# 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

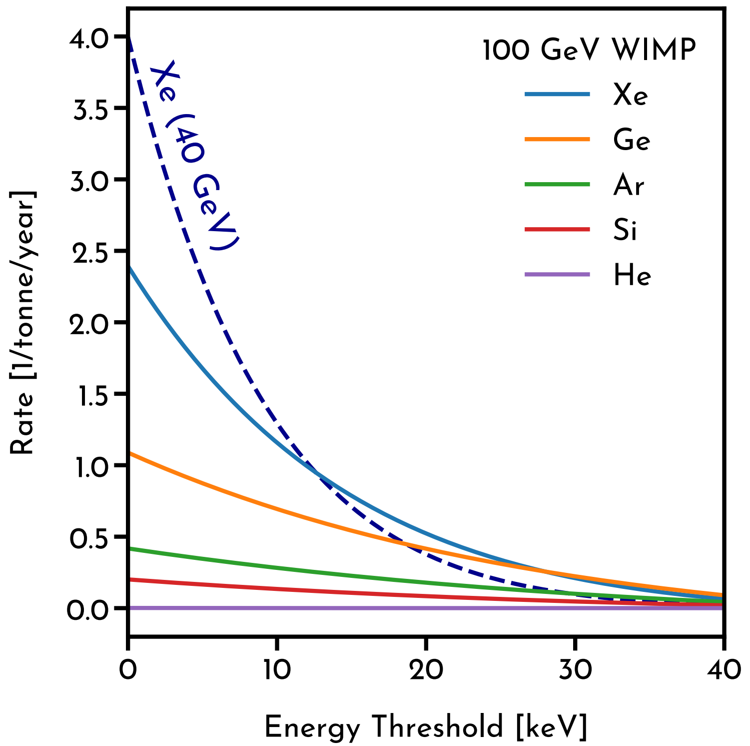
fct Fundação para a Ciência e a Tecnologia

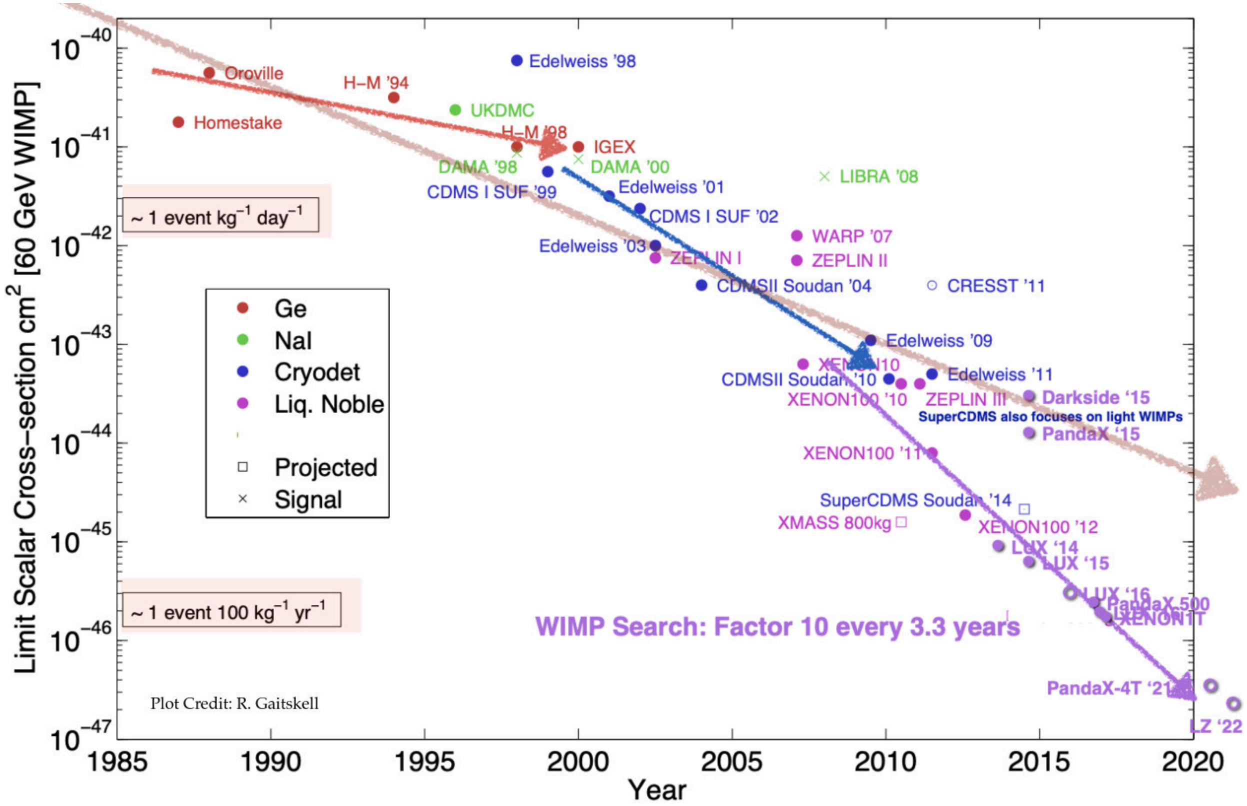
Swiss National Science Foundation

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

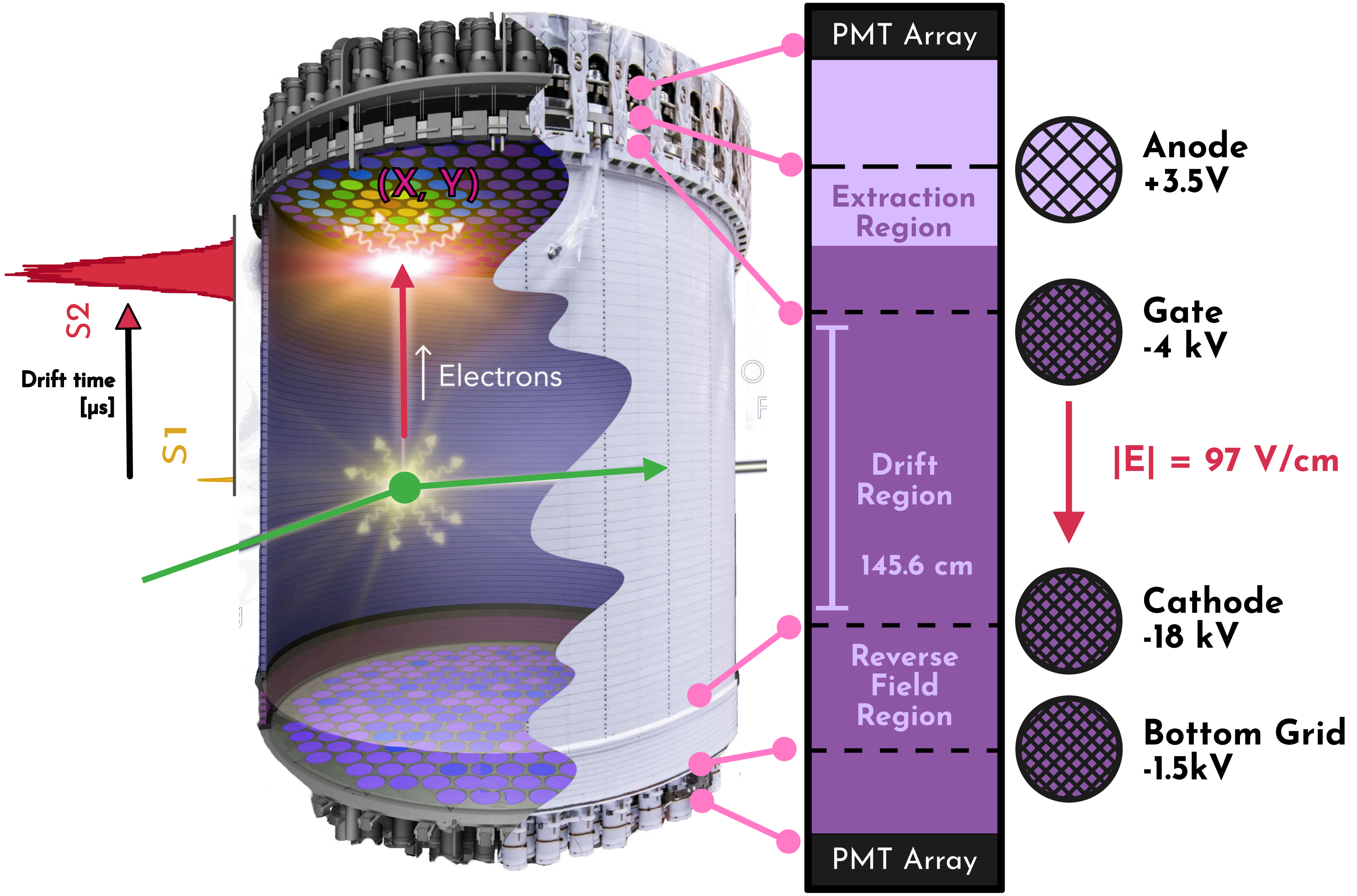


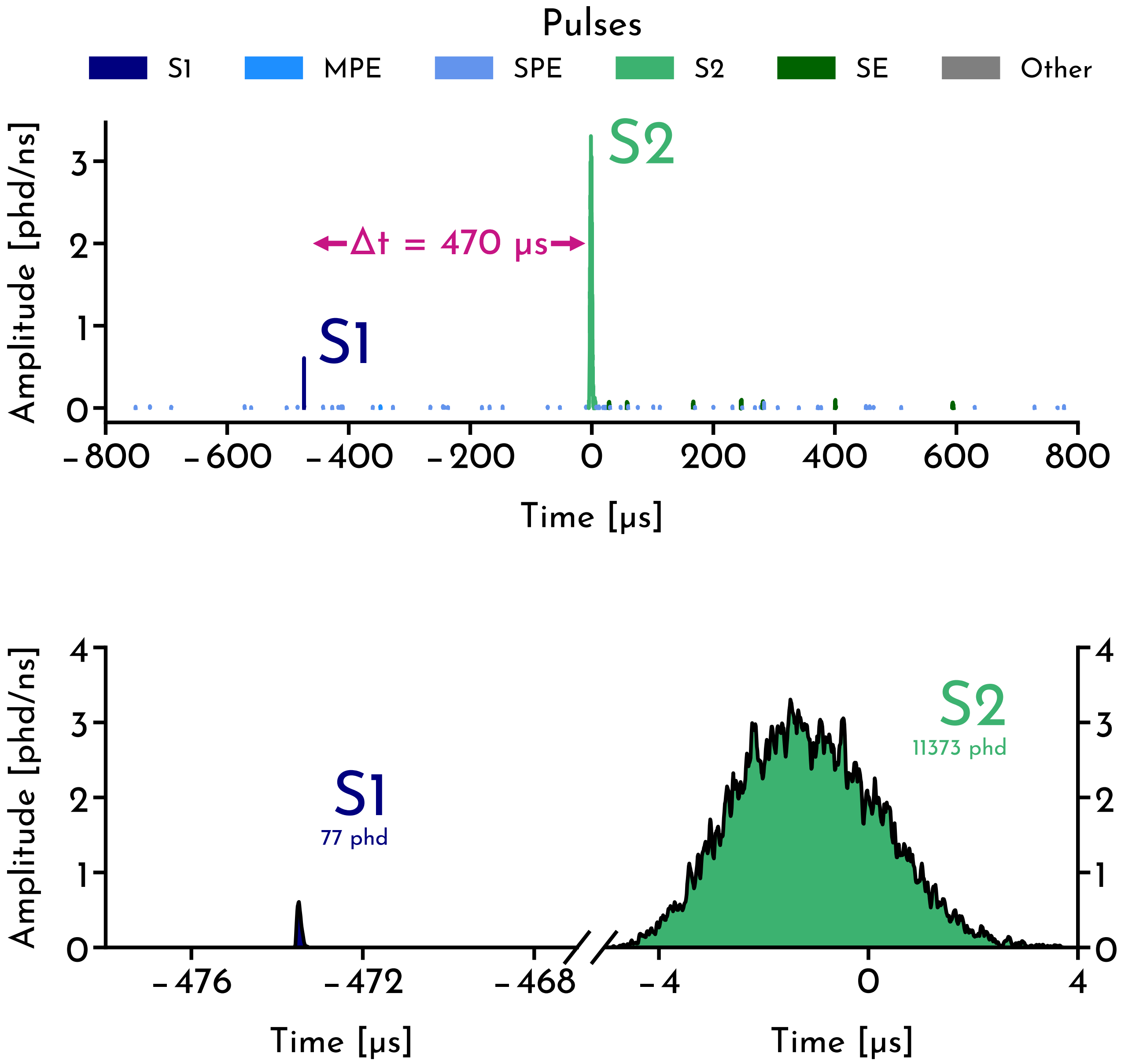

- Proven track record for ~2 decades
- Scalable technology
  - Kg to multi-tonne scale

