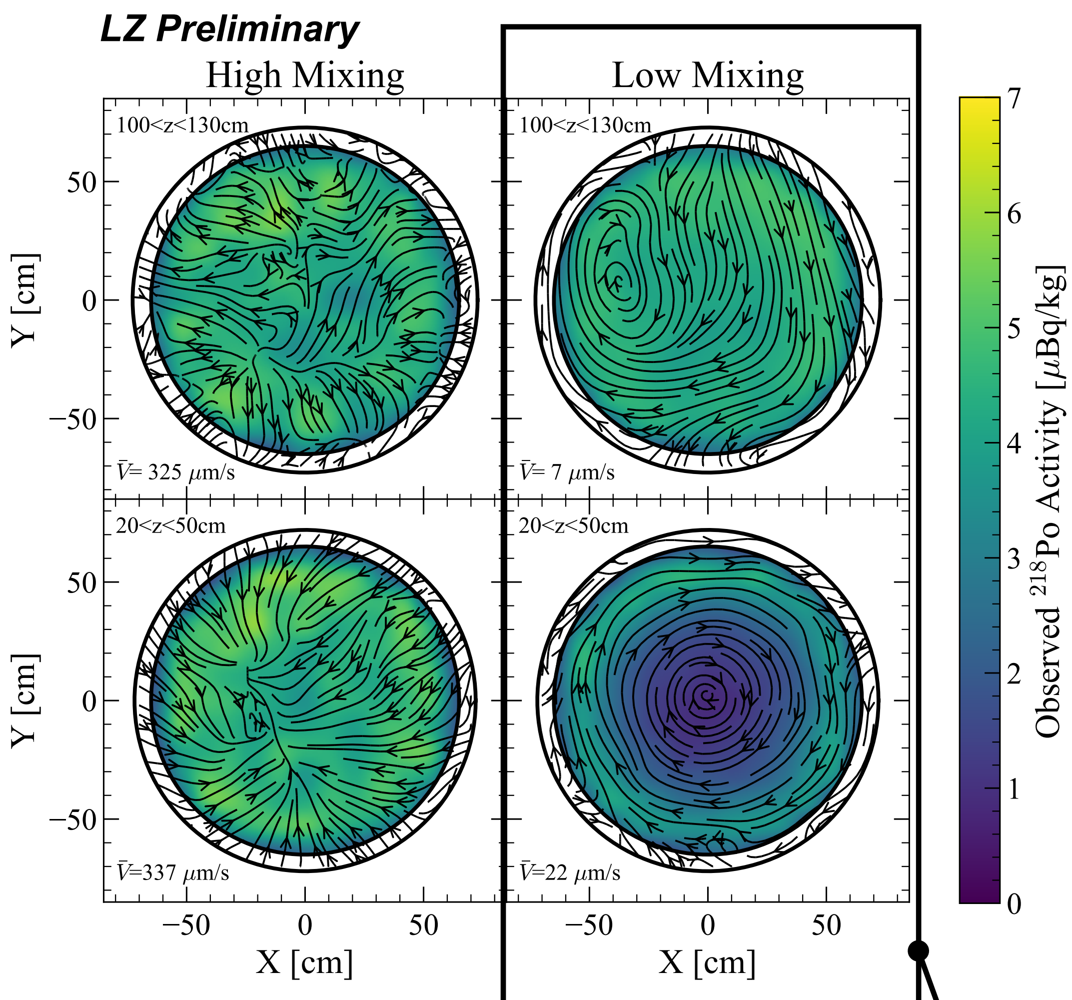


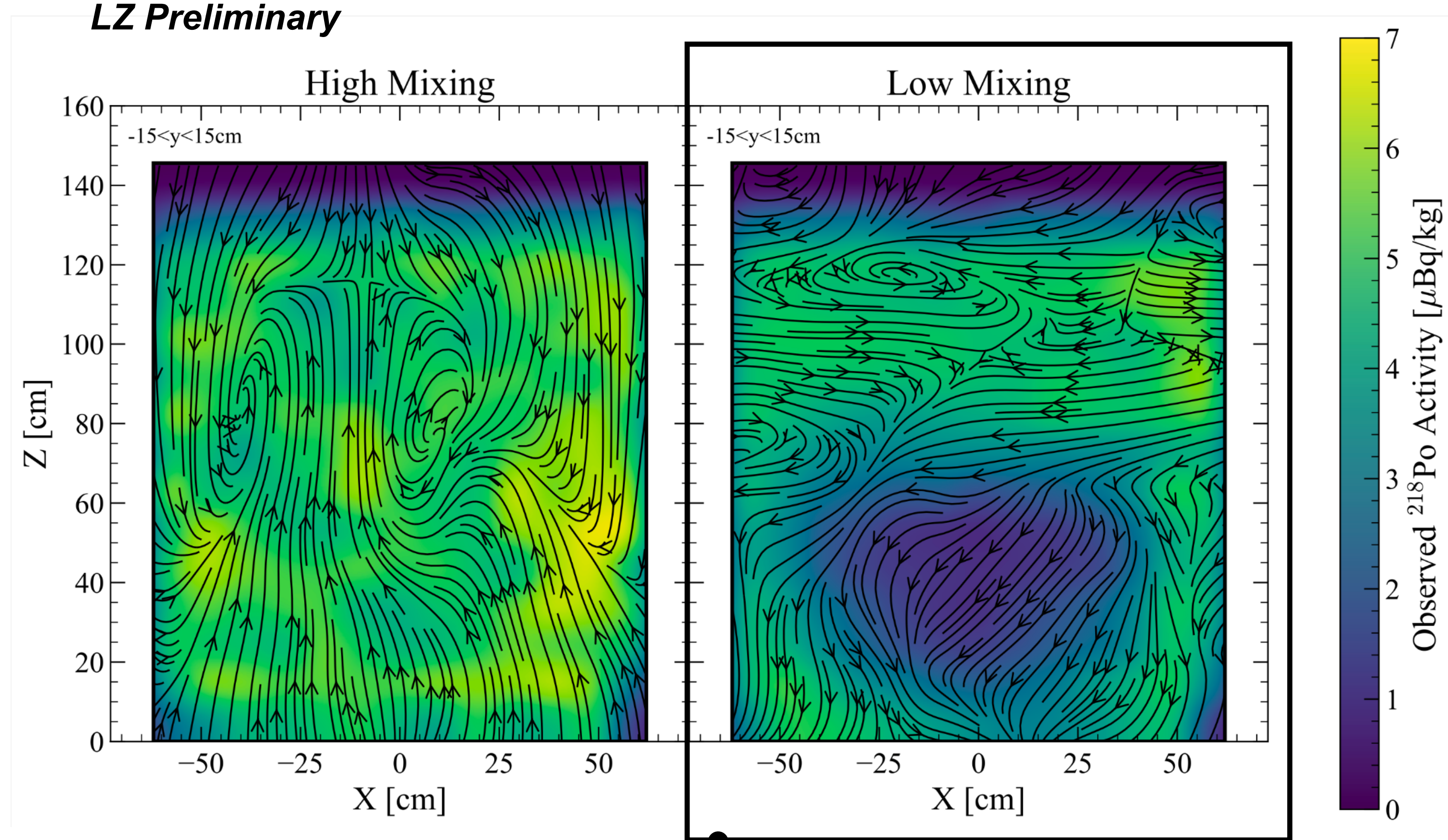


- Extensive mitigation:
  - **Screening** of detector materials
  - **Radon-reduced clean room** (~2000x reduction) at the SURF Surface Assembly Laboratory (SAL)
  - **In-line Radon Removal System** (iRRS)
- Resulting **Pb-214 activity in TPC ~ 4 μBq/kg**

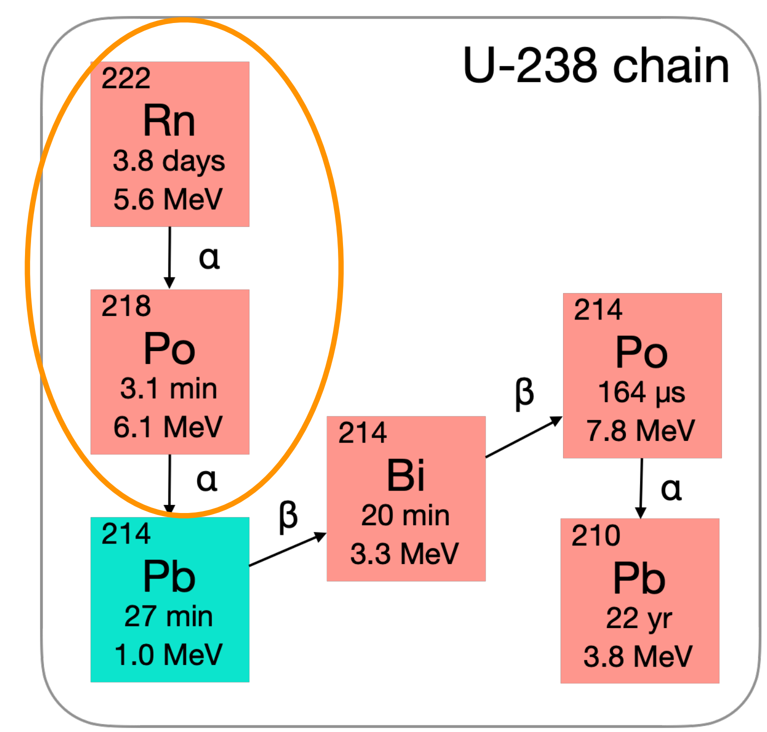
LZ radioactivity & cleanliness controls program
Eur. Ph. Journal C, vol. 80, 1044 (2022)

Radon Tagging



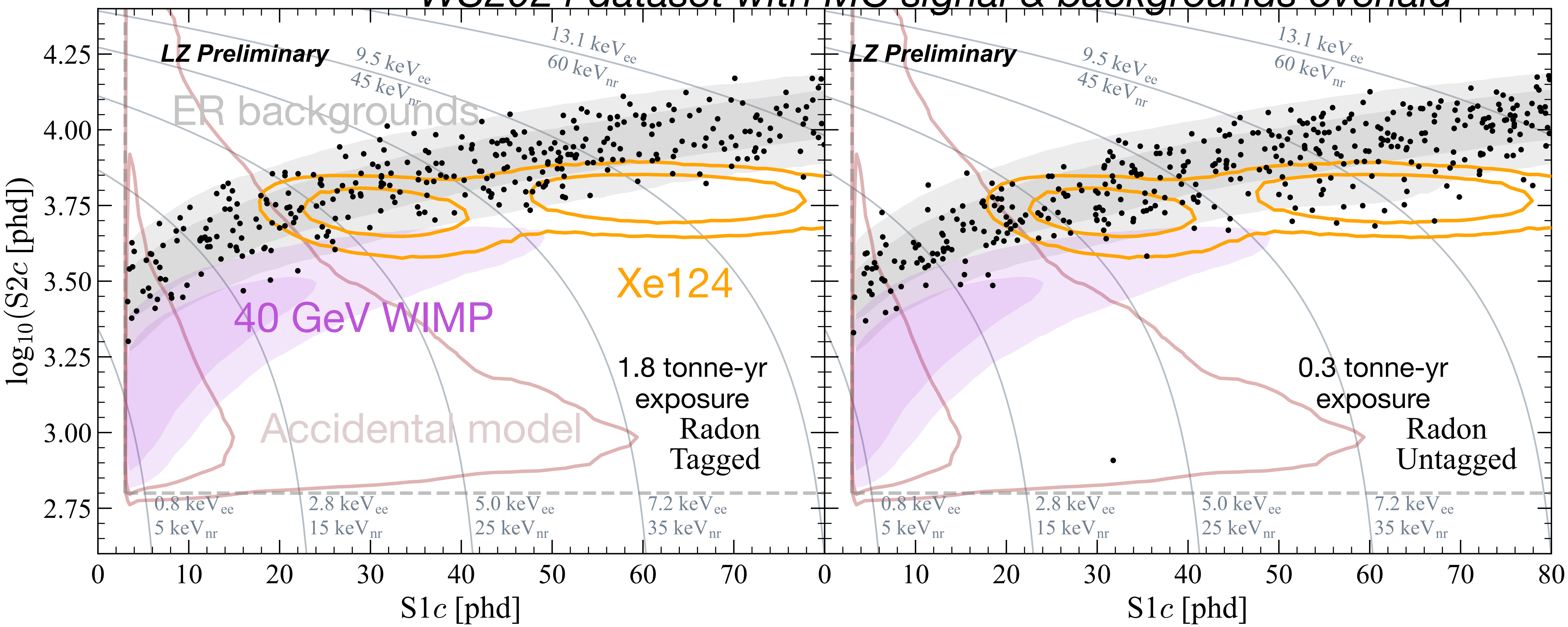


- Operational control can create **predictable flow state:**
  - Velocity ~ O(10 μm/s)
  - **Flow mapping** with Rn-222/Po-218 pairs
  - Flow map can be used to **predict the path of Pb-214** and isolate its decays



