Dark Matter: LUX and LZ

Harry Nelson / LUX, LZ & UCSB

DBD16 at Osaka

November 10, 2016
Benchmark Process

Spin-Independent Glue: n/p indifferent, coherent, $\sigma \approx A^{(2-4)}$

Xenon: $A \approx 131$
### Xenon

- **Dense Liquid**
- **Natural Scintillator**
- Long lived radioisotopes are $2\nu\beta\beta$ decays, very long half lives
- 9 `stable’ isotopes
- 2 with unpaired neutron

<table>
<thead>
<tr>
<th>$^A_Z\text{Xe}$</th>
<th>$\tau_{1/2}$ or $f$</th>
<th>$J^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{122}\text{Xe}$</td>
<td>20 h</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{123}\text{Xe}$</td>
<td>2.1 h</td>
<td>$(1/2)^+$</td>
</tr>
<tr>
<td>$^{124}\text{Xe}$</td>
<td>0.10 %</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{125}\text{Xe}$</td>
<td>17 h</td>
<td>$(1/2)^+$</td>
</tr>
<tr>
<td>$^{126}\text{Xe}$</td>
<td>0.09 %</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{127}\text{Xe}$</td>
<td>36 d</td>
<td>$(1/2)^+$</td>
</tr>
<tr>
<td>$^{128}\text{Xe}$</td>
<td>1.91 %</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{129}\text{Xe}$</td>
<td>26.4 %</td>
<td>$(1/2)^+$</td>
</tr>
<tr>
<td>$^{130}\text{Xe}$</td>
<td>4.1 %</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{131}\text{Xe}$</td>
<td>21.2 %</td>
<td>$(3/2)^+$</td>
</tr>
<tr>
<td>$^{132}\text{Xe}$</td>
<td>26.9 %</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{133}\text{Xe}$</td>
<td>5.2 d</td>
<td>$(3/2)^+$</td>
</tr>
<tr>
<td>$^{134}\text{Xe}$</td>
<td>10.4 %</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{135}\text{Xe}$</td>
<td>9.1 h</td>
<td>$(3/2)^+$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>8.9 % ($2.2\times10^{21}$ y)</td>
<td>0$^+$</td>
</tr>
</tbody>
</table>
The Milky Way

\[ n \approx \frac{0.3 \text{ GeV}}{M_D c^2} \times \frac{1}{\text{cm}^3} \]

\[ \beta \approx 0.8 \times 10^{-3} \]
Signal: Nuclear Recoils (NR) from WIMPs
Lead, South Dakota

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Sanford Underground Research Facility

Davis Cavern 1480 m (4200 mwe) LUX Water Tank

LUX/LZ Here
The LUX collaboration

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Kevin Lesko Senior Scientist
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Peter Sorensen Scientist
Simon Florucci Project Scientist
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University of South Dakota
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Chao Zhang Postdoc

University of Wisconsin
Kimberly Palladino PI, Asst Professor
Shaun Alsum Graduate Student
LUX Installed (Fall 2012)
In the tank and detailed cross section

- 370 kg xenon
- 250 kg active region
- \( \approx 100 \) kg fiducial mass
Liquid Xenon TPC Principle

Z position from S1 – S2 timing

X-Y positions from S2 light pattern

Reject gammas (Electron Recoils) by charge (S2) to light (S1) ratio.

Baseline > 99.5% rejection.

ionization electrons

UV scintillation photons (~175 nm)
Typical Event in LUX

- S1 summed across all channels: 0 to 0.8 amplitude (phe/10 ns) vs time (μs)
- S2 summed across all channels: 0 to 12 amplitude (phe/10 ns) vs time (μs)
- 95% single photoelectrons > threshold
- Triggered on S2

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Gamma Ray Environment

Signal: <10 keV$_{ee}$
HNN Calibration

NR: n from DD: double scatter, event by event $E_{\text{Xe}}$

ER: $T=^3\text{H}$ in $\text{CH}_3\text{T}$

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Double Scatter Neutrons – Ionization for NR

Energy from kinematics

Slices in energy

Sys. uncertainty due to
S2 corrections,
g2, and neutron
source energy spectrum

Sys. uncertainty due to position
reconstruction energy bias correction

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High Statistics LUX Calibrations

Electron Recoil (ER) Background
tritiated methane
(100,000’s)

Nuclear Recoil (NR) Signal
single-scatter DD neutrons

Cut/Count: <0.5% “leak”
LUX WIMP Search Data Guide

● WS2013 run: 95 live days
  ▶ First result, published 2014
  ▶ Improved with calibrations: published 2016
  □ Low mass WIMPs

