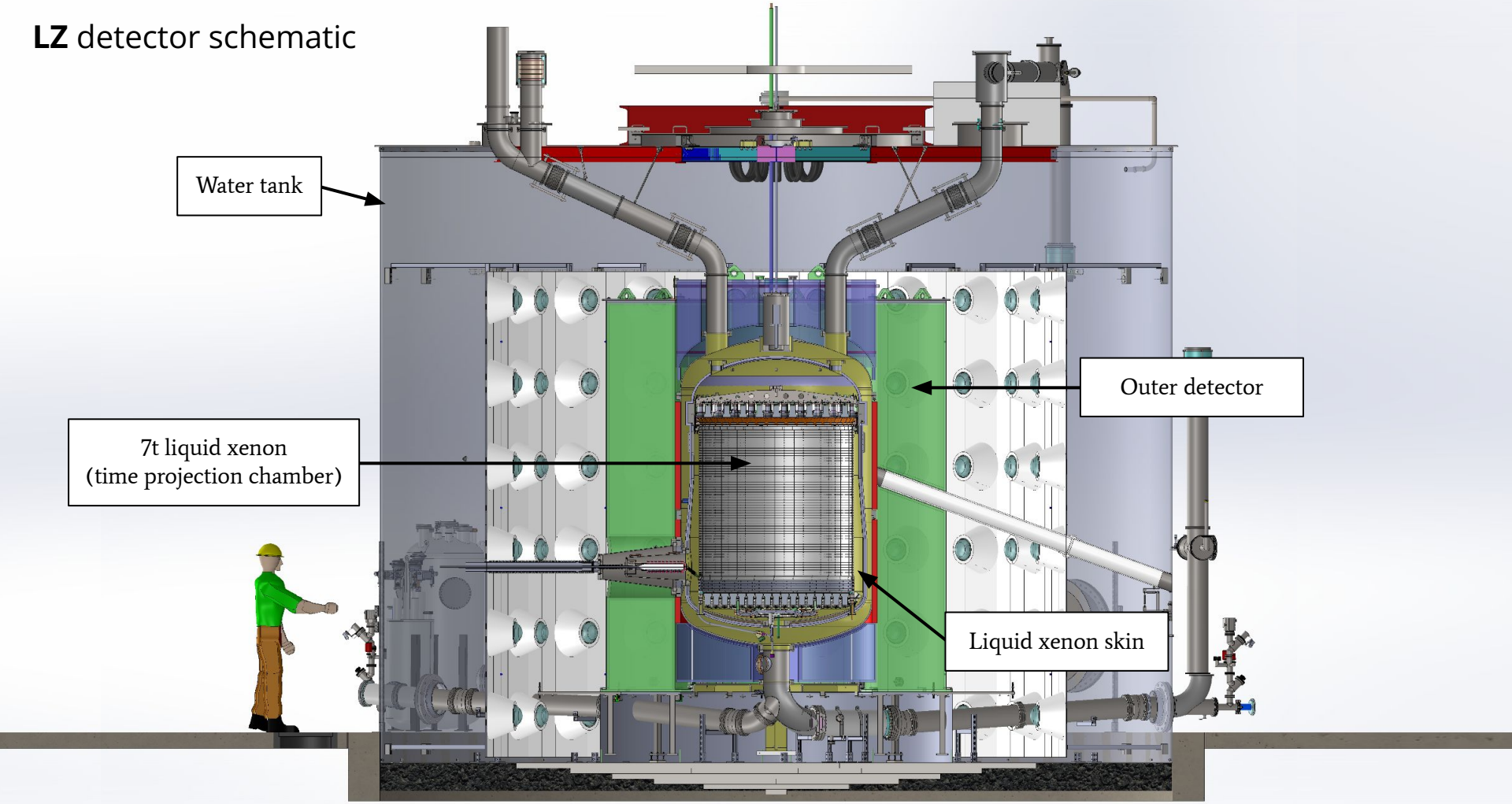
Latest LZ WIMP results

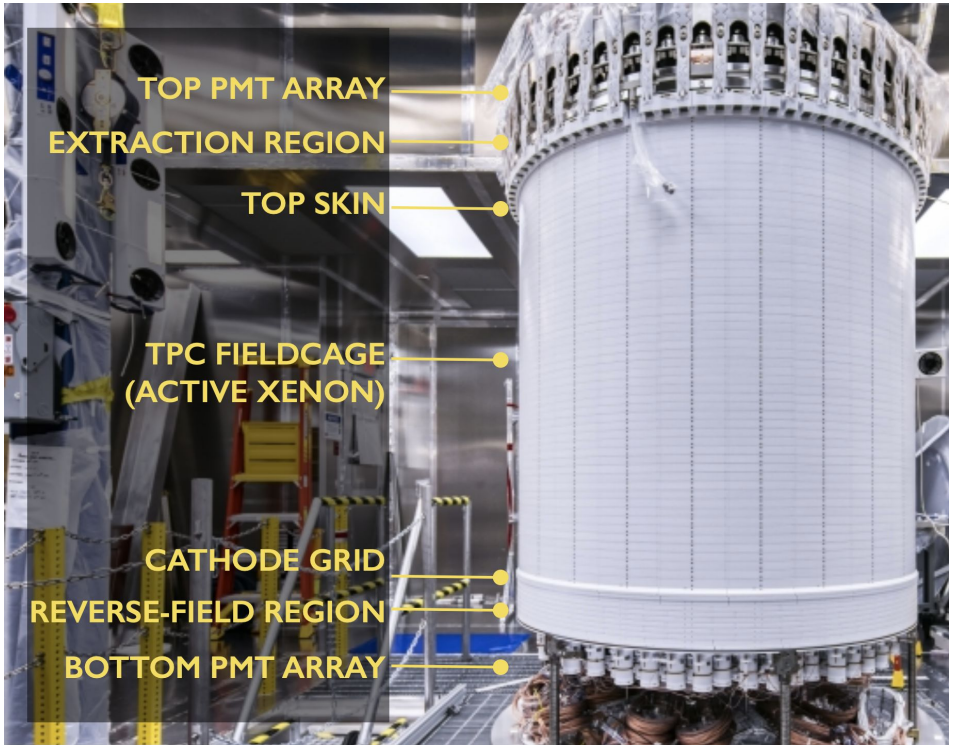
CIPANP – 10 June 2025

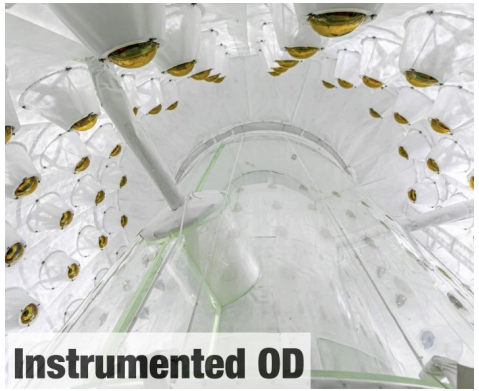
Chami Amarasinghe, UCSB
On behalf of the LZ collaboration

LZ detector schematic



The LZ detectors

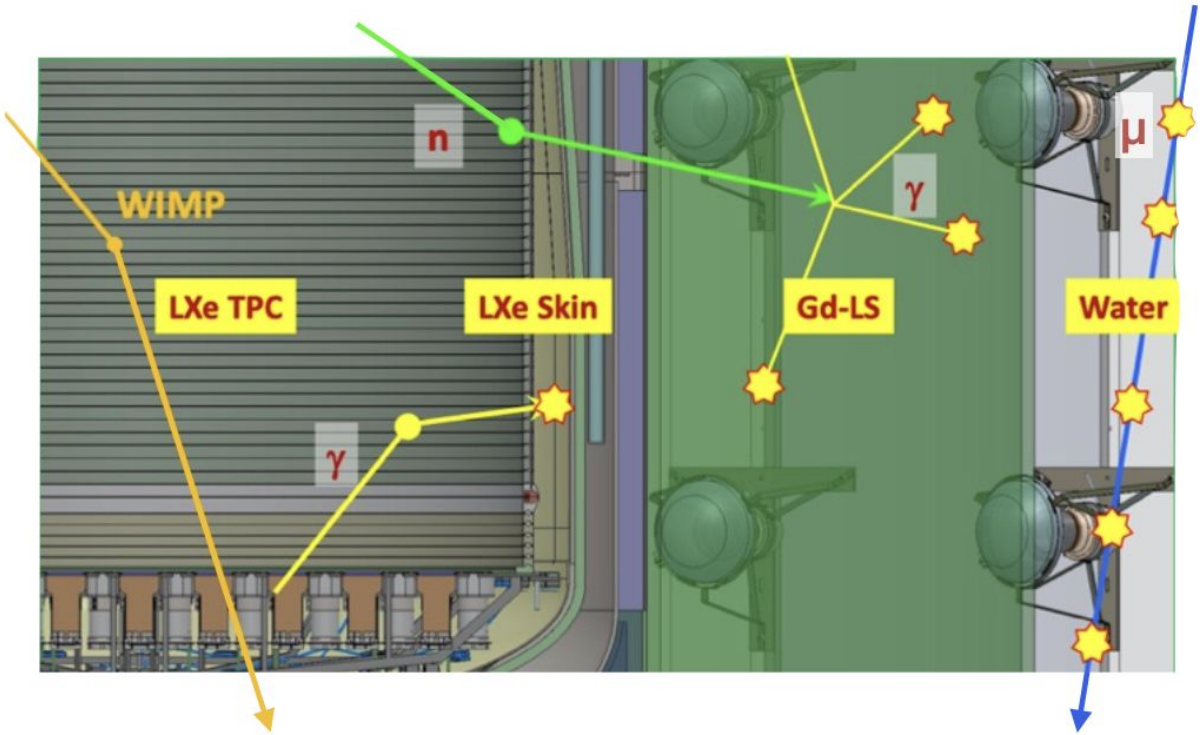




LZ veto system

Backgrounds scatter multiple times – WIMPs only once

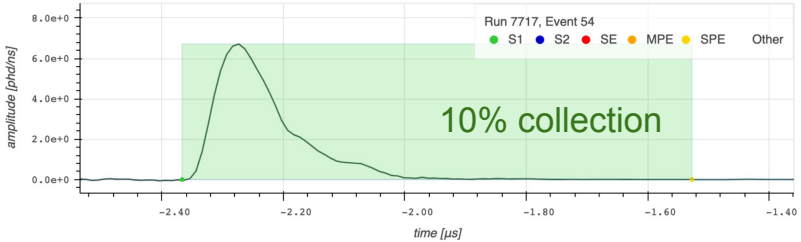
Veto system designed to reject and characterize gamma and neutron backgrounds



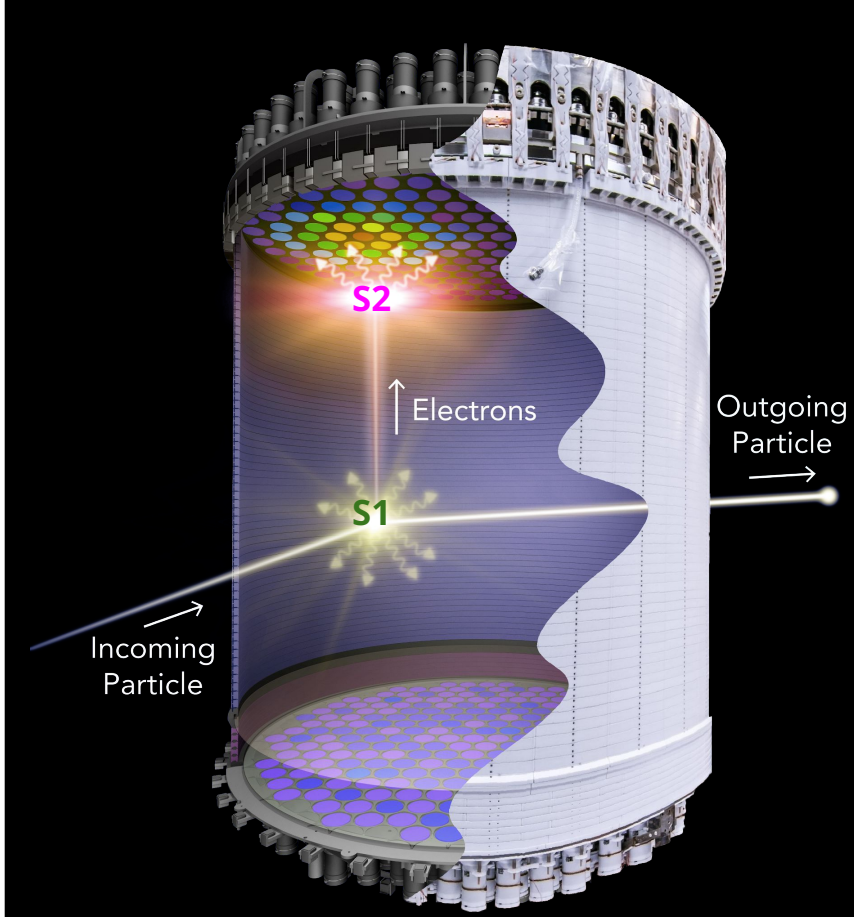
Signal production in liquid xenon

Energy deposits produce ions and excitons

Excitons + recombined ions → **S1** (prompt scintillation)



