An Effective Field Theory Analysis of the LUX WIMP Search

Nicole A. Larsen
Yale University
The LUX Collaboration

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Xenon as a Direct Detection Target

- High density (3 g/cm$^3$) and high atomic mass (A = 131 g/mol)
- Scintillates brightly in the near-UV (178 nm) with fast (ns) response time
- Excellent ionization threshold and long electron drift lengths (~1 m)
- High abundance of odd isotopes => spin-dependent sensitivity.

- No long-lived intrinsic backgrounds
- Scalable to multi-ton size
- Self-shielding possible with 3D reconstruction
Dual-Phase TPCs: Principle of Operation

- The target is cooled to condensation point => liquid topped by a thin layer of gas.
- An incident particle excites/ionizes a target atom, which emits primary scintillation (“S1”) light.
- Ionization electrons produced are drifted upwards by an applied electric field and extracted into the gas phase, where they are accelerated rapidly and caused to scintillate again (“proportional” or “S2” light).

3D imaging possible:
Timing between the S1 and S2 pulses yields z-position.
PMT hit patterns yield xy-position.

ER/NR discrimination possible:
Nuclear recoils produce dense tracks
Electron recoils produce less-dense tracks
=> (S2/S1)$_\gamma$ >> (S2/S1)$_{\text{neutron}}$
The Large Underground Xenon Experiment

370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass

LUX Internals

122 2” PMTs (Hamamatsu R8778)
- QE (175 nm) ~33%
- U/Th ~9/3 mBq/PMT

HV Grids

Radiation shield

PTFE reflector panels

Dodecagonal field cage

Copper PMT holding plate

Counterweight

2 x 61 PMT Array

PTFE “trifoils”
LUX First Underground Run - Highlights

• 85.3 livedays of data collected
• Xenon purity: e⁻ drift length 87-135 cm
  • Continuous circulation at 250 kg/day through an external purifier
  • Monitored weekly using $^{83m}$Kr injections
• Drift field: 181 V/cm (speed 1.5 mm/\(\mu\)s) with 99.6% ER discrimination
• Light collection efficiency: 14%
  (includes detector geometry and PMT QE; 3D corrections provided by $^{83m}$Kr calibrations)
• Fiducial mass: 118.3 +/- 6.5 kg
  • Selection based on $\alpha$ events from grids and teflon
• WIMP-search window: ~3-25 keVnr
## Event Selection and Cuts

<table>
<thead>
<tr>
<th>Cut</th>
<th>Explanation</th>
<th>Events Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Triggers</td>
<td>S2 Trigger &gt;99% for S2_raw&gt;200 phe</td>
<td>83,673,413</td>
</tr>
<tr>
<td>Detector Stability</td>
<td>Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages</td>
<td>82,918,901</td>
</tr>
<tr>
<td>Single Scatter Events</td>
<td>Identification of S1 and S2. Single Scatter cut.</td>
<td>6,585,686</td>
</tr>
<tr>
<td>S1 energy</td>
<td>Accept 2-30 phe (energy ~ 0.9-5.3 keVee, ~3-18 keVnr)</td>
<td>26,824</td>
</tr>
<tr>
<td>S2 energy</td>
<td>Accept 200-3300 phe (&gt;8 extracted electrons)</td>
<td>20,989</td>
</tr>
<tr>
<td></td>
<td>Removes single electron / small S2 edge events</td>
<td></td>
</tr>
<tr>
<td>S2 Single Electron Quiet Cut</td>
<td>Cut if &gt;100 phe outside S1+S2 identified +/-0.5 ms around trigger (0.8% drop in livetime)</td>
<td>19,796</td>
</tr>
<tr>
<td>Drift Time Cut away from grids</td>
<td>Cutting away from cathode and gate regions, 60 &lt; drift time &lt; 324 us</td>
<td>8731</td>
</tr>
<tr>
<td>Fiducial Volume radius and drift cut</td>
<td>Radius &lt; 18 cm, 38 &lt; drift time &lt; 305 us, 118 kg fiducial</td>
<td>160</td>
</tr>
</tbody>
</table>

Only simple, obvious cuts – no tuning beyond selecting a threshold, higher energy cutoff, and fiducial volume.
The LUX First WIMP-Search Result

- After all selection cuts, 160 candidate events left in the fiducial volume
- Distribution is consistent with electron recoil background and no WIMP signal with a p-value of 0.35 from Profile-Likelihood Ratio Analysis with incorporated background models, detector effects, and efficiencies
The LUX First WIMP-Search Result And Beyond...

