Since 1933, we have had strong evidence that a large fraction of the mass of the Universe is hidden to us. Today, after decades of efforts both theoretical and observational, this "Dark Matter enigma" remains one of Physics' hottest topics. In this talk I will attempt to cover the basics of Dark Matter physics and what makes the case for its existence so compelling. We will then review the various ways in which one can detect it, before focusing in particular on the LUX experiment, a liquid xenon detector currently being operated at the Sanford Underground Laboratory in Lead, South Dakota.
Cosmic Matters

The Case for Dark Matter
What is the Universe made of?

- Dark Energy: 73%
- Dark Matter: 23%
- Heavy elements: 0.03%
- Neutrinos: 0.3%
- Stars: 0.4%
- Intergalactic Gases, others: 4%
Observational Evidence
(at the galactic level)

- **First evidence**: 1933 F. Zwicky (initially with galaxies clusters)

Stars radial velocities dictated by gravitation laws **do not match** observation
→ It is as if a large, unseen mass exists in the galaxy

- Since then, more clues:
  - Cosmological Microwave Background (CMB) puts constraining limits on each component of the universe
  - Dark Matter needed to explain the formation of large cosmic structures
Just Invisible Regular Matter?

- Could it just be matter we simply cannot see? For instance: giant planets, interstellar gas clouds, tiny neutron stars, black holes...
- Those have been looked for in the past two decades, most notably through **gravitational lensing**
- Can explain at most 5% of the missing mass → Not nearly enough!
• **Basic idea**: each galaxy is surrounded by a homogeneous (?) cloud of massive, neutral, very weakly interacting particles, with a total mass ~5x of everything else

• Such a particle is generically called a **WIMP**, its exact nature remaining to be determined

• Halo’s properties dictated by observations

  → We know how much total mass there is, and we can make educated guesses on the velocities distribution, particle mass, etc… with large (x3-100 !) uncertainties

• Massive neutrino already eliminated

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DM “wind” on Earth: $\sim 10^5/\text{cm}^2/\text{s}$ (for a 100 GeV particle)

Or: $\sim 5$ particles in a water bottle at any one time
Beyond the Standard Model

→ Example: the Neutralino:

\[ \chi = \alpha \tilde{\gamma} + \beta \tilde{Z} + \gamma \tilde{H}_1^0 + \delta \tilde{H}_2^0 \]

Lightest Supersymmetric Particle (LSP) and its own antiparticle

- **Indirect detection:**
  - Detection of WIMP annihilation products

- **Possible Signatures:**
  - Nuclear vs electronic recoil
  - Recoil energy spectrum shape
  - Directionality of interactions (earth, sun)
  - Annual flux modulation
  - Diurnal direction modulation
  - No multiple interactions
  - Consistency between targets of different natures

- **Direct detection:**
  - WIMP scattering on nuclei

- **Production at accelerators**

![Diagram showing Earth's orbit around the Sun and a vector indicating 30 km/s and 232 km/s]
Needle in a Haystack

Direct Detection of Dark Matter
Direct Detection Possibilities

- Ionization
  - Ge
  - Liquid Xe, Ar
  - NaI, Xe
  - Ge, Si

- Light
  - ~few % energy
  - very fast scintillating material

- Heat
  - ~20% energy
  - ~100% energy
  - slow cryogenics

- Energy absorption materials:
  - CaWO$_4$, BGO
  - Al$_2$O$_3$, LiF
Many International Efforts

Picture from L. Baudis, 2012
Background Challenges

- **Search sensitivity (low energy region <<100 keV)**
  - Current Experimental Limit < 1 event /kg /year
  - Goal < 1 event /tonne /year

- **Activity of typical Human?**
  - ~10 kBq (10^4 decays per second, 10^9 decays per day)

- **Environmental Gamma Activity**
  - Unshielded 10^7 evt/kg/day (all values integrated 0–100 keV)
  - This can be easily reduced to ~10^2 evt/kg/day using 25 cm of Pb

