New Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

Scott Haselschwardt
Lawrence Berkeley National Lab*
on behalf of the LZ Collaboration

TeVPA 2024 - Chicago
August 26, 2024

*Now at University of Michigan
haselsco@umich.edu

The LZ (LUX-ZEPLIN) Collaboration

@lzdarkmatter

https://lz.lbl.gov

250 scientists, engineers, & technical staff
38 institutions

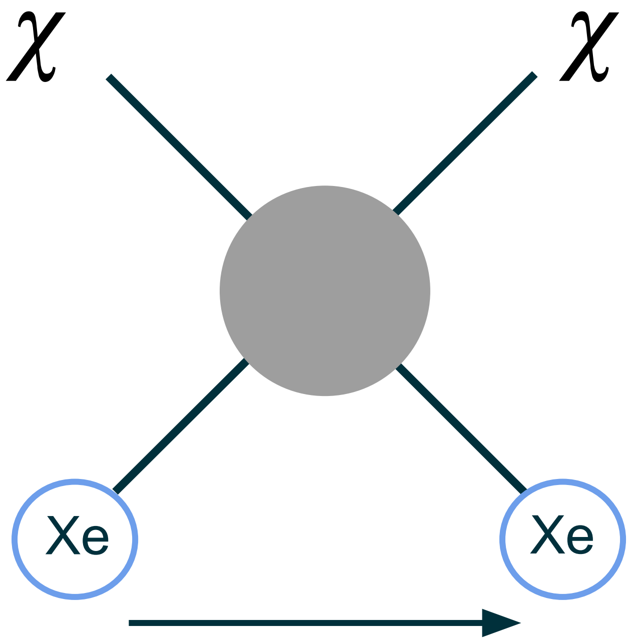
- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra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

US Europe Asia Oceania

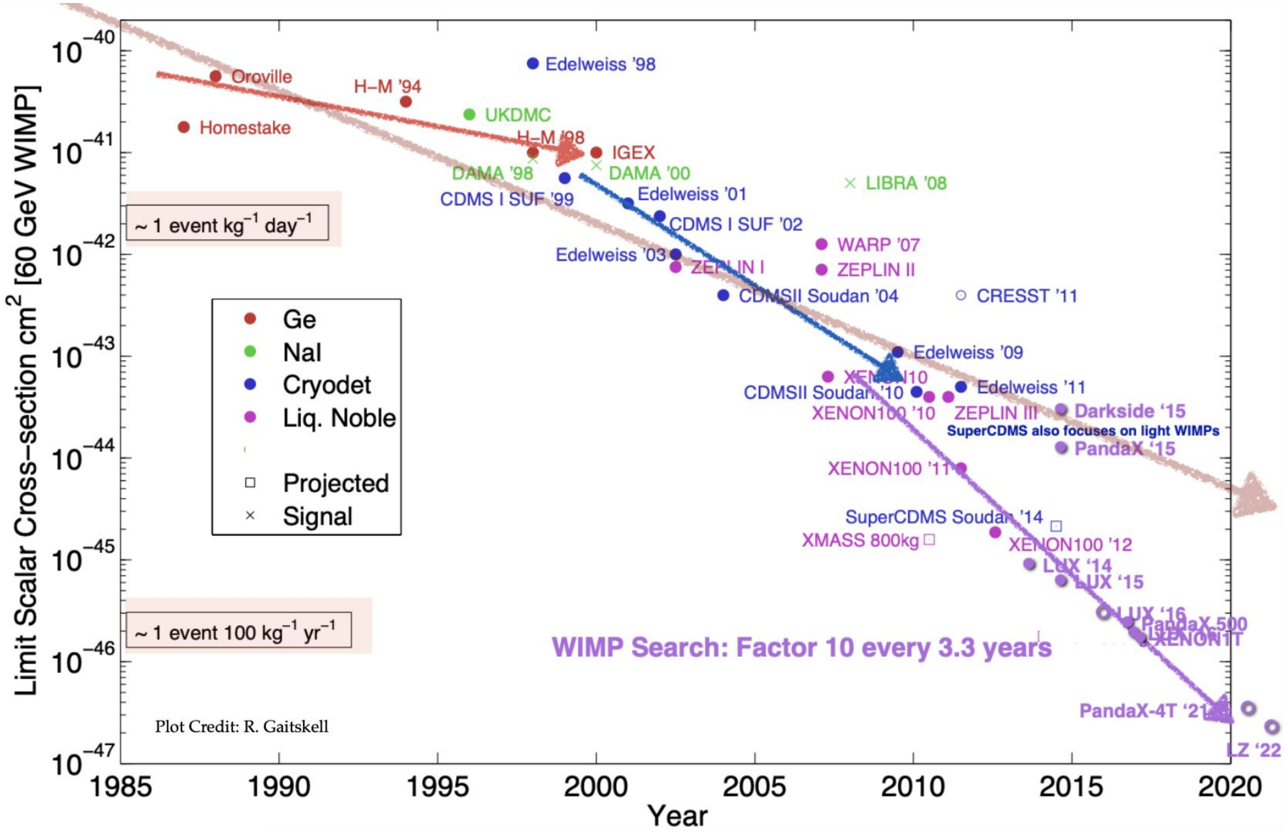
Science and Technology Facilities Council
Swiss National Science Foundation
Fundação para a Ciência e a Tecnologia
SANFORD UNDERGROUND RESEARCH FACILITY
Institute for Basic Science

Direct dark matter searches with xenon

LZ primarily searches for
anomalous nuclear recoils
caused by galactic dark matter particles



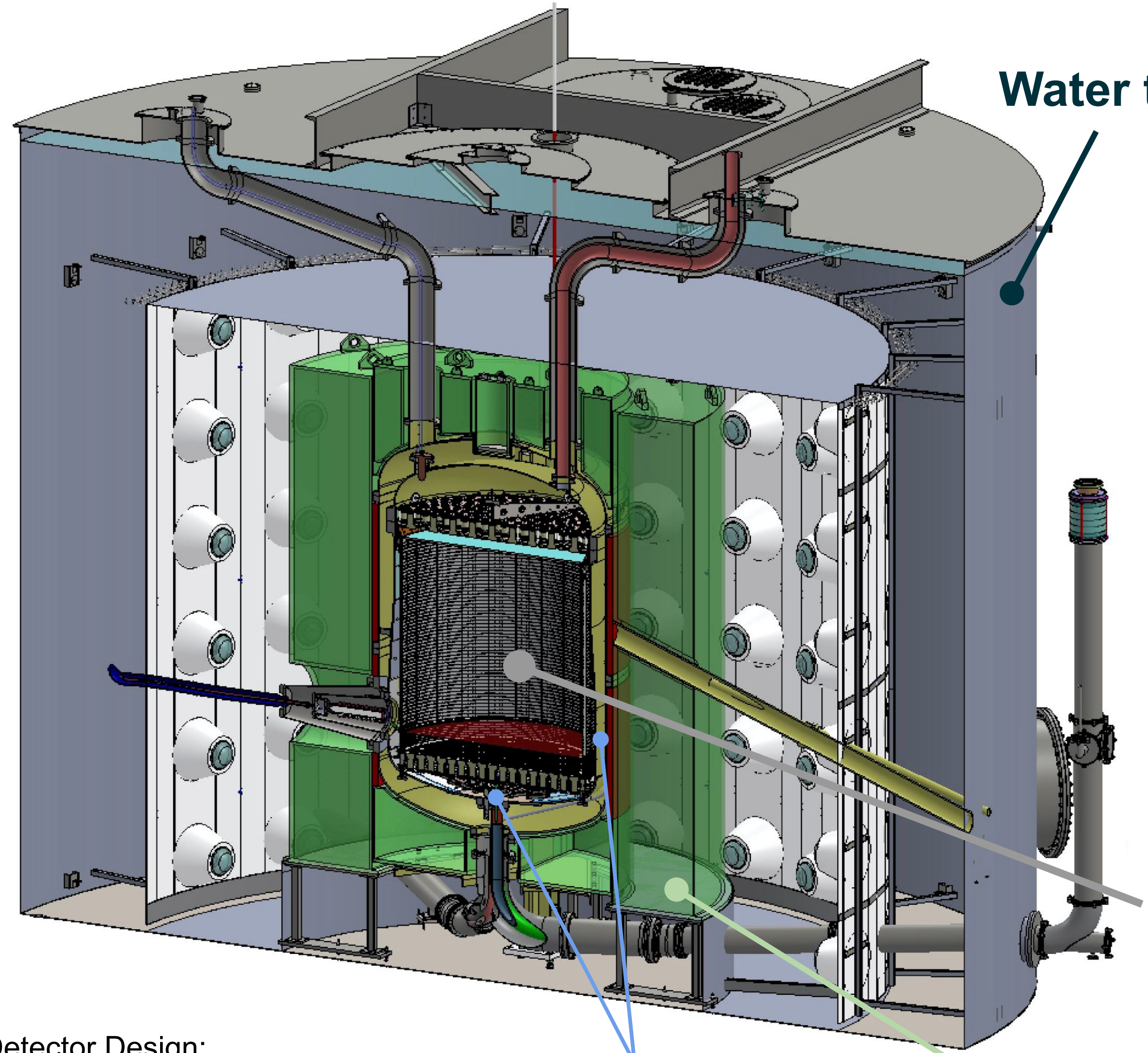
These dark matter particles
might be **WIMPs**
(but they don't have to be)



- **LXe TPCs lead the field**
- **~1 keV thresholds** w/ **background discrimination** and **scalable target medium**
- **Excellent energy resolution** enables further searches, e.g. ^{136}Xe $0\nu\beta\beta$ and more

The LZ Experiment

Located in the **Davis Campus** on the 4850' level of **Sanford Underground Research Facility (SURF)**

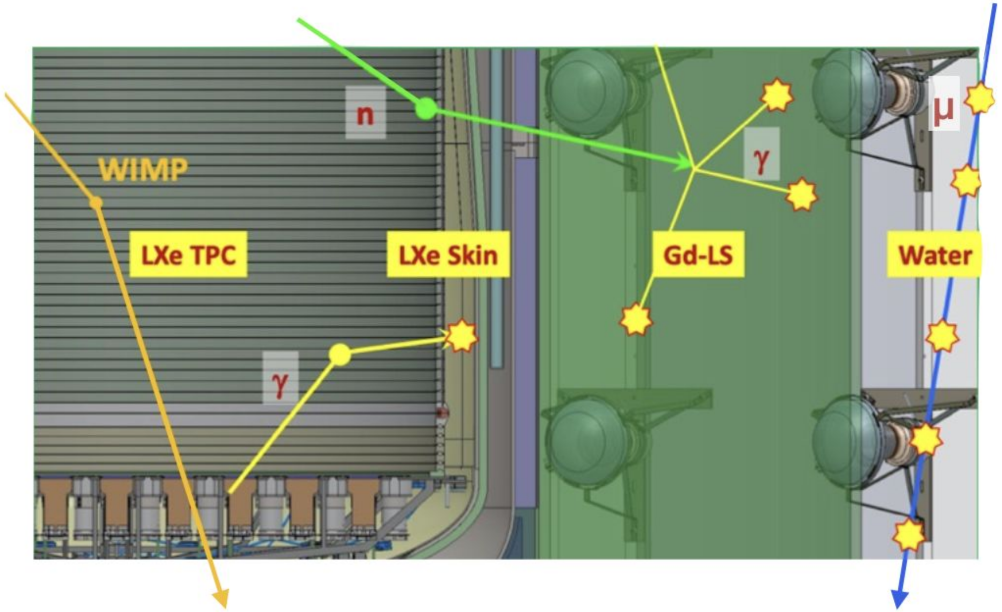


Water tank

7 tonne active liquid xenon time projection chamber (TPC)

Xe Skin veto

Outer Detector neutron + μ veto



Xe Skin & Outer Detector characterize and reject γ + *neutron* backgrounds!

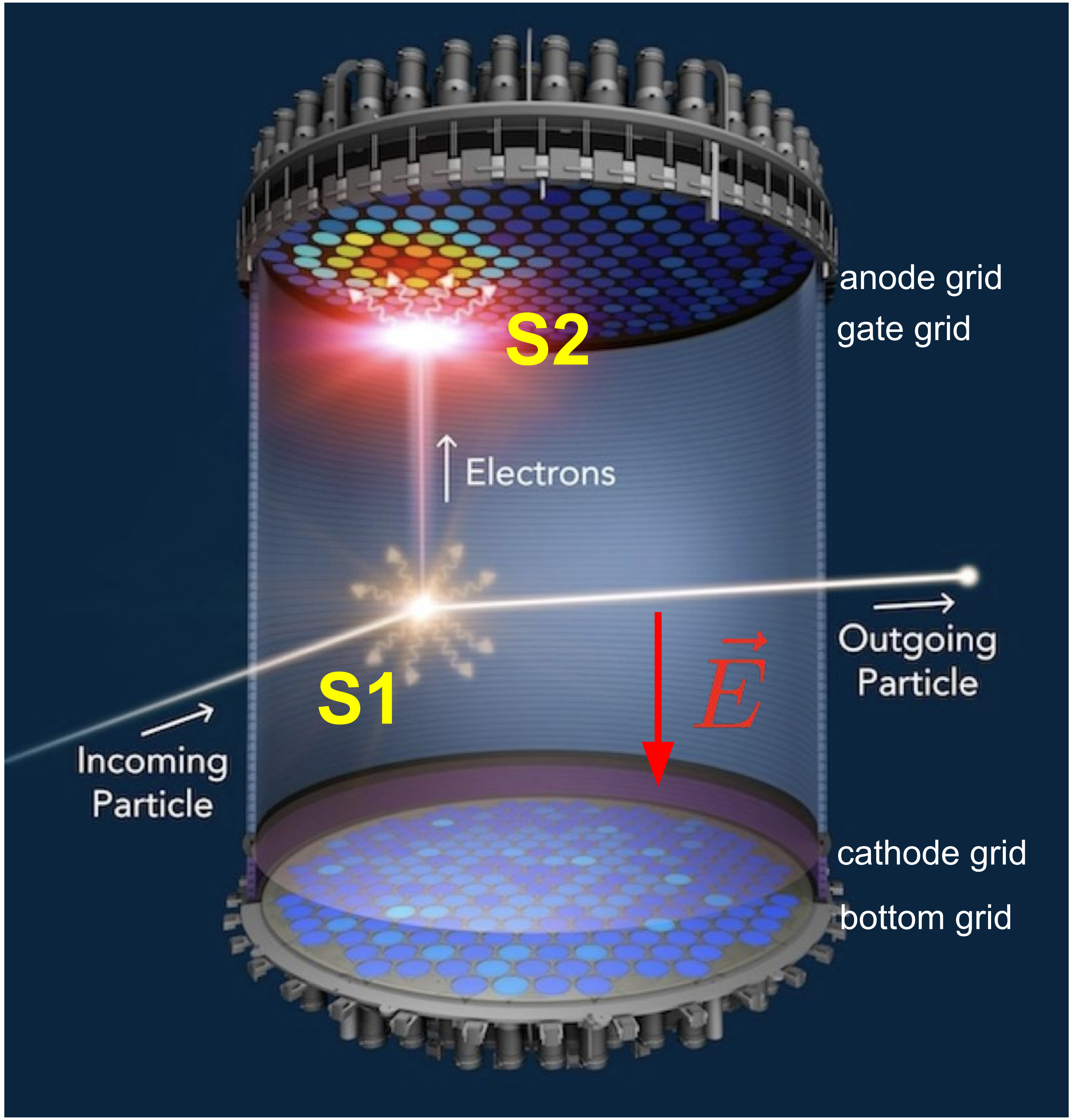
LZ Detector Design:
NIMA, **953** 163047 (2020)

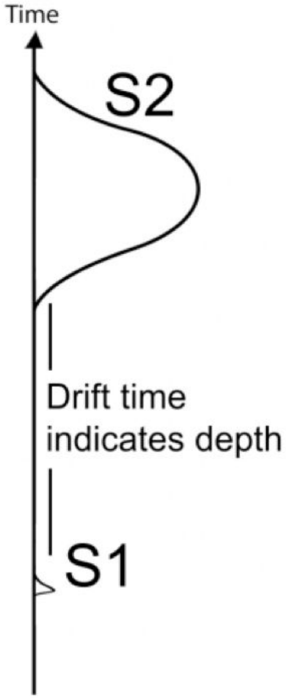
Liquid Xe TPC Operational Principle

- Prompt scintillation (S1) & delayed ionization (S2) observables
- Top PMT array hit pattern gives (x,y)
- Time between S1 & S2 gives depth

LZ's TPC:

- 1.5 m ∅ x 1.5 m tall
- 7 tonne active liquid xenon
- Electrostatic grids establish E-fields for electron drift & extraction:
    - bottom, cathode, gate, anode

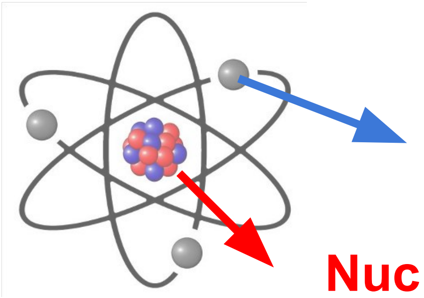




Liquid Xe TPC Operational Principle

- Prompt scintillation (S1) & delayed ionization (S2) observables
- Top PMT array hit pattern gives (x,y)
- Time between S1 & S2 gives depth

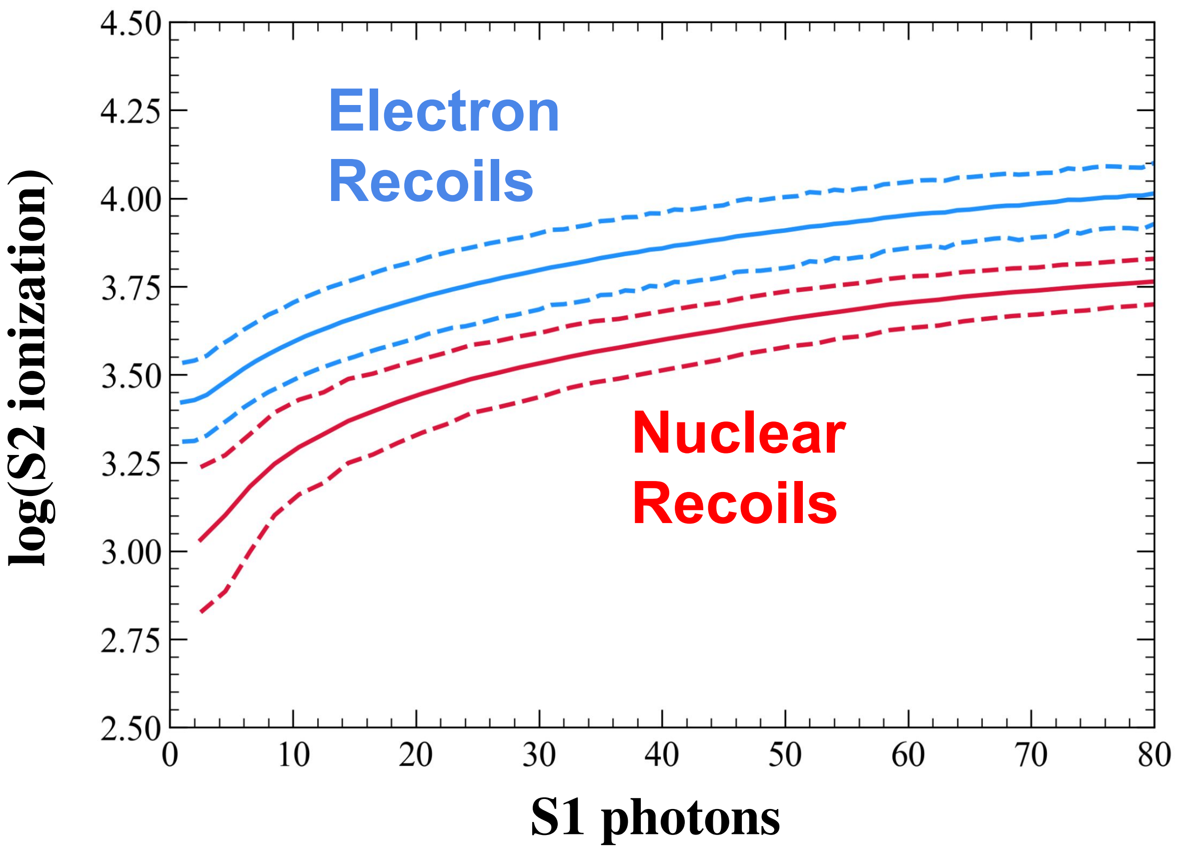
S2/S1 ratio provides **particle ID** or **"discrimination"**



