

# LUX-ZEPLIN

## High Energy Nuclear Recoil 2024

Ewan Fraser

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## First Constraints on WIMP-Nucleon Effective Field Theory Couplings in an Extended Energy Region From LUX-ZEPLIN

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Megan Carter's Viva - September 1st 2026  
Now @ Penn State - LZ+ Postdoc

2022 High Energy Nuclear Recoil Search  
Lead Author - Billy Boxer PhD (2016-2020)

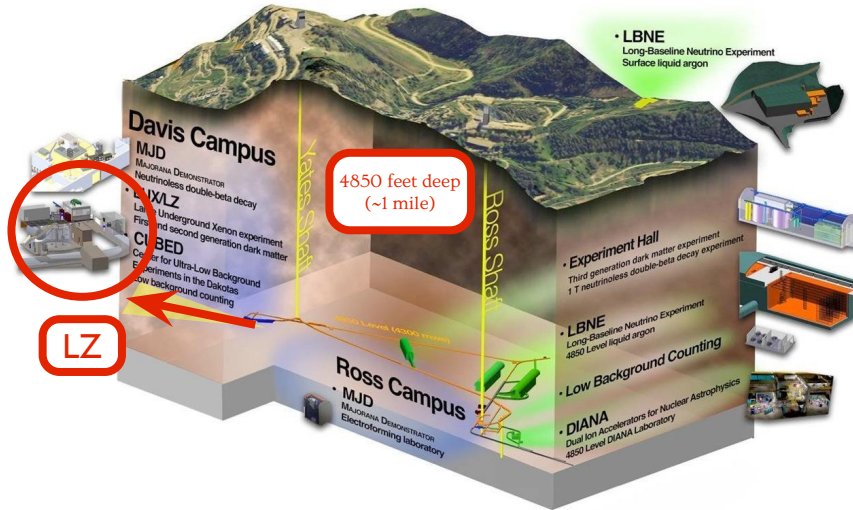
# LZ at SURF

## ❑ LUX-ZEPLIN is a Dark Matter direct detection experiment

- ❑ Rare event search - radiopure - WIMPs
- ❑ Natural abundance of  $^{136}\text{Xe}$  -  $0\nu\beta\beta$  search
- ❑ Running until 2028 - collecting 1000 livedays of data

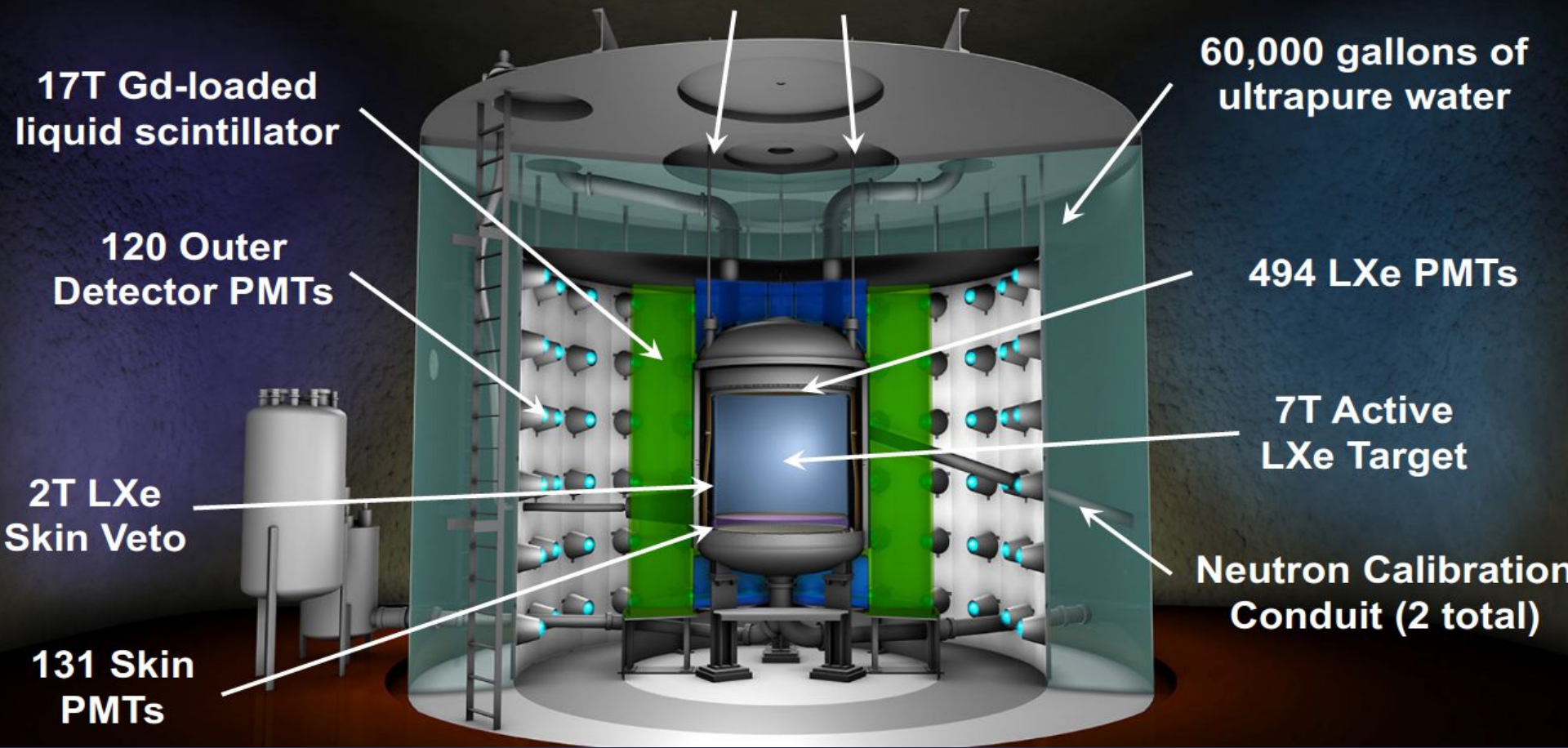
## ❑ Located at Sanford Underground Research Facility

- ❑ SURF - Homestake Mine, Lead, South Dakota
- ❑ ~1 mile underground, Davis Cavern
- ❑ Rock overburden reduces cosmic ray muon flux by  $O(10^6)$

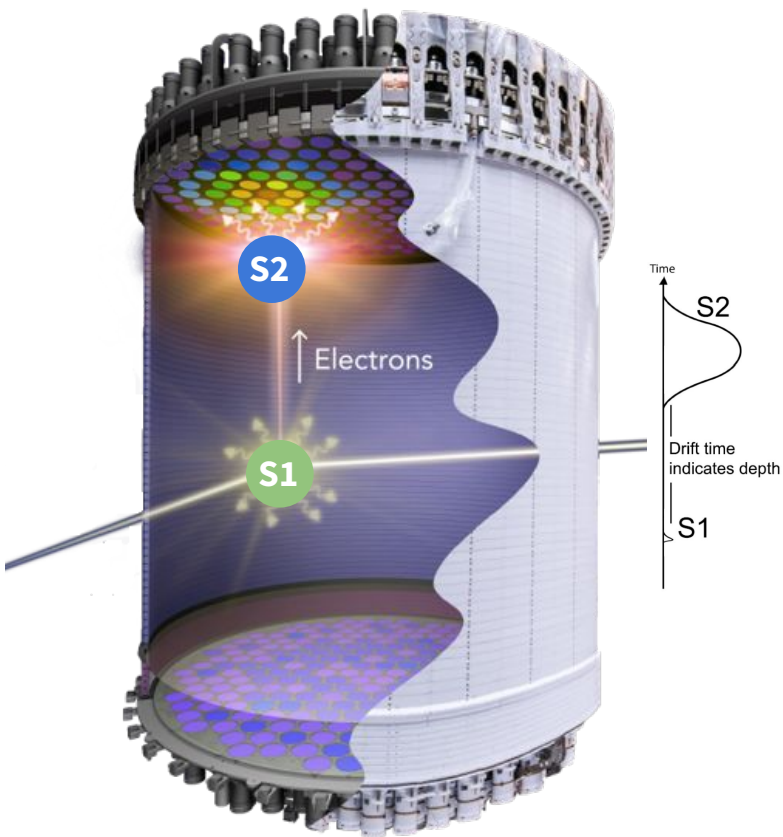


# LZ - Experiment for Direct Detection of WIMP Dark

## Calibration Source Deployment Tubes (3 Total)



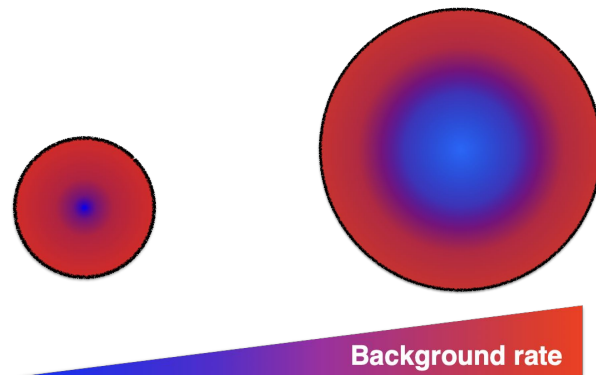
# Xenon Dual Phase Time Projection Chamber



Single Scatter interaction in TPC

Xenon Dual Phase Time Projection Chamber (TPC):

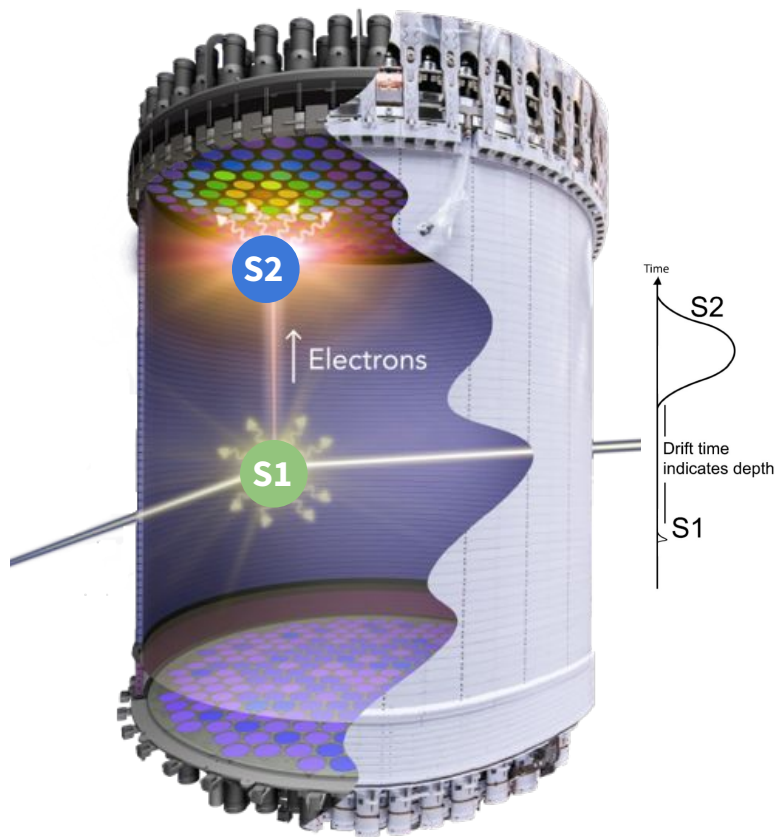
- ❑ LXe target, GXe extraction region
- ❑ S2 hit pattern, Drift Time - (x, y, z)
- ❑ Energy deposited reconstructed from - S1, S2
- ❑ **Particle discrimination - S1:S2 ratio**



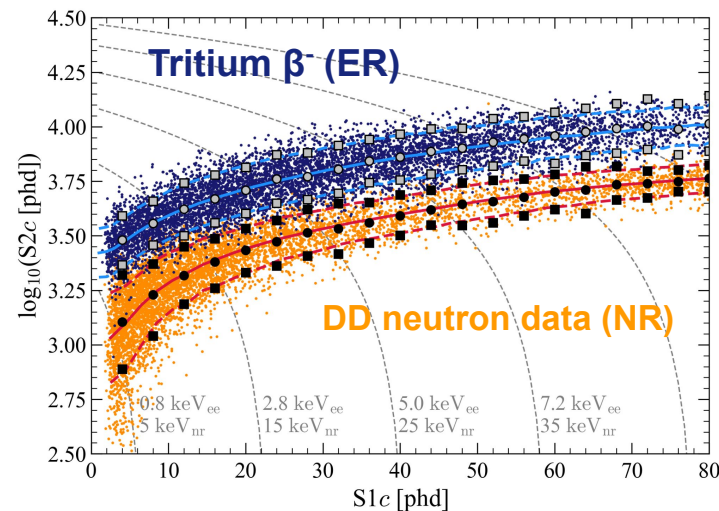
Why xenon?:

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

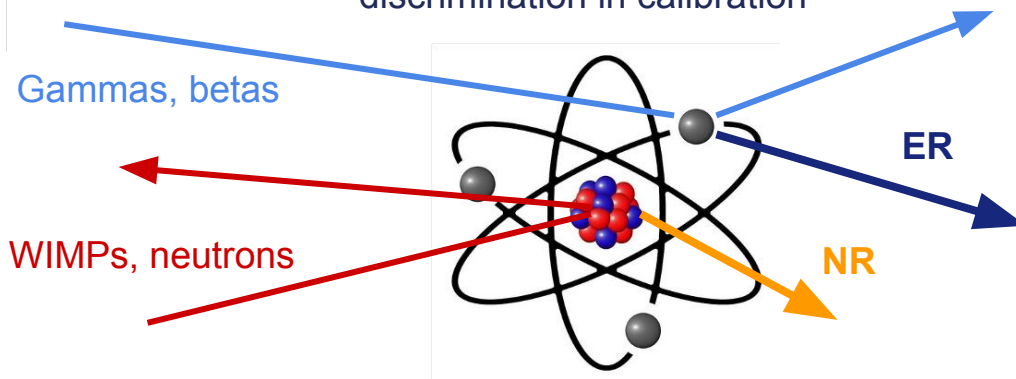
# Xenon Time Projection Chamber Principles



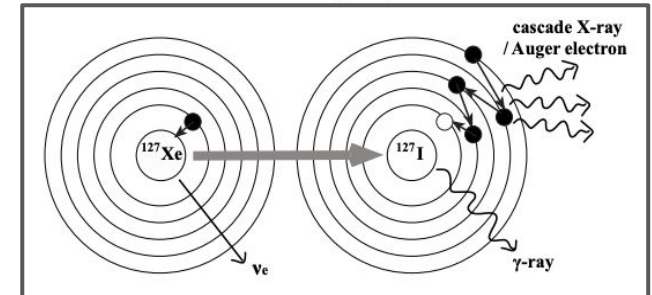
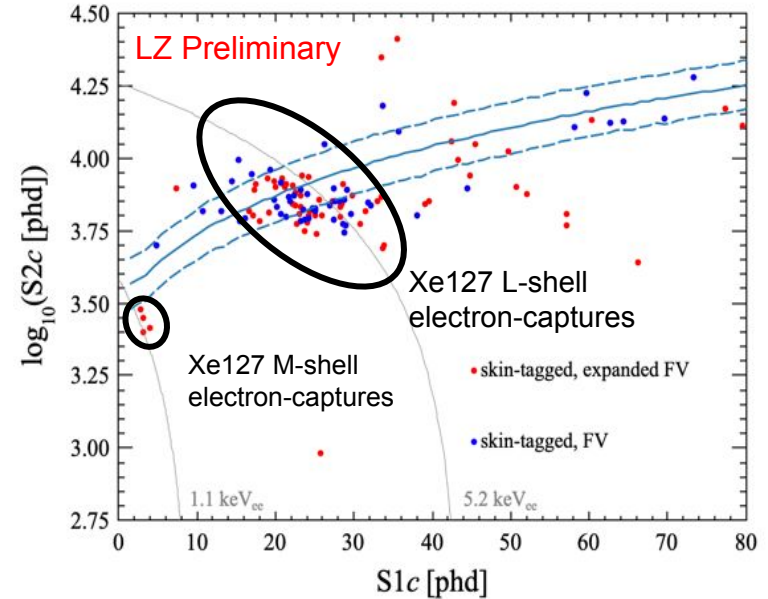
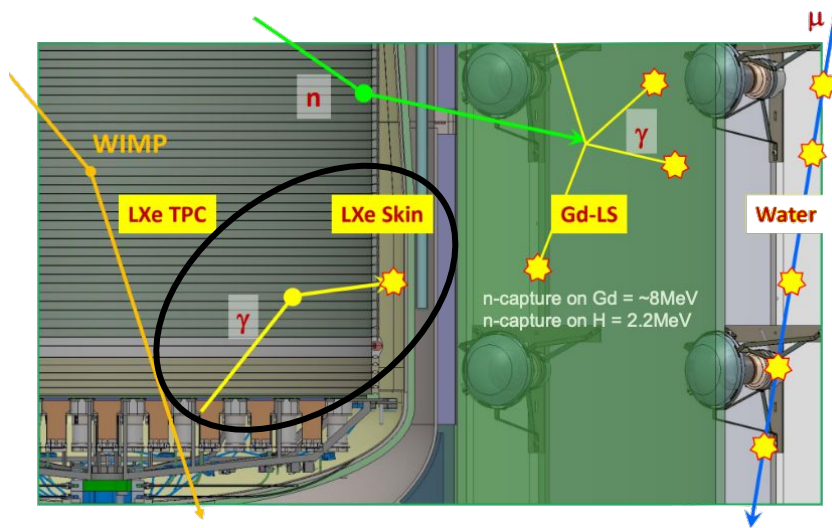
Single Scatter interaction in TPC



