Recent Dark Matter results from the LUX-ZEPLIN (LZ) Experiment

Albert Baker
on behalf of the LZ collaboration

PD24

20th November 2024

LZ Collaboration

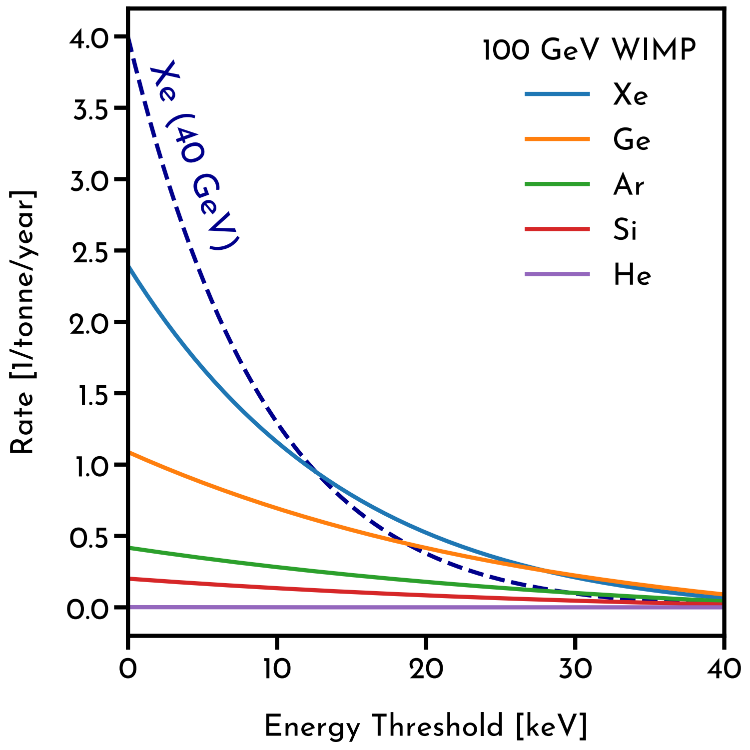
- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra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

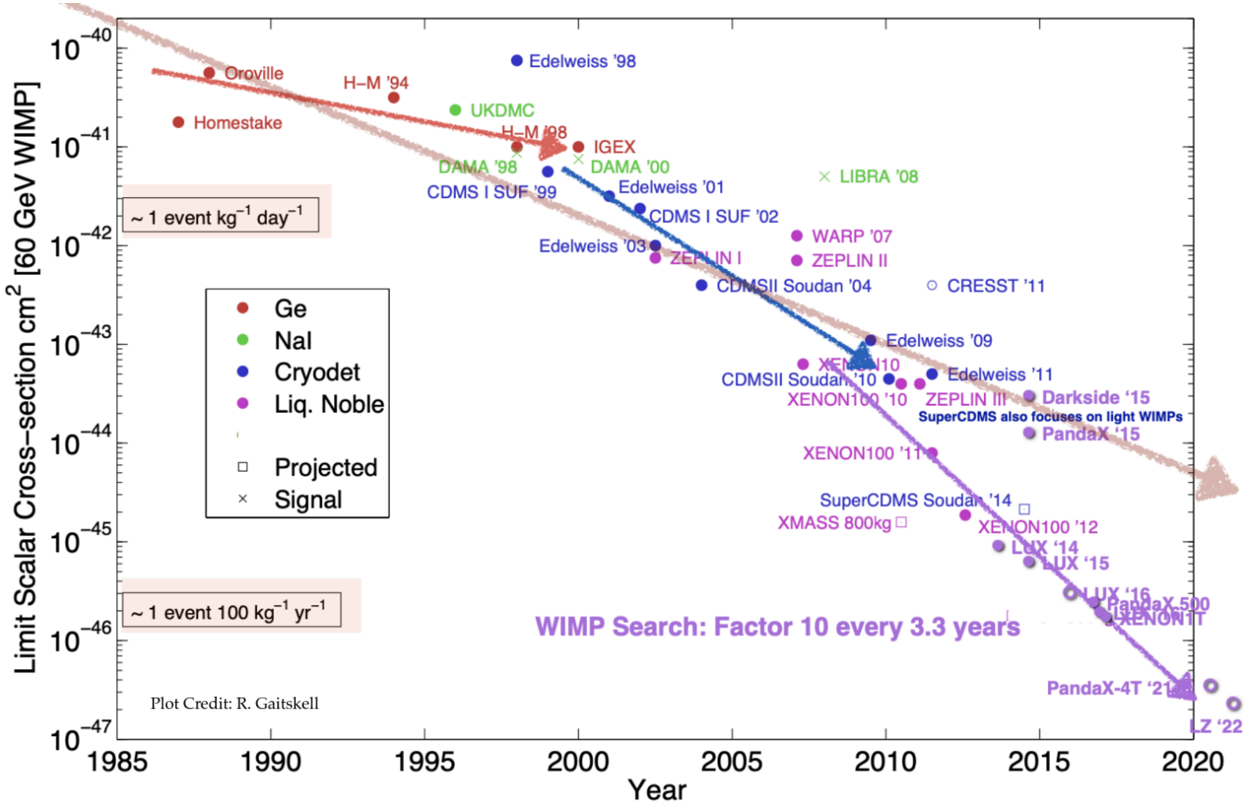
38 Institutions, 250 scientists, engineers, and technical staff

SANFORD UNDERGROUND RESEARCH FACILITY | UKRI Science and Technology Facilities Council | Department of Energy, United States of America | fct Fundação para a Ciência e a Tecnologia | Swiss National Science Foundation | ibs Institute for Basic Science

Xenon detectors for dark matter searches

- Large nucleus
  - Significant coherent nuclear scaling ($\sigma \sim A^2$)
- Significant self shielding due to high liquid density (3 g/cm^3)
- Noble gasses are easy to purify
  - Dedicated processes for Rn and Kr removal

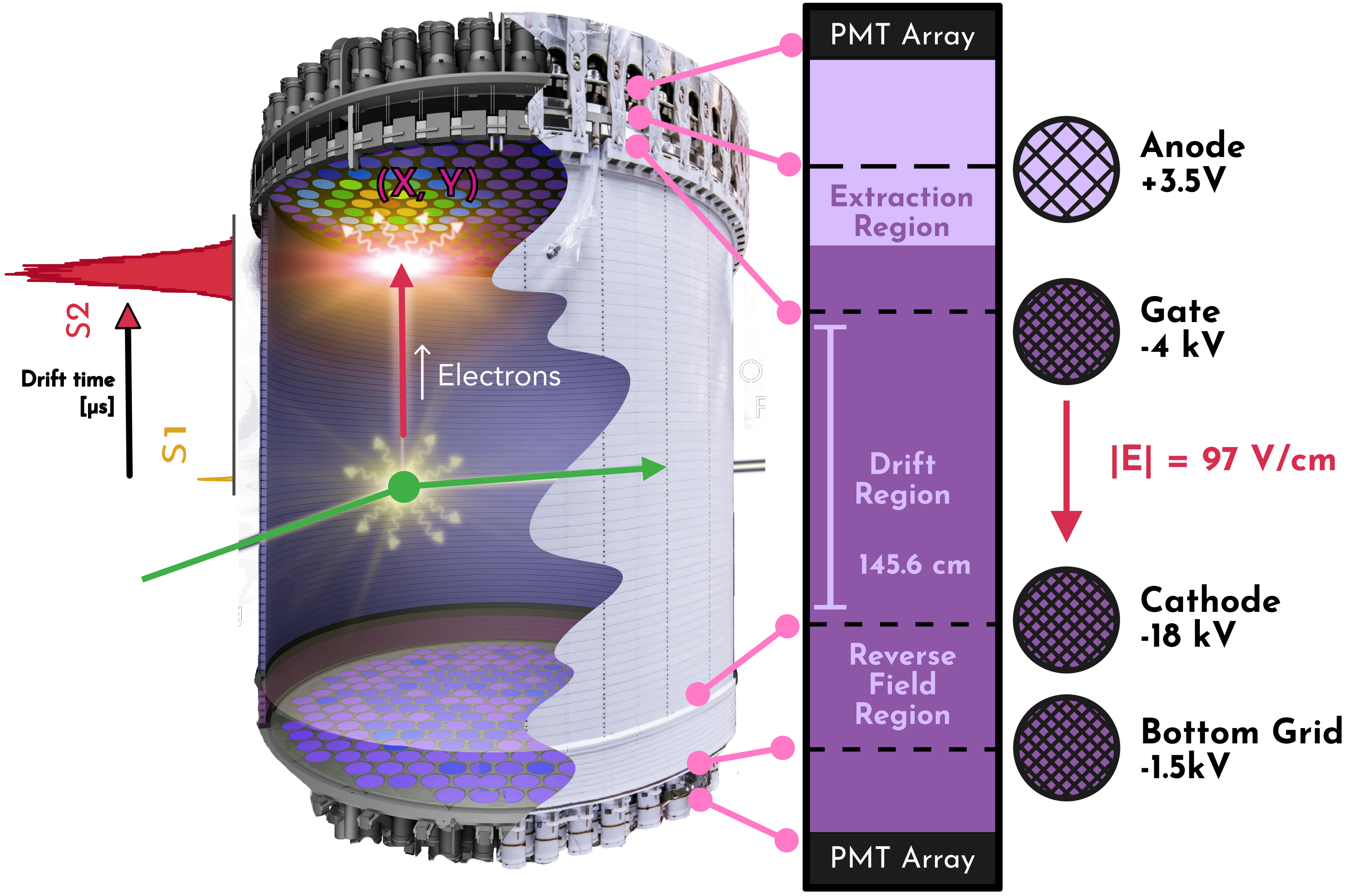




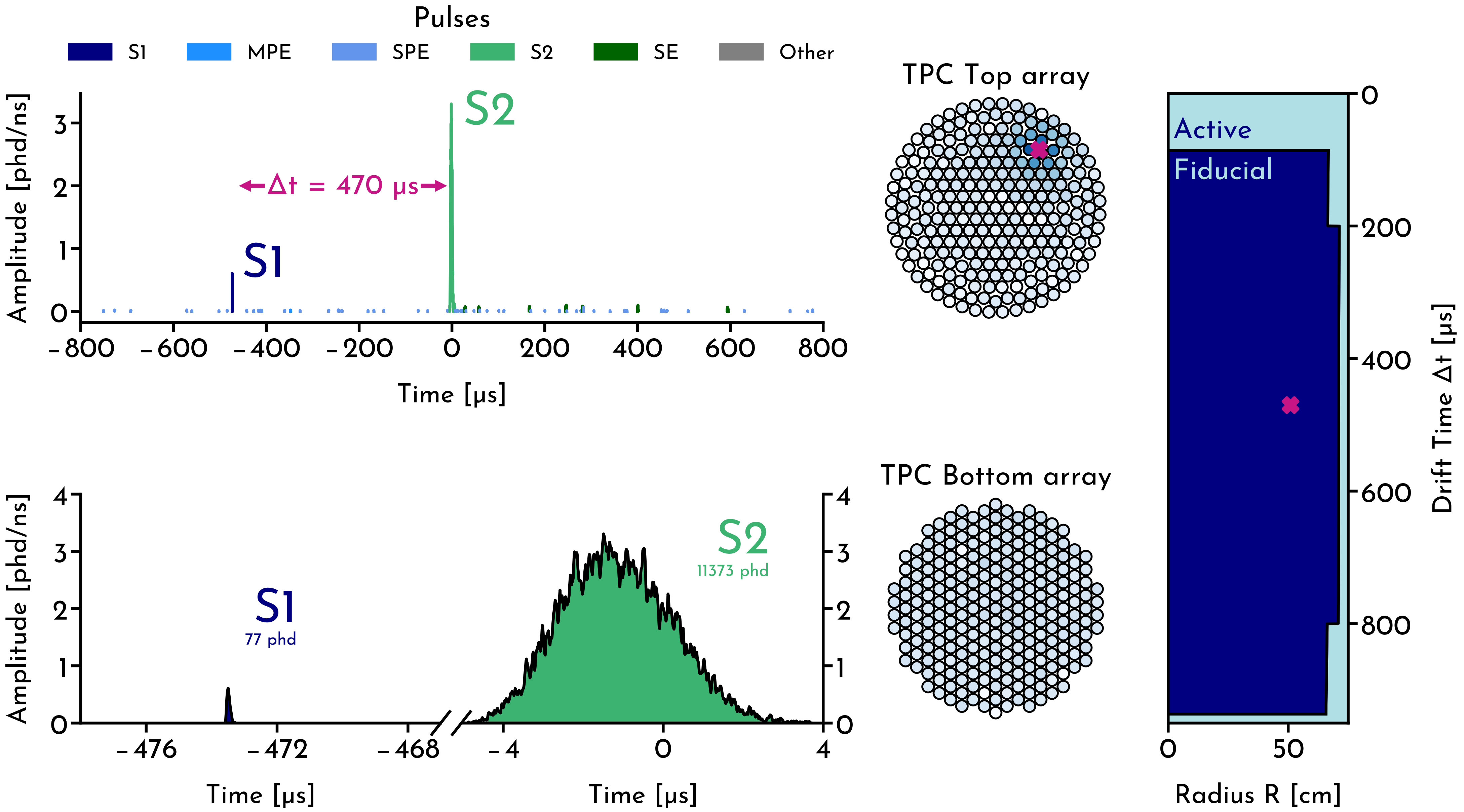
- Proven track record for ~2 decades
- Scalable technology
  - Kg to multi-tonne scale

Two-phase Time Projection Chambers (TPCs)