Radon Tagging

WS2024 dataset with MC signal & backgrounds overlaid

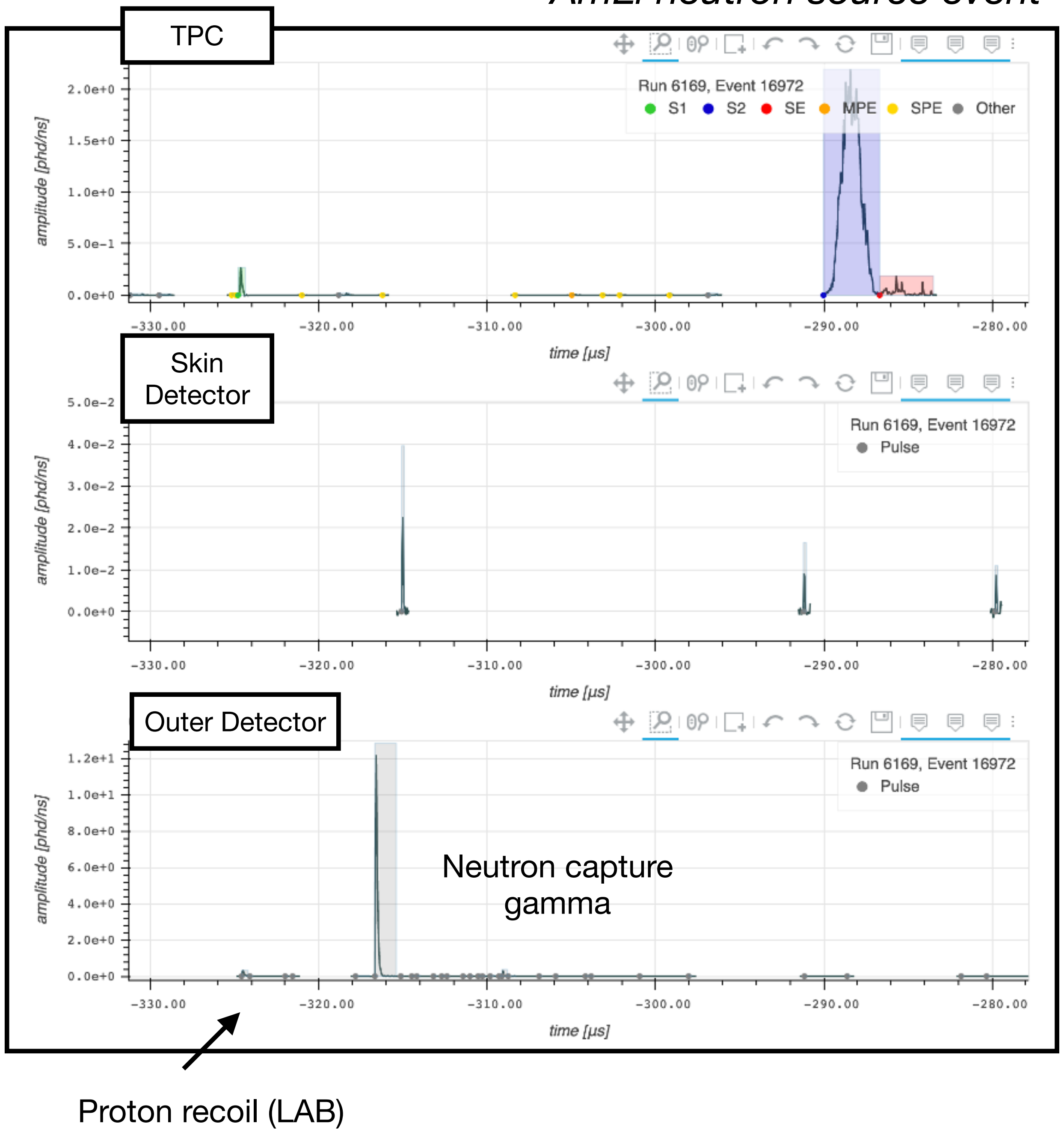


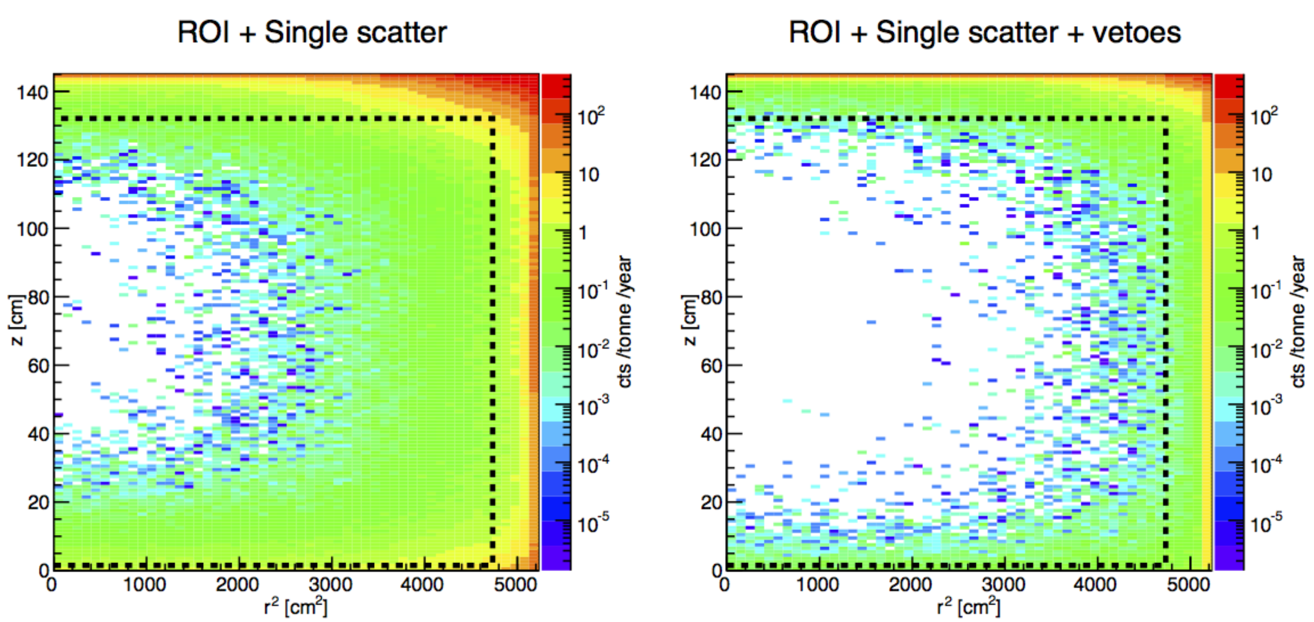
- Pb-214 tag efficiency: 60 +/- 4% efficiency in Low Mixing state
  - Efficiency determined high energy alpha fits
- Tagged events are not removed, but included in the likelihood as a separate bin
  - Useful sideband to understand backgrounds
- Untagged exposure with stable flow has a remaining Pb-214 activity of **1.8 +/- 0.3 μBq/kg** —> 2x reduction!

Neutron background

- Neutron sources:
  - Radioactivity in detector components & cavern
  - Muon-induced sources
- Dedicated Outer Detector (OD) with gadolinium-doped liquid scintillator to veto neutrons
  - High neutron capture cross-section

AmLi neutron source event





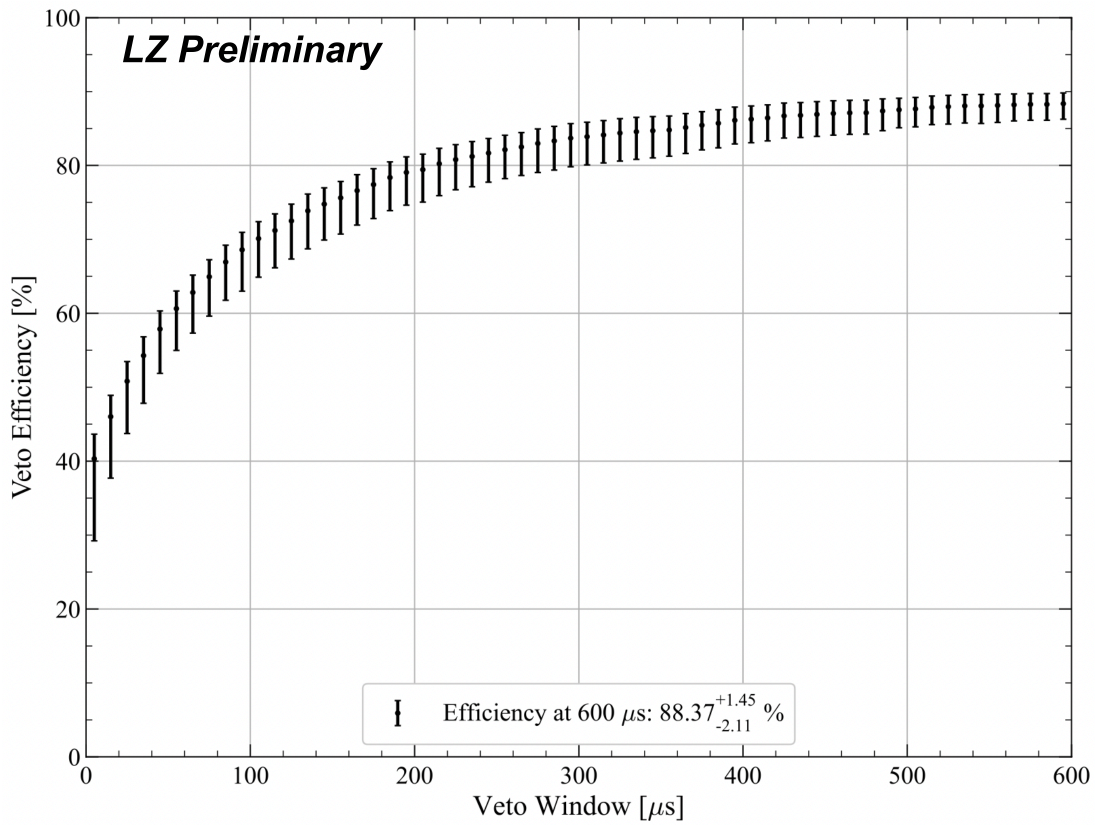
Simulated NR background (including ER leakage)

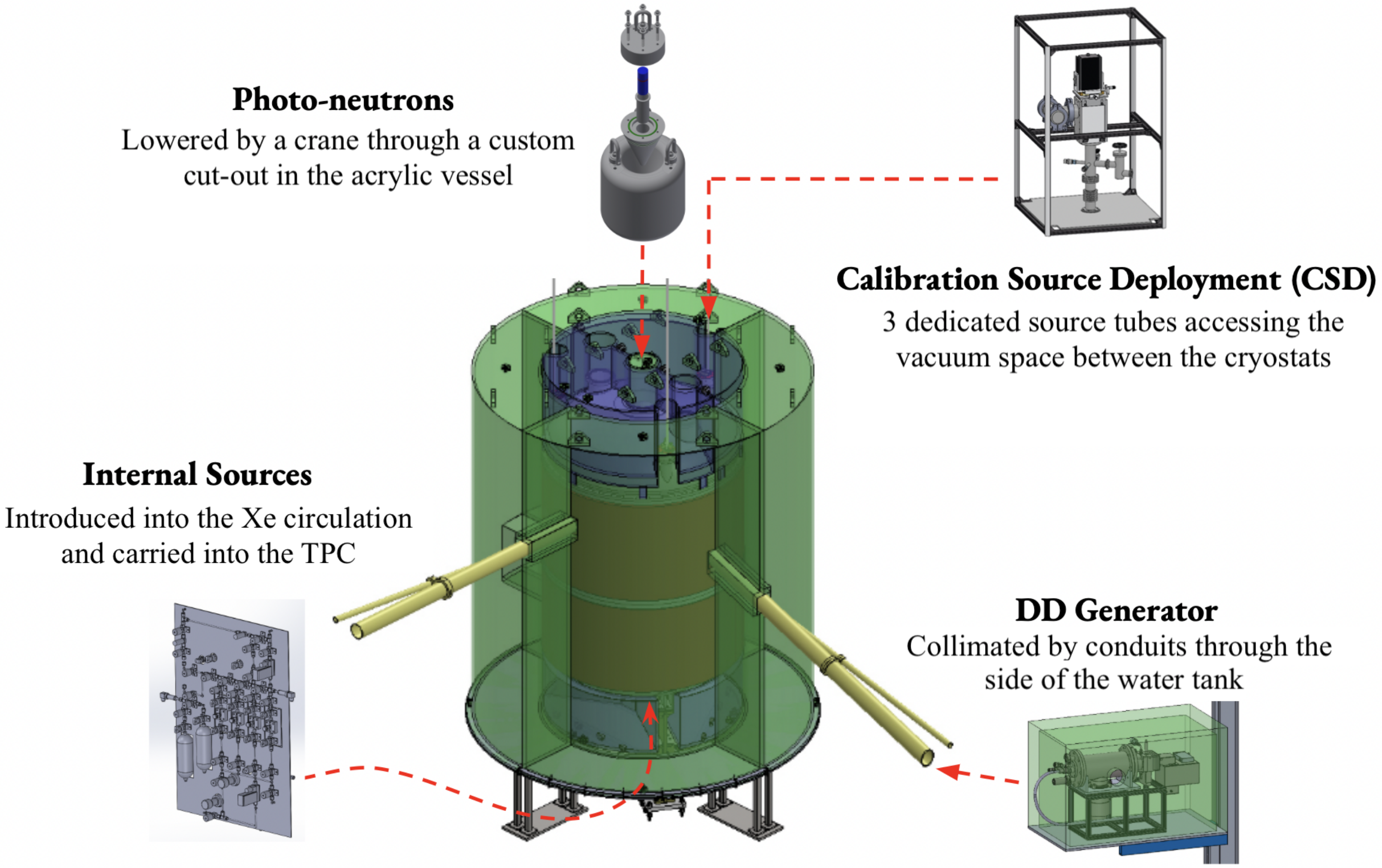
LZ TDR LBNL-1007256

Neutron veto

- Use neutron calibration sources deployed in CSD system to understand veto efficiency
- *AmLi veto efficiency:* **89 +/- 3%**
- *Background neutron veto efficiency* with AmLi measurement input**: 92 +/- 4%**
- Can also use veto tag to construct sideband which constrains neutron rate
- Best-fit neutron counts in WS2024: **0.0 +/- 0.2**