# Two-phase Time Projection Chambers (TPCs)

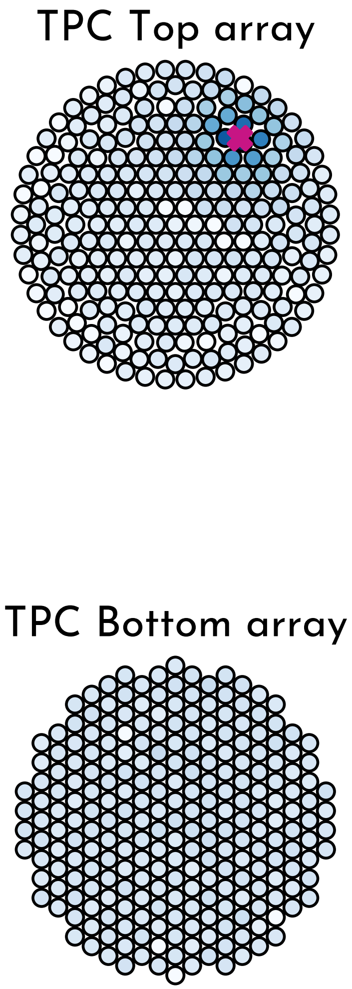
- Liquid target with thin vapour layer
- Time resolved scintillation and ionisation signals
  - Light = prompt scintillation (**S1**)
  - Charge = delayed electroluminescence of ionisation electrons (**S2**)
- 3D vertex reconstruction:
  - (X, Y) from S2 hit pattern
  - Z from the time electrons take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



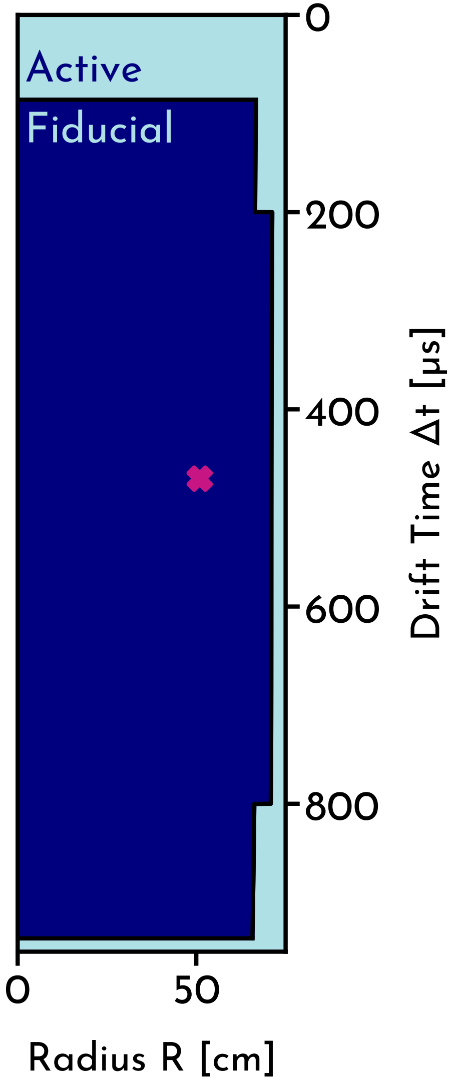

[1] V. N. Lebedenko et al. Phys. Rev. D 80, 052010
[2] H. Araújo arXiv:2007.01683



Pulses
S1
MPE
SPE
S2
SE
Other
S2
S1
←Δt = 470 μs→
Amplitude [phd/ns]
Time [μs]
S1
77 phd
S2
11373 phd
Amplitude [phd/ns]
Time [μs]
Time [μs]

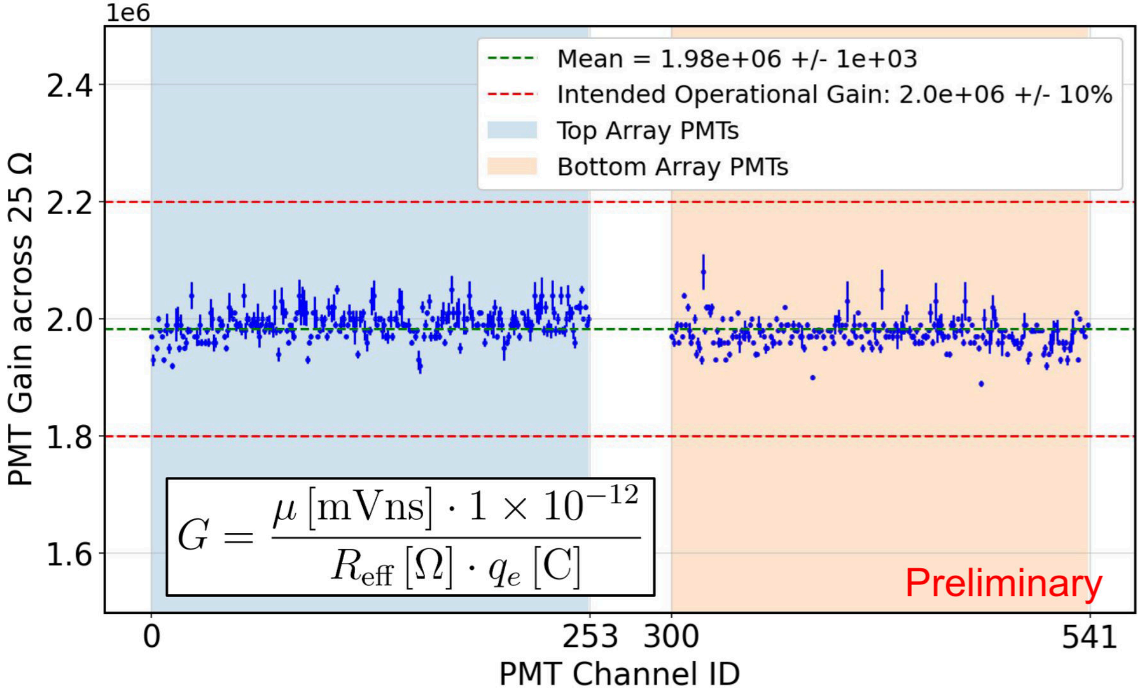
TPC Top array
TPC Bottom array

Active
Fiducial
Drift Time Δt [μs]
Radius R [cm]

# 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

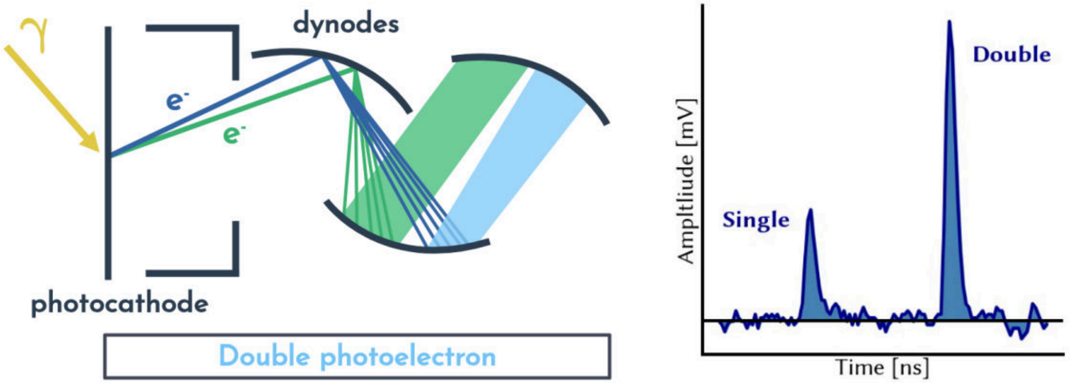


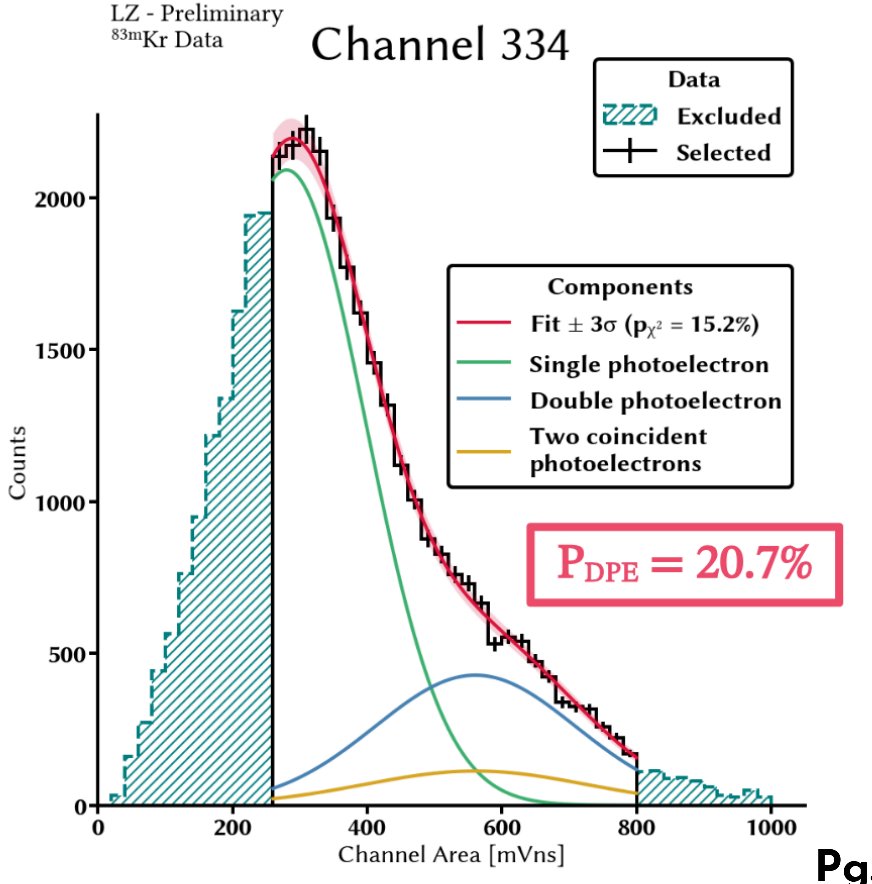

- Operated at $2\times10^6$ gain
  - 94% single photoelectron detection efficiency
  - Dual amplification output
    - High gain: single photon sensitivity
    - Low gain: improves MeV-scale sensitivity (0ν2β)
- PMT's are regularly calibrated using dedicated LED system

[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
  - $1[\text{phd}] = \frac{1}{1+p_{\text{DPE}}} \times [\text{phe}]$



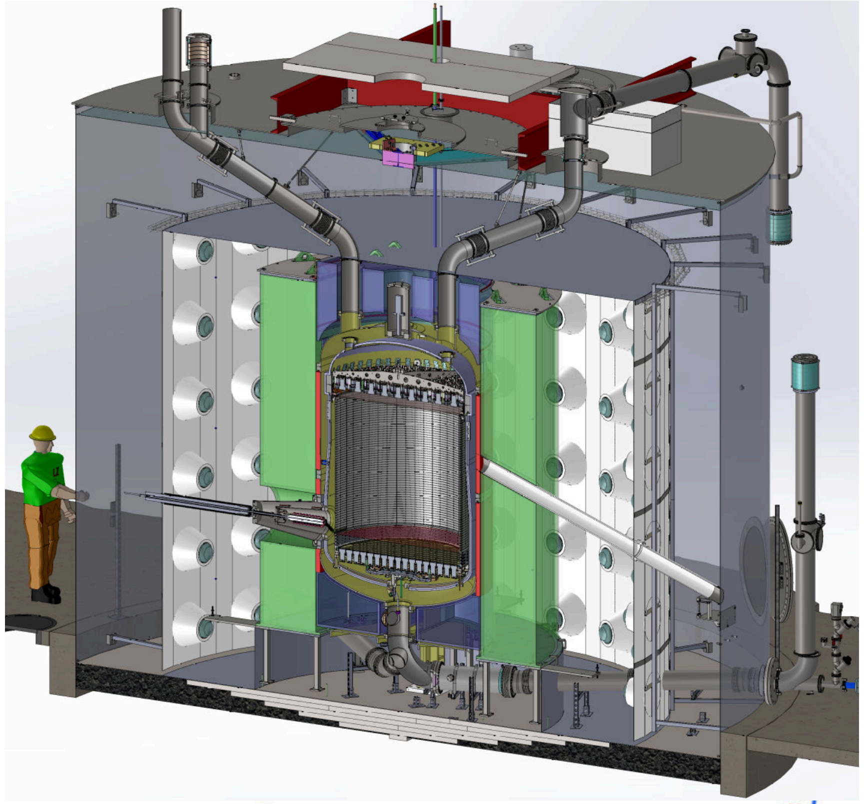



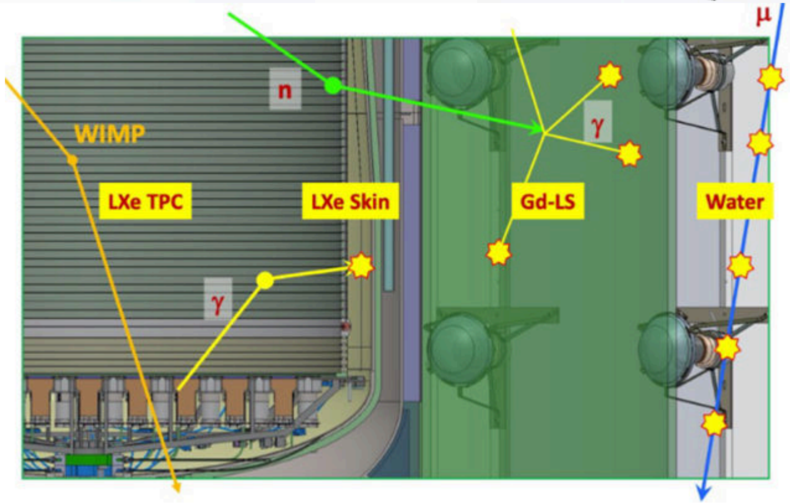


[1] Fujii et. al. NIM-A 795 (2015) 293-297
[2] Faham et. al. JINST 10 (2015) 09, P09010
[3] B. López Paredes et. al. Astroparticle Physics 102 (2018) 56-66