- To date, LUX has set the world’s best limit on spin-independent WIMP-nucleon elastic scattering cross-section:
  \[7.6 \times 10^{-46} \text{ cm}^2\] for 33 GeV-WIMPs

- Since the end of the first run:
  - New NR calibration using mono-energetic neutrons from DD source \(\Rightarrow\) improved sensitivity at low masses
  - Re-analysis with improved low energy threshold to be published this summer

- 300-live-day run currently underway
  - Extending sensitivity by a factor of \(\sim 5\)
  - Discovery still possible!

LUX 2013 result: PRL.112.091303 (arXiv:1310.8214)
Direct Detection Basics

• In general, the formula for scattering rate of WIMPs off a target is:

\[
\frac{dR}{d|q^2|} = \langle \frac{\rho_0}{m_\chi m_A} \frac{d\sigma}{d|q^2|} \rangle
\]

<...> denotes average over the WIMP velocity distribution

• The differential cross-section for spin-independent WIMP-nucleon elastic scattering is:

\[
\frac{d\sigma}{d|q^2|} = \frac{1}{\pi v^2} |M|^2 = \frac{\sigma_0 A}{4 \mu_A^2 v^2} F^2(q) = \frac{\sigma_0}{4 \mu_N^2 v^2} A^2 F^2(q)
\]

We can only factor the scattering matrix amplitude $|M|^2$ in this way if the interaction does not vanish for small momentum transfers $q$.

SI, SD interactions are the only interactions that do not vanish in the zero-momentum-transfer limit – this is why direct detection experiments like LUX typically only present SI and SD limits.
New WIMP-Nucleon Interactions

- SI+SD-only analyses assume that momentum transfers involved in WIMP-nucleus scatters are nonrelativistic.

- However:
  - The usual SI and SD interactions could be suppressed...
  - Momentum transfer is not necessarily small on a parton scale...

There are several momentum- and velocity-dependent interactions also allowed by basic symmetry considerations.

- Novel nuclear responses such as angular-momentum-dependent (LD) and angular-momentum/spin-dependent (LSD) responses are allowed.
- These LD and LSD responses can interfere with the SI and SD responses.

Anand et al. arXiv: 1308.6288, 1405.6690
Cirelli et al. arXiv:1307.5955
Studying the New Interactions

**GOAL 1:** Investigate the extent to which momentum/velocity-dependent interactions affect our signal in xenon.

**GOAL 2:** For a given target material (xenon), optimize analysis techniques to best probe these momentum/velocity-dependent interactions.

**GOAL 3:** (General) Check that the array of direct detection target materials currently in use do not leave any “blind spots” in WIMP parameter space.
The Effective Field Theory Setup

- WIMP-nucleon elastic scattering is analogous to a four-fermion contact interaction in standard weak interaction theory.

\[
\mathcal{L}_{\text{int}} = c \psi_{\chi}^* O_{\chi} \psi_{\chi} \psi_N^* \mathcal{O}_N \psi_N = \sum_{i=1}^{N} \left( c_i^{(n)} O_i^{(n)} + c_i^{(p)} O_i^{(p)} \right)
\]

- The general interaction Lagrangian:

- Restrict to operators \( O_i \) that are Galilean-invariant and Hermitian.
- Remaining \( O_i \)'s are combinations of WIMP spin \( S_\chi \) nucleon spin \( S_N \), incident velocity \( \nu^2 \), and momentum transfer \( q^2 \).
- Allow the \( O_i \)'s to be at most quadratic in \( \nu \) (i.e. restrict to exchange of a spin-0 or spin-1 boson) and \( q \) (absorb higher powers of \( q \) into form factors).
The Set of Allowed EFT Operators