Electron Recoils
(β decays, γ rays, ν-e$^-$)

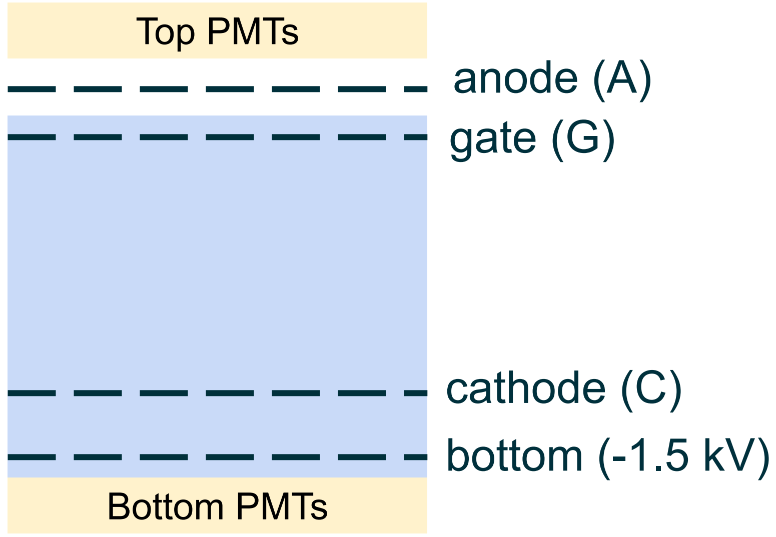
Nuclear Recoils
(WIMPs, neutrons)

Primary dark matter search space:



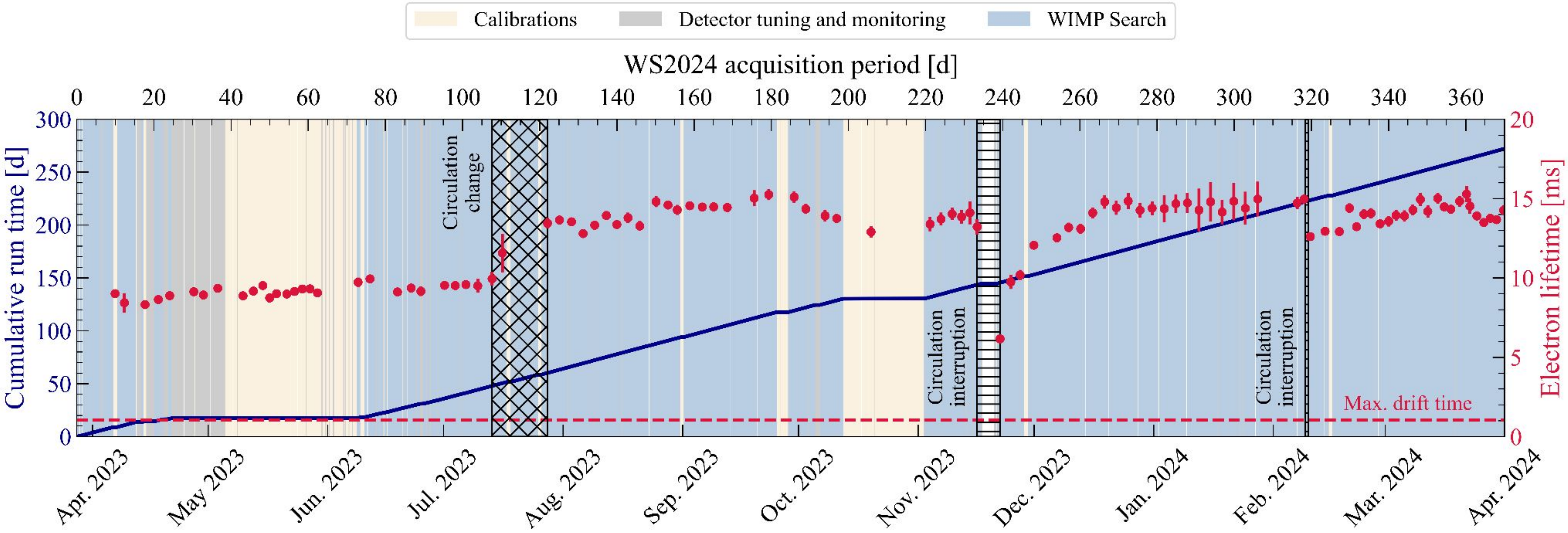
Important Changes Since LZ's 1st Result (WS2022)

- Following WS2022, carried out various campaigns related to detector optimization:
  - grid voltages
  - Xe circulation
  - trigger configuration
  - calibrations
- **Lowered extraction region *ΔV*** by 0.5 kV to reduce spurious emission
- **Cathode lowered** in response to light emission observed in Skin
  - ER/NR discrimination not affected
- **LZ detector is performing very well!**



Run	C/G/A Voltage [kV]	Drift Field [V/cm]	Analysis live time [d]
WS2022	-32/-4/+4	193	60
WS2024	-18/-4/+3.5	97	220

WIMP Search 2024 (WS2024)



- Data from March '23 - March '24 - analysis here is a **220 live-day** exposure
- **Science data-taking periods have 95.2% up time**

phd = photons detected

Calibrations

Electron recoils (background):

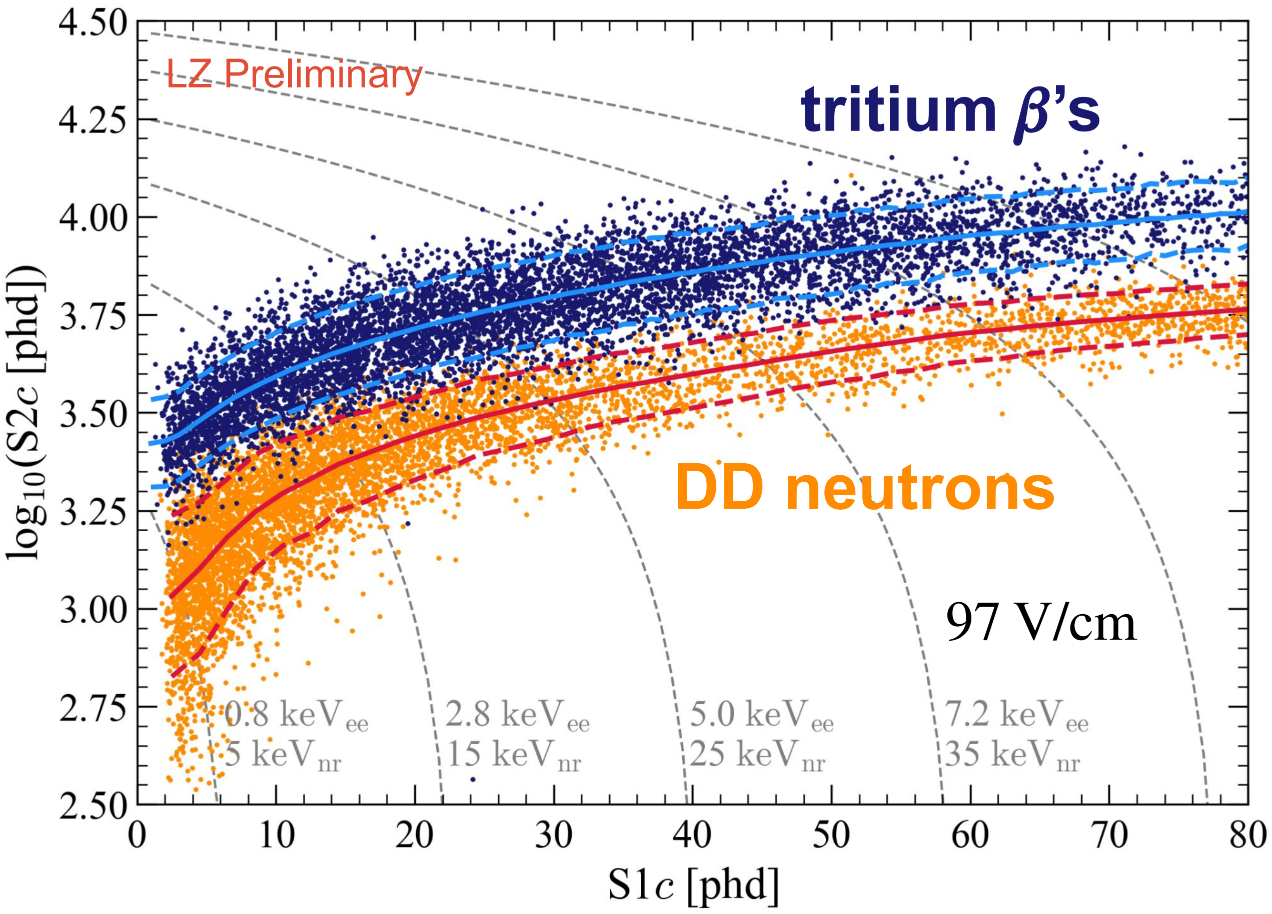
- high stats (~156k evts) injection of radiolabeled methane containing ^{3}H (18.6 keV) & ^{14}C (156 keV)
- spatially homogeneous β decays
- Others: injected ^{83m}Kr, ^{131m}Xe, activation lines

Nuclear recoils (signal):

- high stats (~11k evts) run of DD generator: collimated 2.45 MeV neutrons
- Also: AmLi neutrons in calibration tubes

Above tune NEST*-based response model

- light gain: **0.112 ± 0.002 phd/photon**
- charge gain: **34.0 ± 0.9 phd/electron**
- single electron size: **44.5 phd**



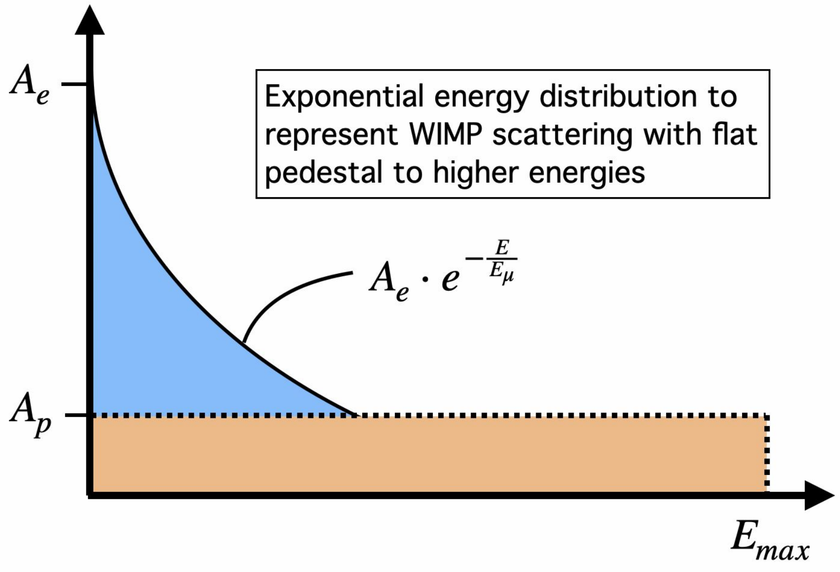
99.9% discrimination of flat ER background below median 40 GeV (same as WS2022)

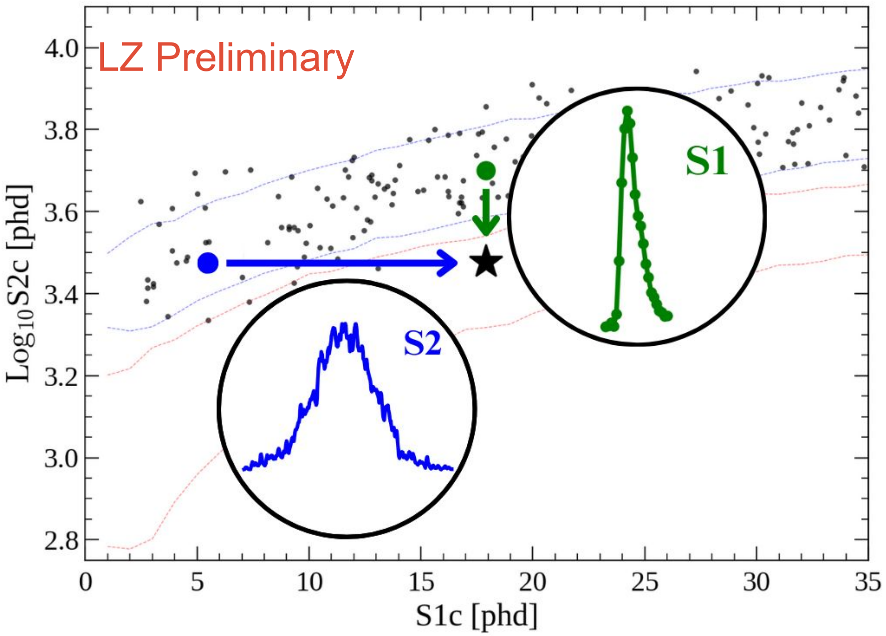
**See Greg Rischbieter's NEST talk this afternoon*

**only 8k events of each shown for clarity

Bias mitigation via ‘salt’

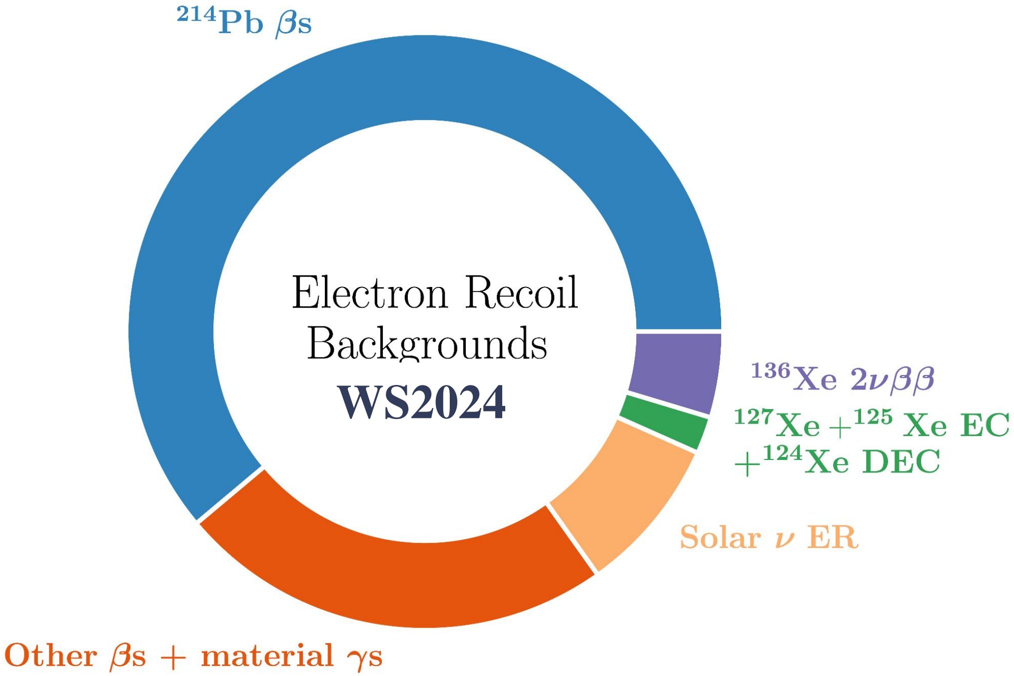
- **“Salting” -** inject fake signal events randomly during science data collection
- Events manufactured using S1s & S2s from **sequestered calibration data**
- Number of injected events is bounded from above by WS2022 upper limit
- Events follow **exponential+flat spectrum** (exact parameters randomly generated, kept hidden)
    - covers WIMP and higher-energy NR regions of interest
- Identity of salt events revealed after analysis inputs are finalized for final inference





Background Model Overview

- Dissolved β emitters:
  - **^{214}Pb** (^{222}Rn), ^{212}Pb (^{220}Rn), ^{85}Kr, ^{136}Xe ($\beta\beta$)
- Dissolved EC decays (x-ray/Auger cascades):
  - $^{127/125}$Xe from neutron calibration activation
  - **^{124}Xe (double EC)**, 0.095% nat. abundance
- Instrumental: **Accidental coincidences**
- Solar ν's: ^{8}B+*hep* (NR), pp+^{7}Be (ER)
- Long-lived γ emitters in detector materials:
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- Neutrons from spontaneous fission and (α,n) in detector materials



