Projected WIMP sensitivity of the LUX-ZEPLIN dark matter experiment

Maria Elena Monzani for the LZ Collaboration

SLAC
NATIONAL ACCELERATOR LABORATORY
Kavli Institute for Particle Astrophysics and Cosmology

IDM, July 24, 2018
Moore’s Law of Direct Detection

Ge, NaI no discrimination

Ge, w/discrim.

LXe, w/discrim.

LUX

XENON-1T

LZ = 1.6 × 10^{-48} \text{ cm}^2

(XENON-nT)
LZ as a Discovery Instrument

Instrumentation conduits

Cathode high voltage feedthrough

Existing water tank

Gadolinium-loaded liquid scintillator veto

Liquid Xe HX

Outer detector PMTs

7 tonne active volume liquid Xe TPC. 10 tonnes total
The Xenon TPC Detector

SECTION VIEW OF LXE TPC

- Top PMT array
  - 253 PMTs
- Side Skin PMTs
- TPC field cage

GAS PHASE AND ELECTROLUMINESCENCE REGION

- LXe surface
- Weir trough
- Skin PMT
  - 131 Skin PMTs

HV CONNECTION TO CATHODE

- Cathode grid
- Reverse-field region
- Side skin PMT mounting plate
- Bottom PMT array
  - 241 PMTs
Measurement-driven detector model

Projected TPC light collection efficiency 12%

Characterization of LZ PMTs @ Imperial College London

LZ Reflectivity Measurements @ LIP Coimbra

arXiv: 1801.01597

arXiv: 1612.07965
High Statistics Calibrations in LUX

Electron Recoil (ER) (Tritiated methane)

Nuclear Recoil (NR) (DD neutron gun)

LUX 2015: 1.1 keVnr cutoff

LUX 2014: 3 keVnr cutoff

arXiv: 1512.03506
LZ Detector Response

NR, light

ER, light

NR, charge

ER, charge

arXiv: 1802.06039
## Complete Model of LZ Detector

<table>
<thead>
<tr>
<th>Detector Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Detection Efficiency (PDE)</td>
<td></td>
</tr>
<tr>
<td>PDE in liquid ((g_1)) [phd/ph]</td>
<td>0.119</td>
</tr>
<tr>
<td>PDE in gas ((g_{1,\text{gas}})) [phd/ph]</td>
<td>0.102</td>
</tr>
<tr>
<td>Single electron size [phd]</td>
<td>83</td>
</tr>
<tr>
<td>Effective charge gain ((g_2)) [phd/e]</td>
<td>79</td>
</tr>
<tr>
<td>PTFE-LXe reflectivity</td>
<td>0.977</td>
</tr>
<tr>
<td>LXe photon absorption length [m]</td>
<td>100</td>
</tr>
<tr>
<td>PMT efficiency at 175 nm</td>
<td>0.269</td>
</tr>
<tr>
<td>Other Key Parameters</td>
<td></td>
</tr>
<tr>
<td>Single phe trigger efficiency</td>
<td>0.95</td>
</tr>
<tr>
<td>Single phe relative width (Gaussian)</td>
<td>0.38</td>
</tr>
<tr>
<td>S1 coincidence level</td>
<td>3-fold</td>
</tr>
<tr>
<td>S2 electron extraction efficiency</td>
<td>0.95</td>
</tr>
<tr>
<td>Drift field ([V \text{ cm}^{-1}])</td>
<td>310</td>
</tr>
<tr>
<td>Electron lifetime [(\mu\text{s})]</td>
<td>850</td>
</tr>
</tbody>
</table>
Populate edges: Skin and Outer detector tag
# External Backgrounds