- Liquid target with thin vapour layer
- Time resolved scintillation and ionisation signals
  - Light = prompt scintillation (**S1**)
  - Charge = delayed electroluminescence of ionisation electrons (**S2**)
- 3D vertex reconstruction:
  - (X, Y) from S2 hit pattern
  - Z from the time electrons take to drift to surface
- Discriminate electron (ER) and nuclear (NR) recoils using S2/S1
  - 1 part in 10,000 in ZEPLIN-III [1,2]

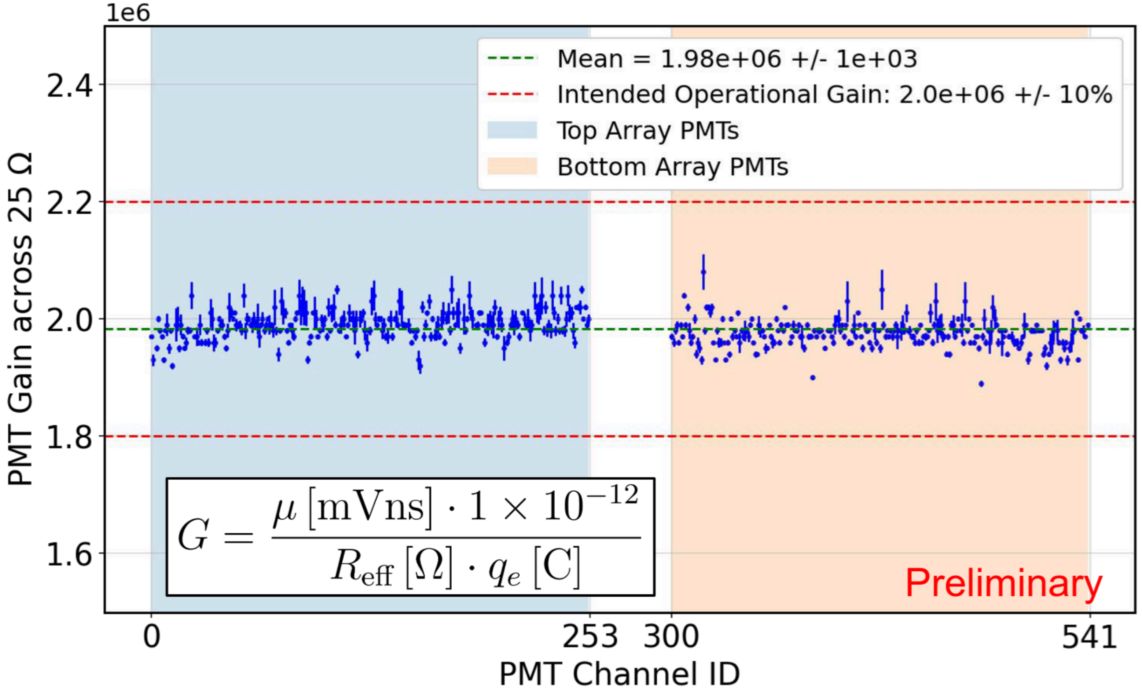


[1] V. N. Lebedenko et al. Phys. Rev. D 80, 052010
[2] H. Araújo arXiv:2007.01683


Pulses
S1
MPE
SPE
S2
SE
Other
S2
Δt = 470 μs
S1
Amplitude [phd/ns]
Time [μs]
-800
-600
-400
-200
0
200
400
600
800
S1
77 phd
S2
11373 phd
-476
-472
-468
-4
0
4
TPC Top array
TPC Bottom array
Active
Fiducial
Radius R [cm]
Drift Time Δt [μs]

TPC PMTs

- 494 Hammamatsu R11410-22 PMTs
  - Based on the commercial R11410-20 model
    - Designed for low temp. dark matter experiments
    - High QE, 32%
  - Ultra-low background (**1/1000th** of base model) [1]
  - 477 (96.6%) operational after ~4 years of operations

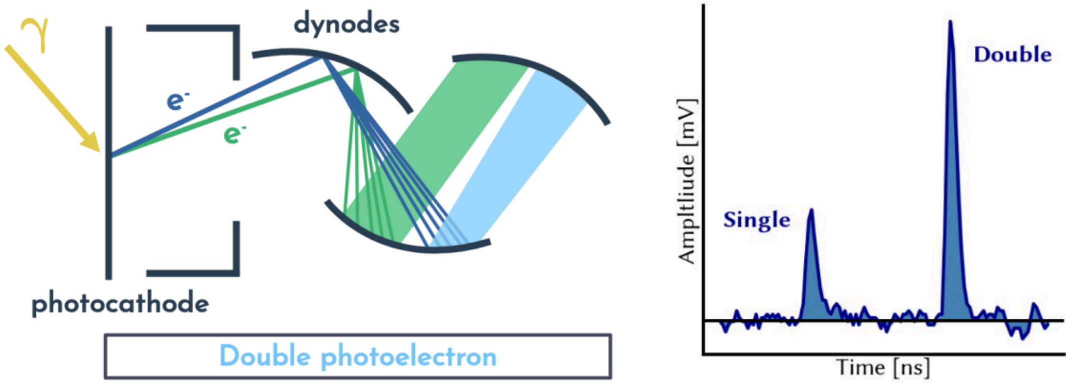


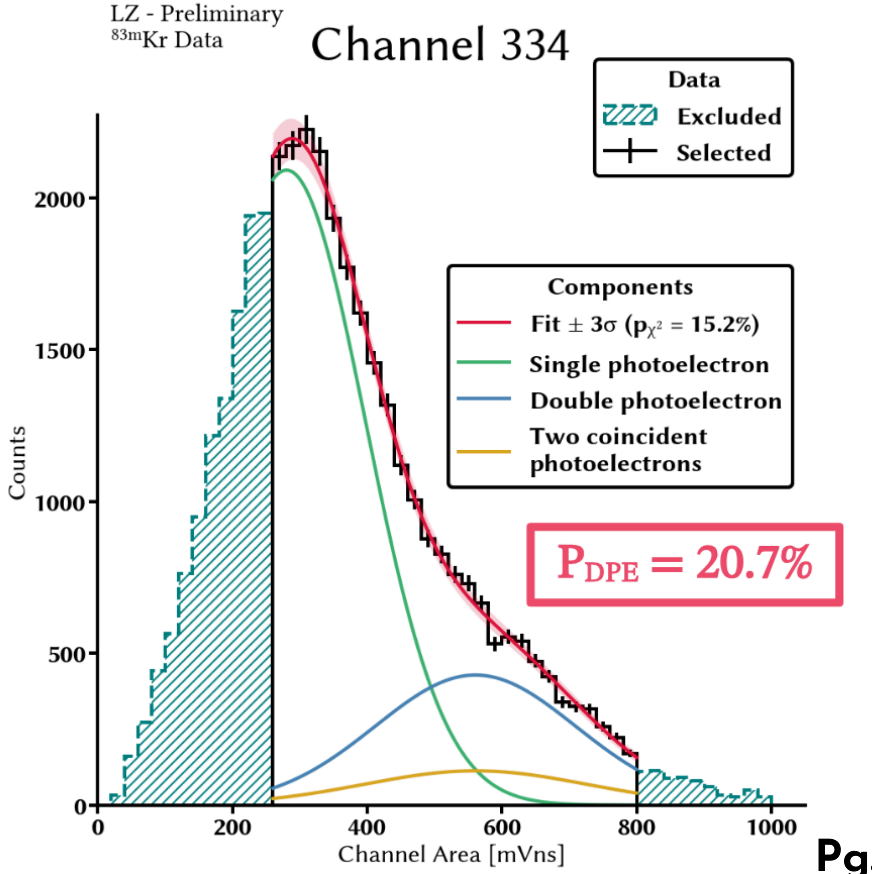
- Operated at 2×10^6 gain
  - 94% single photoelectron detection efficiency
  - Dual amplification output
    - High gain: single photon sensitivity
    - Low gain: improves MeV-scale sensitivity (0ν2β)
- PMT's are regularly calibrated using dedicated LED system

[1] Mount et. al. arXiv:1703.09144

TPC PMTs (DPE)

- Sensitive to **VUV light** (174.8 nm for S1 [1])
  - Double photoelectron emission (**DPE**) [2]
    - Occurs in **~22.6%** of VUV photon detections [3]
  - Twice the average response with same time profile
- Dedicated measurement from subset of PMTs at Imperial
  - Observed linear relationship with QE
  - Evidence for triple photoelectron emission (TPE) @ 0.6% [3]
- In-situ calibration performed in LZ using ^{83m}Kr
- Quote signals in "photons detected" [phd]
  - Accounts for mean effect at high energies
  - $1[\text{phd}] = \frac{1}{1+p_{\text{DPE}}} \times [\text{phe}]$

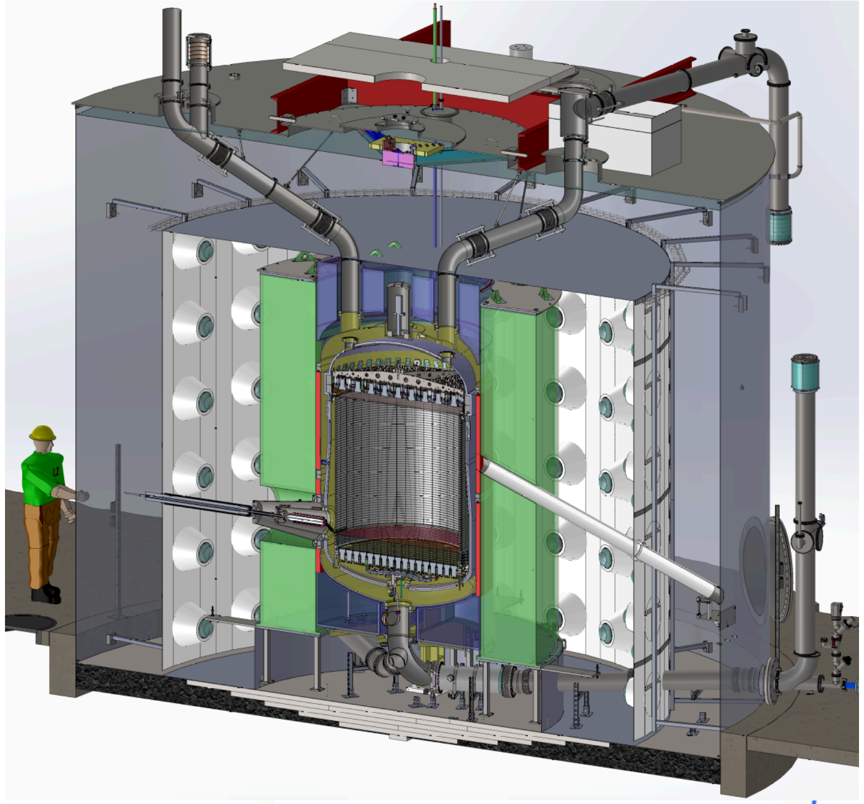


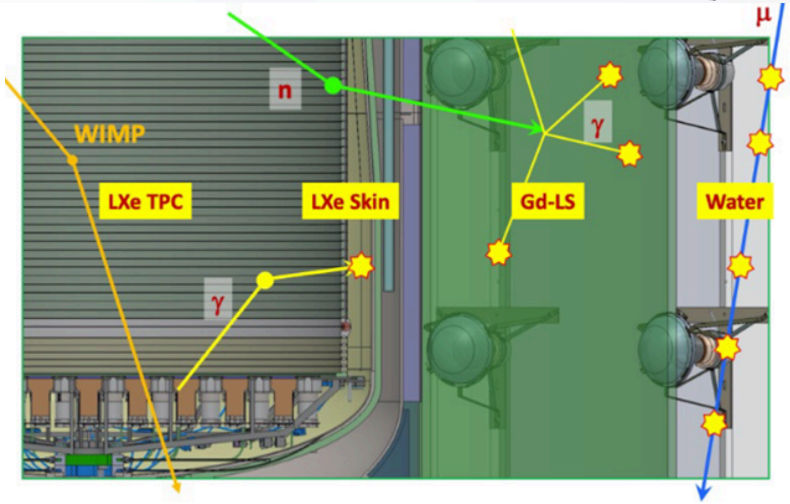


[1] Fujii et. al. NIM-A 795 (2015) 293-297
[2] Faham et. al. JINST 10 (2015) 09, P09010
[3] B. López Paredes et. al. Astroparticle Physics 102 (2018) 56-66

Veto detectors

- Outer detector (OD):
  - 120 8" Hamamatsu R5912 PMTs
    - 99% operational
  - Gd-loaded liquid scintillator
  - Detects neutrons via γ-rays from neutron capture
- Skin xenon veto:
  - Instrumented xenon outside the TPC
  - Detects primary γ-rays from components/target
- Vital to measure and constrain neutron backgrounds
  - **92 ± 4 %** neutron veto efficiency from simulations
  - 89 ± 3 % neutron veto efficiency derived from AmLi calibrations





