Latest Results from the LZ Dark Matter Experiment

Qing (Shilo) Xia

Lawrence Berkeley National Laboratory

On behalf of the LZ Collaboration

Ricap-24 - Rome, Italy
Sept. 24, 2024

LZ in the News

ARTICLE • MYSTERIES OF MATTER

LZ Experiment Sets New Record in Search for Dark Matter

By Lauren Biron
August 26, 2024

LUX-ZEPLIN Experiment Narrows The Search For Elusive Dark Matter

August 26, 2024 | U.S. Department of Energy

EDUCATION

QUICK READS

Scientists at underground lab announce progress in hunt for dark matter

BY: SEARCHLIGHT STAFF - AUGUST 26, 2024 3:48 PM

08-26-2024

Unending search for elusive dark matter sets a new record

By Eric Ralls
Earth.com staff writer

ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

NEWS PARTICLE PHYSICS

The possibilities for dark matter have just shrunk — by a lot

The LZ experiment reports no signs of dark matter in their latest search

By Emily Conover
AUGUST 26, 2024 AT 1:00 PM

NEWS | PHYSICS

Hunt for dark matter particles bags nothing—again

The massive LUX-ZEPLIN detector leaves few hiding places for hypothetical particles called WIMPs

26 AUG 2024 • 6:00 PM ET • BY ADRIAN CHO

NewScientist

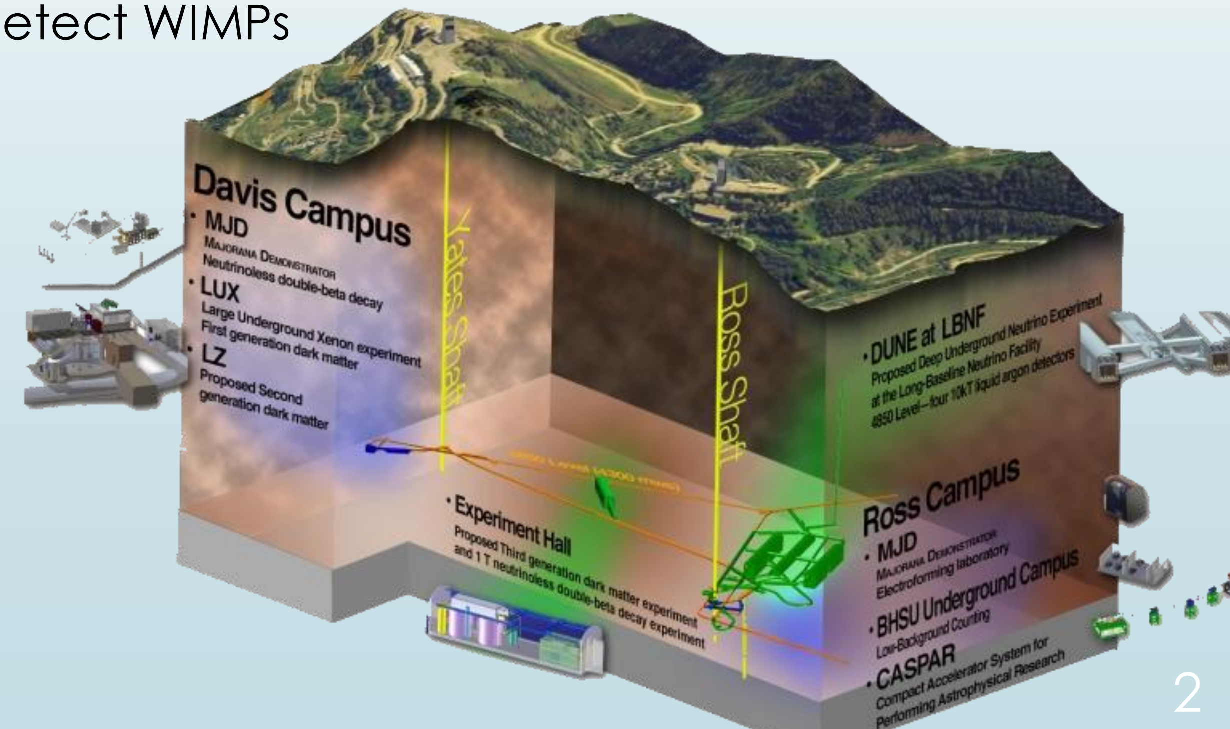
Physics

Another blow for dark matter as biggest hunt yet finds nothing

The hunt for particles of dark matter has been stymied once again, with physicists placing constraints on this mysterious substance that are 5 times tighter than the previous best

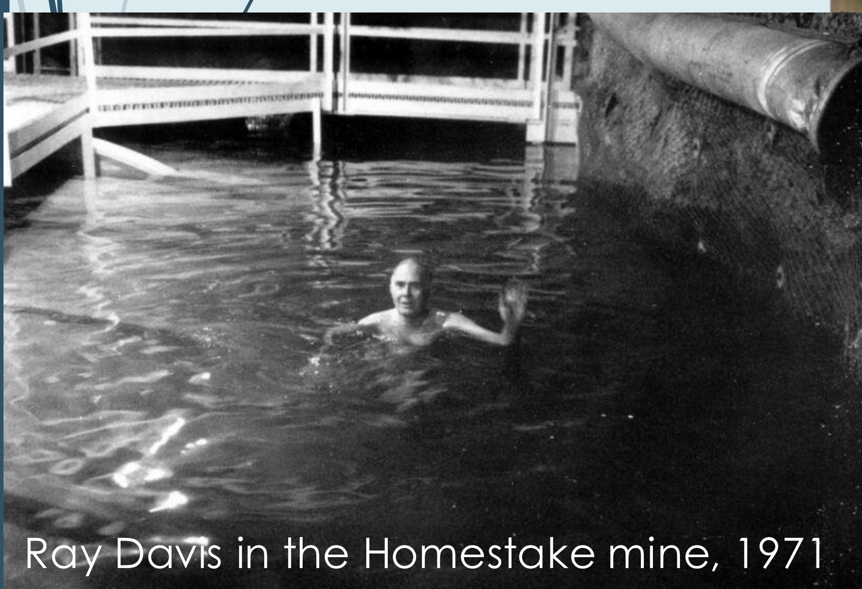
LZ @ Sanford Underground Research Facility

- SURF in Lead, South Dakota is the deepest underground lab in the U.S.
- LZ is located on the 4850 level ~1.5 km underground
- ~10^6 reduction in cosmic muon flux
- Primary goal is to detect WIMPs

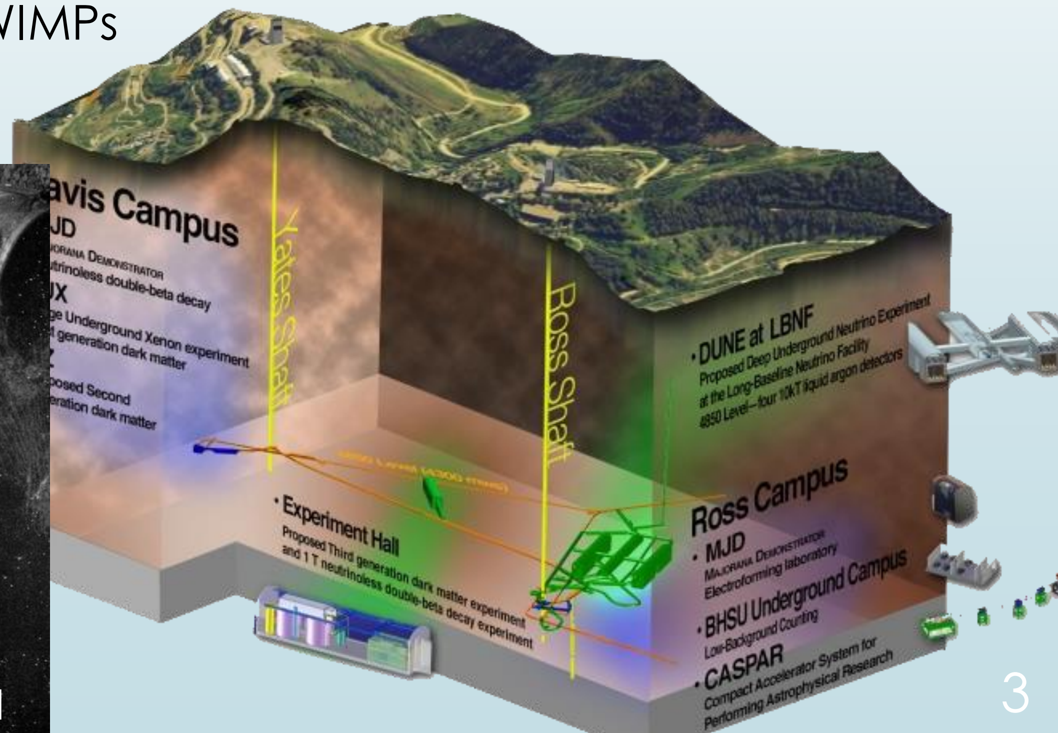


LZ @ Sanford Underground Research Facility

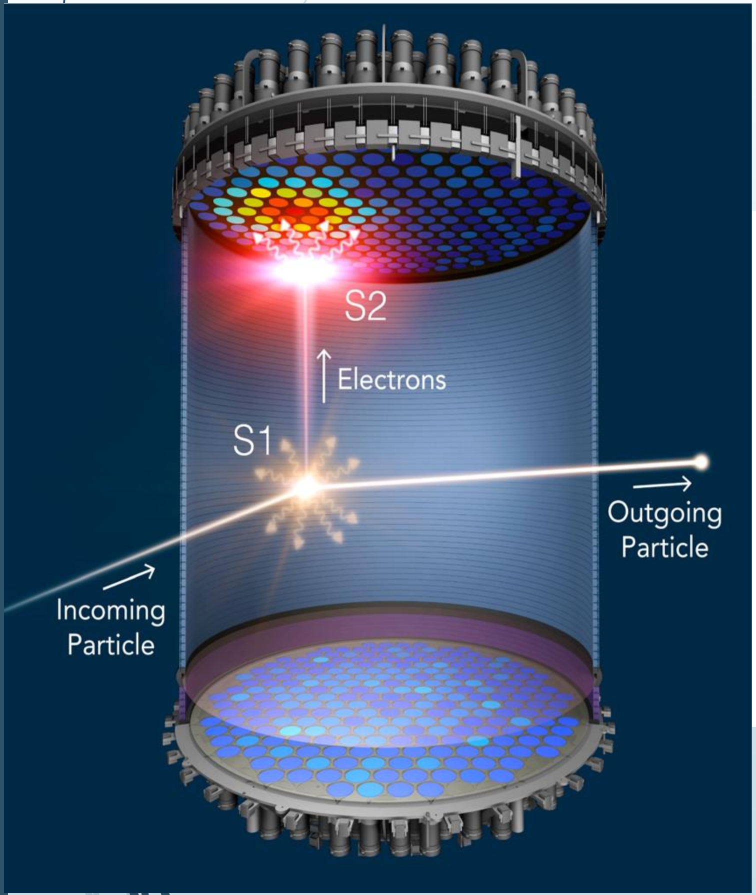
- SURF in Lead, South Dakota is the deepest underground lab in the U.S.
- LZ is located on the 4850 level ~1.5 km underground
- ~10^6 reduction in cosmic muon flux
- Primary goal is to detect WIMPs

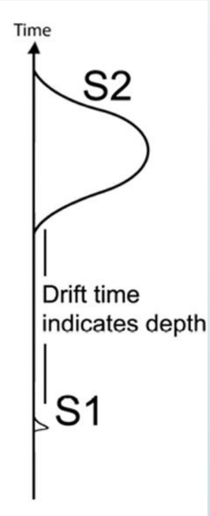


Ray Davis in the Homestake mine, 1971

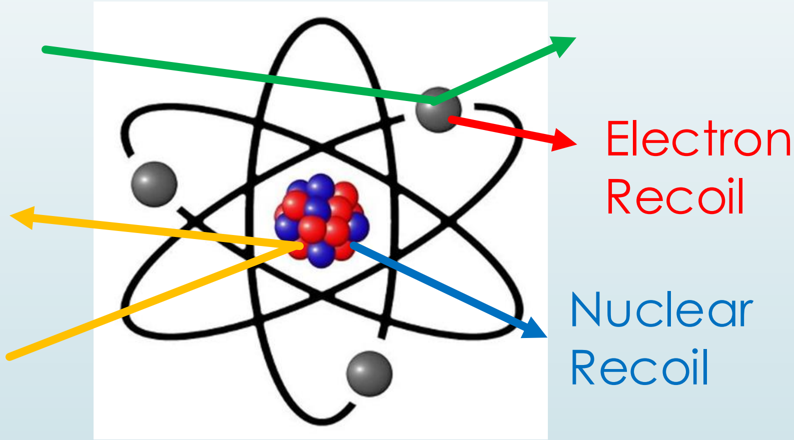


Dual Phase Xenon Time Projection Chamber (TPC)





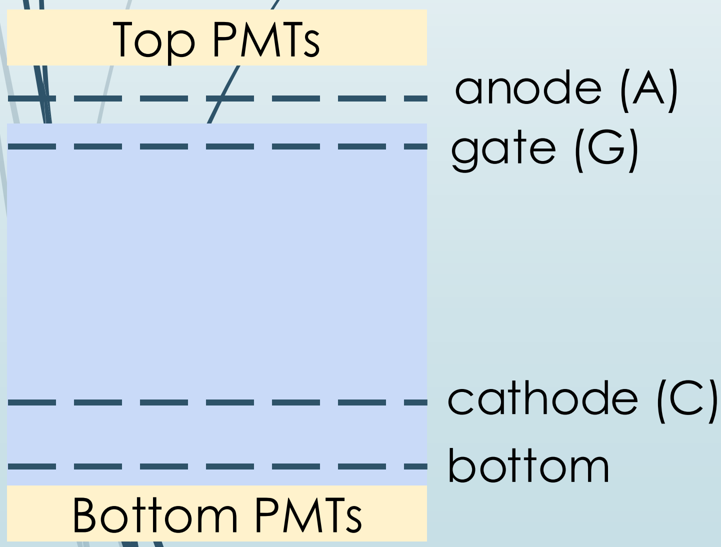
- Signal vs. background discrimination
  - Charge (S2)/ light (S1) ratio is different between electron recoil (ER) and nuclear recoil (NR)



- Electrons and gammas interact with atomic electrons, produce ER
- WIMPs (and neutrons) interact with Xe nuclei, produce NR

Grid Voltage Changes since LZ's First WIMP Search

- Anode voltage lowered to reduce spurious light and charge emission
- Cathode voltage lowered to mitigate light emission from the Skin detector observed after the first WIMP search
- **ER/NR discrimination is not impacted**