# 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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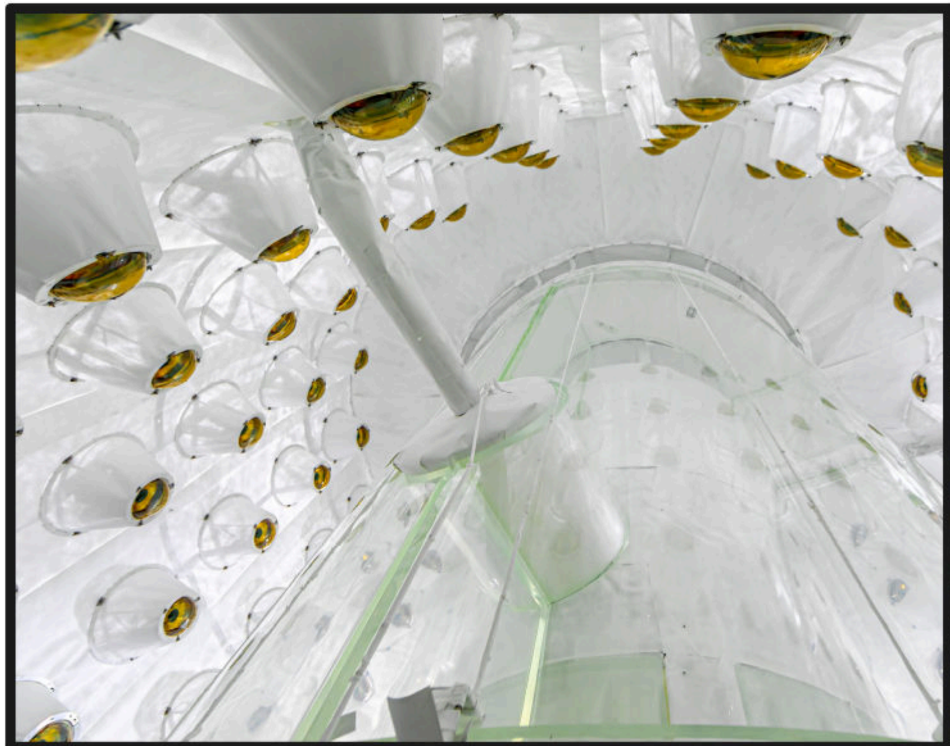


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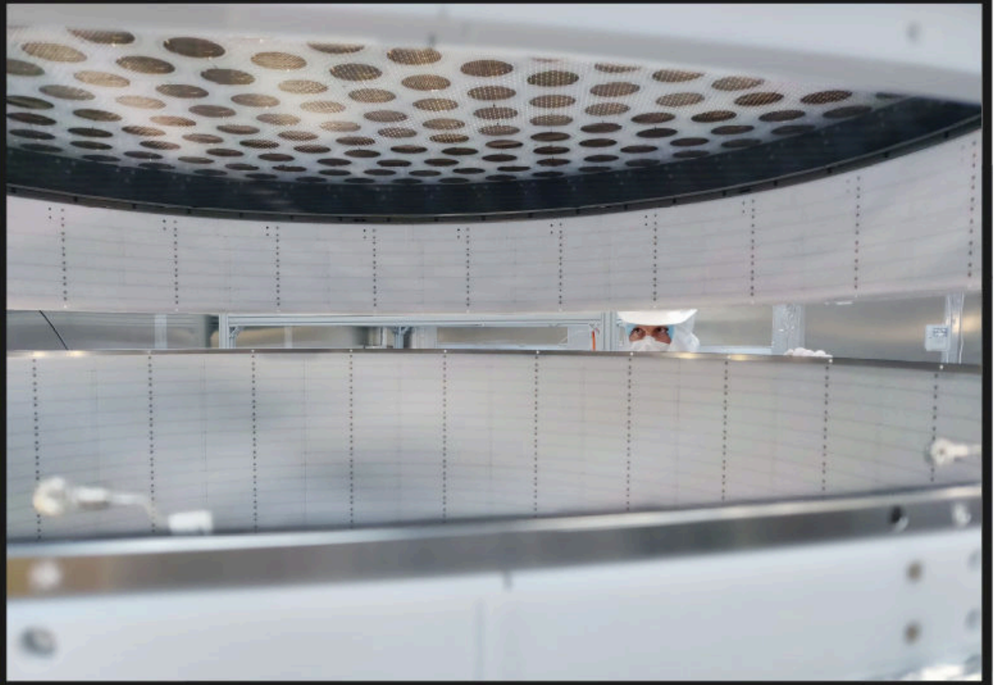
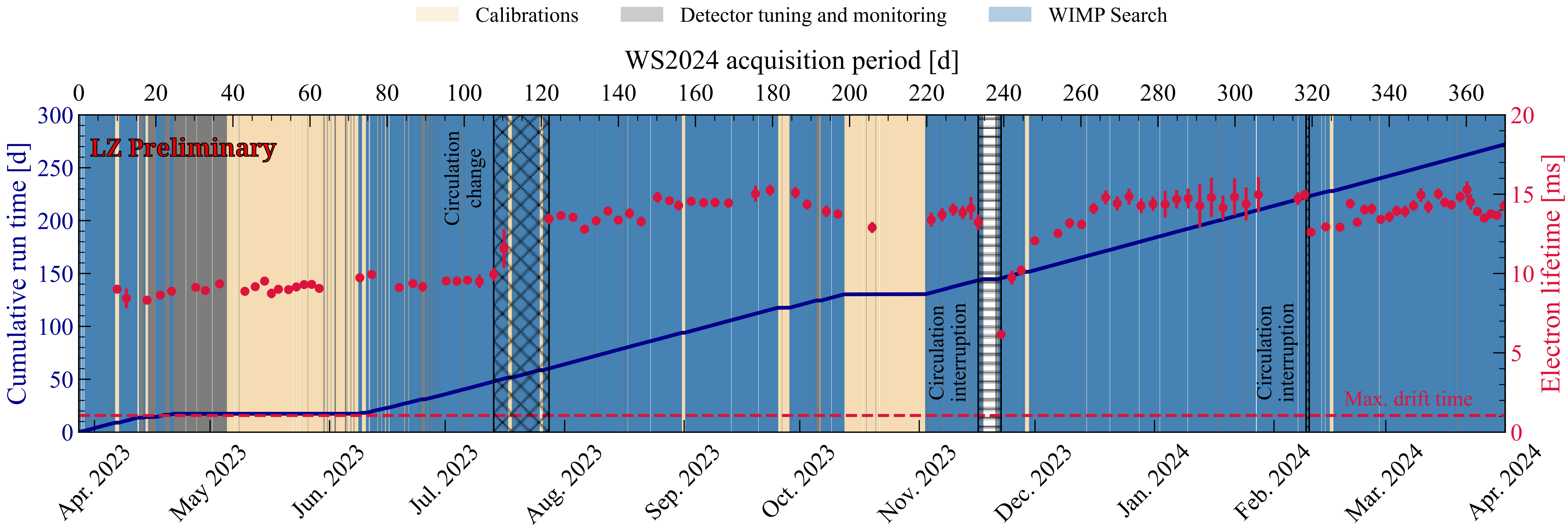


# 2024 Science Run

- 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

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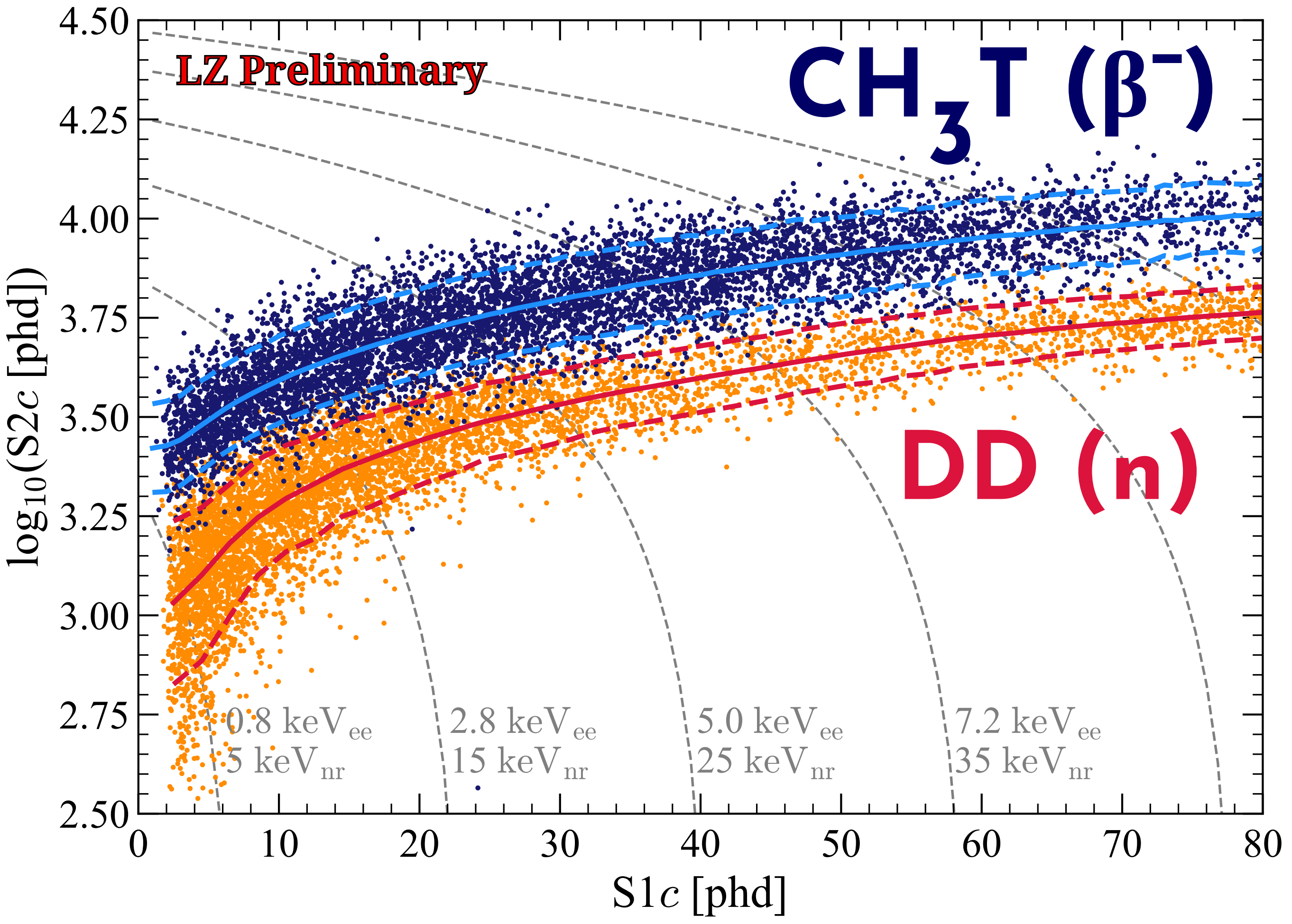
# Calibrations