TPC Underground 2019

Installation complete 2020

Science data from 2021

World leading WIMP limits 2022

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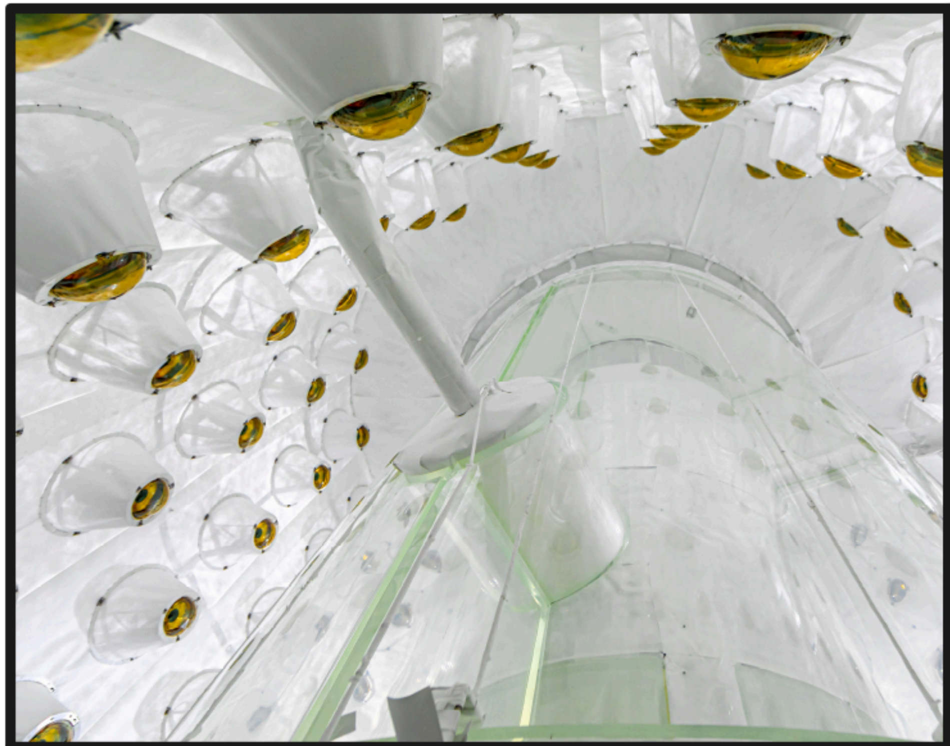

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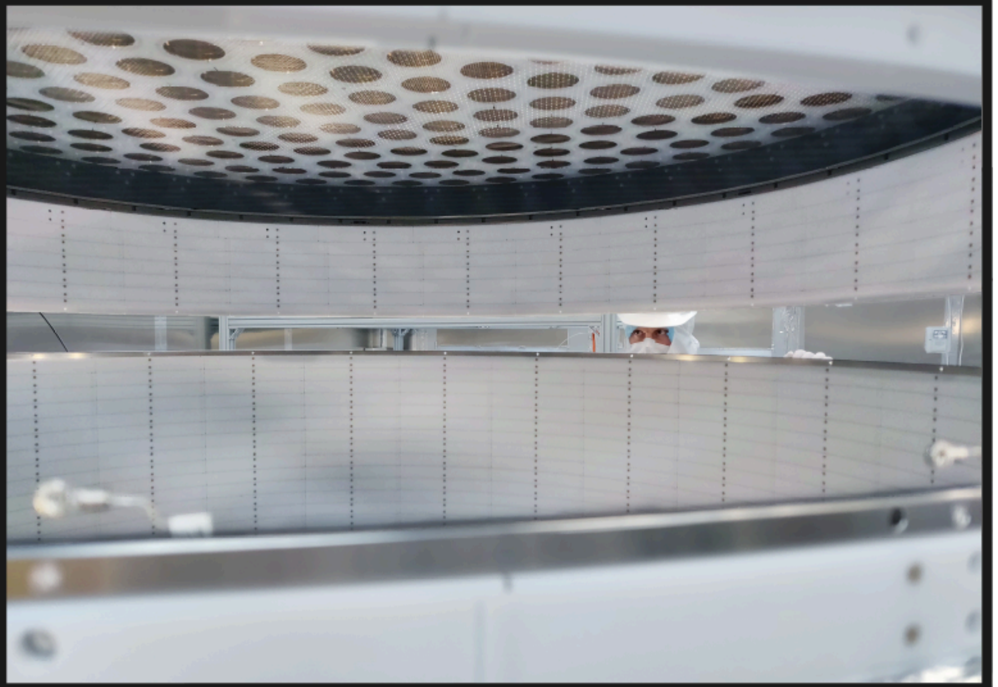
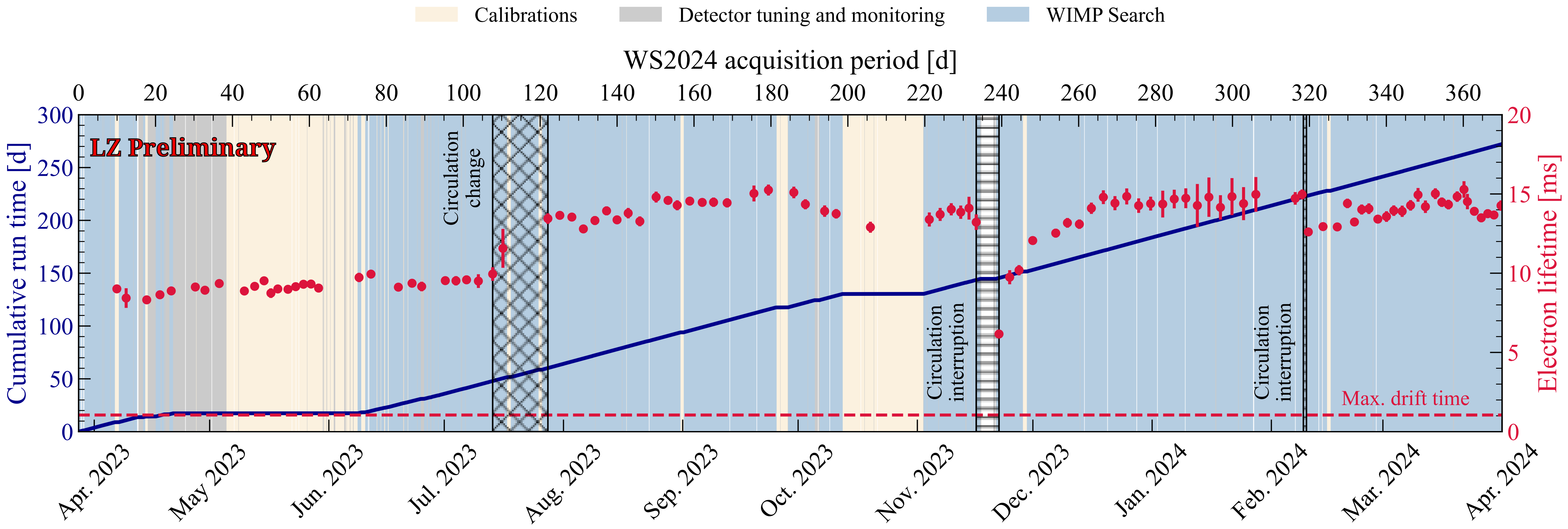


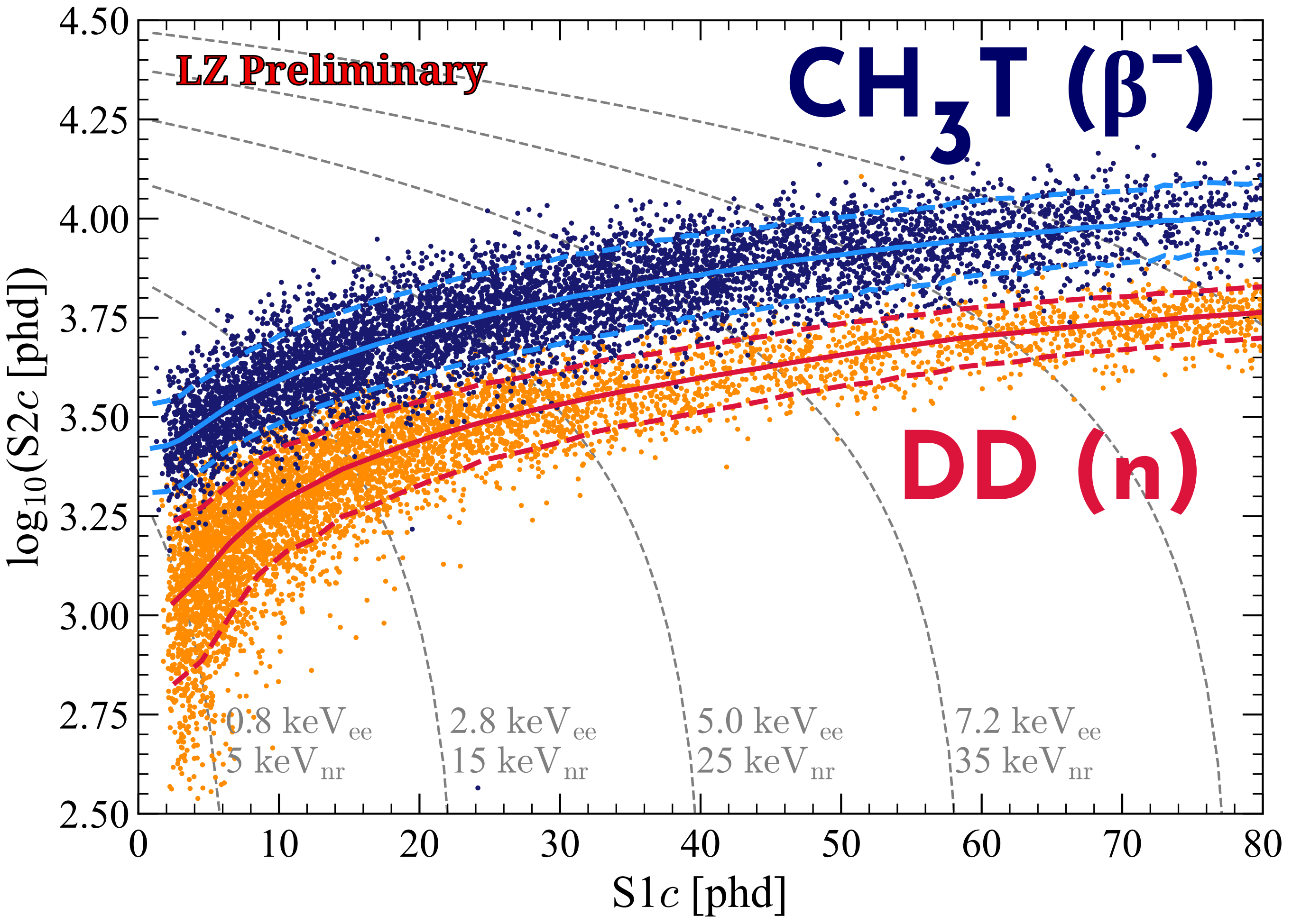
2024 Science Run

- Acquired data for ~370 days
  - 95.2% detector up-time
  - **220 live-day exposure**
- Performed intermittent calibrations
- High target purity throughout
  - Minimal suppression of charge (S2) signals



Calibrations

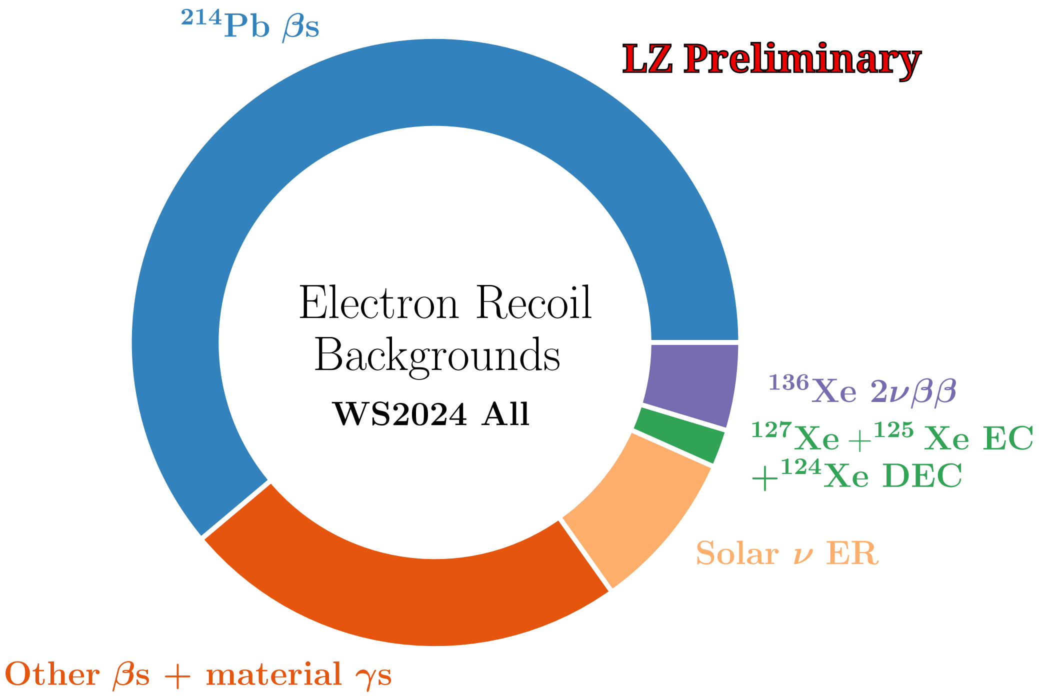
- Electronic recoils (background)
  - Tritium radiolabelled methane & ^{14}C
  - Mono-energetic ^{83m}Kr
- Nuclear recoils (signal)
  - DD neutron generator (2.45 MeV neutrons)
  - An AmLi source [1], which emits low energy (<1.5 MeV) neutrons, can be positioned at nine different depths
- NEST model:
  - Light gain (g_1): **0.112 ± 0.002 phd/photon**
  - Charge gain (g_2): **34.0 ± 0.9 phd/electron**
  - Single electron amplification: 44.5 phd
  - **99.9% discrimination** of β below 40 GeV WIMP median



Calibrations paper: J. Aalbers et al 2024 JINST 19 P08027
[1]: A.B.M.R. Sazzad et al 2023 JINST 18 P05006

