Dark matter searches with the LUX and LUX-ZEPLIN detectors

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LUX and LZ Collaborations

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December 5-6, 2016
The LUX detector is done detecting.

The primary result is out. So is the detector.

Taking stock
- a new standard for detector calibrations
- world-leading SI WIMP-nucleon exclusion accepted for publication
- demonstrated operations of 100s-kg-to-ton-scale detector at SURF
- more physics results to come!

...and now we look forward to LZ
The LUX detector

- 122 Hamamatsu photomultiplier tubes—61 in top and bottom arrays
  - optimized for 175nm sensitivity
  - made for LUX’s cryogenic and low-BG needs (R8778)
- Dodecagonal active volume with 0.5 m “diameter” (face to face), 0.5 m height (cathode to gate)
- Interior paneling (PTFE) maximizes light collection
  - highly reflective (>99%) for 175 nm in LXe
- Active LXe mass: 250 kg
Background minimization in LUX

- **Internal**
  - We count and then build with low-background materials (Cu, Ti)
  - Fiducialization takes advantage of xenon’s “self-shielding”
    - Come inside ~few cm of LXe, away from radioisotopes in materials and Rn plate-out on surfaces.

- **Intrinsic**
  - Dedicated purification system for Kr removal from Xe via chromatographic separation.
    - Avoid $^{85}$Kr (beta decay)

- **External**
  - 70,000-gallon water tank with active PMT veto system for muon tagging
  - Overburden for reduction of cosmic backgrounds

Example of LXe Self-Shielding from LUX2013 Data

Cathode

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<tr>
<th>log$_{10}$(DRUee)</th>
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<tr>
<td>0</td>
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<td>-0.5</td>
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<td>-1</td>
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<td>-1.5</td>
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<tr>
<td>-2</td>
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<td>-2.5</td>
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<tr>
<td>-3</td>
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</table>

Measured DRU (89 livedays, 89 eff)

3.6$\pm$0.3 mdru
LUX ran (LZ will run) in the LBNL-operated Sanford Underground Research Facility in Lead, South Dakota.

Next door to the Majorana Demonstrator on the 4850′ level of SURF.

The Davis Cavern, part of the 4850′ level of SURF, offers a factor of $\sim 10^7$ reduction in the rate of cosmic muons.
Calibration #1: $^{83}\text{m} \text{Kr}$

Pulse area normalization

Trace the edge of the $^{83}\text{m} \text{Kr}$ $(r,\text{drift})$ event distribution to map the edge of the detector’s active region into $S2$ coordinates.

$^{83}\text{Rb}$

- $T_{1/2} = 86.2 \text{ d}$
- $E = 32.15 \text{ keV}$
- $T_{1/2} = 1.83 \text{ h}$
- $E = 9.4 \text{ keV}$$^{83}\text{Kr}$
- $T_{1/2} = 154 \text{ ns}$
- $E = 9.4 \text{ keV}$

$^{83}\text{Kr}$

- $T_{1/2} = 86.2 \text{ d}$
- $E = 9.4 \text{ keV}$
Calibration #2: $^{3}\text{H}$

The reliable injection \textit{and removal} of tritiated methane for electronic recoil calibration and yields measurements.

- Tritium notes:
  - $Q = 18.6$ keV
  - Mean = 5 keV
  - Peak = 2.5 keV
  - $t_{1/2} = 12.3$ years

- Demonstrated full removal after LUX2013
- Mid-run calibrations in LUX2014-16: totally fine!
Calibration #3: DD neutrons

In situ Deuterium-Deuterium neutron calibration for nuclear recoils
Calibration #3: DD neutrons

*In situ* Deuterium-Deuterium neutron calibration for nuclear recoils

![Image of neutron conduit pipe]

**Top hit pattern:**
- **x-y localization**
- **Δt:** z' separation
- **θ:** energy calculation

\[ E_y = E_e \frac{4m_n m_{Xe}}{(m_n + m_{Xe})^2} \left( 1 - \cos \theta \right) \]

Samuel Chan, Carlos Faham for the LUX Collaboration

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**Graph:**
- **WIMP-nucleon cross section (zm)**
- **WIMP-nucleon cross section (cm²)**

SuperCDMS 2014
SuperCDMS 2015
DarkSide-50 2015
PandaX 2015
XENON100 2012
LUX 2014
LUX 2015

**Assumed yields of zero below 3 keVnr in first analysis**
Calibration #3: DD neutrons

*In situ* Deuterium-Deuterium neutron calibration for nuclear recoils

\[
E_y = E_n \frac{4m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos \theta}{2}
\]

Measurement down to 1.1 keVnr critical for low mass sensitivity
Calibrating and modeling for LUX2014-16

Gray density: CH$_3$T calibration (ER)

Orange density: DD calibration (NR)

Solid lines: NEST model, ER, NR band mean

Dashed lines: NEST model, 10-90 percentile.
Data are compared to models in an un-binned, 2-sided profile-likelihood-ratio (PLR) test.

