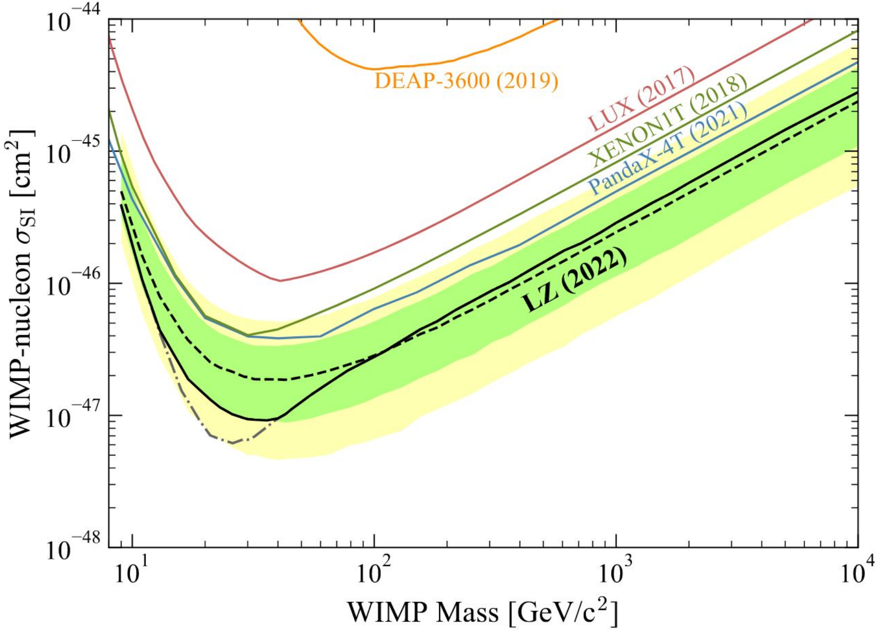
Update on the LUX-ZEPLIN experiment's search for dark matter

IDM @L'Aquila
July 8th, 2024
Ibles Olcina

Outline



LZ upper limit on the spin-independent WIMP-nucleon cross section from 2022

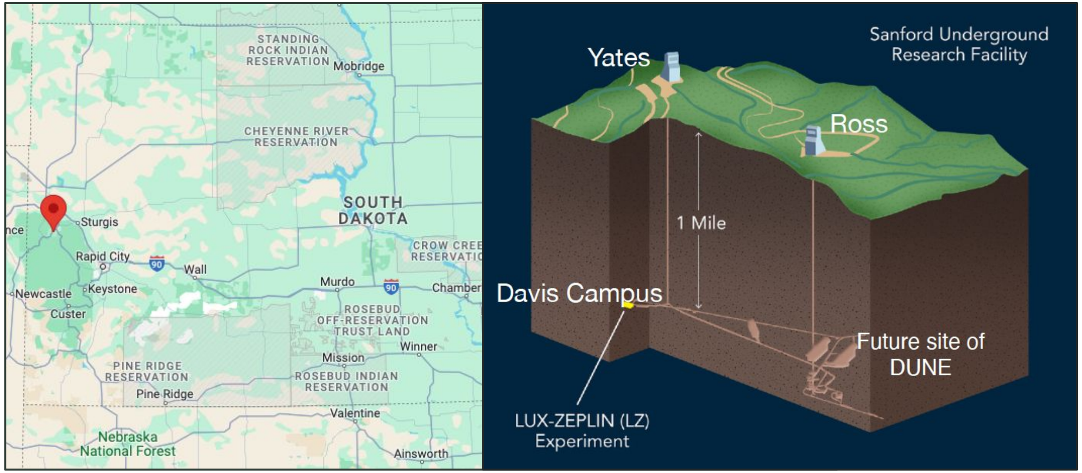
- How we got here
- What are we doing
- What's in the horizon

How we got here

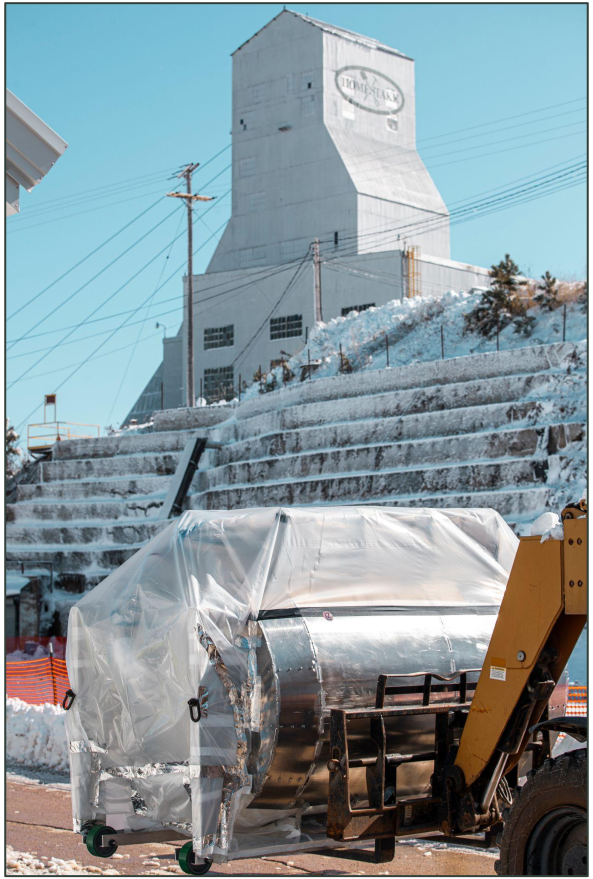
The LZ experiment

Searching for dark matter underground

- Located at the Sanford Underground Research Facility (SURF), in South Dakota
- 1 mile deep (4.3 km.w.e)



SURF is located in Lead, SD. LZ is in the Davis Campus, 4850 feet underground.



Transport of the TPC underground from the surface laboratory

Largest Xe TPC in the world

- 1.5 m tall and wide
- 7 tonnes of liquid xenon
- 494 x 3'' PMTs distributed in two arrays
- 4 wire mesh electrodes:
  - Anode
  - Gate
  - Cathode
  - Bottom
- Field cage composed of titanium rings embedded in teflon (PTFE) panels

Electron extraction field region

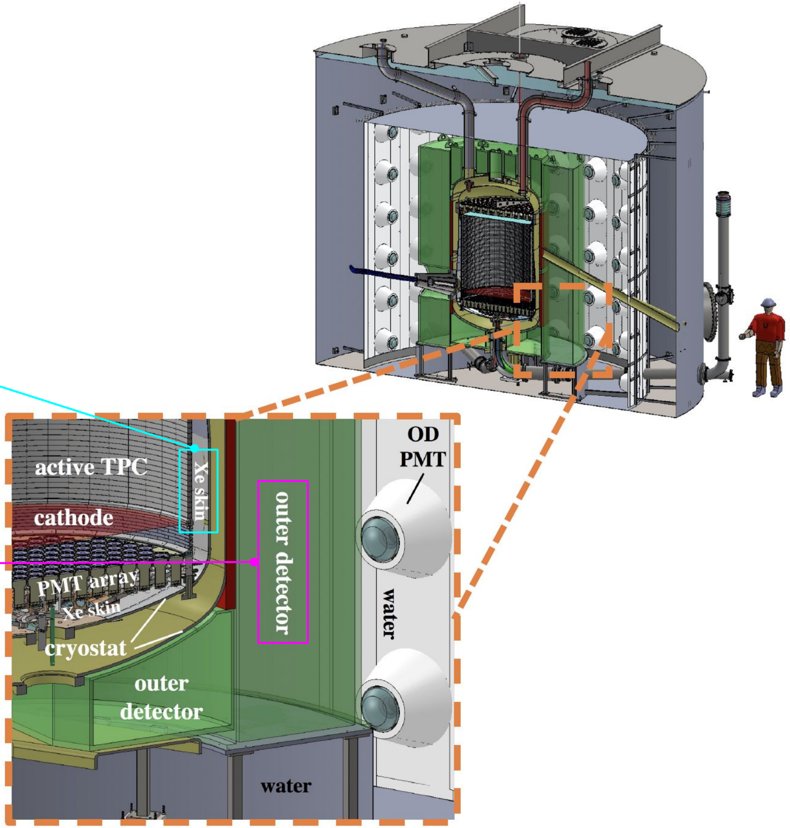
Electron drift field region

Reverse field region

Multi-detector system

- Integrated veto system to reject effectively multi-site background events:
  - **Xe Skin**
    - 2 tonnes of liquid Xe
    - Anti-coincidence detector for γ-rays
    - Optically isolated from TPC
  - **Outer detector (OD)**
    - 17 tonnes of Gd-loaded liquid scintillator in acrylic vessels
    - Anti-coincidence detector for γ-rays and neutrons