LZ Calibrations paper
arXiv:2406.12874





Accidental backgrounds

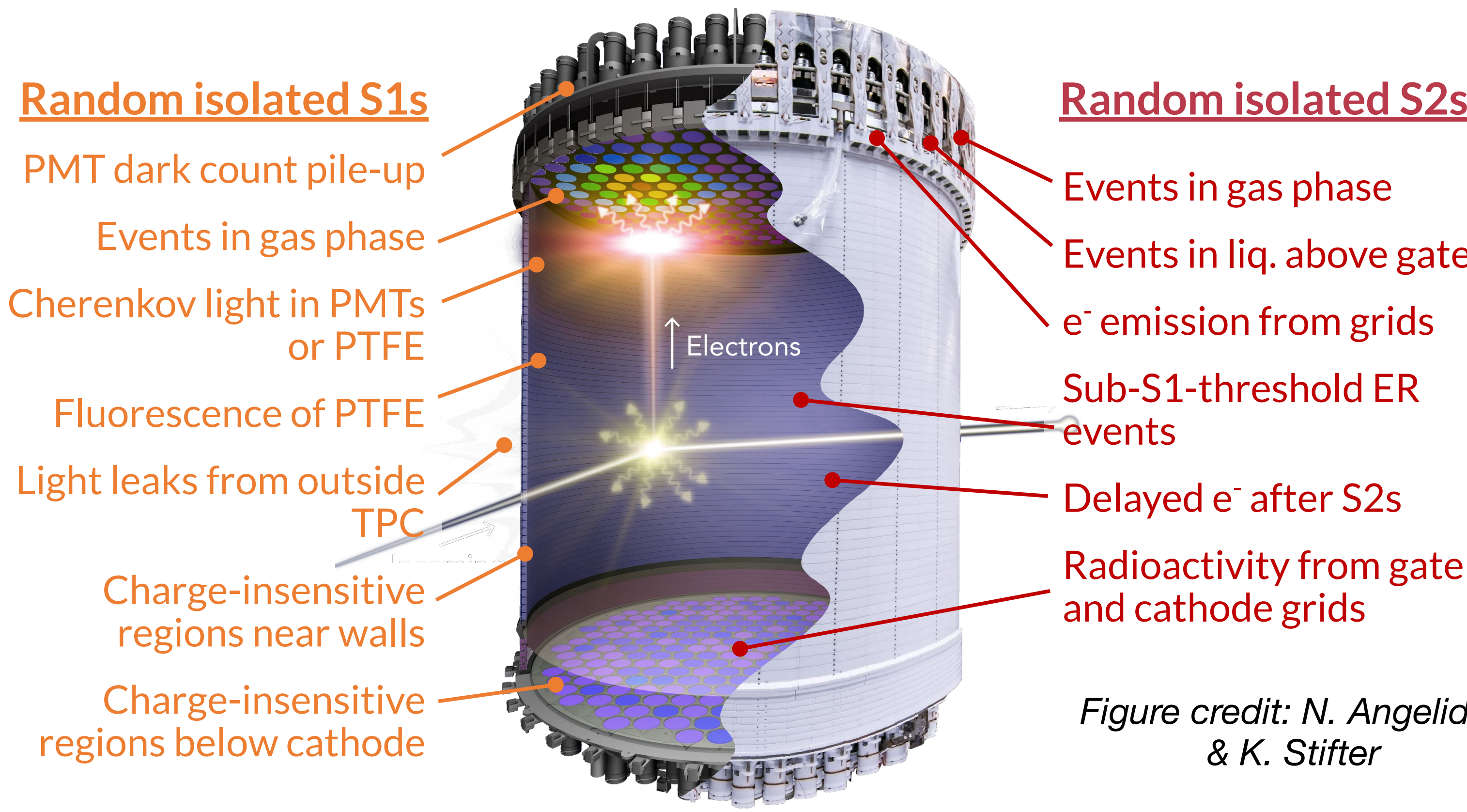
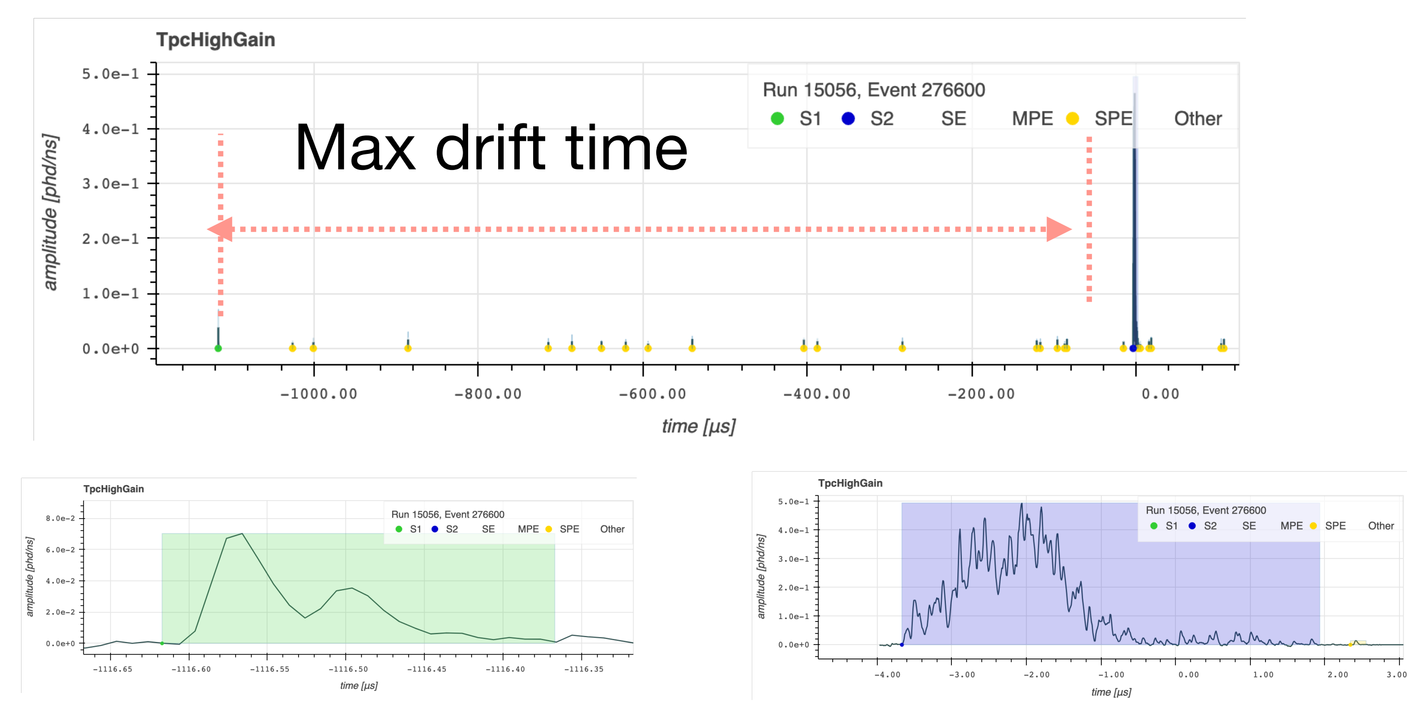


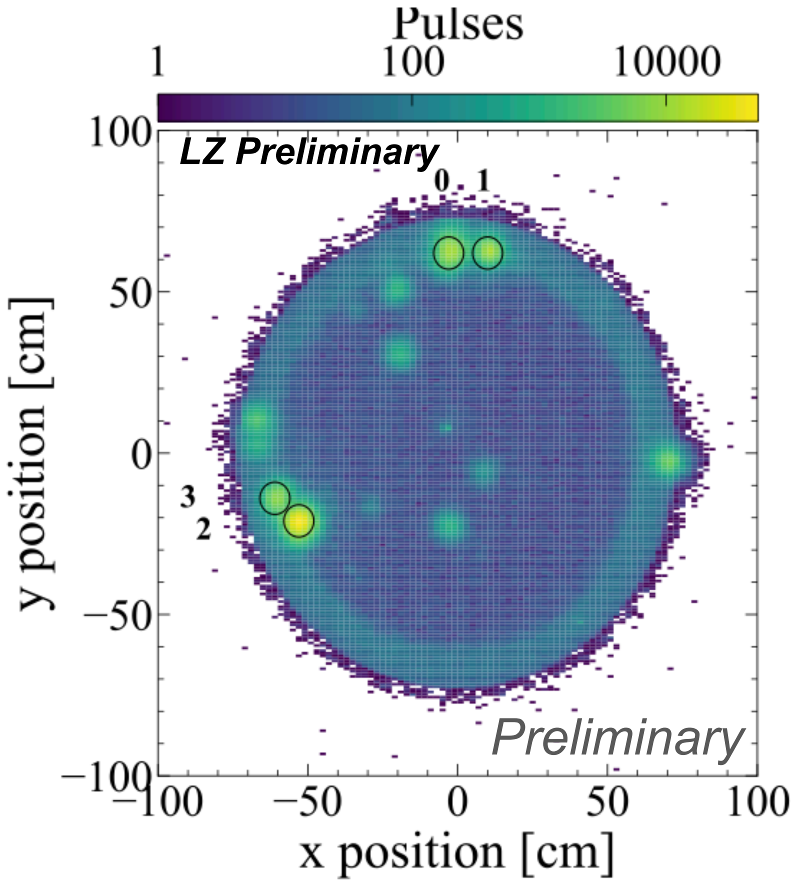
Figure credit: N. Angelides & K. Stifter

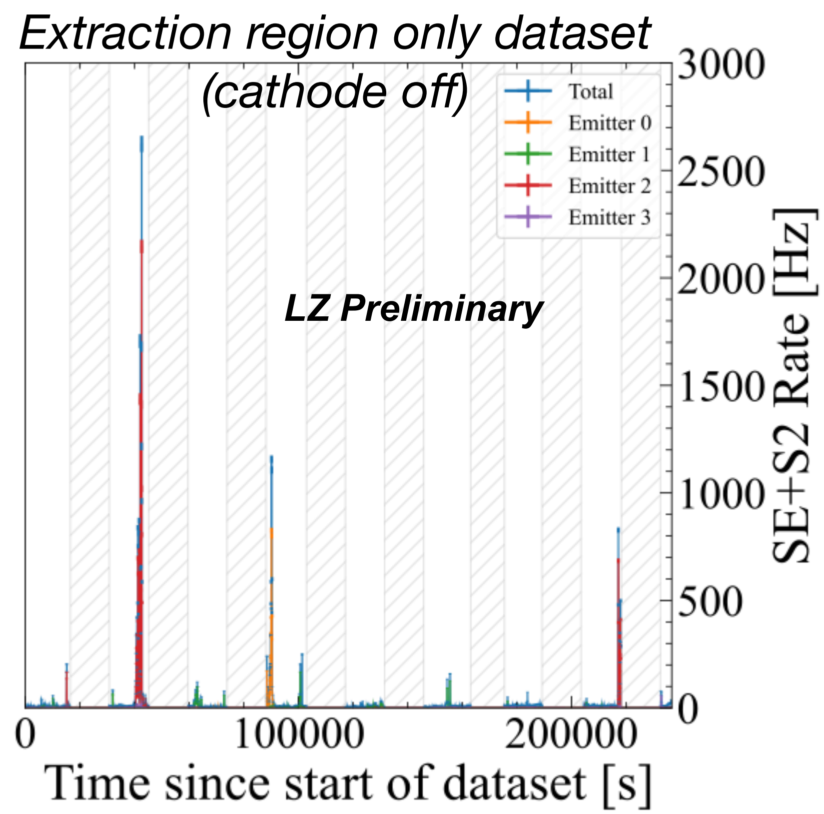
- Many sources of spurious S1s and S2s
- Can randomly pair together within a drift time—> **Accidental S1-S2 event**



- Low energy background
- Spurious S2s are a key background for low energy S2-only searches!