See Ann Wang's talk on backgrounds this afternoon

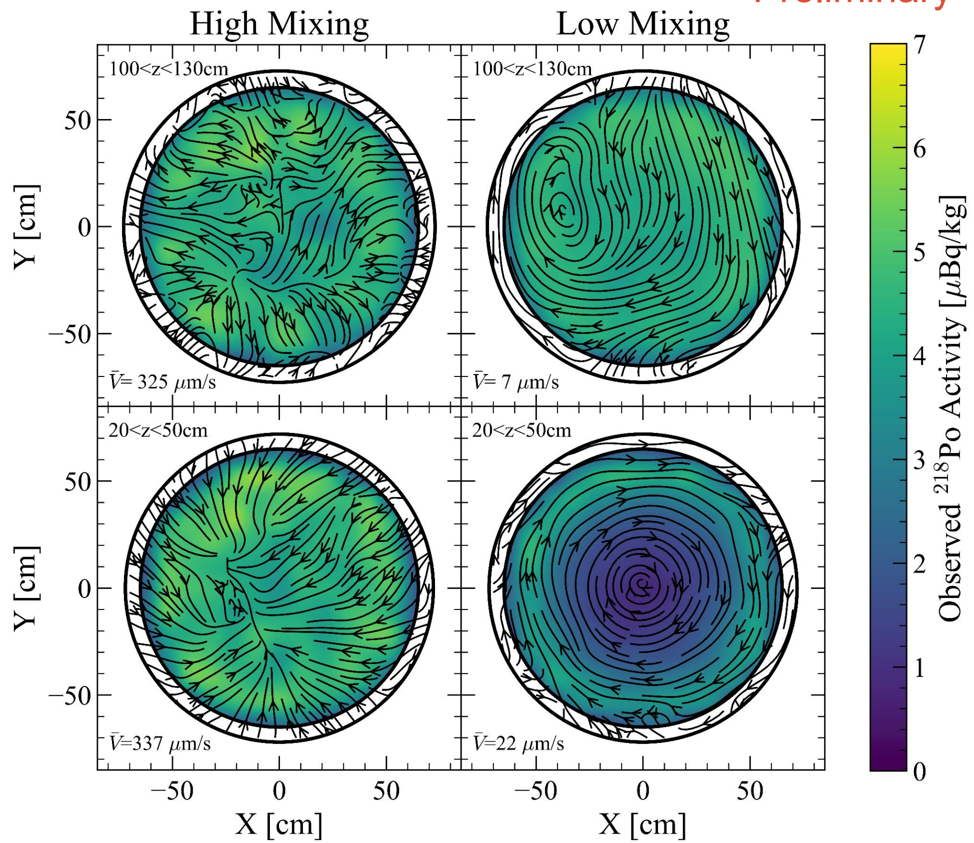
Controlling LXe Flow to Reduce Backgrounds

LZ Preliminary

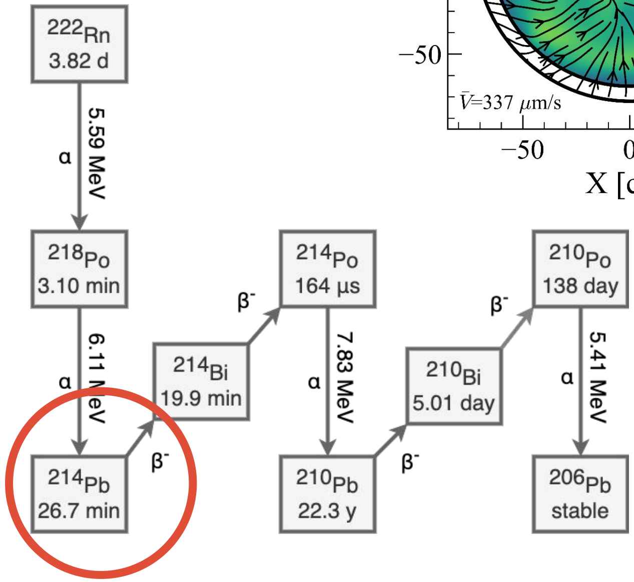
Fine control of TPC+LXe temperatures allow control of LXe flow pattern

Data in WS2024 acquired in two flow states:

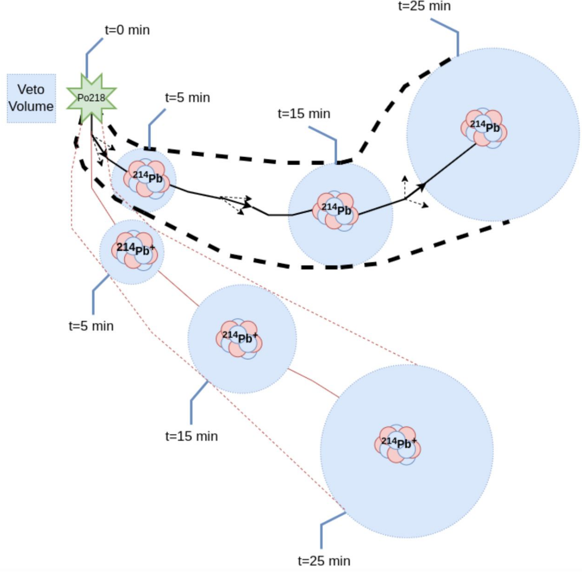
1. **High Mixing** - turbulent flow, uniform distribution of Rn & injected sources
2. **Low Mixing** - laminar-like flow, creates convective cells



In **low mixing** state, use **^{222}Rn-^{218}Po coincidences to map liquid flow** to **efficiently tag ^{214}Pb β's**

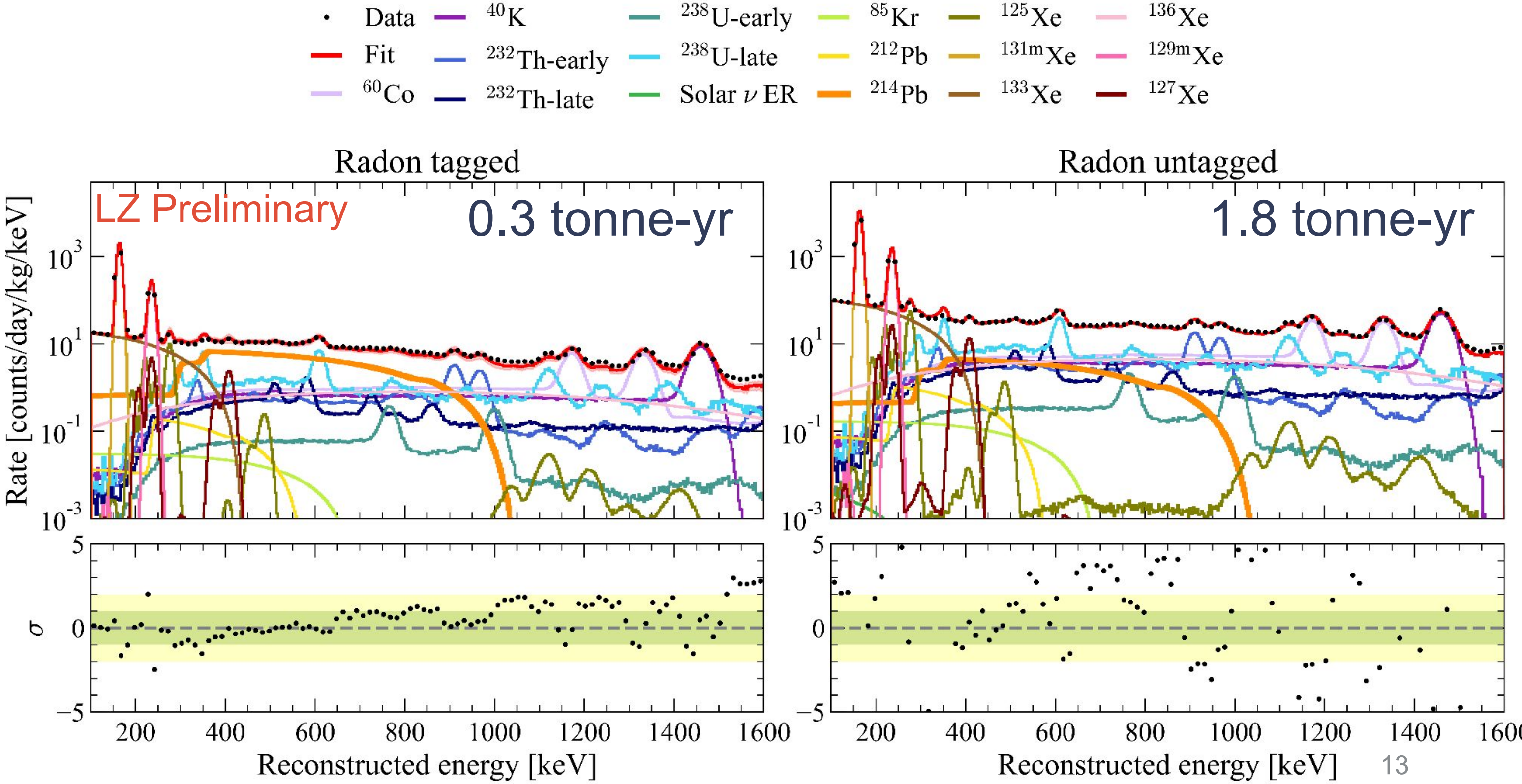


Active tagging of ^{214}Pb



- "Radon tag" uses field & flow model to predict locations of charged and neutral ^{214}Pb
- Reduces ^{214}Pb to **1.8 ± 0.3 μBq/kg in untagged sample** (compare to 3.9 ± 0.6 μBq/kg in total exposure)
- **Tagged & untagged samples used in final inference**
  - no 'loss of exposure'

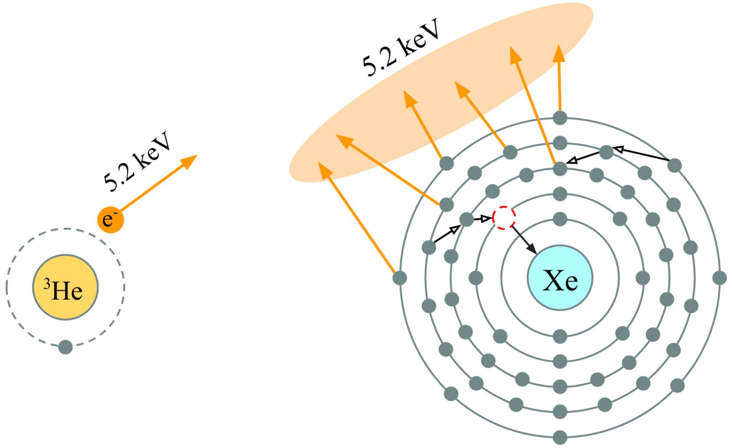
	% of ^{214}Pb	% of Exposure
Tagged	60±4	15
Untagged	40±4	85



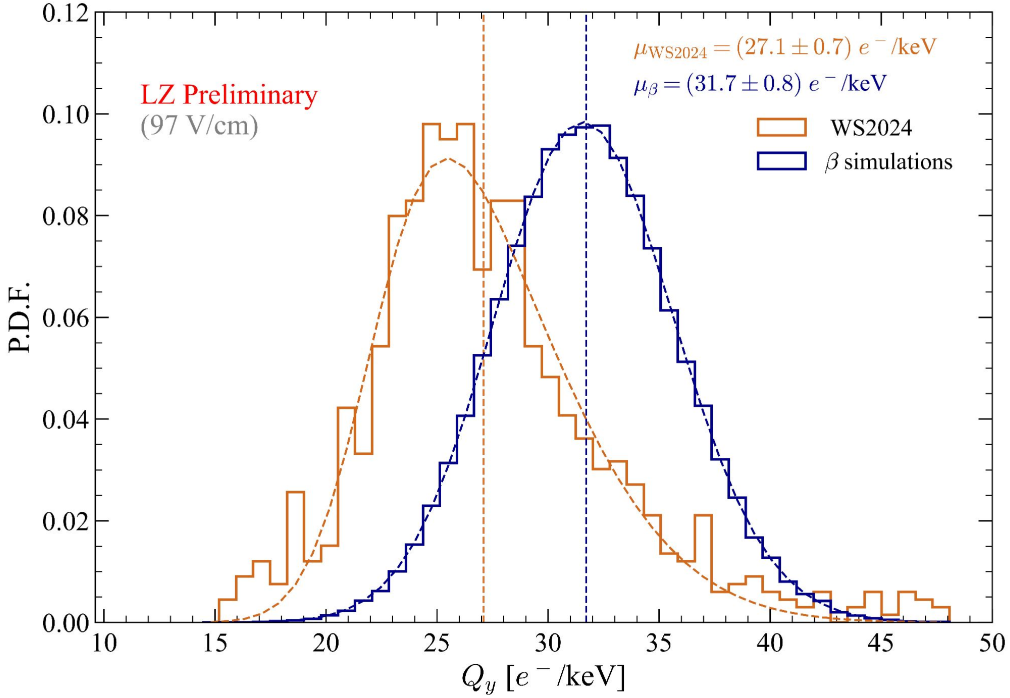
Electron Capture (EC) Decay Backgrounds

Single EC: ^{127,125}Xe - NR calibration activation
Double EC: ^{124}Xe - 0.095% nat. abundance

X-ray+Auger from L-shell (5.2 keV) EC give field-dependent **suppressed charge yield** in comparison to β's of the same energy



Single EC charge yield suppression measured in small chamber* and using LZ *in-situ* in both WS2022 & WS2024



Preliminary** WS2024 ratio: $\mathbf{Q_L/Q_\beta = 0.86 \pm 0.01}$

*Temples et al, *Phys. Rev. D* **104**, 112001 (2021)

**dedicated publication on these measurements in progress

Modeling ^{124}Xe Double Electron Captures

Primary ^{124}**Xe signals** in WIMP region are LM and LL capture @ **5.98 keV & 10 keV**

***in-situ* rate measurement** of half-life uses KK, KL, KM, KN capture peaks:

- expect **19.4 ± 3.9 events** [7.1 (LM-shell) + 12.3 (LL-shell)]

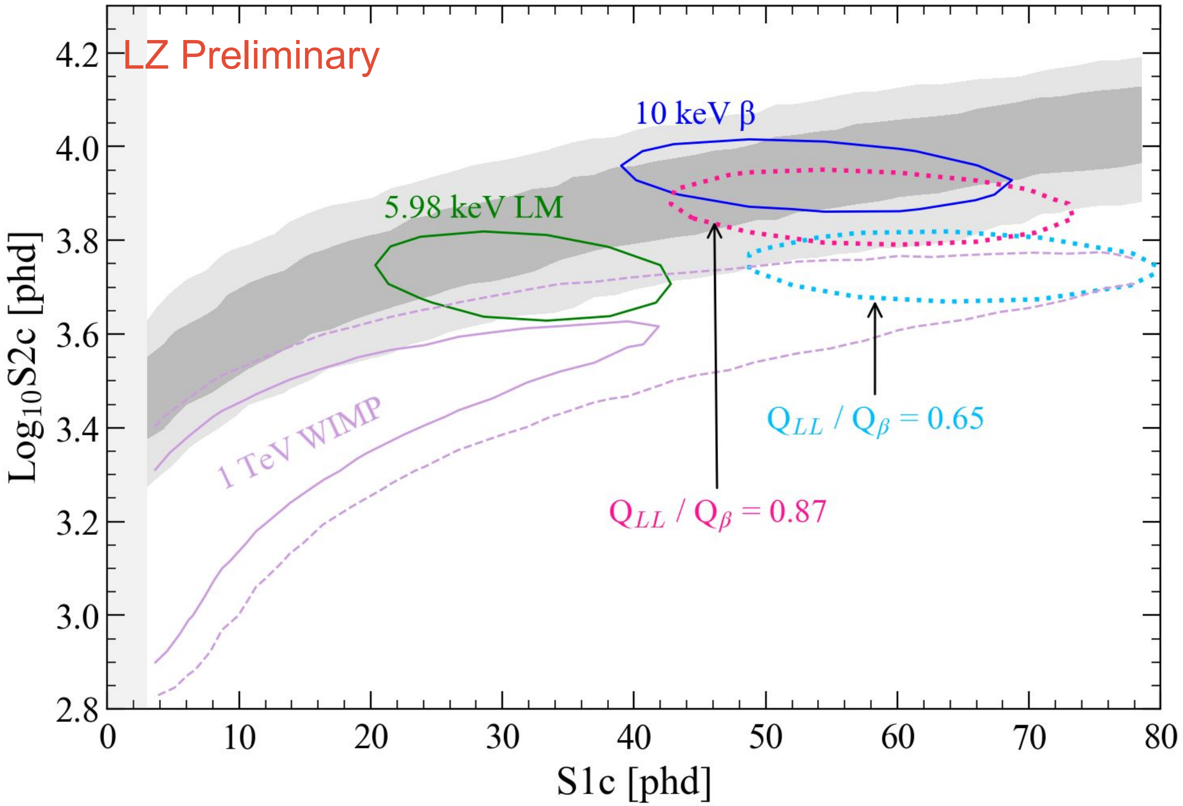
Expect LL captures display further charge yield suppression due to increased ionization density relative to single-L capture

→ **Background model allows ^{124}Xe LL-capture suppression to vary:**

$$0.65 < Q_{LL}/Q_{\beta} < 0.87$$

2x L-shell ionization density (→ 0.65)

L-shell capture suppression (→ 0.87)



Modeling ^{124}Xe Double Electron Captures

Primary ^{124}**Xe signals** in WIMP region are LM and LL capture @ **5.98 keV & 10 keV**

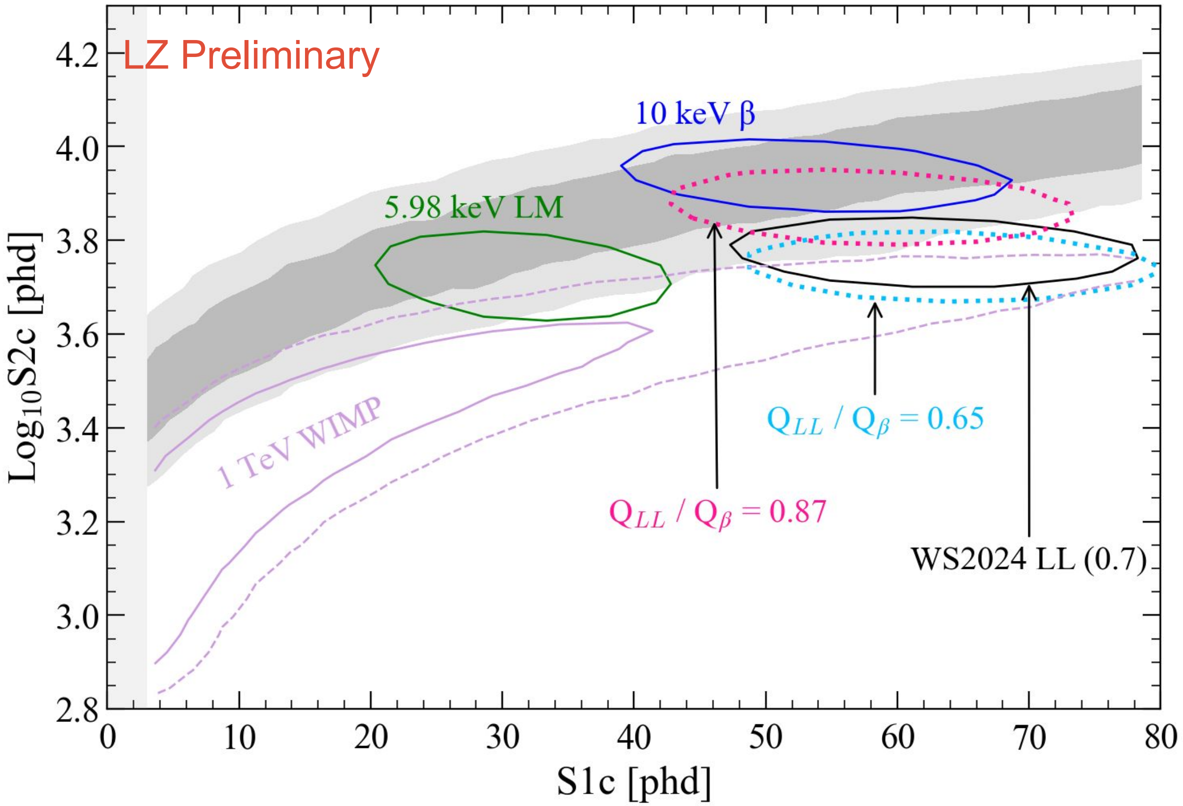
in-situ rate measurement of half-life uses KK, KL, KM, KN capture peaks:

