UNIVERSITY OF LIVERPOOL

Status of LUX-ZEPLIN

WIMP Search 2024

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Research Associate

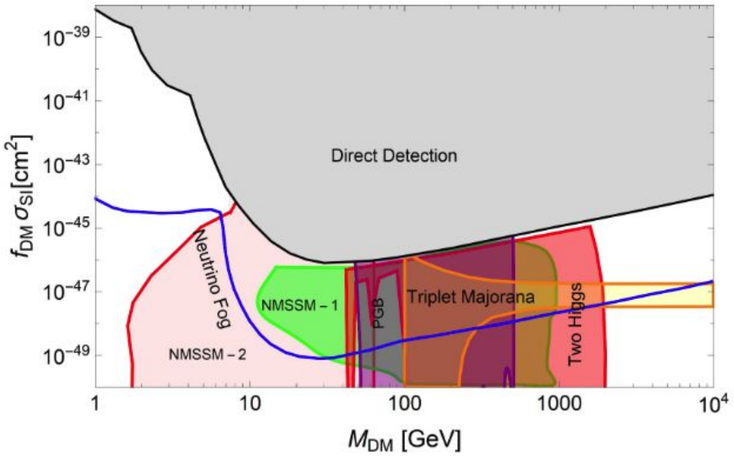
January 2025

Contents:

WIMP Direct Detection - Briefly

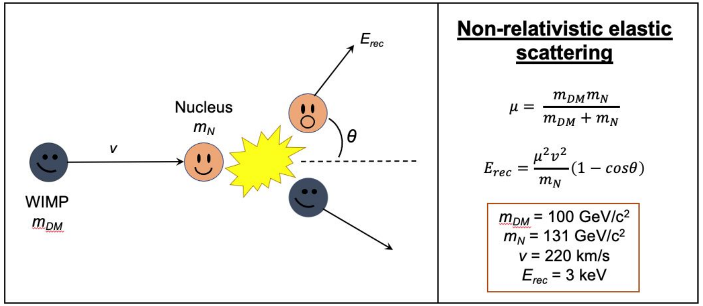
- Well motivated candidate is a “WIMPy” thermal relic
  - MeV - 100 TeV scale particle (cosmological bounds)
  - Weak scale interactions leads to correct relic density
  - Theoretical models independently predict particles with the correct properties

- Direct Detection
  - Solar System travels through Milky Way’s Dark Matter Halo
  - Very high flux of WIMPs pass through the earth
  - Challenge - Interaction is an exceptionally rare process
  - Challenge - Background radiation is everywhere



Snowmass CF1-WP1 - arXiv:2203.08084

Fill a detector with your favorite material and wait for WIMPs to scatter off it



LZ Collaboration - 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

Science and Technology Facilities Council

Swiss National Science Foundation

FCT Fundação para a Ciência e a Tecnologia

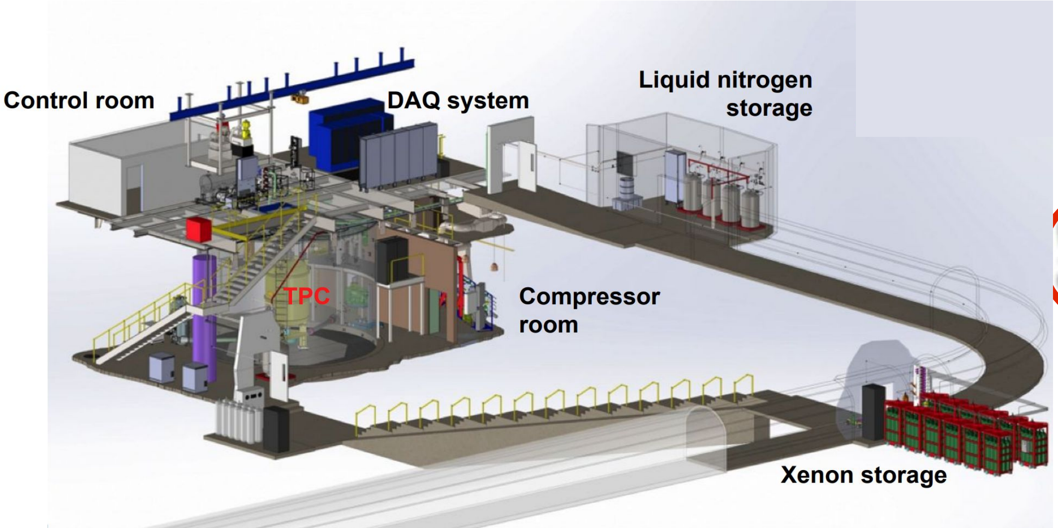
SANFORD UNDERGROUND RESEARCH FACILITY

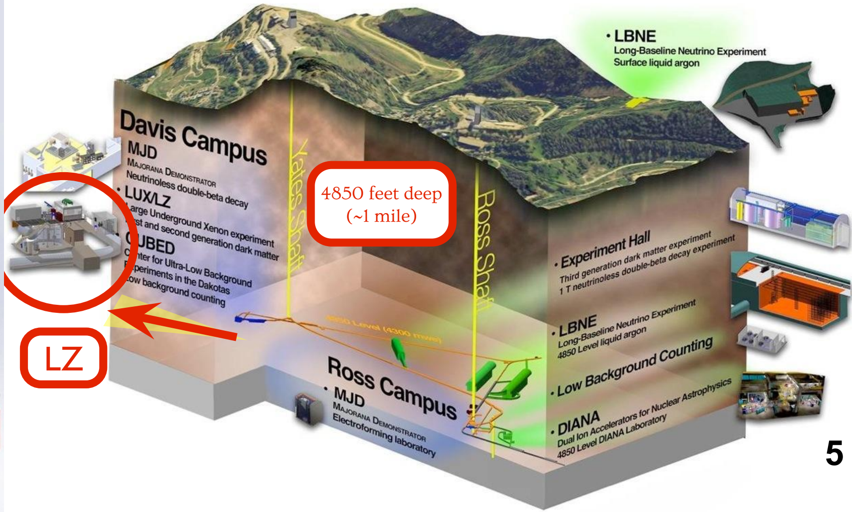
ibs Institute for Basic Science

Thanks to our sponsors and participating institutions!

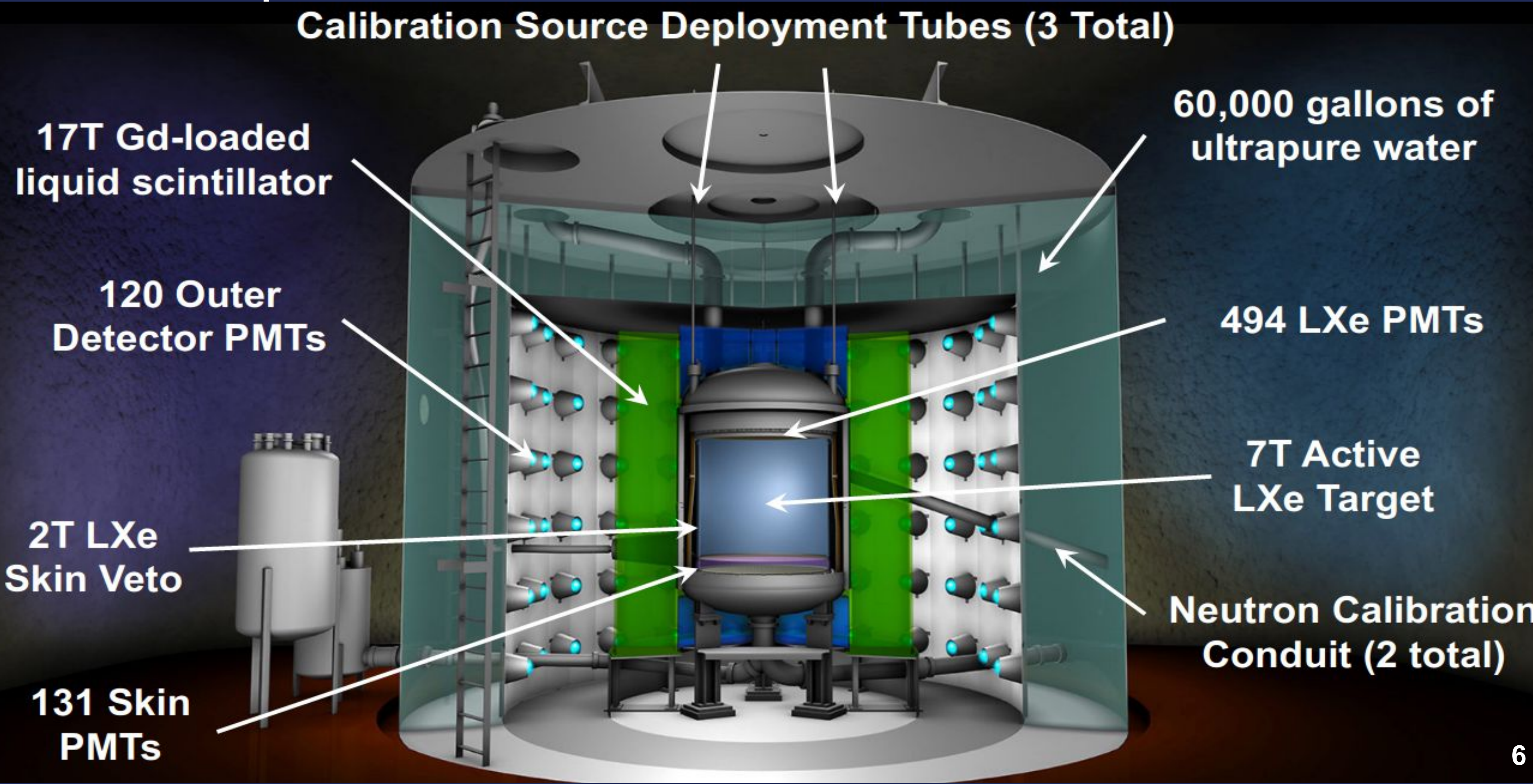
LZ at SURF

- LUX-ZEPLIN at Sanford Underground Research Facility
  - SURF - Homestake Mine, Lead, South Dakota
  - ~1 mile underground, Davis Cavern
  - Rock overburden reduces cosmic ray muon flux by $O(10^6)$