Escape electrons drifted and extracted → **S2**



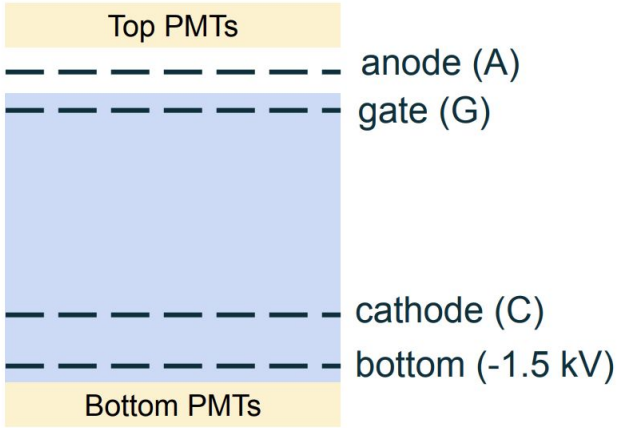
Changes since WIMP Search 2022 result

Phys. Rev. Lett. 131 (2023) 4, 041002

First result WS2022 set leading limits with 60d livetime

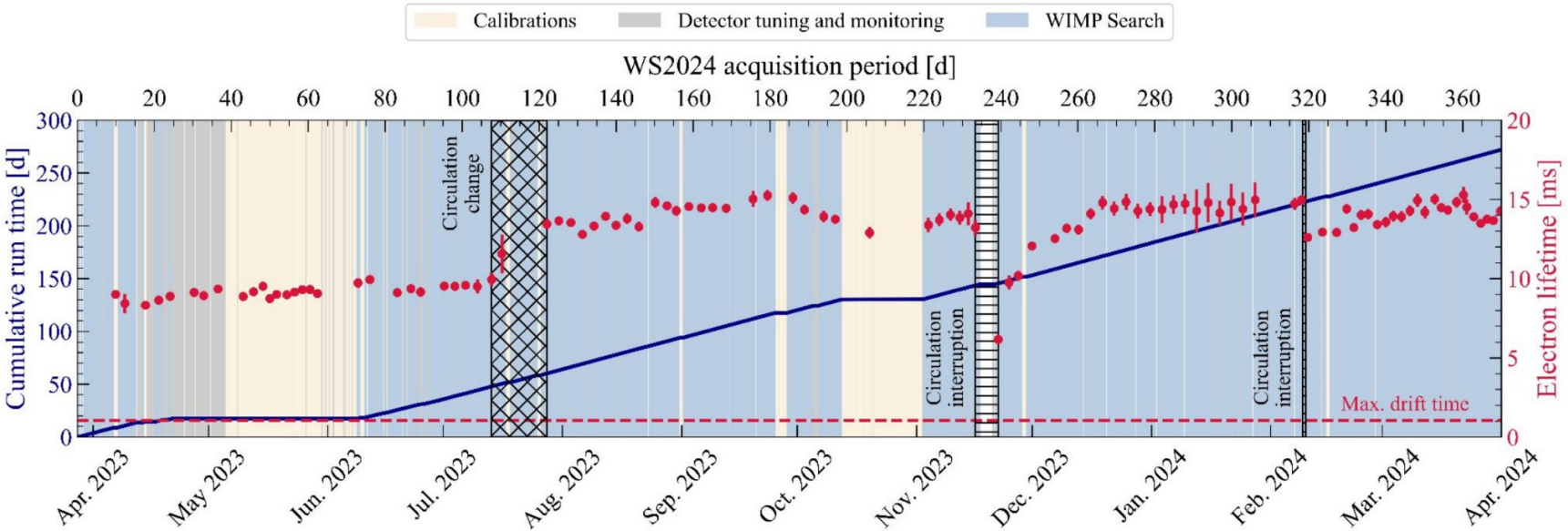
Detector campaigns since WS2022

- Lowered drift and extraction fields
  - To reduce spurious emissions
- Established xenon flow states with circulation changes



	C/G/A voltage [kV]	Drift field [V/cm]	g1 [phd/photon]	g2 [phd/electron]	Analysis livetime [d]
WS2022	-32/-4/+4	193	0.114	47.1	60
WS2024	-18/-4/+3.5	96.5	0.112	34.0	220

WIMP Search 2024 (WS2024)



- 220 live-day exposure from March ‘23 to March ‘24
- Excellent electron-lifetime, greater than 8ms for most of the run

Calibrations

Backgrounds predominantly **electron recoils**, WIMPs always **nuclear recoils**

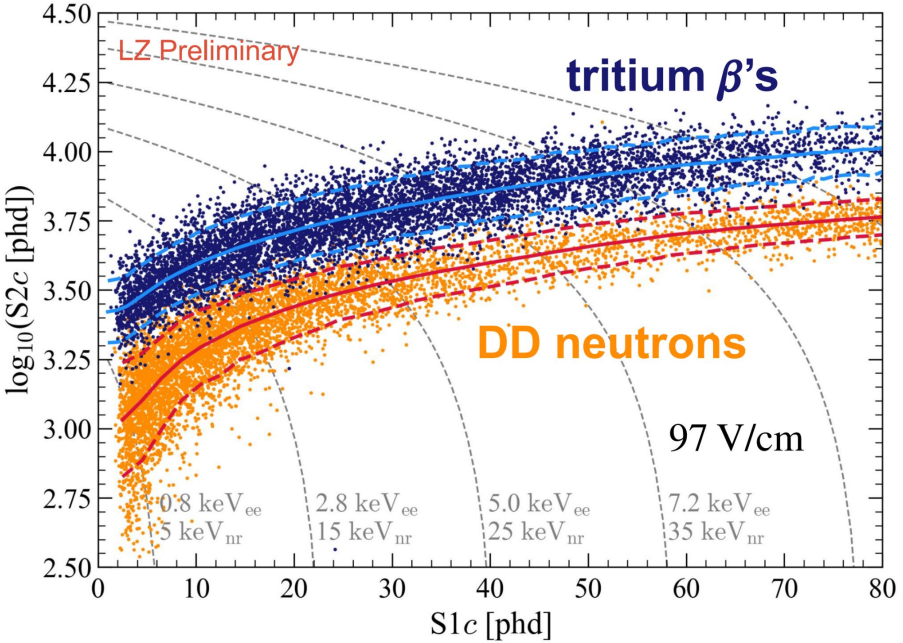
ER calibration:

- High-stats (156k) tritium β decays – injected radiolabeled methane with 3H and 14C

NR calibration:

- Monoenergetic 2.45 MeV neutrons from DD fusion generator

Other calibrations: ^{131m}Xe, ^{83m}Kr, activation lines, AmBe and AmLi neutrons,



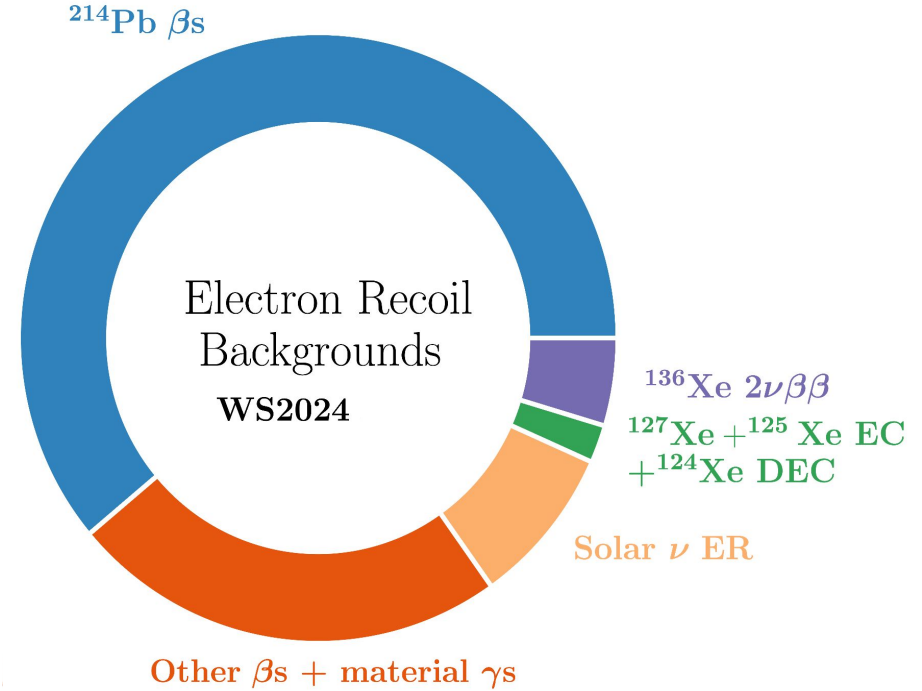
Only 10% of tritium plotted (to match DD stats)

~99.9% discrimination of flat ER background with 50% acceptance for 40 GeV WIMP

Same discrimination as WS2022

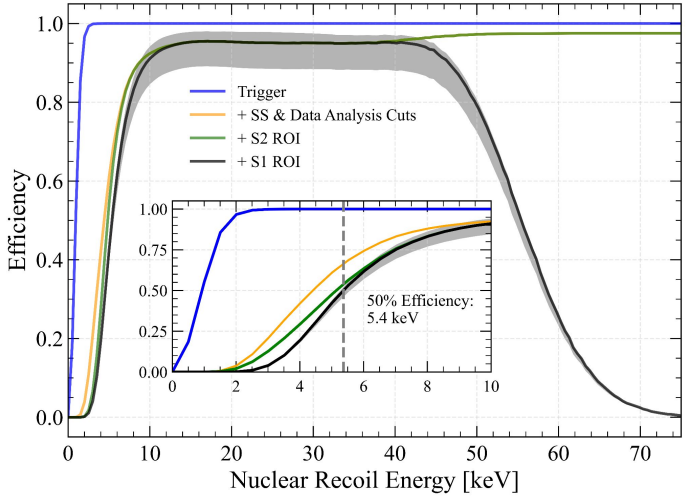
Backgrounds

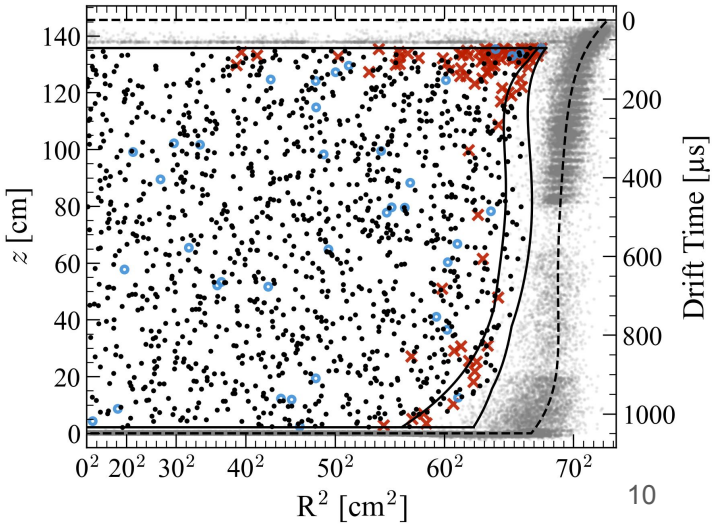
- Dissolved β emitters:
  - **^{214}Pb** (^{222}Rn), ^{212}Pb (^{220}Rn), ^{85}Kr, ^{136}Xe ($\beta\beta$)
- Dissolved EC decays (x-ray/Auger cascades):
  - $^{127/125}$Xe from neutron calibration activation
  - **^{124}Xe (double EC)**, 0.095% nat. abundance
- Solar ν's: ^{8}B+*hep* (NR), pp+^{7}Be (ER)
- Long-lived γ emitters in detector materials:
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- Accidental coincidences (expect 2.8 ± 0.6 counts)
- Neutrons from spontaneous fission and (α,n) in detector materials (~0)