See talk by A. Uson
(July 8th, Parallel 1)



[NIM A, 163047 (2019)]

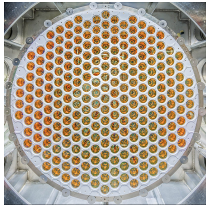
Background mitigation

- Rock overburden
  - Muons reduced by ~10^6 at the 4850 cavern in SURF
- Material selection
  - Extensive material screening campaign to select radiopure materials [Eur.Phys.J.C 80 11, 1044], [Astropart. Phys. 96, 1]
- Strict cleanliness protocol
  - TPC assembled in Rn-reduced cleanroom (class 1000)
  - Extensive dust control underground
- Xenon purification
  - Off-site Xe distillation for Kr removal
  - In-line Rn removal system

Dust inspection of the TPC with UV light

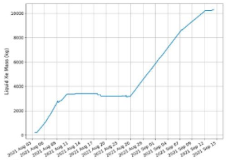
Distillation columns at SLAC (US)

Timeline



PMTs arrive

TPC assembled and moved underground

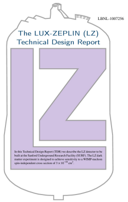


Start of Xe fill

First science data!

2017 2018 2019 2020 2021 2022 2023

TDR release

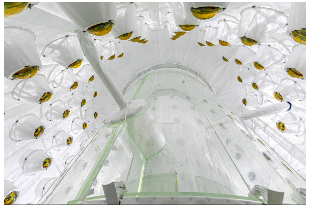


Cryostats arrive

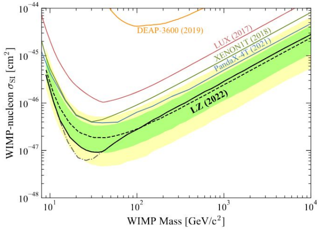
Grids complete

Sealed up

OD fill



First WIMP search results announced



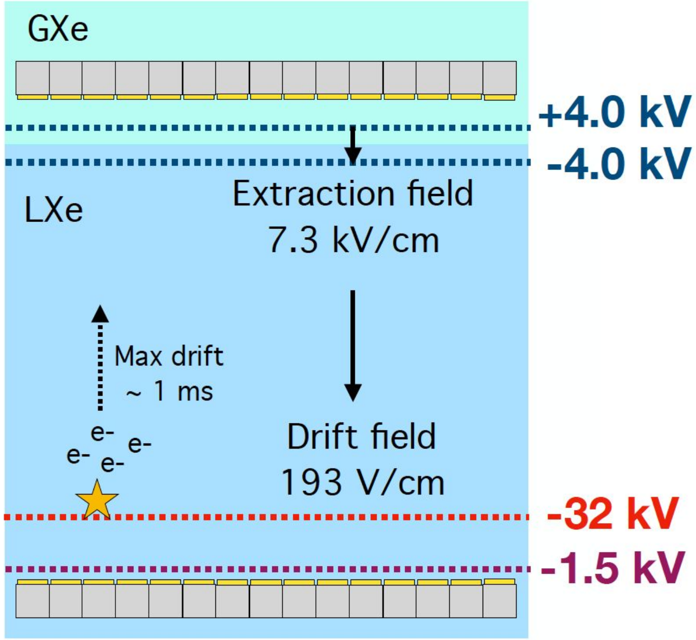
First science run

Run details

- Data collected from end of 2021 to mid-2022
- WIMP search livetime of 60 days
- Engineering run
    - Demonstrate physics capability of the detector systems
    - Data not blinded or salted (analysis cuts tuned on sideband data)

Stable detector

- >97% of PMTs stayed operational
- Stable liquid temperature and gas pressure
- Uniform drift field (193 V/cm)
- High electron lifetime (> 5 ms)

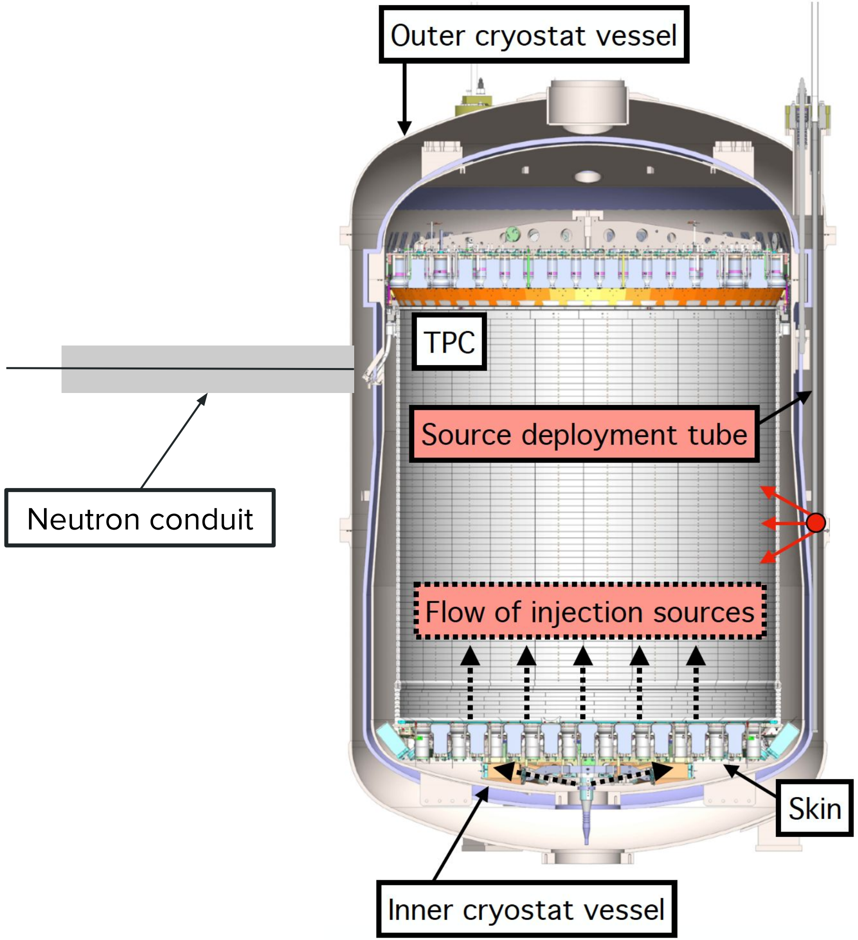


A uniform drift field of 193 V/cm was maintained during the entire SR1 period

Calibrations

A full suite of calibration sources was used to calibrate the detector response of the TPC, Skin, and OD

- ER calibrations
  - Injection sources: CH3T (β; 18.6 keV endpoint), ^{83m}Kr (γ; 32.1 and 9.4 keV), ^{220}Rn (α, β, γ; various energies)
  - Sealed sources (e.g. ^{54}Mn, ^{228}Th) deployed via three tubes around the TPC
- NR calibrations
  - AmLi source: deployed via same three tubes around the TPC
  - YBe source: deployed to the top of the cryostat vessel
  - DD neutron generator: delivered down a ~3-meter conduit through the water tank

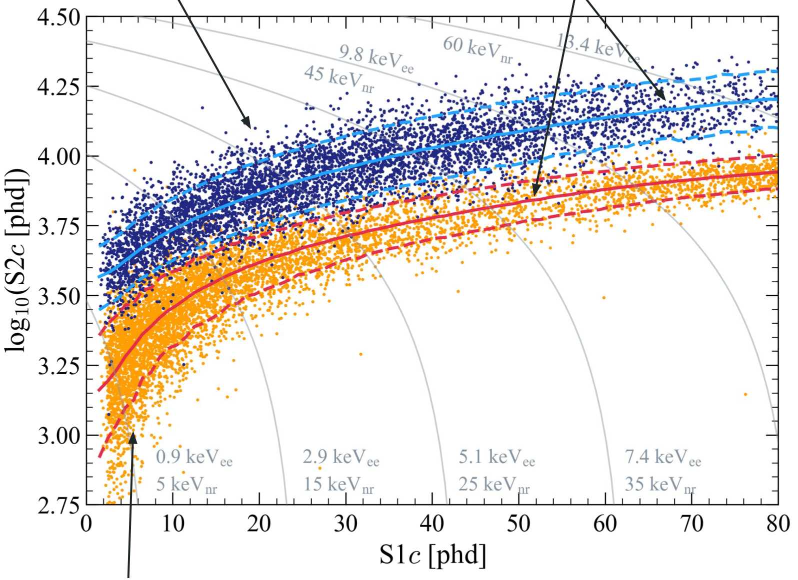


Detector model

- *NEST-based electron recoil model tuned to tritium data (CH3T), then propagated to nuclear recoil model and verified with DD data.
- Detector parameters:
  - Light gain of g1 = 0.114 ± 0.002 phd/ph
  - Charge gain of g2 = 47.1 ± 1.1 phd/e-
  - Single electron size = 58.5 phd
  - 99.9% discrimination below the NR median
- A header file with the LZ tuned detector is available for public use [NEST GitHub project]