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



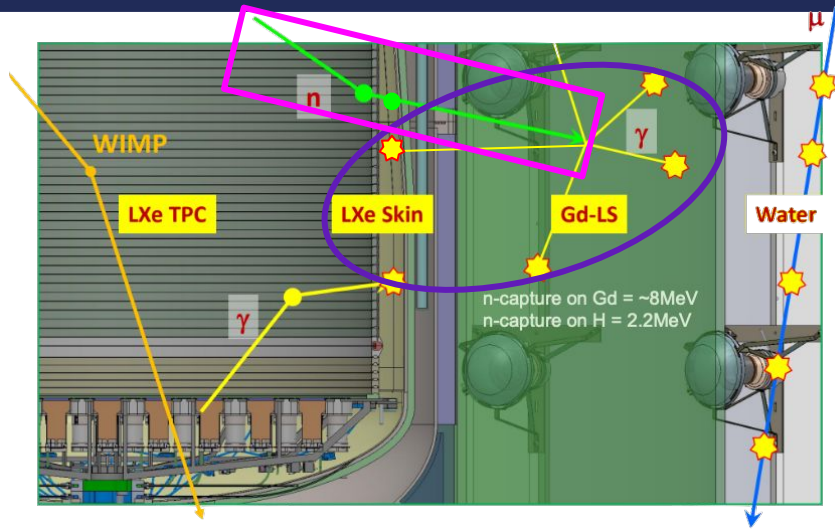
# LXe Skin



Courtesy of Jack Bargemann APS April 2023

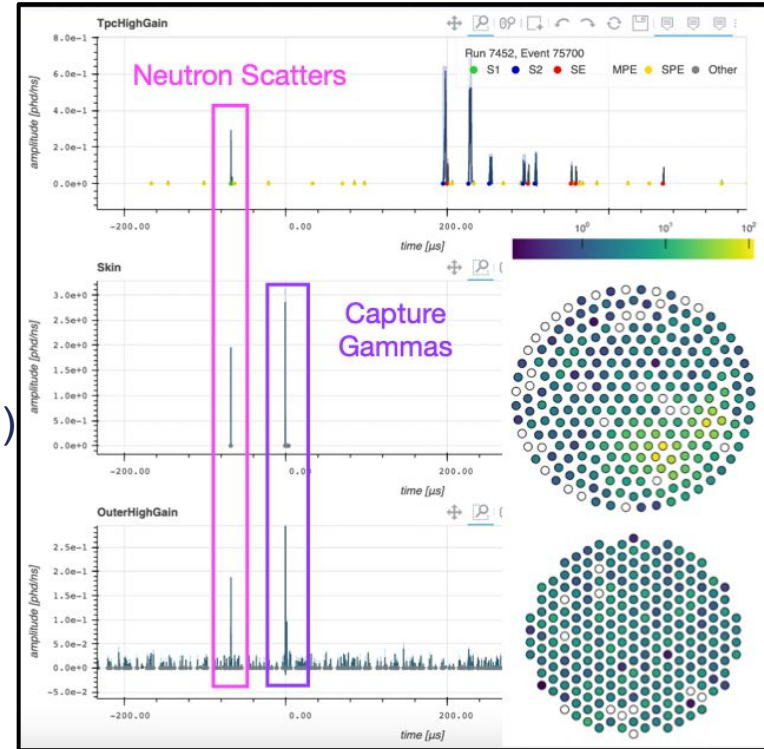
7

# Outer Detector



- 17 tonne of **Gd-loaded liquid scintillator** (120 8" PMTs)
- LZ has **~90% Single Scatter neutron veto efficiency**
  - Delayed Veto: > 250ns and < 600us**
- ~50Hz of background above 100-200 keV threshold
  - Gd alphas,  $^{14}\text{C}$  betas
  - ~3% false veto rate (deadtime)**

Waveform example of a tagged neutron multiple scatter:



# Rare Event Search Techniques - Radioassays

- ❑ Materials for LUX-ZEPLIN underwent an extensive radio-cleanliness campaign [[Eur. Phys. J. C 80, 1044](#)]
  - ❑ **Fixed contamination**, e.g:
    - ❑ Decay Chains  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{232}\text{Th}$
    - ❑ Gamma emitting isotopes
      - ❑ ( $^{40}\text{K}$ ,  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$  etc.)
  - ❑ **Radon emanation**
    - ❑ Rn, resulting from Th and U decay chain dissolves in LXe
  - ❑ **Surface contamination** (e.g. dust)
- ❑ Potential components undergo Radioassay
  - ❑ Measure specific activity (Bq/kg) of decay chains and radioisotopes

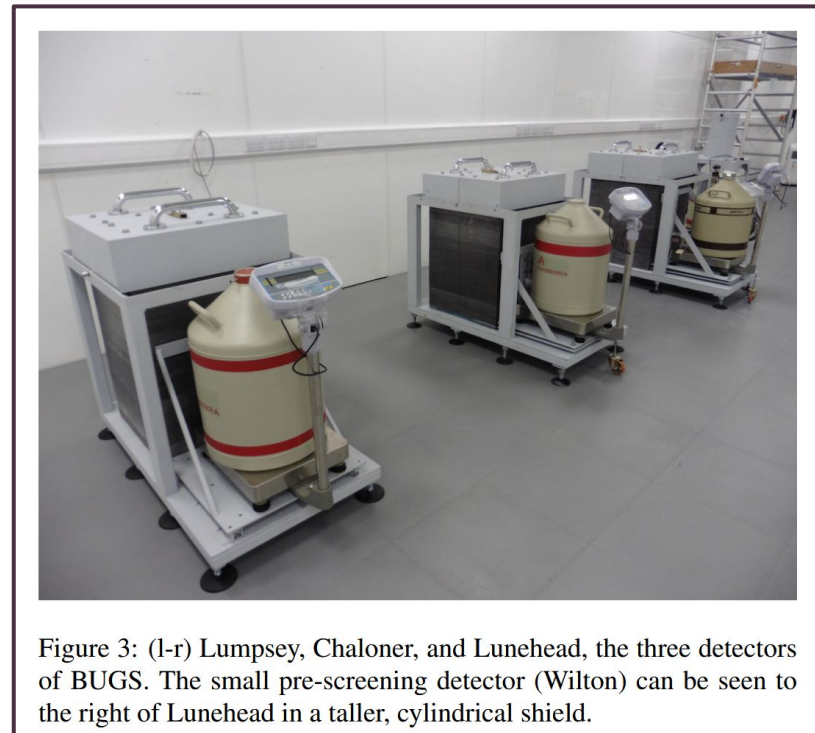


Figure 3: (l-r) Lumpsey, Chaloner, and Lunehead, the three detectors of BUGS. The small pre-screening detector (Wilton) can be seen to the right of Lunehead in a taller, cylindrical shield.

HPGe detectors at Boulby Underground Laboratory  
[Astro. Phys. V. 97 2018 P. 160-173](#)

# Rare Event Search Techniques - Radioassays

- Materials for LUX-ZEPLIN underwent an extensive radio-cleanliness campaign

[[Eur. Phys. J. C 80, 1044](#)]

More Decay Chains



- Fixed contamination, e.g:
    - Decay Chains  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{232}\text{Th}$
    - Gamma emitting isotopes
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  - Radon emanation
    - Rn, resulting from Th and U decay chain dissolves in LXe
  - Surface contamination (e.g. dust)
- Potential components undergo Radioassay
- Measure specific activity (Bq/kg) of decay chains and radioisotopes

More Samples

| Sample                     | Supplier                        | Detector  | Mass [kg] | Units  | $^{238}\text{U}_e$ | $^{238}\text{U}_l$ |
|----------------------------|---------------------------------|-----------|-----------|--------|--------------------|--------------------|
| PTFE Screws                | Product Components Corporation  | MERLIN    | 0.08      | mBq/kg | <145               | <44                |
| Bellows                    | Palatine Precision Ltd          | Roseberry | 0.54      | mBq/kg | 14(7)              | 8.0(20)            |
| Viton O-Rings              | Dichtomatik                     | Lunhead   | 0.37      | mBq/kg | 171(26)            | 62(8)              |
| Elastomer Cord             | Dichtomatik                     | Chaloner  | 0.35      | mBq/kg | <19                | 572(20)            |
| PEEK Monofilament          | Accu-Glass Products Inc         | MERLIN    | 0.02      | mBq/kg | <1060              | <320               |
|                            |                                 | Chaloner  |           | mBq/kg | 1500(500)          | 1200(500)          |
| Krytox                     | Chemours                        | Roseberry | 0.07      | mBq/kg | <43                | 46(12)             |
| Aluminium Sheet            | Hydro Aluminium Rolled Products | Chaloner  | 0.37      | mBq/kg | 293(100)           | 64(16)             |
| PTFE Screws                | Product Components Corporation  | MERLIN    | 0.07      | mBq/kg | <154               | <74                |
| Styrodur Foam              | eFoam UK                        | Chaloner  | 0.22      | mBq/kg | <33                | 45(20)             |
| Polyisocyanurate Foam      | eFoam UK                        | Lunhead   | 0.20      | mBq/kg | <150               | <28                |
| 20mm Stainless Steel Sheet | Nironit                         | SOLO      | 9.9       | mBq/kg | <7.4               | 0.87(43)           |
| Multi-Layer Insulation     | RUAG                            | Roseberry | 0.66      | mBq/kg | 18(8)              | 10(3)              |
| Titanium Lathe Swarf       | Loterios                        | Lunhead   | 0.16      | mBq/kg | <109               | <19                |
| Titanium Drill Swarf       | Loterios                        | Chaloner  | 0.46      | mBq/kg | 7.0(40)            | 8.0(50)            |
| Sodium Bicarbonate         | Genesis Alkali                  | MERLIN    | 0.39      | mBq/kg | <27                | 123(25)            |
| Stainless Steel Plates     | Nironit                         | MERLIN    | 9.7       | mBq/kg | <2.5               | <0.70              |
| AeroGel Thermal Wrap 8 mm  | BuyAerogel                      | MORGAN    | 0.10      | mBq/kg | <181               | <25                |
| Cream 3D Printed Material  | GoPrint3D                       | Lunhead   | 0.03      | mBq/kg | <1000              | 100(42)            |
| Stainless Steel Fasteners  | Oxford Bearings Ltd             | Lunhead   | 1.5       | mBq/kg | <75                | <4.0               |
| Aluminium Tape             | RUAG                            | Merrybent | 0.29      | mBq/kg | <7.0               | 40(6)              |
| Titanium Coupons           | Timet                           | MORGAN    | 2.0       | mBq/kg | <9.7               | <1.1               |
| HDPE Plates                | Direct Plastics                 | Chaloner  | 0.55      | mBq/kg | 14(5)              | <6.9               |
| Blue 3D Printed Material   | GoPrint3D                       | Chaloner  | 0.04      | mBq/kg | <25                | <23                |
| Yellow 3D Printed Material | GoPrint3D                       | Merrybent | 0.03      | mBq/kg | <12                | 150(25)            |
| PTFE Screws & Washers      | McMaster Carr                   | MERLIN    | 0.05      | mBq/kg | <142               | <80                |
| Welding Wire               | Loterios                        | Belmont   | 0.03      | mBq/kg | <21                | <37                |
| Cable Ties                 | Mouser Electronics              | SOLO      | 0.06      | mBq/kg | <182               | <13                |
| Kapton Tiles               | Fracock (McMaster Carr)         | MORGAN    | 0.18      | mBq/kg | <25                | <4.6               |

Subset of the LZ radioassay results

# Rare Event Search Techniques - Sidebands

Sideband:

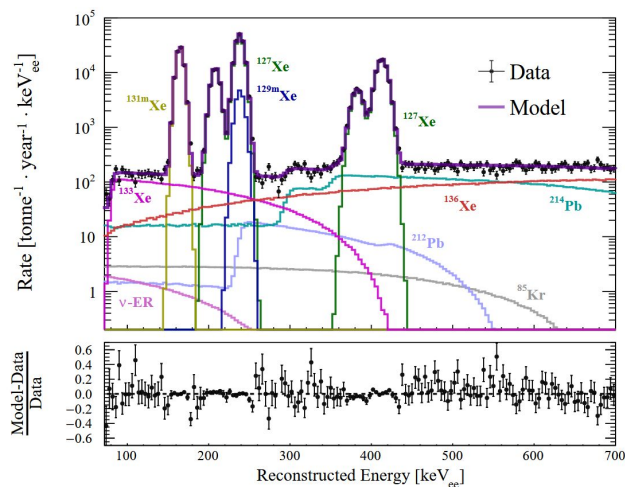
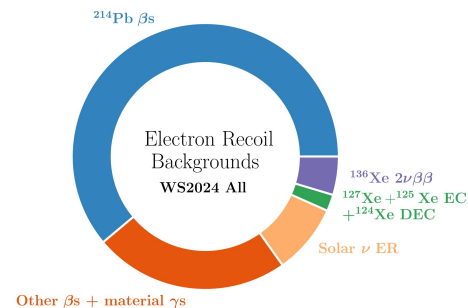
- ❑ Data other than your “science sample”
  - ❑ Useful for constraining background
  - ❑ **In-situ**

Typical LXe TPC examples

- ❑ Fits at higher energies
  - ❑ Gammas & Betas
- ❑ Alphas inform the activity of dissolved Rn
- ❑ Veto-tagged samples
  - ❑ Prompt Gammas, Delayed Neutrons

$^{214}\text{Pb}$ :

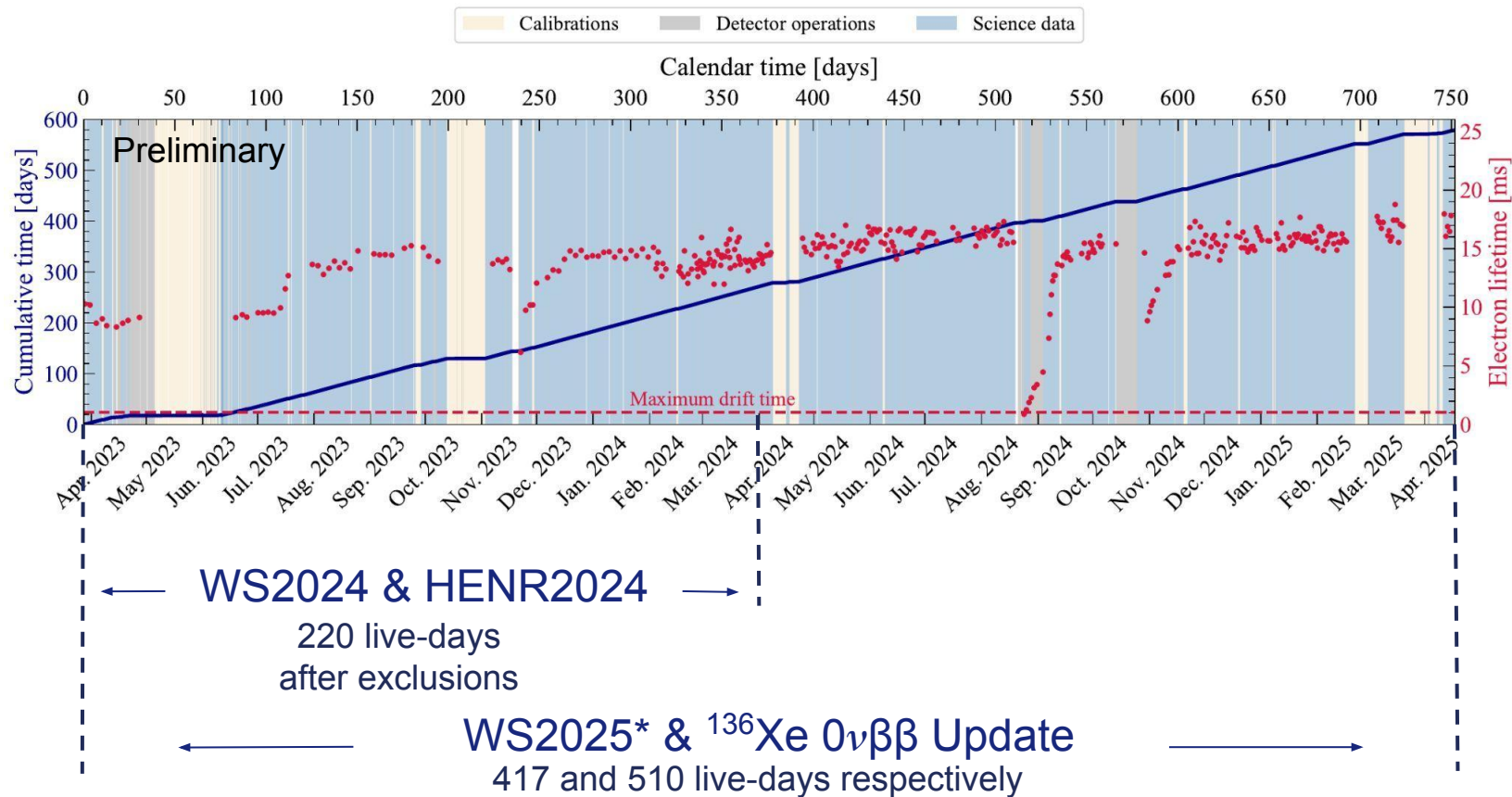
- ❑  $\beta$ -decay up to  $\sim 1$  MeV
  - ❑ Decays to the ground state br 11%