Data selection

- High-rate and detector instability periods removed - 86% live time retention
- S1- & S2-based cuts target accidental events
  - Impacts final signal acceptance
  - Validated with calibration (tritium, AmLi, DD)
- Fiducial volume: 5.5 ± 0.2 tonne mass
- Skin/OD veto anti-coincidence
- Observed 1220 events (expected 1210)

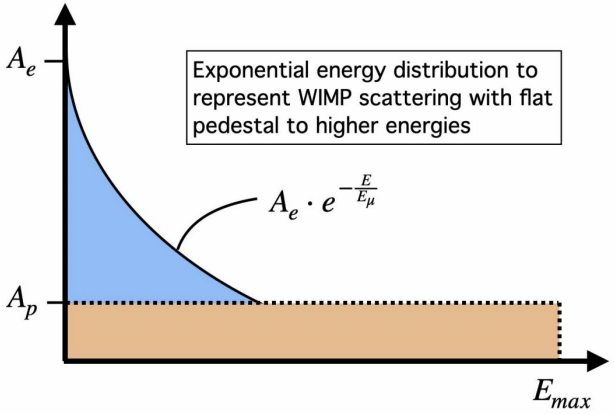


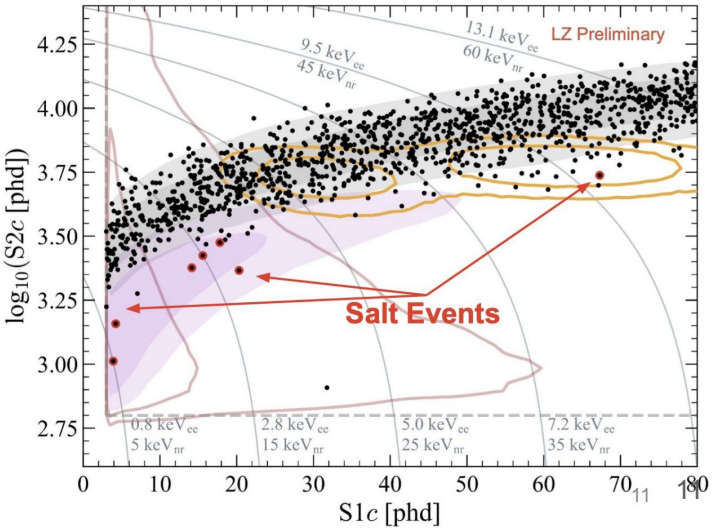


Skin/OD
Coincidence Window:
prompt (300 ns)
delayed (600 µs)

Bias mitigation via salting

- **Salt:** fabricated signals randomly injected into raw data stream
- Salt rate hidden from analyzers and bound by WS2022 upper limit
- Events stitched together using S1s & S2s from sequestered calibration data
- Covers WIMP and higher-energy NR regions
- **Unsalting** after analysis finalized

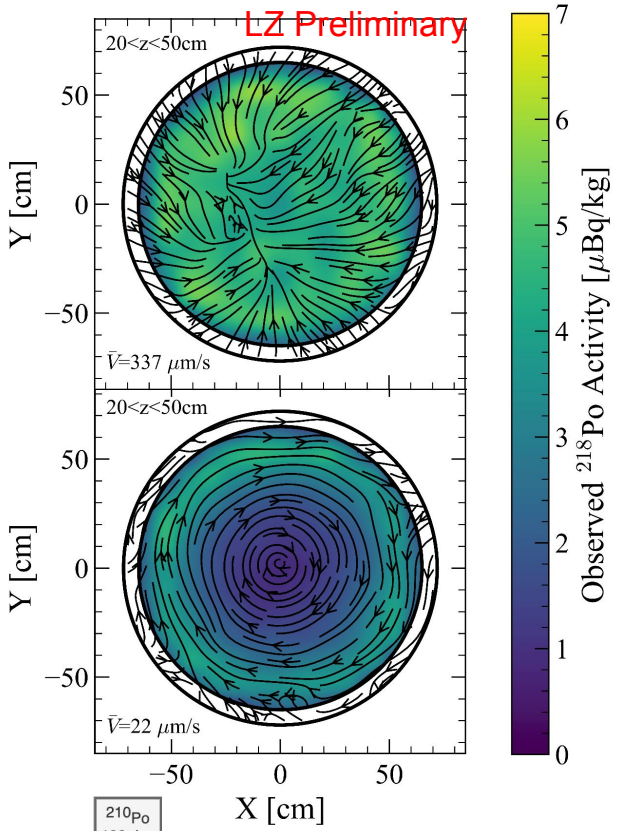


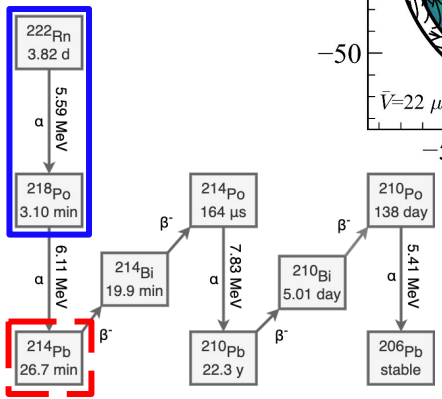


Xenon flow patterns

Circulation system allows control of xenon flow states in TPC

- High mixing
  - turbulent
  - desired for calibration injections
- Low mixing
  - laminar flow
  - radon-quiet central volume
- **Flow measured by Rn-Po alpha pairs**
- **Allows prediction of 214Pb motion**
  - **Dominant background can be tagged!**



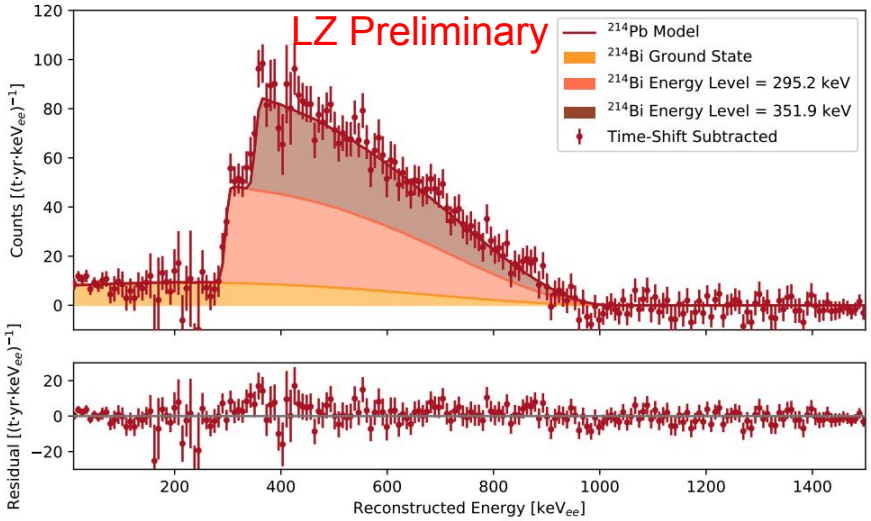


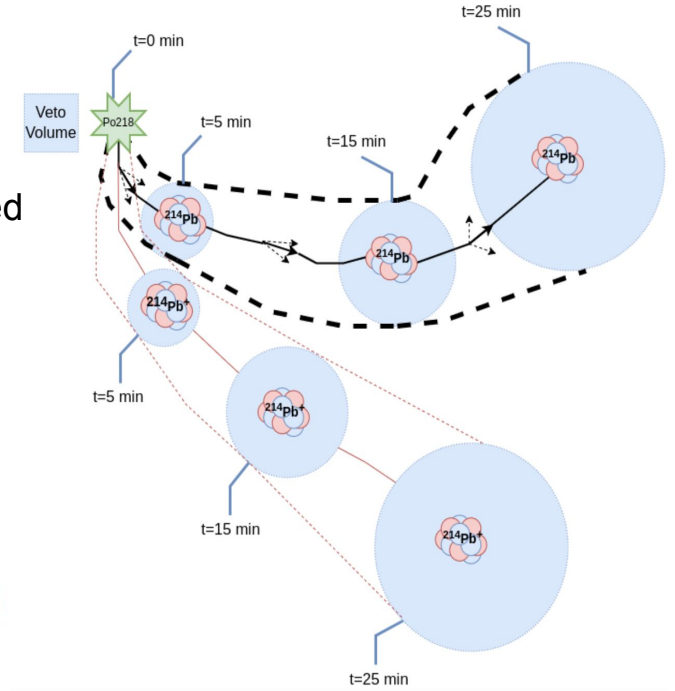
Also see *Phys. Rev. D* **110** 012011 (2024) - XENON Collaboration

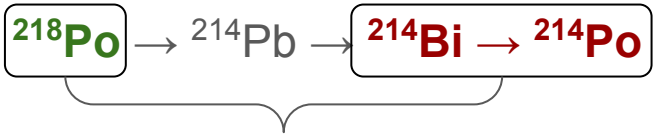
Active tag of 214Pb

“Radon-tag” uses field & flow model to predict locations of charged and neutral 214Pb

Tagged events reconstruct the 214Pb β-spectrum!







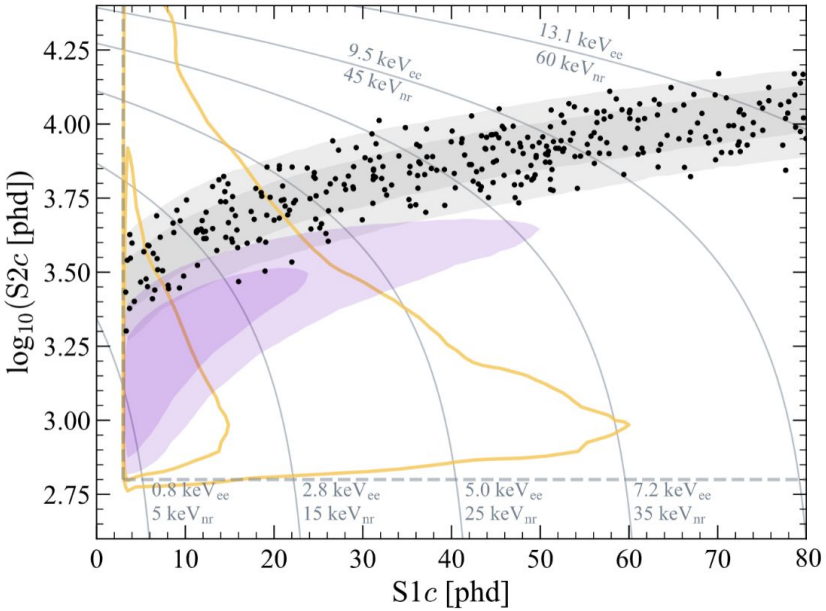
214Pb activity in WS:

- **3.9 ± 0.6 μBq/kg** in total exposure
- **1.8 ± 0.3 μBq/kg** in untagged sample