Tritium calibration events (blue)

ER and NR bands as predicted by the LZ NEST model



DD calibration events (orange)

[PhysRevLett.131.041002]

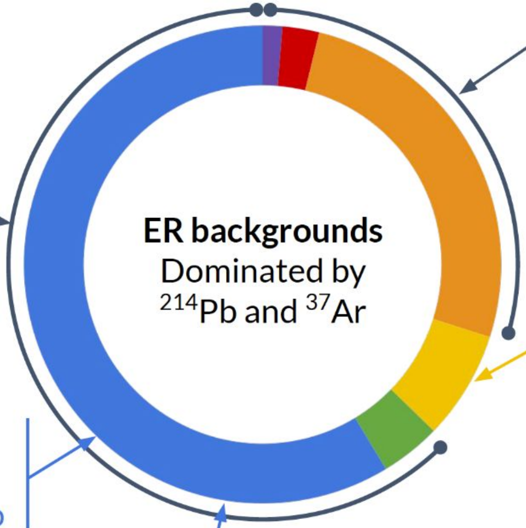
*[NEST website]

Background model

Broad range due to large nuclear model uncertainties on cosmic-ray-induced spallation [Phys. Rev. D 105, 082004]

Total expected **ER** counts in ROI in first run: **276** + [0, 291] from ^{37}Ar

Total expected **NR** counts in ROI in first run: **0.15**



Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

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

Solar neutrinos (ER)
- pp + ^{7}Be + ^{13}N

Includes γ-emitters in detector materials
- ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

Flat-spectrum (in ROI) ERs

NR backgrounds:
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

The accidentals background

- Caused by uncorrelated S1 and S2 pulses occurring within a physical drift time
  - Challenging to distinguish from valid single scatters
- Unphysical Drift Time (UDT) events serve as a proxy to model these events
  - Limited by statistics!
- We followed a data-driven approach to build the accidentals background model
  - Combining two half-events at the waveform level
  - Treated in the same way as real data

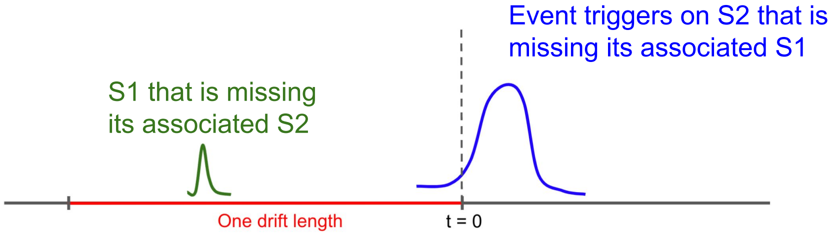
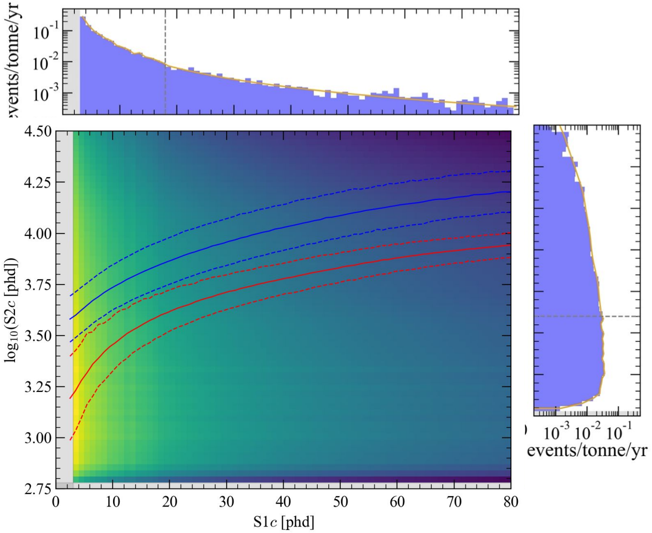
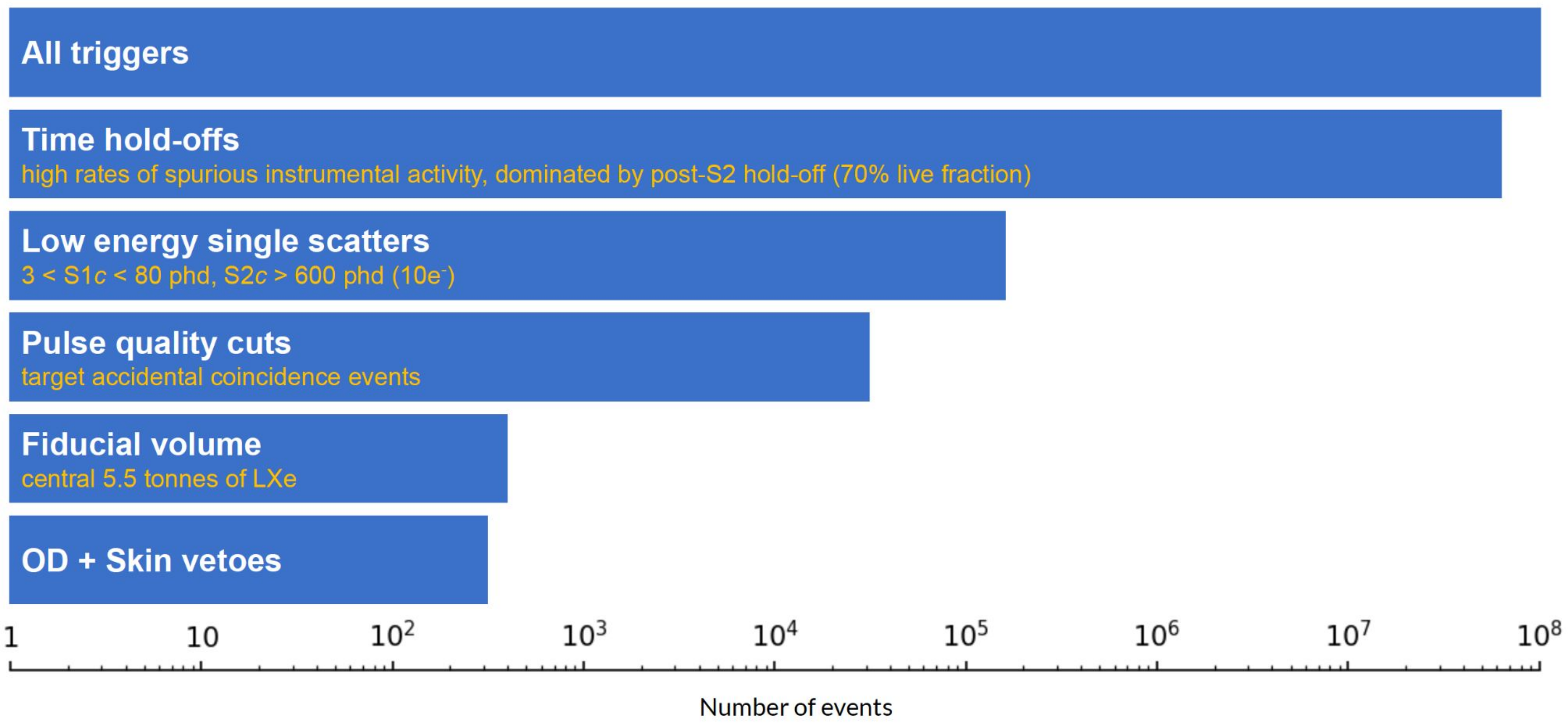


