Dark Matter Searches in the 21st Century

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Matter - Energy Budget

- Dark Matter: 25%
- Dark Energy: 70%
- Baryons: 5%
Outline of Talk

• Brief Introduction
  • Cosmology Today

• Principles of Dark Matter Detection
  • Direct Detection
  • Indirect detection

• Experimental Implementations
  • DAMA/Libra
  • CDMS
  • Xenon
  ...

• Current Limits & Looking to the future
The Optical View on the Universe

- Galaxy cluster properties provide a strong handle on cosmology
- Large in the sky: can’t be confused with anything else
- Can be seen up to large distances (z ~1.5)
The X-ray View on the Universe

- Galaxy cluster properties provide a strong handle on cosmology

- Large in the sky: can’t be confused with anything else

- Can be seen up to large distances ($z \sim 1.5$)

- Mass determined from temperature of x-ray emitting gas
The X-ray View on the Universe

- Galaxy cluster properties
Optical + weak-lensing
The Bullet Cluster

White: Visible Light = Galaxies
Red: X-rays = Intergalactic Plasma
Blue: Dark Matter map derived from Weak Lensing

Clowe et al. 2006
Chasing the WIMP

• We “know” that Dark Matter must
  • Have some mass: (due to its gravitational effect)
  • Has a certain annihilation cross section: (based on the current total matter density of the Universe)
  • Have been non-relativistic early on in cosmological time: (based on the formation of clusters in the early universe)

• There exists “several” theoretical candidates for such a particle

• I will focus on one particular candidate
  • The lightest supersymmetric particle commonly referred to as the neutralino
  • If we have time at the end, I will talk briefly about axions
Dark Matter Searches:
I - Principles and Design Considerations
Principles of Direct Detection
Principles of Direct Detection

- Elastic scattering of the neutralino off of a nucleus:
  - Can occur via spin-dependent/independent channels
  - Must be able to detect the small amount of energy imparted to the recoiling nucleus
  - Distinguish this event from the overwhelming number of background events.
Principles of Direct Detection

- How does a neutralino interact with a nucleus (or how do you calculate its cross section?)

\[
\chi \rightarrow \chi \quad \sigma_{X-N}=? \\
\chi \rightarrow p \quad \sigma_{X-p}=? \\
\chi \rightarrow q \quad \sigma_{X-q}=? \\
\chi \rightarrow q \quad \sigma_{X-X}=\text{known}
\]
Little Bit more Detail on Cross Section

• **WIMP-quark scalar interaction:**
  
  $\sigma_{0\text{-scalar}}(q\rightarrow0) = \frac{4m_r^2}{\pi} \left[Zf_p + (A-Z)f_n\right]^2 \sim$
  we assume $f_p \approx f_n \rightarrow \sigma_{0\text{-scalar}} \propto A^2$

• **WIMP-quark spin interaction:**

  $\sigma_{0\text{-spin}}(q\rightarrow0) = \frac{32}{\pi} G_F^2 \left(1/J \left[a_p<S_p> + a_n<S_n>\right]\right)^2 J(J+1)$
Principles of Direct Detection

**Input from Particle Physics**

\[ \sigma_0 = \left( \frac{m_r}{m_{r-p}} \right)^2 A^2 \sigma_{\chi-p} \]

**Knowledge of Nuclear Structure**

\[ F^2(Q) = \left[ \frac{3j_1(qR_1)}{qR_1} \right]^2 \exp\left(- (qs)^2 \right) \]

\[ \frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_{\chi} m_r^2} F^2(Q) T(Q) \]

**Choice of Target Nucleus**

\[ m_r = \frac{m_{\chi} m_N}{m_{\chi} + m_N} \]

\[ m_{r-p} = \frac{m_{\chi} m_p}{m_{\chi} + m_p} \]

**Input from Astrophysics**

\[ T(Q) = \exp\left(-v_{min}^2/v_0^2\right) \]

\[ v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}} \]

\[ v_0 \approx 220 \text{ km/s} \]
Exercise

• What is the minimum velocity needed $v_{\text{min}}$ for a WIMP with mass $m_X$ to produce a 10 keV recoil in a nucleus of mass $m_N$?

