University of BRISTOL

Search for dark matter interactions at high recoil energy with the LUX-ZEPLIN experiment

Sam Eriksen
On behalf of the LZ Collaboration
TeVPA 2026

The LUX-ZEPLIN 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
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- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison
- University of Zürich

US Europe Asia Oceania

LZ Collaboration Meeting
July 2026 at University of Bristol

US Department of Energy

Science and Technology Facilities Council

Fundação para a Ciência e a Tecnologia

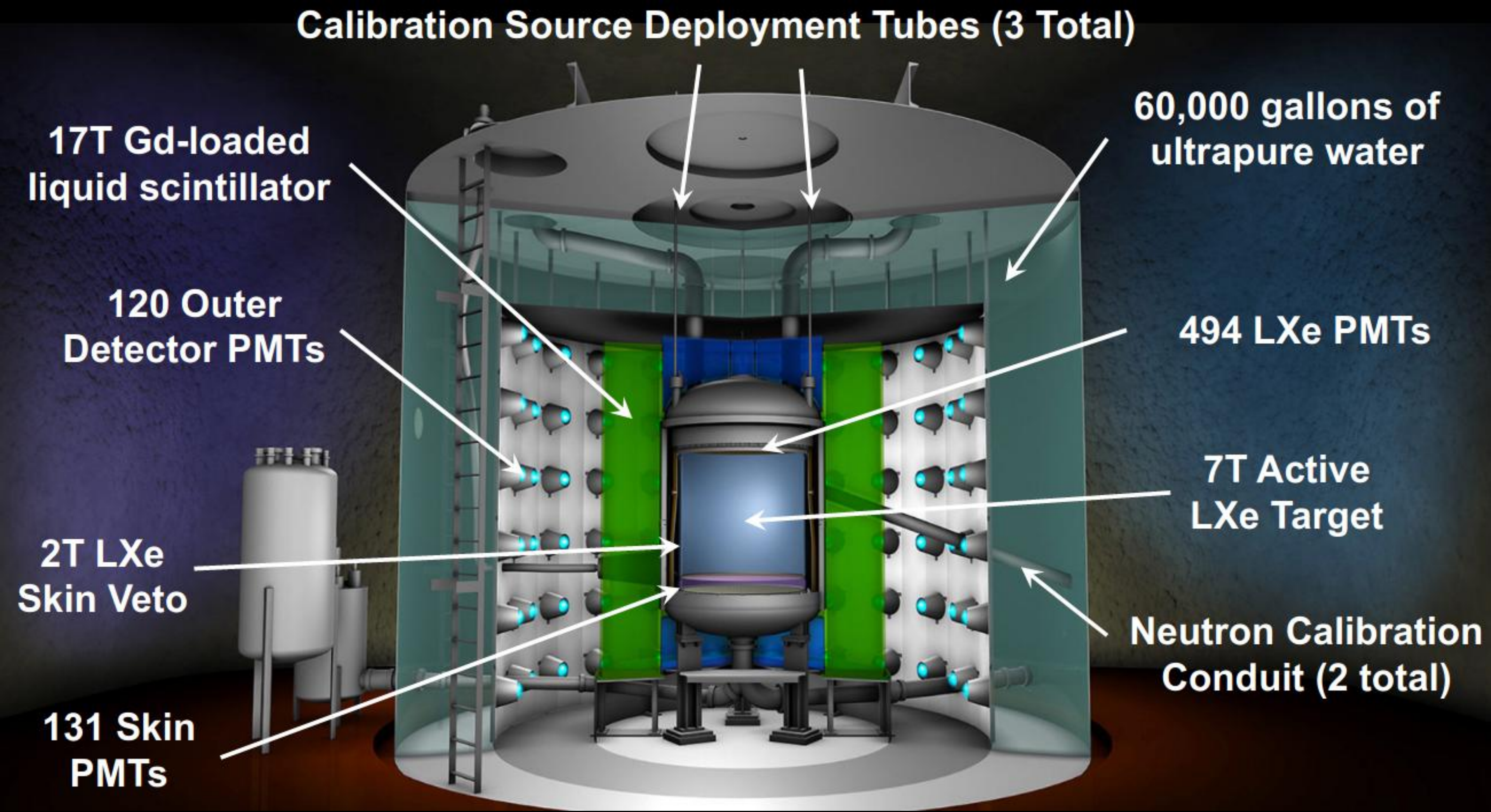
Sanford Underground Research Facility

Swiss National Science Foundation

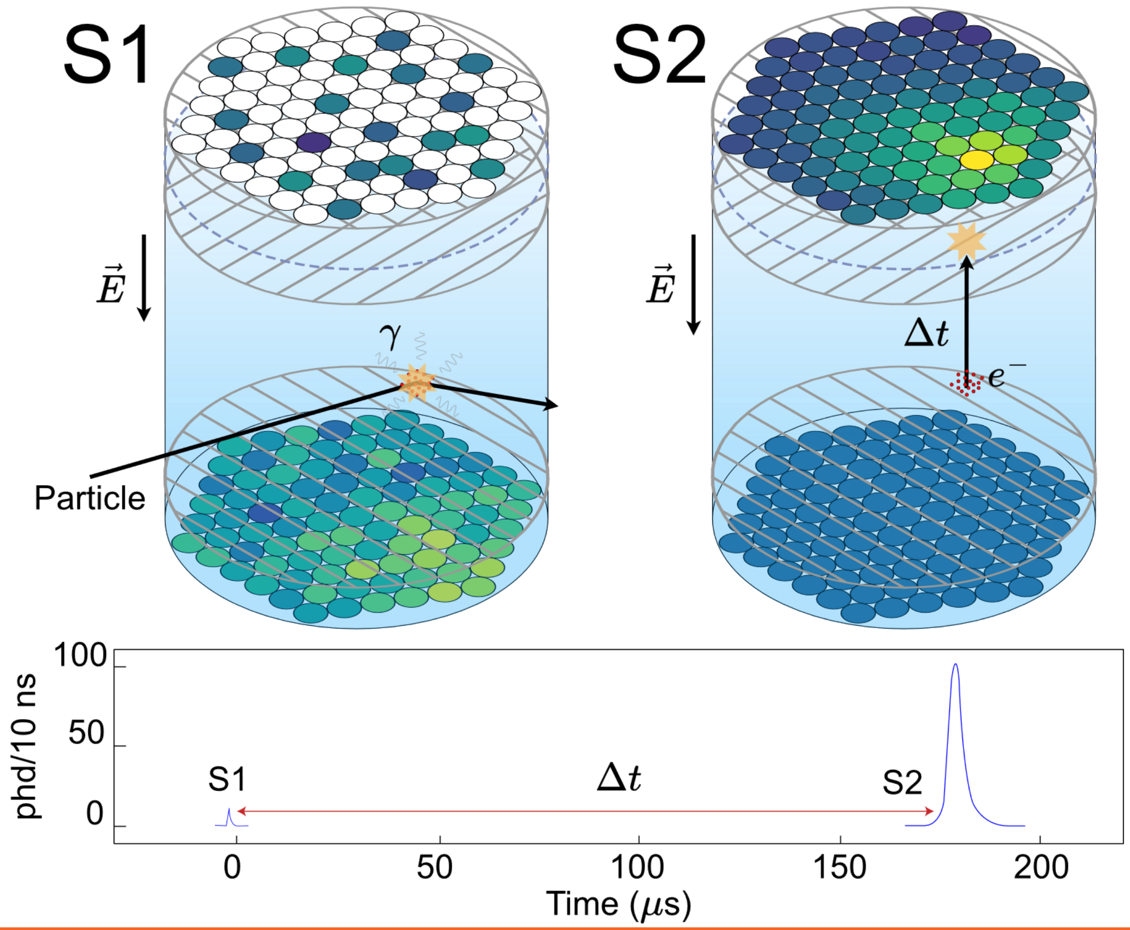
Institute for Basic Science

ARC Centre of Excellence for Dark Matter Particle Physics

Thanks to our sponsors and participating institutions!

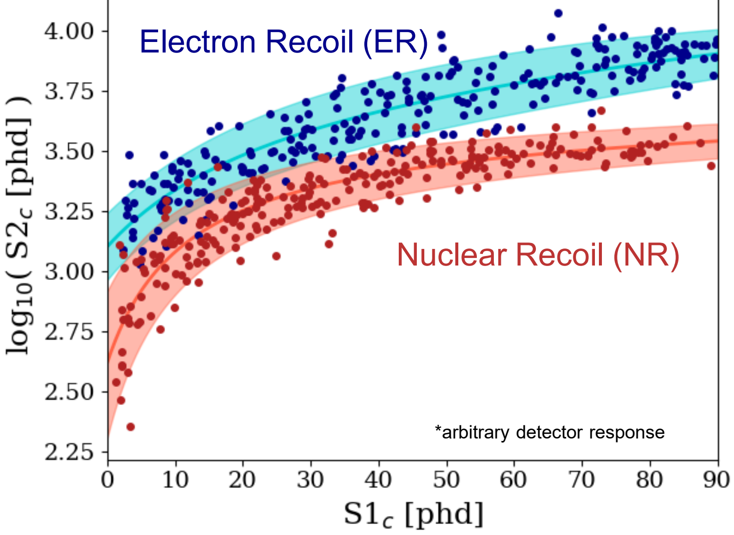

Calibration Source Deployment Tubes (3 Total)
17T Gd-loaded liquid scintillator
60,000 gallons of ultrapure water
120 Outer Detector PMTs
494 LXe PMTs
7T Active LXe Target
2T LXe Skin Veto
Neutron Calibration Conduit (2 total)
131 Skin PMTs

WIMP Detection Principle with LUX-ZEPLIN



Dual Phase Time Projection Chamber

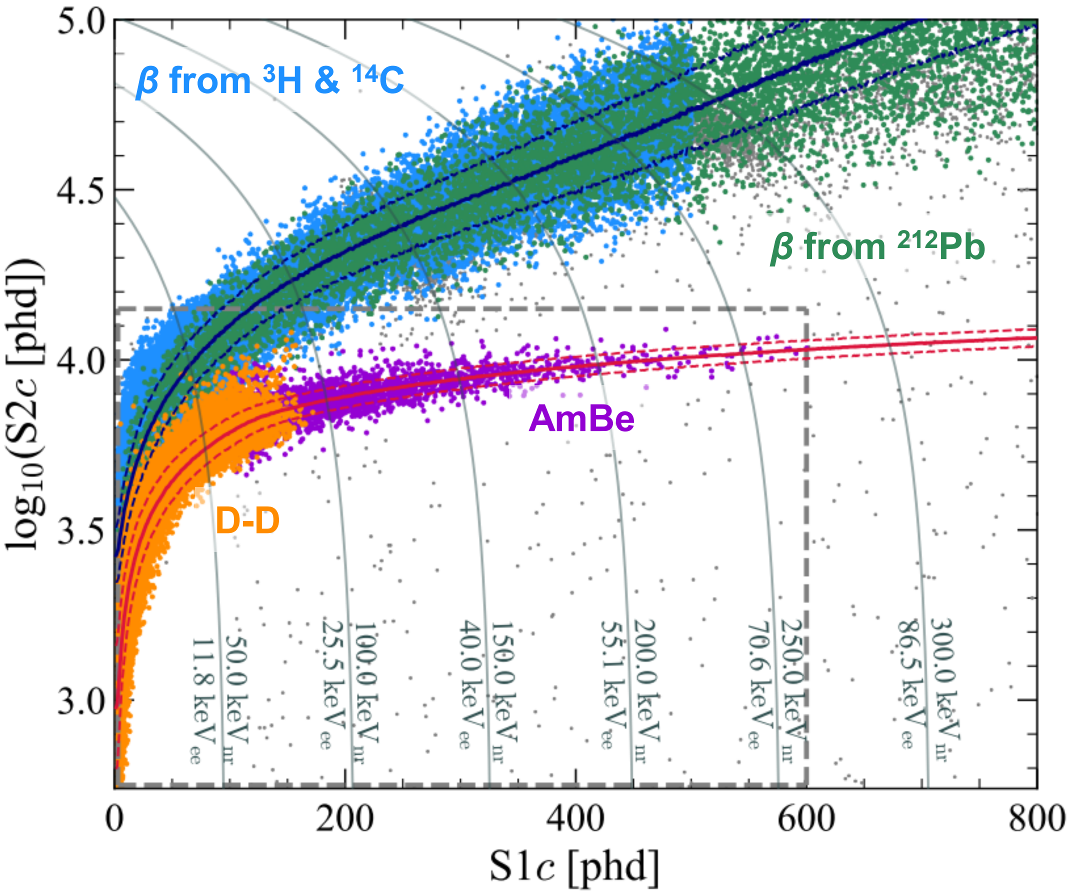
- Primary scintillation light (S1)
- Secondary scintillation induced from free charge (S2)
- 3D reconstruction allows for fiducialisation
- ER/NR discrimination from S1:S2 ratio



Calibrations

- **Electron Recoils (background-like)**
  - Methane injection:
    →^{3}H (0-18.6 keV_{ee})
    →^{14}C (0-156 keV_{ee})
  - ^{220}Rn injection: ^{212}Pb (0-569 keV_{ee})
  - Monoenergetic injections:
    →^{83m}Kr (32.1 + 9.4 keV_{ee})
    →^{131m}Xe (164 keV_{ee})

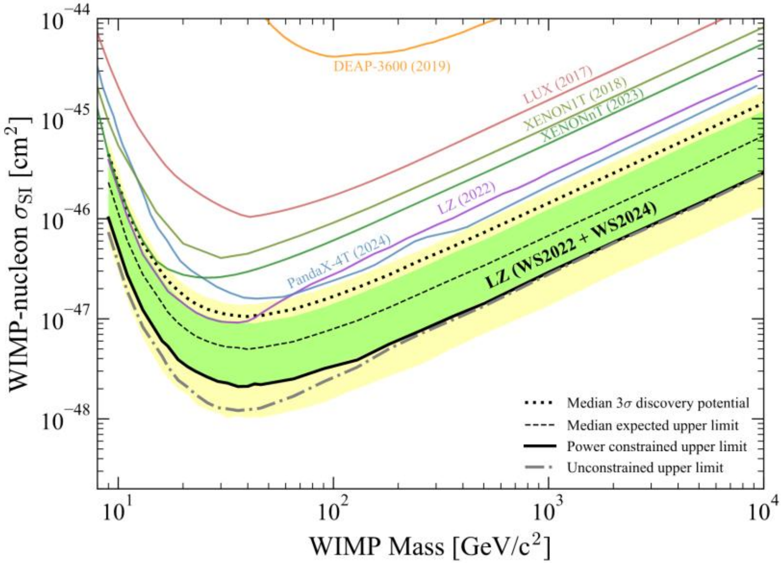
- **Nuclear Recoils (signal-like)**
  - D-D neutrons (0-74 keV_{nr})
  - AmBe neutrons (0-350 keV_{nr})

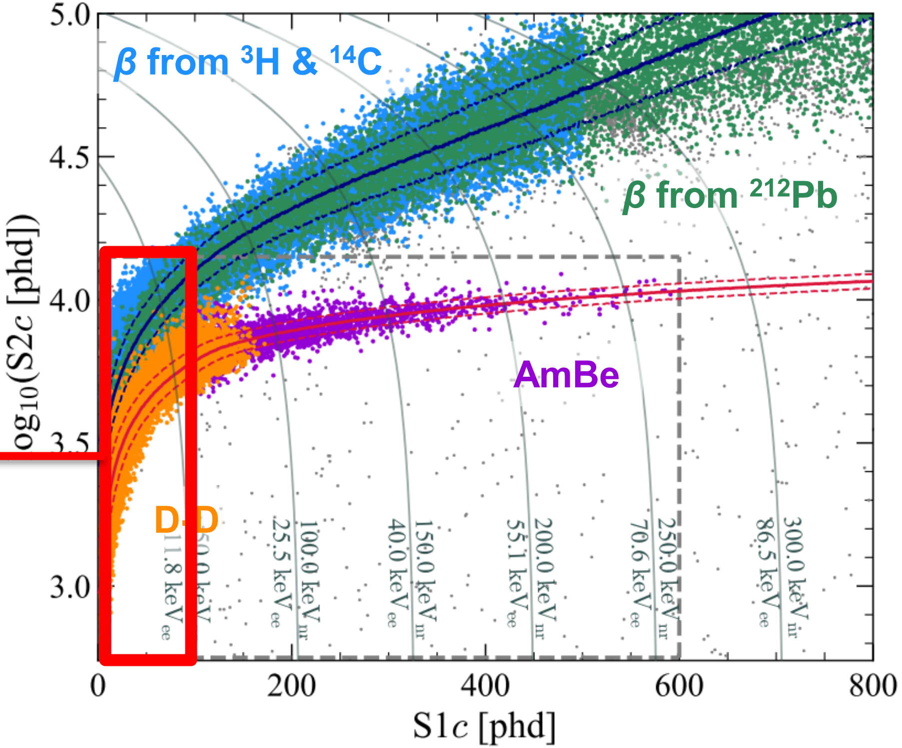


Going to higher energies

- Typical WIMP searches focus on SI & SD scattering
  - ~exponentially decreasing spectra
  - analyses focus on < 55 keV recoils

- Previous LZ analysis set world leading limits on SI interactions: Phys. Rev. Lett. **135**, 011802