Diagram of an accidental event



Accidentals PDF after smoothing

Data selection

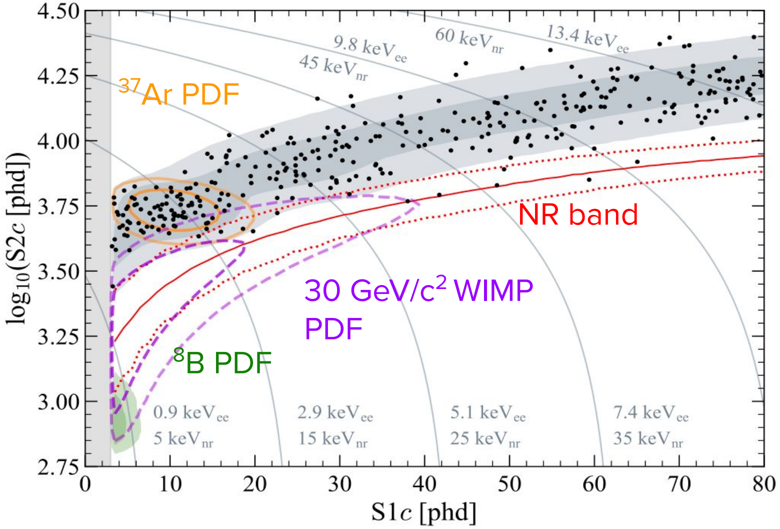


Results: best fit

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

[PhysRevLett.131.041002]

ER background model
(1- and 2-σ bands)



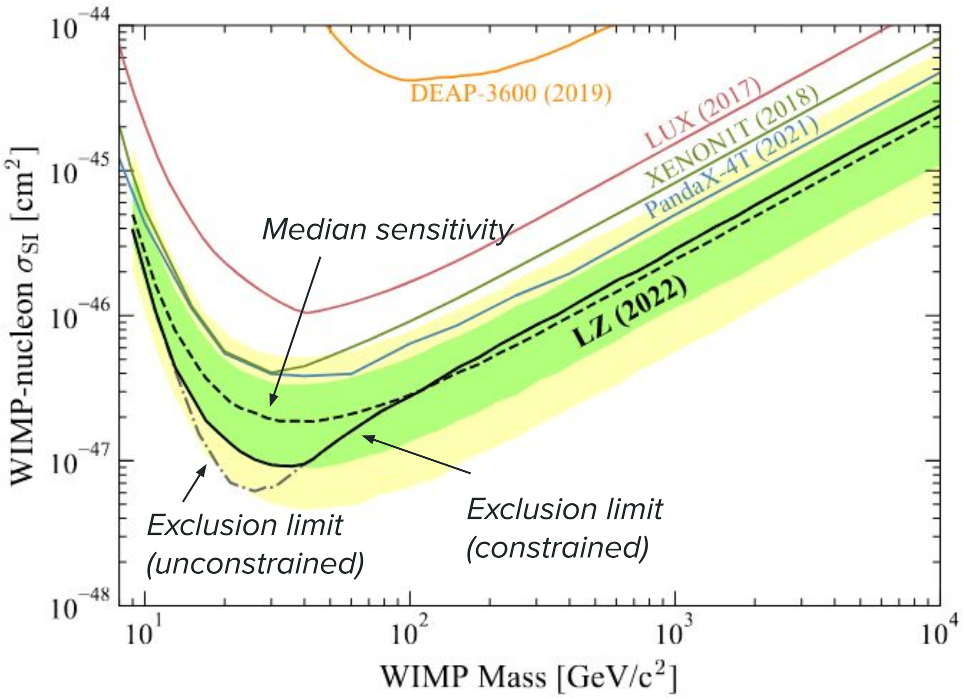
335 events remain after applying all data analysis cuts for an exposure of 60 livedays and 5.5 tonne fiducial volume

A best-fit value compatible with 0 events is observed at all WIMP masses

Results: upper limits

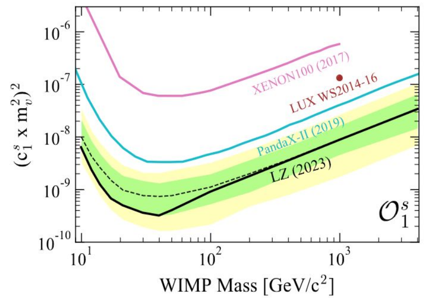
Spin-independent WIMP-nucleon scattering

- 90% CL upper limit of 9.2x10^{-48} cm^2 at 36 GeV/c^2 WIMP mass
- Frequentist, two-sided, profile likelihood ratio (PLR) test statistic
- Power constrained at the -1 sigma band
  - Following conventions from the community white paper
    [Eur. Phys. J. C 81, 907]

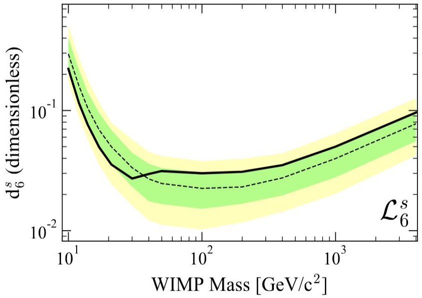


[PhysRevLett.131.041002]

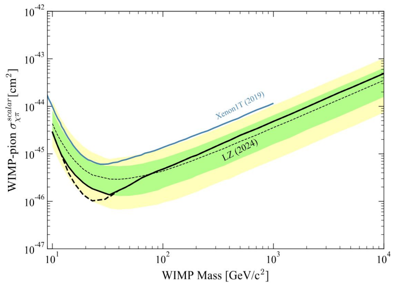
Other searches with the first science dataset



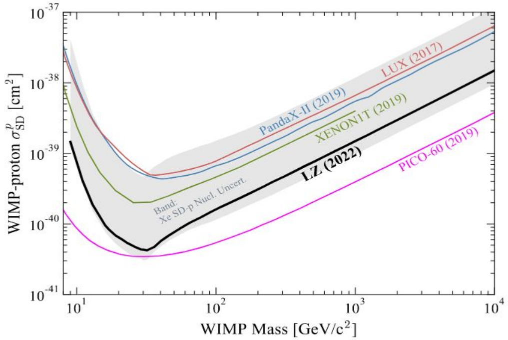
WIMP-nucleon EFT couplings
[Phys. Rev. D 109, 092003]



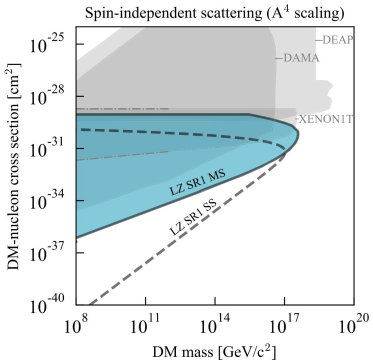
Covariant EFT lagrangians
[arXiv:2404.17666]



WIMP-pion coupling
[arXiv:2406.02441]



Spin-dependent dark matter searches
[PhysRevLett.131.041002]

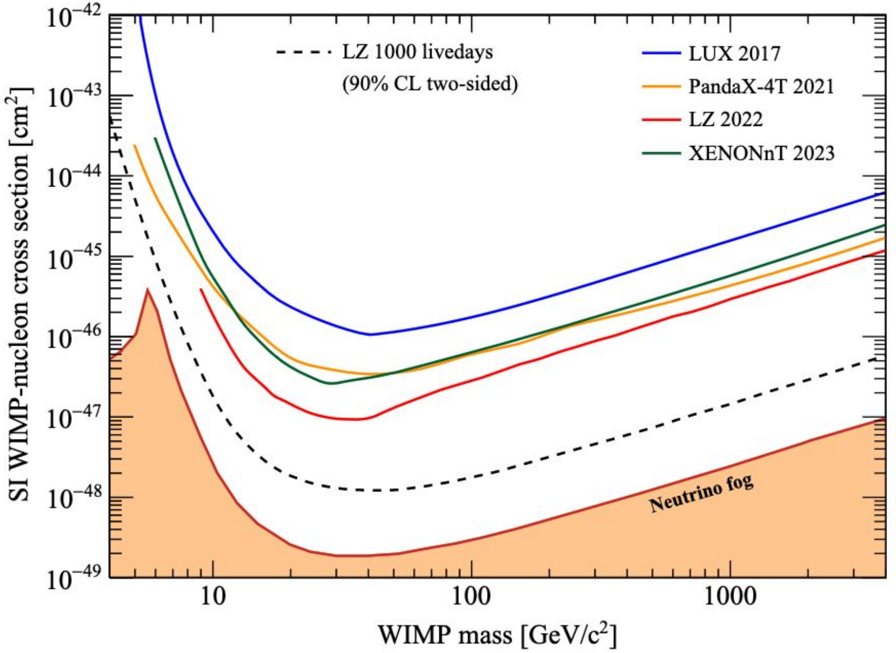


Ultraheavy dark matter
[PhysRevC.102.014602]