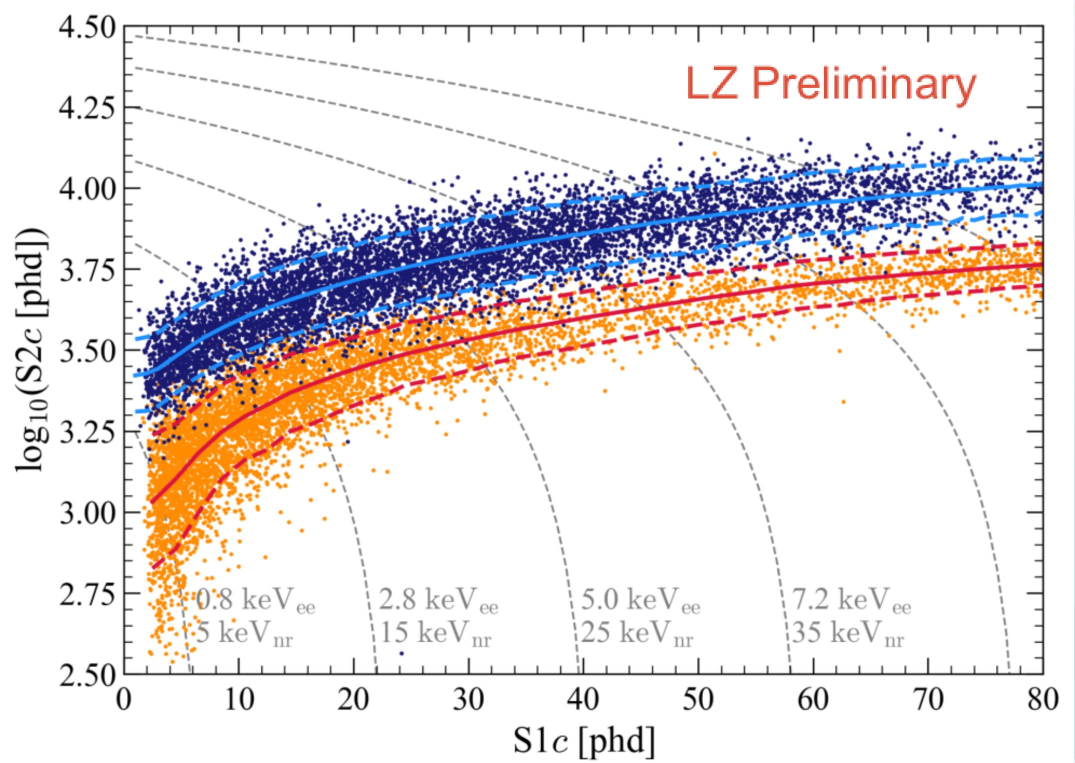


Run	C/G/A Voltage [kV]	Drift Field [V/cm]	Livetime [d]
WS2022*	-32/-4/+4	193	60
WS2024**	-18/-4/+3.5	97	220

*Dec. 2021 – May 2022
**March 2023 – March 2024

Calibration Data in WS2024

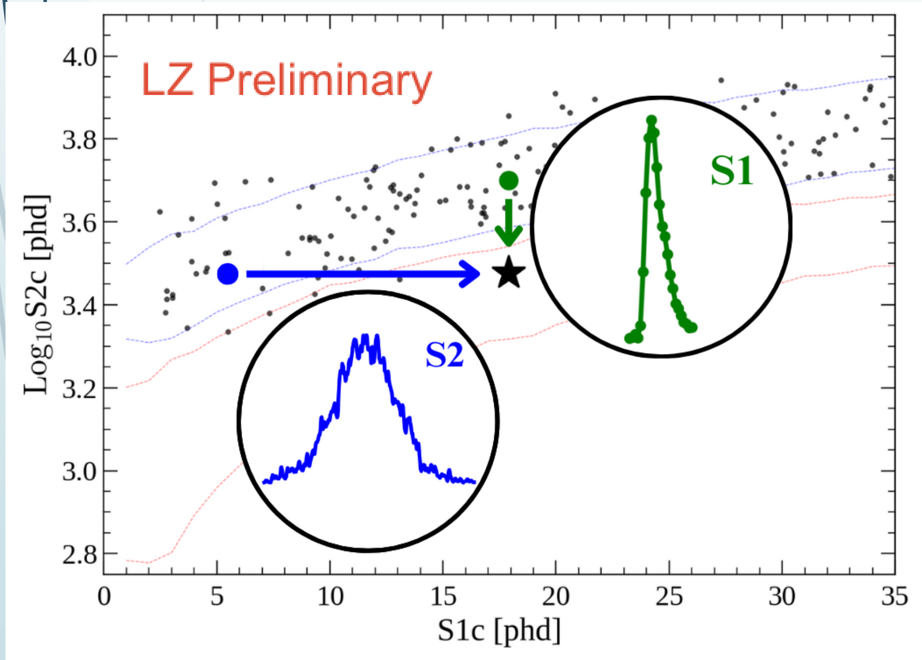
- Dark blue points: Tritium beta data (ER)* (continuum betas up to 18.6 keV)
- Orange points: DD neutron data (NR)* (2.45 MeV neutrons produced through Deuterium-Deuterium fusion)
- **ER/NR discrimination: 0.2% ER leakage past the median of the NR population**
  - Light gain g1= 0.112 ± 0.002 phd/photon
  - Charge gain g2 = 34.0 ± 0.9 phd/electron

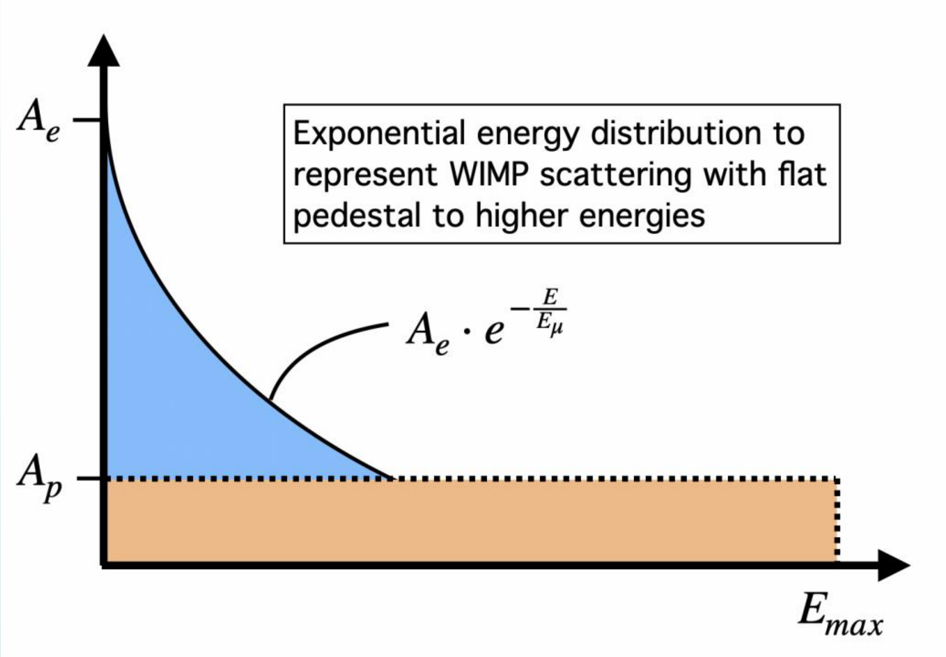


*Details about calibration source deployment: J. Aalbers *et al* 2024 *JINST* **19** P08027

Bias Mitigation in WS2024

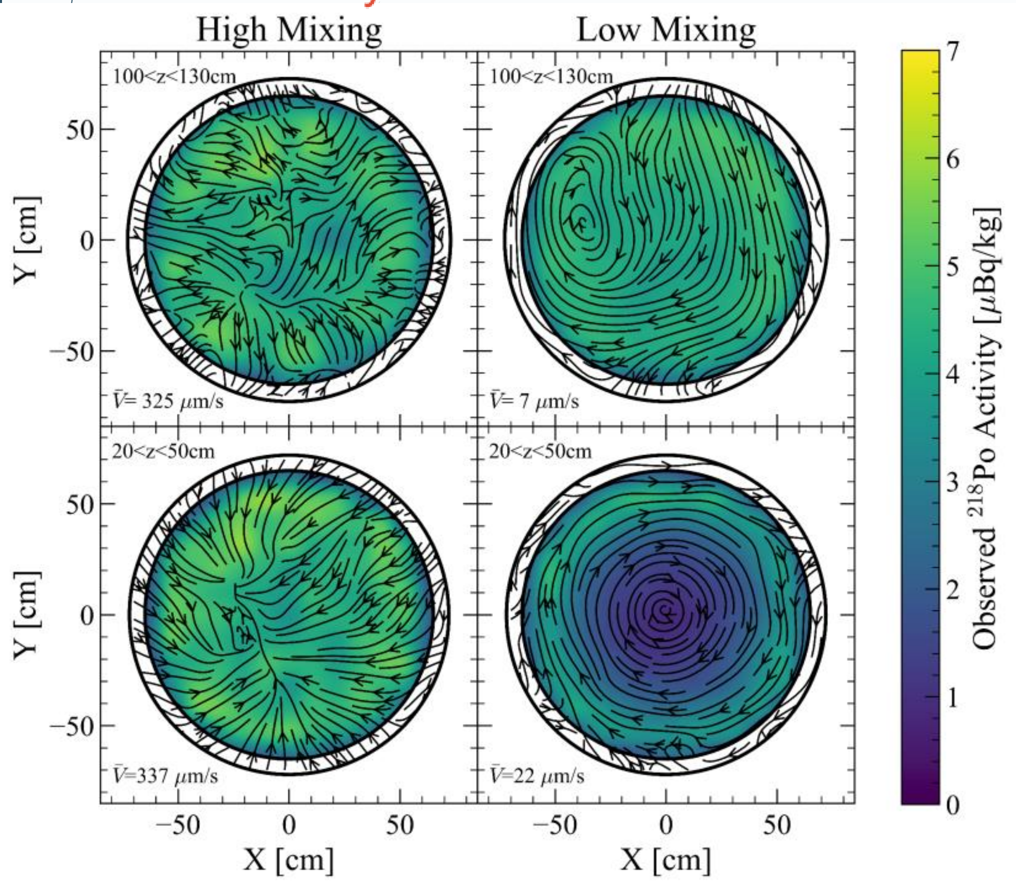
- Bias mitigation via ‘salting’: fake WIMP signals injected randomly during data taking (rate bounded by WS2022 cross section)
- Salt events are revealed only after all analysis inputs are finalized

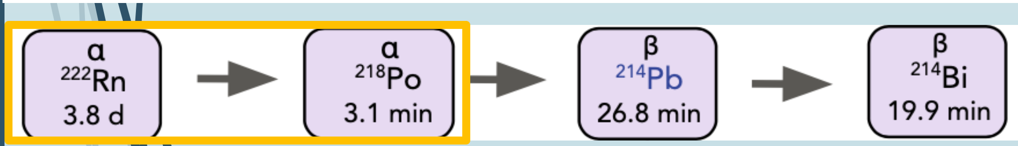




LXe Flow Control for Background Reduction in WS2024

LZ Preliminary

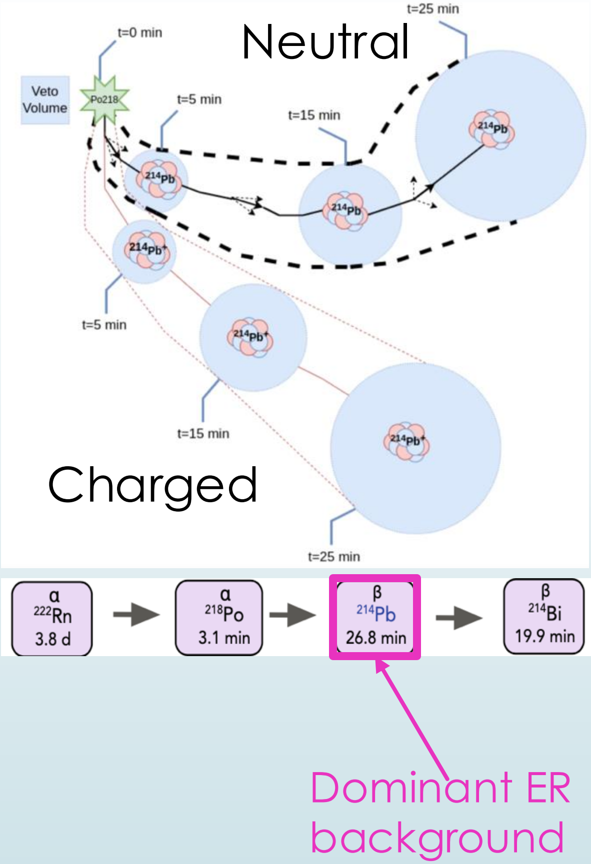




- Data collected in **two flow states** through circulation and cooling systems control
- High Mixing (40.9 live days)
  - Turbulent flow
  - Uniform distribution of injected calibration sources
- Low Mixing (179.1 live days)
  - Laminar-like flow
- **Liquid flow mapping using ^{222}Rn-^{218}Po coincidences**

^{214}Pb tagging in the Low-mixing State in WS2024

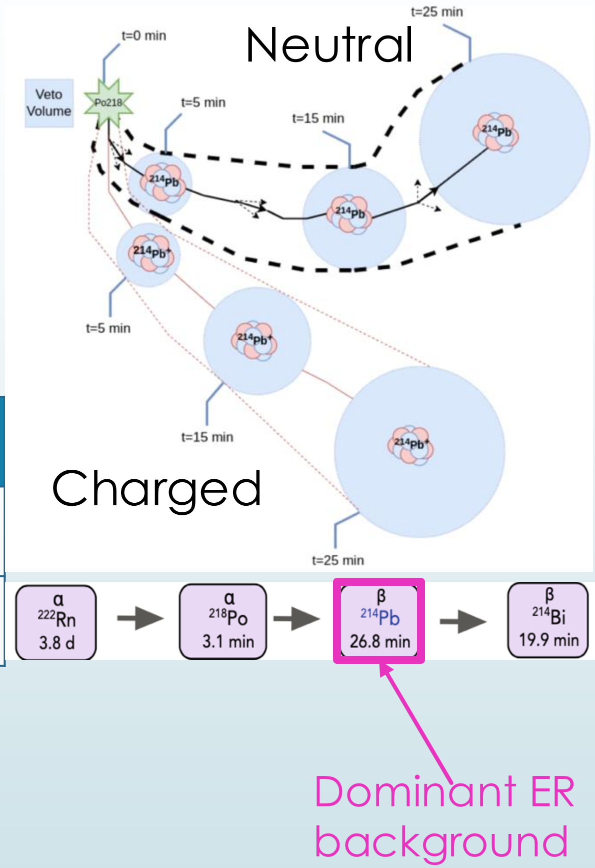
- Liquid flow map enables tagging of ^{214}Pb background in the low-mixing state
- **Both tagged and untagged populations are used in the final analysis**
- ^{214}Pb reduced to 1.8 ± 0.3 μBq/kg in the untagged population (3.9 ± 0.6 μBq/kg in the total exposure)



^{214}Pb tagging in the Low-mixing State in WS2024

- Liquid flow map enables tagging of ^{214}Pb background in the low-mixing state
- **Both tagged and untagged populations are used in the final analysis**
- ^{214}Pb reduced to 1.8 ± 0.3 μBq/kg in the untagged population (3.9 ± 0.6 μBq/kg in the total exposure)

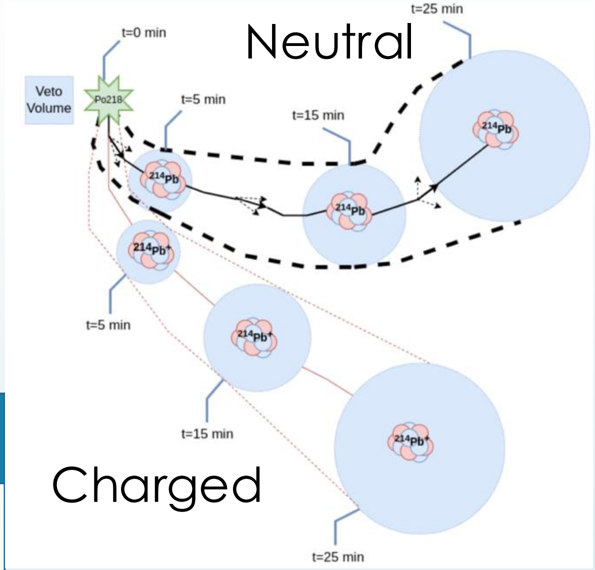
	^{214}Pb fraction	Exposure (low-mixing state)
Tagged	60±4 %	0.3 tonne-yr
Untagged	40±4 %	1.8 tonne-yr

