# Status of the LUX-ZEPLIN Experiment

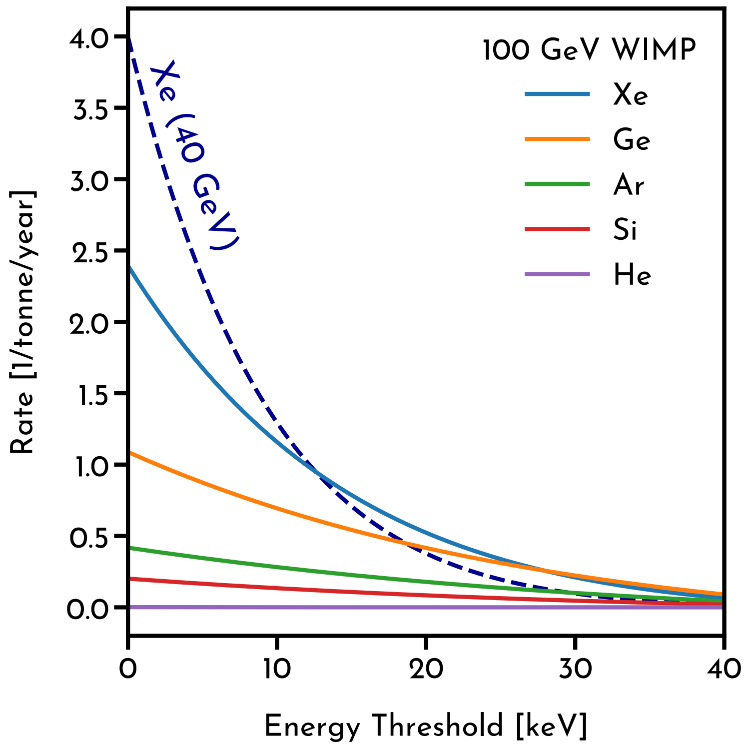
**Albert Baker**
on behalf of the LZ collaboration