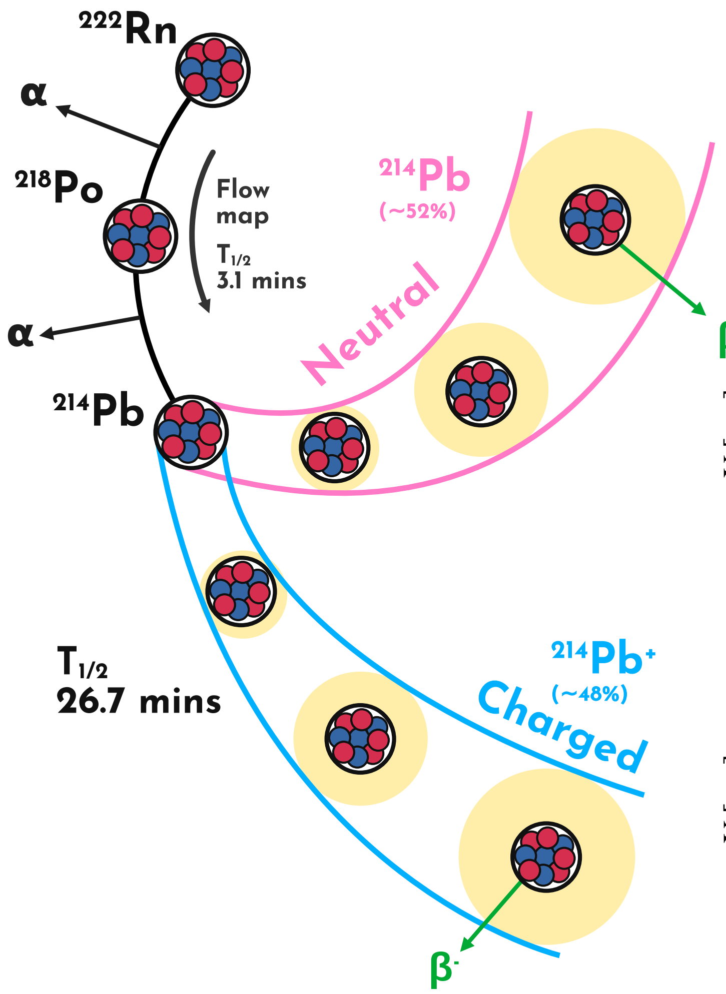
Background Model

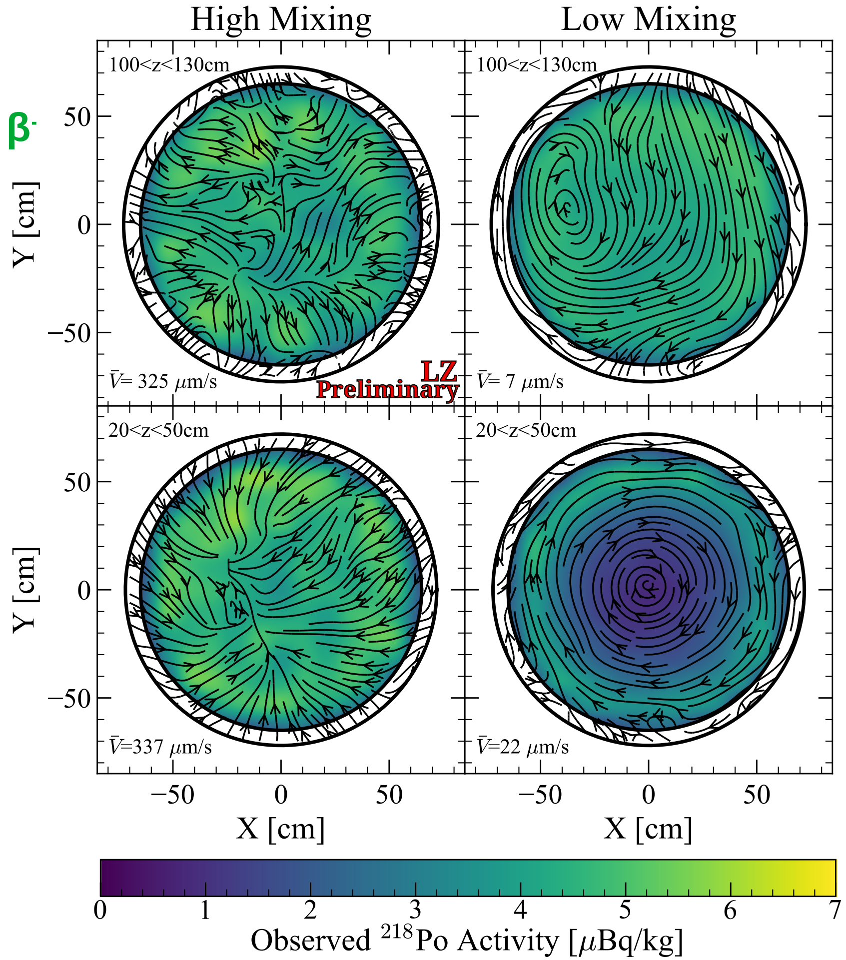
- Understand backgrounds from in-situ measurement of sidebands and assays
- Expect 1207 ER background events in WS2024:
  - ^{214}Pb β-decay is dominant at 60%
  - Double electron capture
  - Solar neutrinos
- Expect 0.18 NR CEvNS events
  - Excluded by region of interest for dedicated search
- Neutrons from spontaneous fission in detector components and (α,n) reactions
- Accidental backgrounds from isolated S1 and S2 pulses



Radon tagging to remove dominant ^{214}Pb background

- Circulation/cooling systems control Xe flow
- High mixing state
  - Uniform injected calibration sources
- Low mixing state
  - Confinement of central volume
  - **Rn backgrounds can't reach the centre**
- Map Xe flow with Rn and Po decays
- Predict location of future ^{214}Pb decays
  - Observe ^{218}Po α-decay
  - Tag interactions around Xe streamlines
  - Track for 81 minutes (~3 × ^{214}Pb $\tau_{1/2}$)
  - Tag incorporated into statistical analysis
  - **~60% tagging efficiency**





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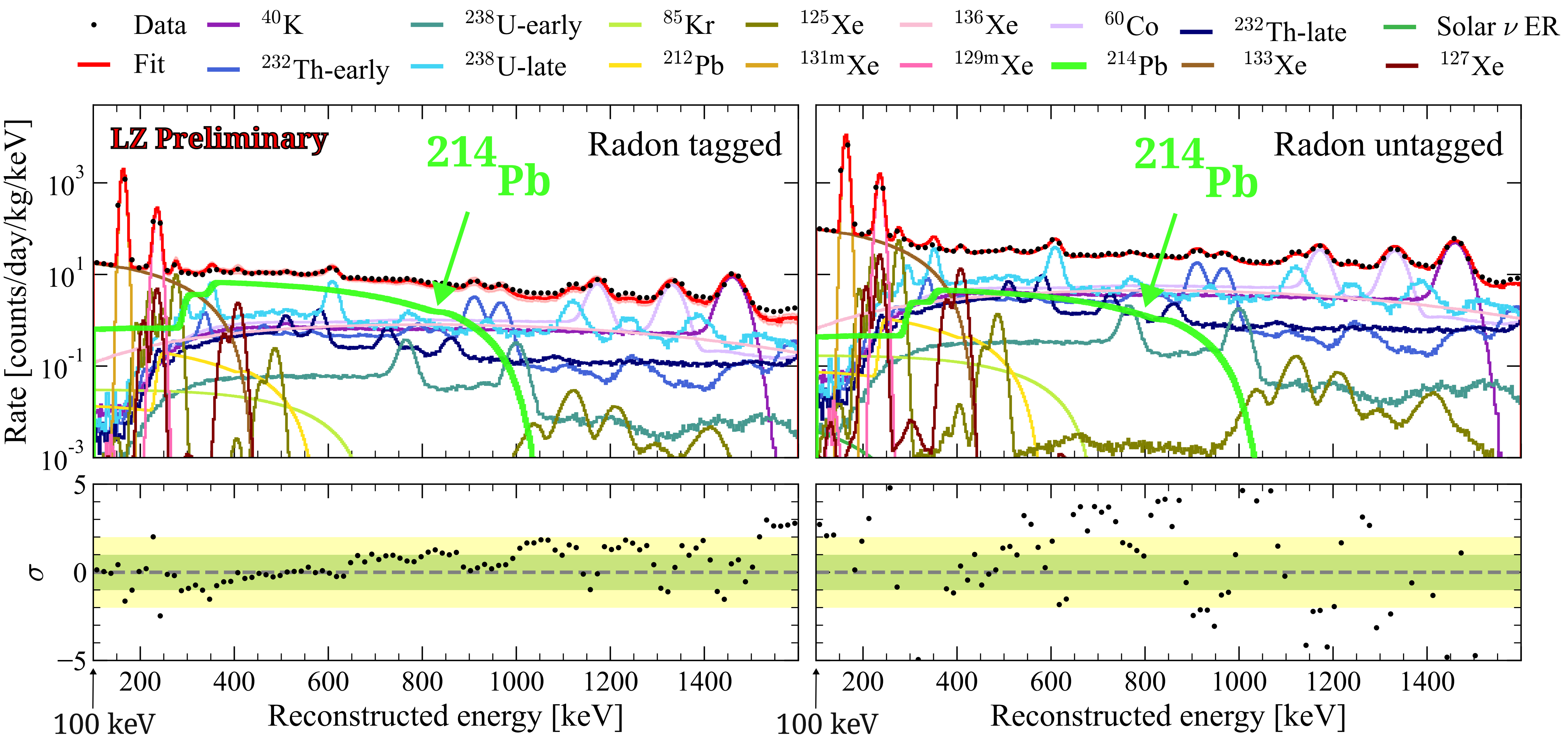
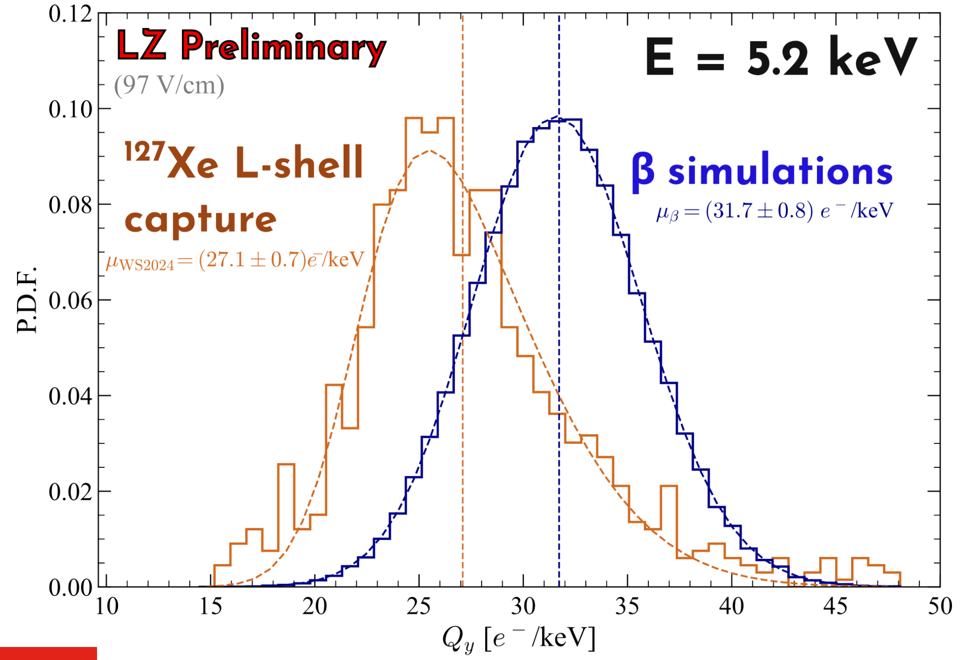
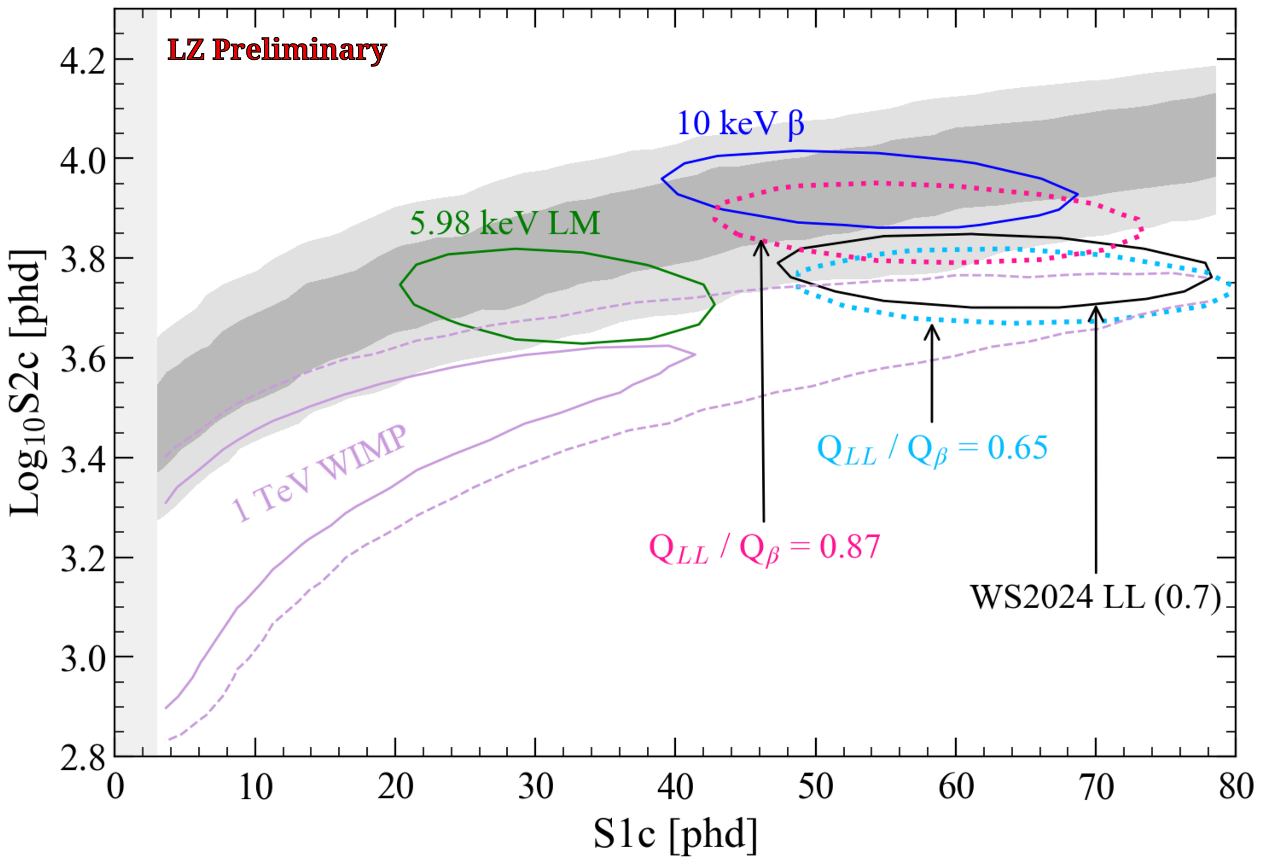


