Do WIMPs Rule?
The LUX & LZ Experiments and the Search for Cosmic Dark Matter

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Standard cosmology: An inventory of the universe

SDSS-III / BOSS

WMAP

from Perlmutter, Phys. Today

3 Kelvin cosmic microwave background

Baryon acoustic oscillations

supernovae

Matter density

Energy density

(units of critical density)

No Big Bang

Union2 SN Ia Compilation

BAO

CMB

Flat

Tytler & Burles
WIMP Hypothesis

- Early Universe as Particle Factory
  - Not enough protons and neutrons produced in the Big Bang

A new type of particle: WIMPs = weakly interacting massive particles

Massive: source of gravity     Weakly-interacting: not star forming

\[ E=mc^2 \]
cross section → annihilation rate
cross section $\rightarrow$ annihilation rate
WIMP freezeout

- WIMP pairs produced in equilibrium
- Annihilation stops when number density falls too low
  \[ H > \Gamma_A \sim n_\chi \langle \sigma_A v \rangle \]
  → annihilation rate slower than Hubble expansion ("freeze out")
  → mean free time > age
- For \( \Omega_\chi \approx 1 \)
  - M \sim 10-1000 GeV
  - \( \sigma_A \) \sim electroweak

Production = Annihilation \( (T\geq m_\chi) \)
Production suppressed \( (T<m_\chi) \)
Freeze out

~exp(-m/T)

\[ \frac{N}{N_{EQ}} \]

\[ \frac{m_\chi}{T} \] (time \( \rightarrow \))

Comoving Number Density

Jungman, Greist, Kamionkowski 1996

SUSY/LSP?
Dark Matter in Galactic Halos

Vera Rubin and Kent Ford, 1978
Scattering experiment

WIMP

dark matter halo

density, speed

$10^{16}$ WIMPs/year

$10^{-16}$ light years

detector

Cross section: WIMP scatters once in a light year of lead

Rate ~ few events / year
WIMP search - c.1988: converted *neutrino* detector

- Germanium ionization detector at the Oroville Dam, CA searching for double beta decay - progenitor to Majorana

![Graph showing recoil energy transfer to nucleus event rate vs. Q (keV)].

The graph illustrates the event rate (events/kg/day/keV) on the y-axis and the recoil energy transfer to the nucleus (Q, keV) on the x-axis. Notable isotopes include $^{68}\text{Ga}$, $^{65}\text{Cu}$, $^{49}\text{Ti}$, $^{55}\text{Mn}$, and $^{3}\text{H}$ end point, which are marked on the graph. The red line indicates the ruled out heavy neutrinos as DM.

*From Jungman et al. (D.O. Caldwell et al.)*
WIMP search - c.1988: converted neutrino detector

- Germanium ionization detector at the Oroville Dam, CA searching for double beta decay - progenitor to Majorana

![Graph showing event rate vs. recoil energy transfer to nucleus](image.png)

**Event rate**

<table>
<thead>
<tr>
<th>WIMP Mass [GeV]</th>
<th>Cross-section [cm²] (normalised to nucleon)</th>
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<tbody>
<tr>
<td>$10^{-44}$</td>
<td>1</td>
</tr>
<tr>
<td>$10^{-43}$</td>
<td>10</td>
</tr>
<tr>
<td>$10^{-42}$</td>
<td>100</td>
</tr>
</tbody>
</table>

From Jungman et al. (D.O. Caldwell et al.)
Energy deposition

- WIMP
  - 1% energy
  - Fastest
  - No surface effects

- Ionization
  - 10% energy

- Light
  - 1% energy
  - Fastest
  - No surface effects

- Phonons/heat
  - 100% energy
  - Slowest
  - Cryogenics
An active field with many approaches!

2-phase nobles:
- ZEPLIN
- XENON
- WARP
- LUX/LZ
- ArDM
- Darkside

1% energy fastest

10% energy

Ionization

CoGent (HPGe)
- DMTPC (gas dir.)
- DRIFT (gas dir.)

