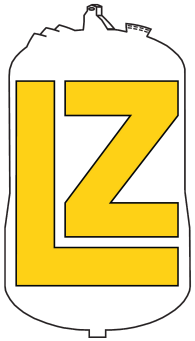
UNIVERSITY OF LIVERPOOL



Status of LUX-ZEPLIN

First Dark Matter Searches

April 2024

Ewan Fraser

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

Science and Technology Facilities Council

FCT Fundação para a Ciência e a Tecnologia

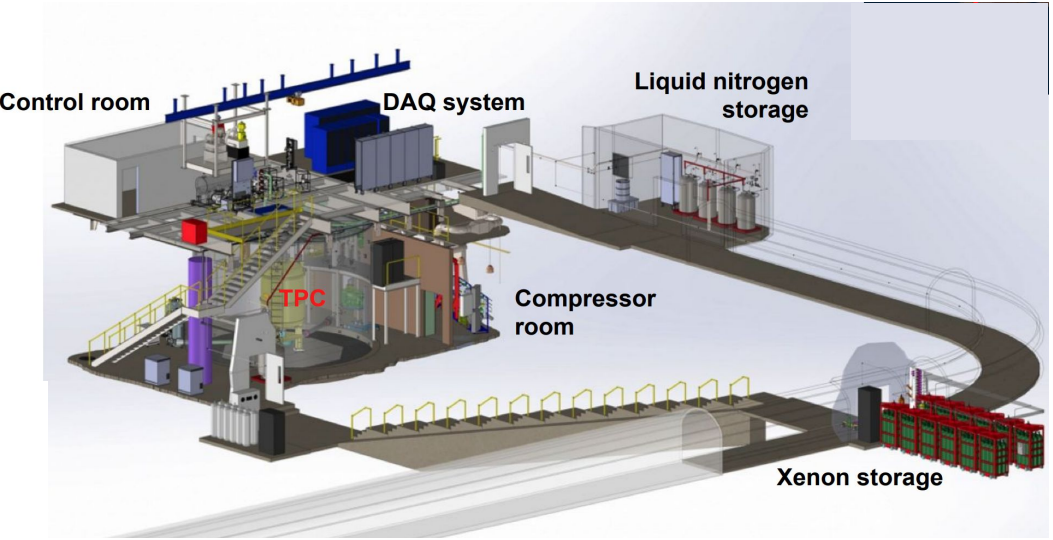
Sanford Underground Research Facility
South Dakota Science and Technology Authority

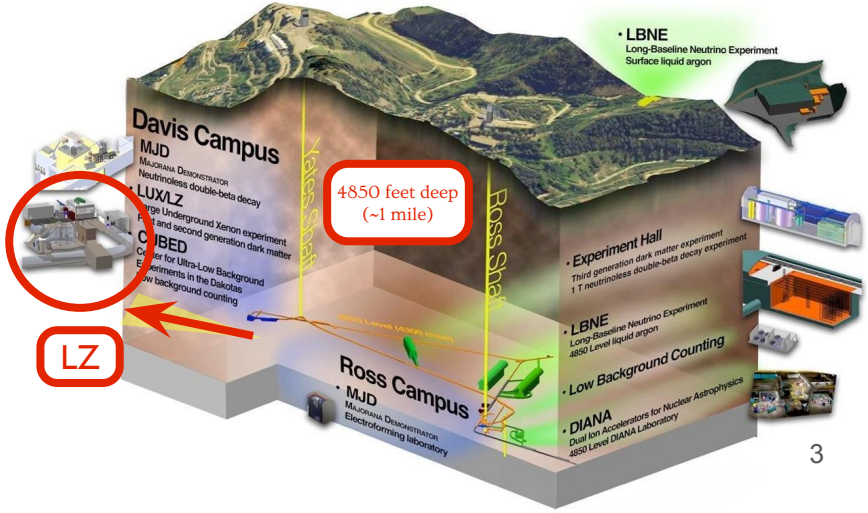
ibs Institute for Basic Science

Thanks to our sponsors and participating institutions!