- 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

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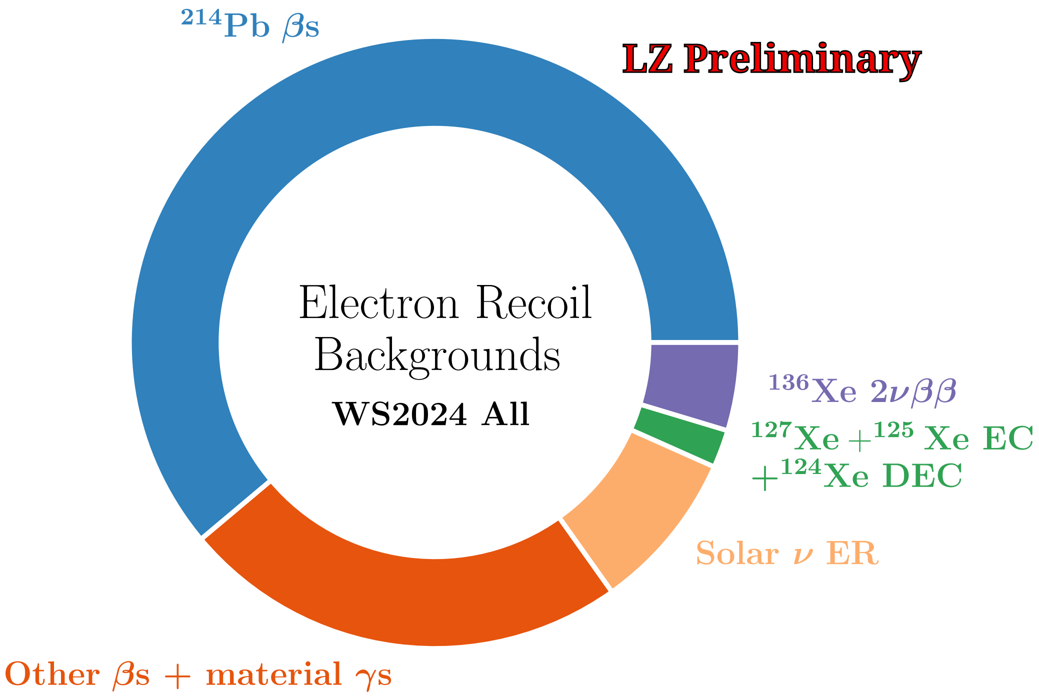
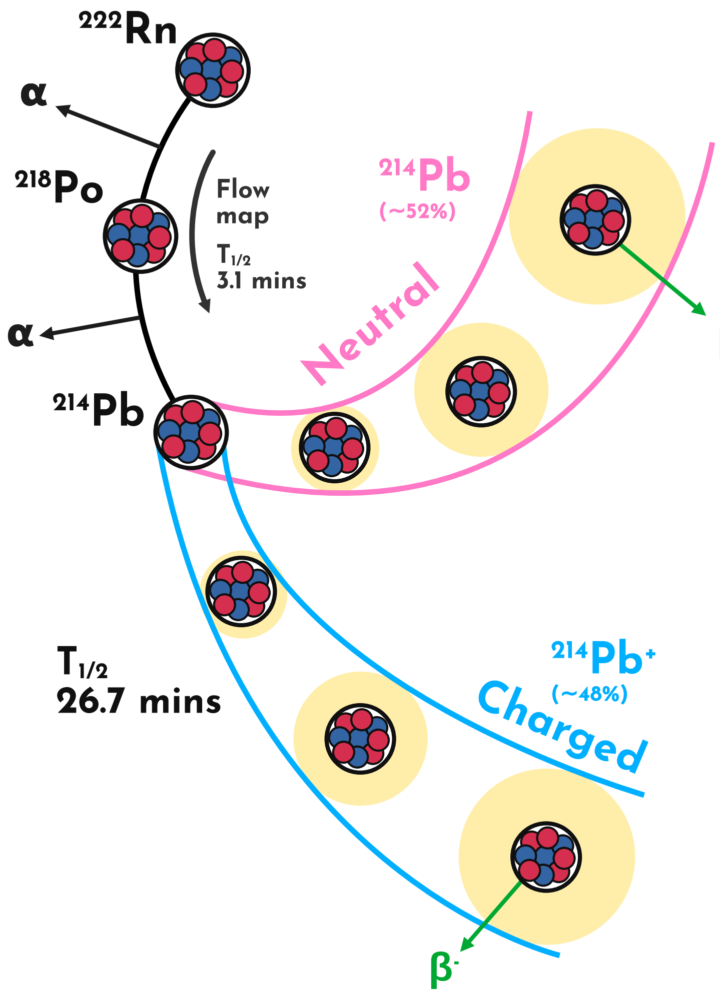
# Background Model

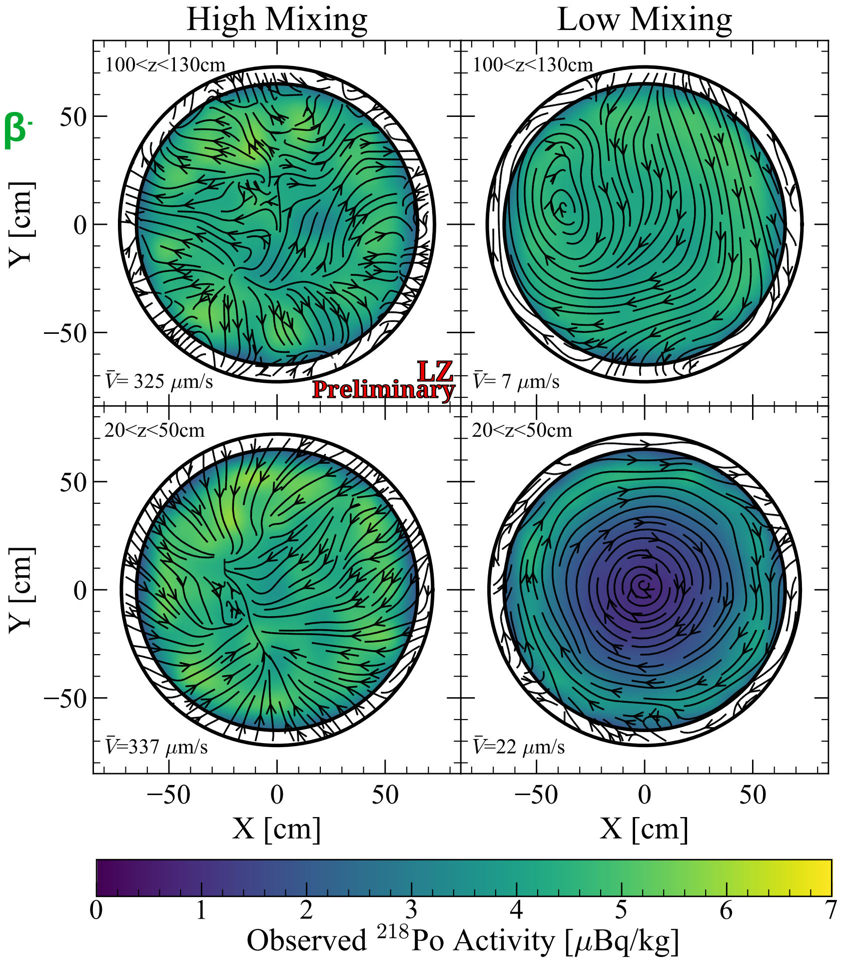
- Understand backgrounds from in-situ measurement of sidebands and assays
- Expect 1207 ER background events in WS2024:
  - $^{214}$Pb β-decay is dominant at 60%
  - Double electron capture
  - Solar neutrinos
- Expect 0.18 NR CEvNS events
  - Excluded by region of interest for dedicated search
- Neutrons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

