Dark Matter Searches with the LZ Detector

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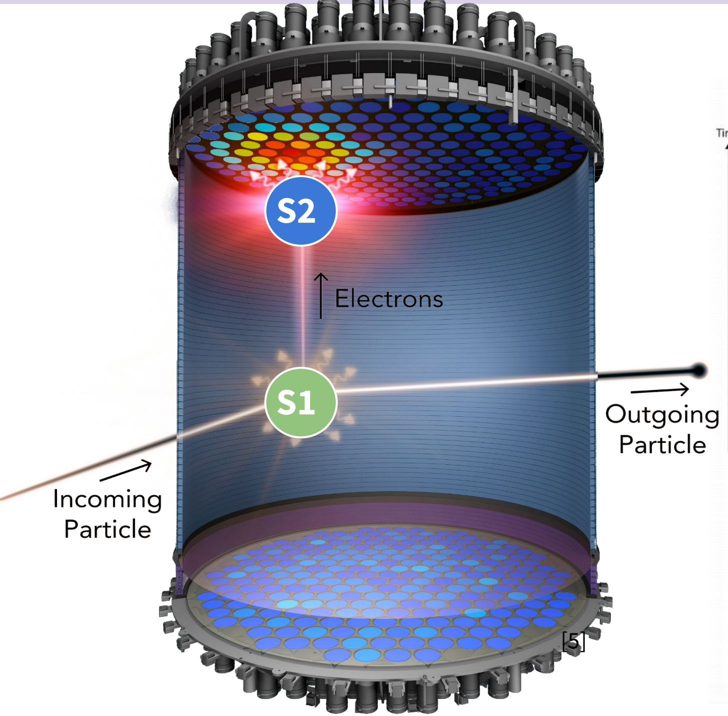
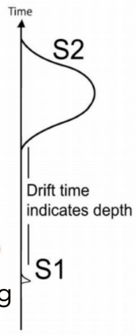
5th March 2024

Les Rencontres de Physique de la Vallée d'Aoste

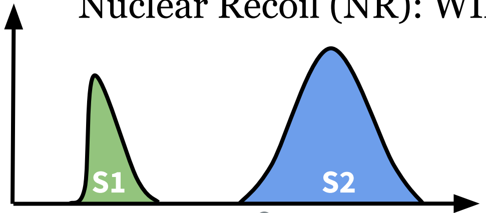
Dual-phase Xenon TPCs

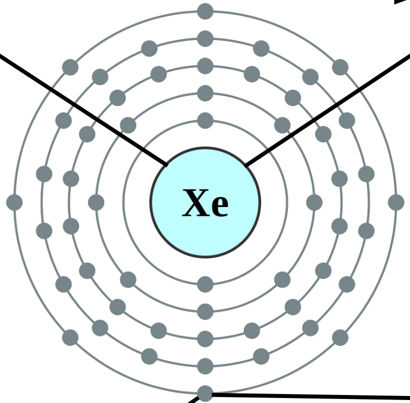




3D position reconstruction from Δt and PMT hits

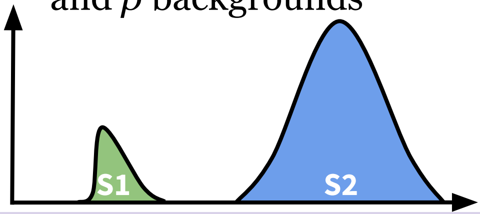
Nuclear Recoil (NR): WIMPs, neutrons





ER/NR discrimination from ratio of S1 and S2

Electron Recoil (ER): γ and β backgrounds



S1 Prompt scintillation light collected by PMTs

S2 Electroluminescence from liberated electrons extracted into gas layer by uniform electric fields

The 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

US Europe Asia Oceania

38 Institutions, 250 scientists, engineers, and technical staff

https://lz.lbl.gov/
@lzdarkmatter

LZ Collaboration Meeting at SURF, 2023

UKRI Science and Technology Facilities Council

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

Sanford Underground Research Facility
South Dakota Science and Technology Authority

ibs Institute for Basic Science

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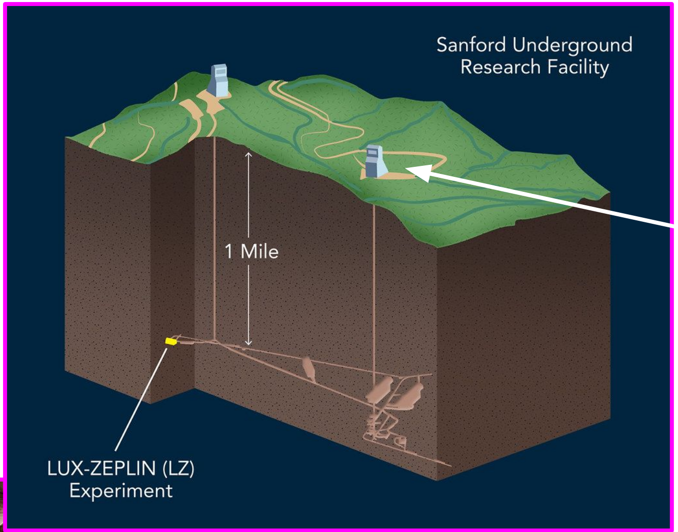
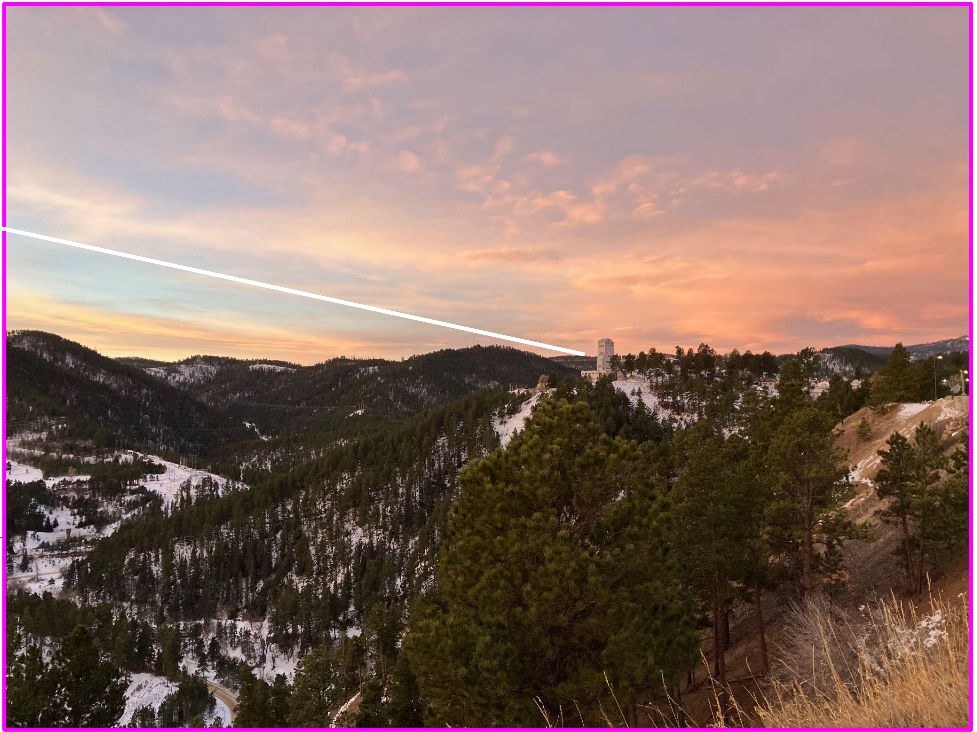
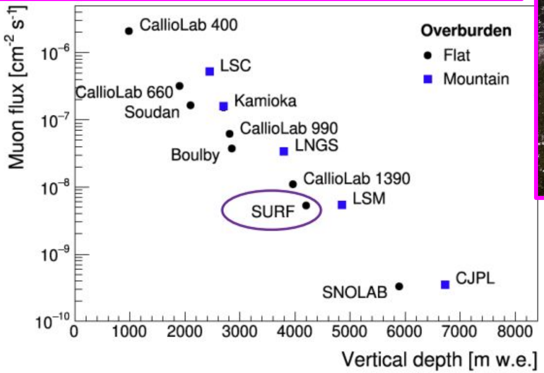
The Sanford Underground Research Facility





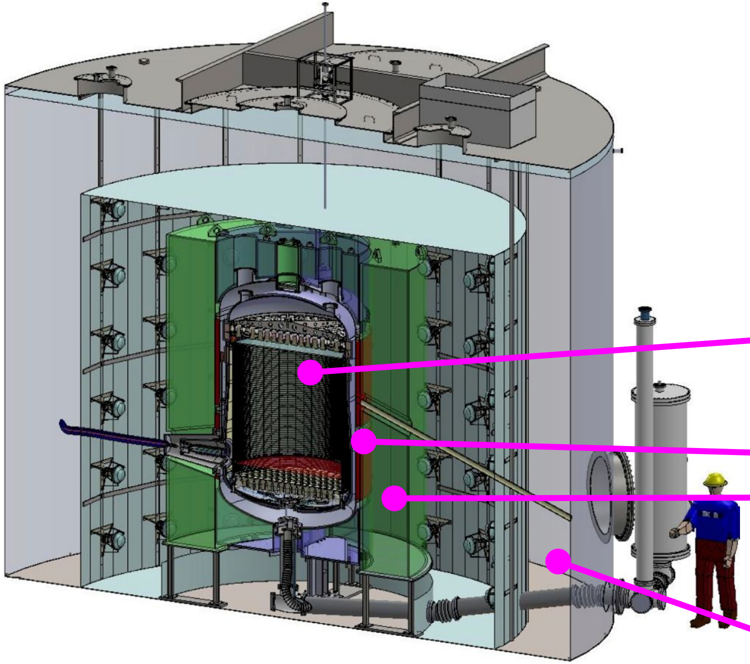


LZ is located in the Davis Cavern, 1478 m underground in Lead, South Dakota

The LUX-ZEPLIN Detector

NIM A, 163047 (2019)

A multi-detector experiment:



