The LZ Dark Matter Experiment

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Dark Matter Evidence

- Dark Energy: 68%
- Dark Matter: 27%
- Ordinary Matter: 5%

**Motion of galaxies and galaxy clusters**
- Bulge, disk, and halo
- Bulk of luminous matter: $v \sim r^{-1/2}$
- Spiral galaxies: $v \sim \text{const}$
- Data points

**Cosmological Evidence (CMB, BAO, Supernovae...)**
- Coma cluster
- $\langle T \rangle = 2.725 \, \text{K}$

**Gravitational Lensing (weak/strong)**
- Bullet Cluster
- Kochanski, Dell'Antonio, Tyson
- BAO (SDSS)
- Gas (X-ray) Mass (lensing)
Dark Matter Detection

Indirect Detection
(DM annihilation)
HAWC, ANTARES,
Fermi, IceCube,
MAGIC, CTA, AMS,
HESS, VERITAS, GAPS…
Dark Matter Detection

Accelerator Searches
(DD production)
LHC, LDMX
Dark Matter Detection

Direct Detection
Different Targets / Technologies: NaI, Ge, Si, Ar, Xe, RF and many more…

Generally model independent
- can search for a variety of candidates
Dark Matter Detection

Direct Detection
- Different Targets / Technologies: NaI, Ge, Si, Ar, Xe, RF
- Generally model independent
- can search for a variety of candidates
WIMPs Direct Detection

• WIMPs scatter off nuclei (NR)
  ✦ Expect recoils \( O(10 \text{ keV}) \)
  ✦ Expect < 1 event / tonne / year

• Backgrounds
  ✦ Gammas and electrons - scatter off atomic electrons (ER)
  ✦ Neutrons - also scatter off nuclei (NR)
  ✦ Neutrinos! new enemy. ER, NR. Can’t be shielded against

**Signal:** Nuclear Recoil (calibrate with neutrons)

**Background:** Electron Recoil
Dual Phase Noble Liquid TPC

- Excellent 3D imaging capability
  - Z position from S1 - S2 timing
  - XY positions from S2 light pattern

- Ratio of charge (S2) to light (S1)
  => Signal vs Background discrimination

99.8% discrimination, 50% NR acceptance
A Typical Event

S1 summed across all channels

- Time (μs): -0.2 to 0.4
- Amplitude (phe/10 ns): 0 to 0.6

S2 summed across all channels

- Time (μs): 179 to 184
- Amplitude (phe/10 ns): 0 to 8

LUX

1.5 keV electron recoil
(2 phe S1, near threshold)
Sanford Underground Research Facility (SURF) in Lead, SD

4850 feet deep (~1 mile)

Muon flux reduced by $10^7$ (4.3 km.w.e)

Ray Davis, noble prize winner

Lead, SD
LZ Detector Overview

- **Xenon TPC**
  - Total mass: 10 T
  - Active mass: 7 T
  - Fiducial: 5.6 T

- **3-component veto system:**
  - Water tank
  - Gd-loaded scintillator
  - Instrumented LXe Skin

LZ detector paper: *NIM A, 163047 (2019)*
Xenon TPC

- 1.5 m diameter x 1.5 m height
- 7T active LXe (5.6T fiducial)
  - x50 more than LUX
  - x6 XENON1T
- 50 kV cathode HV
- 494x 3” PMTs
- Gas circulation @ 500 slpm (turnover full mass in 2.4 days)
- Instrumented Xe skin region, outside the field cage
PMT arrays

Hamamatsu R11410 (3”)

- Top array: 253 PMTs
- Bottom array: 241 PMTs
Assembled TPC

- Detector integration started in December 2018 at Surface Assembly Laboratory (SURF) ~13,500 working hours.

Insertion into inner cryostat vessel
Ti Cryostat

- Intensive R&D program identified low activity titanium material (*Astropart. Phys.* 96, 1-10 (2017))
- Arrived at SURF May 14, 2018
Transport of TPC Underground

October 2019
Underground deployment

Lower inner cryostat vessel into outer cryostat vessel

Water tank

Making up cathode connections (under N2 purge)
LZ Cryogenics

- Cooling provided by thermosyphon technology (also used in LUX)

Thermosyphon principle

Sketch of cooling system

Thermosyphon Control Panel

Cryocooler LN Tank

Chilled water

Liquid nitrogen bath

LN storage vessel

Evaporator (attached to LXe tower / detector)

Condenser

Detector evaporator

N2 gas return

Vessel fins

Heater under clamp

LN supply

Copper flexible straps
Circulation System

Cryo-tower for xenon condensing (shown here in a test setup)

Water tank

Test cryostat

Xe tower

Water tank flange

Transfer Lines

Xenon purification unit from SAES using hot zirconium getter

Xenon storage in underground alcove at SURF

Gas compressors for xenon circulation
Circulation System & Commissioning

- Design gas circulation rate: 500 slpm
  ✦ Turnover full xenon mass every 2.4 days
- Purification using hot zirconium getter
  ✦ Removes non-noble impurities
- Underground commissioning completed
  ✦ Exercise xenon delivery, circulation, and recovery systems with a modest liquid xenon payload in a full-height test cryostat prior to the installation of the LZ TPC
  ✦ Up to 600 slpm demonstrated

Sampling Systems
(Mobile and Stationary)

500-600 slpm demonstrated in testing
Current Status

- Significant progress in the assembly of the TPC and associated systems
  - TPC complete and moved underground; HV cathode connection installed; Circulation testing complete
- Out of concern for the health of our staff and to slow the spread of the COVID-19 virus:
  - Shut down in mid-March; Reopened at reduced capacity in the summer
- Work continues while following institutional, local, and national guidelines
  - LZ construction almost complete!

