Latest results from the LUX-ZEPLIN Experiment

Paulo Brás, on behalf of the LUX-ZEPLIN Collaboration

View of the Yates shaft, Homestake mine, Sanford Underground Research Facility (SURF), Lead, SD, USA

TeV Particle Astrophysics
TeVPA
Valencia 2025

LUX-ZEPLIN (LZ) Collaboration

@lzdarkmatter
https://lz.lbl.gov/

38 Institutions, 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

US Europe Asia Oceania

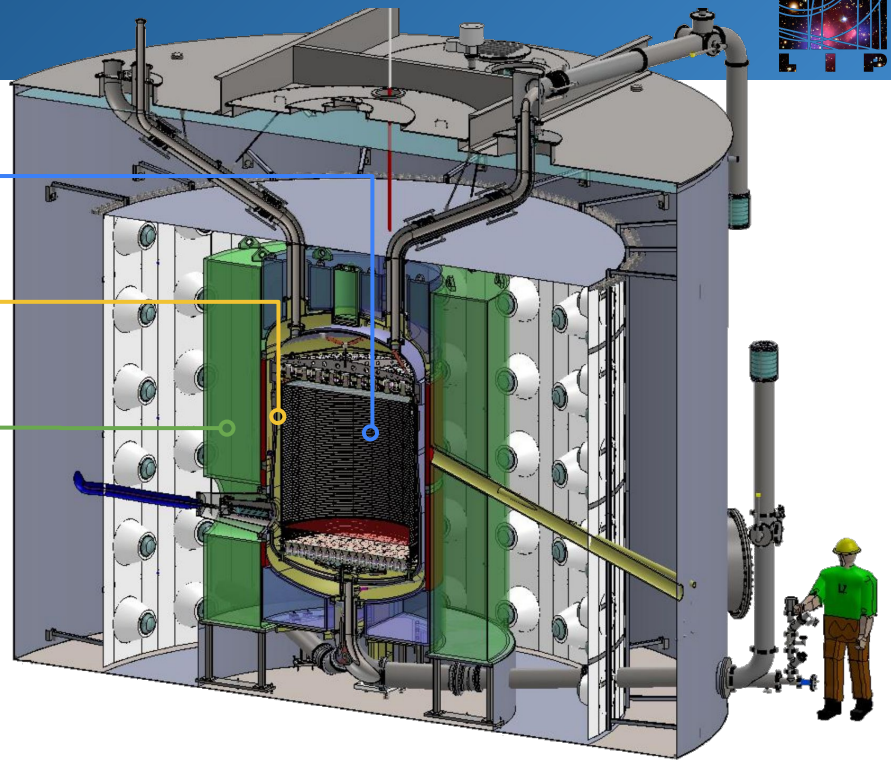
Thanks to our sponsors and participating institutions!

The LUX-ZEPLIN experiment

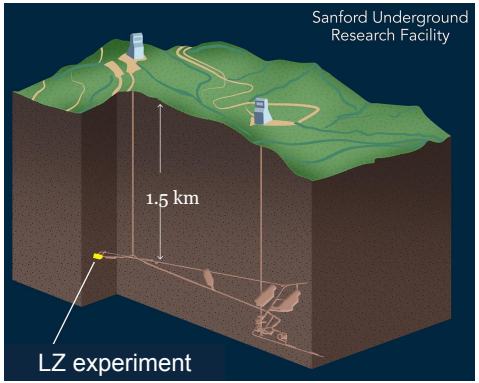
7 tonne dual-phase Xe ultra-low background TPC, 494 PMT readout (>96% operational)

2 tonne Xe "Skin" detector surrounding the TPC, 131 PMT readout

17 tonne Gd-loaded liquid scintillator Outer Detector, 120 PMT readout



Installed 1.5 km deep at Sanford Underground Research Facility (SURF) in SD, USA:

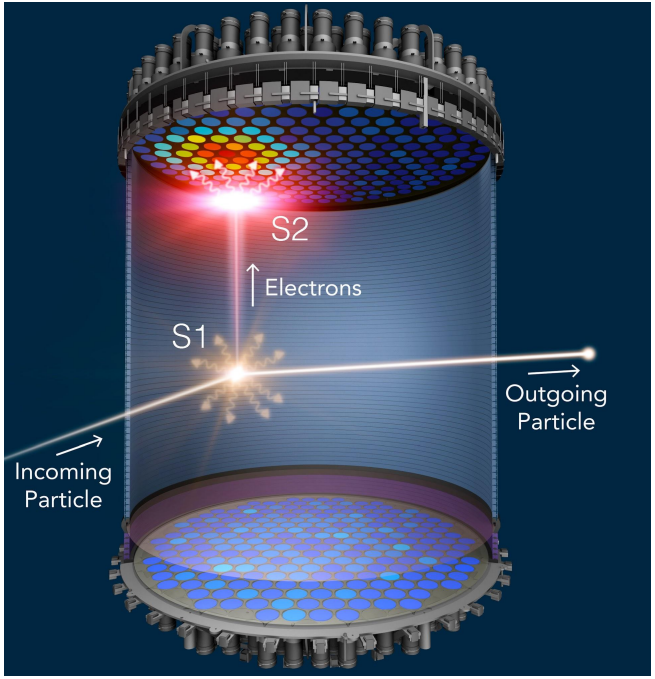


➔ 4300 m.w.e

➔ >10^6 muon attenuation

LZ is designed for **dark matter** searches, but has a broad science program: 0νββ decay in Xe-136, neutrino physics, etc.

LZ dual-phase TPC: operating principle



Energy deposition in LXe target produces 2 signals:

- Prompt Xe scintillation (**S1**)
- Delayed electro-luminescence in gas (**S2**) from drifted ionization

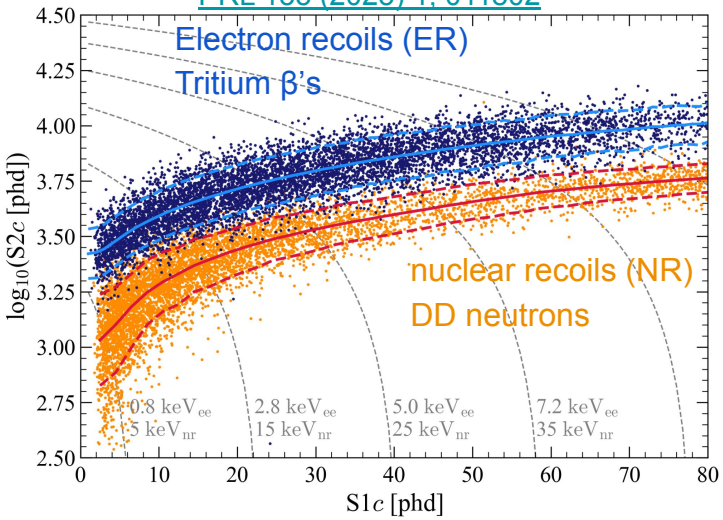
$$E = LW\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

W≈13.7 eV;
L is a quenching factor
g1 & g2 are detector parameters

Detector response (WS2024):

- light gain (g1): 0.112(2) phd*/photon
- charge gain (g2): 34.0(9) phd/electron

PRL 135 (2025) 1, 011802



Xenon response is modeled with Noble Element Simulation Technique (NEST) JINST 6 P10002

➔ Vertical position is obtained from S2-S1 time difference

➔ XY position reconstructed from S2 light pattern in the top PMT array

*photons detected (phd)