<https://arxiv.org/pdf/2211.17120>

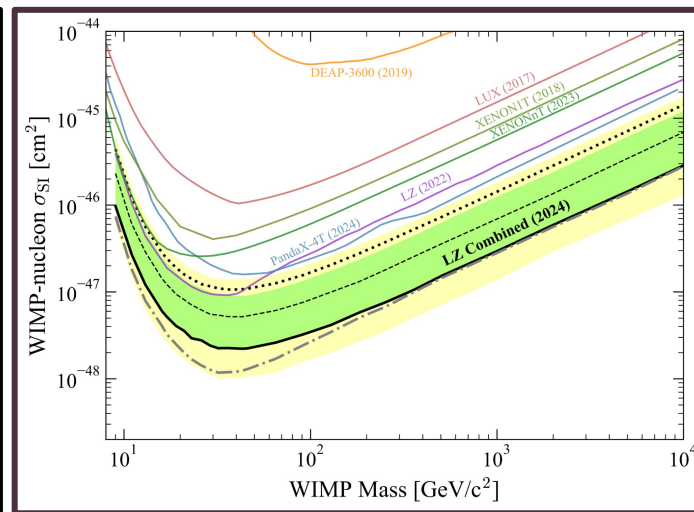
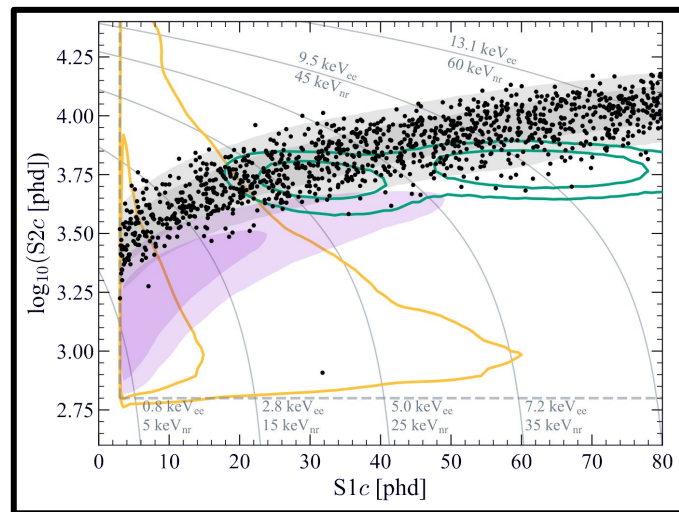
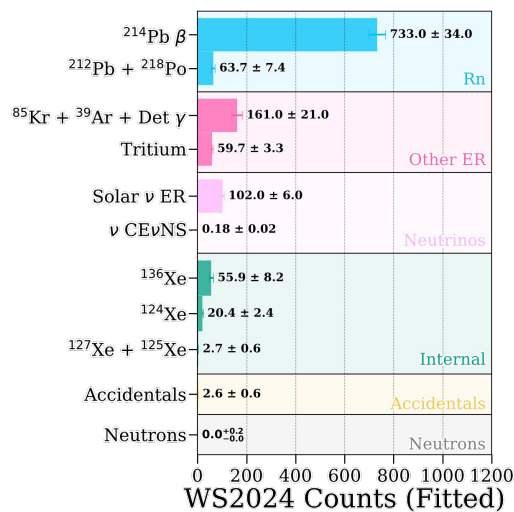
# Direct Detection of Dark Matter

# LZ Timeline



\*Light Dark Matter Search 2025

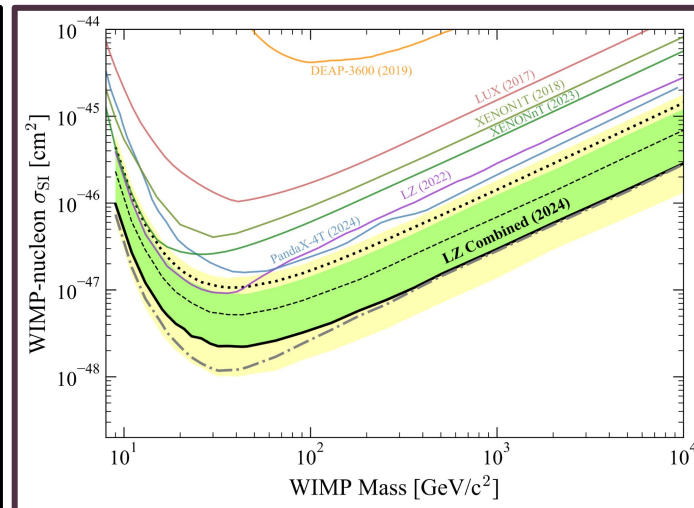
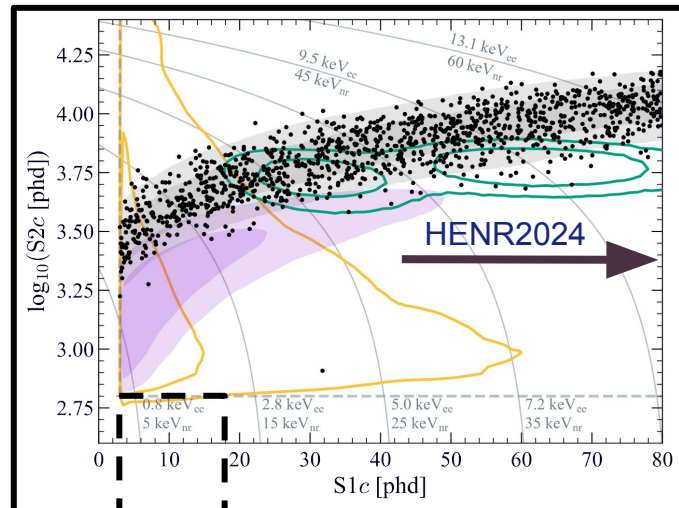
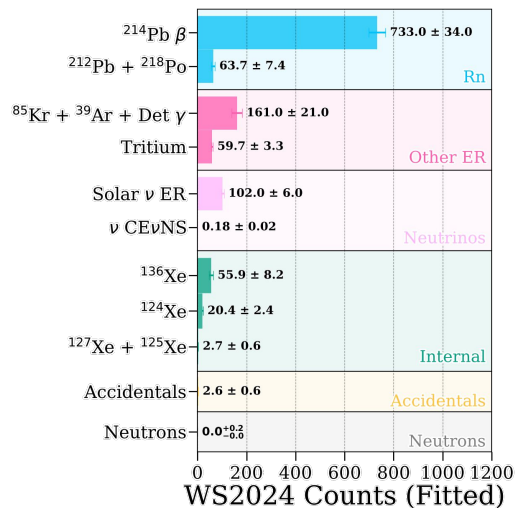
# WS2024 - Result



— Accidental —  $^{24}\text{Xe } 2\nu\text{ECEC}$  —  $40 \text{ GeV}/c^2 \text{ WIMP}$

- ❑ Region of interest  $\sim 5\text{--}55 \text{ keV}_{\text{nr}}$
- ❑ Best fit no. of WIMPs is 0 at all tested masses ( $9 \text{ GeV}/c^2 - 10 \text{ TeV}/c^2$ )
- ❑ World leading sensitivity to WIMP nucleon cross-section
  - ❑ Elastic spin independent & dependent interactions considered

# WS2024 - Result



WS2025

- ❑ WS2025 - Light Dark Matter Search
  - ❑  $\sim 1\text{--}6 \text{ keV}_{\text{nr}}$
  - ❑ WIMP masses tested  $3\text{--}9 \text{ GeV}/c^2$
- ❑ HENR2024 - High Energy Nuclear Recoils
  - ❑  $\sim 5\text{--}270 \text{ keV}_{\text{nr}}$

# High Energy Nuclear Recoil Search - Motivation

Extension of WIMP search to higher recoil energies

- ☐ Interactions that have **momentum transfer dependence**

Operators & Lagrangians

- ☐ **Non-relativistic effective field theory**
- ☐ Fifteen independent operators  $\mathcal{O}_i$
- ☐ Set of 20 Lagrangians  $\mathcal{L}_i$

**Inelastic Dark Matter**

- ☐ Models of Dark Matter with mass states that are nearly degenerate

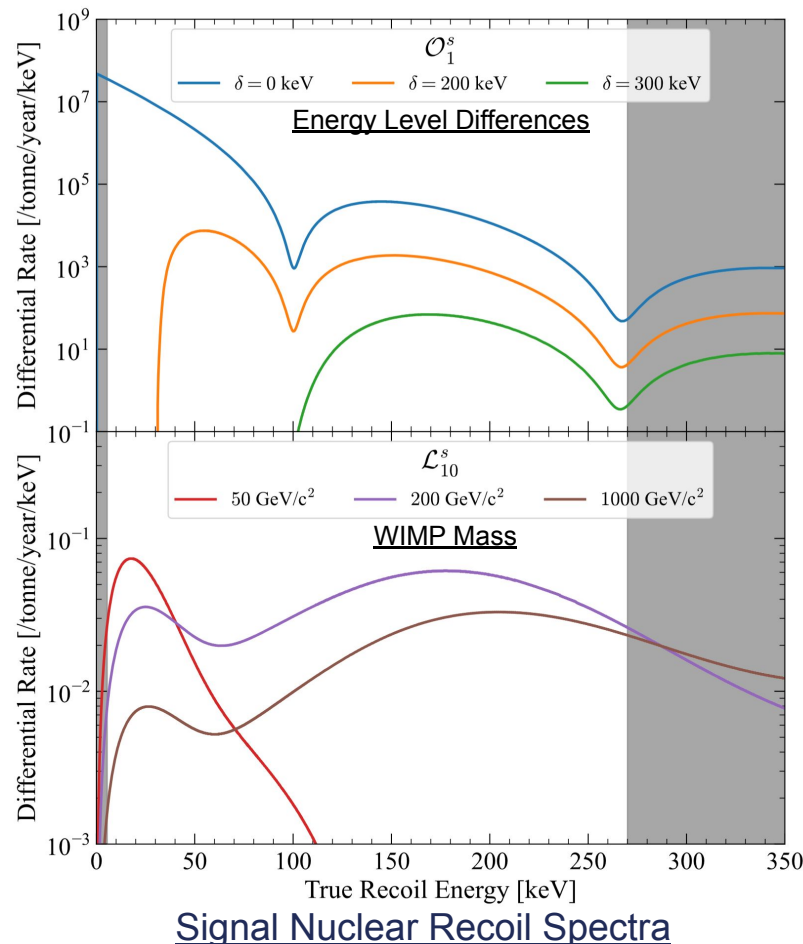
Specific example models shown

- ☐ Two illustrative examples for this result
- ☐ Inelastic spin independent scatter  $\mathcal{O}_1^s$
- ☐ Magnetic moment interaction  $\mathcal{L}_{10}^s$

[Fitzpatrick et al. J. Cosmol. Astropart. Phys. 02, 004 \(2013\)](#)

[Smith et al. Phys. Rev. D \*\*64\*\*, 043502 \(2001\)](#)

[Bramante et al. Phys. Rev. D \*\*94\*\*, 115026 \(2016\)](#)



Signal Nuclear Recoil Spectra

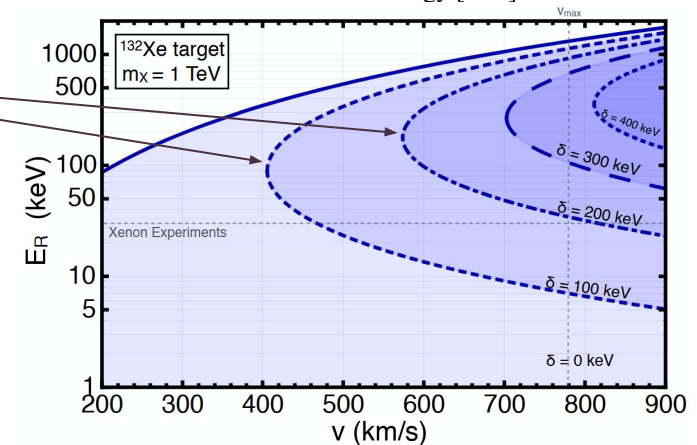
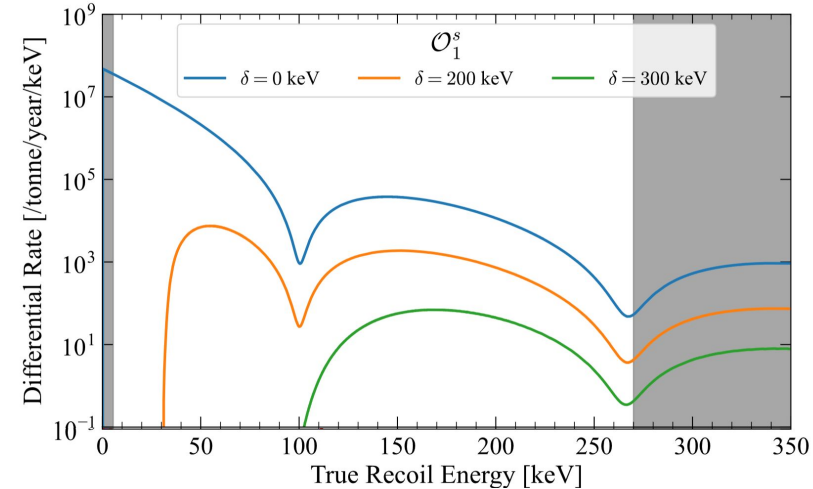
# Brief Introduction to Inelastic Dark Matter

## Inelastic Dark Matter:

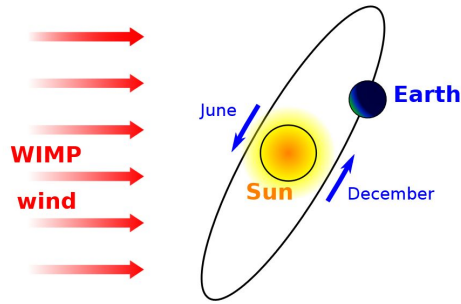
- ❑ Two mass states that are nearly degenerate
  - ❑ Assumption: Elastic scattering is suppressed
  - ❑ Only Inelastic interactions occur
- ❑ WIMP kinetic energy is transferred to excited state
  - ❑ WIMP loses more momentum to the Xe nucleus
    - ❑ As momentum is conserved
  - ❑ Minimum WIMP velocity ( $v_{\min}$  is higher)

$$v_{\min} = \frac{1}{\sqrt{2E_R m_N}} \left( \frac{E_R m_N}{\mu} + \delta \right)$$

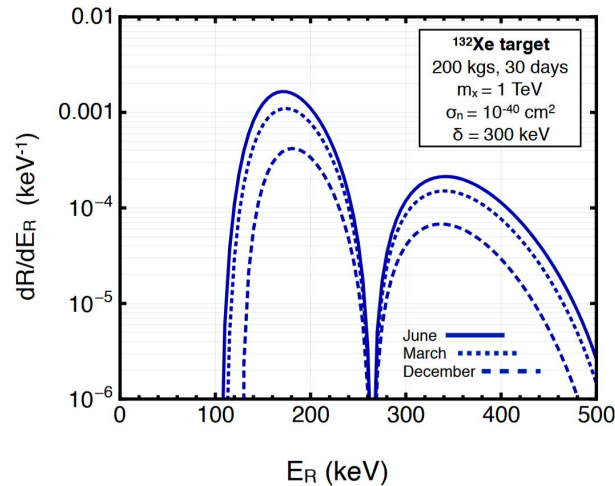
- ❑ Lines of  $v_{\min}(E_R)$



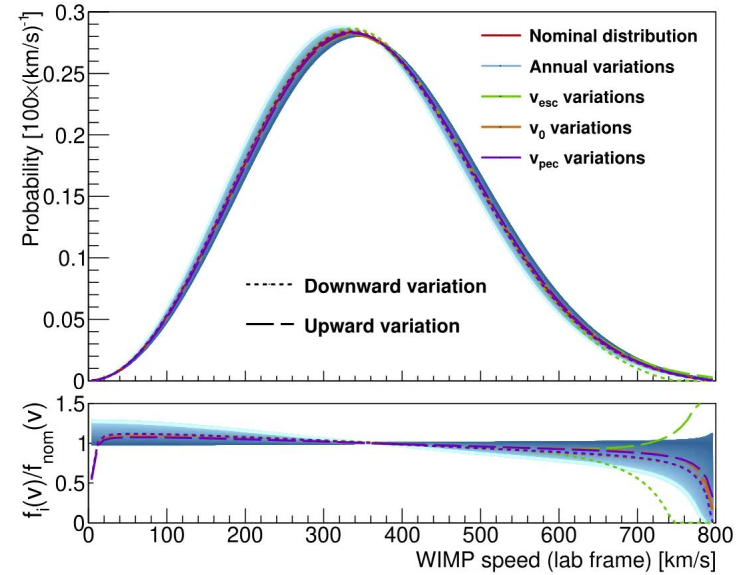
# Brief Introduction to Inelastic Dark Matter



Annual modulation cartoon -  $\pm 15$  km/s



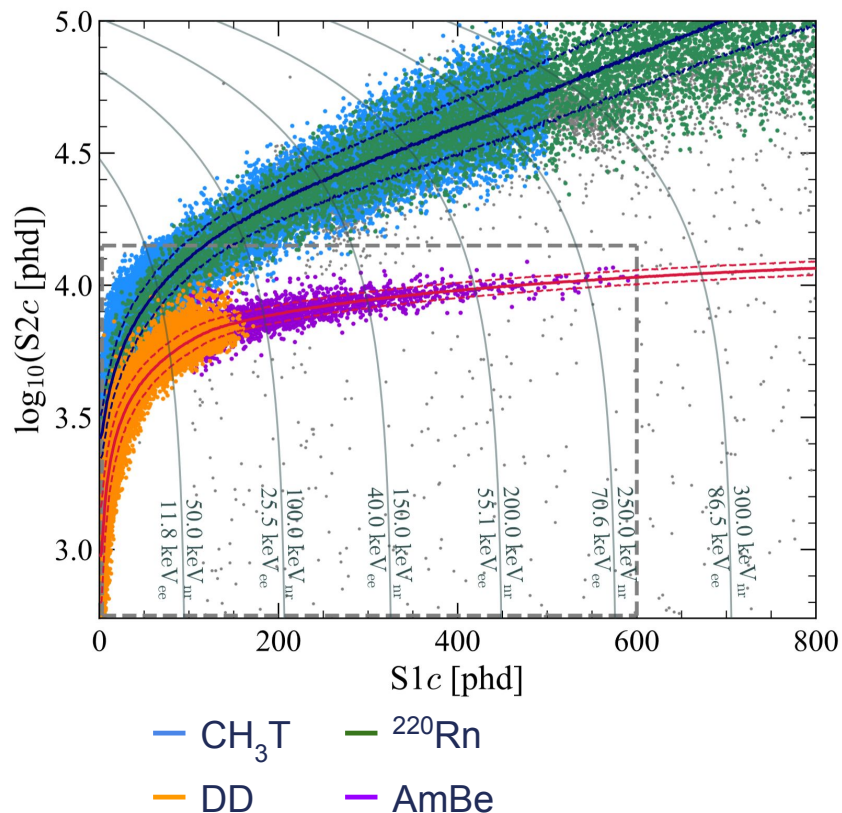
Inelastic Differential recoil rate depend on annual modulation