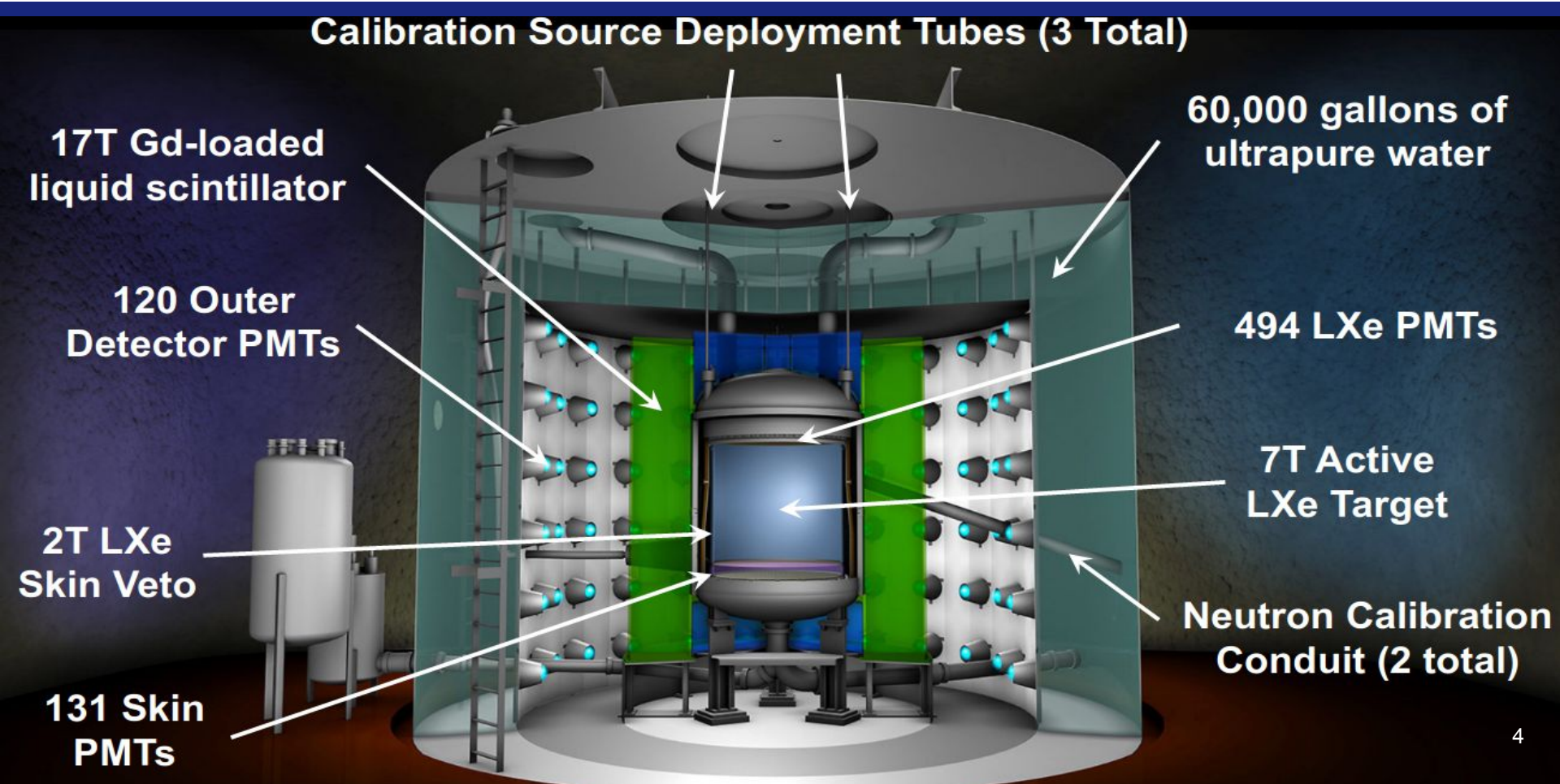
LZ at SURF

- LUX-ZEPLIN 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)

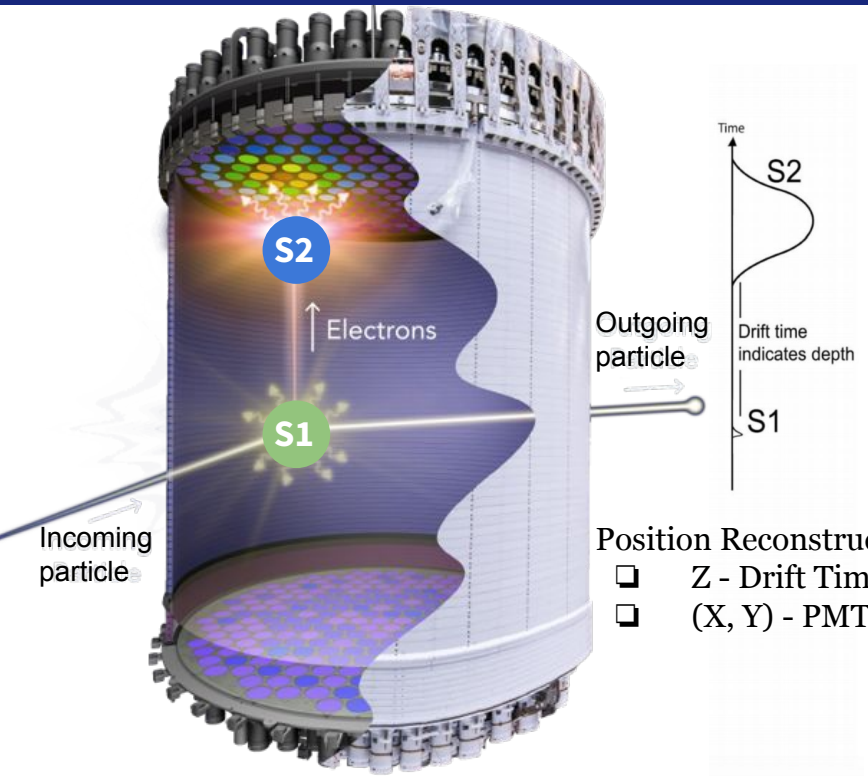




LZ - Experiment for Direct Detection of WIMP Dark Matter



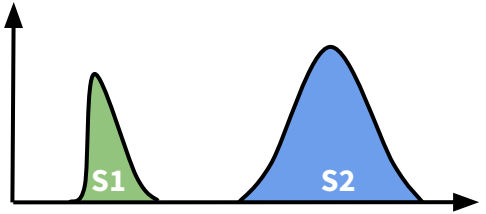
Dual-phase Xenon TPCs



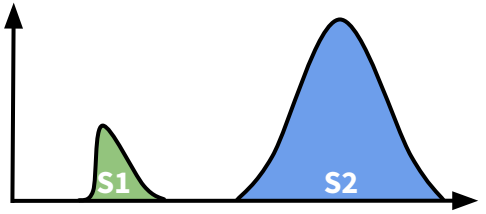
Position Reconstruction:

- ❏ Z - Drift Time
- ❏ (X, Y) - PMT hit pattern

Nuclear Recoil (NR): WIMPs, neutrons



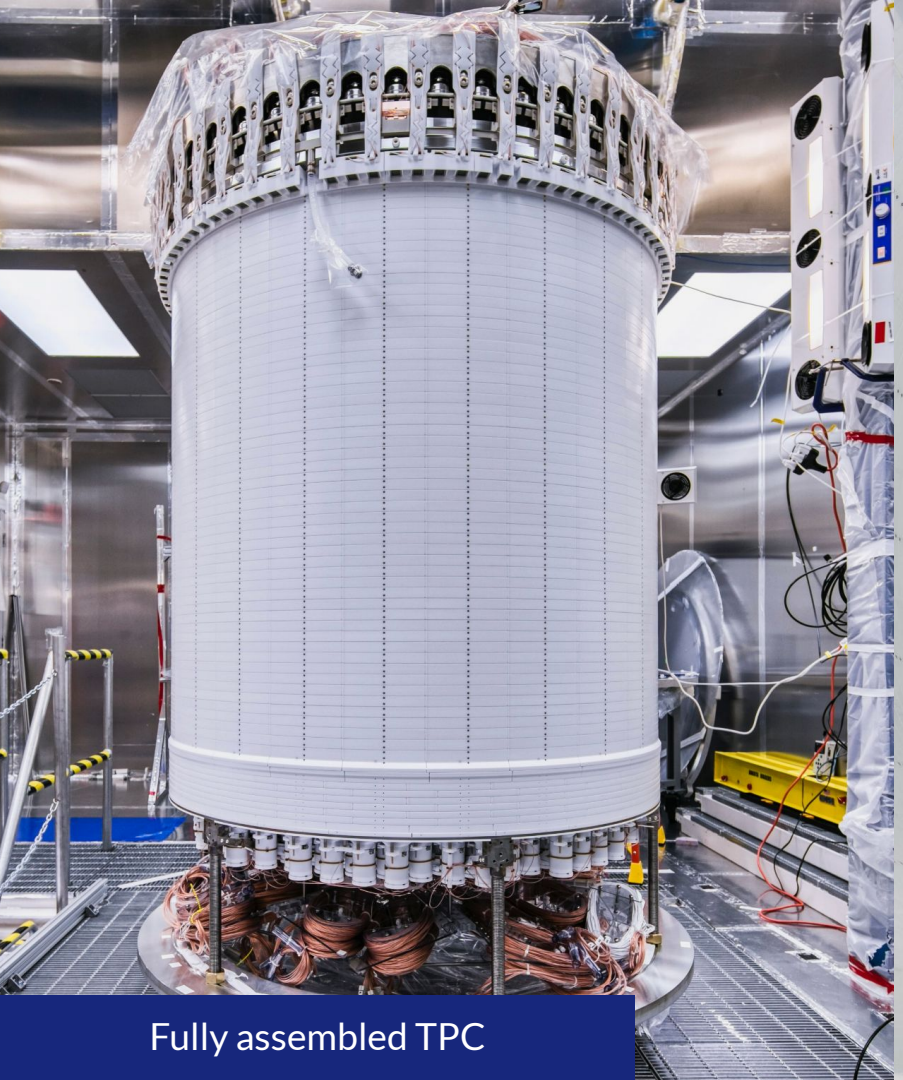
Electron Recoil (ER): γ and β backgrounds