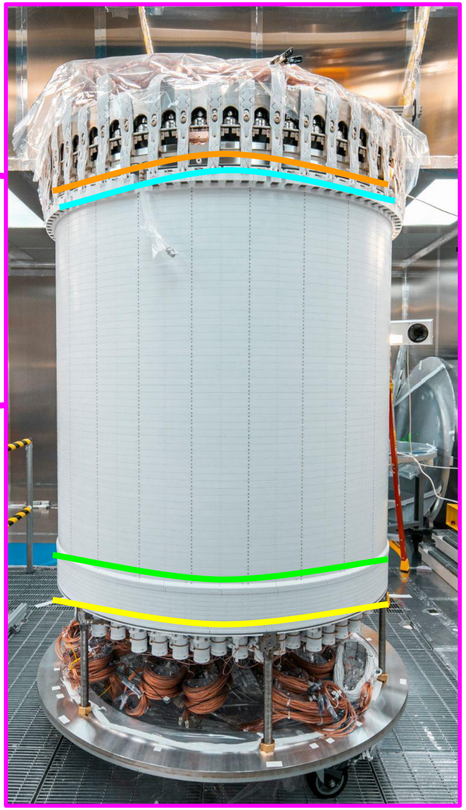
Dual-phase **TPC** containing 7 t active xenon

- 1.5 m height and diameter
- Lined with highly-reflective PTFE
- Four grids (anode, gate, cathode, bottom)

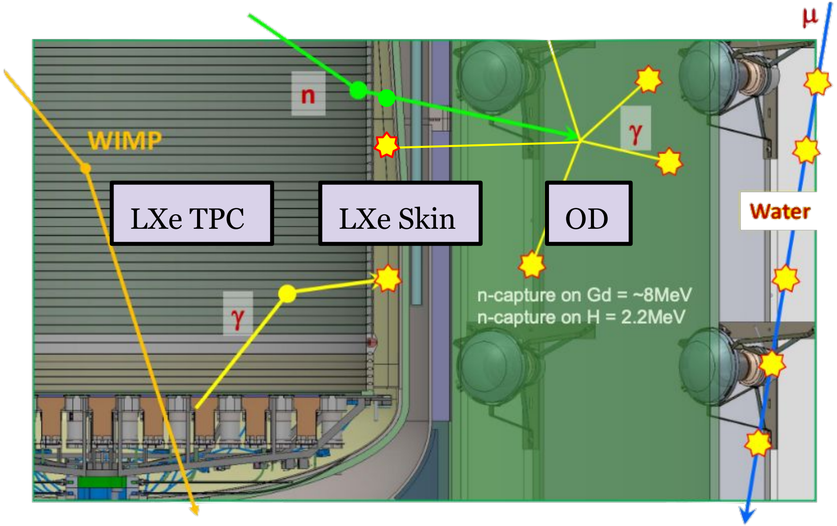
Active veto systems:

- **Skin**
- **Outer Detector** (OD)

Water tank containing 228 t of ultrapure water provides further shielding



Veto Anti-Coincidence Systems



Skin:

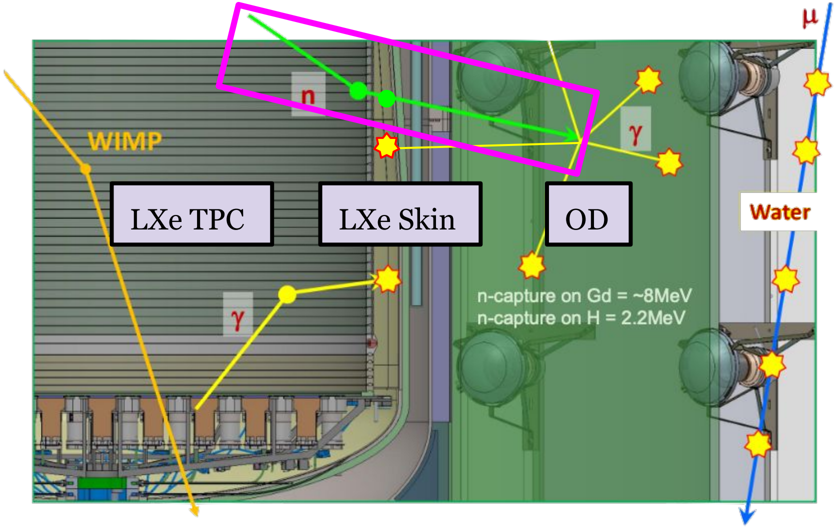
- Contains 2 t LXe
- Optically isolated
- Anti-coincidence detector for γ rays

OD:

- Contains 17 t Gd-loaded liquid scintillator
- Anti-coincidence detector for γ rays and neutrons

Each detector observed by additional PMTs

Veto Anti-Coincidence Systems



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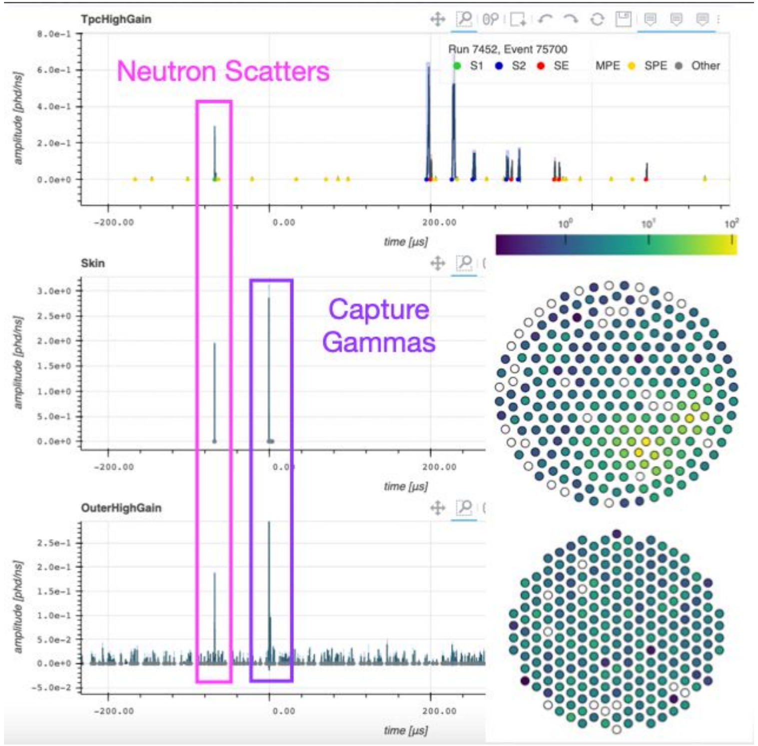
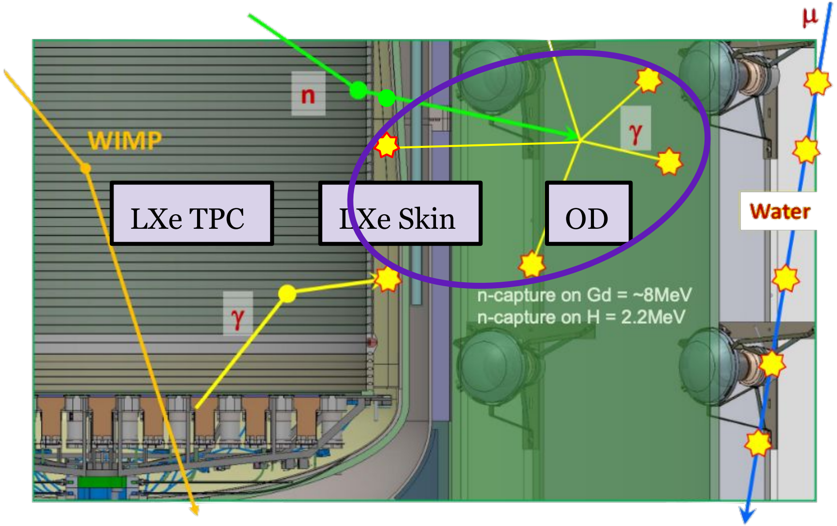
Example neutron event:



Veto Anti-Coincidence Systems



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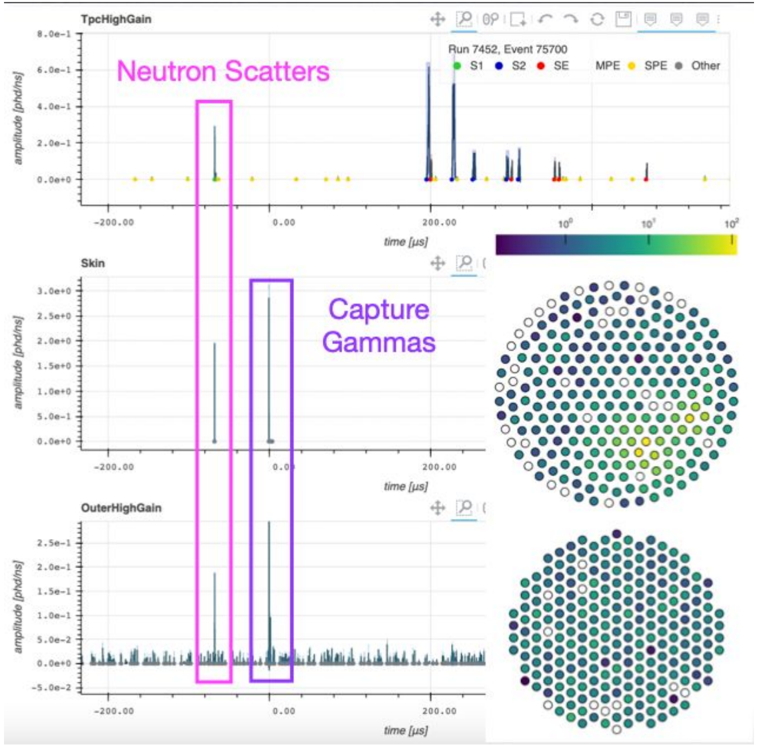