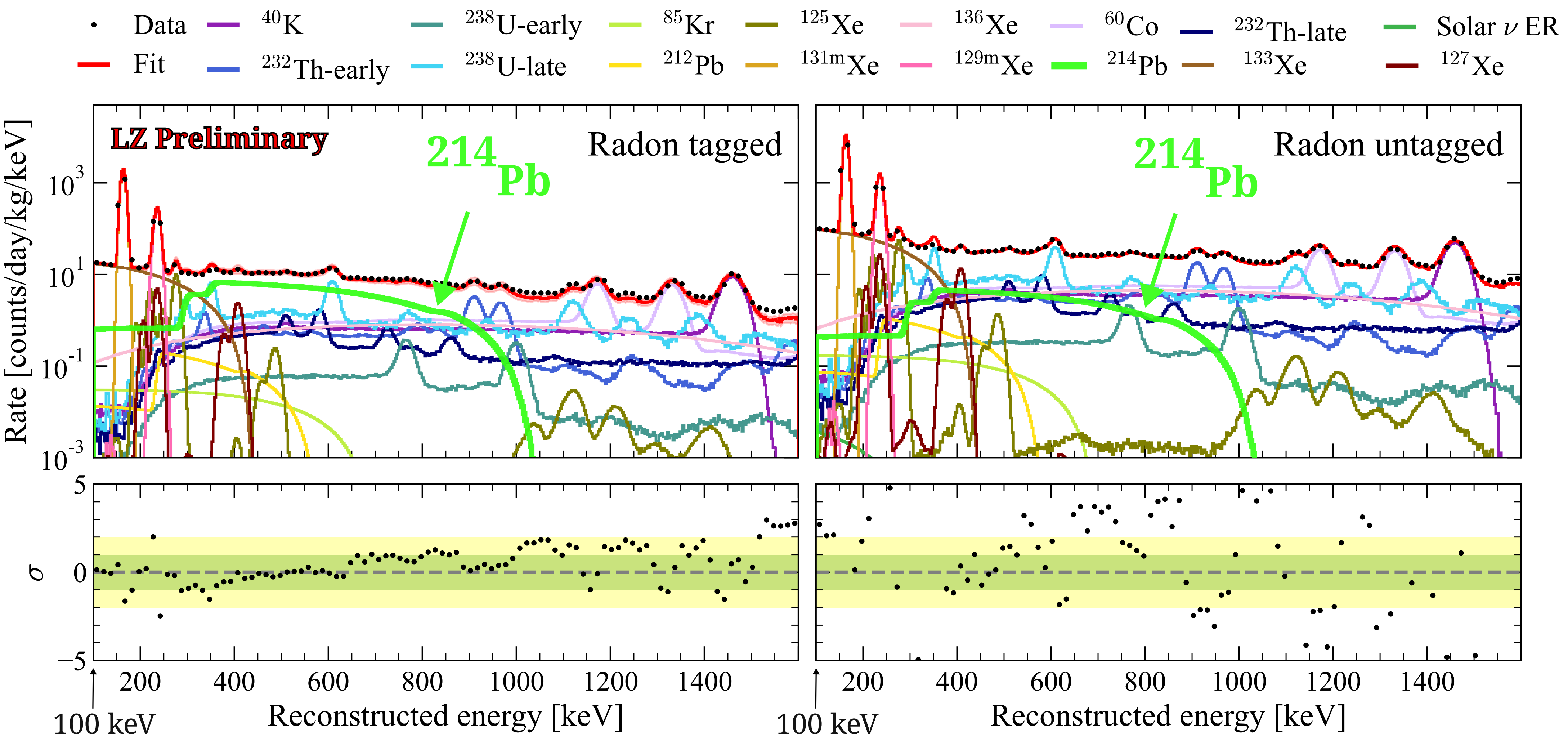


# Radon tagging to remove dominant $^{214}$Pb background

- 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**



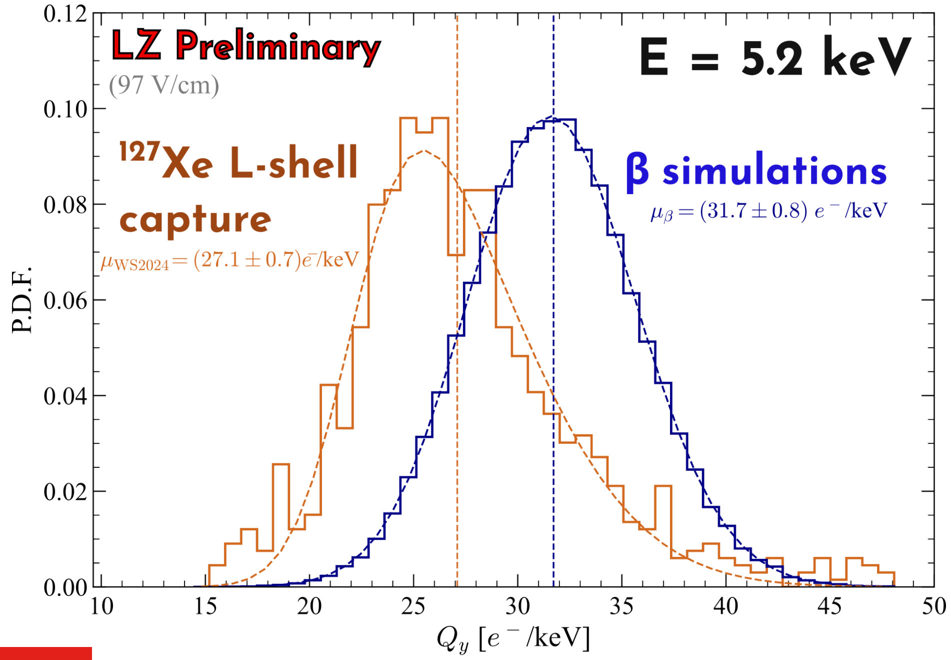



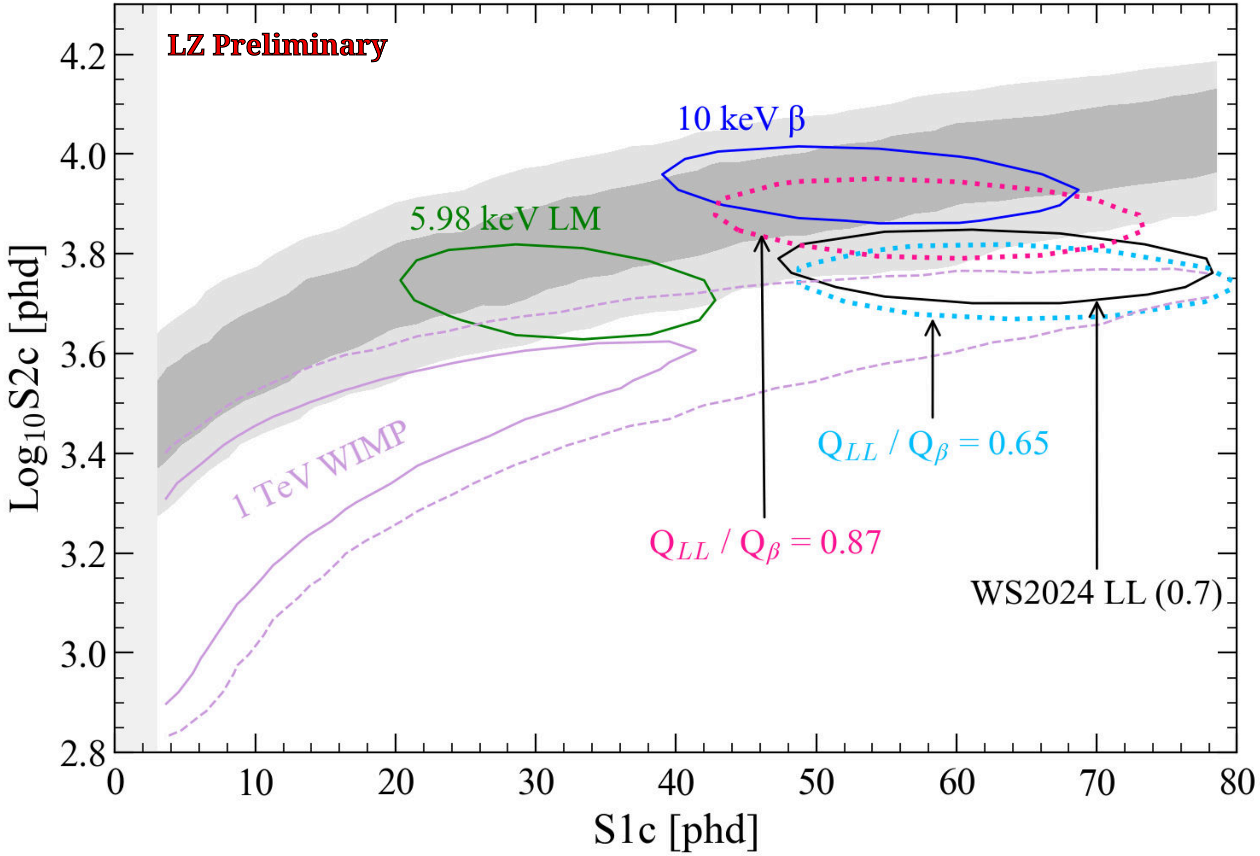



- Tagging reduces $^{214}$Pb background by a factor 2.1
  - 3.9 ± 0.6 μBq/Kg (total) → 1.8 ± 0.3 μBq/Kg (untagged)
- N.B.: plots are above the WIMP region-of-interest (ROI)
- $^{133}$Xe restricted above 81 keV (and ROI) by γ-ray emission
- $^{133}$Xe a short-lived activation product from preceding neutron 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: **$Q_L/Q_\beta$ = 0.86±0.01** [4]



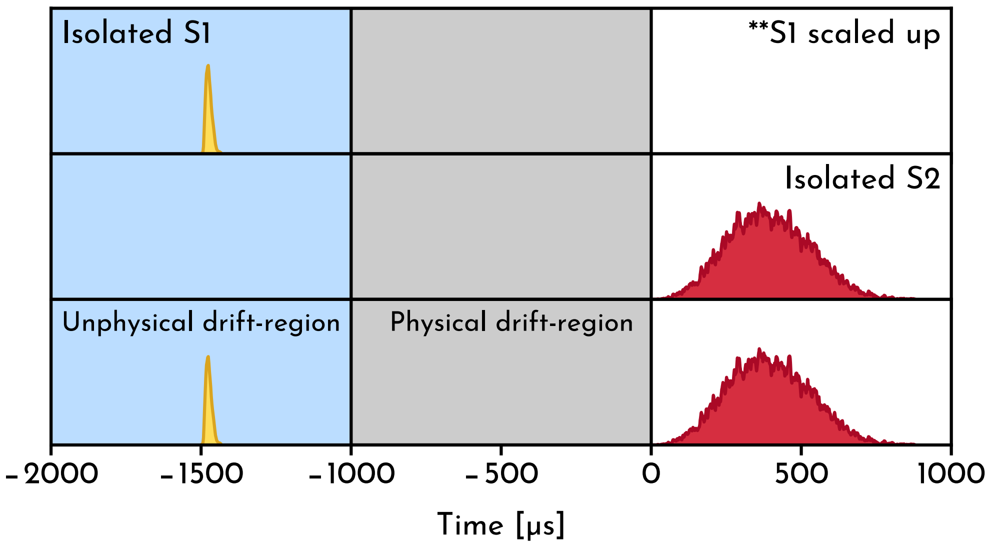



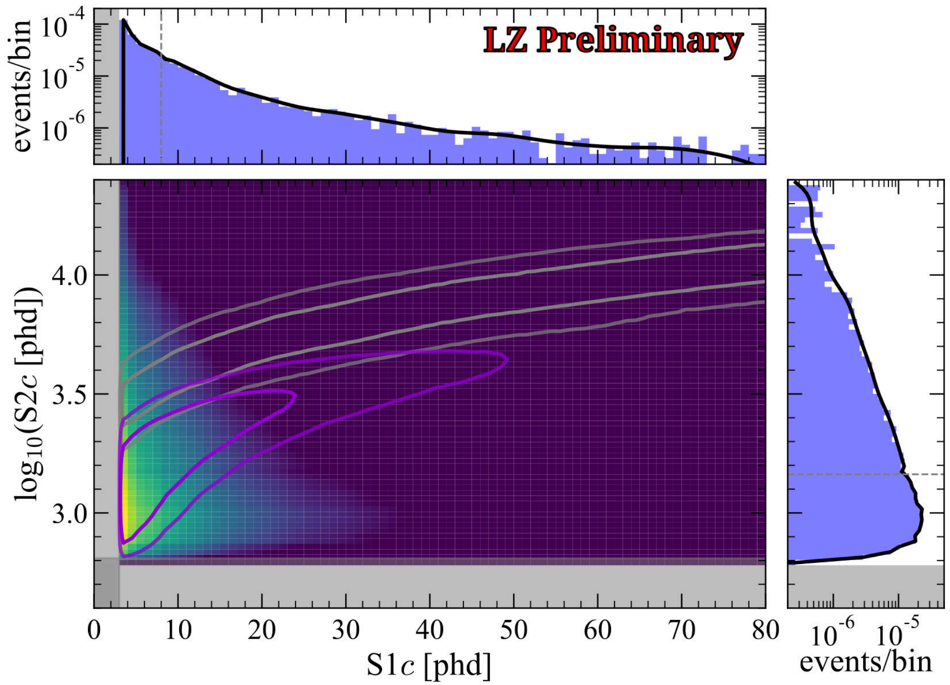


[1] XENON1T Nature 568, 532-535 (2019)
[2] LZ arXiv:2408.17391
[3] Previously measured by XELDA (Temples et al, Phys. Rev. D 104, 112001 (2021))
[4] dedicated publication in progress

# Accidental background

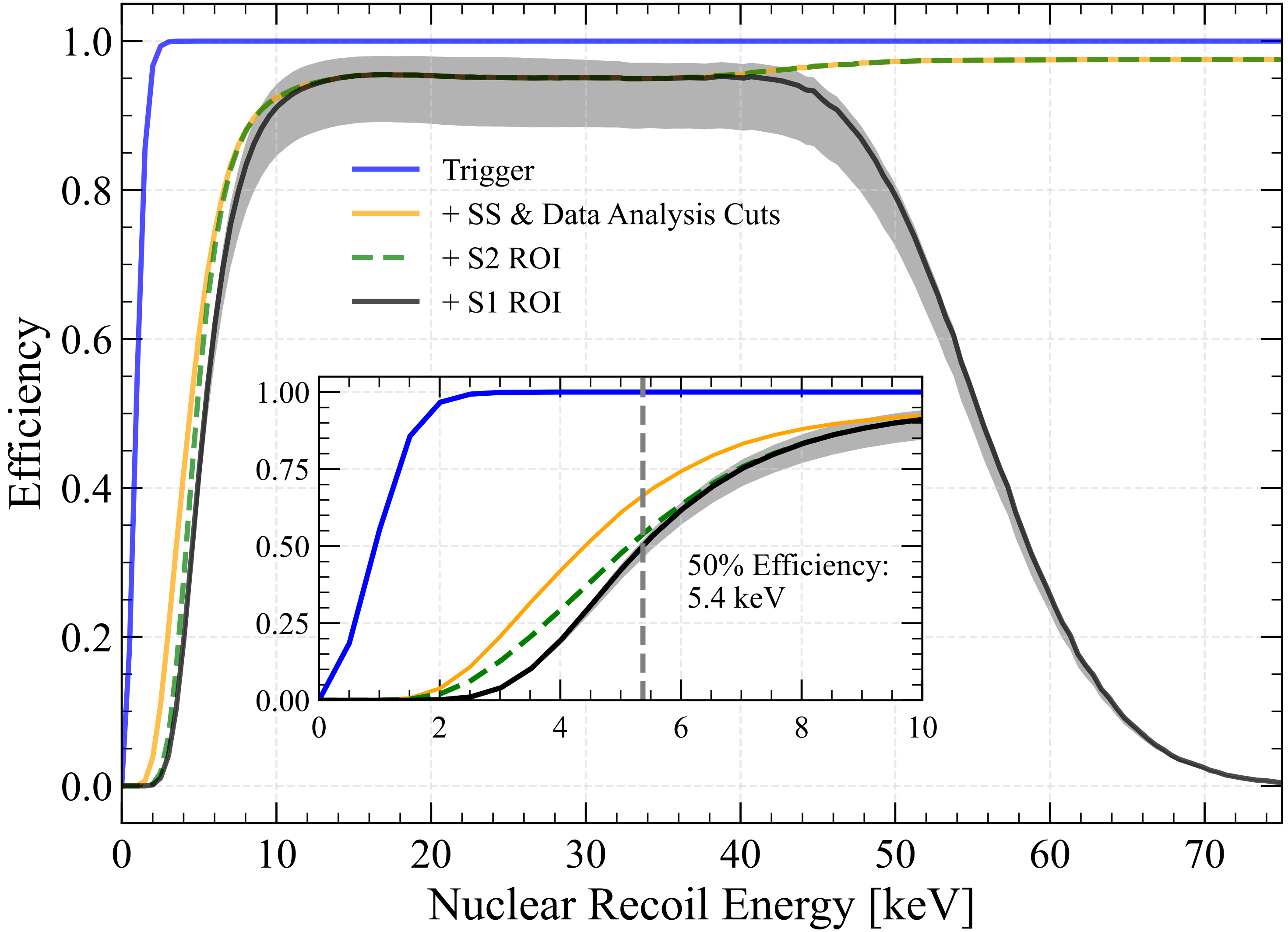
- Pile-up of unrelated S1-like and S2-like pulses
  - Looks like a single scatter and can mimic a WIMP
- Fraction of these have an unphysical drift time
  - Population to calculate rate with physical drift-time
- Model as product of isolated S1-like and S2-like pulses
- Distribution peaks at the low 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



