Dark Matter Searches with the LZ Detector

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Les Rencontres de Physique de la Vallée d'Aoste
Dual-phase Xenon TPCs

- **S1** Prompt scintillation light collected by PMTs
- **S2** Electroluminescence from liberated electrons extracted into gas layer by uniform electric fields

3D position reconstruction from $\Delta t$ and PMT hits

Electron Recoil (ER): $\gamma$ and $\beta$ backgrounds

Nuclear Recoil (NR): WIMPs, neutrons

ER/NR discrimination from ratio of S1 and S2
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

38 Institutions, 250 scientists, engineers, and technical staff

LZ Collaboration Meeting at SURF, 2023

Thanks to our sponsors and participating institutions!
LZ is located in the Davis Cavern, 1478 m underground in Lead, South Dakota.
The LUX-ZEPLIN Detector

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 $\gamma$ rays

OD:
- Contains 17 t Gd-loaded liquid scintillator
- Anti-coincidence detector for $\gamma$ rays and neutrons

Each detector observed by additional PMTs
Veto Anti-Coincidence Systems

Example neutron event:

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

**Skin:**
- Contains 2 t LXe
- Optically isolated
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**OD:**
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Each detector observed by additional PMTs
LZ Assembly (2018 - 2021)

TPC Assembly

Moving the cryostat

Lowering the TPC into the cryostat

The bottom PMT array

An LZ electrode

The Outer Detector

Anna David

Dark Matter Searches with the LZ Detector
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 (≫ 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

g₁ (light gain) = 0.114 ± 0.002 phd/photon

g₂ (charge gain) = 47.1 ± 1.1 phd/e⁻

99.9% ER discrimination below NR band median
Background Model

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

**Solar neutrinos (ER):**
- $^{85}$Kr
- $^{13}$N
- $^{7}$Be
- $^{13}$N

**γ-emitters in detector materials:**
- $^{238}$U chain
- $^{232}$Th chain
- $^{40}$K
- $^{60}$Co

**Solar neutrino backgrounds:**
- $^{8}$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**

**NR backgrounds:**
- Neutron emission from spontaneous fission and ($\alpha$,n)
- $^{8}$B solar neutrinos
- SR1 total = **0.15 events**

**ER Backgrounds**
- SR1 total = **276 events**
  + [0,291] from $^{37}$Ar

**Dissolved β-emitters:**
- $^{214}$Pb ($^{222}$Rn daughter)
- $^{212}$Pb ($^{220}$Rn daughter)
- $^{85}$Kr
- $^{136}$Xe (2νββ)
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

<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 $\pm$ 36</td>
<td>222 $\pm$ 16</td>
</tr>
<tr>
<td>$\nu$ ER</td>
<td>27.3 $\pm$ 1.6</td>
<td>27.3 $\pm$ 1.6</td>
</tr>
<tr>
<td>$^{127}$Xe</td>
<td>9.2 $\pm$ 0.8</td>
<td>9.3 $\pm$ 0.8</td>
</tr>
<tr>
<td>$^{124}$Xe</td>
<td>5.0 $\pm$ 1.4</td>
<td>5.2 $\pm$ 1.4</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>15.2 $\pm$ 2.4</td>
<td>15.3 $\pm$ 2.4</td>
</tr>
<tr>
<td>$^8$B CE$\nu$NS</td>
<td>0.15 $\pm$ 0.01</td>
<td>0.15 $\pm$ 0.01</td>
</tr>
<tr>
<td>Accidentals</td>
<td>1.2 $\pm$ 0.3</td>
<td>1.2 $\pm$ 0.3</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>276 $\pm$ 36</td>
<td>281 $\pm$ 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 $\pm$ 17</td>
</tr>
</tbody>
</table>

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

![Graph showing background fits and combined fit to data]
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

![Graph showing spin-independent limits for different WIMP masses and detector sensitivities.]

- Observed limit
- - - Median expected sensitivity

Most stringent limit of $9.2 \times 10^{-48}$ cm² for a 36 GeV/c² WIMP
Effective Field Theory Results

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

\[ \mathcal{L}_{\text{int}} = \sum_{N=n,p} \sum_i d_i^{(N)} O_i \bar{X} \bar{N} \]

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

arXiv:2312.02030 (2023)
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 $3.9 \times 10^{17}$ GeV/c$^2$
- Competitive per-nucleus limits and world-leading per-nucleon limits
Low-energy ER Results

- 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
• 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

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

[https://xlzd.org](https://xlzd.org)  
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

\[
E = W \cdot \left( \frac{S_{1c}}{g_1} + \frac{S_{2c}}{g_2} \right) \rightarrow \frac{S_{2c}}{E} = -\left( \frac{g_2}{g_1} \right) \cdot \left( \frac{S_{1c}}{E} \right) + \frac{g_2}{W}
\]

\[W = \text{excitation energy of 13.5 eV}\]
Backgrounds: Radon

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

\begin{align*}
^{222}\text{Rn} & \quad 3.8 \text{ d} \\
\alpha (5.6 \text{ MeV}) & \\
^{218}\text{Po} & \quad 3.1 \text{ min} \\
\alpha (6.1 \text{ MeV}) & \\
^{214}\text{Pb} & \quad 27 \text{ min} \\
\beta^- & \rightarrow^{214}\text{Bi} \\
20 \text{ min} & \rightarrow^{214}\text{Po} \\
\beta^- & \rightarrow 160 \mu\text{s} \\
\alpha (7.8 \text{ MeV}) & \\
\end{align*}
Backgrounds: $^{37}$Ar

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

\[ \text{SR1 total} = \boxed{276 \text{ events}} \]
$+[0,291]$ from $^{37}$Ar

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

- Accidental coincidences of isolated $S_1$ and $S_2$ pulses can occur within max. drift time
- Rate: definite accidental events with drift time $> \text{max. drift time}$
- Distribution: fake events from lone $S_1$ and $S_2$ pulses stitched together
- Analysis cuts remove with $>99.5\%$ efficiency

Definite Accidental Event

Max. drift time

Accidental coincidences of isolated $S_1$ and $S_2$ pulses can occur within max. drift time.
Rate: definite accidental events with drift time $> \text{max. drift time}$
Distribution: fake events from lone $S_1$ and $S_2$ pulses stitched together
Analysis cuts remove with $>99.5\%$ efficiency
Limit Shape

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

- 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**
Spin-Dependent Limits

WIMP-neutron Scattering

WIMP-proton Scattering

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

Grey bands = theoretical uncertainty on Xe nuclear structure factor

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