Searching for Dark Matter with LZ

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Exploring the Dark Universe
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LXe as Dark Matter Target

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

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 ($\sim$ 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

Self shielding is powerful

~keV energy
deposit

~MeV
gamma

Must cross full
volume without
interacting

LUX - 100 kg (active)
PandaX-II - 329 kg (fid)
Xenon1T - 1 tonne (fid)

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

Center for Underground Physics (Korea)

Imperial College London (UK)

LIP Coimbra (Portugal)

MEPhI (Russia)

STFC Rutherford Appleton Laboratory (UK)

University College London (UK)

University of Bristol (UK)

SUPA, University of Edinburgh (UK)

University of Liverpool (UK)

University of Oxford (UK)

University of Sheffield (UK)

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 ≈ 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

Water
tank

Gd-loaded
liquid scint.

Xe heat
exchanger

7 ton
LXe TPC

Cathode
HV
feedthrough

Neutron beam pipe

LZ design notes

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

Xe TPC+skin

TPC+skin+OD

Background suppression by veto

- Two component outer detector
- **With veto, detector components are**
- **in a subdominant background!**

Xe TPC only

Xe TPC+skin

TPC+skin+OD

Internal backgrounds

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

Radon emanation measurements

EXO sample inside UA emanation chamber

Dust is a killer!

Internal backgrounds

- Contributes half our radon budget
- Emanation measurements of “clean room dust”
- Requirement of $<500 \text{ ng/cm}^2$ 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	Mass (kg)	Composite	U early (mBq/kg)	U late (mBq/kg)	Th early (mBq/kg)	Th late (mBq/kg)	Co60 (mBq/kg)	K40 (mBq/kg)	n/yr (inc. S.F. rej.)	ER (cts)	NR (cts) (w/ SF rej.)
Upper PMT Structure	40.5	Y	3.90	0.23	0.49	0.38	0.00	1.46	2.53	0.05	0.000
Lower PMT Structure	69.9	Y	2.40	0.13	0.30	0.24	0.00	0.91	6.06	0.05	0.001
R11410 3" PMTs	91.9	Y	71.63	3.20	3.12	2.99	2.82	15.41	81.83	1.46	0.013
R11410 PMT Bases *	2.8	Y	287.74	75.80	28.36	27.93	1.43	69.39	34.65	0.36	0.004
R8778 2" PMTs	6.1	Y	137.50	59.38	16.88	16.88	16.25	412.50	52.80	0.13	0.008
R8520 Skin 1" PMTs	2.2	Y	60.50	5.19	4.75	4.75	24.20	332.76	4.60	0.02	0.001
R8520 Skin PMT Bases *	0.2	Y	212.95	108.46	42.19	37.62	2.23	123.61	3.62	0.00	0.000
PMT Cabling	103.5	Y	29.83	1.47	3.31	3.15	0.65	33.14	2.65	1.43	0.000
TPC PTFE	184.0	N	0.02	0.02	0.03	0.03	0.00	0.12	22.54	0.06	0.008
Grid Wires	0.75	N	1.20	0.27	0.33	0.49	1.60	0.40	0.02	0.00	0.000
Grid Holders	62.2	Y	1.20	0.27	0.33	0.49	1.60	0.40	6.33	0.27	0.002
Field Shaping Rings	91.6	Y	5.41	0.09	0.28	0.23	0.00	0.54	10.83	0.23	0.004
TPC Sensors	0.90	Y	21.09	13.51	22.89	14.15	0.50	26.29	24.77	0.01	0.002
TPC Thermometers	0.06	Y	335.50	90.46	38.48	25.02	7.26	3,359	1.49	0.05	0.000
Xe Recirculation Tubing	15.1	Y	0.79	0.18	0.23	0.33	1.05	0.30	0.64	0.00	0.000
HV Conduits and Cables	137.7	Y	1.9	2.0	0.5	0.6	1.4	1.2	4.9	0.04	0.001
HX and PMT Conduits	199.6	Y	1.25	0.40	2.59	0.66	1.24	1.47	5.33	0.06	0.001
Cryostat Vessel	2406.1	N	1.59	0.11	0.29	0.25	0.07	0.56	123.70	0.63	0.013
Cryostat Seals	33.7	Y	73.91	26.22	3.22	4.24	10.03	69.12	38.78	0.45	0.002
Cryostat Insulation	23.8	Y	18.91	18.91	3.45	3.45	1.97	51.65	69.83	0.43	0.007
Cryostat Teflon Liner	26.0	N	0.02	0.02	0.03	0.03	0.00	0.12	3.18	0.00	0.000
Outer Detector Tanks	3199.3	Y	0.16	0.39	0.02	0.06	0.04	5.36	77.96	0.45	0.001
Liquid Scintillator	17640.3	Y	0.01	0.01	0.01	0.01	0.00	0.00	14.28	0.03	0.000
Outer Detector PMTs	204.7	Y	570	470	395	388	0.00	534	7,587	0.01	0.000
Outer Detector PMT Supports	770.0	N	1.20	0.27	0.33	0.49	1.60	0.40	14.30	0.00	0.000
Subtotal (Detector Components)										6.20	0.070
222Rn (2.0 μBq/kg)										722	-
220Rn (0.1 μBq/kg)										122	-
natKr (0.015 ppt g/g)										24.5	-
natAr (0.45 ppb g/g)										2.47	-
210Bi (0.1 μBq/kg)										40.0	-
Laboratory and Cosmogenics										4.3	0.06
Fixed Surface Contamination										0.19	0.37
Subtotal (Non-v counts)										921	0.50
Physics Backgrounds											
136Xe 2νββ										67	0
Astrophysical ν counts (pp+7Be+13N)										255	0
Astrophysical ν counts (8B)										0	0**
Astrophysical ν counts (Hep)										0	0.21
Astrophysical ν counts (diffuse supernova)										0	0.05
Astrophysical ν counts (atmospheric)										0	0.46
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