Tag volume tuned by comparing flow-prediction & BiPo observation

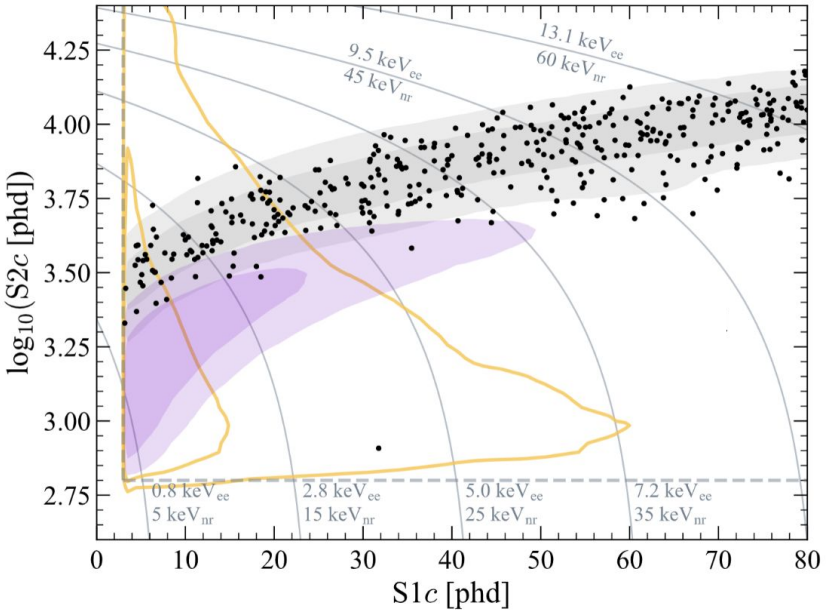
Flow-tag in 2024 WIMP search

Tagged (radon-rich)



- **60 ± 4 %** of ^{214}Pb in **15%** exposure
- consistent with tritium calibration

Untagged (radon-poor)



- excessive ER leakage

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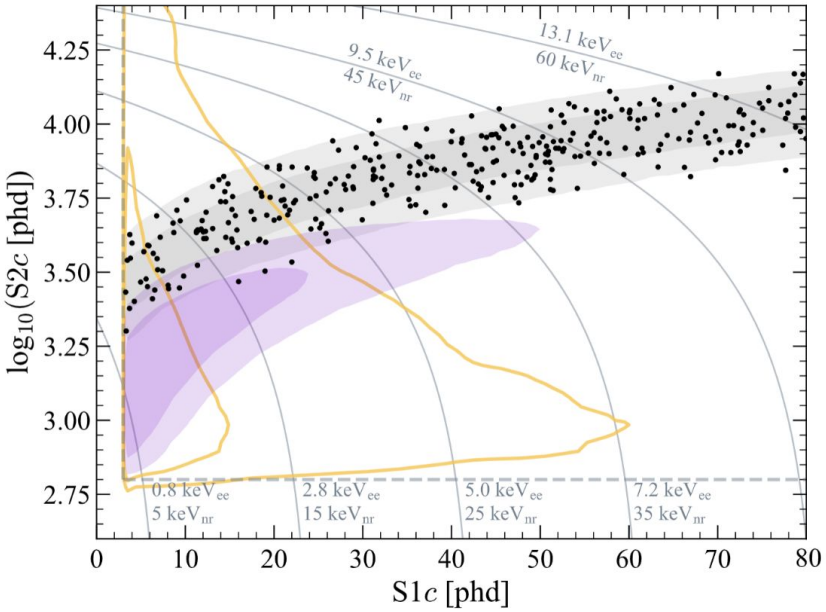

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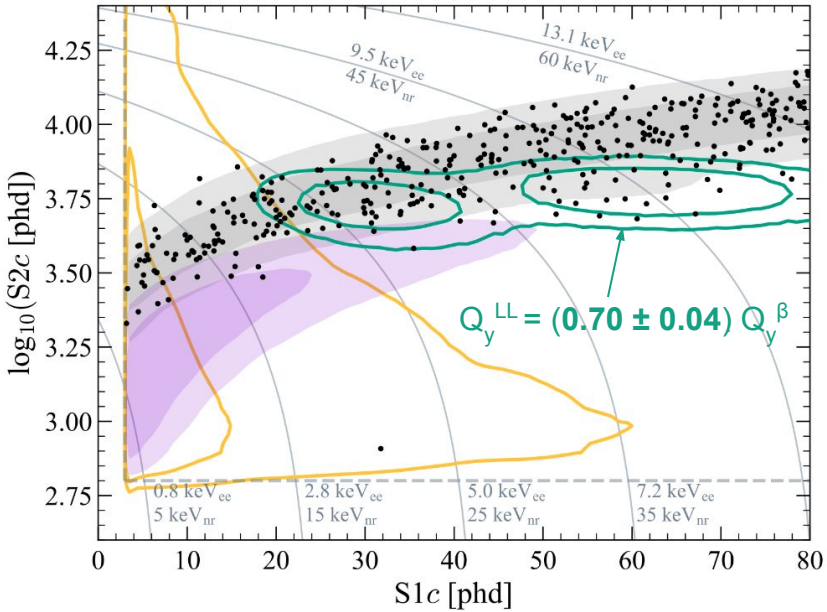
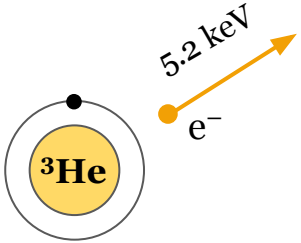
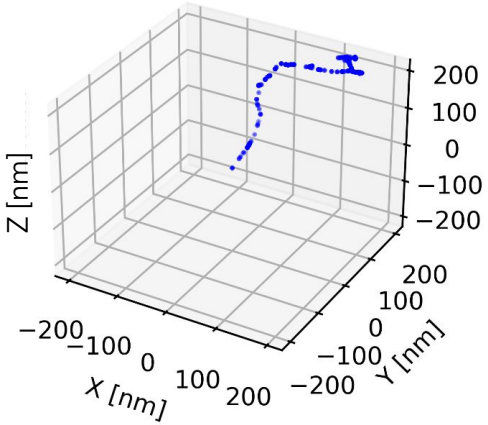
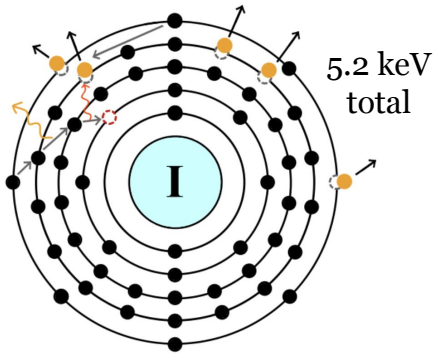


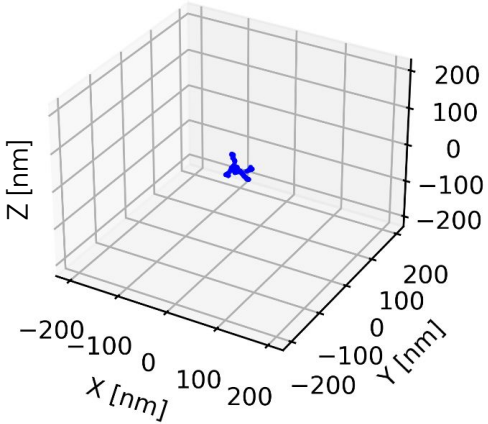
- excessive ER leakage
- double-electron-capture of ^{124}Xe
- ~20 counts – Qy floated in fit

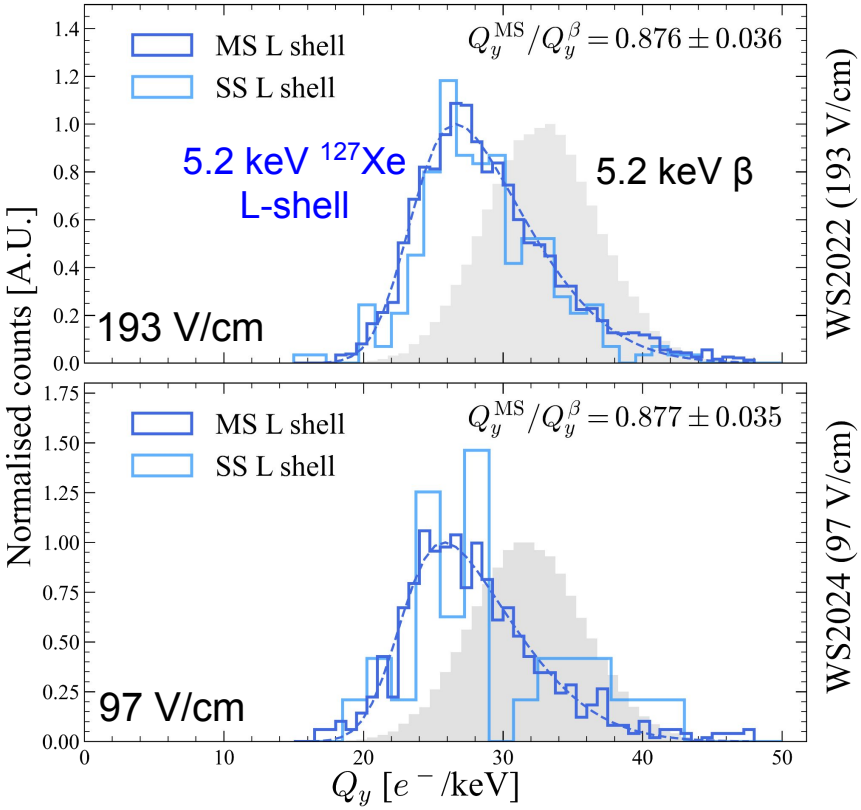
Ionization density impacts signal production – 127Xe EC











LZ Collaboration: 2503.05679
(accepted to PRD)

^{124}Xe LL recombination modeling

More ionization density → more recombination

- Thomas-Imel: Phys. Rev. A. 1987; 36(2): 614

10 keV LL has twice ionization density of L

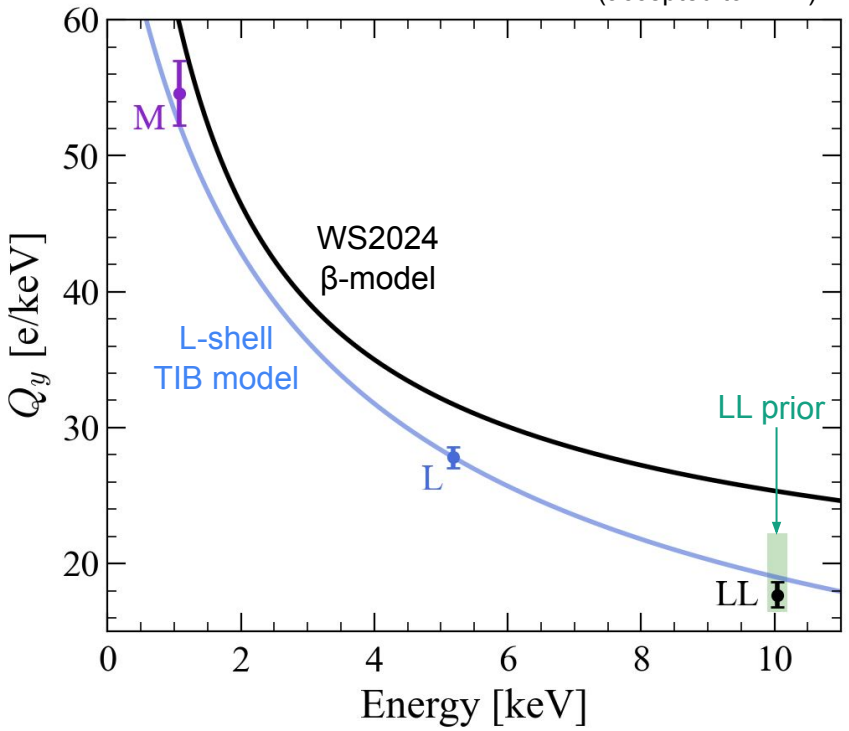
- same Auger electron range
- twice number of ions