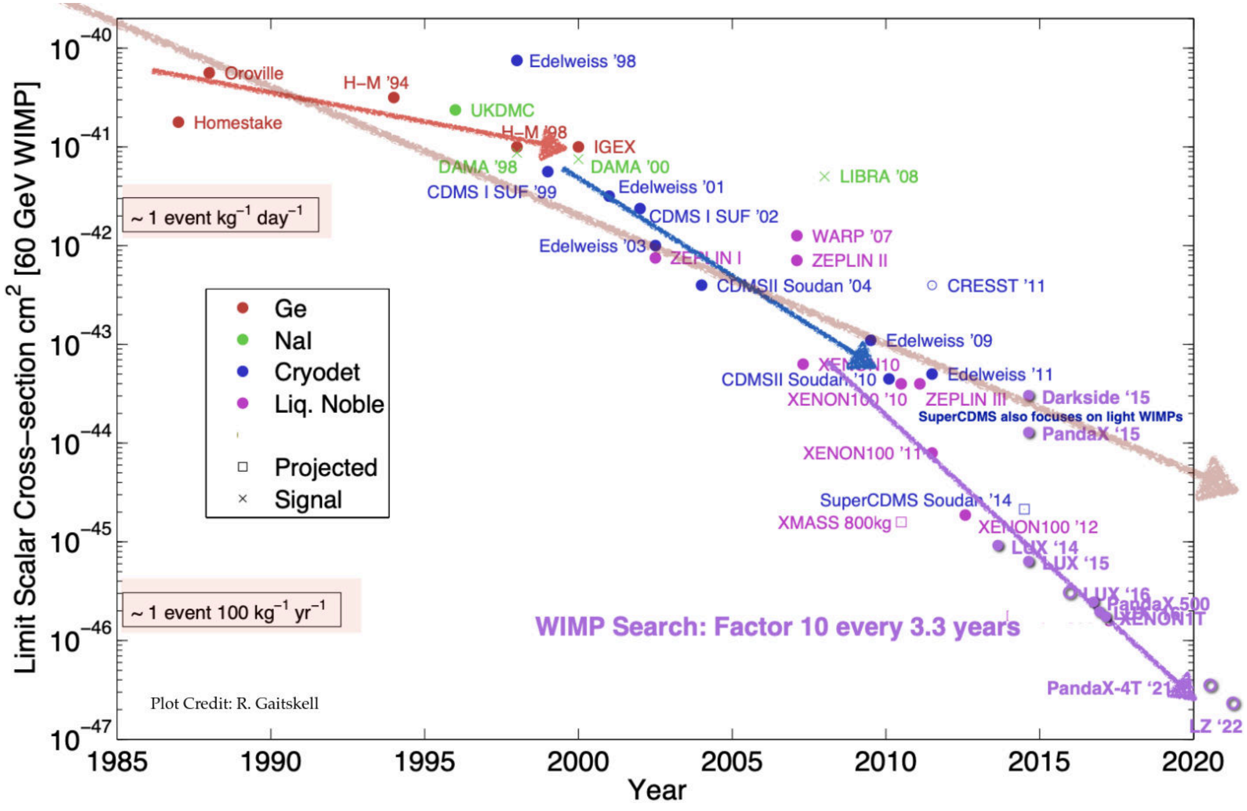
**DMUK**

7th January 2025

# Xenon detectors for dark matter searches

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

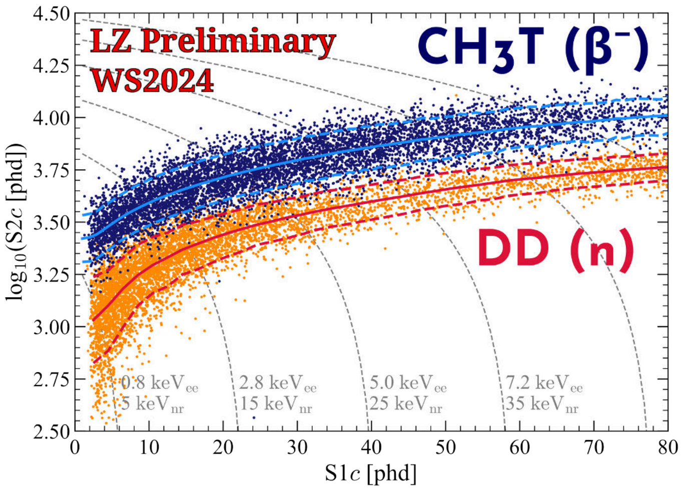


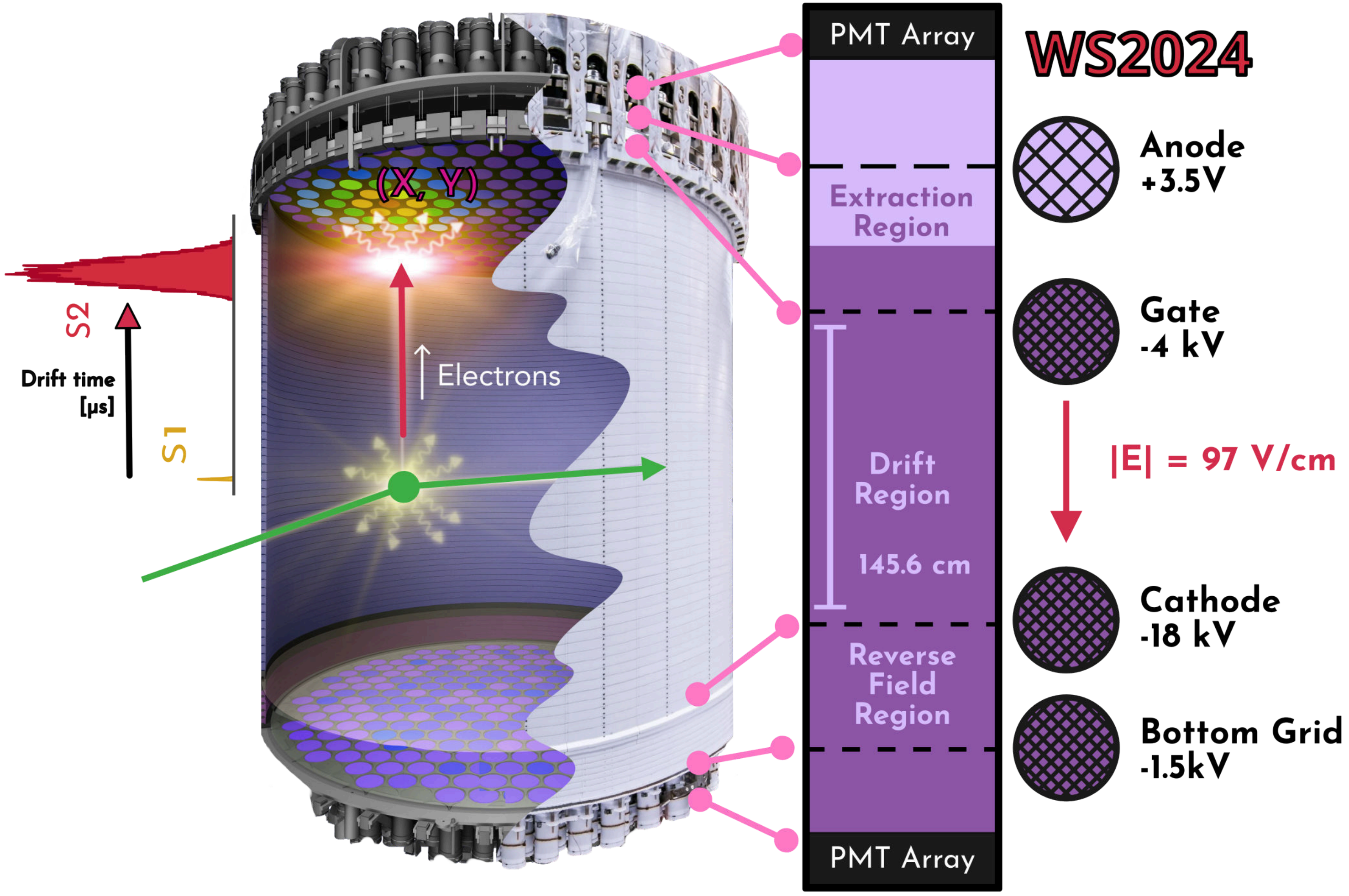



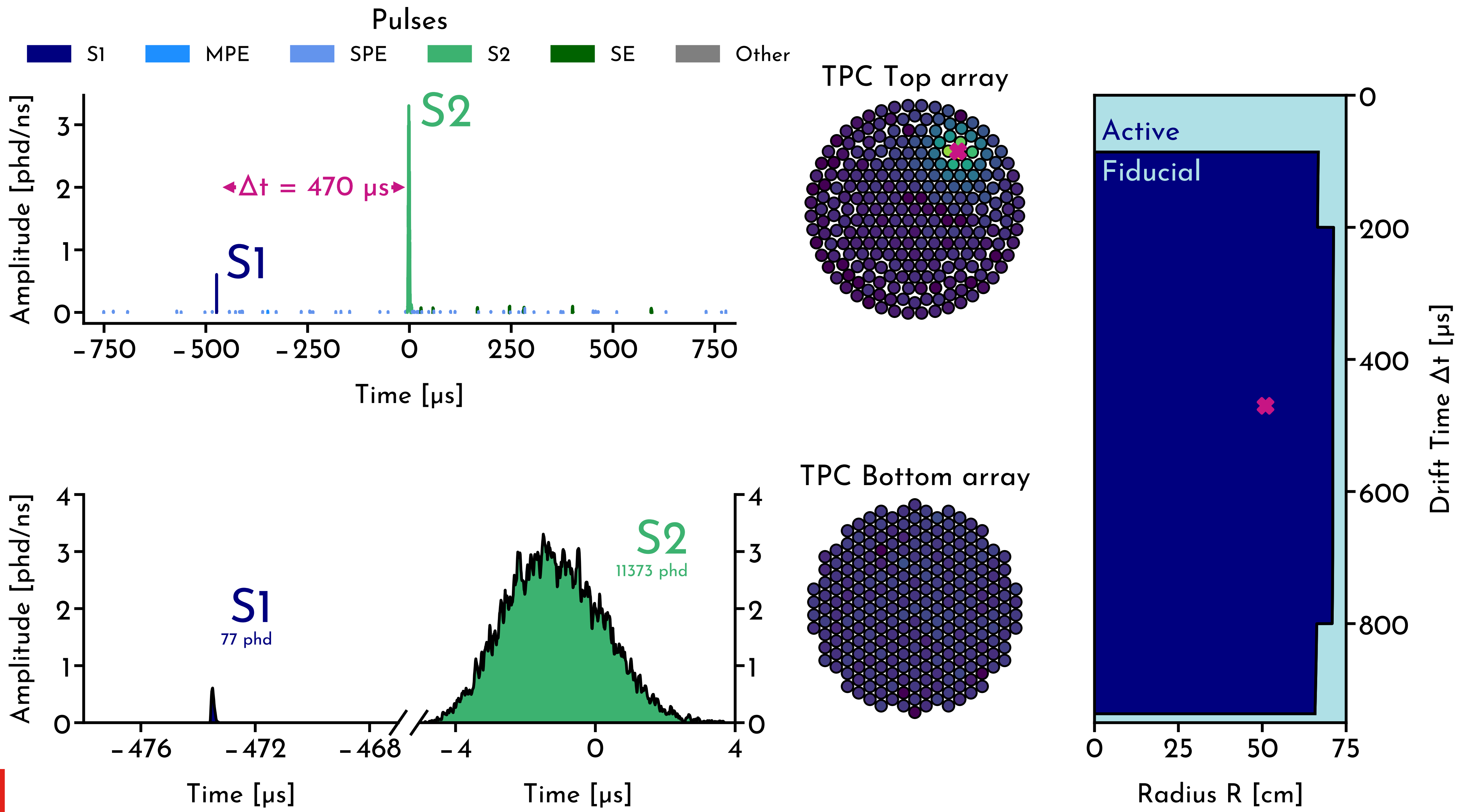

- Proven track record for ~2 decades
- Scalable technology
  - kg to multi-tonne scale

# 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 electrons drift time
- Discriminate electron (ER) and nuclear (NR) recoils using S2/S1

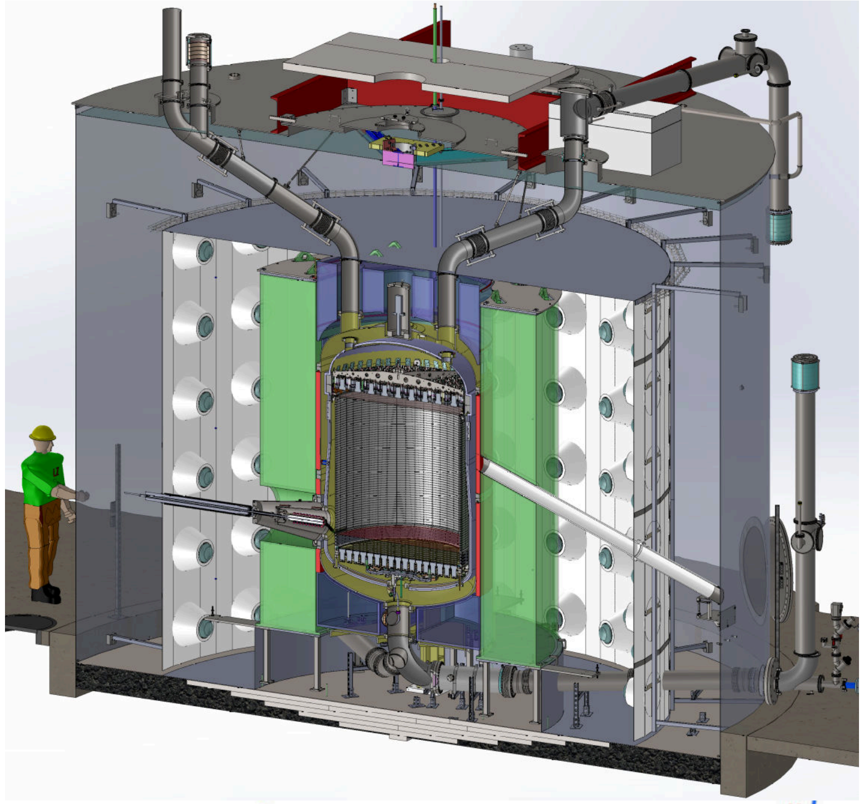


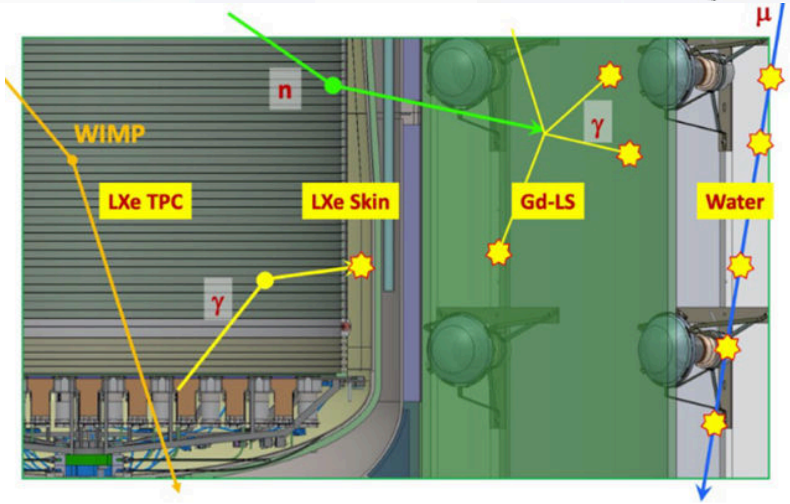




Pulses
S1
MPE
SPE
S2
SE
Other
Amplitude [phd/ns]
S2
S1
Δt = 470 μs
Time [μs]
S1
77 phd
S2
11373 phd
Time [μs]
Time [μs]
TPC Top array
TPC Bottom array
Active
Fiducial
Drift Time Δt [μs]
Radius R [cm]

# Veto detectors

- Outer detector (OD):
  - 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
  - Achieved high neutron veto efficiency in WS2024
    - 89 ± 3 % derived from AmLi calibrations
    - **92 ± 4 %** from background neutron simulations