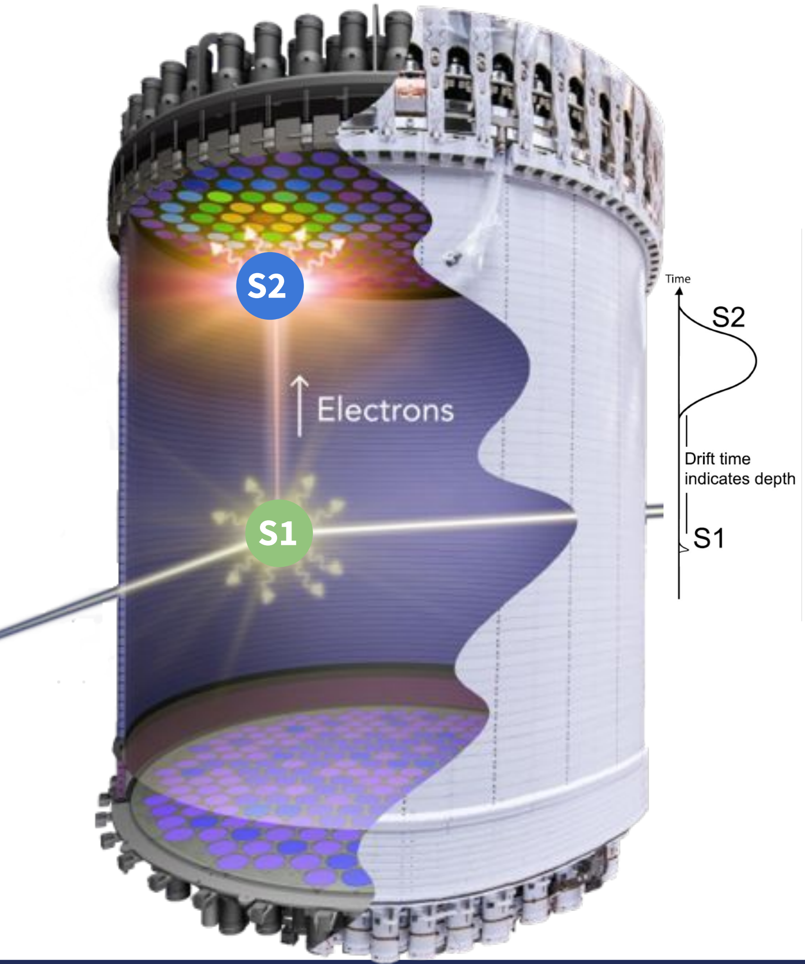




LZ - Experiment for Direct Detection of WIMP Dark

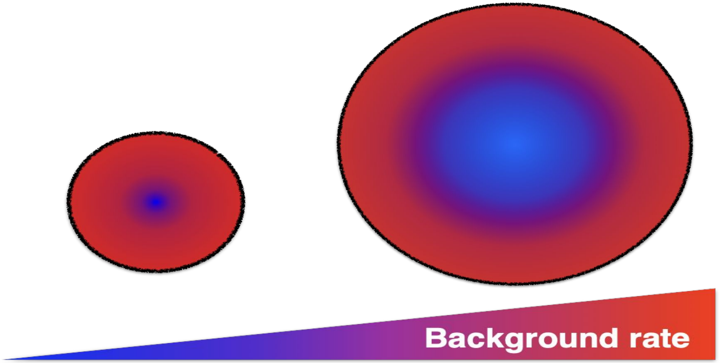


LXe TPC Principles



Why LXe?:

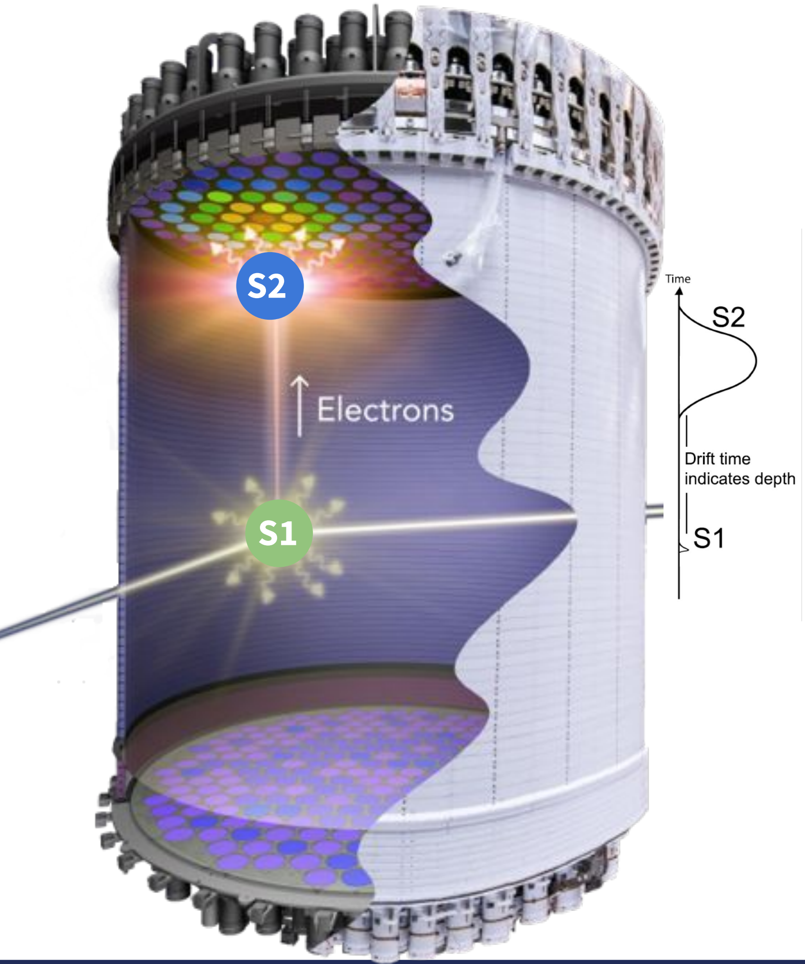
- Highest charge & light yields of all noble elements
- Commercially available & easily purified
- Dense → short attenuation lengths - self-shielding
- Scalable → potential for large target mass

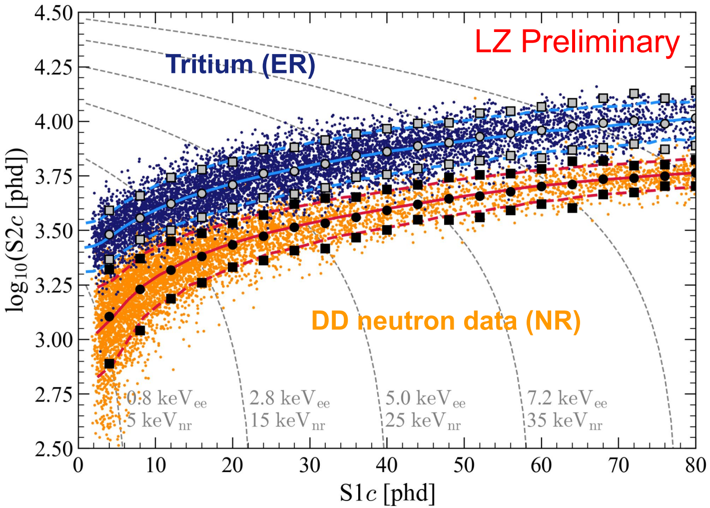


Time Projection Chamber:

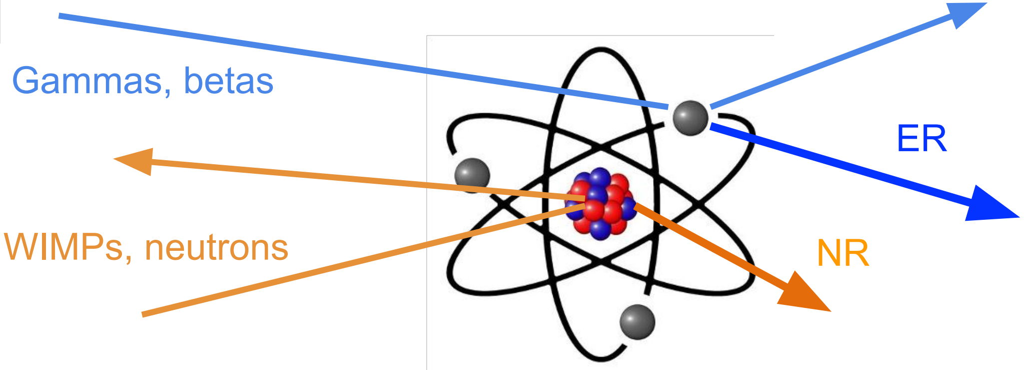
- S2 hit pattern, Drift Time - (xy, z)
- Energy deposited reconstructed from - S1, S2
- Particle discrimination - S1:log(S2)