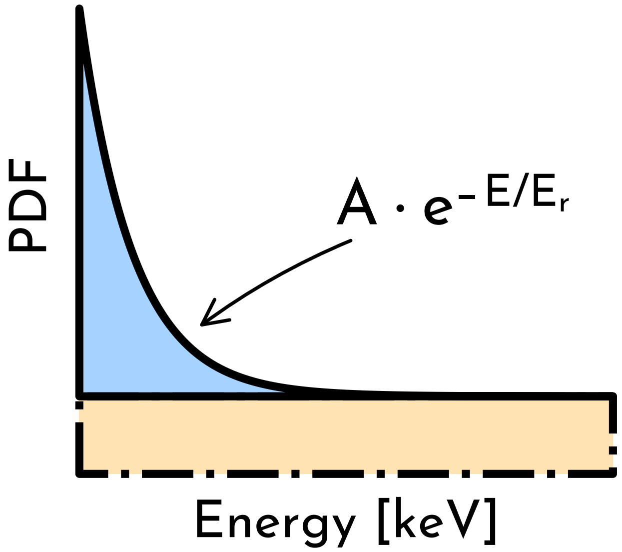
# Signal Acceptance

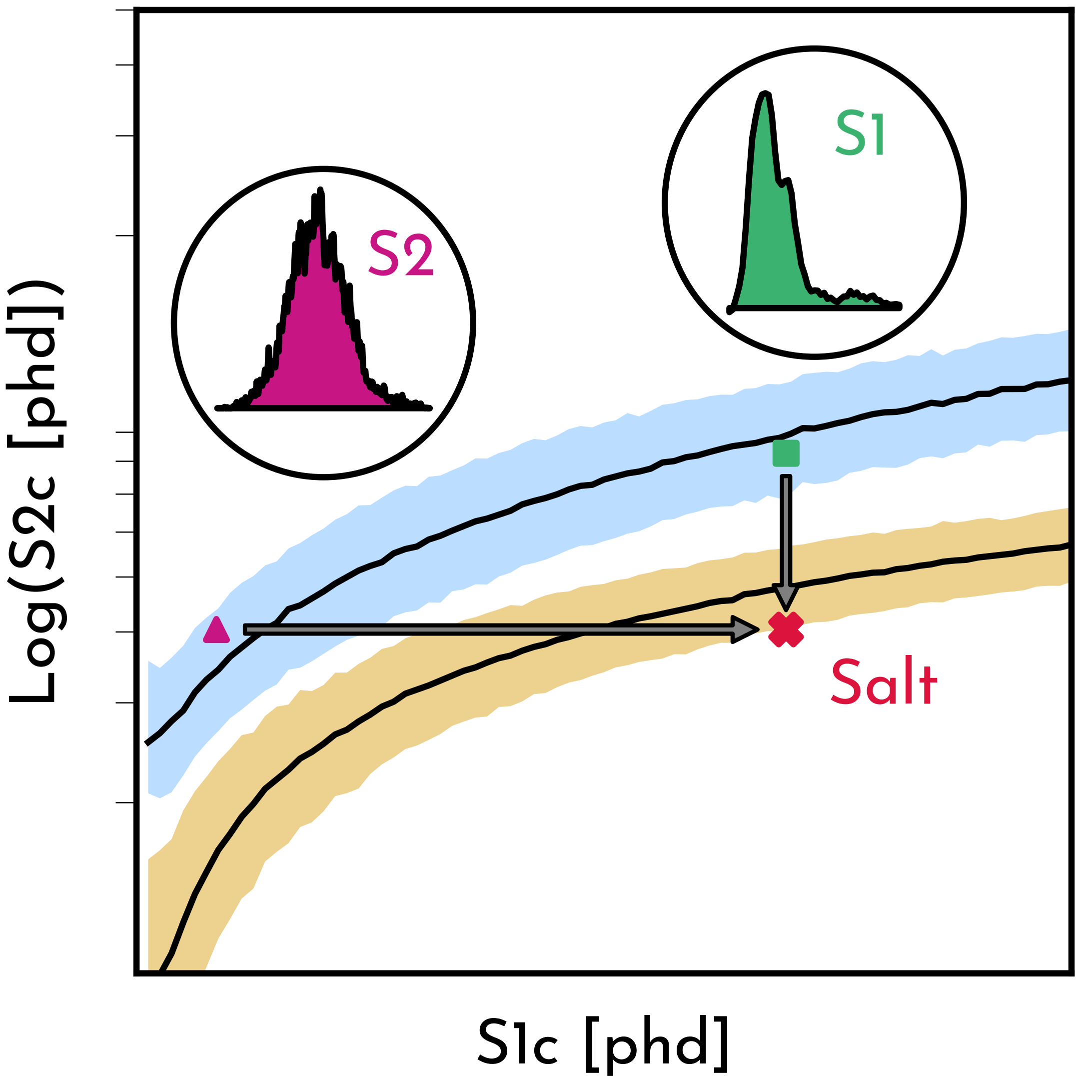
- Region of interest (ROI):
  - $S1_c$ = (3, 80) phd
  - $S2_c$ = (645, $10^{4.5}$) phd
    - Excludes $^8B$ for dedicated analysis
- Multiple event and pulse level cuts
  - FV, ROI, single scatter
  - Veto anti-coincidence
    - Delayed neutron capture
    - Prompt γ-ray interactions
  - S1 & S2 based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



# Bias Mitigation (Salting)

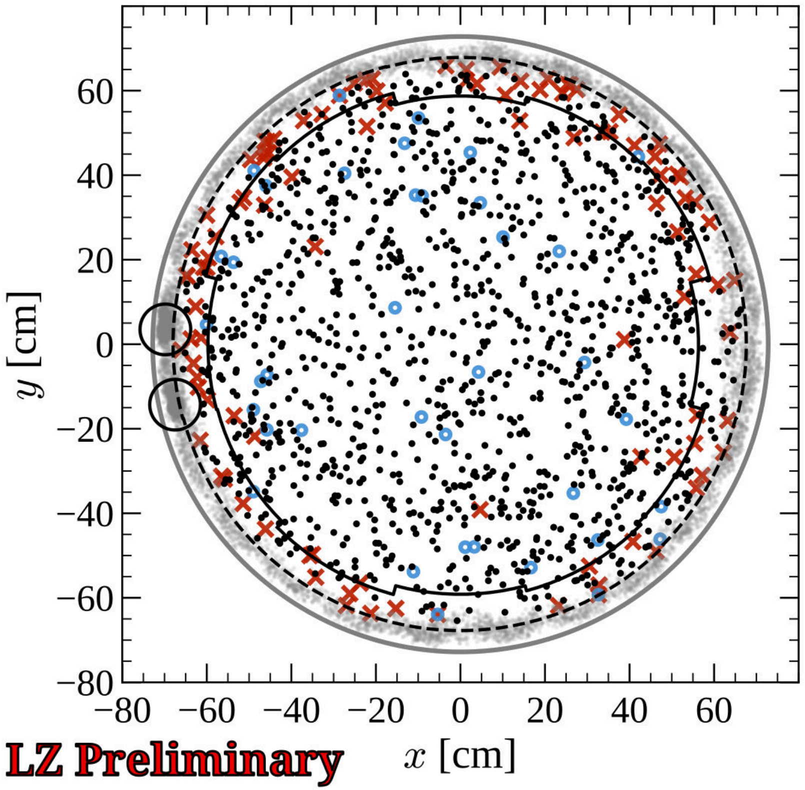
- Inject fake events (salt) into the data stream
- Generated by pairing S1 and S2 pulses from calibration
  - Embed measured waveforms back into the data stream
- Events sampled as follows:
  - Unknown rate below LZ's WS2022 result
  - Recoil spectra of a WIMP of unknown mass
  - Additional contribution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

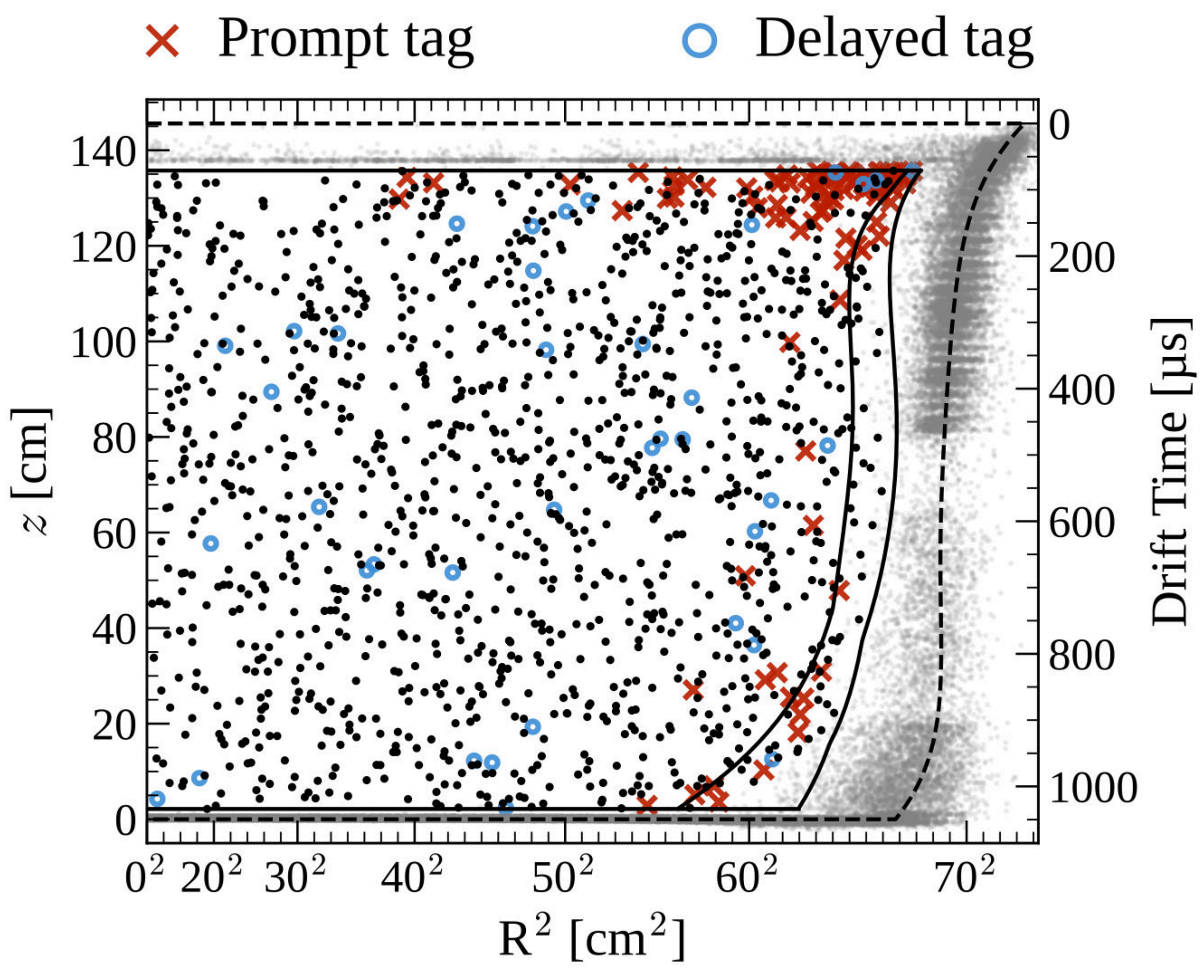


# Event positions, fiducial volume (FV), and vetos

- 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**

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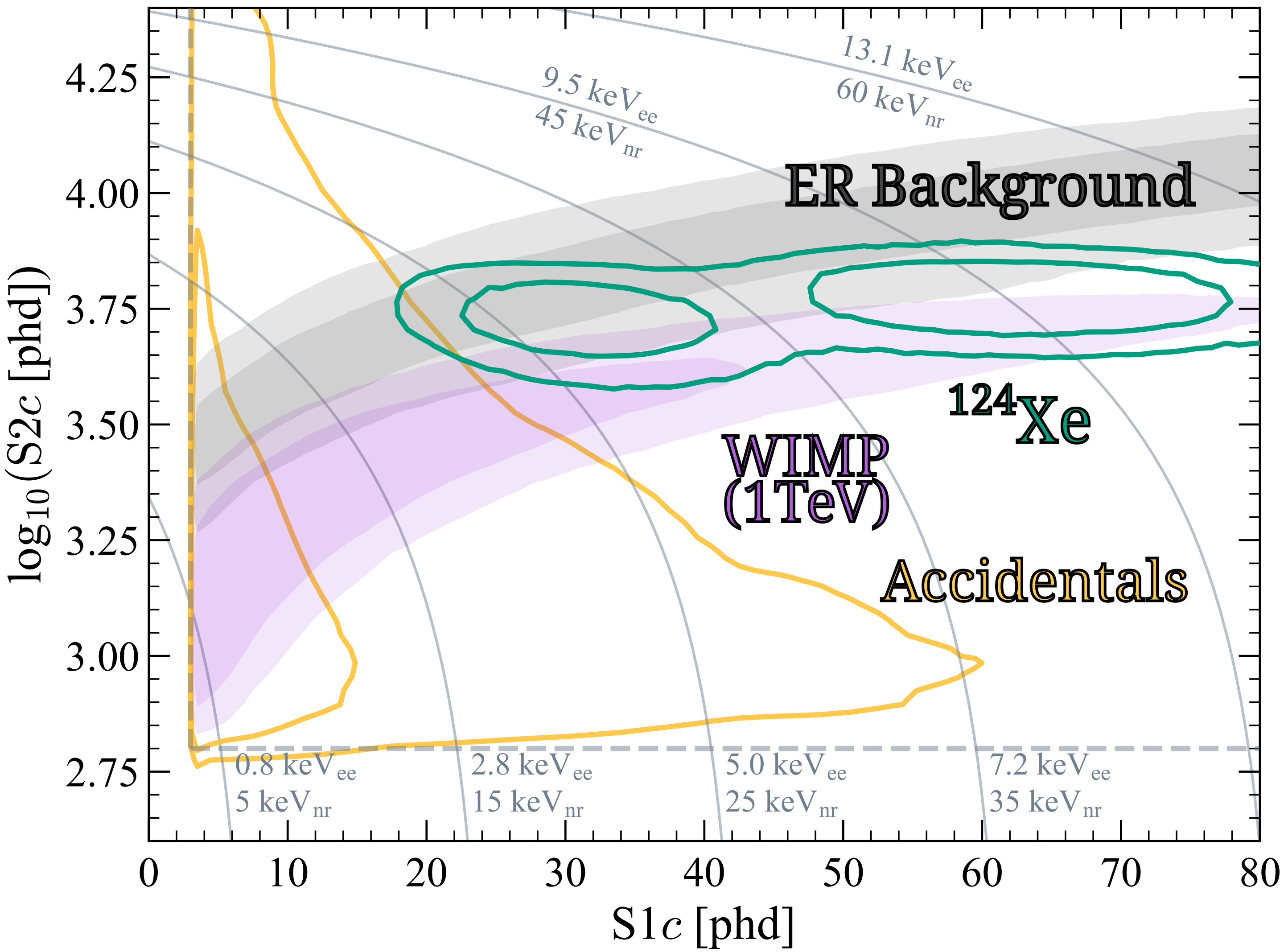
LZ Preliminary