ER/NR discrimination from **ratio of S1 and S2**

S1 Prompt scintillation light

S2 Electroluminescence from electrons accelerated across phase change in extraction region



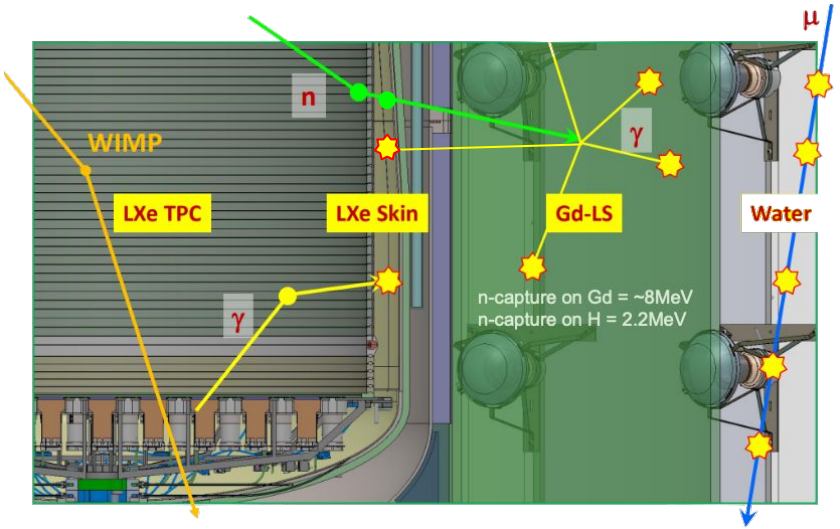
Fully assembled TPC

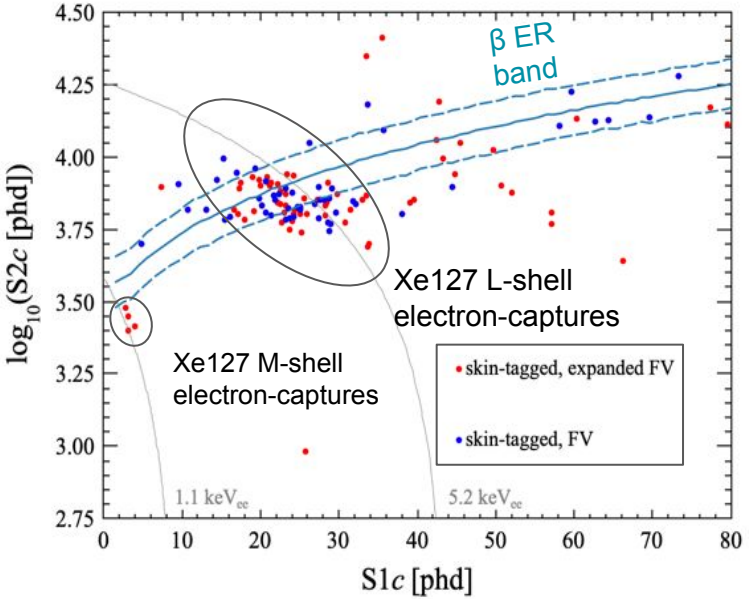
Bottom PMT array and field cage

UG TRANSPORTATION

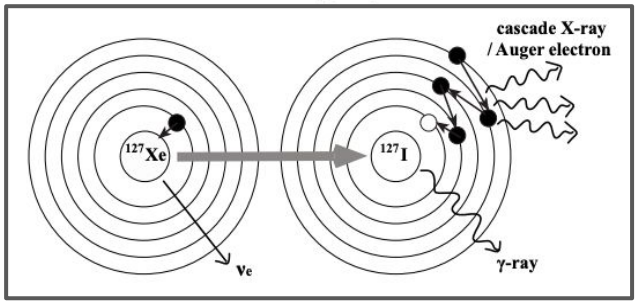
INNER CRYOSTAT INSERTION

LXe Skin Detector



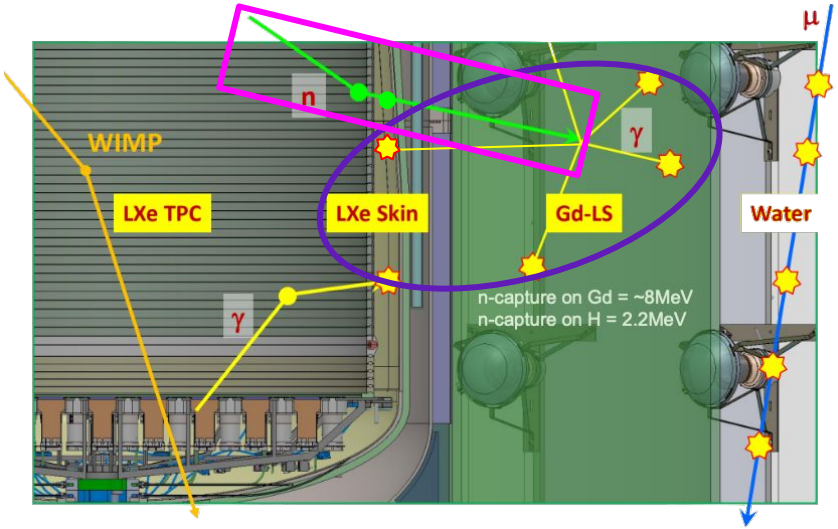


- **2 tonne** of LXe surrounding the TPC
- 131 1” or 2” PMTs
- Anti-coincidence veto for **γ-rays** with **78±5% efficiency**
- Reduction of important ER background rates
  - E.g. ^{127}Xe decay via electron capture



