Searching for WIMPs and other new physics with LZ

Shilo Xia
Lawrence Berkeley National Laboratory
On behalf of the LZ collaboration
LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

- 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

250 scientists, engineers, and technical staff

Thanks to our sponsors and participating institutions!

https://lz.lbl.gov/
LZ @ Sanford Underground Research Facility (SURF)

- LZ uses 10t of xenon to search for WIMP dark matter
- The detector is on the 4850 level (~1.5 km underground) → ~10^6 reduction in cosmic muon flux
The LZ Detector

**LZ**

**SURF, USA**

*Outer Detector (OD)*

- 17T Gd-loaded liquid scintillator

[Diagram showing various components of the LZ Detector, including:
- Calibration source deployment tubes (3 total)
- 60,000 gallons of ultrapure water
- 494 LXe PMTs
- TPC
- 7T active LXe target
- Neutron calibration conduit (2 total)
- 120 veto PMTs
- 2T LXe skin veto
- 131 skin PMTs]
Signal vs. background discrimination
- Charge (S2)/ light (S1) ratio is different between electron recoils (ER) and nuclear recoils (NR)

Electrons and gammas interact with atomic electrons, produce ER
WIMPs (and neutrons) interact with Xe nuclei, produce NR
Calibration Data

- Dark blue points: Tritium beta data (ER) (continuum betas up to 18.6 keV)
- Orange points: DD neutron data (NR) (2.45 MeV neutrons produced through Deuterium-Deuterium fusion)
- ER/NR discrimination: <0.5% ER leakage past the median of the NR population

LZ Collaboration, Phys. Rev. Lett. 131, 041002 (2023)
Main backgrounds in Science Run 1

Reconstructed data energy spectrum vs. background model:

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected Events</th>
<th>Fit Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}\text{Pb}$</td>
<td>$164 \pm 35$</td>
<td>$-$</td>
</tr>
<tr>
<td>$^{212}\text{Pb}$</td>
<td>$18 \pm 5$</td>
<td>$-$</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$</td>
<td>$32 \pm 5$</td>
<td>$-$</td>
</tr>
<tr>
<td>Det. ER</td>
<td>$1.4 \pm 0.4$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\beta$ decays + Det. ER</td>
<td>$215 \pm 36$</td>
<td>$222 \pm 16$</td>
</tr>
<tr>
<td>$\nu$ ER</td>
<td>$27.1 \pm 1.6$</td>
<td>$27.2 \pm 1.6$</td>
</tr>
<tr>
<td>$^{137}\text{Xe}$</td>
<td>$9.2 \pm 0.8$</td>
<td>$9.3 \pm 0.8$</td>
</tr>
<tr>
<td>$^{124}\text{Xe}$</td>
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<td>$15.1 \pm 2.4$</td>
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<tr>
<td>$^{8}\text{B}$ CE$\nu$NS</td>
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<td>$0.15 \pm 0.01$</td>
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<td>Subtotal</td>
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$^{37}\text{Ar}$ | $[0, 288]$      | $52.5^{+9.6}_{-8.9}$ |
| Detector neutrons | $0.0^{+0.2}_{-0.1}$ | $0.0^{+0.2}_{-0.2}$ |
| $30\text{GeV}/\text{c}^2$ WIMP | $-$ | $0.0^{+0.6}_{-0.1}$ |
| Total            | $-$             | $333 \pm 17$ |

Main backgrounds in Science Run 1

Reconstructed data energy spectrum vs. background model:

[Graph showing energy spectrum and background sources]

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Science Run 1 WIMP Search Data

- Shaded gray region: best fit ER background model
- Purple curves: 1σ and 2σ contours of a 30 GeV/c² WIMP
- Red curves - NR band
- Shaded green region: $^8$B neutrino
- Orange ellipses: contours of $^{37}$Ar
- 335 events observed within 60 ± 1 live days, $\text{FV}=5.5 \pm 0.2 \text{ t}$

*LZ Collaboration* *Phys. Rev. Lett.* **131**, 041002 (2023)
LZ’s First WIMP Search Result

- No evidence of WIMPs at any mass from Science Run 1 (60 live days of data)
- Most stringent upper limit on WIMP-nucleon cross section (spin-independent) for WIMPs above 9 GeV/c²

- **Green** and **yellow** bands: 1σ and 2σ sensitivity bands
- **Solid black line**: exclusion limit
- **Gray dot-dash line**: exclusion limit before applying the power constraint
- **Dashed-black line**: median expected sensitivity

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WIMP-Nucleon Effective Field Theory (EFT)

- Why EFT?
  - All possible mechanisms for the WIMP-nucleon interaction are considered
  - Allows comparison of experiments using different target nuclei

- Non-relativistic dark matter EFT:
  \[ \mathcal{L}_{\text{int}} = \sum_i c_i O_i \]

  - 15 Galilean-invariant operators up to quadratic order in \( \frac{q}{m_N} \), built with four Hermitian quantities