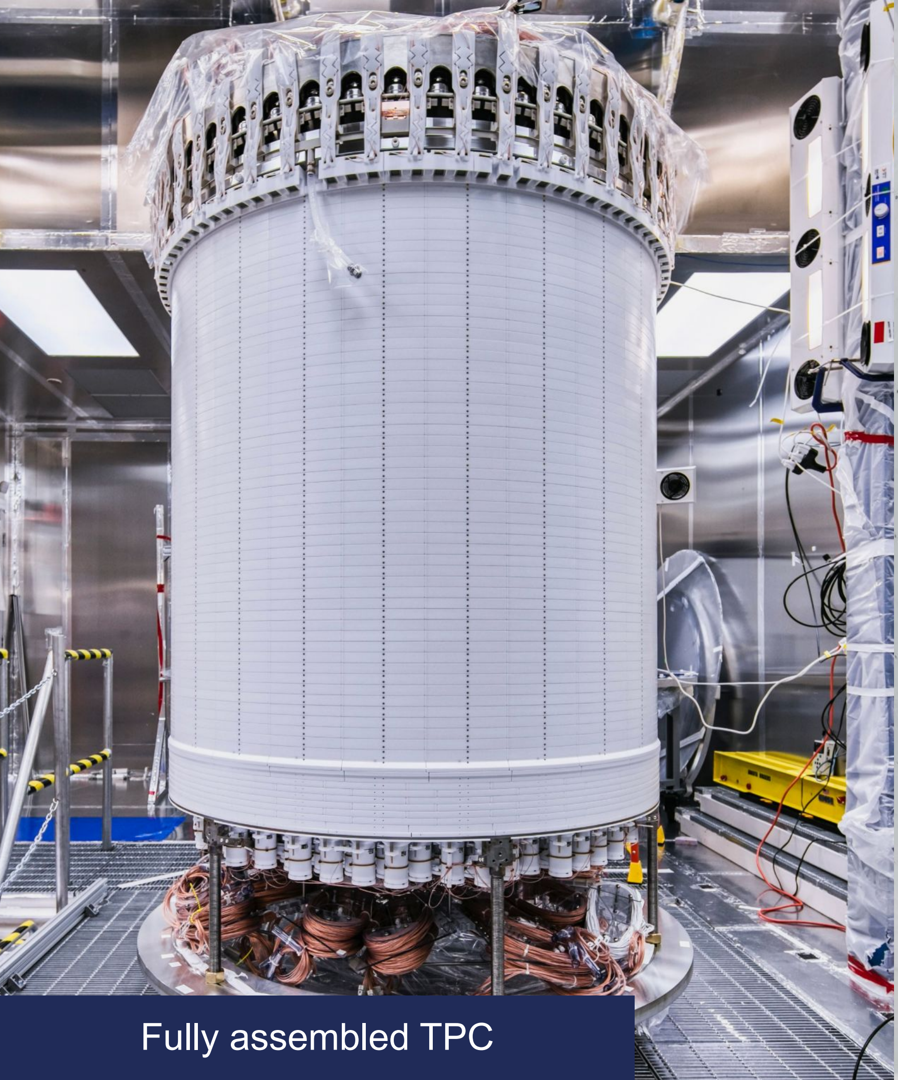
LXe TPC Principles

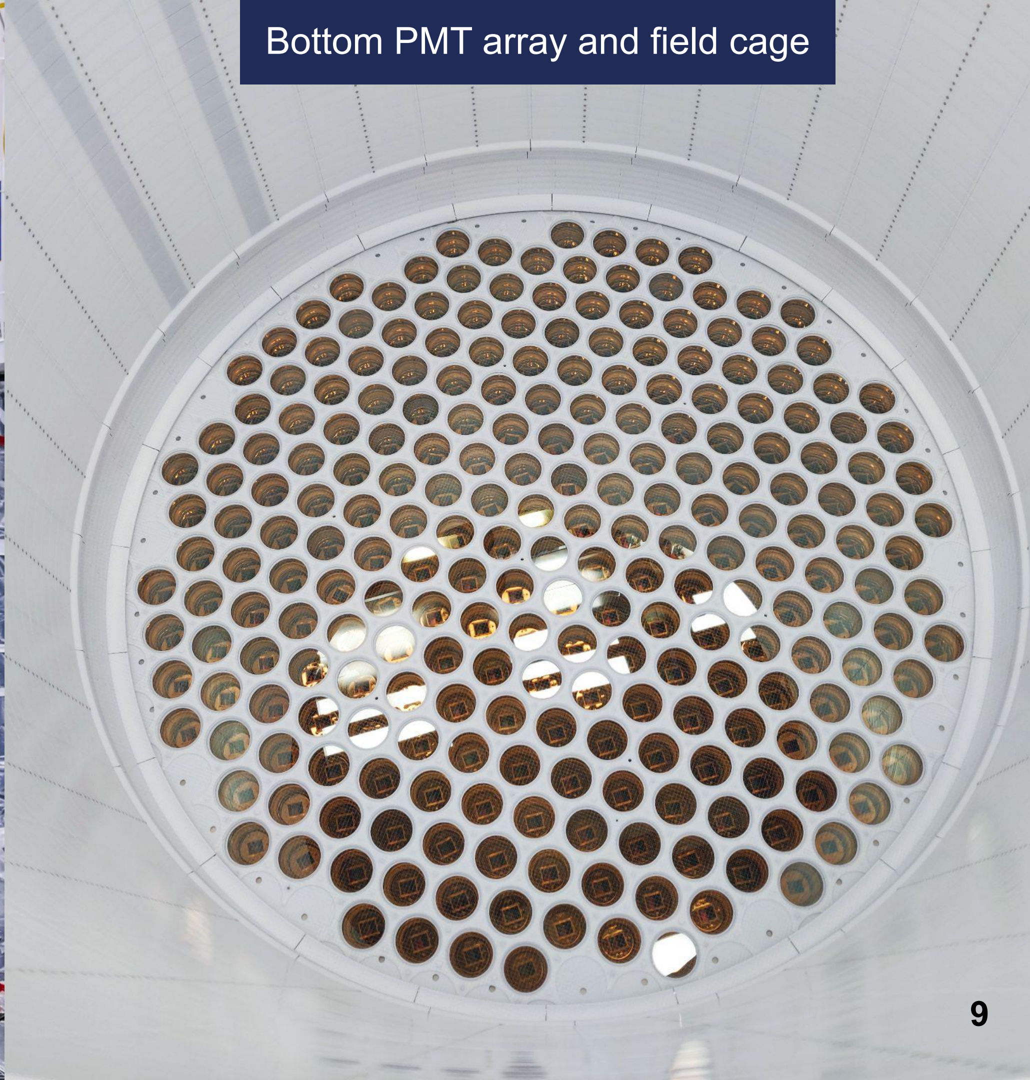




2024 Electronic Recoil (ER) and Nuclear Recoil (NR) discrimination in calibration



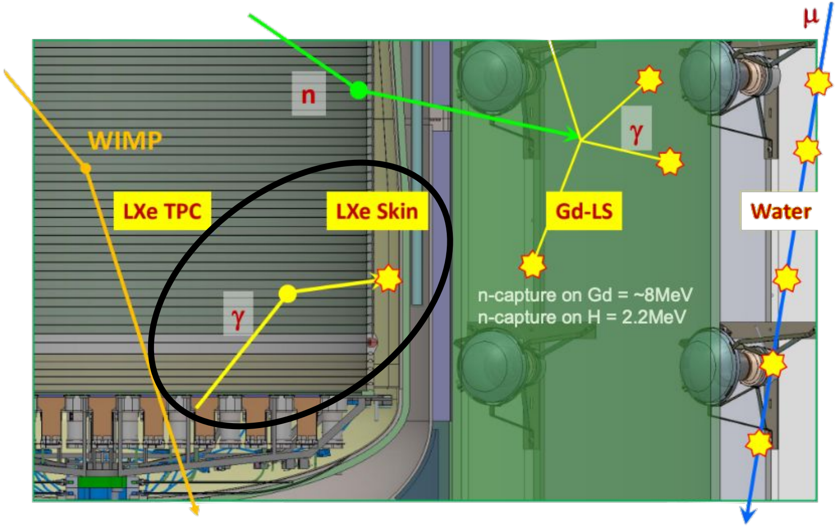

Fully assembled TPC

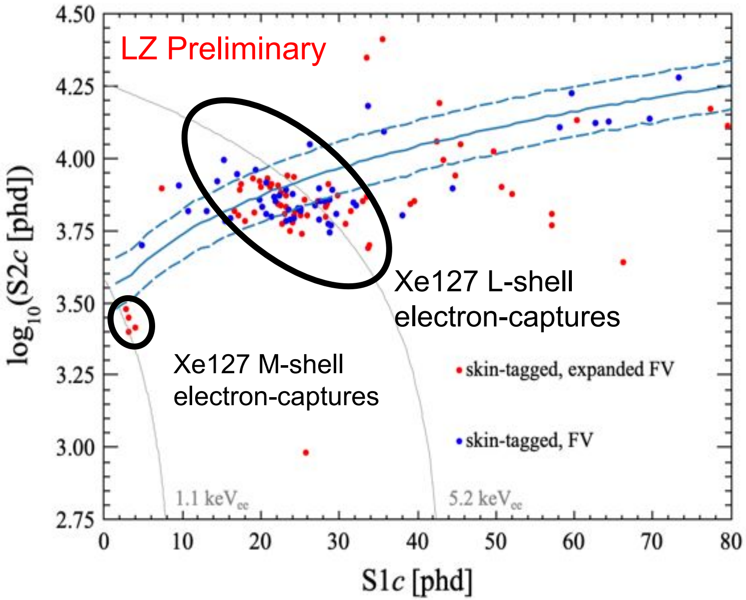

Bottom PMT array and field cage

INNER CRYOSTAT INSERTION

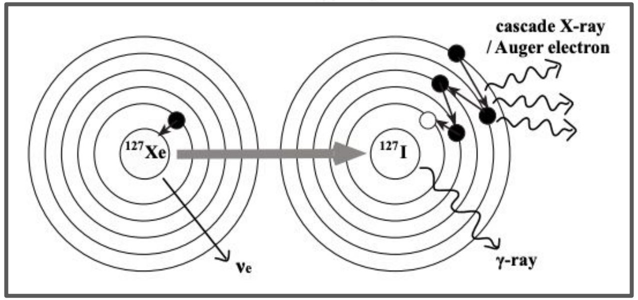
UG TRANSPORTATION

LXe Skin



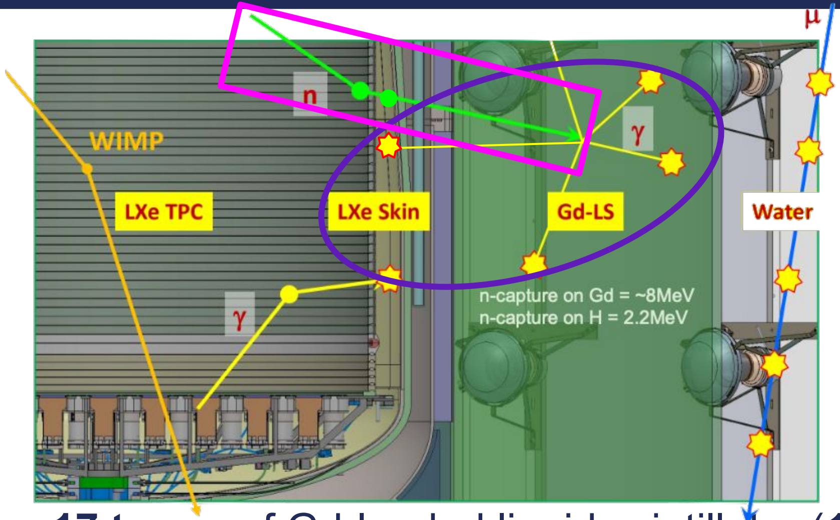


- **2 tonne** of LXe surrounding the TPC
- 131 1” or 2” PMTs
- Anti-coincidence veto for **γ-rays** with **78±5% efficiency**
- Reduction of important ER background rates
  - E.g. ^{127}Xe decay via electron capture