• What is the maximum recoil energy $E_{\text{max}}$ that a WIMP with mass $m_X$ and velocity $v_X$ can produce in a nucleus of mass $m_N$?
Woods–Saxon Form Factor

\[ A^2 \times \text{Form Factor } F(Q) \]

\[ \text{Recoil \ [keV]} \]

\[ \text{Kinetic Energy \ [keV]} \]

\[ \text{WIMP velocity distribution} \]

\[ \text{WIMP Velocity distribution} \]

\[ \text{Recoil spectrum of mono-energetic WIMP} \]

Input Functions
Principles of Direct Detection

• Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy \( \sim \) few \( \times \) 10 keV

• For spin-indep. event rate scales as \( A^2 \)

• For spin-dep. event rates determined by the spin of the nucleus \( \sim J \)
Principles of Direct Detection

- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy \( \sim \text{few x 10 keV} \)
  
  - For spin-indep. event rate scales as \( A^2 \)
  - For spin-dep. event rates determined by the spin of the nucleus \( \sim J \)
  - Featureless exponential energy spectrum

- no obvious peak, knee, break, ... that determines \( M_X \) or \( v_0 \)

- hard to distinguish from background
Principles of Direct Detection

• The physics discussed so far is required for choosing the “ideal” target nucleus for maximizing the rate of Dark Matter interactions in your experiment

• Equally important considerations:
  • When dealing with $10^{26}$ nuclei, must consider the physical behavior of the solid/liquid/gas which the nuclei form
  • How can we extract/measure the recoil information in a given medium
  • What are the background issues associated with this material
Principles of Direct Detection

• Various experimental methods exist for measuring such an energy deposition
  • Scintillation in crystals / liquids
  • Ionization in crystals / liquids
  • Thermal / athermal heating in crystals
  • Bubble formation in liquids / gels

• Easy in principle, hard in practice
  • Significant uncertainties/unknowns in estimating DM event rates / energy spectrum
  • Background rates overwhelm the most optimistic DM scattering rates !!
Looking for a very small needle in a big haystack
Detector Physics to the Rescue
Detector Physics to the Rescue

Signal

Nuclear Recoils

\[ E_r \approx 10^{-3} \]

Dense Energy Deposition

\( \chi \)

Background

Electron Recoils

\( v/c \approx 0.3 \)

Sparse Energy Deposition

\( \gamma \)

Density/Sparsity: Basis of Discrimination
Event Discrimination = Particle ID

• Scattering from an atomic nucleus vs an atomic electron leads to different physical effects in most materials

• Sensitivity to this effect effectively reduces background
  • Dark Matter is expected to interact “exclusively” with the nucleus while backgrounds interact predominantly with the electrons
The performance we need from our detectors

Backgrounds can’t be eliminated entirely
Neutrons: Unrejected background

- Neutrons recoil off of atomic nuclei, thus appearing as WIMPS

- Neutrons come from
  - Environmental radioactivity
    - Slow / low energy
    - Can be addressed with shielding
  - Spallation due to cosmic muons
    - Fast / energetic = un-shieldable
    - Must go deep underground to avoid

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![Graph: Relative Particle Flux at Underground Laboratories](image)

- Muon Flux
- Neutron Flux

Laboratory Depth [m.w.e.]

- WIPP
- Soudan
- Kamioka
- Boulby
- Gran Sasso
- Frejus
- Homestake
- Sudbury
Directional Signal

• Temporal variation of the WIMP signal provides a means to distinguish it from background

• Variation can happen in the:
  - Energy spectrum
  - Event rate
  - Recoil direction

• All such variations depend on direction of the earth through the WIMP “wind”
Annual Modulation

WIMP Isothermal Halo (assume no co-rotation) \( v_0 \sim 230 \text{ km/s} \)