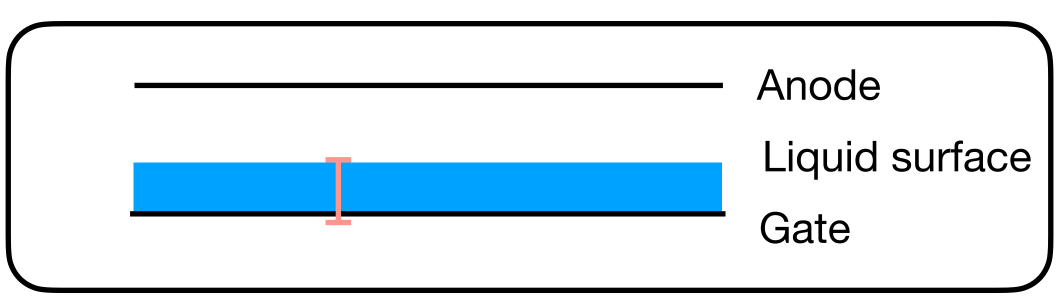
Accidental backgrounds: grid emission

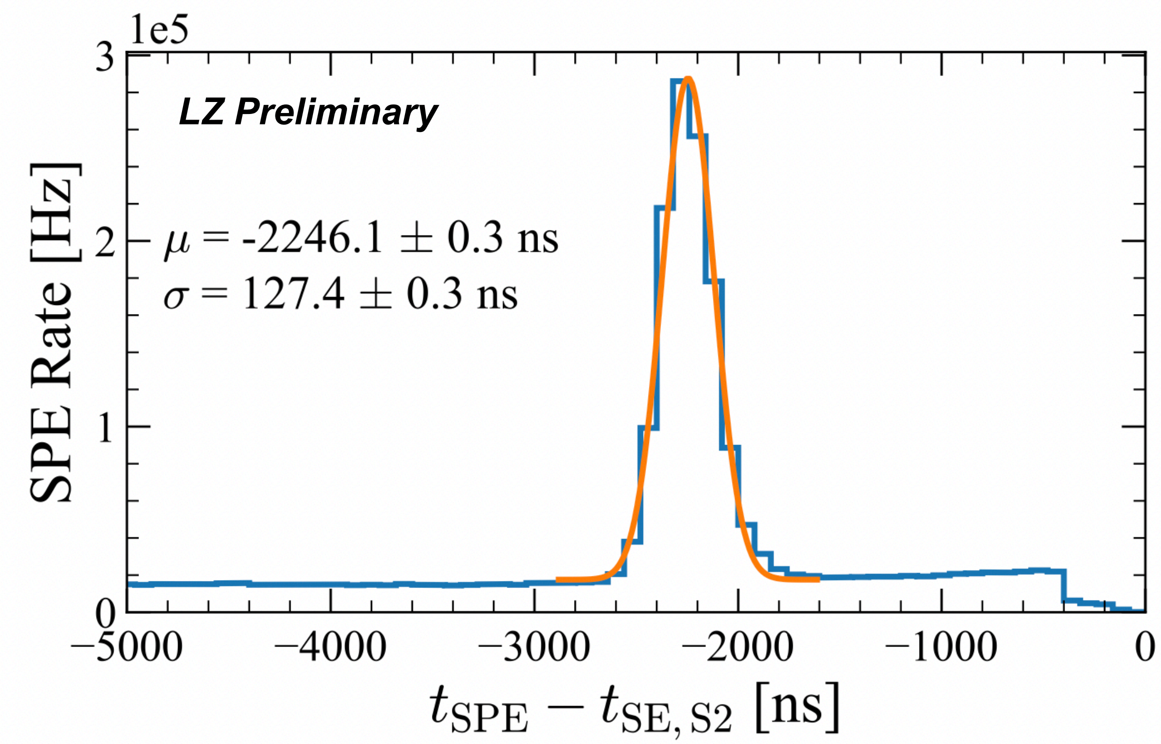




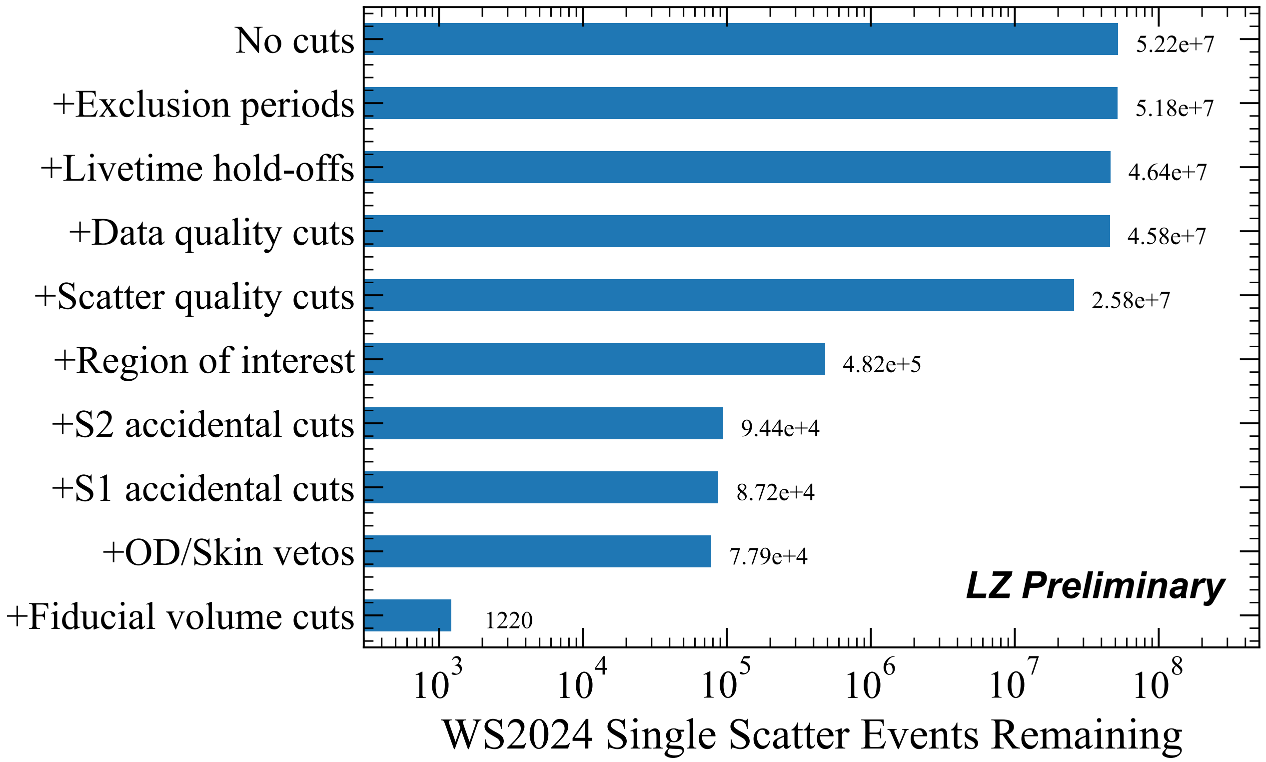
- Example of spurious S2 source: “hotspots”, or localized electron emission
- S2 rates spike in hotspots

- Likely origin: gate electrode
  - See photon ~2.2 us before S2, corresponding to drift time between gate and liquid surface

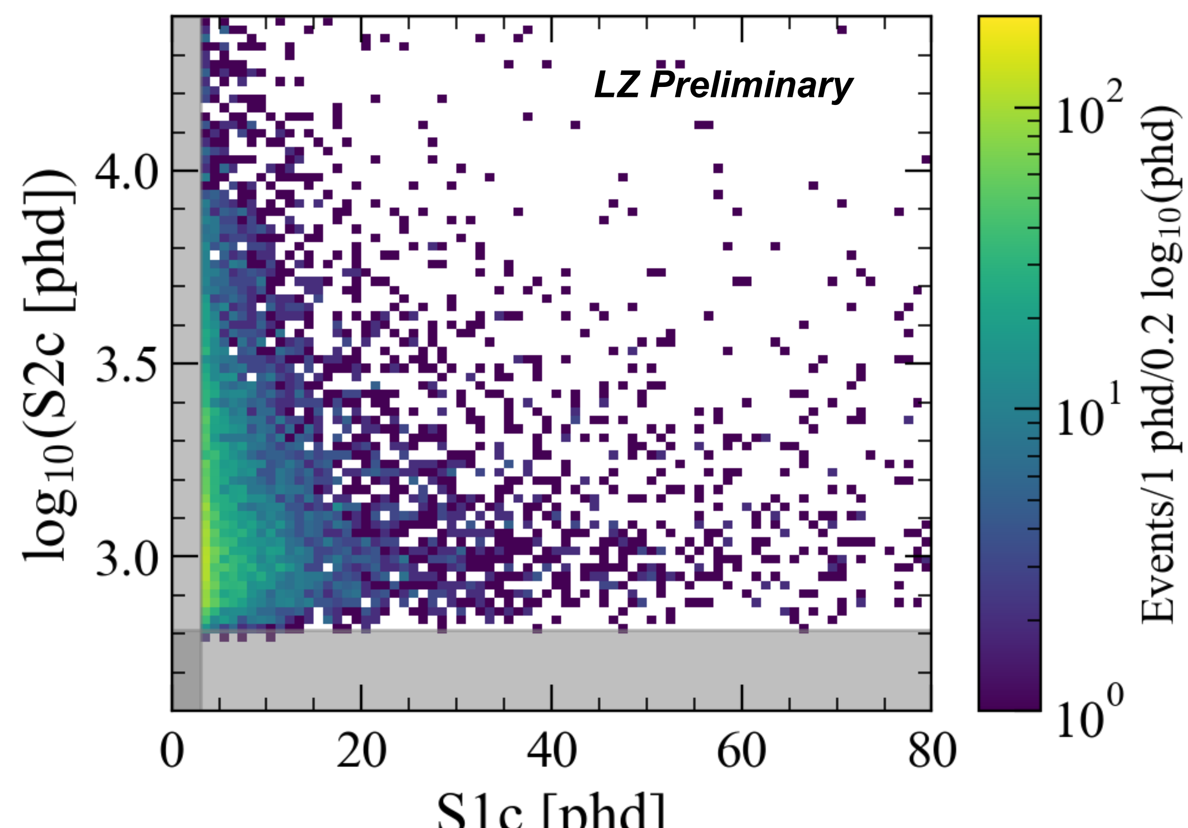




Accidental modeling



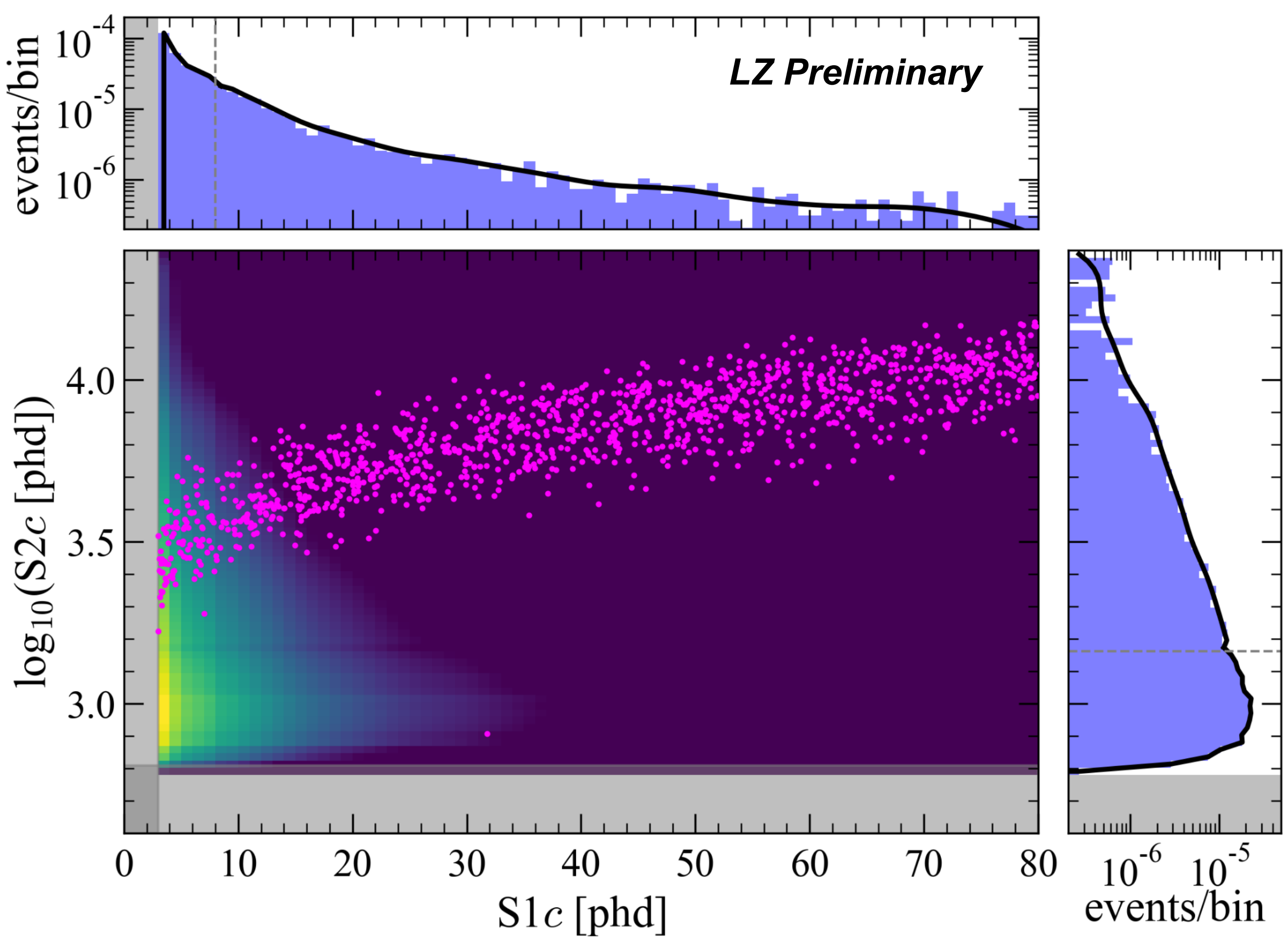
- **Dedicated cuts** to target anomalous signatures remove ~99.5% of accidentals
- Cuts were tuned on calibration data & sidebands
- Remaining events are **modeled** by producing “Chopstitch” events from spurious S1s and S2s from data —> **generate PDF**
    - Events combined at waveform level

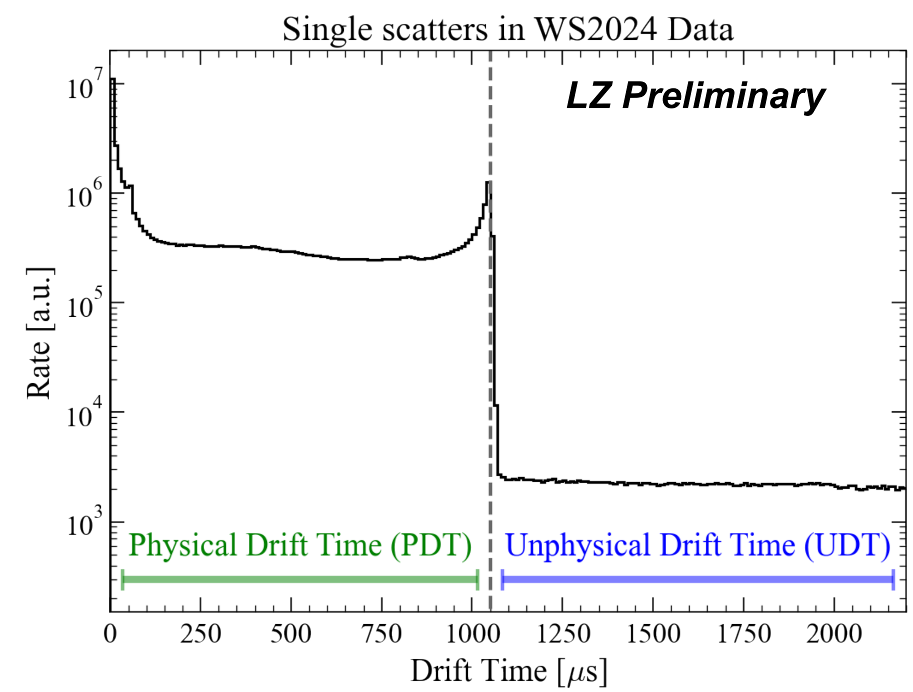


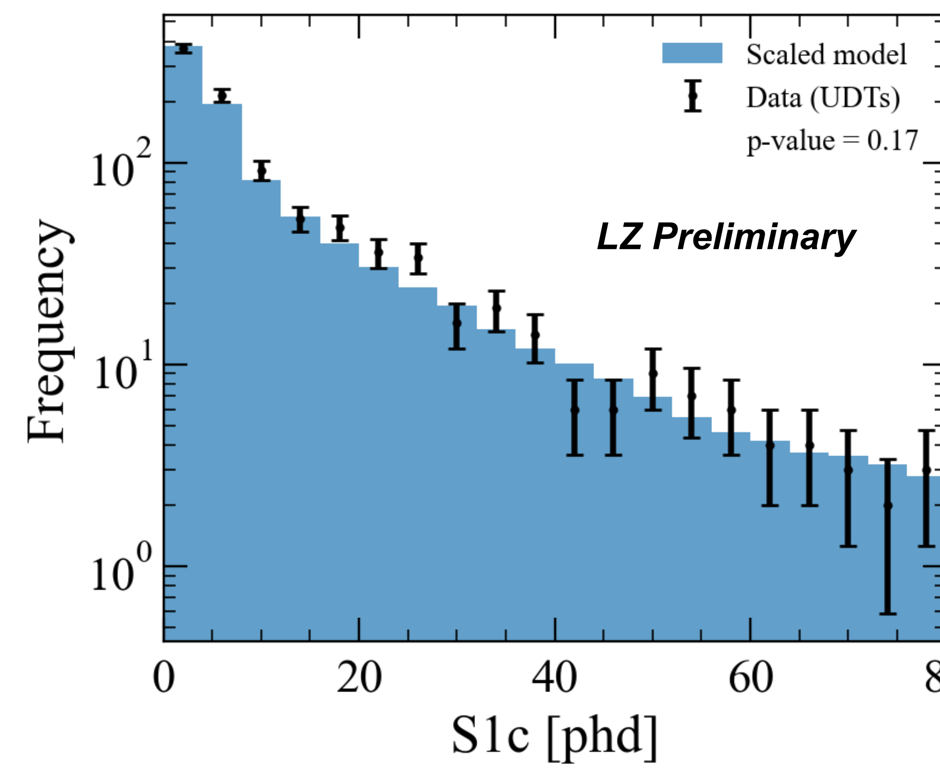
Accidental Chopstitch distribution after cuts

Accidental modeling

- To **constrain the rate & to validate the model**, use Unphysical Drift Time (UDT) events
- Validate Chopstitch distributions with UDT distributions







Predicted accidental counts in WS2024:
2.8 +/- 0.6 in 220 live days (0.14 μHz)

Summary

- Backgrounds in LZ are mitigated through
  - Design choices
  - Radioassay and cleanliness program
  - Analysis techniques
- Strong understanding of backgrounds and background modeling enable world-leading dark matter sensitivity
- Outlook for full LZ exposure is promising
- Thank you!