Direct Detection Conventions - Eur. Phys. J. C **81**, 907

# High Energy Nuclear Recoil Search - Calibration

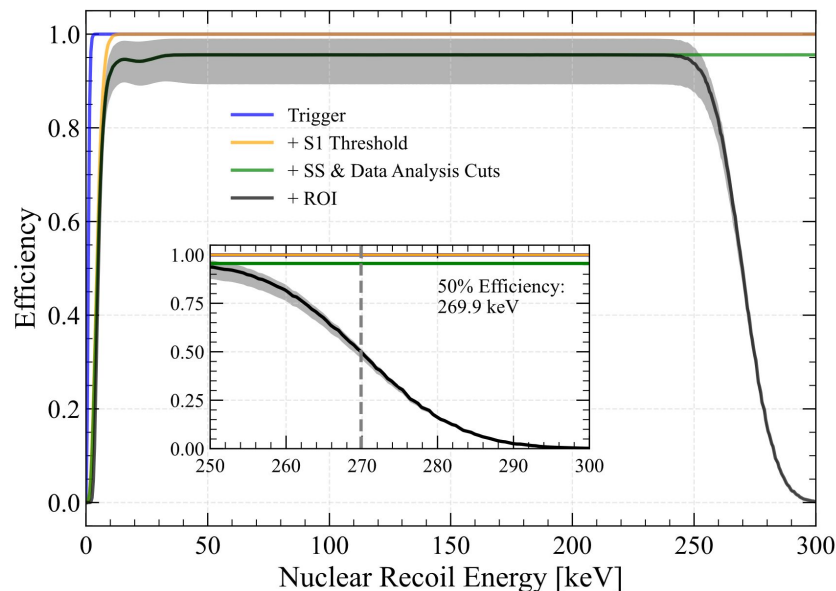
## Calibrations for HENR2024



- ❑ Injected ER calibration:
  - ❑ **Tritiated methane**
    - ❑  $^3\text{H}$  (18.6 keV  $\beta^-$ )
    - ❑  $^{14}\text{C}$  (156 keV  $\beta^-$ )
  - ❑  **$^{220}\text{Rn}$  Injection**
    - ❑  $^{212}\text{Pb}$  (569 keV  $\beta^-$ )
  - ❑  $^{83\text{m}}\text{Kr}$ ,  $^{131\text{m}}\text{Xe}$ 
    - ❑ Spatial & temporal corrections
    - ❑ (xy, z) resolution at  $1\sigma$  (<1cm, <1cm)
- ❑ External NR calibration:
  - ❑ Collimated DD (2.45 MeV)
  - ❑ **Deployed source AmBe (Up to ~11 MeV)**
- ❑ 99.8% discrimination of  $\beta^-$  under flat NR band median
  - ❑ Measured between ~5-55 keV<sub>nr</sub>
- ❑ Electron lifetime >8ms (depends strongly on LXe purity)
  - ❑ max  $e^-$  drift time ~1ms.

# High Energy Nuclear Recoil Search - Signal Efficiency

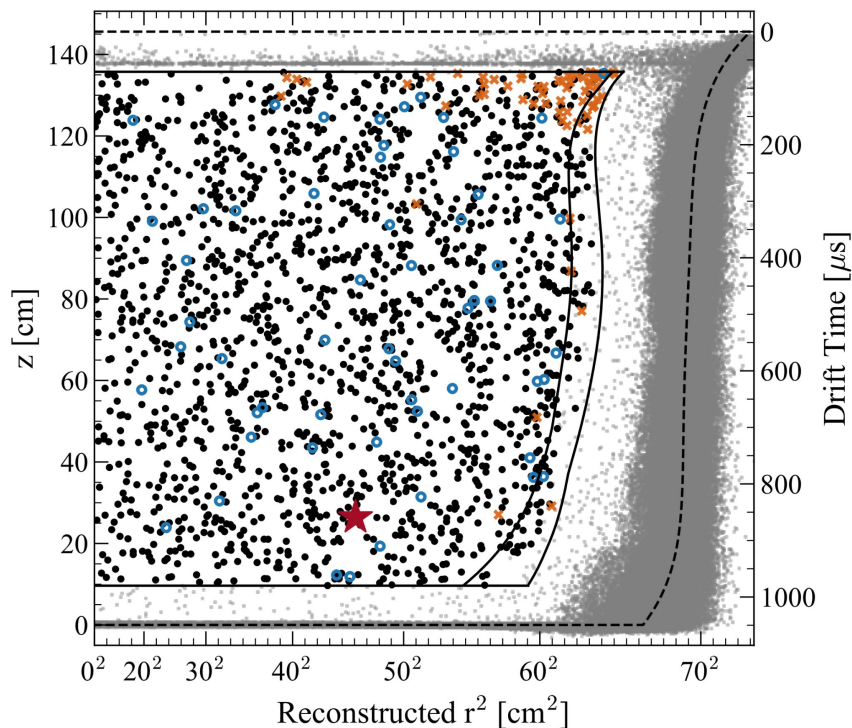
Signal Efficiency for HENR2024



- ❑ Single scatter - one interaction site
- ❑ Region of interest (ROI)
  - ❑  $3 < S1c < 600$  photons detected (phd)
  - ❑  $S2 > 14.5$  electrons (645 phd)
  - ❑  $\log_{10}(S2c) < 10^{4.15}$
- ❑  $\sim 5 \text{ keV} < \text{Nuclear Recoil Energy} < \sim 270 \text{ keV}$
- ❑ Exclusions
  - ❑ High Rate Periods
  - ❑ Detector Instability
- ❑ Cuts on S1 & S2 parameters to remove accidentals
  - ❑ Acceptance evaluated on calibration data

# High Energy Nuclear Recoil Search - Fiducial Volume

## Fiducial Volume for HENR2024



- Delayed Veto
- Inside FV
- ✕ Prompt Veto
- Outside FV

★ LZ230616

### Fiducial Volume Definition:

- Fiducial volume: azimuthally & drift time-dependent
  - $< 10^{-4}$  charge loss ("wall") events
- **~10cm of LXe away from charge insensitive regions**
  - Reverse Field Region (RFR) below the cathode
  - LXe adjacent to the TPC wall
- 4 mean free paths for  $^{214}\text{Pb}$  352 keV  $\gamma$ -ray

### Anti-coincidence Vetoes:

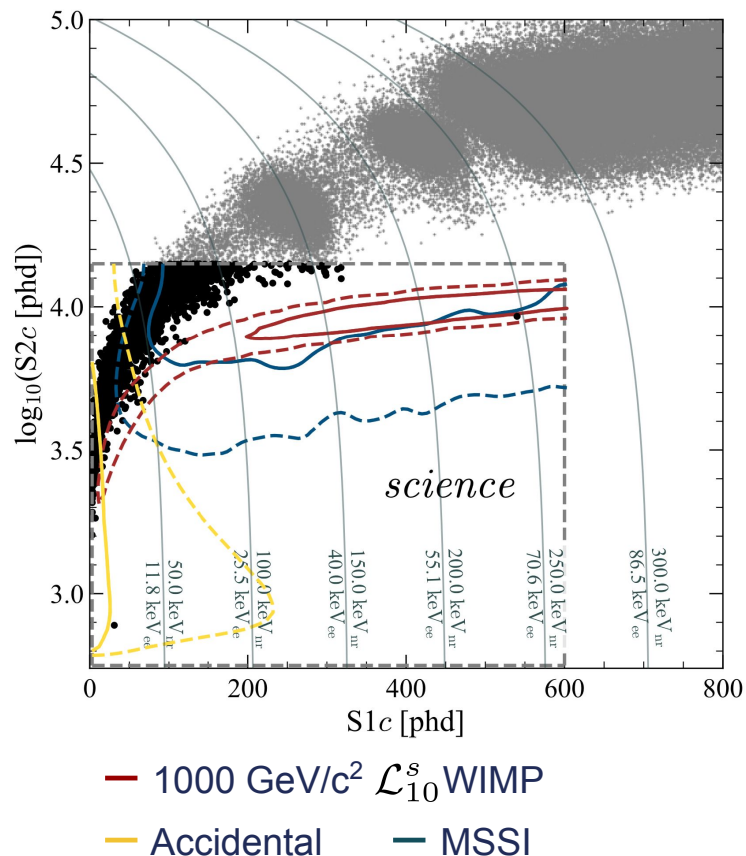
- Skin & Outer Detector
  - **Prompt Veto:** ~90% veto efficiency of  $\gamma$ -ray
    - Validated against Xe127 decays
  - **Delayed Veto:** ~90% veto efficiency of neutrons
    - Neutron capture up to 600 $\mu\text{s}$  after S1
    - ~3% false veto rate (deadtime)

### Analysis Volume:

- Mass:  $4.7 \pm 0.2$  tonnes
- Exposure:  $2.8 \pm 0.1$  tonne-years

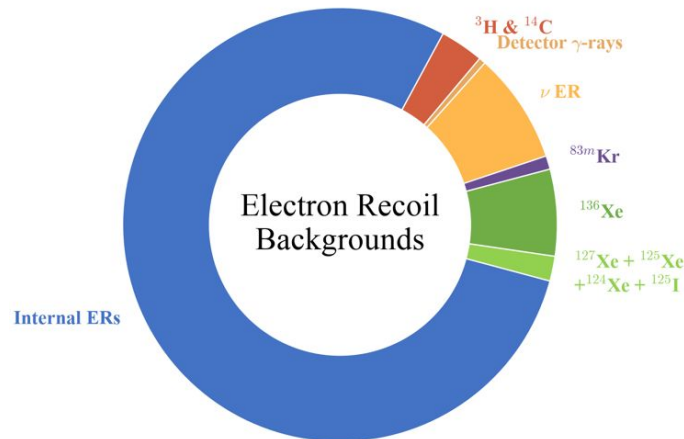
# High Energy Nuclear Recoil Search - Event Selection

## Data Selection for HENR2024



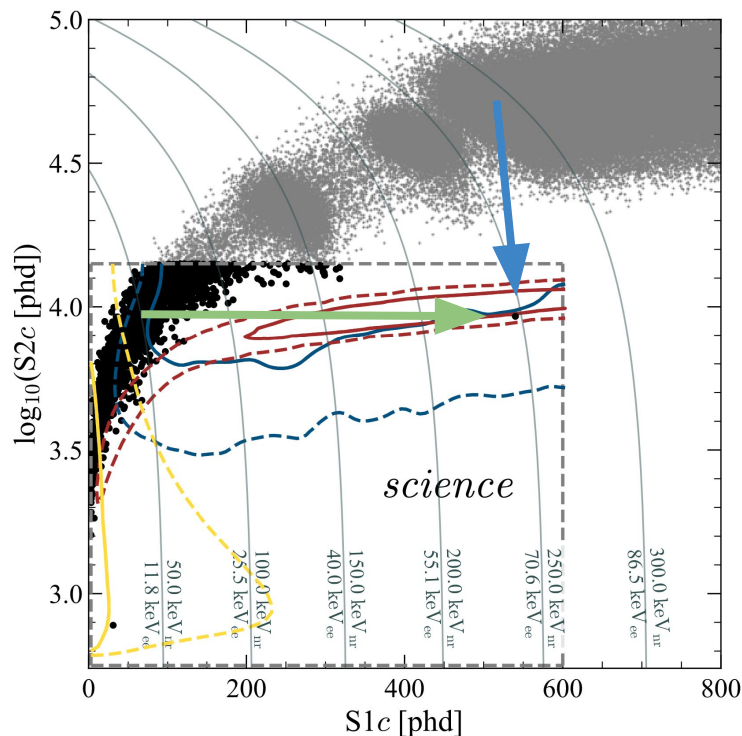
## Electronic Recoil

- ❑ Dissolved  $\beta$  emitters:
  - ❑  $^{214}\text{Pb}$  ( $^{222}\text{Rn}$ ),  $^{212}\text{Pb}$  ( $^{220}\text{Rn}$ ),  $^{85}\text{Kr}$ ,  $^{136}\text{Xe}$  ( $\beta\beta$ )
- ❑ Dissolved EC decays (x-rays/Auger electrons)
  - ❑  $^{127}\text{Xe}$ ,  $^{125}\text{Xe}$ ,  $^{125}\text{I}$  produced by activation from neutron calibration
  - ❑  $^{124}\text{Xe}$  (double EC), 0.095% natural abundance
- ❑ Solar  $\nu$ 's:  $\text{pp} + ^7\text{Be} + \text{CNO}$  (ER)
- ❑ Detector ER,  $\gamma$  emitters from detector materials
  - ❑  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ,  $^{60}\text{Co}$  decay chains



# High Energy Nuclear Recoil Search - Event Selection

## Data Selection for HENR2024



— 1000 GeV/c<sup>2</sup>  $\mathcal{L}_{10}^s$  WIMP

— Accidental — MSSl

Event of interest Occurred on **16 June 2023 (LZ230616)**

- 248 ± 23<sub>stat</sub> ± 23<sub>sys</sub> keV compatible with nuclear recoil
- ~25 cm from cathode and TPC wall

### Background considerations:

#### Signal Suppression

- S2** - Suppression of -70%
  - Unexpected loss of electrons in transit?
- S1** - Enhancement of +450 phd

#### Instrumental

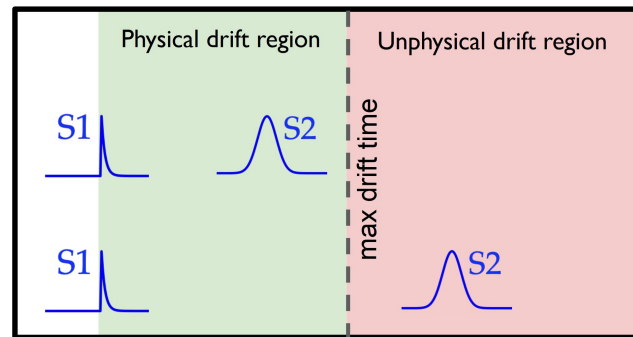
- Accidentals - random coincidence of isolated S1 and S2s
- MSSI - Multiple scatter single ionisation

#### Nuclear Recoil

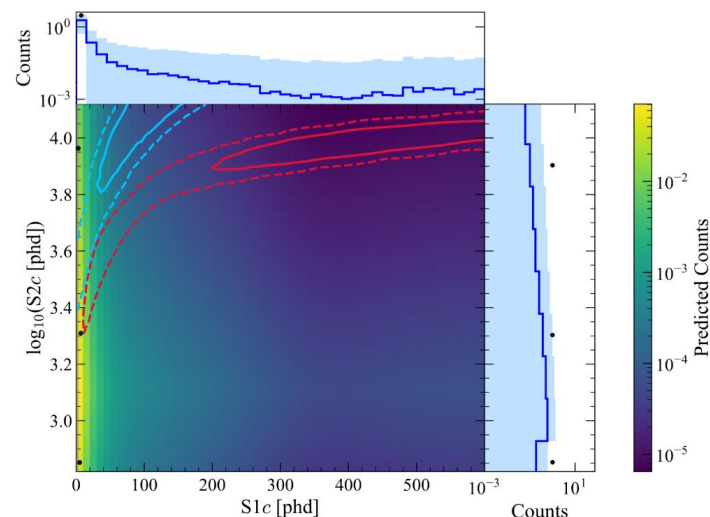
- CEvNS - <sup>8</sup>B + hep, Atmospheric neutrinos
- Neutrons from USF and ( $\alpha$ ,n) in detector materials

# High Energy Nuclear Recoil Search - Accidentals

- ❑ **Accidental (random) coincidence of uncorrelated isolated S1 and S2 pulses**
  - ❑ Random drift times, some of which are unphysical
- ❑ 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.
    - ❑ High statistics manufacture dataset - chopstitch
- ❑ Analysis cuts have an 99.5% rejection power



Accidentals Cartoon



Post-Cuts Accidentals PDF and UDTs

# High Energy Nuclear Recoil Search - MSSl Definition

## Multiple Scatter Single Ionisation (MSSl)

- ❑ Instrumental Background
  - ❑ Scatter inside Fiducial Volume and a scatter in a charge insensitive region
- ❑ Results in a **enhanced S1**, and one S2

## Charge insensitive regions

- ❑ S2 isn't drifted to the extraction region
- ❑ Reverse field region below the cathode: 13.75cm tall
- ❑ Near TPC wall: ~3mm around field rings