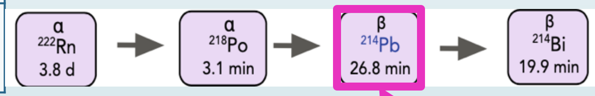


^{214}Pb tagging in the Low-mixing State in WS2024

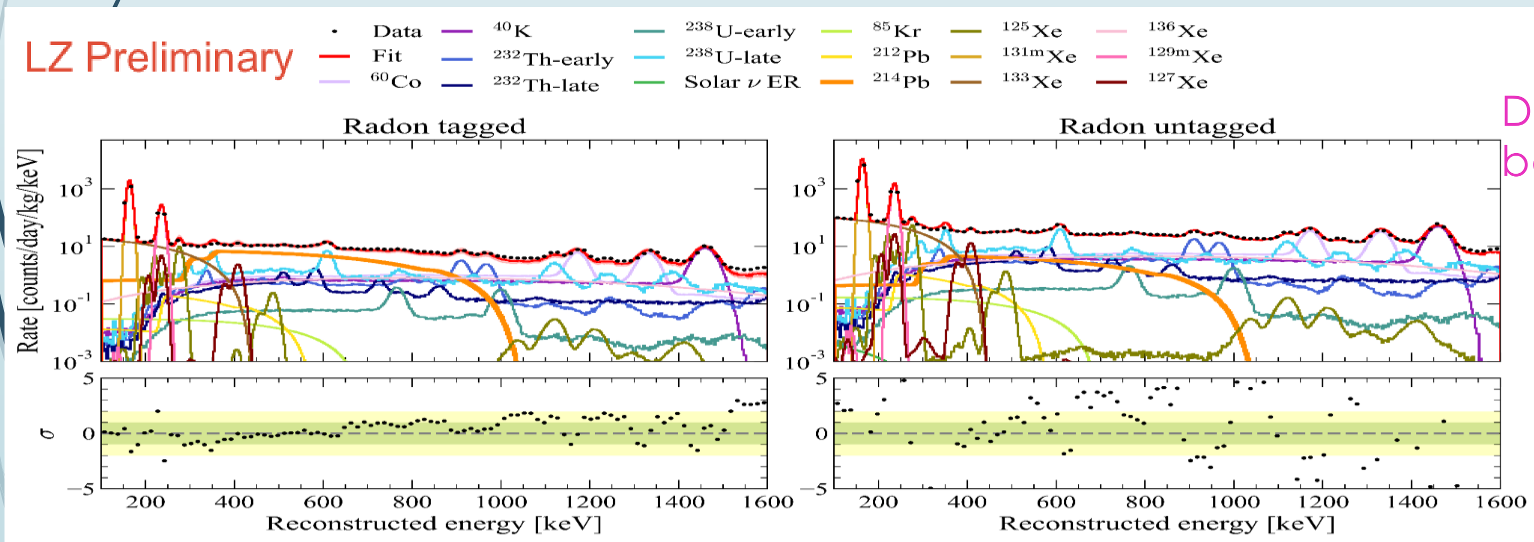
- Liquid flow map enables tagging of ^{214}Pb background in the low-mixing state
- **Both tagged and untagged populations are used in the final analysis**
- ^{214}Pb reduced to 1.8 ± 0.3 μBq/kg in the untagged population (3.9 ± 0.6 μBq/kg in the total exposure)

	^{214}Pb fraction	Exposure (low-mixing state)
Tagged	60±4 %	0.3 tonne-yr
Untagged	40±4 %	1.8 tonne-yr





Dominant ER background

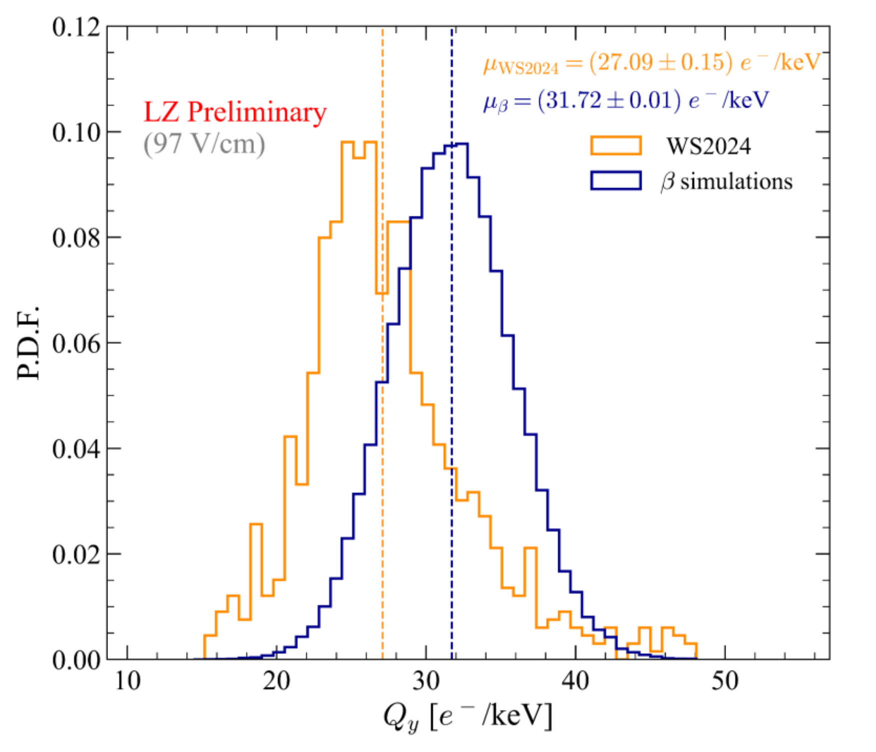


Electron Capture Decay Backgrounds

Isotope	Decay mode	Primary energy in WIMP search region	Half-life
$^{127,125}Xe$ (neutron source activation)	Single EC	5.2 keV (L-shell)	36.3d (^{127}Xe) 16.9h (^{125}Xe)
^{124}Xe (0.095% nat. abundance)	Double EC	5.98 keV (LM shell) & 10 keV (LL shell)	$(1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ year (LZ preliminary *)

Electron Capture Decay Backgrounds

Isotope	Decay mode	Primary energy in WIMP search region	Half-life
$^{127,125}Xe$ (neutron source activation)	Single EC	5.2 keV (L-shell)	36.3d (^{127}Xe) 16.9h (^{125}Xe)
^{124}Xe (0.095% nat. abundance)	Double EC	5.98 keV (LM shell) & 10 keV (LL shell)	$(1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ year (LZ preliminary *)

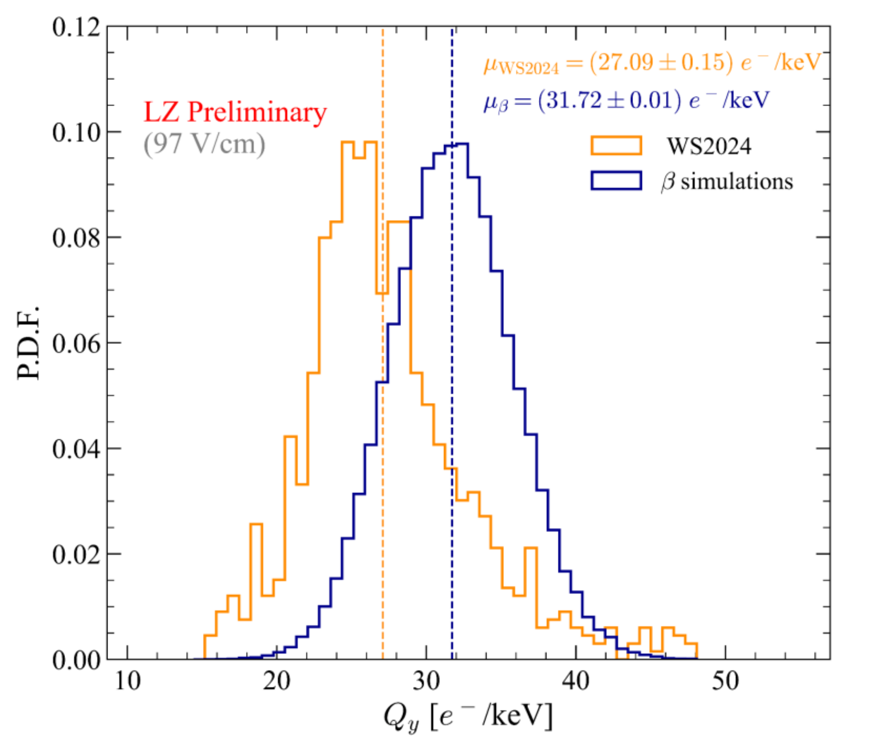


- **Single L-shell EC charge yield is suppressed compared to β's of the same energy**
  - Measured in XELDA*
  - Preliminary result from WS2024: $Q_{EC}/Q_\beta = 0.86 \pm 0.01$

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

Electron Capture Decay Backgrounds

Isotope	Decay mode	Primary energy in WIMP search region	Half-life
$^{127,125}Xe$ (neutron source activation)	Single EC	5.2 keV (L-shell)	36.3d (^{127}Xe) 16.9h (^{125}Xe)
^{124}Xe (0.095% nat. abundance)	Double EC	5.98 keV (LM shell) & 10 keV (LL shell)	$(1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ year (LZ preliminary *)



- **Single L-shell EC charge yield is suppressed compared to β's of the same energy**
  - Measured in XELDA*
  - Preliminary result from WS2024: $Q_{EC}/Q_\beta = 0.86 \pm 0.01$
- **^{124}Xe LL captures is expected to display further charge yield suppression compared to single-L capture**

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

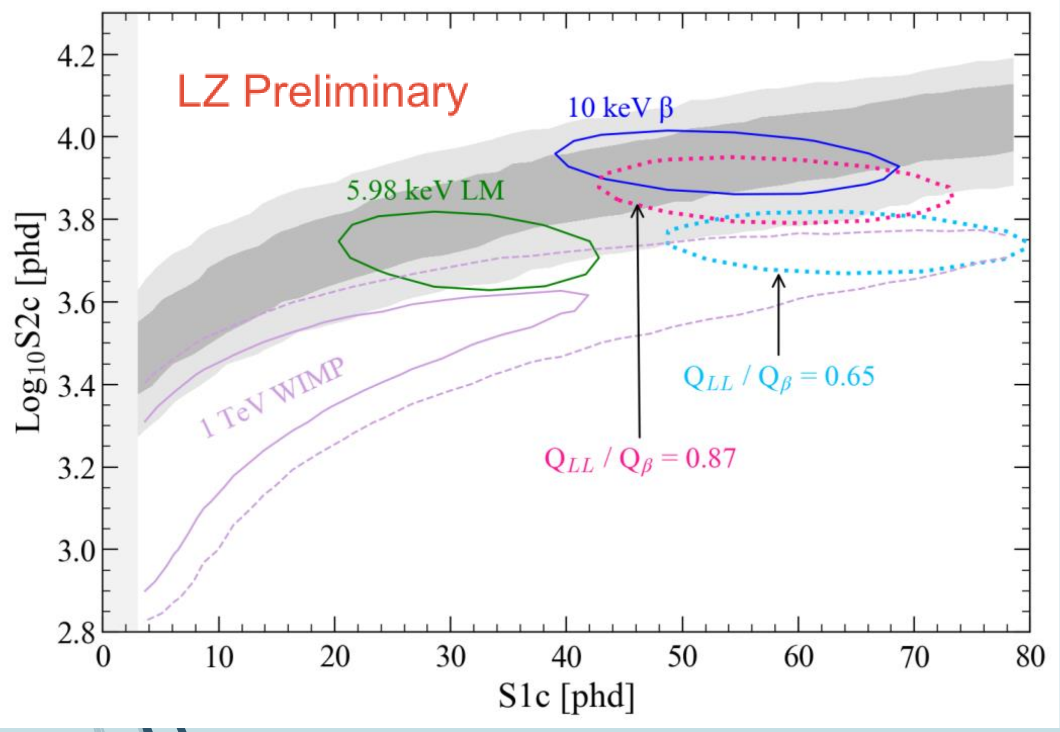
^{124}Xe Double Electron Capture Background Modelling

- Background model allows ^{124}Xe LL-capture charge yield suppression to vary:

$$(Q_{\mathrm{LL}}/Q_{\beta}) \in [0.87, 0.65]$$

single-L capture suppression (0.87)

2x ionization density (0.65)



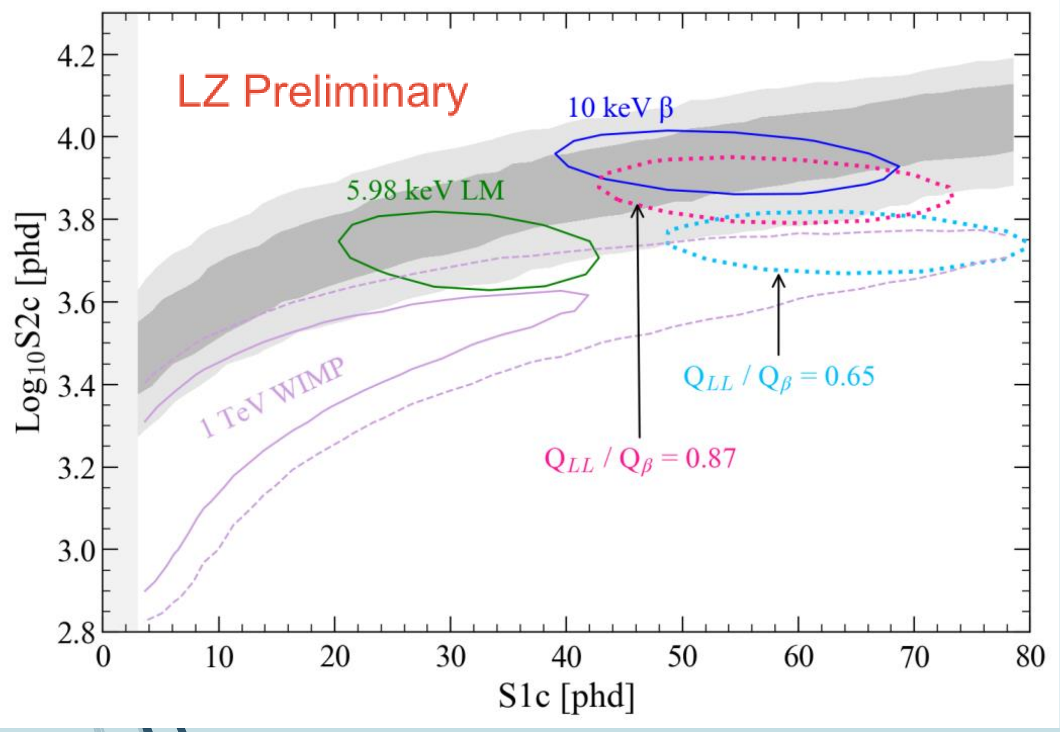
^{124}Xe Double Electron Capture Background Modelling

- Background model allows ^{124}Xe LL-capture charge yield suppression to vary:

$$(Q_{LL}/Q_{\beta}) \in [0.87, 0.65]$$

single-L capture suppression (0.87)

2x ionization density (0.65)