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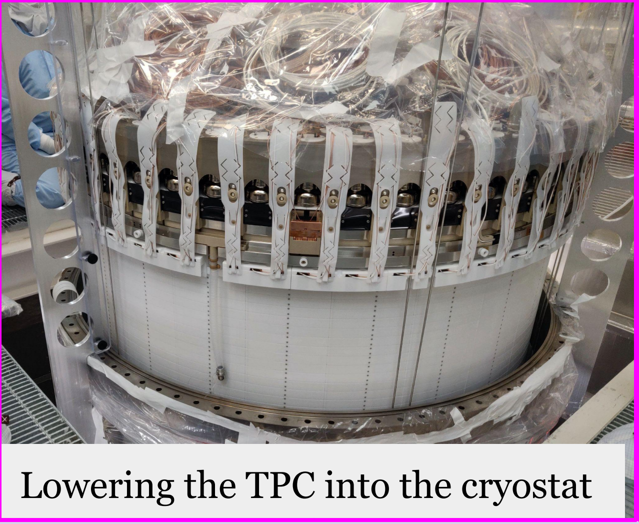
LZ Assembly (2018 - 2021)

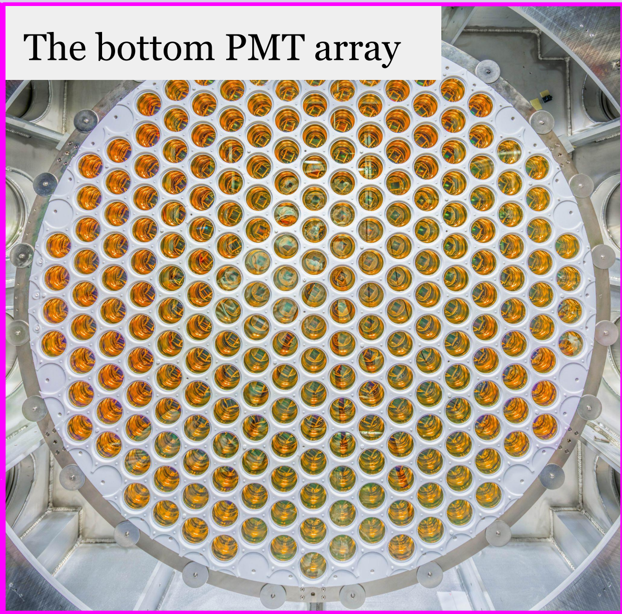
TPC Assembly



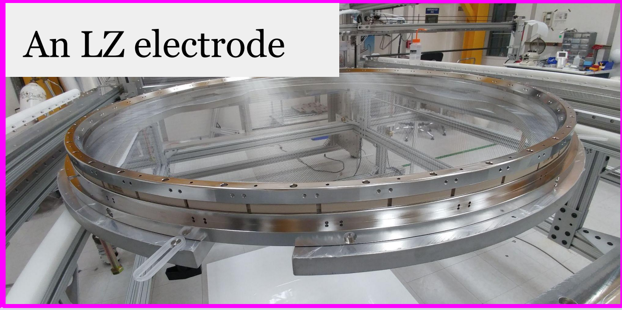
Lowering the TPC into the cryostat

Moving the cryostat

The Outer Detector

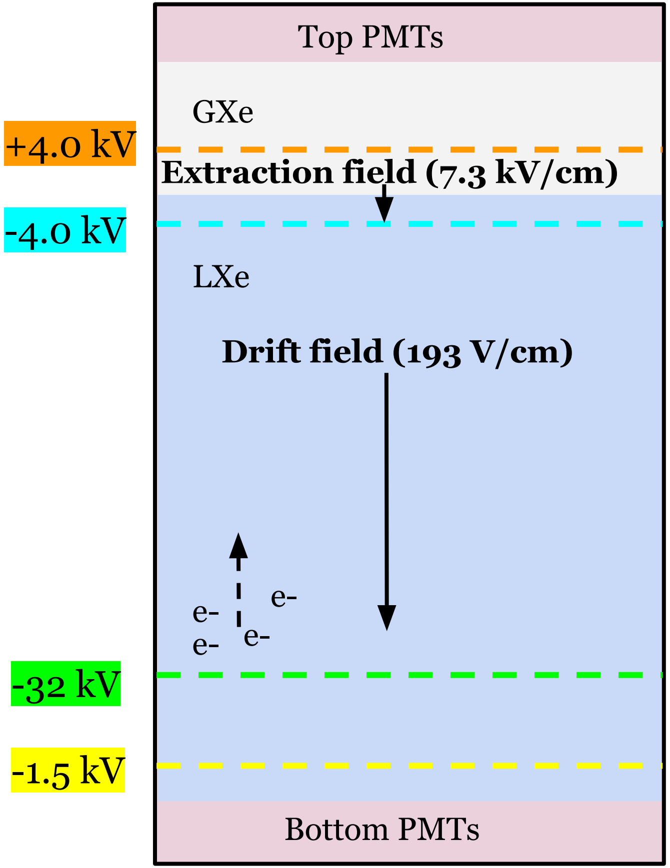


The bottom PMT array



An LZ electrode

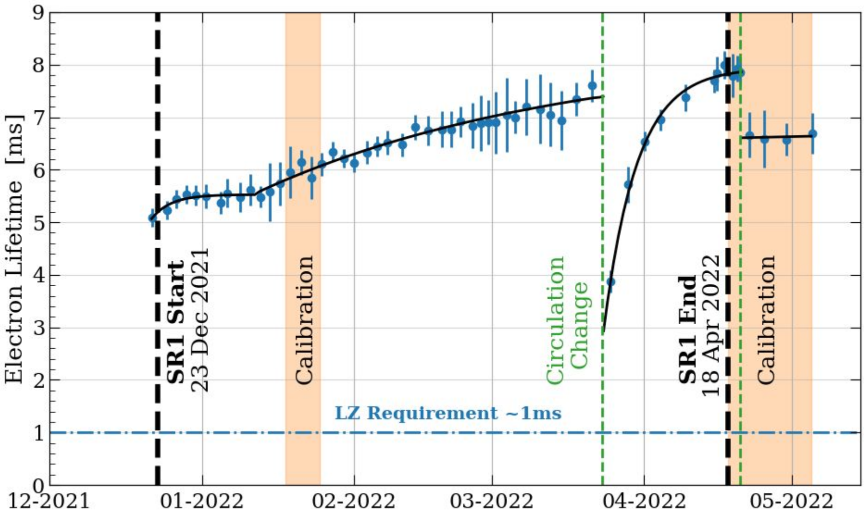
First Science Run (SR1)



60 live days of data (following removal of exclusion periods)

Stable detector conditions:

- Temperature: 174.1 K
- Gas pressure: 1.791 bar

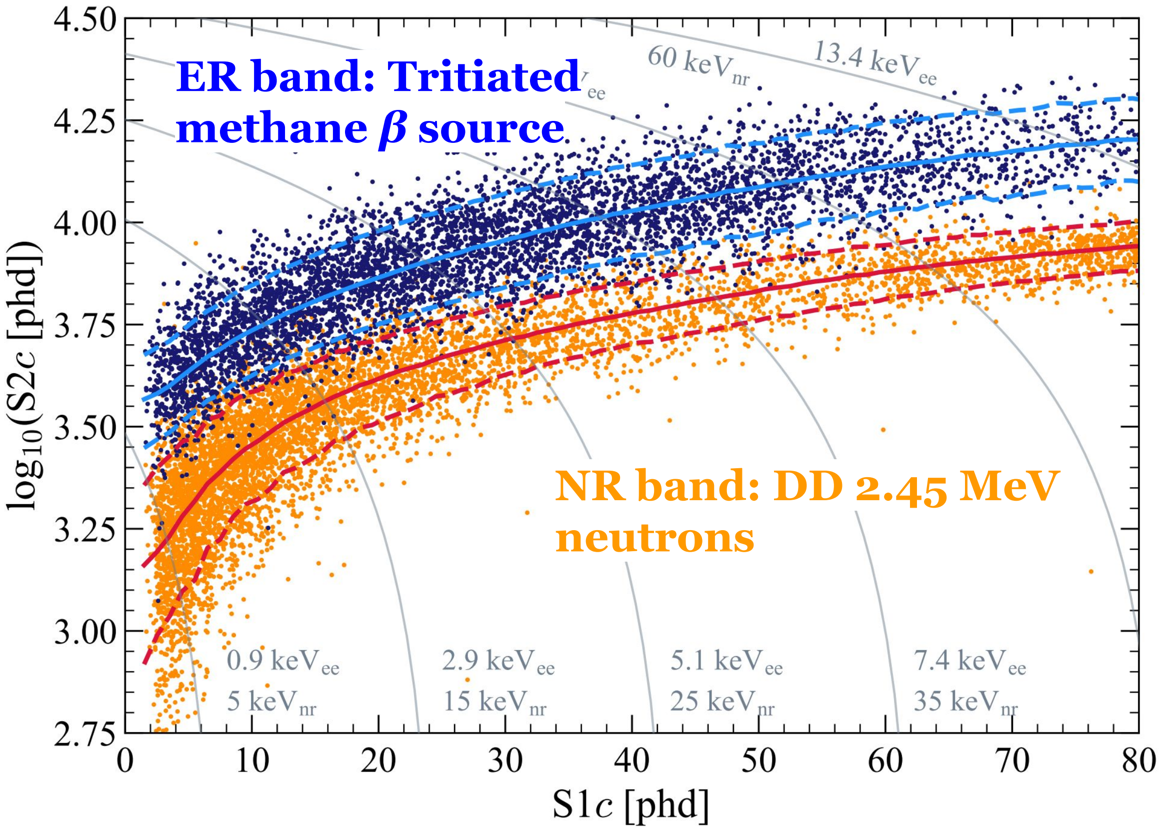


Electron lifetime of 5-8 ms throughout ($\gg$ max. drift time of 951 μs)

Continuous Xe purification at 3.3 t/day

Demonstration run: no blinding, but analysis developed on side bands/calibration data