LZ (LUX-ZEPLIN) Collaboration: 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

- 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.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison
- University of Zürich

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Science and Technology Facilities Council

Swiss National Science Foundation

FCT Fundação para a Ciência e a Tecnologia

SANFORD UNDERGROUND RESEARCH FACILITY

Institute for Basic Science

<u>Check out other LZ talks!</u>

- *LZ Status talk* by Scott Haselschwardt
- *Millicharged particle search talk* by Yongheng Xu

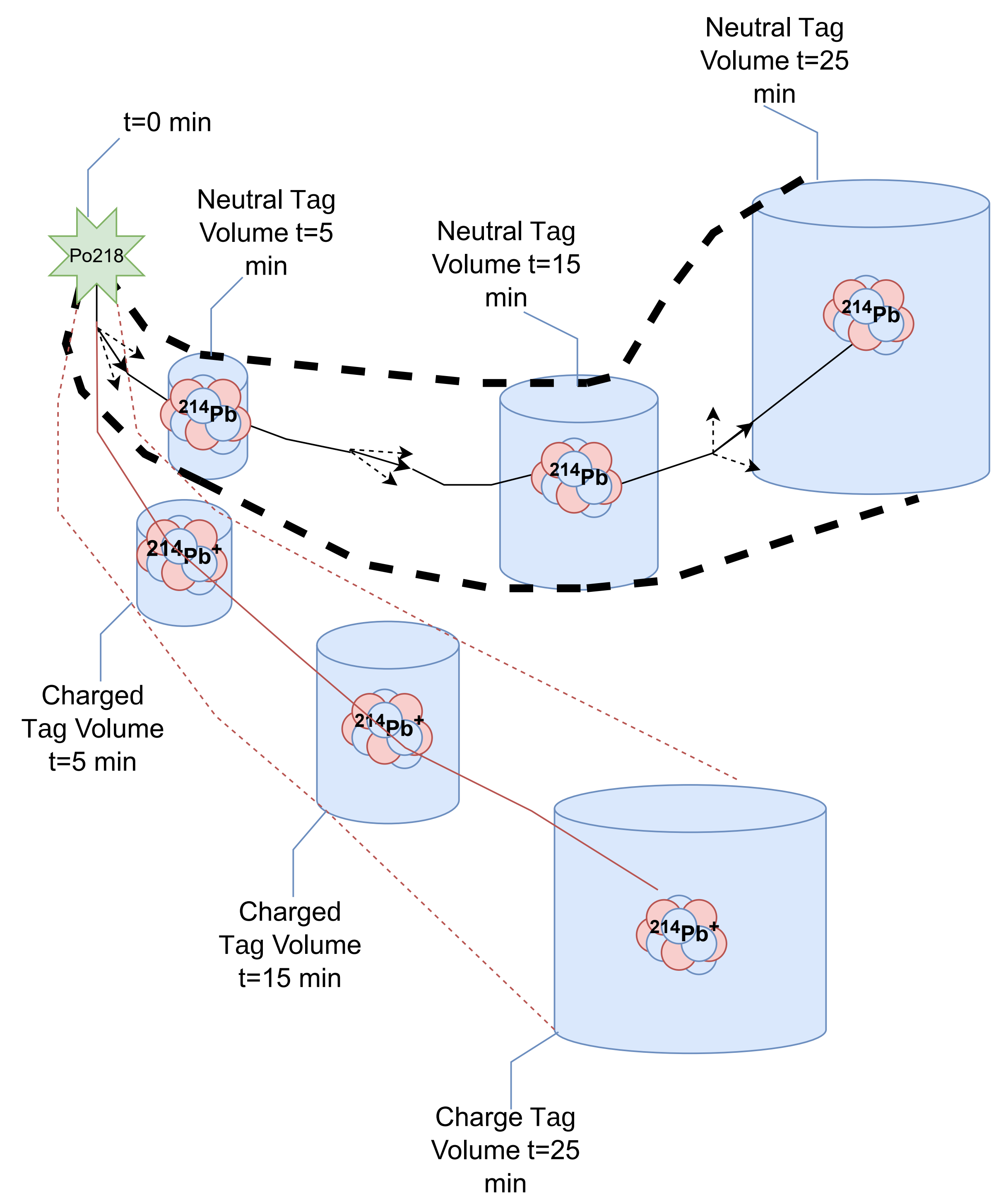
Backup

Background model fit (WS2024)

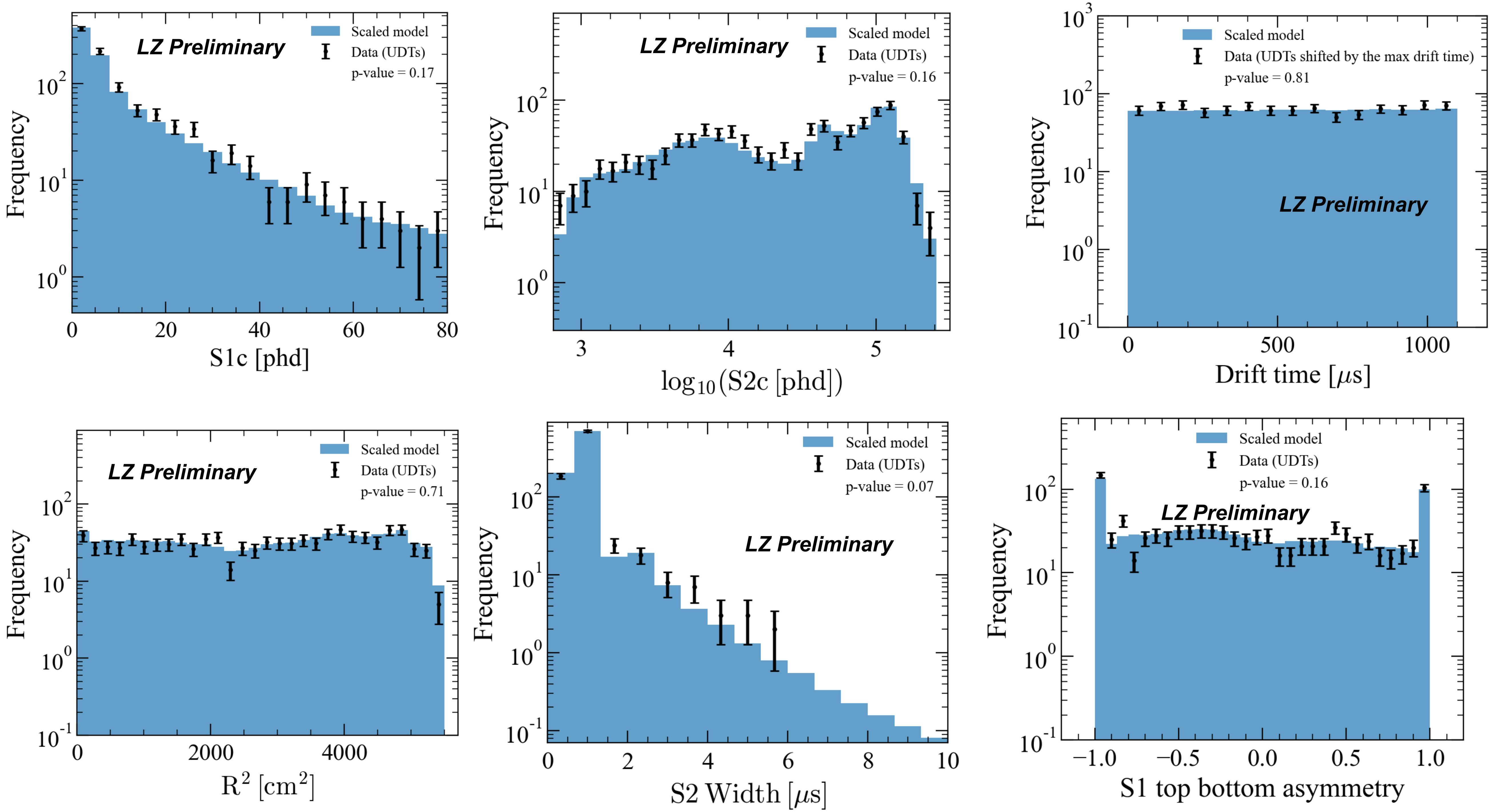
Source	Pre-fit Constraint	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
Solar ν ER	102 ± 6	102 ± 6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.8 ± 8.2
^{8}B+*hep* ν NR	0.06 ± 0.01	0.06 ± 0.01
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
Accidentals	2.8 ± 0.6	2.6 ± 0.6
Detector neutrons	–	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42

Radon details

- *Pb-214 rate estimates:*
  - (1) Measure rate from Po-218 alphas & model flow
  - (2) Fit to single scatter distribution in side band
- Spectrum comes from arXiv:2007.1368
- *Flow map:*
  - Apply loose selection to select pairs close in time and position
  - Separate charged and neutral Po-218 using the vertical velocity information
  - Rn-222 and Po-218 pairs can then be used to measure fluid flow for neutral & charged separately
  - Tagged volume increases with time after initial decay