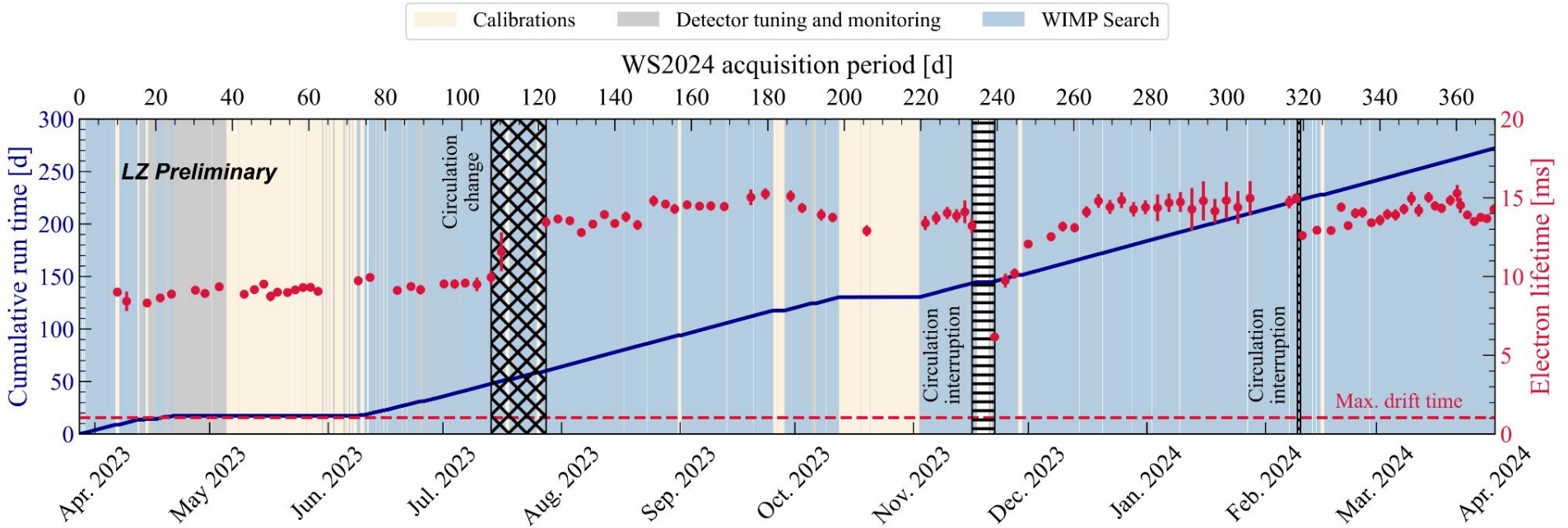
Science Data Timeline

WS2022: Dec 2021 to May 2022 [PRL 131 (2023) 4, 041002]

WS2024: Mar 2023 to Mar 2024 [PRL 135 (2025) 1, 011802]

- High Xe purity, stable detector conditions.
- Circulation change in July 2023

	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

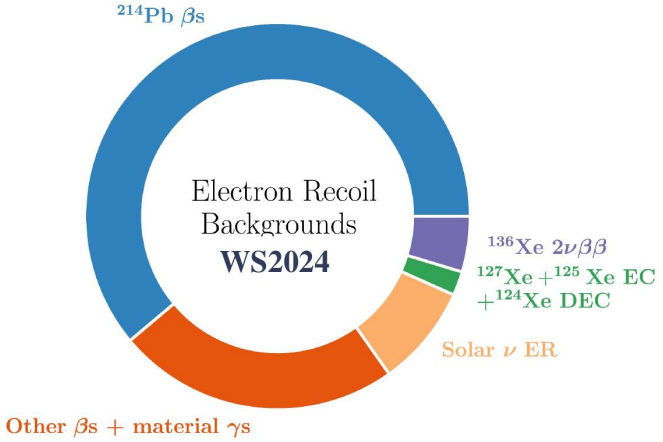


Backgrounds model (WIMP search)

(PhysRevD.108.012010)

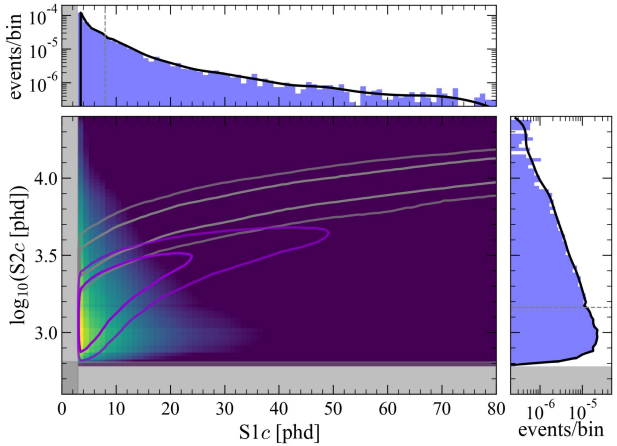
ER Backgrounds (WS2024: 1207 exp. counts)

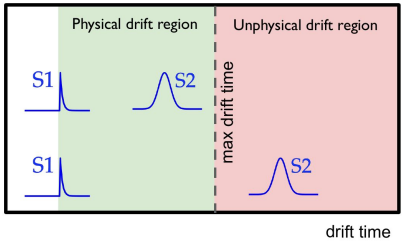
- Dissolved beta emitters:
  - **^{214}Pb** (^{222}Rn), ^{212}Pb (^{220}Rn), ^{85}Kr, ^{136}Xe (2β)
- Dissolved EC decays (x-ray/Auger cascades):
  - ^{127}Xe, ^{125}Xe (EC) from neutron activation
  - ^{124}Xe (double EC)
- Long-lived γ emitters in detector materials:
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- Solar pp and ^{7}Be neutrinos (ER)



Instrumental Backgrounds (WS2024: 2.8 exp. counts)

- Accidental Coincidences: uncorrelated S1 and S2 pulses
  - Rate from unphysical drift time events
  - Shape from manufactured accidental events





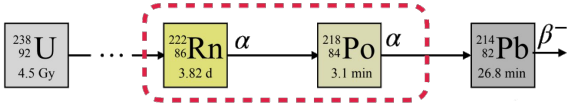
NR Backgrounds (WS2024: 0.18 exp. counts)

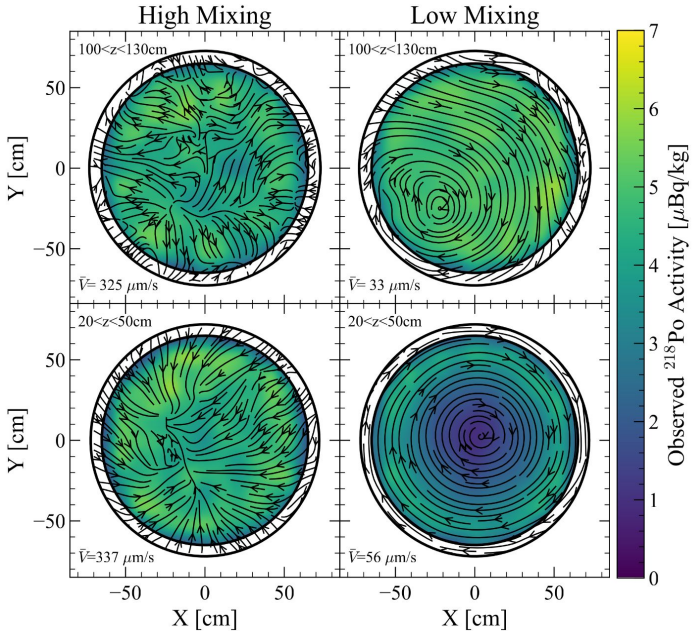
- Neutrons from spontaneous fission and (α,n)
- Solar ^{8}B and hep neutrinos (CEvNS)

New Features: Rn tagging, LXe flow, and EC decays

Control of LXe flow via TPC temperature, map using ^{222}Rn-^{218}Po pairs ⇒ tag ^{214}Pb decays **(63 ±6^{stat} ±7^{sys}) % eff**

➔ See Nicolas Angelides talk today at 17:00!

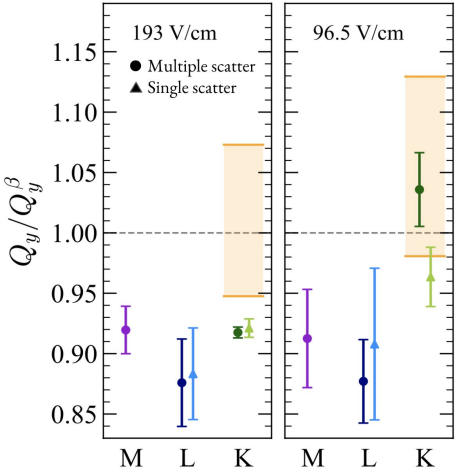


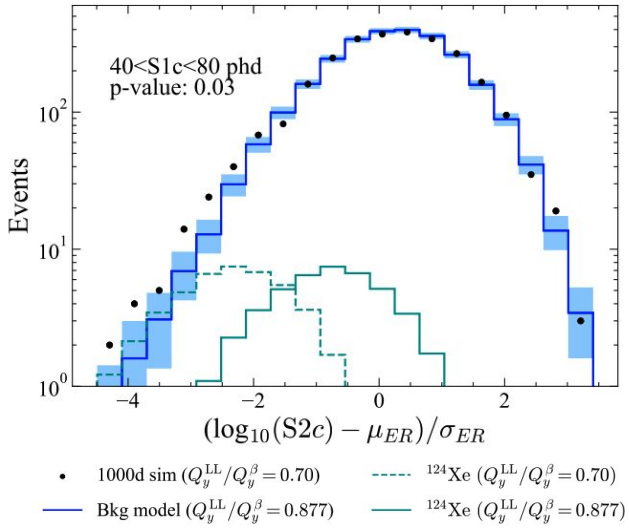


arXiv.2508.19117 (submitted to PRD)

