Improved WIMP scattering limits from the LUX experiment

Wing To
LUX Collaboration
SLAC / Stanford University
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Outline

- Large Underground Xenon (LUX)
- First Run3 Analysis (90 live-days)
- Improved Analysis of Run3 Data  arxiv:1512.03506
- Preparation for Run4 (300 live-days) Data

Improved WIMP scattering limits from the LUX experiment


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Our Universe

- 4.9% Visible Matter
- 26.8% Dark Matter
- 68.3% Dark Energy

Weakly Interacting Massive Particles

- Weak! Interaction cross-section $\sigma < 10^{-45}\text{cm}^2$ @ 33 GeV mass
- Massive ~ 100 GeV range

WIMP – Xenon interaction

- WIMPs scatters off normal matter and imparts small amount of energy
- Excited atom releases this energy
  - Heat (Loss)
  - Scintillation Light (S1)
  - Ionization (S2)
Located 4850 ft (1.5km) underground in the Davis Cavern in Lead South Dakota

- Xenon at 165K
- Thermo Isotropy
- S2/S1 Reconstruct
- Extracts Electrons
- ~99% reflectivity VUV light
- Applied 180 V/cm drift field
- S1 Reconstruction

370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass
Dual Phase Xenon TPC

- Particle interacts with the Xenon and deposits ~ keV of Energy
- Prompt Scintillation Light (S1)
- Delay & Localized Charge on the top PMT array (S2)
- Drift time of the electrons

\[
E = \frac{1}{\mathcal{L}(E)} \cdot \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \cdot W.
\]

- \( W = 13.7 \text{ eV} \)
- \( g_1 = \text{Light Collection} \)
- \( g_2 = \text{Extraction Eff, Light} \)
- \( \mathcal{L}(E) = \text{Lindhard Factor} \)
  
  Fraction of Energy Loss to Heat
Original Run3 Analysis

- Exclusion down ~ 6 GeV
- Energy threshold: 3 keV (slide2)
- 85.3 Live-days with 118 kg of fiducial mass (10k kg-days)
- $2 \leq S1 \leq 30$ Phe
- $S2 > 200$ Phe
- Event Radius < 18 cm
- 160 Events observed in data after selection cuts

First LUX Run3 Exclusion Limits

- LUX
- Xenon100 (225 days)
- Xenon100 (100 days)
- Edelweiss II
- ZEPLIN III
- CDMS II
PMT Pulses

- Vacuum UV correction between liquid and gas (A. Currie)
- Spike Counting for S1 Improved Pulse classification (S. Shaw)
- Fixed biases in pulse area measurements (T. Biesiadzinski, S. Shaw)
- Improved XY position Reconstruction (C. Silva)
- S2 energy from both Top and Bottom Array (C. Silva)
- Energy Calibration for Electronic Recoil Events (A. Dobi)
- Inclusion of low energy Nuclear Recoil Events (J. Verbus)
- Improve background models (B. Tennyson, C. Lee)
- Improved signal model full Energy -> S1 / S2 simulation (W. To)
- Created a new sensitivity and limits framework using Profile Likelihood Ratio (W. To)

Exclusion Curves
Data-Driven Energy Calibration

\[ E = \frac{1}{\mathcal{L}(E)} \cdot \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \cdot W. \]

\[ S_2/E = \frac{n_e}{(n_e + n_\gamma)} \cdot \frac{g_2}{W} \quad \text{and} \]

\[ S_1/E = \frac{n_\gamma}{(n_e + n_\gamma)} \cdot \frac{g_1}{W}, \]

- **X-intercept**
  - \( n_\gamma \rightarrow 0; \ S_2/E = g_2/W \)

- **Y-intercept**
  - \( n_e \rightarrow 0; \ S_1/E = g_1/W \)

\text{Run03 WS Doke Plot}

\[ g_1 = 0.1167 \pm 0.003 \]
\[ g_2 = 12.05 \pm 0.83 \]
Neutron DD Calibration

- Mono-energetic: 2.45 MeV fired into LUX
- Two line segments so the energy of the middle scatter is known

- \( Q_y \) = Charge Yield (S2 Size/ E)
- \( L_y \) = Light Yield (S1 Count /E)
- Fit to Lindhard/Berzukov model to get L(E)

\[
E = \frac{1}{L(E)} \cdot \left( \frac{S1}{q_1} + \frac{S2}{q_2} \right) \cdot W.
\]

Nuclear recoil energy (keV)
Background Model

- Detector Material: Gamma rays from Co-60, K-40, Tl-208, Bi-214
  - Global Fit to 3 MeV
  - Asymmetric source from top and bottom
- Internal Background (in Xenon): Ar-37, Kr-85m, Xe-127

Wall Background:
- Rn222-Pb206
- Occurs on the wall at 24.2-5 cm
- Resolution Leaks into below 18 cm
- Charge Loss
- Inclusion of Wall Bkg increase Fiducial Radius to 20 cm