Calculation: $Q_y^{LL} = (\mathbf{0.75 \pm 0.04})\, Q_y^{\beta}$

Fit in WS: $Q_y^{LL} = (\mathbf{0.70 \pm 0.04})\, Q_y^{\beta}$

Also see cross-track recombination model from Xu et. al. 2503.07562

LZ Collaboration: 2503.05679
(accepted to PRD)



WS2024+2022 combined limit

Frequentist, 2-sided profile likelihood ratio test statistic

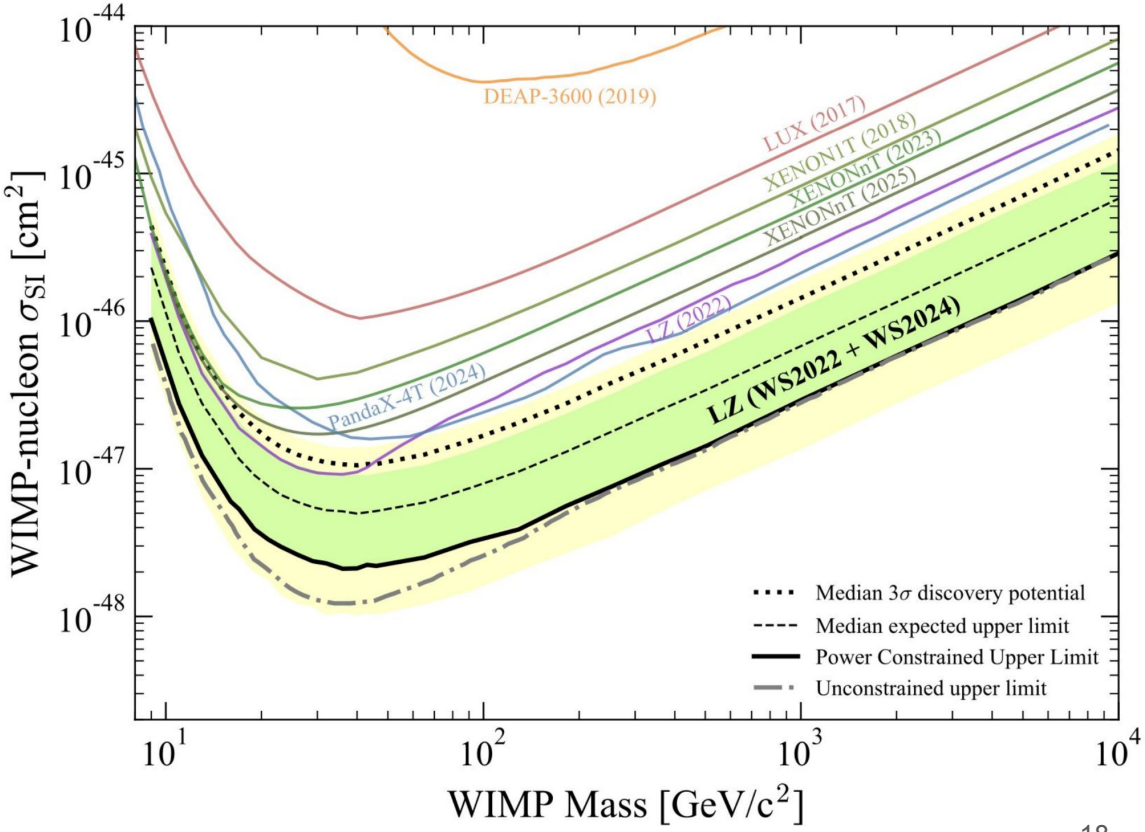
Upper limit is power constrained @ -1σ sensitivity band per DM conventions: EPJC 81 907 (2021)

Under-fluctuation from

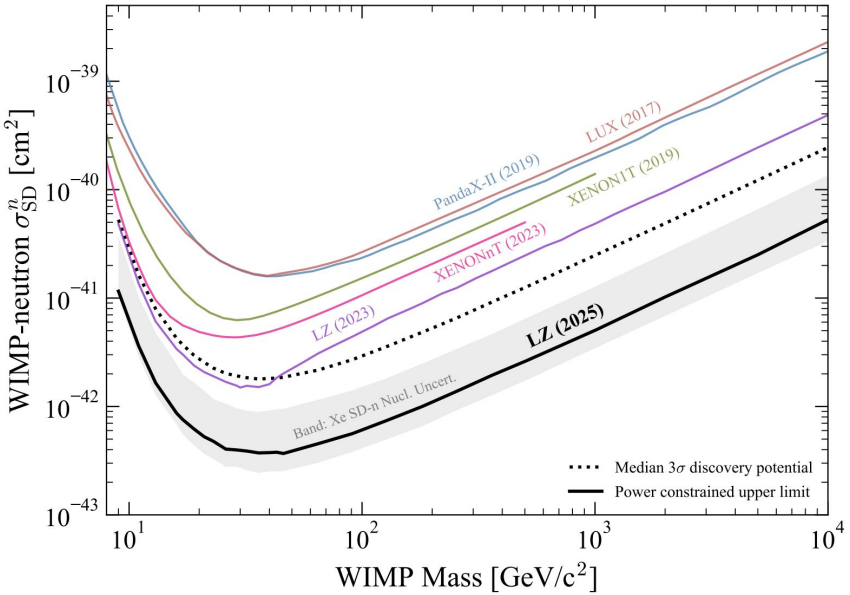
- observed arrangement of accidental events
- combination with WS2022

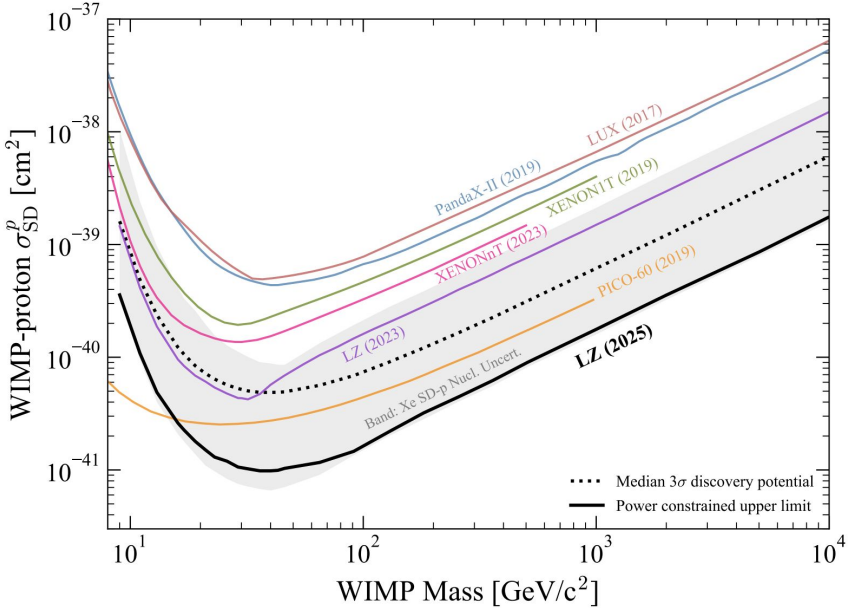
Combined min cross section:

σSI= 2.2 x 10^{-48} cm^2 @ 43 GeV/c2



WS2024+WS2022 Combined Spin Dependent Limits





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

Conclusions

- LZ set leading limits on WIMPs
- Novel analyses and observations:
  - Demonstrated 60% reduction of primary ER background with flow-based tagging – first use of this technique for a dark matter result – paper in prep
  - First observation of suppressed charge yield from LL-shell captures of 124Xe
- LZ expected to collect data until 2028

Other DM results by LZ: EFT, covariant EFT, WIMP-pion, Axions and ER searches, ultra-heavy DM, millicharged, cosmic-ray boosted DM

On the horizon: 0v2β, 8B

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

250 scientists, engineers, and technical staff

@lzdarkmatter

https://lz.lbl.gov/

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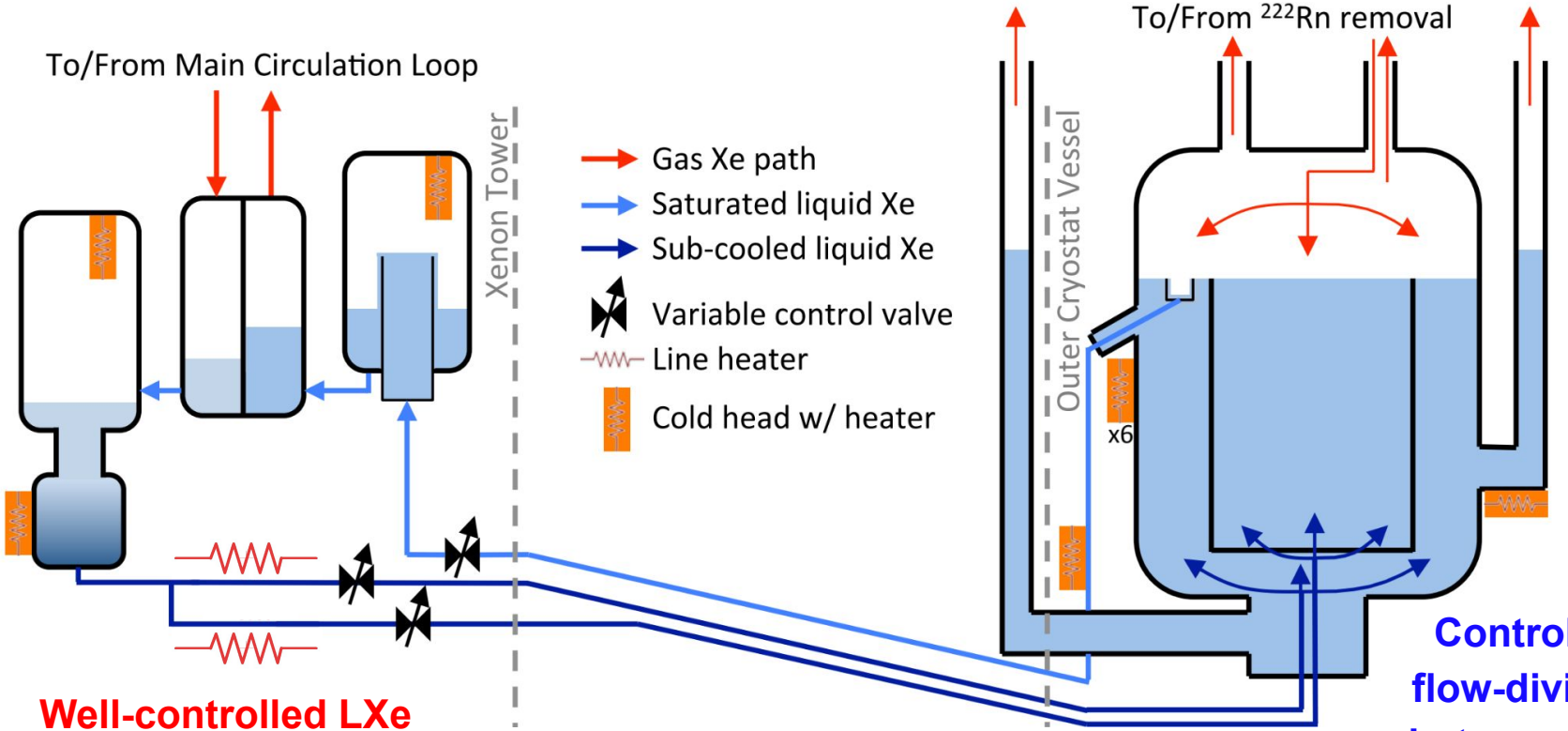
Liquid xenon flow control