- expect **19.4 ± 3.9 events** [7.1 (LM-shell) + 12.3 (LL-shell)]

Expect LL captures display further charge yield suppression due to increased ionization density relative to single-L capture

Best fit to WS2024 data:

$$Q_{LL}/Q_{\beta} = 0.70 \pm 0.04$$



Accidental Coincidence Background

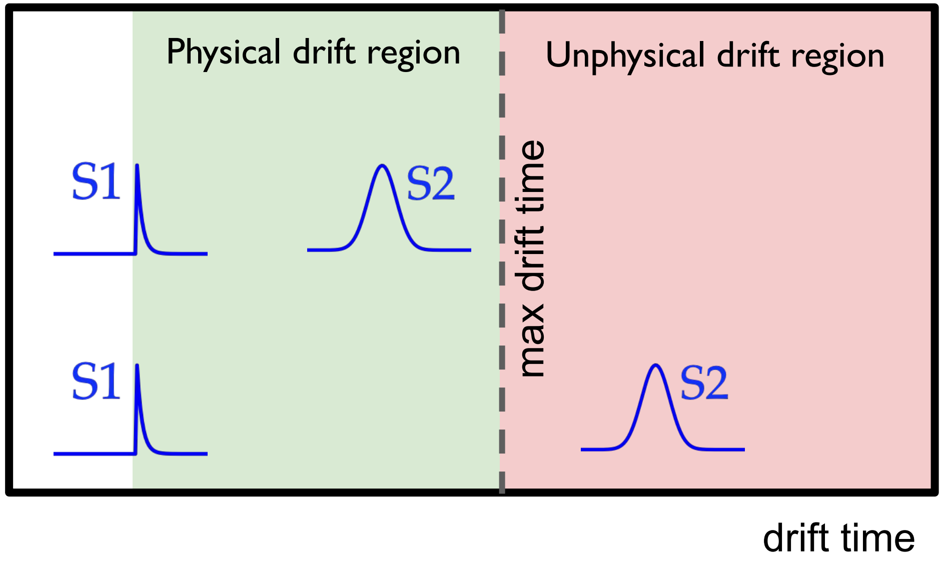
Caused by pile-up of uncorrelated S1 and S2 pulses

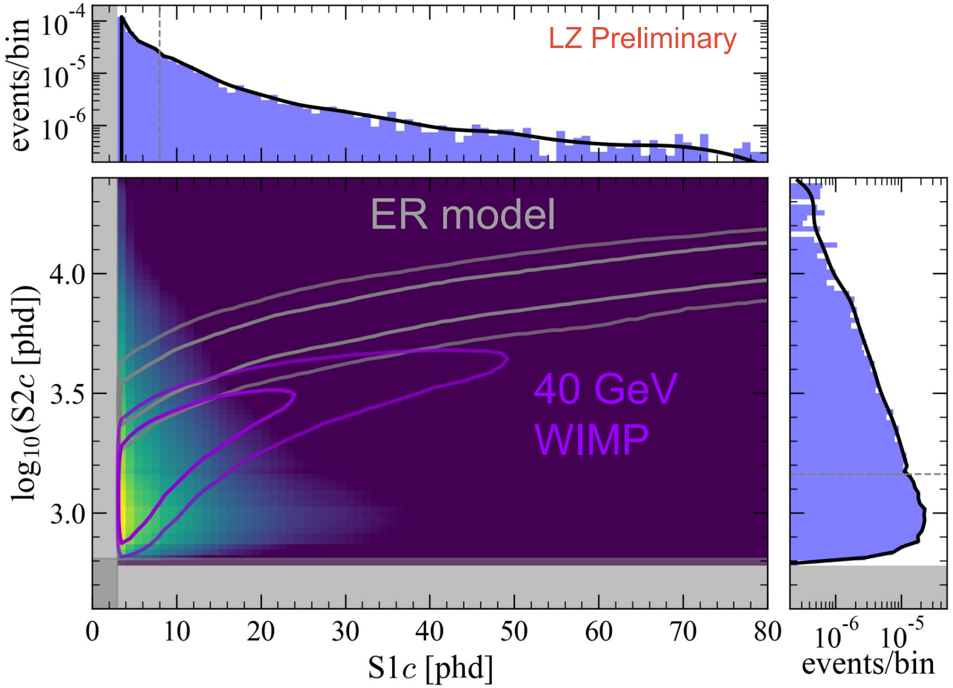
LZ's model is *data driven*:

- ***Rate*** derived from unphysical drift time (UDT) events & cut efficiencies assessed on manufactured accidental events
- ***Shape*** constructed by applying all analysis cuts to manufactured accidental events (combined isolated S1 & S2 waveforms)

Expected counts: 2.8 ± 0.6

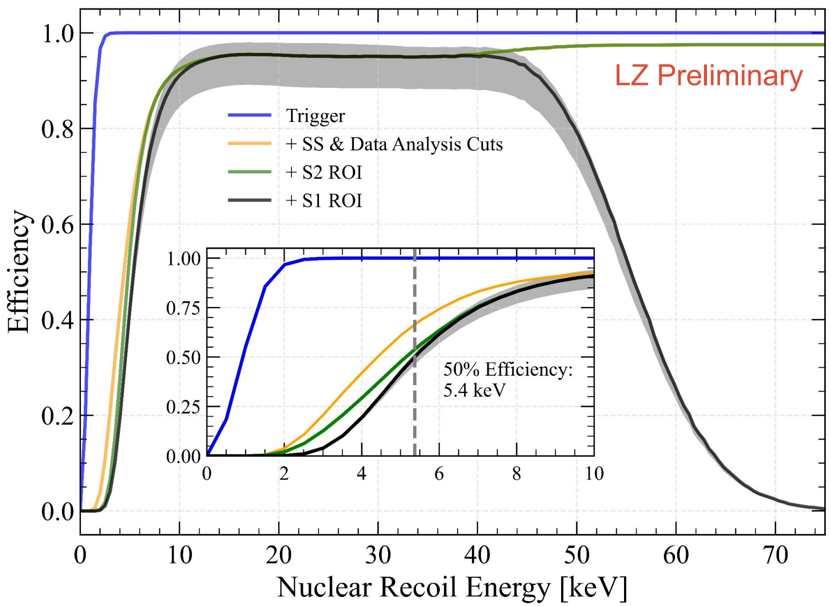
- sys uncert dominated by differences in cut survival fractions between manufactured accidentals and UDTs

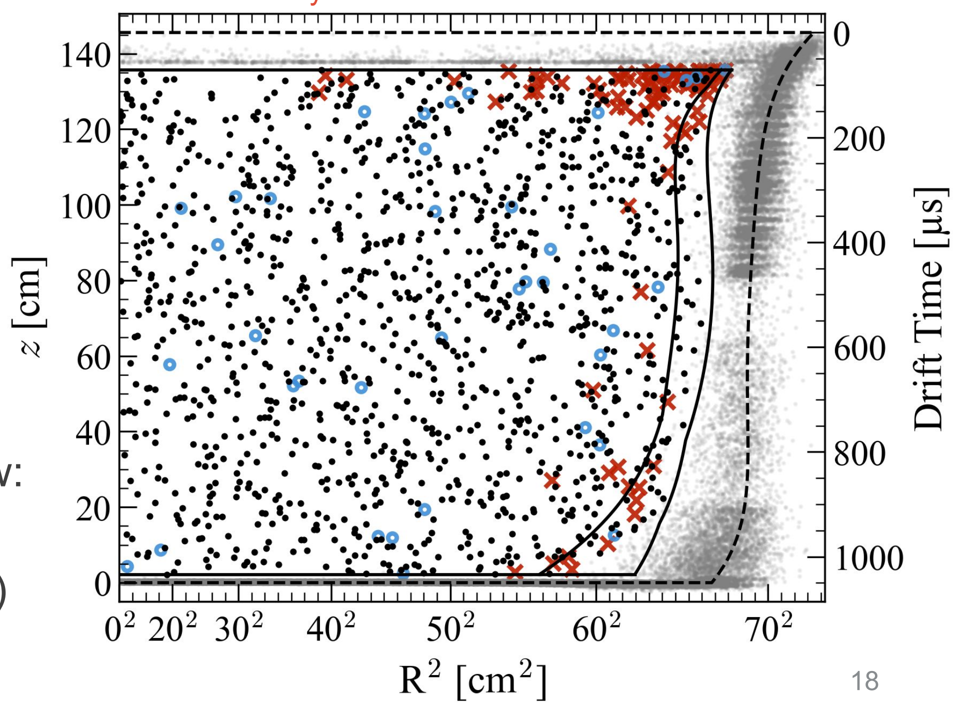




Data selection

- **Time exclusions** remove periods of high-rate, detector instability, hold-off following large S2s (“e-trains”)
  - 86% live time retention
- **S1- & S2-based cuts** target pulse pathologies typical of accidental events
  - Impacts final signal acceptance
  - Quantified with calibration data sets (tritium, AmLi, DD)
- **Fiducial volume cut:** azimuthally & drift time-dependent fiducial volume chosen for <0.01 “wall” events: **5.5 ± 0.2 tonne mass**
- **Skin/OD veto anti-coincidence**

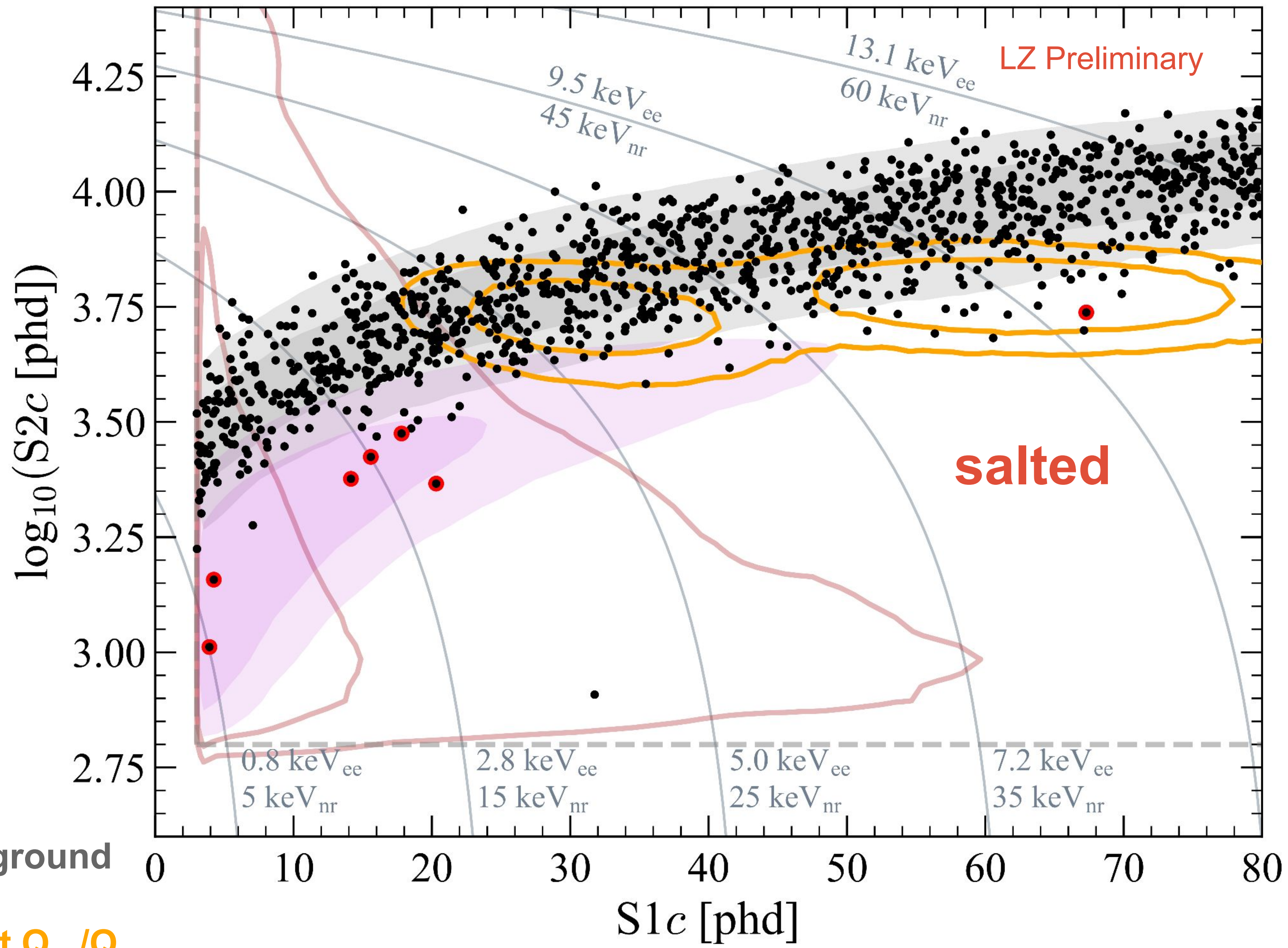




Skin/OD
Coincidence Window:
✕ prompt (300 ns)
○ delayed (600 μs)

WS2024 data set - 7 salt events in red

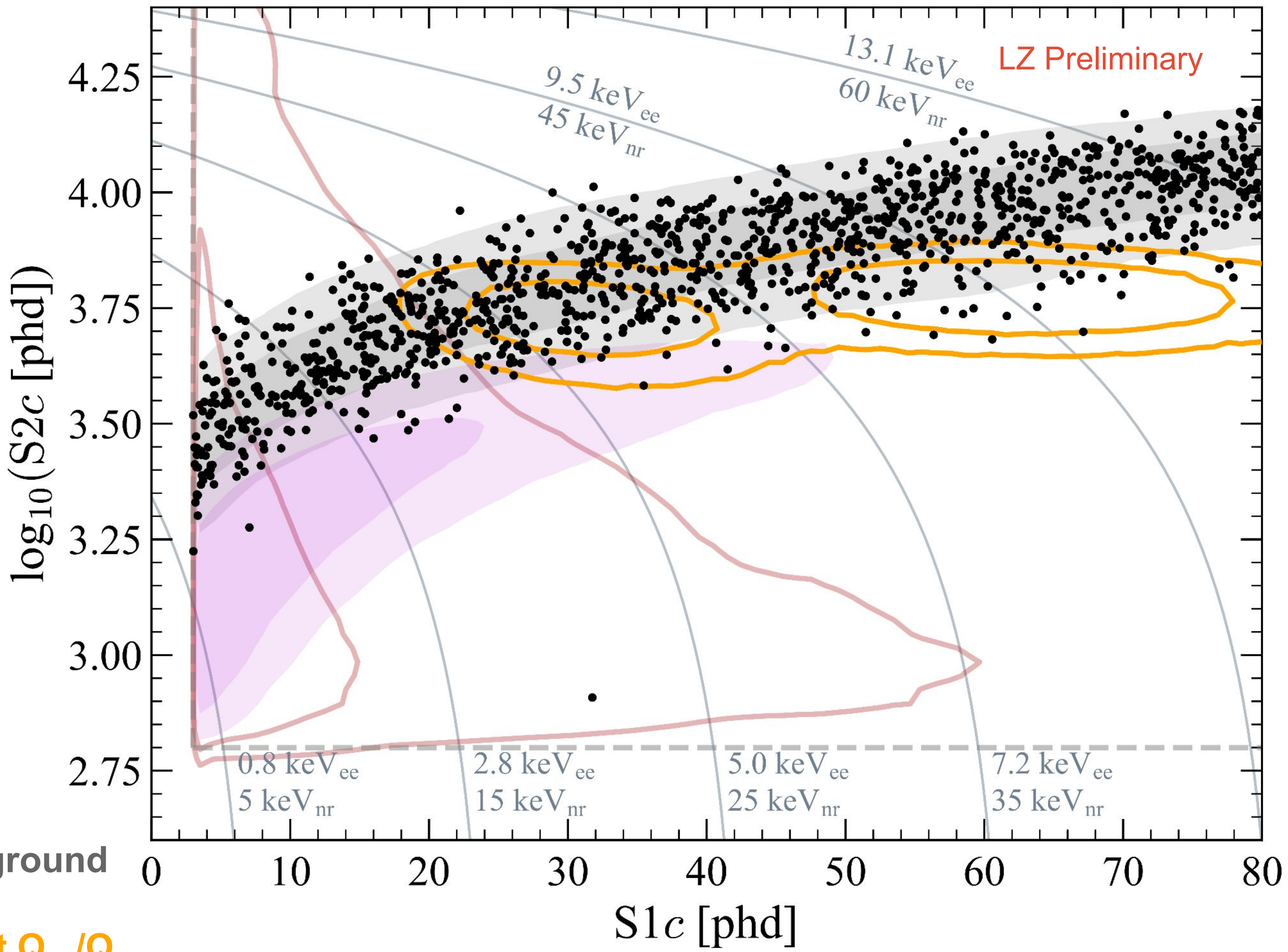
- 8 salt events revealed - **7 of which pass all analysis cuts - consistent with expected efficiency**



Total ER background
Accidentals
^{124}Xe @ best-fit Q_{LL}/Q_{β}
40 GeV/c^2 WIMP

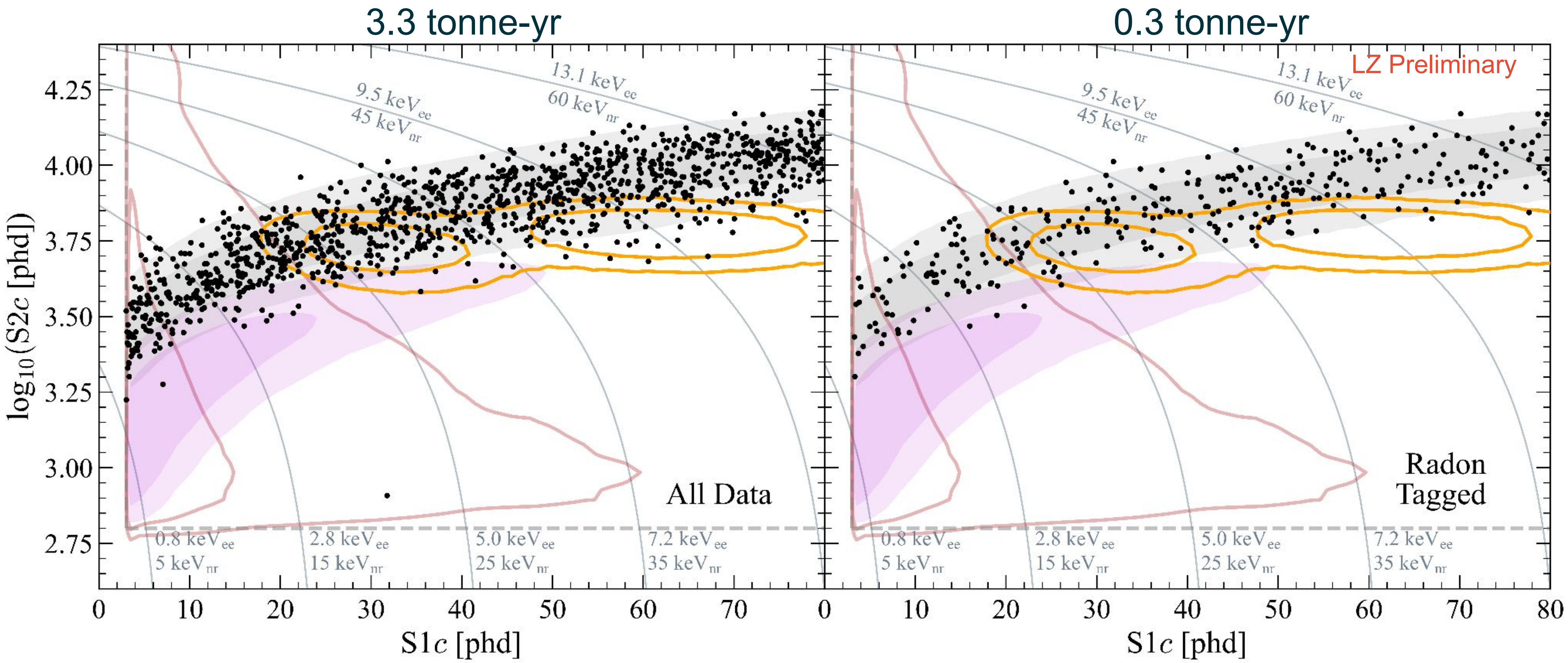
WS2024 final data set - salt removed

- Likelihood inference region of interest:
  - 3 < S1c < 80 phd
  - S2 > 645 phd (14.5 electrons)*
  - S2c < $10^{4.5}$ phd
- S2 threshold **set above salted ^{8}B & low-mass WIMP region**
- **1220 events** remain after unsalting
- **220 live days x 5.5 t = 3.3 tonne-yr**



