First results from the WIMP dark matter search with the LZ experiment

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for the LZ Collaboration

TeVPA and direct dark matter search

- Atmospheric Cherenkov telescopes: ~TeV.
- PeV neutrinos: ~10^3 TeV.
- UHECR: up to 10^{20} eV = 10^8 TeV.
- GR excess from the GC: ~GeV -> 10^{-3} TeV.
- GR in MeV range: ~10^{-6} TeV.
- Direct dark matter searches: 1-10 keV -> down to 10^{-9} TeV.

LZ (LUX-ZEPLIN) Collaboration

37 institutions; 250 scientists, engineers, and technicians

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

- 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 & Technology
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Laboratory
- 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

US UK Portugal Korea Australia

Thanks to our sponsors and participating institutions!

US Department of Energy
Office of Science

Science and Technology Facilities Council

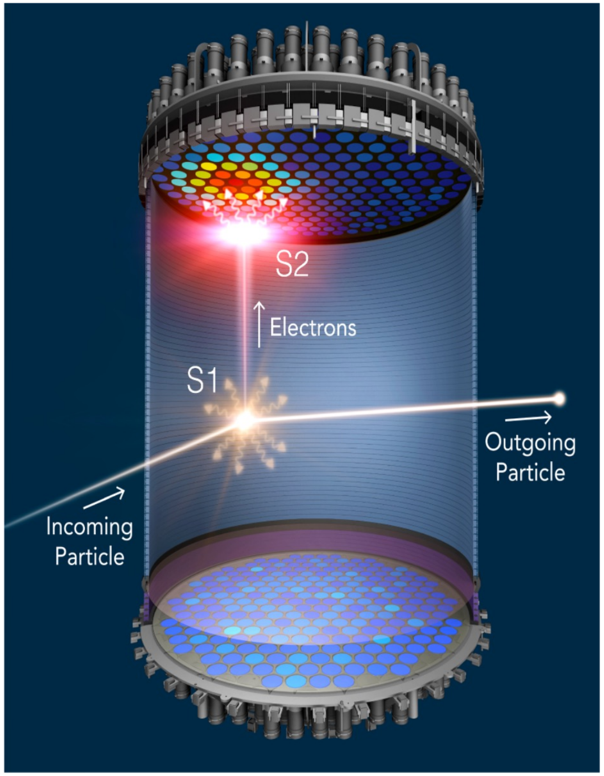
FCT Fundação para a Ciência e a Tecnologia

Sanford Underground Research Facility
South Dakota Science and Technology Authority

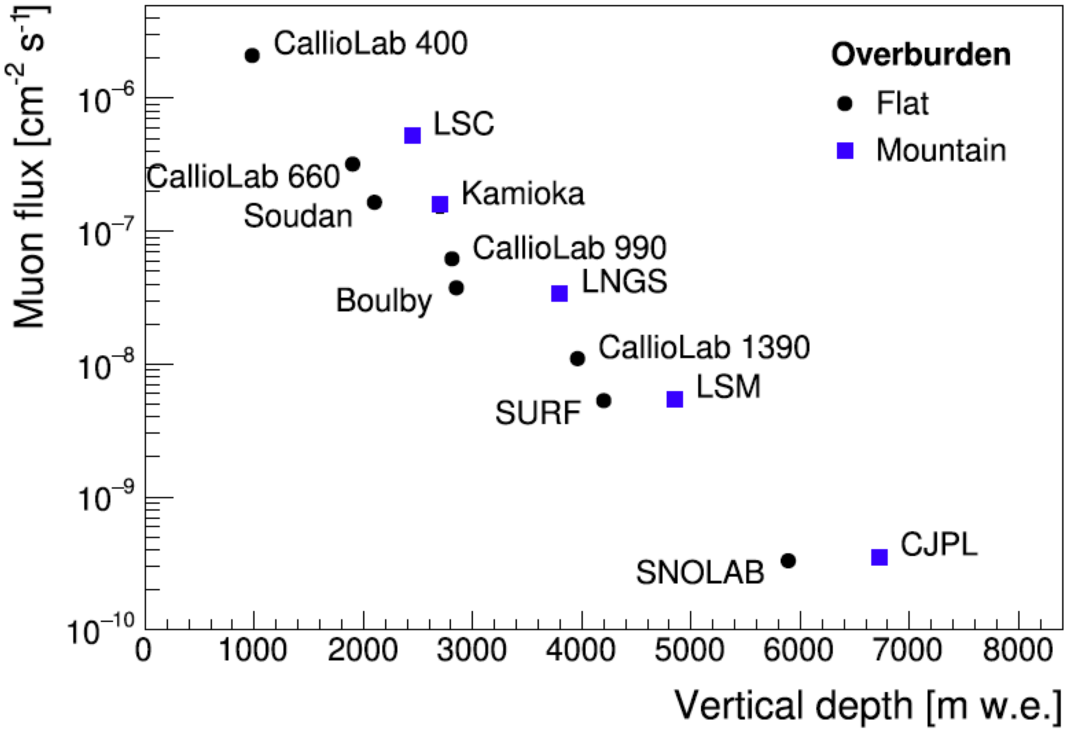
Institute for Basic Science

Detection principle in LXe

- Choice of LXe target and dual-phase technology:
  - Xenon – good scintillator
  - Dense → self-shielding and high mass within a limited volume.
  - Electric field partly prevents electron-ion recombination
  - primary scintillation S1
  - secondary electroluminescence in the gas S2
  - High atomic weight → A^2 enhancement of the cross-section for spin-independent interactions
- 3D imaging and fiducialisation
  - S1 - S2 time delay,
  - pattern of S2 light.
- Good discrimination between electron recoils (ERs) and nuclear recoils (NRs) – more on this later.



LZ location



- LZ location: Sanford Underground Research Facility (SURF), South Dakota, USA.
- About 4850 feet underground; ~4300 m w. e.
- Muon flux is about 6×10^{-9} cm^{-2} s^{-1}.

