The LZ Dark Matter Experiment
Dark Matter

- First suggested by Fritz Zwicky in the 1930 while studying the Coma Cluster
- Later studied by Vera Rubin in the 1970’s
- At large radii within galaxy clusters, the rotational velocity of galaxies within the cluster does not go to zero
- The explanation: there is extra mass that neither absorbed nor emitted light, referred to as dark matter
Growing Evidence

Galactic rotation curves, BAO, CMB, gravitational lensing, and other measurements point to 27% of the universe being composed on non-baryonic dark matter.
The Bullet Cluster

- Above: image of two galaxies passing through each other, showing the hot gas (red) and center-of-mass from gravitational lensing (blue)

- Strongest evidence to data that dark matter phenomenon is not due to Modified Newtonian Dynamics
Weakly Interacting Massive Particles

- Weakly Interacting Massive Particles (WIMPs) are a leading candidate dark matter particle
- Only interact with baryonic matter through the weak force => very hard to detect!
- WIMPs, if they exist, could make up ALL the dark matter (this is known as the WIMP Miracle)
- Require physics beyond the standard model, typically either super symmetry or extra dimensions
WIMP Direct Detection

- Look for anomalous number of low-energy events in a large detector
- Requires low energy threshold (10’s of keV or lower!)
- Requires separating nuclear recoils (WIMP-like) from electron recoils (gamma-like)
- LUX looked for 1 event in ~100 kg in 85 days, for reference that’s less than
  - A banana (~10 decays/s)
  - A bicycle tire (.3 decays/s)
  - A liter of air outdoors (~1 decay/min.)
- LZ aims for 1000X better than this!
Liquid Xenon TPC Principle

Z position from S1 – S2 timing
X-Y positions from S2 light pattern

Reject gammas by charge (S2) to light (S1) ratio. Expect > 99.5% rejection.
- 160 events observed in fiducial volume between 2 and 30 phe S1
- 99.6% electron recoil (ER) discrimination with 50% acceptance for nuclear recoils (NR)
Spin-independent WIMP Limits

XENON100 (2012)-225 live days
LUX (2013)-85 live days: 90% upper limit
→ $10^{-21}$ barn!
Improving Sensitivity

- 300 day run planned for 2014-2015
- Still not background limited
- Expect a factor of 5 improvement in sensitivity!
- Lots of parameter space still to explore

- Dashed orange band represents fundamental neutrino background
Neutrino Backgrounds

- At some point, neutrino backgrounds become significant in dark matter searches.

- Although the flux of solar neutrinos is high, they’re mostly at low-energy.

- This is why they only matter for light WIMPs (> 10 GeV).

Plot taken from Billard et. al, arXiv:1307.5458v3
Neutrino Backgrounds (NR)

- Coherent neutrino scattering: neutrino scatters off nucleus as one object (for $E_\nu < 50$ MeV)
- Indistinguishable from event-by-event from WIMPs
- Not a problem for LZ above 4 keVnr
- $^8$B neutrinos could be a background in low-threshold analyses

Plot taken from Billard et. al, arXiv:1307.5458v3
Neutrino Backgrounds (ER)

- In Xe, can reject ~99.5% of ER while keeping 50% of NR

- Imagine a
  - 5 ton detector
  - ~5 keVee window
  - 3 years of operation
  - => ~1 irreducible background event
  - (unless ER discrimination can be improved...)

Plot taken from Baudis et. al, arXiv: 1309.7024v2, assumes 99.5% rejection of electron recoils
Union of LUX and ZEPLIN + others

Brookhaven National Laboratory
Brown University
Case Western Reserve University
LBNL/UC, Berkeley
Lawrence Livermore Lab
SLAC
SD School of Mines & Technology
SD Science and Technology Authority
Texas A&M University
University of Alabama
UC, Davis
UC, Santa Barbara
University of Maryland
University of Rochester
University of South Dakota
University of Wisconsin
Washington University
Yale University

University College London
University of Oxford
University of Sheffield
Edinburgh University
Imperial College London
LIP-Coimbra
MEPHI, Moscow
STFC Rutherford Appleton Laboratory
STFC Daresbury Laboratory

18 US and 9 European institutions
• 7 tons of active xenon
• Three layers
  – Water shield
  – Scintillator
  – Xenon (active and skin)
PMTs in xenon skin help to tag external backgrounds!
• Gd-doped linear alkyl benzene (LAB) used for tagging outgoing neutrons

• $^{155}\text{Gd}$ and $^{157}\text{Gd}$ have particularly high neutron capture cross sections

• Result of capture: 8 MeV gamma cascade
  – Very clear signature!

