Direct Dark Matter Searches
Overview

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Silver (25 y) Jubilee of DDMS…
Insanity is doing the same thing over and over again and expecting different results… Rita Mae Brown

(my apologies, most slides stolen!)
Historical Analogs…

- Rutherford & Chadwick between 1920-1932 conducted many unsuccessful experiments to discover the neutron
  - Joliot-Curie clue
  - Technique is now used in WIMP searches

- 110 years of neutrino physics
  - Beta decay in 1900 or so
  - … (Parity violation! R.T. Cox et al., PNAS 14, 544 (1928) ) …
  - 2020… complete mixing/mass matrix?
  - Majorana Mass?
How does Dark Matter interact with us?

- Gravitationally... astrophysics utilizes...

- Not via conventional electromagnetic or strong couplings (dark, no peculiar terrestrial nuclei with an extra particle bound).... however, axions!
  - Gluon field doesn’t violate CP, weak interaction does

- Could be via `conventional’ weak interaction... focus of most terrestrial experiments...
  - WIMP miracle... thermal equilibrium in Big Bang
  - SUSY favors a stable lightest superpartner
Generic Feynman Diagrams

\[ \sigma_{\text{nucleon}} \]

WIMP $\chi$

Spin-Dependent $c_{Z\chi\chi}$

Spin-Independent $c_{H\chi\chi}$
Fig. 3. The maximum halo density of heavy standard Dirac neutrinos (as an example of particles with weak spin-independent interactions) is shown, consistent with the observed count rate, as a function of their mass. The solid line shows the 68% confidence level and the dashed line shows the 95% confidence level.

cosmogenic radioactive contamination. In this way the background has been reduced by about a factor

Fig. 4. The regions in mass–cross section space excluded at the 68% confidence level are shown. The halo cannot be composed of particles that interact with nuclei through spin-independent interactions whose coupling constant (normalized to the coupling of massive Dirac neutrinos to baryons) lies above the solid line. Nor can the halo be composed of particles that interact with nuclei through spin-dependent interactions whose coupling constant (normalized as above) lies above the dashed line.
Apparent `beam’

Sun: $v/c = \beta \approx 0.7 \cdot 10^{-3}$
(Earth’s motion modulates)

Particles in `halo’:
$\rho_{\text{dark}} \approx 0.3 \text{ GeV/cm}^3$
(extrinsic systematic)

Velocity Dispersion?
Gaussian… maybe axions have less
Direct Detection

- Momentum Transfer

Convert a to photon – detect it

\[ a^0 \rightarrow \gamma \]

Axion

Massive Particle

Cause target recoil – detect it – (nuclei) 10’s of keV
Axion Parameter Space…

Diagram showing the parameter space for axions with axes for mass $m_A$ (eV) and coupling strength $g_{A\gamma}$(GeV$^{-1}$). Regions include Laser Experiments, Solar-Magnetic, Solar-Germanium, Telescope, Microwave Cavity, HB Stars, CAST, KSVZ, DFSZ, and SN1987A.
Key ADMX Innovation... AC SQUID Amp

- GHz SQUIDs have been measured with $T_N \sim 50$ mK
- Near quantum-limited noise
- This provides an enormous increase in ADMX sensitivity
The ADMX Experiment

ADMX SQUID-based detector

Field compensation magnet for SQUIDs

SQUID amplifier

All new experiment package
Axion Lineshapes in ADMIX

- Unvirialized KSVZ Axion
  - $V_{\text{flow}}$: 45 km/s
  - $V_{\text{disp}}$: 60 km/s
- Virialized KSVZ Axion
  - $V_{\text{flow}}$: 220 km/s
  - $V_{\text{disp}}$: 160 km/s
Direct Detection

- Momentum Transfer

Convert a to photon – detect it

massive particle

\[ m \rightarrow v_0 \rightarrow \text{target} \]

massive particle

Cause target recoil – detect it – (nuclei) 10’s of keV
Signal Shape

[Graph showing signal shapes for different elements (Xe-132, Ge-73, Ar-40, Si-28, Ne-20) as a function of energy (Er) and events per kg/day/keV.]
WIMP SI Parameter Space “race to the bottom”
WIMP SD Parameter Space

(a) Interactions on neutron

DAMA (no channeling)

ZeplinIII

XENON 10

(b) Interactions on proton

DAMA (no channeling)

Picasso

COUPP

IceCube ($\rightarrow b\bar{b}$)

SuperK

IceCube ($\rightarrow W^+W^-$)
Historical Trend (“Livingston Plot”)
10’s-1000’s of KeV from $\gamma$ are easy to detect…

Sodium Iodide (Light) (DAMA, ANAIS)

Germanium (Ionization) (COGENT, CDMS…)

Figure II–1. Comparison of NaI(Tl) and Ge(Li) detector resolution (refer to Table II–1 for peak identification).

