Dark Matter Searches

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At a Mine’s Bottom, Hints of Dark Matter

By DENNIS OVERBYE
Published: December 17, 2009

An international team of physicists working in the bottom of an old iron mine in Minnesota said Thursday that they might have registered the first faint hints of a ghostly sea of subatomic particles known as dark matter long thought to permeate the cosmos.

The particles showed as two tiny pulses of heat deposited over the course of two years in chunks of germanium and silicon that had been cooled to a temperature near absolute zero. But, the scientists said, there was more than a 20 percent chance that the pulses were caused by fluctuations in the background radioactivity of their cavern, so the results were tantalizing, but not definitive.

Gordon Kane, a physicist from the University of Michigan, called the results “inconclusive, sadly,” adding, “It seems likely it is dark matter detection, but no proof.”

Dr. Kane said results from bigger and thus more sensitive
Newton’s Law of Gravity describes the motion of planets around Sun well.

\[ \frac{Mv^2}{r} = \frac{GMm}{r^2} \]
Does this work for Stars in a Galaxy? No!

Watch how fast a star rotates around the center...

What it should look like  What it actually looks like
Universe Budget: Mostly Unidentified

Standard Model of Cosmology?

Data from SuperNovae, CMB and Clusters agree!
Bullet Cluster: Dark Matter Really Exists!

Spectacular “Direct Gravitational Evidences” in recent years!

- Two clusters pass right through each other. DM continues to move
- Baryonic Matter (seen in X-ray) gets left behind due to drag

Dark Matter Halo

Data well explained by lots of “Dark Matter” we can’t see

Mostly clumped at the center due to gravity

Lots of it in a “halo” around the entire galaxy
Dark Matter exists ...

What is it made of? Can we detect it?
Guess: Dark Matter in the Universe is made up of LOTS of particles that we haven’t discovered yet! Got created in the Early Universe like everything else and are still here today!

Big Bang!
Then Universe gets bigger

Today: 5 times more Dark Matter than Atoms in the Universe
Coincidence or Clue?

$\chi^0$

Supersymmetry

$\sigma_{\text{ann}} \sim \text{weak}$
gives $\Omega_{\chi} = \frac{1}{4}$

No known SM particle fits!

Current DM Abundance Explained by Massive Particle with Weak $\sigma$

TeV scale SUSY gives Massive Stable Particle With Weak $\sigma$

Compelling evidence to for LSP $\chi^0$ WIMP
Four roads to dark matter:

- **Gravitational**
- **Direct**
- **Indirect**
- **Production**
**Indirect Detection**

**Goal:** Find byproducts of Dark Matter Annihilation in our Galaxy

**Challenges:** Distinguishing from other astrophysical processes

*Diagram showing WIMP annihilation, Neutrinos, Photons, Antimatter, and what to look for.*

*Graph showing data from PAMELA and FERMI.*

*Image of incoming gamma ray and electron-positron pair.*
Direct Production at Accelerators

**Goal**: Produce Massive Neutral Particles and Measure their Properties

**Challenges**:

WIMP Mass Reach? At most 300GeV @ LHC as per MSSM

Indirect Detection: Missing Energy

Can’t Directly say if DM: Still need Direct Detection
Ok... It’s slightly more complicated than this
Direct Detection: Can we directly observe WIMPs?

**Goals**: WIMPs exist everywhere in the Galaxy halo.

- Earth Ploughs through this Dark Matter Halo
- So, WIMPs will collide with us (detector)
- Observe such collisions and discover/understand the WIMPs

Out there & may interact on earth!
Common Challenges to WIMP Discovery

• The Weakly Interacting Massive Particle (WIMP) acts very weakly
• A billion WIMPs may pass through you before even one actually INTERACTS (leaves energy in you)
• We are surrounded by lots of radioactivity which can fake WIMP!

$\rho \sim 1/3 \text{ GeV/cm}^3$

NUTRITIONAL WARNING: may contain few 100-GeV WIMPs. 10 billion WIMPs may pass through each second.
WIMP Direct Detection

Think about billiard ball scattering. We are just playing on a $50M Table!