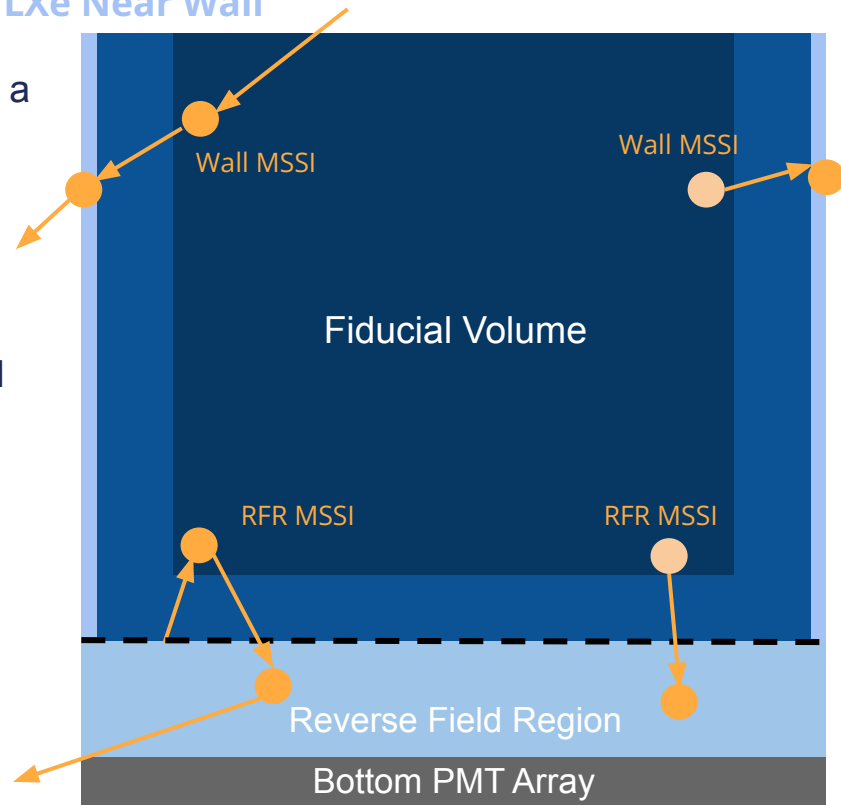
## Background model components:

- ❑  **$\gamma$ -rays from detector materials**
  - ❑ Activities from radioassay
- ❑  $^{214}\text{Pb } \beta^- \rightarrow ^{214}\text{Bi } \gamma\text{-ray}$ 
  - ❑ Has  $\gamma$ -rays 87% of the time

## Expectation

- ❑  $0.005 \pm 0.005$  counts in science sample.
- ❑ **~90% prompt veto efficiency**

## Charge Insensitive LXe Near Wall



MSSl Cartoon

# High Energy Nuclear Recoil Search - MSSl Definition

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- ❑ Instrumental Background
  - ❑ Scatter inside Fiducial Volume and a scatter in a charge insensitive region
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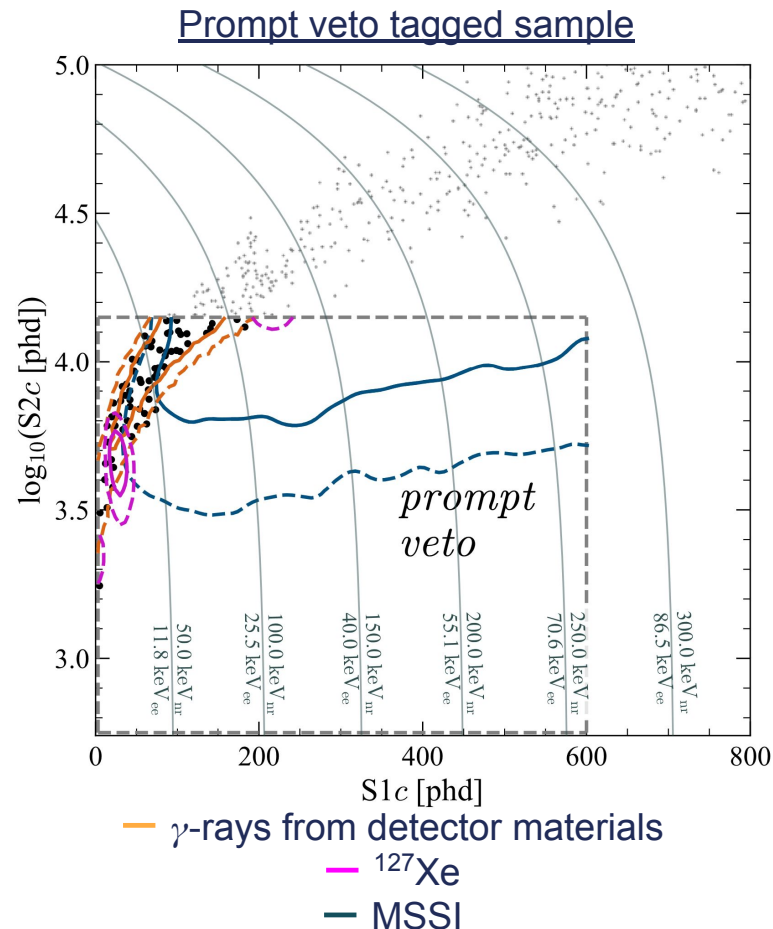
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  - ❑ Has  $\gamma$ -rays 87% of the time

## Expectation

- ❑  $0.005 \pm 0.005$  counts in science sample.
- ❑ **~90% prompt veto efficiency**



# High Energy Nuclear Recoil Search - Neutrons

## Calibration:

- ❑ Single scatter neutron veto efficiency:  $92 \pm 4 \%$ 
  - ❑ Delayed neutron capture on Gd and H in Outer Detector
  - ❑ Also can tag prompt gammas and neutron thermalisation

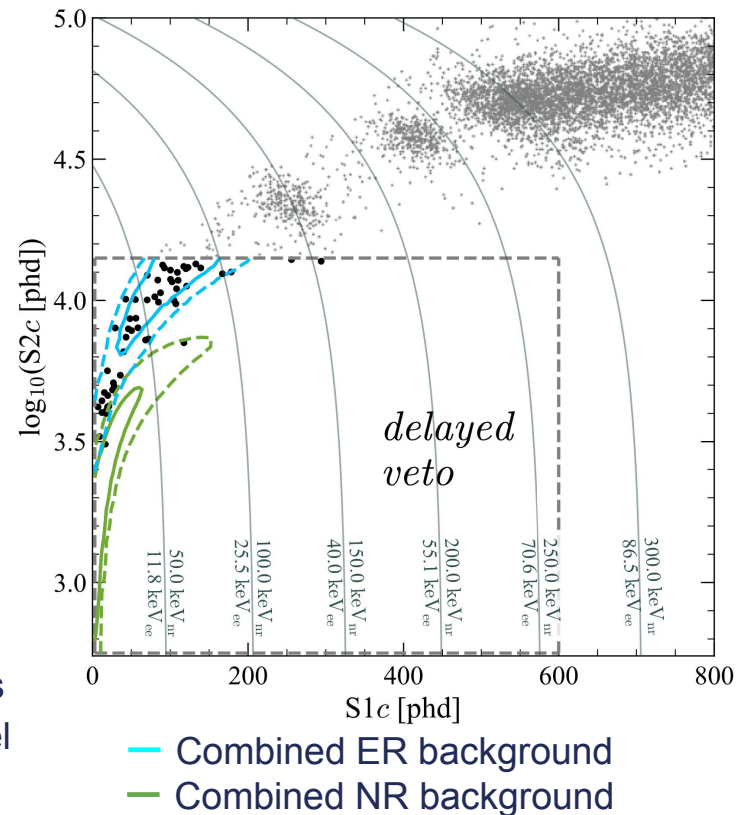
## Background Model:

- ❑  $(\alpha, n)$  and uranium spontaneous fission (USF) simulations
  - ❑ Based on radioassay
- ❑ USF single scatters suppressed due to resulting  $n$  &  $\gamma$  multiplicity
- ❑  $(\alpha, n)$  kinetic energy predominantly low kinetic energies

## Sidebands:

- ❑ To produce an  $250 \text{ keV}_{\text{nr}}$  a neutron would require  $8 \text{ MeV KE}$
- ❑ Fit of the delayed veto sample gives a result of  $[0-1.3]$  neutrons
- ❑ Multiple scatter analysis also consistent with background model
  - ❑ Both consistent with radioassay predictions

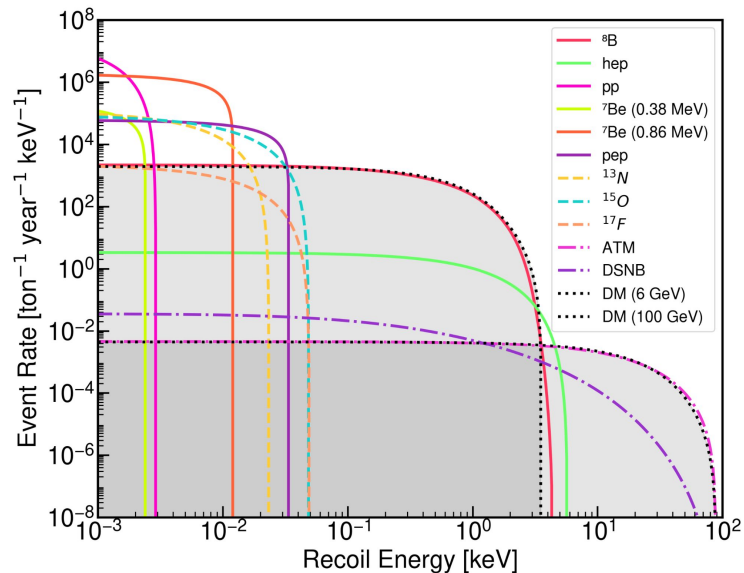
## Delayed veto tagged sample



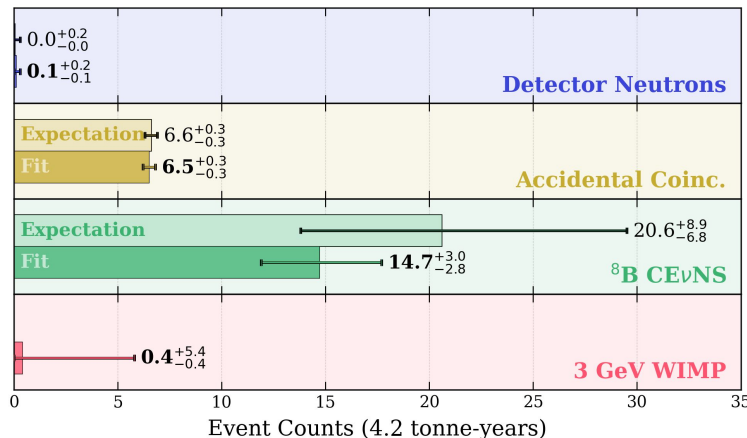
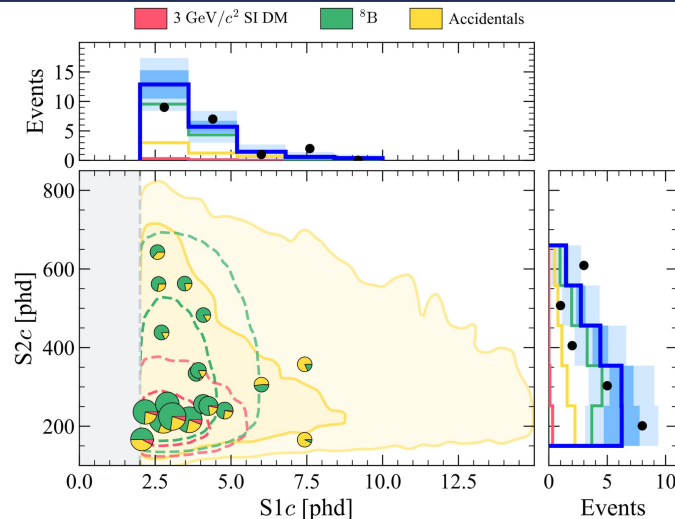
# Light Dark Matter Search 2025 - CE $\nu$ NS

<https://arxiv.org/pdf/2512.19784>

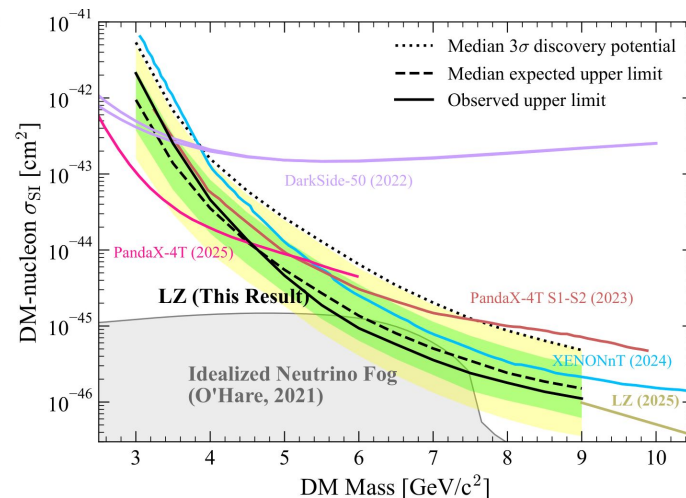
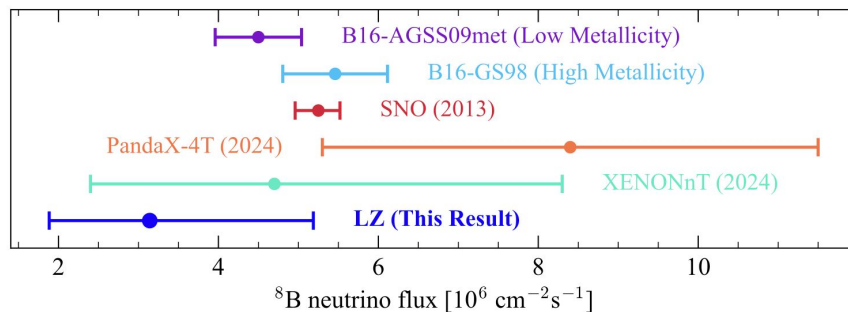
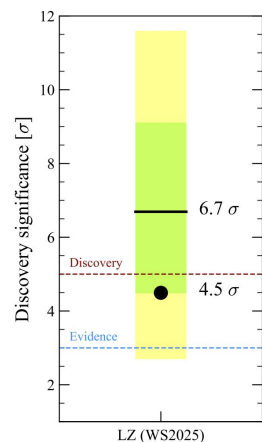
## Expected neutrino nuclear recoil spectra



- ❑ Search for 3-9  $\text{GeV}/c^2$  WIMPs
  - ❑ Lower energy region of interest:  $\sim 1\text{-}6 \text{ keV}_{\text{nr}}$
- ❑ Largest background  $^8\text{B}$  solar neutrinos
  - ❑ CE $\nu$ NS



# Light Dark Matter Search 2025 - CE $\nu$ NS



- 4.5 $\sigma$  discovery significance for  $^8\text{B}$  CE $\nu$ NS in LXe
- Flux in agreement with neutrino background predictions
- World leading sensitivity to WIMPs 5  $\text{GeV}/c^2$  - 9  $\text{GeV}/c^2$

# High Energy Nuclear Recoil Search - Background Fit

## Background Fit

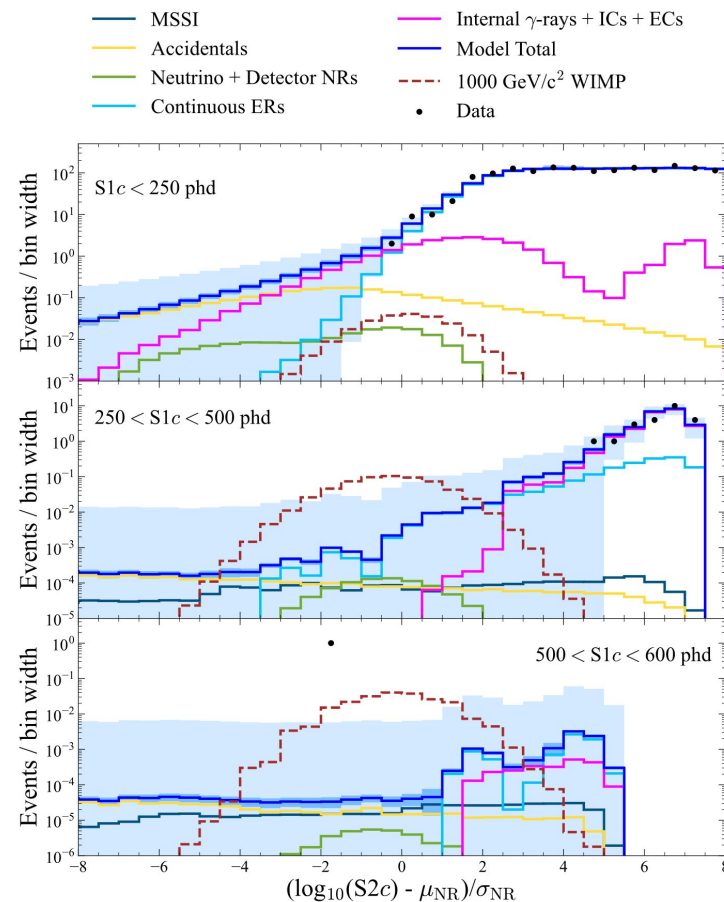
- ❑ Science, Prompt & Delayed tagged samples fit simultaneously
- ❑ Integral of  $500 < S1c < 600$  phd
  - ❑ **Model:  $0.0106 \pm 0.0008$  (sys) counts**
  - ❑ **Data: 1 event, LZ230616**

## Statistical Inference

- ❑ Profile likelihood ratio to test compatibility between signal and background-only hypotheses
- ❑ A **subset of models** have a background-only rejection significance of up to  $3.4\sigma$ 
  - ❑ **Best fit number of WIMPs of  $1 \pm 1.4$**