LZ detector design

NIMA, 953, 163047 (2020)

Titanium cryostat

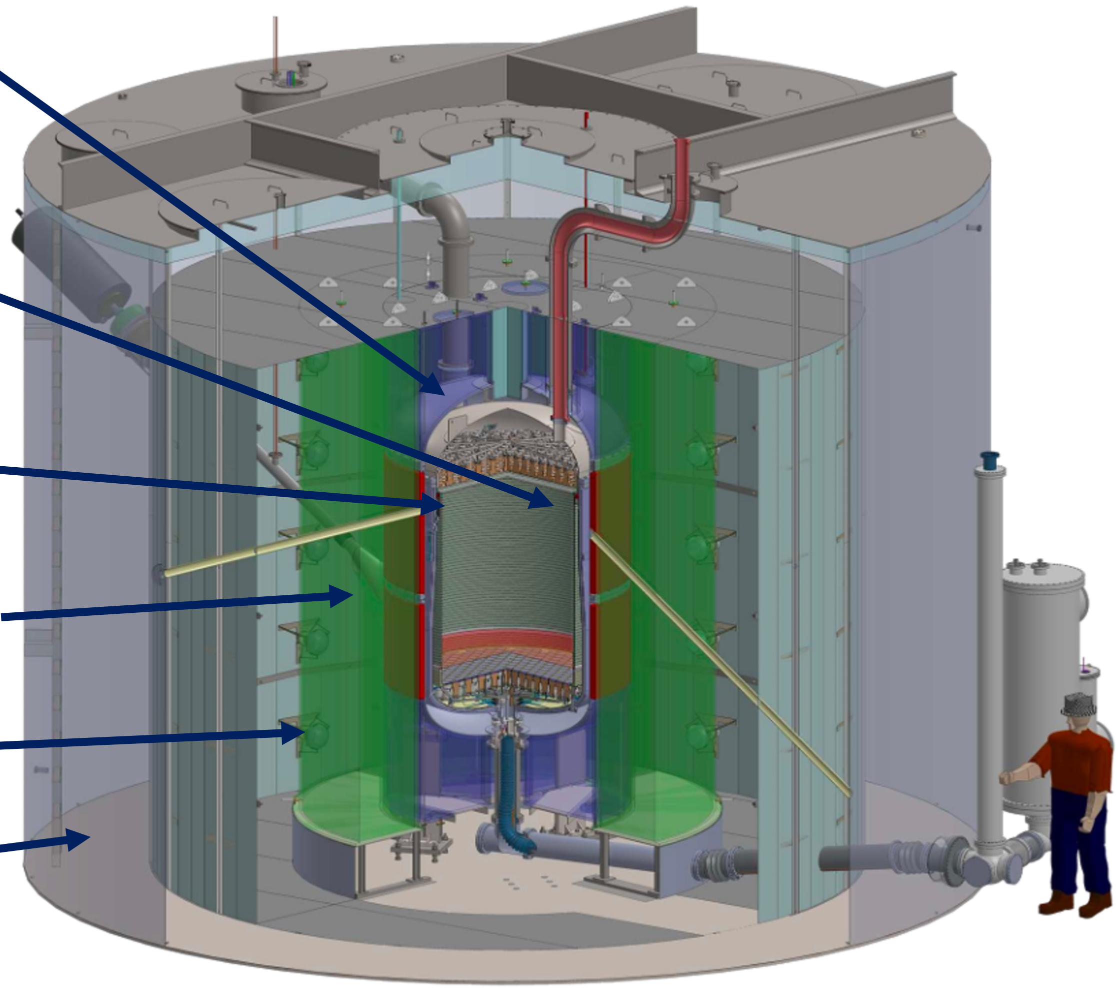
Liquid xenon (LXe)
time projection
chamber (TPC);
7 tonnes of LXe

LXe skin (veto)