Best Sensitivity when WIMP and Target Nucleus Mass Match

\[ v/c = \beta \approx 0.7 \times 10^{-3} \]

\[ E_R \approx \frac{\mu^2 v^2}{m_{\text{Ge}}} \]
\[ \approx 40^2 \times (0.7 \times 10^{-3})^2 / 73 \]
\[ \approx 10 \text{ keV} \]
\[ \approx \text{x-ray energy! Easy!} \]
## Catalog of Recoil Experiments

<table>
<thead>
<tr>
<th>Site</th>
<th>Experiment</th>
<th>Technique</th>
<th>Target</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Baksan (Russia)</td>
<td>IGEX</td>
<td>Ionisation</td>
<td>3kg Ge</td>
<td>Operational</td>
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<tr>
<td></td>
<td>ORPHEUS</td>
<td>SSD</td>
<td>0.5kg Sn</td>
<td>Operational</td>
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<td>Boulby (UK)</td>
<td>NaI</td>
<td>Scintillator</td>
<td>5kg NaI</td>
<td>Completed</td>
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<td></td>
<td>NaIAD</td>
<td>Scintillator</td>
<td>50kg NaI</td>
<td>Operational</td>
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<td></td>
<td>ZEPLIN I</td>
<td>Scintillator</td>
<td>5kg Lx</td>
<td>Operational</td>
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<td></td>
<td>ZEPLIN II/III</td>
<td>Scintillator/Ionisation</td>
<td>30kg/7kg Xe</td>
<td>Operational</td>
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<td>ZEPLIN-MAX</td>
<td>Scintillator/Ionisation</td>
<td>1000kg Xe</td>
<td>Construction</td>
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<td></td>
<td>DRIFT-I</td>
<td>TPC</td>
<td>0.2kg Cs₂</td>
<td>Planned</td>
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<td></td>
<td>DRIFT-10</td>
<td>TPC</td>
<td>2kg Cs₂</td>
<td>Planned</td>
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<td>Canfranc (Spain)</td>
<td>COSME</td>
<td>Ionisation</td>
<td>0.2kg Ge</td>
<td>Completed</td>
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<td></td>
<td>IGEX</td>
<td>Ionisation</td>
<td>2.1kg Ge</td>
<td>Operational</td>
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<td></td>
<td>ANAIS</td>
<td>Thermal</td>
<td>107kg NaI</td>
<td>Construction</td>
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<td></td>
<td>ROSEBUD</td>
<td>Thermal</td>
<td>Al₂O₃,Ge₃CaWO₄</td>
<td>Operational</td>
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<tr>
<td>Frejus (France)</td>
<td>Saclay-NaI</td>
<td>Scintillation</td>
<td>10kg NaI</td>
<td>Completed</td>
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<td>EDELWEISS I</td>
<td>Thermal/Ionisation</td>
<td>0.07kg Ge</td>
<td>Completed</td>
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<td>EDELWEISS II</td>
<td>Thermal/Ionisation</td>
<td>1.3kg Ge</td>
<td>Operational</td>
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<td>Gran Sasso (Italy)</td>
<td>Hdlberg/Mscw</td>
<td>Ionisation</td>
<td>2.7kg Ge</td>
<td>Completed</td>
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<td>HDMS</td>
<td>Ionisation</td>
<td>0.2kg Ge</td>
<td>Operational</td>
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<td>Genius</td>
<td>Ionisation</td>
<td>100kg Ge</td>
<td>Planned</td>
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<td>DAMA</td>
<td>Ionisation</td>
<td>100kg NaI</td>
<td>Operational</td>
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<td>LIBRA</td>
<td>Ionisation</td>
<td>250kg NaI</td>
<td>Construction</td>
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<td>Xenon</td>
<td>Scintillation</td>
<td>6kg Xe</td>
<td>Operational</td>
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<td>CRESST-I</td>
<td>Scintillation</td>
<td>1kg Al₂O₃</td>
<td>Operational</td>
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<td>CRESST-II</td>
<td>Thermal/Scintillation</td>
<td>10kg CaWO₄</td>
<td>Construction</td>
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<td>CUORIÇINO</td>
<td>Thermal</td>
<td>40kg TeO₂</td>
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<td>CUORE</td>
<td>Thermal</td>
<td>760kg TeO₂</td>
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<td>Kamioke (Japan)</td>
<td>XMAS</td>
<td>Scintillator/Ionisation</td>
<td>3kg Xe</td>
<td>Planned</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1000kg Xe</td>
<td>Operational</td>
</tr>
<tr>
<td>Otto-Cosmo (Japan)</td>
<td>Elegants V</td>
<td>Scintillation</td>
<td>NaI</td>
<td>Operational</td>
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<tr>
<td></td>
<td>Elegants VI</td>
<td>Scintillation</td>
<td>CaF₂</td>
<td>Operational</td>
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<td>LiF</td>
<td>Thermal</td>
<td>LiF</td>
<td>Operational</td>
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<td>Rustrel (France)</td>
<td>SIMPLE</td>
<td>SDD</td>
<td>Freon</td>
<td>Operational</td>
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<tr>
<td>Stanford (USA)</td>
<td>CDMS-1</td>
<td>Thermal/Ionisation</td>
<td>0.1kg Si, 1kg Ge</td>
<td>Completed</td>
</tr>
<tr>
<td>Soudan (USA)</td>
<td>CDMS-II</td>
<td>Phonons/Ionisation</td>
<td>0.3ks Si, 0.75kg Ge</td>
<td>Construction</td>
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<td>CryoArray</td>
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<td>2 kg Si, 7 kg Ge</td>
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<td></td>
<td>100-1000 kg Ge</td>
<td>Planned</td>
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<tr>
<td>??? (USA)</td>
<td>XENON</td>
<td>Scintillator/Ionisation</td>
<td>1000 kg Xe</td>
<td>Planned</td>
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<tr>
<td>Sudbury (Canada)</td>
<td>PICASSO</td>
<td>SDD</td>
<td>1g Freon</td>
<td>Operational</td>
</tr>
</tbody>
</table>
WIMP-detection Experiments Worldwide