- **Activity intrinsic to the detector construction materials**
  - Main concerns: PMTs, PMT Bases, Cryostat, PTFE, etc.
- **Comprehensive radio-assay campaign for detector materials**:
  - gamma-screening, ICP-MS, NAA; ~1000 assays so far, ~600 to go
- **Excellent self-shielding properties of LXe, plus active veto system to suppress (& characterize residual) backgrounds**
- **Expected counts in 1,000 live days in an indicative 5.6-tonne fiducial mass in [1.5-6.5] keV_{ee} (ER) and [6-30] keV (NR):**

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Mass (kg)</th>
<th>(^{238} \text{U}_{e} )</th>
<th>(^{238} \text{U}_{l} )</th>
<th>(^{232} \text{Th}_{e} )</th>
<th>(^{232} \text{Th}_{l} )</th>
<th>(^{60} \text{Co} )</th>
<th>(^{40} \text{K} )</th>
<th>n/yr</th>
<th>ER (cts)</th>
<th>NR (cts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMT systems</td>
<td>308</td>
<td>31.2</td>
<td>5.20</td>
<td>2.32</td>
<td>2.29</td>
<td>1.46</td>
<td>18.6</td>
<td>248</td>
<td>2.82</td>
<td>0.027</td>
</tr>
<tr>
<td>TPC systems</td>
<td>373</td>
<td>3.28</td>
<td>1.01</td>
<td>0.84</td>
<td>0.76</td>
<td>2.58</td>
<td>7.80</td>
<td>79.9</td>
<td>4.33</td>
<td>0.022</td>
</tr>
<tr>
<td>Cryostat</td>
<td>2778</td>
<td>2.88</td>
<td>0.63</td>
<td>0.48</td>
<td>0.51</td>
<td>0.31</td>
<td>2.62</td>
<td>323</td>
<td>1.27</td>
<td>0.018</td>
</tr>
<tr>
<td>Outer detector (OD)</td>
<td>22950</td>
<td>6.13</td>
<td>4.74</td>
<td>3.78</td>
<td>3.71</td>
<td>0.33</td>
<td>13.8</td>
<td>8061</td>
<td>0.62</td>
<td>0.001</td>
</tr>
<tr>
<td>All else</td>
<td>358</td>
<td>3.61</td>
<td>1.25</td>
<td>0.55</td>
<td>0.65</td>
<td>1.31</td>
<td>2.64</td>
<td>39.1</td>
<td>0.11</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Before S2/S1 discrimination)</td>
<td>subtotal</td>
<td>9</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Active Veto System

- 0.61 m thick Gd-loaded scintillator
- instrumented Xenon “skin”
- we can tag neutrons and gammas

In-situ monitoring of residual backgrounds

NR: Before Veto

~10 evts in 5.6 tonne FV

NR: After Veto

~1 event in 5.6 tonne FV
Backgrounds – Uniform through volume

- ER
- Rn/Kr β decay
- NR

Solar (pp)

Solar (8B)
Atmospheric, SN
Neutrino Backgrounds

- Elastic $\nu$-e interactions (signal is an electron recoil):
  - Solar neutrinos: $pp$, $^7\text{Be}$, $^{13}\text{N}$
  - Neutrinoless $\beta\beta$ decay of $^{136}\text{Xe}$

- Coherent elastic $\nu$-A interactions (irreducible background):
  - Solar Neutrinos: $^8\text{B}$ and hep (below nominal threshold)
  - Atmospheric and diffuse supernova neutrinos

- Expected counts in 1,000 live days in an indicative 5.6-tonne fiducial mass in [1.5-6.5] keV$_{ee}$ (ER) and [6-30] keV (NR):

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<th>$^{40}\text{K}$</th>
<th>n/yr</th>
<th>ER (cts)</th>
<th>NR (cts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics $^{136}\text{Xe}$ 2$\nu\beta\beta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>67</td>
<td>-</td>
</tr>
<tr>
<td>Solar neutrinos: $pp + ^7\text{Be} + ^{13}\text{N}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>255</td>
<td>-</td>
</tr>
<tr>
<td>Diffuse supernova neutrinos (DSN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Atmospheric neutrinos (Atm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>0.46</td>
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<td></td>
<td></td>
<td></td>
<td>subtotal</td>
<td>322</td>
</tr>
</tbody>
</table>

