After LUX: The LZ Program

(LUX-ZEPLIN)

The Large Underground Xenon (LUX) dark matter search experiment is currently being deployed at the Sanford Laboratory at Homestake in South Dakota (see Rick Gaistkell's talk), as a precursor to DUSEL. In partnership with more international institutions, we are already thinking about the next (two) experiment(s) that will follow: LZ-S (3 t) and LZ-D (20 t).
The LZ Program at one glance

- **LUX** 350 kg
- **LZS** 3 Ton
- **Davis Cavern Water Tank**
- **LZD** 20 Ton

Dimensions:
- LUX: 0.5 m
- LZS: 0.87 m
- Vacuum: 3.89 m
- LZD: 2 m
- Vacuum: 5.97 m

S. Fiorucci - Brown University
The LZ Program

- LUX (14 US institutions) + New collaborators from Zeplin III and US institutions
  - Imperial College, London
  - STFC Rutherford Appleton Lab
  - STFC Daresbury Laboratory
  - ITEP, Moscow
  - University of Edinburgh
  - Moscow Engineering Physics
  - Institute LIP, Coimbra

- Two phases: LZ-S (3 t), LZ-D (20 t) from 2012 → 2022+

UK and PT groups to join LUX late 2010, subject to local agencies approval
LUX Innovations for LZ

- Davis Cavern Infrastructure, water shield: ready for up to 3 ton instrument
- Heat exchanger, high flow rate Xe purification system
- Remote feedthroughs and cryogenics
- Low-background titanium cryostat
- Scalable internals construction
- Scalable trigger and DAQ (DDC-8)
- $^{83m}\text{Kr}$, $^3\text{H}$ calibration sources
- Automated Control and Emergency Recovery systems
- Safety review process
LZ Program: New Features

- 3" PMTs at ~1 mBq radioactivity level
- Liquid Scintillator shield/veto
- Internal active plastic veto
- Internal imaging system

...That’s it. Progress on sensitivity comes chiefly with:
  - Increasing the Xe mass
  - Scaling up existing LUX technology
  - Xe self-shielding is driving the background rates down dramatically
LZ Program: Shielding

- Simulations results for LZ-S
  - Power of Xe self-shielding
  - Additional rejection thanks to external scintillator veto

- LZ-D: Requires a 12m x 12m shield
  - Dimensions driven by $\mu$-induced high E neutrons
  - All other external backgrounds ($\gamma$ & $n$) subdominant

Low Energy Electron Recoil Events

Low Energy Nuclear Recoil Events
LZ Program: Scintillator Shield/Veto

Scintillator housed as close as possible to LXe
   Ti cryostat especially helpful, want ~1 cm thickness.

Cold (175 K) placement immediately outside LXe.
   Highest efficiency.
   Enhances cryo safety.
   Likely choice: iso-hexane + flour. Expect factor 2-3 less light than pseudocumene. Enhanced flammability.

Warm: tradeoff in performance

Program of low temperature scintillator study, combined with MC studies

Goal: ≥ 10 reduction of gamma, neutron rates in LXe.

Final decision on scintillator veto option based on performance, safety.
Under LZ S4 development program: DUSEL R&D

Larger diameter - twice collection area. Radioactivity/area further reduced.

In 2009 initially fab of and tested Hamamatsu 3” R11065 in LXe
- Tested QE/LXe operation - all PMTs performed identically as R8778
- Well understood, stable performance.
- High gains >5x10^6 mean that no additional amplifiers required. Electronics within cryostat are limited to passive components with very low/ well understood radioactive backgrounds.

Developed new ultra low background 3” PMTs for LXe: R11410mod
- Background measured U/Th <1/1 mBq/PMT (90% CL) - No U/Th signal seen
- This comfortably exceeds background requirements for LZ-D detector
- Upgraded Hamamatsu Super bialkali photocathodes will also be available to move QE above 40%

Requirement is for 1000 x 3” PMT for LZ-D (Production yields and cost well understood)
Architecture developed for LUX

2 years operational experience on full-size prototype (LUX 0.1).
~70 thermometers, 5 P&ID control points.