- CDMS I
- CDMS II
- CanFranc
- Coupp
- CRESST I/II
- Cuore
- DAMA/LIBRA
- DRIFT 1/2
- EDELWEISS I/II
- ELEGANT V&VI
- Enlighten
- GENIUS TF
- IGEX
- IGEX
- KIMS
- LiF
- LUX
- NEWAGE
- ORPHEUS
- Picasso
- PicASSo
- TEXONO
- Zeplin I/II/III/MAX
- COUPP
- DRIFT 1/2
- EDELWEISS I/II
Rate of Electromagnetic Background

Strategies: shield against radioactive backgrounds

$40\text{K}: 7 \times 10^4 \gamma/\text{day}$

$(E \approx 1.5 \text{ MeV})$

Rate about 20 / (kg-day)!

Shield it!
What Nature has to Offer
Background Rejections ‘R’ Us

Action Plan: Reduce and Reject …
Traditional Ionization Detector

\[ E_R \approx 10\text{'s keV} \]

What rate? (in, say, 1kg)

Backgrounds?

\ldots\ldots \text{Gamma rays, neutrons, surface beta-decay}
Different Particles, Different Interactions

Dense deposition \( v/c \approx 10^{-3} \)
Poor Ionization Efficiency

Sparse deposition \( v/c \approx 0.3 \)
Excellent Ionization Eff.

Recoil difference provides Discrimination
Detection and Discrimination Methods

- CDMS, EDELWEISS
- CRESST II, ROSEBUD
- ZEPLIN II, III, LUX, XMASS, XENON10
- DAMA
- NAIAD, ZEPLIN I, DRIFTI, II

**Energy Resolution**
- keV: CRESST II, ROSEBUD
- meV: CRESST, PICASSO, COUPP
- eV: IGEX, DRIFTI, II
- Q: ionization, phonons

**Energy Types**
- ionization
- phonons
- scintillation

**Interaction Types**
- WIMPs and Neutrons scatter from the Atomic Nucleus
- Photons and Electrons scatter from the Atomic Electrons

**Detectors**
- NAIAD, ZEPLIN I, DRIFTI, II
- CDMS, EDELWEISS
- CRESST II, ROSEBUD
- ZEPLIN II, III, LUX, XMASS, XENON10
- DAMA
Use discrimination and shielding to maintain a Nearly Background Free experiment with cryogenic semiconductor detectors.