➔ ^{127}Xe & ^{125}Xe L-shell EC (5.2 keV) in-situ measurement in LZ: **Q_L/Q_β = 0.877 ± 0.035**

➔ ^{124}Xe LL double EC (10 keV) best fit WS2024: **Q_{LL}/Q_β = 0.70 ± 0.04**





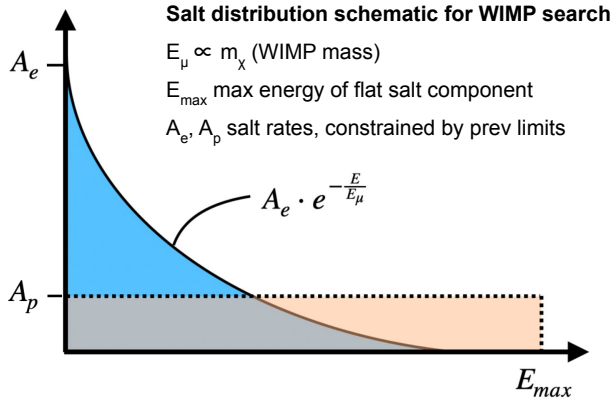
PRD 112 (2025) 1, 012024

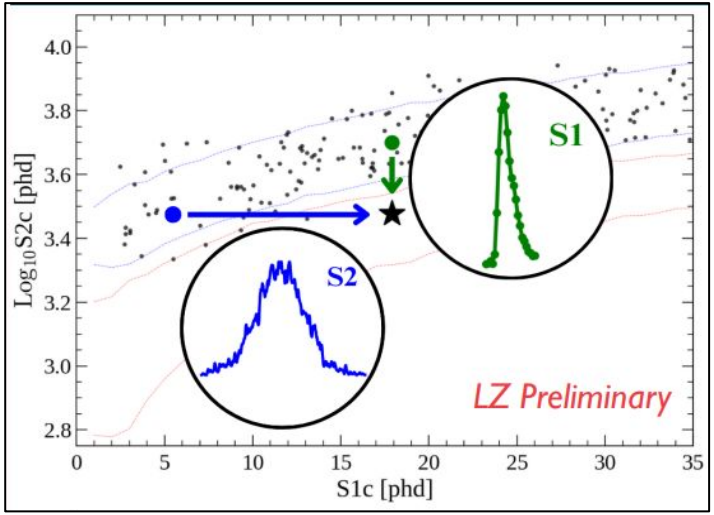
Bias mitigation via ‘salt injection’

“**Salting**” - fake signal events randomly injected during science data collection

- ★ Events manufactured using S1s & S2s from sequestered calibration data
- ★ Number of injected events is bounded from above by LZ WS2022 upper limit
- ★ Exponential+flat spectrum (exact parameters randomly generated, kept hidden)

Identity of salt events revealed after analysis inputs are finalized for final inference

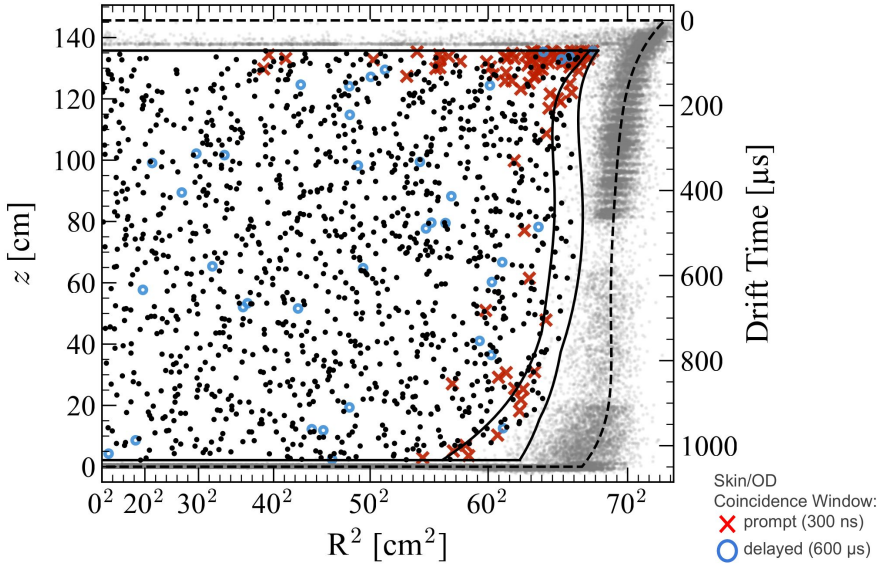


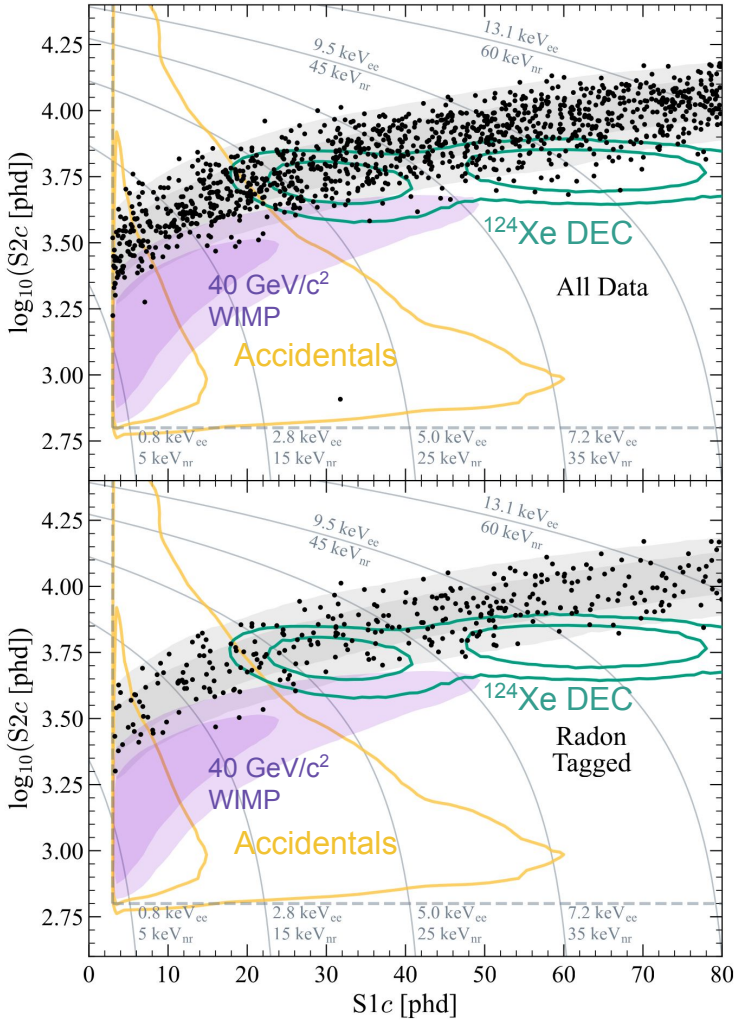


WS2024 dataset (post-unsalting)

Region of interest: $3 < \mathbf{S1_c} < 80$ phd in ≥3 PMTs
$14.5 < \mathbf{S2_c} < 710$ e⁻

- ★ 220 live days × 5.5 t = **3.3 t·yr**
- ★ 1220 events remain <u>after unsalting</u>
- ★ Excellent agreement with background-only model