5 un-binned PLR dimensions:
- Spatial: r, φ, drift-time (the S2 coordinates)
- Energy: S1 and log₁₀(S2)

1 binned PLR dimension:
- Event date

The data in the upper-half of the ER band (BG-only region) were compared to the model (plot at right) to assess goodness of fit.
Full exposure spin-independent WIMP-nucleon exclusion

Treat LUX2013 as “date bin 0” of LUX2014-16 with its ER and NR model the same in all four drift (z) bins. Re-run the PLR.
The full LUX exposure is $4.75 \times 10^4$ kg⋅days
  - 130 kg⋅years

Minimum of $1.1 \times 10^{-46}$ cm$^2$ at a mass of 50 GeV/c$^2$
  - corresponds to 3.2 signal events
  - power constrained at -1σ

Context:
  - more than 10x improvement upon XENON100
  - More exposure coming from PandaX (~2-5x)
  - XENON1T (~8-10x) and LZ (~100x) on the horizon

Read more!
The LUX-ZEPLIN detector

LZ (LUX)
Active mass: 7 T (0.25 T)
Run time: 1000 d (427 d)
Minimum $\sigma_{SI}$:
1.1e-48 cm$^2$ (1.1e-46 cm$^2$)
Fiducial mass: 5.6 T (0.1 T)
Active veto volumes

- TPC field cage is not pressed up against the cryostat wall for two reasons
  - high fields
  - background rejection

Image from CPAD talk by Ethan Bernard, UC Berkeley
Plans for successful cathode high voltage delivery

Motivation: unintended light production must be avoided.
- field-emission electrons from surface defects on conductors
- uncontrolled buildup of charge on insulators

We know this is hard to do:
Xenon10: data at 13 kV
Xenon100: planned for 30 kV; data at 16 kV
LUX: planned for “up to 100 kV”; data at 10 kV
LZ: 2.5x LUX drift length! Designing for 100 kV with requirement of 50 kV

A simple 2.5x-scale-up of LUX does not work…
- high fields between TPC wall and cryostat
- high fields between cathode and bottom PMTs
- high fields around the cathode feedthrough
Plans for successful cathode high voltage delivery

- 50 kV baseline voltage with a goal of 100 kV
- LZ: 300 (600) V/cm
- LUX: 180 V/cm
- Controlled grading of potential between HV cable ground braid termination and center conductor connection to LZ cathode
- Flared inner cryostat allows more space, meaning lower fields around TPC field rings with the highest voltage
- Extensive field simulations to minimize peak fields in LXe
Effect of the vetoes

- Nine acrylic tanks, 60 cm thick, holding 17.5 tonnes of Gadolinium-loaded scintillator (LAB, linear alkylbenzene)

- 97% efficient for neutron detection

- Borrowing technology for scintillator and tanks (as well as people) from Daya Bay

- In combination with the instrumented LXe “skin,” the fiducial mass expands from 3.8 to 5.6 tonnes
Backgrounds

- Vetoes help immensely with the BG from materials. The larger backgrounds then become radon (and krypton)
- Radon
  - Emanates from most materials
  - 20 mBq req., 1 mBq goal
  - Main assembly at SURF will have reduced Rn air system
- Krypton-85
  - Remove to <15 ppq using gas chromatography
  - Setting up to process 200 kg/day at SLAC

<table>
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<tr>
<th>Item</th>
<th>Mass (kg)</th>
<th>U (mBq/kg)</th>
<th>Th (mBq/kg)</th>
<th>Co-60 (mBq/kg)</th>
<th>K-40 (mBq/kg)</th>
<th>n/yr</th>
<th>ER (cts)</th>
<th>NR (cts)</th>
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<td>R11410 PMTs</td>
<td>91.9</td>
<td>71.6</td>
<td>3.1</td>
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<td>2025+</td>
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<td>5+ years of underground science</td>
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Projected sensitivity (1000 days)
Summary and next steps

❖ LUX has excluded SI WIMP-nucleon cross-sections down to 0.11 zeptobarns (at a mass of 50 GeV/c²)
  ❖ Full exposure search is on arXiv and accepted for publication in PRL
❖ More LUX results from 3+ years of UG operation on the way
  ❖ DM: improved spin-dependent sensitivity, new axion/ALP, EFT, …
  ❖ There is a lot more still to learn from LUX data!
❖ LUX-ZEPLIN (LZ) experiment is approaching construction
  ❖ 7000 kg active mass, 100x LUX sensitivity, starting in 2020
  ❖ Multiple instrumented vetoes for background minimization
  ❖ Cleanliness protocols being followed to minimize Rn, the largest background
  ❖ Cryostats, PMTs, and outer detector are in production; Xe is being acquired
  ❖ CD-3 in January 2017