● WS2014-16 run: 332 live days
  ▶ Calibrate drifts in the detector
  ▶ Raw data here

● Show combined limit curve
Combined Limit Curve

- DarkSide-50 2015
- XENON100 2016
- PandaX-II 2016
- LUX WS2013
- LUX WS2013+WS2014–16

WIMP-nucleon cross section [zb]

WIMP-nucleon cross section [cm²]

WIMP Mass [GeV/c²]
LZ = LUX + ZEPLIN

37 Institutions, 217 People

- Black Hills State University
- Brookhaven National Laboratory (BNL)
- Brown University
- Fermi National Accelerator Laboratory (FNAL)
- Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
- Lawrence Berkeley National Laboratory (LBNL)
- Lawrence Livermore National Laboratory (LLNL)
- Northwestern University
- Pennsylvania State University
- SLAC National Accelerator Laboratory
- South Dakota School of Mines and Technology
- South Dakota Science and Technology Authority (SDSTA)
- STFC Rutherford Appleton Laboratory (RAL)
- Texas A&M University
- University at Albany (SUNY)
- University of Alabama
- University of California (UC), Berkeley
- University of California (UC), Davis
- University of California (UC), Santa Barbara
- University of Maryland
- University of Massachusetts
- University of Michigan
- University of Rochester
- University of South Dakota
- University of Wisconsin-Madison
- Washington University in St. Louis
- Yale University

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At Oxford, August 2016
LZ 7 t LXe active – fits in LUX Water Tank

Passed DOE CD-1, CD-2, partially CD-3;
Complete CD-3 expected Jan. `17
Operations: Apr. `20
LZ System
7 tonne active mass
liquid Xe TPC, 10 tonnes total

Cathode
high voltage
feedthrough

Liquid Xe
heat exchanger

Neutron beampipe

Instrumentation conduits

Existing water tank

Gadolinium-loaded liquid scintillator

Outer detector PMTs
Impact of the Outer Detector

Fiducial mass fraction: from $\approx 50\%$ to $\approx 80\%$

In case of a suspected signal, the Outer Detector provides cross checks on backgrounds
Backgrounds – Uniform Through LXe Volume

\[ \nu \]
- Solar (pp)

\[ \nu \]
- Solar (\(^8\)B)
- Atmospheric, SN

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ER

Kr/Rn \( \beta \) decay

NR
LZ Simulation - shapes crucial

(Normalization not representative of rates)
NR Background Tallies – 1000 days, 5.6 t

- $^8$B Nuclear Recoils – like 6 GeV WIMP
  - Sensitive to low threshold detector response
  - $\approx 7$ (baseline) to $\approx 300$ (goal)

- Other nuclear recoils
  - $\approx 0.5$ nearby material, strong spatial dependence
    - dominant: dust!
  - $\approx 0.7$ due to neutrinos, uniform in LXe
    - dominant: atmospheric
ER Background Tallies – 1000 days, 5.6 t

- pp solar $\approx 255$
- $^{136}\text{Xe } 2\nu\beta\beta \approx 67$ (very low energy)
- Nearby material $\approx 11$ (strong spatial dependence in LXe)

- Internal Radioactive Gases, uniform in LXe
  - 72 (goal) to $\approx 1000$ (baseline)
  - Dominantly $^{222}\text{Radon emanation}$
  - Vigorous screening program
Baseline Simulation 1000 days, 5.6 t

- Background - ER
- WIMP (3σ significance, 40 GeV) $6 \times 10^{-48}$ cm$^2$
- $^8$B

The graph shows the log10(S2/S1) vs. S1 [phd] with different energy levels indicated:
- 1 keV$_{ee}$
- 5 keV$_{nr}$
- 3 keV$_{ee}$
- 14 keV$_{nr}$
- 5 keV$_{ee}$
- 22 keV$_{nr}$

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Projected Sensitivity (Spin Independent)

LZ projected, 1000 days, 5.6 tonnes

- 90% CL Median CDR   CD1/3a
- 90% CL Median (Baseline) TDR, CD3
- 90% CL Median (Goal) TDR, CD3

LZ Baseline $\sigma(40 \text{ GeV}) = 2.3 \times 10^{-48} \text{ cm}^2$
LZ Goal $\sigma(40 \text{ GeV}) = 1.1 \times 10^{-48} \text{ cm}^2$

LZ Baseline $\approx 7$ $^8$B NR
LZ Goal $\approx 300$ $^8$B NR
$^{136}\text{Xe } 0\nu\beta\beta - 1000 \text{ days, } 5.6 \text{ t in LZ}$

● Challenges

▸ Experiment optimized for $1.5-10 \text{ keV}_{ee}$
▸ More shielding of $^{208}\text{Tl}$, $^{214}\text{Pb}$ gammas needed
▸ Power of spatial shape, Bragg ID, etc..