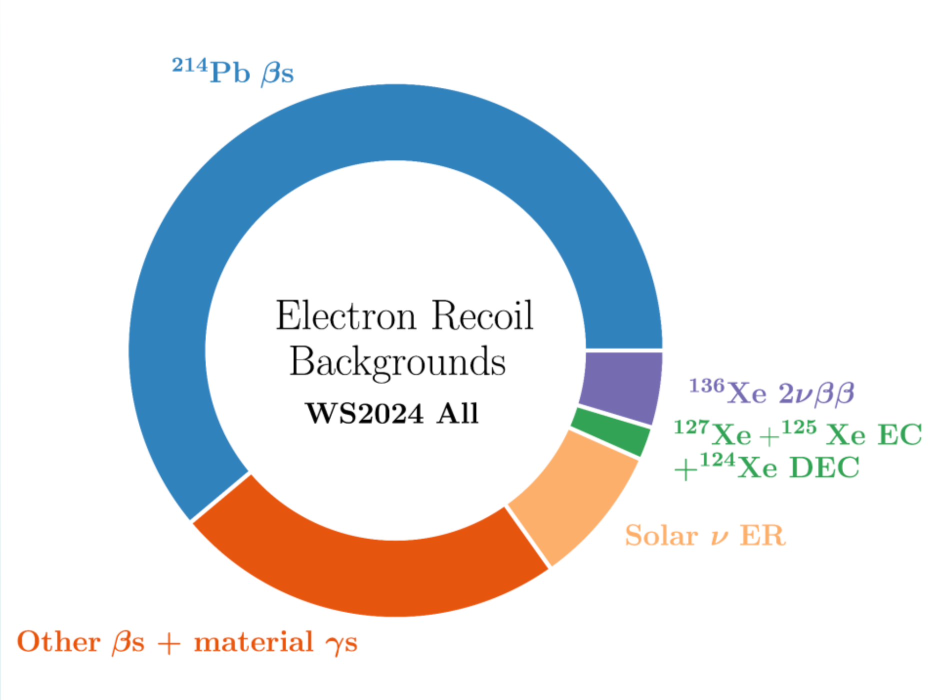


Best fit result in WS2024:
Q_{LL}/Q_{β} = 0.70 ± 0.04

Predicted event rate using KK capture (64.3 keV):
19.4 ± 3.9 events [7.1 (LM-shell) + 12.3 (LL-shell)]

Backgrounds in WS2024

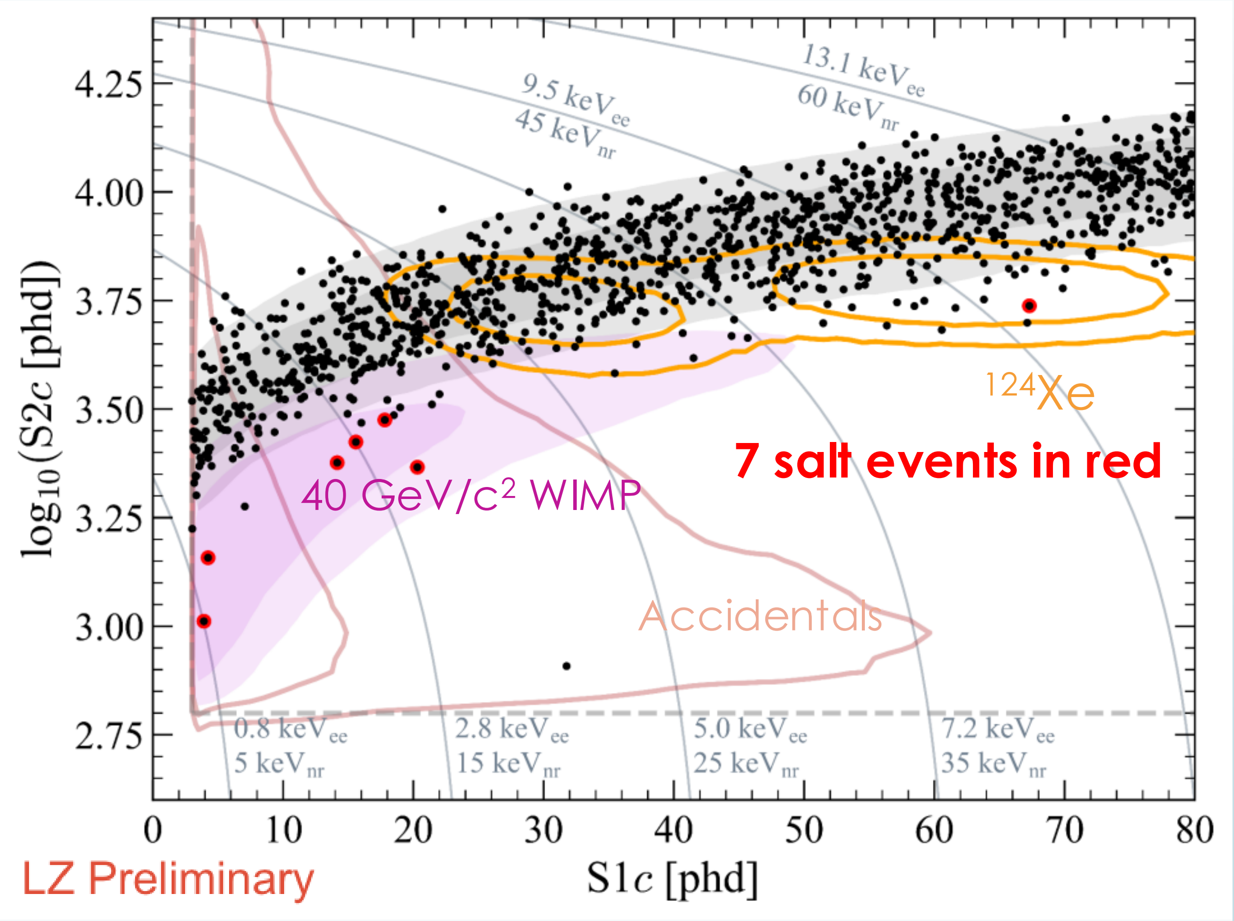
- ER backgrounds:



- NR backgrounds
  - Detector material neutrons
  - Solar + Atmospheric neutrinos
- Accidental coincidences background

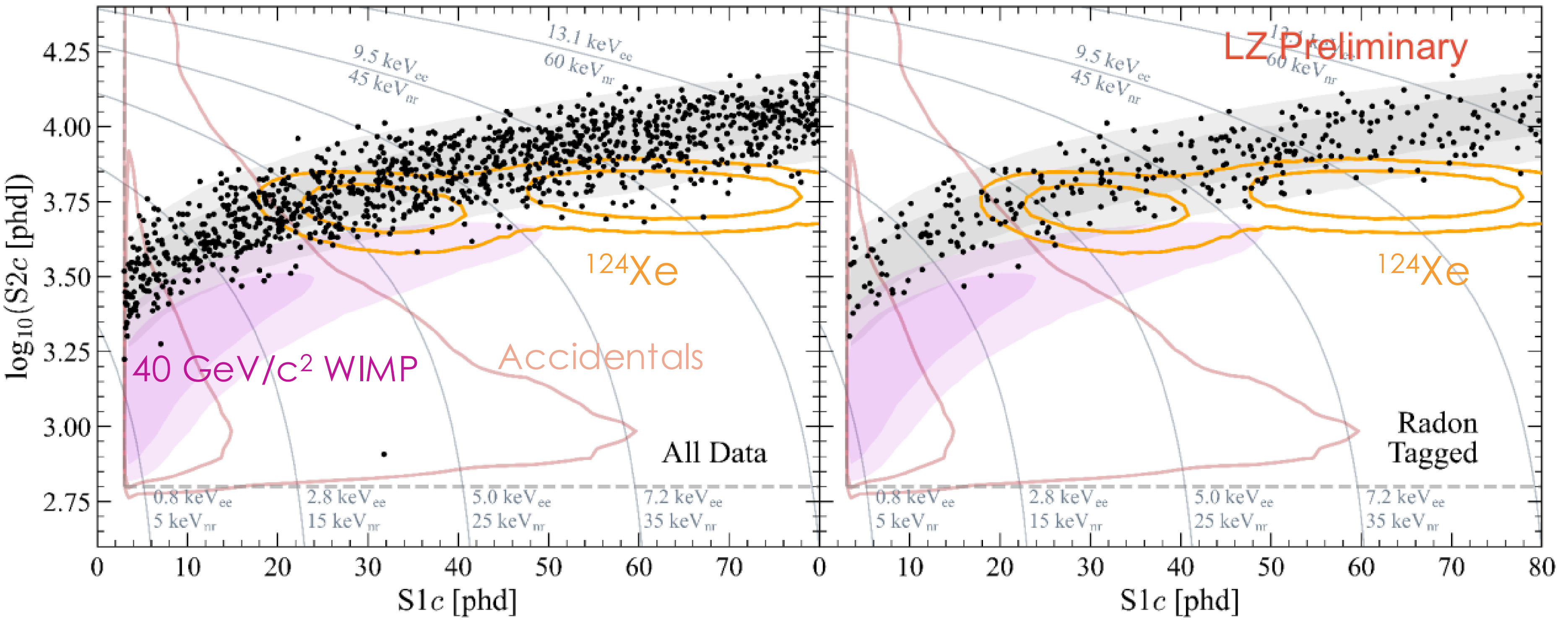
WS2024 WIMP Search Data (salted)

- 220 live days x 5.5 t = 3.3 tonne-yr
- 7 events pass all analysis cuts out of 8 total injected (consistent with evaluated efficiency)
- 1220 events after unsalting



WS2024 Final WIMP Search Data (salt removed)

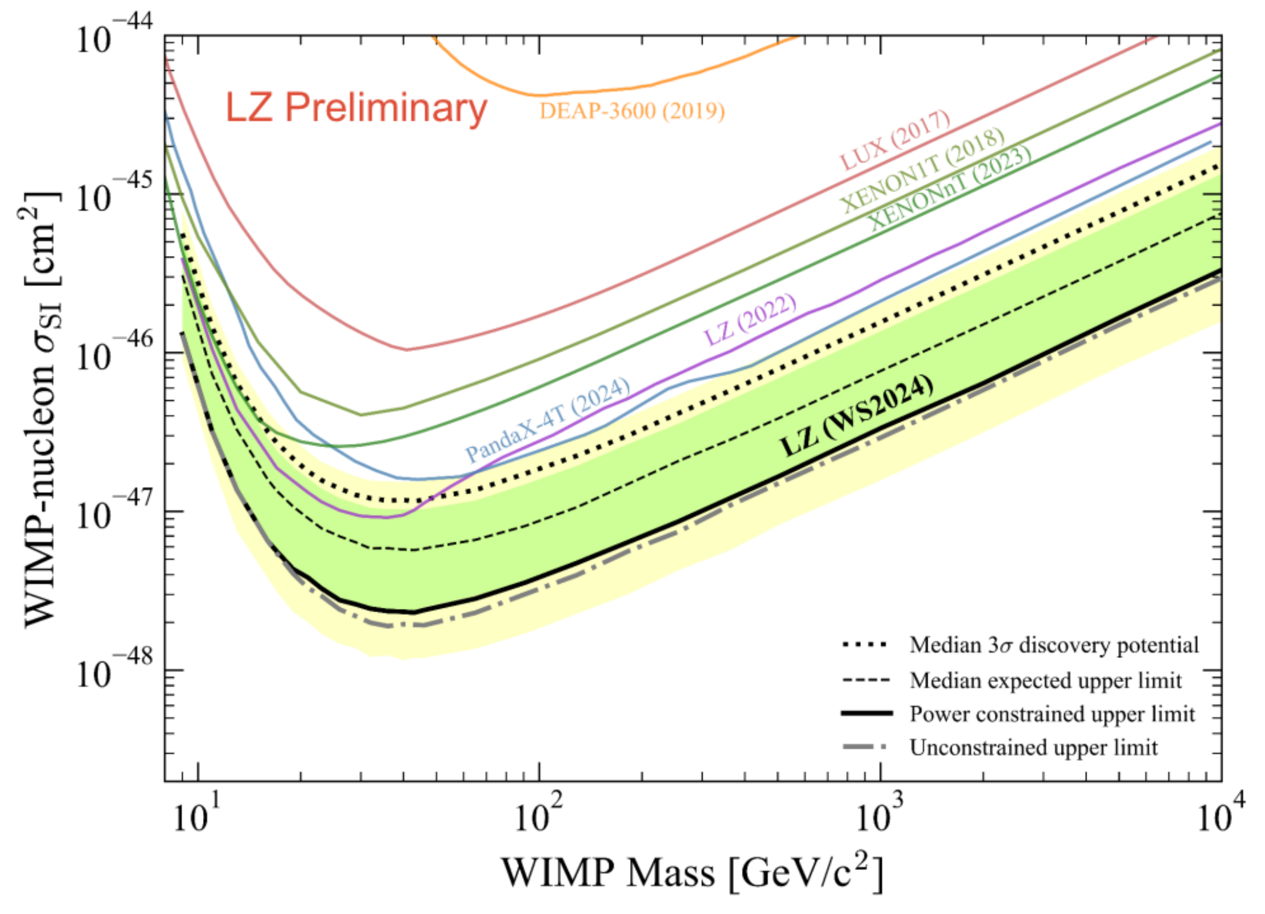
All data (3.3 tonne-yr): Radon-tagged set (0.3 tonne-yr):



Radon tagged (^{214}Pb rich) sample does not contain leakage from ^{124}Xe!

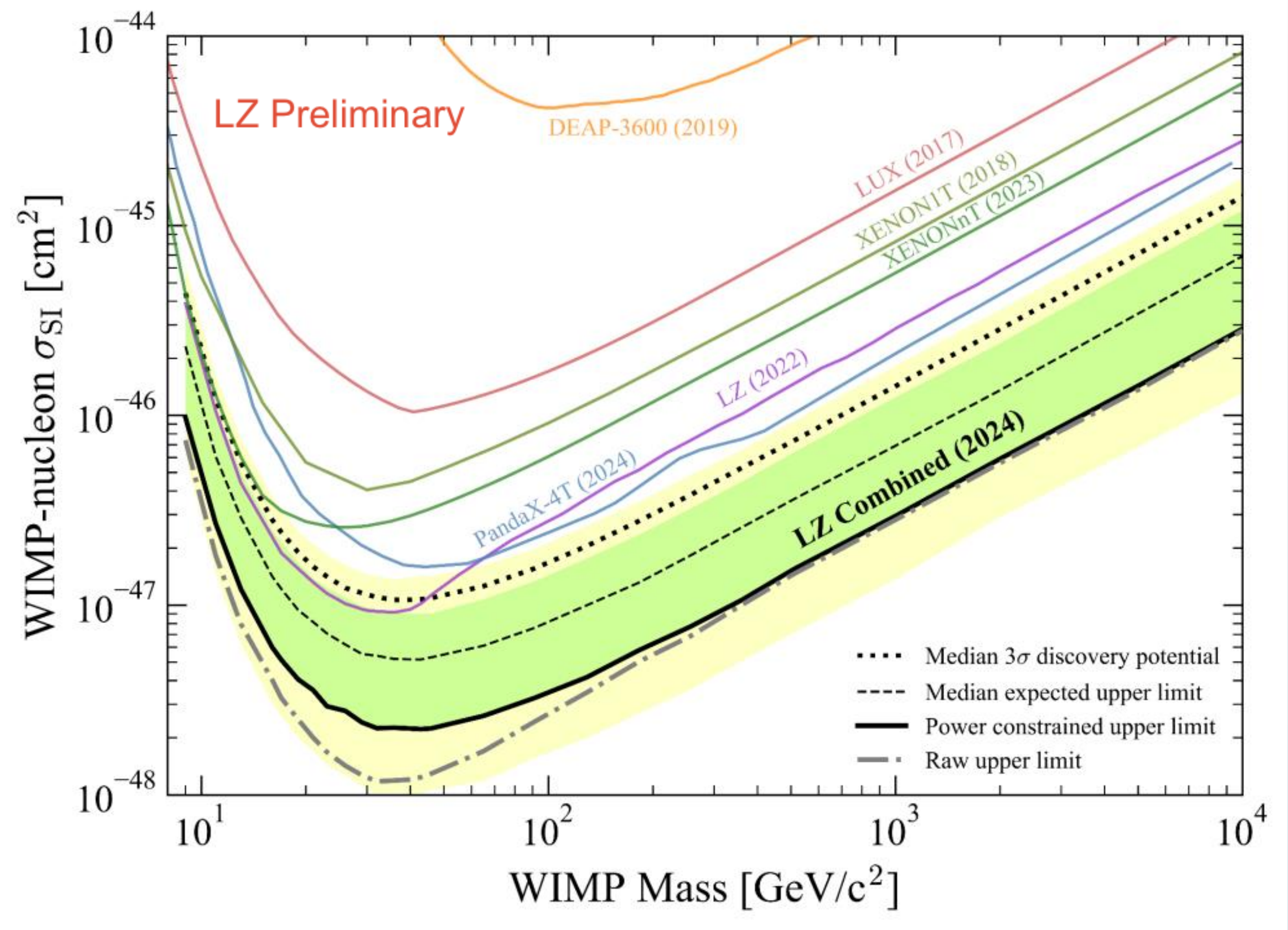
WS2024-only Limit on Spin-independent WIMP-nucleon Cross Section