Subtotal (Non- ν counts)
Physics Backgrounds
^{136}Xe $2\nu\beta\beta$
Astrophysical ν counts (pp+7Be+ ^{13}N)
Astrophysical ν counts (^8B)
Astrophysical ν counts (Hep)
Astrophysical ν counts (diffuse supernova)
Astrophysical ν counts (atmospheric)
Subtotal (Physics backgrounds)
Total
Total (with 99.5% ER discrimination, 50% NR efficiency)

921	0.50
67	0
255	0
0	0**
0	0.21
0	0.05
0	0.46
322	0.72
1,240	1.22
6.22	0.61

- 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

Detector Parameter	Reduced	Baseline	Goal
Light collection (PDE)	0.05	0.075	0.12
Drift field (V/cm)	160	310	650
Electron lifetime (μ s)	850	850	2800
PMT phe detection	0.8	0.9	1.0
N-fold trigger coincidence	4	3	2
^{222}Rn (mBq in active region)	13.4	13.4	0.67
Live days	1000	1000	1000

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

Sensitivity projections (1000 days)

WIMP signal region

Sensitivity projections (1000 days)

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!
- XENONIT 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 ~ 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

Some LXe physics

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_{eff} , Quenching factor
 - Two energy scales keV_{ee} and keV_{nr}
- Leads to different behavior with field
- Also leads to ER/NR discrimination

Requires calibration

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

Fiducial volume determination

Position-based SI corrections

Requires calibration

- LUX has really done great work here
 - Tritiated methane (CH_3T) - to measure low energy ER band

Low energy ER

Measured in both light and charge

Requires calibration

- 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

Leads to background rejection

Grey contours indicate lines of constant energy

Some LXe physics

E. Aprile et al., Phys. Rev. Lett. **97**, 081302 (2006)

For 122 keV ER, 56 keV NR

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