Liquid nitrogen (LN) thermosyphon backbone.
Extremely high capacity, remotely deployed, multiple cold heads,
tunable to low power for fine control.
Intrinsically safe: passive, insensitive to power loss.

Probable LN generation on site to avoid LN transport.

“Conventional” system for pre-cooling scintillator
LZ Program: Internals

Large area grid prototyping
  Scale will increase for 0.5 m to 2m and maintain acceptable deflection

Low mass field ring development
  Minimize mass for veto

Investigation of active plastic to enhance veto capability
  LXe compatibility
  Maximize light collection

Development of internal imaging system for enhanced monitoring
  Internal fiberscope to view liquid surface and components

Multi-ton scale will require scale up of TPC components including grids, field rings and insulator supports. Components must also be compatible with external veto.
Integrate preamp and postamp. Consider the use of differential signals. (Harvard)

Eliminate summers and discriminators. Replace Struck ADCs with DDC-8 digitizers. (Rochester)

LUX-350 electronics will be reused for the scintillator and water shield signals. (UC Davis)

Use new DDC-8 platform for both trigger and DAQ. (Rochester)
LZ Program: Internal Calibration Sources

Essential to have internal calibration source for large-volume Xe detectors

Two methods developed for LUX to be used by LZ:

Energy calibration: $^{83m}$Kr (Yale)
Electron recoil discrimination: Tritium source (Maryland)

Tritiated methane (CH$_3$T) First test of removal from LXe: >90%

$^{83m}$Kr: 1.8 hr half-life
LZ Program: Example of background MC for LZ-D

- Gamma Radiation: Hit Map for 5 - 25 keV$_{ee}$ deposits, Scint. Veto

(Left) Self-shielding of gamma events from U/Th/K/Co at edge of detector
  e.g. PMTs $\sim$1 mBq

(Below) Energy dependence of ER signals and backgrounds after 99.5% rejection
  Also shown is WIMP signal for comparison (scaled to keVee)
LZ Program: LZ-D, ultimate search?

- Electron Recoil signal limited by p-p solar neutrinos
  - Subdominant with current background rejection
- Nuclear Recoil background: coherent neutrino scattering
  - $^8$B solar neutrinos
  - Atmospheric neutrinos
  - Diffuse cosmic supernova background
- LZ-D reaches this fundamental limit for direct WIMP searches

LZ-D also sensitive to $\beta\beta^0\nu$ decay in natural xenon up to lifetimes of $\sim 1.3 \times 10^{26}$ years!

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Cosmogenic Backgrounds for large underground Xenon detectors

• Unprecedented sensitivity reach means we need to look into previously overlooked cosmogenic backgrounds
  • Reference: p-p solar neutrinos irreducible background $\sim 10^{-5} / \text{keV}_{\text{ee}} / \text{kg/d}$ (before 99.5% ER rejection)
  • Neutrons from muon spallation
    • in the rock (well known background for years, killed by water shield)
    • in the xenon
  • Negative muon capture $\rightarrow$ leads to neutron emission + radioactive isotopes in Xe
    • in xenon
    • in water
  • Photonuclear neutron production in the water
  • Fast neutron activation of xenon
  • Thermal neutron capture on xenon
  • More processes currently being checked and studied...