R vs. S2 of Wall BG

S2 > 200 phd
LUX First Analysis Fiducial
r < 18 cm
C.Lee
• First Result used S1 as a proxy for Energy \{ \text{E(S1) = 6}^{\text{th}} \text{ Degree Poly} \} \\
• Noble Element Simulation Technique, M. Sydagzis et al, arxiv:1106.1613 \\
• Implement full NEST simulation in the sensitivity calculation \\
• NEST parameter are derived from DD-data \\
• All parameters including \( g_1, g_2 \) and \( L(E) \) are allow to vary in fits \\

\[
\log(S2) \text{ vs } S1, \text{ mWimp} = 3.500000\text{GeV}
\]

\[
\log(S2) \text{ vs } S1, \text{ mWimp} = 33.000000\text{GeV}
\]
• Limits calculation switched to physical quantity of cross-section instead of number of events
• Signal Model is generated on the fly
  • Parameters can be varied during fits
  • Profile over parameter space
• Nuisance Parameters
  • Both Signal Strength and Shape could be changed by the NPs
  • The kappa factor in L(E) is found to be dominated in Signal Strength
  • g2 is found to be dominated in Signal Shape.
  • kappa is allowed to for all mass points
  • g2 only floats above 4 GeV (huge increase in computing time)
• Each individual background contribution also have a NP
• The likelihood ratio is calculated with all NPs variation so we get a profile of the model parameters (PLR)
• “Goodness-Of-Fit” between Data and Background Model
Re-Analysis Dataset

- $1 \leq S1 \leq 50$ Phd
- $S2 > 150$ Phd
- Energy Threshold = 1.1 keV
- 10 additional days from dataset with tiny amount of Kr-83 from calibration
- 95 Live-days x 145 kg = 13800 kg-days (increase of 40%)
- Total of 591 events
• 95 Live days * 145 kg of Exposure
• Observed 591 Events
• Background Model Predicted: 589 Events
• Signal Model of various masses are included into the fit with Lindhard k and g2 allowed to float
• cross-section for all masses fit to < 1e-4 zb

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Constraint</th>
<th>Fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lindhard $k$</td>
<td>0.174 ± 0.006</td>
<td>-</td>
</tr>
<tr>
<td>$S_2$ gain ratio: $g_{2,DD}/g_{2,WS}$</td>
<td>0.94 ± 0.04</td>
<td>-</td>
</tr>
<tr>
<td>Low-$z$-origin $\gamma$ counts: $\mu_{\gamma,\text{bottom}}$</td>
<td>172 ± 74</td>
<td>165 ± 16</td>
</tr>
<tr>
<td>Other $\gamma$ counts: $\mu_{\gamma,\text{rest}}$</td>
<td>247 ± 106</td>
<td>228 ± 19</td>
</tr>
<tr>
<td>$\beta$ counts: $\mu_\beta$</td>
<td>55 ± 22</td>
<td>84 ± 15</td>
</tr>
<tr>
<td>$^{127}$Xe counts: $\mu_{Xe-127}$</td>
<td>91 ± 27</td>
<td>78 ± 12</td>
</tr>
<tr>
<td>$^{37}$Ar counts: $\mu_{Ar-37}$</td>
<td>-</td>
<td>12 ± 8</td>
</tr>
<tr>
<td>Wall counts: $\mu_{\text{wall}}$</td>
<td>24 ± 7</td>
<td>22 ± 4</td>
</tr>
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</table>
New Exclusion Limits

Improved Low Mass Threshold lowered to 1.1keV

Boron-8 Solar Neutrino. Currently contributes to 0.1 Evt to our Bkg

33 GeV $\sigma = 4 \times 10^{-46}$ cm$^2$

Increased exposure of 40% and better background / signal models
• LUX is currently taking data until the end of 2016
• Additional 300+ live-days of data
• Increase exposure by a factor of 4
• Preliminary estimate approximately factor of 2 improvement in WIMP sensitivity
• Improved Modeling of the E-field in LUX
• Better background models with full 3D information (φ)
• Improve treatments of nuisance parameters in order to allow variation at low masses
  • Large number of events needs to be generated currently
  • Avoid this by parameterizing s1 and s2
• Reanalysis of LUX first 90 live-days of data improved the sensitivity by factor of 2 at 33 GeV
• Pushed lowest mass limits from 6 GeV to 3.4 GeV
• Improvements from PMT Pulses to Final Limits calculation were implemented
• Additional calibration sources allowed us to use data drive methods for background and signal modeling
• Work is meant to be carried over to 300+90 live-days of data being collected until end of 2016
• PRD with analysis detail coming soon.
• SD and Axion limits are also coming out
Exclusion of CMSSM

SuperCDMS Soudan LT, 90% C.L.
XENON100, 2012, 225 live days (7650 kg-days), SI
LUX (2013) 85d 118kg (SI, 90% CL)
LUXRun3Reana2015 (SI, 90% CL)
Trotta et. al., 2008, CMSSM
Bayesian: 95% contour, SI

Cross-section [cm$^2$] (normalised to nucleon)

WIMP Mass [GeV/c$^2$]
More On VUV Photons

**Single Photo-electron**

![Graph showing single photo-electron distribution](image1)

- Photon $\rightarrow$ PMT photocathode $\rightarrow$ single electron
  - Except...
    - Xe scintillation: 175 nm (7.1 eV). Calibration LEDs: 470 nm (2.6 eV)
- Two photo-electrons about 20% of the time in Xe
  - phe (photoelectrons) $\rightarrow$ phd (detected photons)
Spatial Uniformity
• Radial parametrization of the corrected Mercury radius vs. S2 size
Radial comparison data vs. wall model below NR mean

Counts / 0.1 cm

- *wall model*
- *data*
• $^{222}$Rn, 3.8 days, **alpha decaying** to...
• $^{218}$Po, 3.10 minutes, **alpha decaying** to...
• $^{214}$Pb, 26.8 minutes, **beta decaying** to...
• $^{214}$Bi, 19.9 minutes, beta decaying to...
• $^{214}$Po, 0.1643 ms, alpha decaying to...
• $^{210}$Pb, which has a much longer half-life of 22.3 years, beta decaying to...
• $^{210}$Bi, 5.013 days, beta decaying to...
• $^{210}$Po, 138.376 days, alpha decaying to...
• $^{206}$Pb, stable.