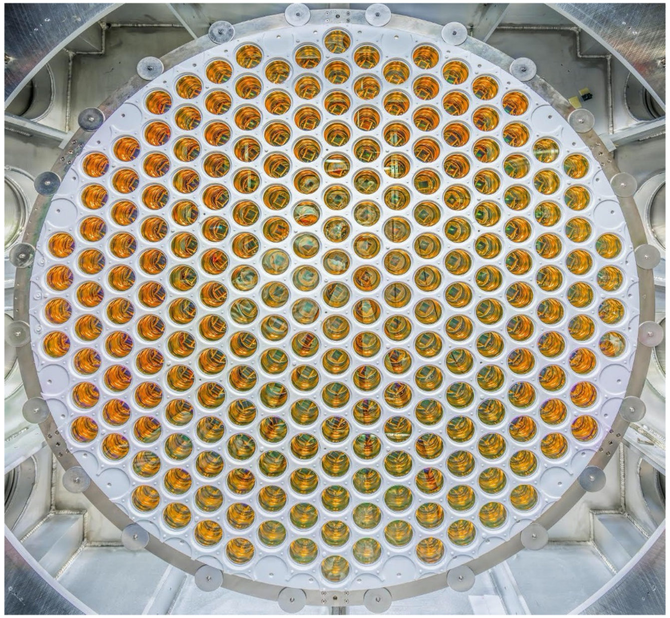
Outer detector, liquid scintillator

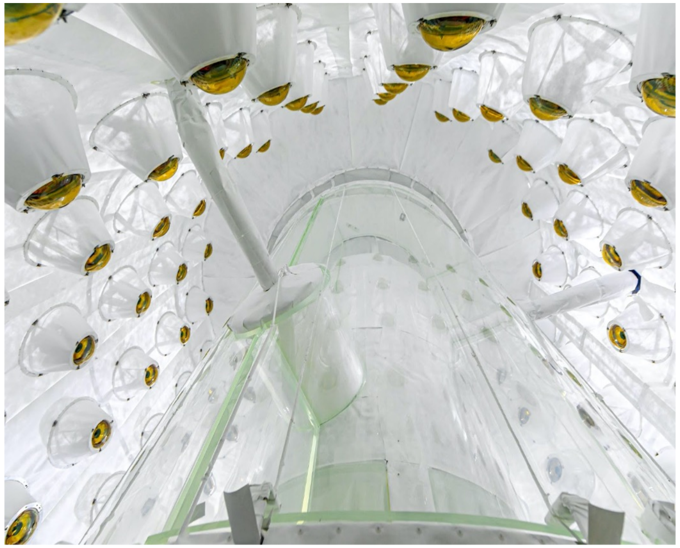
Outer detector PMTs

Water tank

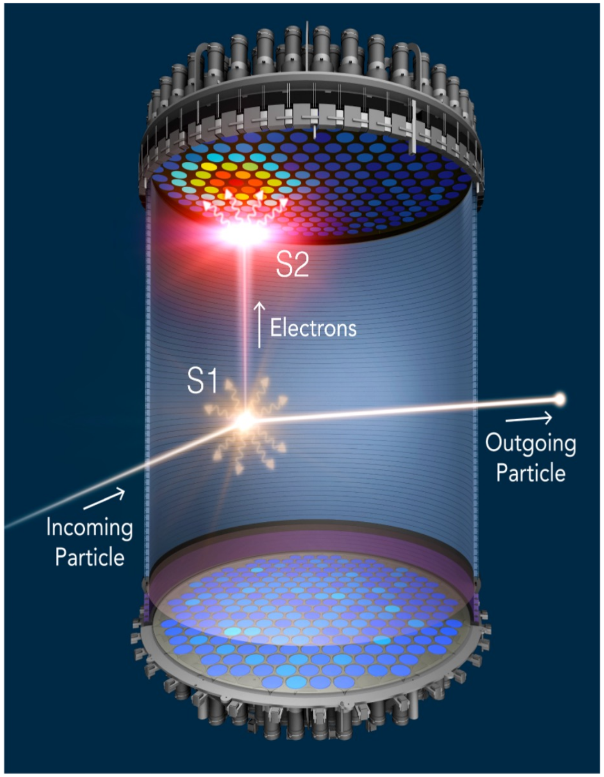


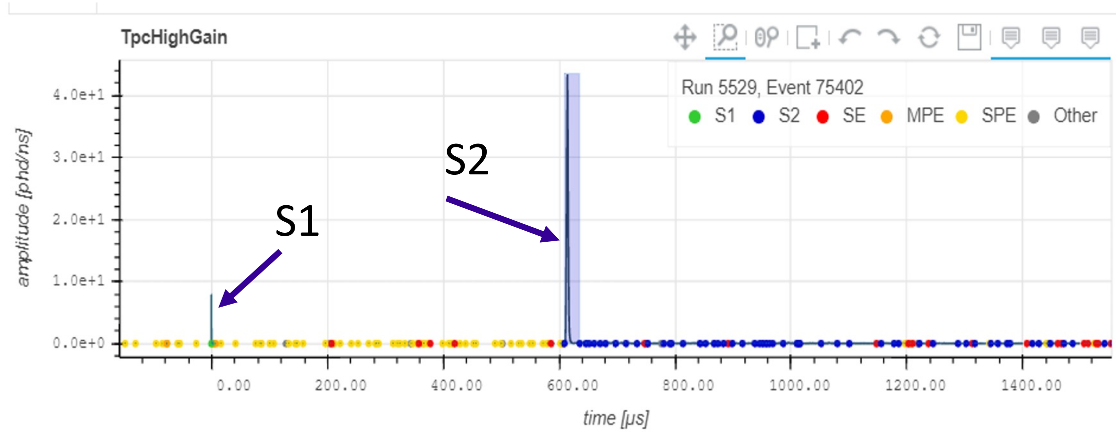
LZ realisation

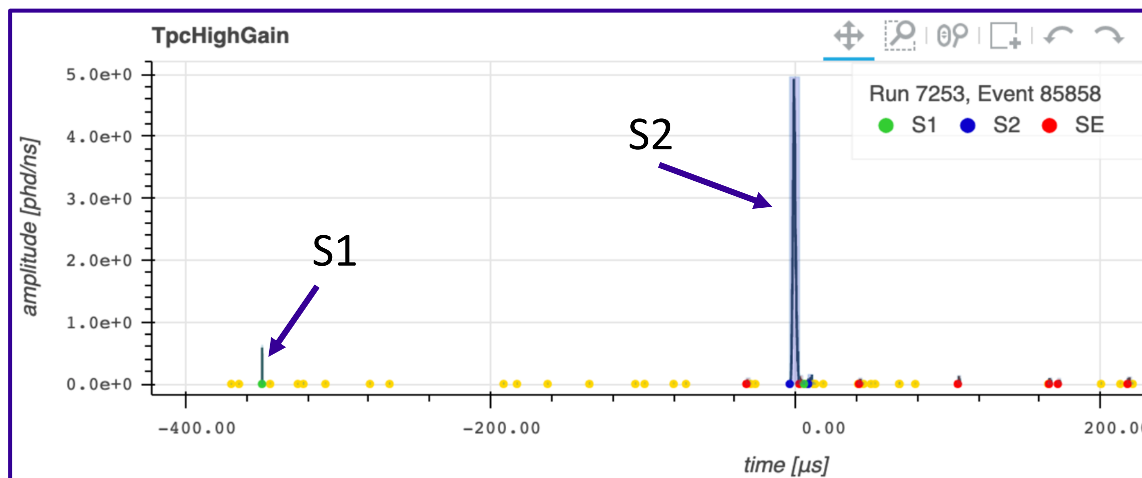




Example events in the LZ TPC

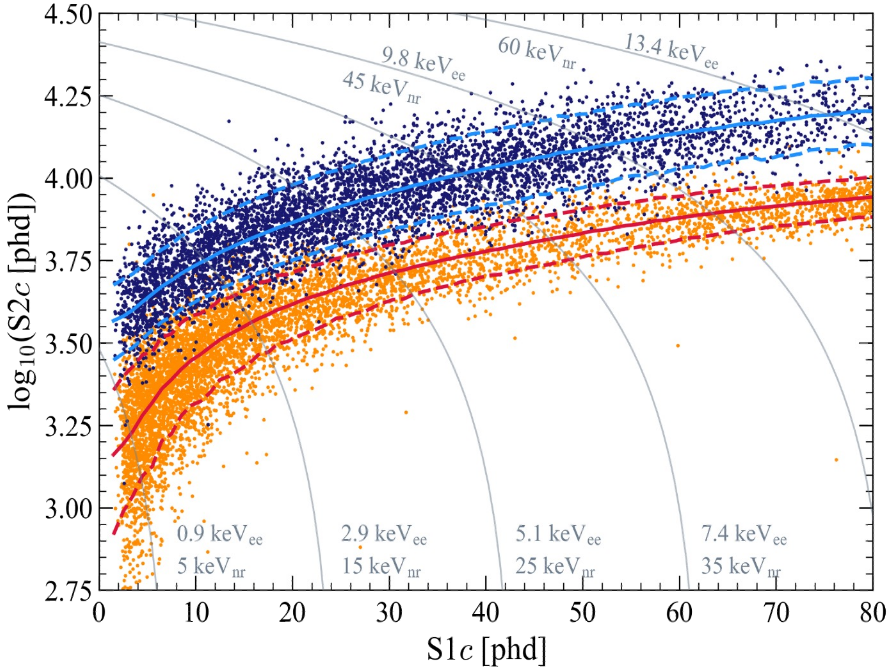






- Can trigger on S1 (top).
- Or on a much larger S2 (bottom).

Extensive calibration campaign



- Key principle of discrimination:
  - Difference between S2 pulses in ER and NR events for a fixed S1 pulse.