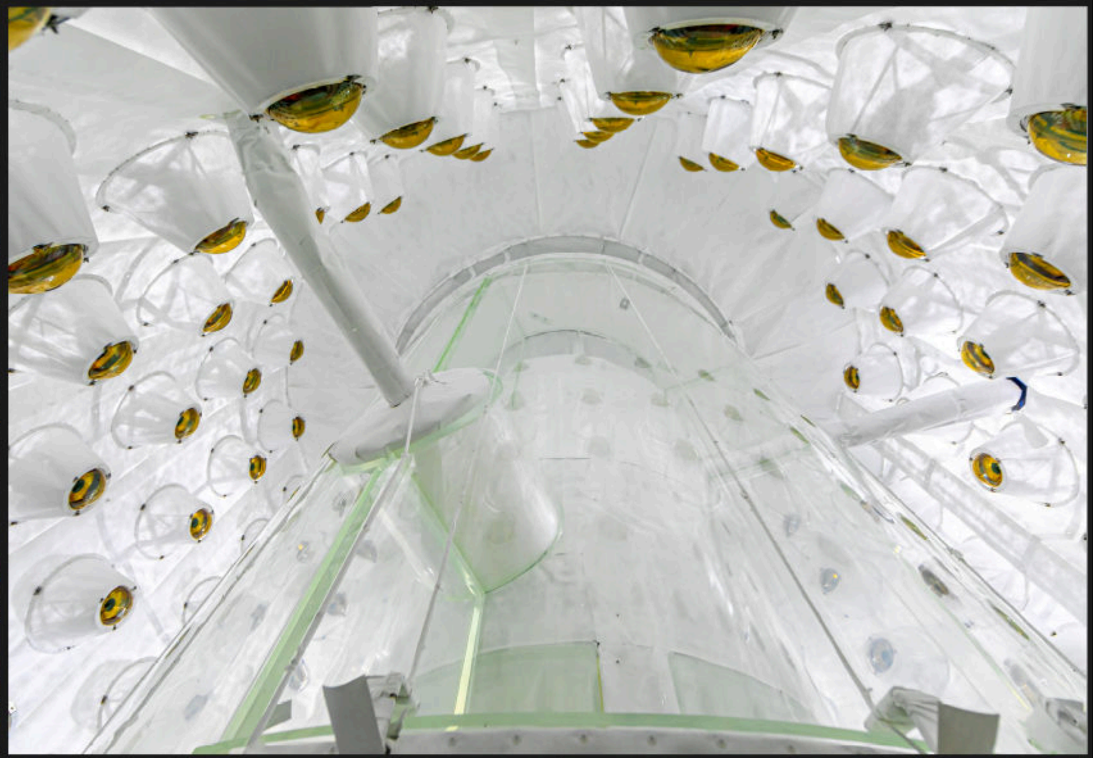



TPC Underground 2019

Installation complete 2020

Science data from 2021

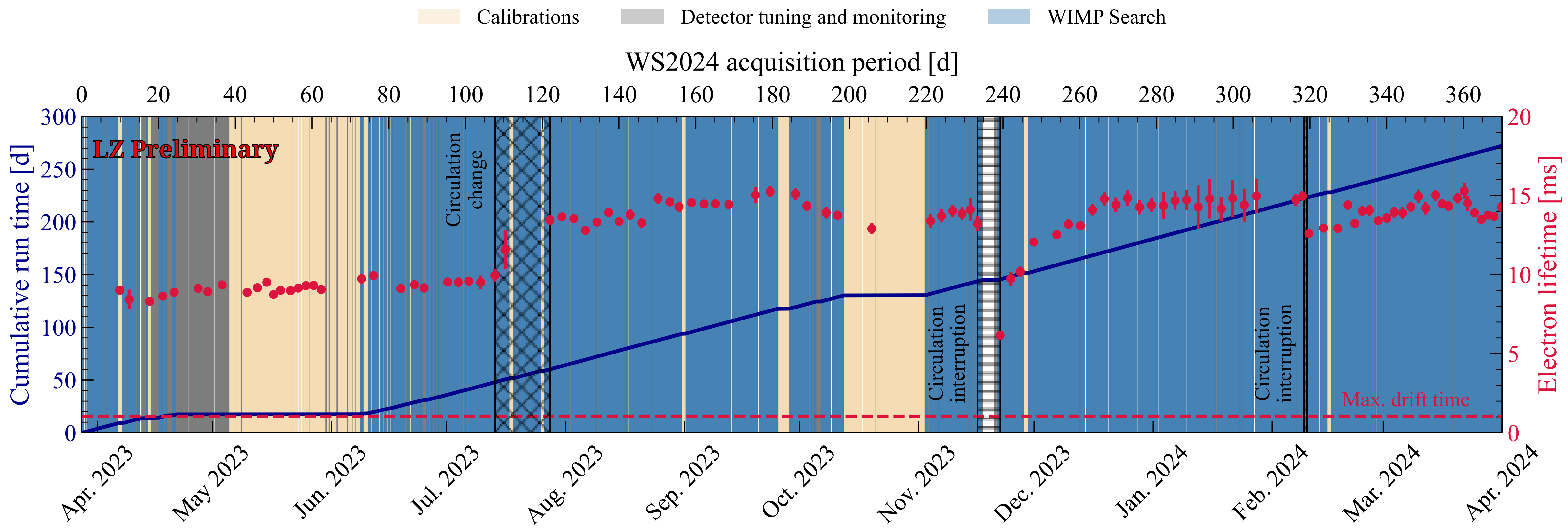
World leading WIMP limits 2022

# 2024 Science Run (WS2024)

WIMP Search 2024 paper arXiv:2410.17036

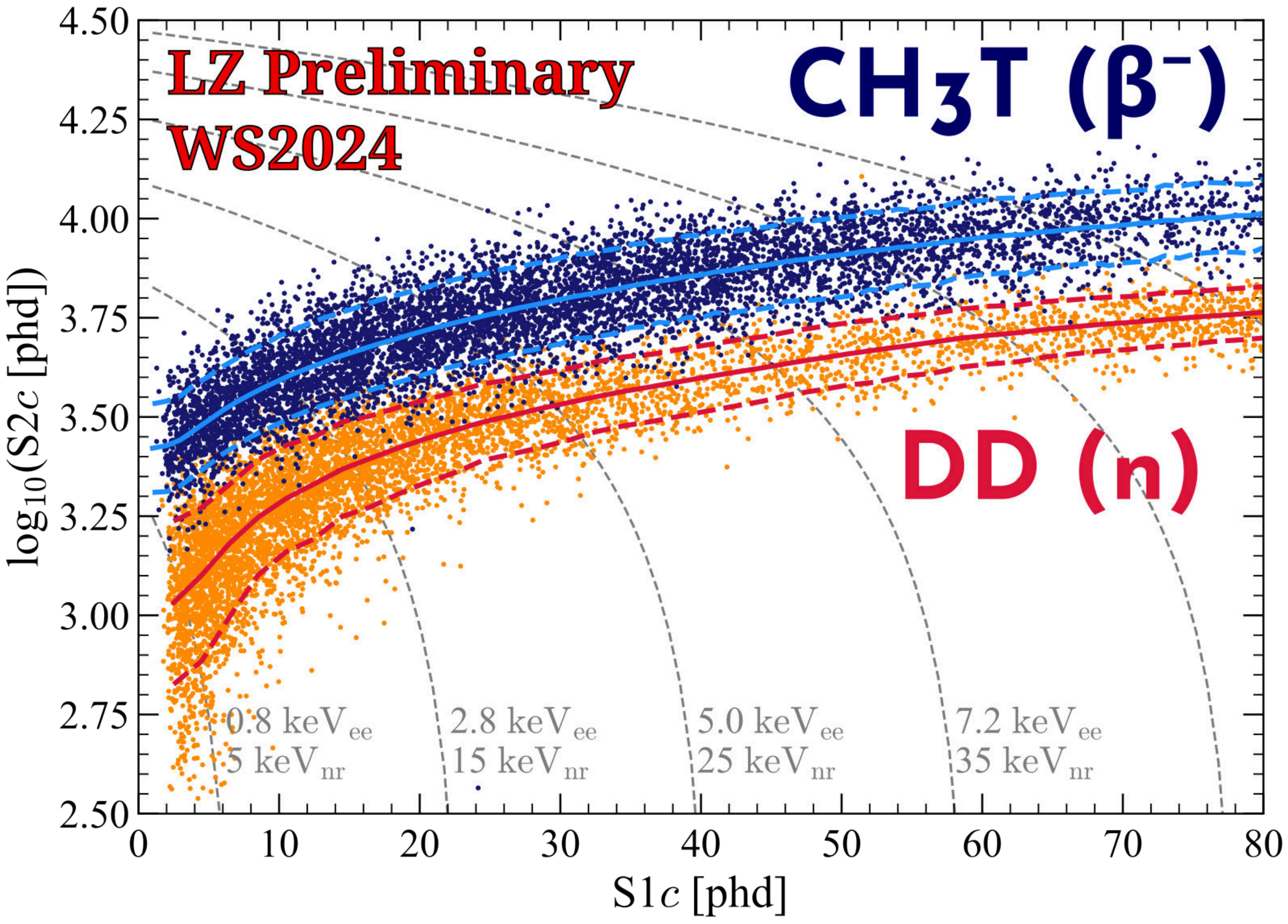
- Acquired data for ~370 days with 95.2% detector up-time
  - **220 day exposure after data quality cuts**
- Performed intermittent calibrations
- High target purity throughout
  - Minimal suppression of charge (S2) signals



# Calibrations in WS2024

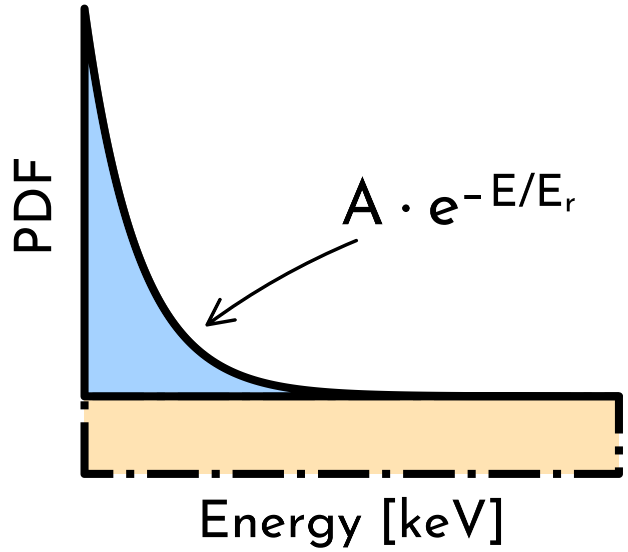
LZ calibration systems | 2024 JINST 19 P08027

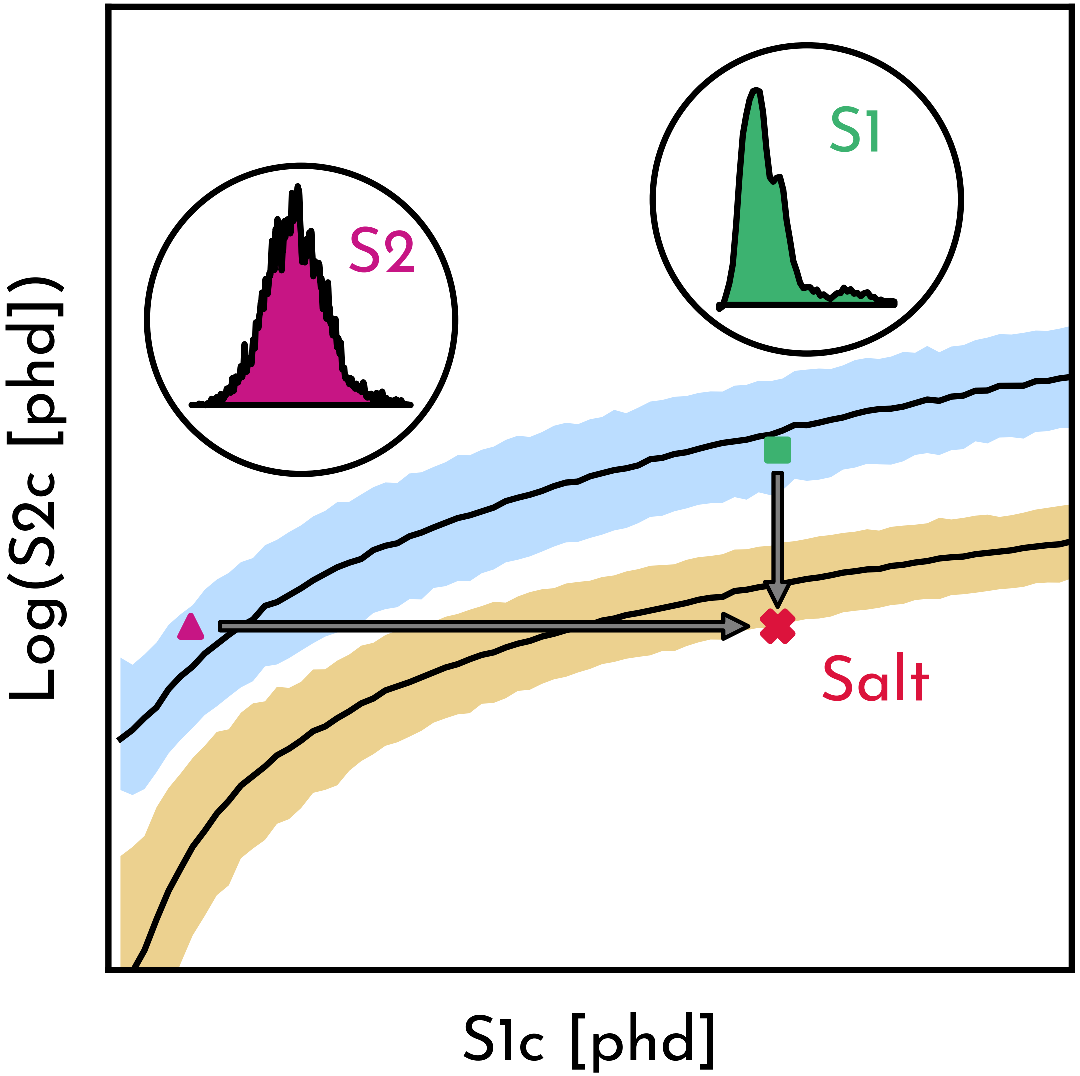
- Electronic recoils (background)
  - Tritium radio-labelled methane & $^{14}C$
  - Mono-energetic $^{83m}Kr$
- Nuclear recoils (signal)
  - DD neutron generator (2.45 MeV neutrons)
  - An AmLi source, which emits low energy (<1.5 MeV) neutrons, can be positioned at nine different depths
- WS2024 NEST 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



