Searching for Dark Matter with LZ

Hugh Lippincott, Fermilab for the LZ Collaboration

Exploring the Dark Universe
July, 2017
## LXe as Dark Matter Target

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Solution</th>
<th>Liquid Xenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely rare</td>
<td>Large mass</td>
<td>Very dense - 3 tonnes in 1 m³</td>
</tr>
<tr>
<td>Energy depositions of ~10 keV or below</td>
<td>Low energy thresholds</td>
<td>~60-70 electrons + photons / keV</td>
</tr>
<tr>
<td>Backgrounds - Impurities</td>
<td>Purification</td>
<td>Noble gases are (mostly) easy to purify</td>
</tr>
<tr>
<td>Backgrounds - Detector</td>
<td>Self shielding</td>
<td>Low MFP for ionizing radiation</td>
</tr>
<tr>
<td>Backgrounds - Internal/Detector</td>
<td>Discrimination</td>
<td>Charge to light ratio gives particle ID</td>
</tr>
</tbody>
</table>
Two phase Xenon Detectors

- Interaction in the xenon creates:
  - Scintillation light (~10 ns) - called S1
  - Ionization electrons
  - Electrons drift through electric field to liquid/gas surface
  - Extracted into gas and accelerated creating proportional scintillation light - called S2
Two phase Xenon Detectors

- Excellent 3D reconstruction (~mm)
- Z position from S1-S2 timing
- XY position from hit pattern of S2 light
- Allows for self shielding, rejection of edge events
- Ratio of charge (S2) to light (S1) gives particle ID
- Better than 99.5% rejection of electron recoil (ER) events
Self shielding is powerful

WIMP scattering
Self shielding is powerful

~keV energy deposit

~MeV gamma

Must cross full volume without interacting
$\text{LUX}$

$\text{LZ} \times 10^{-48} \text{ cm}^2$

$\text{Ge, NaI no discrimination}$

$\text{Ge, w/discrim.}$

$\text{LXe, w/discrim.}$

$\text{ZEPLIN-III}$

$\text{LUX}$

$\text{ZEPLIN-III}$

$\text{LXe, w/discrim.}$

$\text{CDMS}$

$\text{Darkside}$

$\text{SCDMS}$

$\text{LZ} < 3 \times 10^{-48} \text{ cm}^2$

$\text{(XENON nT)}$
Sixth and last, we add a small uniform background in addition to the signal and the background for all masses.

FIG. 4: The spin-independent WIMP-nucleon cross section as a function of WIMP mass at 90% confidence level (CL) for the current run of XENON1T.

The data is consistent with the background-only hypothesis. Fig. 4 shows the cross-section limits as a function of WIMP mass at 90% CL for this run of XENON1T. In green and yellow are the 1- and 2 standard deviation (SD) limits, respectively, and in red are the 3-SD limits. The limits are calculated using an extended unbinned profile likelihood test statistic.

More mass!
LZ = LUX + ZEPLIN

38 Institutions, 217 People

Black Hills State University
Brookhaven National Laboratory (BNL)
Brown University
Fermi National Accelerator Laboratory (FNAL)
Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Lawrence Berkeley National Laboratory (LBNL)
Lawrence Livermore National Laboratory (LLNL)
Northwestern University
Pennsylvania State University
SLAC National Accelerator Laboratory
South Dakota School of Mines and Technology
South Dakota Science and Technology Authority (SDSTA)
STFC Rutherford Appleton Laboratory (RAL)
Texas A&M University

University at Albany (SUNY)
University of Alabama
University of California (UC), Berkeley
University of California (UC), Davis
University of California (UC), Santa Barbara
University of Maryland
University of Massachusetts

University of Michigan
University of Rochester
University of South Dakota
University of Wisconsin-Madison
Washington University in St. Louis
Yale University
Collaboration meeting last week at SURF
Scale Up $\approx 50$ in Fiducial Mass