Earth 30 km/s (15 km/s in galactic plane)

\[
v_e = v_0 \left[ 1.05 + 0.07 \cos \left( \frac{2\pi(t - t_p)}{1 \text{ yr}} \right) \right]
\]

\[
f(v)dv = \frac{vdv}{v_e v_0 \sqrt{\pi}} \left\{ \exp \left[ -\frac{(v - v_e)^2}{v_0^2} \right] - \exp \left[ -\frac{(v + v_e)^2}{v_0^2} \right] \right\}
\]

\[
T(Q) = \frac{\sqrt{\pi}}{2} v_0 \int_{v_{min}}^{\infty} \frac{f(v)dv}{v} = \frac{\sqrt{\pi} v_0}{4v_e} \left[ \text{erf} \left( \frac{v_{min} + v_e}{v_0} \right) - \text{erf} \left( \frac{v_{min} - v_e}{v_0} \right) \right]
\]
Exercise

• Even under the assumption of a standard non-rotating, isotropic halo, the velocity distribution of WIMPS is not truly Maxwellian. It has a cutoff at $v_{\text{max}}$, where $v_{\text{max}}$ is the escape velocity of the WIMP at the radius of the sun in the galaxy. If $v_{\text{max}} = 600 \text{ km/s}$ what is the total mass $M_G$ of the milkyway contained inside the solar orbit radius?
Diurnal Modulation

The mean recoil direction rotates over one sidereal day.

The distribution of the angle $\alpha$ between the solar motion and recoil directions: peaks at $\alpha=180^\circ$. 
The Dark Matter Reach of an Experiment

The reach, or sensitivity, of an experiment can be quantified as a function of four parameters:

- The background rate: $B$
- The background misidentification fraction: $\beta$
- The signal acceptance fraction: $\alpha$
- And the exposure: $MT$ (where $M$ is the mass of the detectors and $T$ is the duration of the experiment)
Experimental Reach: Non-Discriminating

• For experiments which do not distinguish between signal and background:

  • \( \beta = 1, \ 0 < \alpha < 1 \)

  • For the case of zero observed events, the 90% confidence level sensitivity (\( S_{90} \)) is:

    \[
    S_{90} \propto \frac{2.3}{\alpha MT}
    \]

    the sensitivity improves linearly with exposure

  • When some background events (\( N_{bkg} \)) are observed, the limits becomes:

    \[
    S_{90} \propto \frac{N_{bkg} + 1.28 \sqrt{N_{bkg}}}{\alpha MT} \quad \rightarrow \quad \frac{B}{\alpha} + \frac{1.28}{\alpha} \sqrt{\frac{\beta B}{MT}}
    \]

  • So, as soon as background is “accurately” observed, i.e. \( <N_{bkg}> = BMT \), the sensitivity stops improving
Experimental Reach: Discriminating

• For experiments which do distinguish between signal and background:
  
  • Define a continuous parameter $\eta$. $\eta$ is any event parameter on which $\beta$ and $\alpha$ can depend, i.e. $\beta(\eta)$ and $\alpha(\eta)$
  
  • The statistical sensitivity ($S_{stat}$) is:
    
    $$S_{stat} = \sqrt{\frac{\beta(1 - \beta)}{(\alpha - \beta)^2}} \sqrt{\frac{B}{MT}}$$
    
  • Let $Q = \beta(1-\beta)/(\alpha-\beta)^2$, the value of $\eta$ can be chosen to minimize $Q$.
  
  • For discriminating detectors, values of $Q \sim 10^{-3}$ are achievable, leading to a very low sensitivity (this is a good thing)
  
  • When some background events ($N_{bkg}$) are observed, the limit continues to improve with the square root of $MT$
Dark Matter Detection References


Principles of Indirect Detection
Principles of Indirect Detection

\[ \phi = \frac{\langle \sigma_{\text{ann}} \nu \rangle \rho_{\chi}^2}{m_{\chi}^2} g \]

Input from Particle Physics
- \( \sigma_{\text{ann}} \): annihilation cross section
- \( m_{\chi} \): WIMP mass