(Before S2/S1 discrimination)
Uniform ER Internal Backgrounds

- Kr, Ar requirement: 0.015 ppt (g/g) \( ^{\text{nat}} \text{Kr} \), 0.45 ppb (g/g) \( ^{\text{nat}} \text{Ar} \)
  - Demonstrated 2-pass \( ^{\text{nat}} \text{Kr} \) reduction at 10\(^9 \) (10\(^7 \) required)
  - Kr removal process also efficient at eliminating Ar

- Radon estimate: 1.81 \( \mu \text{Bq/kg} \) \(^{222} \text{Rn} \), 0.09 \( \mu \text{Bq/kg} \) \(^{220} \text{Rn} \)
  - Extensive Rn emanation assay campaign in progress
  - 1.53 \( \mu \text{Bq/kg} \) from Rn emanation, 0.28 \( \mu \text{Bq/kg} \) from dust

- Surface Contamination: Radon Daughters (\(^{210} \text{Pb} \)) and dust
  - \(^{210} \text{Pb} \), \(^{210} \text{Bi} \) plate-out: less than 0.5 mBq/m\(^2 \) on the TPC walls
  - Generic dust contamination < 500 ng/cm\(^2 \) on all wetted surfaces
### Uniform ER Internal Backgrounds

- Expected counts in 1,000 live days in an indicative 5.6-tonne fiducial mass in [1.5-6.5] keV$_{ee}$ (ER) and [6-30] keV (NR):

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<th>$^{232}$Th$_l$</th>
<th>$^{60}$Co</th>
<th>$^{40}$K</th>
<th>n/yr</th>
<th>ER (cts)</th>
<th>NR (cts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Contamination</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust (intrinsic activity, 500 ng/cm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Plate-out (PTFE panels, 50 nBq/cm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$^{210}$Bi mobility (0.1 µBq/kg LXe)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ion misreconstruction (50 nBq/cm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>0.16</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{210}$Pb (in bulk PTFE, 10 mBq/kg PTFE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>0.16</td>
<td>0.12</td>
</tr>
</tbody>
</table>

(Before S2/S1 discrimination) subtotal 40 0.39

<table>
<thead>
<tr>
<th>Xenon contaminants</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn (1.81 µBq/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>681</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$^{220}$Rn (0.09 µBq/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>111</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$^{nat}$Kr (0.015 ppt g/g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$^{nat}$Ar (0.45 ppb g/g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

(Before S2/S1 discrimination) subtotal 819 0
### Counts/1000 days: WIMP-search ROI

**Nominal:** 5.6 ton fiducial, 1000 live-days

~1.5 - 6.5 keV, single scatters, no coincident veto

<table>
<thead>
<tr>
<th>Background Source</th>
<th>ERs</th>
<th>NRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Components</td>
<td>9</td>
<td>0.07</td>
</tr>
<tr>
<td>Dispersed Radionuclides — Rn, Kr, Ar</td>
<td>819</td>
<td>—</td>
</tr>
<tr>
<td>Laboratory and Cosmogenics</td>
<td>5</td>
<td>0.06</td>
</tr>
<tr>
<td>Surface Contamination and Dust</td>
<td>40</td>
<td>0.39</td>
</tr>
<tr>
<td>Physics Backgrounds — 2β decay, neutrinos*</td>
<td>322</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Total (after 99.5%ER discrimination, 50% NR efficiency)</strong></td>
<td><strong>5.97</strong></td>
<td><strong>0.52</strong></td>
</tr>
</tbody>
</table>

* not including 8B and hep
Residual background spectra, nominal FV

Nominal: 5.6 ton fiducial, 1000 live-days
Single scatters, no coincident veto, before ER/NR discrimination