- Each nuclear form factor $F_{ij}$ associated with the EFT operators can be written as a linear combination of five macroscopic nuclear responses that depend only on the nuclear physics: (arXiv:1203.3542)

\[
\begin{align*}
O_1 &= 1 \chi 1_N \\
O_2 &= (v^\perp)^2 \\
O_3 &= i \vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp) \\
O_4 &= \vec{S}_\chi \cdot \vec{S}_N \\
O_5 &= i \vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp) \\
O_6 &= (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N}) \\
O_7 &= \vec{S}_N \cdot \vec{v}^\perp \\
O_8 &= \vec{S}_\chi \cdot \vec{v}^\perp \\
O_9 &= i \vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N}) \\
O_{10} &= i \vec{S}_N \cdot \frac{\vec{q}}{m_N} \\
O_{11} &= i \vec{S}_\chi \cdot \frac{\vec{q}}{m_N}
\end{align*}
\]

- SI Interaction
- SD Interaction
- Cannot obtain at lowest order
Converting Between the EFT Operators and the Macroscopic Nuclear Responses

<table>
<thead>
<tr>
<th></th>
<th>M (SI)</th>
<th>$\Sigma''$ (SD long.)</th>
<th>$\Sigma'$ (SD trans.)</th>
<th>$\Delta$ (LD)</th>
<th>$\Phi''$ (LSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_1$</td>
<td>$q$-indep.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$O_3$</td>
<td></td>
<td>$\sim q^4$, $q^2v^2$</td>
<td></td>
<td></td>
<td>$\sim q^4$</td>
</tr>
<tr>
<td>$O_4$</td>
<td></td>
<td>$q$-indep.</td>
<td>$q$-indep.</td>
<td>$\sim q^4$</td>
<td></td>
</tr>
<tr>
<td>$O_5$</td>
<td></td>
<td>$\sim q^4$, $q^2v^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$O_6$</td>
<td></td>
<td>$\sim q^4$</td>
<td></td>
<td></td>
<td>$\sim q^4$</td>
</tr>
<tr>
<td>$O_7$</td>
<td></td>
<td></td>
<td>$\sim q^2$, $v^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$O_8$</td>
<td></td>
<td>$\sim q^2$, $v^2$</td>
<td></td>
<td>$\sim q^2$</td>
<td></td>
</tr>
<tr>
<td>$O_9$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sim q^2$</td>
</tr>
<tr>
<td>$O_{10}$</td>
<td></td>
<td></td>
<td></td>
<td>$\sim q^2$</td>
<td></td>
</tr>
<tr>
<td>$O_{11}$</td>
<td></td>
<td>$\sim q^2$</td>
<td></td>
<td>$\sim q^2$</td>
<td></td>
</tr>
</tbody>
</table>
Comparing Target Materials

- Estimate the number of predicted events as:

\[
\frac{dN}{dE_R} \sim 5000 \text{keV}^{-1} \left( \frac{\text{exposure}}{\text{kg} \cdot \text{day}} \right) \left( \frac{100 \text{GeV}}{m_\chi} \right)^3 L^2_{\text{int}}
\]

- Comparing the interaction terms for different targets:

<table>
<thead>
<tr>
<th></th>
<th>(S_n^2)</th>
<th>(S_p^2)</th>
<th>(L_n^2)</th>
<th>(L_p^2)</th>
<th>((S_n \cdot L_n)^2)</th>
<th>((S_p \cdot L_p)^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>(8 \cdot 10^{-5})</td>
<td>0.2</td>
<td>0.04</td>
<td>0.05</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Na</td>
<td>0.0004</td>
<td>0.06</td>
<td>0.1</td>
<td>0.8</td>
<td>5.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Ge</td>
<td>0.02</td>
<td>(5 \cdot 10^{-6})</td>
<td>1.1</td>
<td>0.003</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>I</td>
<td>0.004</td>
<td>0.07</td>
<td>0.4</td>
<td>2.</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Xe</td>
<td>0.02</td>
<td>(2 \cdot 10^{-5})</td>
<td>0.4</td>
<td>0.04</td>
<td>500</td>
<td>300</td>
</tr>
</tbody>
</table>

(arXiv:1211.2818)

- Xenon is sensitive to not only SD WIMP-neutron interactions, but also to the new LD (\(\Delta\)) and LSD (\(\Phi''\)) interactions for both nucleons.
SI and LD WIMP-n Recoil Spectra

- $O_1$ (the usual SI interaction) and $O_{11}$ both produce an SI response, but the spectra have different slopes due to different $q$-dependence.
- $O_5$ and $O_8$ each produce both an LD and an SI response, again with different $q$-dependence.
- For $m_{\text{WIMP}}$ large, the EFT spectra stay relatively flat out to $\sim$few hundred keV.
The two types of SD response (transverse and longitudinal to the momentum transfer $q$) exhibit distinctly different behaviors.