**LZ**
- Total mass – 10 T
- WIMP Active Mass – 7 T
- WIMP Fiducial Mass – 5.6 T

**LUX**
Sanford Underground Research Facility

Davis Cavern 1480 m
(4200 mwe)
LUX Water Tank

LZ Here
LZ

Water tank

Xe heat exchanger

Cathode HV feedthrough

Neutron beam pipe

7 ton LXe TPC

Gd-loaded liquid scint.
LZ design notes

- More mass (x50 more than LUX, x6 more than Xenon1T)

- 494 3” PMTs on TPC

- Significant HV/grid engineering (no xenon experiment has achieved HV goals so far)

- Requirement: 50 kV  Goal: 100 kV

- Sophisticated veto system - maximizes fiducial volume

- LXe “skin” - 93 1” PMTs + 38 2” PMTs

- 120 outer detector PMTs

- Radioactivity, radioactivity, radioactivity!
System test at SLAC

- Main test platform for LZ
- Same cryogenics/control
- Phase I (ongoing)
- Full LZ fields in scaled prototype TPC
  - Can HV be achieved with sparking or light emission?
- Prototype circulation
  - LZ architecture and compressor
- Phase II will test grids
Background suppression by screening

- Every component is screened and simulated for radioactivity
  - E.g. cryostat made of the most radiopure titanium in the world: < 0.05 counts in 1000 days after cuts
- Similar campaign working with Hamamatsu on PMTs
- Backed up by extensive quality assurance during production
Background suppression by veto

- Two component outer detector
- Gd-loaded liquid scintillator
- Instrumented skin

Xe TPC only

- Fiducial mass: 3.3 T

Xe TPC+skin

- Fiducial mass: 4.2 T

TPC+skin+OD

- Fiducial mass: 5.6 T
Background suppression by veto

- Two component outer detector
  - Gd-loaded liquid scintillator
  - instrumented skin

With veto, detector components are a subdominant background!

- Xe TPC only
- Xe TPC+skin
- TPC+skin+OD

Fiducial mass: 3.3 T
Fiducial mass: 4.2 T
Fiducial mass: 5.6 T
Internal backgrounds

- Radon, Krypton, Argon
- Distributed throughout the liquid volume
- ER backgrounds (can discriminate, thankfully)
- Radon requirement (goal) of 20(1) mBq

Radon emanation measurements

Dust is a killer!
Internal backgrounds

• Contributes half our radon budget

• Emanation measurements of “clean room dust”

• Requirement of <500 ng/cm^2 of dust in LZ

  • Goal of 5 ng/cm^2

  • SNO achieved 20 ng/cm^2, BOREXINO 1 ng/cm^2

  • 1 gram total!

• Cleanliness protocols, witness plate protocols, packaging protocols

Dust is a killer!
### Intrinsic Contamination Backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
<th>Composite</th>
<th>U early (mBq/kg)</th>
<th>U late (mBq/kg)</th>
<th>Th early (mBq/kg)</th>
<th>Th late (mBq/kg)</th>
<th>Co60 (mBq/kg)</th>
<th>K40 (mBq/kg)</th>
<th>n/yr (inc. S.F. rej.)</th>
<th>ER (cts)</th>
<th>NR (cts) (w/ SF rej.)</th>
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<td>Upper PMT Structure</td>
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<td>0.49</td>
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<td>14.30</td>
<td>0.00</td>
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</table>

**Subtotal (Detector Components)**: 6.20 0.070

**Subtotal (Non-ν counts)**: 921 0.50

**Physics Backgrounds**

<table>
<thead>
<tr>
<th></th>
<th>ER (cts)</th>
<th>NR (cts) (w/ SF rej.)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Astrophysical ν counts (8B)</td>
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<td>0**</td>
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<td>Astrophysical ν counts (Hep)</td>
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<td>0.21</td>
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<tr>
<td>Astrophysical ν counts (diffuse supernova)</td>
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<tr>
<td>Astrophysical ν counts (atmospheric)</td>
<td>0</td>
<td>0.46</td>
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</tbody>
</table>