Semiconducting calorimeters:
- CDMS
- Edelweiss

Phonons/heat

100% energy slowest

Superheated liquids:
- Picasso
- Simple
- Coupp
- PICO

Inorganic scintillators:
- DAMA/LIBRA
- KIMS

Single-phase liquid nobles:
- DEAP
- MiniCLEAN
- XMASS

CRESST II

TARGET

low radioactivity
background immunity
large mass / stable operation
shielded
low energy threshold

1% energy fastest
Shielding Gamma Rays

Water, 2.6 MeV gammas

1 m water shielding

Liquid Xe, 2.6 MeV gammas

1 m liquid Xe

Water

100 keV
500 keV
2614 keV

Liquid Xenon

100 keV
500 keV
2614 keV
The Large Underground Xenon Detector

250 kg active LXe @ 170 K
S1, S2 event energy
S2 event xy location
S1-S2 timing z location
S2/S1 recoil type
The LUX Experiment

Inside the LUX/LZ water tank
Sanford Underground Research Facility
4850-foot deep Davis Cavern
Homestake Gold Mine
Lead, SD

photo credits: Matt Kapust, SURF
Sanford Underground Research Facility

Former Homestake Gold Mine
Backgrounds: neutrons

- Cosmic ray muons down by 10,000,000x
- Neutron scatter
- Nuclear disintegration
- Neutron moderated by water shield
- Gammas in Water
Internal dangers: radioactive $^{85}$Kr

- 10-yr $T_{1/2}$ beta decay
- Can’t self-shield
- Noble gas: non-reactive
- $\approx 130$ ppb in purchased Xe
  - LUX background “floor” from 122 PMTs $\approx 20$ ppt Kr/Xe

$^{85}$Kr $\rightarrow$ $^{85}$Rb + e$^-$ + $\nu$

Chromatography
Gas charcoal chromatography Kr removal
400 kg Xe at Case: 130 ppb to 4 ppt

Detection of krypton at the part-per-trillion level
C. Hall, UMD: Assay with ppt sensitivity
50 kg / week processed for LUX
Raw signals in LUX

Depth from timing difference

Lateral location from top PMT Array
Signal production in liquid Xe

- Excitation
- Ionization
- Recombination
- VUV photon, 175nm
- Heat
- Electron Recoils

$\text{Xe}$

$\text{Xe}^+$

$\text{Xe}_2^+$

$\text{Xe}^*$

$\text{Xe}_2^*$

S1

S2
Signal production in liquid Xe

- Excitation: \( \text{Xe} \rightarrow \text{Xe}^+ \) and \( \text{Xe}^* \)
- Ionization: \( \text{Xe}^+ \rightarrow \text{Xe}^{2+} \)
- Recombination: \( \text{Xe}^{2+} \rightarrow \text{Xe}^+ + \text{e}^- \)
- VUV photon, 175 nm: \( \text{Xe}^2* \rightarrow \text{Xe} + \text{Xe} + \text{VUV photon} \)

Nuclear Recoils: \( \text{Xe} + \text{Xe} \)
Understanding light and charge

Puzzling low energy behavior

Comprehensive model, only 2 fit parameters  (Dahl, PhD thesis, 2009)

Robust Monte Carlo framework: NEST  (M. Szydagis et al., JINST 6, p10002 (2011))
Background and Signal Distinction

More charge, less light

Background

in situ LUX calibrations

Signal

Internal tritium source (purified away with $\tau \sim 7$ hours)
WIMP signal

- Signal region: a quiet place where low-energy single-scatter nuclear recoils away from the walls can emerge from among:
  - external gamma rays into the fiducial volume
  - wall events (206Pb)
  - dissolved backgrounds (Rn-progeny, 85Kr, 127Xe)
  - delayed electrons from previous large S2’s
Event selection

Requirements for WIMP search candidate events

• S2 trigger (at least 2 trigger ch. ≥ 8 phe within 2 µs) [lower threshold than S1]
• 2 phe (2-fold coincidence) ≤ S1 ≤ 30 phe [quiet enough to see this in ‘look back’]
• 200 phe (8 e-) ≤ S2 ≤ 3300 phe [require good xy measurement]
• total area of other pulses in the event < 100 phe [confusion from previous large S2's]
LUX WIMP Search, 85 live-days, 118 kg

ERO Calibration 99.6±0.1% leakage below NR mean, so expect 0.64 +/- 0.16 for 160 events

ER band / 118 kg fiducial

160 events in ER
Extended Likelihood Treatment

\[ L_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn/222}}}{N!} \prod_{i=1}^{N} \left( N_s P_s(x; \sigma, \theta_s) + N_{Compt} P_{ER}(x; \theta_{Compt}) + N_{Xe-127} P_{ER}(x; \theta_{Xe-127}) + N_{Rn} P_{ER}(x; \theta_{Rn}) \right) \]

Observables: \( x = (S_1, \log_{10}(S_2/S_1), r, z) \)

Parameter of interest: \( N_s \)

Nuisance parameters: \( N_{Compt}, N_{Xe-127}, N_{Rn/Kr-85} \)

Modeled WIMP signal, including resolution and efficiencies
Spin Independent Cross Section Upper Limit