# 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

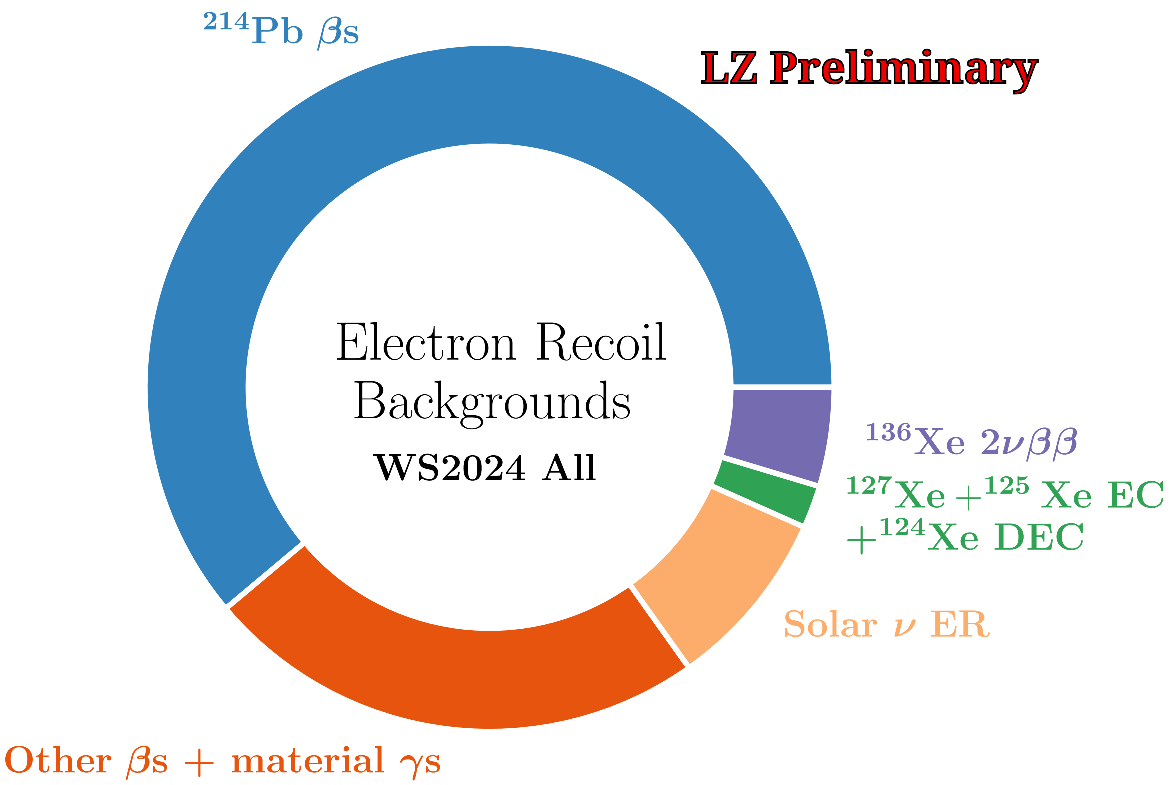


# WS2024 Background Model

- 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 (DEC)
  - Solar neutrinos
- Expect 0.18 NR CEνNS 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

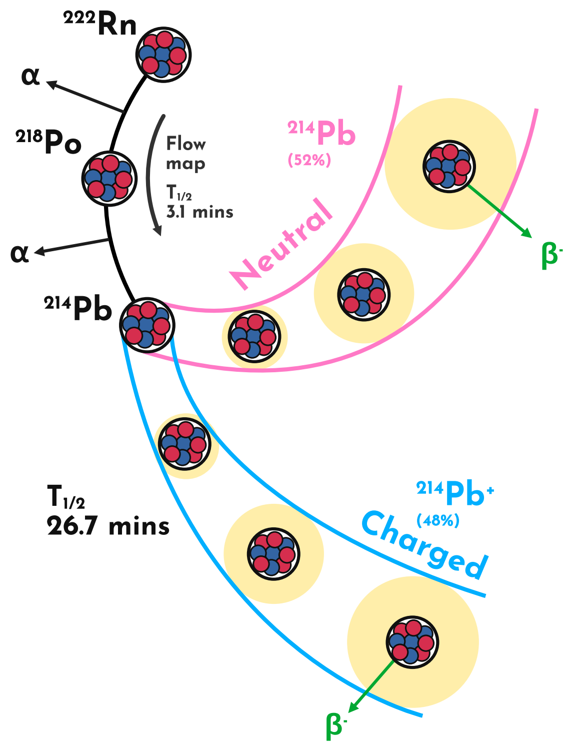
WS2022 background model | Phys. Rev. D 108, 012010



# Radon tagging

See Simran's talk 5:00 PM

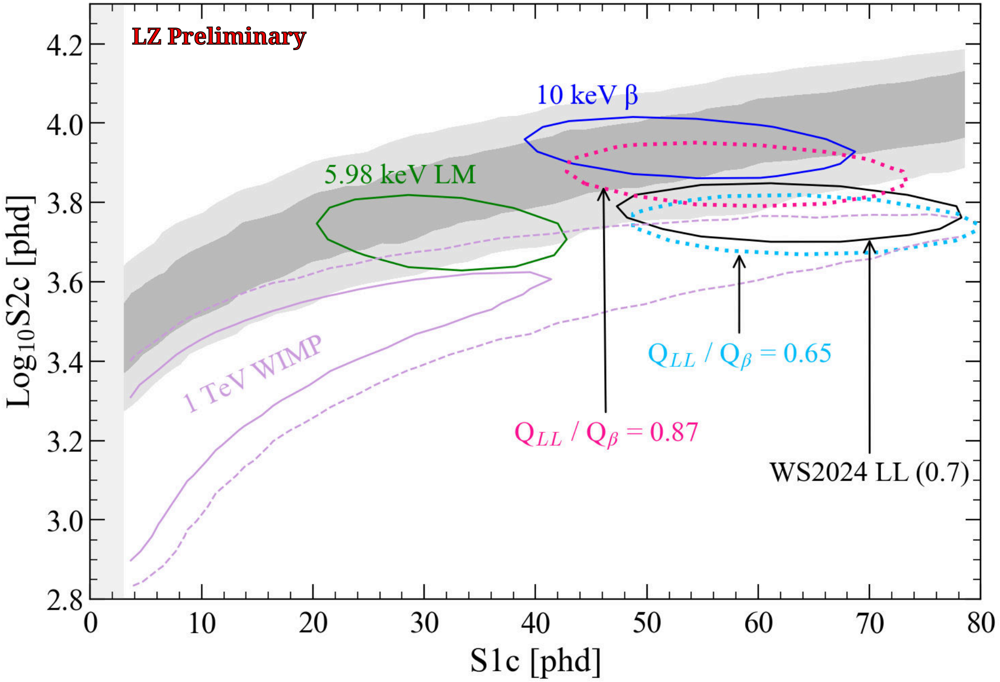
- Predict future $^{214}Pb$ decays
  - Observe $^{218}Po$ α-decay
  - Tag interactions around Xe streamlines
  - Track for 81 minutes (~3 × $^{214}Pb$ $\tau_{1/2}$)
  - Tag incorporated into statistical analysis
  - **~60% tagging efficiency**




# Electron Captures (EC)

See Olivia's talk 4:45 PM

- Background in LZ (5.2 keV L-shell):
  - Single EC: $^{125/127}Xe$ - from neutron activation
  - Double EC: $^{124}Xe$ - **$T_{1/2} \sim 10^{22}$ years!** [1,2]
- EC suffers from charge suppression [3]
  - **Looks more NR like than normal**




[1] XENONnT measurement Nature 568, 532–535 (2019)
[2] LZ measurement J. Phys. G: Nucl. Part. Phys. 52 015103
[3] XELDA measurement Phys. Rev. D 104, 112001 (2021)



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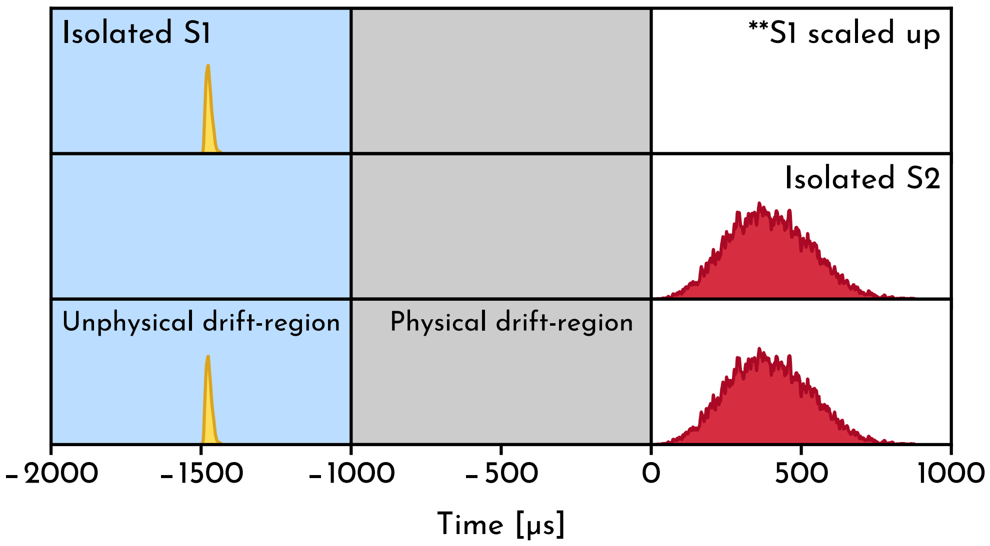
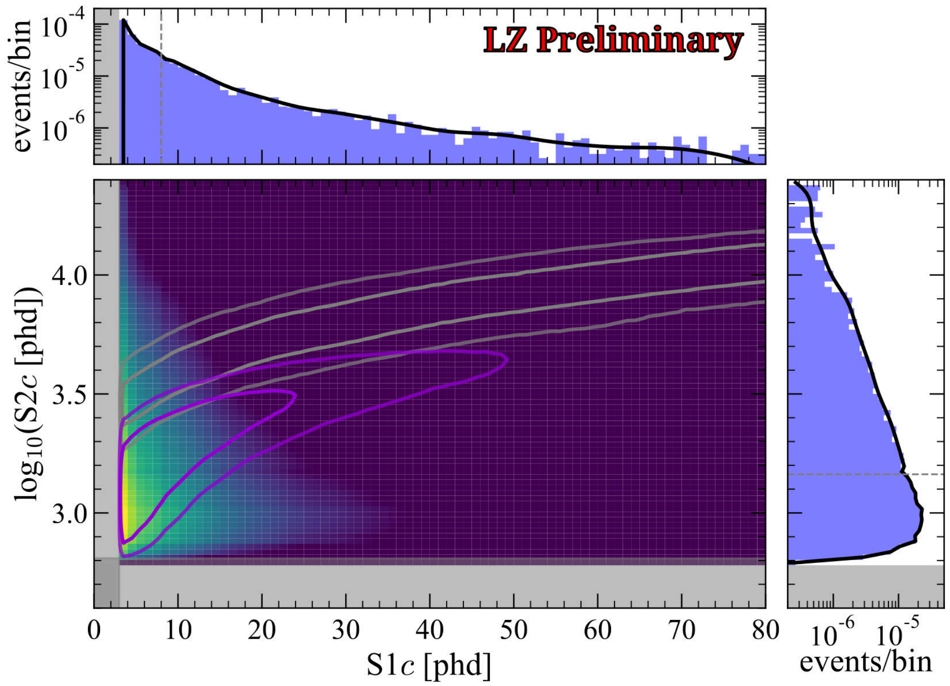
# Accidental background