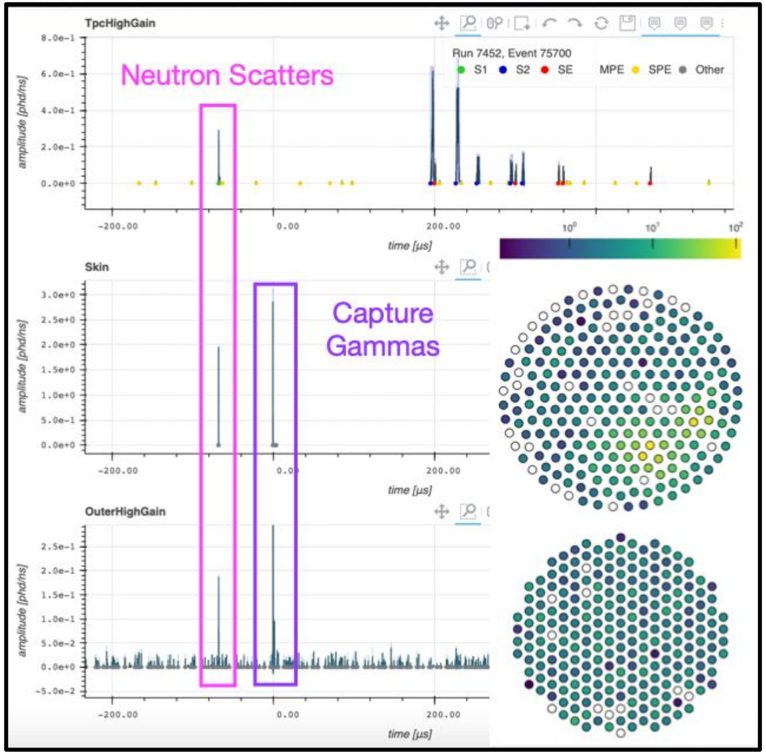


Courtesy of Jack Bargemann APS April 2023

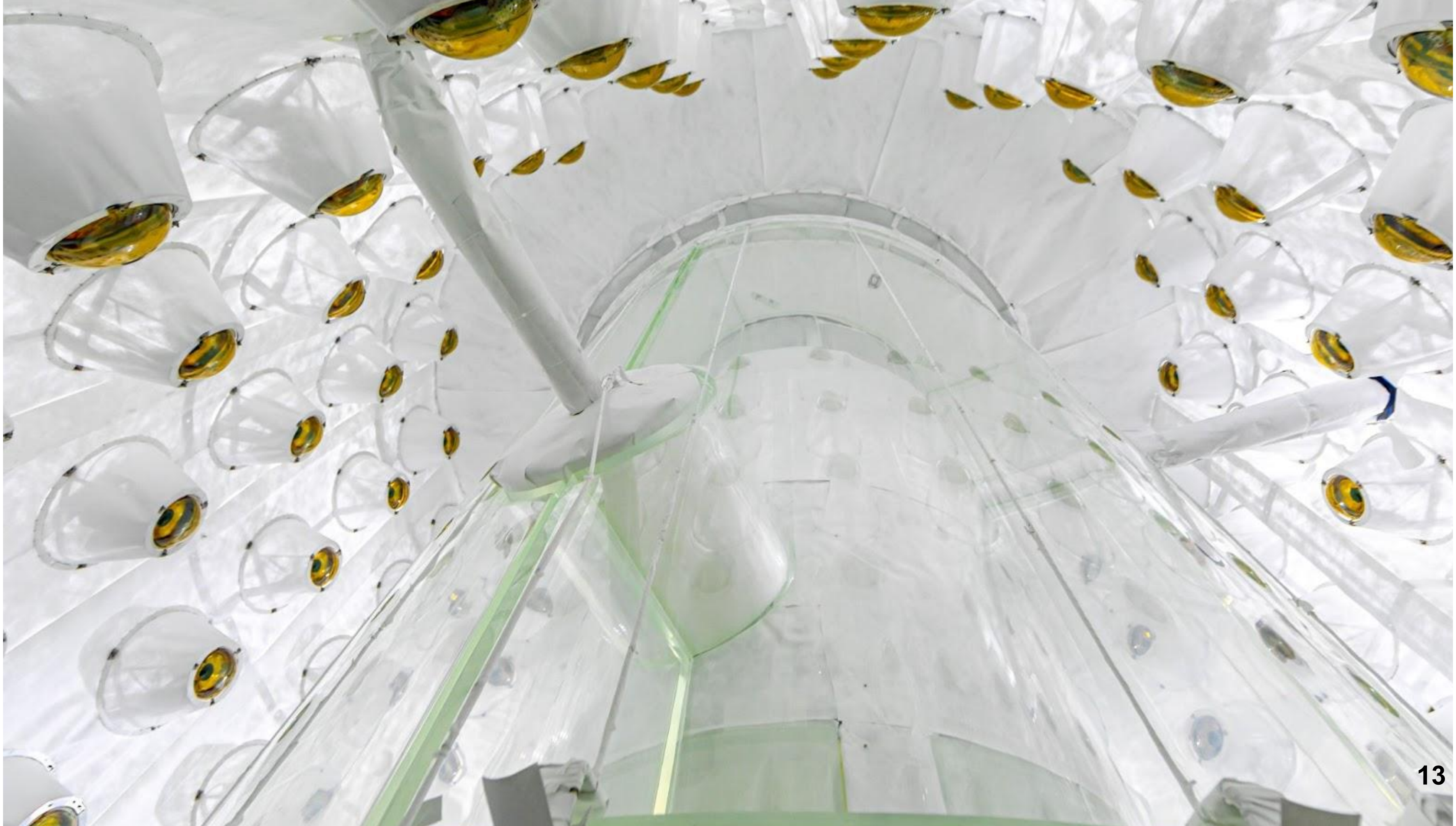
Outer Detector



Waveform example of a tagged neutron multiple scatter:



- **17 tonne** of Gd-loaded liquid scintillator (120 8" PMTs)
- Infinite volume of Gd-LS has a 30us capture time for a thermal neutron
- LZ has ~90% Single Scatter neutron veto efficiency
- ~50Hz of background above 100-200 keV threshold
  - Gd alphas, ^{14}C betas



WIMP Search 2024

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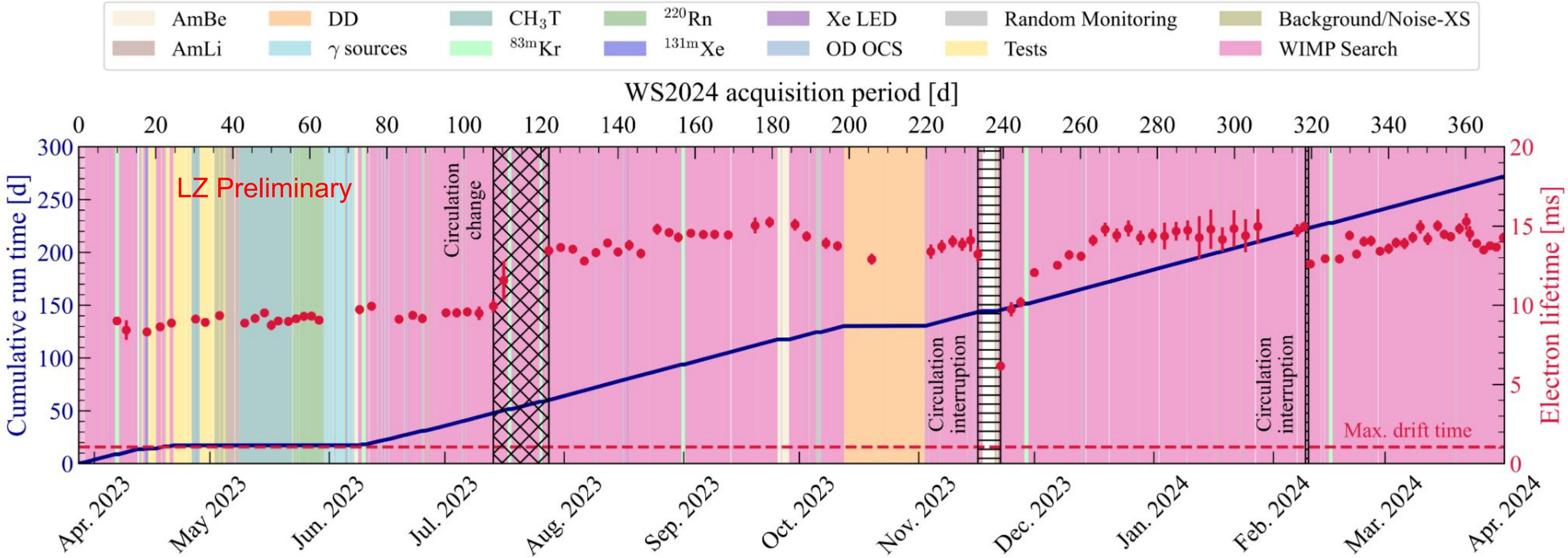
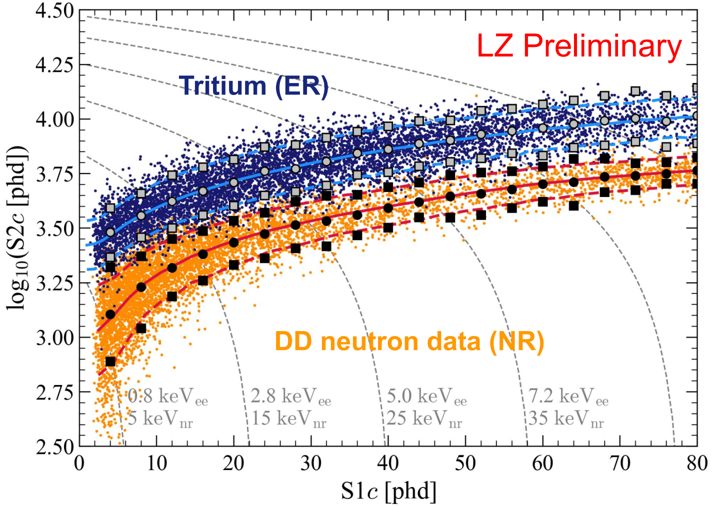


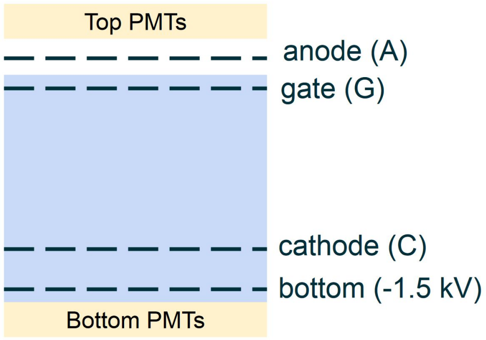
- 220 live-days, one calendar year March ‘23 to March ‘24
- Milestones:
  - Bias mitigation (“salting”) began July 3rd
  - Circulation change July 12th

Calibrations

- ER calibration: 156k evts radiolabeled methane
  - ^{3}H (18.6 keV β^-) & ^{14}C (156 kev β^-)
- NR calibration: 11k neutron evts!
  - Collimated DD 2.45 MeV & CSD AmLi (α,n)
- 99.8% discrimination of β^- under flat NR band median
- Injected ^{83m}Kr, ^{131m}Xe sources, spatial & temporal corrections
  - (xy, z) resolution at 1σ (<1cm, <1mm)
- Electron lifetime >8ms (depends strongly on LXe purity)
  - max e^- drift time ~1ms.