- CH_3T disperse source – βs from tritium decay ⟶ ERs (blue)
- DD generator – neutrons ⟶ NRs (orange)

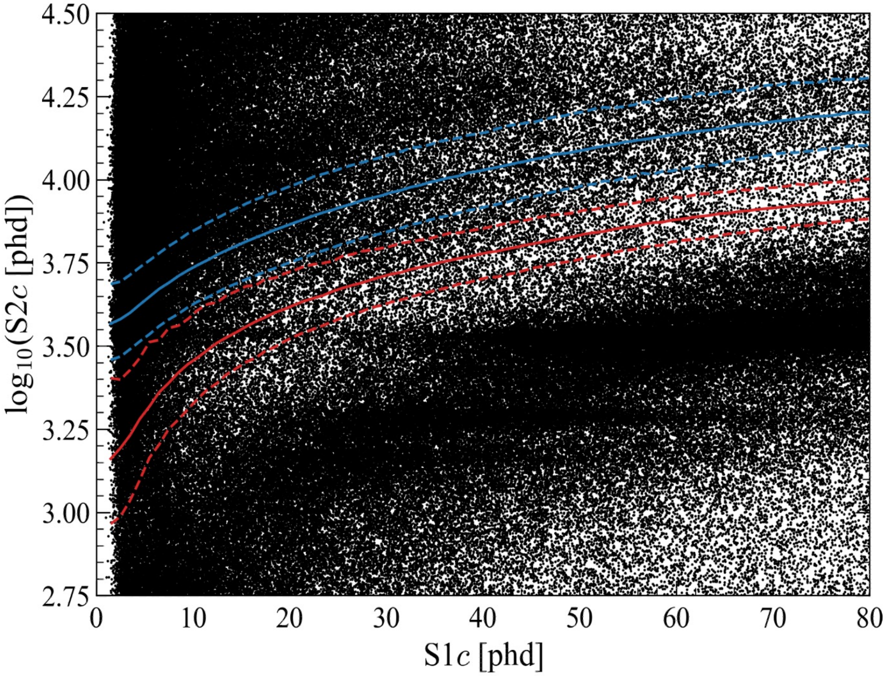
- Solid blue (red) lines: median of the ER (NR) simulated distributions.
- Dashed lines: 10 % and 90 % quantiles of the distributions.
- Thin grey lines: contours of constant electron-equivalent energy (keVee) and nuclear recoil energy (keVnr).
- Other beta, gamma, alpha and neutron calibration sources: ^{220}Rn, ^{131m}Xe, ^{83m}Kr, AmLi …

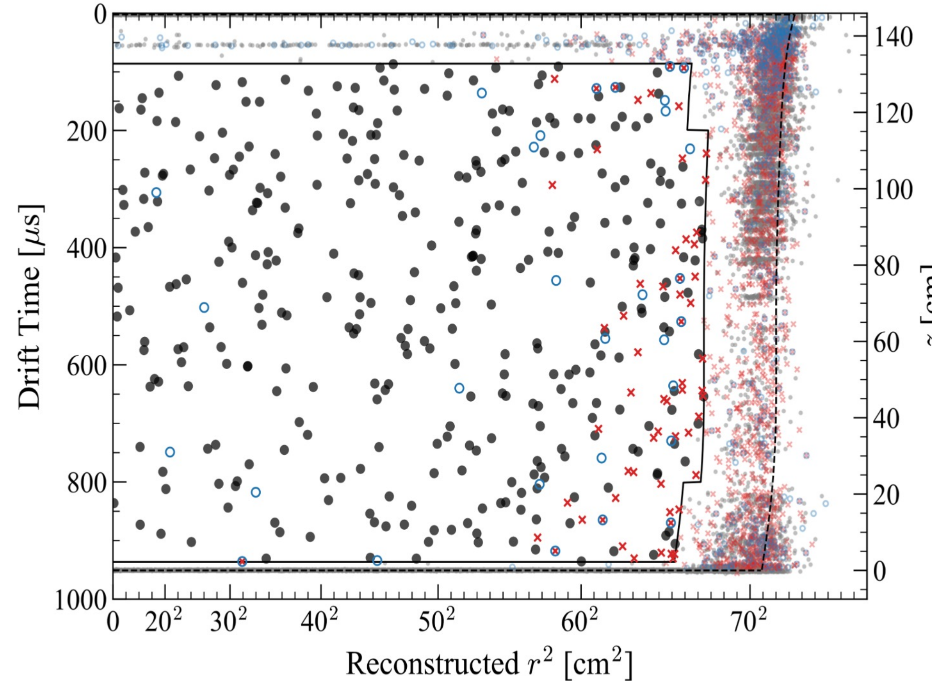
PRL, 131, 041002 (2023); special paper on calibration in preparation.