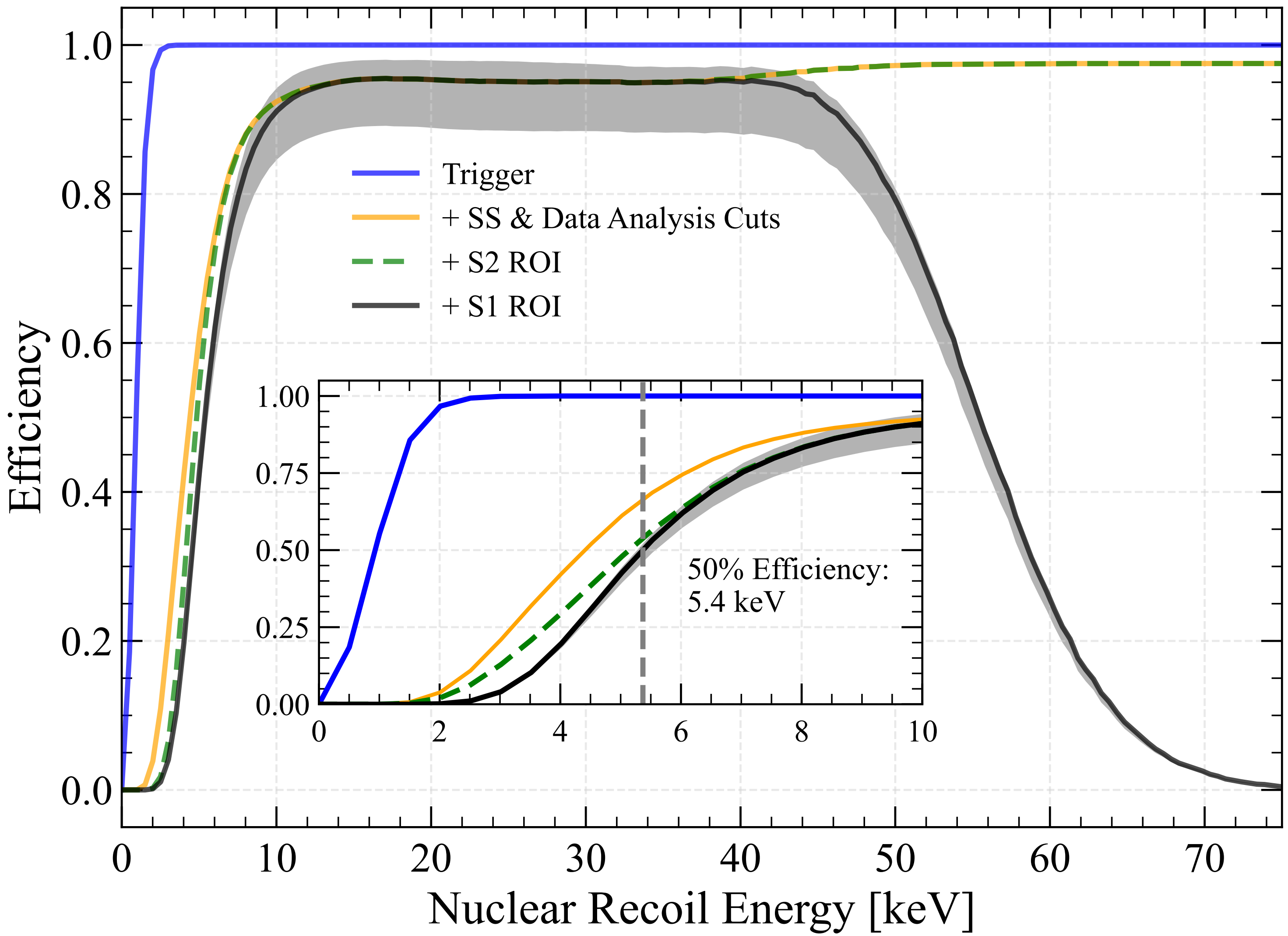
- Pile-up of unrelated S1-like and S2-like pulses
  - Looks like a single scatter and can mimic a WIMP
- Fraction of these have an unphysical drift time
  - Population to calculate rate with physical drift-time
- Model as product of isolated S1-like and S2-like pulses
- Distribution peaks in the low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



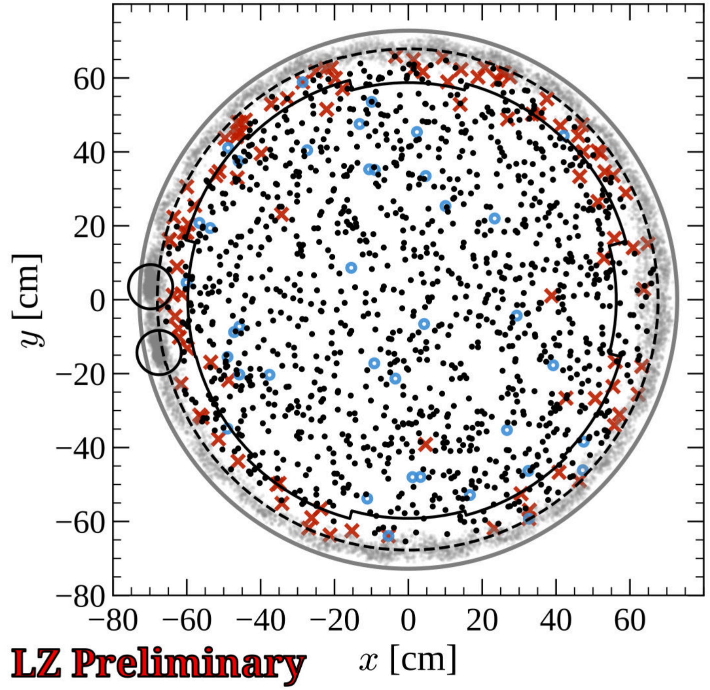
# Signal Acceptance

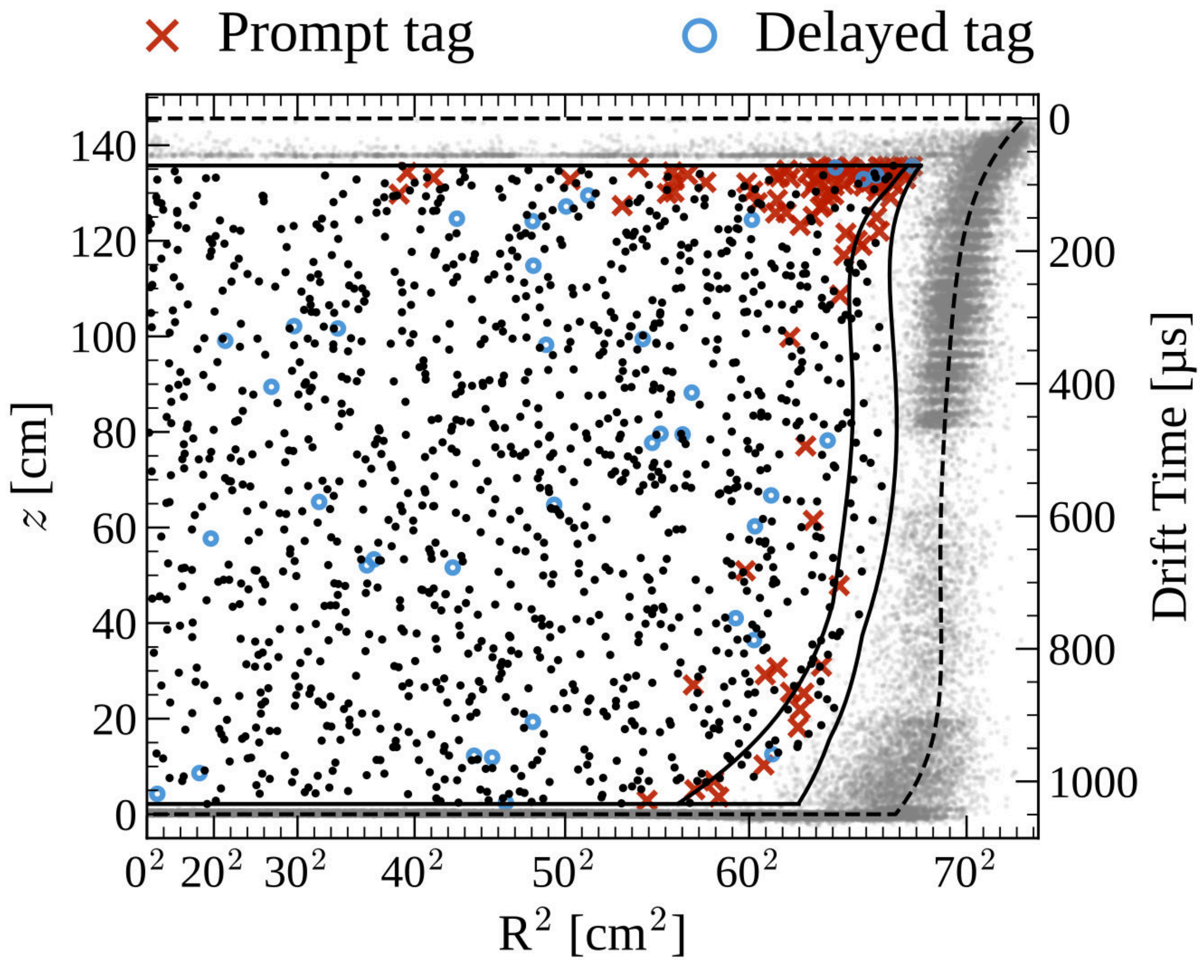
- Region of interest (ROI):
  - $S1_c$ = (3, 80) phd
  - $S2_c$ = (645, $10^{4.5}$) phd
    - Excludes $^8B$ for dedicated analysis
- Multiple event and pulse level cuts
  - FV, ROI, single scatter
  - Veto anti-coincidence
    - Delayed neutron capture
    - Prompt γ-ray interactions
  - S1 & S2 based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



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

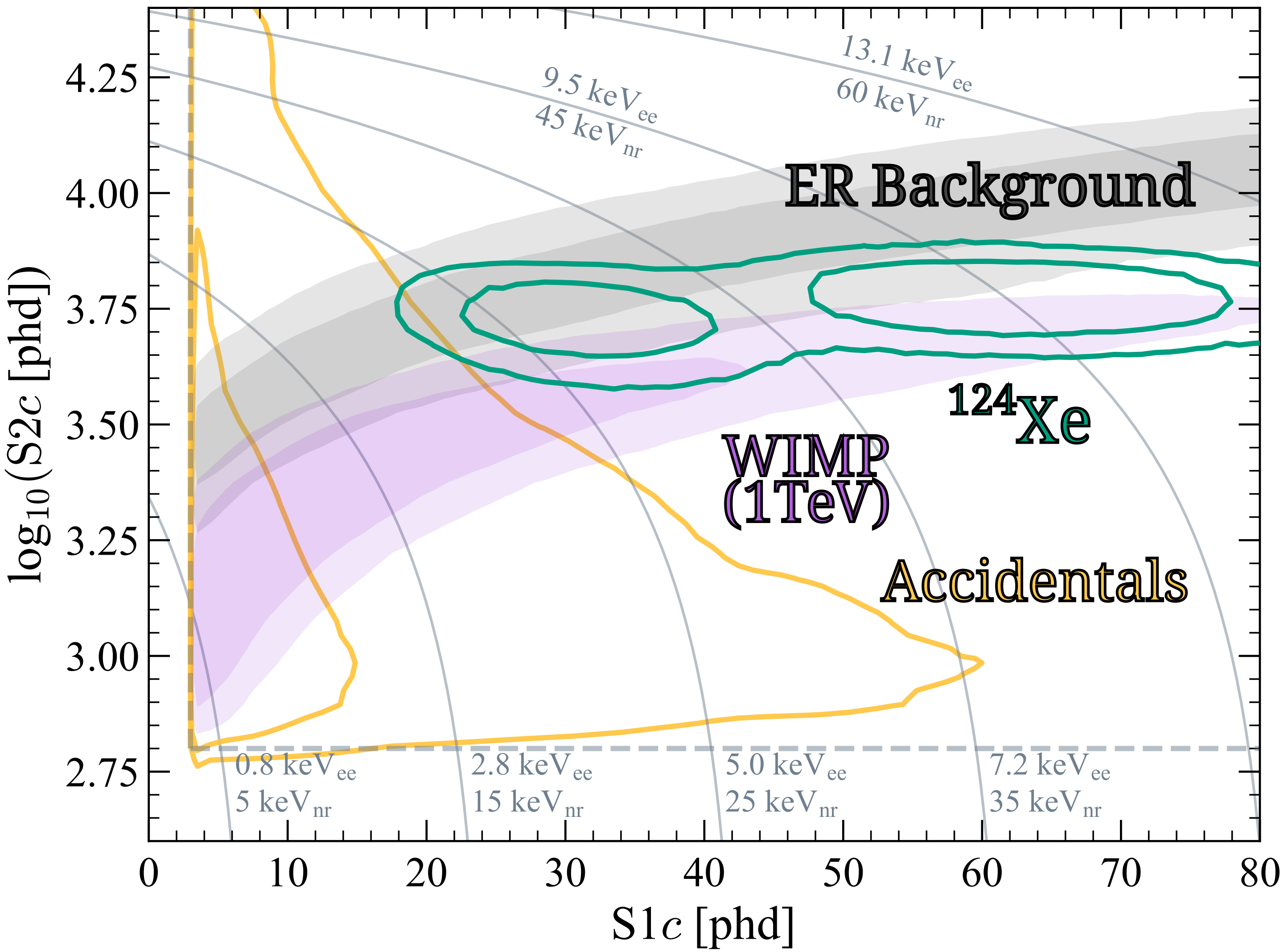
- Majority of backgrounds are peripheral
  - Self-shielding prevents infiltration
- Reject the majority of backgrounds with a fiducial cut
  - Azimuthal dependence added for WS2024
    - Full range shown by two solid lines in z-$R^2$ plane
  - Defined to admit **<0.01 wall background events**
- Fiducial mass of **5.5 ± 0.2 tonnes**