• Activation of the xenon $\rightarrow$ many isotopes, looked at all significant ones (> 200 !)
  • Searching for “Naked beta” emitters or “semi-naked beta” emitters
    • No coincident radiation (or not detected)
    • Potentially low energy deposition in WIMP search range [5–25 keVee]
    • Statistical chance of leakage into nuclear recoil region (< 0.5%)
  • Example: $^{137}\text{Xe}$ (from neutron activation of natural Xe)
    • 67% BR to naked 4.1 MeV beta
    • 30% BR to 3.7 MeV beta + 450 keV gamma
    • Probability for a 450 keV gamma to “escape” from 10 cm of Xe = 0.3 %
  • Calculated single event rates in [5- 25 keVee]
    • From muon capture on xenon: $\sim 10^{-9} / \text{keV}_{\text{ee}} / \text{kg/d}$
      (assuming a muon flux of $5 \times 10^{-9} / \text{cm}^2 / \text{s}$)
      (assuming a stopping muon fraction of 0.5 % per 100 g/cm$^2$ of Xe)
    • From thermal neutron activation of xenon: $\sim 5 \times 10^{-8} / \text{keV}_{\text{ee}} / \text{kg/d}$
      (assuming a thermal neutron flux of $5 \times 10^{-7} / \text{cm}^2 / \text{s}$)
    • From fast neutron activation of xenon: $\sim 10^{-7} / \text{keV}_{\text{ee}} / \text{kg/d}$
  • ALL well below the p-p solar neutrino background rate
Cosmogenic Backgrounds for large underground Xenon detectors

- Neutron production

<table>
<thead>
<tr>
<th>Neutron Type</th>
<th>Source Volume</th>
<th>Neutron Production</th>
<th>Ratio into LXe</th>
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</thead>
<tbody>
<tr>
<td>Cosmic Muon Induced Spallation Neutrons</td>
<td>Shielding Water</td>
<td>2.45e-03/s</td>
<td>1.39e-05</td>
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<td></td>
<td>Liquid Scintillator</td>
<td>8.01e-05/s</td>
<td>2.30e-02</td>
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<td></td>
<td>LXe Target</td>
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<tr>
<td>Capture Muon Induced MeV Neutrons</td>
<td>Shielding Water</td>
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<tr>
<td></td>
<td>Liquid Scintillator</td>
<td>1.06e-05/s</td>
<td>1.17e-02</td>
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<td></td>
<td>LXe Target</td>
<td>8.07e-03/s</td>
<td>1</td>
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<tr>
<td>Photon-Nucleus Produced ~200 keV Neutrons</td>
<td>Shielding Water</td>
<td>1.09e-06/s/ppt</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Liquid Scintillator</td>
<td>1.03e-07/s/ppt</td>
<td>2.62e-03</td>
</tr>
</tbody>
</table>

Neutron production rate in different volumes of a 20-tonne Xe detector with a 1-m thick liquid scintillator around the cryostat.

The “Ratio into LXe” represents the fraction of produced neutrons which actually enter the active volume according to preliminary Monte-Carlo. It does not take into account the chance or the multiplicity of interaction.

- Thermal Neutron Flux
  - Thermal neutron flux in detector subject to effects of water shield
  - Currently running neutron propagation MC to make sure current estimate (based on flux outside of shield) is not too far off.
  - Current safety margin ~10^2

- Muon Flux
  - Total flux vs depth relation well-known. Homestake 4850 ft: \( \Phi_\mu \sim 5 \times 10^{-9} \) /cm^2/s
  - For Cosmogenic Background: Need stopping muon flux in H_2O, Xe, Liq. Scint
    - Modern references on low-energy muons underground surprisingly sparse
    - In contact with various groups to find or make a measurement
    - However: Would have to be > 10^3 larger than current estimates to be an issue
LUX schedule is symbiotic with Sanford development. Science in 2012. Developing engineering and safety protocols.

LZ-S utilizes Davis Complex. Large physics return for cost. Construction retires risks for LZ-D.