Second measurement to distinguish nuclear recoils
Direct Detection: Signal and Main Background

**Signal**

Nucleus Recoils

\[ E_r \]

\[ v/c \approx 7 \times 10^{-4} \]

dense energy deposition
ionization efficiency low
distinct ionization energy scale

\[ \chi^0 \] (calibrate: neutron)

**Background**

Electron Recoils

\[ E_r \]

\[ v/c \approx 0.3 \]

Sparse Energy Deposition

Differences the Basis of Particle ID
Who Does What

- One instrumental signal; look for annual modulation, do pulse shape analysis, or shield.
  - Solids: DAMA/LIBRA, ANAIS (NaI, 100’s kg); KIMS (CsI, 100 kg) (light)
  - Liq: XMASS (Xe, 800kg), DEAP-3600 (Ar, 1000kg)
- Double Signal (much discussion of E scales)
  - CDMS/Edelweiss – phonons + ionization – Ge/Si
  - Liquid/Gas – Xenon-100/LUX (Xe, 350kg); Darkside (Ar, 50kg) – light + ionization
- Phase Change – COUPP, SIMPLE
  - Only nuclear recoils grow bubbles
CDMS-II

23x our WIMP-search background
Enabled by vastly improved DAQ!

Barium (γ)

Low Yield… Surface e−

Ionization Yield

Recoil Energy (keV)

252Cf (n)
SuperCDMS Detector Improvements
An Evolving Detector

**CDMS II**
- Single-sided
- 1 cm thick
- 3” diameter
- 250 g Ge
- 2 charge + 4 phonon
- 5 towers of 6 det each

**SuperCDMS Soudan**
- Double-sided
- 2.5 cm thick
- 3” diameter
- 620 g Ge
- 2 charge + 2 charge
- 4 phonon + 4 phonon
- 5 towers of 3 det each

**SuperCDMS SNOLAB**
- Double-sided
- 3.3 cm thick
- 4” diameter
- 1.38 kg Ge
- 2 charge + 2 charge
- 6 phonon + 6 phonon
- 24 towers of 6 det each
SuperCDMS Surface Rejection

SuperCDMS Soudan Data: Surface Event Rejection

$^{210}\text{Pb} \rightarrow ^{210}\text{Bi}^* / ^{210}\text{Bi} \rightarrow ^{210}\text{Po}$ which then alpha decays to $^{206}\text{Pb}$

Demonstrated Rejection (Soudan, 900 live hours with $^{210}\text{Pb}$ source)
$<2.9 \times 10^{-5}$ @ 63% WIMP fiducial cut

Demonstrated Rejection (surface test facility with $^{109}\text{Cd}$ source)
$<2.9 \times 10^{-5}$ @ 74% WIMP fiducial cut
2-Phase Nobel Liquid

Top PMT Array

Bottom PMT Array

\((S_2/S_1)_{\text{wimp}} < (S_2/S_1)_{\text{gamma}}\)
Separation... less impressive than CDMS
Xenon-100 Fiducial (LUX 1.7X linear dim)
The LUX Experiment (Sanford Lab/SD)

- 370 kg xenon
  - 300 kg active region cryostat
  - 100 kg fiducial
- 122 PMTs 2” round
- Low-background Ti cryostat
LUX being built
LUX Is Installed
LUX Is Underwater
LUX Details

- Helped commission a new laboratory
- Circulate/purify Xenon at 300 kg/day
  - Xenon-100 about 40 kg/day
- Xenon heat from condensation used to drive evaporation (heat exchanger)
- 0.8 kV/cm drift field
- Water Tank
- Surface Operation; underground gas run, $^{83m}Kr$
- Cooldown started yesterday!
- Checkout / short open run / long blinded run
10,000 days gives us until September 20, 2014

John Donne circa 1600…

If thou been borne to strange fights,
Things invisible to see,
Ride ten thousand daies and nights,
Till age snow white haires on thee
THANKS!

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."
The COUPP program

- COUPP-4: A 2-liter chamber - shallow site in 2009, at SNOLAB since September, 2010
- COUPP-60: A 30-liter chamber commissioning at Fermilab, goal is to move to SNOLAB within a year

U. Chicago / Indiana U South Bend / Fermilab / SNOLAB / Virginia Tech
DEAP 3600

DEAP Acrylic Vessel with Light Guide “Stubs” July 2012
Detector Construction

- 2009.11: PMT holder and PMT installation
- 2010.09: Construction Completed