Again the slope of the spectrum depends on the $q$-dependence of the operator.

$O_3$ (green) is the only LSD operator. Its spectrum increases sharply to around 50 keV and does not begin to decrease until ~300 keV for heavy WIMPs.
## Optimizing the WIMP-Search Window

Table: The minimum upper bound on the WIMP-search window in keVnr for the WIMP-search region to contain 50% or 90% of the integrated spectrum

<table>
<thead>
<tr>
<th></th>
<th>Operator</th>
<th>50-GeV WIMP</th>
<th>500-GeV WIMP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td>90%</td>
</tr>
<tr>
<td>SI</td>
<td>Standard SI</td>
<td>10.8</td>
<td>27.3</td>
</tr>
<tr>
<td></td>
<td>O₁</td>
<td>9.9</td>
<td>24.6</td>
</tr>
<tr>
<td></td>
<td>O₁₁</td>
<td>16.4</td>
<td>34.4</td>
</tr>
<tr>
<td>SI + LD</td>
<td>O₅</td>
<td>15.3</td>
<td>32.8</td>
</tr>
<tr>
<td></td>
<td>O₈</td>
<td>9.3</td>
<td>23.0</td>
</tr>
<tr>
<td>SD</td>
<td>Standard SD</td>
<td>8.6</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td>O₄</td>
<td>10.0</td>
<td>27.6</td>
</tr>
<tr>
<td></td>
<td>O₆</td>
<td>33.6</td>
<td>64.1</td>
</tr>
<tr>
<td></td>
<td>O₉</td>
<td>14.4</td>
<td>38.6</td>
</tr>
<tr>
<td></td>
<td>O₁₀</td>
<td>22.2</td>
<td>49.0</td>
</tr>
<tr>
<td></td>
<td>O₇</td>
<td>14.4</td>
<td>38.6</td>
</tr>
<tr>
<td>SD + LSD</td>
<td>O₃</td>
<td>26.3</td>
<td>49.2</td>
</tr>
</tbody>
</table>

For many of the new momentum-dependent operators, we require a search window of up to several hundred keVnr to capture most of the signal.
Constraints on Representative Operators

• On the next slide I show projected cut-and-count limits for the LUX 2013 run and for LZ (the 7-ton successor to LUX)

• Relevant parameters:

<table>
<thead>
<tr>
<th></th>
<th>LUX 2013</th>
<th>LZ (Projected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Mass</td>
<td>118 kg</td>
<td>5600 kg</td>
</tr>
<tr>
<td>Livetime</td>
<td>85.3 d</td>
<td>1000 d</td>
</tr>
<tr>
<td>Standard energy window</td>
<td>3-25 keVnr</td>
<td>6-30 keVnr</td>
</tr>
<tr>
<td>Background events expected</td>
<td>0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Events observed</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

- For “optimized” energy window (different upper threshold for each operator depending on peak of spectrum) assume background scales linearly with size of window (very conservative).
- For LZ assume num. events observed = num. background events expected.
Constraints on Representative Operators
Effects of Changing the Energy Window

$O_5$ WIMP-nucleon scattering (M and $\Delta$), 50-GeV WIMP

$O_5$ WIMP-nucleon scattering (M and $\Delta$), 500-GeV WIMP
Summary and Next Steps

• Direct detection experiments traditionally only present limits on interactions that vanish in the zero-momentum-transfer limit (SI and SD), but there are 8 other operators that can produce momentum-dependent SI and SD responses as well as new nuclear responses (LD, LSD)

• Signal models have been generated and both cut-and-count and PLR limits (not shown) have been produced for the LUX 2013 run, and cut-and-count limit projections have been produced for LZ

• Extending the WIMP search window allows us to optimize signal-to-background based on where the each operator’s spectrum peaks

• At higher recoil energies pulse-shape cuts and other discrimination techniques can be used to help with signal-to-noise ratio (ongoing investigation)

• Compare to SuperCDMS paper (ArXiv 1503.03379v1)