Calibrations



Band fits performed using NEST v2.3.7

g_1 (light gain) = 0.114 ± 0.002 phd/photon

g_2 (charge gain) = 47.1 ± 1.1 phd/e^-

99.9% ER discrimination below NR band median

Background Model

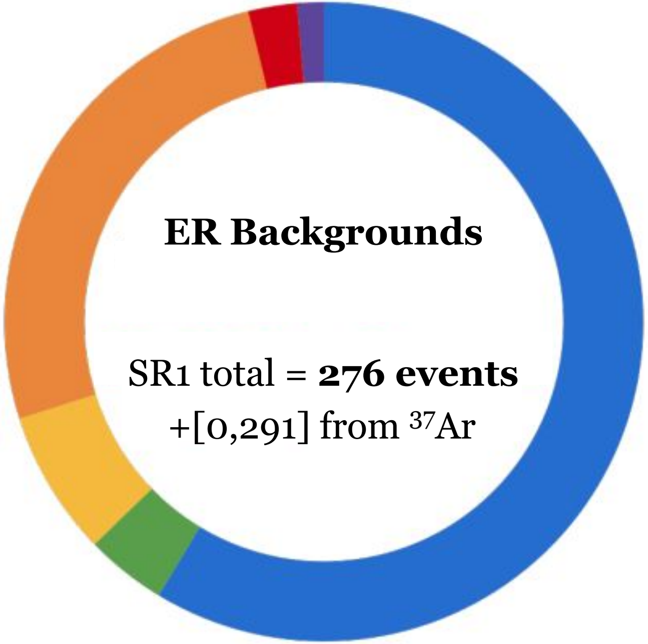
Phys. Rev. D 108, 012010 (2023)

γ-emitters in detector materials:

- ^{238}U chain
- ^{232}Th chain
- ^{40}K
- ^{60}Co

Dissolved e-captures (mono-energetic x-ray/Auger cascades):

- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)



Solar neutrinos (ER):

- pp
- ^{7}Be
- ^{13}N

NR backgrounds:

- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos
- SR1 total = **0.15 events**

Accidental Coincidences:

- Unrelated S1 and S2 pulses classified as single scatter events
- SR1 total = **1.2 events**

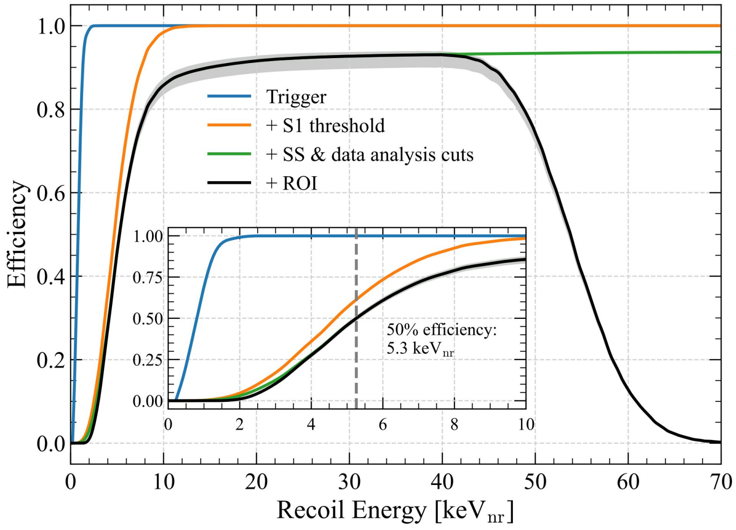
Dissolved β-emitters:

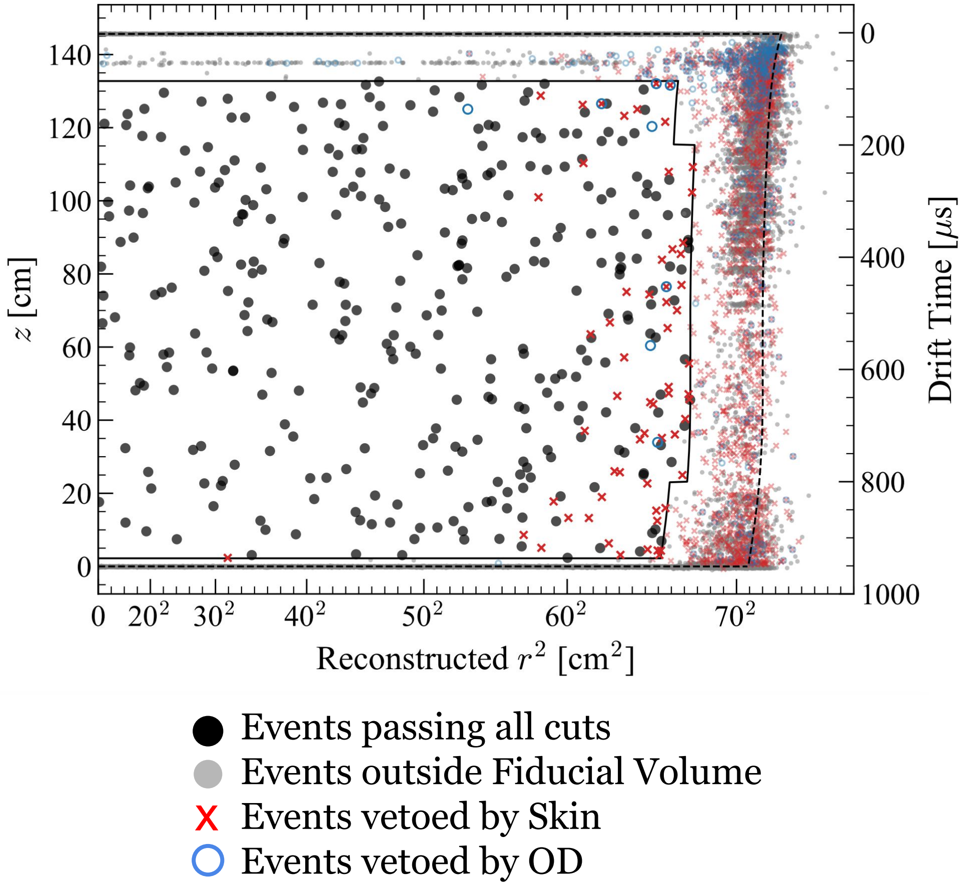
- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr
- ^{136}Xe ($2\nu\beta\beta$)

Data Quality Analysis

Analysis cuts:

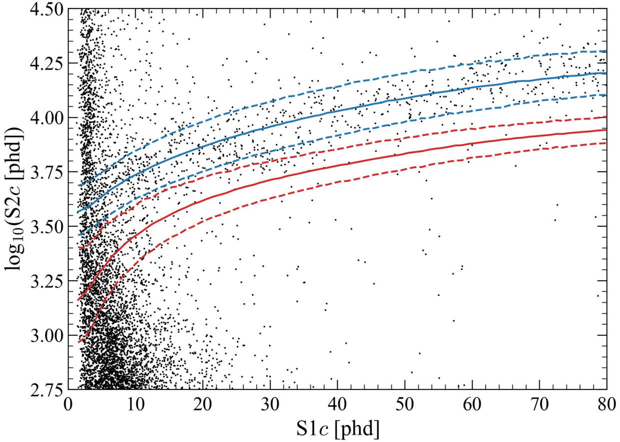
- Remove time periods with instabilities and high rates
- Remove accidentals using pulse-based cuts
- Define WIMP Region of Interest and 5.5 t Fiducial Volume
- Veto events with coincident signal in Skin or OD