Event selection and background suppression

- S1 pulse: 3-fold coincidence between 3 PMTs.
- Only single-scatter events. Events with multiple S2 pulses are removed (WIMP cannot scatter twice).
- Pulses in the TPC in coincidence with the outer detector (OD) or skin are removed (definitely a background).
- Select events in the fiducial volume (FV).
- Look at low energies (more on this later); select events in ROI: S1*c* < 80 phd.

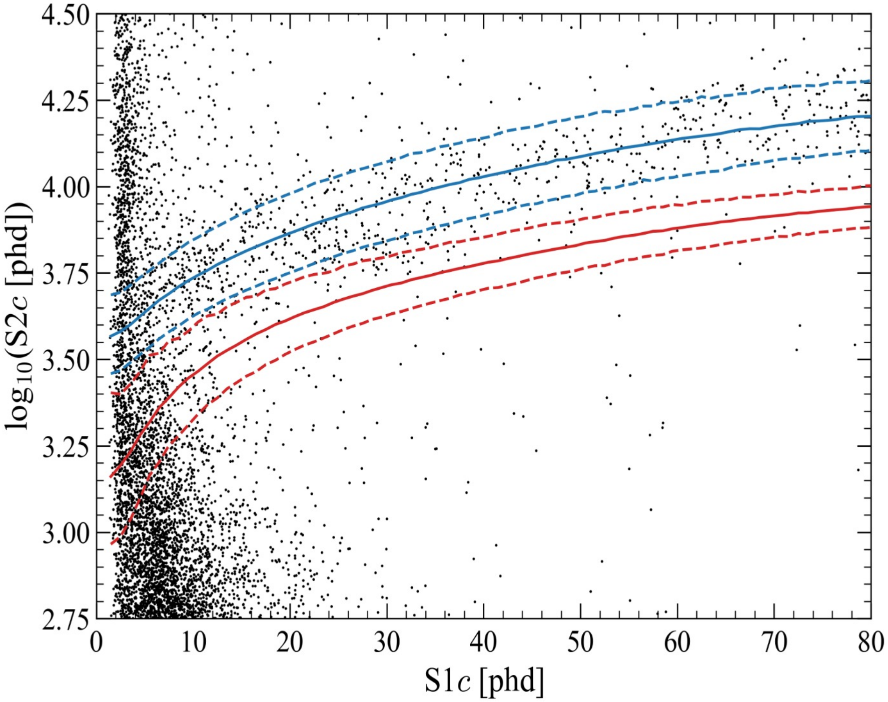
Event selection (cuts)

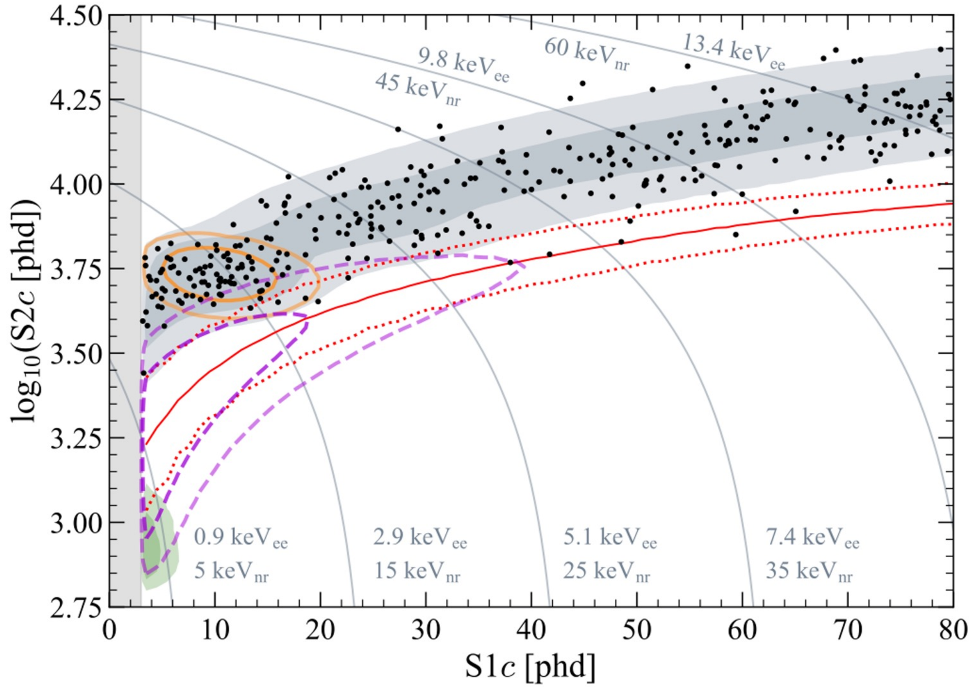




- Start with the left plot. All single-scatter events before any other cut.
- Most events are outside the FV (5.5 ± 0.2 tonnes) – right plot. This is expected from the background from detector components (mainly alphas and betas from the surfaces).
- Grey points: events passing all cuts except for FD.
- Blue circle: events failing OD tag veto.
- Red crosses: events failing LXe skin veto cut (mostly ^{127}Xe).
- Black points: events passing all cuts.

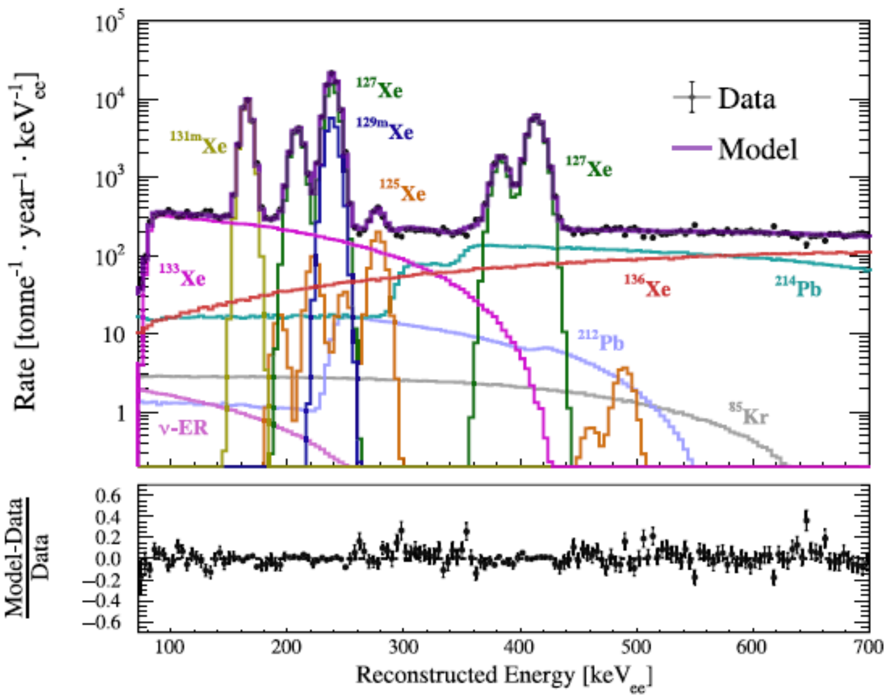
Event selection (cuts)