Well-controlled LXe temperature

Controlled flow-division between skin and TPC

Tagged ^{214}Pb spectrum

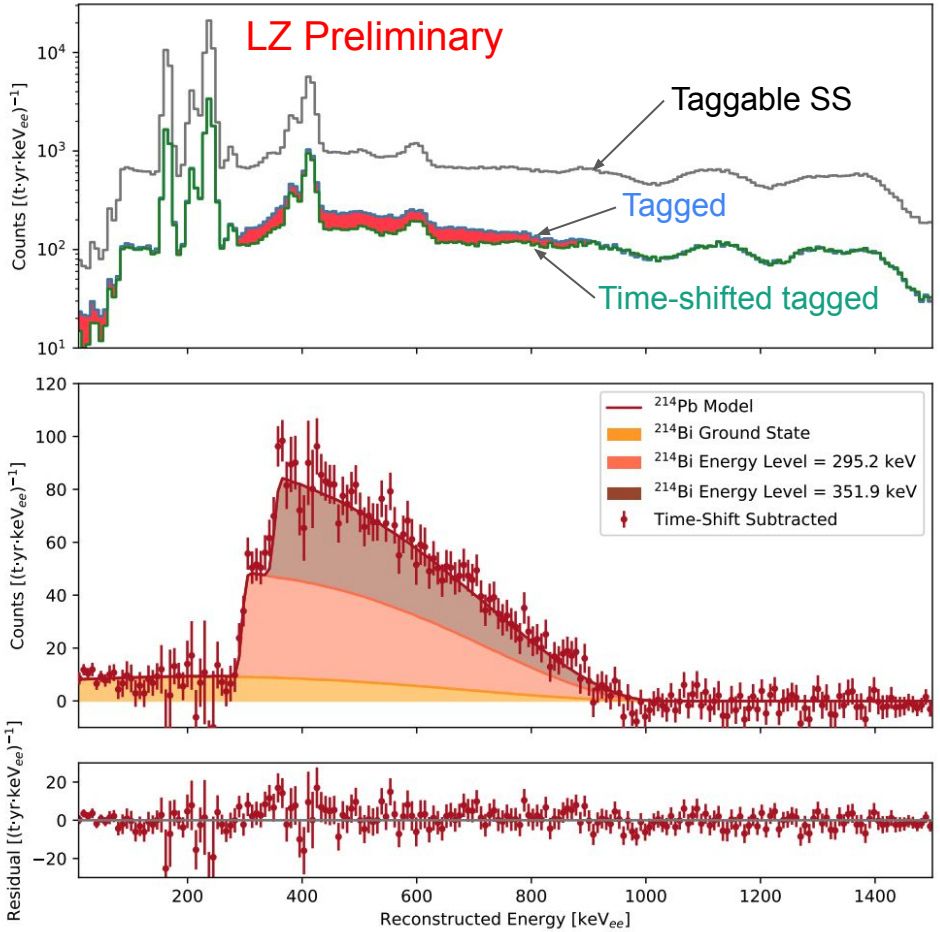
Difference between …

- tagged single scatters
- data-driven accidentals spectrum from time-shifted tag

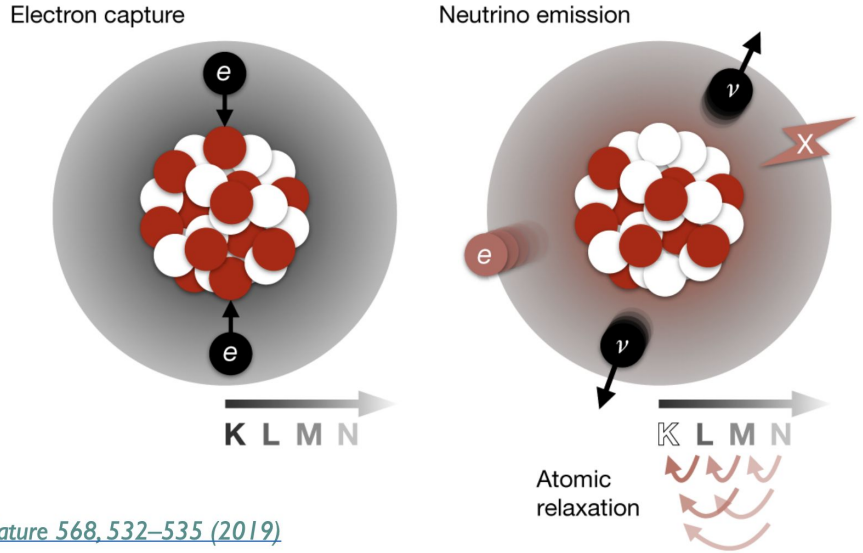
… gives

Accidentals-subtracted ^{214}Pb spectrum

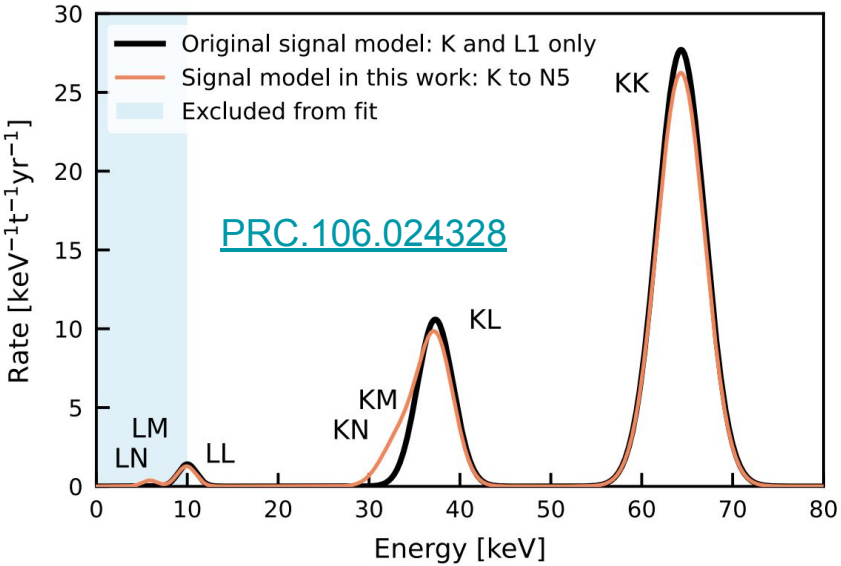
- 1018 keV Q-value of ^{214}Pb β-decay
- shoulders of γ/IC-emitting states



124Xe double electron capture explains leakage



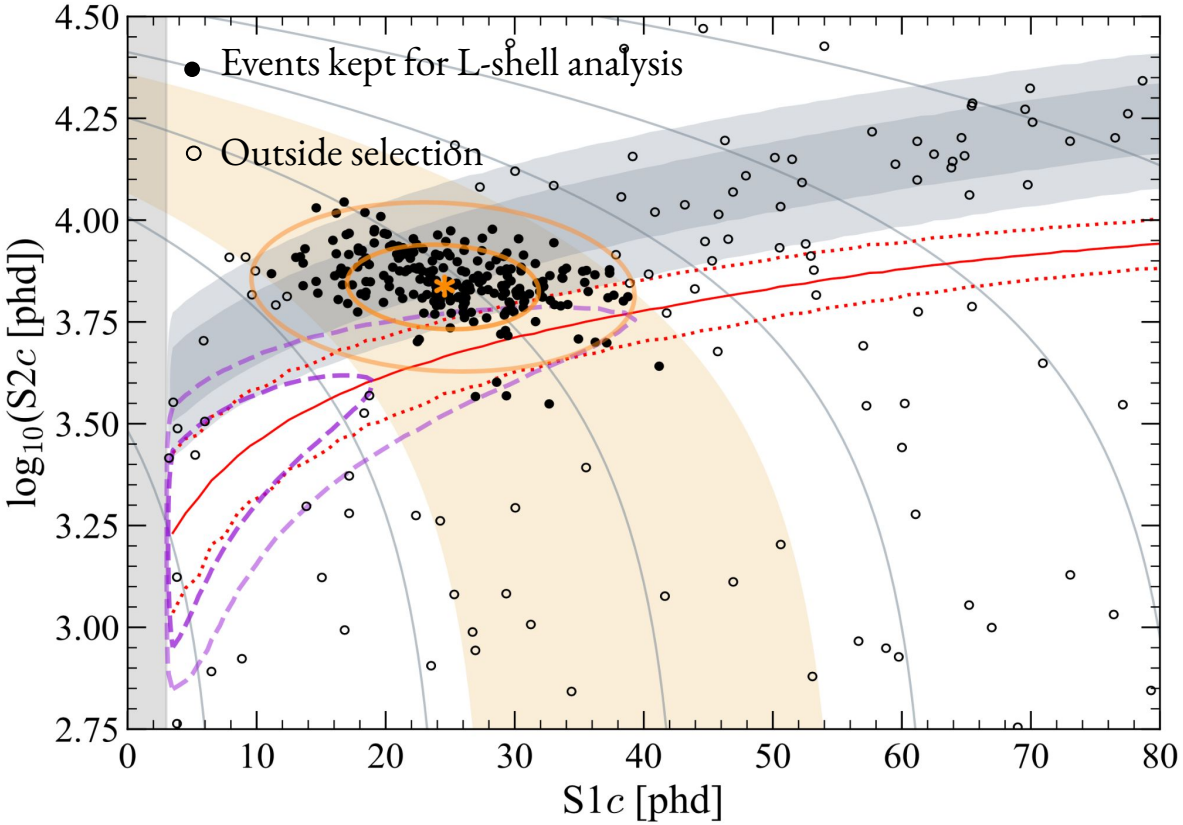
Nature 568, 532–535 (2019)



"World's rarest decay" - $T_{1/2} = (1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ yr (LZ measurement)

~5 kg in fiducial volume (0.1% nat. abund.)
LM (6.0 keV) & LL-shell (10.0 keV) relevant for WIMP search

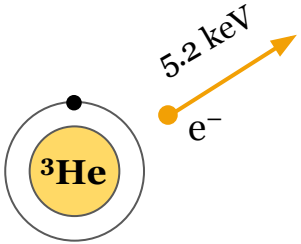
Skin-tagged ^{127}Xe L-shell EC

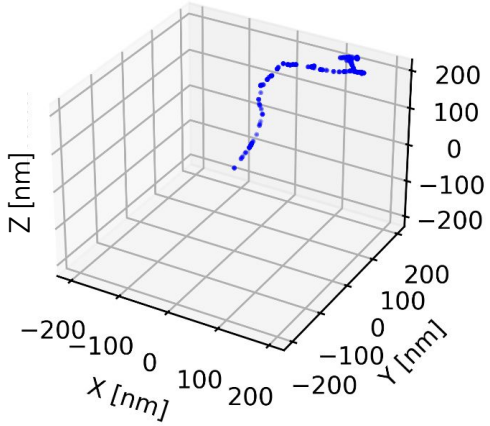


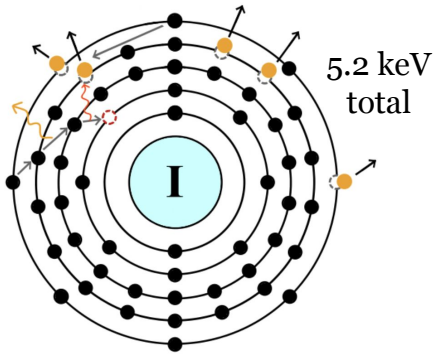
Lower charge yield than β-decays → recombination enhancement

- Cosmogenically activated ^{127}Xe in WS2022 (plot)
- In WS2024, used neutron-activated ^{125}Xe

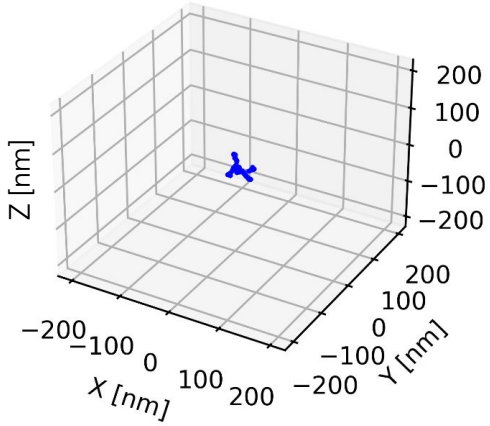
XELDA predicted additional recombination



