The LZ Experiment for Dark-Matter Search

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How to Detect Dark Matter: Liquid Xenon 2-phase TPC’s

• WIMP scatters on Xe nucleus in liquid xenon (LXe).

• Energy detected as prompt photons (S1 light), and drifted electrons.

• Drift time gives z position.

• Detection of electroluminescence from drifted electrons (S2-light) localizes X,Y.

• Position resolution removes multi-site backgrounds.

• S2/S1 separates Electron Recoil (ER) from Nuclear Recoil (NR) => Powerful background discrimination.

• Single photon and electron detection possible => low threshold
LUX+ZEPLIN:

ZEPLIN-III
- 6.8 kg liquid Xe (fiducial)
- 3.9x10^{-8} pb exclusion
- ZEPLIN-II was one of 1st 2-phase DM Detector.

LUX
- \sim 100 kg LXE
- 33,000 kg\cdot days
- 0.22 zb exclusion (at 50GeV)
- Best sensitivity in word at time of completion.
- Now on display at Sanford Visitor Center.
LZ collaboration
36 institutions ~250 scientists, engineers, and technicians

1) Center for Underground Physics (Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) Royal Holloway University of London (UK)
6) STFC Rutherford Appleton Lab (UK)
7) University College London (UK)
8) University of Bristol (UK)
9) University of Edinburgh (UK)
10) University of Liverpool (UK)
11) University of Oxford (UK)
12) University of Sheffield (UK)
13) Black Hill State University (US)
14) Brandeis University (US)
15) Brookhaven National Lab (US)
16) Brown University (US)
17) Fermi National Accelerator Lab (US)
18) Lawrence Berkeley National Lab (US)
19) Lawrence Livermore National Lab (US)
20) Northwestern University (US)
21) Pennsylvania State University (US)
22) SLAC National Accelerator Lab (US)
23) South Dakota School of Mines and Technology (US)
24) South Dakota Science and Technology Authority (US)
25) Texas A&M University (US)
26) University at Albany (US)
27) University of Alabama (US)
28) University of California, Berkeley (US)
29) University of California, Davis (US)
30) University of California, Santa Barbara (US)
31) University of Maryland (US)
32) University of Massachusetts (US)
33) University of Michigan (US)
34) University of Rochester (US)
35) University of South Dakota (US)
36) University of Wisconsin – Madison (US)
LZ: Next Generation

Keep the backgrounds and thresholds low, and “just” go bigger!

- More xenon (simple)
- Higher voltage
- Less xenon wastage

**LZ**
- Total mass – 10 T
- WIMP Active Mass – 7 T
- WIMP Fiducial Mass – 5.6 T

**LUX**
- Total mass – 0.37 T
- Active mass 0.25 T
- Fiducial mass 0.1T

Sanford Underground Research Facility
Lead, South Dakota, USA

Davis Campus Water Tank
4850 ft level.
LZ Detector Overview

Water Shield

Xe TPC

-50kV HV

Gd-LS

LXe

Neutron pipe

j.nima.2019.163047
• PTFE walls, Ti field rings
• Top/bottom PMT arrays holding ~494 3” PMTs total in Ti/PTFE structure.
• 4 grid voltages, cathode, gate, anode, and lower array ground shield.
• 99.5% ER discrimination
• 50kV cathode voltage.
Titanium Cryostat

- UK responsibility
- Test Fit in Milan
- Intensive Low activity titanium R&D (arXiv1702.02646)

- Titanium chosen in part to improve OD veto performance (thinner than Cu).
- Outer vessel (OCV) only, installed in Davis Cavern since summer 2019.
Cathode HV

- Many past Xe experiments struggled to reach ~15kV or less. (ex: Xenon-100, EXO-200, LUX)
- For LZ drift length, 50kV required (300 V/cm).
- Designed to 100kV.
- Extensive testing and prototyping.
- 120kV reached in liquid argon.
- 50kV tested in LXe.
- Tapered inner vessel reduces fields while saving xenon.
- TPC Field rings designed to minimize stray fields.
LXe Skin Veto Detector

- 2 tonnes of LXe surrounding TPC but not wasted.
- Instrumented with 93 1” new Hamamatsu PMT’s, 38 2” PMTs (recovered from LUX)
- Creates standoff from field-ring potentials.
- Suppresses alpha-n and other multi-site backgrounds.
- Everything is PTFE covered for light collection.

D. Leonard, CUP, TeVPA 2019
Outer Detector (OD)

- Anti-coincidence for $\gamma$ and n.
- 17 tons of Gd loaded LS (LAB)
- Segmented, $4\pi$ “hermetic” coverage.
- 120 8” R5912 PMT’s (used in Daya Bay, etc), +HV
- LS Distilled at BNL
- Screened in Davis cavern.

\textbf{arXiv:1808.05595} NIMA 2019 05 055

- Goal: veto backgrounds efficiently but still minimize backgrounds to reduce dead-time.
OD PMT testing and installation.