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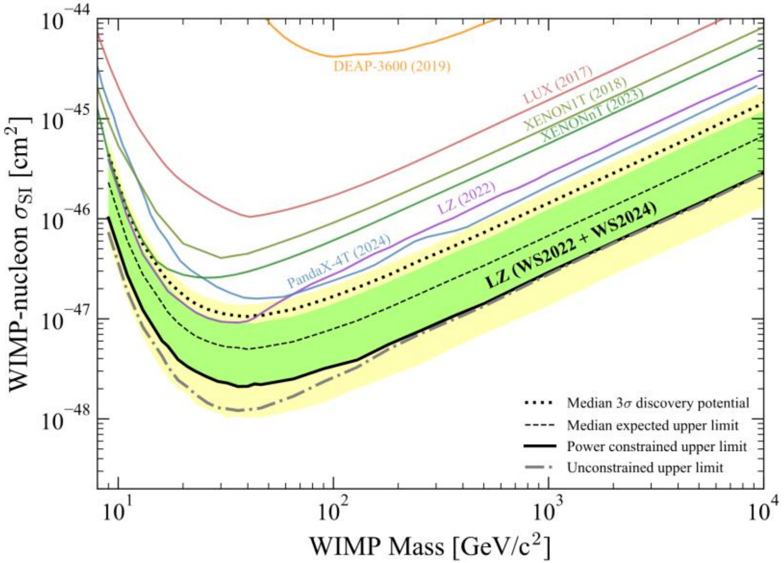
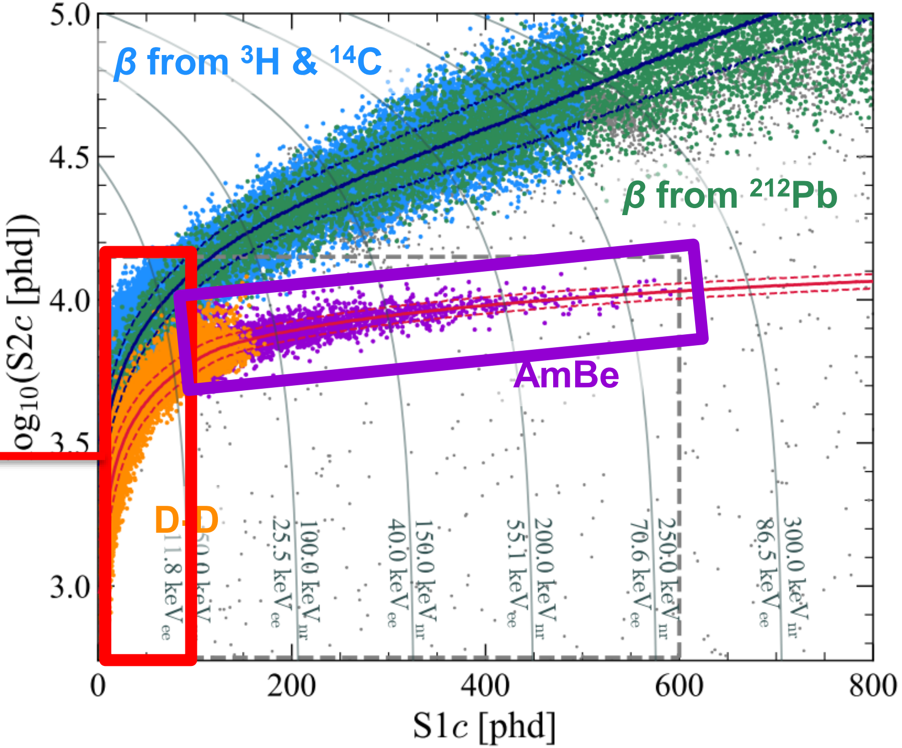
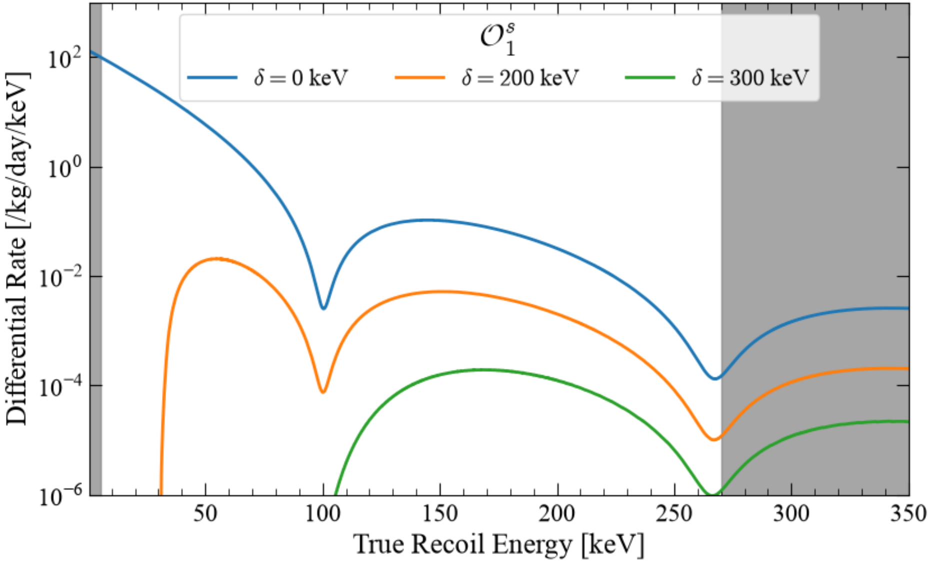




Interaction models at higher energies

- DM scattering can result in recoil spectra peaked at higher energies if:
  - Interaction has momentum dependent coupling
  - inelastic scatter
    - DM models with nearly degenerate mass states, separated by delta [keV]

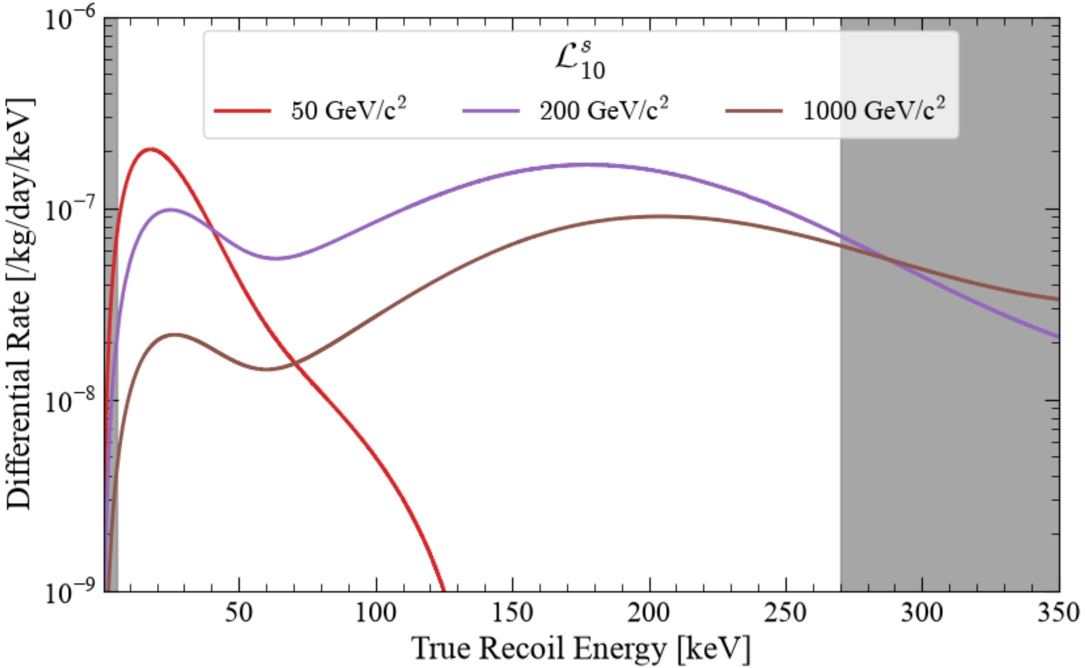
$$v_{min} = \frac{1}{\sqrt{2E_R m_N}}\left(\frac{E_R m_N}{\mu} + \delta\right)$$



[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)]

In our latest analysis, we've performed a search for:

- Signals described through an EFT
- 616 models in total
- $\mathcal{L}_1 - \mathcal{L}_{20}$
- Inelastic SI ($\mathcal{O}_1$) + inelastic SD ($\mathcal{O}_4$)
- This talk will use $\mathcal{L}_{10}$ as an example
  → A magnetic moment interaction

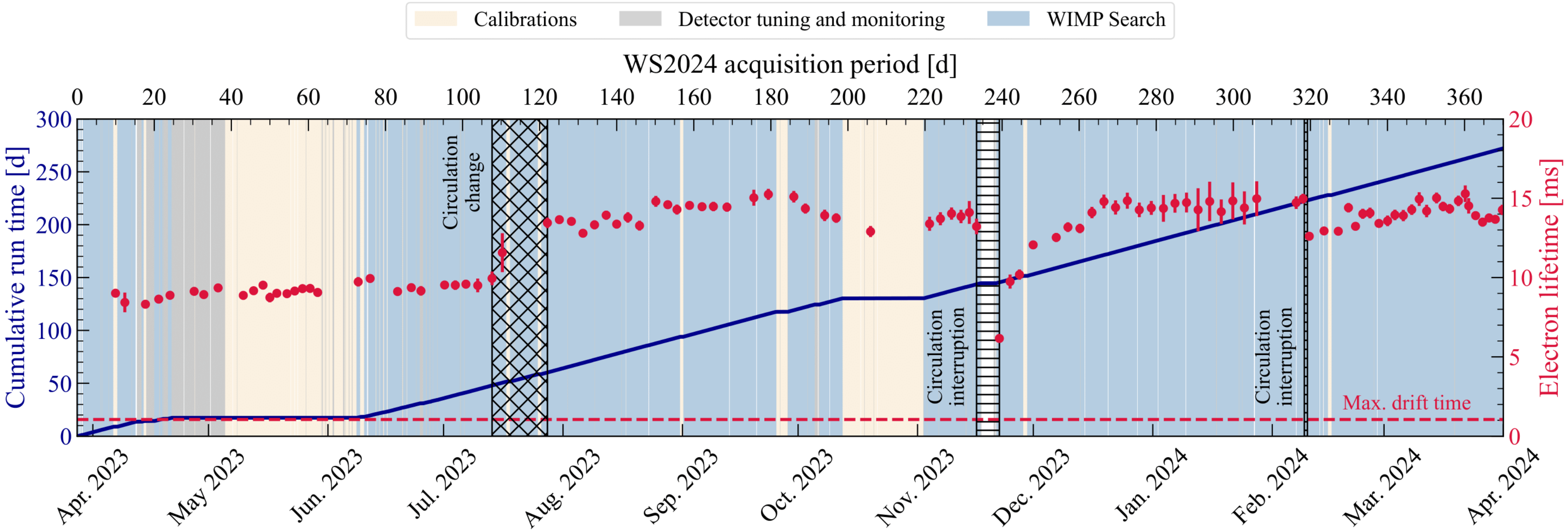


Fitzpatrick et al. J. Cosmol. Astropart. Phys. 02, 004 (2013)
Anand et al. Phys. Rev. C 89, 06551 (2014)

Analysis Data Period

Acquired data for ~370 days

- 95.2% detector up-time
- 220 live-days of exposure after data quality cuts



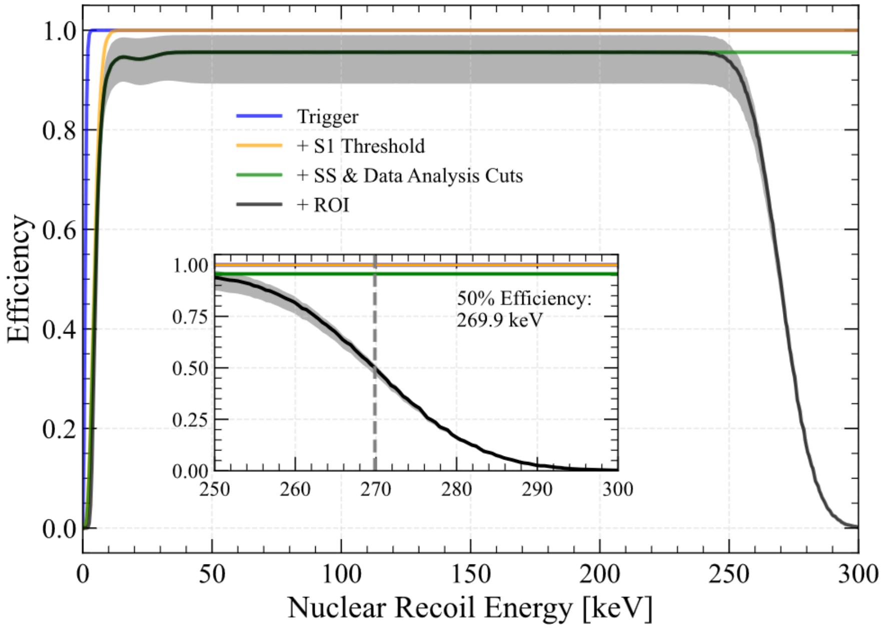
Analysis Selection

On collected data, apply a series of selections:

Region of Interest
- $3 < S1c < 600$ phd
- $S2 > 645$ phd
- $10^{2.75} < S2c < 10^{4.15}$

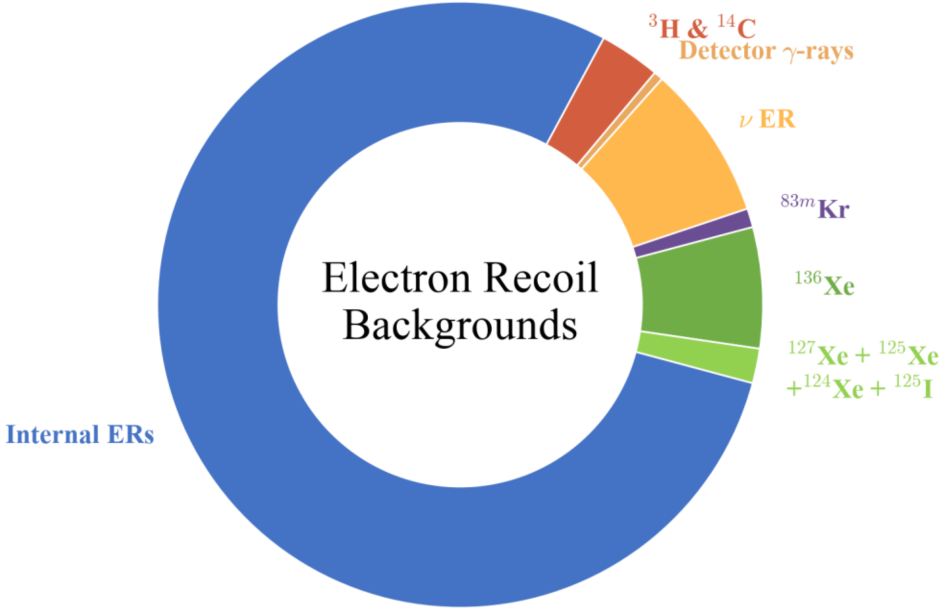
Time exclusions
- Periods of high rate
- Detector instability

S1 and S2 cuts
- Pathologies targeting unphysical waveforms
- Acceptance quantified on calibration data



Backgrounds

- **Dissolved β emitters (Internal)**
  - ^{214}Pb, ^{212}Pb, ^{85}Kr, ^{136}Xe
- **Dissolved EC decays**
  - Neutron activated: ^{127}Xe, ^{125}Xe, ^{125}I
  - ^{124}Xe double EC
- **Instrumental**
  - Accidentals coincidences
  - Multiple scatter single ionisation (MSSI)
- **Solar Neutrinos**
  - ER: pp + ^{7}Be
  - NR: ^{8}B + hep, Atmospheric
- **Detector Components (long-lived γ sources)**
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- **Calibration**
  - Injected: ^{83m}Kr, ^{3}H, ^{14}C
- **Neutrons from detector materials**
  - Spontaneous fission
  - (α,n)



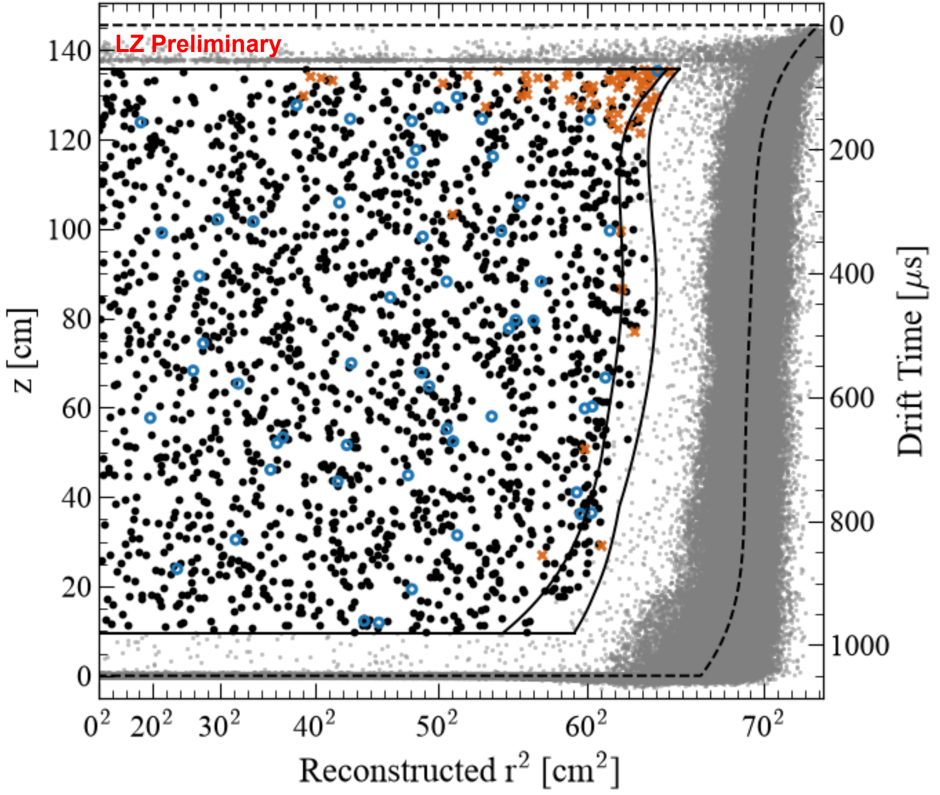
Fiducial Volume

To limit backgrounds from detector materials, plateout, and abnormalities from non-uniform electric fields near the edges

Wall backgrounds
- Limit wall contribution to < 10^{-4} events in exposure
- At least 4 MFP for γ-rays from the dominant MSSI source (352keV from ^{214}Pb)

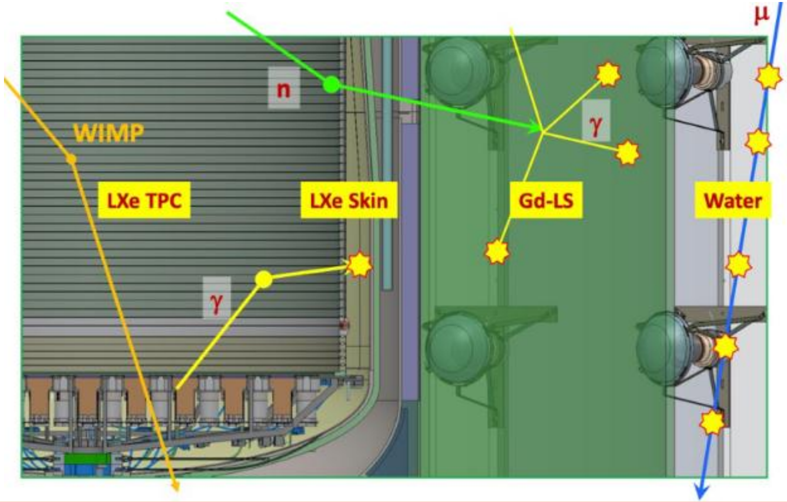
Cathode
- At least 4 MFP for γ-rays from the dominant MSSI source (352keV from ^{214}Pb)