Total ER background
Accidentals
^{124}Xe @ best-fit Q_{LL}/Q_{β}
40 GeV/c^2 WIMP

WS2024 Final Dataset - all data & Rn-tagged set



Radon tagged (^{214}Pb rich) sample
<u>does not</u> contain leakage from ^{124}Xe

Total ER background
Accidentals
^{124}Xe @ best-fit Q_{LL}/Q_{β}
40 GeV/c^2 WIMP

Breakdown of combined likelihood

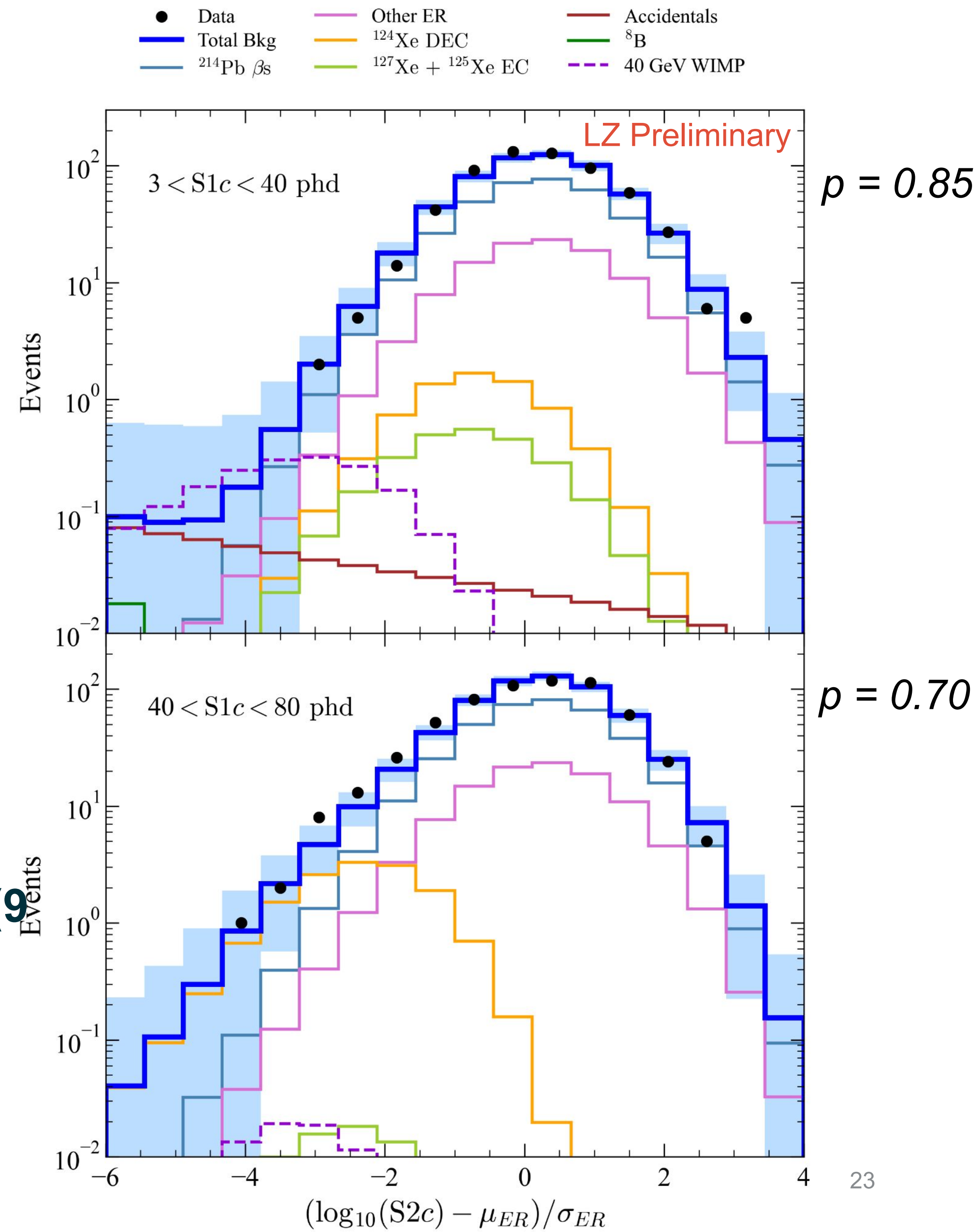
	1	2	3	4	5	6
	High Mixing	**Radon Tag Inactive**	**Radon Tagged**	**Radon Untagged**	**Skin/OD Vetoed**	**WS2022**
Exposure [tonne-yr]	0.6	0.6	0.3	1.8	n/a	0.9

- Likelihood combines **six samples** for final analysis
- WS2024: samples 1-4, **totaling 3.3 tonne-year**
- Skin/OD-tagged sample (5) provides **direct constraint of neutron background** rate
    - neutron tagging efficiency: 92 ± 1%
- WS2022 sample (6) unmodified 1st WIMP result → maximize sensitivity

WS2024 Fit Results

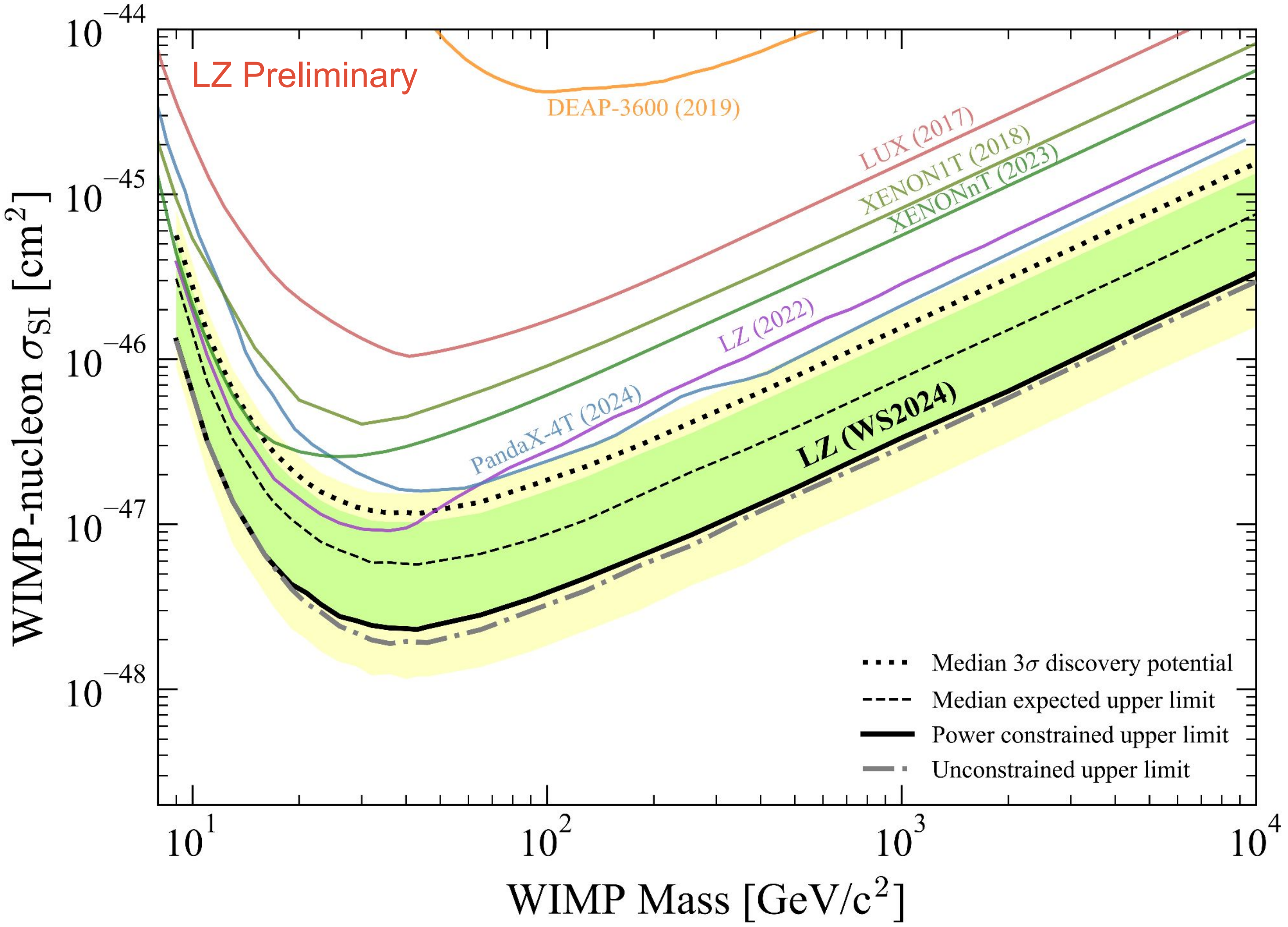
Source	Pre-fit Constraint	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
Solar ν ER	102 ± 6	102 ± 6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 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

- **Best fit of *zero* WIMPs at all tested masses (9 GeV – 10 TeV)**
- **Excellent agreement w/ background-only model**



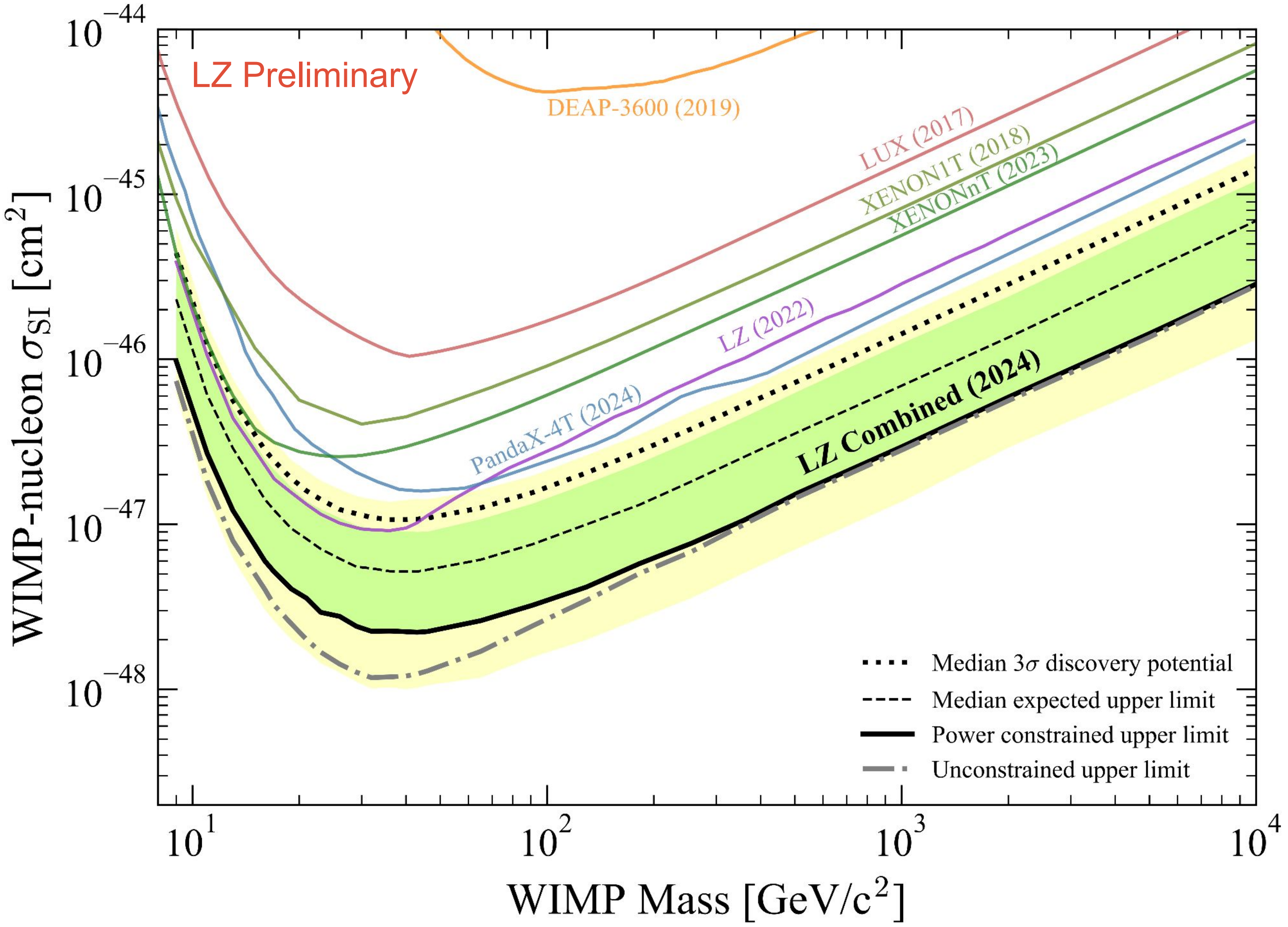
WS2024-only Spin Independent Limit

- Frequentist, 2-sided profile likelihood ratio test statistic
- Upper limit is power constrained @ -1σ sensitivity band per DM conventions: *EPJC* **81** 907 (2021)
- Under fluctuation results from observed arrangement of accidental events in WIMP region
- **WS2024-only min cross section: σ_{SI}= 2.3 x 10^{-48} cm^2 @ 43 GeV/c^2**

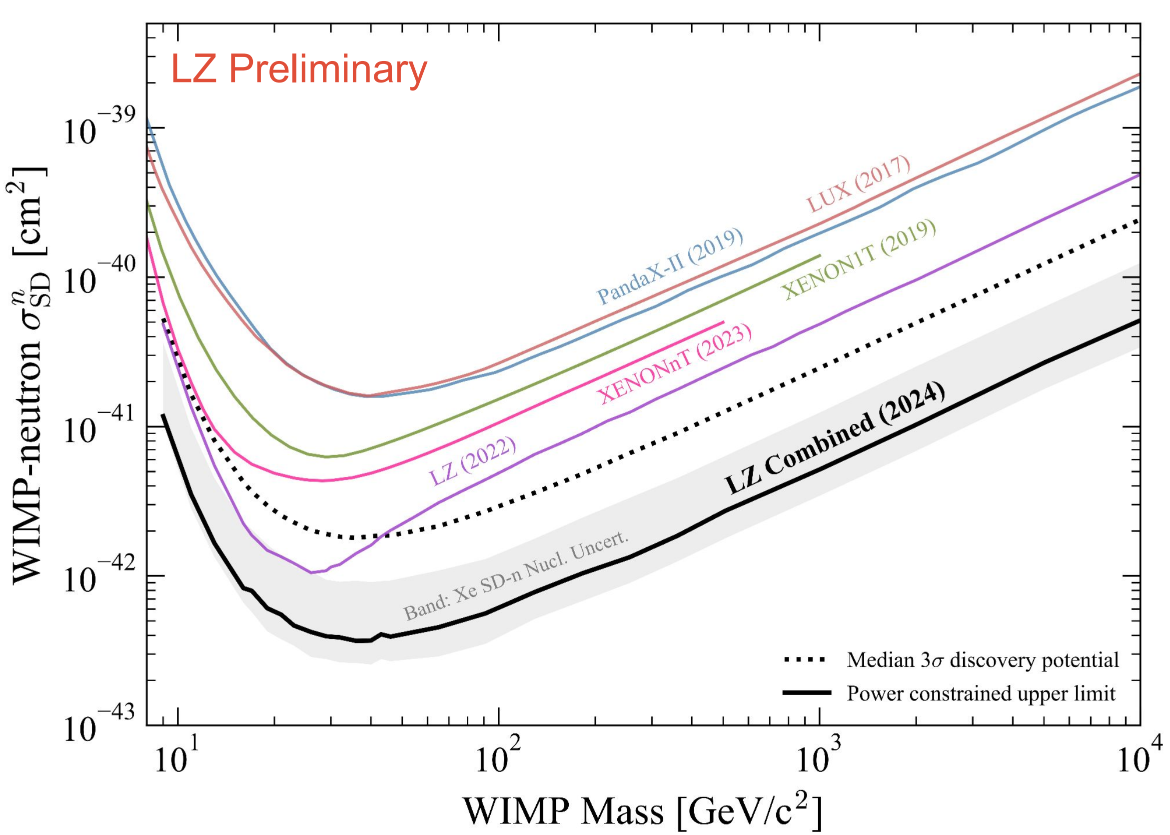


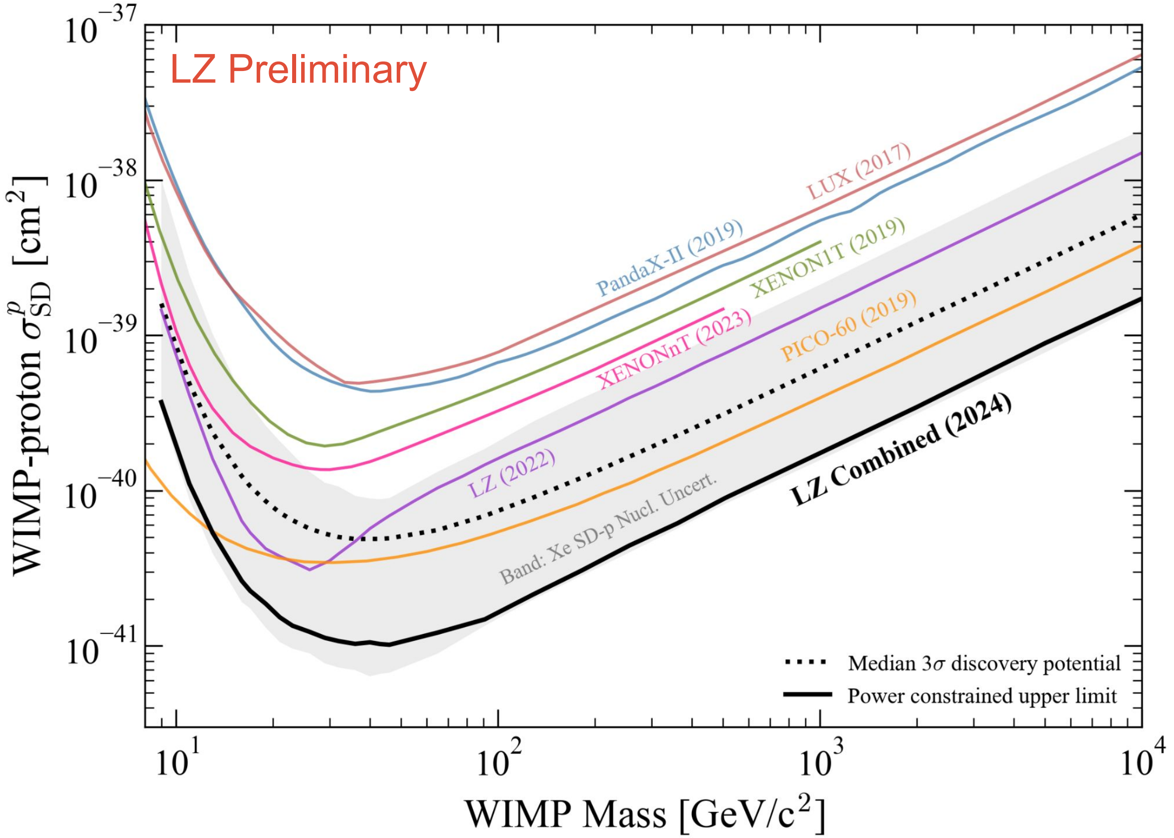
WS2024+WS2022 Combined Spin Independent Limit