What are we doing

WIMP search prospects

- LZ continues to take data with ongoing improvements to detector operation and data analysis
- LZ plans to take 1000 live days of data (x17 more exposure)
- Still a large swath of parameter space left to explore!
    - Projected sensitivity of 1.4 x 10^{-48} cm^2 at 40 GeV/c^2 in the full exposure [Phys. Rev. D 101, 052002]
    - Motivated by many *beyond-the-standard model theories



*[Ann.Rev.Nucl.Part.Sci. 70 (2020) 425-454], [Eur. Phys. J. C (2022) 82: 31], [Eur. Phys. J. C (2022) 82: 992]

Analysis improvements

Bias mitigation

- The goal is to overcome human biases in the analysis of the data
- We are “salting” the data:
  - Use two calibration events to create one salt event and inject it in the data
  - Remove them after the analysis cuts and background model is frozen
- Salting process validated through two mock data challenges
- Types of salt:
  - Normal WIMP salt (> 10 GeV/c^2)
  - Light WIMPs/^{8}B salt (< 10 GeV/c^2)

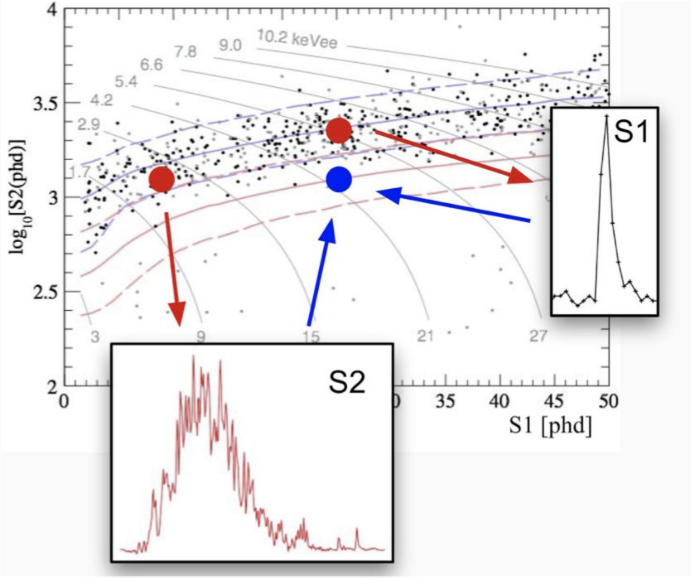


Illustration of the salting generation mechanism in LUX

Analysis improvements

Radon tagging

- Laminar flow in the TPC allows for construction of a liquid Xe flow model using ^{222}Rn-^{218}Po decays
- This feature can be exploited to create exclusion voxels evolving in time
    - Reduces the low energy background induced by ^{214}Pb (a dominant ER background!)
    - Also used by XENON1T, with a tagging efficiency of 6.2% and exposure loss of 1.8% [arXiv:2403.14878]
- **Preliminary:** ~68% tagging efficiency for an exposure "loss" of ~9% in the first science run
    - Not really a loss if you include it in your likelihood!

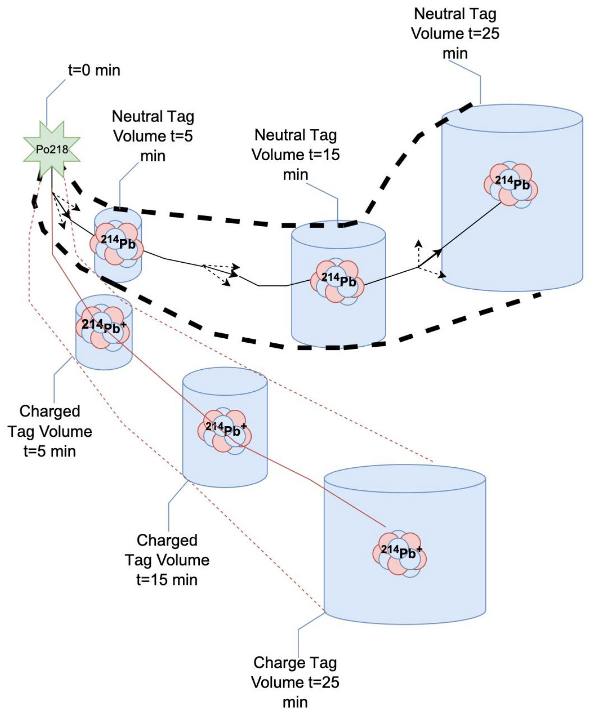
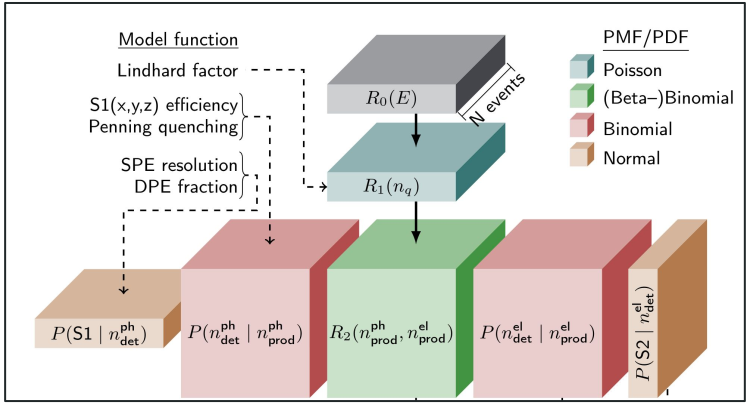


Diagram of the path followed by a ^{218}Po-^{214}Pb pair following a neutral (dashed black) or charged (dotted red) ion trajectory

Analysis improvements

Statistical analysis

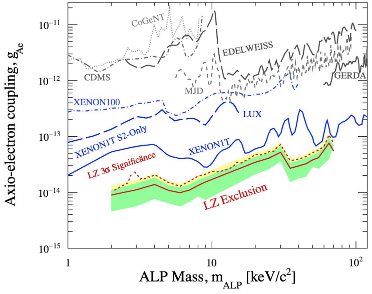
- Combined likelihood with first science run data, veto-tagged data, and Rn-tagged data
- Using the public code [flamedisx]
  - Allows for the expansion of the number of dimensions and free-floating parameters
  - Offers an alternative (and faster) way of treating shape-varying parameters to template morphing
  - Python-based and GPU-scalable

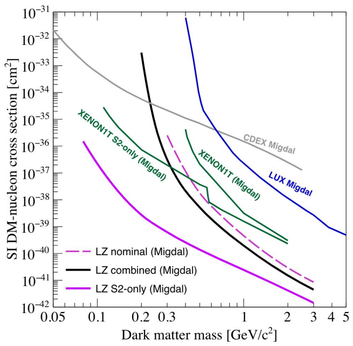


Evaluation model of the WIMP recoil rate by flamedisx [Phys. Rev. D 102, 072010]

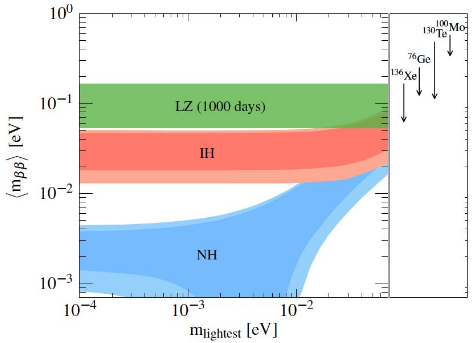
Other searches

Axion-like particles
[Phys. Rev. D 104, 092009]



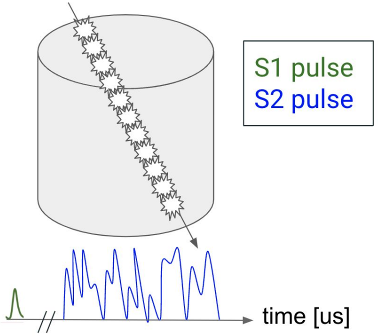


ER-inducing Migdal effect
[arXiv:2101.08753]