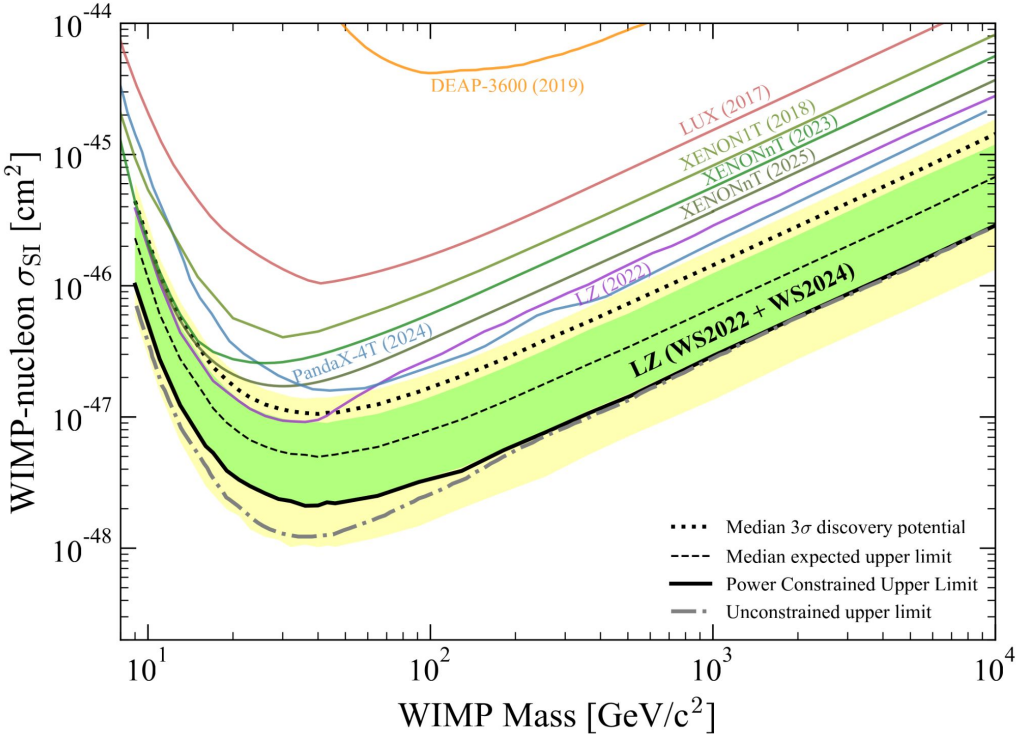


WS2024+WS2022 Spin-Independent Limit

PRL 135 (2025) 1, 011802

- ★ Best fit of zero WIMPs at all tested masses (9 GeV – 10 TeV)
- ★ Frequentist, 2-sided profile likelihood ratio test statistic
- ★ Upper limit is power constrained at -1σ sensitivity band per DM conventions [EPJC 81 907 (2021)]
- ★ Additional under fluctuation from combination with WS2022 result
- ★ Best limit from combined analysis: $\sigma_{SI} = 2.2 \times 10^{-48}$ cm^2 @ 40 GeV/c^2

World-leading result!

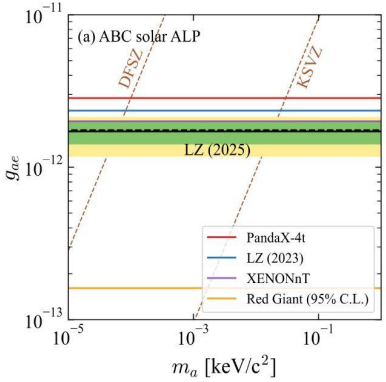


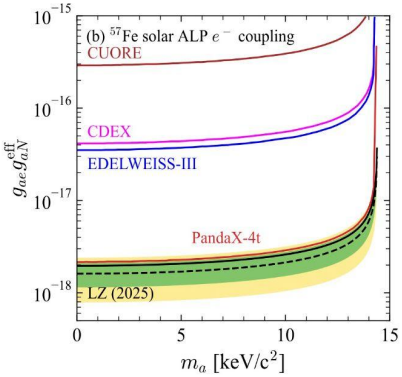
Electronic Recoil (ER) searches

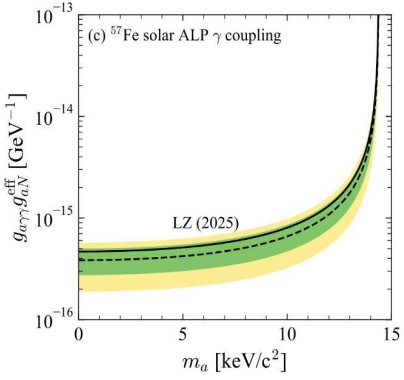
Heavy solar axion-like particles (ALPs)

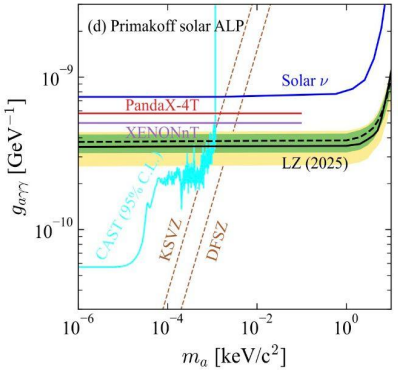
★ Most stringent constraints

LZ preliminary



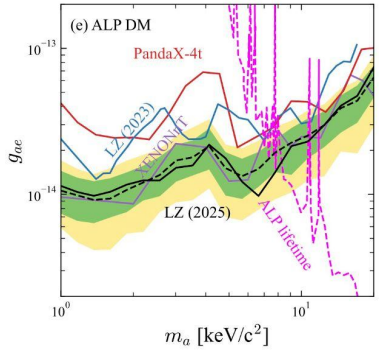


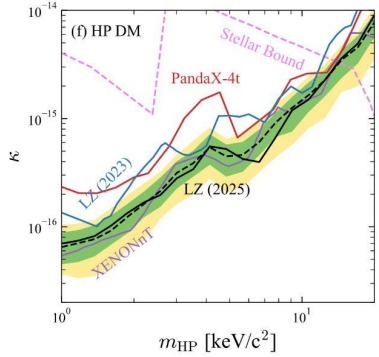




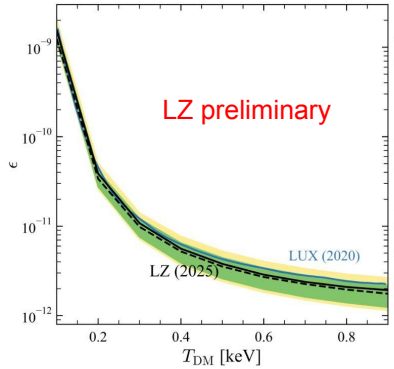
Bosonic halo DMs (ALPs and dark photons)

LZ preliminary

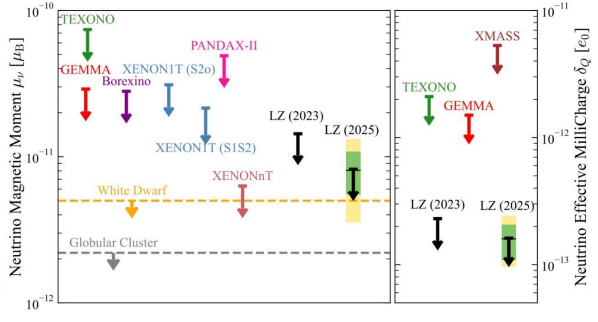




Mirror dark matter



Neutrino EM properties



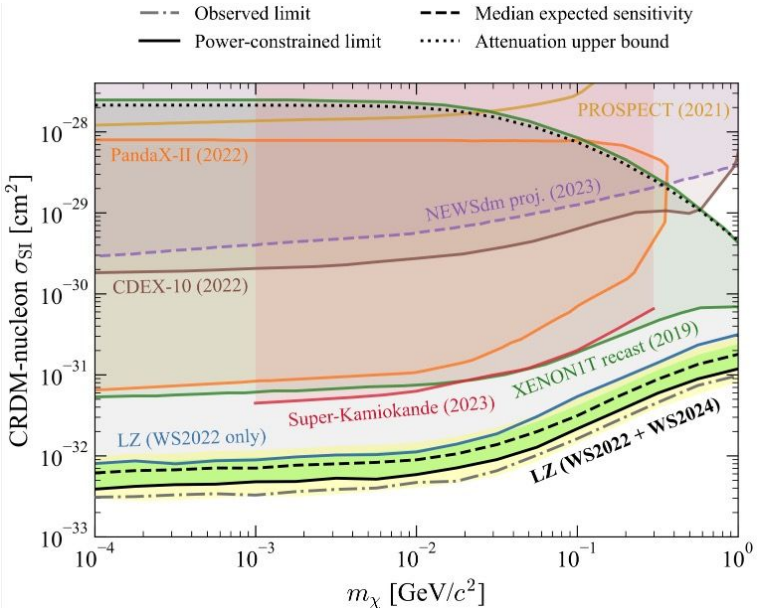
LZ preliminary

Other recent DM search results

Cosmic ray-boosted dark matter

Phys.Rev.Lett. 134 (2025) 24, 241801

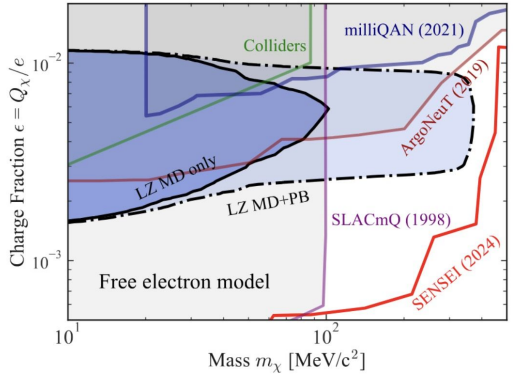
- ★ Data compatible with background-only
- ★ Most stringent constraints (×10)