● Preliminary estimates... $\approx 1\text{t fiducial}$

▸ Unenriched... $\approx 10^{26} \text{ y}$
▸ $90\% \ ^{136}\text{Xe}$... $\approx 10^{27} \text{ y}$

● If a WIMP signal emerges, change the isotopic abundance Xe target, to understand WIMP interaction with nuclei
Summary

● 2-phase liquid xenon TPCs push the frontier of WIMP sensitivity, and LUX led the way for a few years

● LUX has substantially advanced the art of calibration

● LZ will operate in April 2020 and is projected to achieve best spin independent sensitivity better than $3 \times 10^{-48} \text{cm}^2$, and start to see irreducible neutrino background
THANKS!
Astrophysics... 84.5% of the matter in the universe is different than us.

Weakly Interacting Massive Particle (WIMP)
The WIMP

\[ \chi^0 \rightarrow q, \ell, \gamma, g \ldots \]

\[ \Omega_{\chi^0} / \Omega_{\text{ordinary}} \approx 5 \]

\[ M_{\chi} c^2 \approx 100 \text{ GeV} \]

`Weak Scale`

\[ \bar{q}, \bar{\ell}, \gamma, g \ldots \]
Direct Detection

\[ \chi^0 \rightarrow q, \ell, \gamma, g \ldots \]

\[ \sigma \approx 10^{-(40 \to 50)} \text{cm}^2 \]

\[ 10^{-(4 \to 14)} \text{pb} \]
# Comparison of Nobles

<table>
<thead>
<tr>
<th>Element</th>
<th>A (nat)</th>
<th>Atm (ppmv)</th>
<th>bp (K)</th>
<th>Sc. E. (eV)</th>
<th>Density (gm/cm³)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>4.00</td>
<td>5.2</td>
<td>4.2</td>
<td>16</td>
<td>0.13</td>
<td>Great Pulse Shape Disc</td>
</tr>
<tr>
<td>Neon</td>
<td>20.2</td>
<td>18</td>
<td>27</td>
<td>16</td>
<td>1.2</td>
<td>“</td>
</tr>
<tr>
<td>Argon</td>
<td>39.9</td>
<td>9300</td>
<td>87</td>
<td>9.8</td>
<td>1.4</td>
<td>“</td>
</tr>
<tr>
<td>Krypton</td>
<td>83.8</td>
<td>1.1</td>
<td>121</td>
<td>8.3</td>
<td>2.4</td>
<td>(^{85}\text{Kr}) (Reactors)</td>
</tr>
<tr>
<td>Xenon</td>
<td>131.3</td>
<td>0.09</td>
<td>165</td>
<td>7.1</td>
<td>3.1</td>
<td>Lower energy scint/lumi</td>
</tr>
<tr>
<td>Radon</td>
<td>≈222</td>
<td>(10^{-19})</td>
<td>211</td>
<td>4.4</td>
<td></td>
<td>Emanation afflicts above</td>
</tr>
</tbody>
</table>

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LUX being built
Signal and Background

Nucleus Recoils
$E_r \approx 30 \text{ keV}_{\text{nr}}$
$v/c \approx 0.8 \times 10^{-3}$

Electron Recoils
$E_r \approx 6 \text{ keV}_{\text{ee}}$
$v/c \approx 0.15$

$\chi^0$ (calibrate: neutron)

$\gamma$, $e^-$ (calibrate: tritium injection)

Discrimination – detector’s ability to distinguish these
Solution: Time / Space Bins

4 event date bins X 4 z-slices = 16 ‘segments’
NOTE: This is still the old run. Still needs to be updated with the 1 year’s worth of new data.