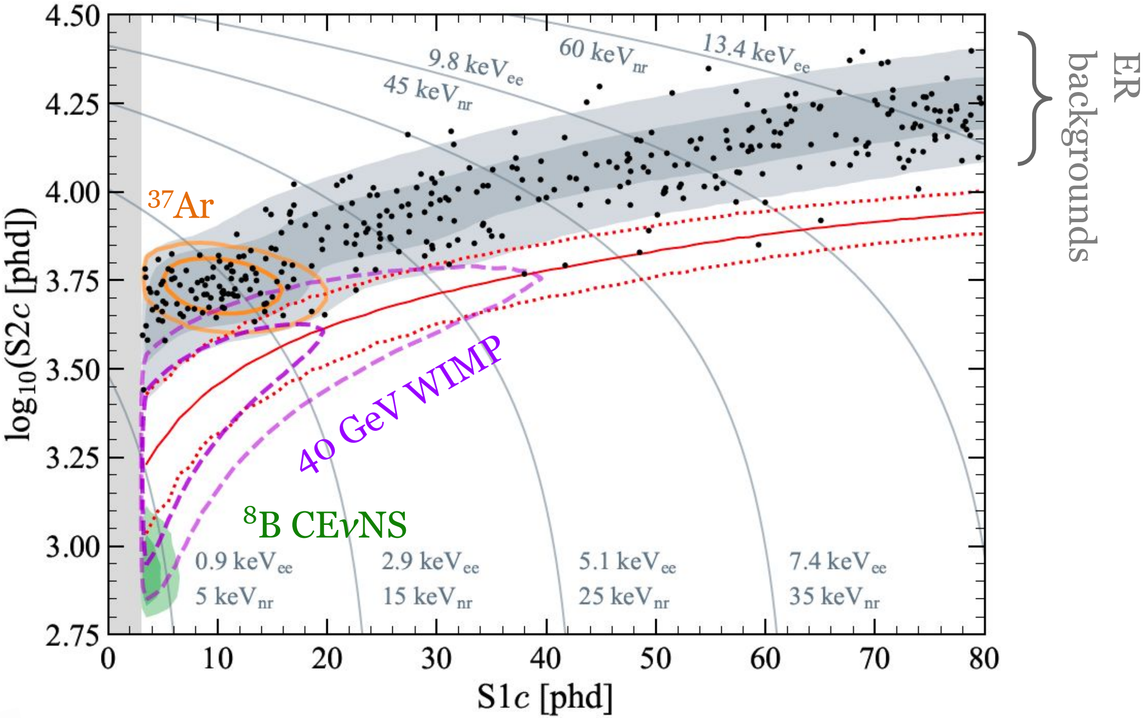


Final SR1 Dataset

Single Scatter events with FV cut only



+ Analysis Cuts



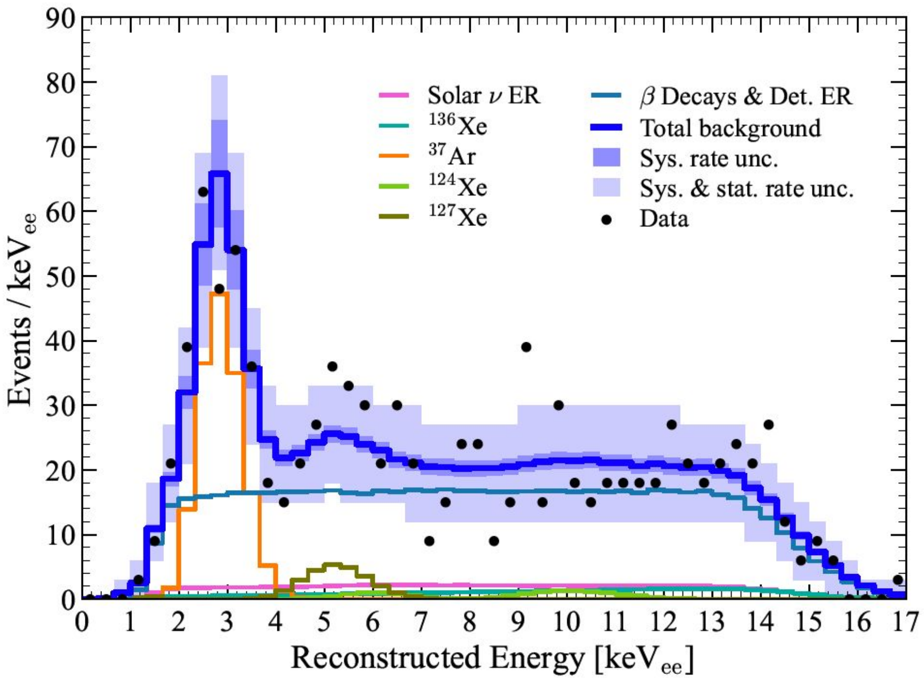
335 events

Background Fits

Profile likelihood fit in $\log_{10}$(S2c) vs S1c space

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Background model | Combined fit to data

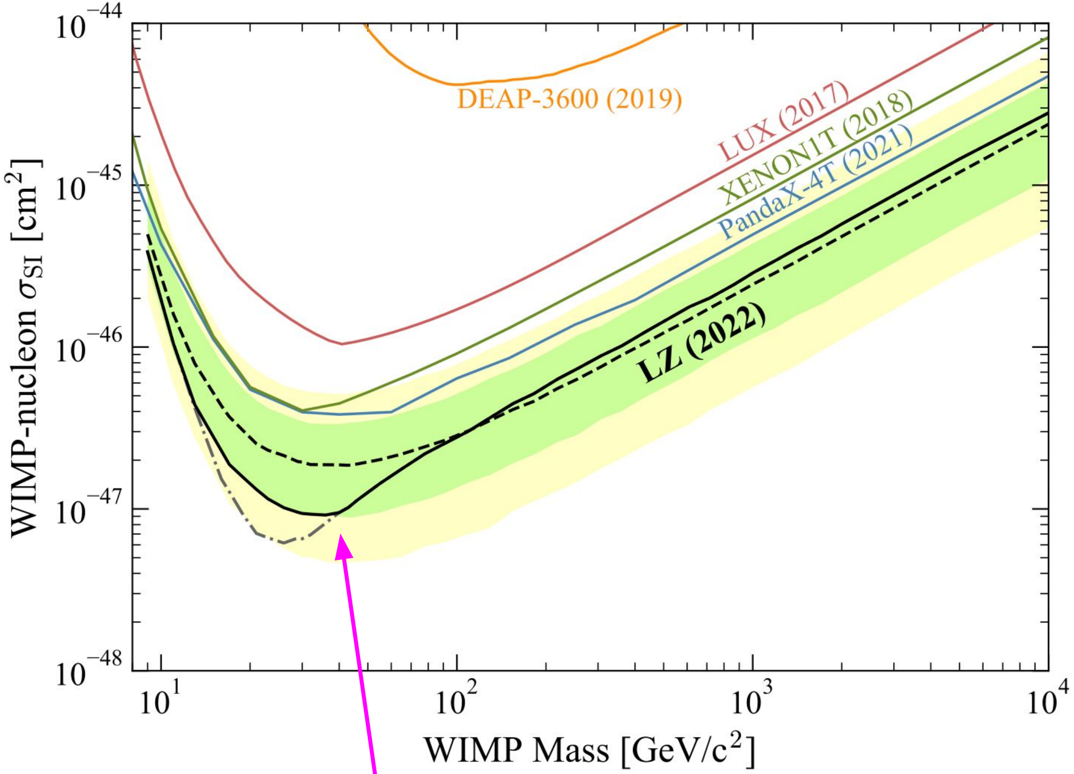


Best fit with **zero WIMP events** at all WIMP masses

Spin-Independent Limits

- Two-sided PLR test statistic, power constrained to -1σ [1]
- No evidence for WIMPs
- World-leading exclusion limit for masses > 9 GeV/c²

—— Observed limit
- - - Median expected sensitivity



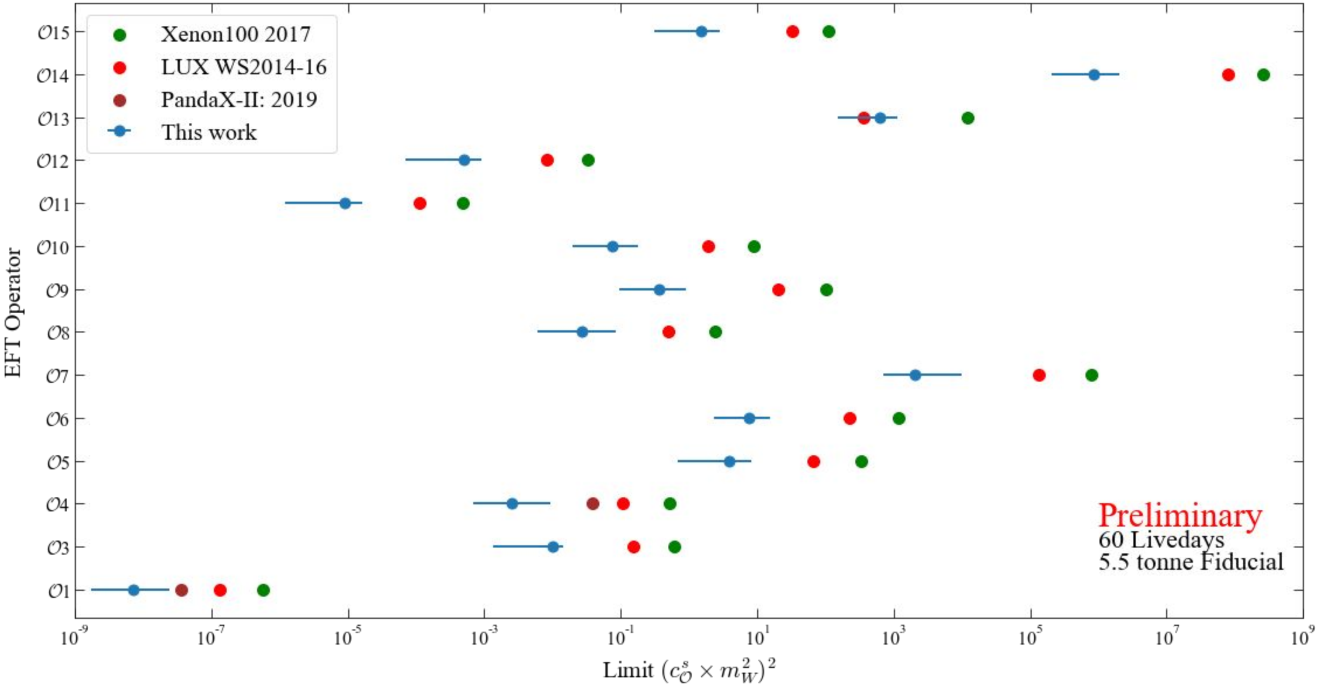
Most stringent limit of 9.2×10^{-48} cm² for a 36 GeV/c² WIMP

Effective Field Theory Results

arXiv:2312.02030 (2023)

- Many theoretical models for DM-SM interactions
- Treat WIMP-nucleon elastic scattering as four-field interaction parameterised by operators

$$\mathcal{L}_{int} = \sum_{N=n,p} \sum_{i} d_i^{(N)} \mathcal{O}_i \bar{\chi}\chi\bar{N}N$$



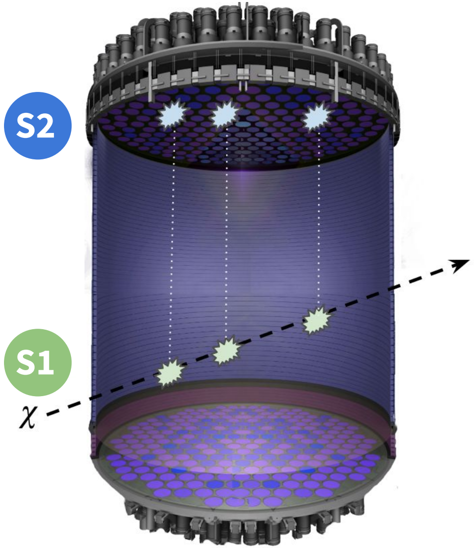
- Upper limit of ROI extended by a factor of 7.5
- **LZ provides the strongest upper limits for all but one operator**