## Global Significance

- ❑ Look elsewhere effect significance correction
  - ❑ Required as testing many signal models
- ❑ **Global significance  $2.6\sigma$**
- ❑ **Tension with background-only hypothesis**



1D Representation of Background Fit

# High Energy Nuclear Recoil Search - Result

LZ Preliminary

## Background Fit

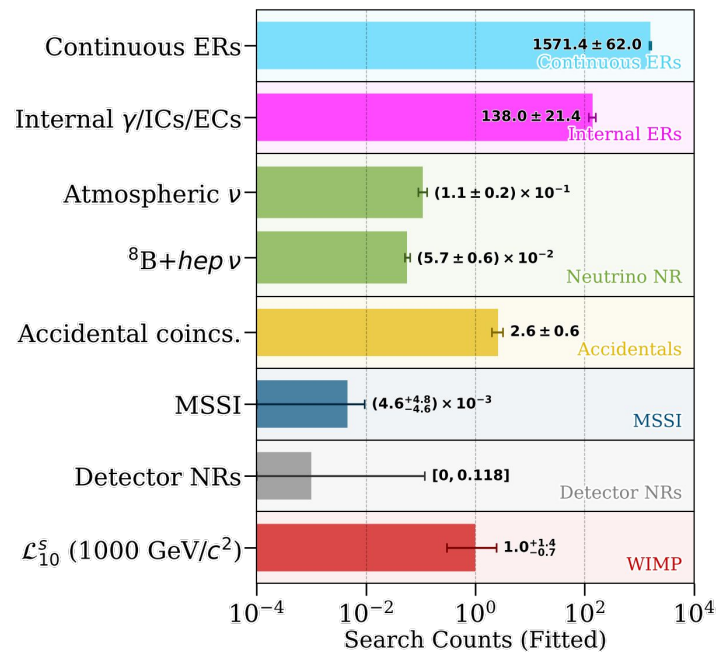
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Background Fit Values

# High Energy Nuclear Recoil Search - Limits

## Background Fit

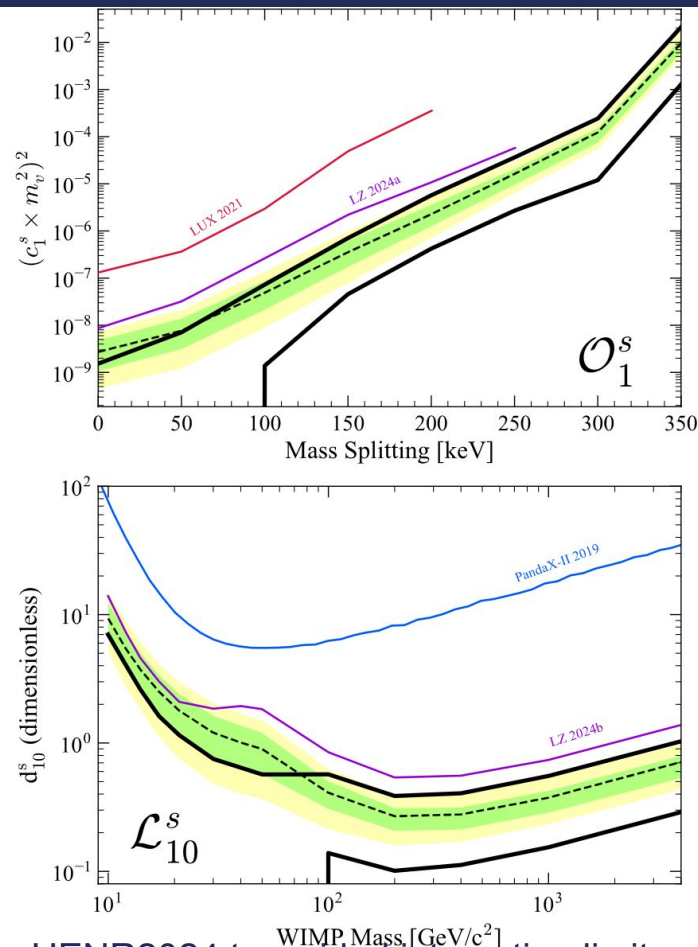
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- ❑ **Global significance  $2.6\sigma$**
- ❑ **Tension with background-only hypothesis**



HENR2024 two-sided interaction limits 32

# Summary

## WIMP Search 2024 - Phys. Rev. Lett. 135, 011802

- ❑ Region of interest  $\sim 5\text{-}55 \text{ keV}_{\text{nr}}$
- ❑ World leading sensitivity to WIMP-nucleon cross-section
  - ❑  $(9 \text{ GeV}/c^2 - 10 \text{ TeV}/c^2)$  WIMP masses

## High Energy Nuclear Recoil Search 2024 - arXiv:2609.02823

- ❑ Region of interest  $\sim 5\text{-}270 \text{ keV}_{\text{nr}}$  with 220 livedays
- ❑ 16 June 2023 (LZ230616) -  $248 \pm 23_{\text{stat}} \pm 23_{\text{sys}} \text{ keV}_{\text{nr}}$
- ❑ Background-only hypothesis rejected global p-value  $2.6\sigma$

## Light Dark Matter Search 2025 - Phys. Rev. Lett. 137, 091806

- ❑ Lower energy region of interest:  $\sim 1\text{-}6 \text{ keV}_{\text{nr}}$
- ❑ World leading sensitivity to WIMPs  $5 \text{ GeV}/c^2 - 9 \text{ GeV}/c^2$
- ❑  $4.5\sigma$  discovery significance for  $^8\text{B}$  CE $\nu$ NS in LXe

## Upcoming $^{136}\text{Xe}$ $0\nu\beta\beta$ Search - A. Musalhi – TeVPA 2026

- ❑ 510 liveday search
- ❑ Competitive limit
  - ❑  $\sim 3.0 \times 10^{25}$  years half-life

# LZ (LUX-ZEPLIN) Collaboration, 39 Institutions, 250 scientists, engineers, and technical staff



<https://lz.lbl.gov/>



@lzdarkmatter

- 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
- Purdue 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
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- 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



LZ Collaboration Meeting at University of Bristol, June 2026



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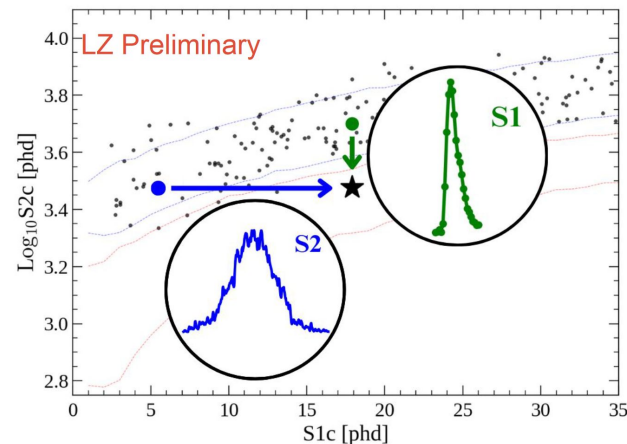
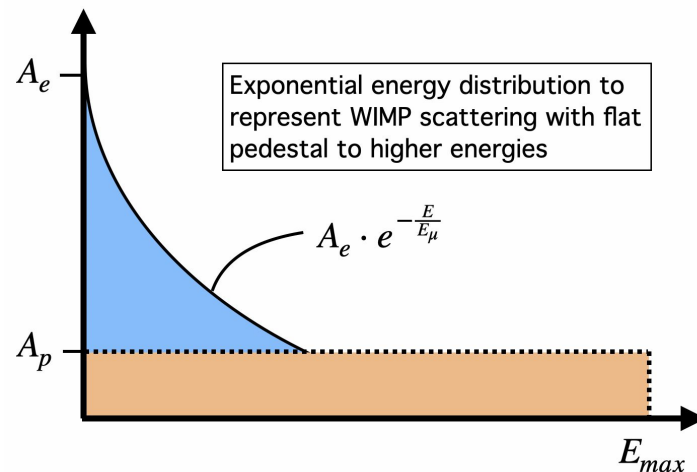
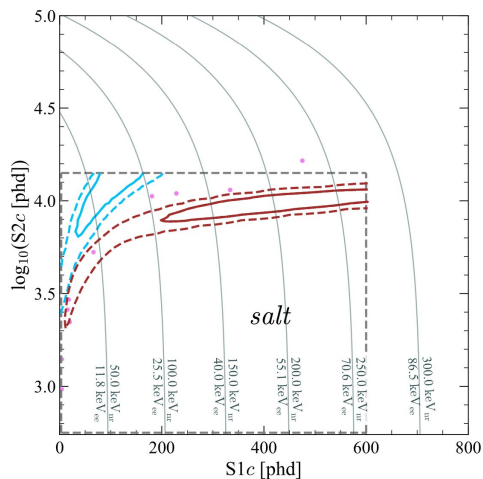
US Europe Asia Oceania

Thanks to our sponsors and participating institutions!

# Backup HENR2024

# 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



# High Energy Nuclear Recoil Search - Accidentals

- Accidental (random) coincidence of uncorrelated isolated S1 and S2 pulses

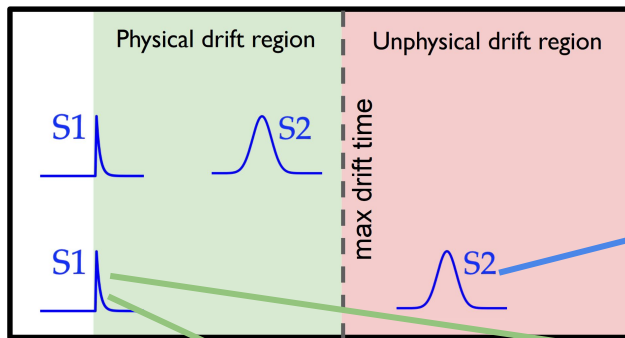
- LZ's accidentals model:

- Rate:** Measure rate of unphysical drift time (UDT) single scatters. Analysis cut efficiencies analysed using manufactured accidental events.

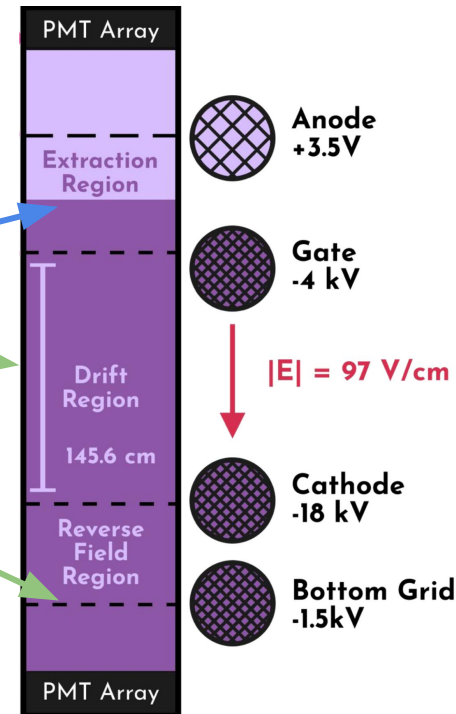
- Shape:** Manufactured by combining isolated S1 and S2 waveforms and applying analysis cut efficiencies.

- High statistics manufacture dataset - chopstitch

- Analysis cuts have an 99.5% rejection power

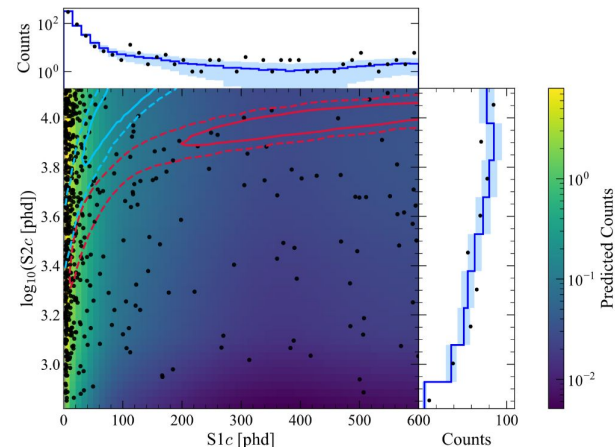


Accidentals Cartoon

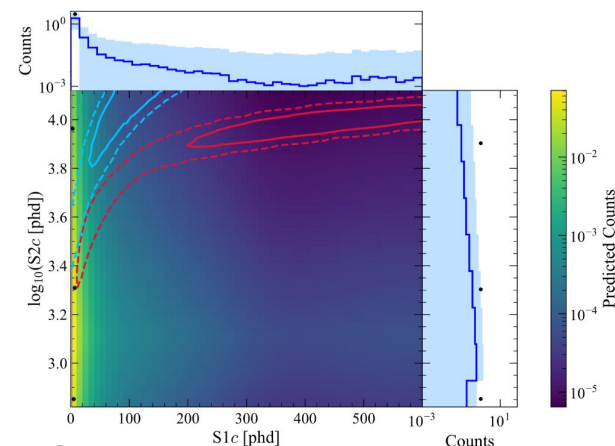


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- ❑ Analysis cuts have an 99.5% rejection power



Pre-Cuts Accidentals PDF and UDTs



Post-Cuts Accidentals PDF and UDTs

# High Energy Nuclear Recoil Search - MSSI Definition

## Multiple Scatter Single Ionisation (MSSI)

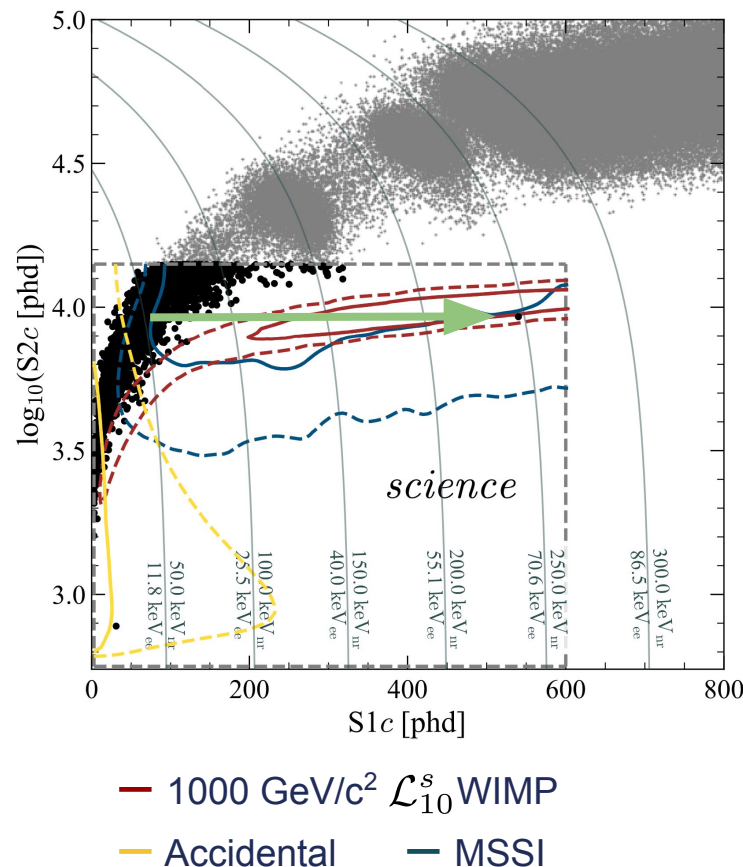
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## Charge insensitive regions

- ❑ S2 isn't drifted to the extraction region
- ❑ Reverse field region below the cathode: 13.75cm tall
- ❑ Near TPC wall: ~3mm around field rings

## S1 enhancement

- ❑ To create an event similar to LZ230616
- ❑ S2 is consistent with a  $12 \pm 2$  keV ER
- ❑ Additional S1 from a charge insensitive region, either:
  - ❑  $78 \text{ keV} \pm 7 \text{ keV}$  ER near the wall
  - ❑  $204 \pm 50 \text{ keV}$  ER in the RFR



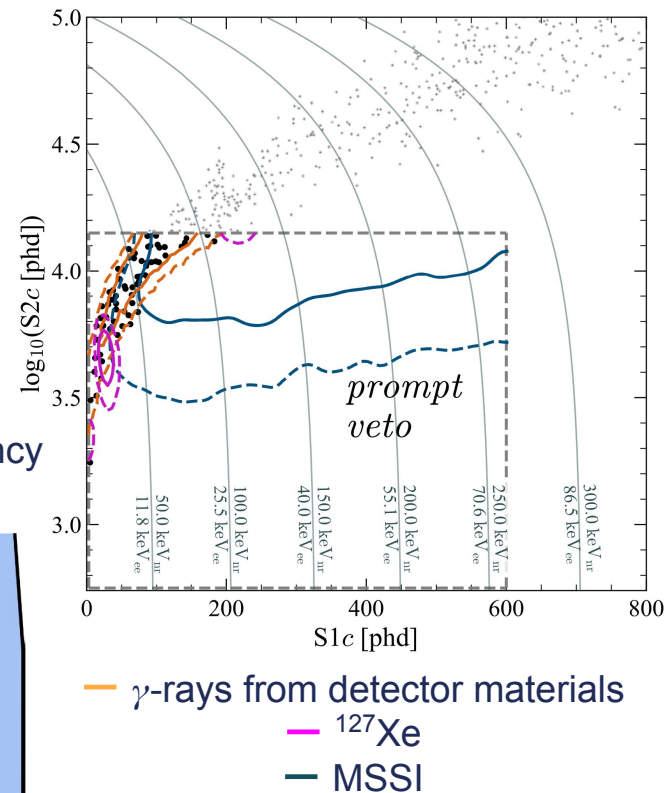
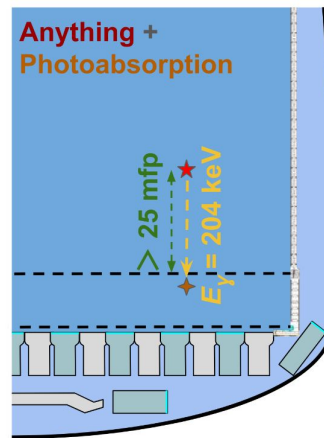
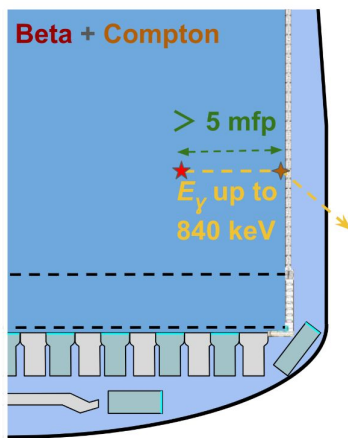
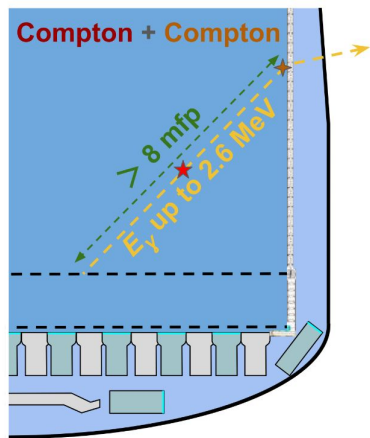
# High Energy Nuclear Recoil Search - MSSl Modelling