- No evidence of WIMPs at any mass
- WS2024 min cross section: σ_{SI}= 2.3 x 10^{-48} cm^2 @ 43 GeV/c^2
- Upper limit (solid black) is power constrained @ -1σ sensitivity band



WS2022+WS2024 Combined Limit Results

- No evidence of WIMPs at any mass
- Combined min cross section: σ_{SI}= 2.2 x 10^{-48} cm^2 @ 43 GeV/c^2
- Upper limit (solid black) is power constrained @ -1σ sensitivity band



Summary and Outlook

- LZ has set new record on the WIMP-nucleon cross section limit with a total exposure of 4.2 tonne-year
  - More than x4 improvement compared to WS2022
  - First use of flow map-based ^{214}Pb tagging technique leads to 60% reduction of primary ER background
  - First observation of charge-suppressed ^{124}Xe double electron capture
- LZ will continue taking data until 2028 (1000 live days) with 'salt' events injected for bias mitigation
- Future physics searches: ^{8}B CEνNS, low-mass WIMPs, neutrinoless double beta decay, supernova neutrinos, etc.

Thank you!

@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

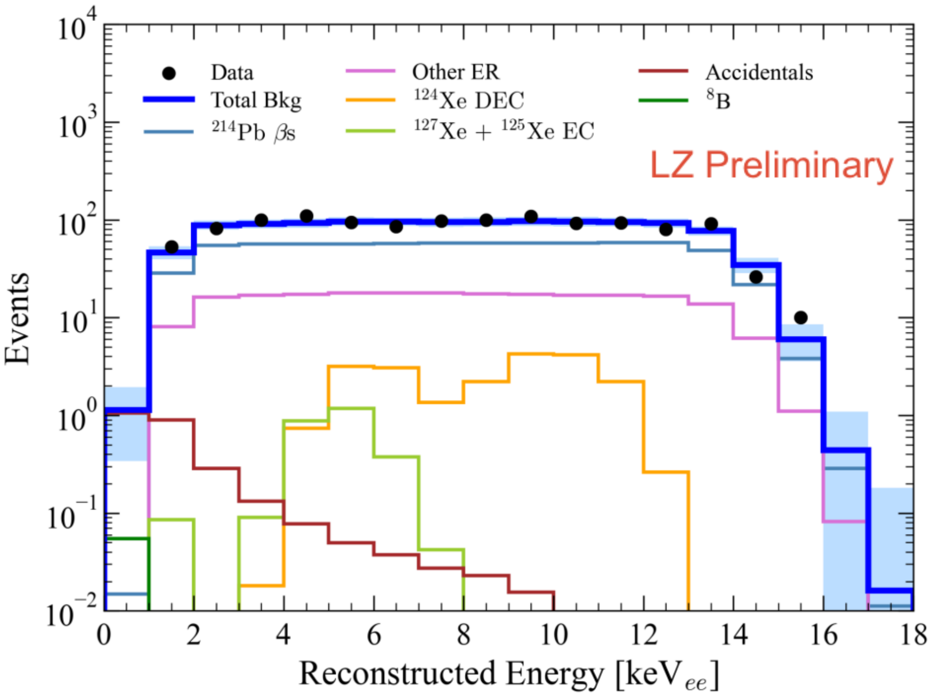
Science and Technology Facilities Council
Swiss National Science Foundation
FCT Fundação para a Ciência e a Tecnologia
SANFORD UNDERGROUND RESEARCH FACILITY
Institute for Basic Science

Backup Slides

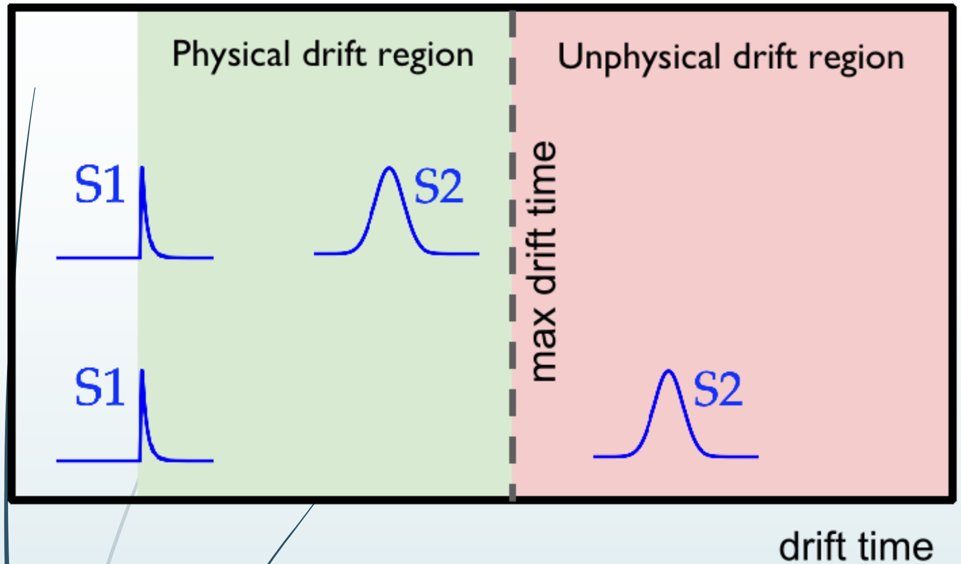
WS2024-only Fit Results

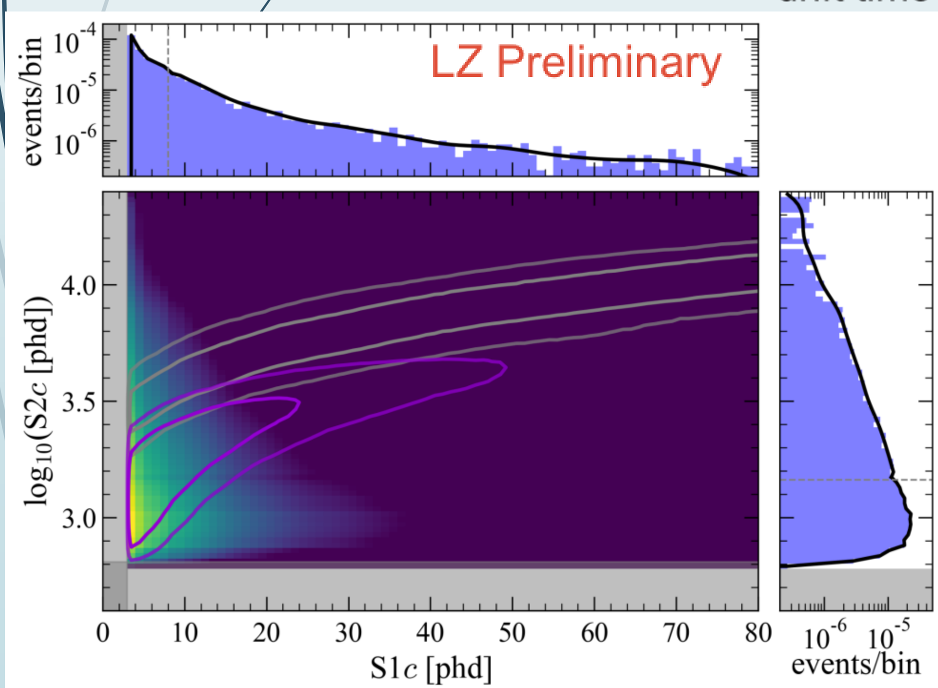
- Profile likelihood analysis performed in S1 vs. logS2 space
- Best background-only fit projected onto 1D reconstructed energy yields p-value of 0.28

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



Accidental Coincidence Background

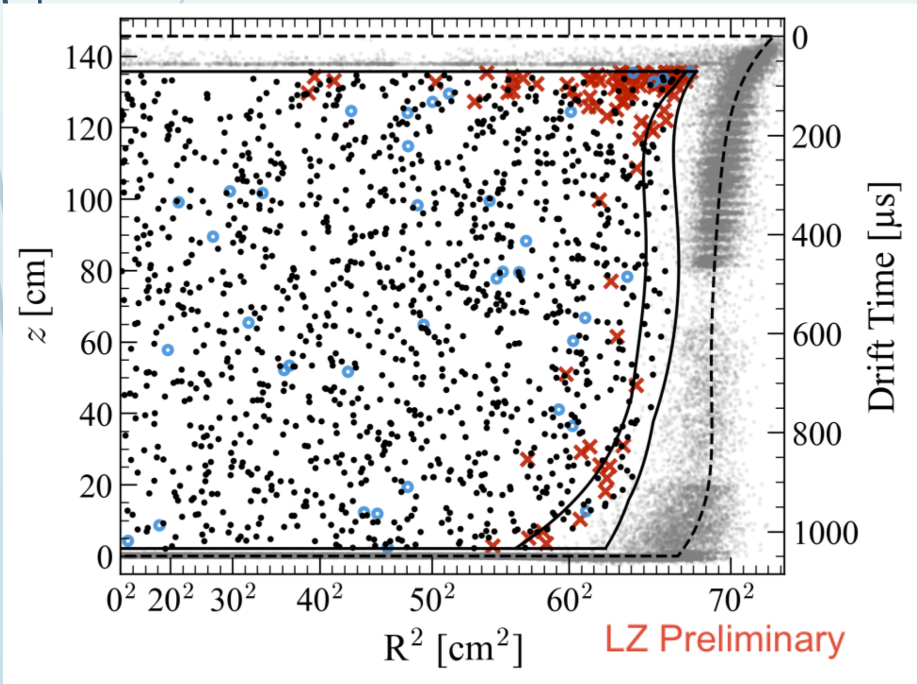




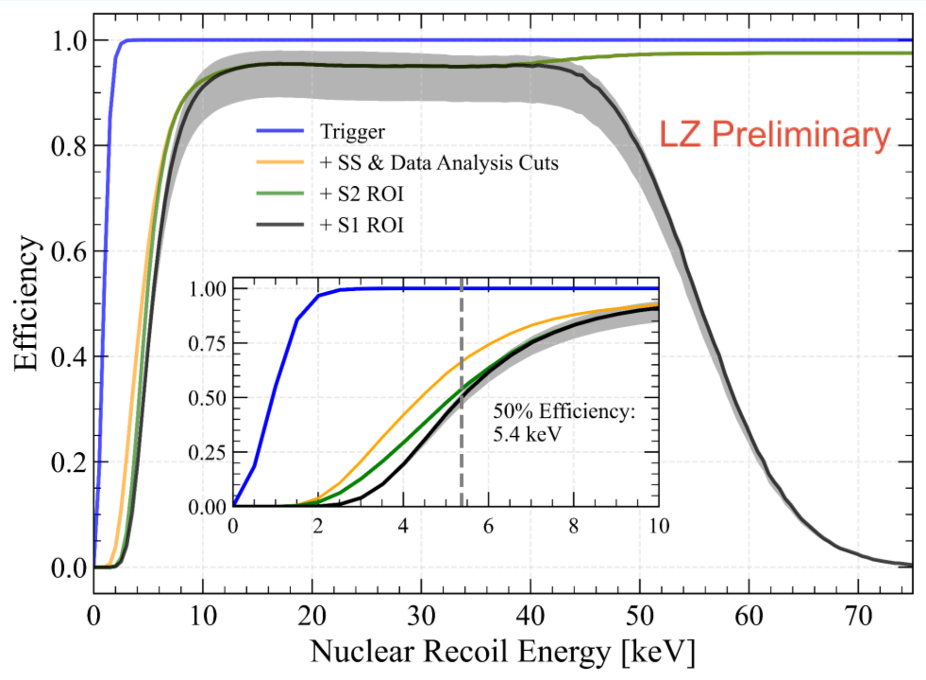
- Accidental coincidence between uncorrelated S1 and S2 pulses within physical drift time
- Events with unphysical drift time (UDT) are used to constrain accidental coincidence background rate
- Model PDF built from combining isolated S1 and S2 pulses passing all analysis cuts
- Expected counts: 2.8 ± 0.6 (sys.)

WS2024 Data Selection

Analysis cuts	Targeted effect
Livetime exclusions	High rate, detector instability, hold-off following large S2s (e-/photon trains)
S1- and S2- based data quality cuts	Pulse pathologies typical of accidental coincidence
Fiducial volume	Wall background
Skin/OD veto	Neutrons and gammas



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



All cuts developed on non-WIMP ROI data

Likelihood breakdown

WS2024 totaling 3.3 tonne-year

Unmodified first WIMP search result

	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

WS2024 Skin/OD-tagged events provide **direct constraint of neutron background** rate (neutron tagging efficiency: 92 ± 1%)

Statistical Analysis

Total log likelihood :

$$\mathcal{L}_{\mathrm{Combined}} = \mathcal{L}_{\mathrm{WS2022}} \times \mathcal{L}_{\mathrm{High\ mix}} \times \mathcal{L}_{\mathrm{Rn\ veto\ inactive}} \times \mathcal{L}_{\mathrm{Rn\ tagged}} \times \mathcal{L}_{\mathrm{Not\ Rn\ tagged}} \times \mathcal{L}_{\mathrm{Skin+OD\ tagged}}$$

- $\mathcal{L}_{\mathrm{WS2022}}$: models+data from 1st LZ result [*PRL* 131, 041002 (2023)]
- $\mathcal{L}_{\mathrm{High\ mix}}$: events in high mixing circulation state, contains residual ER calibration events
- $\mathcal{L}_{\mathrm{Rn\ veto\ inactive}}$: events in times when Rn-Po flow mapping not reliable (circ. stoppages, etc)
- $\mathcal{L}_{\mathrm{Rn\ tagged}}$: events in Rn veto periods/regions - rich in ^{214}Pb!
- $\mathcal{L}_{\mathrm{Not\ Rn\ tagged}}$: complement of above - depleted in ^{214}Pb & rich in *signal*
- $\mathcal{L}_{\mathrm{Skin+OD\ tagged}}$: events w/coincident activity in Skin & OD vetoes - provides direct constraint on neutron background rate via 92 ± 4% neutron efficiency