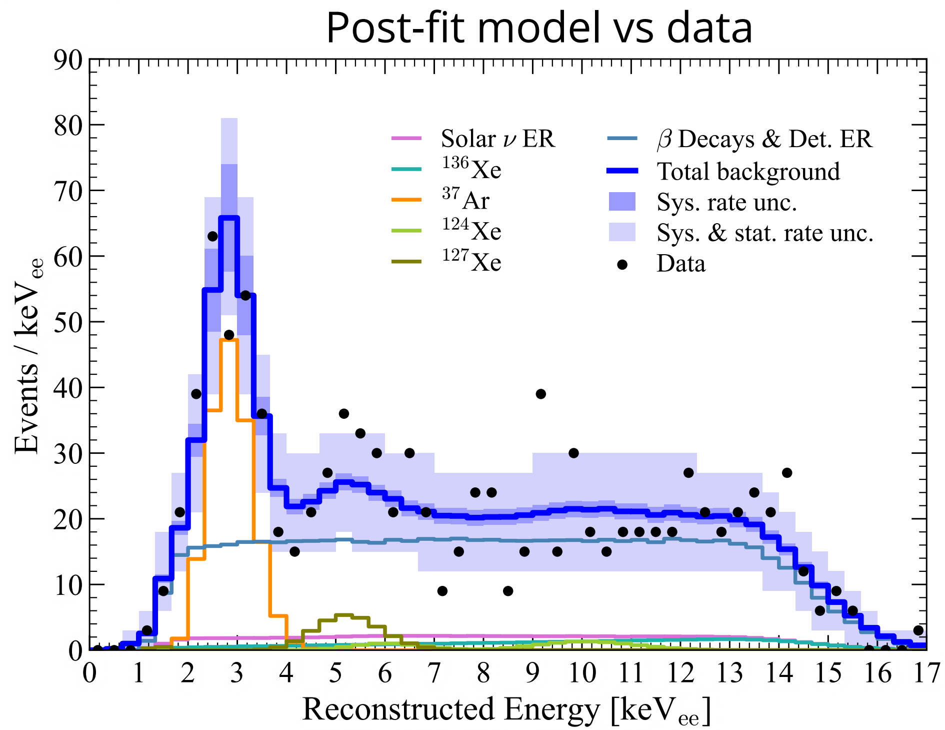




- After fiducialisation – left plot.
- Remove accidental coincidences – right plot.
- Data: 335 events in 60 ± 1 days of live time and 5.5 tonne fiducial mass.
- Orange contours: ^{37}Ar at 1σ and 2σ.
- Pink dashed contours: signal from 30 GeV/c^2 WIMPs 1σ and 2σ.
- No excess over expected background.

Energy spectra





- Spectra of energy depositions in the LXe TPC: extended energy range – left; ROI for WIMP search – right.
- Dark blue: model (systematic) uncertainties.
- Light blue: model and statistical uncertainties.

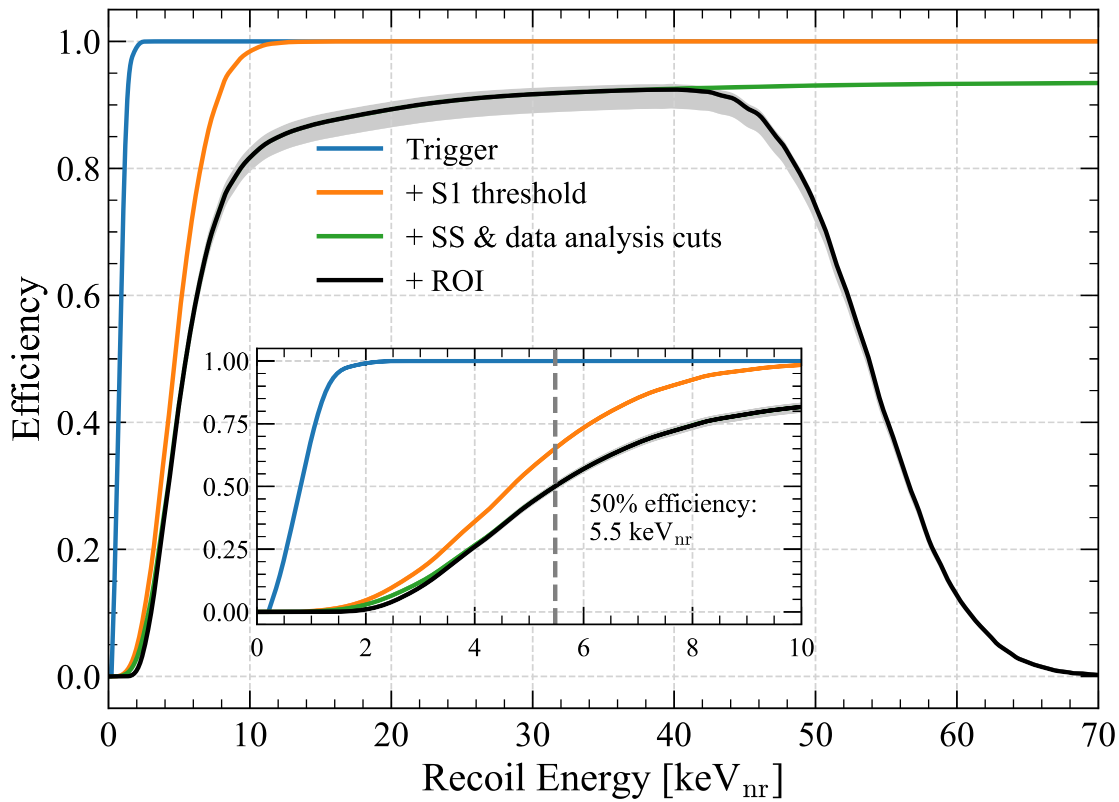
Phys. Rev. D 108, 012010 (2023)

Fit to the data

Source	Expected Events	Fit Result
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

- Events from various sources in 60 days × 5.5 t exposure.
- Column 2: expectations with uncertainties; uncertainties are used to constrain the fit.
- Column 3: fit to the data.
- Measured: 335 events in the ROI.
- No excess over background expectation.

