LUX.
Some thoughts on large detectors.
Comments on Xe microphysics.

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LUX

- 300 kg Xe, expected 100 kg fiducial
- At Sanford lab, Homestake SD.
- First water-shielded large dark matter detector
Surface Facility at Sanford Lab

- Old Warehouse
- Occupancy starting Dec 09
- LUX has been:
  - Assembling detector
  - Helping create Sanford Lab
Surface Operations
Davis Campus @ SURF

4850 ft

1964

1964

$8.1M outfitting contract - March 2011.
LUX Status

- Cryogenic run - May 2011
- Full run now underway
- Davis Cavern: Beneficial occupancy March 2012
- Full running: Fall 2012

During Lunch

Underwater
<table>
<thead>
<tr>
<th>Institution</th>
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<tbody>
<tr>
<td>Brown</td>
</tr>
<tr>
<td>Case</td>
</tr>
<tr>
<td>Maryland</td>
</tr>
<tr>
<td>LLNL</td>
</tr>
<tr>
<td>LIP-Coimbra</td>
</tr>
<tr>
<td>Rochester</td>
</tr>
<tr>
<td>South Dakota</td>
</tr>
<tr>
<td>SDSMT</td>
</tr>
<tr>
<td>Texas A&amp;M</td>
</tr>
<tr>
<td>UC Berkeley/LBNL</td>
</tr>
<tr>
<td>UC Davis</td>
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<tr>
<td>UC Santa Barbara</td>
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<td>Yale</td>
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</table>

Oct 2011, Sanford Lab
Projected Reach of LUX

- No expected background in 100 kg x 300 days
- “Beneficial occupancy” underground - March 2012
- Full running - Fall 2012

Simulated LUX data
(100 kg fiducial, 100 days)

\[ m_X = 100 \text{ GeV/c}^2 \]
\[ \sigma = 5 \times 10^{-45} \text{ cm}^2 \]

LUX
- 100 kg x 300 days

LZS 1.5 ton

LZD 20 ton

XENON100
(40 kg fiducial, 100 days) - ~800 ER event
LUX Upgrade

• Replace old PMTs with new
  – Requires only new array holders, detector reassembly
  – BG well below measured limits: total background reduced by 40%

• Much cleaner potential nuclear recoil signal
• Increase in fiducial mass
• Target - 2013

<table>
<thead>
<tr>
<th>PMT</th>
<th>$^{238}$U [mBq/PMT]</th>
<th>$^{232}$Th [mBq/PMT]</th>
<th>$^{40}$K [mBq/PMT]</th>
<th>$^{60}$Co [mBq/PMT]</th>
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</thead>
<tbody>
<tr>
<td>R8778</td>
<td>9.5±0.6</td>
<td>2.7±0.3</td>
<td>66±2</td>
<td>2.6±0.1</td>
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<tr>
<td>R11410 MOD</td>
<td>&lt;0.4</td>
<td>&lt;0.3</td>
<td>&lt;8.3</td>
<td>2.0±0.2</td>
</tr>
</tbody>
</table>
Some thoughts on scaling up this technology
Self-shielding in liquid xenon

Effective for detectors large compared to $\sim 10$ cm gamma penetration distance: few 100 kg and up.

$$P(L) \approx \frac{L}{\lambda} e^{-\frac{L}{\lambda}}$$

PMT

Single, low-energy Compton scatter

300 kg LUX

Self-shielding of gammas in a liquid Xe TPC

Mean Background in Fiducial (dru)

Fiducial Mass (kg)

$O = 1$ count in 1000 days with 99.75% rejection
Shielding

- 4 m water shield + 4850 ft depth adequate up to at least 20 ton scale.
- Liquid scintillator shield. Effective for
  - Internal neutrons
  - Internal gammas
  - External, high-energy neutrons
- Titanium cryostat material
  - Significant new construction material for low background experiments
  - No measured contamination at limits of Oroville capability (< ~0.2 mBq/kg)
  - Enables active shield
175K scintillator shield

ISOHexane scintillator, housed immediately outside LXe, at LXe temperature. Goal: > 10-fold gamma veto + highly efficient neutron veto.
Kr Removal

- $^{85}\text{Kr}$ - beta decay
  - Need Kr/Xe: 10 ppt, LZS 0.5 ppt, LZD 0.05 ppt
  - Commercial Xe/Kr ~ few ppb
  - Chromatographic system: < 2 ppt @ 2 kg/day production

- Scaling up current system
  - 60 kg charcoal column
  - Vacuum phase “recovery” stage
  - High capacity Xe condenser

Kr-Xe cocktail: no noticeable saturation up to 4 kg Xe per cycle
Xe purification and analysis

- Gas phase getter purification - standard
- Very high efficiency two-phase heat exchanger
  - Removes large thermal penalty to recondense
- In ~60 kg prototype, obtained purity in few days
- Cold-trap enhanced mass spectrometry: first sensitivity to required impurity levels