Background model components:

- ❑  $\gamma$ -rays from detector materials
  - ❑ Activities from radioassay
- ❑  $^{214}\text{Pb } \beta^- \rightarrow ^{214}\text{Bi } \gamma\text{-ray}$ 
  - ❑ Has  $\gamma$ -rays 87% of the time
  - ❑  $^{214}\text{Pb } \beta^-$  activity constrained by  $^{218}\text{Po}$  &  $^{214}\text{Po } \alpha$  activities

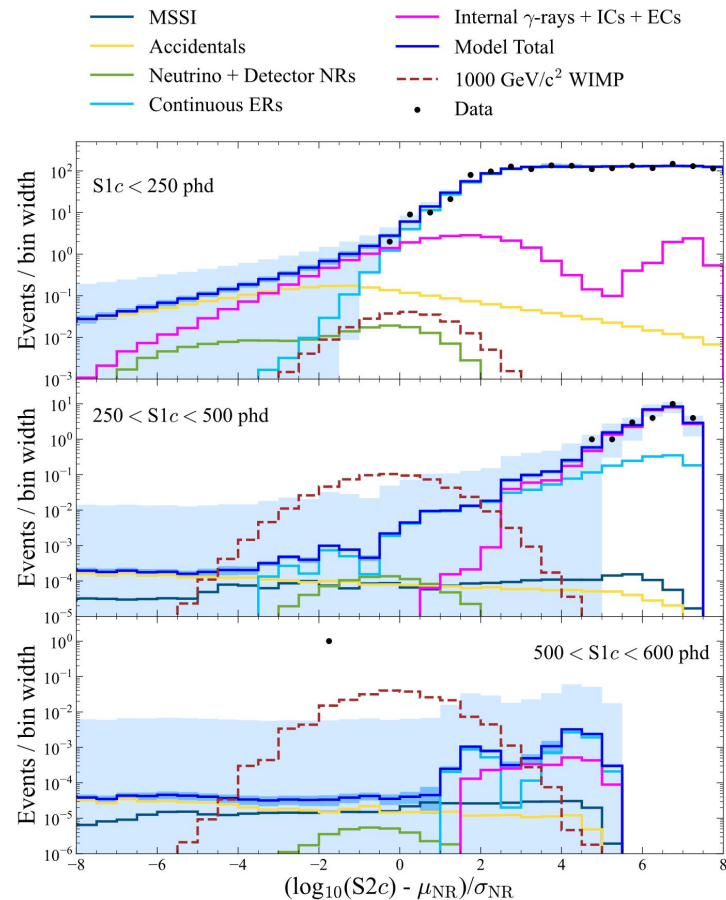
Expectation

- ❑ Suppressed by FV volume choice
- ❑  $0.005 \pm 0.005$  counts in science sample.  $\sim 90\%$  prompt veto efficiency

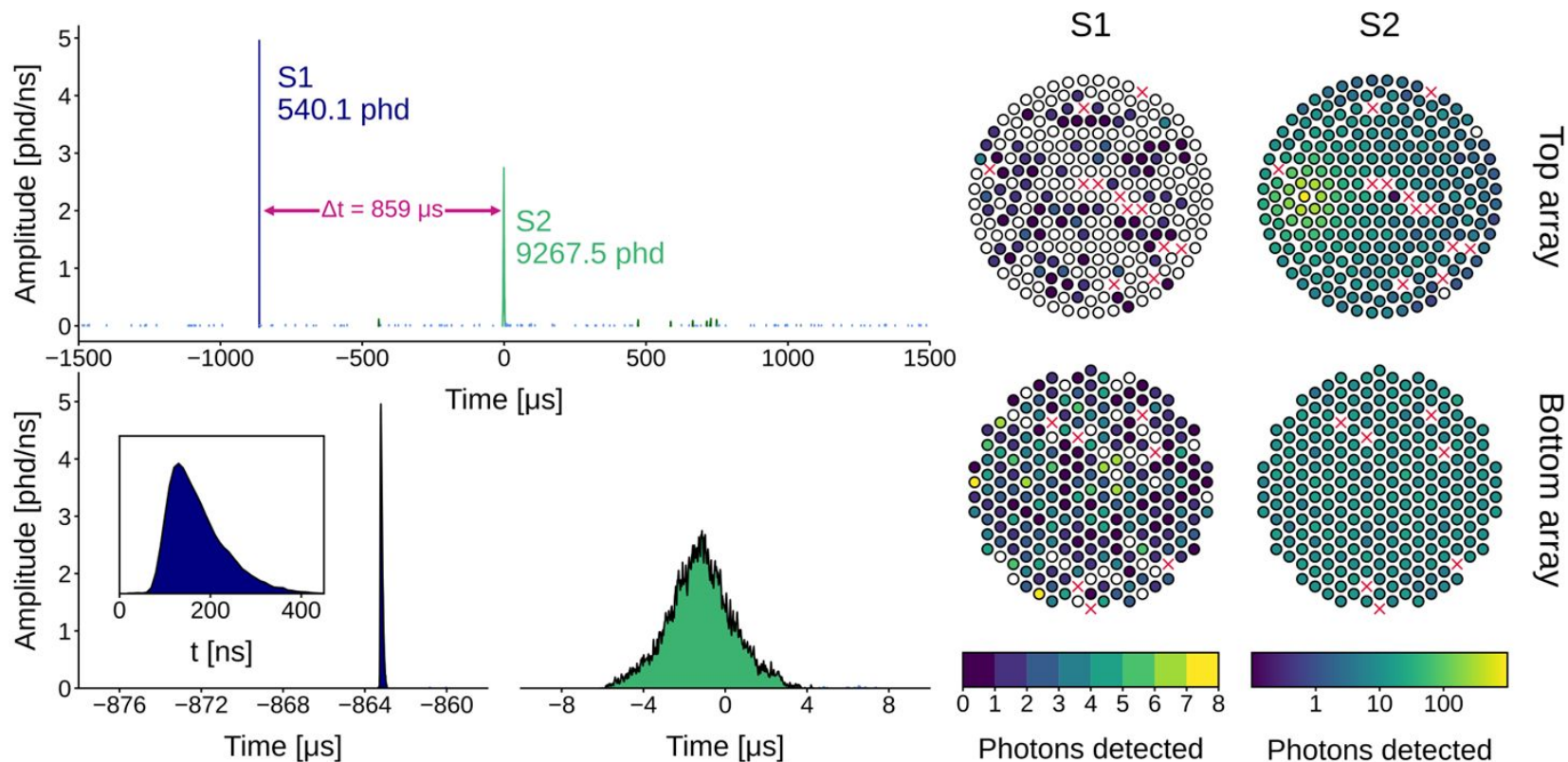


# High Energy Nuclear Recoil Search - Result

| Source                                  | Expected Events                | Fit Result                           |
|-----------------------------------------|--------------------------------|--------------------------------------|
| Internal $\beta$ decays                 | $1341 \pm 160$                 | $1340 \pm 43$                        |
| $\nu$ ER                                | $140.6 \pm 8.4$                | $140.3 \pm 8.4$                      |
| $^{136}\text{Xe}$                       | $110.0 \pm 16.5$               | $114.2 \pm 16.1$                     |
| $\text{CH}_3\text{T}$ & $^{14}\text{C}$ | $55.3 \pm 3.1$                 | $55.2 \pm 3.1$                       |
| $^{124}\text{Xe}$                       | $21.0 \pm 6.3$                 | $22.6 \pm 5.0$                       |
| $^{83\text{m}}\text{Kr}$                | $17.1 \pm 5.1$                 | $17.0^{+3.5}_{-3.3}$                 |
| $^{125}\text{I}$                        | $8.9 \pm 2.7$                  | $9.8 \pm 2.3$                        |
| Detector ERs                            | $8.5 \pm 3.4$                  | $9.4^{+1.7}_{-1.6}$                  |
| Accidental coins.                       | $2.7 \pm 0.6$                  | $2.6 \pm 0.6$                        |
| $^{127}\text{Xe} + ^{125}\text{Xe}$     | $1.5 \pm 0.3$                  | $1.2 \pm 0.3$                        |
| Atmospheric $\nu$                       | $(1.1 \pm 0.2) \times 10^{-1}$ | $(1.1 \pm 0.2) \times 10^{-1}$       |
| $^8\text{B} + \text{hep}\nu$            | $(5.7 \pm 0.6) \times 10^{-2}$ | $(5.7 \pm 0.6) \times 10^{-2}$       |
| MSSI                                    | $(4.9 \pm 4.9) \times 10^{-3}$ | $(4.6^{+4.8}_{-4.6}) \times 10^{-3}$ |
| Detector NRs                            | —                              | $[0, 0.118]$                         |
| $1000 \text{ GeV}/c^2$ WIMP             | —                              | $1.0^{+1.4}_{-0.7}$                  |
| Total counts                            | —                              | $1713 \pm 39$                        |
| Observed counts                         | —                              | 1710                                 |



# High Energy Nuclear Recoil Search - Waveform



# High Energy Nuclear Recoil Search - Date of Event

Previous calibrations in source deployment tubes:

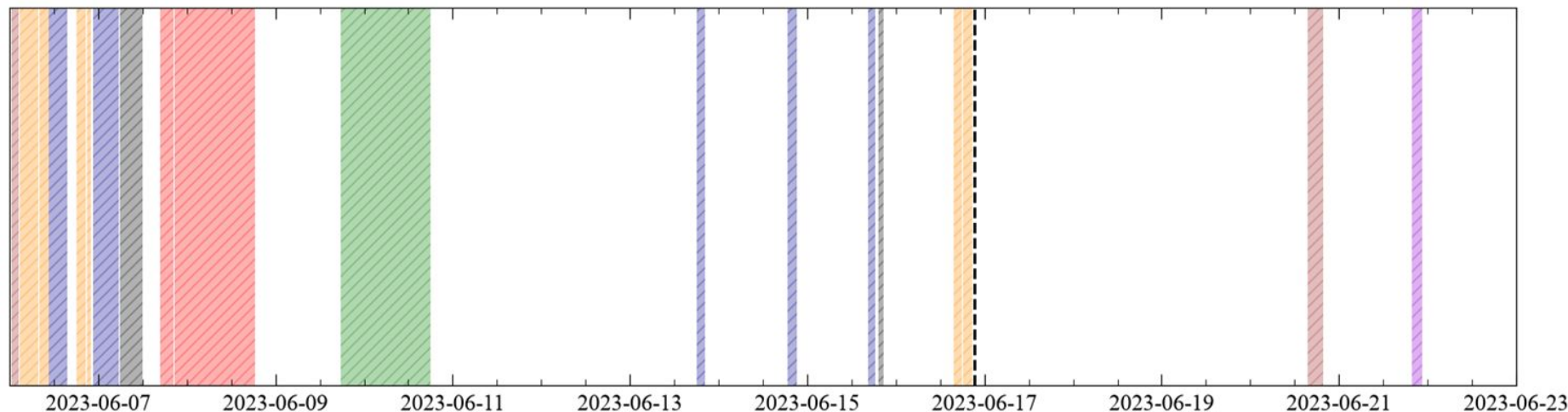
$^{57}\text{Co}$  removed 25 mins earlier

not a concern as occurred on opposite side of detector

$^{57}\text{Co}$  are low energy  $\gamma$ -rays used for calibrating the Skin and OD.

AmBe on 8 June 2023

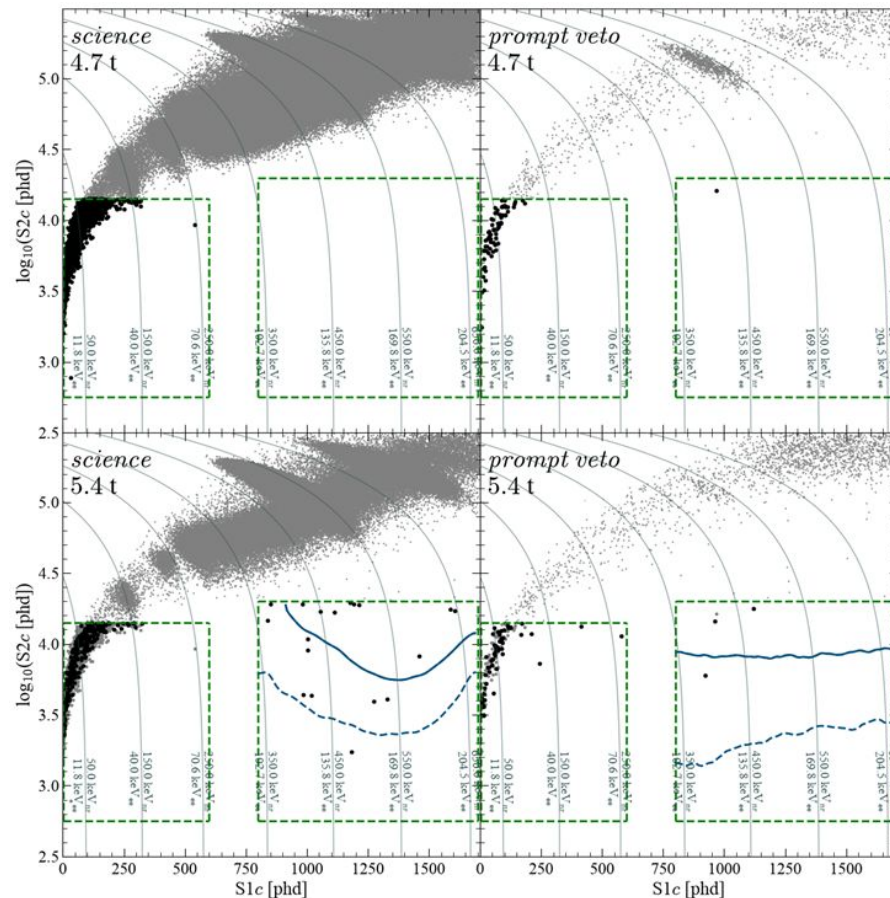
one week before



Legend:  $^{57}\text{Co}$   $^{83\text{m}}\text{Kr}$  AmBe  $^{22}\text{Na}$   $^{54}\text{Mn}$   $^{228}\text{Th}$   $^{131\text{m}}\text{Xe}$  LZ230616

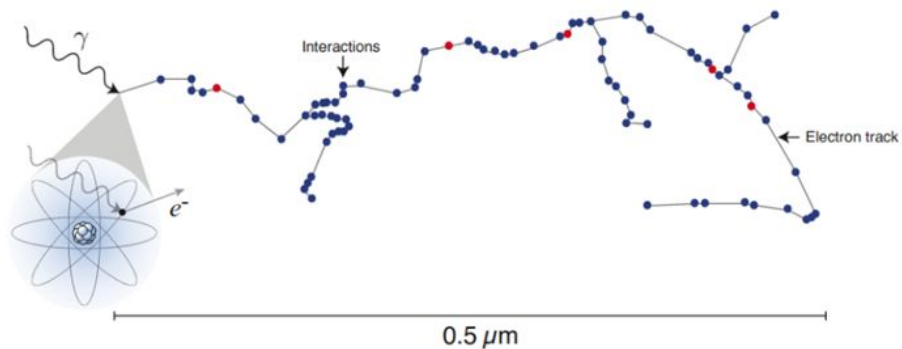
# High Energy Nuclear Recoil Search - MSSl

- MSSl model
  - o **Rate:** Derived from simulations. Validated in higher energy region
  - o **Shape:** Validated in looking at high energy region and closer to charge dead regions
- Expectation
  - o FV aggressively removes MSSl events
  - o  $0.0049 \pm 0.0049$  in science sample
  - o  $94 \pm 2\%$  prompt tagging efficiency

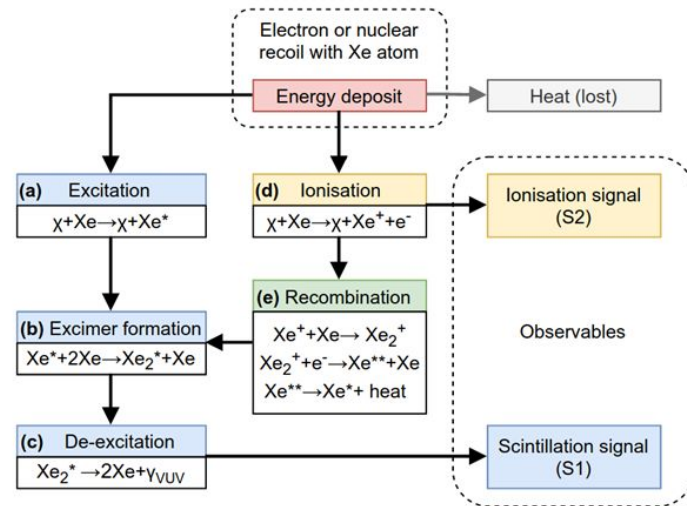
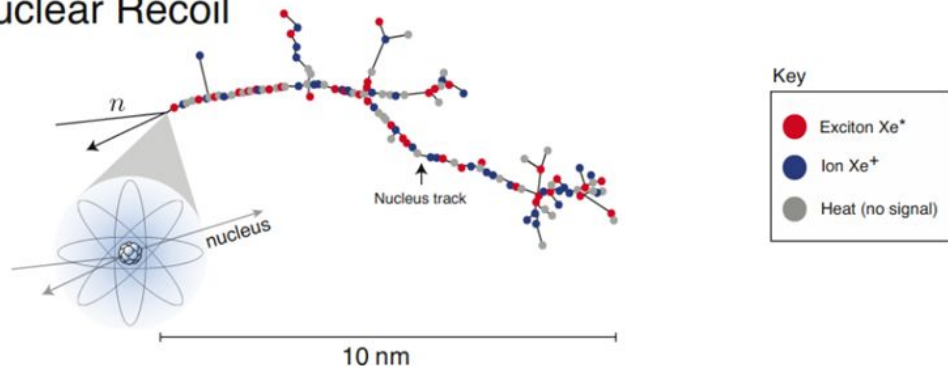


# High Energy Nuclear Recoil Search - Observables

## Electron Recoil



## Nuclear Recoil



# High Energy Nuclear Recoil Search - CRM

- Muons cascades can produce neutrons
  - o Neutrons can be O(GeV) in energy
  - o Likely aligned with muon direction
  - o Accompanied by other products
- If a muon enters any of the detectors, it is observed, and the event is removed. It is only a dangerous background if
  - o The neutron is the only particle to enter any detector system
  - o Simulations of mono-energetic neutrons (50 MeV – 1GeV) indicate **80 ± 4%** tagging efficiency.