- Tagging reduces ^{214}Pb background by a factor 2.1
  - 3.9 ± 0.6 µBq/Kg (total) ➔ 1.8 ± 0.3 µBq/Kg (untagged)
- N.B.: plots are above the WIMP region-of-interest (ROI)
- ^{133}Xe restricted above 81 keV (and ROI) by γ-ray emission
- ^{133}Xe a short-lived activation product from preceding neutron calibration

Electron Captures (EC)

- Background in LZ (5.2 keV L-shell):
  - Single EC: $^{125/127}Xe$ - from NR activation
  - Double EC: ^{124}Xe - **$T_{1/2} \sim 10^{22}$ years!** [1,2]
- EC increases recombination [3]
  - **Looks more NR like than normal**
- Prelim. WS2024 measurement: **Q_L/Q_β = 0.86±0.01** [4]

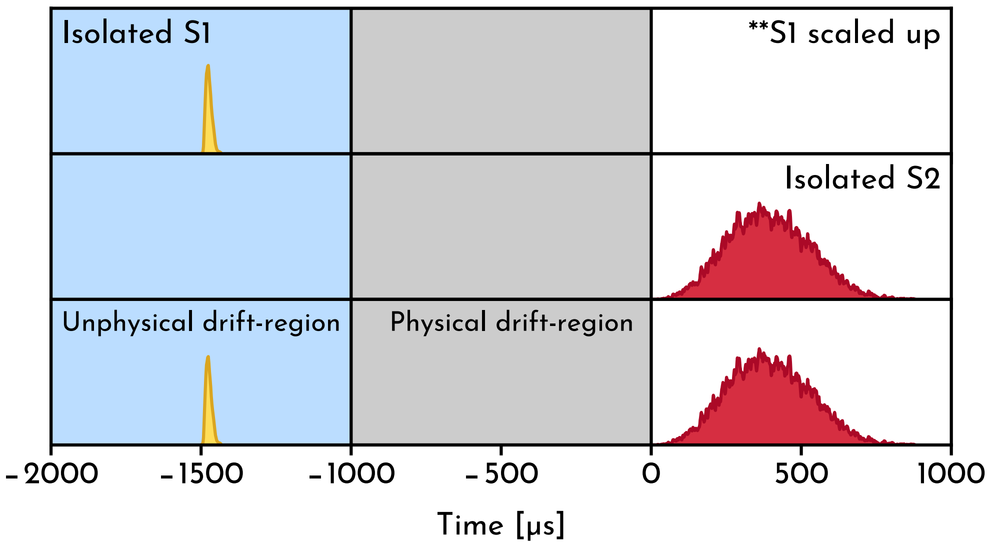


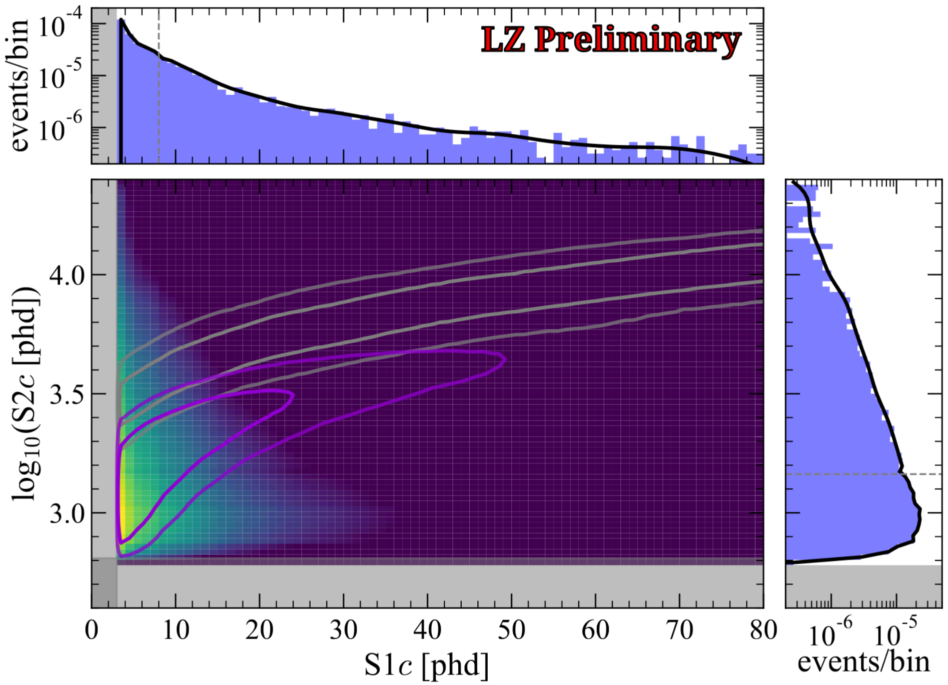


[1] XENON1T Nature 568, 532–535 (2019)
[2] LZ arXiv:2408.17391
[3] Previously measured by XELDA (Temples et al, Phys. Rev. D 104, 112001 (2021))
[4] dedicated publication in progress

Accidental background

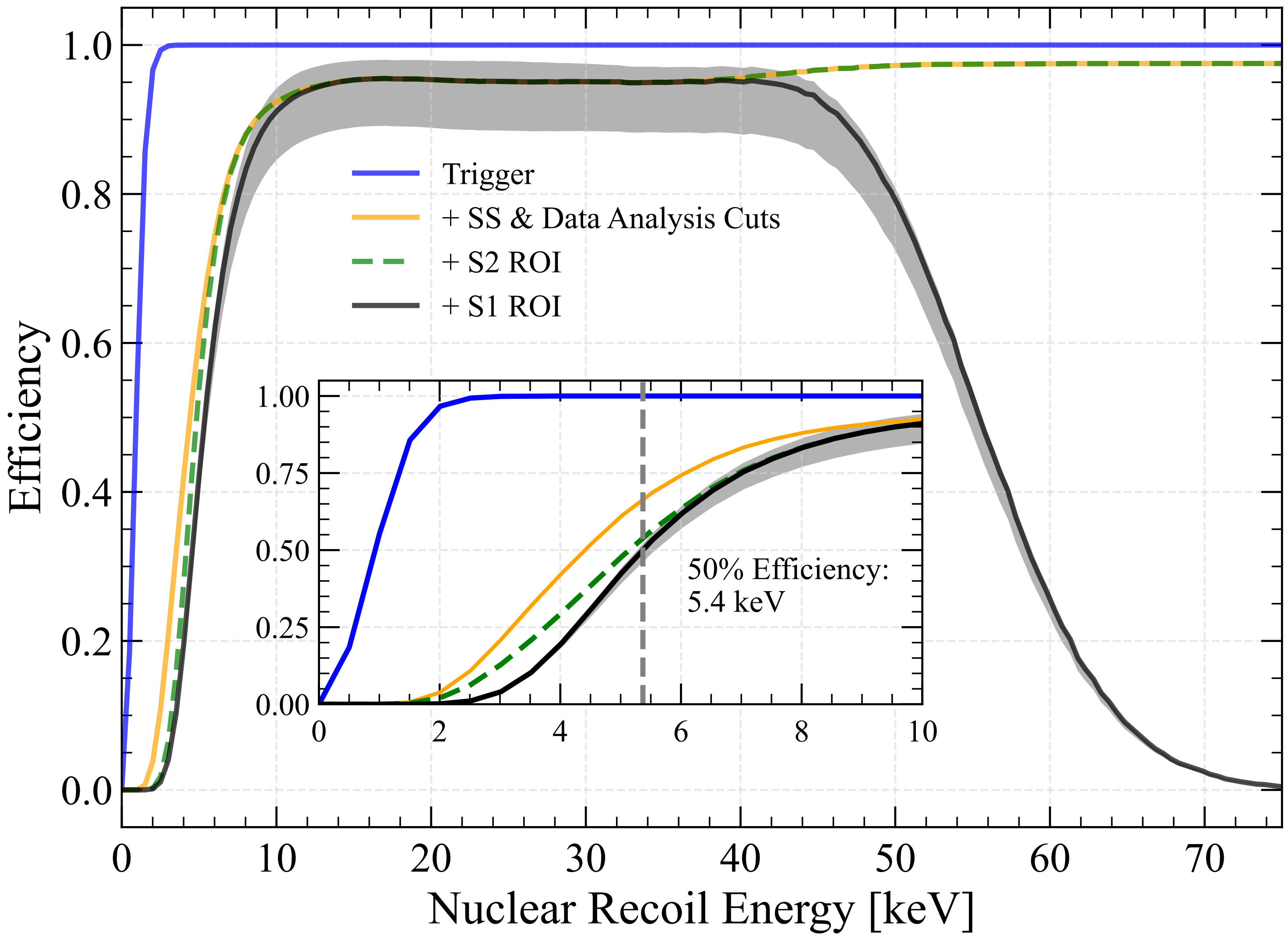
- Pile-up of unrelated S1-like and S2-like pulses
  - Looks like a single scatter and can mimic a WIMP
- Fraction of these have an unphysical drift time
  - Population to calculate rate with physical drift-time
- Model as product of isolated S1-like and S2-like pulses
- Distribution peaks at the low NR energy region
- Analysis cuts specifically tested on and tuned for this background
  - 99.5% rejection efficiency
  - Expect 2.8 ± 0.6 events in WS2024





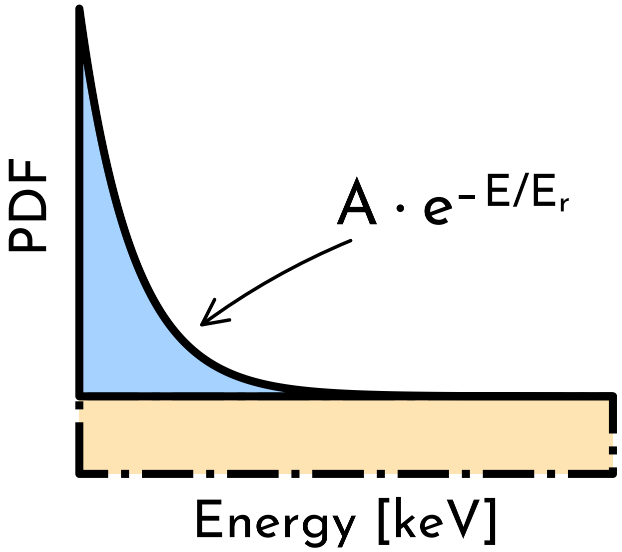
Signal Acceptance

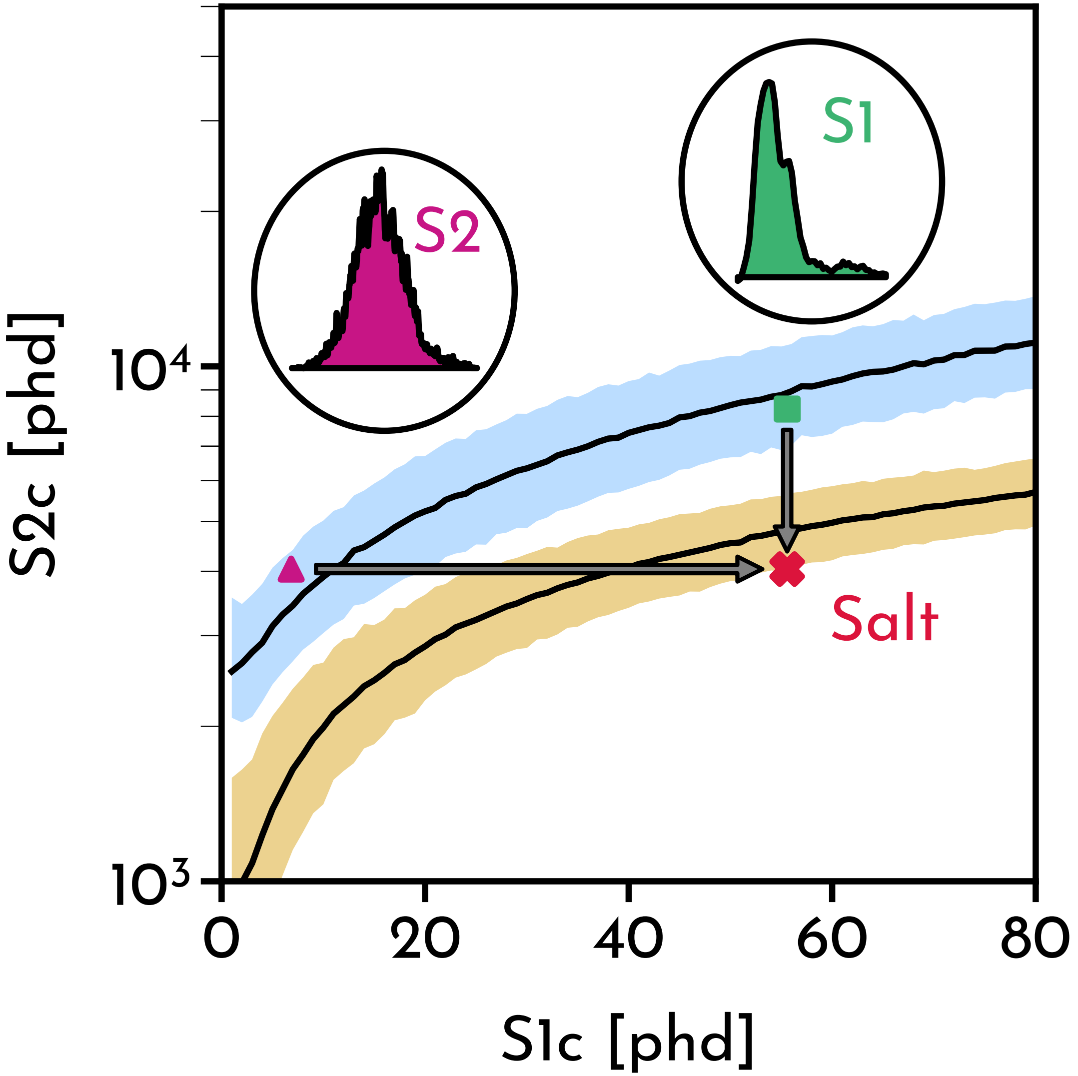
- Region of interest (ROI):
  - $S1_c$ = (3, 80) phd
  - $S2_c$ = (645, $10^{4.5}$) phd
    - Excludes ^8B for dedicated analysis
- Multiple event and pulse level cuts
  - FV, ROI, single scatter
  - Veto anti-coincidence
    - Delayed neutron capture
    - Prompt γ-ray interactions
  - S1 & S2 based cuts targeting accidentals
- Cuts developed using data outside ROI
- 50% efficiency at 5.4 keV