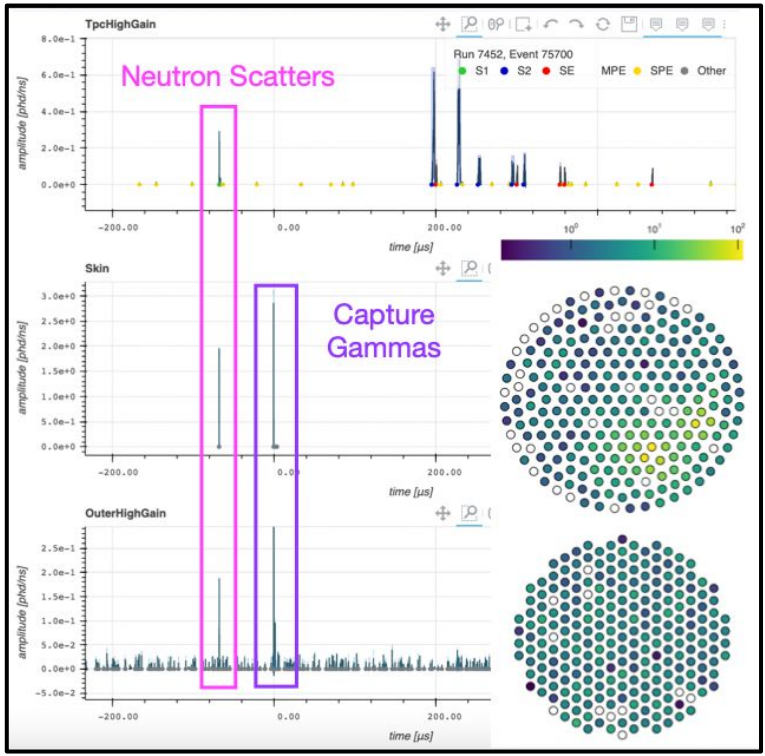
Courtesy of Jack Bargemann APS April 2023