- PMTs tested in Korea and Brandies.
- Tested all 120 (plus spares) for gain, dark-rate, SPE response, afterpulsing etc.
- HPGe screened for activity.

Installation in spring 2020

Dark box at CUP

Test installation at SURF with Dummy PMTS
OD Dead Time

- GdLS neutron capture time ~ 30µs: 2.2 or 8 MeV total gamma energy.
- Window conservatively planned for 500 µs, 200 keV threshold (~25P.E.) => 96.5% neutron rejection.
- 5% Dead time goal requires < 100 Hz for 500 µs veto.
- Cavern activity measured with NaI about 4x below assumptions => ~ 30 Hz arXiv:1904.02112
- PMT measured activity < ~ 20Bq/PMT of each $^{238}U$, $^{232}Th$, $^{40}K$ => ~1Hz.
- Scintillator and other items ~ 20Hz.
- Total, around 50Hz, half of goal.

Multiple-afterpulsing deadtime modelled

\[
\frac{N_2}{N_1} = \frac{F_a}{N_1} / N_2
\]

500us veto time window

D. Leonard, CUP, TeVPA 2019
Veto Performance (Skin +OD)

Enables Fiducial volume increase from 3.2 tonnes to 5.6 tonnes.

Without veto rejection:
~10 events in 5.6 tonnes FV in 1000 days

With veto rejection:
~1 event in 5.6 tonnes FV in 1000 days

Single site nuclear recoil events in 6-30 keV region of interest
TPC Construction

- Arrays constructed at Brown in low Rn, Dust-filtered enclosure.
- PTFE covered, light-tight field rings test assembly completed at LBNL.
- TPC grids being woven, with electron emission treatment (arXiv:1801.07231)
- Assembly completed and installed in inner vessel, fall, 2019.
TPC Moves to Underground

- Arrives in Davis Cavern in October, 2019 (left)
- Now preparing for installation in Rn reduced tent. (right)
Xe Recirculation

- Recirculation and purification systems completed and leak tested, Fall 2019.
- Commissioning tests are starting.

Xe bottles now onsite for after $^{85}$Kr removal.
LZ Backgrounds: 5.6 tonnes, 1000 days, 1.5 to 6.5 keV

<table>
<thead>
<tr>
<th>Background Source</th>
<th>ER (cts)</th>
<th>NR (cts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Components</td>
<td>9</td>
<td>0.07</td>
</tr>
<tr>
<td>Surface Contamination</td>
<td>40</td>
<td>0.39</td>
</tr>
<tr>
<td>Laboratory and Cosmogenics</td>
<td>5</td>
<td>0.06</td>
</tr>
<tr>
<td>Xenon Contaminants</td>
<td>819</td>
<td>0</td>
</tr>
<tr>
<td>222Rn</td>
<td>681</td>
<td>0</td>
</tr>
<tr>
<td>220Rn</td>
<td>111</td>
<td>0</td>
</tr>
<tr>
<td>natKr (0.015 ppt g/g)</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>natAr (0.45 ppb g/g)</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Physics</td>
<td>322</td>
<td>0.51</td>
</tr>
<tr>
<td>136Xe 2νββ</td>
<td>67</td>
<td>0</td>
</tr>
<tr>
<td>Solar neutrinos (pp+7Be+13N)</td>
<td>255</td>
<td>0.05</td>
</tr>
<tr>
<td>Diffuse supernova neutrinos</td>
<td>0</td>
<td>0.46</td>
</tr>
<tr>
<td>Atmospheric neutrinos</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1195</td>
<td>1.03</td>
</tr>
<tr>
<td>with 99.5% ER discrim., 50% NR eff.</td>
<td>5.97</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Background Control:
- Two active vetos
- Charcoal chromatography for $^{85}$Kr and $^{39}$Ar removal. natKr/Xe $\rightarrow$ 0.015ppt
- Radio-assay: HPGe, ICP-MS, NAA
- Rn emanation screening (2 μBq/kg targets)
- Rn removal > 10x 
doi:10.1016/j.nima.2018.06.076
- Rn and dust surface control:
  - Rn reduced cleanrooms,
  - Dust witness measurements <500ng/cm$^3$ on LXe surfaces.
  - TPC plateout <0.5mBq/m$^2$

arXiv:1802.06039
Simulated exposure, 1000 days, 5.6 tonnes
Calibration Systems

- Tubes between cryostat vessels for deployment of sources
  - Gamma, (α,n), etc
  - System being tested in UK
- Photoneutron sources
  - Deployed on top of cryostat
  - Ex: $^{88}$Y Be, NR endpoints at 2.7 keV$_{nr}$ & 4.6 keV$_{nr}$
  - Mechanical tests at LBNL
- D-D neutron generator
  - $10^9$ 2.45 MeV neutrons/s
  - Multi-scatter tags energy
  - D2O scatter for reduced energy.
- Xe-injected internal sources
  - CH3T: $T_{1/2}=12.3\text{y}$ 1.82keVβ (few months)
  - $^{83}$mKr: $T_{1/2}=1.8\text{h}$, 41keV IC e⁻ (weekly)
  - Advanced prototyping @ U. Mass
  - 6 hour removal
  - Techniques proven in LUX.
Spin Independent WIMP Sensitivity

- Baseline sensitivity: $1.6 \times 10^{-48} @ 40\text{GeV/c}^2$, 1000 days, 5.6 tonne fiducial mass.