Bias Mitigation (Salting)

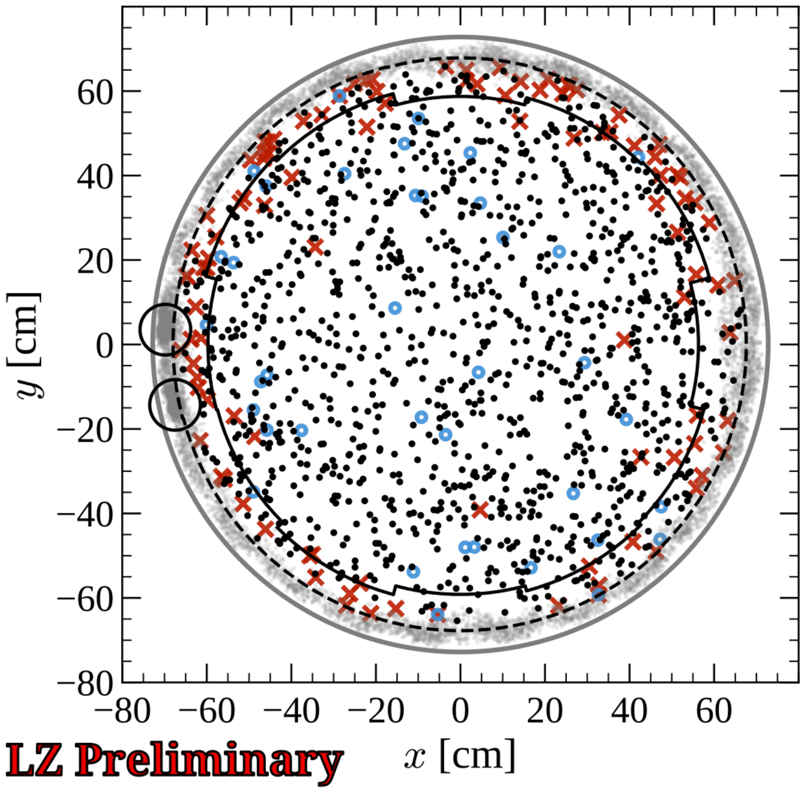
- Inject fake events (salt) into the data stream
- Generated by pairing S1 and S2 pulses from calibration
  - Embed measured waveforms back into the data stream
- Events sampled as follows:
  - Unknown rate below LZ's WS2022 result
  - Recoil spectra of a WIMP of unknown mass
  - Additional contribution for high mass WIMP searches with flat NR spectrum
- Allows us to understand the ROI whilst minimising bias

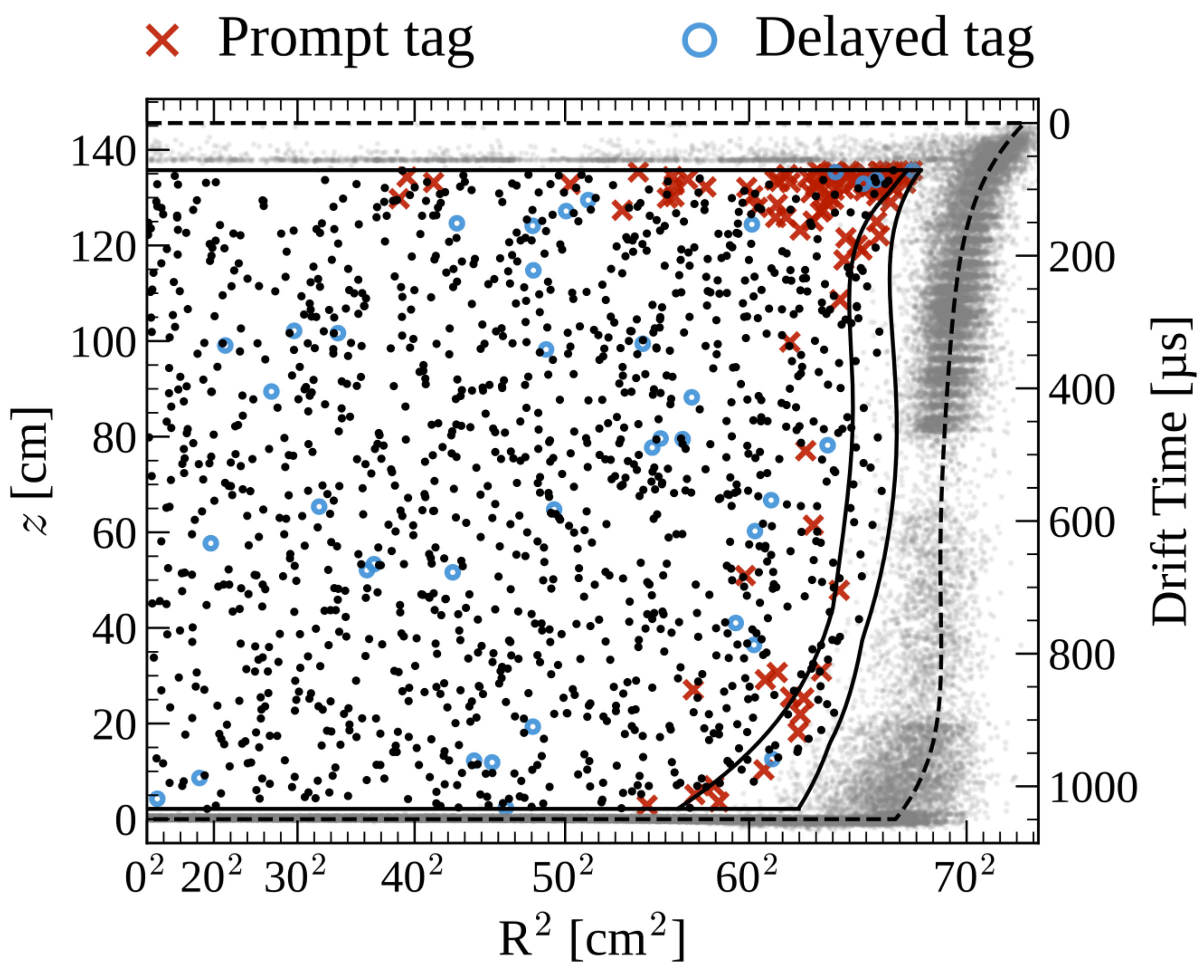




Event positions, fiducial volume (FV), and vetos

- Majority of backgrounds are peripheral
  - Self-shielding prevents infiltration
- Reject the majority of backgrounds with a fiducial cut
  - Azimuthal dependence added for WS2024
  - Defined to admit **<0.01 wall background events**
- Fiducial mass of **5.5 ± 0.2 tonnes**

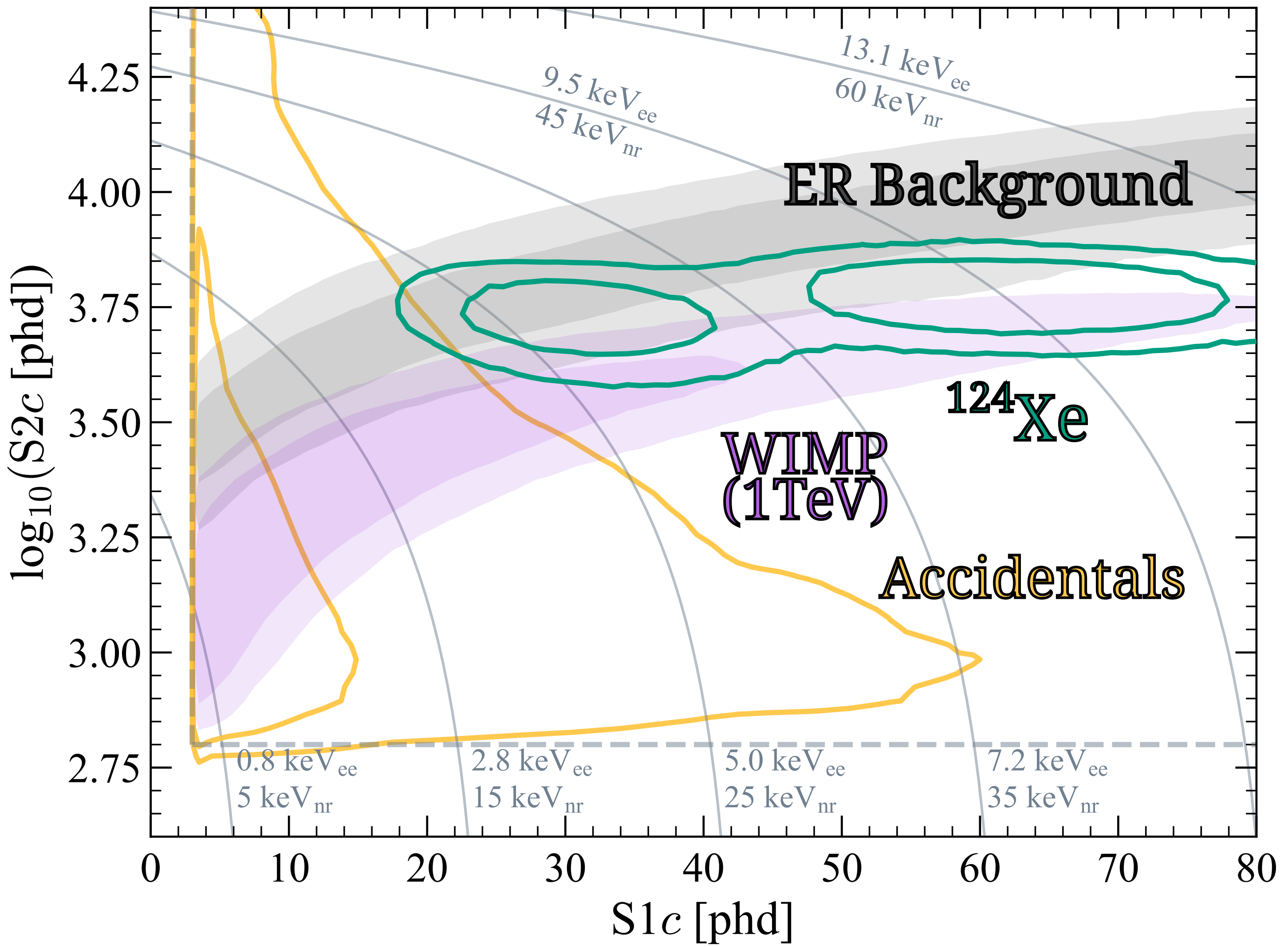




LZ Preliminary

Expected result 2024

- Statistical analysis in $Log_{10}(S2_c)$-$S1_c$ space
  - $S1_c$ = (3, 80) phd
  - $S2_c$ = (645, $10^{4.5}$) phd
    - Excludes ^{8}B for dedicated analysis
- Generate templates of each fit component using simulations
  - In-situ measurements & assays provide rate priors
  - Find the best fit of each component for several WIMP masses
- WIMP template (PDF) has a longer tail for larger masses
  - They all peak at low energies