- Frequentist, 2-sided profile likelihood ratio test statistic
- Upper limit is power constrained @ -1σ sensitivity band per DM conventions: *EPJC* **81** 907 (2021)
- Additional under fluctuation from combination with WS2022
- **Combined min cross section: σ_{SI}= 2.2 x 10^{-48} cm^2 @ 43 GeV/c^2**



WS2024+WS2022 Combined Spin Dependent Limits





Grey bands show theoretical uncertainties on SD form factors
Solid black show power constrained limits

Conclusions & Outlook

- LZ is the **world's most sensitive WIMP direct detection experiment** with combined **total exposure of 4.2 tonne-year**
- Demonstrated **60% reduction of primary ER background** w/ flow-based tagging
  - **First use of this technique for a dark matter result**
- **First observation** of suppressed charge yield from LL-shell captures of ^{124}Xe
- **LZ continues to take quality science data** with 'salt' events injected for active bias mitigation - data collection continues to 2028
- Many **physics searches on the horizon**: ^{8}B CEνNS, low-mass WIMPs, ER-based searches, neutrinoless double beta decay, and more*!

**See Yongheng Xu's talk on LZ's millicharged particle search this afternoon*

Thank you!

Thanks to our sponsors and
38 participating institutions!

U.S. Department of Energy
Office of Science

UKRI Science and Technology Facilities Council

SANFORD UNDERGROUND RESEARCH FACILITY

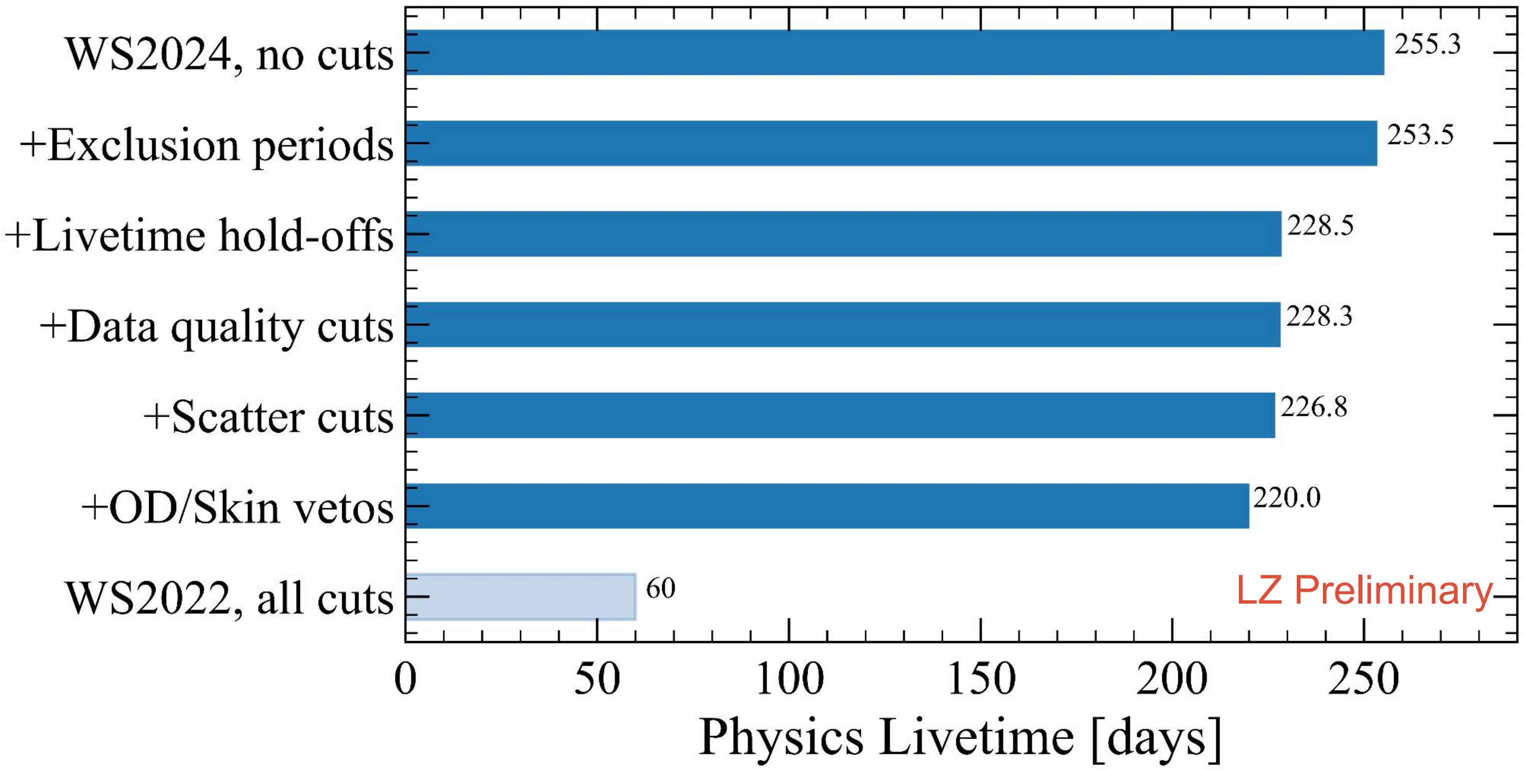
fct Fundação para a Ciência e a Tecnologia