# Analysis of WS2024

- Statistical analysis in $\text{Log}_{10}(S2_c)$-$S1_c$ 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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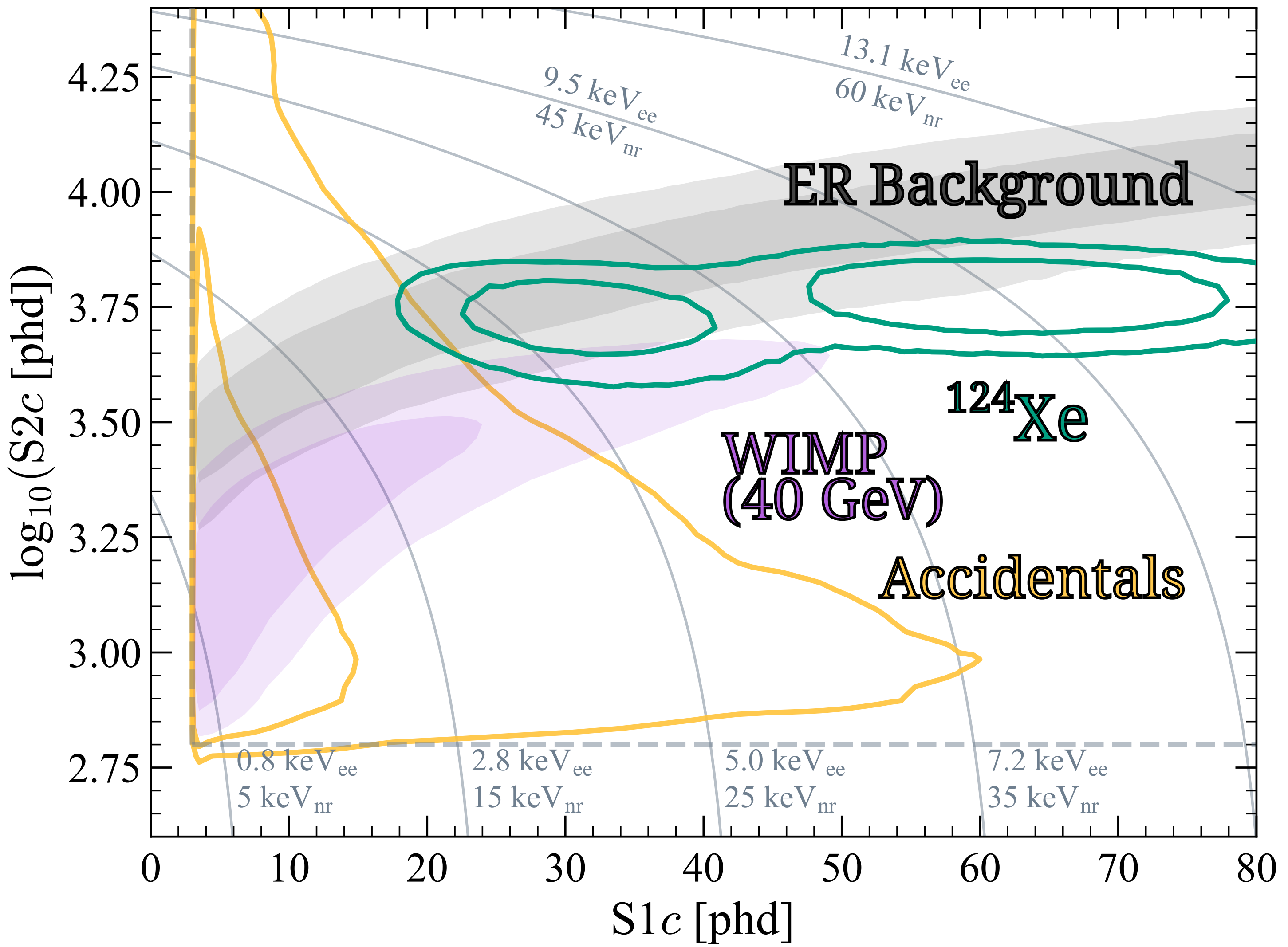

# Salted WS2024 result

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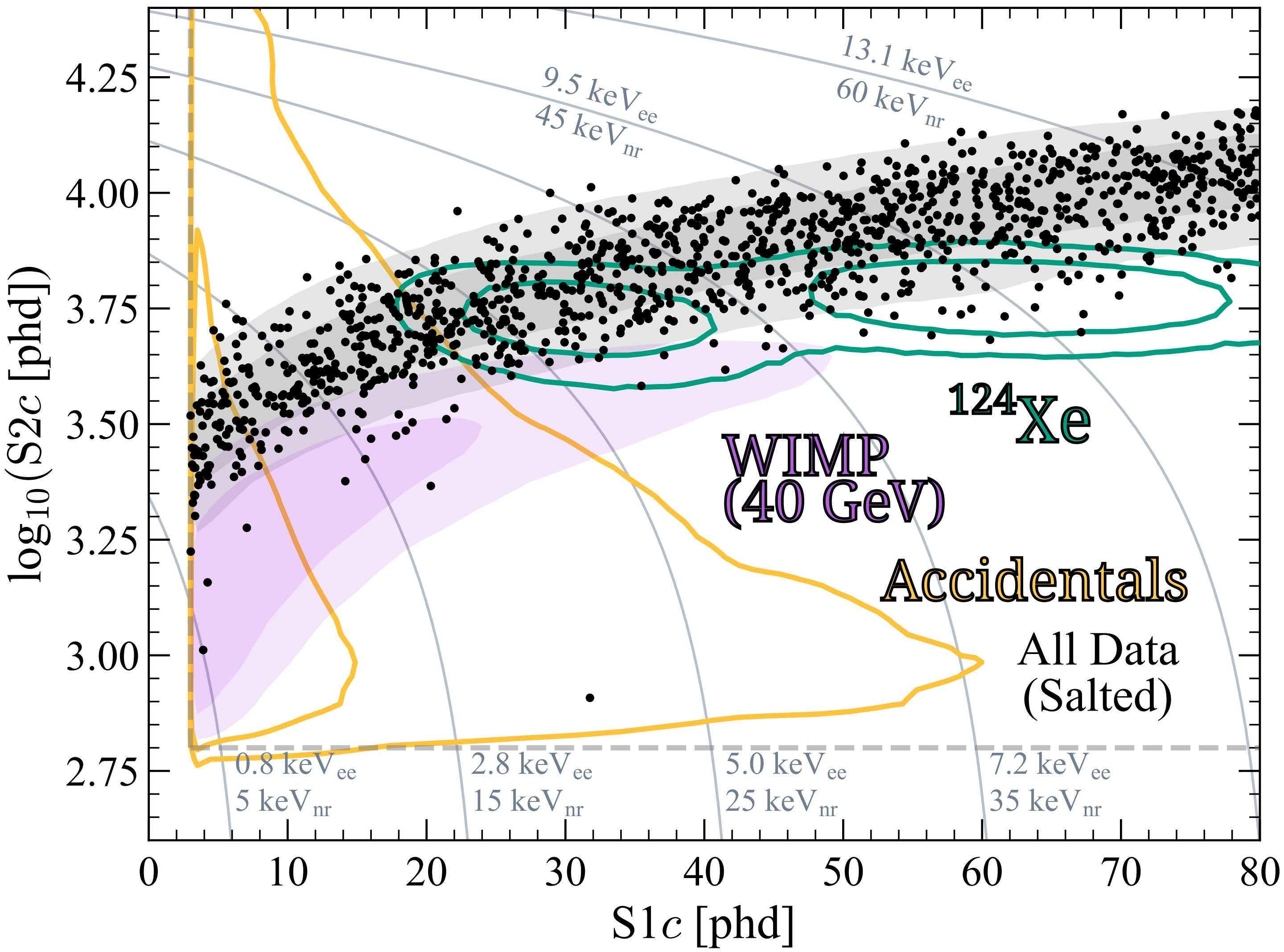
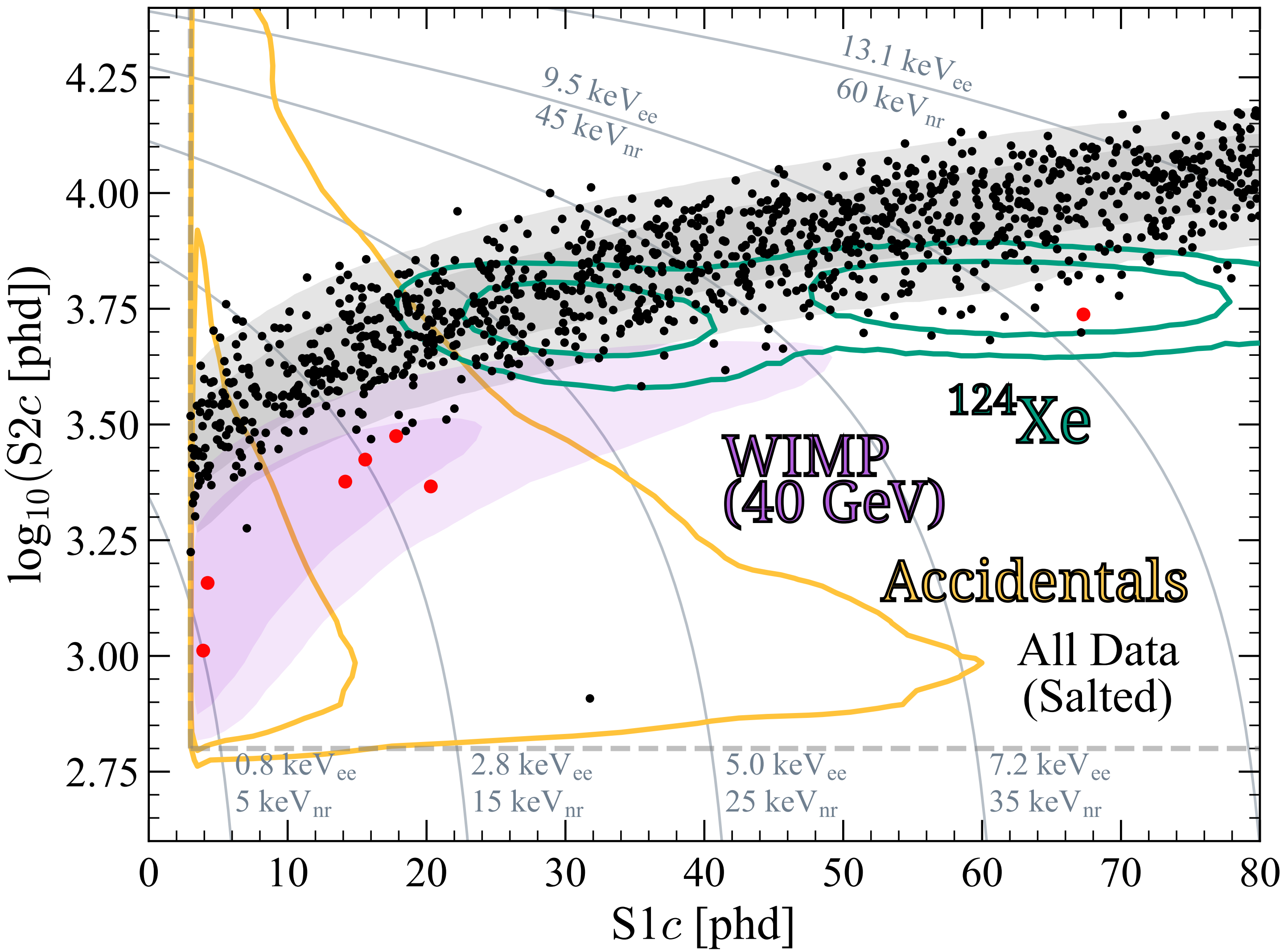
  - $S1_c$ = (3, 80) phd
  - $S2_c$ = (645, $10^{4.5}$) phd
    - Excludes $^{8}B$ for dedicated analysis
- Injected artificial events (salt) from calibration for bias mitigation
- Exposure of 220 days × 5.5 tonnes:
  - 3.3 tonne-years