![Diagram showing timeline of events](image-url)
Background sources and mitigation

- Detector materials
  - Nothing went into the detector without screening
  - Radio-assay campaign with 13 HPGe detectors, ICPMS, neutron activation analysis

- Rn emanation
  - Four screening sites
  - All major parts emanated before assembly
  - Target Rn activity: 2 $\mu$Bq/kg

- Rn daughters and dust on surfaces
  - TPC assembly in Rn-reduced cleanroom
  - Dust <500 ng/cm² on all LXe wetted surfaces
  - Rn-daughter plate-out on TPC walls <0.5 mBq/m²

- Xenon contaminants — $^{85}$Kr, $^{39}$Ar
  - Charcoal chromatography at SLAC

- Cosmogenics and externals
  - 4300 m.w.e. underground at SURF in Lead, SD
  - Instrumented Xe skin region
  - Gd-LS outer detector
  - High purity water shield

Many sources of BG
Many methods for BG mitigation

Kr Removal System

- 10 tonnes of Xe in hand
- Gas chromatography to remove Kr from Xe
  - Demonstration of 0.06 ppt in R&D at SLAC
- Production in progress
How to maximize the WIMP target mass?

- No veto

Xe-TPC only

Fiducial Volume
3.2 tonnes
Xenon “Skin” veto

PTFE tiling in ICV & Bottom side skin assembly

- Anti-coincidence detector for $\gamma$-rays
- 2 tonnes of LXe surrounding the TPC
- 1” and 2” PMTs at the top and bottom of the skin region
- Lined with PTFE to maximize light collection efficiency
Outer Detector

- Suppression of neutron-induced nuclear recoil rate \( \Rightarrow \) maximize fiducial volume.
  - 17 tonnes Gd-loaded liquid scintillator in acrylic vessels
  - 120 8” PMTs mounted in the water tank
  - Observe \( \sim 8 \text{ MeV} \) γ-rays from thermal neutron capture
  - >95% efficiency for tagging neutrons
  - Draw on experience from Daya Bay

All Side Tanks in! 12/1/2018
How to maximize the WIMP target mass?

- Three-component veto system:
  - Water tank
  - Xenon “skin”
  - Gd-loaded scintillator

- Tag individual neutrons and gammas
  >95% efficiency for tagging neutrons

- Characterize backgrounds \textit{in situ}
  → Enables discovery potential

Combined veto system allows to define fiducial a volume of 80% of active volume
### Expected backgrounds for 5.6 T fiducial - 1000 days

<table>
<thead>
<tr>
<th>Background Source</th>
<th>ER (cts)</th>
<th>NR (cts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Components</td>
<td>9</td>
<td>0.07</td>
</tr>
<tr>
<td>Surface Contamination</td>
<td>40</td>
<td>0.39</td>
</tr>
<tr>
<td>Laboratory and Cosmogenics</td>
<td>5</td>
<td>0.06</td>
</tr>
<tr>
<td>Xenon Contaminants</td>
<td>819</td>
<td>0</td>
</tr>
<tr>
<td>Radon is the dominant background!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>681</td>
<td>0</td>
</tr>
<tr>
<td>$^{220}$Rn</td>
<td>111</td>
<td>0</td>
</tr>
<tr>
<td>$^{nat}$Kr (0.015 ppt g/g/)</td>
<td>24.5</td>
<td>0</td>
</tr>
<tr>
<td>$^{nat}$Ar (0.45 pub g/g)</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>Physics</td>
<td>258</td>
<td>0.51</td>
</tr>
<tr>
<td>$^{136}$Xe $2\nu\beta\beta$</td>
<td>67</td>
<td>0</td>
</tr>
<tr>
<td>Solar neutrinos (pp+$^7$Be+$^{13}$N)</td>
<td>191</td>
<td>0*</td>
</tr>
<tr>
<td>Diffuse supernova neutrinos</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>Atmospheric neutrinos</td>
<td>0</td>
<td>0.46</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1131</td>
<td>1.03</td>
</tr>
<tr>
<td>with 99.5% ER discrim., 50% NR eff.</td>
<td>5.66</td>
<td>0.52</td>
</tr>
</tbody>
</table>

*Not including $^8$B or hep


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Carmen Carmona - Penn State  
APS April 2020
Expected backgrounds for 5.6 T fiducial - 1000 days

- Simulation of a 1000 day run of LZ

Projected Sensitivity (5.6 T exposure, 1000 live days)


90% CL minimum of $1.4 \times 10^{-48}$ cm$^2$ at 40 GeV/c$^2$
Thank You!

2021 will be an exciting year for direct detection!

~36 institutions, 250 scientists, engineers, technicians
Backup Slides
ER searches

- Sensitive to electron recoils from many types of new physics including
  - Neutrino magnetic moment
  - Solar axions (axio-electric effect)
  - Axion like particles
- Paper in preparation describing LZ sensitivity to these signals
Non-WIMP sensitivity - $0\nu\beta\beta$

- $^{136}\text{Xe}$ Q value at 2458 keV
- Nominal 1% energy resolution at Q value
- $T_{1/2}$ (90% C.L.) $> 1 \times 10^{26}$ years in 1000 live days, inner 1 tonne fiducial mass