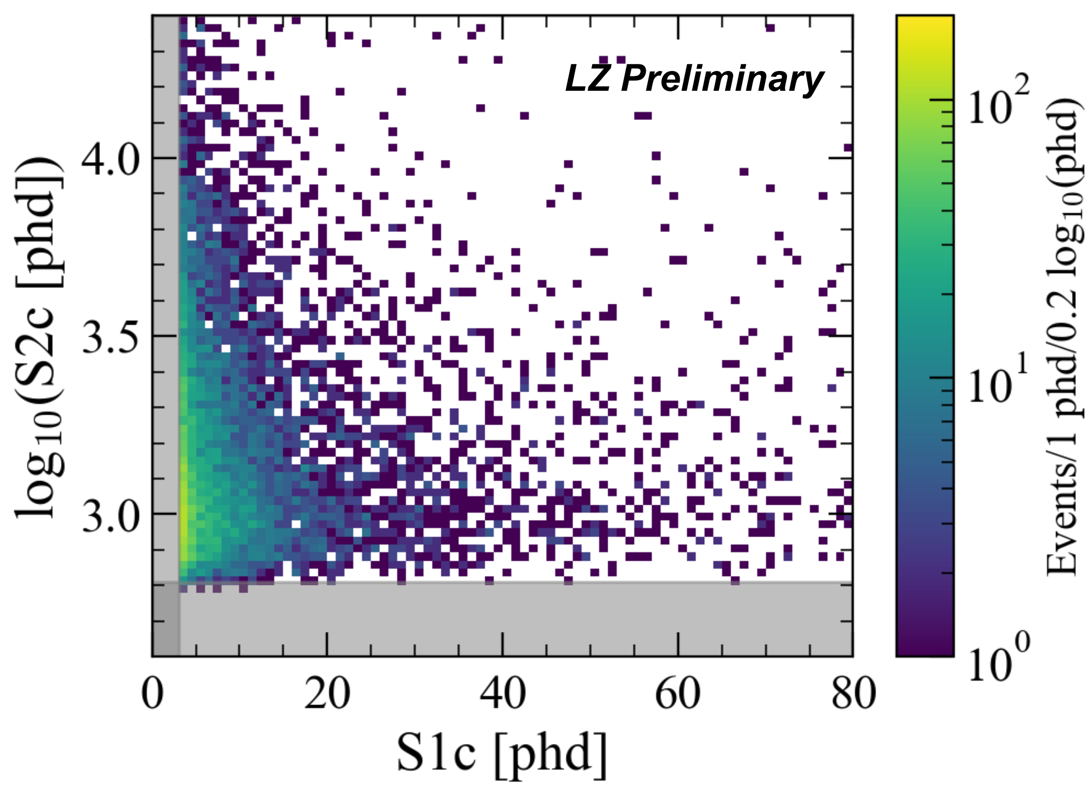


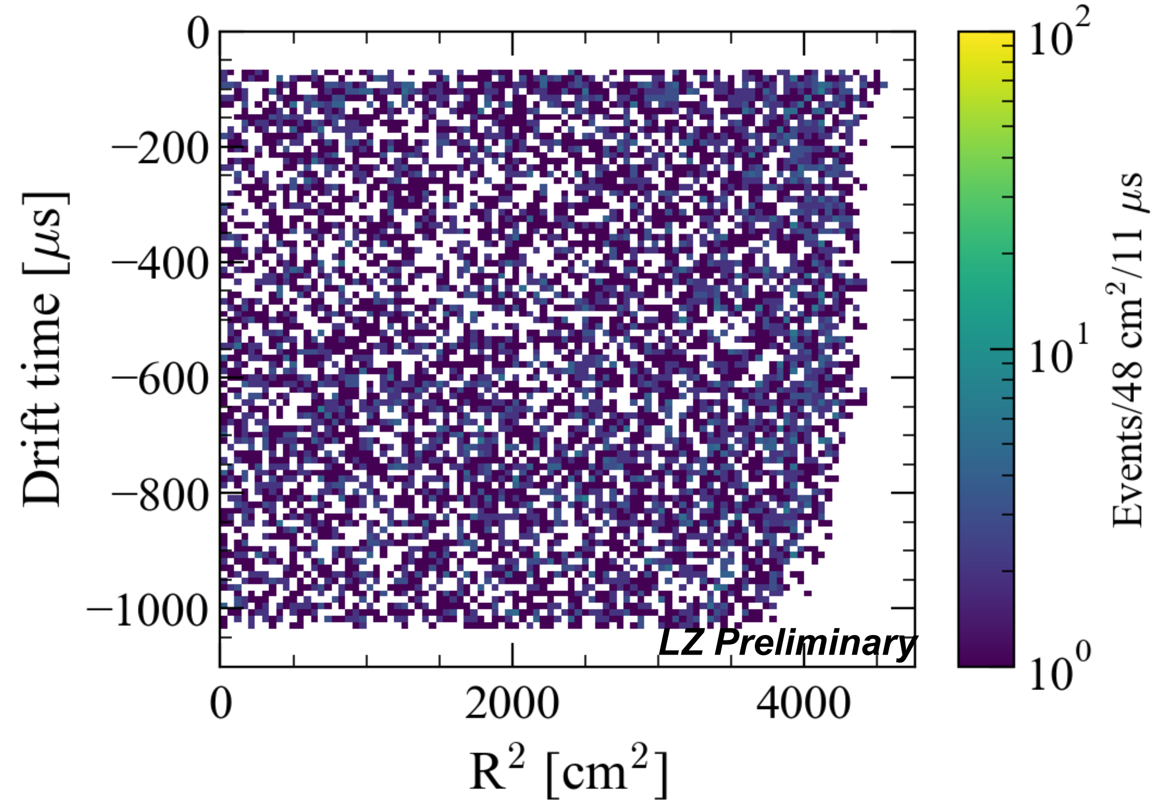
Accidental chopstitch vs UDT agreement

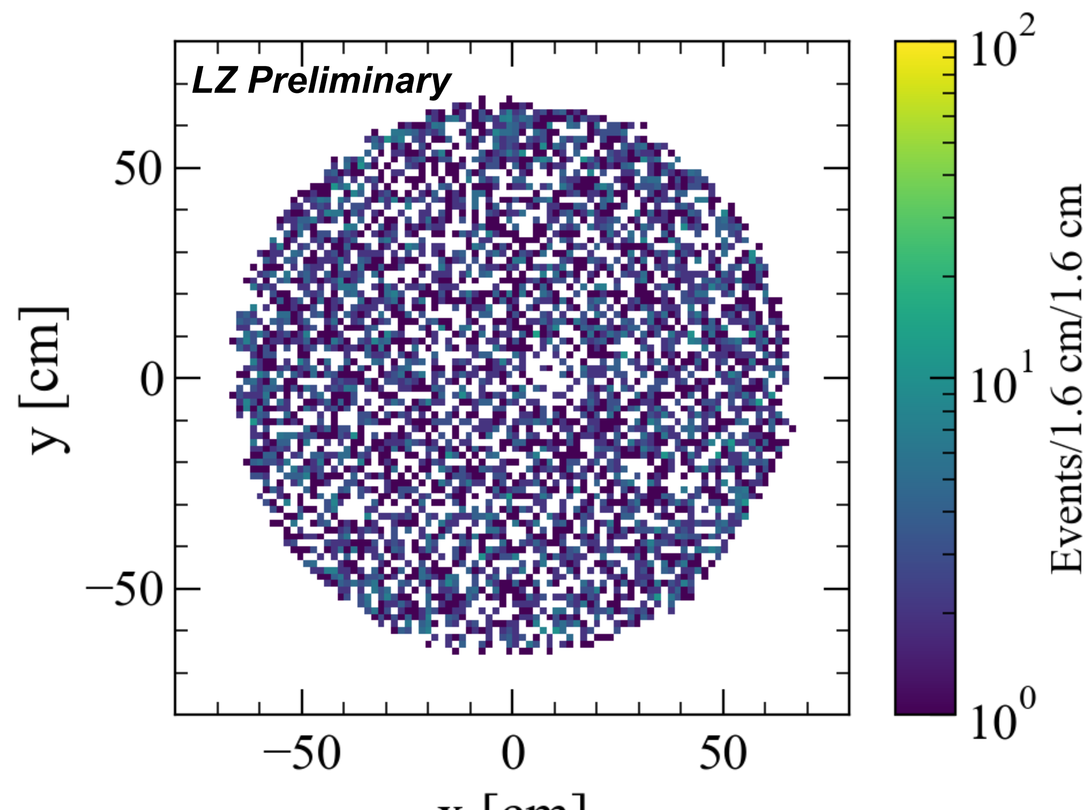


- Demonstrated agreement between chopstitch and UDT distributions

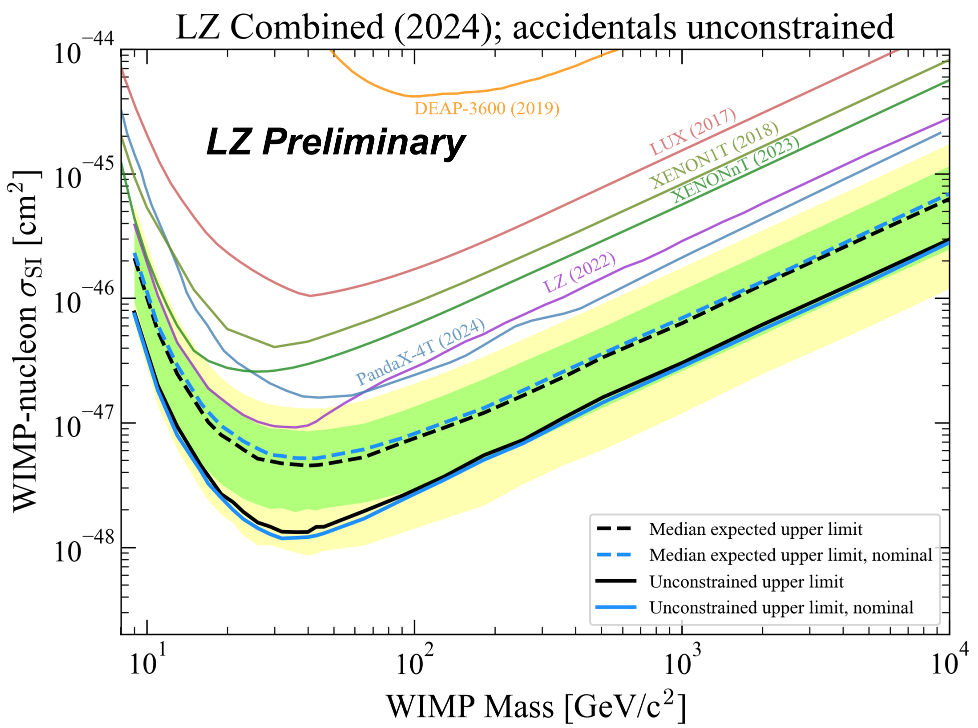
Chopstitch distributions

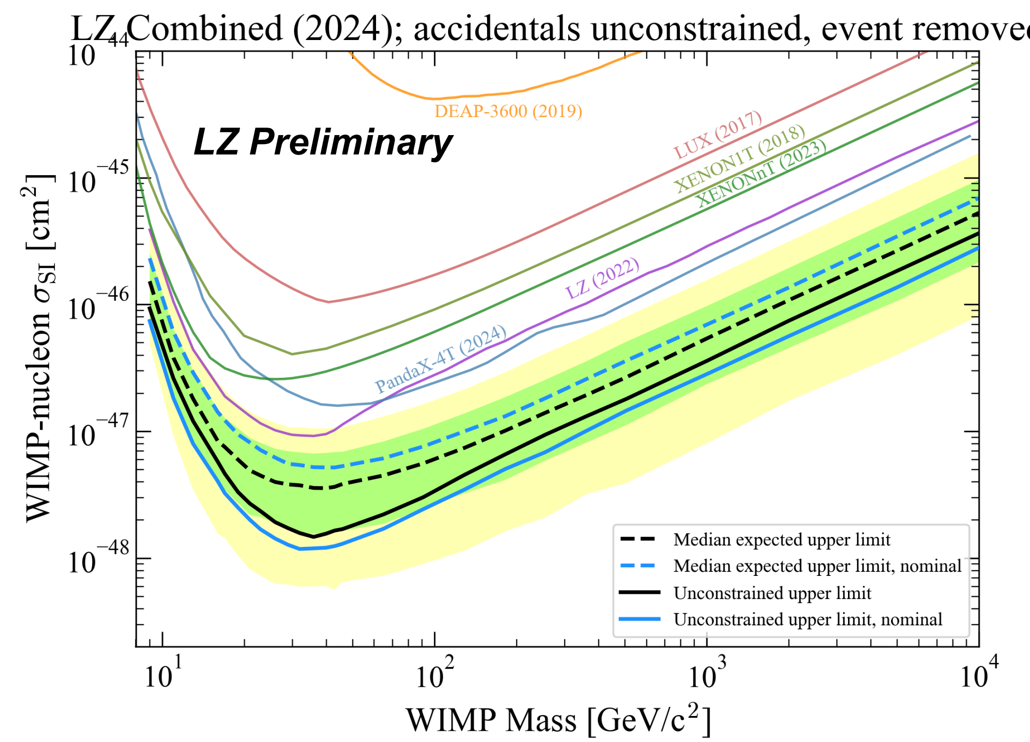




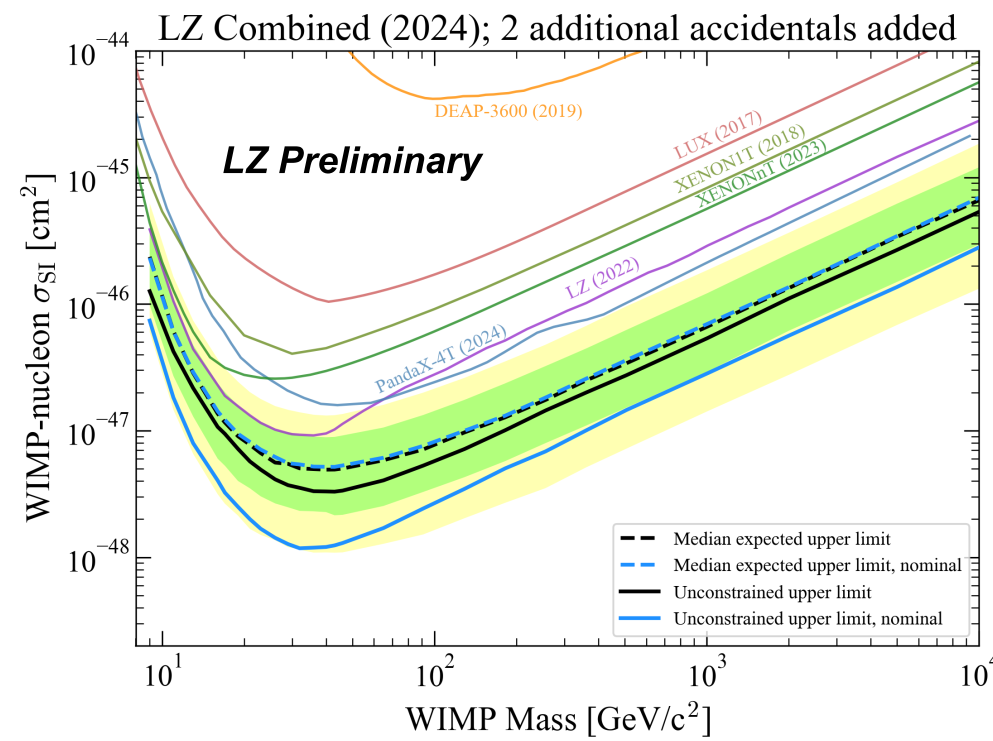


Effect of accidentals on the limit

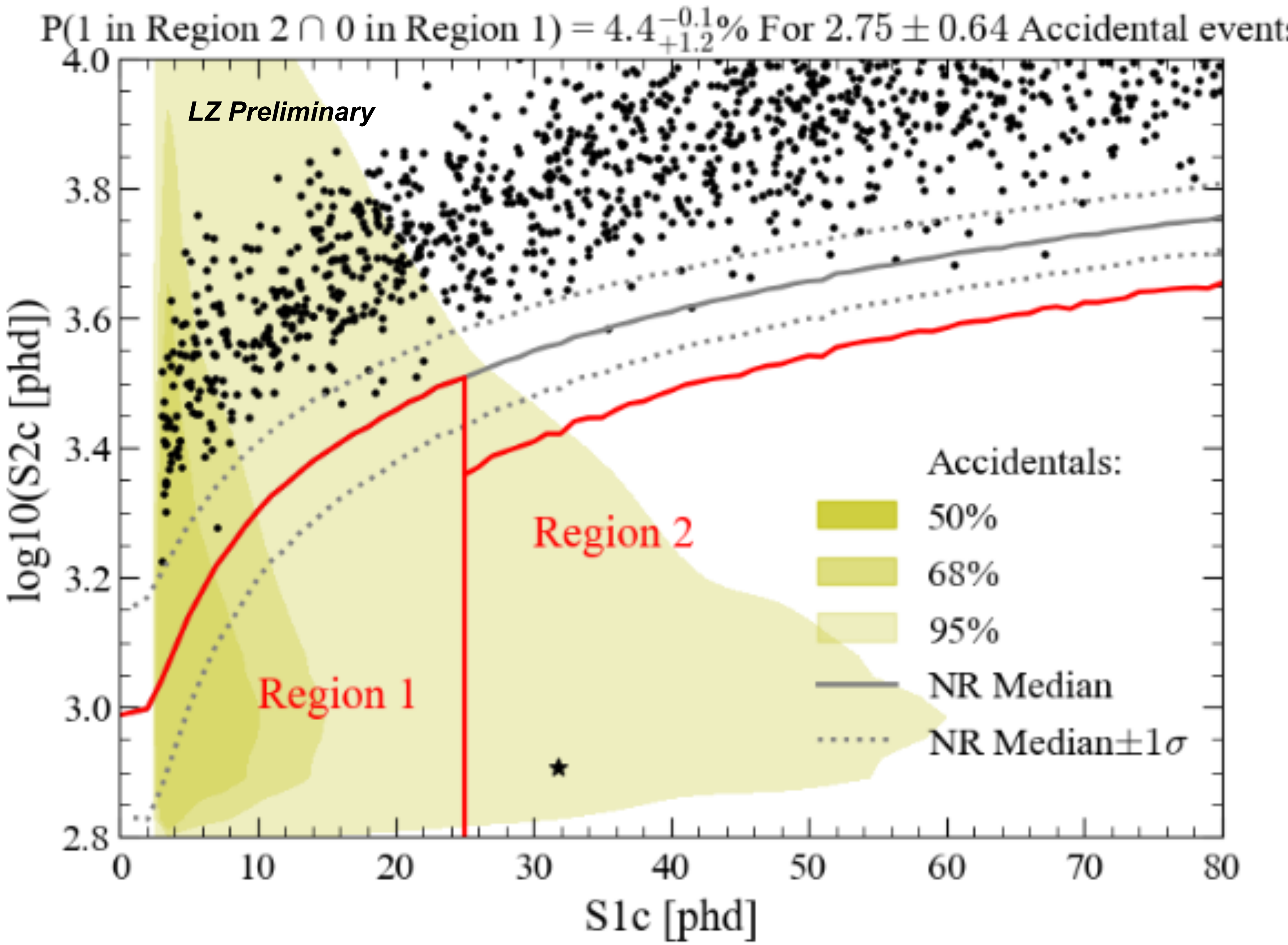




- Tests conducted to probe effect of accidentals on limit
- (1) Effect of removing fit constraint on accidentals
  - Best-fit counts: 1.4
- (2) Effect of removing constraint & accidentals-like event in WS2024 dataset
  - Best-fit counts: 0
- (3) Effect of adding two accidentals events