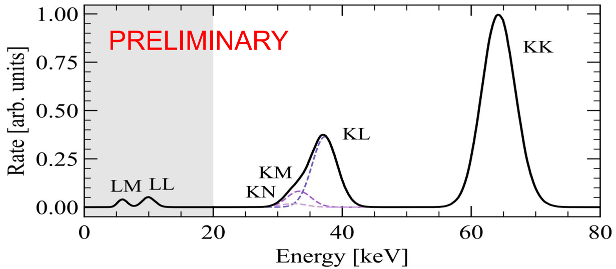


Neutrinoless double beta decay of ^{136}Xe
[PhysRevC.102.014602]

LZ



Lightly ionizing particles (LIP)

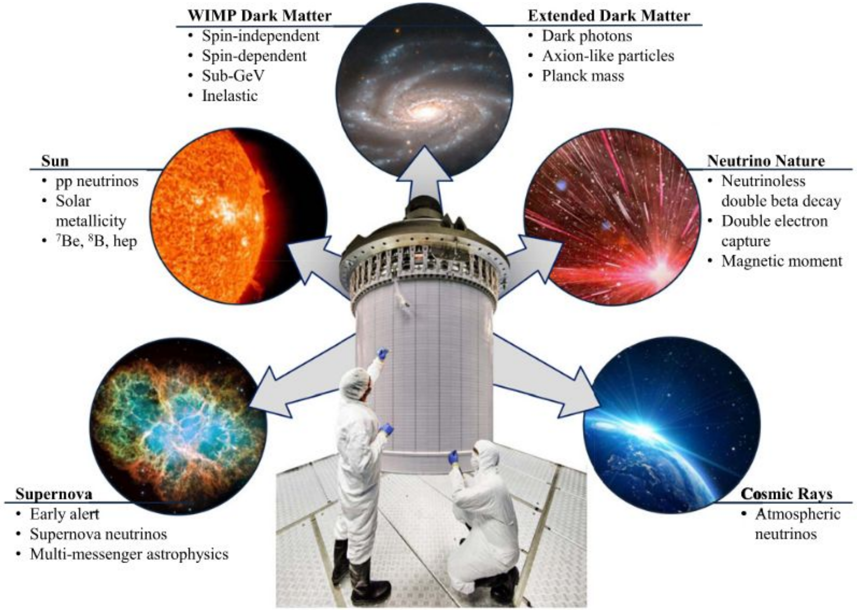


Two-neutrino double electron capture of ^{124}Xe

What’s in the horizon

XLDZ

- Three major experiments (XENON, LZ, and DARWIN) are joining forces
  - Consortium formed in 2021; formal collaboration to be established later this summer
- XLZD will not simply be a larger dark matter experiment, but rather the definitive xenon observatory for dark matter and neutrino physics
- Rich physics program:
  - Closing the gap on the WIMP hypothesis
  - Measurement of astrophysical neutrino signals: solar, supernova, atmospheric
  - Competitive search for neutrinoless double beta decay in ^{136}Xe



[J. Phys. G: Nucl. Part. Phys. 50 013001]

We’ve been busy! [https://xlzd.org]

KIT Karlsruhe (GE), June 2022

UCLA (US), April 2023

See talk by L. Baudis (July 11th, Parallel 1)

RAL (UK), April 2024

Brown University (US), June 2024

Conclusions

- The LZ experiment is working to specs
    - All detectors are performing well
    - Backgrounds are within expectation
- With its first science run of 60 livedays, LZ uncovered new dark matter parameter space
- LZ continues to take data and a broad physics program lies ahead for its complete 1000 liveday exposure
- The xenon community is joining forces to build the ultimate xenon rare event observatory (XLZD)

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

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 & 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

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Swiss National Science Foundation

FCT Fundação para a Ciência e a Tecnologia

Sanford Underground Research Facility

ibs Institute for Basic Science

Thanks to our sponsors and participating institutions!

Back-up

Direct detection of WIMPs

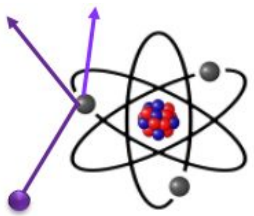
Goal: search for low-energy scatterings (~1-100 keV) of a galactic dark matter particle and a target nucleus on Earth

Types of signals

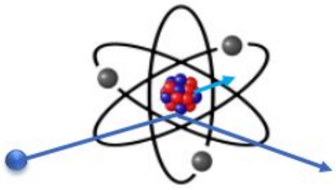
- Electron recoils (ER): gamma-rays, beta particles, ν-e scattering
- Nuclear recoils (NR): neutrons, coherent elastic ν-N scattering (CEνNS), WIMP

Main backgrounds

- Radon progeny attached to surfaces
- Cosmogenic activation
- Dispersed radioisotopes
- Astrophysical neutrinos



Electron recoil



Nuclear recoil

Dual-phase xenon TPC

A single scatter (SS) in the “active” region results in:

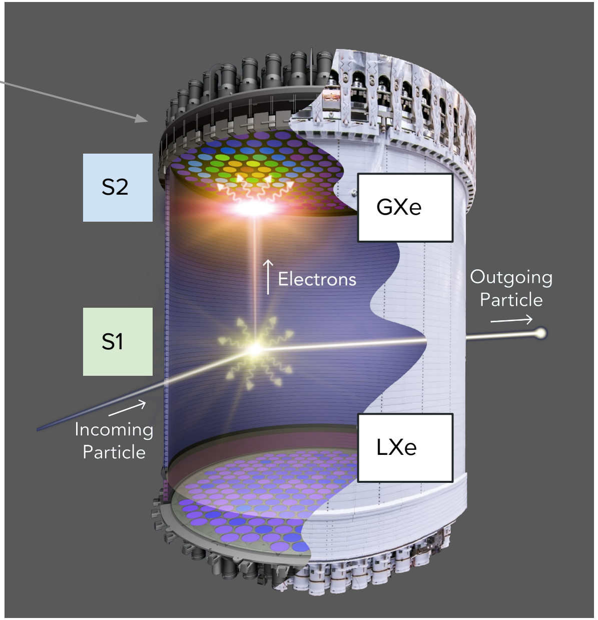
- Prompt scintillation signal in the liquid phase (S1)
- Secondary scintillation signal in the gaseous phase (S2)

The light signals are recorded by two arrays of photomultiplier tubes (PMTs) located at the top and bottom of the detector.

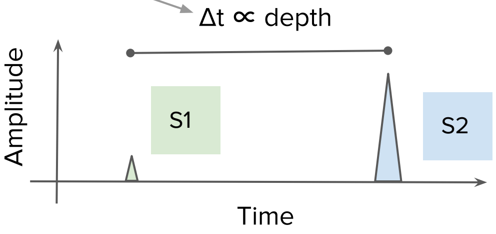
Advantages:

- Low detection threshold (~3 keV)
- 3D position reconstruction
- Self-shielding from xenon
- Absence of long-lived radioisotopes in natural xenon
- Excellent ER/NR discrimination

PMT hit map gives XY position



Time difference gives Z position



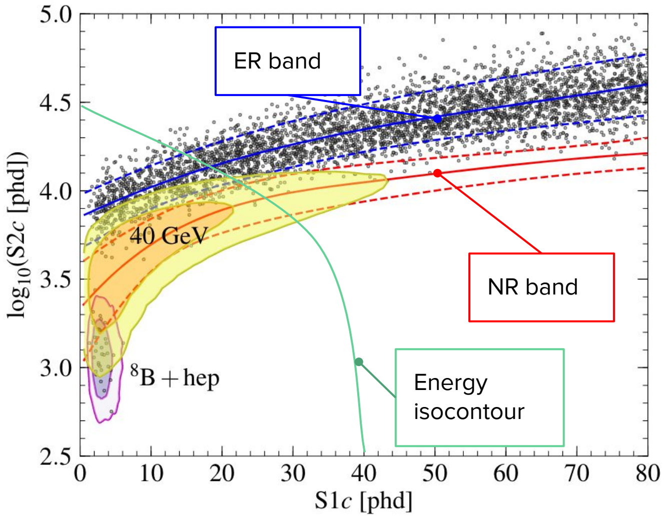
ER/NR discrimination

Any ionisation electron that is not captured by a positive ion will escape the interaction site as a free electron and contribute to the S2 signal.