Statistical Analysis

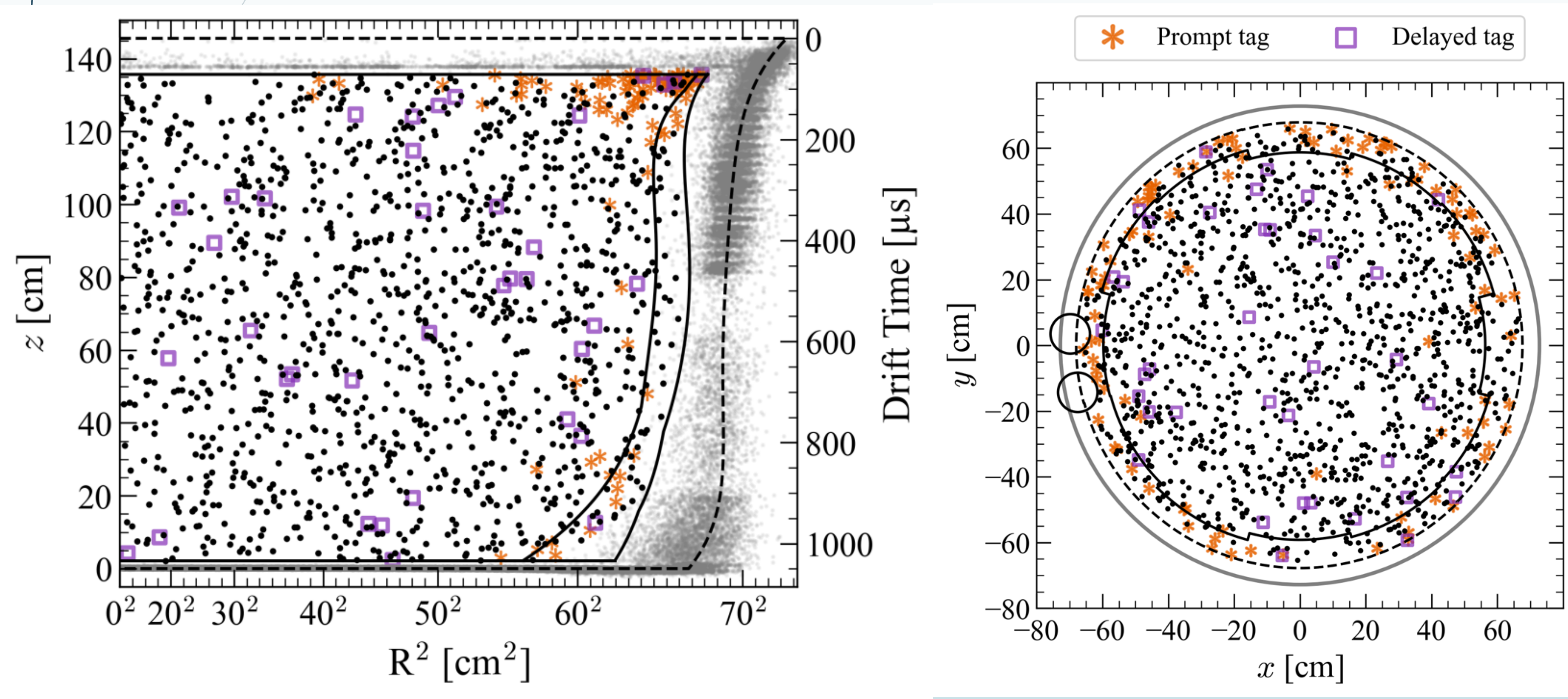
Total log likelihood :

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

$\mathcal{L}_{\text{WS2022}}$	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 via 92 ± 4% neutron efficiency