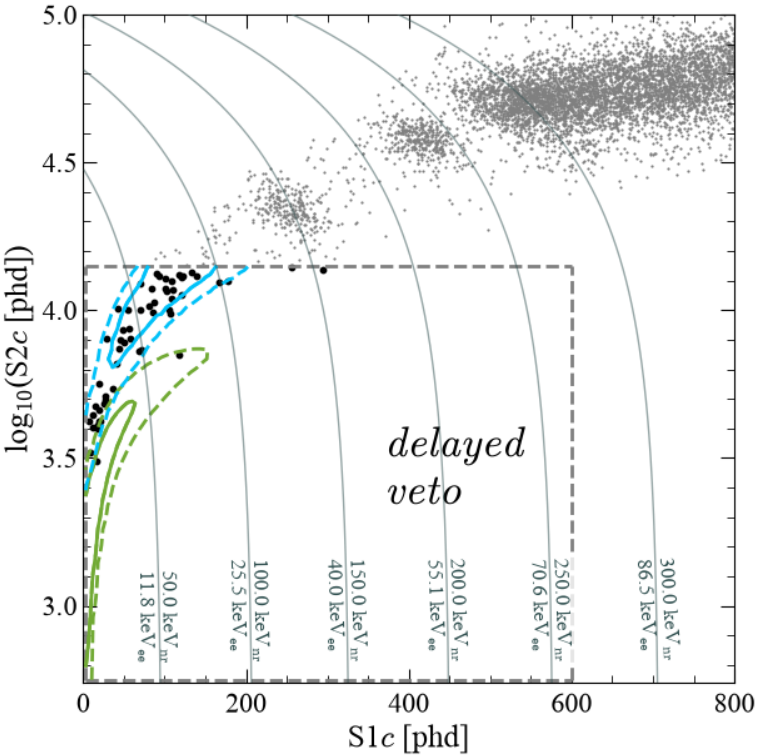
Analysis volume
- **4.7 +/- 0.2 tonnes**
- Analysis exposure: **2.8 tonne-years**



Data are separated into 3 samples based on Skin/OD tag

- **Delayed veto**
  - Skin signal > 300 keV or OD signal > 200 keV
  - Within 600 μs of S1
  - Tags and constrains neutrons

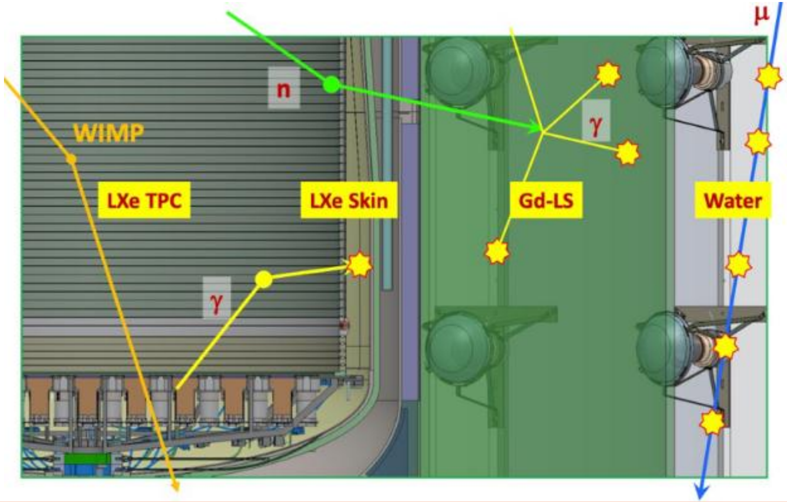


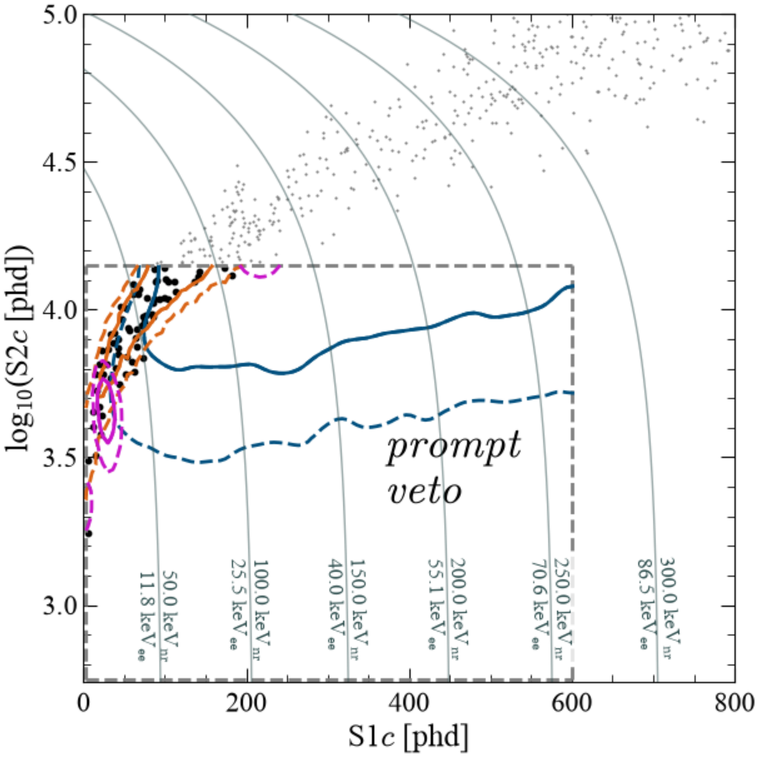


Contours: Neutrons
ER Backgrounds

Data are separated into 3 samples based on Skin/OD tag

- **Prompt veto**
  - Skin signal > 2.5 phd and within +/- 0.25 μs of S1
  - OD signal > 4.5 phd and within +/- 0.3 μs of S1
  - Tags and constrains ^{127}Xe, Detector γ-rays, MSSI, and neutrons



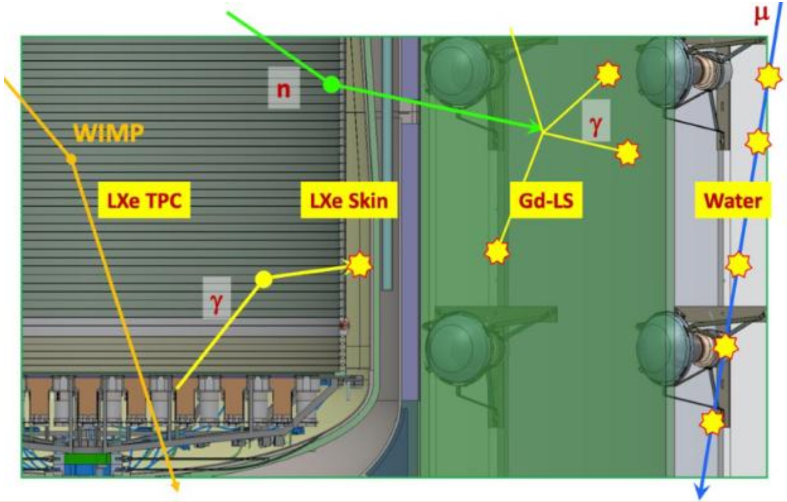


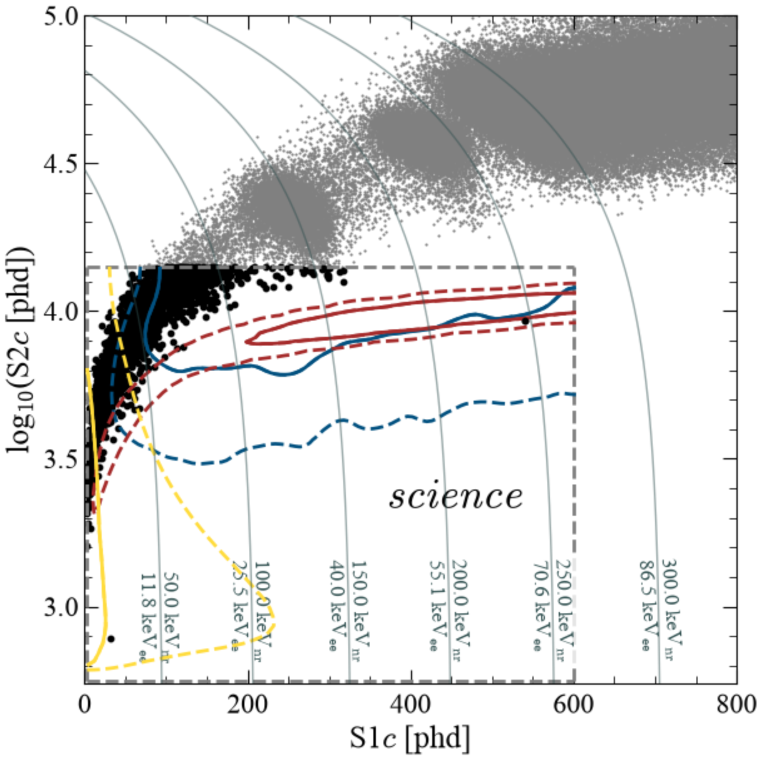
Contours: Detector ER
^{127}Xe MSSI

Datasets

Data are separated into 3 samples based on Skin/OD tag

- **Science**
    - No tag in veto systems



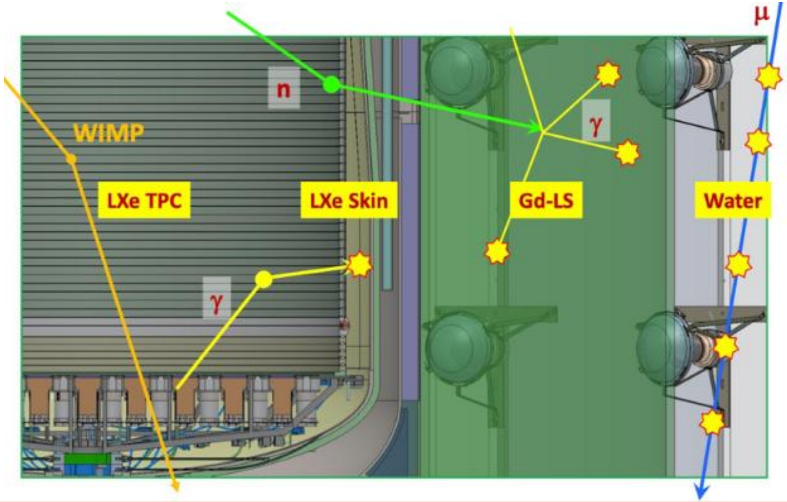


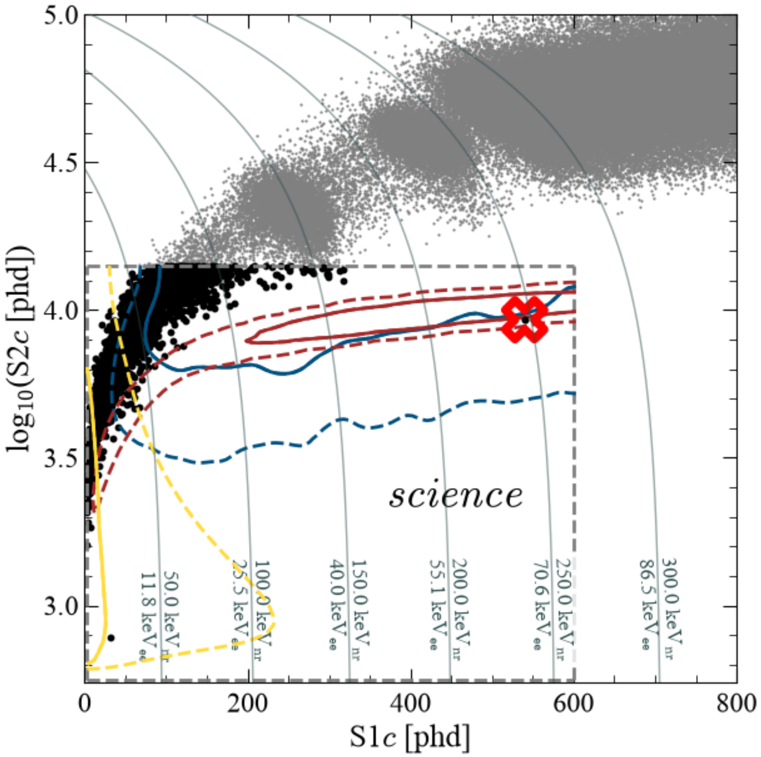
Contours: L10s 1000 GeV/c^2
Accidental Coincidences MSSI

Data are separated into 3 samples based on Skin/OD tag

- **Science**
  - No tag in veto systems

- One high energy signal-like event remains
  - S1c = 540.1 phd
  - S2c = $10^{3.98}$ phd

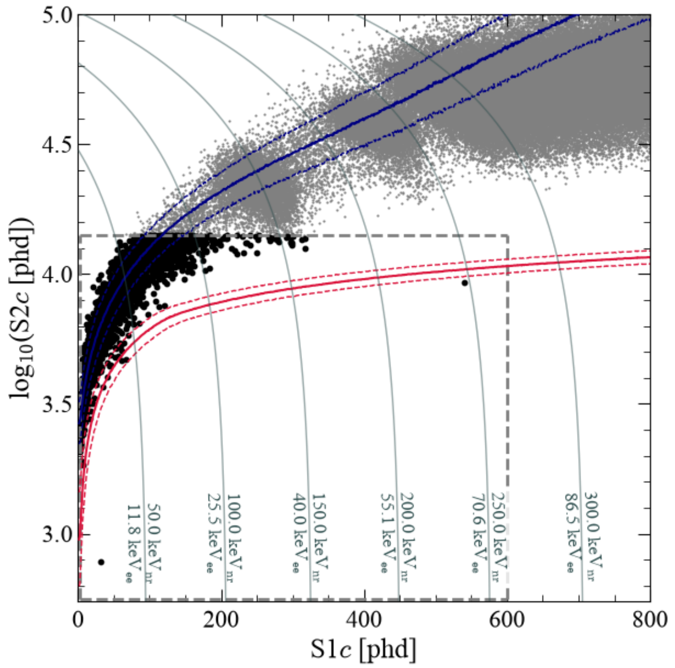


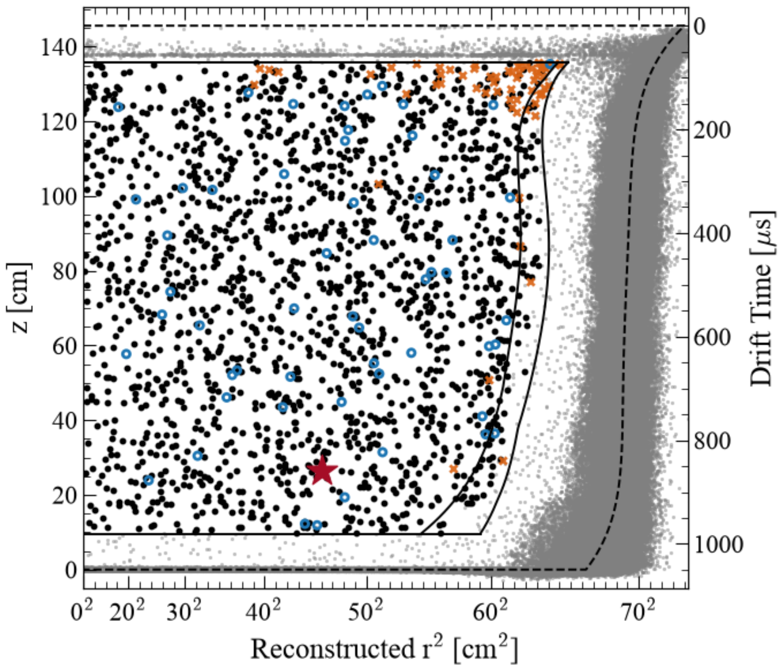


Contours: L10s 1000 GeV/c^2
Accidental Coincidences MSSI

A single event - LZ230616

- Occurred on 16 June 2023 (LZ230616)
- **248 ± 23_{stat} ± 23_{sys} keV** compatible with elastic nuclear recoil
- 26.4 cm from cathode
- 26.9 cm from TPC wall





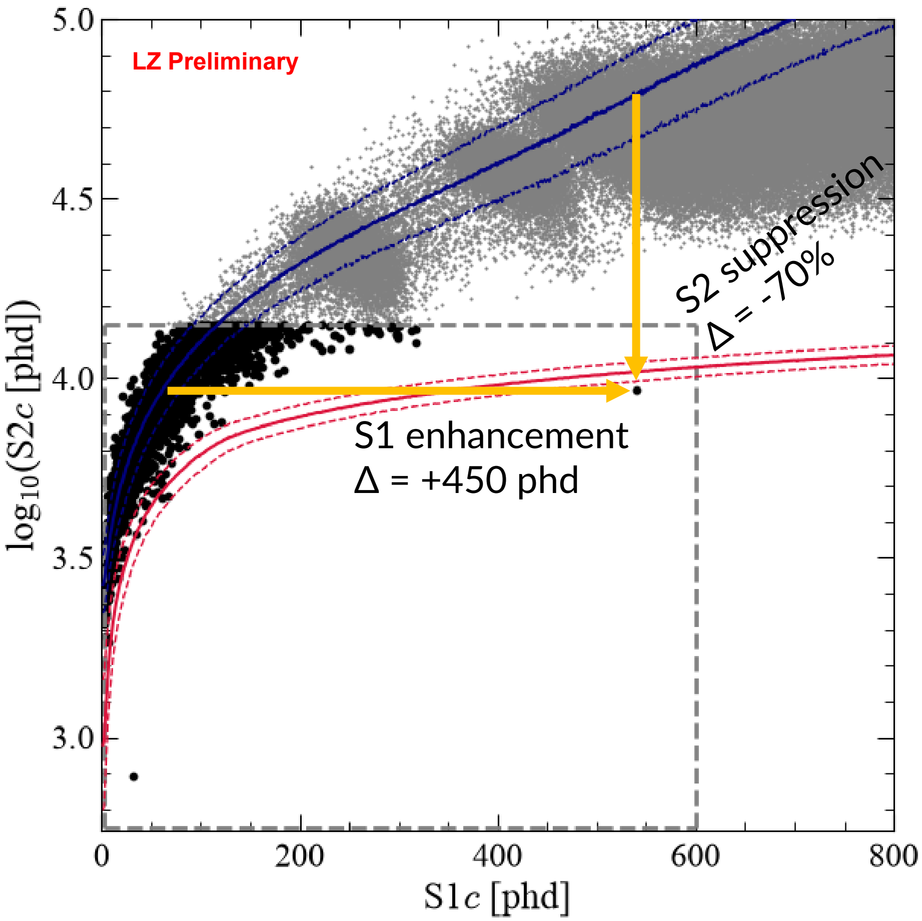
Topologies that can cause NR-like events