**Shielding**
- Passive (Mine Depth, Pb, Poly)
- Active (muon veto shield)

**Energy Measurement**
- Phonon (True recoil energy)
- Charge (Reduced for Nuclear)

**Position measurement X-Y-Z**
- From phonon pulse timing

**Nuclear/Electron Recoil Discrimination**
ZIP Detectors

(Z-sensitive Ionization and Phonon)

Phonon side: 4 quadrants of athermal phonon sensors
Energy & Position (Timing)

Charge side: 2 concentric electrodes (Inner & Outer)
Energy (& Veto)

Operated at ~40 mK for good phonon signal-to-noise
Anatomy of an event

-3V

Hot charge carriers (3eV/pair)

0V

Quasi-diffusive THz phonons
Ballistic Neganov-Luke phonons
Ballistic low-frequency phonons
Sensors held in equilibrium between Normal and Super Conducting. Highly sensitive to small energy deposit. Fast signal. SQUID Readout
Excellent Energy, Position Resolution

Am$^{241}$:
$\gamma$ 14, 18, 20, 26, 60 keV

Cd$^{109}$:
$\gamma$ 22 kev
i.c. electr 63, 84 KeV

Cd$^{109}$ + Al foil:
$\gamma$ 22 kev
The Pioneers

Blas Cabrera, Stanford

Bernard Sadoulet, Berkeley
Why deep Underground? Avoid Cosmic Rays

Limited our earlier results…moved to a deep mine
Why Soudan@-40°

Soudan Mines: M, UMN, FNAL
690 meters underground
2090 meters water equivalent

μ’s

μ’s

Most muons slow down and stop in the rock
CDMS Apparatus Outside In

Surround detectors with active muon veto

Use passive shielding to reduce $\gamma$/Neutrons
• Lead and Copper for photon
• Polyethylene for low-energy neutron

Neutron background negligible in Soudan, for recent runs
CDMSII Final Result (2010)

2 Signal Candidates!

20% chance of fluctuation from 0.8 ± 0.2 background
In the presence of 2 events (no bg subtraction):
No Discovery yet. What Next?

Signal/Background Improvement: Lower Background, More and Better Detectors at Cheaper Costs!
CDMS R/Evolution

Sensitivity $\propto$ Mass. Background $\propto$ Surface. Detector Cost $\propto$ # of Dets

**CDMS, Soudan (4kg)**
- 3” x 1 cm 0.25 kg
- 2 Yrs, 16 dets = 1700 kg-d

**SuperCDMS, Soudan (15kg)**
- 3” x 1” iZIP 0.64 kg
- 2 Yrs, 25 dets = 8000 kg-d

**SuperCDMS, SNOLab (100kg)**
- 4” x 1.33” iZIP 1.5 kg
- 2 Yrs, 70 dets = 100000 kg-d

**GEODM, DUSEL (1500kg)**
- 6” x 2” iZIP 5 kg
- 2 Yrs, 300 dets = 1.5M kg-d

**To reach the goals:**
- increase mass
- decrease background leakage
TAMU Dedicated Fab

Instruments Donated by: Maxim Integrated Products, Texas Instruments, ST Microelectronics

Research supported by DOE, NSF,
The Sensors
Photolithographically Patterned Ge Detector

[Description of the diagram showing a schematic of Al, Ge, Si, phonons, and their interactions with a Ge or Si detector.]
Large (~$5M) Investment of Resources

• > $1 million of semiconductor fabrication instruments donated by semiconductor industries: Maxim Integrated Products, Texas Instruments, ST Microelectronics (Fabs moving to Asia!)

