WIMP Hunting in the Black Hills: the LZ Dark Matter Experiment

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Dark Matter
Dark Matter

Bullet Cluster
- Gravitational lensing measurements suggest two cores of non-interacting heavy material → two galaxy clusters collided
- Mass from lensing is distributed differently to the mass from electromagnetic radiation → this mass is “dark”

Cosmic Microwave Background
- Relic radiation from after recombination ~379,000 years ago, now measured as a thermal radiation of 2.7 K
- Distribution of anisotropies gives us information on the dark matter energy density of the universe
Dark Matter Detection

WIMP Hypothesis:

- Dark matter is a **heavy, neutral particle** that does not (observably) interact electromagnetically.
- Its relic density can be achieved through particles **annihilating with cross sections on the weak scale** → weakly interacting massive particles.
Liquid Xenon has proven the most prolific target and has provided the greatest gains in sensitivity.
Direct Detection

Expected signal: a Xe nuclear recoil

WIMP-nucleon scattering:
- Spin Independent: scalar, coherent across nucleus, $\sigma \propto A^2$
- Spin Dependent: axial vector, needs unpaired nucleon

Needs a medium that produces something detectable after a nuclear recoil, and if possible a way to discriminate between signal (DM) and background ($\gamma$, e-, n)

Why Xenon?
- High atomic mass: spin-independent cross section enhanced by $A^2$ dependence for scattering
- Has unpaired nucleons ($^{129}$Xe, $^{131}$Xe) for sensitivity to spin-independent scattering
- Dense, excellent self-shielding properties
- Intrinsically radiopure

WIMP Signals in a Dual-Phase Xenon Detector

Need a low background environment, well shielded from cosmic rays and with minimal radioactivity
Direct Detection with Dual-Phase LXe TPCs

- Primary signal is **nuclear recoil** of a xenon atom. Most backgrounds are electron recoils.
- Two signals: scintillation (S1) in LXe and ionisation (S2) in GXe
  - **ER/NR discrimination** from ratio of S1 and S2 signals
- 3D position reconstruction - XY from PMT array, Z from $\Delta t$ between S1 and S2
The LZ Collaboration

1) Center for Underground Physics (South Korea)
2) LIP-Centro (Portugal)
3) MIEM (Russia)
4) Imperial College London (UK)
5) Royal Holloway University of London (UK)
6) STFC Rutherford Appleton Lab (UK)
7) University College London (UK)
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23) South Dakota School of Mines and Technology (US)
24) South Dakota Science and Technology Authority (US)
25) Texas A&M University (US)
26) University at Albany (US)
27) University of Alabama (US)
28) University of California, Berkeley (US)
29) University of California, Davis (US)
30) University of California, Santa Barbara (US)
31) University of Maryland (US)
32) University of Massachusetts (US)
33) University of Michigan (US)
34) University of Rochester (US)
35) University of South Dakota (US)
36) University of Wisconsin – Madison (US)
37) Washington University in St. Louis (US)
38) Yale University (US)

38 institutions across the US, UK, Portugal and South Korea

250 scientists, engineers, and technicians
The Sanford Underground Research Facility

[Image of the Sanford Underground Research Facility]
The LZ Detector
The LZ Detector

- 17T Gd-loaded liquid scintillator
- 60,000 gallons of ultrapure water
- 120 veto PMTs
- 494 LXe PMTs
- 131 skin PMTs
- 2T skin veto
- 7T active LXe target
- Neutron calibration conduit (2 total)
- Calibration source deployment tubes (3 total)
“Sally for Scale”

LZ Acrylic Vessel  LUX Outer Cryostat  LZ Outer Cryostat

* I am 5’2" / 160 cm
10T total Xenon, undergoes:
- Krypton removal at SLAC*
  - Gas charcoal chromatography
  - Goal: < 300 ppq $^{\text{nat}}\text{Kr}/\text{Xe}$
- Online purification of GXe
  - Hot zirconium getter removes electronegative impurities
  - Full 10T purified every 2.4 days
- Radon removal
  - Inline radon removal system uses activated carbon trap, 10x reduction of radon in 1 pass

* see talk by D. Ames, Friday at 11am

The LZ Krypton Removal Chromatography System
Time Projection Chamber

- 2 PMT arrays of Hamamatsu R11410-20 PMTs (494 total)
- 4 electrodes/grids woven on specialized looms and passivated to reduce e-emission*
- 57 field rings embedded in reflective PTFE → 310V/cm drift field
- TPC completed August 2019
- Inserted into ICV at surface assembly lab