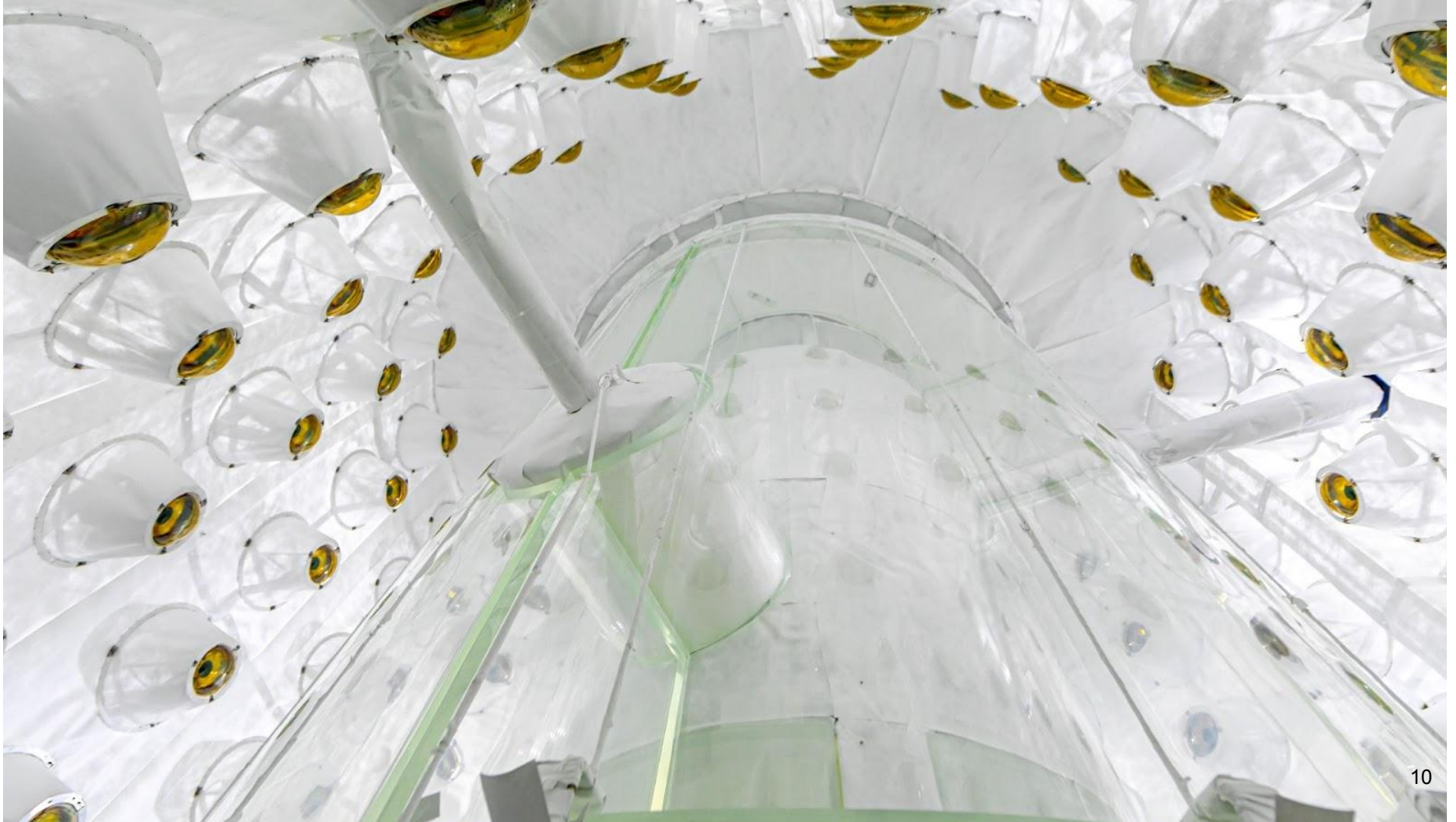
Gd-LS Outer Detector



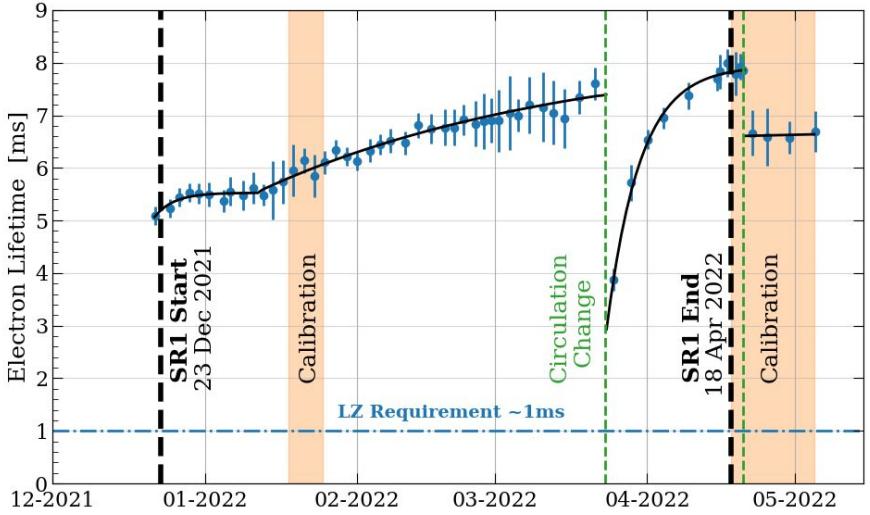
- **17 tonne** of Gd-loaded liquid scintillator (120 8” PMTs)
- **89±3% SS neutron tagging efficiency**
  - Measured with AmLi neutron calibration
- Neutron capture up to 1200 μs after the S1
  - ~5% livetime reduction
- Used to constrain the rate of SS neutron background

Waveform example of a tagged neutron multiple scatter:

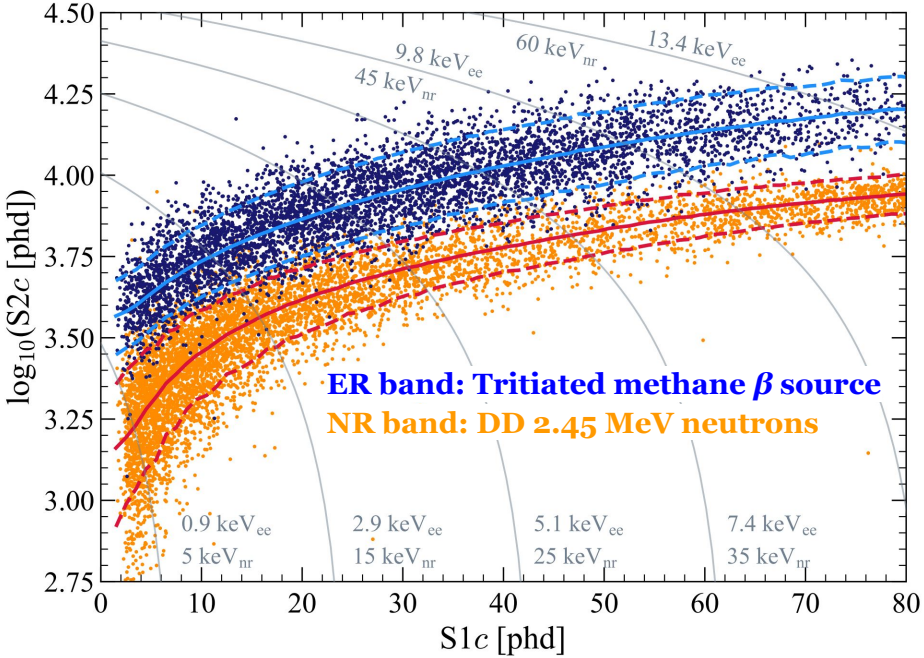




First Science Run: Stability and Calibrations



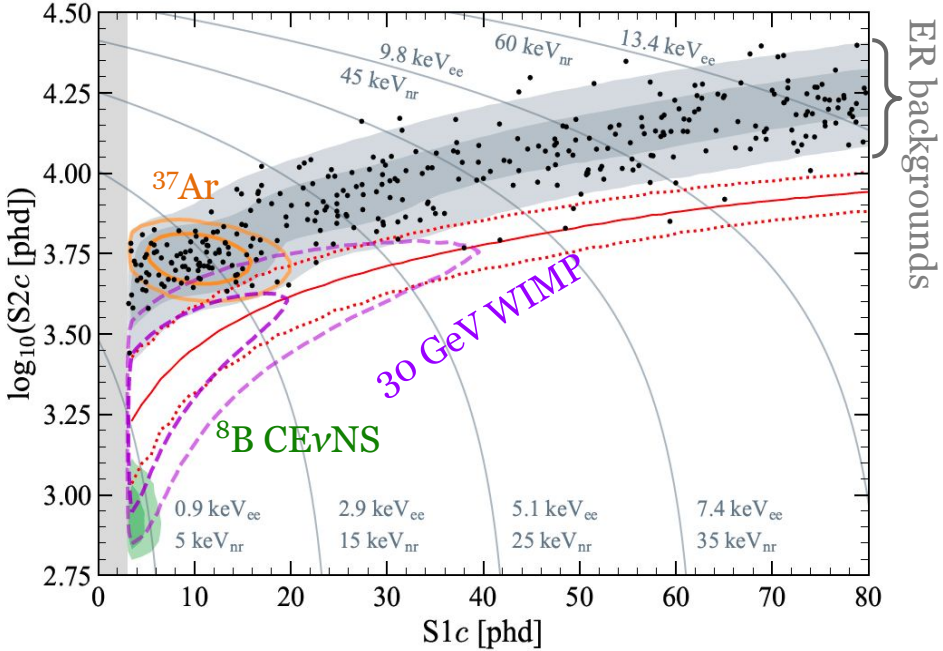
- Dec 23rd '21 - May 12th '22 (**60 live days**)
- > 97% of PMTs operational
- Liquid T = 174.1 K (**0.02% variation**)
- Gas P = 1.791 bar(a) (**0.2% variation**)
- Liquid level stable within **10 microns**
- Gas Circulation ~ **3.3 t/day**