8 MeV of gammas

Neutron (from $(\alpha,n)$ or $\mu$ spallation)
Fiducial Volume and Vetoes

Total Bkgd: All Analysis Cuts
Total Bkgd: All Analysis Cuts + LxSkin Veto
Total Bkgd: All Analysis Cuts + LS + LxSkin Veto

2.8 Tons
Skin Veto
4.1 Tons
+ Gd-LAB
5.6 Tons

Tuesday, April 8, 14
There backgrounds are all reducible:

- **Gamma-rays** come mainly from PMTs => get lower radioactivity PMTs
- Can also take advantage of xenon self-shielding
- **$^{127}$Xe** is a cosmogenic with a 36.4 day half-life => decays away with time underground
- Reduce **$^{85}$Kr** using chromatography
# Estimated LZ Background

<table>
<thead>
<tr>
<th>Item</th>
<th>$^{238}\text{U}$</th>
<th>$^{232}\text{Th}$</th>
<th>$^{40}\text{K}$</th>
<th>ER Counts</th>
<th>NR Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti Cryostat</td>
<td>0.62 mBq/kg</td>
<td>0.61 mBq/kg</td>
<td>2.48 mBq/kg</td>
<td>(2.1) 2.1 (10.5)</td>
<td>(0.03) 0.04 (0.22)</td>
</tr>
<tr>
<td>PTFE panels</td>
<td>0.01 mBq/kg</td>
<td>0.002 mBq/kg</td>
<td>0.06 mBq/kg</td>
<td>(0.002) 0.002 (0.01)</td>
<td>(0.0006) 0.0009 (0.004)</td>
</tr>
<tr>
<td>3” PMT</td>
<td>3 mBq/PMT</td>
<td>3 mBq/PMT</td>
<td>30 mBq/PMT</td>
<td>(5.3) 7.9 (26)</td>
<td>(0.003) 0.02 (0.07)</td>
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<tr>
<td>Other</td>
<td>Various</td>
<td>Various</td>
<td>Various</td>
<td>3.5</td>
<td>(0.04) 0.04 (0.06)</td>
</tr>
<tr>
<td>Extra-TPC</td>
<td></td>
<td></td>
<td></td>
<td>(11) 14 (40)</td>
<td>(0.05) 0.10 (0.35)</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td></td>
<td></td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Kr + Rn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>234</td>
</tr>
<tr>
<td>Neutrinos</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.61</td>
</tr>
<tr>
<td>Totals</td>
<td>Raw</td>
<td></td>
<td></td>
<td>(291) 294 (312)</td>
<td>(0.66) 0.71 (0.96)</td>
</tr>
<tr>
<td></td>
<td>99.5% ER rejection, 50% NR acceptance</td>
<td></td>
<td>(1.46) 1.47 (1.56)</td>
<td>(0.33) 0.36 (0.48)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td></td>
<td></td>
<td>(1.79) 1.83 (2.04)</td>
<td></td>
</tr>
</tbody>
</table>

Tuesday, April 8, 14
## Estimated LZ Background

**All numbers approximate!**

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<tr>
<th>Item</th>
<th>$^{238}\text{U}$</th>
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<th>$^{40}\text{K}$</th>
<th>ER Counts</th>
<th>NR Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti cryostat</td>
<td>1 mBq/kg</td>
<td>1 mBq/kg</td>
<td>2 mBq/kg</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>PTFE Panels</td>
<td>.01 mBq/kg</td>
<td>.001 mBq/kg</td>
<td>.1 mBq/kg</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3” PMTs</td>
<td>3 mBq/kg</td>
<td>3 mBq/kg</td>
<td>30 mBq/kg</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Other (TPC)</td>
<td>Various</td>
<td>Various</td>
<td>Various</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>TPC Total</td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>0</td>
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<tr>
<td>Kr + Rn</td>
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<td></td>
<td></td>
<td>50</td>
<td>0</td>
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<tr>
<td>Neutrinos</td>
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<td></td>
<td></td>
<td>250</td>
<td>0.5</td>
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<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td>Raw</td>
<td>332</td>
</tr>
<tr>
<td>ER Reject</td>
<td>99.5%</td>
<td>NR Accept</td>
<td>50%</td>
<td>~2</td>
<td>0.25</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td></td>
<td></td>
<td>~2</td>
<td></td>
</tr>
</tbody>
</table>