Contribution evaluated through simulation

- MUSUN generated distribution [1]
- 1200 years of LZ exposure simulated with no signal-like deposits
- Validated against Geant4 + FLUKA sims [2,3]
- Normalised to flux:  $5.09 (\pm 0.08_{\text{stat.}} \pm 0.10_{\text{sys.}}) \times 10^{-9} \text{ cm}^{-2}\text{s}^{-1}$  [4]

90% confidence level upper limit of  $4.6 \times 10^{-4}$

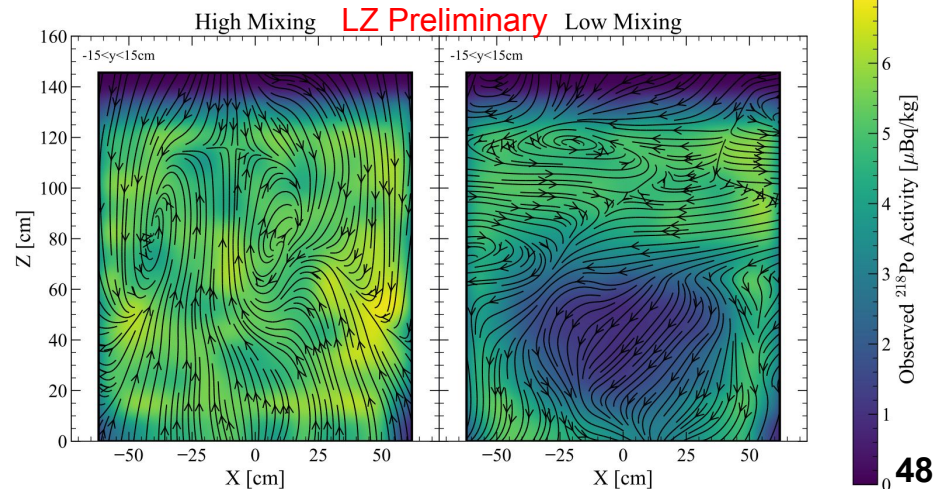
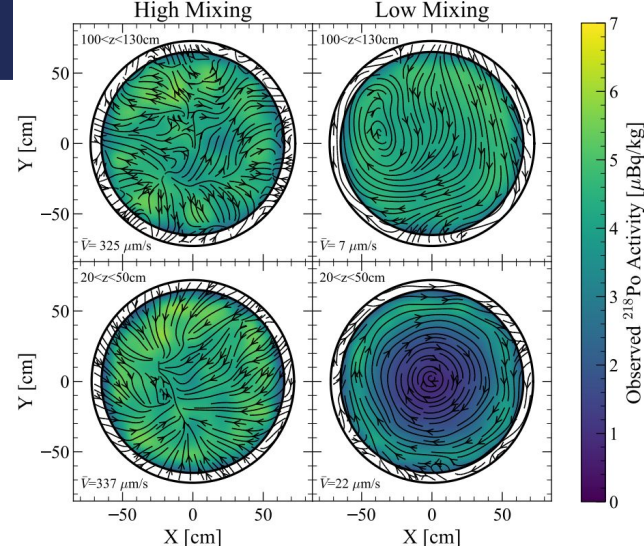
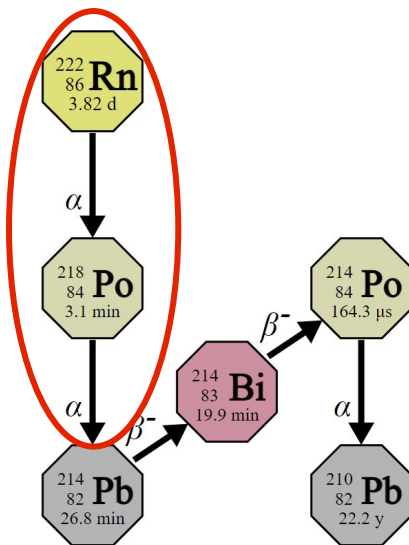
| Selection       | #                 |
|-----------------|-------------------|
| $\mu$ generated | $2.1 \times 10^9$ |
| + n in Lxe      | $5.6 \times 10^5$ |
| + SS            | 230               |
| + in FV         | 19                |
| + in ROI        | 0                 |

- [1] [Com. Phys. Comms 180 \(2009\)](#)
- [2] [Nucl.Instrum.Meth. A545 \(2005\) 398-411](#)
- [3] [arXiv:2310.16586](#)
- [4] [arXiv:2602.16799](#)

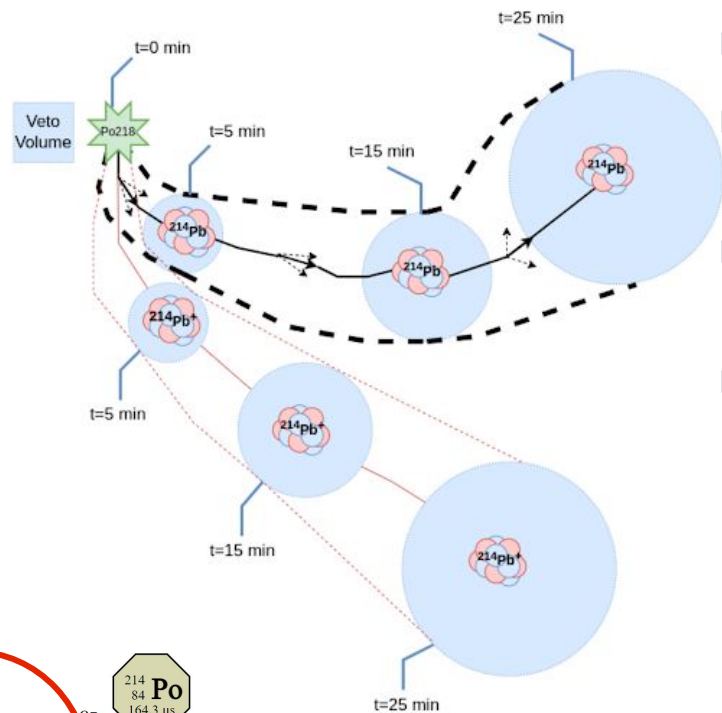
# Backup WS2024

# 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

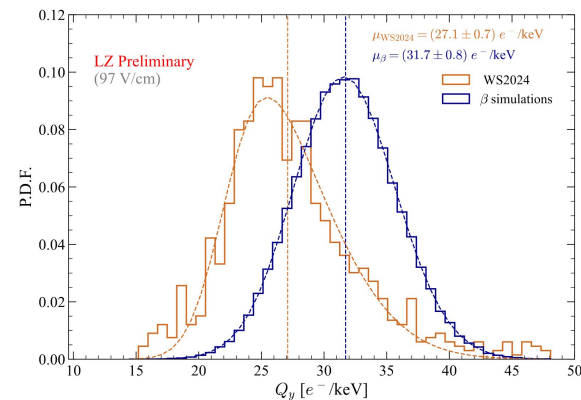
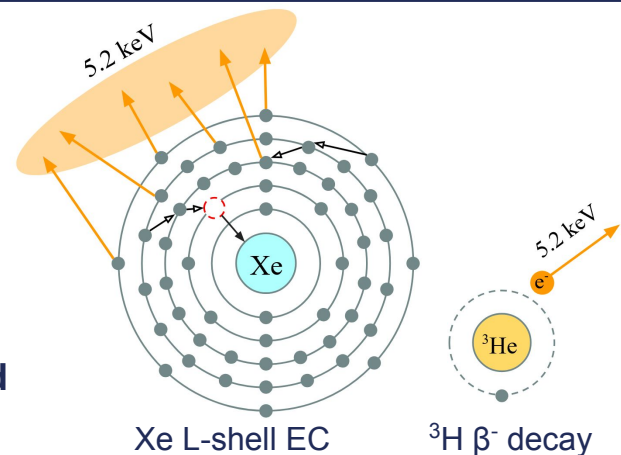


- ❑ “Naked”  $^{214}\text{Pb}$   $\beta$  make up majority of ER background
- ❑ Combine LXe flow maps & electric field maps to predict volumes likely to contain charged or neutral  $^{214}\text{Pb}$ .
- ❑ Reduces  $^{214}\text{Pb}$  to  $1.8 \pm 0.3 \mu\text{Bq/kg}$  in untagged sample
  - ❑  $3.9 \pm 0.4 \mu\text{Bq/kg}$  in total exposure
- ❑ Tagged and untagged samples both fitted for WS2024

| Sample   | % $^{214}\text{Pb}$ | % Exposure |
|----------|---------------------|------------|
| Tagged   | $60 \pm 4$          | 15         |
| Untagged | $40 \pm 4$          | 85         |

# Electron Capture Backgrounds

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

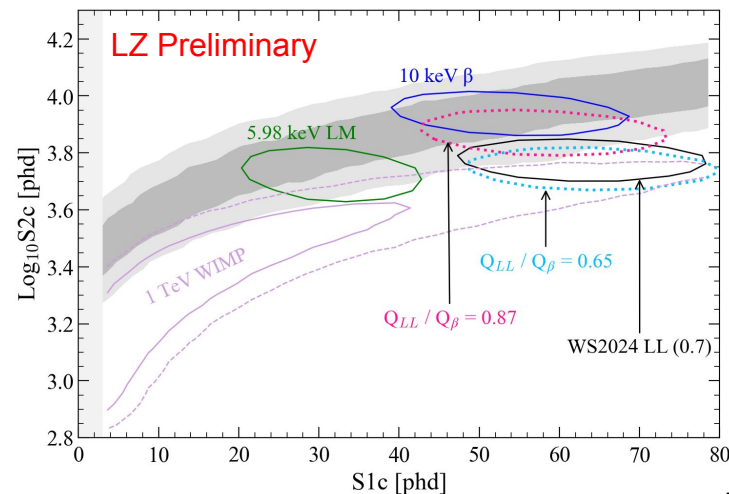
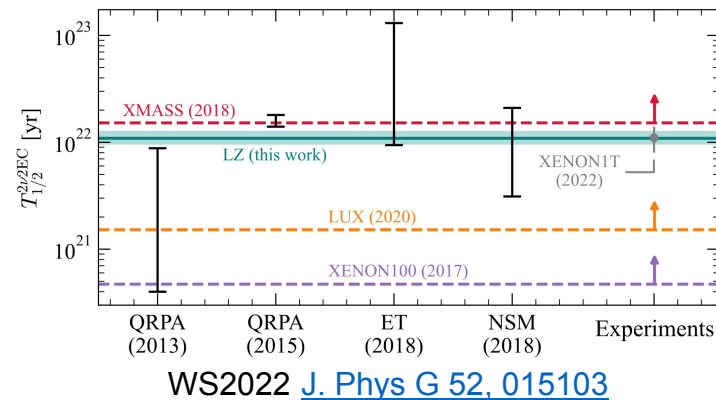


- Skin tagged Xe L-shell EC
- $\beta$  simulation

\*Preliminary, dedicated publication in progress

# $^{124}\text{Xe}$ Double Electron Capture

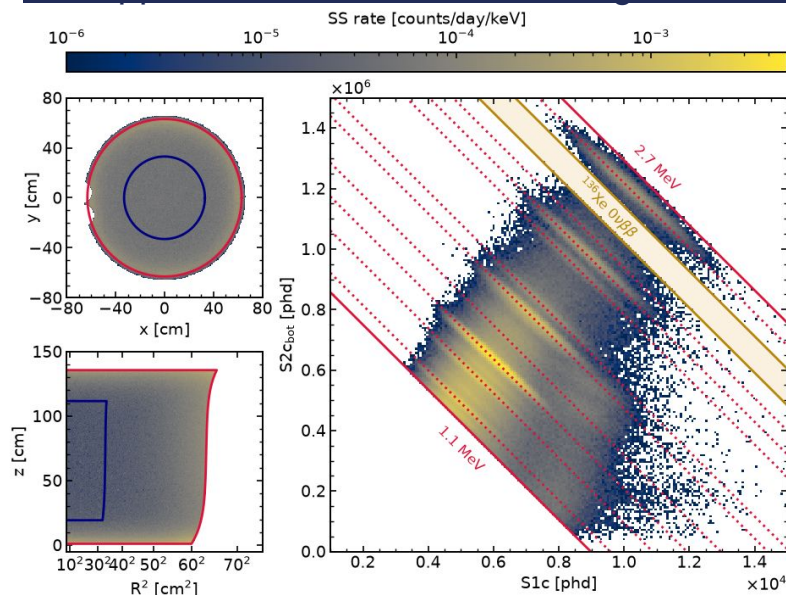
- ❑  $^{124}\text{Xe}$   $2\nu\text{ECEC}$   $T_{1/2} = (1.09 \pm 0.14^{\text{stat}} \pm 0.05^{\text{sys}}) \times 10^{22}$  years
  - ❑ World's longest directly measured half-life
- ❑ In-situ  $T_{1/2}$  measurement of KK (64.3 keV) captures -  $(65 \pm 5)\%$
- ❑ LL (10 keV) and LM (6 keV) are WS backgrounds
- ❑ LM modelled with same as single L-shell charge suppression
  - ❑  $Q_{\text{LM}}/Q_{\beta} = Q_{\text{L}}/Q_{\beta}$
- ❑ For LL expect further charge yield suppression due to higher ionization density.
- ❑ Vary  $Q_{\text{LL}}/Q_{\beta}$  in fitting of our data  $0.65 < Q_{\text{LL}}/Q_{\beta} < 0.87$ 
  - $2\times$  ionization density
  - $Q_{\text{L}}/Q_{\beta}$
- ❑ Best fit to WS2024 data:  $Q_{\text{LL}}/Q_{\beta} = 0.70 \pm 0.04$



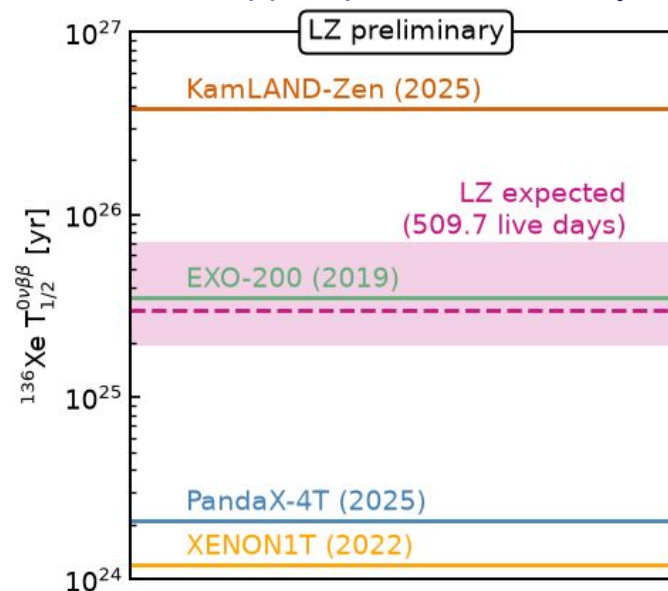
# Backup $0\nu\beta\beta$

# Search for $0\nu\beta\beta$ with $^{136}\text{Xe}$ - Event Selection

## $^{136}\text{Xe}$ $0\nu\beta\beta$ Volumes and Extended Region of Interest



## $^{136}\text{Xe}$ $0\nu\beta\beta$ Expected Sensitivity



- ❑ Soon to be released  $^{136}\text{Xe}$   $0\nu\beta\beta$  analysis
  - ❑ Energy only statistical inference
- ❑ Inner volume
  - ❑ Low background expectation
  - ❑ Excellent energy resolution - 0.66%  $Q_{\beta\beta}$
- ❑ Competitive limit without  $^{136}\text{Xe}$  enrichment
  - ❑ Natural  $^{136}\text{Xe}$  abundance  $\sim 9\%$