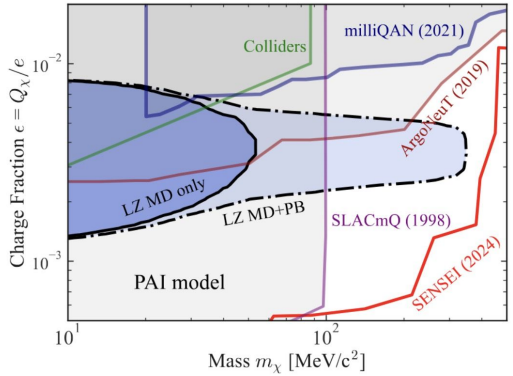


Atmospheric millicharged particles

Phys.Rev.Lett. 134 (2025) 24, 241802

- ★ Production channels: meson decay (MD) and proton bremsstrahlung (PB)
- ★ Characteristic event signature, quasi-background free
- ★ No observed events in WS2022 dataset





Conclusions

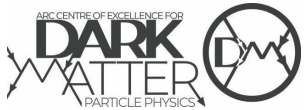
LZ combined 4.2 tonne-year exposure yields new **world-leading WIMP search result**.

1. First implementation of radon tagging in DM result, with 60% reduction in ER background
2. First measurement of charge-suppression in ^{124}Xe DEC
3. LZ is discovery ready!
4. Extensive search for new physics in the ER channel in an extended ROI yields several world leading constraints.

LZ will continue to take quality science data (salted) for the next few years:

5. Multiple physics channels on the horizon: ^{8}B CEvNS, low-mass WIMPs, ^{136}Xe 0νββ decay, and more!

Thank You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BACKUP: Detector Response Calibration

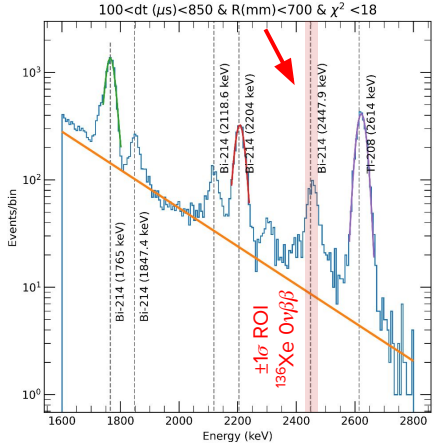
JINST 18 (2023) 04, C04007

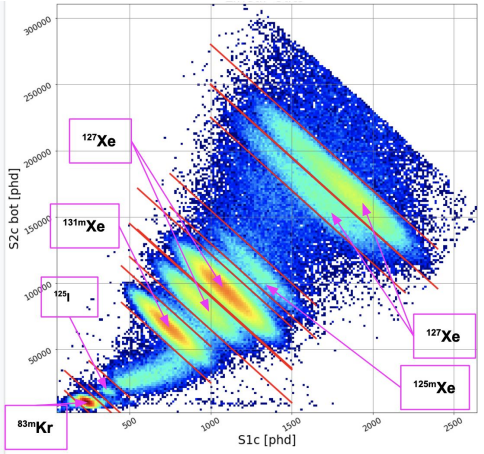
- Electron recoils (background-like):
  - Radiolabeled methane
    ^{3}H (18.6 keV) & ^{14}C (156 keV)
  - Injected ^{83m}Kr, ^{131m}Xe
  - Activation lines
- Nuclear recoils (signal-like):
  - DD generator 2.45 MeV neutrons
  - AmLi neutrons in calibration tubes

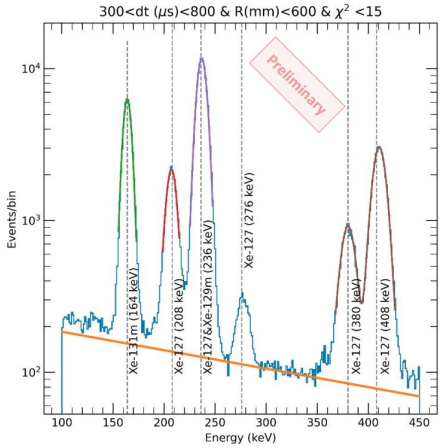
- light gain: **0.112 ± 0.002 phd/photon**
- charge gain: **34.0 ± 0.9 phd/electron**
- single electron size: **44.5 phd**

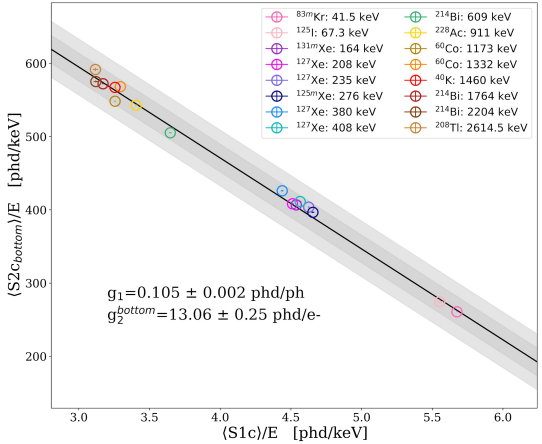
Unprecedented energy resolution for liquid xenon detectors:

0.64 ± 0.02 % (σ/E) for ^{208}Tl 2614 keV









BACKUP: EC Backgrounds

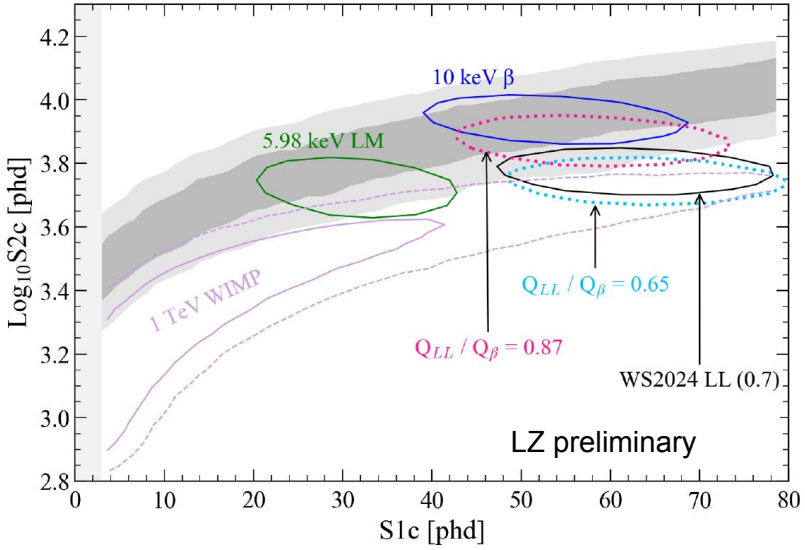
Phys.Rev.D 112 (2025) 1, 012024

Higher ionization density from X-ray+Auger in EC result in charge yield suppression compared to β's of the same energy

👉 ^{127}Xe & ^{125}Xe L-shell EC (5.2 keV) in-situ measurement in LZ: **$Q_L/Q_\beta = 0.86 \pm 0.01$**

Double EC in ^{124}Xe from LM (5.98 keV) and LL (10 keV) expected to display further suppression

- LM modelled with same as single L-shell charge suppression
- Background model allows ^{124}Xe LL-capture suppression to vary: **$0.65 < Q_{LL}/Q_\beta < 0.87$**



Best fit: $Q_{LL}/Q_\beta = 0.70 \pm 0.04$
(WS2024 LL, black contour)

(see next slides with data and the fit)