- 5 sigma discovery potential: $6.7 \times 10^{-48}$ (5.6 tonnes, 1000 days livetime) → Below Xenon1T sensitivity projection for 2-tonne-year exposure.

arXiv:1802.06039

D. Leonard, CUP, TeVPA 2019
## LZ Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>April</td>
<td>LZ collaboration forms</td>
</tr>
<tr>
<td>2014</td>
<td>July</td>
<td>LZ Project selected by US DOE, NSF&lt; &amp; UK STFC</td>
</tr>
<tr>
<td>2015</td>
<td>April</td>
<td>CD-1 Review, conceptual design</td>
</tr>
<tr>
<td>2016</td>
<td>April</td>
<td>CD-2 Review, project baseline</td>
</tr>
<tr>
<td>2017</td>
<td>January</td>
<td>CD-3 Review, construction start</td>
</tr>
<tr>
<td>2018</td>
<td>February</td>
<td>Wimp sensitivity paper (arXiv:1802.06039)</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td>Titanium cryostat delivered to SURF</td>
</tr>
<tr>
<td>2019</td>
<td>Oct</td>
<td>TPC moves underground</td>
</tr>
<tr>
<td>2020</td>
<td>Spring</td>
<td>OD and electronics install., Cryogenics comissiong.</td>
</tr>
<tr>
<td>2020</td>
<td>Summer</td>
<td>Ready for operations (CD4)</td>
</tr>
</tbody>
</table>
The End of the Talk
<table>
<thead>
<tr>
<th>Isotope</th>
<th>What</th>
<th>Purpose</th>
<th>Deployment</th>
<th>Custom?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium</td>
<td>beta, $Q = 18.6$ keV</td>
<td>ER band</td>
<td>Internal</td>
<td>N</td>
</tr>
<tr>
<td>$^{83m}$Kr</td>
<td>beta/gamma, 32.1 keV and 9.4 keV</td>
<td>TPC ($x,y,z$)</td>
<td>Internal</td>
<td>Y</td>
</tr>
<tr>
<td>$^{131m}$Xe</td>
<td>164 keV $\gamma$</td>
<td>TPC ($x,y,z$), Xe skin</td>
<td>Internal</td>
<td>Y</td>
</tr>
<tr>
<td>$^{220}$Rn</td>
<td>various $\alpha$'s</td>
<td>xenon skin</td>
<td>Internal</td>
<td>N</td>
</tr>
<tr>
<td>AmLi</td>
<td>($\alpha,n$)</td>
<td>NR band</td>
<td>CSD</td>
<td>Y</td>
</tr>
<tr>
<td>$^{252}$Cf</td>
<td>spontaneous fission</td>
<td>NR efficiency</td>
<td>CSD</td>
<td>N</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>122 keV $\gamma$</td>
<td>Xe skin threshold</td>
<td>CSD</td>
<td>N</td>
</tr>
<tr>
<td>$^{228}$Th</td>
<td>2.615 MeV $\gamma$, various others</td>
<td>OD energy scale</td>
<td>CSD</td>
<td>N</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>back-to-back 511 keV $\gamma$'s</td>
<td>TPC and OD sync</td>
<td>CSD</td>
<td>N</td>
</tr>
<tr>
<td>$^{88}$Y Be</td>
<td>152 keV neutron</td>
<td>low-energy NR response</td>
<td>External</td>
<td>N</td>
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<tr>
<td>$^{205}$Bi Be</td>
<td>88.5 keV neutron</td>
<td>low-energy NR response</td>
<td>External</td>
<td>Y</td>
</tr>
<tr>
<td>$^{206}$Bi Be</td>
<td>47 keV neutron</td>
<td>low-energy NR response</td>
<td>External</td>
<td>Y</td>
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<tr>
<td>DD</td>
<td>2,450 keV neutron</td>
<td>NR light and charge yields</td>
<td>External</td>
<td>N</td>
</tr>
<tr>
<td>DD</td>
<td>272 keV neutron</td>
<td>NR light and charge yields</td>
<td>External</td>
<td>Y</td>
</tr>
</tbody>
</table>
WIMP Discovery Potential

arXiv: 1802.06039

5 sigma discovery potential: $6.7 \times 10^{-48}$ (5.6 tonnes, 1000 days livetime)

Below Xenon1T sensitivity projection for 2-tonne-year exposure.