1. NR background
   - Neutrinos and neutrons

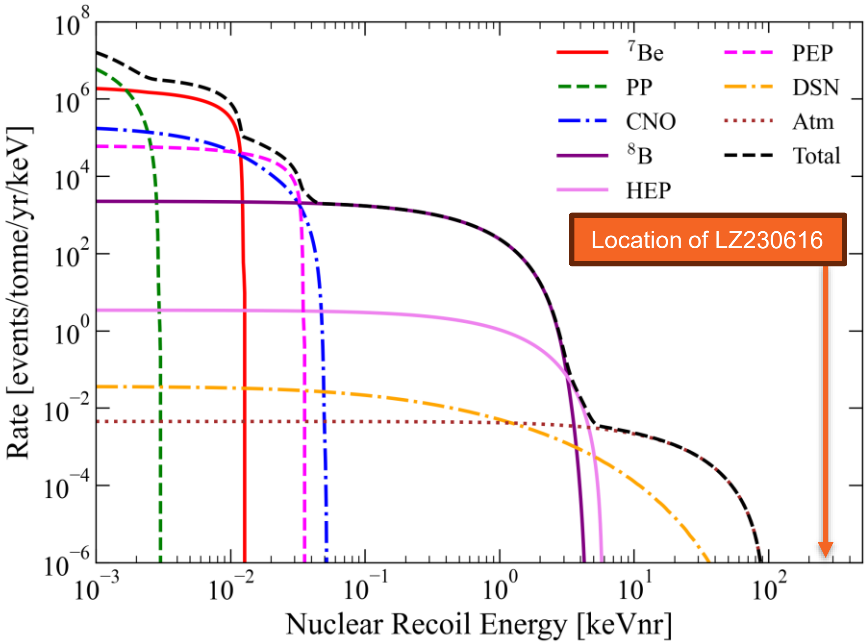
2. Accidental backgrounds

3. S1 enhancement
   - A double scatter where no charge from one of the scatters is collected - this is an MSSI

4. S2 suppression
   - A single scatter where not all the charge is collected, such as blocked grid cell, surface emission problem, or S2 gain sagging



- Coherent elastic neutrino-nucleus scattering (CEvNS) produce NR signals
- A large momentum transfer is required to produce LZ230616.
- In this region, the CEvNS cross section is suppressed



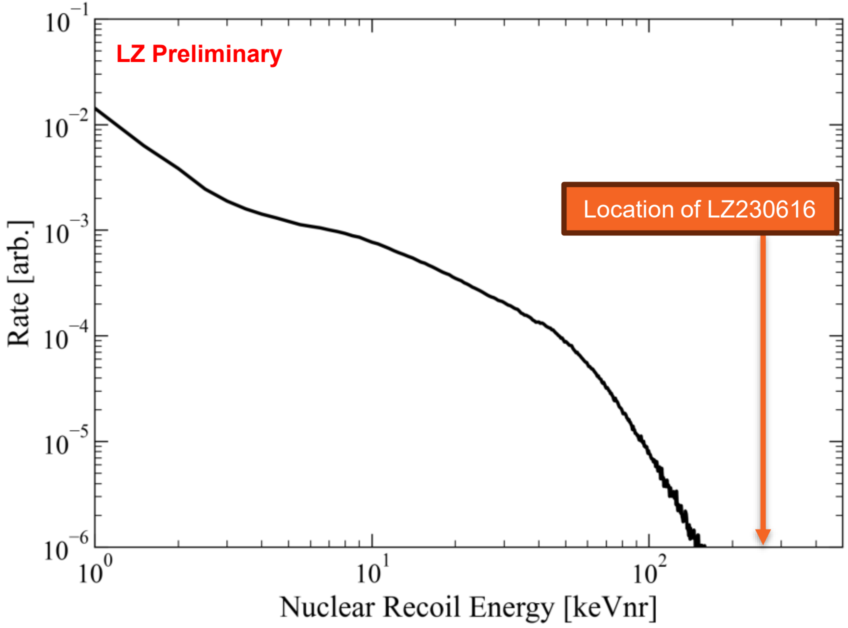
It is highly unlikely to see a single high energy neutrino scatter and no low energy scatters

Backgrounds: Neutrons

- Neutrons > 8 MeV can produce 250 keV elastic scatters
- Sources of neutrons
  - (α,n)
  - spontaneous fission
  - muon cascades
- Elastic scattering is highly forward peaked
- There is a high tagging efficiency for neutrons in Skin/OD
  - Detector component simulations: $\mathbf{92 \pm 4\%}$

It is highly unlikely to see a single high energy neutron scatter and no low energy scatters, and also no tagged neutrons in the veto samples

Expected neutron recoil spectrum from detector materials



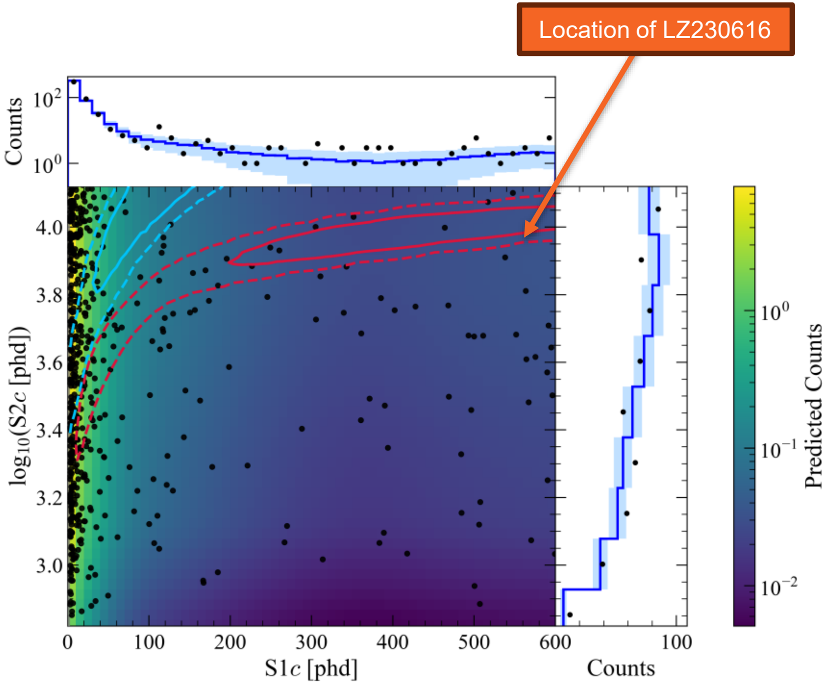
Backgrounds: Accidentals

- Accidental coincidence of uncorrelated S1 and S2 pulses: PhysRevD **108** 012010

- Accidentals model
  - **Rate:** Measure rate of unphysical drift time single scatters. Analysis cut efficiencies analysed using manufactured accidental events
  - **Shape:** Created by combining isolated S1 and S2 waveforms and applying analysis cut efficiencies

- Expectation
  - **2.7 ± 0.6**
  - Analysis cuts have 99.5% rejection power

LZ230616 is in low probability region of accidentals.



Contours: L10s 1000 GeV/c^2
ER Backgrounds

Backgrounds: MSSI

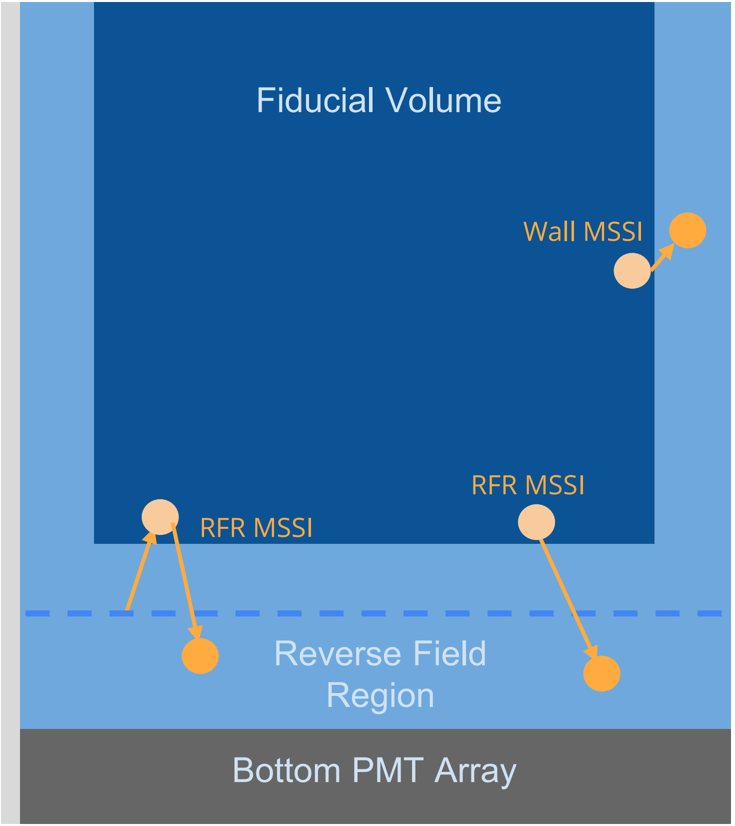
Multiple scattering single ionization (MSSI) event is a multiple scattering where at least one vertex is in a region of incomplete charge collection:

- Reverse field region
- Near the TPC walls

Dominant sources are:

- γ-rays from detector components
- $^{214}\text{Pb} \rightarrow {}^{214}\text{Bi} + e^{-} + \nu_e$ where ^{214}Bi is not in the ground state
  → 352keV most often and 839keV maximum

- Expectation
  - FV aggressively removes MSSI events
  - **0.005 ± 0.005** in science sample
  - **$94 \pm 2\%$** prompt tagging efficiency



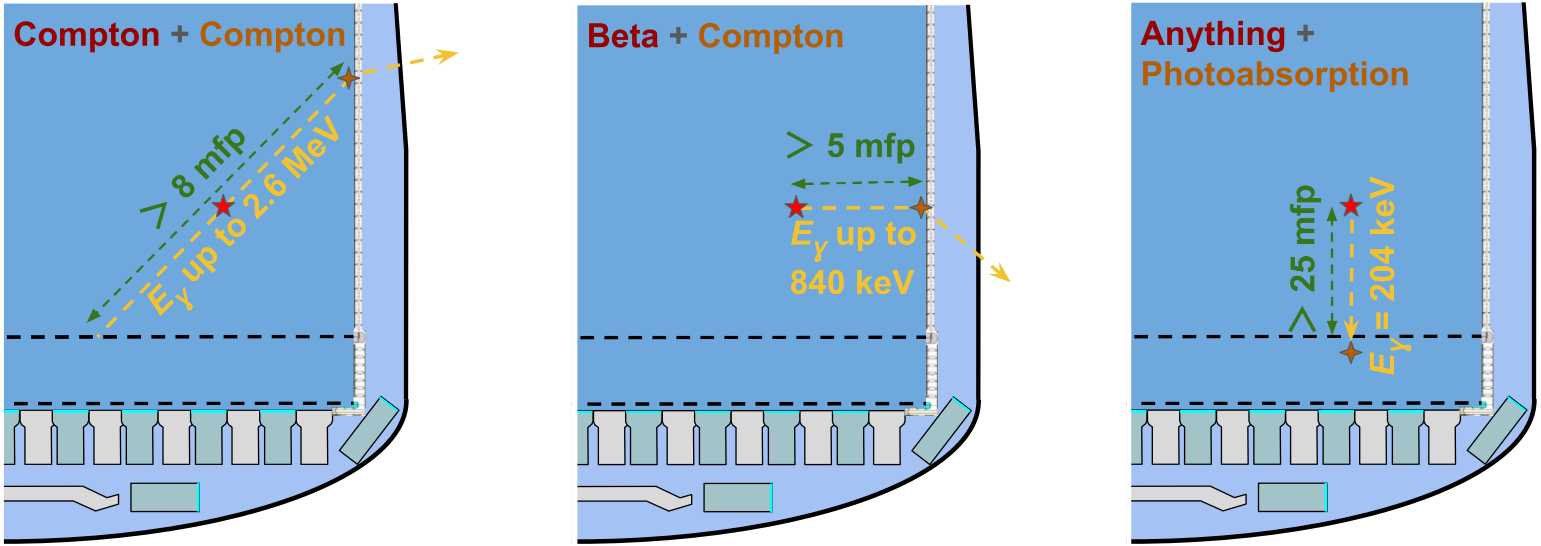
Backgrounds: MSSI

If the event is from MSSI
- S2 of event is a **12 ± 2 keV** scatter in FV

- Missing ~450phd (S1) must be from
  - **204 ± 40 keV** in RFR, or
  - **78 ± 7 keV** by Wall

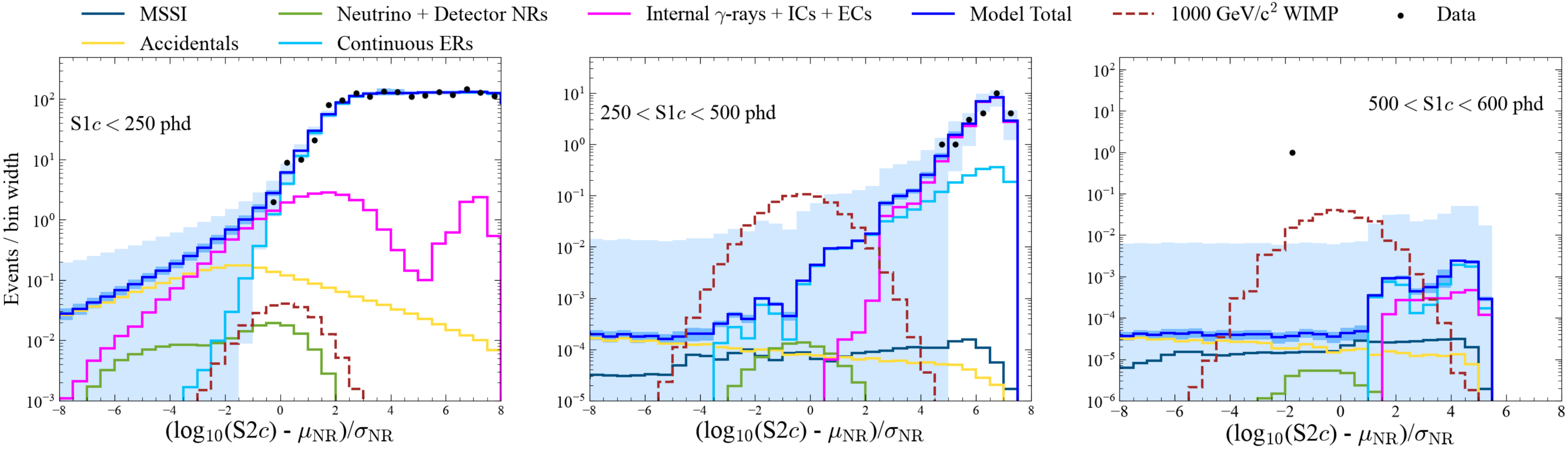
To be caused by MSSI, the γ-ray must:
1. Travel ~25cm
2. Scatter an additional time that doesn't produce an S2
3. Not be seen in the veto detectors

Each of these scenarios are unlikely



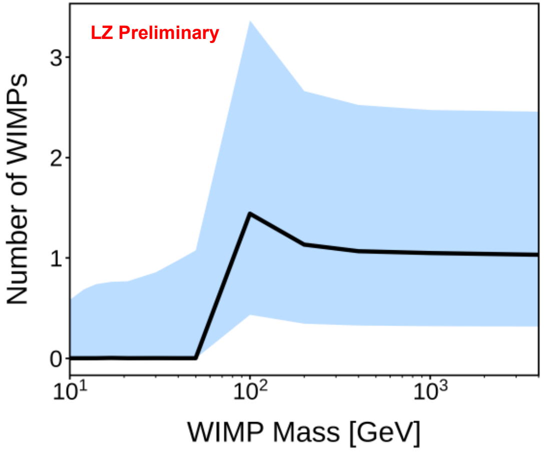
Background Fit

- As energy increases, separation between ER/NRs increases
- Projections of background model compared to NR band mean
- Above S1 > 250 phd background rate drops off significantly
- Integrated background count in 500 < S1c < 600 region is $0.0106 \pm 0.0008_{sys}$



Fit Result: science sample

- The 3 samples are simultaneously fit
- Best fit no. of WIMPs is **1** for masses > 100 GeV/c^2
- Similar result for any signal model with expected recoils at high energy



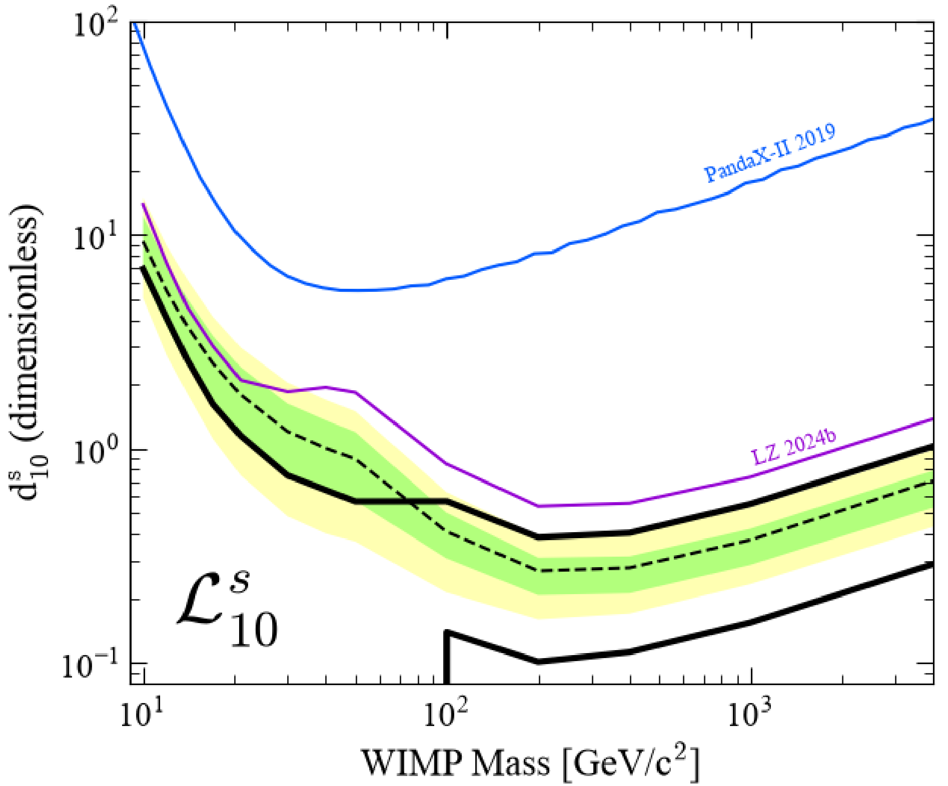
Source	Expected Events	Fit Result
Internal β decays	1341 ± 160	1340 ± 43
ν ER	140.6 ± 8.4	140.3 ± 8.4
^{136}Xe	110.0 ± 16.5	114.2 ± 16.1
CH_3T & ^{14}C	55.3 ± 3.1	55.2 ± 3.1
^{124}Xe	21.0 ± 6.3	22.6 ± 5.0
^{83m}Kr	17.1 ± 5.1	$17.0^{+3.5}_{-3.3}$
^{125}I	8.9 ± 2.7	9.8 ± 2.3
Detector ERs	8.5 ± 3.4	$9.4^{+1.7}_{-1.6}$
Accidental coincs.	2.7 ± 0.6	2.6 ± 0.6
^{127}Xe + ^{125}Xe	1.5 ± 0.3	1.2 ± 0.3
Atmospheric ν	$(1.1 \pm 0.2) \times 10^{-1}$	$(1.1 \pm 0.2) \times 10^{-1}$
^{8}B+*hep* ν	$(5.7 \pm 0.6) \times 10^{-2}$	$(5.7 \pm 0.6) \times 10^{-2}$
MSSI	$(4.9 \pm 4.9) \times 10^{-3}$	$(4.6^{+4.8}_{-4.6}) \times 10^{-3}$
Detector NRs	–	$[0, 0.118]$
1000 GeV/c^2 WIMP	–	$1.0^{+1.4}_{-0.7}$
Total counts	–	1713 ± 39
Observed counts	–	1710