BACKUP: LXe flow and active ^{214}Pb tagging

arXiv.2508.19117 (submitted to PRD)

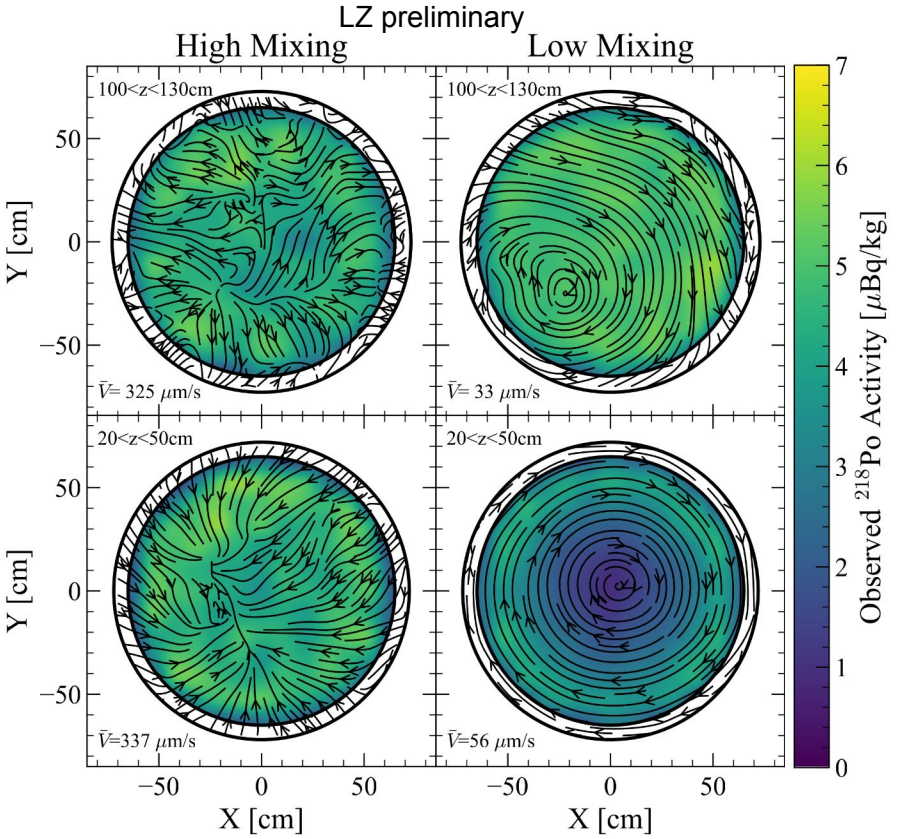
Control of LXe flow via TPC temperature:

1. High Mixing - turbulent-like
2. Low Mixing - laminar-like, convective cells

In low mixing state, use ^{222}Rn-^{218}Po pairs to map liquid flow:

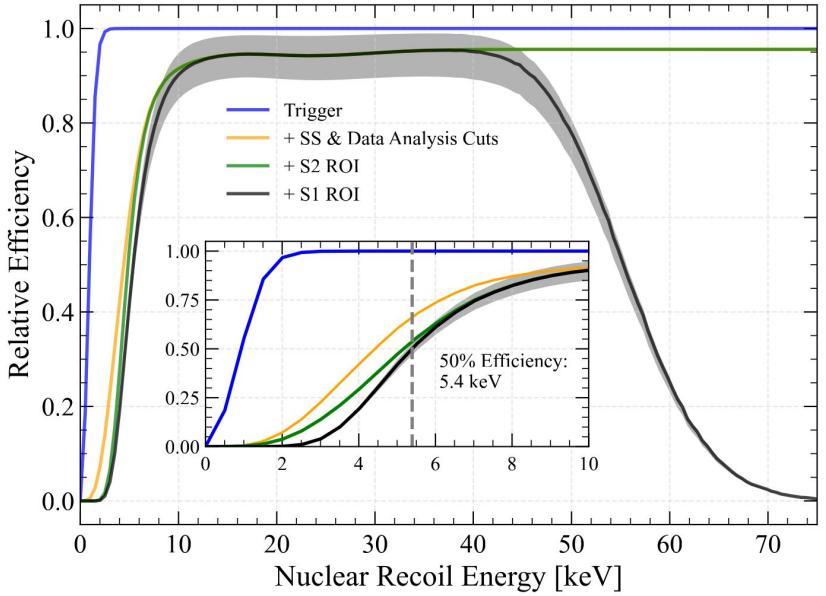
- Predict positions of ^{214}Pb β-decays, tag efficiency: 60±4%
- Reduction of ^{214}Pb BG to 1.8 ± 0.3 μBq/kg during tag-active exposure*
- Tagged & untagged samples used in final inference, no loss of exposure