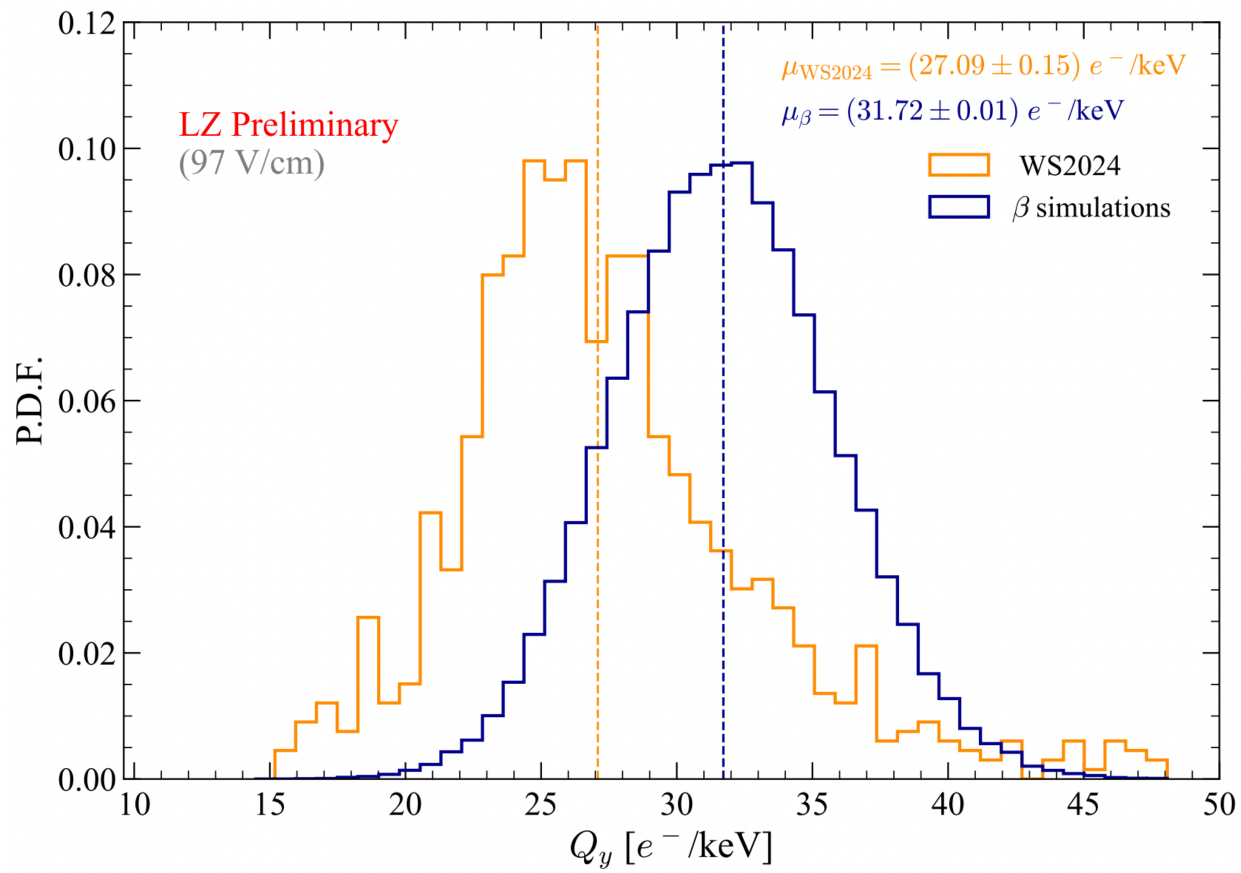
Accidental-like event test

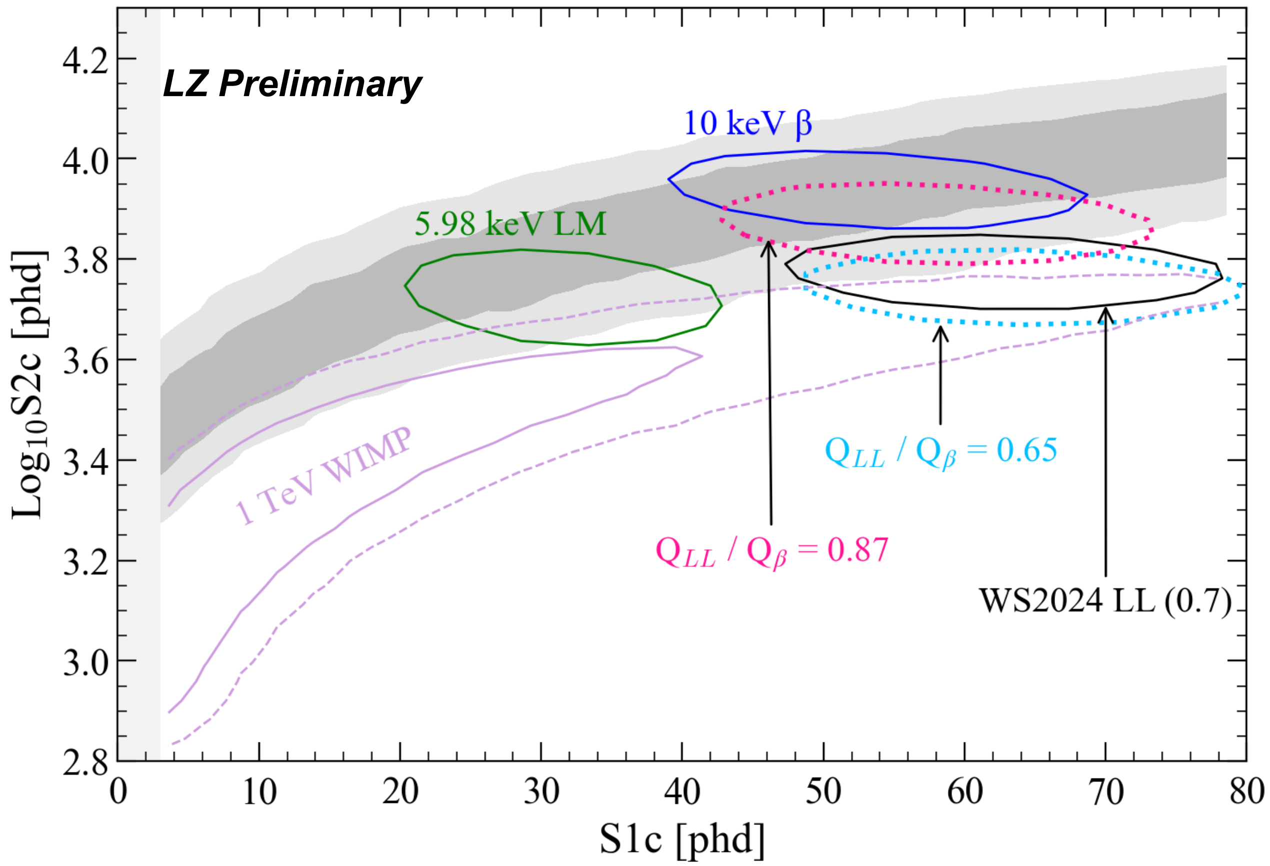


- Probability of seeing 1 event in region 2 and 0 events in region 1: **4.4 -0.1/+1.2 %**

Electron Capture (EC) backgrounds

- Xe-127, Xe-125 activation backgrounds produce ER backgrounds through electron capture (EC)
  - Auger electron & x-rays result in dense track —> more recombination (fewer electrons for S2)
  - Lower charge yield relative to betas

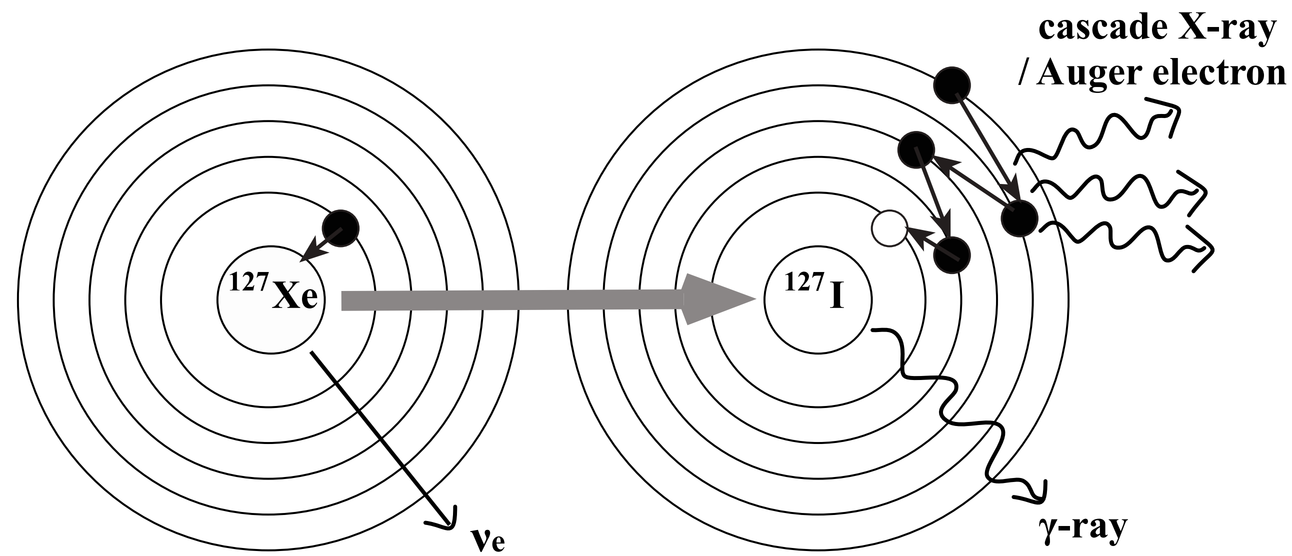




- Effect for Double EC Xe-124 LL expected to be even more pronounced
- Charge suppression incorporated as nuisance parameter
- Constraint varies between size of effect with single EC and effect assuming twice the track density

Electron Capture (EC) backgrounds

- Electron capture process:
  - Electron captured by nucleus
  - Vacancy is filled from an outer shell electron, energy is released as an x-ray or transferred to another electron (Auger electron)
- Excited nuclear state which can de-excite through gamma or internal conversion electron
- Electron capture usually from the K shell
- Lower charge yield relative to equivalent energy betas has been measured by XELDA and LUX