**Subtotal (Physics backgrounds)**: 322 0.72

**Total**: 1,240 1.22

**Total (with 99.5% ER discrimination, 50% NR efficiency)**: 6.22 0.61

---

My summary of the summary table

6 ER, 0.6 NR in 1000 days!
Backgrounds summary

<table>
<thead>
<tr>
<th>Subtotal (Non-ν counts)</th>
<th>921</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics Backgrounds</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>322</td>
<td>0.72</td>
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<td>Total (with 99.5% ER discrimination, 50% NR efficiency)</td>
<td>1,240</td>
<td>1.22</td>
</tr>
<tr>
<td>Total (with 99.5% ER discrimination, 50% NR efficiency)</td>
<td>6.22</td>
<td>0.61</td>
</tr>
</tbody>
</table>

- Lots of neutrinos - significant fraction of both ER and NR counts
- Discrimination cuts are important

My summary of the summary table: 6 ER, 0.6 NR in 1000 days!
Sensitivity projections

- ~6 keVnr threshold in baseline scenario (LUX achieved 4.5 keVnr)
- Driven by S1 trigger coincidence threshold
- Better than 99.5% ER/NR discrimination at this field
Sensitivity projections (1000 days)

- LZ 90%CL Median (Baseline)
- LZ 90%CL Median (Goal)
- CMSSM (1σ)
- CMSSM (2σ)
- Zeplin-III (2011)
- PandaX (2016)
- LUX WS2013+WS2014-16
- XENON1T (2017)

@40 GeV: 2.3e-48 Nominal
1.1e-48 Goal
WIMP signal region

- 40 GeV WIMP
- 1σ
- 2σ
- ER

Log10(S2/S1) vs. S1 [phd]
Sensitivity projections (1000 days)

- Median Significance
- 90% CL Median (Baseline)
- 3σ Median Significance
- 5σ Median Significance

LZ projected

- ν-N coherent scattering
- 1 event
- 3σ significance 1000 tonne-years

1000 tonne-years significance
Schedule

- 2012 - LZ Collaboration formed
- 2014 - LZ Project start
- 2015 - DOE CD-1 approval - Conceptual Design Report (1509.02910)
- 2016 - DOE CD-3 approval - Technical Design Report (1703.09144)
- March 2017 - LUX removed from water tank
- 2018 - Underground construction begins
- 2019 - Commissioning
Schedule

• Competition is fierce!

• XENON1T out with new results, already heading to XENONnT
  • Infrastructure already in place - update of TPC and cryostat

• PandaX also has a strong group

• We’re moving as fast as we can!
Summary

• Liquid xenon TPCs are the leading technology in the search for $\sim 10$ GeV and above WIMPs (spin independent)

• Mature technology, challenge is to make the detectors bigger

• Scaling up raises new technical questions (HV, internal radioactivity, …)

• LZ is poised to achieve a factor $>30$ more sensitivity than current best limits

• The race is on for the next order of magnitude in sensitivity
End
Dark Matter Searches: Past, Present & Future

-1 event kg\(^{-1}\) day\(^{-1}\)

(Gross Masses kg)

~1 event 100 kg\(^{-1}\) yr\(^{-1}\)

~1 event 1 tonne\(^{-1}\) yr\(^{-1}\)

Many of current projections omitted from this plot.
Chapter 4. The ZEPLIN–III Experiment

Figure 4.7: Flowchart of the two processes creating a primary scintillation signal in an elastic recoil in liquid xenon. In the primary interaction both excited and ionised Xe atoms are created. The two branches produce, in their final stages, excited dimer states responsible for the typical scintillation light of the noble gas (\(\lambda = 178\) nm).

Transparency of the medium to its own scintillation light, i.e., the energy of the emitted photons is less than the energy difference between the ground state (of the two separated atoms) and the first atomic excited state, ensures good light collection.

4.2.1 The primary scintillation signal

The scintillation light produced in a particle interaction within the liquid xenon is attributed to two separate processes involving excited atoms and ions. A flow chart of the individual processes, both resulting in the production of VUV scintillation photons and their interconnection, is shown in Fig. 4.7 [126, 127].