Limit on Lagrangians

We set 90% upper and lower confidence-level intervals on all models probed:

- $\mathcal{L}_1 - \mathcal{L}_{20}$
- Inelastic $\mathcal{O}_1$ and $\mathcal{O}_4$ up to δ=350keV
- isoscalar, isovector basis

Confidence intervals on all models probed will be provided in the data release



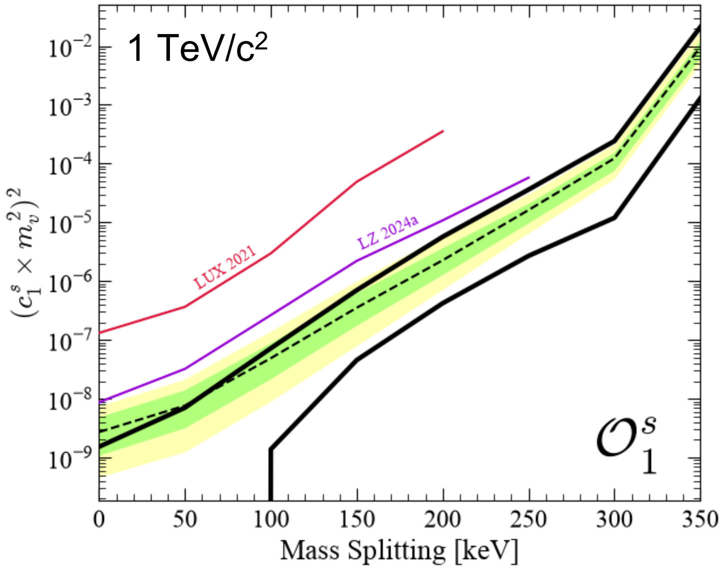
Baxter et al. Euro Phys J C (2021)

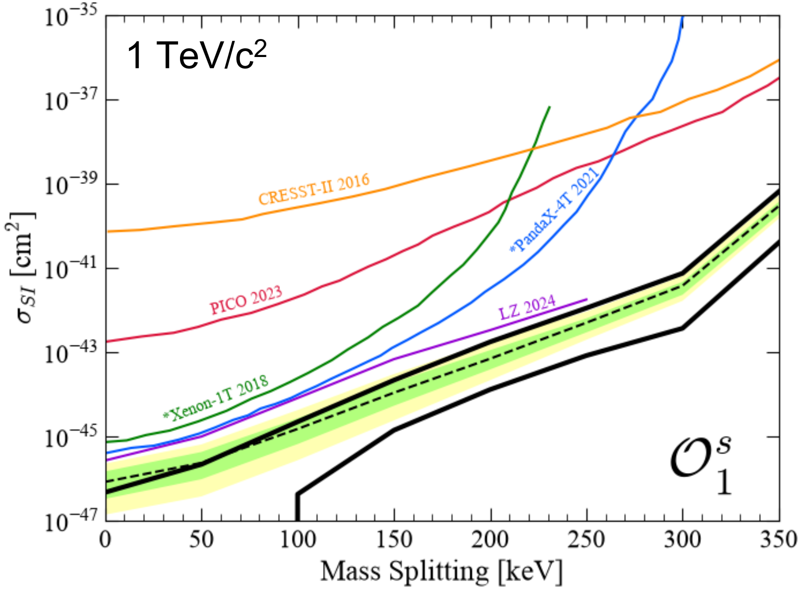
Limit on Inelastics

We set 90% upper and lower confidence-level intervals on all models probed:

- Inelastic $\mathcal{O}_1$ and $\mathcal{O}_4$ up to δ=350keV
- These can be recast into cross-sections

$$(c_1^s \times m_v^2)^2 = \sigma_{SI}^N \frac{\pi \cdot m_v^4}{(\frac{(\hbar c)}{\mathrm{GeV}})^2 \mu_N^2}$$



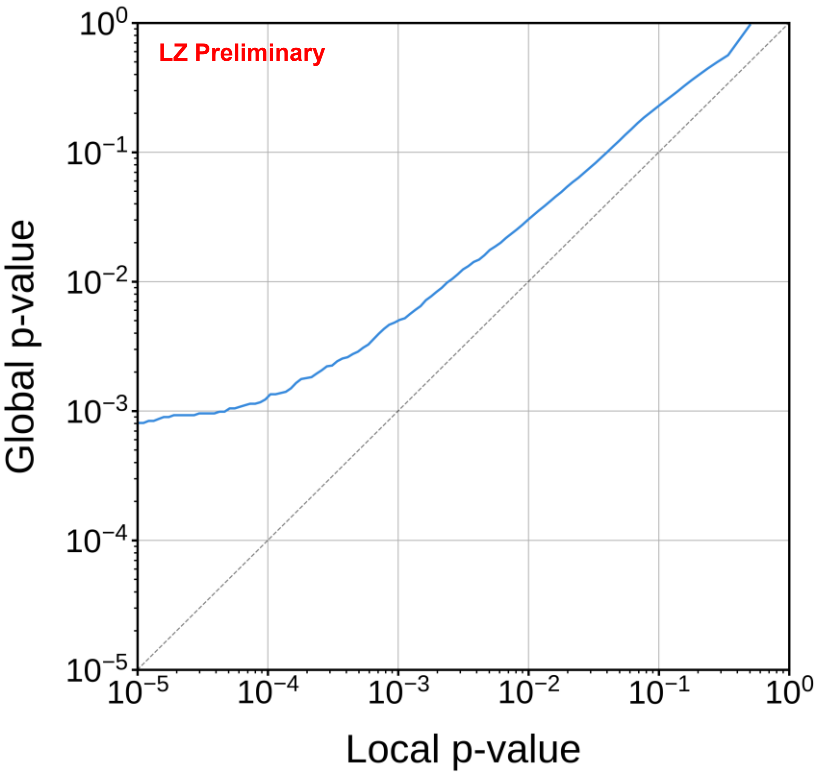


Result significance + Look elsewhere effect

- 616 models tested
- **3.4 σ local** significance
- **2.6 σ global** significance

Multiple models have >3 local significance

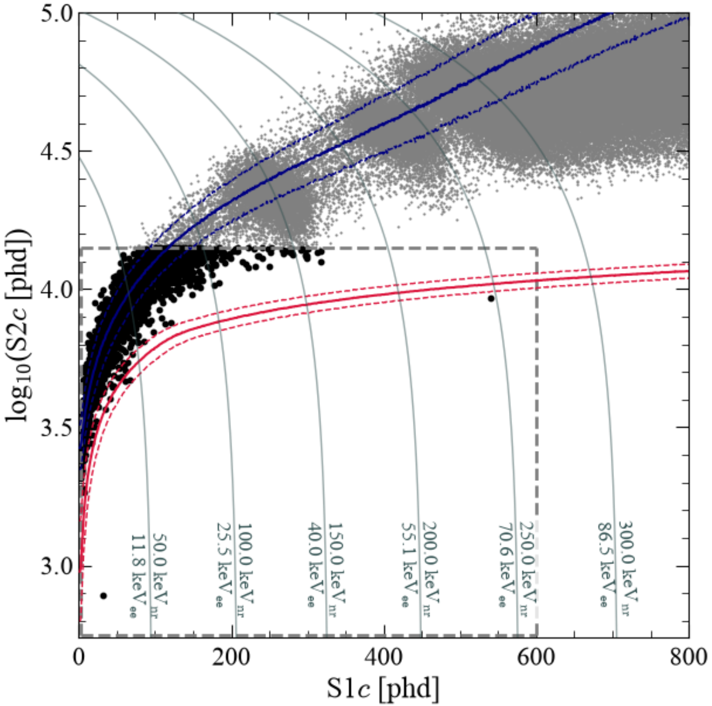
The local significance for all models will be provided in the data release



Baxter et al. Euro Phys J C (2021)

Summary

- Latest LZ search result extends the energy window for DM up to 270 keV_{nr}
  - Total exposure 2.8 tonne-years
- An event was observed in tension with background model
  - on 16 June 2023
  - consistent with a 248 +/- 23 keV_{nr} nuclear elastic scatter
- LZ will continue to take data until at least 2028
  - Towards 1000 live-days



Additional LZ analyses

- SI/SD searches
  → Phys. Rev. Lett. **135**, 011802
- Light DM + neutrinos
  → Dan K talk: 31 Aug
- 0νββ
  → Aiham M talk: 2 Sept
- Cosmic-ray Boosted DM
  → Yongheng X talk: 2 Sept

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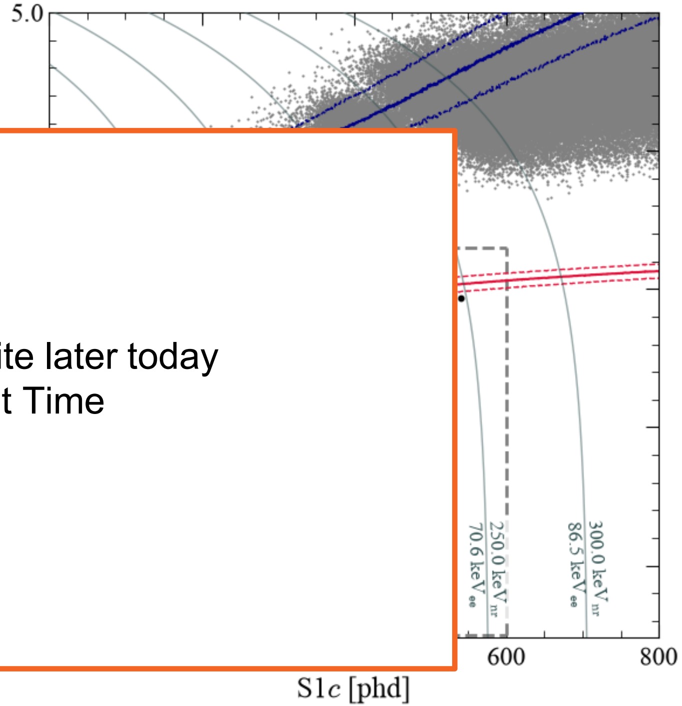

Paper available on Collaboration website later today
Sept 1, 0700 US Pacific Daylight Time
http://lz.lbl.gov

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Backup

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Swiss National Science Foundation

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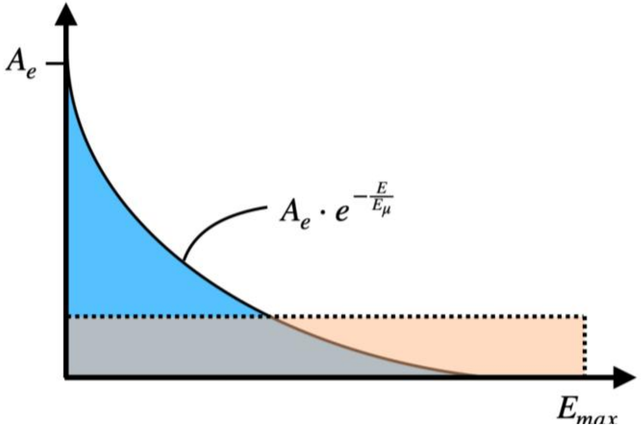
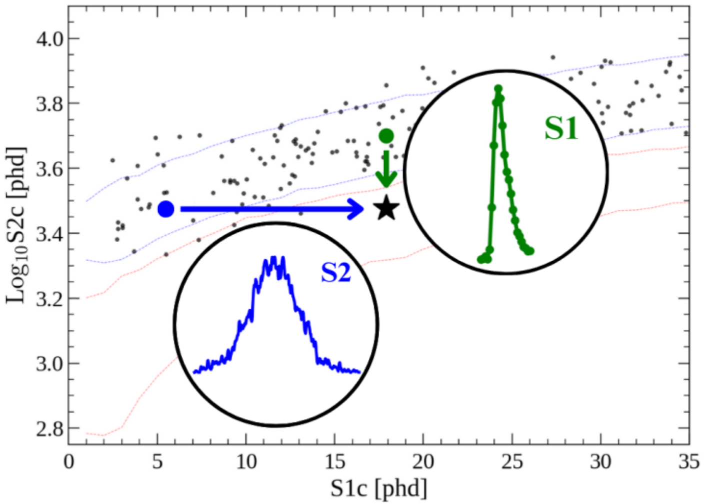
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Bias Mitigation – “salting”

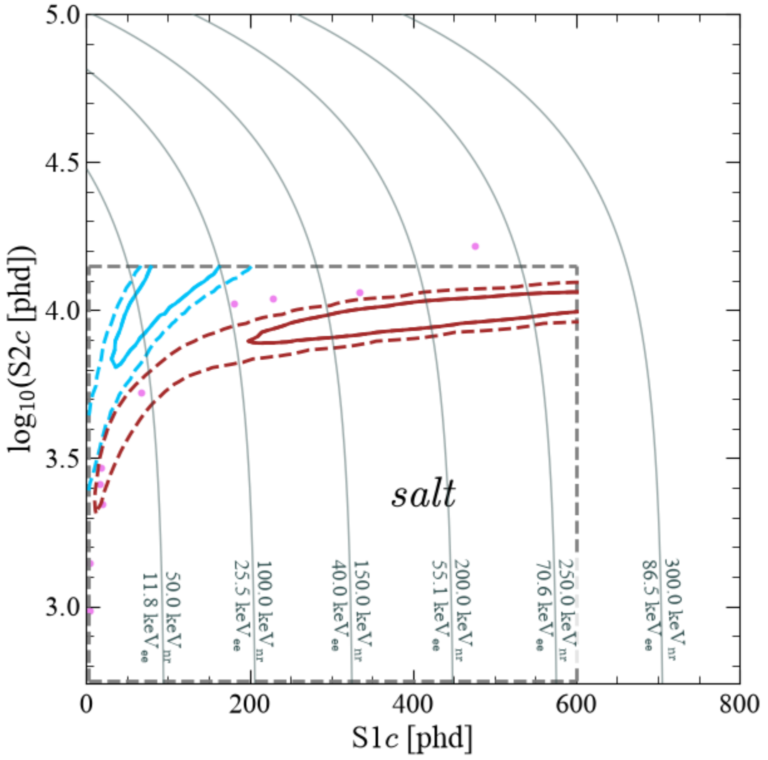
- Inject fake signal events at randomly during science data collection
- Events manufactured using S1s and S2s from sequestered calibration data
- Events follow **exponential + flat** spectrum
- Exact parameters are randomly generated and kept hidden
- Identity of salt events is revealed after analysis inputs are finalised for final inference
- 7 salt events from the exponential component were already revied as part of Phys. Rev. Lett. **135**, 011802





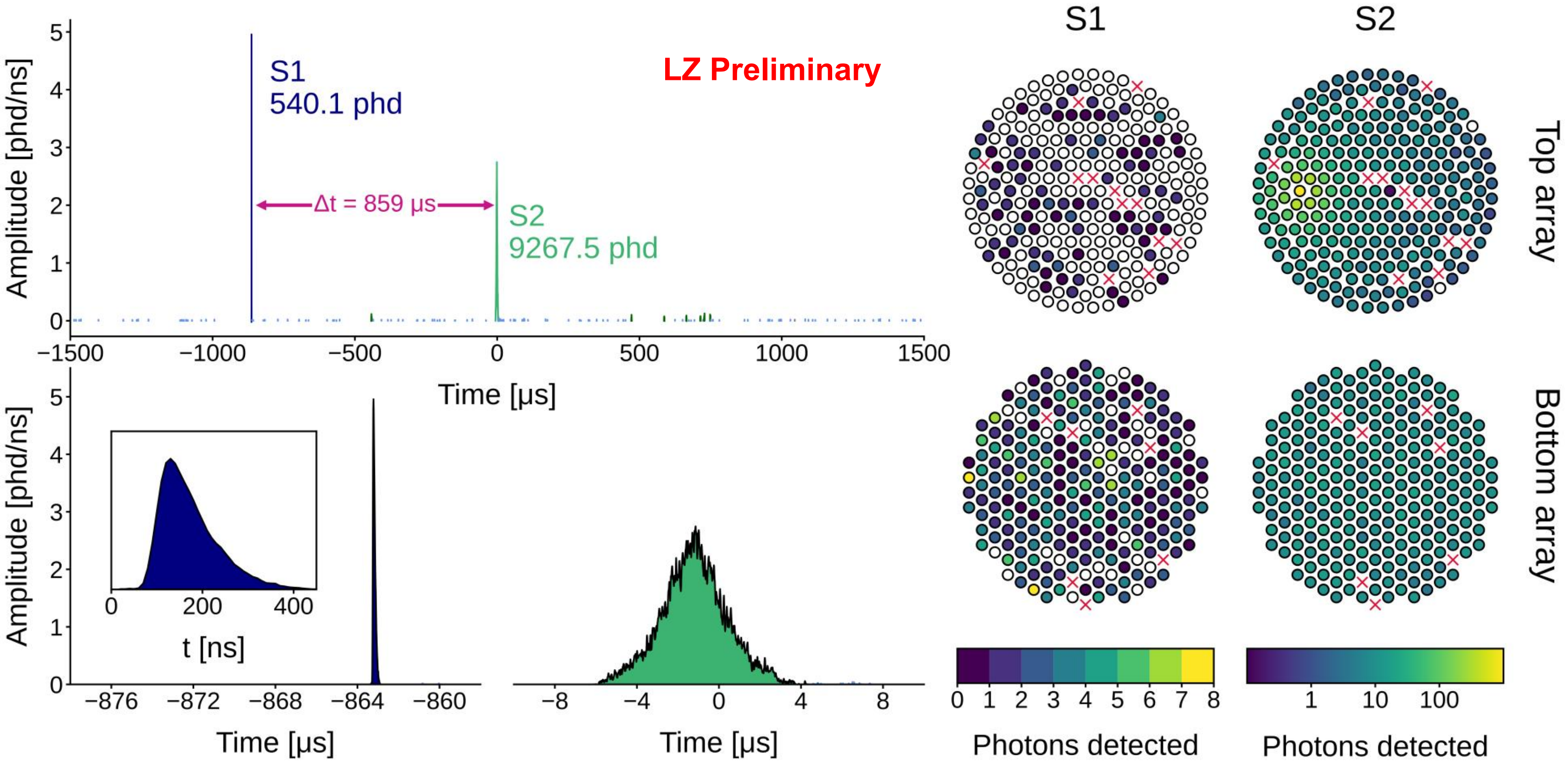
Salt sample

- Un-salting occurred after finalising all selections and models
- Salt is injected as data is acquired
  - This occurred prior to AmBe calibrations
  - An assumption is made on the NR model
- Upon collection of AmBe, the NR model is improved,
  - As such consider this analysis **unblind**
- Un-salting
  - **4 salt events** were revealed
  - **7 salt events** from Phys. Rev. Lett. **135**, 011802