- **Main technique to date: nuclear vs electron recoil discrimination**
  - This is how CDMS II experiment went from 10^2 -> 10^-1 evts/kg/day

- **Moving below this**
  - Reduction in External Gammas: e.g. High Purity Water Shield 4m gives <<1 evt/kg/day
  - Gammas from Internal components - goal intrinsic U/Th contamination toward ppt (10^-12 g/g) levels
  - Detector Target can exploit self shielding for inner fiducial if intrinsic radiopurity is good

- **Environmental Neutron Activity / Cosmic Rays => Go DEEP**
  - (α,n) from rock 0.1 cm^{-2} day^{-1}
  - Since <8 MeV use standard moderators (e.g. polyethylene, or water, 0.1x flux per 10 cm)
  - Cosmic Ray muons generate high energy neutrons 50 MeV - 3 GeV which are tough to moderate
  - Need for depth (DUSEL) - surface muon 1/hand/s, Homestake 4850 ft 1/hand/month
Strategy for the past decade:
- improve detector sensitivity
- reduce background
in order to have a chance to see interactions from WIMPs predicted by supersymmetric models

Today: we reach into the first optimistic models, with detector masses
~hundreds of kg
We still see nothing!

Eventually: we will need multi-ton detectors. Within 10 years, the search for Dark Matter will be over

And if we find nothing…?
Dark Matter Direct Searches – Timeline

![Graph showing Dark Matter Searches: Past, Present & Future](image)

- **Limit Scalar Cross-section cm² [60 GeV WIMP]**
- **Year**
- **Gross Masses kg**
- **1 event kg⁻¹ day⁻¹**
- **1 event 100 kg⁻¹ yr⁻¹**
- **1 event 1 tonne⁻¹ yr⁻¹**

- **Projects and Experiments**:
  - CDMS, XENON, DAMA, Edelweiss, WARP, LIBRA, ZEPLIN, CRESST, LUX, XMASS, XENON100, XENON100'12

**Legend**:
- Ge
- NaI
- Cryodet
- Liq. Noble
- CS2
- Projected
- Signal
Really just a bucket of xenon

The LUX Experiment
The LUX Collaboration

Brown

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John Thomson Senior Machinist
Matthew Szyszkis Postdoc
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Nick Walsh Graduate Student
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Mike Withrell Professor
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Dana Byram Graduate Student
Chris Chiller Graduate Student
Angela Chiller Graduate Student

University of Toronto

Collaboration Meeting, UCSB March 2012

S. Fiorucci – Brown University
Dark Matter Interaction with Xenon

Two signals:

- **S1**: 175 nm photons
- **S2**: Electrons

- **Electron Recoil**
- **Nuclear Recoil** (neutrons, WIMPs)

Graph showing electron recoil and nuclear recoil energy distribution.
The LUX Experiment

- 370 kg xenon
  - 300 kg active region
  - 100 kg fiducial
- 122 PMTs 2” round
- Low-background Ti cryostat
LUX Design – Dual Phase Xenon TPC

- Can measure single electrons and photons
- Charge yield reduced for nuclear recoils
- Excellent 3D imaging
  - Reject multiple scatters
  - Eliminate edge events to take advantage of Xe self shielding
- **Water Tank:** $d = 8 \text{ m}$, $h = 6 \text{ m}$
  - 300 tonnes, 3.5 m thickness on the sides
  - Inverted steel pyramid (20 tonnes) under tank to increase shielding top/bottom

- **Cherenkov muon veto**

- **Ultra-low background facility**
  - Gamma event rate reduction: $\sim 10^{-9}$
  - High-E neutrons ($>10 \text{ MeV}$): $\sim 10^{-3}$

![Graph showing flux attenuation in water with normalized number of incoming particles.](chart.png)
LUX Design – Internals

- 5 HV Grids total, in place and tested
- 122 2" PMT R8778
  - 175 nm, QE > ~30%
  - U/Th ~10/2 mBq/PMT
  - All tested in LUX 0.1 program
- Dodecagonal field cage + PTFE reflector panels
- Copper PMT holding plate