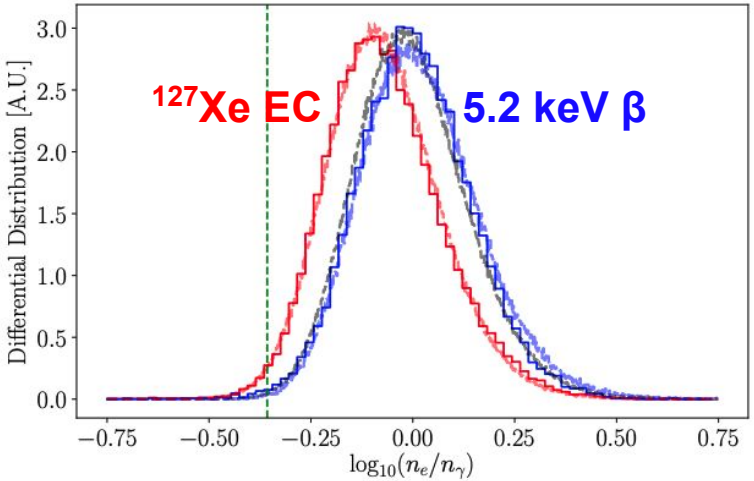




5.2 keV total



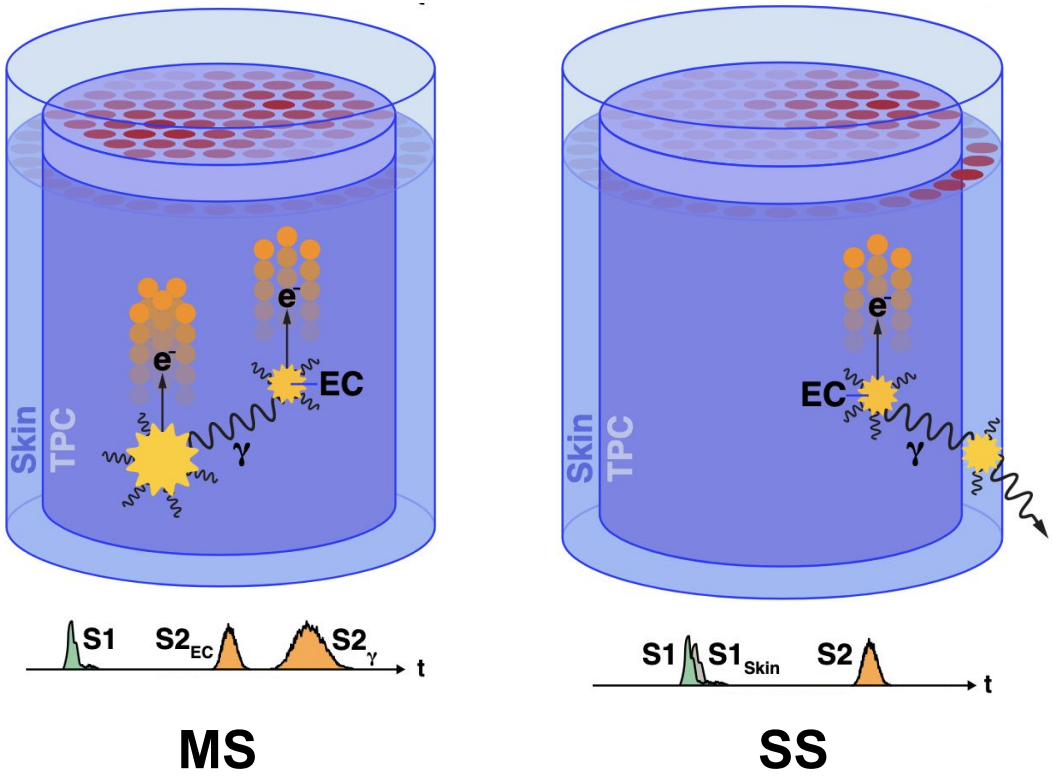
XELDA clearly suggests additional electron-ion recombination in ^{127}Xe single EC



Temples, et. al
Phys. Rev. D 104 (2021) 11, 112001

LZ measurements of single electron capture

LZ Collaboration:
2503.05679
(accepted to PRD)



Two strategies

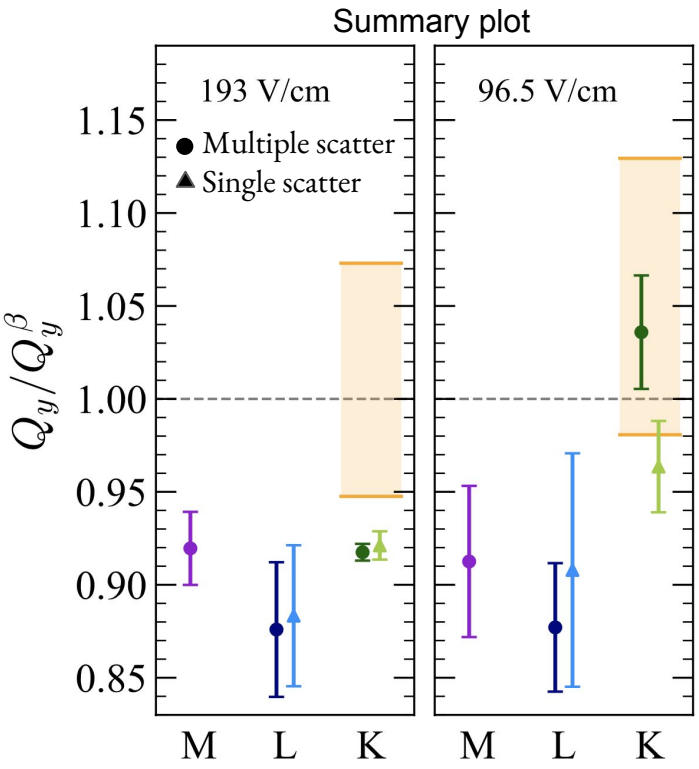
Multiple scatter (left)

- γ resolved separately
- events in bulk, high stats
- charge-only

Single scatter (right)

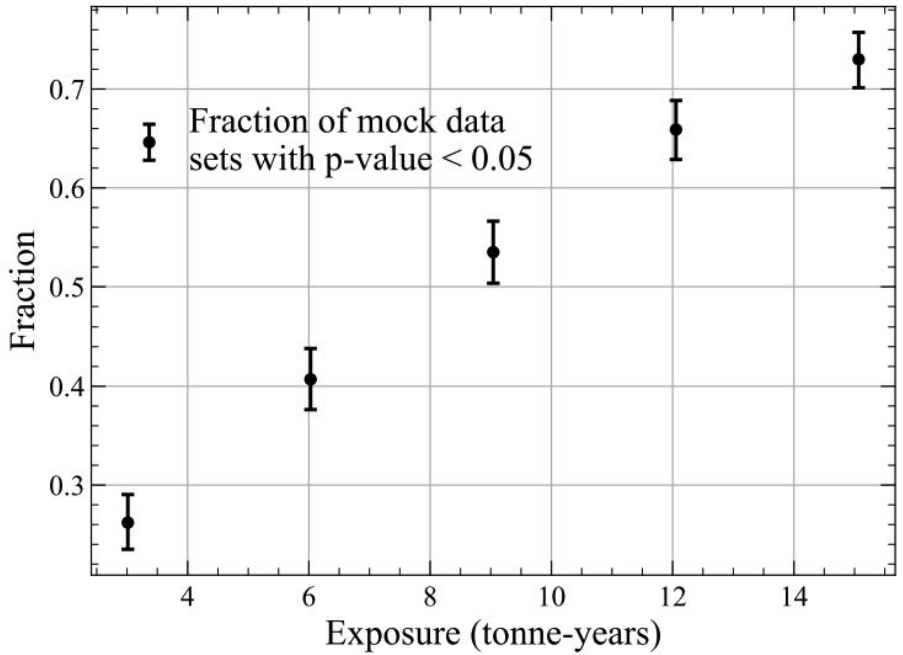
- γ is tagged in Skin
- events near the wall, low stats
- S1–S2 measurement

EC measurement summary



Failing goodness of fits

Failing goodness-of-fit when DEC isn't modeled



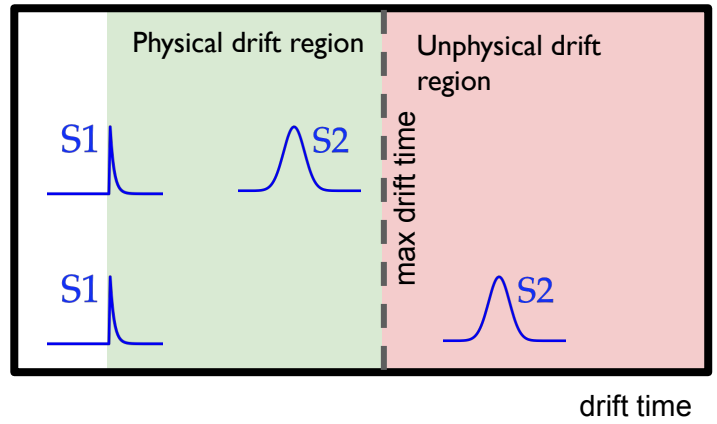
Accidental Coincidence Background

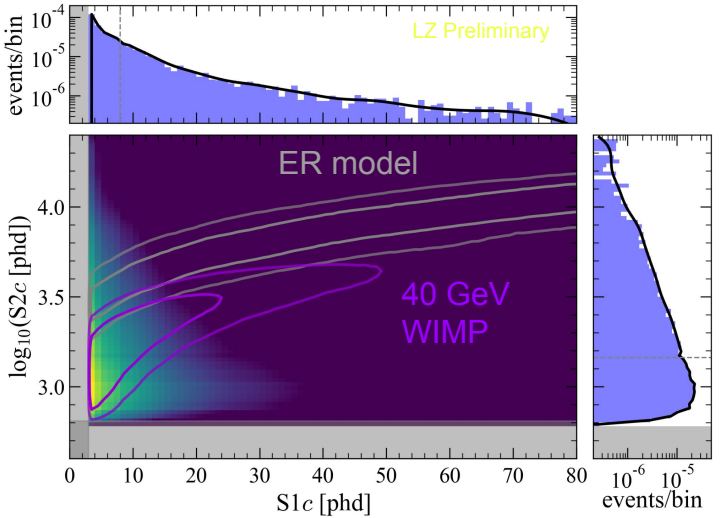
Pile-up of uncorrelated S1 and S2 pulses

LZ's data driven model:

- Rate from unphysical drift time (UDT) events
- Shape from analysis cuts applied to manufactured accidentals

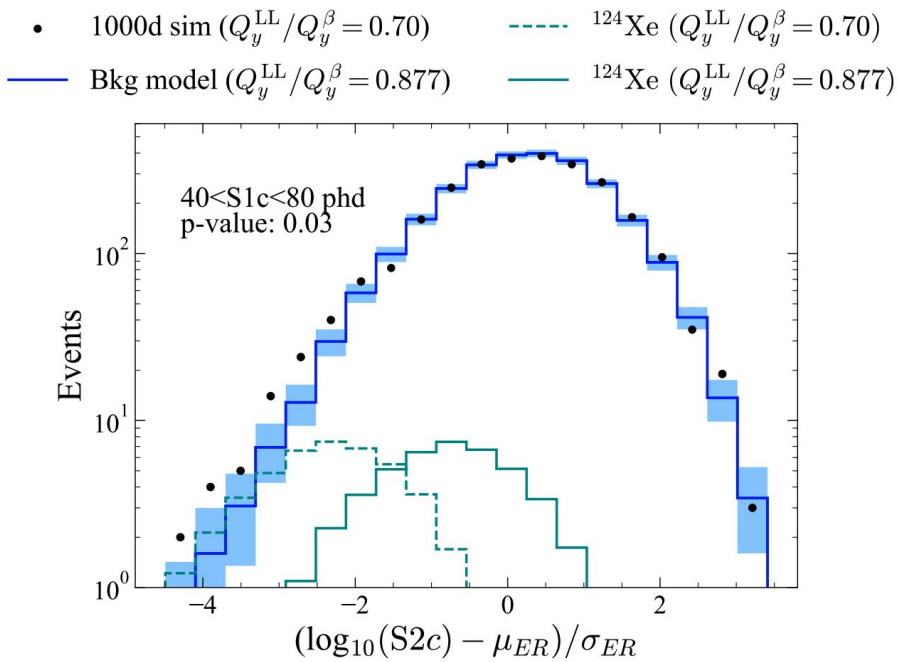
Expected counts: 2.8 ± 0.6





DEC impacts on WIMP searches

- **small impact on LZ projected limits**
  - small overlap between WIMPs and LL
  - larger impacts to EFT
- **major impact to goodness-of-fit**



Mock data (LL model) and background model (no LL model)

Background components

TABLE I. The expected and best-fit counts for different sources in the 3.3 tonne-year exposure of WS2024, including a 40 GeV/c^2 WIMP signal. Flat β-decay components have been separated based on whether they are affected by the flow state or the radon tag, and the neutron counts are derived *in situ*. "Det. γs" refers to γ-ray contributions from detector materials, whose Compton spectra are also flat in the ROI.