ibs Institute for Basic Science

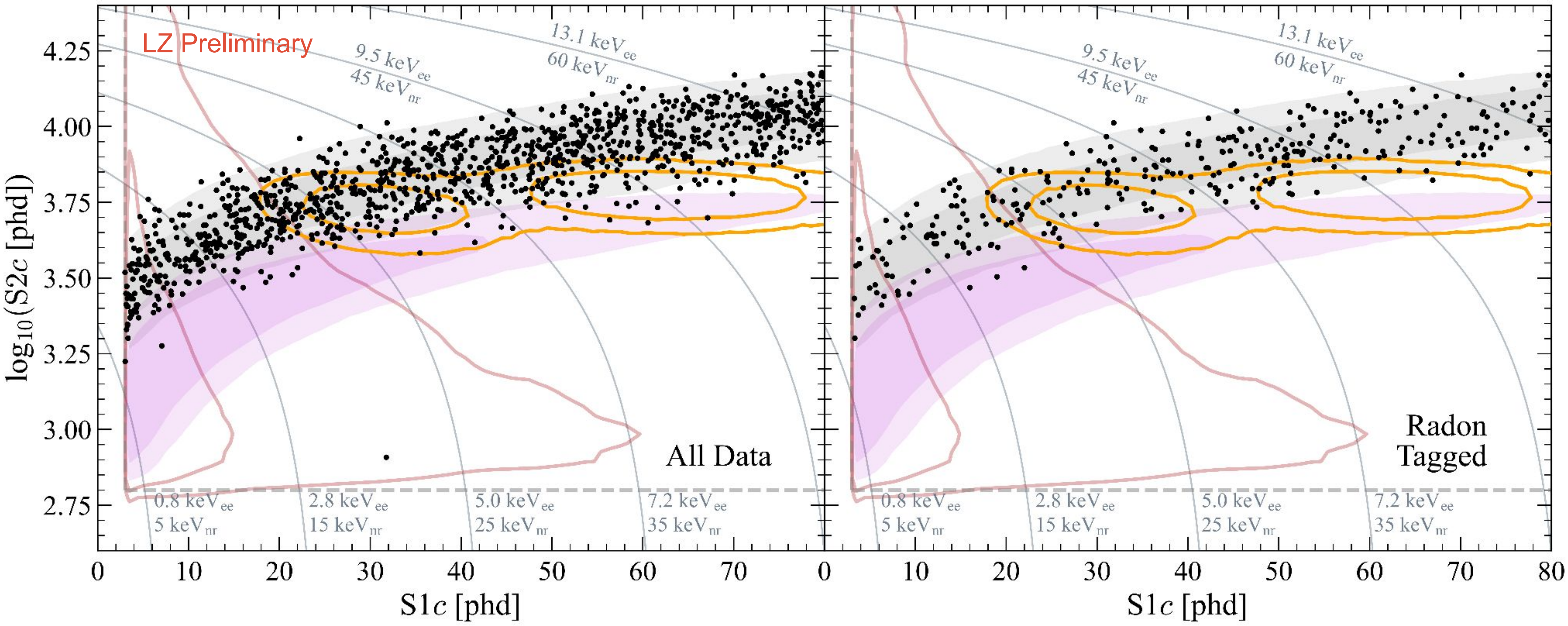
Swiss National Science Foundation

Additional slides

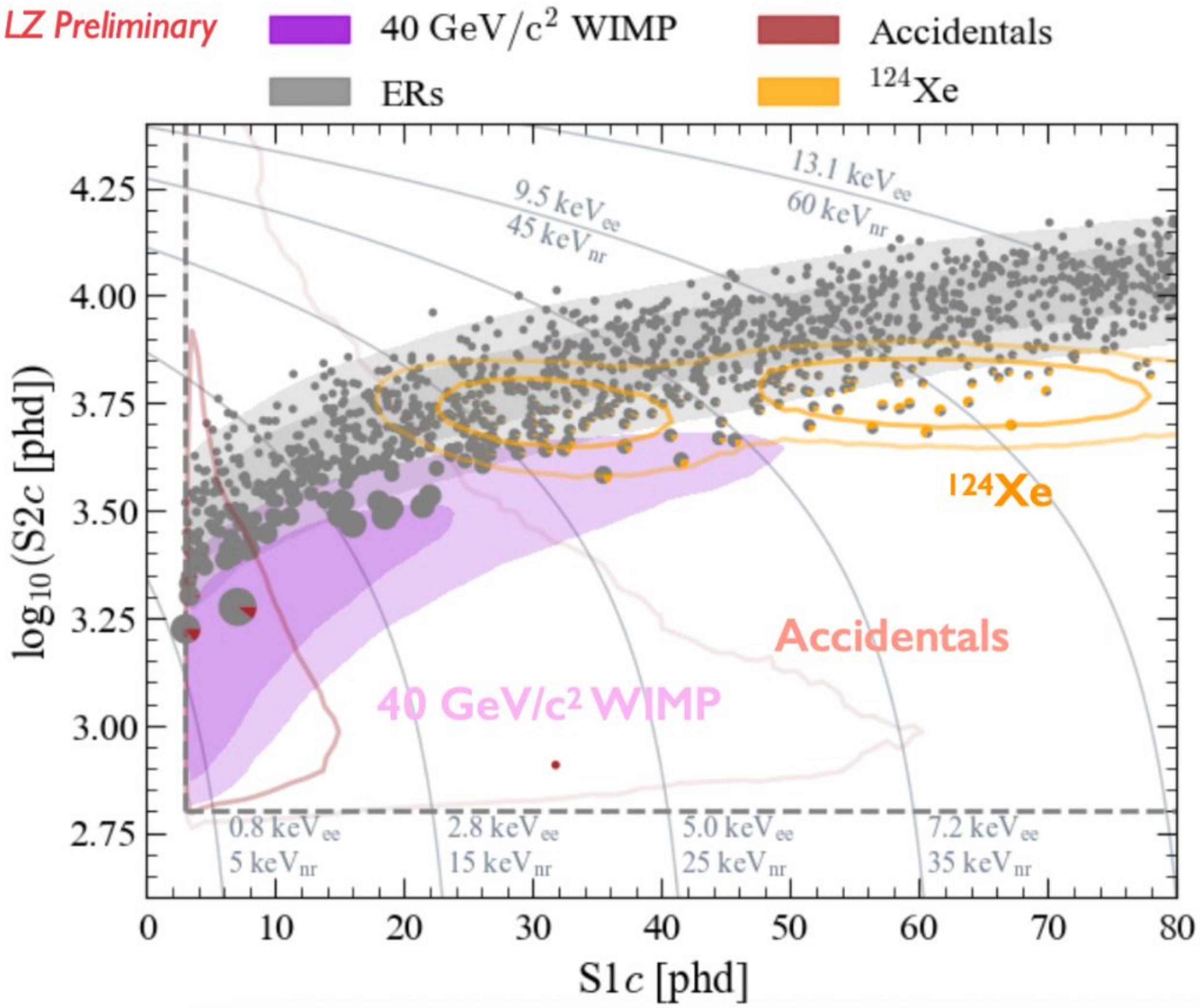
Livetime removal for data quality

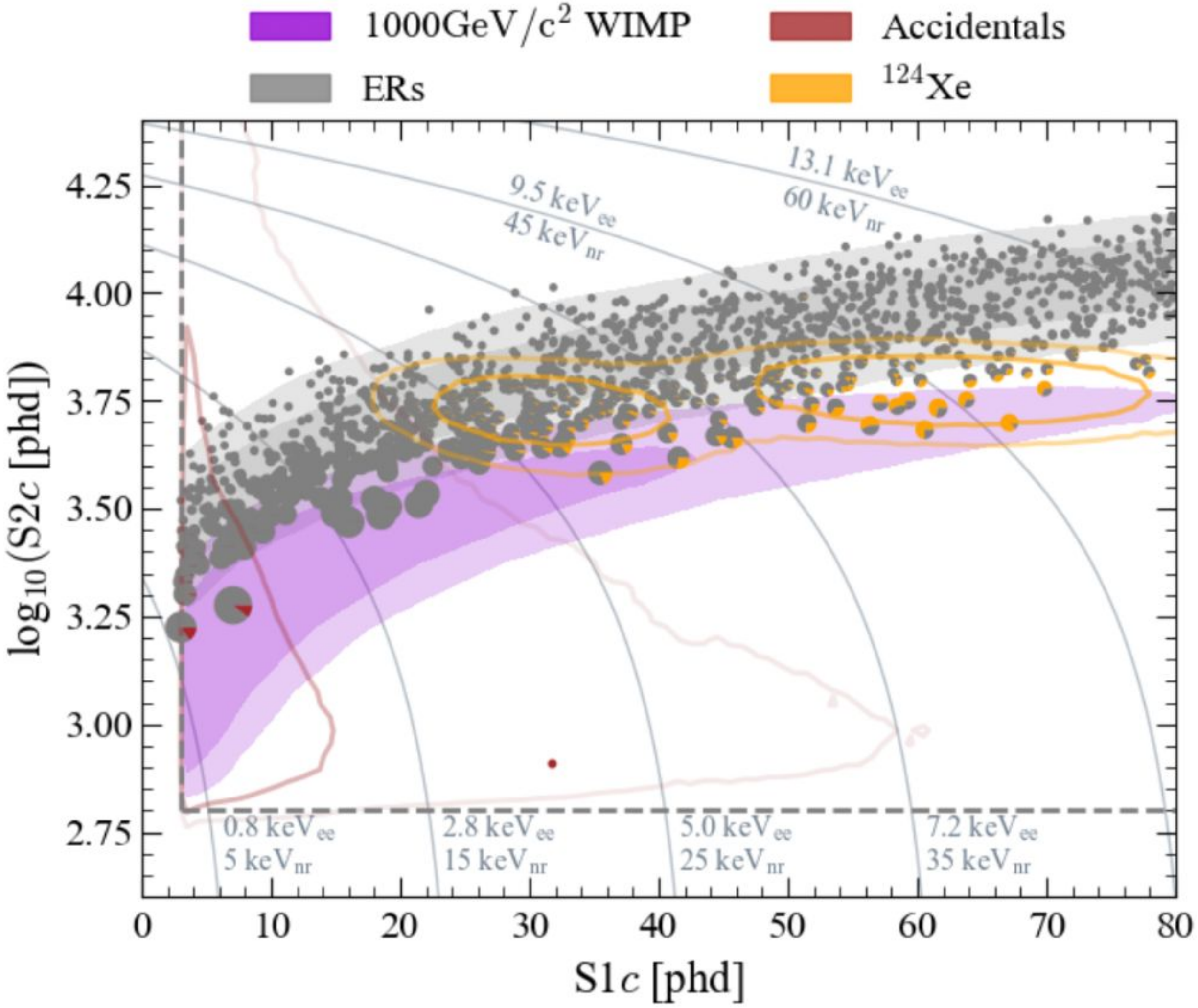


10 TeV/c^2 WIMP

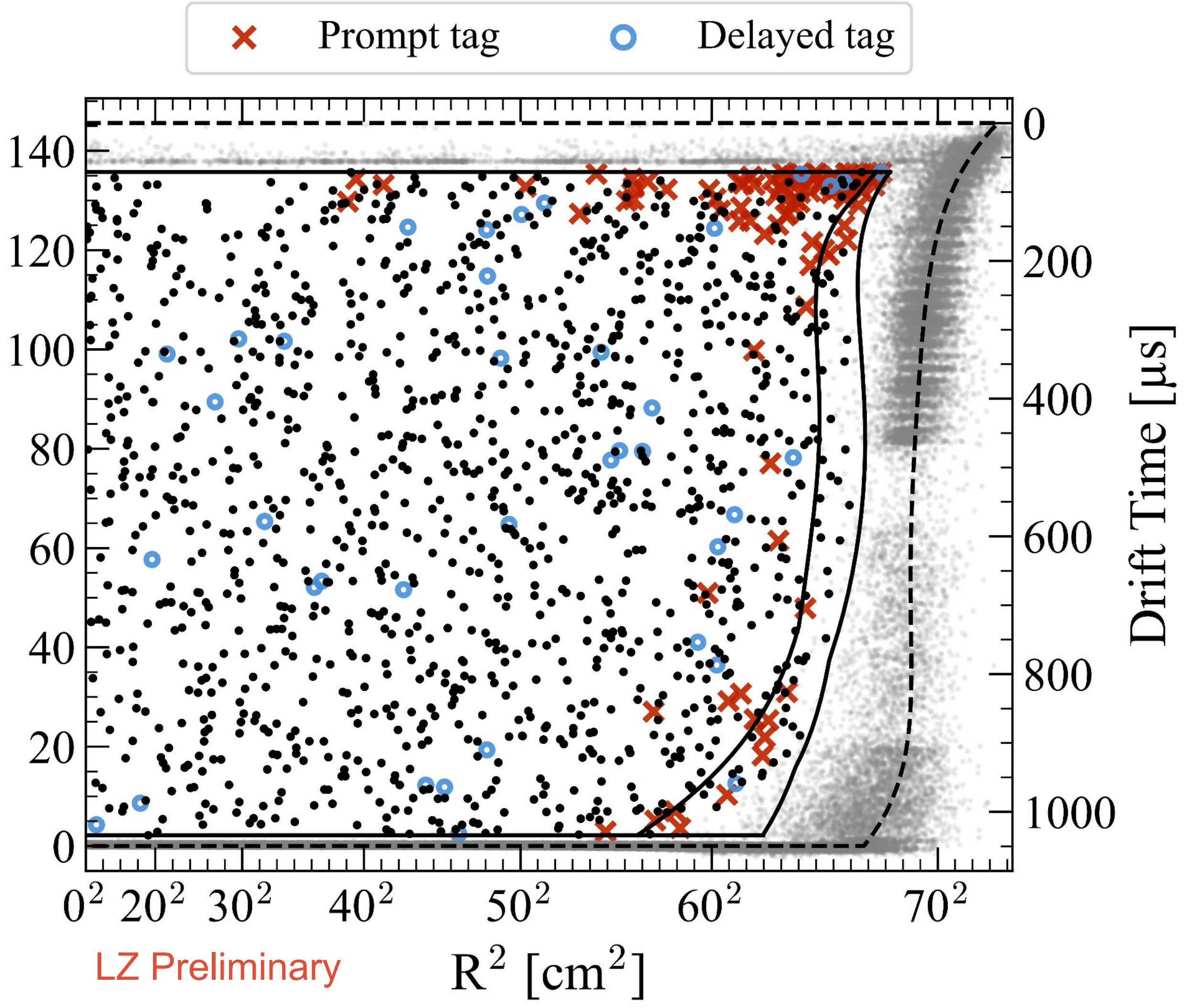


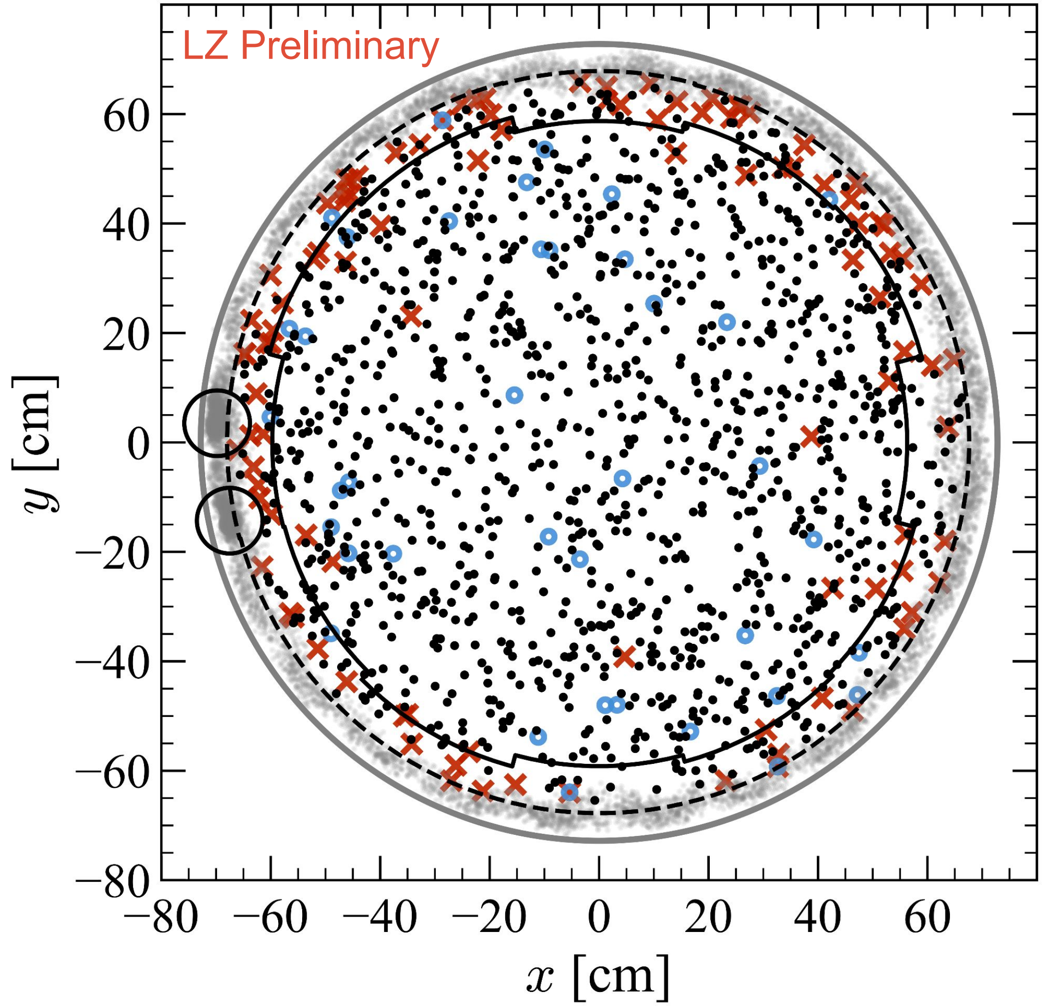
Pie Chart Plots



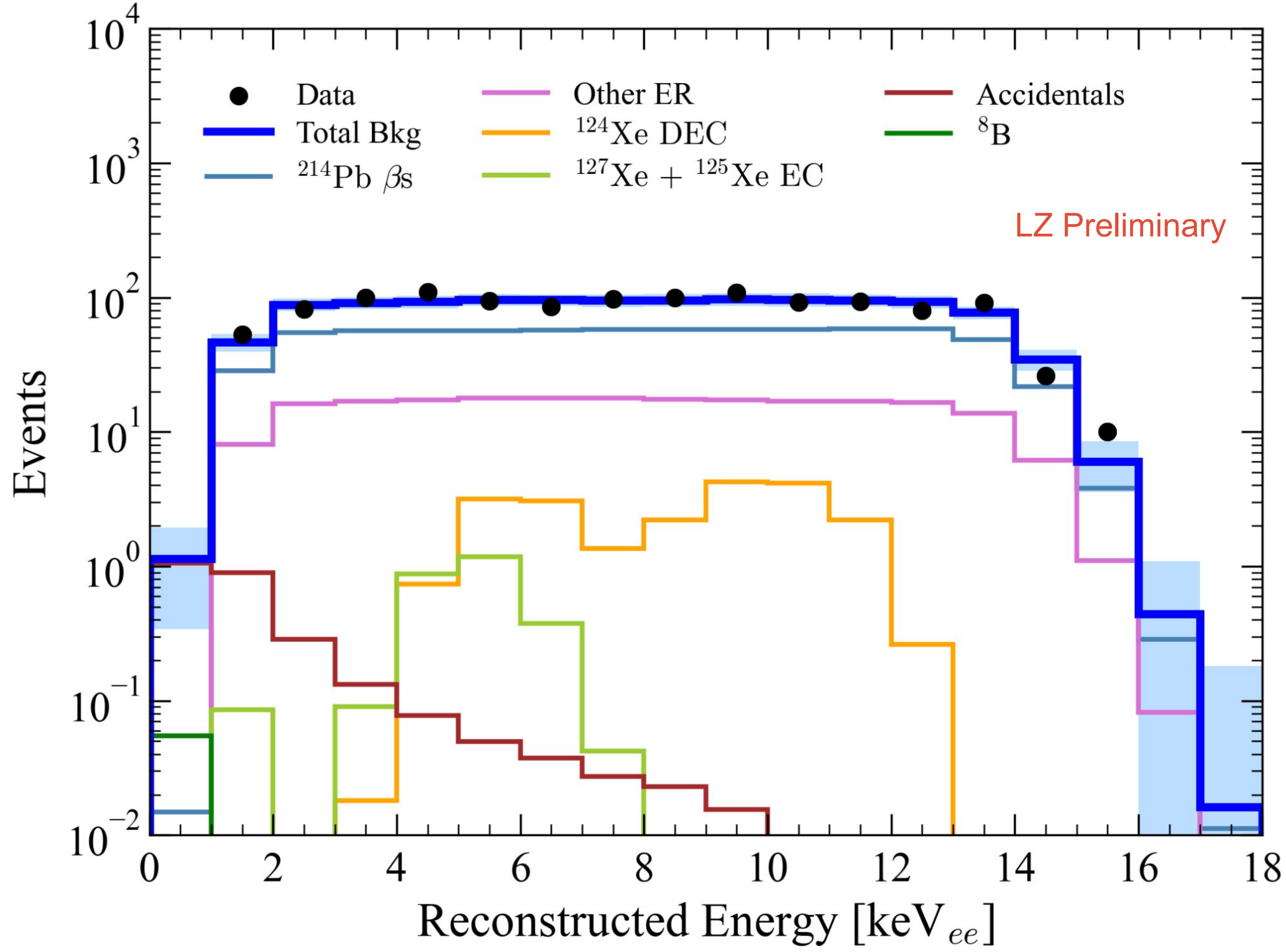


WS2024 data - spatial distributions





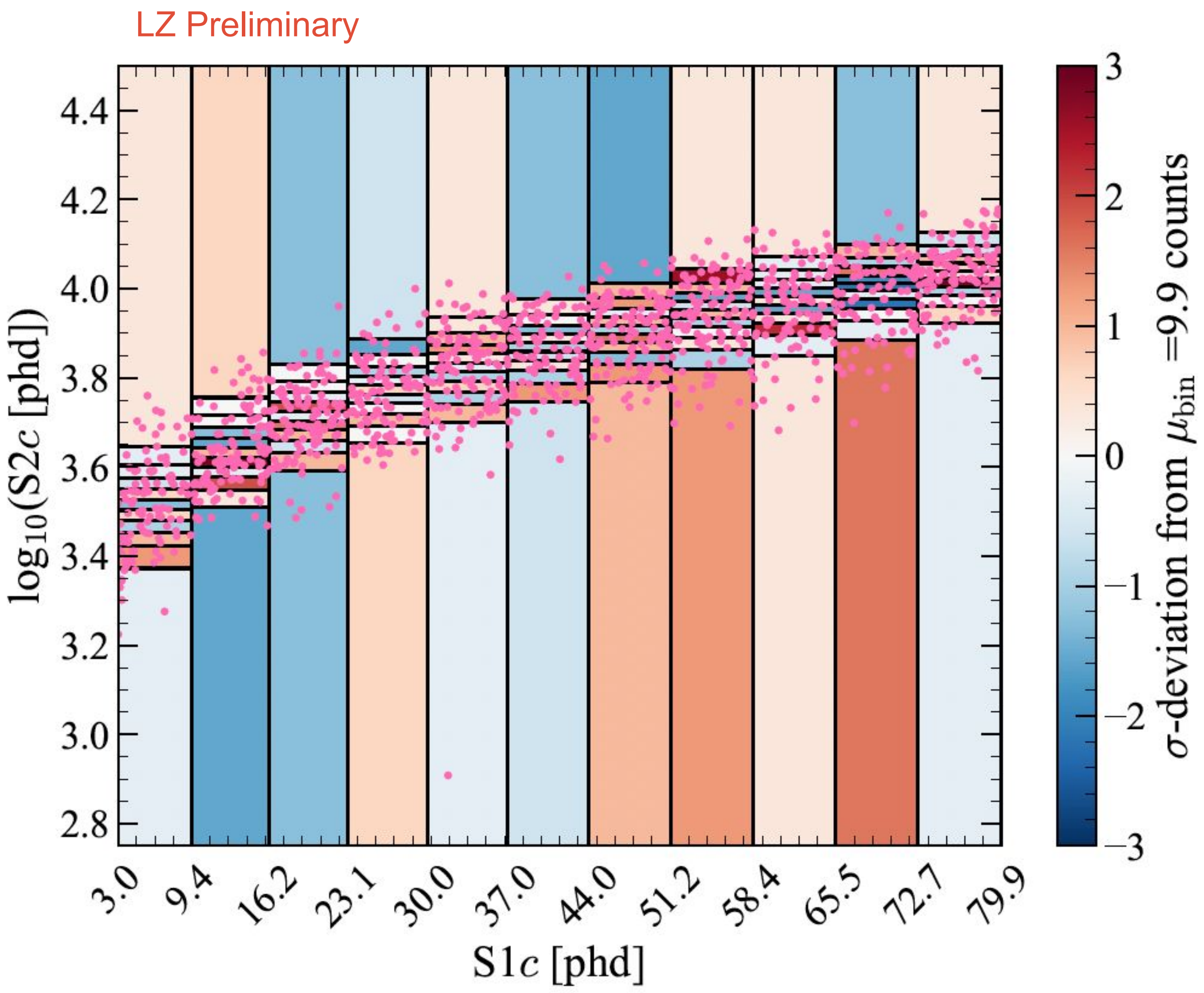
Reconstructed Energy in WIMP Region



p = 0.28

2D goodness-of-fit

p = 0.19



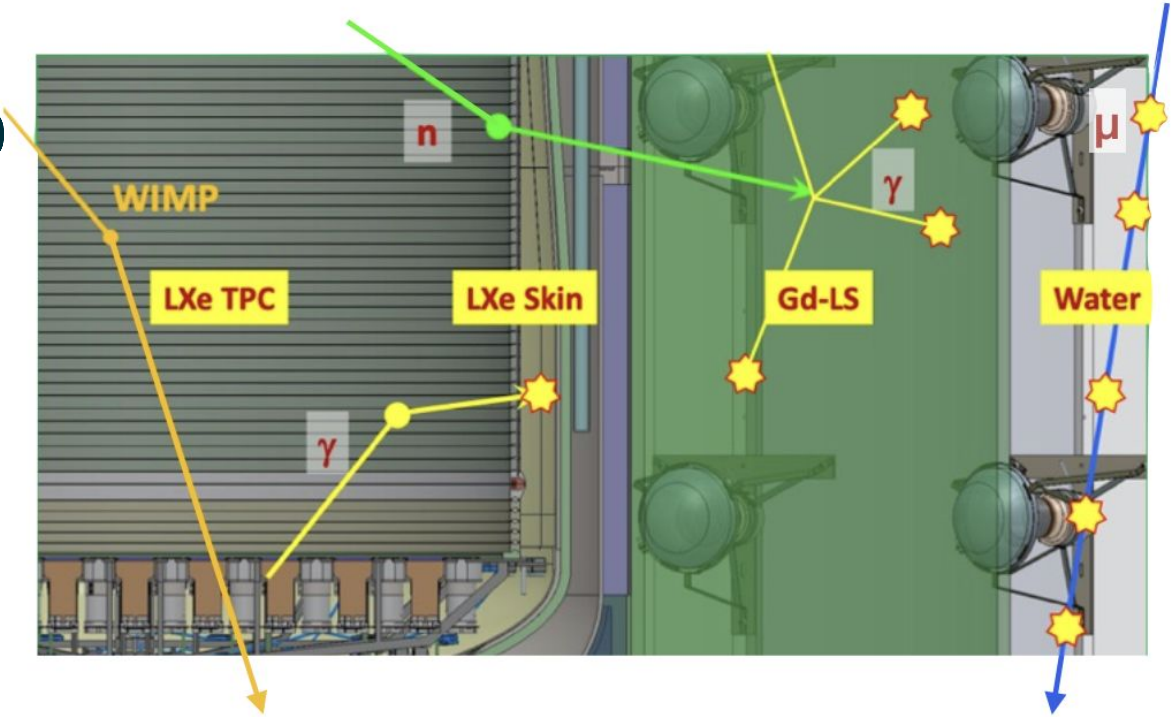
Likelihood Breakdown

$$\mathcal{L}_{\text{Combined}} =$$

$\mathcal{L}_{\text{WS2022}}$	models+data from 1st LZ result [*PRL* 131, 041002 (2023)]
$\times\ \mathcal{L}_{\text{High mix}}$	events in high mixing circulation state, contains residual ER calibration events
$\times\ \mathcal{L}_{\text{Rn veto inactive}}$	events in times when Rn-Po flow mapping not reliable (circ. stoppages, etc)
$\times\ \mathcal{L}_{\text{Rn tagged}}$	events in Rn veto periods/regions - rich in ^{214}Pb!
$\times\ \mathcal{L}_{\text{Not Rn tagged}}$	complement of above - depleted in ^{214}Pb & rich in *signal*
$\times\ \mathcal{L}_{\text{Skin+OD tagged}}$	events w/coincident activity in Skin & OD vetoes - provides direct constraint on neutron background rate

Neutrons & Outer Detector Veto

- **Delayed veto cut** extends to 600 μs w/ 200 & 300 keV OD & skin thresholds to include n-capture on Gd & H
  - capture on Gd gives ~8 MeV in the form of 4-5 gammas on avg
  - capture on H gives single, 2.2 MeV gammas