# 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 $^8B$ 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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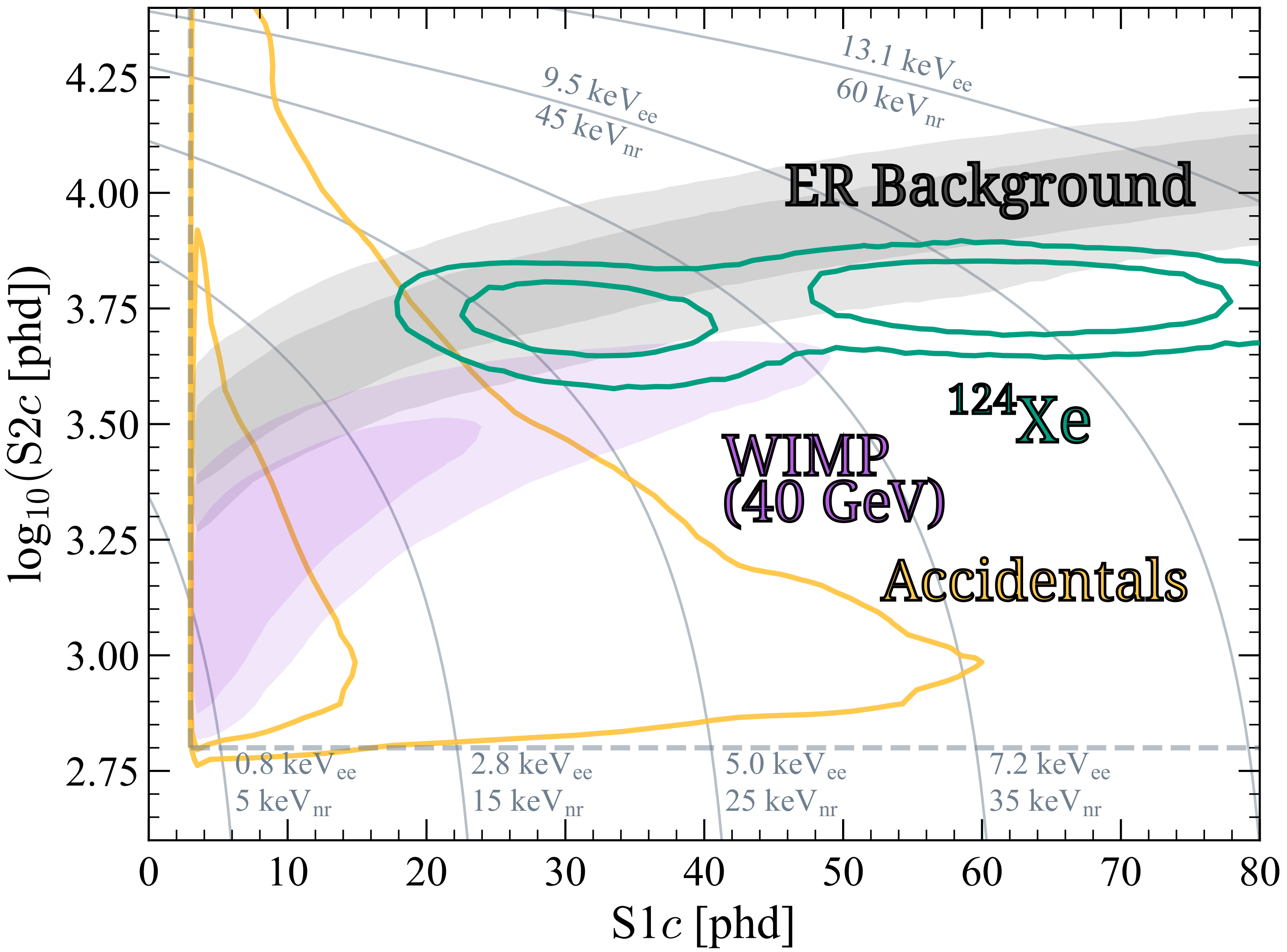


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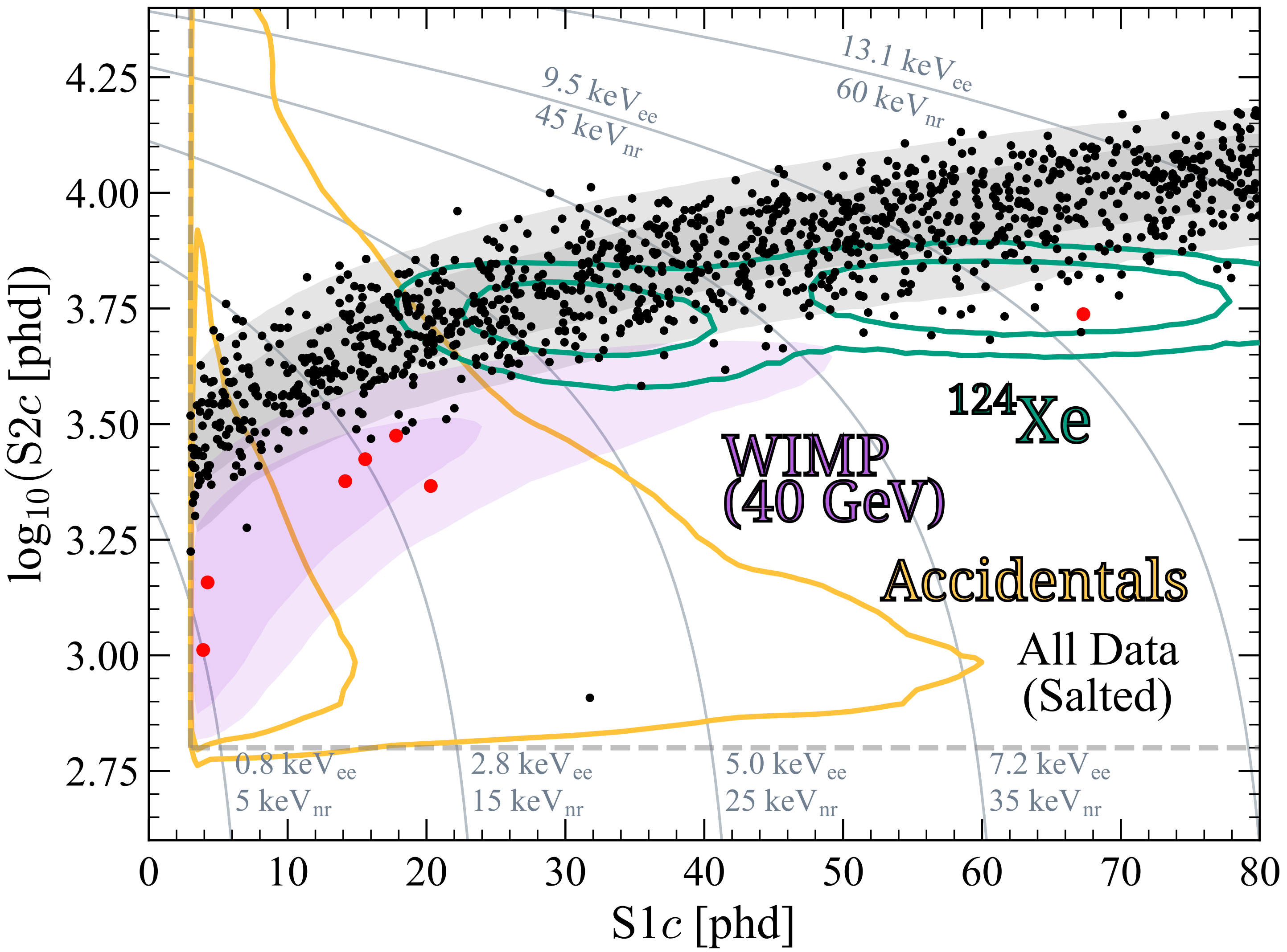
    - Excludes $^8B$ for dedicated analysis
- Exposure of 220 live-days × 5.5 tonnes:
  - 3.3 tonne years
- 8 salt events injected
  - 1 was removed by cuts
  - This is consistent with the signal efficiency



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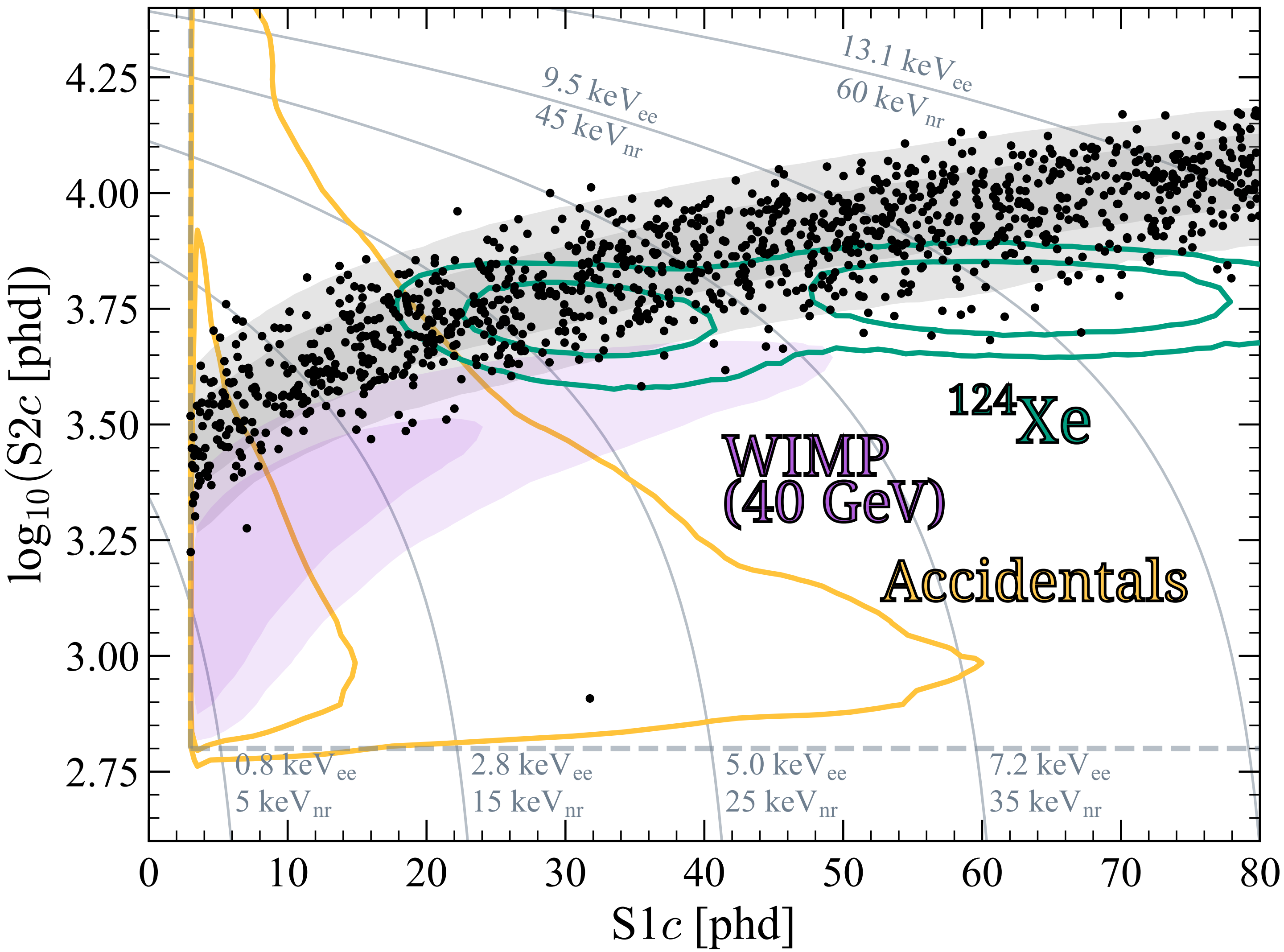
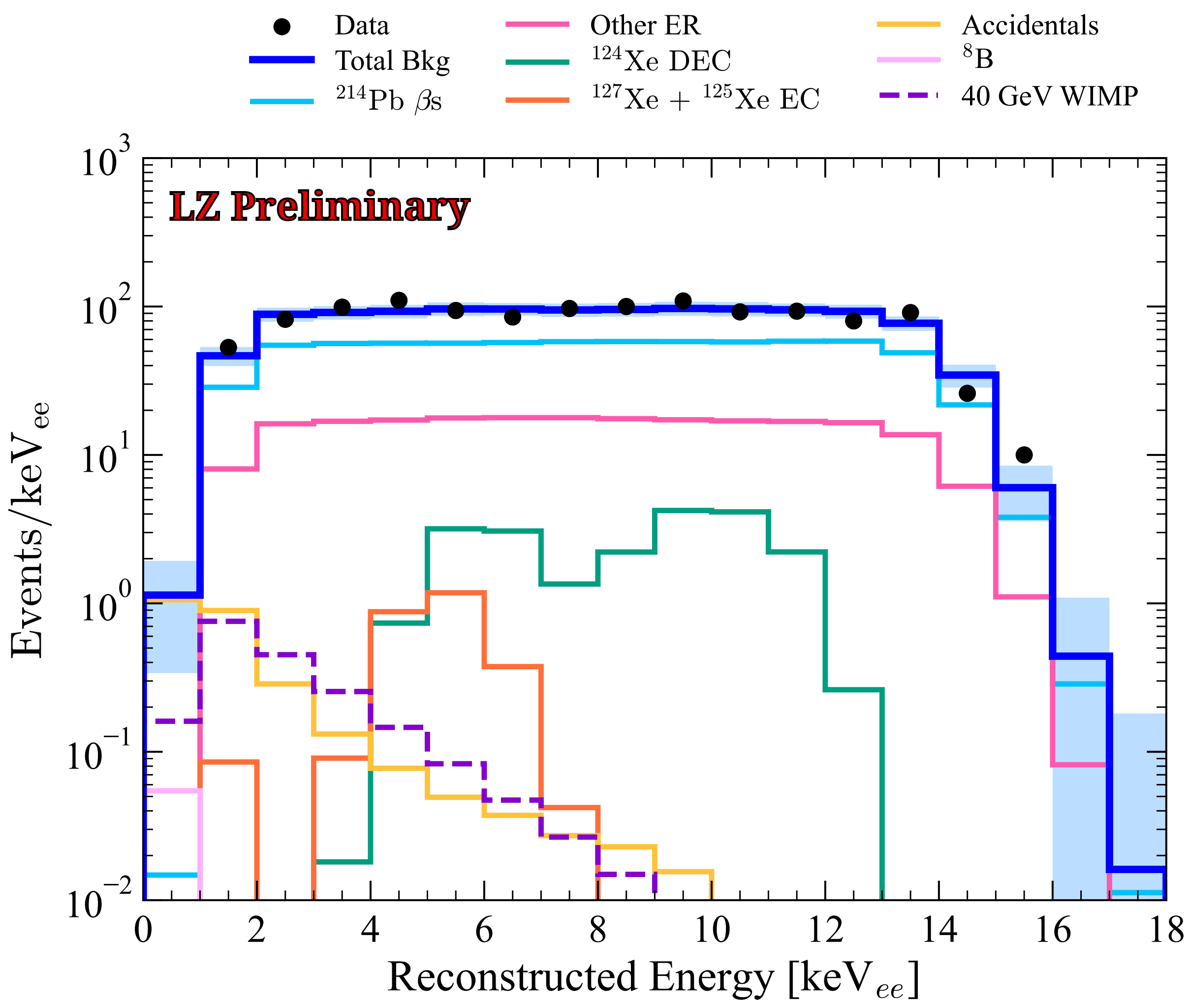
- 1220 events remain after un-salting
- **No changes to analysis post un-salting**



