The Search for WIMPs in the Galactic Halo: the Quest to Detect the Dark Matter

Dan Akerib
Department of Physics
Case Western Reserve University
and
CDMS & LUX Collaborations
What’s missing in the Universe?

– do we understand gravity and the origin of structure and galaxies?
– new form of matter? -origin of the fundamental forces?
– can we find it? -these questions are settled by experiment/observation
Dynamical Evidence: Galactic Halos

Galaxies – 10-100 kpc

\[ V_r = \sqrt{\frac{GM_{\text{total}}(r)}{r}} \]

\[ F_{\text{centripetal}} = F_{\text{gravity}} \]

\[ \frac{mV_r^2}{r} = \frac{GmM_{\text{total}}(r)}{r^2} \]

\[ V_r = \sqrt{\frac{GM_{\text{sun}}}{r}} \]
Dynamical Evidence: Galaxy cluster lensing

Infer total mass density:

\[ \Omega_m = \frac{\rho}{\rho_{\text{crit}}} = 0.30 \pm 0.03 \]

→ dark matter dominates

\[ \rho_{\text{dark}} > 30 \rho_{\text{luminous}} \]
Standard Cosmology

Colley, Turner & Tyson

from Perlmutter, Phys. Today

WMAP

supernovae

vacuum energy density (cosmological constant)

mass density

3 Kelvin cosmic microwave background

WMAP

Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)

No Big Bang

expands forever

recollapses eventually

Supernovae

Clusters

flat

closed

D

H

Ly-α

5555

5560

Wavelength (Å)
What is it? Extraordinary stuff!

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

Convert energy to mass

\[ E = mc^2 \]

- A new type of particle: WIMPs = weakly interacting massive particles
  - Massive: source of gravity
  - Weakly-interacting: not star forming
Still around?

Expanding Universe and Weak Interactions

- WIMP
- anti-WIMP
- quark
- anti-quark
cross section → annihilation rate
cross section $\rightarrow$ annihilation rate
Still around?

Expanding Universe and Weak Interactions – annihilations stop if cross sections are small enough

![Diagram showing WIMP, anti-WIMP, quark, and anti-quark interactions over distance and time.](image)
Still around?

Expanding Universe and Weak Interactions – annihilations stop if cross sections are small enough
WIMP pairs $\chi \bar{\chi}$ produced in dynamic 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 $\Omega_{\chi} \approx 1$
  - $M \sim 10\text{-}1000 \text{ GeV}$
  - $\sigma_A \sim$ electroweak

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

$N_{EQ} \sim \exp(-m/T)$

$T_{FO} \sim m/20$
- Non-relativistic
- 'Cold'

Comoving Number Density

$m_\chi / T$ (time $\rightarrow$)

Dan Akerib
Case Western Reserve University
The LHC: make DM in the Laboratory

The Large Hadron Collider, CERN/Geneva
Annihilation ↔ Scattering

\[ \begin{array}{c}
\text{distance} \\
\text{time}
\end{array} \]

- WIMP
- anti-WIMP
- quark
- anti-quark
Annihilation ↔ Scattering
Annihilation ↔ Scattering
Testing the hypothesis: WIMPs in the Galactic Halo?

WIMPs – the source of Mass in the Rotation Curves?

WIMP-Nucleus Scattering

Assumption: Scatter from a Nucleus in a Terrestrial Particle Detector

Big Problem: weakly interacting. Expect less than one-a-day in a kilogram detector with E~10keV
How do we make measurements?
In physics, we measure voltages...

Particle Detection

It’s simple – detected particle ionizes the gas, collect the charge...

Or detected particle produces a flash of light, which is converted to ‘photoelectrons’...

Or detected particle interacts with a nucleus, which ionizes the gas, which...

Or...
Background Radioactivity
It’s in the air: a practical demonstration

Before...
It’s in the air: a practical demonstration

During...
It’s in the air: a practical demonstration

After…
WIMP search - c.1988

- Germanium ionization detector (UCSB/UCB/LBL)

![Graph showing dR/dQ vs Q (keV) for different isotopes and log cross section vs WIMP Mass (GeV/c^2)].