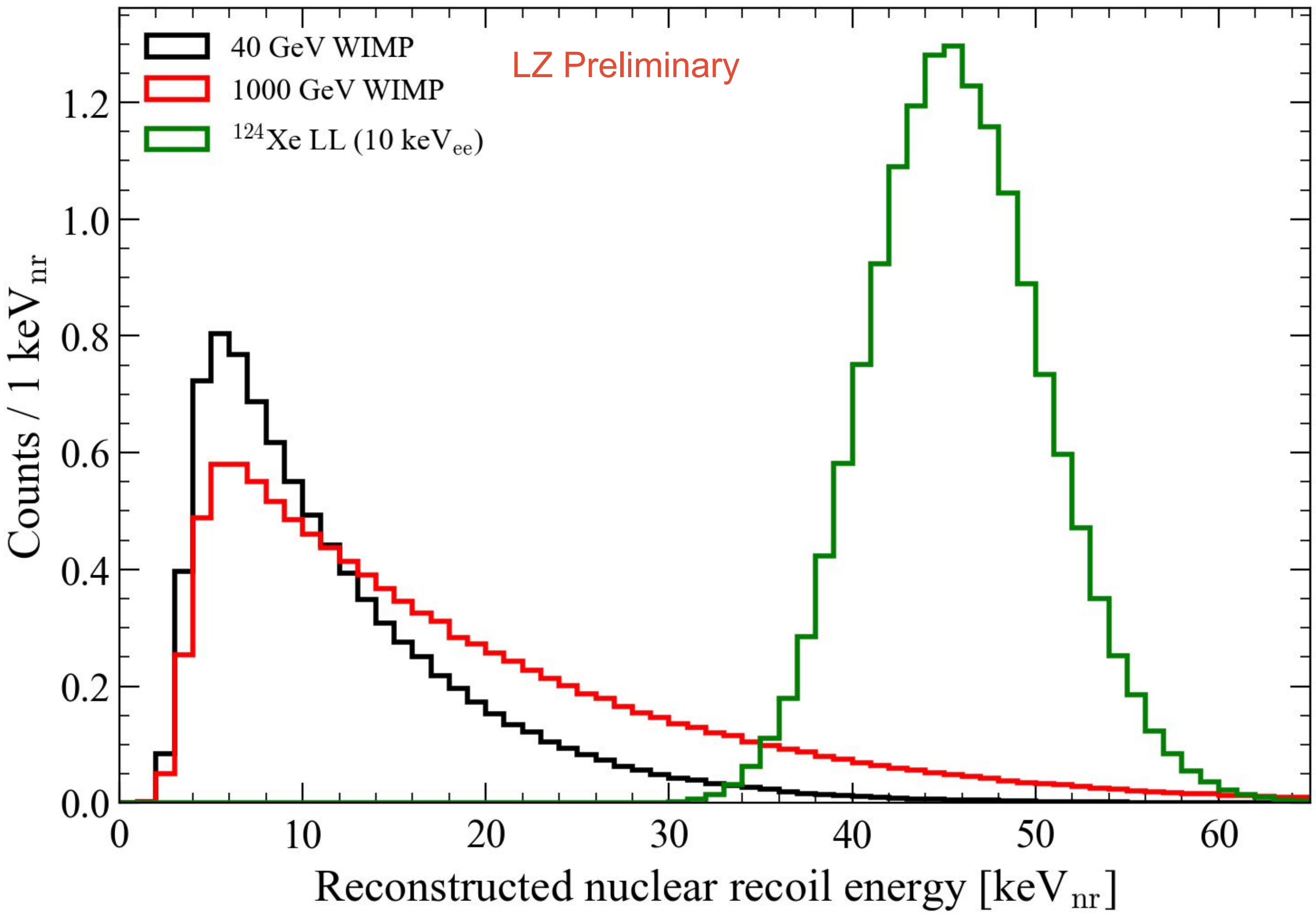


- Measured tagging efficiency for AmLi neutrons: **89 ± 3%**
- Predicted tagging efficiency from tuned simulation of background (SF & (α,n)) neutrons: **92 ± 1%**
  - Accidental tag rate of 3%
  - Used to directly constrain neutron rate in final inference

^{124}Xe LL-shell compared to dark matter spectra

WIMP spectra normalized to LZ's 4.2 tonne-yr median 3σ discovery potential:

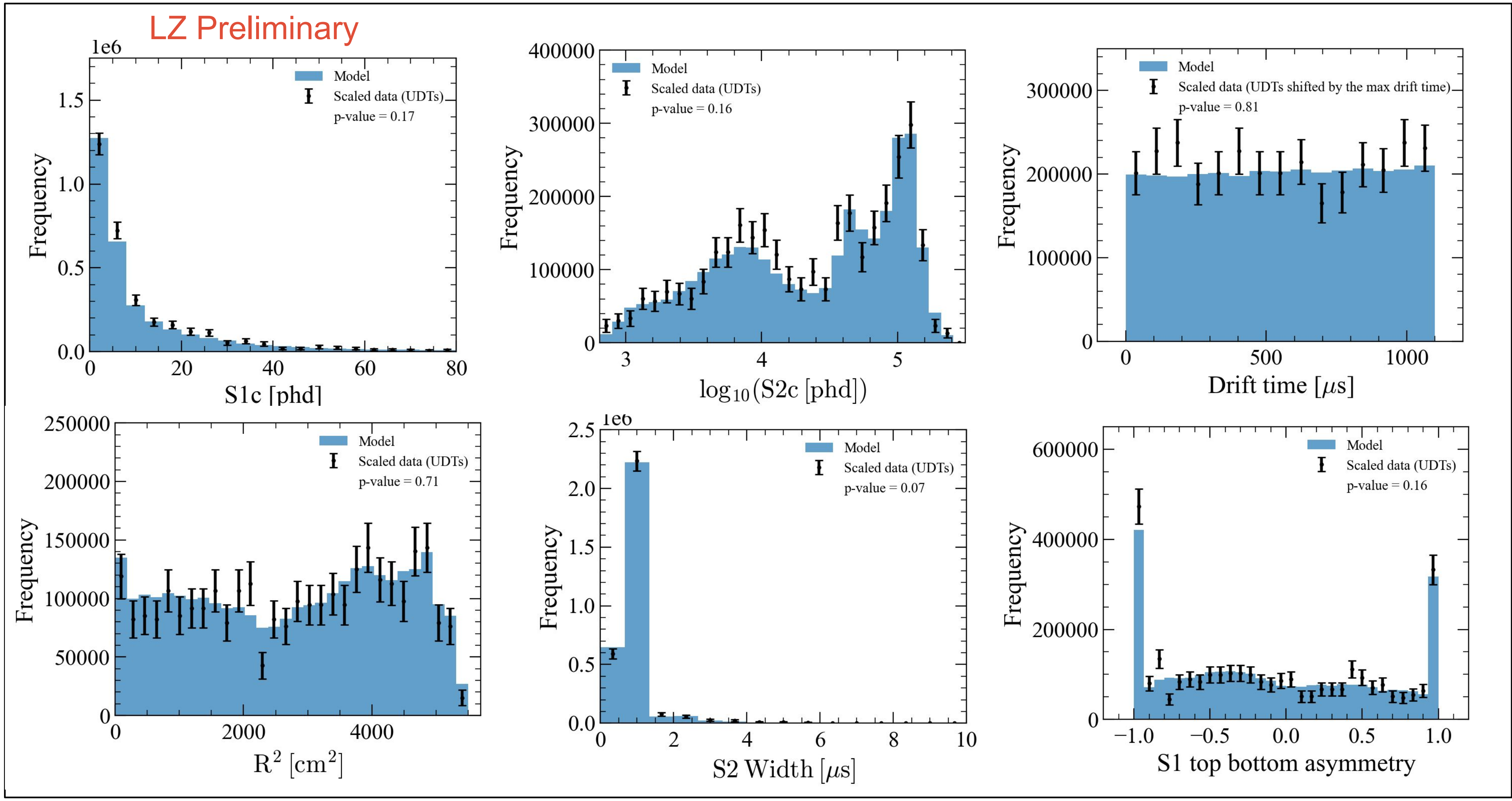
- 9 evts @ 40 GeV
- 11 evts @ 1000 GeV



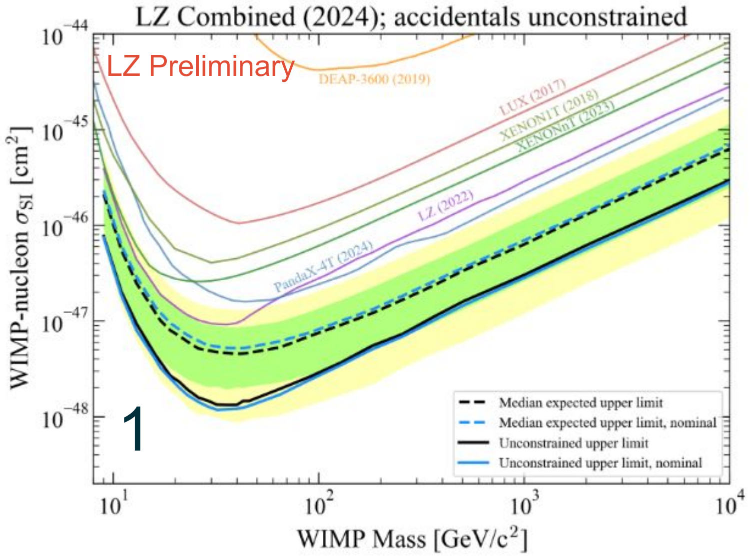
Accidentals: model & unphysical drift sideband comparisons

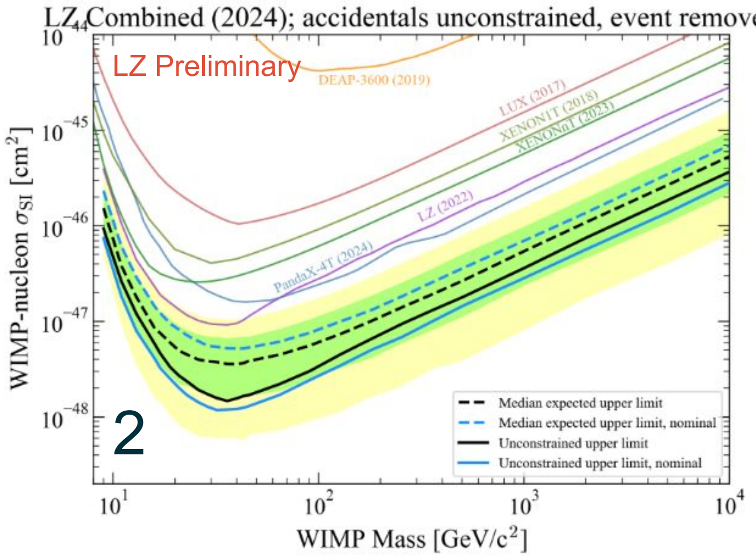
Comparing manufactured accidental events and unphysical drift accidentals

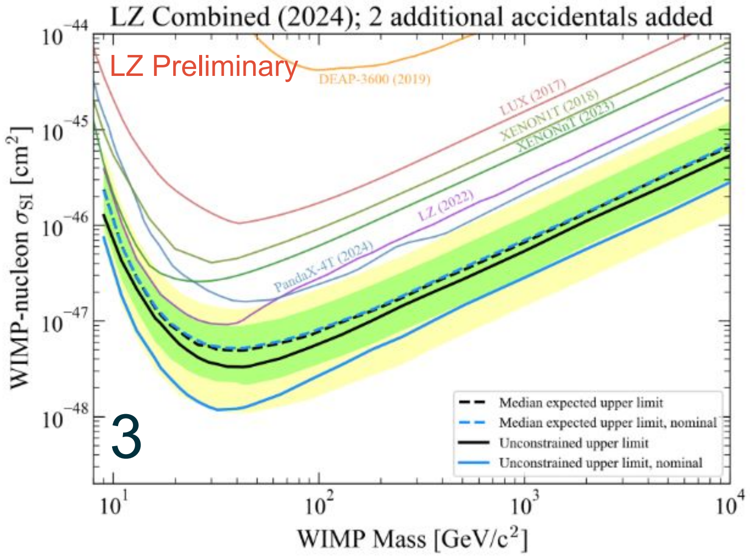
Good agreement before application of S1- and S2-based cuts



Checks of Accidental Bkg Impact on Limit





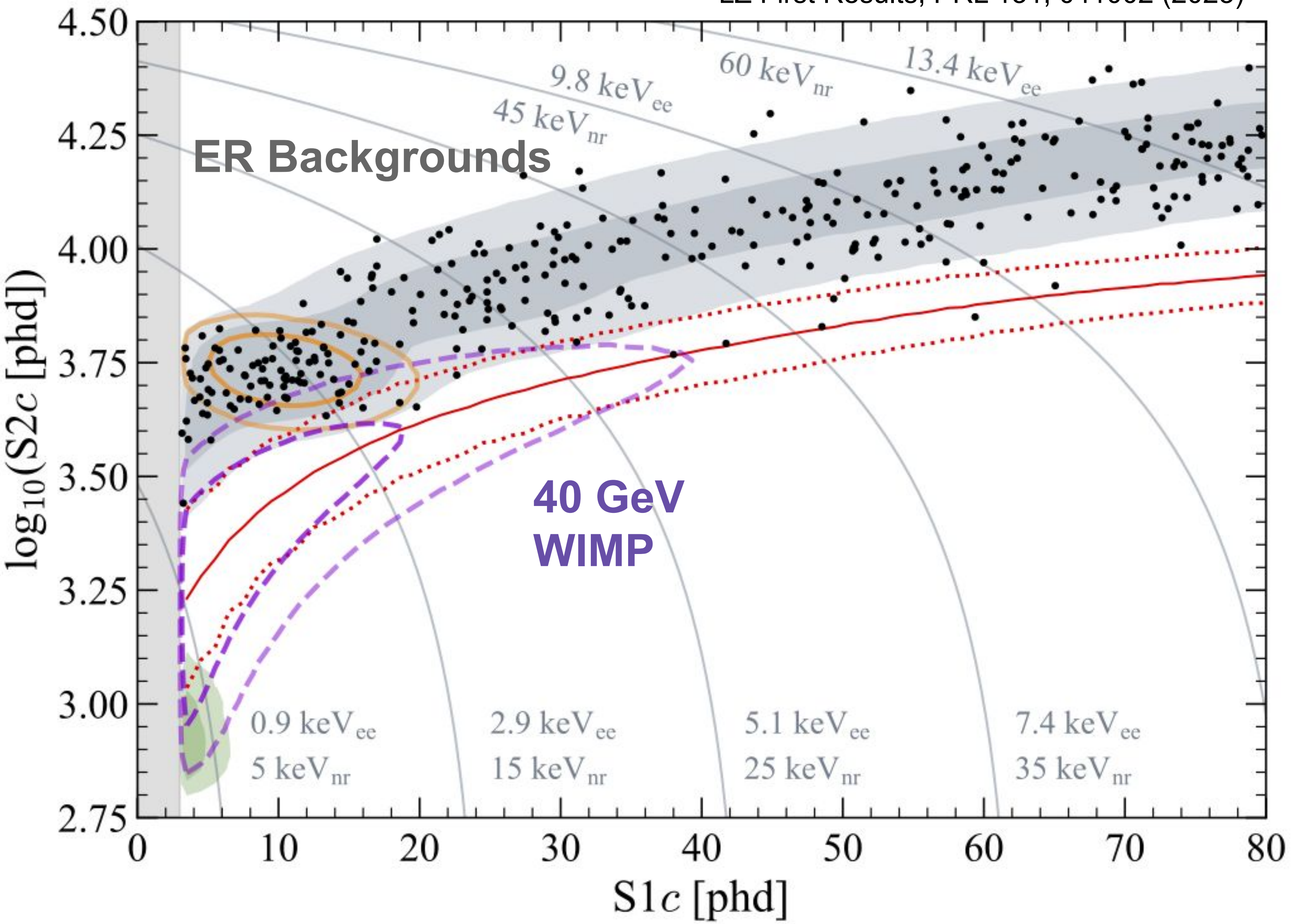


1. Remove accidental rate constraint: best fit drops 2.6 → 1.4
2. Remove constraint & outlier event: best fit drops 1.4 → 0
    a. Outlier event holds model up, over subtracting in the WIMP region
3. Adding fake events - props limit back up
    → under-fluctuation of accidental events in the WIMP region

LZ's first dark matter search result

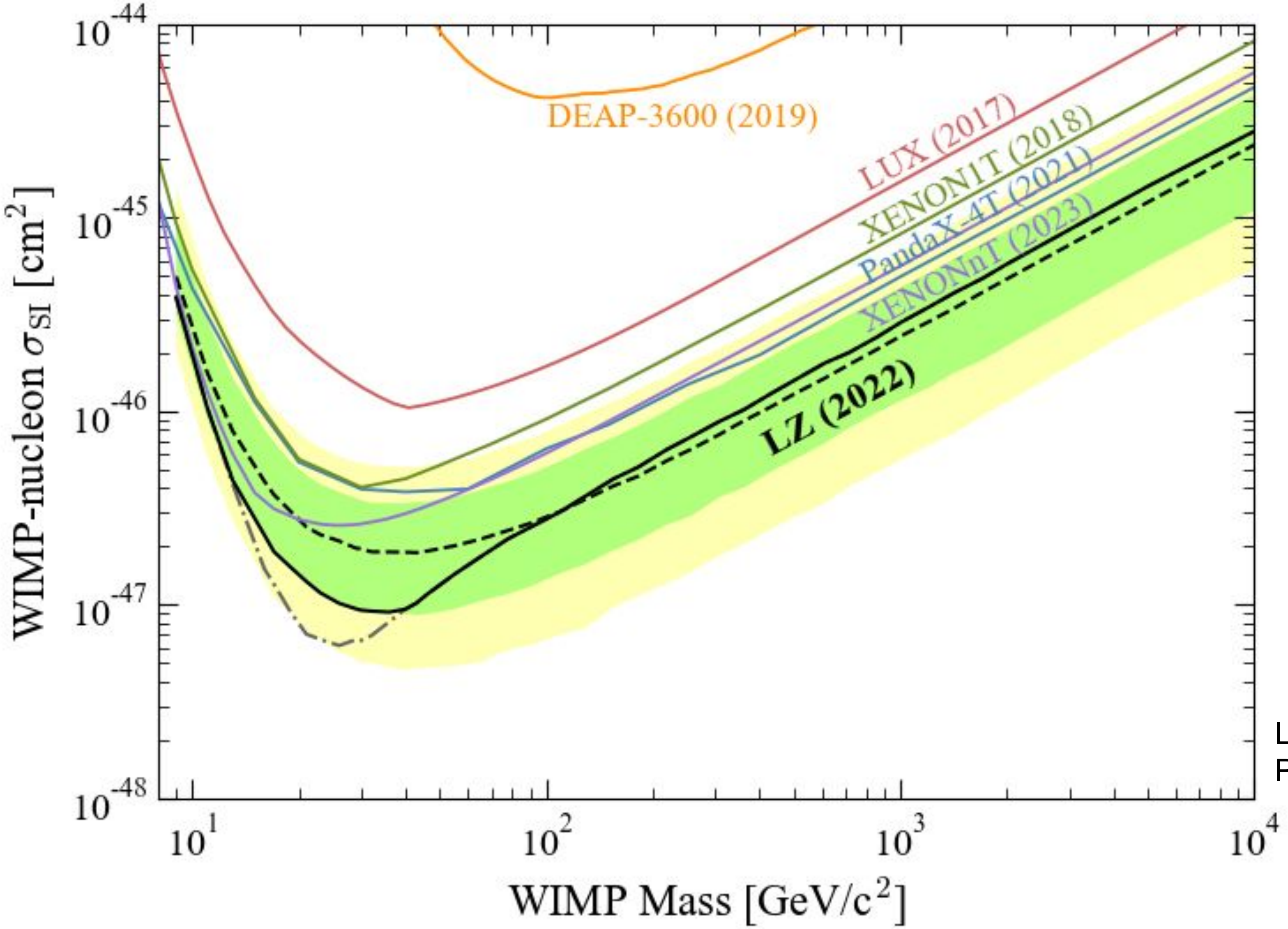
LZ First Results, PRL 131, 041002 (2023)

60 days of data
5.5 tonnes Xe
= 0.9 tonne-yr



LZ’s first dark matter search result

60 days of data
5.5 tonnes Xe
= 0.9 tonne-yr



LZ First Results,
PRL 131, 041002 (2023)

NEST Model of ER leakage vs Drift Field

2211.10726