Data from coldtrap/RGA

Sensitivity: 0.1 ppb O₂
1.0 ppb N₂
0.06 ppb CH₄

Time (s)
0 2000 4000 6000 8000 10000
Power (W)
-5 0 5 10 15 20 25 30 35

Circulation off On: ~400 kg/day

Figure 5.
Data taken during prototype operation showing in the top plot the effect of changing the xenon flow rate on the temperatures. The bottom plot shows the smoothed instantaneous power measured using the components of the experimental setup. Using these temperatures the heat load was determined for all of the major components of the detector. These were then used to adjust the change in the power applied by the PID controlled heater and the total heat load due to circulation was calculated. The result of these calculations is

Circulation off
On: ~400 kg/day

ArXiv: 1002:2742

Sensitivity: 0.1 ppb O₂
1.0 ppb N₂
0.06 ppb CH₄

Xe is constant due to cold trap

Data from coldtrap/RGA

Sensitivity: 0.1 ppb O₂
1.0 ppb N₂
0.06 ppb CH₄

Xe is constant due to cold trap

Open leak valve, bypass gas purifier, flow through gas purifier, bypass gas purifier, close leak valve to measure backgrounds

Electron drift length [m]

Recirculation time [hours]
Thermosyphon Cryogenics

- Uniquely suitable for very large scale.
  - Extremely high capacity: equivalent to ~1 m Ø Cu bar.
  - Remote deployment of multiple cold heads.
  - Tunable to low power for fine control.

- Intrinsically safe against power failure

- Cryogenics + Xe systems vetted by lab safety.

**Thermosyphon configuration testing**

- Large evap; 1.5" diam. 10 ft
- Small evap; 1.5" diam. 10 ft
- Large evap; 0.5" diam. 10 ft
- Loop evap; 2x0.5" diam. 10 ft
- Loop evap; 2x3/8" diam. 10 ft
- ALB test

**First LUX Cooldown**

- ~0.3 K/hr
- ~1 K/hr
Light collection at the multi-ton scale

- Rayleigh scattering: not yet a problem
- PTFE walls: extraordinarily reflective at 175 nm (7eV) — $r \sim 98\%$ or greater: “mirrored box”
- Purity should be achievable - comparable to requirements for charge drift
- With $r \sim 98\%$, should get 2-3 x light of X10, X100: directly lowers threshold

0.1 ppb: 1 km $\Rightarrow$ 2% loss
LZD

- 20 ton scale-up of LZS
- Sited at 4850 ft Homestake single lab module, or expanded SNOLab.
20 Tons hits fundamental neutrino limit

• LZD at 20 tons: $10^{-48}$ cm$^2$ WIMP sensitivity
• Atmospheric and diffuse supernova neutrinos set irreducible background just beyond this
• WIMP/supernova ratio independent of target

Proven materials backgrounds; 99.5% discrimination; < 1 background n.r. event;
Some comments on Xe microphysics, as it affects dark matter detection
Xe microphysics

- What determines band widths?
- What determines band positions?
- What is the best measure of energy?
- Why does discrimination improve at low energy?

Drift Field Dependence

Electron recoils (Background)

Nuclear recoils (Signal)
Energy partitioning

- **Excitations:**
  - Ionization \((N_i)\)
  - Recombined ions \((r)\) -> photons
  - Excited atoms \((N_{ex})\) -> photons
    - Doke: predicts 6%

- **New formalism:**
  
  \[
  n_e = (1 - r) \cdot N_i \\
  n_\gamma = \left( \frac{a}{b} \frac{N_{ex}}{N_i} + r \right) \cdot N_i \\
  E = (n_e + n_\gamma) \cdot W
  \]
  
  - We find \(W=13.7\pm0.2\).
  - Nuclear recoils have additional factor: Lindhard
Nuclear recoils: Lindhard

- keV nuclear recoils move slower than electrons in atoms ($v_{Fermi}$).
- Adiabatic interaction. Electronic excitation due to overlap of shells.
- Equal masses: significant energy “lost” to recoils.
  - (Essentially absent for electron recoils).
- Result: less “electronic excitation” than for electron recoils.
- Described by Lindhard (Copenhagen school, 1960’s)
Recombination - based discrimination

Electron recoils (Background)

Nuclear recoils (Signal)

Electrons

Photons

Recombination

higher Field lower

Electron recoils (Background)

Nuclear recoils (Signal)

Electron recoils (Background)

Nuclear recoils (Signal)
Electron Recoils At 122 keV

Recombination

Energy Dependence

Total
S1 + S2
S1_{stat+inst}
S2_{inst+stat}

Electron recoils

nuclear recoils

Note: small recombination fluctuations
Long-standing puzzles: shapes of e.r. and n.r. bands, field independence of n.r. and low-energy e.r. bands

Nuclear recoils have *same recombination* as electron recoils.
  — Discrimination based on enhanced direction-excitation light for nuclear recoils

Qualitative (but not yet quantitative) understanding of recombination fluctuations
Concluding comments

• Two phase Xe is very powerful technology
  — Large signal
  — Low intrinsic backgrounds
  — Multiple method of background rejection (discrimination, self-shielding, active shielding)

• Low energy potential is high
  — Discrimination good near threshold
  — Factor of 2-3 better light collection might be achievable
  — S2 only data should extend to below ~keV
  — Calibration remains a challenge

• We should try to reach the neutrino limit