Firstly, direct excitation takes place resulting in excitation luminescence by the de-excitation of singlet and triplet states of the created excimer \(\text{Xe}^*\), see Eq. (4.3).

The transition of the excited states occurs at short interatomic distance, where the ground state potential is repulsive and the molecule becomes dissociated. The two possible de-excitations from the lowest electronic excited states are quite different in their characteristic decay time due to the forbidden direct transition of the triplet to the ground state. The latter becomes possible through spin-orbital coupling and the

\[\text{Xe}^* \rightarrow \text{Xe} + \text{Xe} \]

\[\text{Xe}_2^* \rightarrow \text{Xe} + \text{Xe} \]

\[\text{Xe}_2^+ \rightarrow \text{Xe}^+ + \text{Xe} \]

\[\text{Xe}_2^{**} + \text{Xe} \]

Some LXe physics

- Significant difference between ER and NR tracks
- ER lead to more signal than NR
- More NR energy goes into heat and is lost
- Lindhard factor, $L_{\text{eff}}$, Quenching factor
- Two energy scales $\text{keV}_{\text{ee}}$ and $\text{keV}_{\text{nr}}$
- Leads to different behavior with field
- Also leads to ER/NR discrimination

C. Dahl, PhD Thesis
Requires calibration

- LUX has really done great work here
- Kr-83m - Over 1e6 events spread uniformly throughout detector

Fiducial volume determination

Position-based S1 corrections
Requires calibration

- LUX has really done great work here
- Tritiated methane (CH3T) - to measure low energy ER band

Low energy ER

Measured in both light and charge
- LUX has really done great work here
- DD neutron generator to measure NR yields

**Requires calibration**
• LUX has really done great work here
• DD neutron generator to measure NR yields

Requires calibration

Sys. uncertainty due to position reconstruction energy bias correction

Sys. uncertainty due to $S_2$ corrections, $g_2$, and neutron source energy spectrum
Leads to background rejection

Grey contours indicate lines of constant energy
Chapter 4. The ZEPLIN–III Experiment

Figure 4.7: Flowchart of the two processes creating a primary scintillation signal in an elastic recoil in liquid xenon. In the primary interaction both excited and ionised Xe atoms are created. The two branches produce, in their final stages, excited dimer states responsible for the typical scintillation light of the noble gas ($\lambda = 178$ nm).

Transparency of the medium to its own scintillation light, i.e. the energy of the emitted photons is less than the energy difference between the ground state (of the two separated atoms) and the first atomic excited state, ensures good light collection.

4.2.1 The primary scintillation signal

The scintillation light produced in a particle interaction within the liquid xenon is attributed to two separate processes involving excited atoms and ions. A flow chart of the individual processes, both resulting in the production of VUV scintillation photons and their interconnection, is shown in Fig. 4.7 [126, 127].

Firstly, direct excitation takes place resulting in excitation luminescence by the de-excitation of singlet and triplet states of the created excimer Xe$^{\ast}$, see Eq. (4.3). The transition of the excited states occurs at short interatomic distance, where the ground state potential is repulsive and the molecule becomes dissociated. The two possible de-excitations from the lowest electronic excited states are quite different in their characteristic decay time due to the forbidden direct transition of the triplet to the ground state. The latter becomes possible through spin-orbital coupling and the

For 122 keV ER, 56 keV NR
Rn-222 content

- 5x, 67 mBq
- Baseline, 13.4 mBq
- 0.05x, 0.67 mBq

The graph shows the log_{10} (\sigma_s) [pb] as a function of m_\chi [GeV/c^2]. The curves represent different levels of Rn-222 content, with the baseline being 13.4 mBq, and 5x and 0.05x representing 67 mBq and 0.67 mBq, respectively.
PLR (Profile Likelihood Ratio)

- Simple fiducial of 5600 kg (X,Y,Z position info not yet implemented in PLR)
- Dominant ER: Rn, Kr, pp-neutrinos spatially uniform like signal