<table>
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<tr>
<th>WIMP−nucleon cross section (cm²)</th>
<th>LUX (2013)-85 live days</th>
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<tbody>
<tr>
<td></td>
<td>LUX +/-1σ expected sensitivity</td>
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<tr>
<td></td>
<td>XENON100(2012)-225 live days</td>
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<tr>
<td></td>
<td>XENON100(2011)-100 live days</td>
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<tr>
<td></td>
<td>CDMS II Ge</td>
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<tr>
<td></td>
<td>ZEPLIN III</td>
</tr>
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<td>Edelweiss II</td>
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</tbody>
</table>

Low Mass WIMPs

The figure shows the WIMP-nucleon cross section in cm$^2$ as a function of WIMP mass in GeV/c$^2$. Various experiments and their favored regions are indicated, including CDMS II Ge, DAMA/LIBRA, CoGeNT, CRESST, CDMS II Si, and CoGeNT Favored. The XENON100(2012) and LUX (2013) experiments are also plotted. The figure includes a inset showing a detailed view of the WIMP mass vs. cross section.
Next for LUX

![Graph showing WIMP-nucleon cross section vs. m_{WIMP} (GeV/c^2)]

- **DAMA/LIBRA**
- **CoGeNT (2012)**
- **CDMS II Si (2013)**
- **CRESST II**
- **ZEPLIN III**
- **XENON100**
- **CDMS II Ge**

**Updated analysis of 85d**
- improved reconstruction
- lower threshold
- wall distribution into PLR?
- complete DD calibration
- NEST update

**300d run: above +**
- improved extraction field
- $^{127}$Xe decayed away
• 20-fold scale-up from LUX
• Two-component outer detector system
  • 0.75 m thick Gd-loaded LAB scintillator shield (c.f.: Daya Bay)
  • Instrumented Xe “skin”
  • Effective for neutrons and gammas

fits in Davis Cavern

LZ: LUX + ZEPLIN

TPC design

The WIMP target is configured as a double-phase TPC containing 7 tonnes of active LXe. The design is mostly based on the LUX detector, which has demonstrated excellent operational performance at the 300 kg scale. The LZ TPC will be made from 2-cm-wide PTFE rings with 146 cm inner diameter, stacked to the same total height of 146 cm. Hexagonal arrays of 3-inch phototubes (241 units each) are placed in the liquid, facing up, and in the gas phase, facing down, to detect the vacuum ultraviolet (VUV) light emitted when a particle interacts in the detector. The nominal operating pressure is 1.6 bar(a).
LZ Reach and Snowmass

3 year run, limited primarily by (electron recoil) background of \( pp \) solar neutrinos

limited by nuclear scatter background?

reach to \( 10^{-49} \) cm\(^2\) neutrino floor depends on rejecting \( pp \) solar
Lab Activities at SLAC

Fundamental measurements

Removal of trace radioactive $^{85}$Kr with gas charcoal chromatography

LXe vessels w/200 kV feedthrough ports for LZ system test

Test TPC in 100 kg LXe @ 170 K

Purification Tower

HV feedthrough (drift field)

high-flow pneumatically controlled Xe circulation & purification panel
Former BaBar “IR2” complex

- LSST Clean Room
- Repurposed electronics hut: LZ / liquid nobles test stand
- Pump shed
- Xe storage
LZ / liquid nobles test stand

LN thermosyphon and controls

Phase I & II system test

Re-furbished LUX Kr removal for R&D
Kr removal: reduction to 0.015 ppt ~ 10% pp solar ν
10 tons / 60 days @ 200 kg/day X 2 passes

- Xe/Kr chromatography
- Xe recovery
- Xe storage
- cryocooler
- cooled Kr trap
- charcoal
- Xe/Kr
- feed/purge ~ 120 min
- 500 kg
- 50 SLPM Xe
- 80 bar
- 2 bar
- 500 SLPM He
- (Etairon compressor)
- 250 SLPM He
- (dry backing pump)
- 16 kg
- 10 mbar
- 100 mbar
- RGA
- LN cryocooler
- thermosyphon
- automation of all 3 cycles
- feed/purge ~ 120 min
- 500 mbar

Graphical representation of the process:

- Feed/purge duration: ~ 120 min
- 250 SLPM He (Etairon compressor)
- 200 kg capacity
- 24 hour cycle (per condenser)
- 50 SLPM Xe
- 2 bar
- 80 bar
- 10 tons / 60 days @ 200 kg/day X 2 passes
Summary

- Dark matter detection - exciting future
- Liquid xenon TPCs playing key role
- 300-day data set for LUX ~ 4-5x
- LZ approaches neutrino floor
Thank you...

...visit us at luxdarkmatter.org