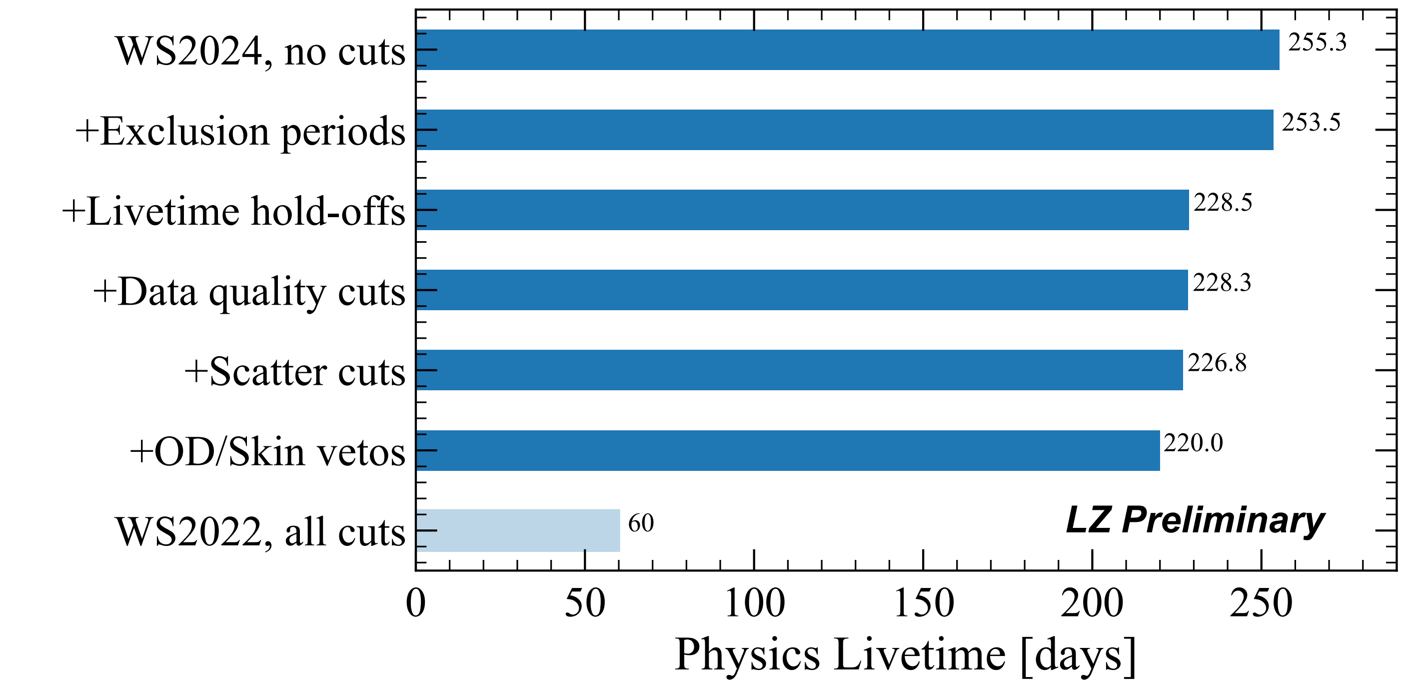


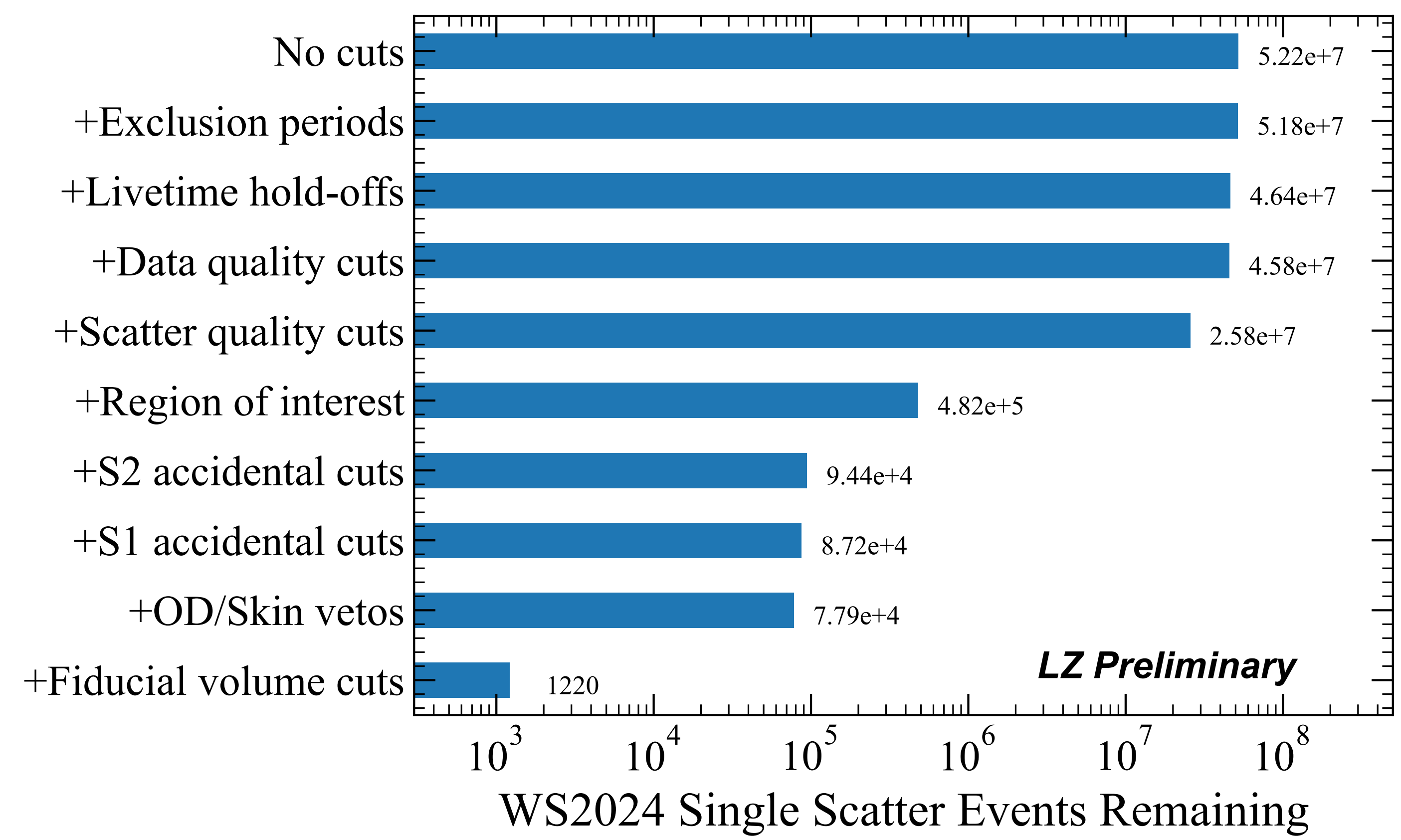
arXiv:1709.00800

- Xe-124 DEC LL and LM are in the energy range for the WIMP search

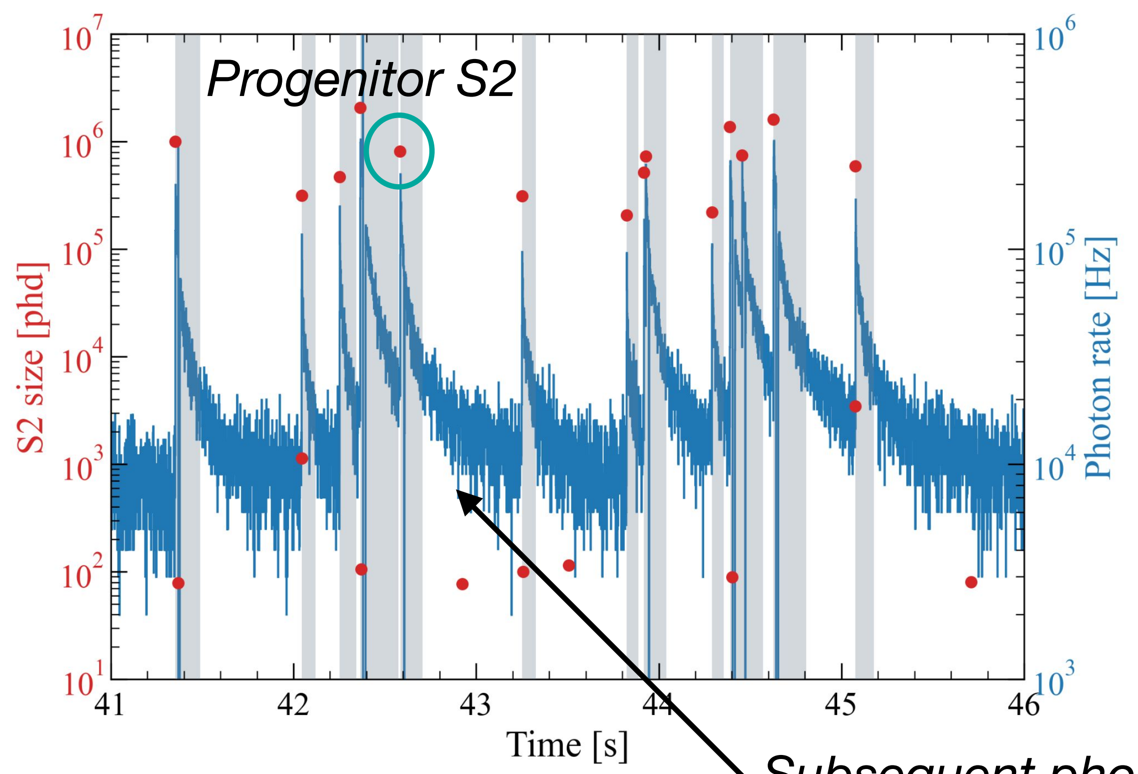
Accidental & data quality cuts

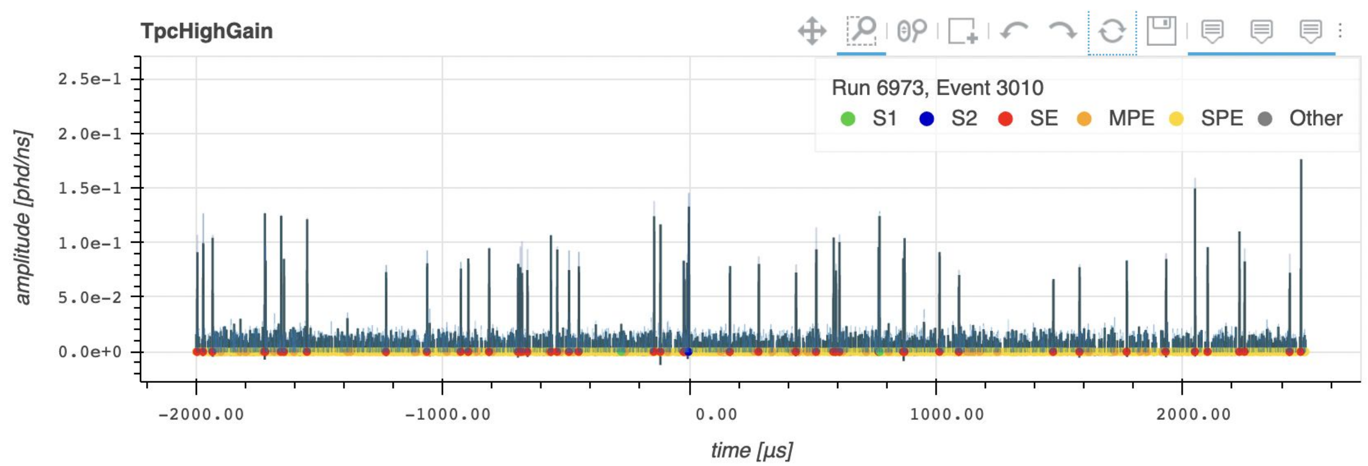
- Dedicated cuts to target anomalous signatures
- Several categories of cuts
  - Lifetime hold-offs removing periods after specific events (e.g. e/photon trains) are applied
  - Periods with high rates of detector activity (e.g. grid emission) or detector operation problems were removed
  - S1 & S2 pulse cuts targeting anomalous pulses were also developed



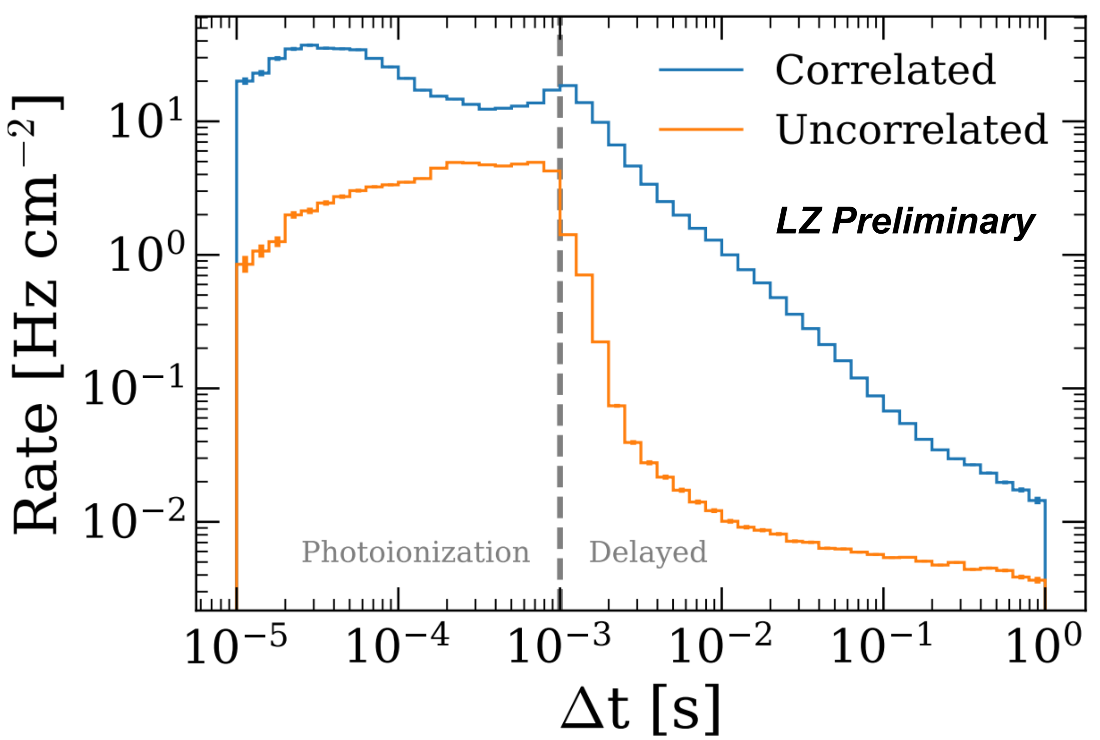


Accidental backgrounds: Delayed electrons/photons





Example of "e/photon train" event

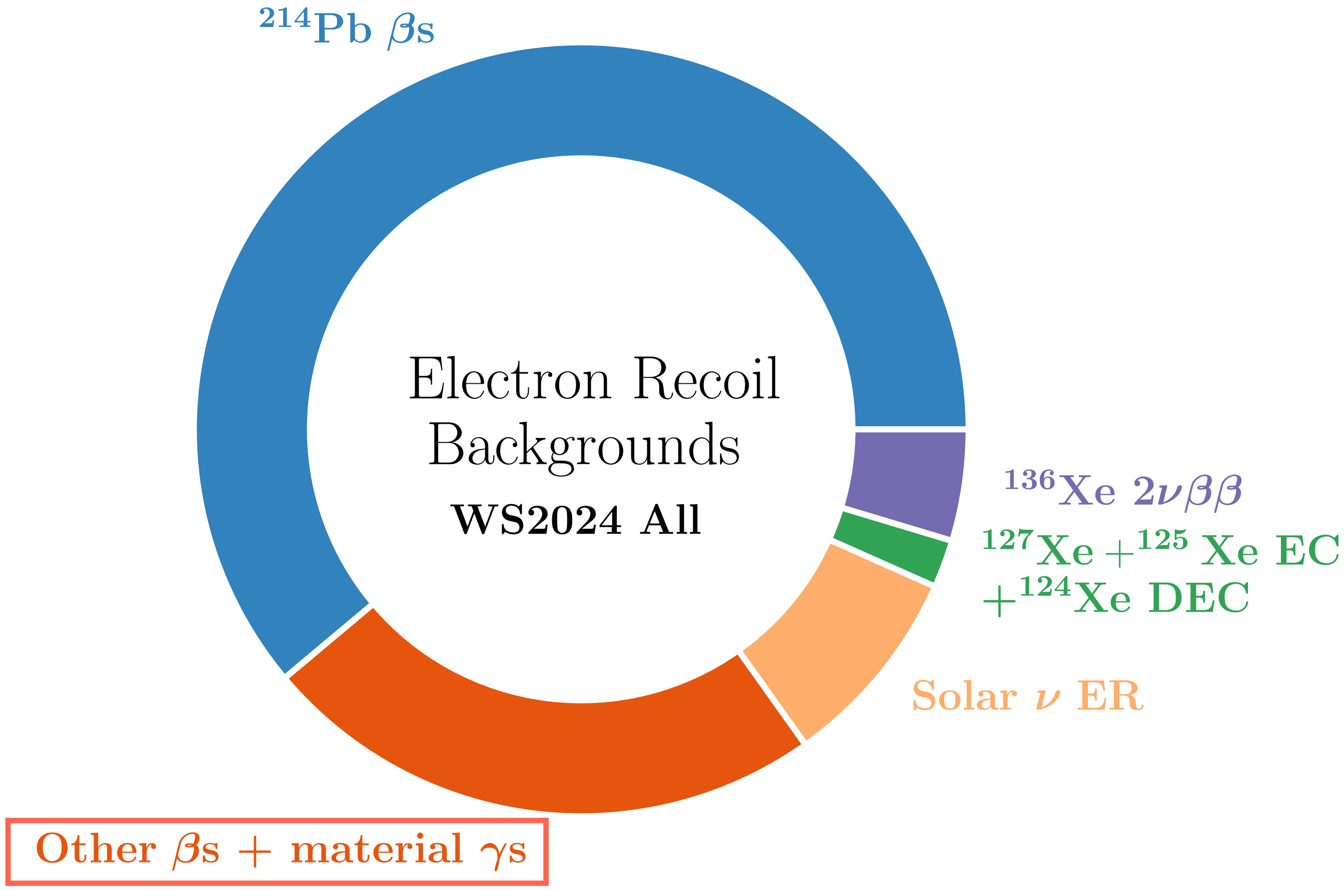


Electron rate following a progenitor S2

- Large pulses in the detector are followed by a so-called "train" of signals
    - Consists of a decaying rate of both small S2s and S1s (electrons & photons)
    - Mitigate this background with an analysis hold-off period after detecting a large S1/S2 pulse
- Decaying electron rate has been characterized and follows a power law (as seen in other LXe experiments)
- ~ 10% of livetime removed due to veto

Other beta backgrounds

- Pb-212 (Rn-220 daughter)
  - Measure Po-212 alphas to constrain rate
- Po-218 (Rn-222 daughter)
  - Infrequently Po-218 beta decays (to At-218)
  - Po-218 alphas are measured and used to inform Po-218 beta decay rate
- Kr-85 & Ar-39
  - Extensive Kr removal program using charcoal chromatography at SLAC to reduce to ~100 ppq
  - Measure natural Kr and Ar in xenon sampling, then calculate relevant isotopic amounts



- CH3T/C-14 from calibration injections (predictable decay rate)
- Other detector ERs (including material gammas) are simulated and normalized using high energy fits