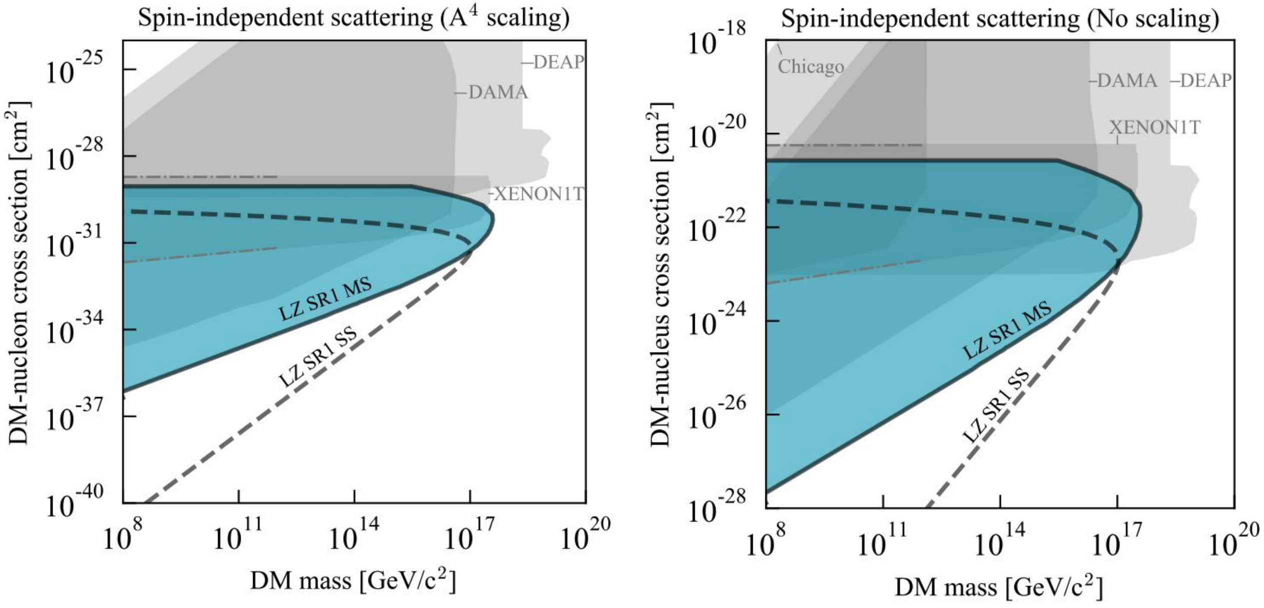
Ultraheavy Dark Matter Results

arXiv:2402.08865 (2024)

Multiply interacting massive particles (MIMPs):

- Higher mass scale than WIMPs (> 10^4 GeV/c^2)
- Expected to scatter several times in the TPC in a straight line

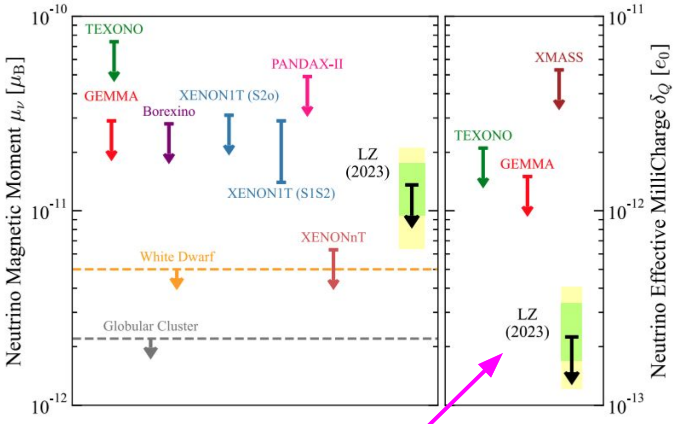




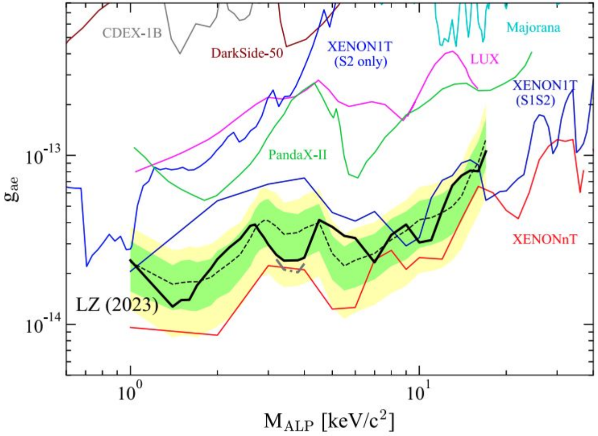
- Maximum mass probed by LZ extended to 3.9×10^{17} GeV/c²
- Competitive per-nucleus limits and world-leading per-nucleon limits

Low-energy ER Results

Phys. Rev. D 108, 072006 (2023)



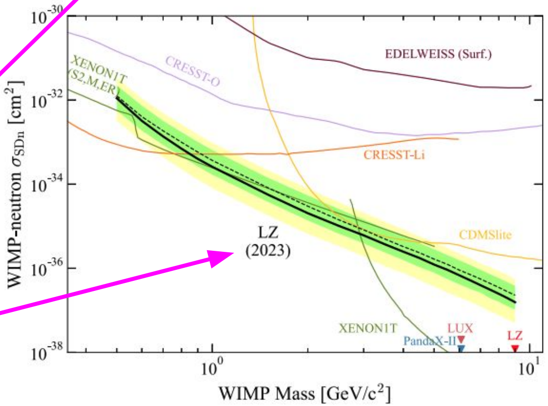
Neutrino magnetic moment and millicharge measurements

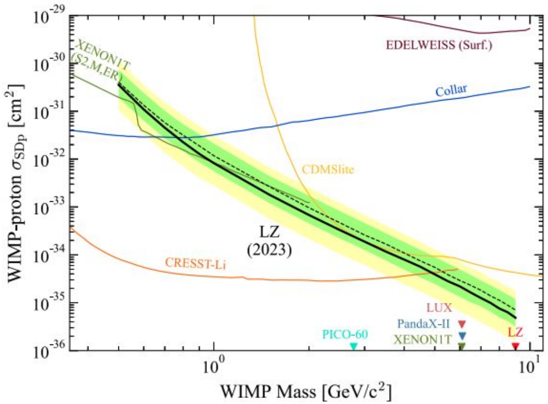


Axion, axion-like particle and hidden photon searches

8 BSM searches

New parameter space excluded



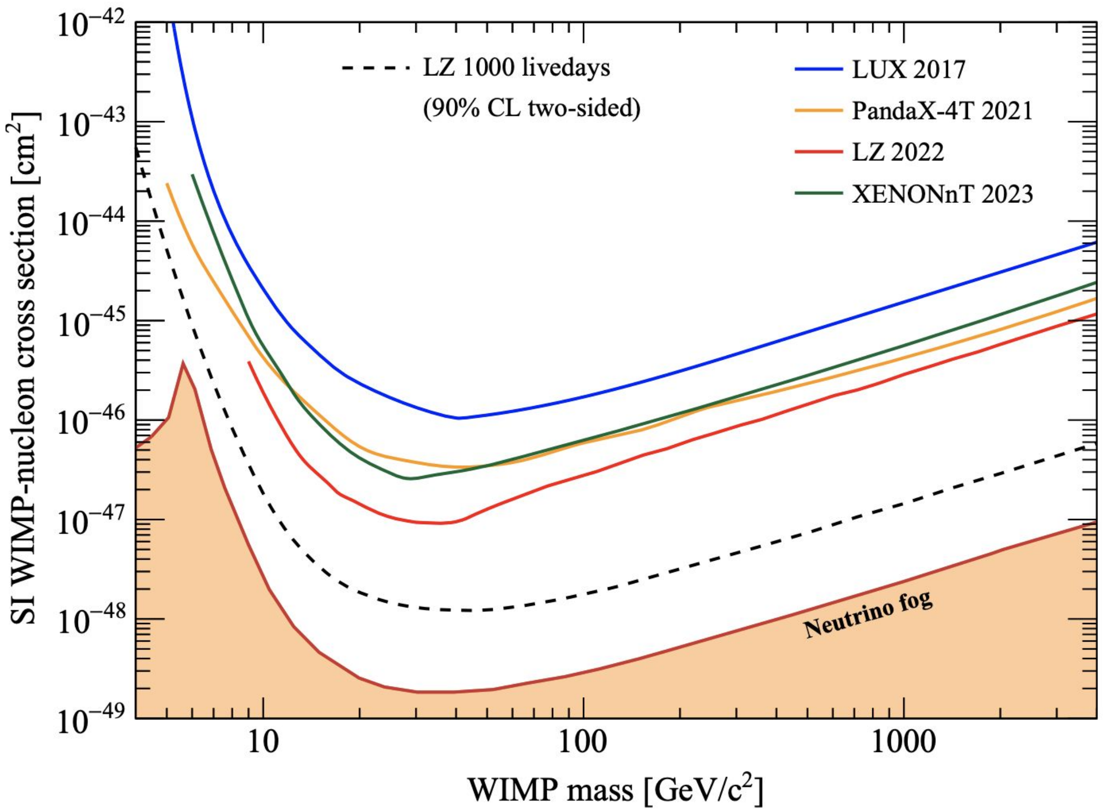


SI and SD WIMP searches using the Migdal mechanism

Future Prospects for LZ

[1] PRD 101, 052002 (2020)
[2] Phys. Rev. C 102, 014602 (2020)

- SR1 covers only **6% of planned full exposure** of 1000 live days [1]
- Lots of parameter space still explorable with LZ
- Began a long science run in "**discovery mode**" with salting for bias mitigation
- **Broad range of physics** available
    - Beyond SR1: S2-only searches, ^{8}B, $0\nu\beta\beta$ [2] etc



Beyond LZ: XLZD Consortium

https://xlzd.org
J. Phys. G: Nucl. Part. Phys. 50 013001 (2023)

- **X**ENON, **LZ** and **D**ARWIN collaborations working towards a G3 xenon observatory
- WIMP sensitivity down to “neutrino fog”
- Plus other dark matter candidates, $0\nu\beta\beta$, atmospheric neutrinos