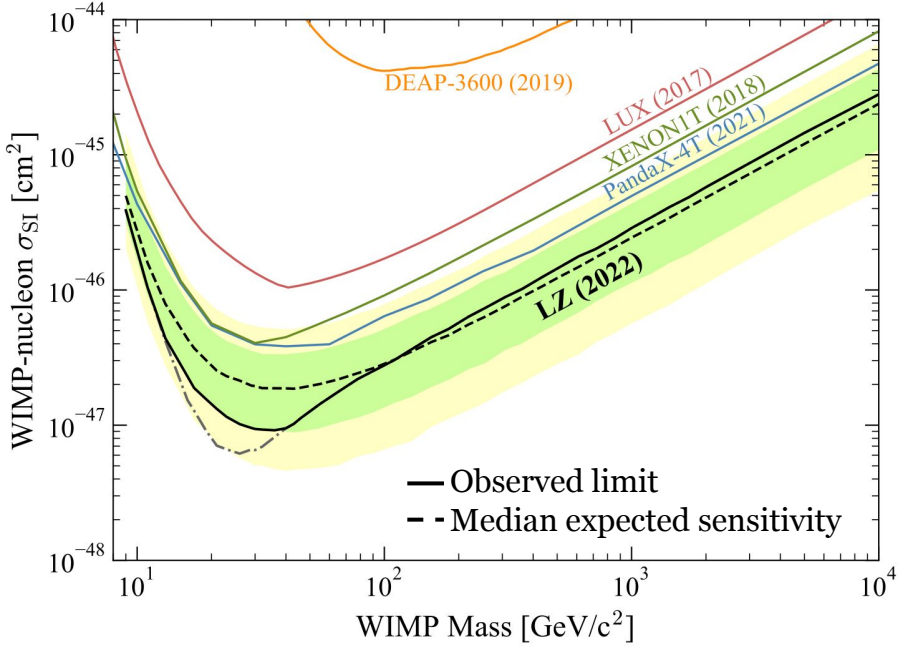


- Band fits performed using NEST v2.3.7
- **g_1 (light gain) = 0.114 ± 0.002 phd/photon**
- **g_2 (charge gain) = 47.1 ± 1.1 phd/e$^-$**
- 99.9% ER discrimination below NR band median

First Science Run: WIMP Search Results

PhysRevLett.131.041002





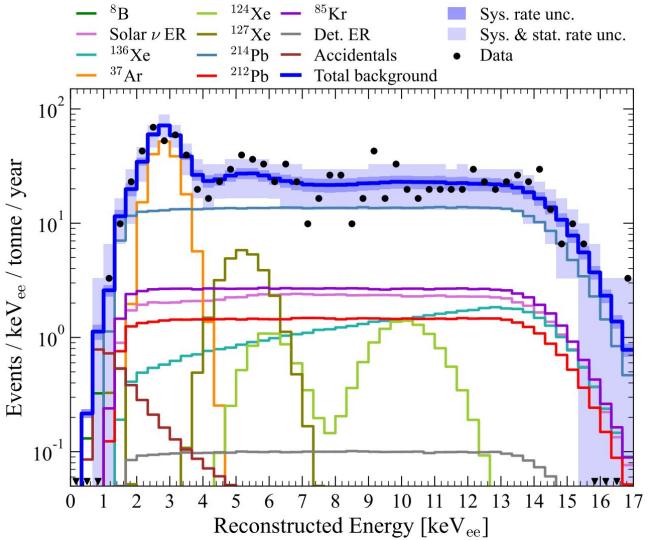
- **335 events** in the final dataset after data quality cuts in 5.5 t fiducial volume
- A profile-likelihood ratio shows the data to be consistent with a background-only hypothesis
- Best fit with **zero WIMP events** at all WIMP masses

- Green and yellow are the 1σ and 2σ median sensitivity bands
- Power constraint at -1σ sensitivity band to account for discovery power
- Best limit of $\sigma_{SI} = 9.2 \times 10^{-48}$ at 36 GeV/c²

Determination of LZ Backgrounds

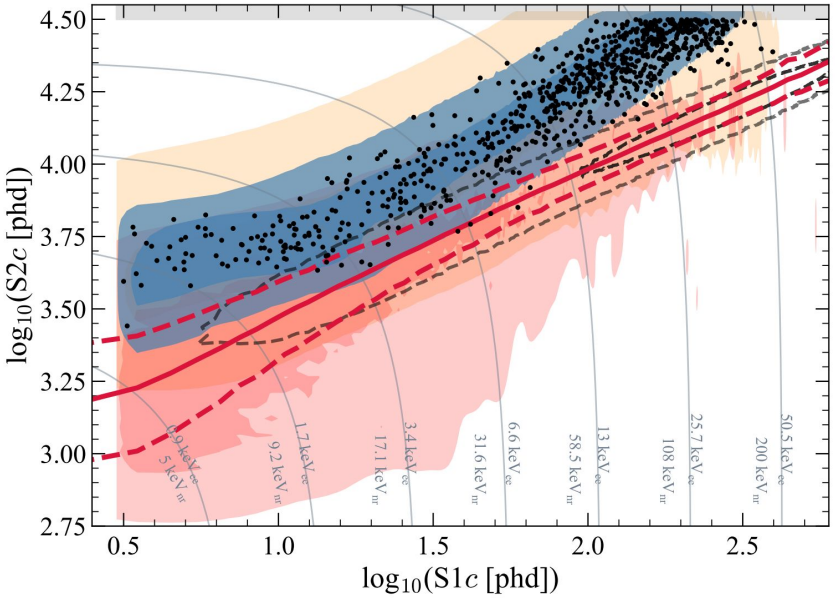
PhysRevD.108.012010

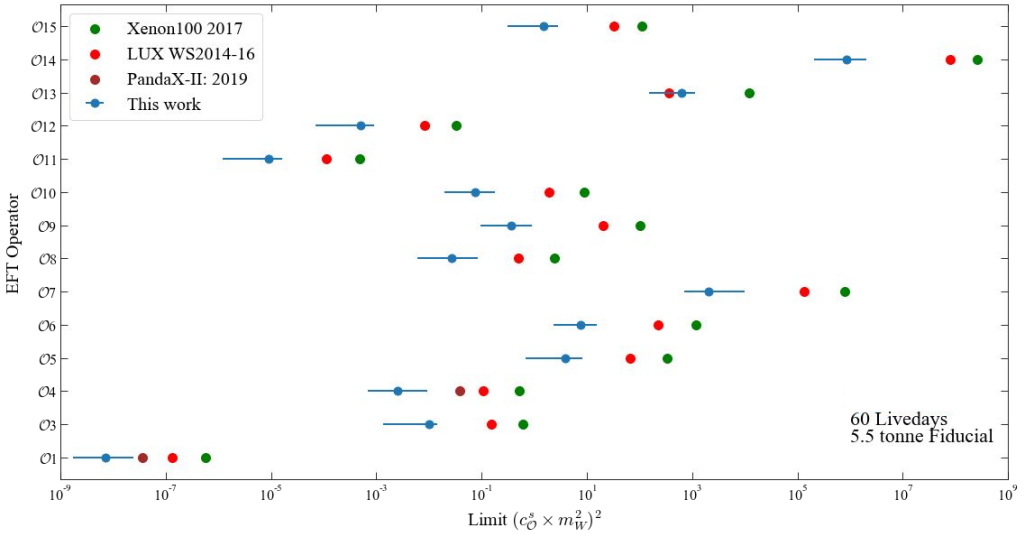
Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.4 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