Input From Astrophysics
- \( \rho \): WIMP density at source
- \( \nu \): WIMP velocity at source
- \( g \): Propagation factor to earth
Annihilation Sources: Where the WIMPS are

- To know where to look for DM annihilation we must ask where is the dark matter to be found:

- A few sources:
  - Towards the center of our galaxy. The WIMP density increases rapidly toward the center of the galaxy leading to $\rho^2$ enhancement in the signal
  - From neighboring dwarf/satellite galaxies

There are the “obvious sources”. Galaxies formed in the gravity well of the dark matter halo

- From the Sun, Earth, Jupiter?
  This are not so obvious sources. What is Dark Matter doing in the Sun?
Annihilation Sources: Where the WIMPS are

- From the Sun, Earth, Jupiter?
  - Dark Matter accumulates over time in the center of large objects
  - The rate of accumulation helps probe the $\chi$-$p$ scattering cross-section

I: WIMP is away from sun. Has velocity $v_\infty$
Annihilation Sources: Where the WIMPS are

- From the Sun, Earth, Jupiter?
  - Dark Matter accumulates over time in the center of large objects
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I: WIMP is away from sun. Has velocity $v_\infty$  

II: WIMP passes through the sun. Has velocity $v_\infty + v_{esc}$
Annihilation Sources: Where the WIMPS are

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  - Dark Matter accumulates over time in the center of large objects
  - The rate of accumulation helps probe the $\chi$-p scattering cross-section

I: WIMP is away from sun. Has velocity $v_\infty$

II: WIMP passes through the sun. Has velocity $v_\infty + v_{esc}$

III: WIMP scatters with an atom in the sun. Has final velocity $v < v_{esc}$
Annihilation Sources: Where the WIMPS are

- From the Sun, Earth, Jupiter?
  - Dark Matter accumulates over time in the center of large objects
  - The rate of accumulation helps probe the χ-ρ scattering cross-section

I: WIMP is away from sun. Has velocity $v_\infty$

II: WIMP passes through the sun. Has velocity $v_\infty + v_{esc}$

IV: WIMP is trapped in the sun. Accumulate over time until $\rho > \rho_c$, annihilation begins

III: WIMP scatters with an atom in the sun. Has final velocity $v < v_{esc}$
Various experimental approaches exist to look for the different annihilation products at vastly differing energy scales:

- **Sub-mm photons**: space based bolometers: e.g. WMAP
- **MeV-GeV photons**: space based calorimeters e.g. EGRET, FERMI
- **1-100 GeV cosmic rays**: space base spectrometers: PAMELA, ATIC, HEAT, FERMI
- **100 GeV-10 TeV photons**: ground based atmospheric cherenkov imaging detectors: HESS, VERITAS, MAGIC, CANGAROO
- **GeV-TeV neutrino**: water/ice based neutrino detectors: Super-K, ANTARES, IceCube ...
Final Products & Energy Scale

• Various experimental approaches exist to look for the different annihilation products at vastly differing energy scales.
Astrophysics From All Altitudes

Direct Detection & Neutrino searches
The Line of Sight Factor

- Indirect detection of Dark Matter decay products (e.g. photons) is sensitive to the annihilation rates along any given line of sight

- Must integrate over all DM densities in any given line of sight
The Propagation Factor

- Diffusive transport of charges cosmic rays requires detailed knowledge of galactic structure
  - Galactic winds can remove DM decay products
  - Diffusive transport parameters may be position dependent
Complementarity with Colliders
Direct Detection and the LHC

• For most generic WIMP candidates information from both accelerators and direct detection experiments is required to fully identify and understand the particle

• e.g. It is hoped / expected that the LHC will be able to produce the Lightest Supersymmetric Particle, however, it will not be able to identify it as the cosmological Dark Matter
Three way Complementarity

Direct Detection
- Discover relic particle
- Constrain $m_X$, $\rho \sigma_{\text{dir}}$
- With LHC input determine $\rho_{\text{local}}$

Indirect Detection
- Discover relic particle
- Constrain $m_X$, $\sigma_{\text{inj}} \rho^2$
- With LHC input determine $\rho_{\text{halo}}$ (or GC)