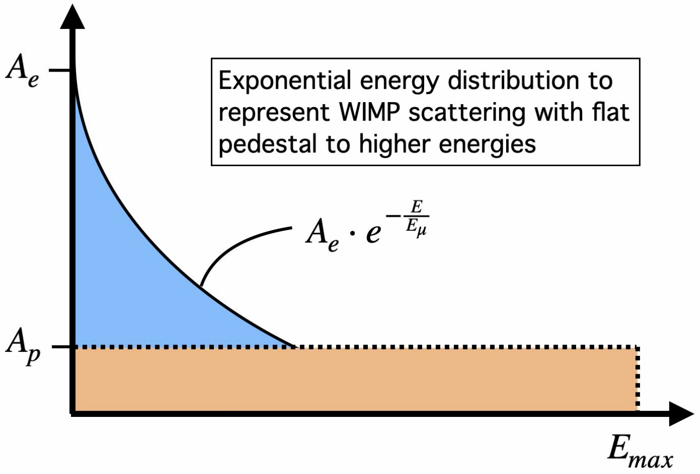


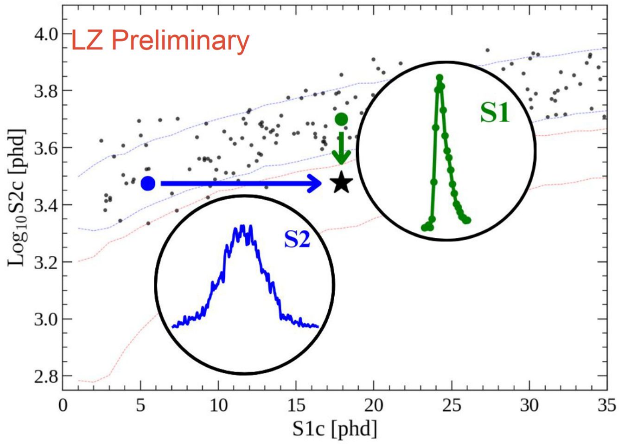
Science Run	C/G/A Voltage [kV]	Drift Field [V/cm]	Analysis live time [days]	g1 (phd/photon)	g2 (phd/e$^-$)
WS2022	-32/-4/+4	193	60	0.114 ± 0.002	47 ± 1.1
WS2024	-18/-4/+3.5	97	220	0.112 ± 0.002	34 ± 0.9



Bias Mitigation

- ❑ "Salting" - fake signal injected randomly
- ❑ Manufactured from sequestered ER & NR calibration data
- ❑ Unknown number of salt events
  - ❑ Rate capped by WS2022 cross-section limit
- ❑ Exponential WIMP recoil spectrum
  - ❑ + flat energy spectrum to cover high energy NR

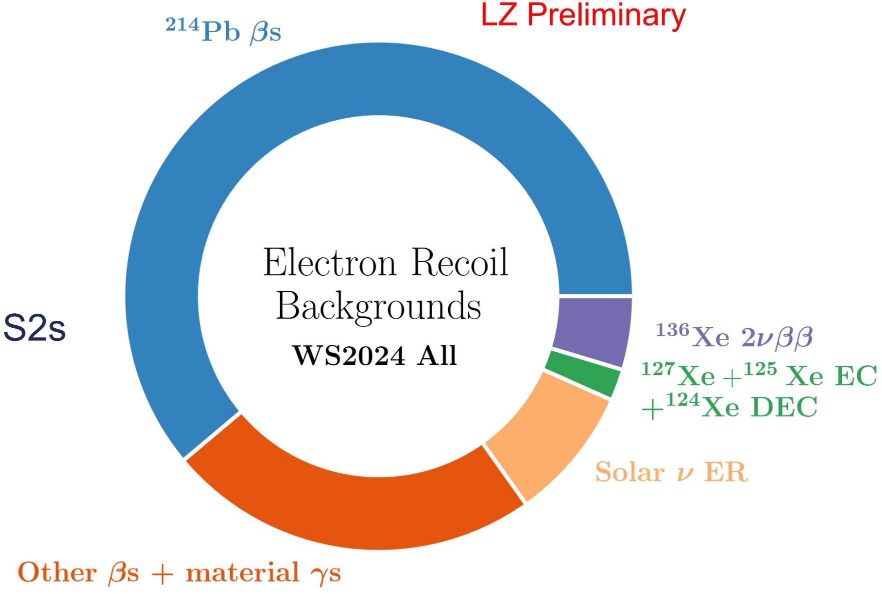




Backgrounds Overview

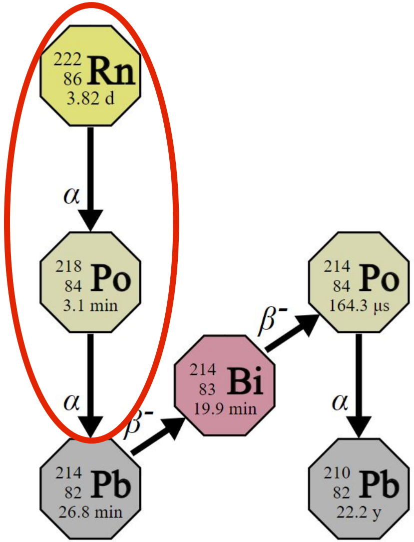
- Dissolved β emitters:
  - ^{214}Pb (^{222}Rn), ^{212}Pb (^{220}Rn), ^{85}Kr, ^{136}Xe (ββ)
- Dissolved EC decays (x-rays/Auger electrons)
  - ^{127}Xe & ^{125}Xe produced by activation from neutron calibration
  - ^{124}Xe (double EC), 0.095% natural abundance
- Solar ν's: ^{8}B (NR), pp+^{7}Be (ER)
- Detector ER, γ emitters from detector materials
  - ^{238}U, ^{232}Th, ^{40}K, ^{60}Co decay chains
- Neutrons from USF and (α,n) in detector materials
- Accidentals - random coincidence of isolated S1 and S2s

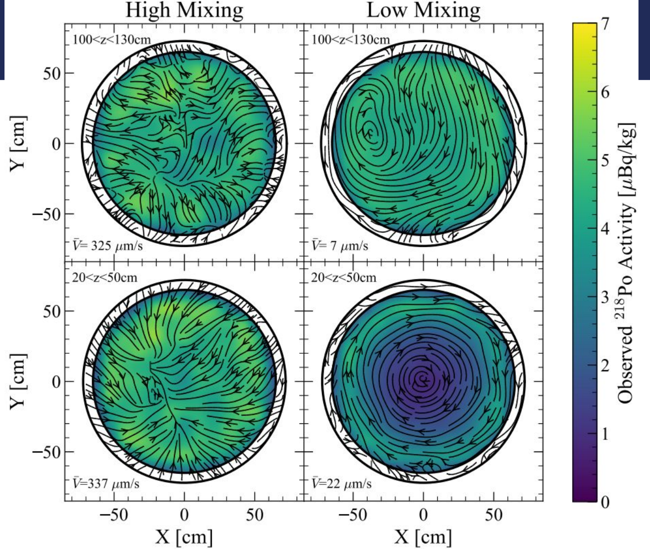
LZ Preliminary

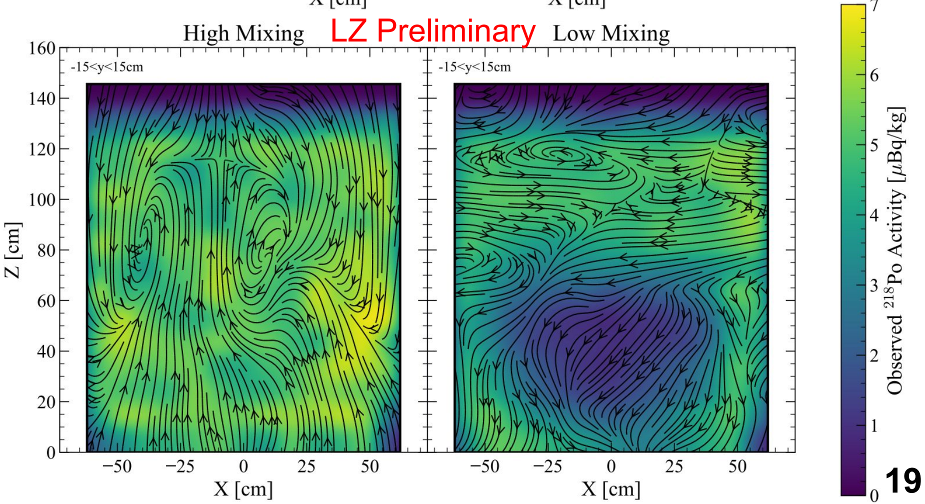


Liquid Xenon Flow

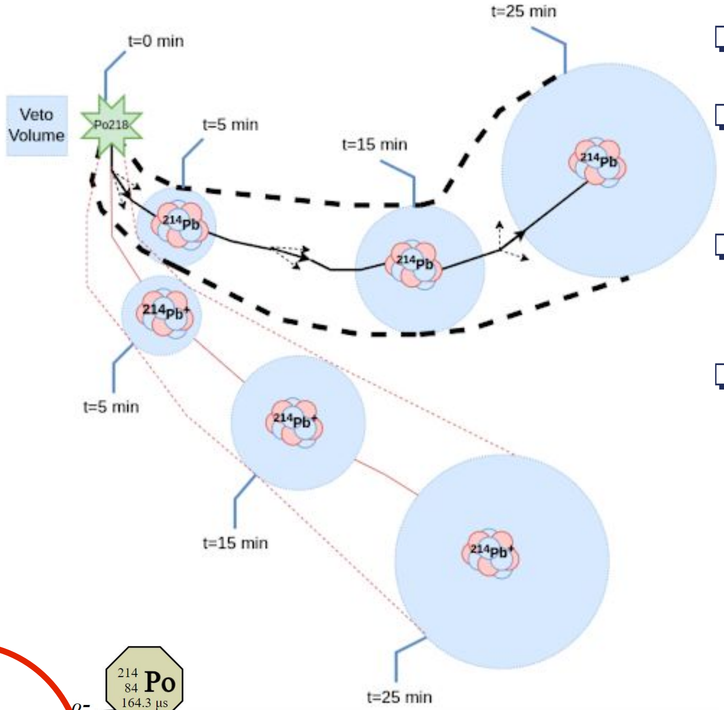
- Fine control of LXe circulation and temperature allows control of LXe flow state
- **High-mixing** state: Turbulent flow, better circulation across TPC, uniform injection of calibration sources
- **Low-mixing** state: Slower, laminar flow. Lower activity in FV, predictable “streamlines”.



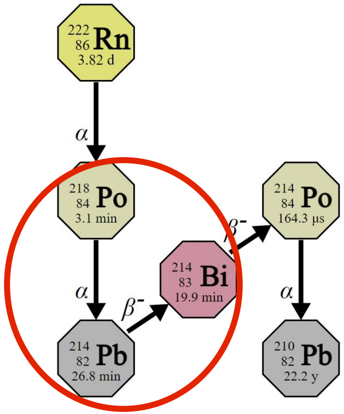




Radon Tag



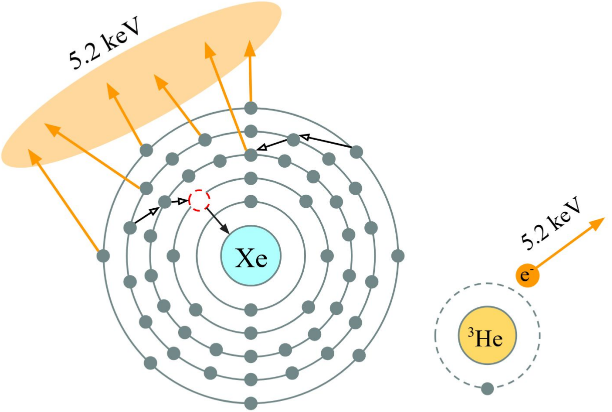
- "Naked" ^{214}Pb β make up majority of ER background
- Combine LXe flow maps & electric field maps to predict volumes likely to contain charged or neutral ^{214}Pb.
- Reduces ^{214}Pb to **1.8 ± 0.3 μBq/kg** in untagged sample
  - 3.9 ± 0.4 μBq/kg in total exposure
- Tagged and untagged samples both fitted for WS2024