Conclusions

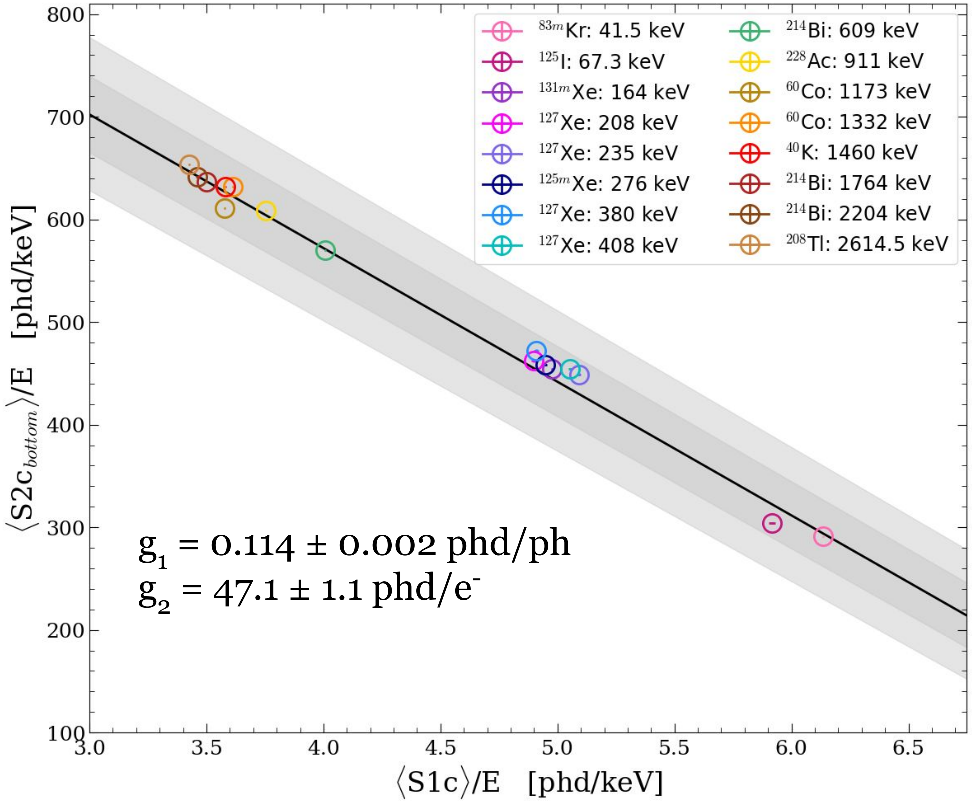
- **World-leading spin-independent WIMP search limit** set using only 6% of planned exposure

- Lots more **WIMP parameter space** and many **other physics** channels to explore with LZ

- **XLZD** consortium working towards the ultimate xenon observatory

Supplementary Slides

Energy Response



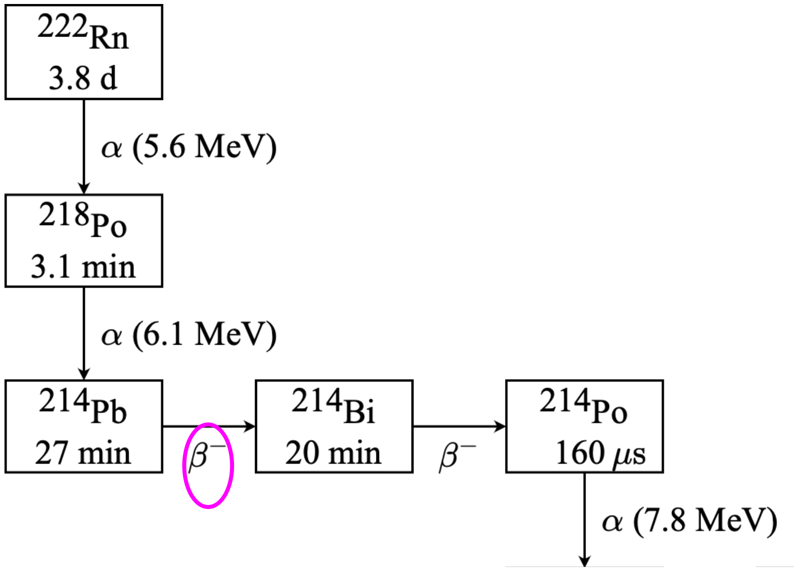
- S1 and S2 signal sizes corrected using ^{131m}Xe background and ^{83m}Kr calibration sources
- Means of corrected measured S1 and S2 signals plotted for sources of known energies on a **Doke plot**

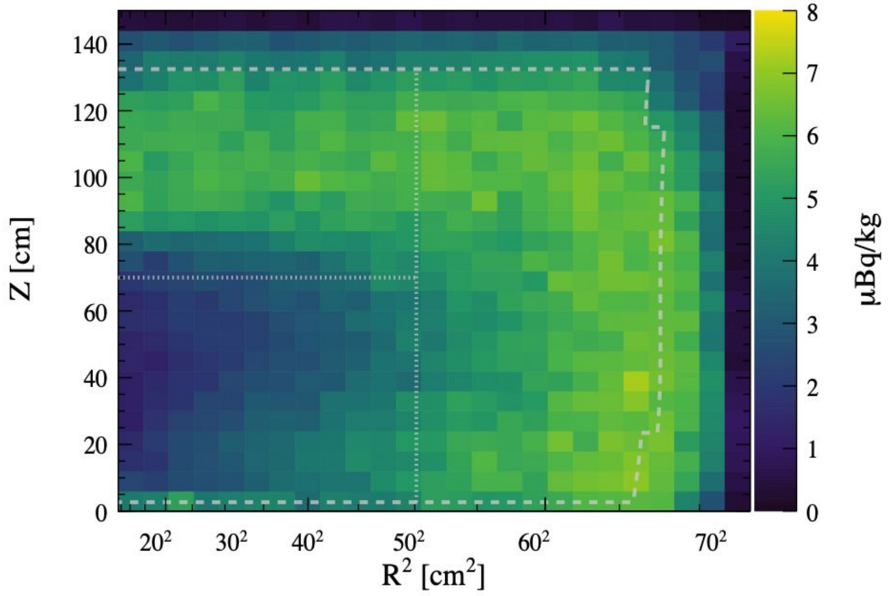
$$E = W \cdot \left(\frac{S1_c}{g1} + \frac{S2_c}{g2}\right) \longrightarrow \frac{S2_c}{E} = -\left(\frac{g2}{g1}\right) \cdot \left(\frac{S1_c}{E}\right) + \frac{g2}{W}$$

W = excitation energy of 13.5 eV

Backgrounds: Radon

- Radon emanates from detector materials into Xe
- Non-uniform spatial distribution
- WIMP background from “naked” β decay of ^{214}Pb
- ^{218}Po and ^{214}Po α decays used to constrain rates