First assembly completed at Sanford Surface Lab: Spring 2010 – Jan 2011
LUX detector – Animated
LUX Design – Deep Underground Operation

Cosmic Rays - Muons

~1 / hand / s

~1 / hand / months

Shhh... it's quiet underground

S. Fiorucci – Brown University
- LXe is a dense target at 3 g/cm³
- Self-shielding allows this technology to greatly benefit from scaling up
The LUX Program

LUX0.1 - CWRU

LUX - Surface

LUX - Underground

2007 – 2009

2010 – 2011

2012+
Running before it jumps

The LUX Experiment: Surface Operations
The Sanford Laboratory at Homestake

Homestake Mine Shaft head

Map of the United States showing the location of Homestake Mine.

Deadwood

Lead
- Full-scale test of LUX deployment
  - Liq/gas system
  - PMT testing
  - DAQ testing
  - S1 trigger efficiency
  - Xe purity

- Exact duplicate of the underground layout for all major systems

- 1 m thick water shield designed to allow limited real data taking, even at the surface
  - Expected Gamma rate ~70 Hz, Neutron rate ~30 Hz, Muon rate ~50 Hz
  - Natural detector limit: 175 Hz (PMT gain stability, < 10% event overlap)
  - Requires: S2 gating, reduced PMT gain

- LUX detector integration on site since November 2009
  - Completed two “Runs” in June 2011, and November 2011 – February 2012
  - Started dismantling to go underground at end of May 2012
“Warehouse” – June 2009
“Warehouse” – November 2009
Surface Lab – August 2010 to February 2011
Outdoor market coming to Lead

Lead Live! set for summer months

By Mark Vangelen
Black Hills Pioneer

LEAD — In addition to ongoing efforts in Lead to revitalize the city's downtown business district, several members of the community have pulled together to organize an outdoor market on Main Street this summer.

Lead resident Chris Coolidge said the market, coined "Lead Live!," will be a family-oriented, recurring event throughout the summer, and will give

See LEAD LIVE — Page 31

Budget forecast comes up

Researchers from the University of California at Davis, watch as the LUX dark matter detector is lowered into a water tank at the surface laboratory at the Sanford Underground Laboratory in Lead.

Photo by Matt Kapust/Sanford Underground Laboratory
Surface Lab – May 2011 : Run 1

Cryogenic Test: Success!
Surface Lab – July to October 2011
Surface Lab – October 2011 to February 2012 : Run 2

Position resolution < 5mm

Electron Lifetime (lux10_20120208T0027)
Preliminary Surface Run Results (stat error only = $\sigma_{jk}$)

$205 \mu s \sim 25 \text{ cm} = \frac{1}{2} \text{ a LUX}$
LUX Run 2 Summary

- List of major achievements already communicated to the World by February 2012

  - Deployed into water tank shield
  - Stable cryogenic control for ~100 days of running
  - Purification at 35 SLPM
  - Heat exchanger efficiency > 98%; < 5 W heat load at 300 kg/day
  - In-situ xenon purity analysis
  - Working PMTs, Trigger, DAQ
  - Excellent light collection (8 phe / keV in center)
  - Drift field to 120 V / cm (limited by electroluminescence on grid)
  - Recovered xenon to storage vessel by cryopumping

- To which one can add: Working slow-control and alarm system, working muon veto, emergency storage system in place, working calibration system (external and internal), reviewed and tested operating and assembly procedures, no (work related) injuries over 17 months and > 38,500 total work hours...

- Negative points:
  - Leak in condenser line limited purification capability (easily fixed)
  - One PMT base stopped working (out of 122; now fixed)
  - Used ~20-30 kg more Xenon to fill detector than anticipated (we have a lot to spare now)
  - Drift field limited by flaws on Cathode grid wires (now replaced and tested)
  - Did not find Dark Matter (neither did anyone else)
Surface Lab – March to July 2012
Boldly going where no detector has gone before

The LUX Experiment: Underground
Sanford Lab – Davis Laboratory

Davis Campus

Water level
Sanford Lab – Davis Laboratory

Majorana Lab
“Transition Space”

100’

Davis Campus, 4850’ level, near Yates shaft
Was flooded until May 2009!