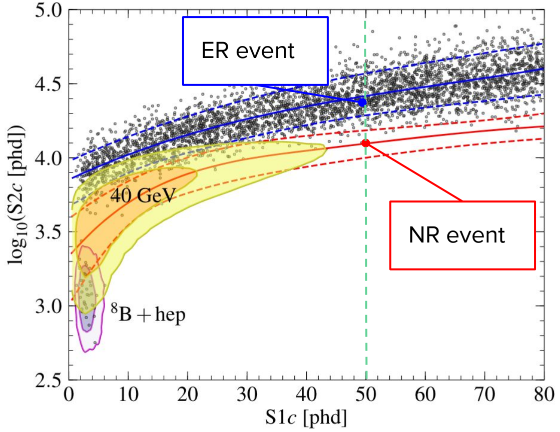
If captured by a Xe ion, it will create an extra Xe excimer and contribute to the S1 signal.

The S1 and S2 signals are *anti*-correlated!

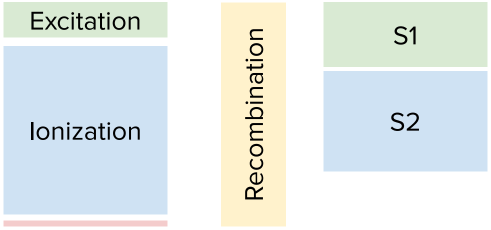
Key idea: The different, initial exciton-to-ion ratio for ERs and NRs results in distinct bands in the S1-S2 plane.



[Phys. Rev. D 101, 052002]

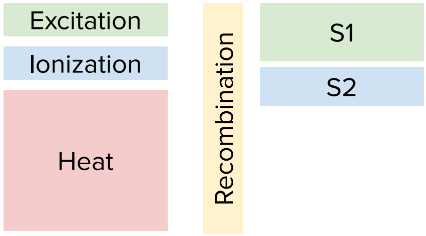


For an S1 signal of 50 photons detected (phd):



ER event of 10 keV

The exciton-to-ion ratio is ~1:10 for ERs and ~1:1 for NRs



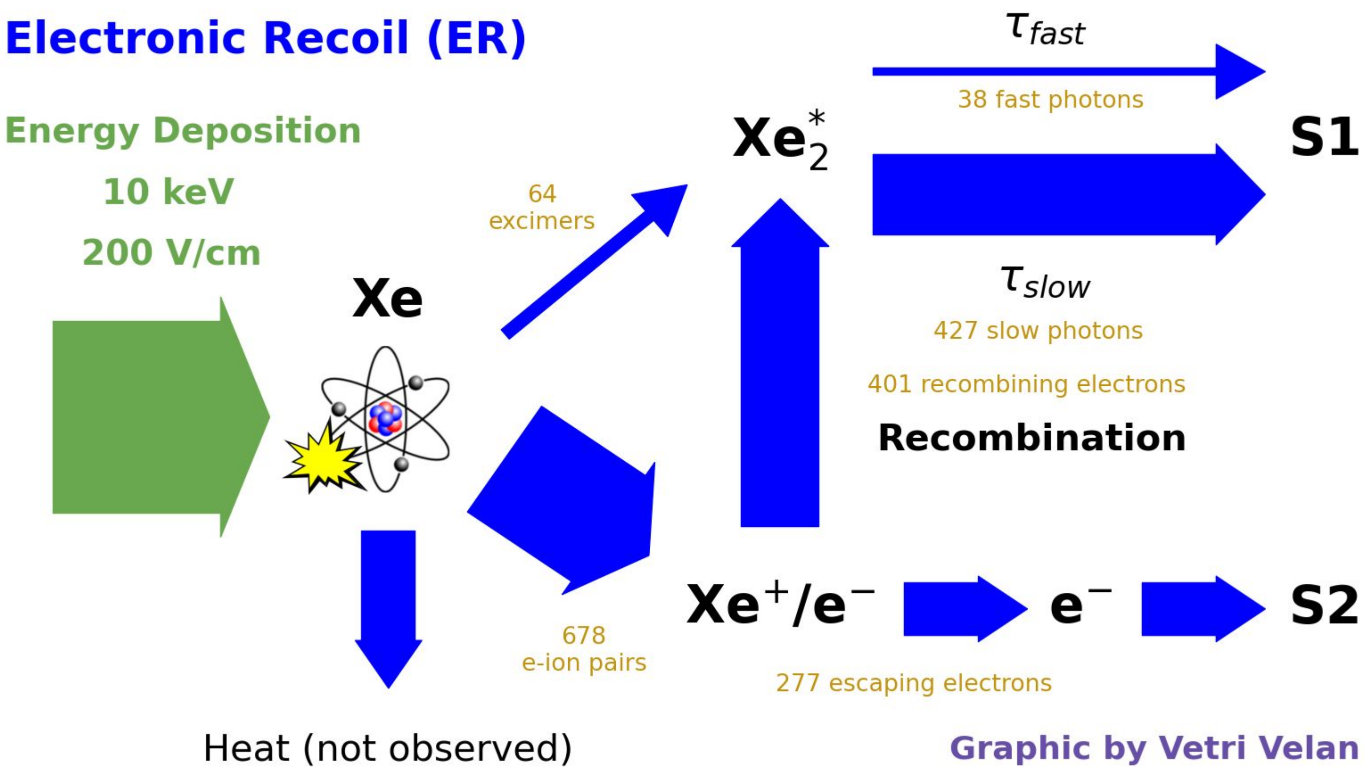
NR event of 40 keV

Outcome: similar S1, but larger S2 for an ER event.

A larger fraction of energy is "lost" to heat in NR events

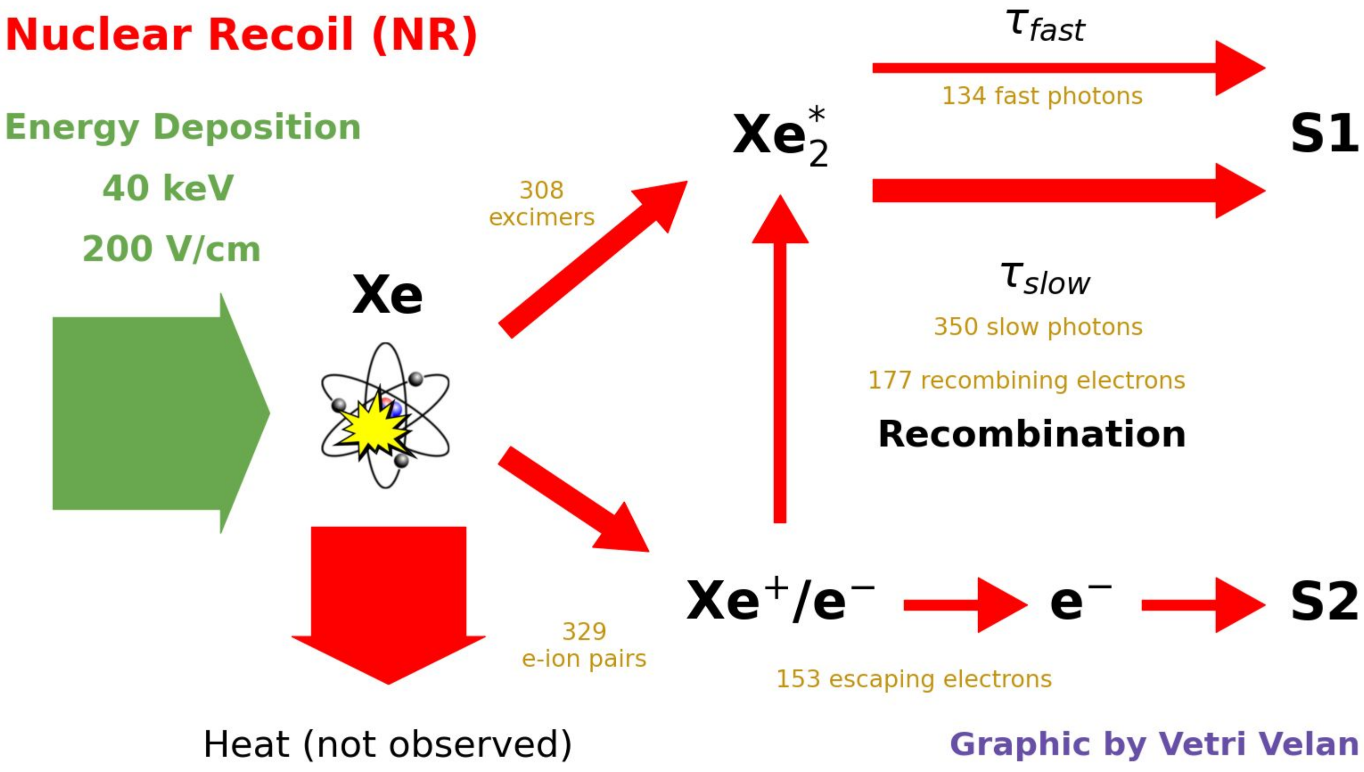
~50% of free electrons are recombined for NRs (~60% for ERs)