• ~ $1 million Start up funds

• ~ $1 million DOE Early Career Award

• ~ $1 million NSF funding to TAMU from DUSEL S4 to develop automated detector fabrication

• $.5 million SuperCDMS, Soudan project funding

• Facility dedicated to SuperCDMS/GEODM detector development and fabrication: Unmatched in any campus!
Fully Automated Sputtering System

- Fully automated operation, robotic load lock and eight 6” det capability
- 1 day turn around, vs 1 week turn around time for Stanford system
Paulette runs $1/2 M Deposition System!
Automated Sputtering System
Photolithography Lab
Full Mask Contact Aligner

0 Required Wirebonds!!!

>30 Required Wire Bonds
Optical Inspection Station for Detectors
Automated Robotic Baking

Almost half of the total fabrication time is spent on manually performing the baking steps, performed 6 times for each wafer.

Developing a fully automated robotic system that handle the baking and cooling steps automatically and store detectors in a purged cooling station.
TAMU Detector

Al and W Films photo lithographically patterned to make sensors on Ge crystal

Technology fully demonstrated with TAMU Facility
Improved Detectors and Characterization

Residual Resistivity Ratio
\[ \frac{R_{300K}}{R_{4K}} \]
Higher is better

TAMU 16 vs Stanford 12

AFM images explain why:
Lower spread in Al grain size means less resistance

Industrial Quality Instruments help!
SEM Image of TES: A Revelation!

Al Collector

W Transition Edge Sensor (TES)

Cooper Pair

Ge or Si

phonons
Vastly Superior Sensors

Al Collector

Cooper Pair

W Transition Edge Sensor (TES)

Ge or Si

Stanford: Al-W Transmission Probability: 0.1%

TAMU: Al-W Transmission Probability > 100x

White layer on side wall W. More = better
Completely Uniform $T_c$ across Wafer

$T_c$ across the detector surface: 20 mK down to 2mK variation!
CDMS R/Evolution

Sensitivity $\propto$ Mass. Background $\propto$ Surface. Detector Cost $\propto$ # of Dets

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- 4”x 1.33” iZIP 1.5kg
- 2 Yrs, 70dets=100000kg-d

**GEODM, DUSEL (1500kg)**
- 6”x 2” iZIP 5kg
- 2 Yrs, 300dets=1.5M kg-d

To reach the goals:
- increase mass
- decrease background leakage
Noble Liquid: Single Phase

- Single Phase Detectors: Rely on self shielding + position reconstruction/pulse shape discrimination (Ar):
  - No event by event discrimination (somewhat in Ar)
  - XMASS (Xe): 100kg fiducial (Japan)
  - MiniClean (Ar): 150kg fiducial (Construction in SNOLab)
  - DEAP-3600: 1ton fiducial (Approved)
Noble Liquid: Dual Phase Xenon

- Self shielding + S2/S1: Event by event NR/ER discrimination
- $^{85}$Kr ($\beta$ source) + diffusive background such as Rn
- Light collection efficiency at low energy is uncertain
- Xenon100: 30 kg fiducial (Operating in Gran Sasso)
- LUX: 100kg fiducial (construction in 2012)
COUPP/PICASSO Bubble Chamber

- Detection of bubble(s) induced by high dE/dx nuclear recoils
- Set threshold to be insensitive to ER
- Low cost room temperature
- Currently limited by Radon
- Recent acoustic rejection of $\alpha$ is very promising
LHC: The WIMP Maker

Will LHC discover SUSY before Direct Detection?
Conclusions

• CDMS (15kg) world leader in ultra low background experiment
  • 0 events in 05, 07 and 2 Events last run (20% chance of background.)

• Next generation 200kg – ton scale SuperCDMS experiments have strong detector R&D programs to enable much bigger and better detectors at cheaper costs

• Many competing technologies and efforts all over the world – almost all major countries and Universities are involved in the race to discover the nature of Dark Matter WIMP

• Very Exciting LHC Complimentarity in next 5 Years
  • LHC can’t say SUSY particle is Dark Matter. Need DM experiments

• Watch out for WIMP discovery in the next few years, solving one of the biggest puzzles of our Universe
The TAMU Group

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Prof. Harris
Mark Platt
Dr. Joel Sander

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Kris Koch (grad)
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A. Aryasam (grad)
James (Tech)
Sriteja (grad)