S. Fiorucci – Brown University
Davis Campus – Construction Schedule

- May 2009: 4850 ft level dewatered
- Aug 31 2009: Began excavation of new drift
- Sep 10 2009: Steel structures removal complete
- Nov 15 2009: Detailed Construction Docs complete
- Jul 2010: Excavation complete
- Feb 2011: Outfitting Documents complete
- Jun 2011: Begin Lab outfitting
- Jun 2012: Lab ready
Davis Laboratory – February 2011

Transition Area

Davis Cavern
Davis Campus – December 2011
Davis Campus – Summer 2012

June 15

July 6

June 25

June 29

August 25

July 12
LUX – Underground Program (1)

- **February 2012: End of Operations at Surface Lab**
  - Start relocating equipment by June 15
  - Detector transported July 11

- **June 2012: Davis beneficial occupancy. Installation ~ 3 months**
  - Bring in subsystems: gas system, Xe storage, electronics…
  - Bring in detector + breakout cart
  - Fill water tank and start water circulation system
  - Meanwhile: Purify the xenon at CWRU (Kr removal)

- **September 2012: LUX detector installed underground**
  - ~6 weeks for all systems check-outs
  - ~5 weeks for cool down and condensing xenon, start circulation
  - ~3 weeks to reach acceptable Xe purity and stable operation

- **January 2013: Start of Science Run**
January 2013: Start of Science Run

- 1 month to first data release
  - In ~15 days of low-background data, we match the current best WIMP sensitivity
- Intermediary result: 60 live days
  - Refine analysis and cuts, efficiencies
  - Improve current best sensitivity by x2 – x3 (dep. on background)
- Science goal = 300 live days of low-background data
  + a few live weeks of calibration data (neutron + gamma)

February 2014: Earliest possible date for end of LUX campaign

- We will certainly have enough interesting additional data to take for several months after the 300 live days

Keep taking data until LZ detector is ready to be built underground.
LUX WIMP Sensitivity Goal

And if that is not enough…?
The endgame is near

**Next: The LZ Program**
LZ Program – Overview

- Born from the joining of LUX and ZEPLIN
- Construction 2014-2016
- Run 2016-2019 (...?)

New features compared to LUX
- Increased Xe mass: 7t total, 5t fiducial
- 482 3" PMTs at ~1 mBq radioactivity level
- Liquid Scintillator shield/veto
- Instrumented « dead » Xe space
- Improved Cherenkov veto coverage

...That’s it. Progress in sensitivity comes chiefly with:
- Increasing the Xe mass
- Scaling up existing LUX technology
- Xe self-shielding is driving the background rates down dramatically

R&D effort ramping up since 2011, Project Management through LBNL
LZ Program – WIMP Sensitivity Reach

XENON100 2012
LUX 300 days
LZ 1000 days

Cross-section [cm²] (normalised to nucleon)

WIMP Mass [GeV/c²]
LZ, ultimate Dark Matter instrument?

- Electron Recoil signal limited by p-p solar neutrinos
  - Subdominant with current background rejection
- Nuclear Recoil background: coherent neutrino scattering
  - $^8$B solar neutrinos
  - Atmospheric neutrinos
  - Diffuse cosmic supernova background
- LZ reaches this fundamental limit for direct WIMP searches

Solar neutrinos were the signal for Ray Davis’ original experiment at Homestake (Nobel 2002)

Now they are LZ’s background!