*Compared to 3.9 ± 0.4 μBq/kg in total exposure

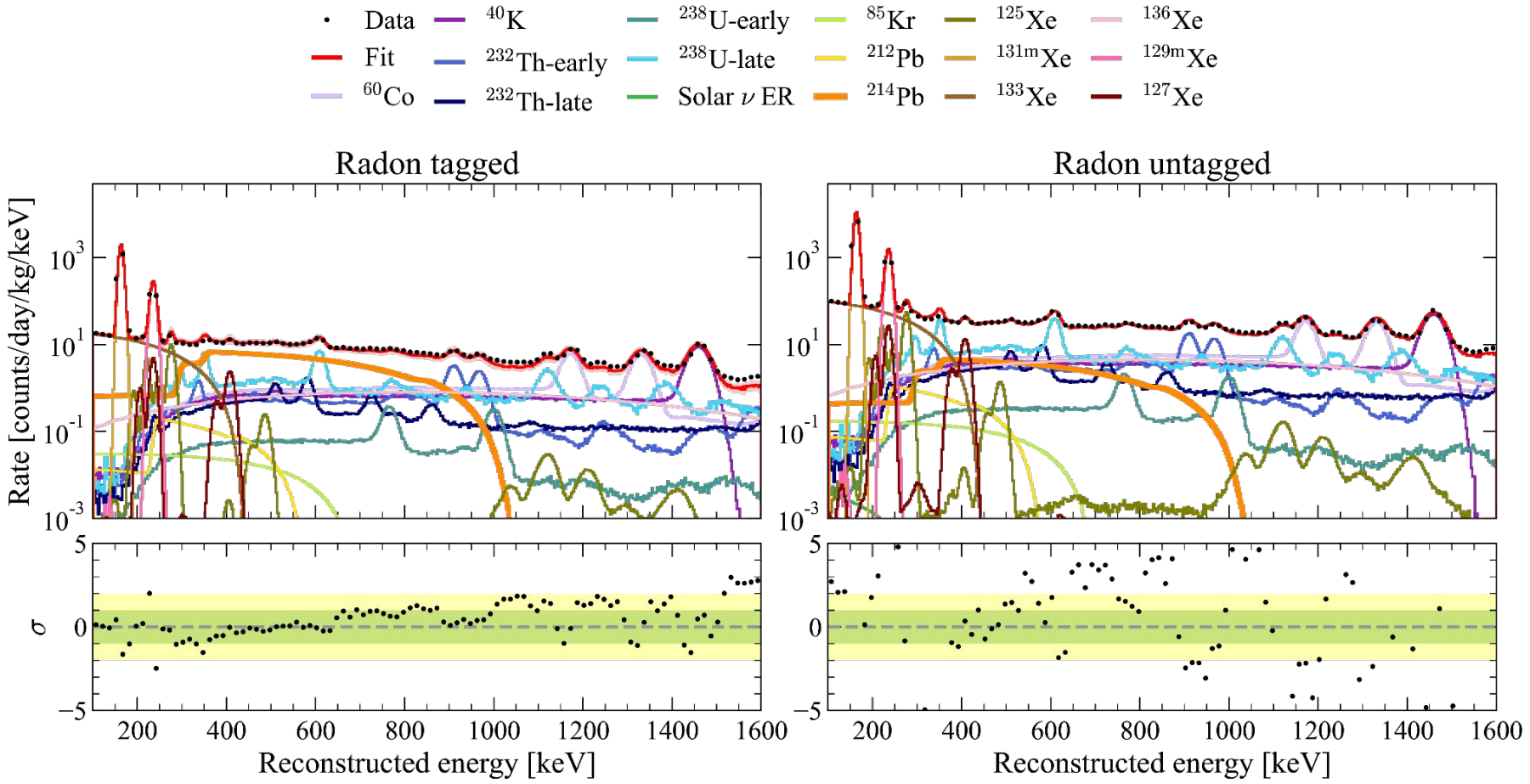


BACKUP: WS2024 Data Selection

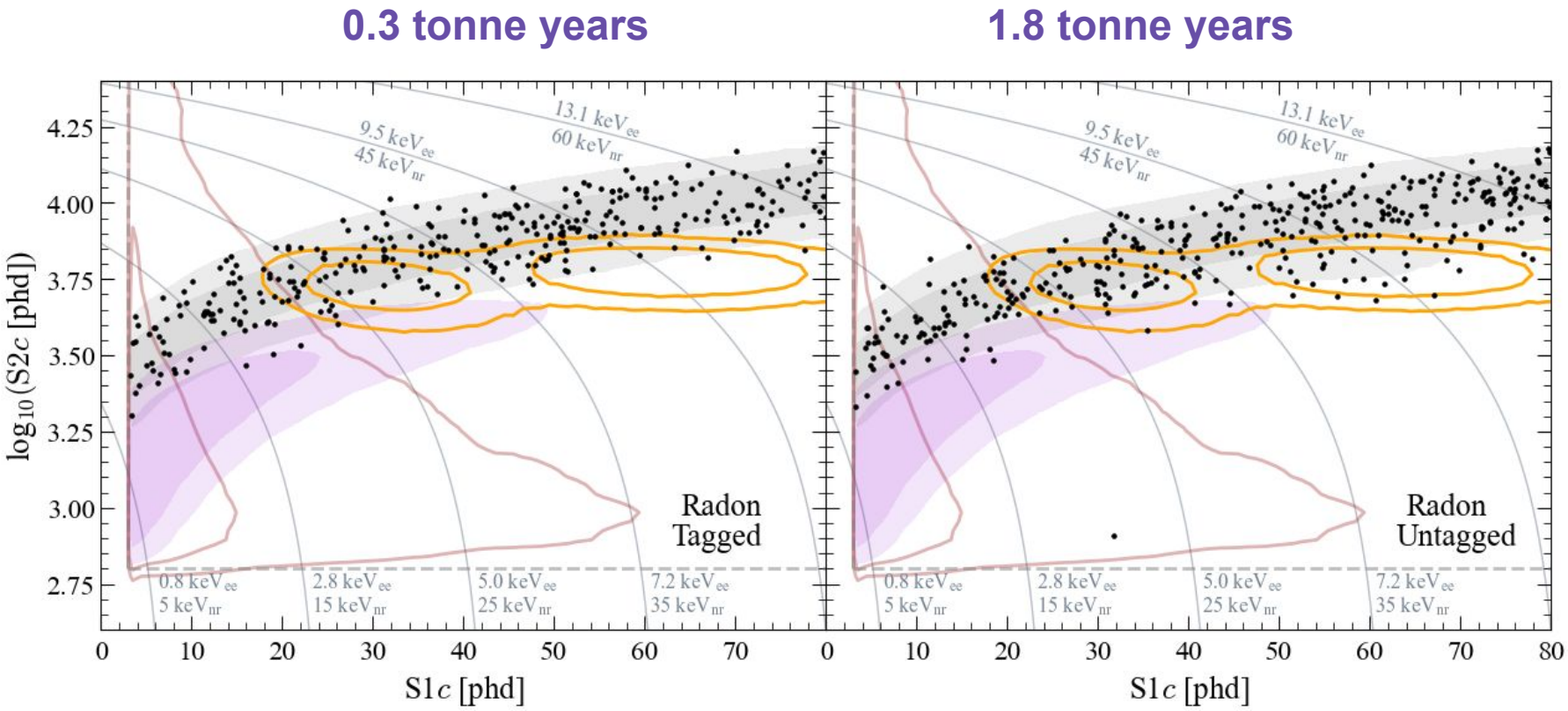
- Data quality cuts: exclusion periods, live time hold-off, S1- & S2-based cuts
- Fiducial volume cut: remove background outside the liquid bulk and near the wall
- Skin/OD veto anti-coincidence, Improved radial acceptance
- Region of interest (ROI)
  - 3 < S1c < 80 phd, signal in >3 PMT
  - 14.5 < S2c < 710 electrons
  - 50% detection efficiency at 5.4 keV (NR)



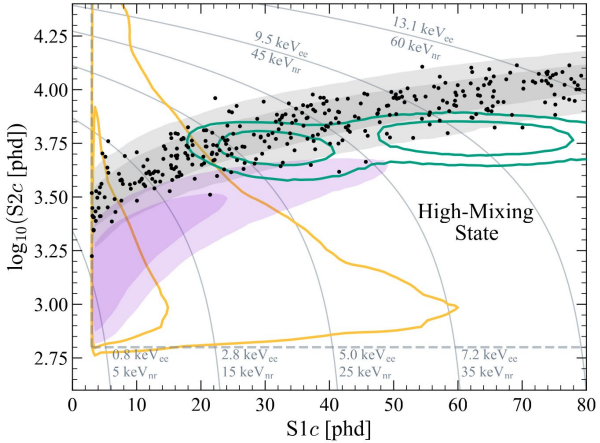
BACKUP: Background model vs data



BACKUP: WS2024 data - Radon tagged vs untagged



BACKUP: 6 WS2024 likelihood datasets

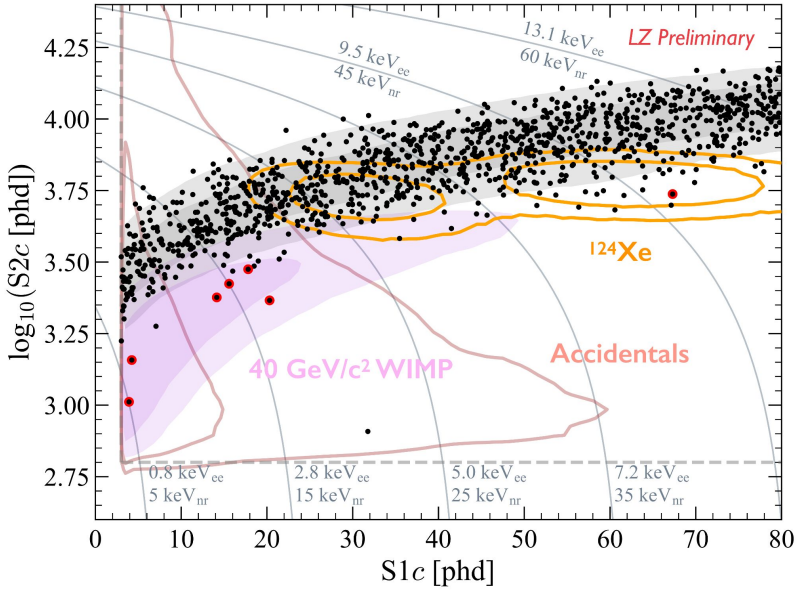


BACKUP: WS2024 data - salted

- ➔ Expected ER counts: **1207** (60% ^{214}Pb)
- ➔ Expected NR counts: **0.18** (CEvNS)

Final exposure of 220 live days * 5.5 tonnes
⇒ **3.3 tonne years**

- 7 salt events pass all analysis cuts
  - out of 8 total injected
  - inline with evaluated signal efficiency
- 1220 events remain after unsalting
- Statistical analysis of these data in observed log10(S2$_c$)-S1$_c$ space
  - no post-unsalting changes to model



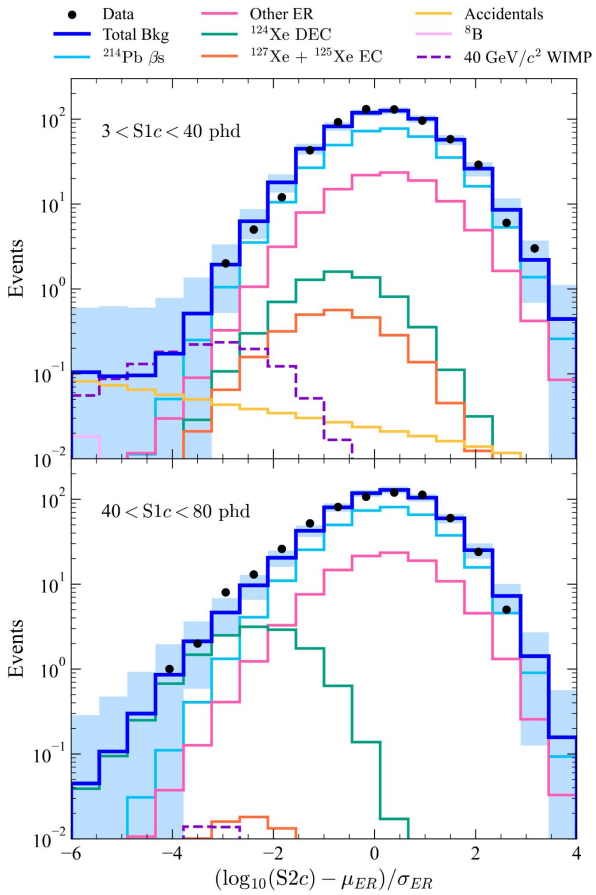
WS2024 final exposure of 3.3 tonne years, 1220 events survive data quality cuts (unsalted data).
Out of 8 total injected salt events, 7 survive analysis.