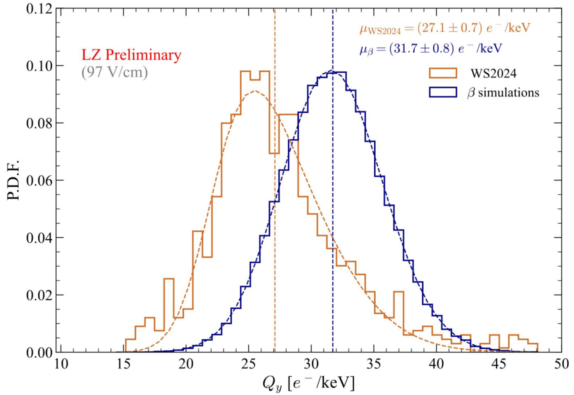
Sample	% ^{214}Pb	% Exposure
Tagged	60 ± 4	15
Untagged	40 ± 4	85

Electron Capture Backgrounds

- ^{125}Xe & ^{127}Xe decay by electron capture (EC)
- Produced by activation from neutrons calibration and cosmogenics
  - Rate in WS2024 << WS2022
- L-shell electron capture (5.2 keV) is a WS background
- Electron capture has a **field-dependent suppressed charge yield**
- Higher ionization density → increased recombination
- LZ WS2022 (193 V/cm): Q_L/Q_β=0.88±0.01*
- LZ WS2024 (97 V/cm): Q_L/Q_β=0.87±0.03*
- Charge suppression first measured in XELDA
  - [PRD 104, 112001 ('21)]



Xe L-shell EC ^3H β^- decay



- Skin tagged Xe L-shell EC
- β simulation

*Preliminary, dedicated publication in progress

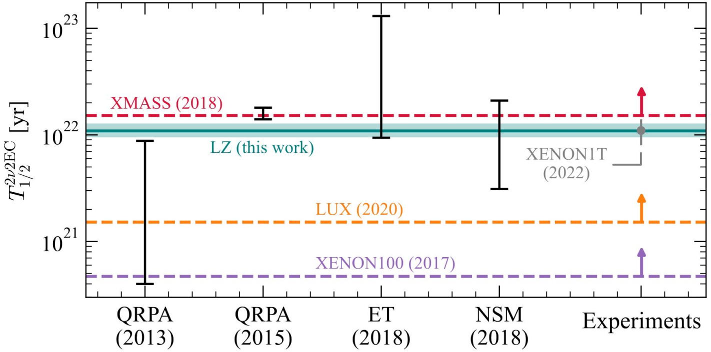
^{124}Xe Double Electron Capture

- ^{124}Xe 2νECEC $T_{1/2}=(1.09\pm0.14^{stat}\pm0.05^{sys})\times10^{22}$ years
  - Worlds longest directly measured half-life
- In-situ $T_{1/2}$ measurement of KK (64.3 keV) captures - (65 ± 5)%
- LL (10 keV) and LM (6 keV) are WS backgrounds
- LM modelled with same as single L-shell charge suppression
  - $Q_{LM}/Q_\beta = Q_L/Q_\beta$
- For LL expect further charge yield suppression due to higher ionization density.
- Vary Q_{LL}/Q_β in fitting of our data $0.65 < Q_{LL}/Q_\beta < 0.87$

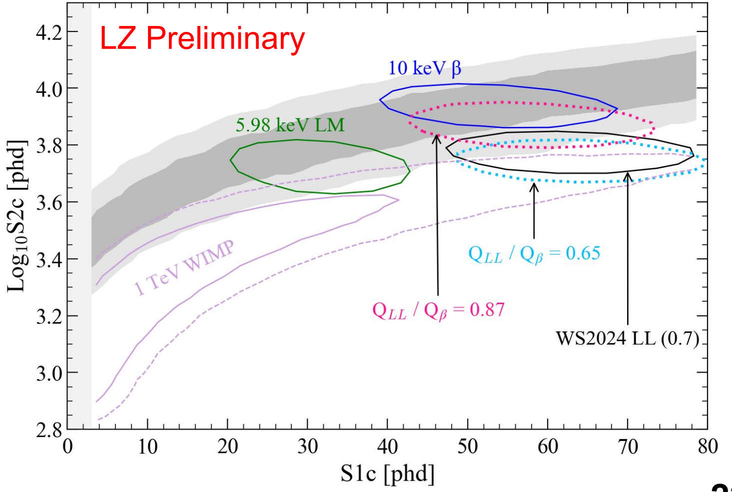
2x ionization density (→ 0.65)

Q_L/Q_β (→ 0.87)

- Best fit to WS2024 data: $Q_{LL}/Q_\beta = 0.70\pm0.04$

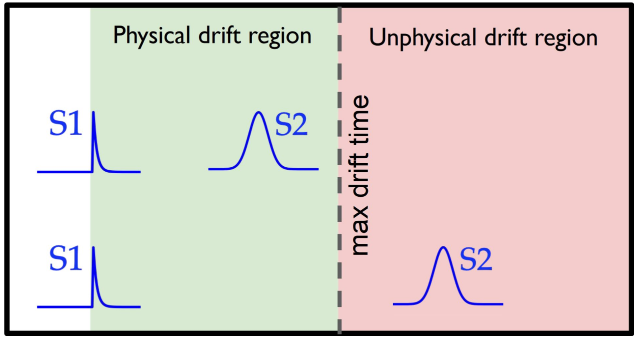


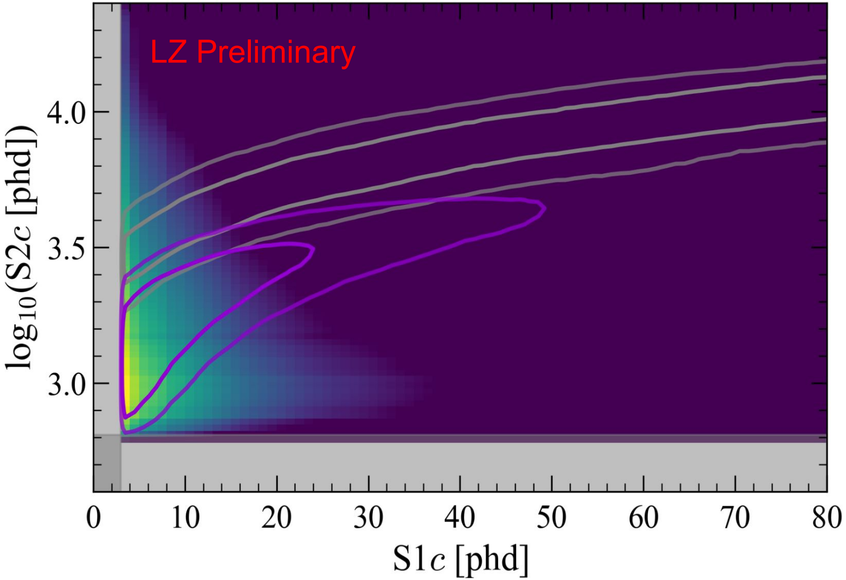
WS2022 J. Phys G 52, 015103



Accidentals Background

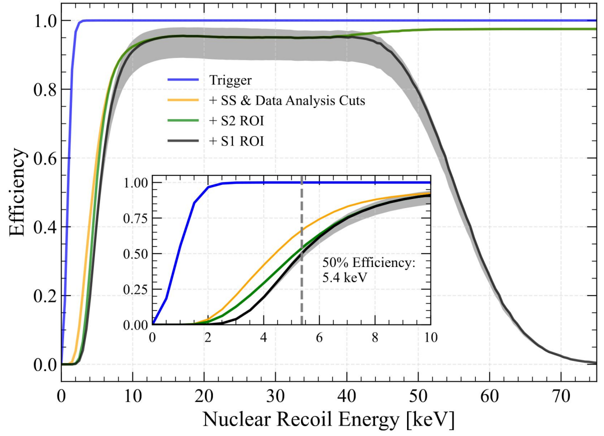
- Accidental coincidence of uncorrelated isolated S1 and S2 pulses
- LZ's accidentals model:
  - **Rate:** Measure rate of unphysical drift time (UDT) single scatters. Analysis cut efficiencies analysed using manufactured accidental events.
  - **Shape:** Manufactured by combining isolated S1 and S2 waveforms and applying analysis cut efficiencies.
- Analysis cuts have an 99.5% rejection power

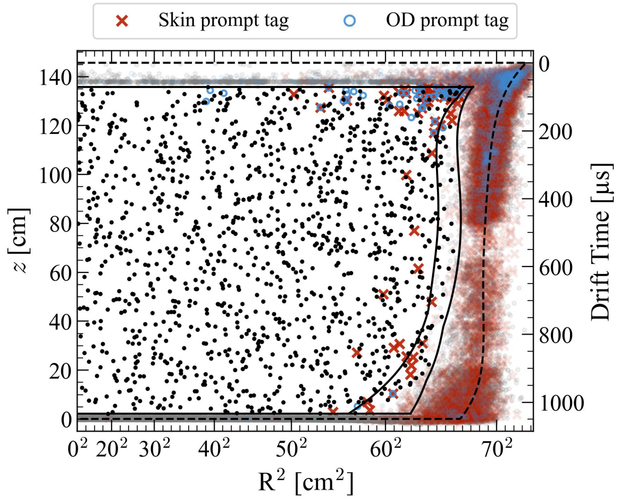




Data Analysis

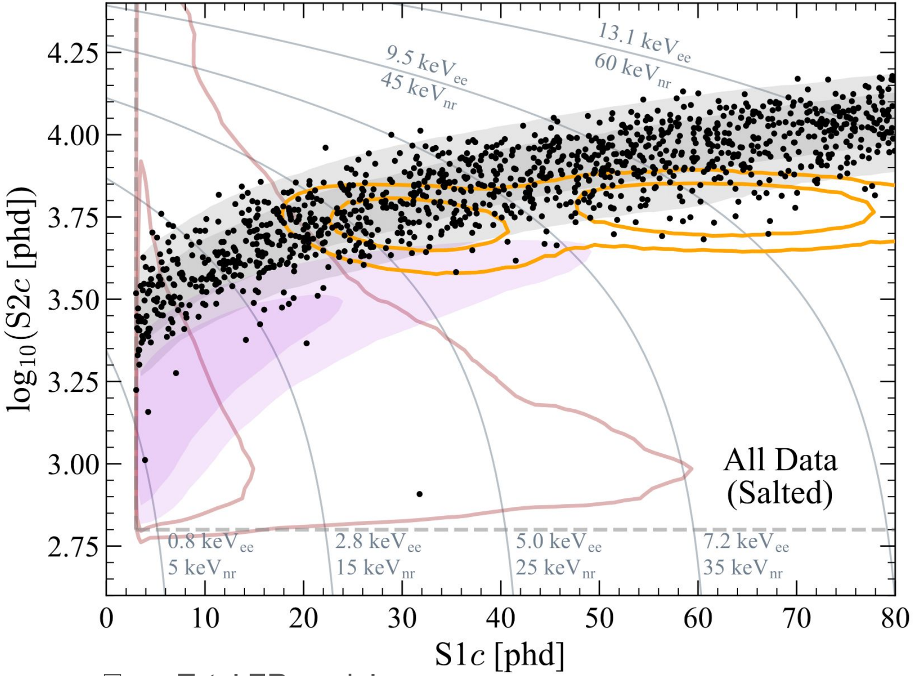
- Region of interest (ROI)
  - 3 < S1c < 80 photons detected (phd)
  - S2 > 14.5 electrons (645 phd)
  - $\log_{10}$(S2c) < 4.5
- Fiducial volume: azimuthally & drift time-dependent
  - < 0.01 charge loss ("wall") events
  - 5.5 ± 0.2 tonne mass
- Single scatter
- Anti-coincidence Skin & OD vetoes
- Cuts on S1 & S2 parameters to remove accidentals





