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

IDM @L’Aquila
July 8th, 2024
Ibles Olcina
Outline

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

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

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

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

- Rock overburden
  - Muons reduced by \(\sim 10^6\) at the 4850 cavern in SURF

- Material selection

- 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
Timeline

2017: TDR release

2018: Cryostats arrive

2019: Grids complete

2020: Sealed up

2021: OD fill

2022: Start of Xe fill

2023: First science data!

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 $g_1 = 0.114 \pm 0.002$ phd/ph
  - Charge gain of $g_2 = 47.1 \pm 1.1$ 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]

*[NEST website]*
Background model

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

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

ER backgrounds
Dominated by $^{214}$Pb and $^{37}$Ar

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 ($\alpha$,n)
- $^8$B solar neutrinos

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

- Accidentals PDF after smoothing
  - Event triggers on S2 that is missing its associated S1
  - S1 that is missing its associated S2
Data selection

- All triggers
- Time hold-offs: high rates of spurious instrumental activity, dominated by post-S2 hold-off (70% live fraction)
- Low energy single scatters: $3 < S1c < 80\, \text{phd}, S2c > 600\, \text{phd}$ (10e)
- Pulse quality cuts: target accidental coincidence events
- Fiducial volume: central 5.5 tonnes of LXe
- OD + Skin vetoes

Number of events

1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8
Results: best fit

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

[PhysRevLett.131.041002]

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 $9.2 \times 10^{-48}$ 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
  - [PhysRevLett.131.041002]
Other searches with the first science dataset

**WIMP-nucleon EFT couplings**


**Covariant EFT lagrangians**


**WIMP-pion coupling**


**Spin-dependent dark matter searches**

[PhysRevLett.131.041002](https://link.to/phys.rev.lett.131.041002)

**Ultraheavy dark matter**

[PhysRevC.102.014602](https://link.to/phys.rev.c.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 $1.4 \times 10^{-48}$ cm$^2$ at 40 GeV/c$^2$ in the full exposure [Phys. Rev. D 101, 052002]
  - Motivated by many *beyond-the-standard model theories

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)
Analysis improvements

Radon tagging

- Laminar flow in the TPC allows for construction of a liquid Xe flow model using $^{222}\text{Rn-}^{218}\text{Po}$ decays
- This feature can be exploited to create exclusion voxels evolving in time
  - Reduces the low energy background induced by $^{214}\text{Pb}$ (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: $\sim68\%$ tagging efficiency for an exposure “loss” of $\sim9\%$ in the first science run
  - Not really a loss if you include it in your likelihood!

Diagram of the path followed by a $^{218}\text{Po-}^{214}\text{Pb}$ 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

ER-inducing Migdal effect
[arXiv:2101.08753]

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

Lightly ionizing particles (LIP)

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

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

LZ
What’s in the horizon
XLZD

- 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

We’ve been busy!  [https://xlzd.org]

KIT Karlsruhe (GE), June 2022

UCLA (US), April 2023

RAL (UK), April 2024

Brown University (US), June 2024

See talk by L. Baudis (July 11th, Parallel 1)
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)
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, $\nu$-e scattering
- Nuclear recoils (NR): neutrons, coherent elastic $\nu$-N scattering (CE$\nu$NS), WIMP

**Main backgrounds**

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

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

The exciton-to-ion ratio is \(~1:10\) for ERs and \(~1:1\) for NRs.

A larger fraction of energy is “lost” to heat in NR events.

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

Outcomes:
- **NR event of 40 keV**: Similar S1, but larger S2 for an ER event.
- **ER event of 10 keV**: S1 and larger S2 for an ER event.
ER event

Electronic Recoil (ER)

Energy Deposition
10 keV
200 V/cm

Xe

64 excimers

678 e-ion pairs

Heat (not observed)

Xe₂

Xe⁺/e⁻

Recombination

38 fast photons

427 slow photons

401 recombining electrons

277 escaping electrons

S1

S2

τ_{fast}

τ_{slow}

Graphic by Vetri Velan
NR event

Nuclear Recoil (NR)

Energy Deposition
40 keV
200 V/cm

Xe

Xe\textsuperscript{2+}

\(134\) fast photons
\(350\) slow photons
177 recombining electrons

\(\tau_{\text{fast}}\)

Recombination

\(\tau_{\text{slow}}\)

Xe\textsuperscript{+}/e\textsuperscript{-}

e\textsuperscript{-}

S1

329 e-ion pairs
153 escaping electrons

Heat (not observed)

Graphic by Vetri Velan
- 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.