Need focus on LZ-S funding and schedule.
LZ Program: SI WIMP Sensitivity

- Projections based on
  - Known background levels
  - Previously obtained $e^-$ attenuation lengths and discrimination factors

100 kg x 300 days

LZ-S (constr: 2012-2013, ops: 2013-2014)
1,200 kg x 500 days

17,000 kg x 1,000 days

- Fiducial volumes selected to match < 1 NR event in full exposure
Additional Slides
# The LUX Collaboration

**Brown**
- Richard Gaitskell: PI, Professor
- Simon Florucci: Postdoc
- Monica Pangilinan: Postdoc
- Luiz de Viveiros: Graduate Student
- Jeremy Chapman: Graduate Student
- Carlos Hernandez Faham: Graduate Student
- David Malling: Graduate Student
- James Verbus: Graduate Student

**Case Western**
- Thomas Shutt: PI, Professor
- Dan Akerib: Professor
- Mike Dragowsky: Research Associate Professor
- Carmen Carmona: Postdoc
- Ken Clark: Postdoc
- Karen Gibson: Postdoc
- Adam Bradley: Graduate Student
- Patrick Phelps: Graduate Student
- Chang Lee: Graduate Student

**Harvard**
- Masahiro Morii: Professor
- Michal Wasenko: Postdoc

**Lawrence Berkeley + UC Berkeley**
- Bob Jacobsen: Professor
- Jim Siegrist: Professor
- Joseph Rasson: Engineer
- Mia ihm: Grad Student

**Lawrence Livermore**
- Adam Bernstein: PI, Leader of Adv. Detectors Group
- Dennis Carr: Senior Engineer
- Kareem Kazkaz: Staff Physicist
- Peter Sorensen: Postdoc

**University of Maryland**
- Carter Hall: Professor
- Douglas Leonard: Postdoc

**Texas A&M**
- James White: Professor
- Robert Webb: Professor
- Rachel Mannino: Graduate Student
- Tyana Stieger: Graduate Student
- Clement Sofka: Graduate Student

**SD School of Mines**
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**University of Rochester**
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**UC Davis**
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- Robert Svoboda: Professor
- Richard Lander: Professor
- Britt Hollbrook: Senior Engineer
- John Thomson: Engineer
- Matthew Szydagis: Postdoc
- Jeremy Mock: Graduate Student
- Melinda Sweeny: Graduate Student
- Nick Walsh: Graduate Student
- Michael Woods: Graduate Student

**UC Santa Barbara**
- Harry Nelson: Professor
- Dean White: Engineer
- Susanne Kyre: Engineer

**All Collaboration meetings, Homestake, March 2010**

Formed in 2007, fully funded DOE/NSF in 2008
LZ Program: PMTs

Current LUX 350 Experiment: Using 122 x 2” R8778 Hamamatsu

Production yields high/very stable - long track record with technology

U/Th 10/2 mBq/PMT

There has been tremendous progress in reducing PMT backgrounds
The level of radioactivity already achieved in these PMTs would be an acceptable baseline for the LZ-S and LZ-D experiments

Demonstrated QE: average=33%, max 39% at 175 nm
Permits factor 3 better phe/keV response in LUX than in XENON100
LZ Program

- **LZ-S**: 3 tonnes detector in Davis water shield (SUSEL)
  - Proposal start: Sept 2009
  - Bigger 3” PMTs already in testing. Goal ~1 mBq/PMT
- **LZ-D**: 20 tonnes detector, part of ISE for DUSEL
  - « ultimate » direct detection experiment

**Requirements**

- Mechanics, safety: LUX 350kg will demonstrate
- Light collection: current understanding 20t scale ok
- Xe purity: LZ-D requires <10^{-14} Kr/Xe, < ~mBq Rn
  - state of art already demonstrated (SNO, Borexino) + Xe much easier to purify
  - work in progress to achieve high reliability

**Backgrounds**

- Goal: < 2 neutron events / 3,000 tonne.days (before acceptance cut)
- PMT background already improved by x2 compared to 2" tubes improvement by x10 likely in near future (currently XMASS has < 1 mBq/PMT)
- Extensive study of cosmogenic backgrounds in progress
  - still subdominant at -4850 ft for 20 tonne scale
Facility requirements: Space

LZD layout nominally consistent with baseline cavern

Water tank dimension critical, 12 m is conservative.

Staging must be carefully considered.