ER event

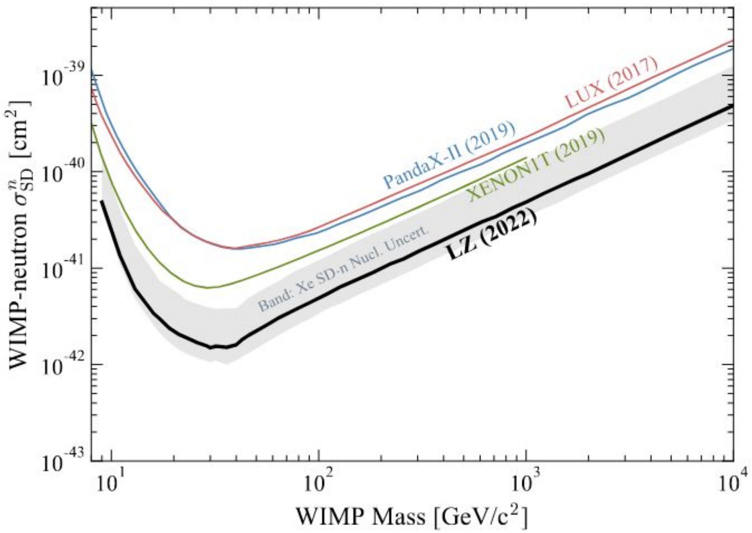


Electronic Recoil (ER)
Energy Deposition
10 keV
200 V/cm
Xe
64
excimers
Xe_2^*
τ_{fast}
38 fast photons
S1
τ_{slow}
427 slow photons
401 recombining electrons
Recombination
678
e-ion pairs
Xe^+/e^-
e^-
S2
277 escaping electrons
Heat (not observed)
Graphic by Vetri Velan

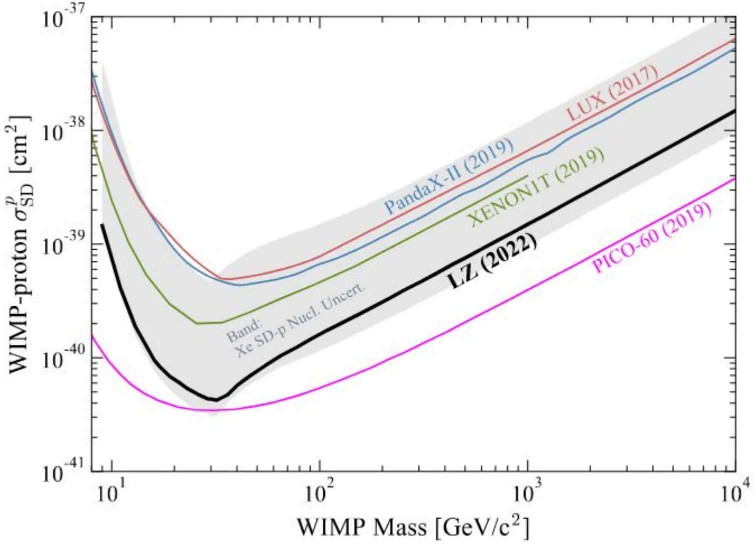
NR event


Nuclear Recoil (NR)
Energy Deposition
40 keV
200 V/cm
Xe
308
excimers
329
e-ion pairs
Xe_2^*
τ_{fast}
134 fast photons
τ_{slow}
350 slow photons
177 recombining electrons
Recombination
S1
Xe^+/e^-
e^-
S2
153 escaping electrons
Heat (not observed)
Graphic by Vetri Velan

Spin-dependent WIMP-neutron scattering

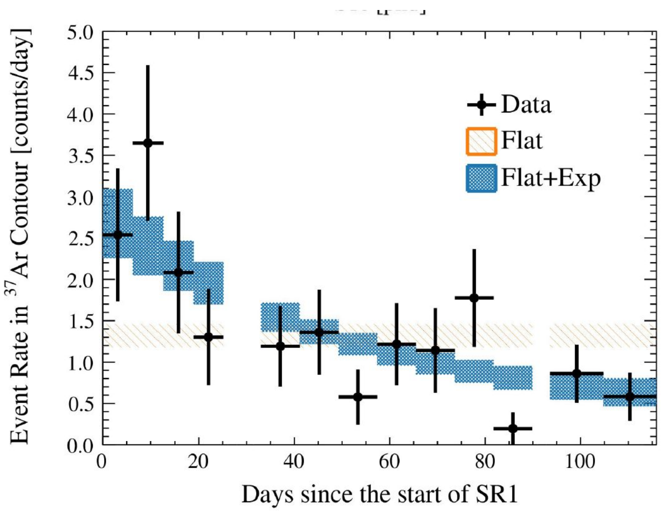


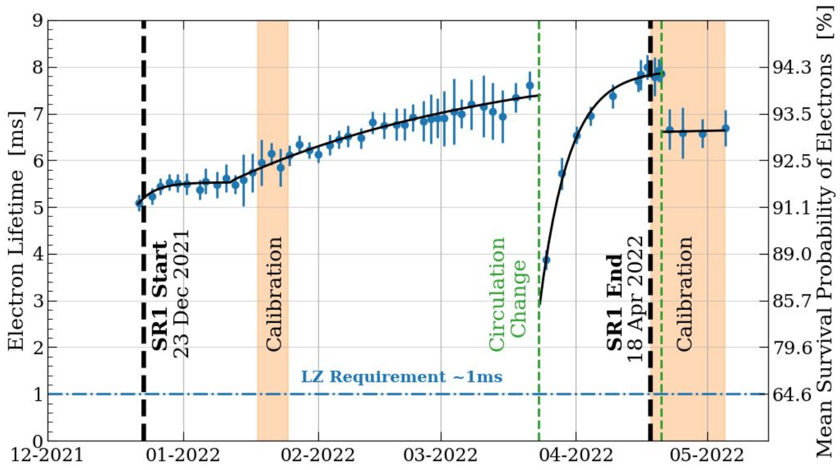
Spin-dependent WIMP-proton scattering



- Xe has two isotopes with unpaired neutrons that have non-zero nuclear spin (^{129}Xe and ^{131}Xe)
  - WIMP-proton sensitivity arises from higher-order nuclear effects
- The grey bands reflect the current uncertainty on nuclear structure factors [Phys. Rev. D 88, 083516]
- LZ currently is the most sensitive experiment in the WIMP-neutron channel

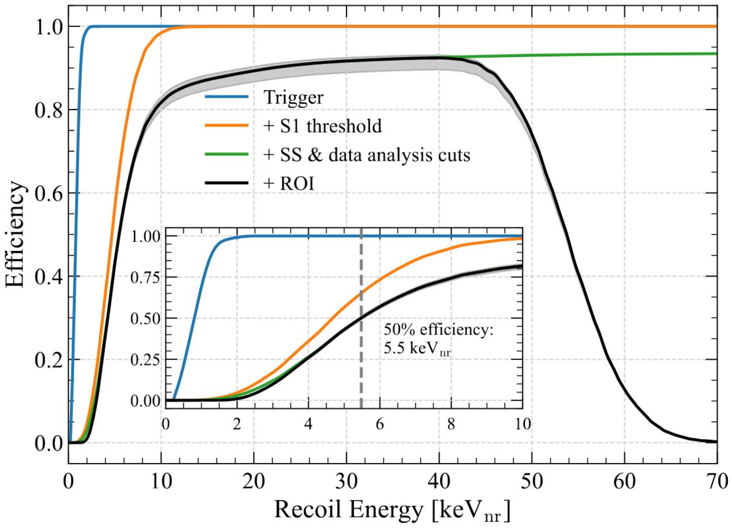
E-lifetime and ^{37}Ar decay in first science run





Analysis details

- The analysis is performed in a fiducial volume (5.5 tonnes), where wall background leakage is negligible
- Bias mitigation: analysis cuts developed on non-WIMP ROI background & calibration data + vetoes (skin & OD)



Signal efficiency evaluated using tritium and AmLi calibration data