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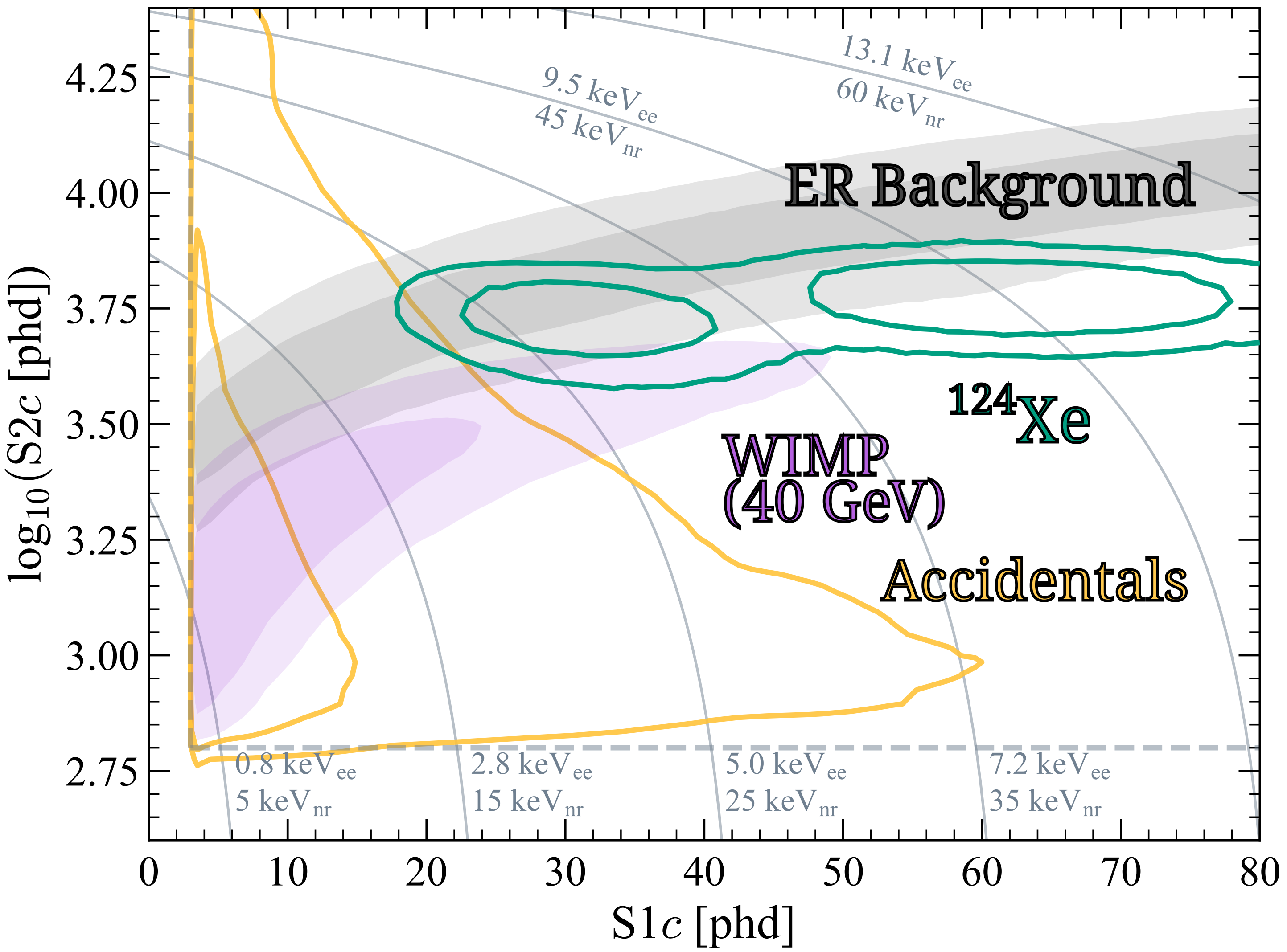

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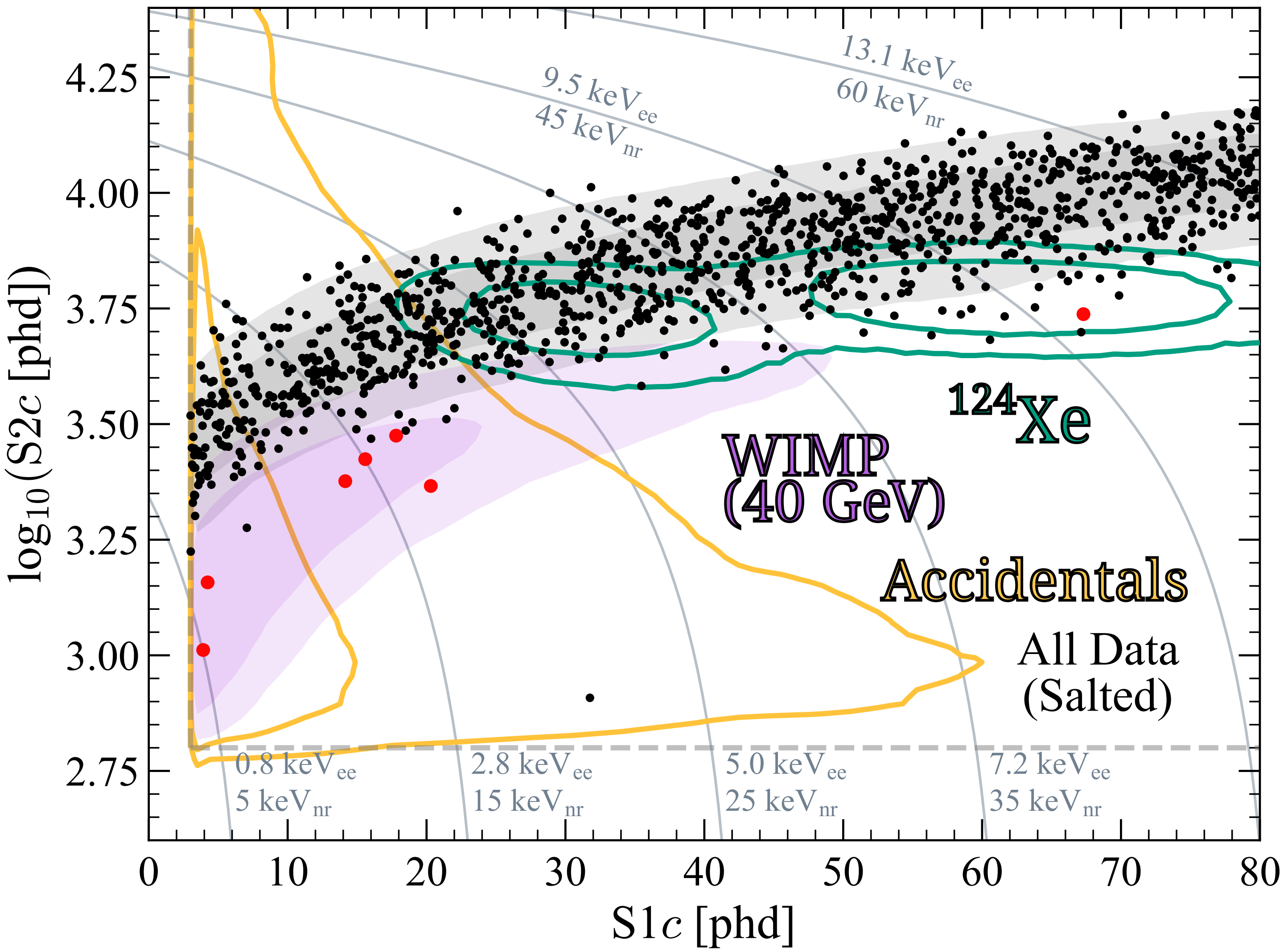
- Exposure of 220 live-days × 5.5 tonnes:
  - 3.3 tonne years
- 8 salt events injected
  - 1 was removed by cuts
  - This is consistent with the signal efficiency



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  - 3.3 tonne years
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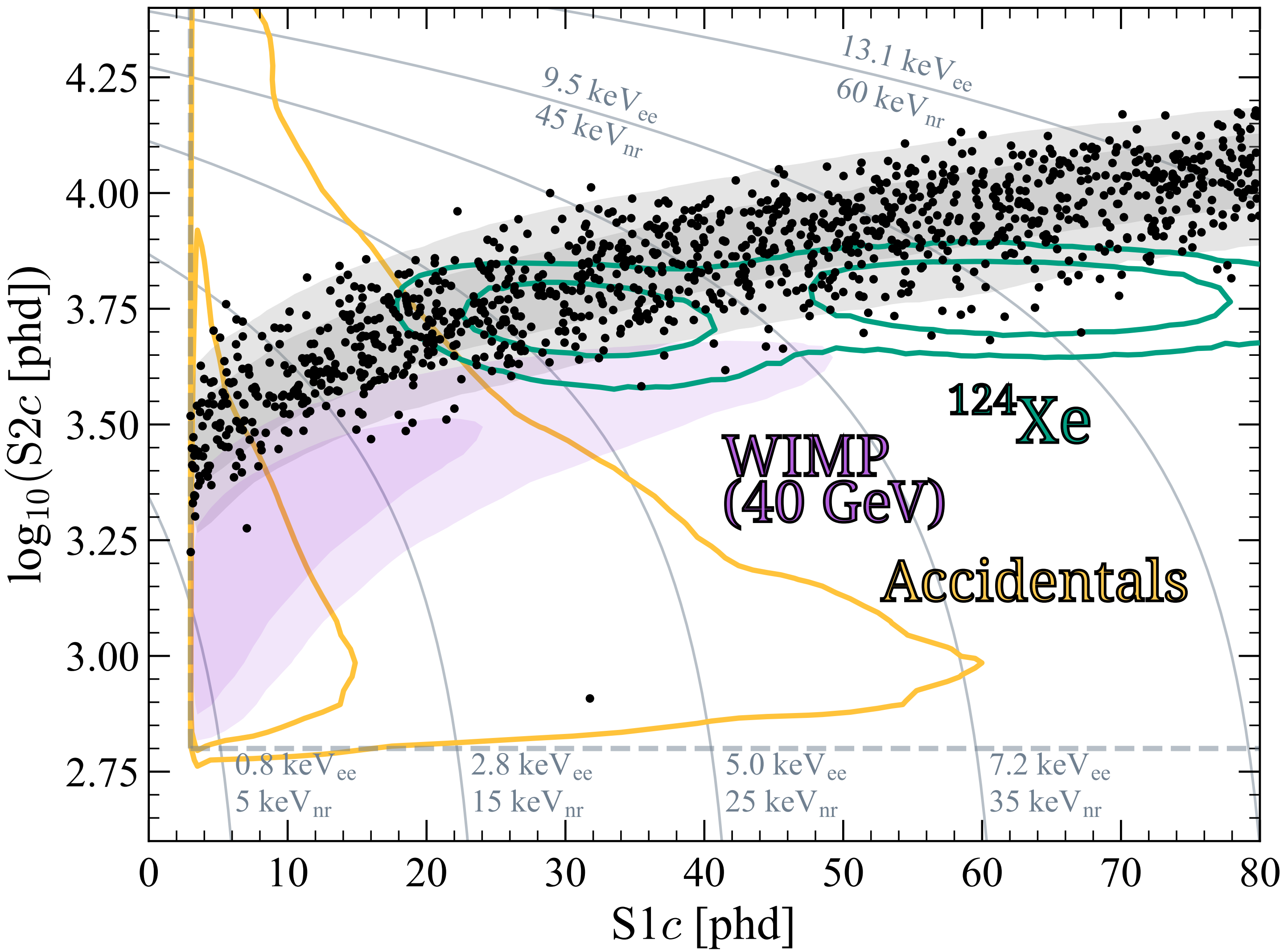
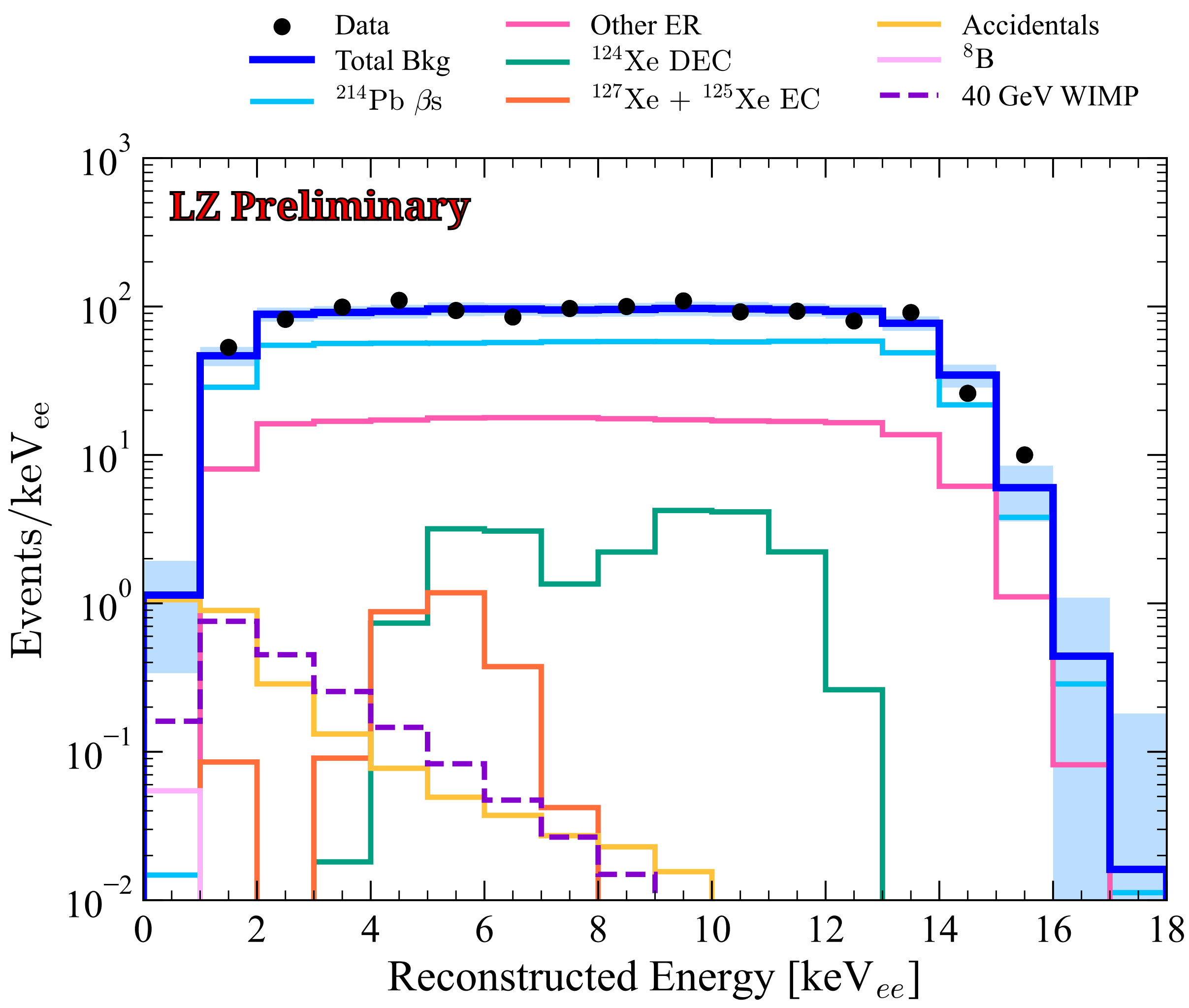
- 1220 events remain after un-salting
- **No changes to analysis post un-salting**