**from Jungman et al. (D.O. Caldwell et al.)**
What nature has to offer

What you hope for!
Different types of particles

WIMPs and Neutrons scatter from the Atomic Nucleus

Photons and Electrons scatter from the Atomic Electrons

Thanks to M. Attisha
The Signal and Backgrounds

**Signal (WIMPs)**
- Nucleus Recoils
  - $v/c \approx 7 \times 10^{-4}$
  - $E_r \approx 10$'s KeV

**Background (gammas/betas)**
- Electron Recoils
  - $v/c \approx 0.3$

*Neutrons also interact with nuclei, but mean free path a few cm*
Recoil Discrimination Demonstrated

WIMPs ‘look’ different – recoil discrimination
Photons and electrons scatter from electrons
WIMPs (and neutrons) scatter from nuclei

\[ E_{\text{charge}} \]
\[ E_{\text{thermal}} \]
\[ E_{\text{recoil}} \]
Recoil Discrimination Demonstrated

WIMPs ‘look’ different – recoil discrimination

Photons and electrons scatter from electrons
WIMPs (and neutrons) scatter from nuclei

![Graph showing recoil discrimination](image-url)

- $E_{\text{charge}}$ vs. $E_{\text{thermal}}$
  - Background
  - Signal

- $E_{\text{recoil}}$

50,000 gamma calibration events

Gammas
‘Cryogenic’ detectors

• Heat sensitive detectors sensitive to *individual particle interactions*.
• Operated near absolute zero ("cryogenic")
• Cryogenic Dark Matter Search (CDMS)

---

• The detectors are cooled in dilution refrigerators to ~20mK

---

1 µm tungsten aluminum fins
Superconducting Films: Ultrasensitive Thermometers

Superconducting films that detect minute amounts of heat

Transition Edge Sensor sensitive to fast athermal phonons

\[ R_{\text{TES}} (\Omega) \]

~ 10mK

\[ T_c \sim 80\text{mK} \]

T (mK)
The Voltages We Measure

Phonons – Charge = Recoil energy
Neutrons: a WIMP-like background

cosmic ray muon

neutron
proton
Got neutrons? Go deep

Most muons slow down and stop in the rock

[Graph showing the logarithmic relationship between depth and muon flux]

Stanford Underground Facility
Underground science: 2030’ deep

The Soudan Mine State Park & Science Laboratory,
The Iron Range of Northern Minnesota
The CDMS II Apparatus

- The Soudan Mine refrigerator includes a low-radioactivity ‘clean room’ shielded environment
- Science data commenced October 2003
- 2000 mwe depth
  - \(~10^5\) reduction in muon flux
  - \(~400\)x reduction in fast neutrons
- New in 2008: first results from first full apparatus
Detector Towers in Soudan

2 towers operated in '03-'04

4.75 kg Ge, 1.1 kg Si

Full 5 towers operating since Oct 2006
Predict Background: $0.6 \pm 0.5$ surface events and $< 0.2$ neutrons
WIMP Search Data: blind analysis

Predict Background: 0.6 ± 0.5 surface events and < 0.2 neutrons
New upper limit on WIMP cross section

121 kg-day exposure  200 kg-d combined

SUSY models

LHC!
2-Phase Liquid Xenon: scintillation + ionization

XENON-10 detector

Incident Particle

E = 1kV/cm
**XENON-10 calibrations & results**

**Gamma Calibration:** 99.5\% rej.

**Neutron Calibration**

\[
\log \left( \frac{S_2}{S_1} \right)
\]


CDMS (2006)

XENON-10

Superheated liquids: immune to EM backgrounds

• Principle: Superheated liquid
  - Requires nucleation energy to overcome surface tension and form bubble
  - Tune thermodynamic parameters
    - Insensitive to min. ionizing and low-energy electron recoils
    - Sensitive to higher-energy-density nuclear recoils
  - Threshold detector - release of stored energy enhances observability
COUPP: Bubble Chamber Revival

- 2-kg CF$_3$I Bubble Chamber – U. of Chicago, U. of Indiana/South Bend, and Fermilab
- Two principal challenges:
  - passivate nucleation from vessel walls
    ⇒ trigger rate ~ laboratory neutron background ✔
  - internal alphas ~ 85% dead time ~ 200 events/day ✔

- 250 kg-days
- 300 mwe deep at FNAL

Quadruple neutron-scatter event

reject wall events
residual bulk events from radon progeny
When spin independent coupling suppressed, rate dominated by axial coupling to unpaired nucleon

from Science 319, 15 Feb 2008
Active / International Field: representative sample

- ZEPLIN-III
- XENON-100
- CRESST CaWO₄
- SuperCDMS
- 60 kg COUPP vessel
- WARP Liq Ar
- DM TPC
- LUX 350
- XMASS LXe
Summary

- Dark matter remains a fundamental mystery -- do we understand gravity?
  - Possible solution lies in new fundamental particle physics
    - Establishing a concordant model requires laboratory and astrophysical meas.
      - particle mass, lifetime, relic density, halo

- Advances in sensitivity
  - New generation of detectors
  - Technology ready for major scale-up
  - Proposed new national lab - DUSEL
  - Next 5-10 years looks very exciting!
Acknowledgments

CDMS Collaboration
Caltech, Case Western Reserve U., Fermilab, Zurich, U of Florida, MIT, Queen’s U., Santa Clara U., Stanford U., Syracuse U., UC Berkeley, UC Santa Barbara, CU Denver, U. of Minnesota

LUX Collaboration
Thank you...