Contours : L10s 1000 GeV/c^2
ER Backgrounds

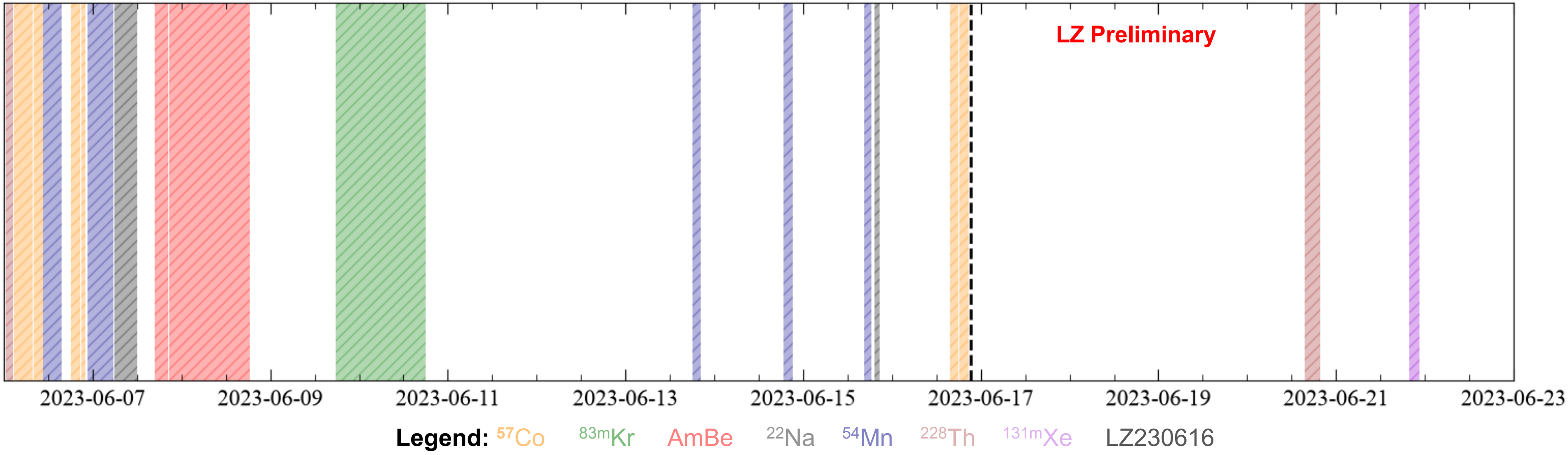
LZ230616 Waveform



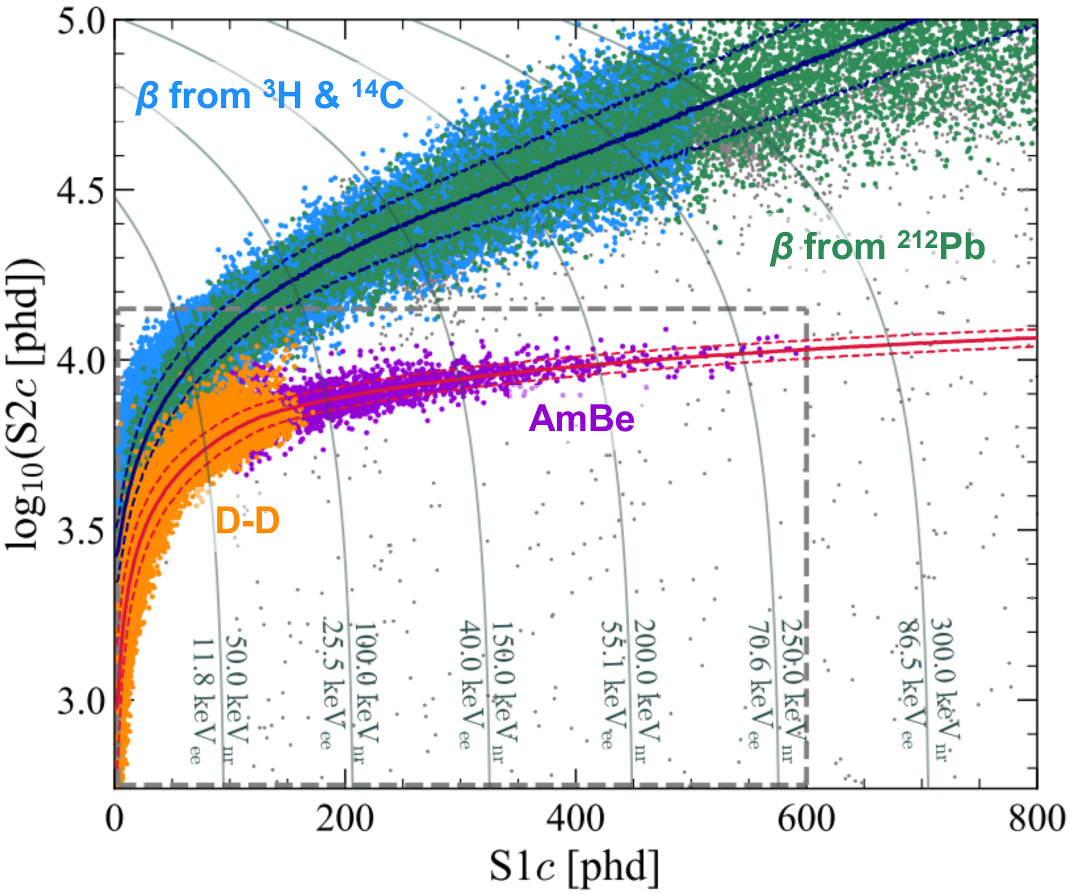
Detector conditions around LZ230616

Previous calibrations in source deployment tubes:

- ^{57}Co removed 25 mins earlier
  → not a concern as occurred on opposite side of detector
  → ^{57}Co are low energy γ-rays used for calibrating the Skin and OD.
- AmBe on 8 June 2023
  → one week before



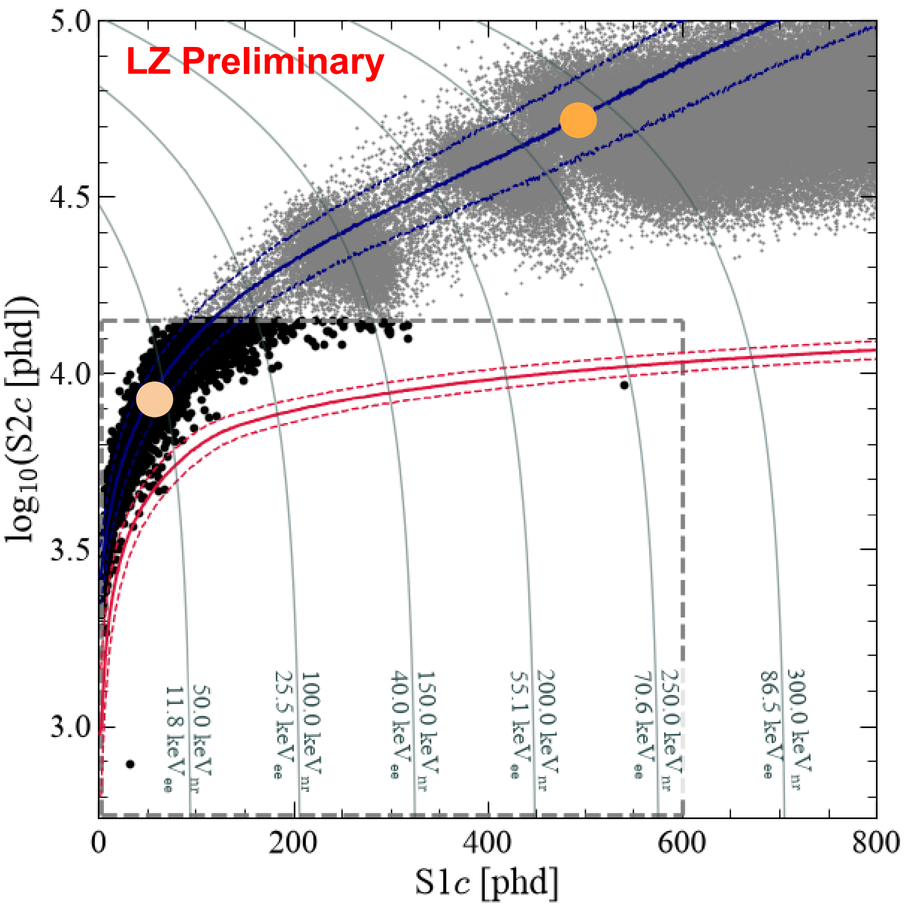
- **Electron Recoils (background)**
  - Methane injection: ^{3}H (18.6 keV), ^{14}C (156 keV)
  - ^{220}Rn injection: ^{212}Pb
  - Monoenergetic injections: ^{83m}Kr, ^{131m}Xe
- **Nuclear Recoils (signal-like)**
  - D-D neutrons (0-74 keV)
  - AmBe neutrons (0-350 keV)
- **Detector Modelling with NESTv2.4.5**
  - Tuned to match calibration data
  - $g_1 = 0.110 \pm 0.002$ phd/photon
  - $g_2 = 34.5 \pm 1.1$ phd/electron
  - Single Electron Size: 44.5 phd



Backgrounds: MSSI

If the event is from MSSI
- S2 of event is a **12 ± 2 keV$_{ee}$** scatter in FV

- Missing ~450phd (S1) must be from
    - **250 ± 80 keV$_{ee}$** in RFR, or
    - **78 ± 7 keV$_{ee}$** by Wall



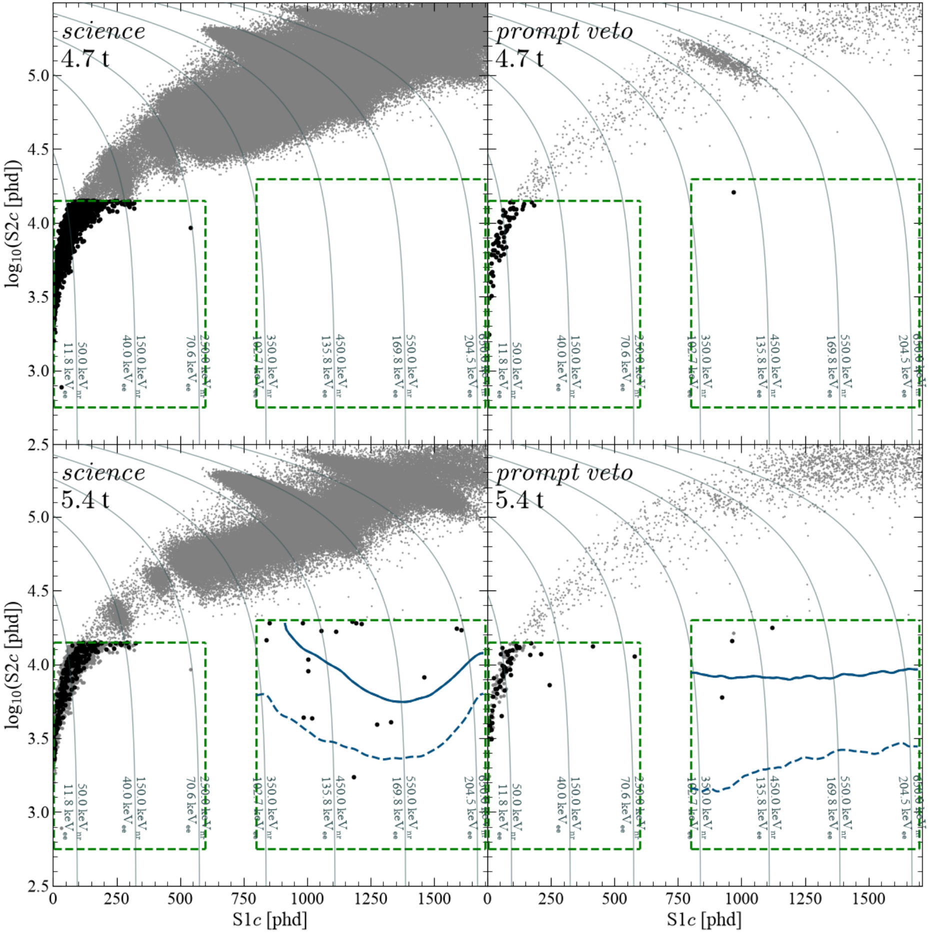
Both S1 and S2 observed

S1 observed and S2 not observed

MSSI validation

- MSSI model
  - **Rate:** Derived from simulations. Validated in higher energy region
  - **Shape:** Validated in looking at high energy region and closer to charge dead regions

- Expectation
  - FV aggressively removes MSSI events
  - **0.0049 ± 0.0049** in science sample
  - **94 ± 2%** prompt tagging efficiency



Likelihood is defined as

$$\mathcal{L}(\theta) = \prod_{i=0}^{2}\left[\text{Pois}(N_i|\mu_{\text{tot},i}) \times \prod_{e=1}^{N_i} \frac{1}{\mu_{\text{tot},i}}\left(\mu_{\text{sig},i}(\vec{\lambda})f_{\text{sig},i}(\vec{x}_e) + \sum_{b=1}^{N_b} \mu_{b,i}(\vec{\lambda})f_{b,i}(\vec{x}_e)\right)\right] \times \prod_{b=1}^{N_b} g_b(\mu_b|\vec{\nu_b})$$

^{127}Xe, Detector γ-rays are constrained by the prompt veto sample through a 88 $\pm$ 2% tagging efficiency

MSSI are constrained by the prompt veto sample through a 94 $\pm$ 2% tagging efficiency

Detector neutrons are constrained by the prompt veto sample a 5 $\pm$ 1% tagging efficiency and by the delayed veto sample by a 87 $\pm$ 2% tagging efficiency

Look elsewhere effect

- Account for the fact that when doing many tests to see if a signal exists in excess of backgrounds, the probability that you get some test that exceeds a certain threshold increases with the number of tests you do

To correct

- Create toy datasets from background-only model
- Perform significance tests on these toy datasets for each all models
- Find the most significant test and record the p-value (local p-value) to get a distribution of most significant p-values

When fitting to real data

- Find the most significant test and compare that to distribution of most significant p-values
- We compare how extreme the observed data is to the other local p-value to get a global p-value.
- This is the probability that we would find a dataset this extreme across all of the model tests that we do

Sideband sample fits

Delayed sample

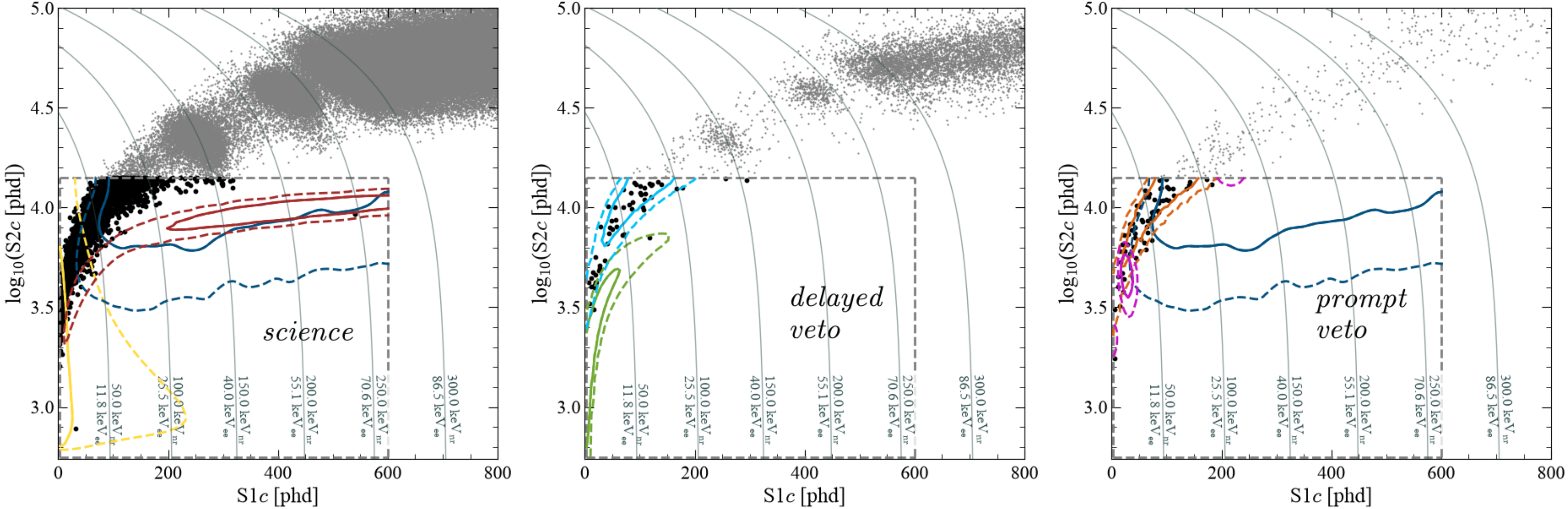
Source	Expected Events	Fit Result
Internal β decays	39.5 ± 4.7	39.4 ± 1.3
ν ER	4.1 ± 0.2	4.1 ± 0.2
^{136}Xe	3.2 ± 0.5	3.4 ± 0.5
CH_3T & ^{14}C	1.6 ± 0.1	1.6 ± 0.1
^{124}Xe	$(6.2 \pm 1.9) \times 10^{-1}$	$(6.6 \pm 1.5) \times 10^{-1}$
^{83m}Kr	$(5.0 \pm 1.5) \times 10^{-1}$	$(5.0 \pm 1.0) \times 10^{-1}$
^{125}I	$(2.6 \pm 0.8) \times 10^{-1}$	$(2.9 \pm 0.7) \times 10^{-1}$
Detector ERs	$(2.5 \pm 1.0) \times 10^{-1}$	$(2.8 \pm 0.5) \times 10^{-1}$
Accidental coincidences	$(8.0 \pm 1.9) \times 10^{-2}$	$(7.7 \pm 1.8) \times 10^{-2}$
^{127}Xe + ^{125}Xe	$(4.5 \pm 1.0) \times 10^{-2}$	$(3.4 \pm 0.9) \times 10^{-2}$
Atmospheric ν	$(3.3 \pm 0.7) \times 10^{-3}$	$(3.3 \pm 0.7) \times 10^{-3}$
^{8}B+*hep* ν	$(1.7 \pm 0.2) \times 10^{-3}$	$(1.7 \pm 0.2) \times 10^{-3}$
MSSI	$(1.4 \pm 1.4) \times 10^{-4}$	$(1.3 \pm 1.0) \times 10^{-4}$
Detector NRs	–	$[0, 1.3]$
1000 GeV/c^2 WIMP	–	$(3.1^{+4.2}_{-2.1}) \times 10^{-2}$
λ_{DN}	$(8.7 \pm 0.2) \times 10^{-1}$	$(8.7 \pm 0.1) \times 10^{-1}$
λ_{PN}	$(5.0 \pm 1.0) \times 10^{-2}$	$(5.0 \pm 0.7) \times 10^{-2}$
Total counts	–	50.4 ± 2.0
Observed counts	–	55