BACKUP: WS2024 Fit Results

Phys.Rev.Lett.-Accepted 9 May, 2025 (arXiv:2410.17036)

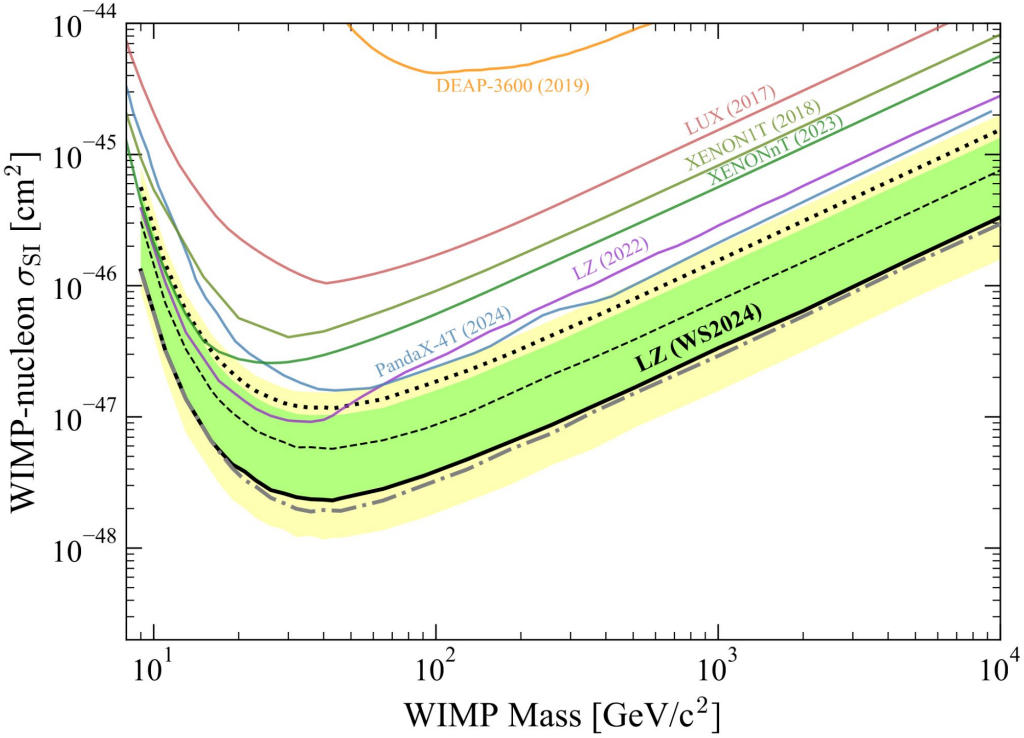
- ★ Excellent agreement with the background-only model
- ★ Best fit of zero WIMPs at all tested masses (9 GeV – 10 TeV)

Source	Pre-fit Expectation	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	55.9 ± 8.2
^{124}Xe DEC	19.4 ± 2.5	20.4 ± 2.4
^{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	$0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1202 ± 41



BACKUP: WS2024-only Spin-Independent Limit

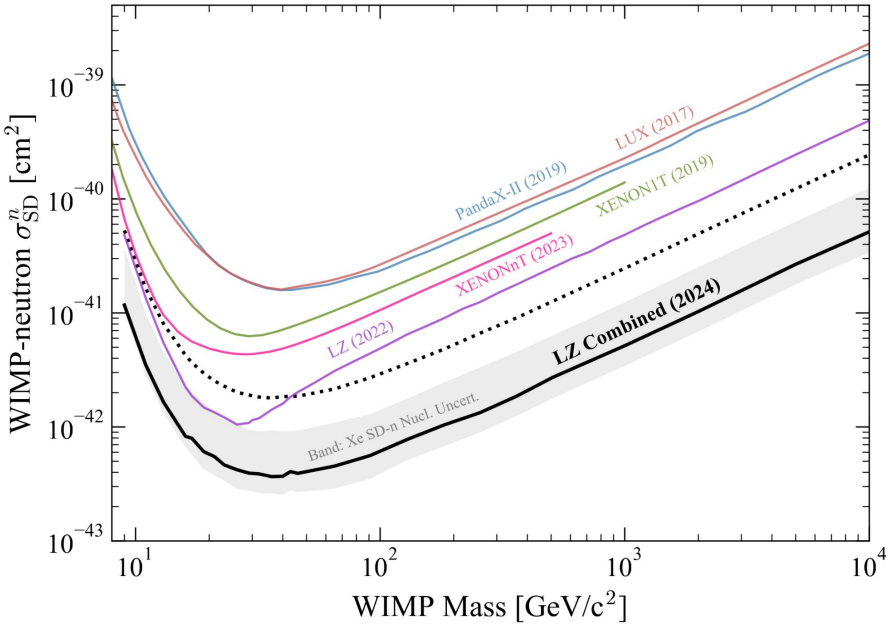
- Frequentist, 2-sided profile likelihood ratio test statistic
- Upper limit is power constrained at -1σ sensitivity band per DM conventions: EPJC 81 907 (2021)
- Under-fluctuation in accidental BGs in the region of largest overlap with WIMP signal PDF
- WS2024-only best limit of:
  σ_{SI} = 2.3 x 10^{-48} cm^2 @ 43 GeV/c^2



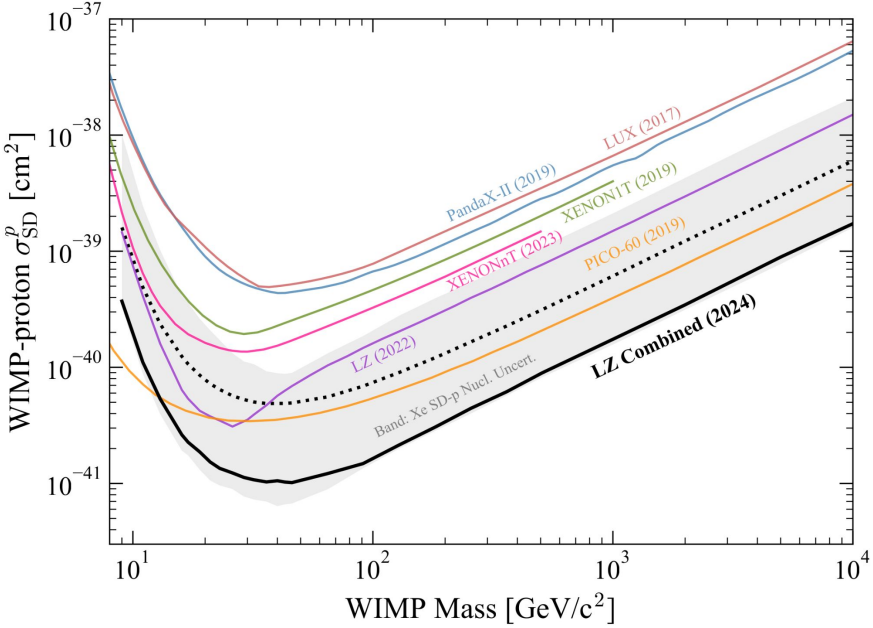
WS2024+WS2022 Spin-Dependent Limits

PRL 135 (2025) 1, 011802

WIMP-neutron Scattering



WIMP-proton Scattering



Uncertainty bands represent the theoretical uncertainty on the Xe nuclear structure factor

Electronic recoil searches

- ★ Two flavours of ER: scatter-like and absorption-like.
- ★ Similar Background budget to WIMP search, extended ROI.
- ★ WS2022 + WS2024, Live time: 280 (60 + 220) days, 5.5 tonnes
- ★ Background only model fits show very good agreement with observation