  \( \vec{S}_X \): WIMP spin  \hspace{1cm} \vec{q} \): momentum transfer

  \( \vec{S}_N \): nucleon spin  \hspace{1cm} \vec{v}_\perp \): WIMP-nucleon relative velocity component perpendicular to \( \vec{q} \)
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Non-relativistic dark matter EFT:
\[ \mathcal{L}_{\text{int}} = \sum_i c_i \mathcal{O}_i \]

- 15 Galilean-invariant operators up to quadratic order in \( \frac{\vec{q}}{m_N} \), built with four Hermitian quantities

\[ \mathcal{O}_1 = 1 \times 1_N, \quad \mathcal{O}_2 = (v^\perp)^2, \quad \mathcal{O}_3 = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right), \]
\[ \mathcal{O}_4 = \vec{S}_X \cdot \vec{S}_N, \quad \mathcal{O}_5 = i \vec{S}_X \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right), \quad \mathcal{O}_6 = \left( \frac{\vec{S}_X \cdot \vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right), \quad \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp, \]
\[ \mathcal{O}_8 = \vec{S}_X \cdot \vec{v}^\perp, \quad \mathcal{O}_9 = i \vec{S}_X \cdot \left( \vec{S}_N \times \frac{\vec{q}}{m_N} \right), \]

Spin-independent

Angular momentum dependent

- Tensor spin orbit
- Spin-dependent

Constraints on WIMP-Nucleon Effective Field Theory Couplings

- LZ has the strongest upper limits on coefficients for nearly all EFT operators

Black – 90% C.L. limit on WIMP-nucleon couplings for operators in the isoscalar bases (2023)
Cyan – PandaX-II (2019)
Magenta – XENON100 (2017)
Brown dot – LUX (2014)

LZ Collaboration arXiv:2312.02030
Ultraheavy Dark Matter

- Dark matter models with masses $>10$ TeV/$c^2$ are weakly constrained
- LZ searches for ultraheavy dark matter particles through looking for multiple scatters forming a straight line, complementing the search in the single scatter channel
- **World leading limit on spin-independent per-nucleon interactions at high DM mass** (up to $\gtrsim 10^{17}$ GeV/$c^2$)

Low Energy ER New Physics Search in LZ

- New physics through ER interactions:
  - Solar axions
  - Neutrino magnetic moment & millicharge
  - ALPs and Hidden photons
  - WIMPs through Migdal Effect

Neutrino electromagnetic properties

- Any observation of neutrino electromagnetic properties is a strong indicator of the neutrino being a Majorana particle
- **World leading limit on neutrino millicharge** $\delta_Q = 2.24 \times 10^{-13} \, e_0$
- LZ’s 90% C.L. on neutrino magnetic moment $\mu_\nu = 1.36 \times 10^{-11} \, \mu_B$

*LZ collaboration, Phys. Rev. D 108, 072006*
Solar axions

- Solar axions interaction with xenon via axio-electric effect
- LZ’s 90% C.L. limit on $g_{ae} = 2.35 \times 10^{-12}$

ALPs + Hidden Photons

- **Axion-Like Particles (ALPs):**
  - Gauge pseudo-scalar boson from BSM global symmetry breaking

- **Hidden (dark) Photons (HPs):**
  - Gauge boson of new ‘dark’ U(1) symmetry

*LZ collaboration, Phys. Rev. D 108, 072006*
Migdal effect: spin-independent WIMPs

- Can also search for WIMPs in ER channel:
  - Migdal effect: a nuclear recoil interaction accompanied by atomic excitation/ionization.
  - Ref: M. Ibe et al., *JHEP*03,194 (2018)

Migdal effect: spin-dependent WIMPs

- LZ has world-leading SDn limit for WIMPs from 1.1 to 3 GeV

LZ collaboration, Phys. Rev. D 108, 072006
LZ’s Future Science Program

- Significant improvement on sensitivity to WIMP-nucleon couplings
- Neutrino studies: $^8$B CEvNS, supernova neutrinos
- Neutrinoless double beta decay/electron capture
- ...

Potential LZ Upgrades

- **HydroX**: H-doping of LZ for low-mass and spin-dependent WIMP search enhancement

- **CrystaLiZe**: Radon background reduction through freezing xenon (×500 exclusion against radon ingress)
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*Phys. Rev. Lett 132, 111801 (2024)*
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References:


Phys. Rev. D 109, L071102(2024)
Future Detectors

- **Ultimate Goal:** Detect Dark Matter or Reach Neutrino Floor/Fog
- **XLZD consortium:** joint effort from XENON, LZ, and Darwin experiments [https://xlzd.org/](https://xlzd.org/)
- Plan for a ~40-80 tonne xenon experiment
- **P5 recommended SURF expansion for a G3 experiment**
- See more details on the website and in the whitepaper: *J. Phys. G50, 013001 (2023)*