Fit results

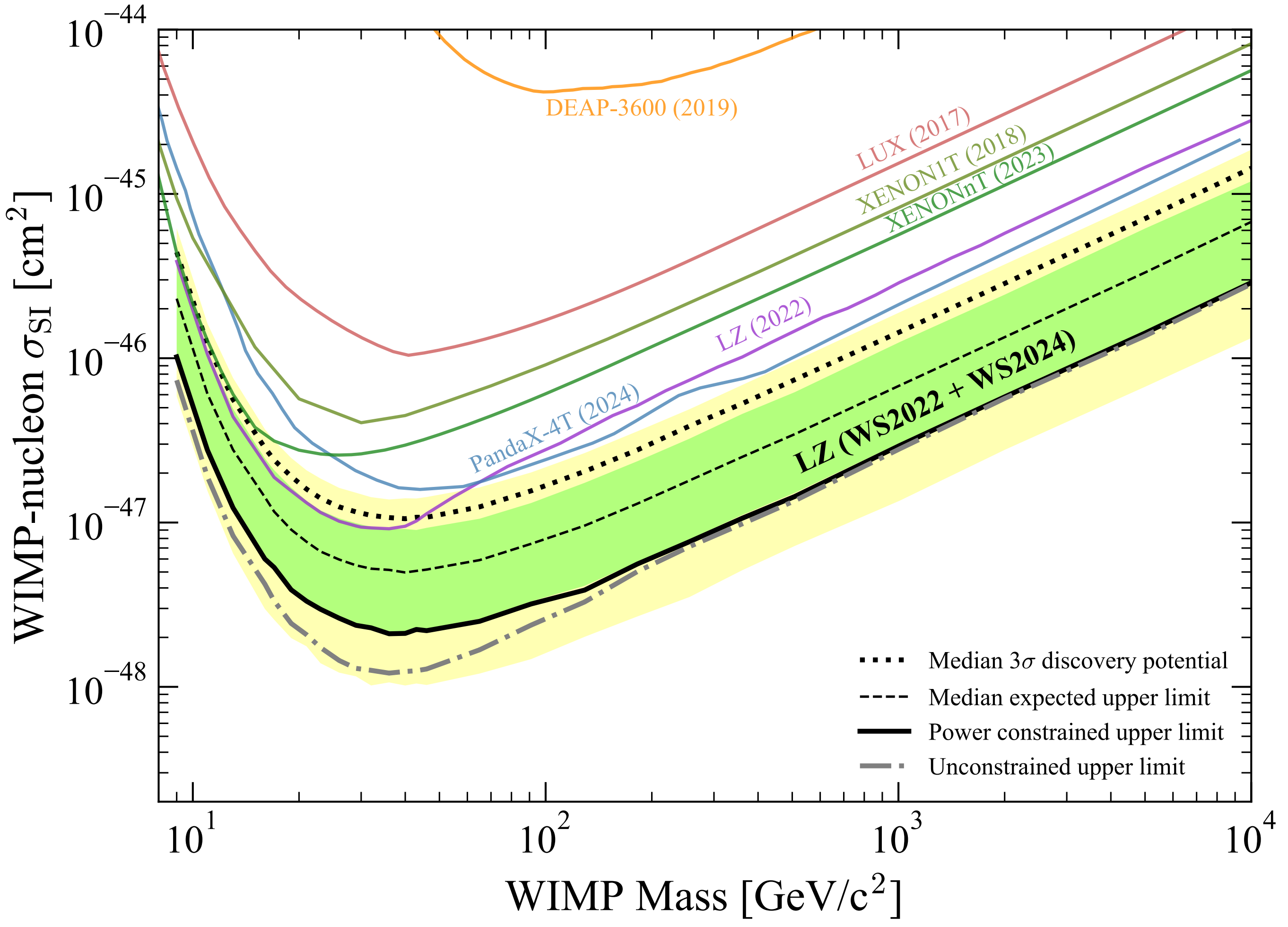
- Best fit of zero WIMPs at all masses (9 GeV → 100 TeV)
- Good agreement with background in all studied spaces

Component	Prior	Best fit
^{214}Pb β-decays	743 ± 88	733 ± 34
^{85}Kr & ^{39}Ar & detector γ-rays	162 ± 22	161 ± 21
Solar ν ERs	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po β-decays	62.7 ± 7.5	63.7 ± 7.4
^{3}H + ^{14}C β-decays	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe 2νββ decays	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
Atm. ν CEνNS	0.12 ± 0.02	0.12 ± 0.02
^{8}B + hep ν CEνNS	0.06 ± 0.01	0.06 ± 0.01
Det. Neutrons		$0.0^{+0.2}$
Accidentals	2.8 ± 0.6	2.6 ± 0.6
Total	**1210 ± 91**	**1203 ± 42**



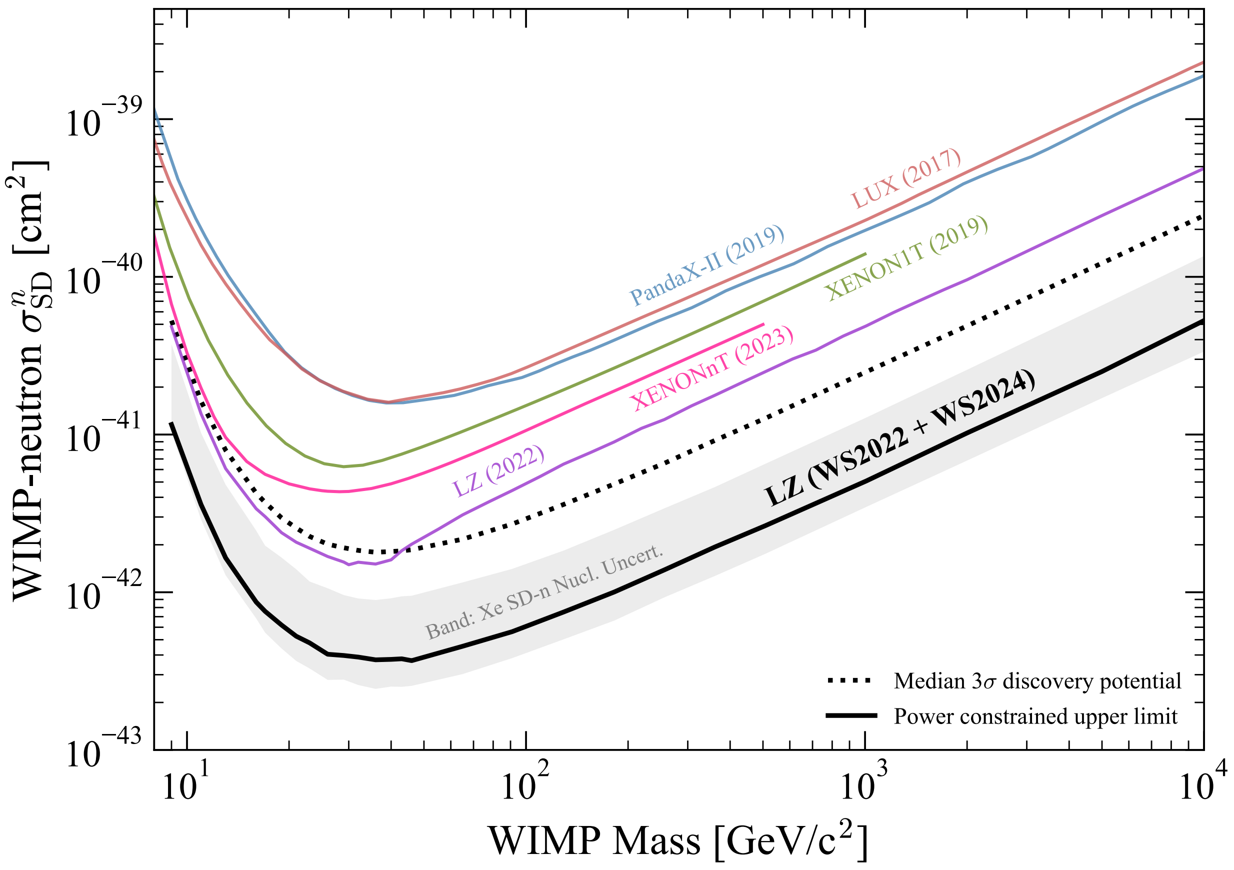
Combined 2024 & 2022 Spin-independant Result

- Total exposure of 4.2 ± 0.1 tonne-years
- Included the 2022 result at an additional likelihood in the PLR
- No changes were performed to the 2022 analysis or dataset
- Peak sensitivity: **2.1×10^{-48} cm^2 @ 36 GeV/c^2**
- Factor of 4 improvement in sensitivity into new parameter space
- The 2022 background under fluctuation still drives the unconstrained limit at low masses

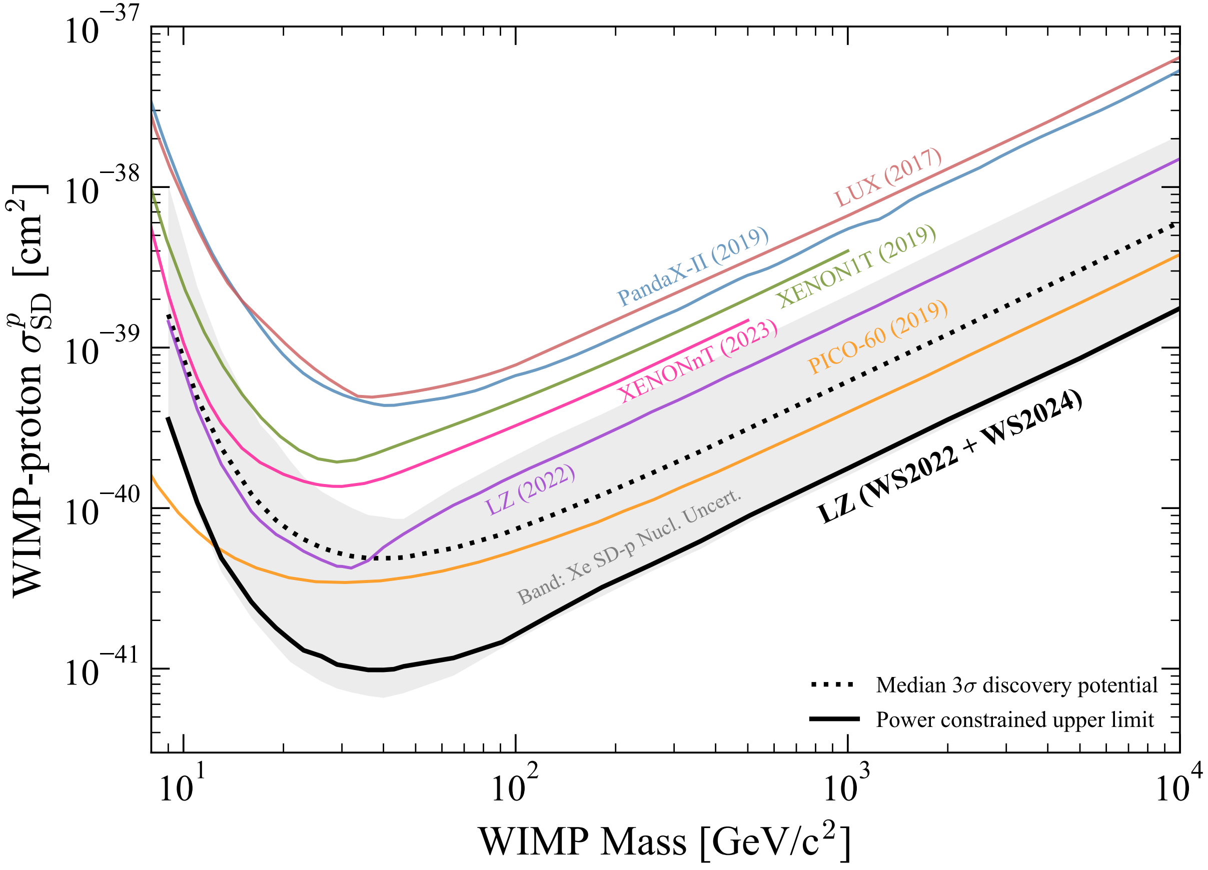


Combined 2024 & 2022 Spin-dependant Results

Neutron



Proton



Conclusions

- World leading limit to WIMP dark matter
- Radon tag reduces main ER background by 60%
- First observation of charge suppression in DEC of ^{124}Xe
- LZ continuing onwards towards 1000 live-days (2028)
  - Multiple other areas of interest (^{8}B CEvNS, $0\nu2\beta$, etc.)

Further information

- WS2024: arXiv:2410.17036 [this work]
- WS2022: Phys. Rev. Lett. 131, 041002
- WS2022 backgrounds: Phys. Rev. D 108, 012010
- ER searches in WS2022: Phys. Rev. D 108, 072006