- Comprehensive review of side-band analysis to determine background rates for LZ physics analysis
  - In-situ determinations consistent with prior ex-situ radioassays
- For example, largest ER background contribution from “naked” beta decays
  - ^{214}Pb rate constraint from fitting in the 80-700 keV region
  - Bounds on this fit determined from the rate of prior and following decays in the ^{220}Rn decay chain
- ^{37}Ar produced by cosmic ray spallation; uncertainty on the spallation yield is about a factor of three
  - Rate of ^{37}Ar allowed to float during the WS fit. Post-fit analysis consistent with ^{37}Ar decay

Effective Field Theory WIMP search [arXiv:2312.02030v2]





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

Model Key

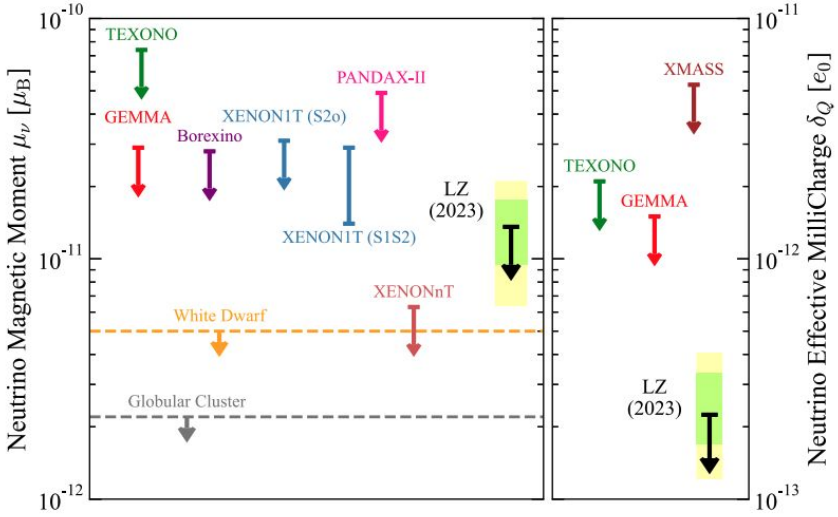
- 1000 GeV/c² $\mathcal{O}_6^s$ WIMP
- Detector NR
- Detector ER
- Combined ER
- NR band from DD

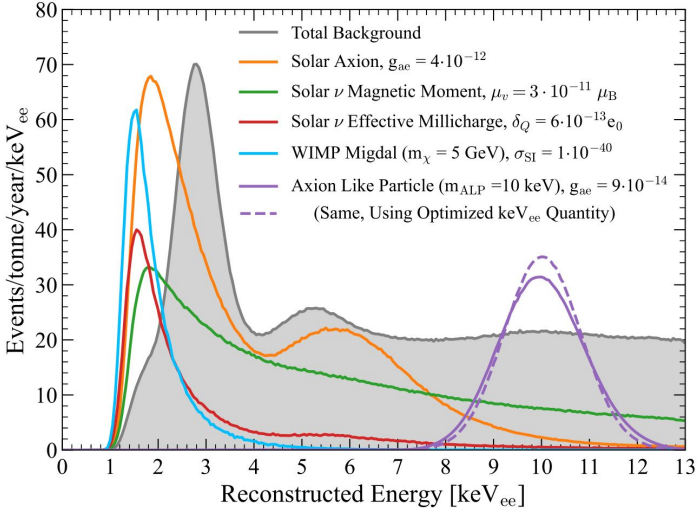
- ❏ EFT treats the WIMP-nucleon elastic scattering as a four-field interaction
- ❏ Linear combination of 15 operators contribute to the Lagrangian
- ❏ Describes a set of possible WIMP-nucleon interactions

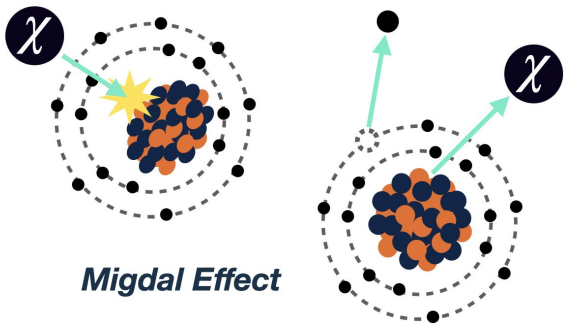
Low Energy Electron Recoil Signals

PhysRevD.108.072006

- Time dependent analysis of ER signals
  - Better sensitivity
  - Flat signal model vs decaying background.
- Wealth of potential signals to explore:
  - Neutrino Magnetic Moment and Millicharge
  - Solar Axions/ALPs and Hidden photons
  - Lower mass limits with the Migdal effect