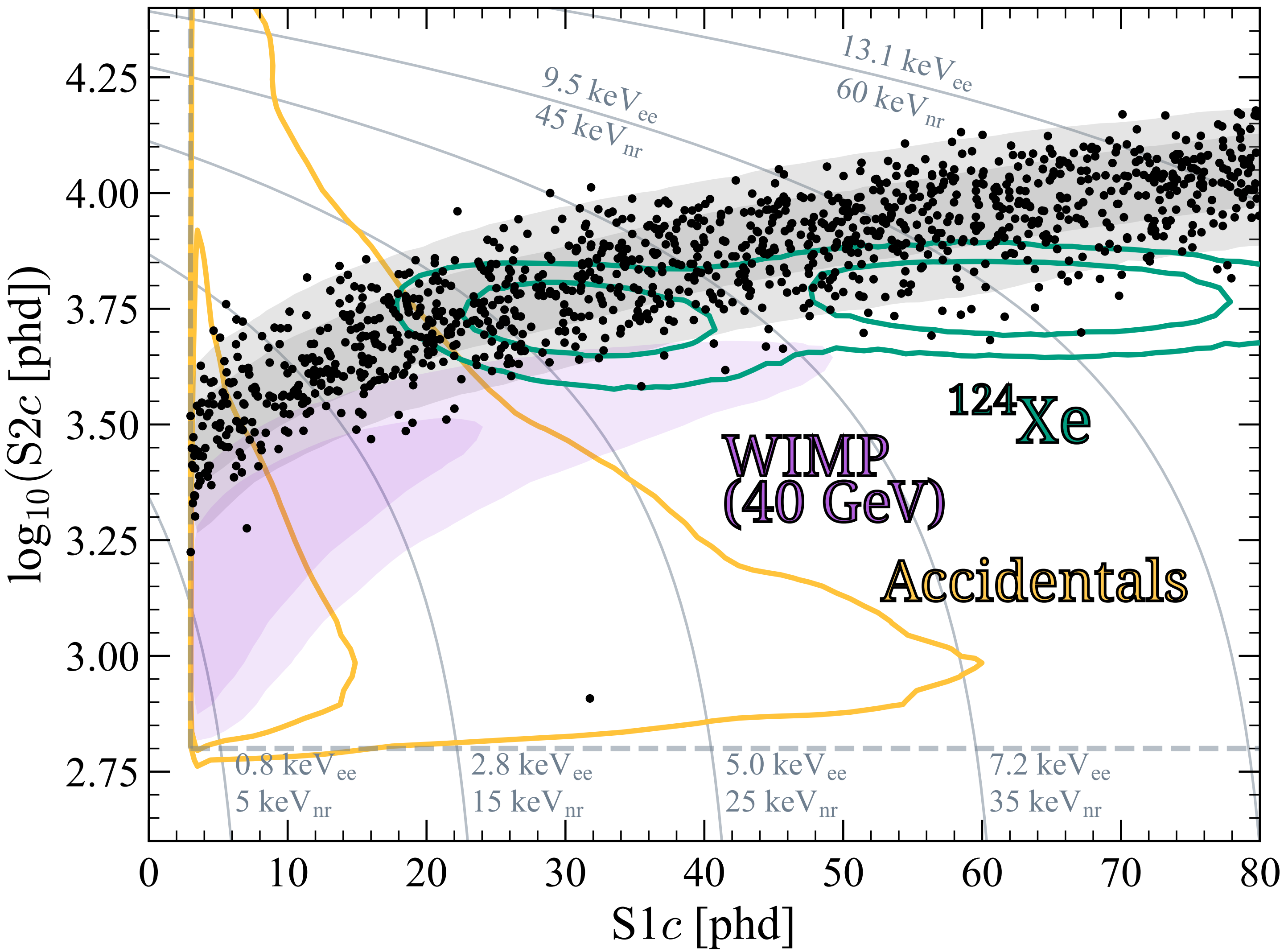
# Unsalted WS2024 result

- Statistical analysis in $\text{Log}_{10}(S2_c)$-$S1_c$ space
  - $S1_c$ = (3, 80) phd
  - $S2_c$ = (645, $10^{4.5}$) phd
    - Excludes $^8B$ for dedicated analysis
- Injected artificial events (salt) from calibration for bias mitigation
- Exposure of 220 days × 5.5 tonnes:
  - 3.3 tonne years
- 8 salt events injected
  - 1 was removed by cuts
  - This is consistent with the signal efficiency



# Unsalted WS2024 result

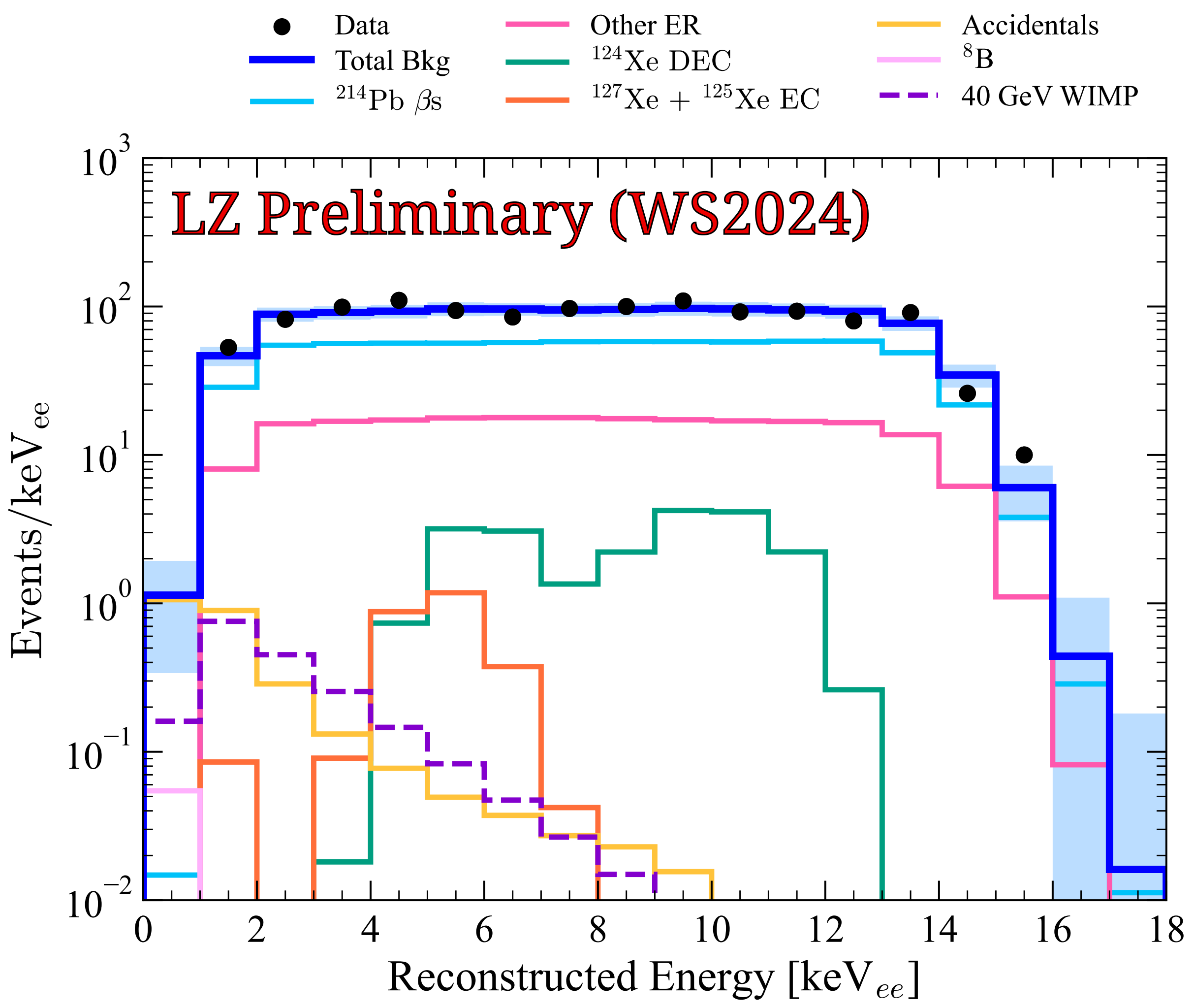
- Statistical analysis in $Log_{10}(S2_c)$-$S1_c$ space
  - $S1_c$ = (3, 80) phd
  - $S2_c$ = (645, $10^{4.5}$) phd
    - Excludes $^8B$ for dedicated analysis
- Injected artificial events (salt) from calibration for bias mitigation
- Exposure of 220 days × 5.5 tonnes:
  - 3.3 tonne years
- 8 salt events injected
  - 1 was removed by cuts
  - This is consistent with the signal efficiency
- 1220 events remain after un-salting
- **No changes to analysis post un-salting**