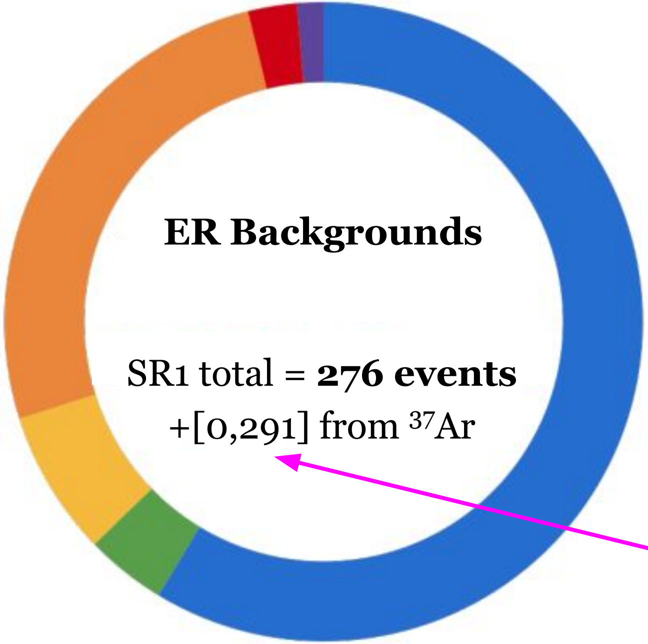


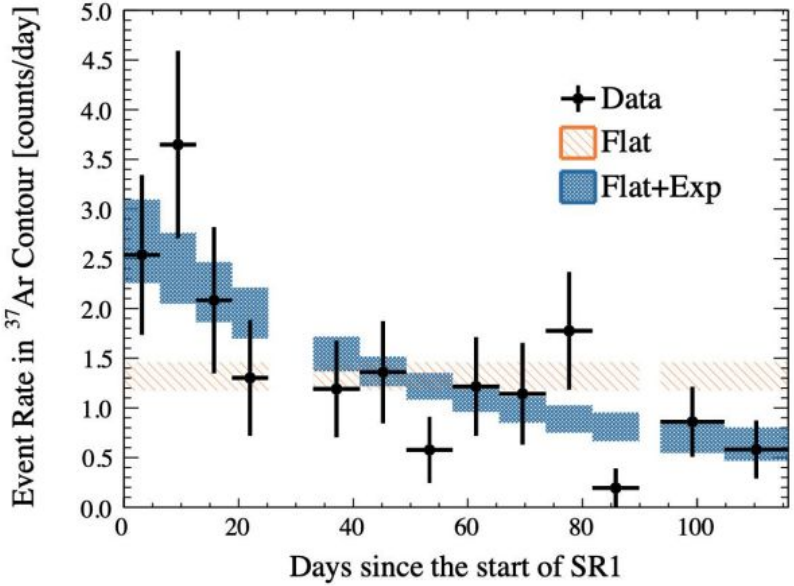


(a) Observed ^{218}Po Distribution

Backgrounds: ^{37}Ar

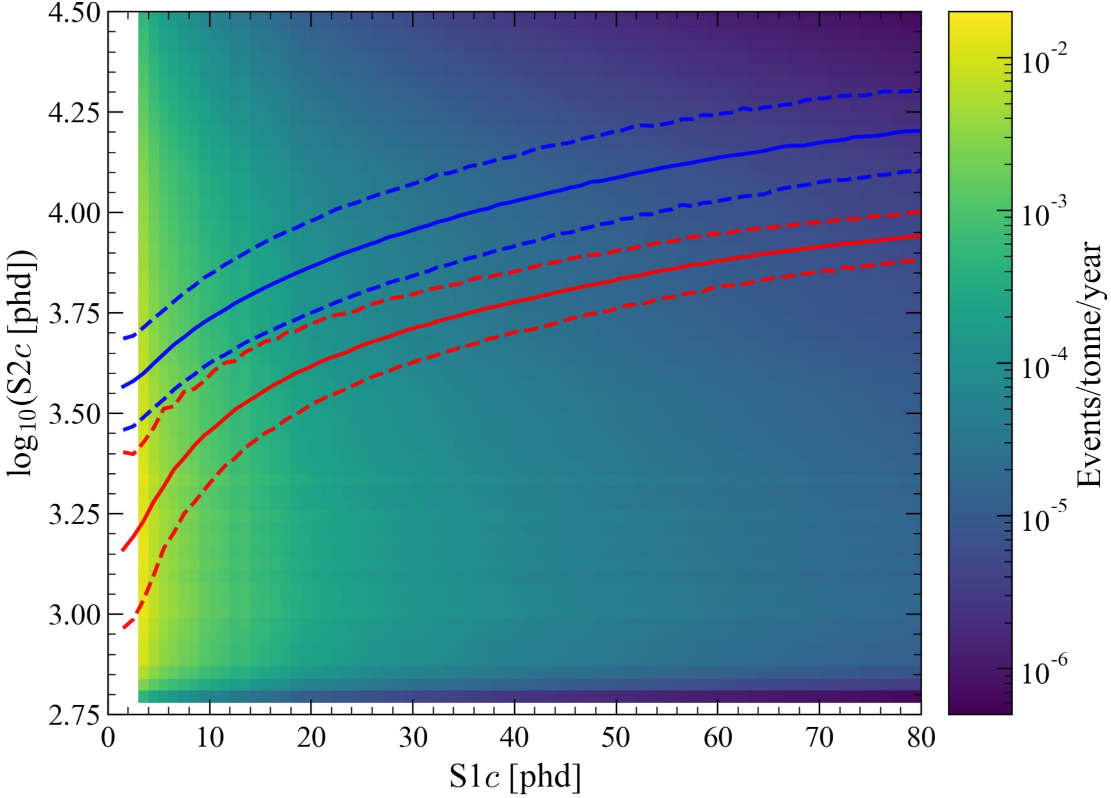
- From cosmic spallation of natural Xe above ground
- $t_{1/2}$ = 35 days - significant during early data-taking



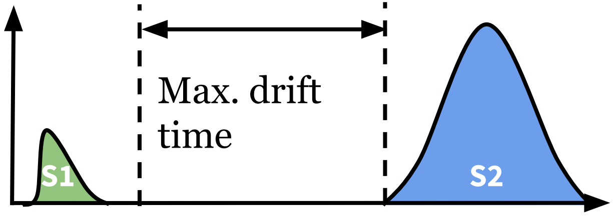


- Exposure during transport was estimated and expected activity calculated
- Large uncertainty

Backgrounds: Accidentals

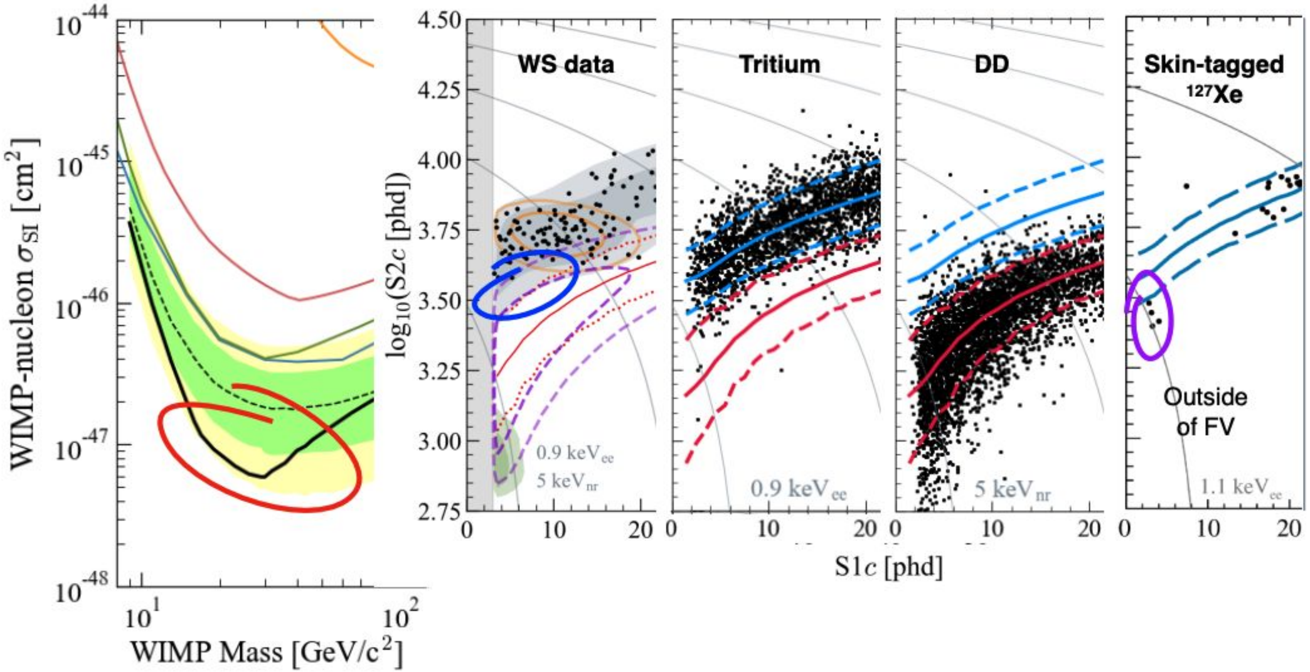


Definite Accidental Event



- Accidental coincidences of isolated S1 and S2 pulses can occur within max. drift time
- Rate: definite accidental events with drift time > max. drift time
- Distribution: fake events from lone S1 and S2 pulses stitched together
- Analysis cuts remove with >99.5% efficiency

Limit Shape



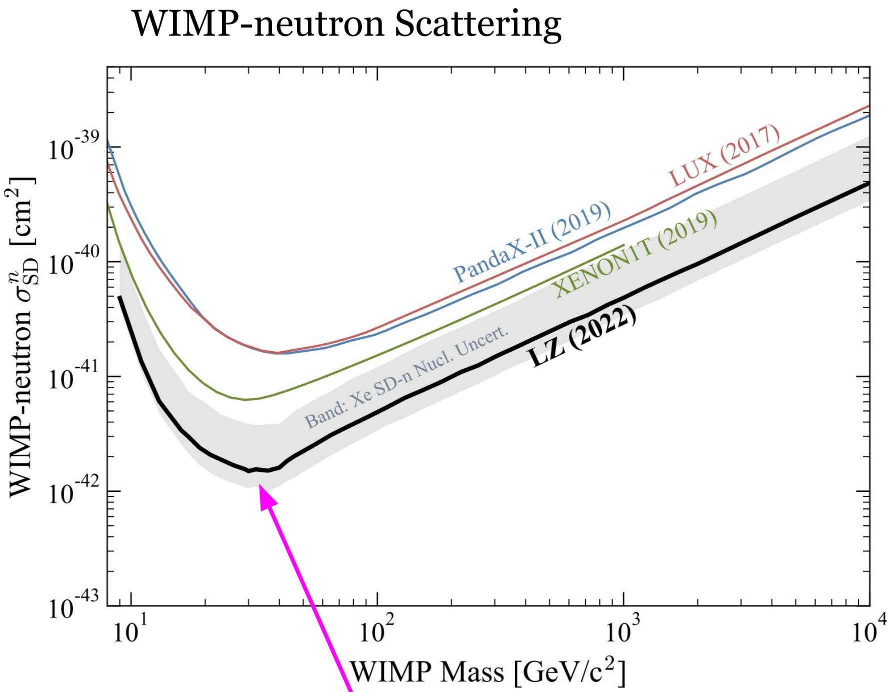
- Tritium and DD calibrations showed that the deficit region was well-covered
- Skin-tagged ^{127}Xe decays near deficit region were also as expected, given the signal acceptance

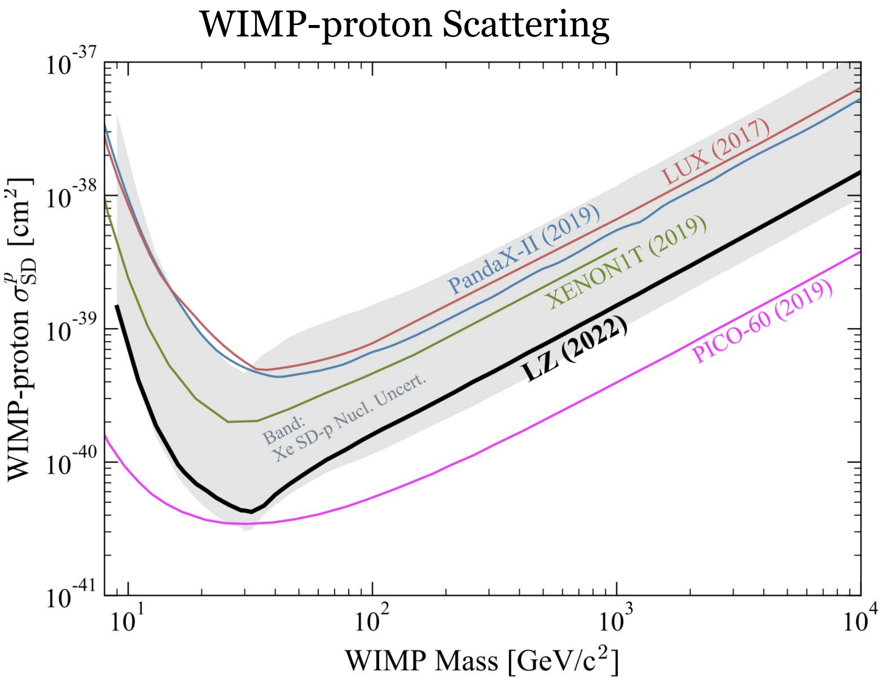
→ **Background under-fluctuation, rather than signal inefficiency that was unaccounted for**

Downward fluctuation in observed upper limit is a result of a **deficit of events under the ^{37}Ar contour**

Spin-Dependent Limits

[Phys. Rev. Lett. 131, 041002 (2023)]





Most stringent limit for SD-n of 1.49×10^{-42} cm^2 for a 36 GeV/c^2 WIMP

Grey bands = theoretical uncertainty on Xe nuclear structure factor