Prompt sample

Source	Expected Events	Fit Result
Internal β decays	$(1.3 \pm 0.2) \times 10^{-1}$	$(1.33 \pm 0.04) \times 10^{-1}$
ν ER	$(1.41 \pm 0.08) \times 10^{-2}$	$(1.40 \pm 0.08) \times 10^{-2}$
^{136}Xe	$(1.1 \pm 0.2) \times 10^{-2}$	$(1.1 \pm 0.2) \times 10^{-2}$
CH_3T & ^{14}C	$(5.5 \pm 0.3) \times 10^{-3}$	$(5.5 \pm 0.3) \times 10^{-3}$
^{124}Xe	$(2.1 \pm 0.6) \times 10^{-3}$	$(2.3 \pm 0.5) \times 10^{-3}$
^{83m}Kr	$(1.7 \pm 0.5) \times 10^{-3}$	$(2.0^{+0.4}_{-0.3}) \times 10^{-3}$
^{125}I	$(8.9 \pm 2.7) \times 10^{-4}$	$(9.8 \pm 2.3) \times 10^{-4}$
Detector ERs	62.2 ± 24.9	$61.6^{+11.5}_{-10.5}$
Accidental coincidences	$(2.7 \pm 0.6) \times 10^{-4}$	$(2.6 \pm 0.6) \times 10^{-4}$
^{127}Xe + ^{125}Xe	11.2 ± 2.4	7.7 ± 2.1
Atmospheric ν	$(1.1 \pm 0.2) \times 10^{-5}$	$(1.1 \pm 0.2) \times 10^{-5}$
^{8}B+*hep* ν	$(5.7 \pm 0.6) \times 10^{-6}$	$(5.7 \pm 0.6) \times 10^{-6}$
MSSI	$(7.7 \pm 7.7) \times 10^{-2}$	$(7.1^{+7.6}_{-7.1}) \times 10^{-2}$
Detector NRs	–	$[0, 0.07]$
1000 GeV/c^2 WIMP	–	$(1.0^{+1.4}_{-0.7}) \times 10^{-4}$
λ_{DN}	$(8.7 \pm 0.2) \times 10^{-1}$	$(8.7 \pm 0.1) \times 10^{-1}$
λ_{PN}	$(5.0 \pm 1.0) \times 10^{-2}$	$(5.0 \pm 0.7) \times 10^{-2}$
λ_{PG}	$(8.8 \pm 0.2) \times 10^{-1}$	$(8.7 \pm 0.2) \times 10^{-1}$
λ_{MSSI}	$(0.94 \pm 0.2) \times 10^{-1}$	$(9.4 \pm 0.2) \times 10^{-1}$
Total counts	–	69.4 ± 11.7
Observed counts	–	66

Datasets

No veto signal **Delayed signal** **Prompt signal**

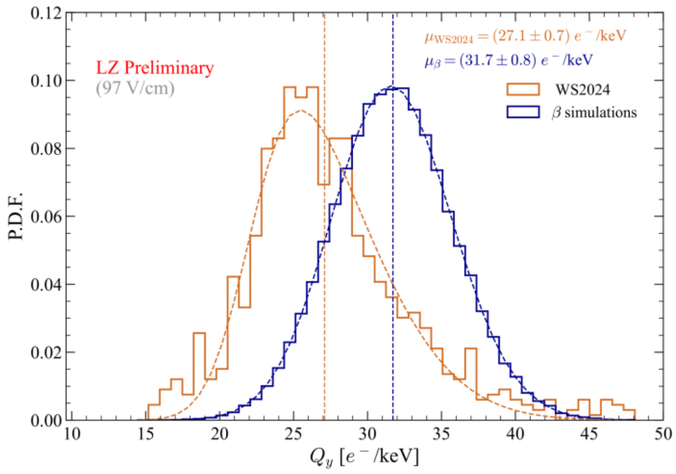


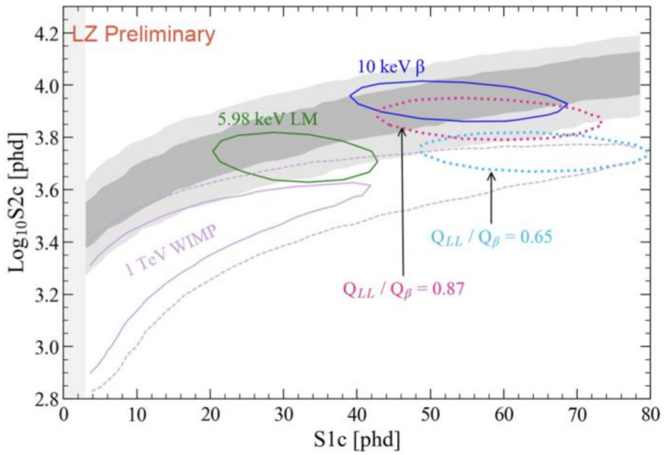
Legend: L10s 1000 GeV/c^2 Accidental Coincidences MSSI Neutrons ER Backgrounds Detector ER ^{127}Xe

EC and DEC Modelling

- **Single Electron Captures**
  - ^{125}Xe and ^{127}Xe from neutron activation
  - L-shell (5.2 keV)
  - X-ray + Auger emission is charge suppressed compared to β
  - Measured in-situ: $Q_L/Q_\beta = 0.87 \pm 0.03$
  - In-situ from skin-tagged and multiple scatter decays

- **Double Electron Capture**
  - ^{124}Xe 0.095% natural abundance
  - LM-shell (5.98 keV) and LL-shell (10 keV)
  - Expect LL decays to be further suppressed $0.65 < Q_{LL}/Q_\beta < Q_L/Q_\beta$
  - Allowed to float in statistical analysis to 2x ionization density
  - Best fit to WS2024 data $Q_{LL}/Q_\beta = 0.70 \pm 0.04$

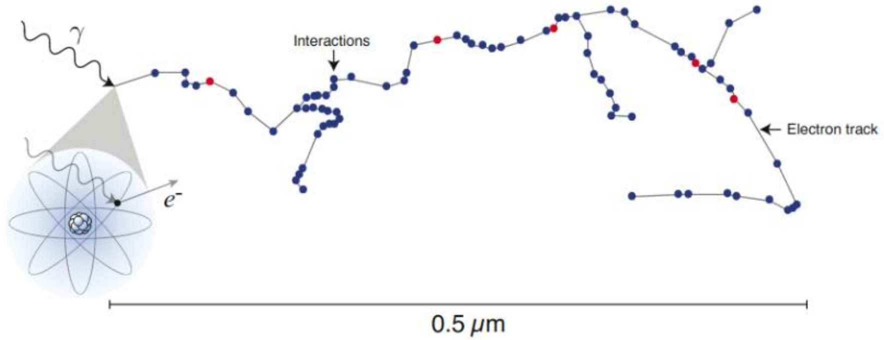




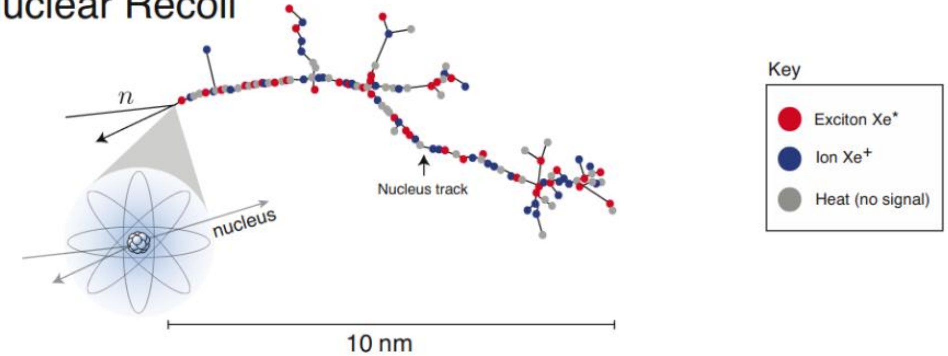
LZ paper on EC charge yields: Phys. Rev. D **112**, 012024

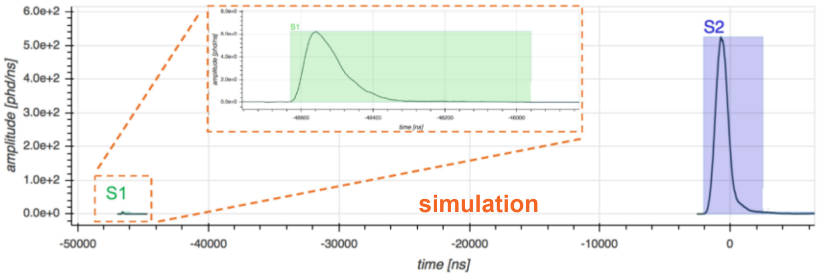
S1 and S2 observables

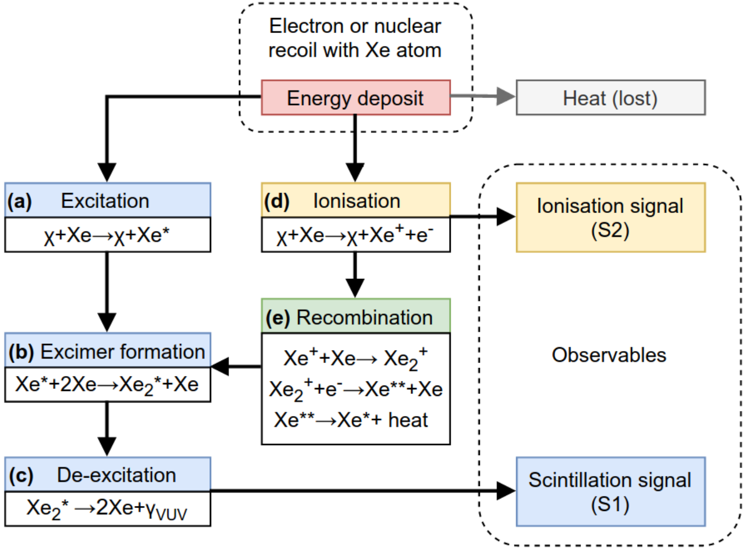
Electron Recoil



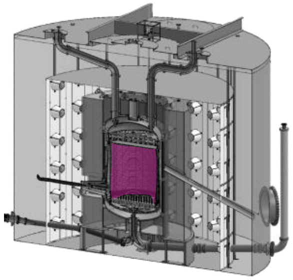
Nuclear Recoil

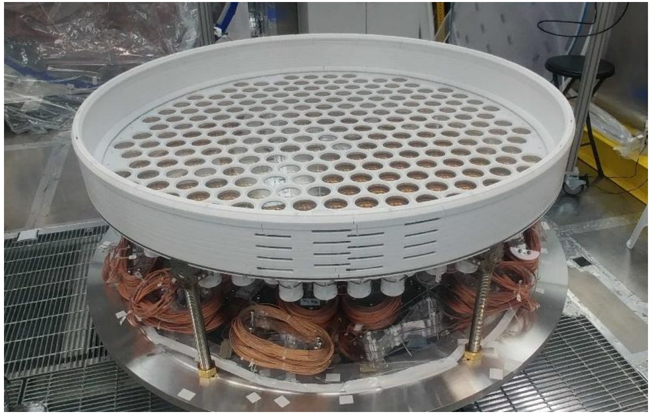


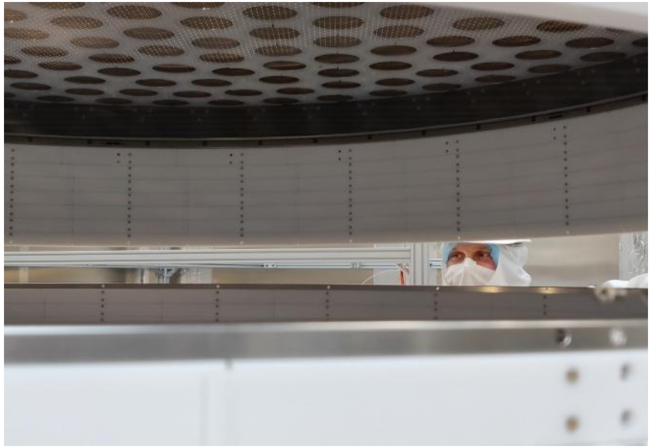




Dual-Phase Time Project Chamber

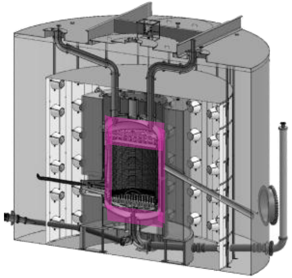


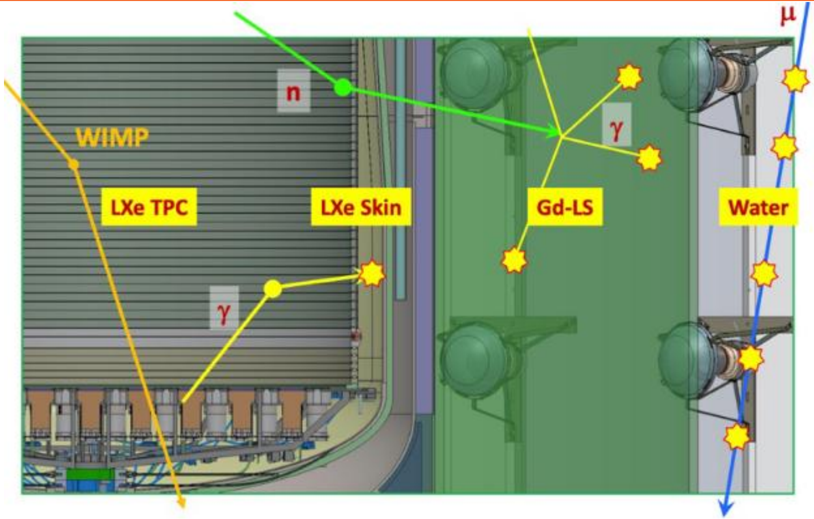


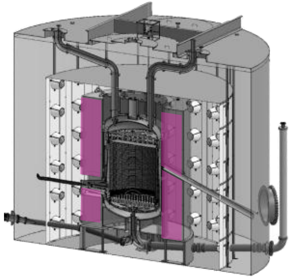


- 1.5 m diameter x 1.5 m height
- 7 tonnes active liquid Xenon
- High Light Collection Efficiency
  - 253 x 3” PMTs Top
  - 241 x 3” PMTs Bottom
  - PTFE walls (97% reflectivity at 175nm)

Veto Detectors





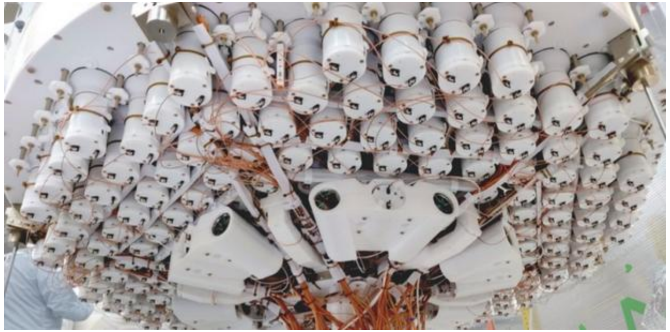


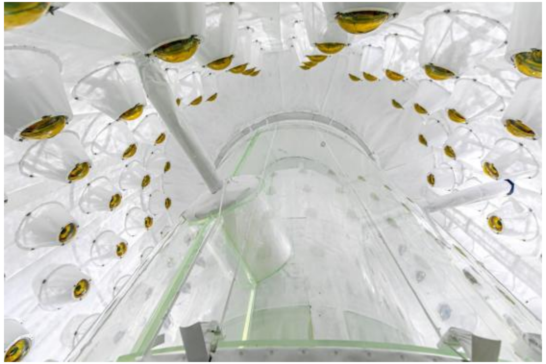
Skin

- 2 tonnes liquid Xenon
- 93 x 1” and 38 x 2” PMTs
- anti-coincidence for *γ-ray*

Outer Detector

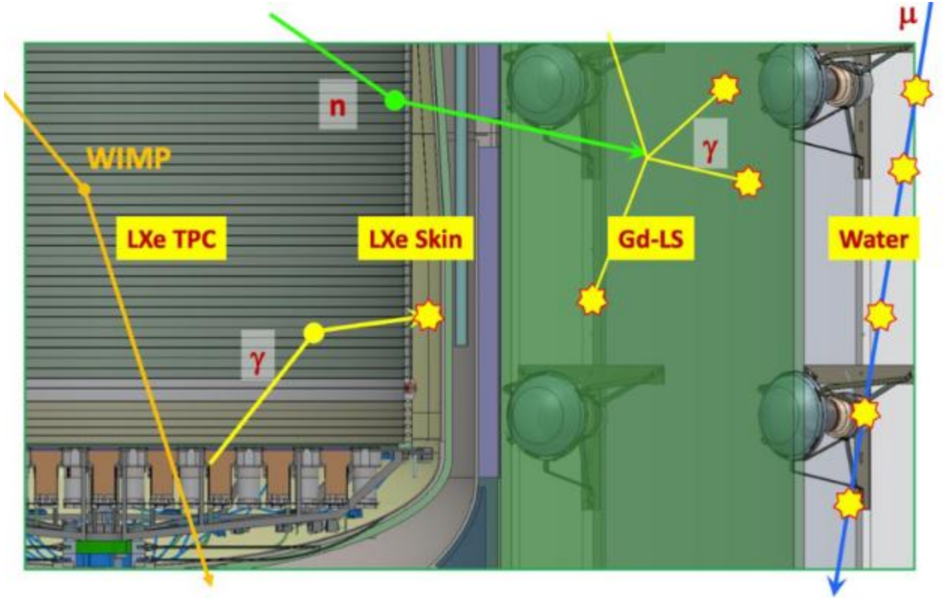
- 17 tonnes Gd-loaded scintillator
- 120 8” PMTs
- anti-coincidence for neutrons and *γ-ray*





Data are separated into 3 samples based on Skin/OD tag

- **Science**
  - No signal in veto systems
- **Delayed veto**
  - Skin signal > 300 keV or OD signal > 200 keV
  - Within 600 μs of S1
  - Constrains neutrons
- **Prompt veto**
  - Skin signal > 2.5 phd and within +/- 0.25 μs of S1
  - OD signal > 4.5 phd and within +/- 0.3 μs of S1
  - Constrains neutrons, ^{127}Xe, Detector gammas and MSSI



NR-EFT

[Phys. Rev. C 89, 065501 (2014)](#)
[JCAPO2 (2013)](#)

- Spin Independent and Spin Dependent interactions rely on the assumption of a zero-momentum transfer. But what if there is some momentum dependency?