WS2024 Data - Salted

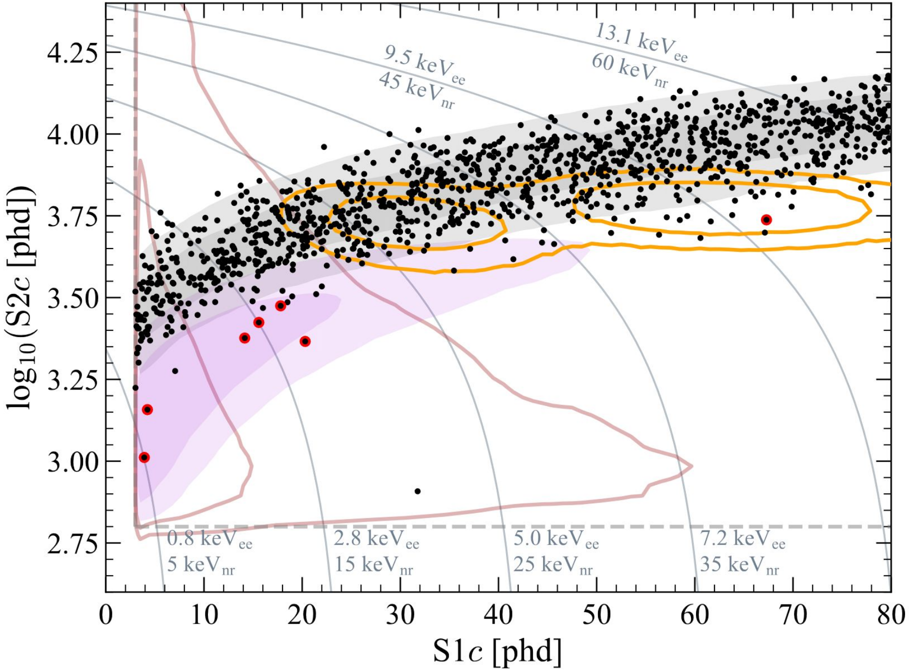
- Final exposure:
  - 220 livedays * 5.5 tonnes = 3.3 tonne years



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

WS2024 Data - Unsalting

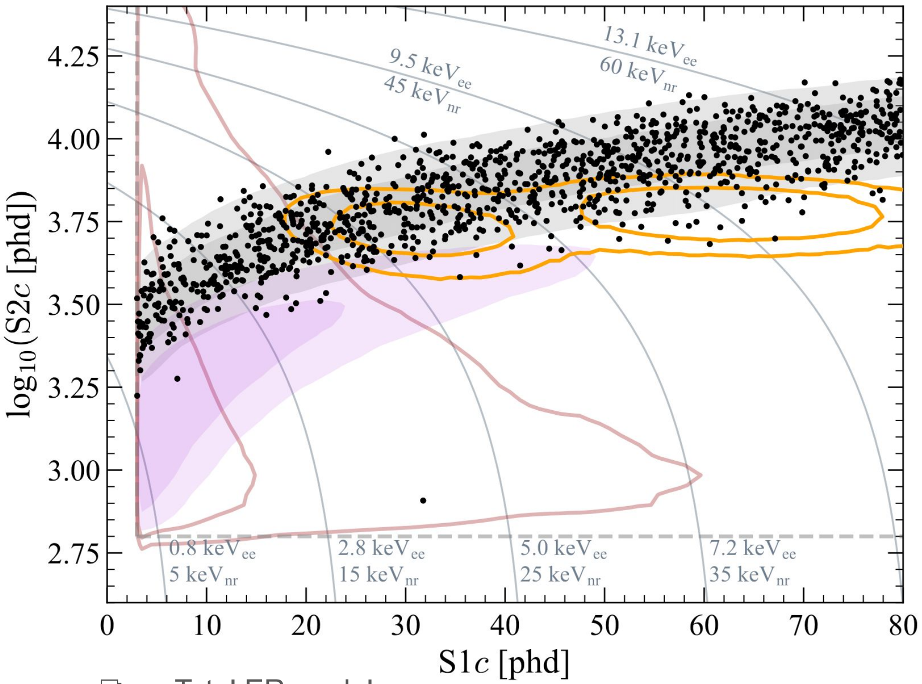
- Final exposure:
  - 220 livedays * 5.5 tonnes = 3.3 tonne years
- 7 salt events present after all cuts
  - 8 injected in WS2024
  - Consistent with evaluated signal efficiency



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

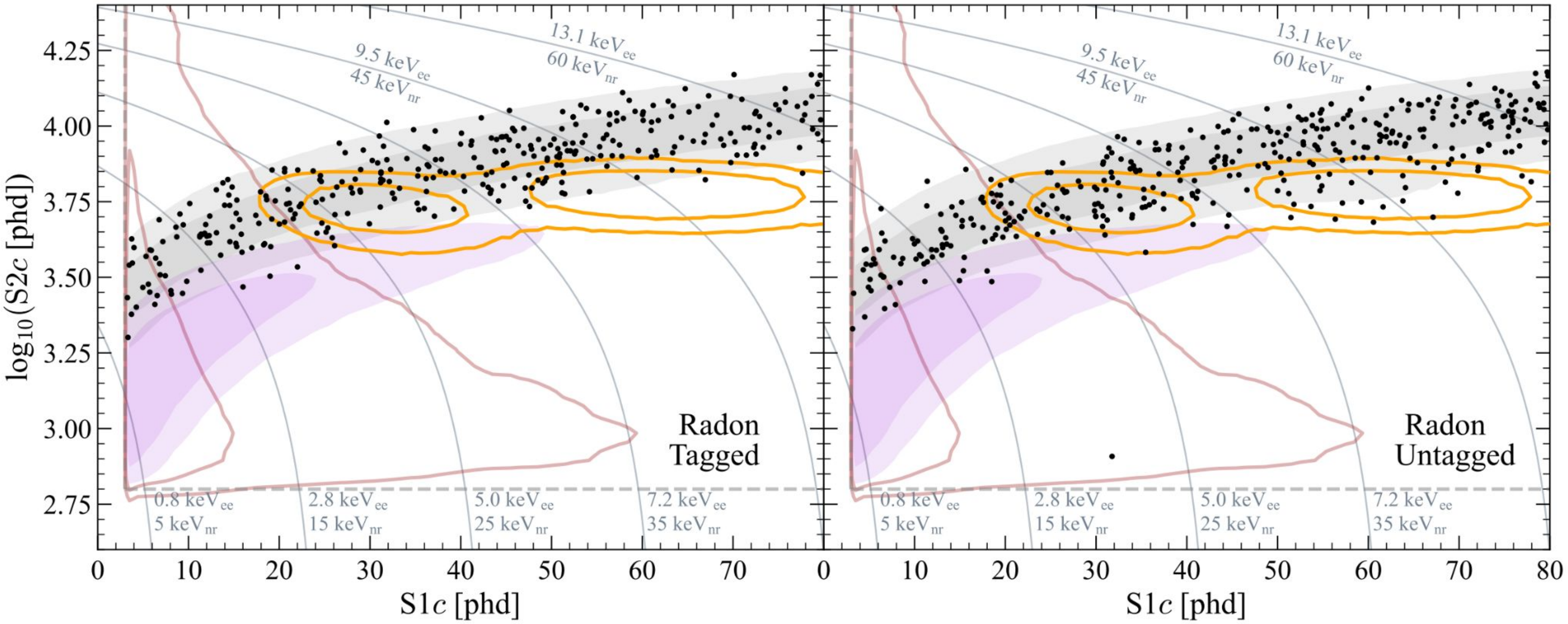
WS2024 Data - Unsalted

- Final exposure:
  - 220 livedays * 5.5 tonnes = 3.3 tonne years
- 7 salt events present after all cuts
  - 8 injected in WS2024
  - Consistent with evaluated signal efficiency
- 1220 events remain after unsalting
- No changes to model required post-unsalting
- Next step: Statistical inference of this data



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

Radon Tagged vs Untagged



0.3 tonne years

1.8 tonne years

Combined Likelihood

Exposure in each sample [tonne years]

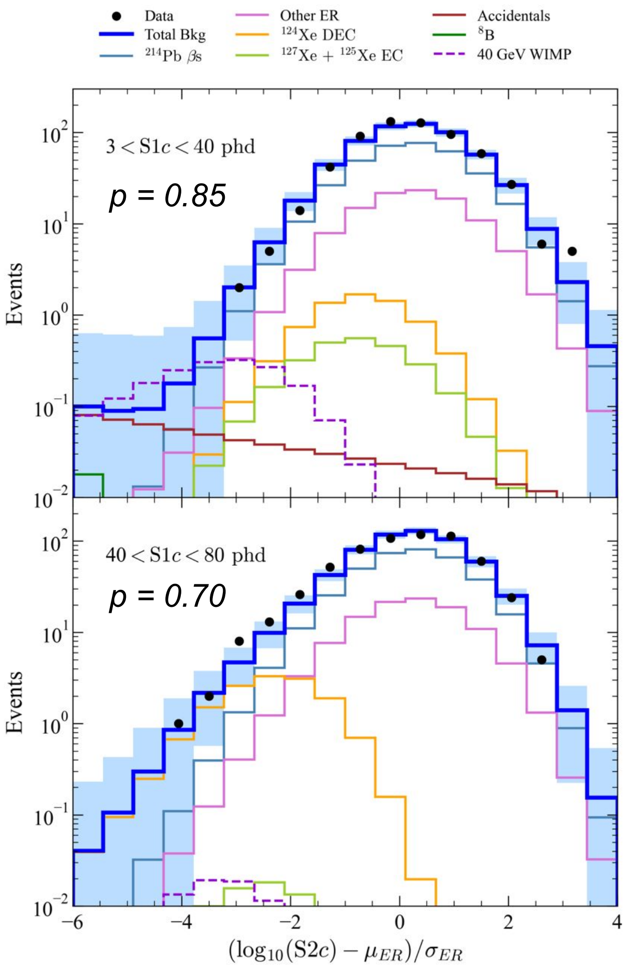
High Mixing State	Radon Tag Inactive	Radon Tagged	Radon Untagged	OD/Skin Vetoed	WS2022
0.6	0.6	0.3	1.8	n/a	0.9

- Likelihood fit contains six samples
- WS2024 represented by first four, totalling 3.3 tonne years
- OD/Skin vetoed - full WS2024 3.3 tonne years - constraint on neutron background
- WS2022 unmodified since original publication → Maximise exposure