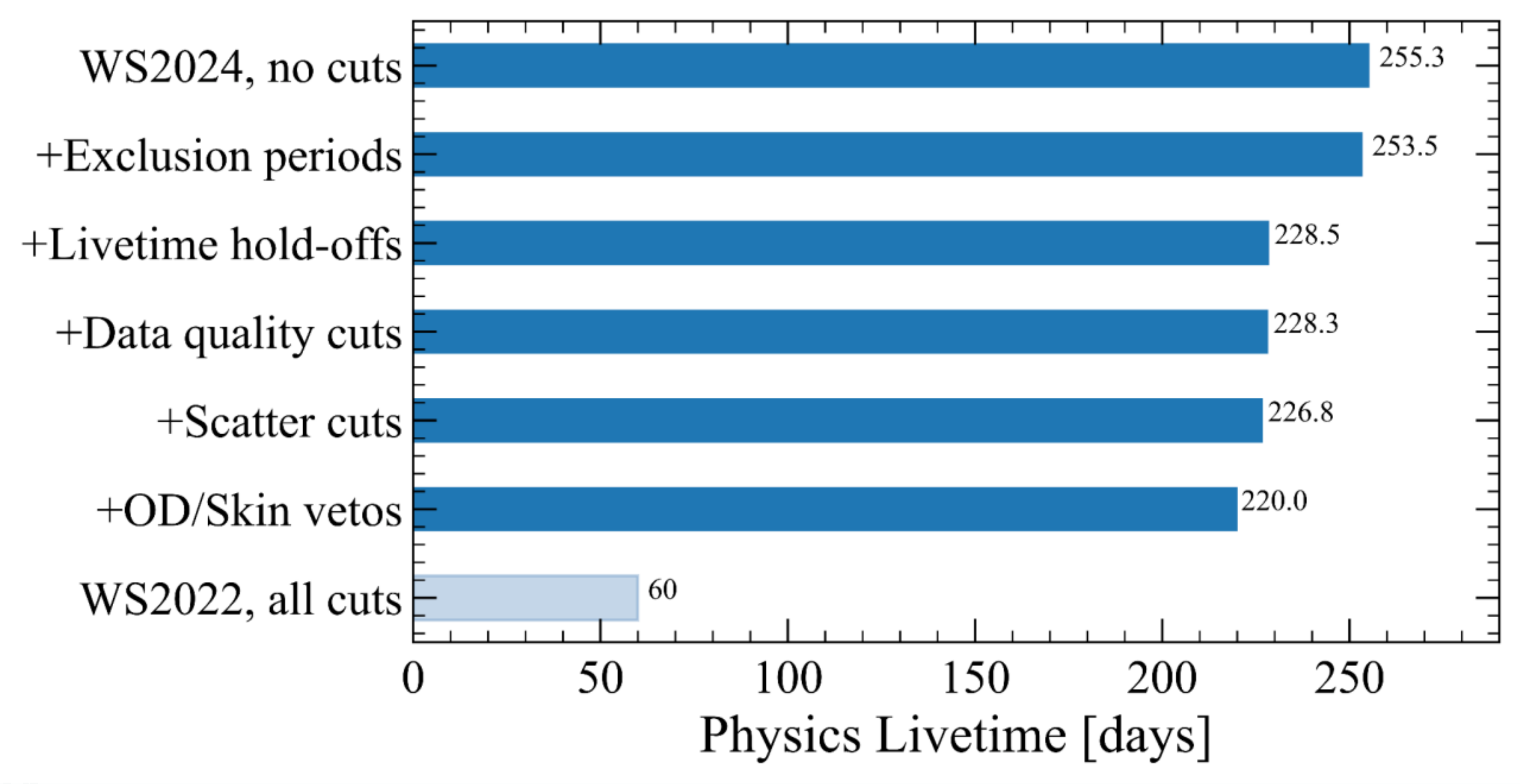
WS2024 Event Position distribution

LZ Preliminary



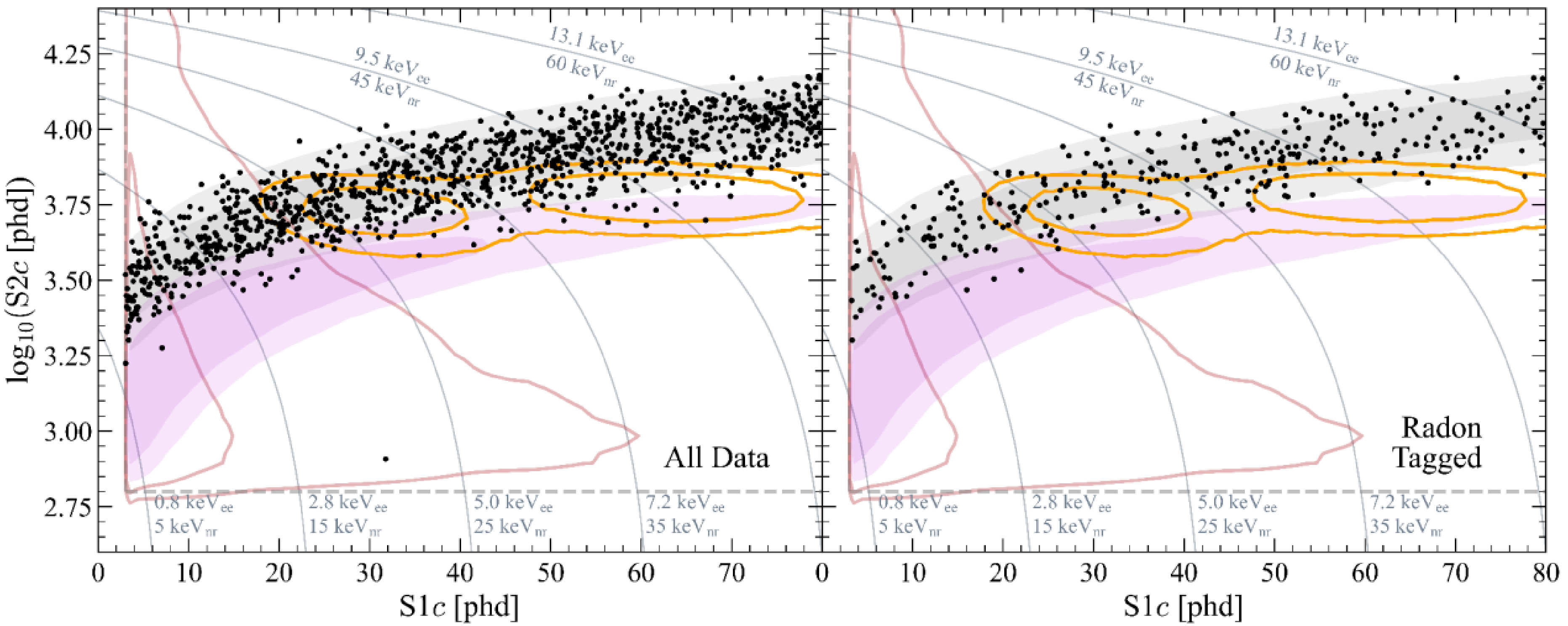
Livetime removal for data quality

LZ Preliminary

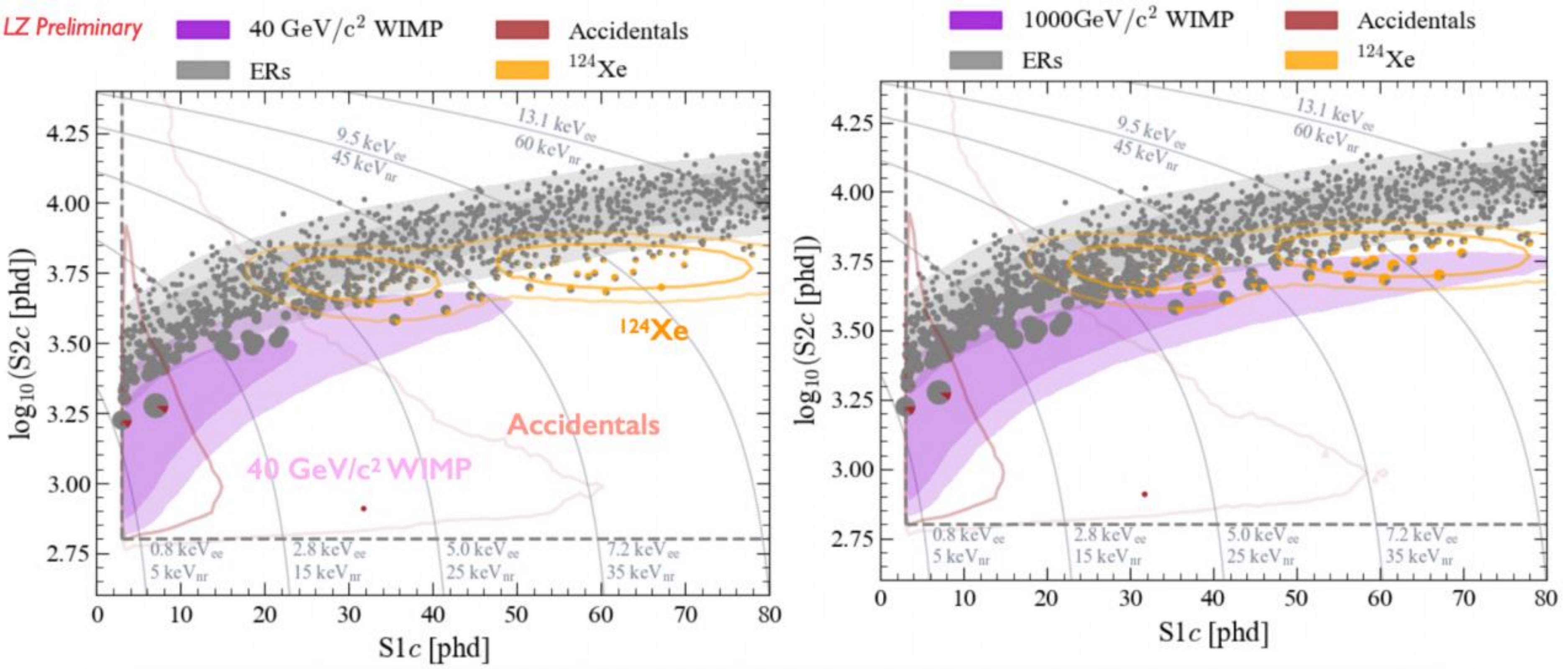


10 TeV/c^2 WIMP

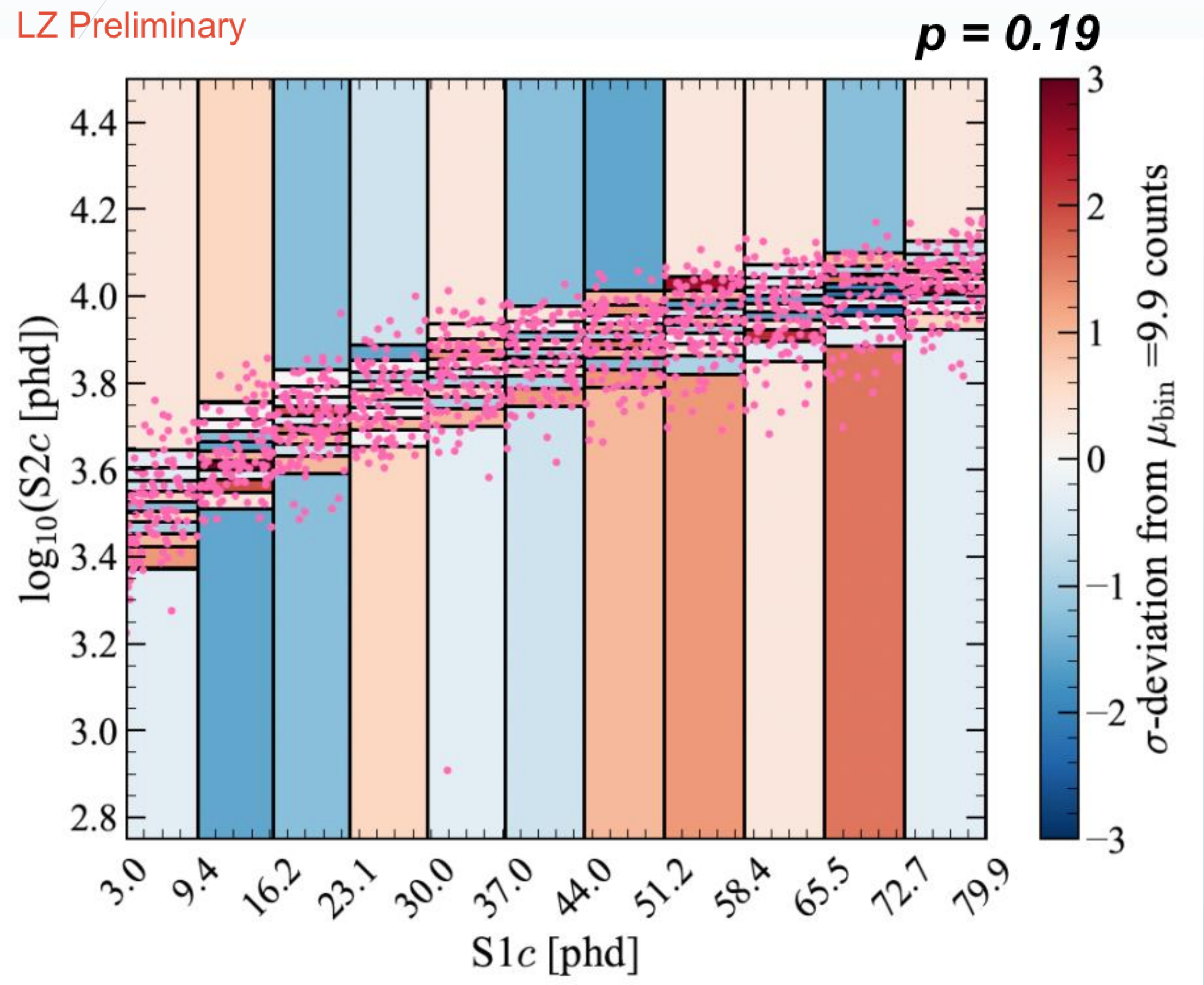
LZ Preliminary



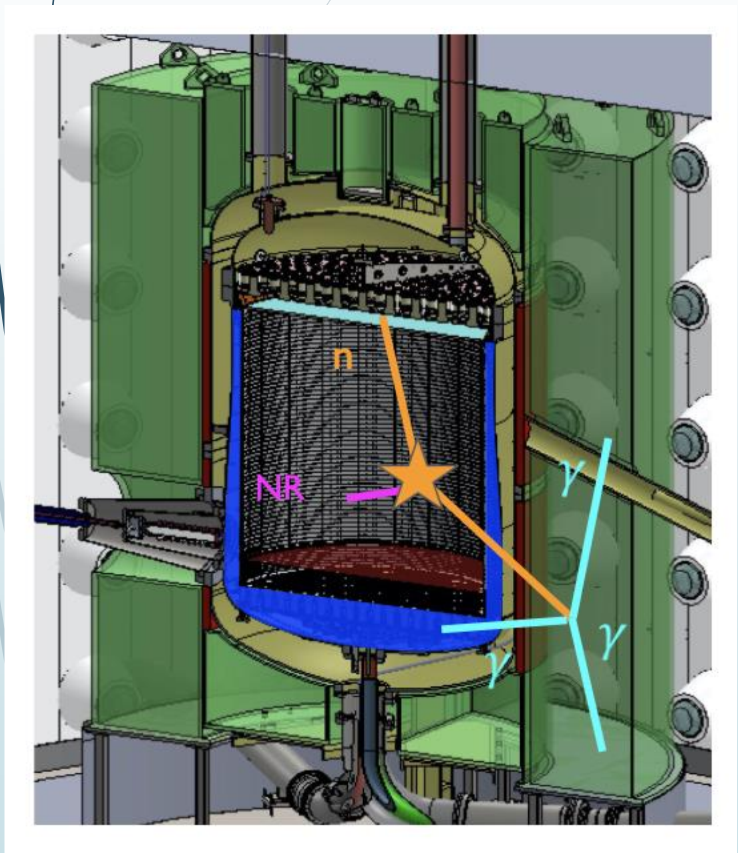
WS2024 Background Events Pie Chart



WS2024 2D Goodness of Fit

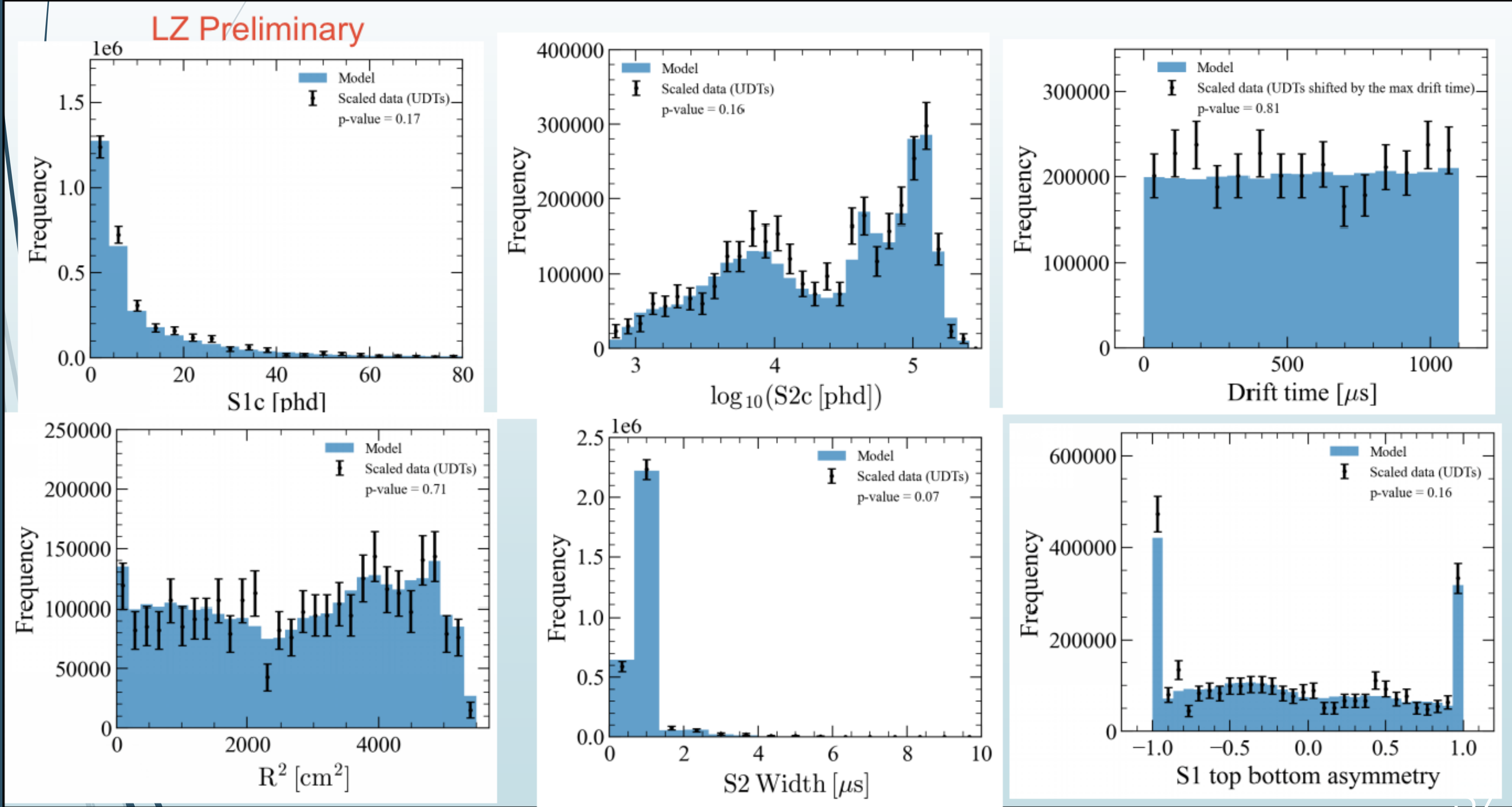


LZ Skin and Outer Detector Vetoes



- 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 gamma
  - Capture on H gives 2.2 MeV gamma
- 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%

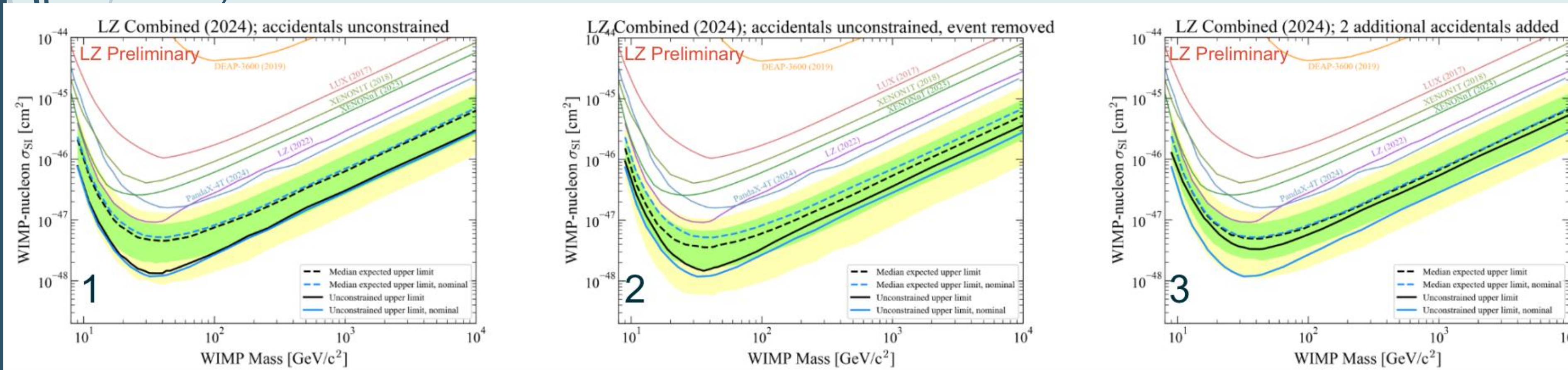
WS2024 Accidental Coincidence: model & unphysical drift sideband comparisons



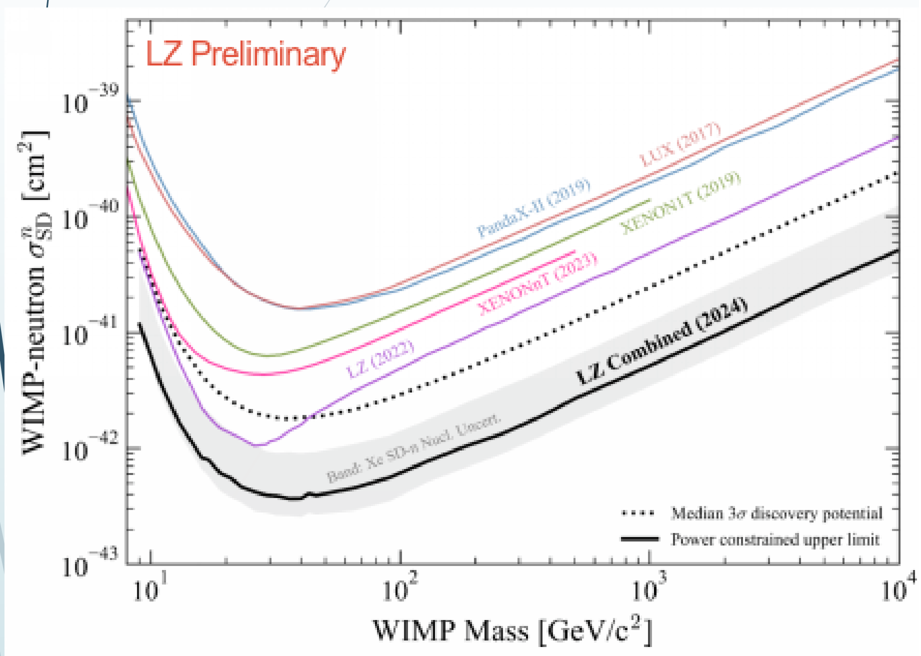
WS2024 Accidental Coincidence Background Impact on Final Limit

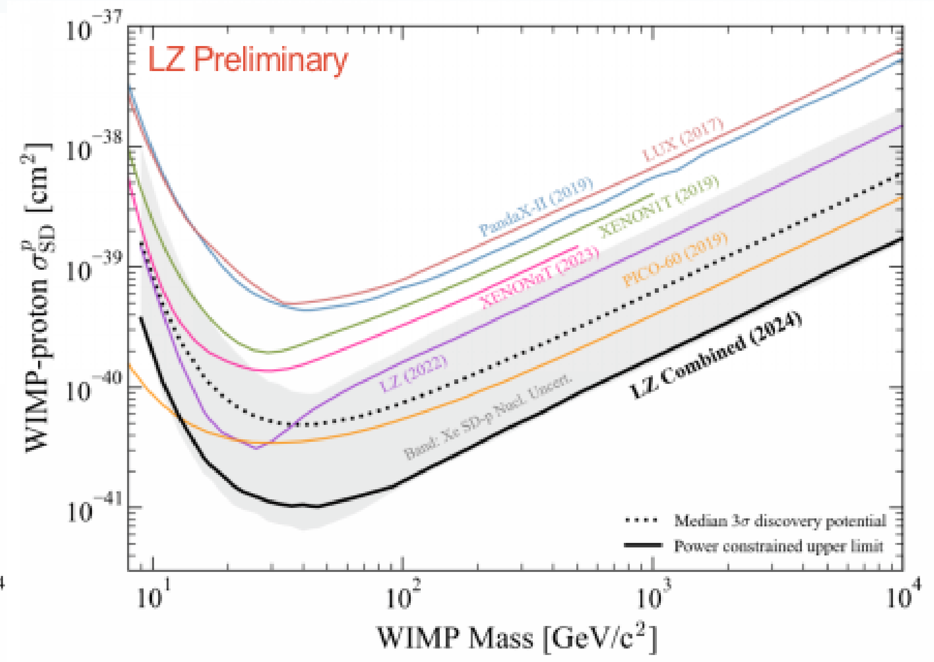
1. Remove accidental rate constraint: best fit drops 2.6 → 1.4
2. Remove constraint & outlier event: best fit drops 1.4 → 0
   Outlier event holds model up, over subtracting in the WIMP region
3. Adding fake events - props limit back up

   → under-fluctuation of accidental events in the WIMP region



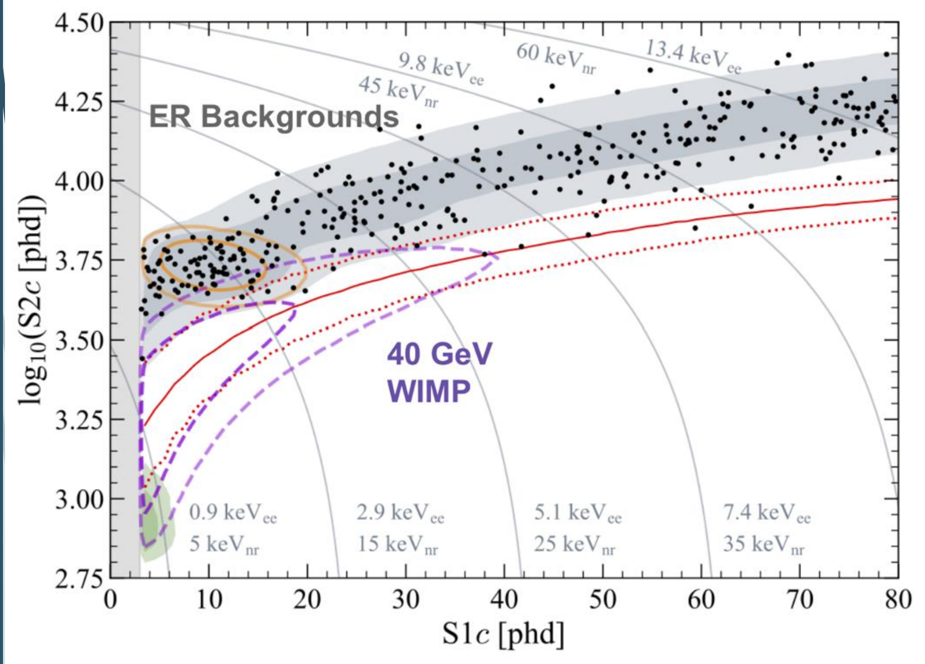
WS2022+WS2024 Combined Spin-dependent WIMP-nucleon Cross Section