- Use an EFT where we treat the WIMP-nucleon elastic scattering as a four-field interaction

$$\mathcal{L}_{int} = \mathcal{O}\chi^{+}\chi^{-}N^{+}\mathrm{N}^{-}$$

- 4 Galilean, Hermitian invariants quantities which describe the interaction

$$i\vec{q},\ \vec{S}_{\chi},\ \vec{S}_{N},\ \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu_N}$$

- We are then left with 15 operators which contribute to the interaction Lagrangian

$$\begin{aligned}\mathcal{L}_{int} &= \sum_i c_i \mathcal{O}_i \\ &= c_1 + ic_3\vec{S}_N\cdot(\vec{q}\times\vec{v}^{\perp}) + c_4\vec{S}_{\chi}\cdot\vec{S}_N \\ &+ ic_5\vec{S}_{\chi}\cdot(\vec{q}\times\vec{v}^{\perp}) + c_6(\vec{S}_{\chi}\cdot\vec{q})(\vec{S}_N\cdot\vec{q}) \\ &+ c_7\vec{S}_N\cdot\vec{v}^{\perp} + c_8\vec{S}_{\chi}\cdot\vec{v}^{\perp} + ic_9\vec{S}_{\chi}\cdot(\vec{S}_N\times\vec{q}) \\ &+ c_{10}\vec{S}_N\cdot\vec{q} + ic_{11}\vec{S}_{\chi}\cdot\vec{q} + c_{12}\vec{S}_{\chi}\cdot(\vec{S}_N\times\vec{v}^{\perp}) \\ &+ ic_{13}(\vec{S}_{\chi}\cdot\vec{v}^{\perp})(\vec{S}_N\cdot\vec{q}) + ic_{14}(\vec{S}_{\chi}\cdot\vec{q})(\vec{S}_N\cdot\vec{v}^{\perp}) \\ &+ -c_{15}(\vec{S}_{\chi}\cdot\vec{q})\left((\vec{S}_N\times\vec{v}^{\perp})\cdot\vec{q}\right)\end{aligned}$$

- Differential Recoil Rate in this case

$$\frac{dR}{dE_R} = \frac{\rho_{\chi}}{32\,\pi m_{\chi}^3 m_N^2}\int_{v>v_{min}}^{\infty}\frac{f(\vec{v})}{v}\sum_{i,j=1}^{15}\sum_{a,b=0,1} c_j^a c_i^b F_{i,j}^{a,b}\, d^3v$$

- This framework can also be mapped onto covariant Lagrangians, allowing for more complex interactions to be studied.

Phys. Rev. C 89, 065501 (2014)
JCAPO2 (2013)

$$\mathcal{L}_{\rm int} = \sum_i c_i \mathcal{O}_i$$

Spin-orbit

Spin Independent

Spin Dependent

Angular Momentum Dependent

Tensor spin orbit

$$= c_1 + ic_3 \vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp) + c_4 \vec{S}_\chi \cdot \vec{S}_N$$
$$+ ic_5 \vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp) + c_6 (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$$
$$+ c_7 \vec{S}_N \cdot \vec{v}^\perp + c_8 \vec{S}_\chi \cdot \vec{v}^\perp + ic_9 \vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$
$$+ ic_{10} \vec{S}_N \cdot \vec{q} + ic_{11} \vec{S}_\chi \cdot \vec{q} + c_{12} \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$
$$+ ic_{13} (\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q}) + ic_{14} (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^\perp)$$
$$+ -c_{15} (\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^\perp) \cdot \vec{q})$$

Exotic: Do not arise from exchange of spin 0 or 1 mediator

Interactions are linear combinations of 6 independent nuclear responses:

- M Spin Independent: Proportional to A^2
- Σ'' Spin Dependent (longitudinal):
- Σ' Spin Dependent (transverse):
  - Favors unpaired neutrons; "usual" SD search is a specific linear combination of these
- Δ Angular Momentum Dep: Depends on nucleon velocity, favors high A
- Φ'' Spin Orbit:
- $\tilde{\Phi}'$ Tensor spin orbit:
  - Favors elements with unfilled orbitals above the S-shell (requires spin >1 target)

Isosclar: $$c^0 = \frac{1}{2}(c^p + c^n)$$

Isovector: $$c^1 = \frac{1}{2}(c^p - c^n)$$

Lagrangians

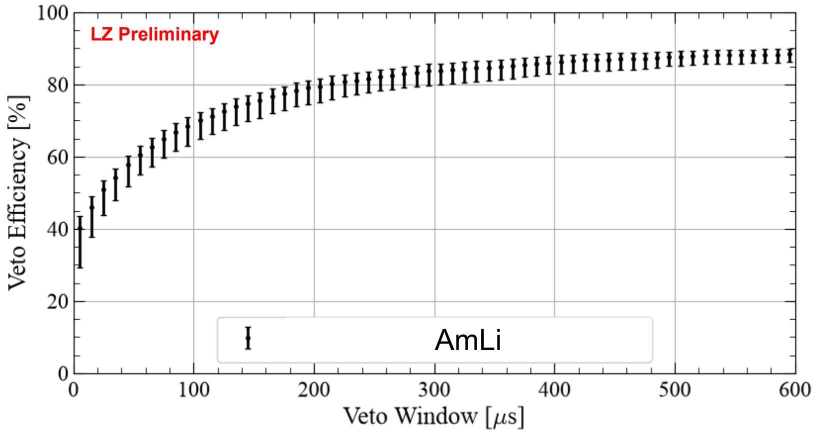
Phys. Rev. C 89, 065501 (2014)
JCAPO2 (2013)

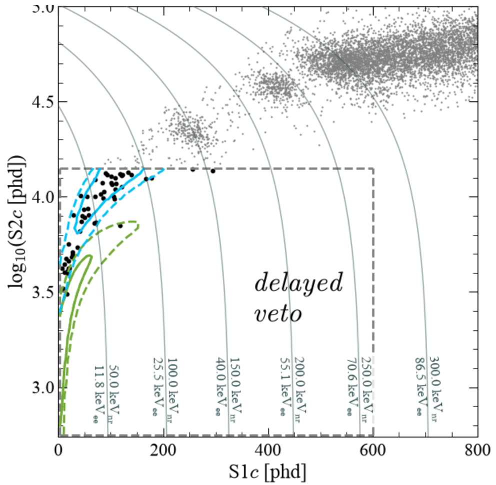
- SD interactions between WIMPs and nucleons can be comprised of magnetic and electric dipole moments, axial vector interference terms, and tensor interactions
- WIMP-nucleon interactions are constructed from bilinear products of scalar and four-vector interactions. Resulting in 20 Lagrangians
- A non-relativistic reduction is done; replacing spinors with low-momentum counterparts

j	$\mathcal{L}^j_{\text{int}}$	$\Sigma_i c_i \mathcal{O}_i$	WIMP-Nucleon interaction
6	$\bar{\chi}\gamma^\mu\chi\bar{N}i\sigma_{\mu\alpha}(q^\alpha/m_M)N$	$(\vec{q}^2/2m_N m_M)\mathcal{O}_1 - 2(m_N/m_M)\mathcal{O}_3 + 2(m_N^2/m_M m_\chi)[(q^2/m_N^2)\mathcal{O}_4 - \mathcal{O}_6]$	Ve-MM
9	$\bar{\chi}i\sigma^{\mu\nu}(q_\nu/m_M)\chi\bar{N}\gamma_\mu N$	$(\vec{q}^2/2m_\chi m_M)\mathcal{O}_1 + (2m_N/m_M)\mathcal{O}_5 - 2(m_N/m_M)[(\vec{q}^2/m_N^2)\mathcal{O}_4 - \mathcal{O}_6]$	MM-Ve
10	$\bar{\chi}i\sigma^{\mu\nu}(q_\nu/m_M)\chi\bar{N}i\sigma_{\mu\alpha}(q^\alpha/m_M)N$	$4[(\vec{q}^2/m_M^2)\mathcal{O}_4 - (m_N^2/m_M^2)\mathcal{O}_6]$	MM-MM
12	$i\bar{\chi}i\sigma^{\mu\nu}(q_\nu/m_M)\chi\bar{N}i\sigma_{\mu\alpha}(q^\alpha/m_M)\gamma^5 N$	$-(m_N/m_\chi)(\vec{q}^2/m_{\text{M}}^2)\mathcal{O}_{10} - 4(\vec{q}^2/m_{\text{M}}^2)\mathcal{O}_{12} - 4(m_N^2/m_{\text{M}}^2)\mathcal{O}_{15}$	MM-ED
18	$i\bar{\chi}i\sigma^{\mu\nu}(q_\nu/m_M)\gamma^5\chi N i\sigma_{\mu\alpha}(q^\alpha/m_M)N$	$(\vec{q}^2/m_{\text{M}}^2)\mathcal{O}_{11} + 4(m_N^2/m_{\text{M}}^2)\mathcal{O}_{15}$	ED-MM

Neutron Efficiency

- Neutron efficiency is measured using AmLi calibrations
  - 89 ± 3%
- Background simulations suggest a higher veto efficiency for neutrons originating from detector components.
  - 92 $\pm 4\%$
- Neutrons are constrained in the fit through the delayed veto and prompt veto samples
  - Fit constrained using sidebands, best-fit: $\mathbf{0^{+0.12}}$
- Separate multiple scatter analysis gives additional prediction
  - $\mathbf{0.02 \pm 0.02}$ neutrons in science sample





Muon cascade neutrons

- Muons cascades can produce neutrons
  - Neutrons can be O(GeV) in energy
  - Likely aligned with muon direction
  - 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
  - The neutron is the only particle to enter any detector system
  - Simulations of mono-energetic neutrons (50 MeV – 1GeV) indicate **80** $\pm$ **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 $\mathbf{4.6 \times 10^{-4}}$

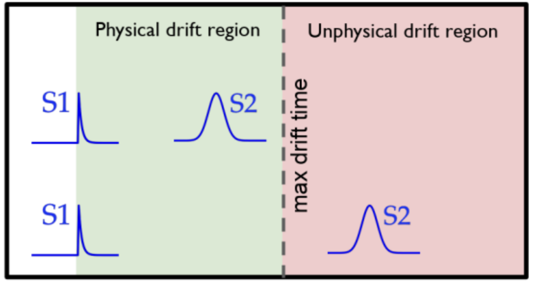
Selection	# LZ Preliminary
μ generated	2.1×10^9
+ n in Lxe	5.6×10^5
+ SS	230
+ in FV	19
+ in ROI	0

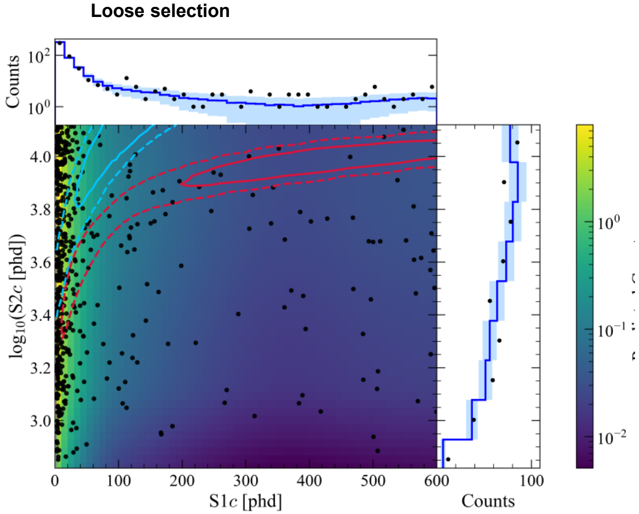
[1] Com. Phys. Comms 180 (2009)
[2] Nucl.Instrum.Meth. A545 (2005) 398-411
[3] arXiv:2310.16586
[4] arXiv:2602.16799

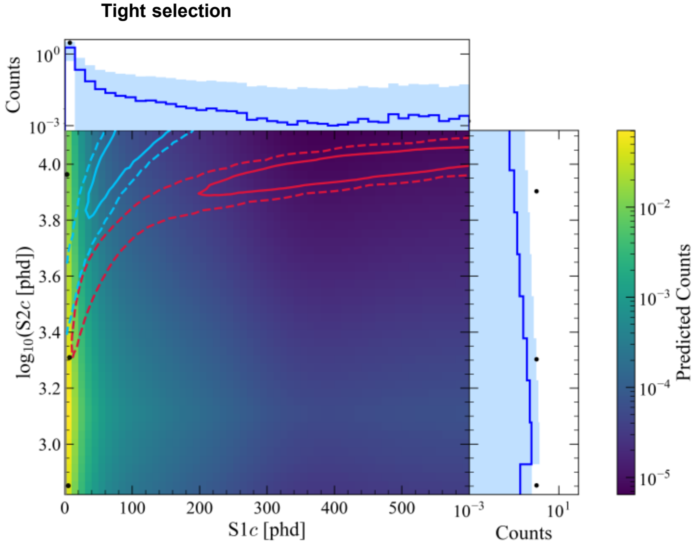
Backgrounds: Accidentals

- Accidental coincidence of uncorrelated isolated S1 and S2 pulses
  - **S1s:** interactions in charge-insensitive regions or pile-up of photoelectron background
  - **S2s:** spurious electron emission from the electrodes

- Create model from drawing random pairs from isolated S1 and S2 populations
- Validate using unphysical drift time events

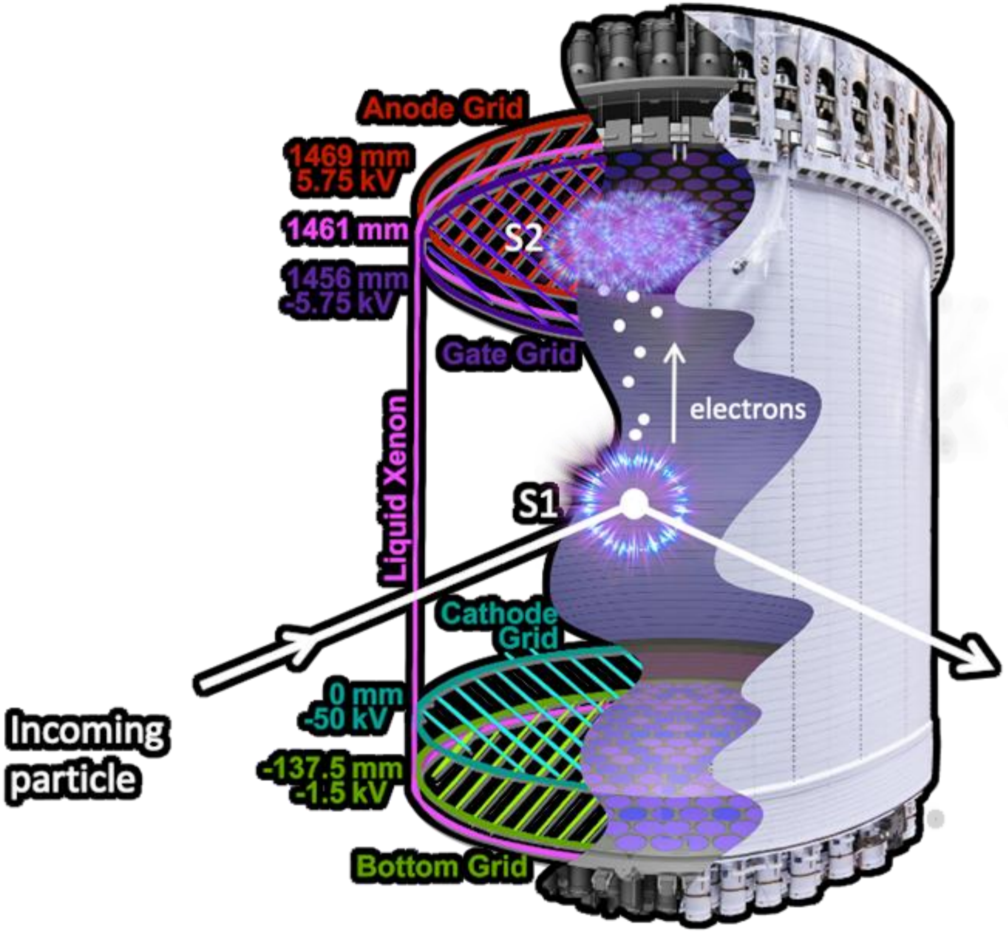






Contours: L10s 1000 GeV/c^2 ER Backgrounds

LZ Detector



Anode Grid
1469 mm
5.75 kV
1461 mm
1456 mm
-5.75 kV
Gate Grid
S2
electrons
Liquid Xenon
S1
Cathode Grid
0 mm
-50 kV
-137.5 mm
-1.5 kV
Bottom Grid
Incoming particle