# Fit results in WS2024

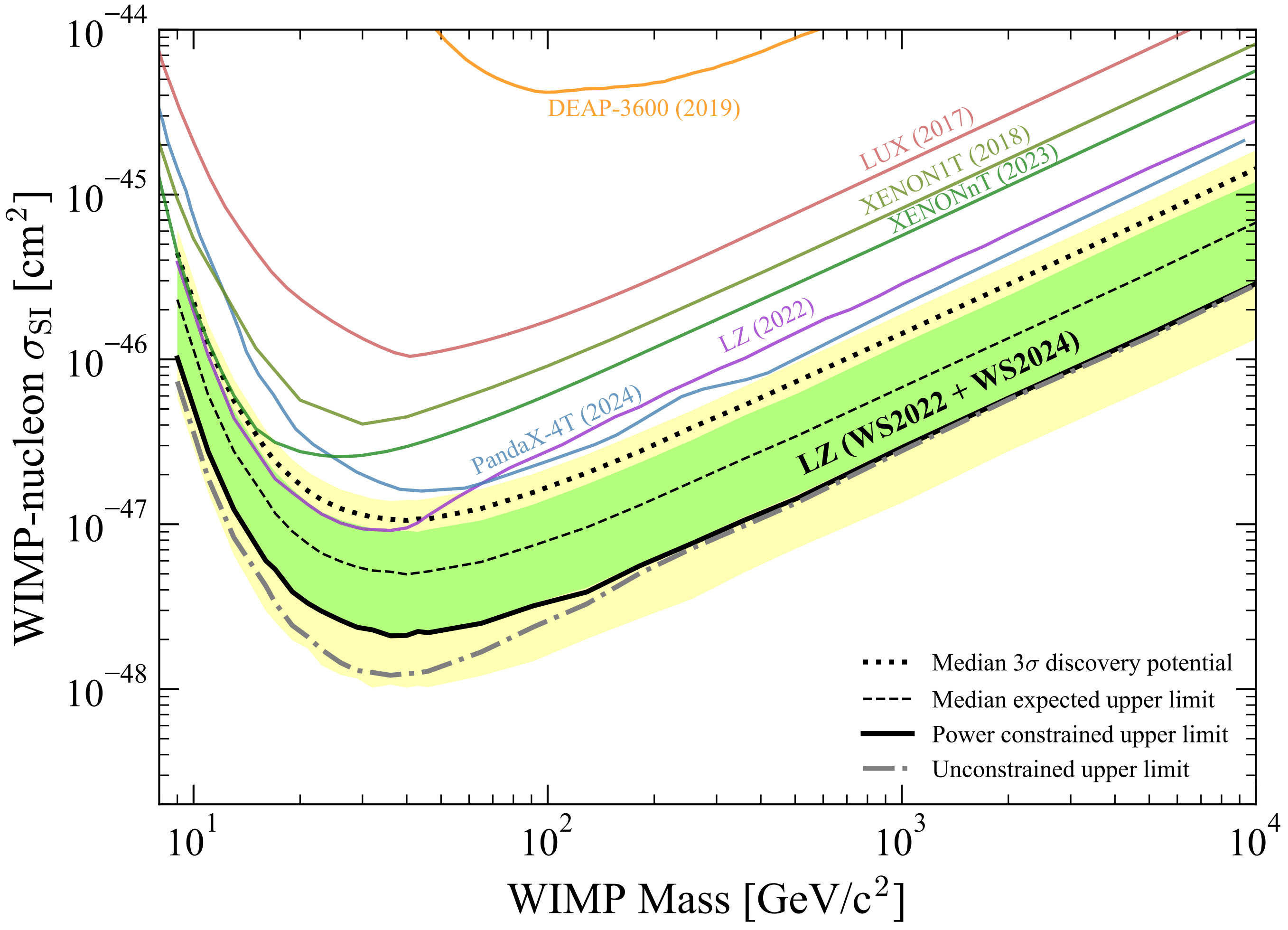
- Best fit of zero WIMPs at all masses (9 GeV → 100 TeV)
- Good agreement with background in all studied spaces

| 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

- Apply a profile likelihood ratio (PLR) analysis to search for WIMPs
  - Analysis power constrained at the -1σ level
- Included the WS2022 likelihood in the PLR
  - No changes to the WS2022 analysis or dataset
- Total exposure of 4.2 ± 0.1 tonne-years
- Peak sensitivity: **$2.1 \times 10^{-48}$ cm$^2$ @ 36 GeV/c$^2$**
- Factor of 4 improvement in sensitivity into new parameter space

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# 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 days of exposure
  - Multiple other areas of interest ($^{8}B$ CEνNS, 0ν2β, etc.)

# More from LZ

| | |
|---|---|
| WIMP search 2024 | arXiv:2410.17036 |
| WIMP search 2022 | Phys. Rev. Lett. 131, 041002 |
| WS2022 backgrounds | Phys. Rev. D 108, 012010 |
| Low energy ER searches in WS2022 | Phys. Rev. D 108, 072006 |
| MIMP dark matter search in WS2022 | Phys. Rev. D 109, 112010 |
| WIMP-nucleon EFT search in WS2022 | Phys. Rev. D 109, 092003 |
| 2ν DEC in Xe-124 | J. Phys. G: Nucl. Part. Phys. 52 015103 |

# 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

LZ Collaboration Meeting
June 2024 at Brown University

SANFORD UNDERGROUND RESEARCH FACILITY

UKRI Science and Technology Facilities Council

fct Fundação para a Ciência e a Tecnologia

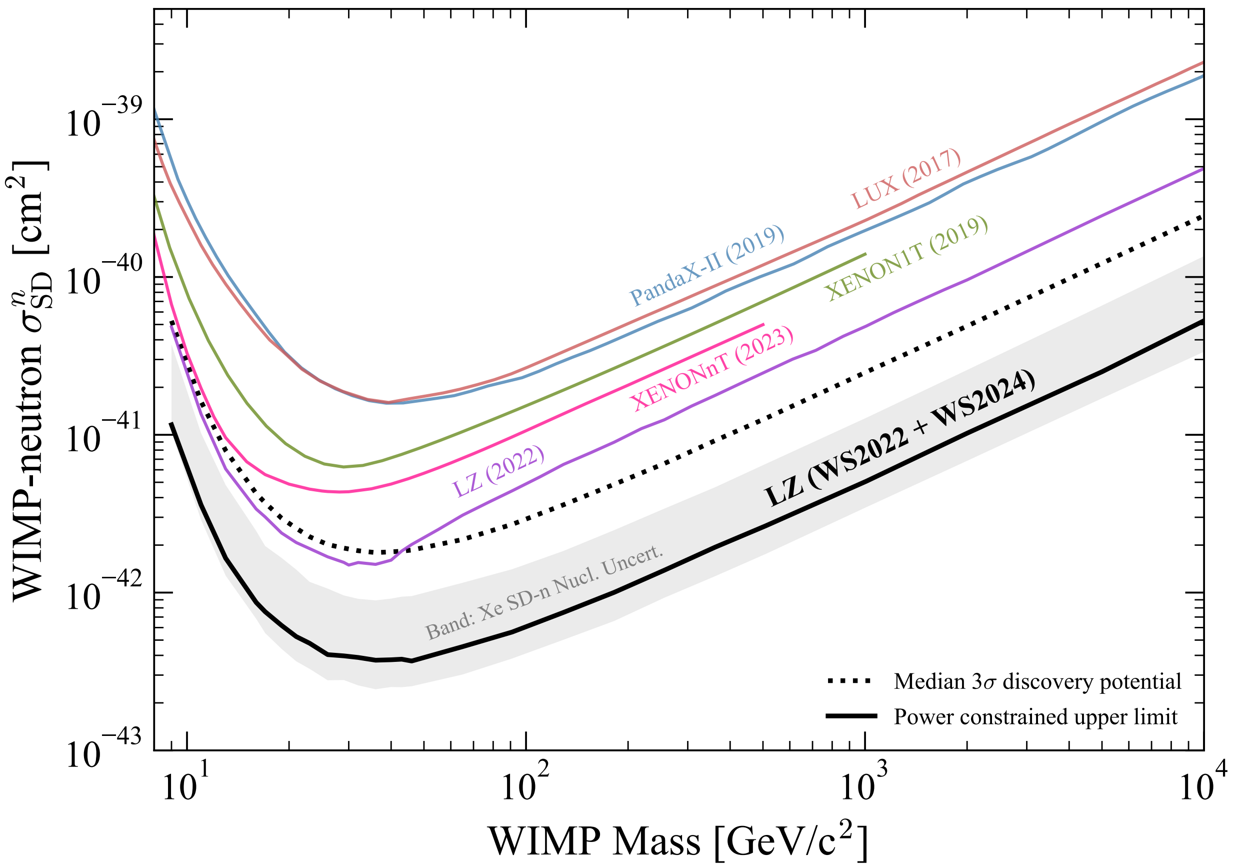
Swiss National Science Foundation

ibs Institute for Basic Science

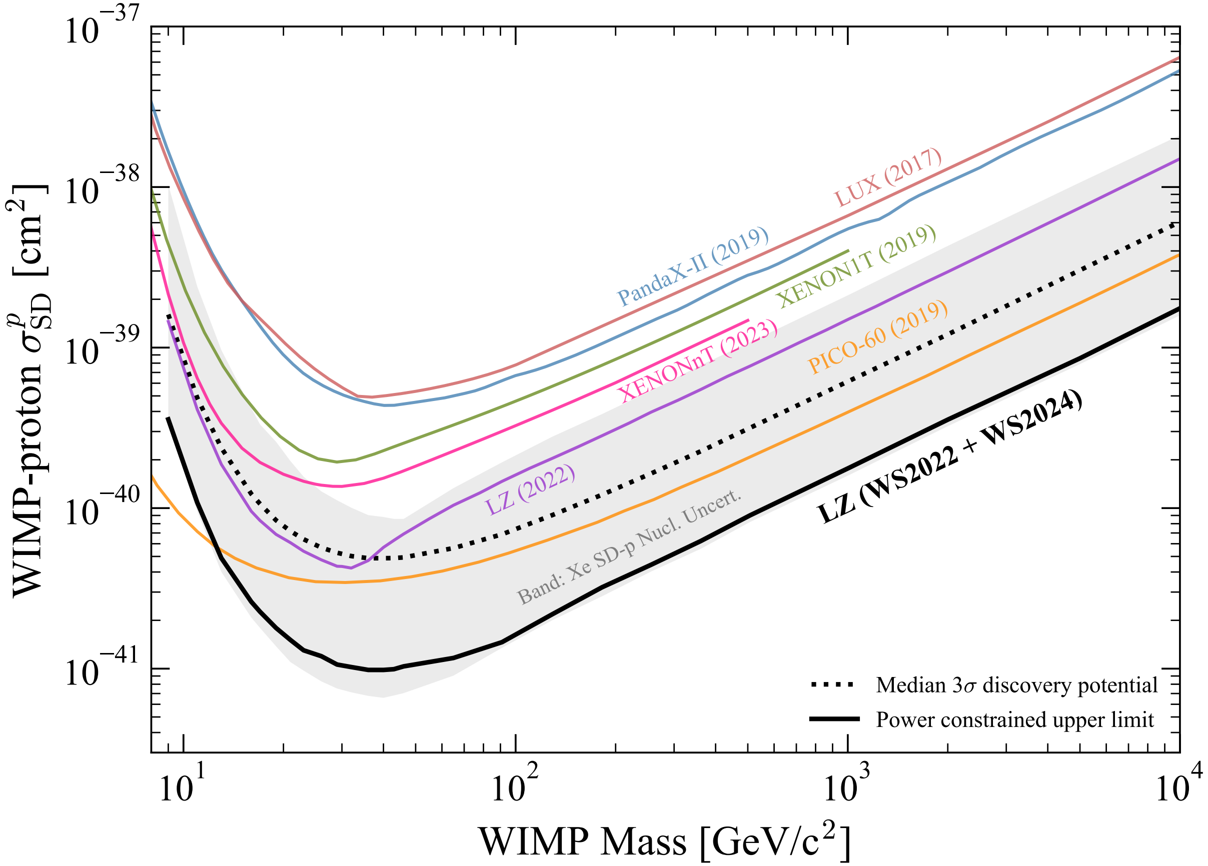
# Backup

# Combined 2024 & 2022 Spin-dependant Results

## Neutron




## Proton

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