Electron Recoils

Nuclear Recoils

Input to PLR Analysis
Putting it all together: LZ Sensitivity Estimate

LZ Sensitivity Paper available on arXiv: 1802.06039

Projected background spectra → WIMP spectra → LZ detector response + NEST → PDFs: (S1, S2) → Profile likelihood ratio (PLR)

NEST models charge + light production in LXe: anchored to LUX + world data

![Graph showing Electron Recoil (ER) Background and Nuclear Recoil (NR) Signal]

Mathematical formula for profile likelihood ratio:

\[ q_\sigma = -2 \ln \lambda = -2 \ln \left( \frac{L(\sigma, \hat{\nu})}{L(\hat{\sigma}, \hat{\nu})} \right) \]

- **q_\sigma**: parameter of interest
- **\lambda**: nuisance parameters
- **n**: observed number of data events
- **\mu**: expected number of data events
- **n_\text{sig}**: number of signal events
- **n_\text{bkg}**: number of events of bkg source b
- **N_{\text{bkg}}**: number of bkg sources

Gaussian function and Poisson distribution used in calculation.
Simulated signal & background, 1000-day run

Expected ~ 36 NR from ν CNS

→ low-energy calibrations!!!

→ light signal (S1)

→ charge signal (S2)
Projected WIMP Sensitivity: Spin Independent

Nominal exposure: 1000 live-days, 5.6 tonne fiducial

LZ sensitivity (1000 live days)
- Projected limit (90% CL one-sided)
- ±1σ expected
- +2σ expected

LUX (2017)
XENON1T (2017)
PandaX-II (2017)

pMSSM11 (MasterCode, 2017)

1 neutrino event
Neutrino discovery limit (CEvNS)

1.6 × 10^{-48} \text{ cm}^2 @ 40 \text{ GeV/c}^2
3σ and 5σ discovery potential

Nominal exposure: 1000 live-days, 5.6 tonne fiducial

LZ sensitivity (1000 live days)
- Projected limit (90% CL one-sided)
- Projected 3σ significance
- Projected 5σ significance

pMSSM11
(MasterCode, 2017)

90% CL XENON1T (2 ty)

1 neutrino event

Neutrino discovery limit (CEνNS)

3σ: $3.8 \times 10^{-48} \text{ cm}^2 \ @ \ 40 \text{ GeV/c}^2$

5σ: $6.7 \times 10^{-48} \text{ cm}^2 \ @ \ 40 \text{ GeV/c}^2$
Sensitivity vs Radon level

Nominal exposure: 1000 live-days, 5.6 tonne fiducial

LZ sensitivity (1000 live days)

Projected limit (90% CL one-sided)

Sensitivity Estimate is robust vs. Radon Level
Spin-dependent sensitivity

Naturally occurring Xe: \(\approx 50\%\) odd-neutron isotopes
\((26.4\% \text{ }^{129}\text{Xe} \text{ and } 21.2\% \text{ }^{131}\text{Xe} \text{ by mass})\)

SD WIMP-neutron:
\(2.7 \times 10^{-43} \text{ cm}^2 \text{ @ } 40 \text{ GeV/c}^2\)

SD WIMP-proton:
\(8.1 \times 10^{-42} \text{ cm}^2 \text{ @ } 40 \text{ GeV/c}^2\)

Spin structure functions from Klos et al, Phys. Rev. D89, 022901 (2014)
Summary and Conclusions

- Data-driven model of LZ sensitivity:
  - As-built detector design
  - Measured component properties
  - Accurate LXe response model

- Detailed background model
  - Powerful vetoing strategy
  - Dominated by dispersed radionuclides
  - PDF model of residual backgrounds

- LZ commissioning in 2020:
  - 1,000 day nominal science run
  - SI WIMP sensitivity: $1.6 \times 10^{-48}$ cm$^2$
  - $3\sigma$ discovery potential: $3.8 \times 10^{-48}$ cm$^2$