Efficiency before and after analysis cuts

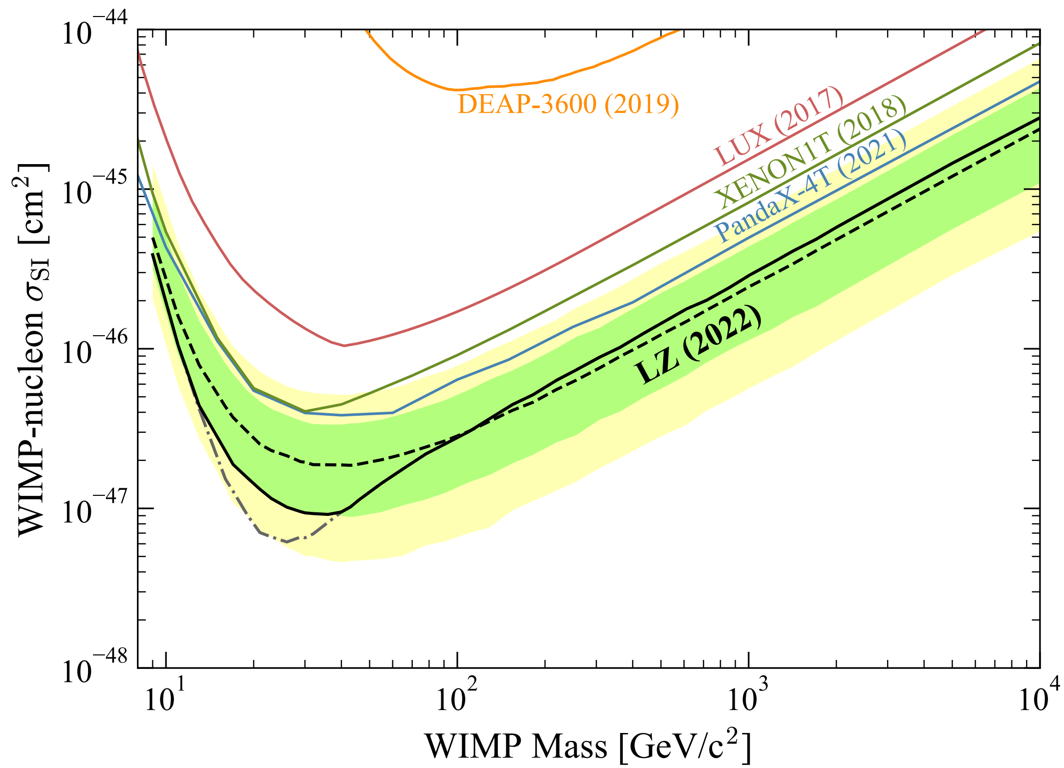


- Efficiencies after various cuts.
- 50% efficiency after cuts is achieved for 5.5 keVnr events.
- Input to the profile likelihood analysis together with the data and model.

Results: SI limits

- The 90% confidence limit (solid black curve) on the spin-independent WIMP cross-section vs WIMP mass.
- Minimum exclusion on spin-independent WIMP-nucleon cross-section of 9.2×10^{-48} cm^2 at 36 GeV.
- Dashed: median expected sensitivity.
- Green and yellow bands: 1σ and 2σ sensitivity bands.
- The grey dash-dotted line: limit before applying the power constraint.
- Some other limits are included (see also recent XENONnT result in PRL, 131, 041003 (2023)).

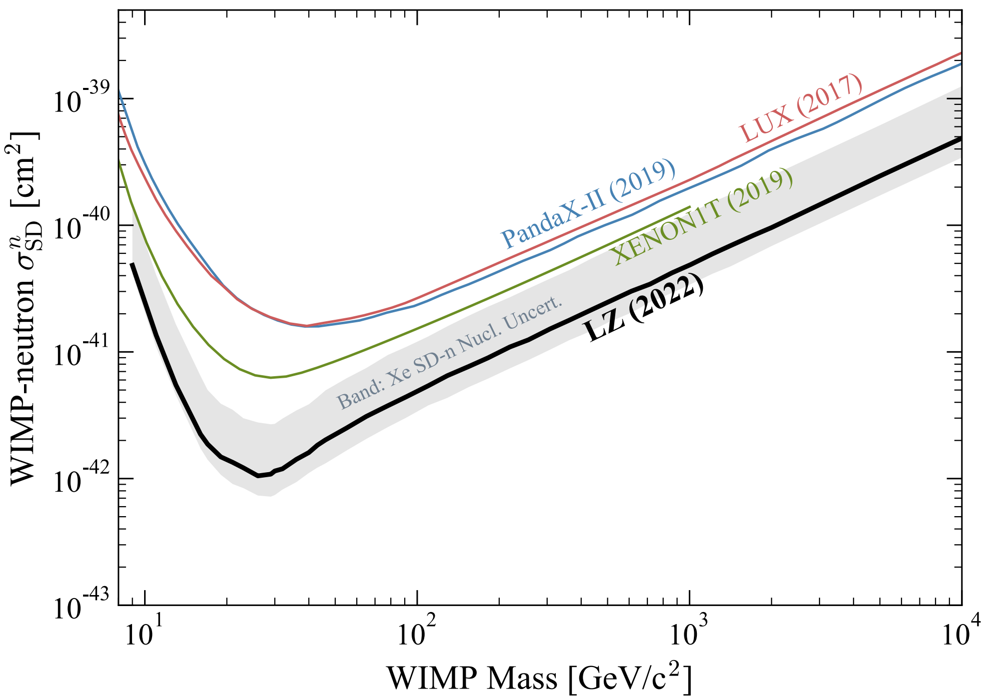
PRL, 131, 041002 (2023)



Results: SD limits

- The 90% confidence limit (black curve) on spin-dependent WIMP-neutron cross-section (Xe has two odd-neutron isotopes).
- Grey shaded area: uncertainty bands from xenon nuclear correction factors.
- Also limits on new physics with low-energy ERs: solar axions, solar neutrino magnetic moment etc, **arXiv:2307.15753 [hep-ex]**.
- More to come: Dark matter in EFT, neutrinoless double-beta decay, rare decays of xenon isotopes etc.