* see talk by R. Linehan, Thurs at 8am
Understanding the impact of high voltage electrodes on low-energy dark matter searches with the LZ dual phase xenon TPC
Liquid Xenon Skin Detector

- 2T of active xenon between the ICV and the TPC field cage
  - Optically isolated from TPC
- 93 1” R8520 PMTs in ice cube trays at the top
- 20 side + 18 dome 2” R11410 PMTs at the bottom
- Expected to be $>95\%$ efficient at tagging $\gamma$-rays
Titanium Vessels

Inner vessel installed in the water tank
December 2019

ICV at the Surface Assembly Lab

ICV and OCV in place in water tank

ICV being lowered into OCV

Rising Stars in Experimental Particle Physics 2021
A neutron is emitted from an \((\alpha,n)\) reaction in the PMTS.

It enters the Outer Detector, slows down and captures on Gadolinium or Hydrogen.

It scatters from a Xe nucleus, causing a nuclear recoil inside the LXe detector.

\(\gamma\)-rays are emitted from the post-capture nucleus.

\(\gamma\)-rays interact in the liquid scintillator, producing photons, which are detected by PMTs.
Outer Detector

2 top vessels

10 segmented acrylic vessels

3 bottom vessels

3 side vessels

17T Gd-loaded liquid scintillator

GdLS Filling System

120 8” PMTs
Outer Detector Installation

Side vessel lowering into water tank

Post-acrylic cleaning yoga

All acrylic vessels in place!

PMT and tyvek installation

Top tank fill system installation

OD construction completed spring 2021
Cleanliness and Background Mitigation

- Detector materials
  - Radio-assay campaign
  - gamma-screening
  - ICPMS
  - NAA
- Rn emanation
  - Four Rn emanation screening sites
  - Two portable Rn assay panels
  - Target Rn activity: 2 μBq/kg
- Rn daughters and dust on surfaces
  - TPC assembly in Rn-reduced cleanroom
  - Dust < 500 ng/cm³ on all LXe contact surfaces
  - Rn-daughter plate-out on TPC walls < 0.5 mBq/m²
- Xenon contaminants
  - ⁸⁵Kr, ³⁹Ar
  - Charcoal chromatography @ SLAC
  - Final natKr/Xe <300 ppq
- Cosmogenics and externals
  - 4300 m.w.e. underground
  - Instrumented Xe skin region
  - GdLS outer detector
  - High purity water shield
Backgrounds

ER Backgrounds:
- $\gamma$-rays & $\beta$-decays from $^{238}\text{U}$, $^{232}\text{Th}$ chains
- $^{60}\text{Co}$, $^{40}\text{K}$
- Xenon lines
- $^{222}\text{Rn}$, $^{220}\text{Rn}$ and $^{85}\text{Kr}$ in the LXe

NR Backgrounds
- Neutrons from $(\alpha,n)$ & spontaneous fission in detector components
- $^8\text{B}$ solar neutrinos
- Wall background (mis-reconstructed ion recoils)

Key for reducing background:
- Fiducialisation (self-shielding)
- Single scatter cuts
- Energy cuts
- Dual veto system (skin and OD)

OD reduces NR backgrounds and allows maximal fiducial volume
LZ Sensitivity Projections

1.4 x 10^{-48} \text{ cm}^2 @ 40 \text{ GeV/c}^2

arXiv:1802.06039
Phys. Rev. D 101, 052002
LZ Physics Reach

LZ physics reach extends beyond vanilla WIMPs:

- Solar axions
- Axion-like particles (ALPs)
- $2\nu\beta\beta$ of $^{134}$Xe with competitive sensitivity to $0\nu\beta\beta$
- Enhanced sensitivity to low mass DM through Migdal effect
- Leptophilic dark matter
- Neutrino magnetic moment
- Mirror dark matter

arxiv:2102.11740
arxiv:2104.13374
Commissioning

Xenon:

- Circulation test completed last year with test cryostat underground
- Achieved designed gas circulation rate of 500 slpm
- TPC has been cooled down to ~185 K

PMTs:

- Fully tested and characterized with LEDs calibration in all three detectors
- OD OCS system fully characterized
  - arxiv:2102.06281
LZ construction is complete!

- We have cold xenon, all PMTs have been tested with LEDs
- Physics data taking this year
- Expected 40x improvement in sensitivity on current limits, also sensitive to non-WIMP physics
- 2022 will be an exciting year!

Thanks!
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