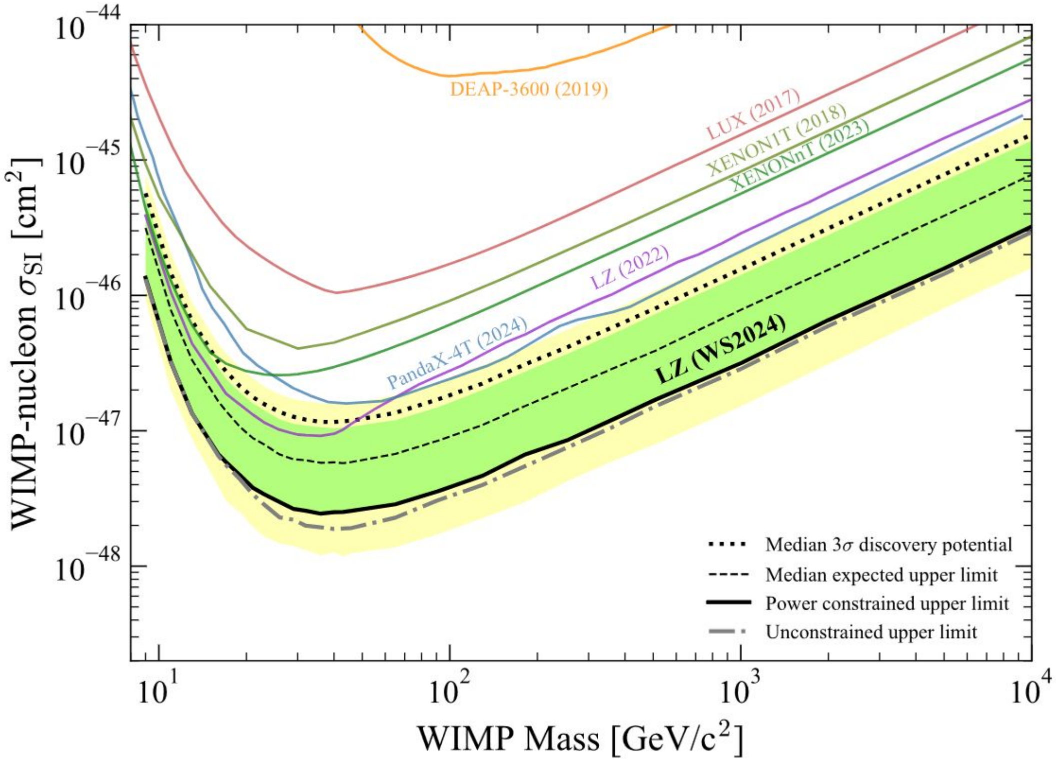
WS2024 Fit Results

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

- ❑ Best fit no. of WIMPs is 0 at all tested masses (GeV- 10TeV)
- ❑ Strong agreement with background only hypothesis

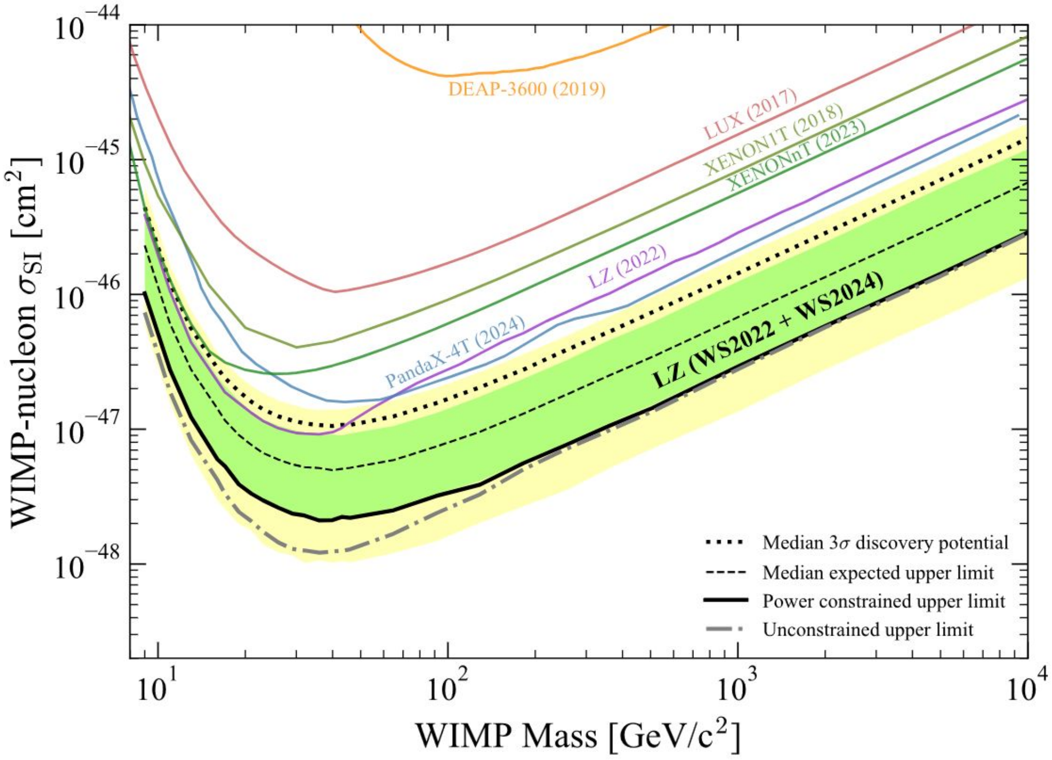


WS2024 Only Sensitivity



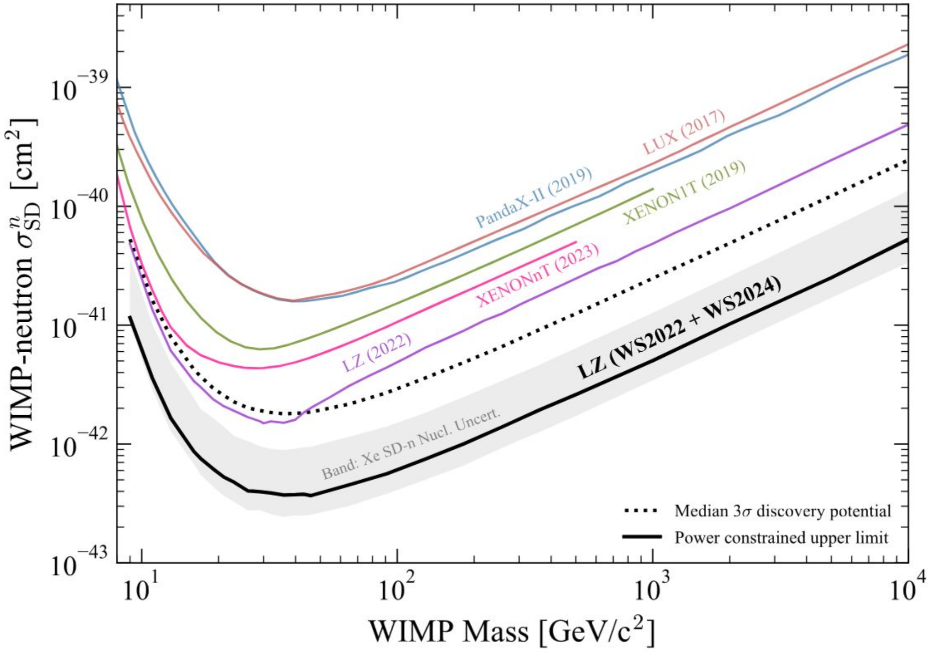
- Two-sided profile likelihood ratio test statistic
- Power constrained at -1σ as per recommended conventions EPJC 81, 907 ('21)
- Under-fluctuation in sensitivity results from arrangement of accidentals background events

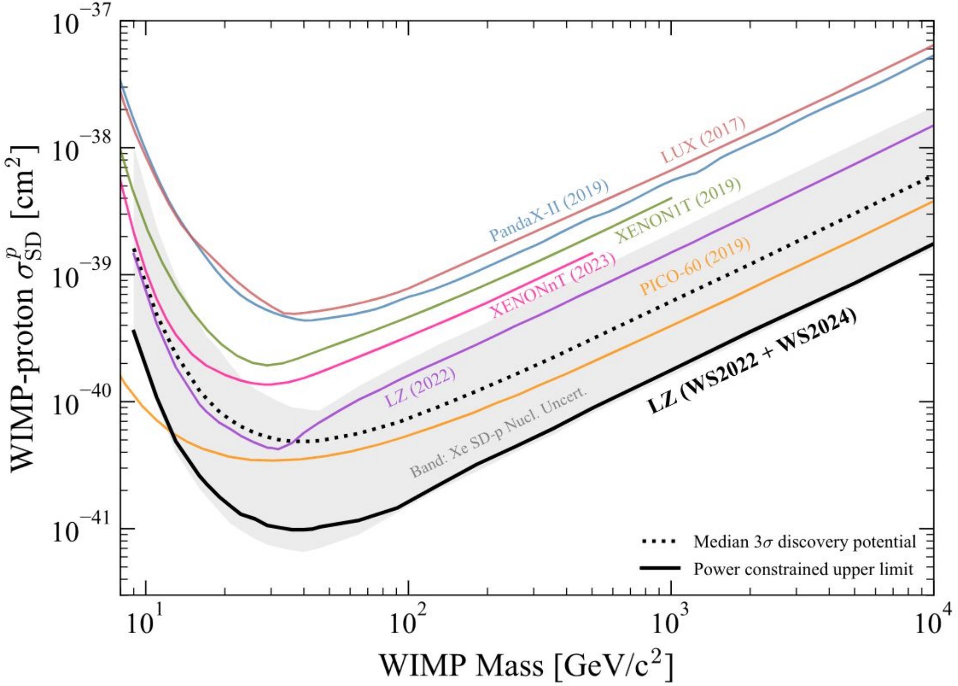
WS2024 + WS2022 Sensitivity



- Two-sided profile likelihood ratio test statistic
- Power constrained at -1σ as per recommended conventions [EPJC 81, 907 ('21)]
- Further under-fluctuation from WS2022 ER background
- Best limit from combined analysis of $\sigma_{SI}=2.1\times10^{-48}cm^2$ for $36GeV/c^2$
- World leading sensitivity!

Spin Dependent Sensitivity





- Spin-dependent limit using odd Xe isotopes
  - ^{129}Xe, spin 1/2, 26.4% natural abundance
  - ^{131}Xe, spin 3/2, 21.2% natural abundance

Conclusions

- **LZ is the world's most sensitive WIMP direct detection experiment**
  - Total exposure 4.2 tonne-years
  - New constraint exceeds previous best constraint by factor >4
- Radon tag developed and deployed for the first time
  - 60% reduction in main ER background ^{214}Pb
- First observation of suppressed charge yield from LL-shell captures of ^{124}Xe
- LZ will continue to take data until 2028, towards 1000 live days
- Many physics searches on the horizon!:
  - ^{8}B CEνNS, low mass WIMPs, ER based searches, $0\nu\beta\beta$