S. Fiorucci – Brown University
Thank you!

If you have remained awake and in the room until now,
Because this was not long enough already…

**Additional Slides**
Comparison of LUX and XENON100 data for the same exposure of 7600 kg.d, from the latest XENON100 result (July 2012). LUX data is simulated from known radioactive background components. The WIMP signal in red corresponds to a 100 GeV/c^2 WIMP with a cross-section at the current best sensitivity limit of 2.5 \times 10^{-45} \text{ cm}^2. The ER background is one order of magnitude lower, allowing for a clearer detection signal or a stronger limit.
Future of Sanford Lab

- **Large Underground Xenon—LUX/LZ**
  - First and second generation dark matter
  - Open May 2012

- **Majorana Demonstrator**
  - Neutrinoless double-beta decay
  - Open May 2012

- **Multi-functional lab module**
  - Third generation dark matter

- **FAARM**
  - Low background assay

- **Temporary Clean Room**
  - Copper electroforming
  - Open January 2011

- **Low background counting facility**

- **LBNE Liquid Argon**
  - 4850 Level laboratory

- **Oro Hondo exhaust shaft**

- **Ross Shaft**

- **Yates Shaft**

- **LBNE Liquid Argon surface laboratory**

- **DIANA**
  - Nuclear astrophysics
LUX 0.1 2007-2009

- Full integration of all LUX subsystems
- 60kg xenon
- 4 PMTs
- Thermosyphon
- Gas handling, circulation
- Electronics chain, DAQ, analysis
- Full test of LUX personnel (postdocs and graduate students)
LUX Design – Low-radioactivity

- **PMTs**
  - 10/2/65 mBq/PMT (U/Th/K) and 2 n/year/PMT
  - However, multiply by x122 and consider the fact that they are right next to the active region...
  - They are the dominant source of internal background
  - In 30,000 kg-days, in fiducial region and in 5-25 keV$_r$, all PMTs would contribute:
    - 0.5 gamma events
    - 0.1 neutron events

- **Titanium Cryostat**
  - Very low radioactivity: <0.4 mBq/kg U+Th
  - Largely subdominant

- **Rn**
  - Cleanroom reduces levels to < 40 Bq/m$^3$.
  - Minimize exposure, increase airflow

- **Kr**
  - Present in commercial Xe at ppm level. Reduced to <2 ppt with charcoal column separation
Circulation at 35 SLPM through purifier by diaphragm pump

In-situ xenon sample RGA analysis\textsuperscript{1} sensitivity:
0.7 ppb $\text{O}_2$ mol / mol
0.5 ppt Kr mol / mol

\textsuperscript{1} A. Dobi et al., NIM-A, Vol. 675, 40-46 (2012) [arXiv:1109.1046]
LUX – Surface Program

- June 2011: **Run 01** (3 weeks)
  - Using Ar gas, 20 PMTs, deploy in water tank
  - Run 01 goals: test all cryogenic systems, DAQ

- July - October 2011: Upgrades for full system
  - Install all PMTs (in clean room), finish plumbing, wire all DAQ

- November 2011 – February 2012: **Run 02**
  - Run 02 goals:
    - Confirm all systems ready for underground
    - Get first data on light collection, xenon purity

- March – July 2012: Last Upgrades and Fixes
  - Start moving equipment underground as early as March 30th
  - Move detector itself July 11, 2012

Great success 8 phe/keV
Limited by leak in internal plumbing; Still promising
The Davis Laboratory @ Homestake

- **Left**: N-S vertical cross-section
- **Top right**: Plan view, level 1
- **Bottom right**: Plan view, Level 0
Cosmic Rays: Muons

- At sea level:
  - Flux ~ 1 cm\(^{-2}\) min\(^{-1}\) for horizontal detectors
  - \(E_{\text{avg}} \sim 4\) GeV
- At Homestake 4850L:
  - Total flux divided by factor \(3.7 \times 10^6\)
  - \(E_{\text{avg}} \sim 320\) GeV

Ref: Mei & Hime astro-ph/0512125
Internal Background Sources

• Screening of all internals and close materials
• Main Dangers
  – Cryostat (largest unshielded mass 325 kg)
  – PMTs and PMT bases (closest to Xe)
  – Xenon contamination