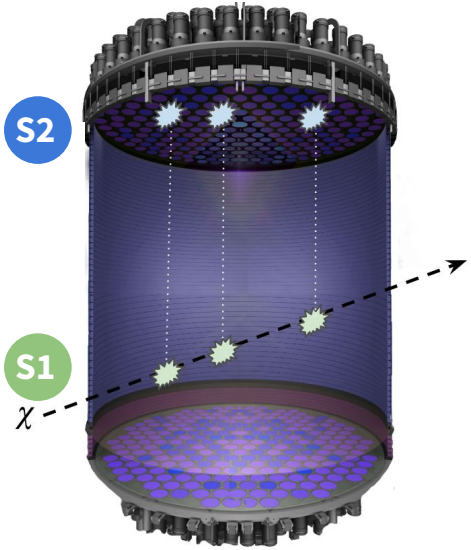


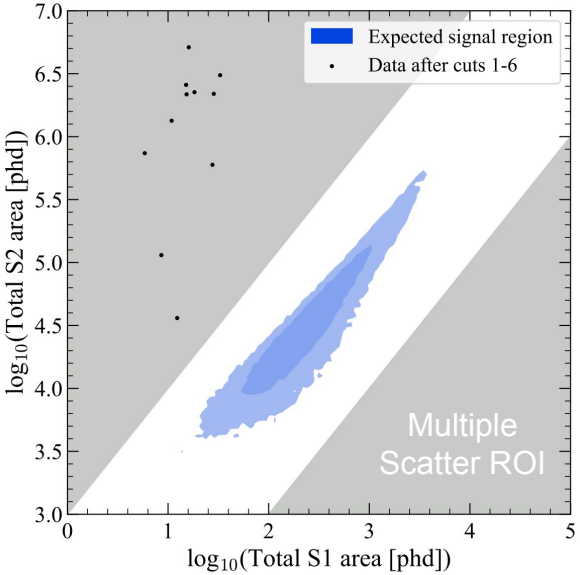


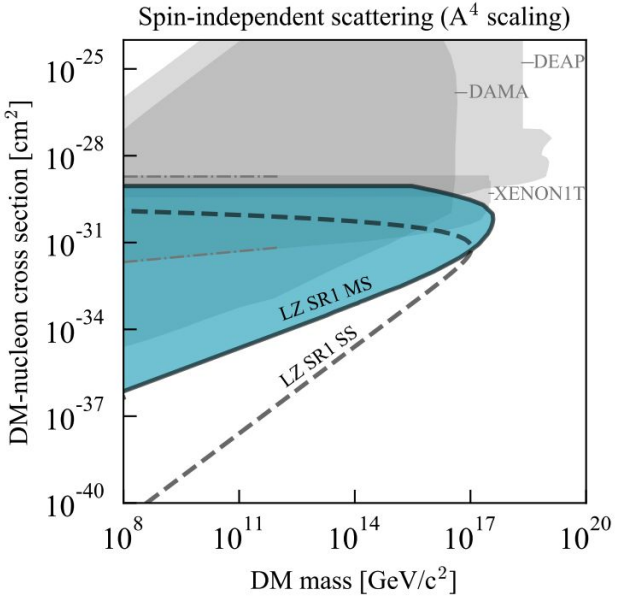


Ultraheavy Dark Matter

arXiv:2402.08865v1







- Multiply Interacting Massive particles (MIMPs)
- Signal: Time ordered multiple scatters along a linear track
- Reconstructed velocity 50-1200 km/s
  - Corresponds to ~μs between S1s
- Unique event topology, < 0.17 expect background events
  - Predominantly single scatter pile-up
- Maximum mass probed by LZ 3.9×10^{17} GeV/c²
- World leading sensitivity

Conclusions

Cutting edge physics:

- **World-leading spin-independent WIMP-nucleon cross-section limit** set using only 60 live days
- **Competitive searches** for physics in low energy electron recoils
- **Extended analysis** for many operators in the EFT high energy nuclear recoil searches
- **New parameter space excluded** by ultra heavy MIMP search

Future work:

- Data taking for further science searches!
- **XLZD** consortium working towards the ultimate xenon observatory

LZ talks at IOP:

- Calculation of Neutron Production in **(alpha, n) Reactions** - Piotr Krawczun - Poster Reception 1
- LZ **Outer Detector** - Sam Woodford - 10:15 Wed 10th (Session D)
- Characterising **Electric Fields** - Sparshita Dey - 11:00 Wed 10th (Session D)
- Multiple Scatter **Neutron Background Measurements** - Jo Orpwood - 11:15 Wed 10th (Session D)
- **Background from environment** for LXe dark matter experiments - Jemima Tranter - 11:30 Wed 10th (Session D)
- **Low energy electron recoil** searches within LZ - Riyat Harkirat - 14:15 Wed 10th (Session D)
- **Fast likelihood functions** for dark matter and rare event searches - Joshua Green - 14:30 Wed 10th (Session D)

Beyond LZ: XLZD Consortium

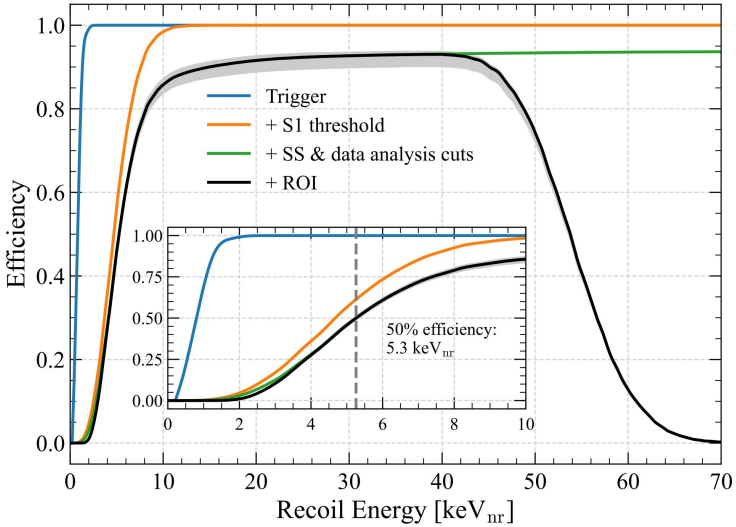
https://xlzd.org
J. Phys. G: Nucl. Part. Phys. 50 013001 (2023)

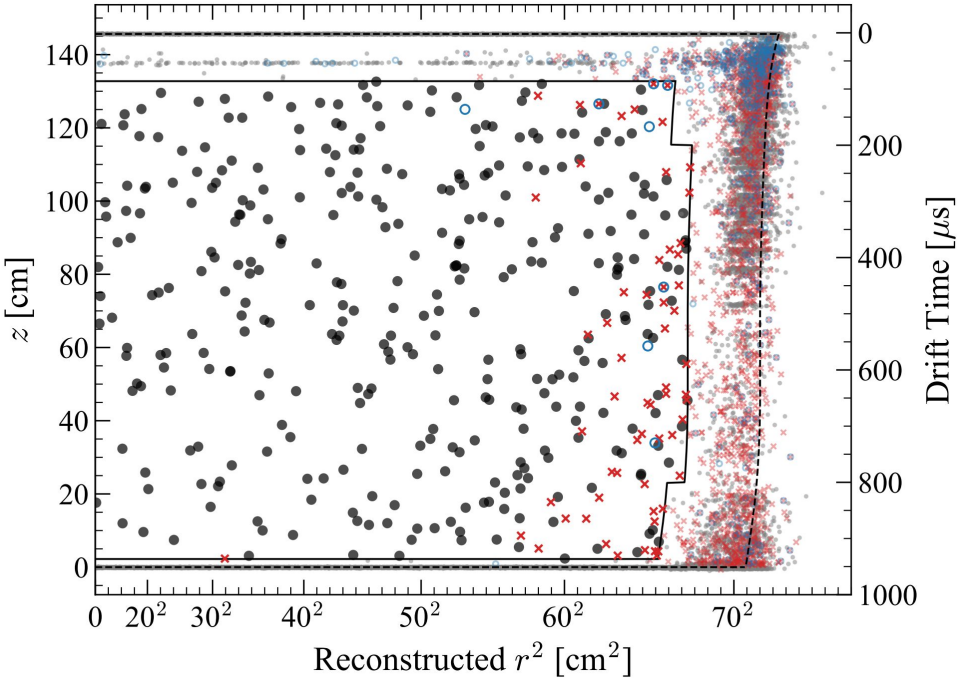
- **X**ENON, **LZ** and **D**ARWIN collaborations working towards a G3 xenon observatory
- WIMP sensitivity down to “neutrino fog”
- Plus other dark matter candidates, $0\nu\beta\beta$, atmospheric neutrinos

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





- Events passing all cuts
- Events outside Fiducial Volume
- Events vetoed by Skin
- Events vetoed by OD