PRL, 131, 041002 (2023)

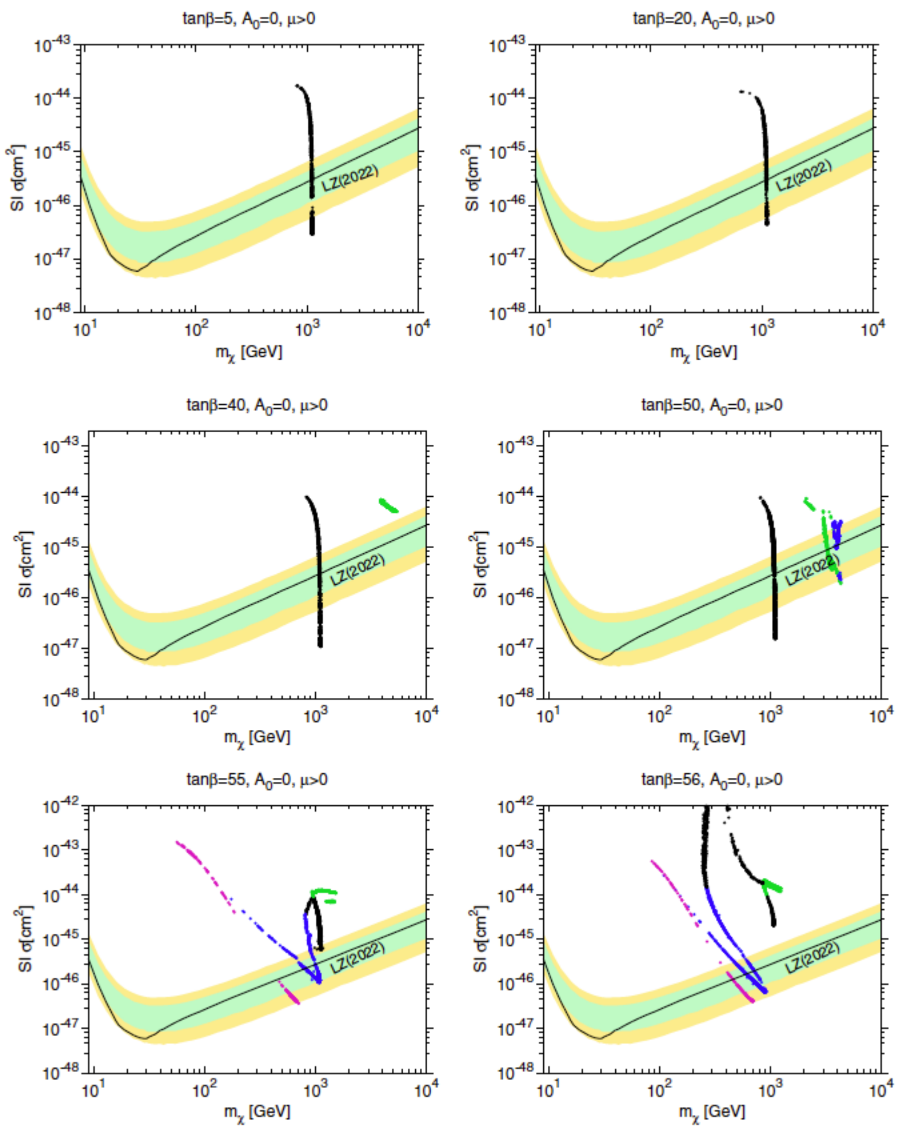


Summary

- LZ experiment has been built and is operating according to design specifications.
  - Excellent performance during engineering, calibration and the first science runs.
  - World-best limits on spin-independent and spin-dependent (WIMP-neutron) cross-sections for a large range of WIMP masses.
  - Limits on BSM physics with low-energy ERs: solar axions etc.
  - Currently the most-sensitive WIMP search experiment in the world for a large range of WIMP masses.
- Many more to come:
  - Dark matter in EFT,
  - $0\nu\beta\beta$ of ^{136}Xe,
  - Extension to low-mass WIMPs,
  - Rare decays in SM.
  - … (see talk by R. Smith on MIUHDM/MIMP in LZ, Thursday, 2 pm, alpha room).
- Following our successful SR1 and subsequent extensive calibrations, LZ is now taking data in a ‘discovery mode’, exploring completely unexplored regions of parameter space towards first discovery of WIMPs.

Summary

- Ellis et al. Eur. Phys. J. C (2023), 83: 246.
- Example spin-independent WIMP-nucleon cross-sections calculated for a set of CMSSM parameters.
- Solid curve and shaded areas: LZ limit (unconstrained) and sensitivity bands.
- Expected LZ sensitivity after 1000 days of live time: 1.4×10^{-48} cm^2 for about 40 GeV/c^2 WIMP mass (**PRD101, 052002 (2020)**).
- Probing untested region of parameter space in CMSSM.



Future of xenon technology

- Joint efforts from XENONnT, LZ and DARWIN to build a multi-purpose xenon-based observatory to search for rare events
  - WIMP search in a wide range of masses and models down to neutrino fog
  - Neutrinoless double-beta decay of ^{136}Xe
  - Other SM and BSM phenomena: rare decays in SM, axions etc.
- Use a well-tested dual-phase xenon technology and veto systems.
- 40-80 tonnes of active xenon.
- XLZD white paper: **J. Phys. G 50, 013001 (2023)**.