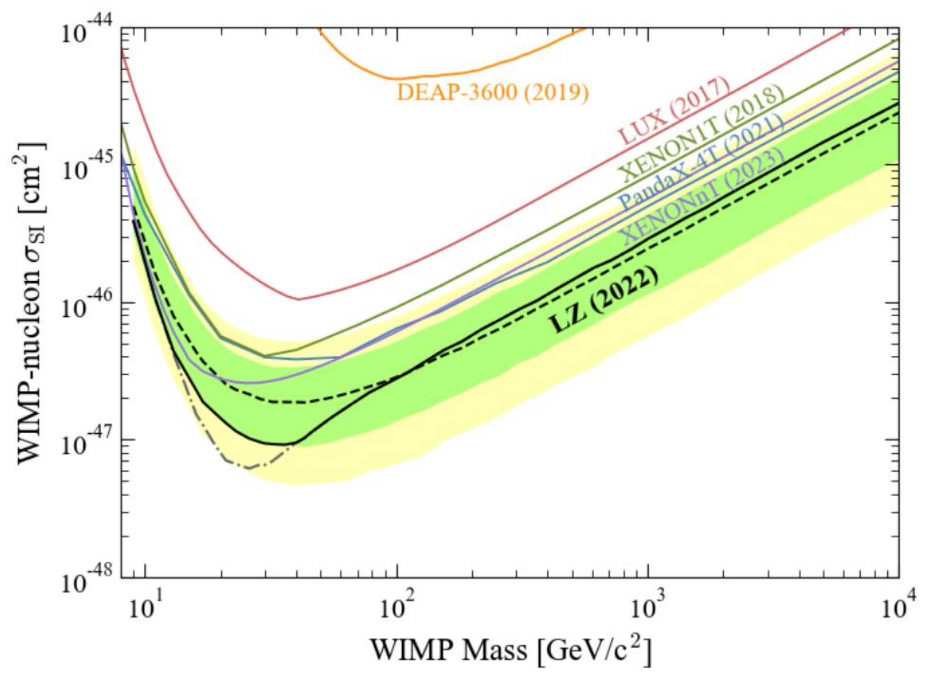




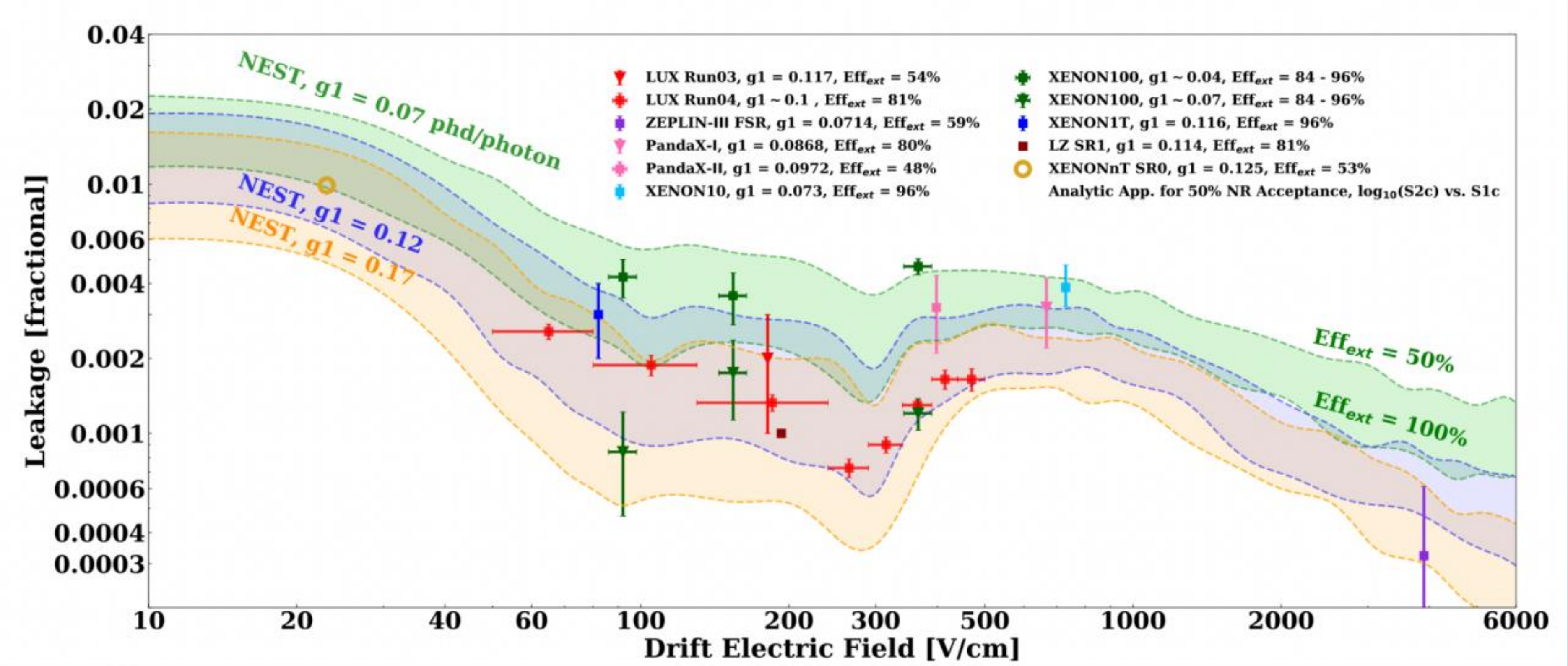
- Grey bands : theoretical uncertainties on SD form factors
- Solid black line: power constrained limits

WS2022 WIMP Search Result





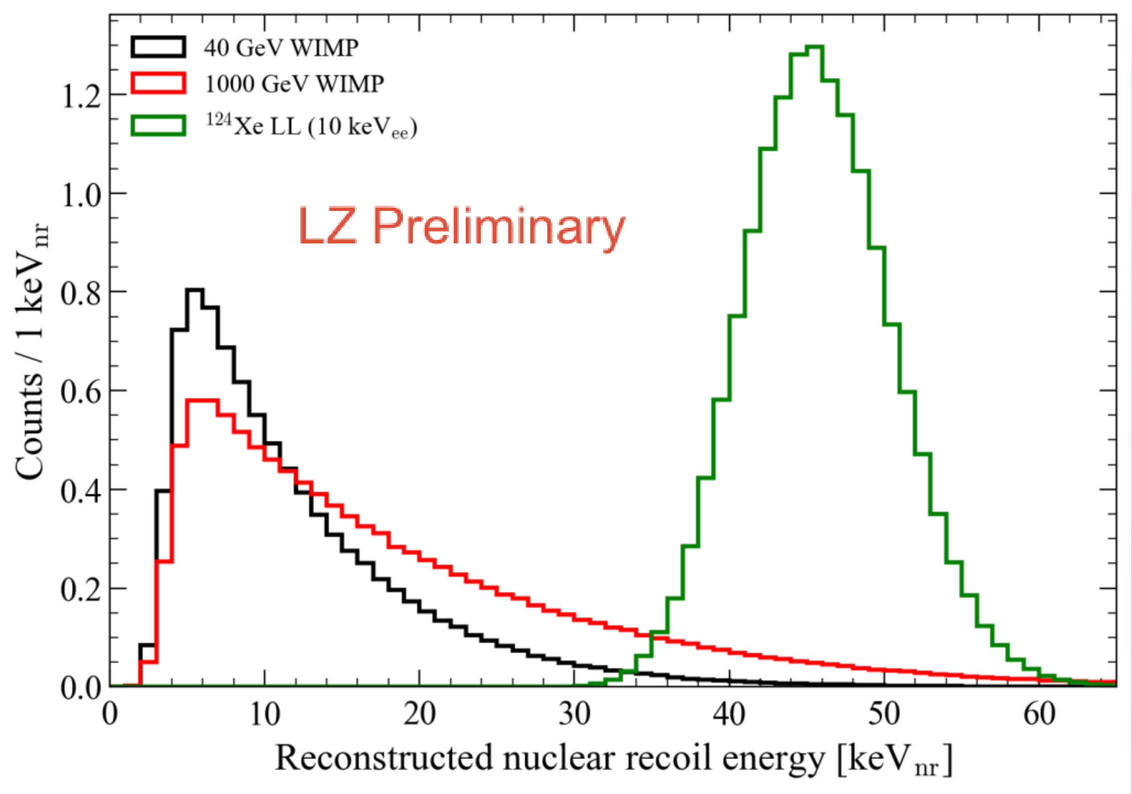
ER leakage vs Drift Field



arXiv:2211.10726

^{124}Xe LL-shell Compared to Dark Matter Spectra

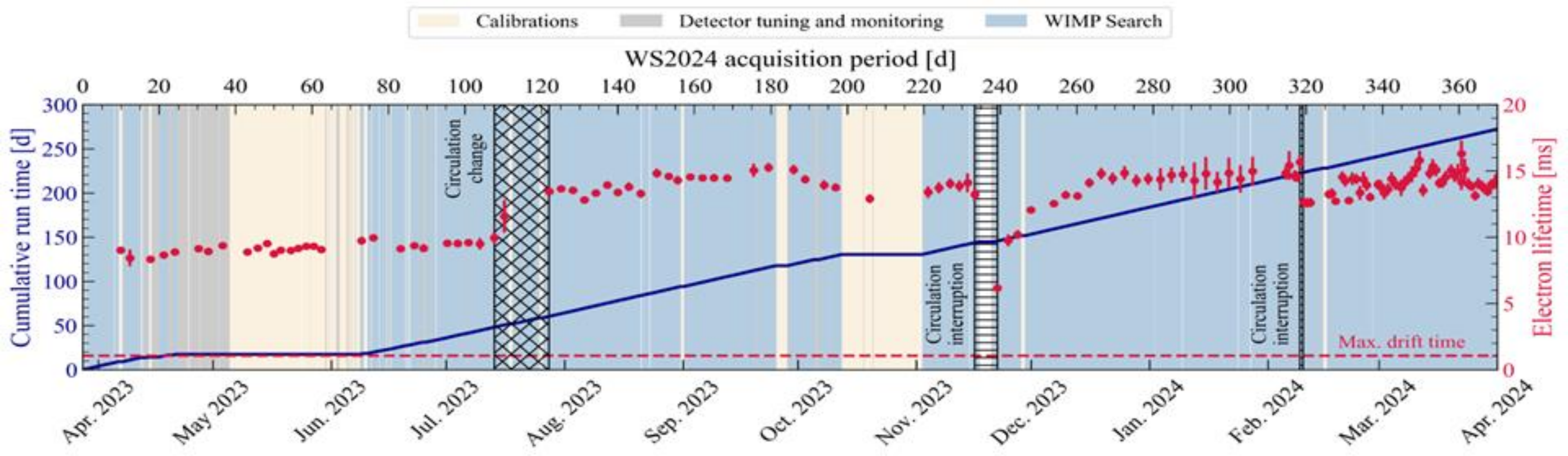
- WIMP spectra normalized to LZ's 4.2 tonne-yr median 3σ discovery potential:
  - 9 evts @ 40 GeV
  - 11 evts @ 1000 GeV



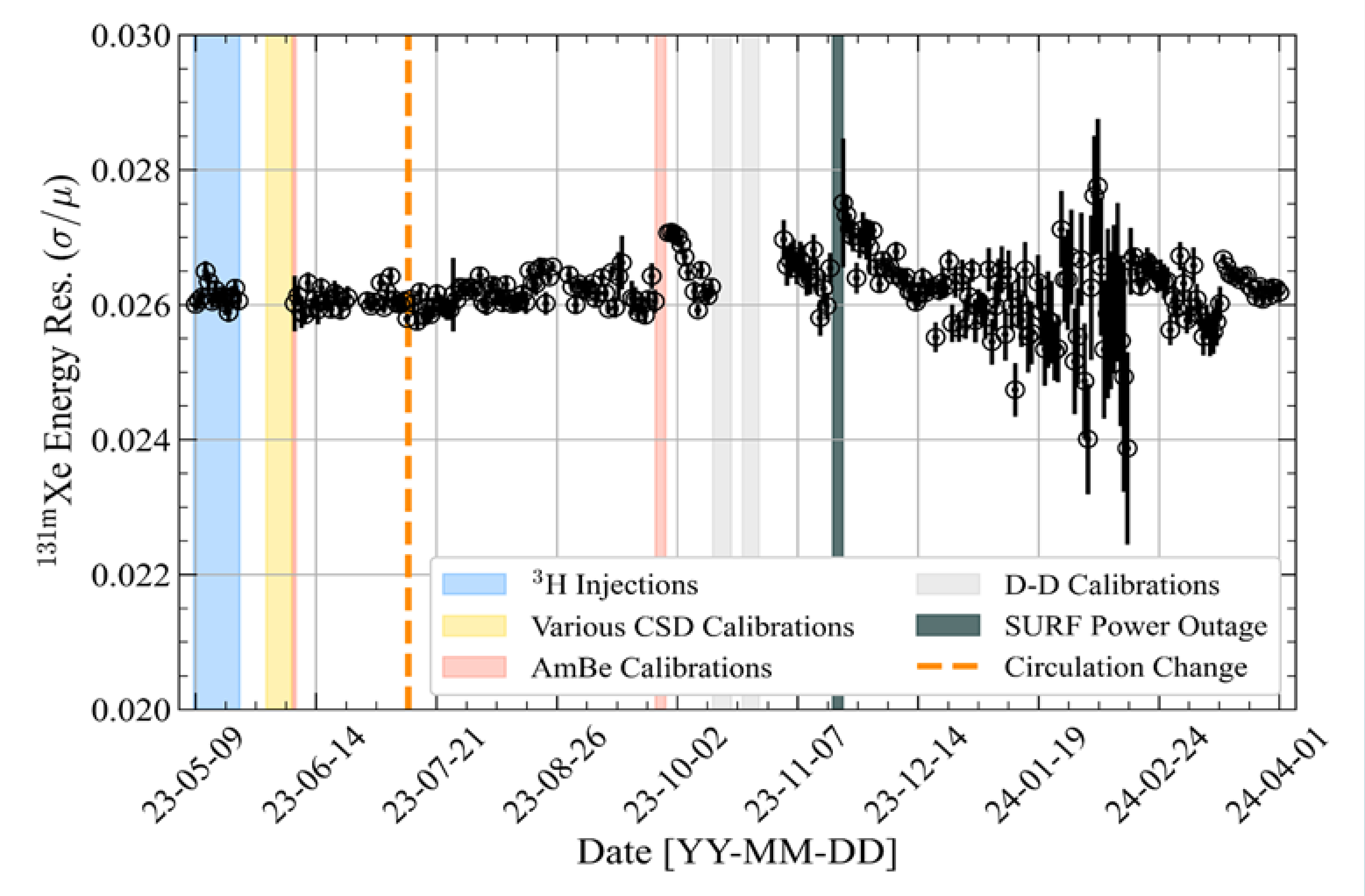
WS2024 Exposure

- Bias mitigation ("salting") began July 3rd, 2023; circulation state change July 12th

LZ Preliminary



Detector stability monitored by ^{131m}Xe



WS2024 Electron Lifetime