**Tuesday, April 8, 14**
Calibrating LZ

- Plot: LUX ER and NR calibrations using tritium and external neutron sources

- How will this be done in LZ?
  - Tritium source was perfect, no need to change it!
  - There are improvements one could make to neutron calibrations
    - DD source (already done in LUX)
    - YBe source
    - AmLi source
Monoenergetic, Collimated Neutrons

Double scatter, n energy gives $E_r$
Two S2’s... calibrate S2
Transfer S2 calibration to S1 with single scatters
DD Neutron Calibrations

- DD gives a very clean calibration of the nuclear recoil response
Ionization (S2)

- Systematic error of 7% from threshold correction for (lowest energy) 0.7-1.0 keV\textsubscript{nra} bin
- Red systematic error bar shows common scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency.
- Current analysis cut-off at 0.7 keV\textsubscript{nra}

Blue Crosses - LUX Measured Q\textsubscript{y}; 181 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)
Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)
Orange Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)
Black Dashed Line - Szydagis et al. (NEST) Predicted Ionization Yield at 181 V/cm
Scintillation (SI)

- LUX $L_{\text{eff}}$ values currently reported at 181 V/cm as opposed to the traditional zero field value.
- X error bars representative of error on mean of population in bin
- Energy scale defined using LUX measured $Q_y$
- Method can be extended below existing 2 keV$_{\text{na}}$ point

Blue Crosses - LUX Measured $L_{\text{eff}}$; reported at 181 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)
Purple Band - Horn Combined Zeplin III FSR/SSR; 3.6 kV/cm, rescaled to 0 V/cm (energy scale from best fit MC)
Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)
Black Dashed Line - Szydagis et al (NEST)
Predicted Scintillation Yield at 181 V/cm
NR Endpoints

- **DD:** mono-energetic 2.45 MeV neutrons => ~75 keVnr end point in Xe

- **AmLi:** broadband ($\alpha$,n) source between 0-1.5 MeV (plot) => ~40 keVnr end point in Xe

- **YBe:** 152 keV mono-energetic ($\gamma$,n) source => 4.5 keVnr end point in Xe


Baseline plan
Under consideration
### Electric Field

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Drift Length</th>
<th>Cathode Voltage</th>
<th>Electric Field</th>
<th>ER Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXO-200</td>
<td>20 cm</td>
<td>-8 kV</td>
<td>376 V/cm</td>
<td>N/A</td>
</tr>
<tr>
<td>XENON100</td>
<td>30 cm</td>
<td>-16 kV</td>
<td>533 V/cm</td>
<td>99.75%*</td>
</tr>
<tr>
<td>ZEPLINIII (1st Science Run)</td>
<td>3.6 cm</td>
<td>-10 kV</td>
<td>3900 V/cm</td>
<td>99.98%</td>
</tr>
<tr>
<td>LUX</td>
<td>50 cm</td>
<td>-10 kV</td>
<td>181 V/cm</td>
<td>99.6%</td>
</tr>
<tr>
<td>LZ Goal</td>
<td>130 cm</td>
<td>-100 kV</td>
<td>770 V/cm</td>
<td>TBD</td>
</tr>
</tbody>
</table>

- Some examples of high voltages achieved in xenon time projection chambers
- Highest voltage so far (in absolute value): 16 kV
- LZ has 3X the drift distance of LUX => need high voltage for the same field
- So the saying goes, “They don’t pay you to plug yourself” but...

* >50% NR Acceptance!
Yale High Voltage R&D

• Epoxy poured feedthrough

• Feedthrough tested up to -200 kV (not in Ar)

• Used for tests of high voltage in LAr
High Voltage in LAr
LAr Test Dewar

- PMT for viewing light related to HV discharge or glow
- Setup is designed for option to purify argon while running; removing electronegatives could affect HV
Projected Sensitivity

LZ - 1000 days
5.6 Ton

Current LUX
Projected LUX
LZ
- Lots of parameter space still to explore
- Dashed orange band represents fundamental neutrino background
Summary

• LZ aims to improve on the sensitivity of LUX by > 100X
• Building on LUX experience from neutron and tritium calibrations
• LZ is start construction some time soon after LUX is complete!