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	55.8 ± 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	[a] $0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42

[a] The expected number of neutron events results from a fit to the sample of veto detector-tagged events. This expectation is not explicitly used in the final combined fit as this sample is included directly in the likelihood, as described in the text.

LZ S2 spectra

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
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^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
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Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
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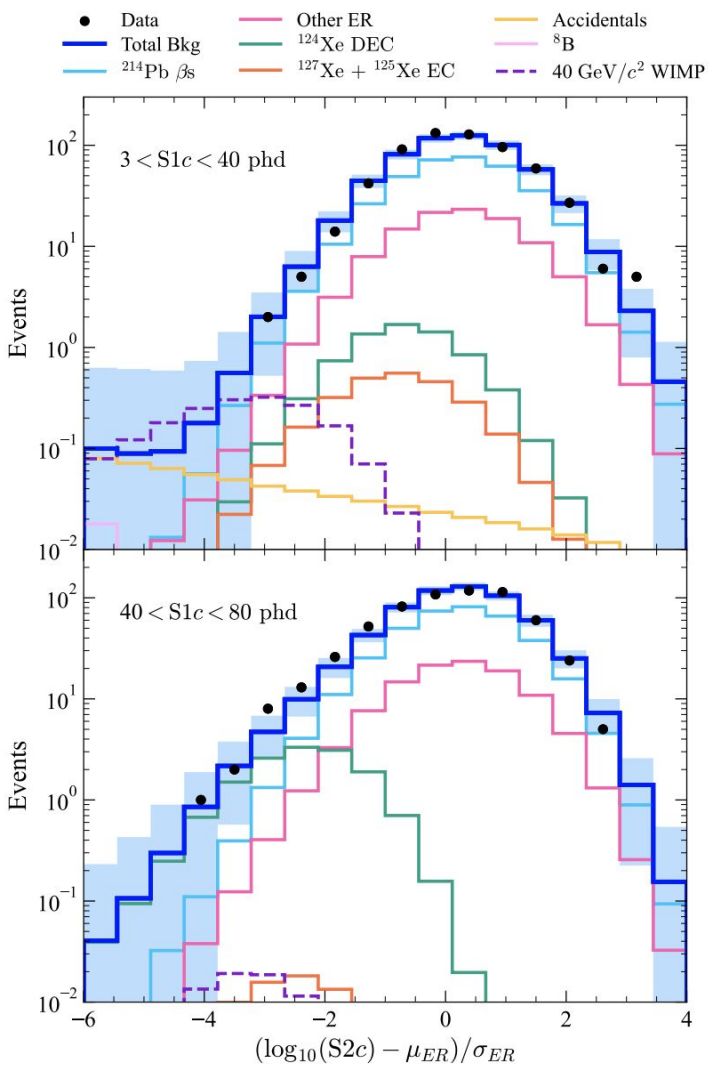
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42

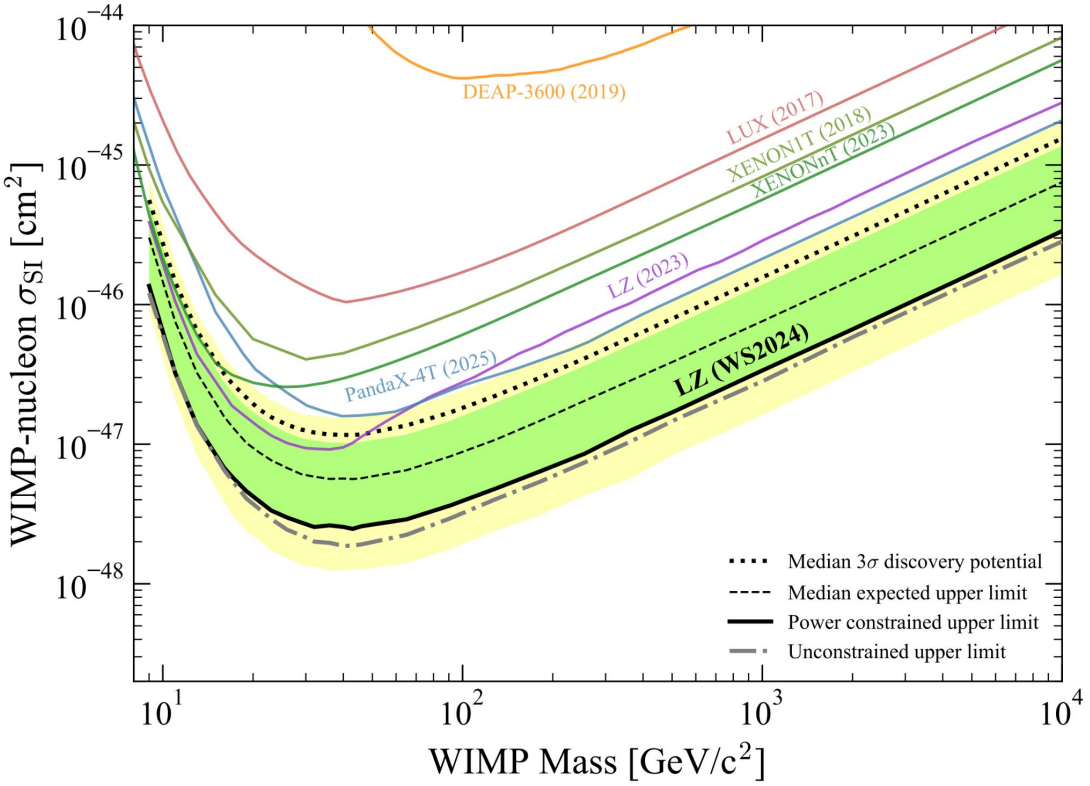


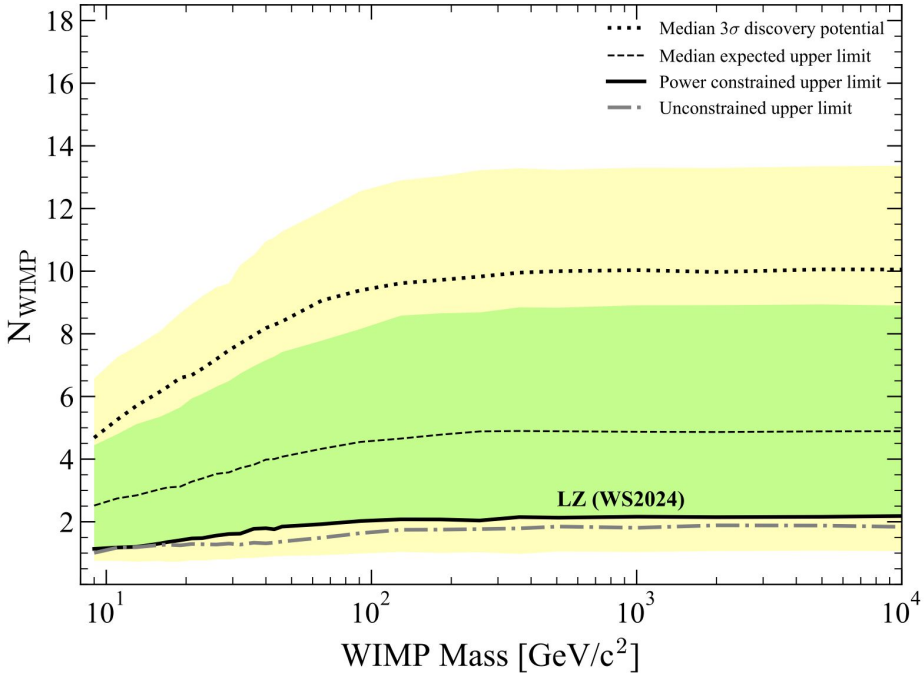
Components of WIMP search likelihood

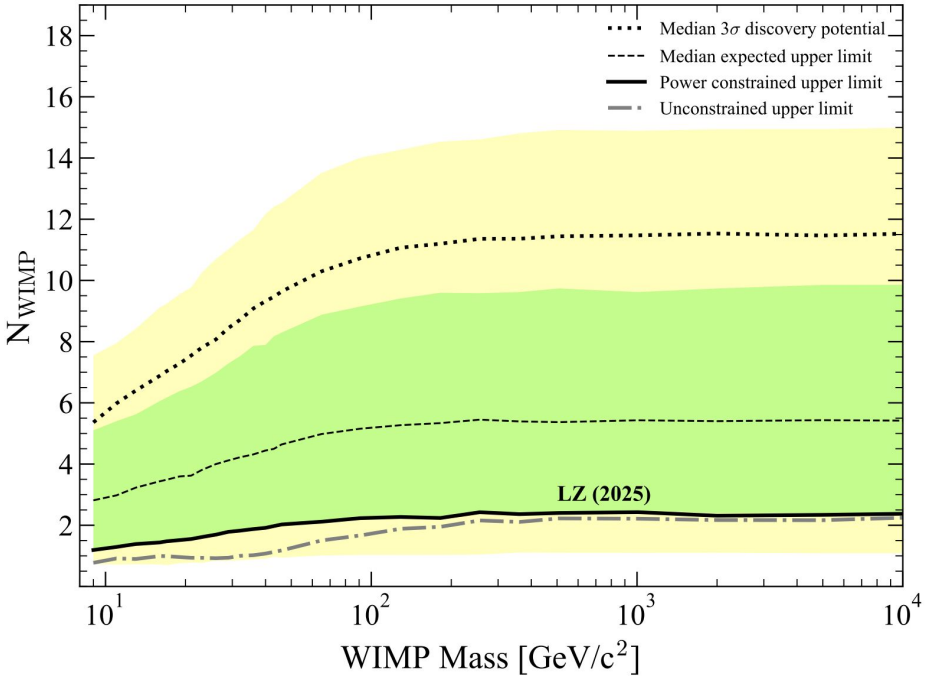
	1	2	3	4	5	6
	High Mixing	**Radon Tag Inactive**	**Radon Tagged**	**Radon Untagged**	**Skin/OD Vetoed**	**WS2022**
Exposure [tonne-yr]	0.6	0.6	0.3	1.8	n/a	0.9

- Likelihood combines **six samples** for final analysis
- Skin/OD-tagged sample (5) provides constraint of neutron background rate
  - Constrained to zero neutrons
  - neutron tagging efficiency: 92 ± 1%
- ^{124}Xe DEC charge yield floated for WS2024-only
- WS2022 sample (6) unmodified 1st WIMP result → maximize sensitivity

WS2024 only


DEAP-3600 (2019)
LUX (2017)
XENON1T (2018)
XENONnT (2023)
LZ (2023)
PandaX-4T (2025)
LZ (WS2024)
Median 3σ discovery potential
Median expected upper limit
Power constrained upper limit
Unconstrained upper limit
WIMP-nucleon σSI [cm2]
WIMP Mass [GeV/c2]
10−44
10−45
10−46
10−47
10−48
101
102
103
104


Median 3σ discovery potential
Median expected upper limit
Power constrained upper limit
Unconstrained upper limit
LZ (WS2024)
N_WIMP
WIMP Mass [GeV/c²]


Median 3σ discovery potential
Median expected upper limit
Power constrained upper limit
Unconstrained upper limit
LZ (2025)
N_WIMP
WIMP Mass [GeV/c²]