# 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** |

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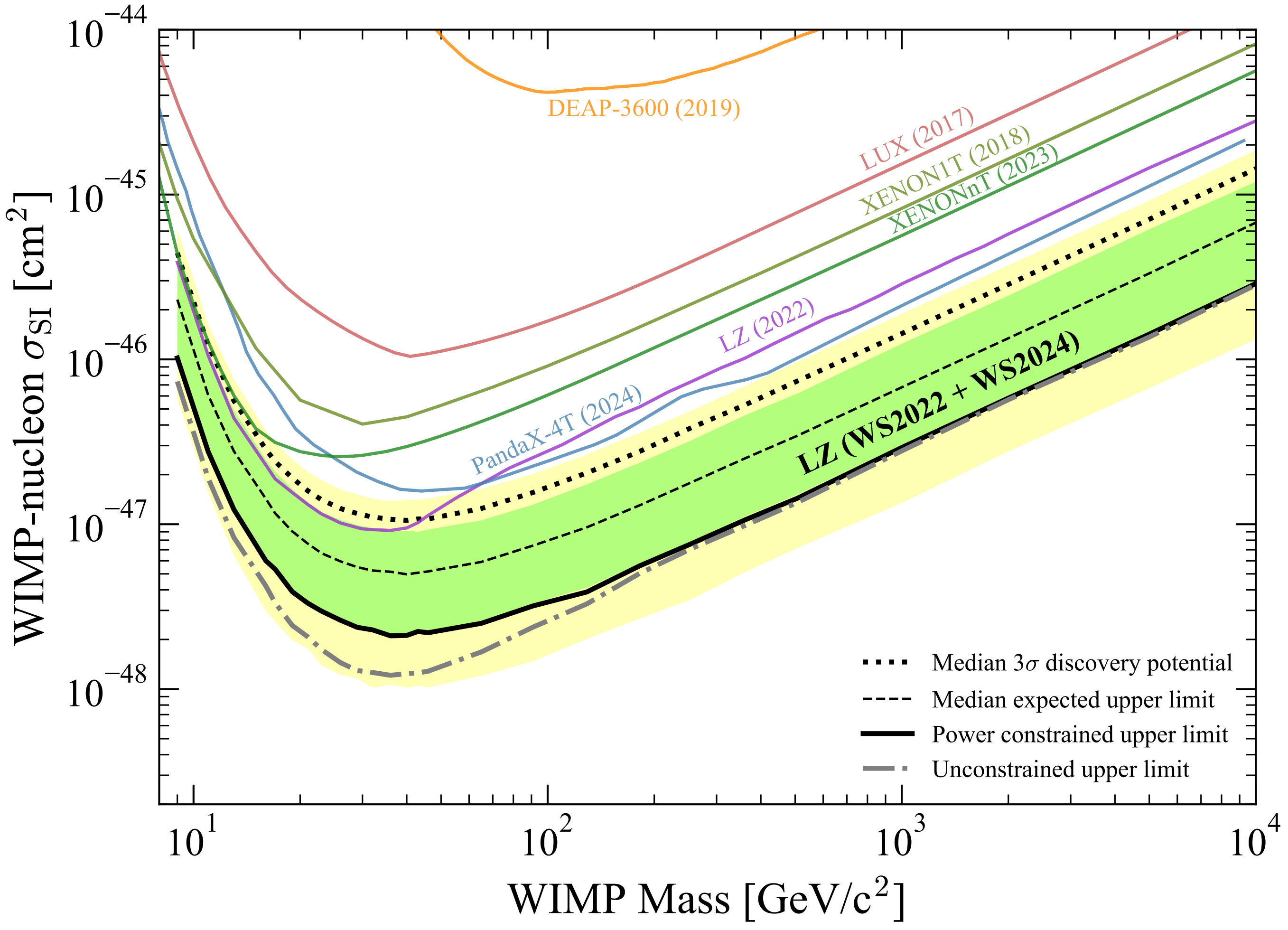
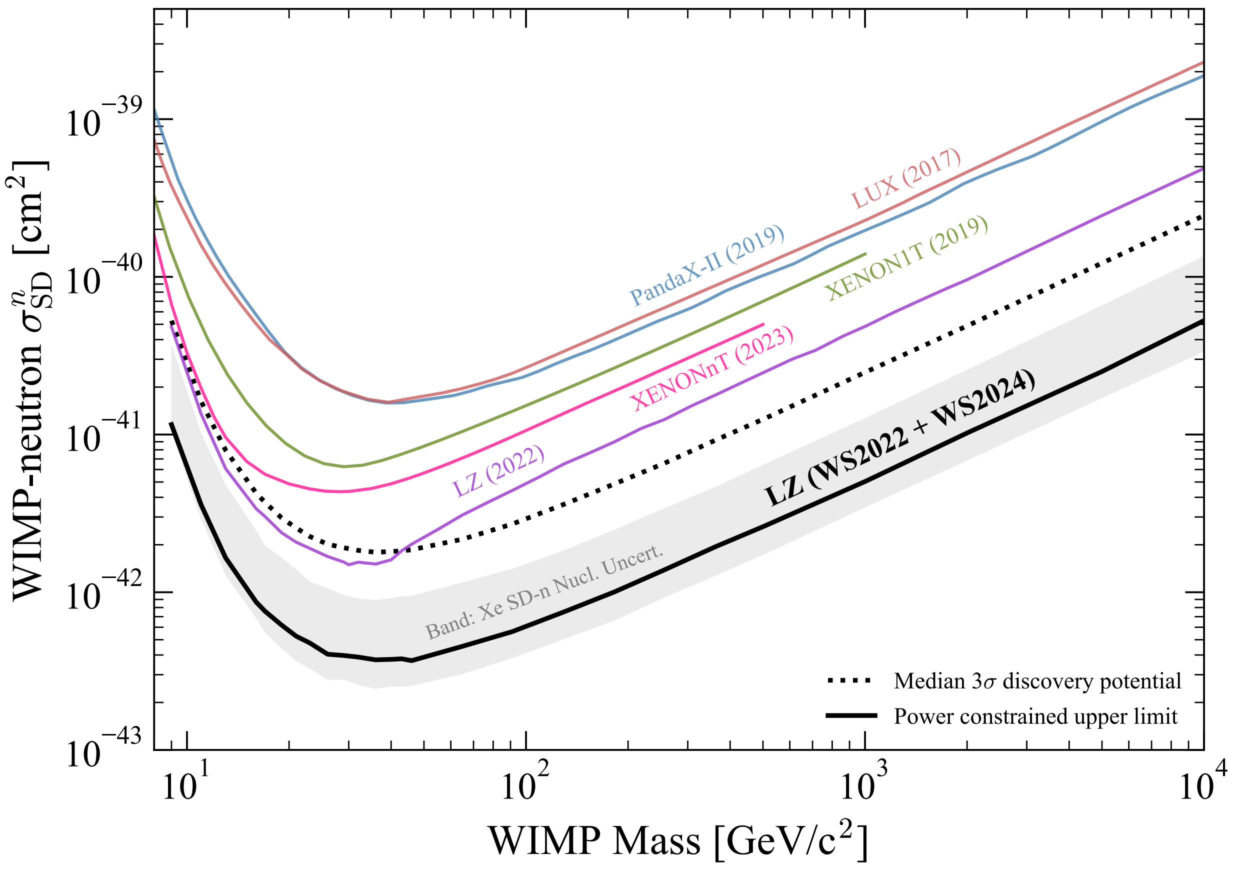
# Combined 2024 & 2022 Spin-independant Result

- 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: **$2.1 \times 10^{-48}$ 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

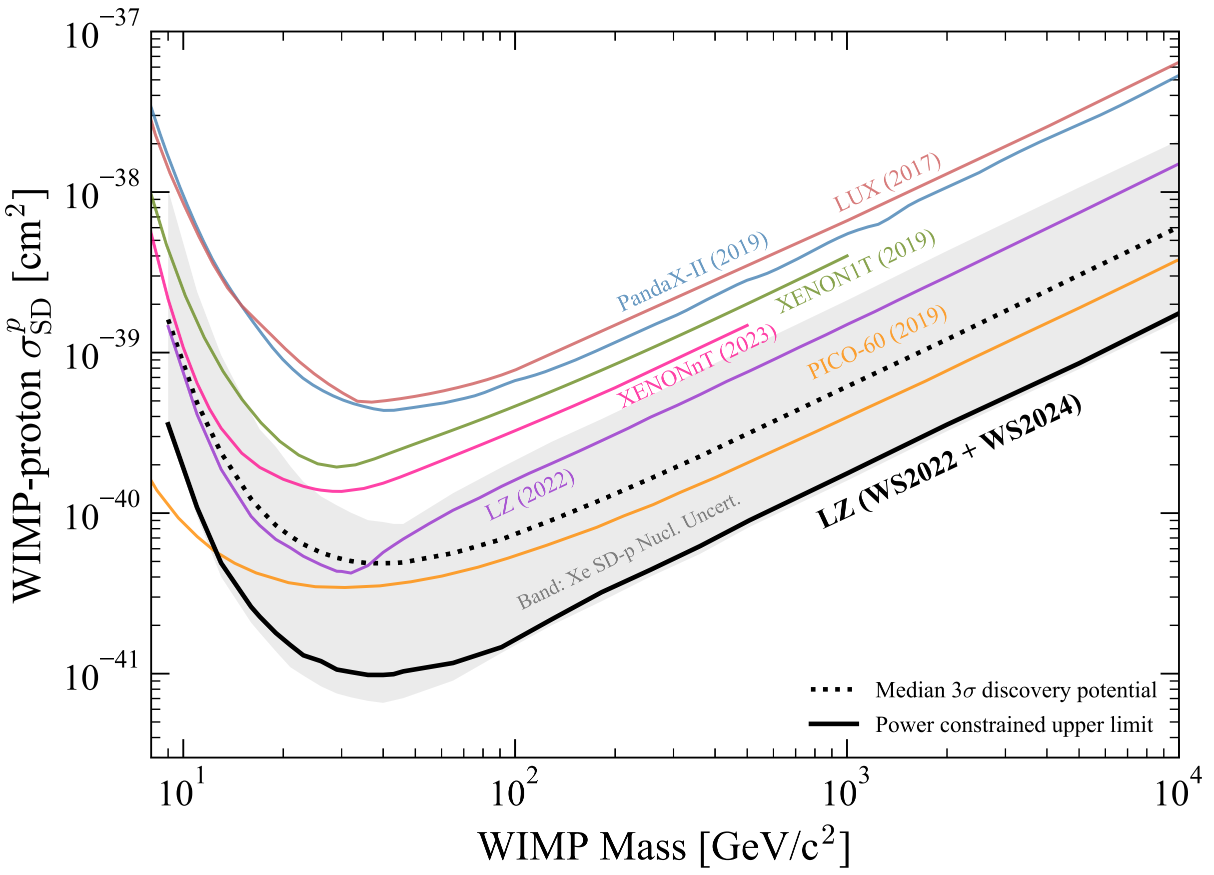


# Combined 2024 & 2022 Spin-dependant Results

## 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