Xenon is the *best* element for neutron coupling (while fluorine is best for protons)
## Fiducial Mass Fraction

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Active Mass (kg)</th>
<th>Fiducial Mass (kg)</th>
<th>F/A (%)</th>
<th>Best Sensitivity (cm²)</th>
<th>Livetime (y)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon 10</td>
<td>13.9</td>
<td>5.4</td>
<td>39</td>
<td>4.5×10⁻⁴⁴</td>
<td>0.16</td>
<td>2008</td>
</tr>
<tr>
<td>Zeplin III</td>
<td>12.6</td>
<td>5.6</td>
<td>44</td>
<td>4×10⁻⁴⁴</td>
<td>0.73</td>
<td>2012</td>
</tr>
<tr>
<td>Xenon 100</td>
<td>66</td>
<td>34</td>
<td>51</td>
<td>2×10⁻⁴⁵</td>
<td>0.61</td>
<td>2013</td>
</tr>
<tr>
<td>LUX</td>
<td>248</td>
<td>118</td>
<td>48</td>
<td>7.6×10⁻⁴⁶</td>
<td>0.26</td>
<td>2015</td>
</tr>
<tr>
<td>LUX</td>
<td>248</td>
<td>100</td>
<td>40</td>
<td>2×10⁻⁴⁶</td>
<td>0.90</td>
<td>2016</td>
</tr>
<tr>
<td>DEAP-3600</td>
<td>3600</td>
<td>1000</td>
<td>28</td>
<td>1×10⁻⁴⁶</td>
<td>3</td>
<td>2017</td>
</tr>
<tr>
<td>Xenon 1T</td>
<td>2000</td>
<td>1160</td>
<td>58</td>
<td>2×10⁻⁴⁷</td>
<td>2</td>
<td>2018</td>
</tr>
<tr>
<td>LZ</td>
<td>7000</td>
<td>5600</td>
<td>80</td>
<td>3×10⁻⁴⁸</td>
<td>3</td>
<td>2021</td>
</tr>
</tbody>
</table>

Fiducial mass fraction: from ≈50% to ≈80%

In case of a suspected signal, the Outer Detector provides cross checks on backgrounds

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## Backgrounds (5.6 t, 1000 live-days) (I)

<table>
<thead>
<tr>
<th>Source</th>
<th>ER</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric neutrinos</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>HEP solar neutrinos</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Diffuse solar neutrinos</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>$\text{pp}^+\text{Be}^+\text{N}$ solar neutrinos</td>
<td>255</td>
<td></td>
</tr>
<tr>
<td>$^{136}\text{Xe} 2\nu\beta\beta$</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal Physics (Uniform in LXe fiducial)</strong></td>
<td>322</td>
<td>0.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>ER</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Internal Surface Contamination</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Laboratory Walls, Cosmogenics</td>
<td>4.3</td>
<td>0.07</td>
</tr>
<tr>
<td>R11410 3” PMTs</td>
<td>1.5</td>
<td>0.01</td>
</tr>
<tr>
<td>PMT Cabling</td>
<td>1.4</td>
<td>-</td>
</tr>
<tr>
<td>Cryostat Vessel</td>
<td>0.6</td>
<td>0.01</td>
</tr>
<tr>
<td>20 other components</td>
<td>3 (27%)</td>
<td>0.05 (10%)</td>
</tr>
<tr>
<td><strong>Subtotal External Backgrounds (Non-Uniform in LXe fiducial)</strong></td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>333</td>
<td>1.2</td>
</tr>
</tbody>
</table>
## Backgrounds (5.6 t, 1000 live-days) (II)

<table>
<thead>
<tr>
<th>Source</th>
<th>ER</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtotal Previous Page</td>
<td>333</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>ER (Baseline / Goal)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{222}$Radon – (2 / 0.1) $\mu$Bq/kg</td>
<td>722</td>
<td>36</td>
</tr>
<tr>
<td>nat$^{85}$Krypton (0.075 / 0.015) ppt g/g</td>
<td>125</td>
<td>25</td>
</tr>
<tr>
<td>$^{220}$Radon aka Thoron – (0.1 / 0.005) $\mu$Bq/kg</td>
<td>122</td>
<td>6</td>
</tr>
<tr>
<td>$^{210}$Bismuth (0.1 / 0.005) $\mu$Bq/kg</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>natArgon (0.45) ppb g/g</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal Internal Backgrounds (Uniform in LXe fiducial)</strong></td>
<td>1012</td>
<td>72</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1344</td>
<td>405</td>
</tr>
<tr>
<td>Efficiency below median of NR band</td>
<td>0.005</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total below median of NR band</strong></td>
<td>6.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Radon Budget Estimate (Preliminary)

• To aid planning of assay schedule, identify areas likely to need mitigation
  − Added Xe gas mitigation system to reduce by 90%
• Estimates based on most comparable measurements
  − Some upper limits
  − Measured at room temperature but most cold * in LZ
    • Corrected only (conservatively) for capacitors, PMT cabling
• Dust
• Total 18.3 mBq
  − On track to achieve requirements
Axions (LUX 95 days, and LZ)

(projection for 3 years)

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