Collider Production
- Discover supersymmetric particles
- Determine physics model behind $m_X$
- Predict $\sigma_{\text{(in-)direct}}$
Dark Matter Searches:
II - Experimental Implementations
Direct Detection Searches
Over 2 dozen experiments worldwide
## Current DM Searches

### TABLE 2  Current status of dark matter experiments (by technology)

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Location</th>
<th>Readout</th>
<th>Target mass</th>
<th>Search dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGEX–DM</td>
<td>Baksan (Russia)</td>
<td>Ionization (77 K)</td>
<td>3 kg Ge</td>
<td>2001–</td>
</tr>
<tr>
<td>IGEX–DM</td>
<td>Canfranc (Spain)</td>
<td>Ionization (77 K)</td>
<td>2 kg Ge</td>
<td>2001–</td>
</tr>
<tr>
<td>GENIUS TF</td>
<td>Gran Sasso (Italy)</td>
<td>Ionization (77 K)</td>
<td>~5 kg Ge $\beta\beta$</td>
<td>2002–2005</td>
</tr>
<tr>
<td>NAIAD</td>
<td>Boulby (UK)</td>
<td>Scintillator (~300 K)</td>
<td>~50 kg NaI array</td>
<td>2001–2005</td>
</tr>
<tr>
<td>LIBRA</td>
<td>Gran Sasso (Italy)</td>
<td>Scintillator (~300 K)</td>
<td>≤250 kg NaI array</td>
<td>2003–</td>
</tr>
<tr>
<td>ANAIS</td>
<td>Canfranc (Spain)</td>
<td>Scintillator (~300 K)</td>
<td>11 kg NaI prototype</td>
<td>2000–2005</td>
</tr>
<tr>
<td>Rosebud</td>
<td>Canfranc (Spain)</td>
<td>Therm. phon. (~20 mK)</td>
<td>≤1 kg Ge, Al$_2$O$_3$</td>
<td>1995–</td>
</tr>
<tr>
<td>CDMS II</td>
<td>Soudan (USA)</td>
<td>Non-therm. phon. + ioniz. (&lt;50 mK)</td>
<td>0.2–1.5 kg Si, 1–4.2 kg Ge</td>
<td>2001–2006</td>
</tr>
<tr>
<td>EDELWEISS II</td>
<td>Fréjus (France)</td>
<td>Therm. phon. + ioniz. (~30 mK)</td>
<td>1 kg Ge</td>
<td>2000–2004</td>
</tr>
<tr>
<td>CRESST II</td>
<td>Gran Sasso (Italy)</td>
<td>Therm. phon. + scint. (~10 mK)</td>
<td>1 kg CaWO$_4$</td>
<td>2000–2006</td>
</tr>
<tr>
<td>CUORICINO</td>
<td>Gran Sasso (Italy)</td>
<td>Therm. phon. (~20 mK)</td>
<td>40 kg T$_2$O$_2$ $\beta\beta$</td>
<td>2002–</td>
</tr>
<tr>
<td>ORPHEUS</td>
<td>Bern (Switzerland)</td>
<td>Superconducting grains (~4 K)</td>
<td>0.5 kg Sn</td>
<td>2001–</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>Rustrel (France)</td>
<td>Superheated droplets (~300 K)</td>
<td>Freon</td>
<td>1999–</td>
</tr>
<tr>
<td>PICASSO</td>
<td>Sudbury (Canada)</td>
<td>Superheated droplets (~300 K)</td>
<td>~10 g–1 kg Freon</td>
<td>2001–</td>
</tr>
<tr>
<td>ZEPLIN I</td>
<td>Boulby (UK)</td>
<td>Scintillator PSD (~150 K)</td>
<td>6 kg LXe</td>
<td>2002–2004</td>
</tr>
<tr>
<td>Xenon</td>
<td></td>
<td>Scint. + Ioniz</td>
<td>10 kg</td>
<td>2006–</td>
</tr>
<tr>
<td>XMASS-DM</td>
<td>Kamioka (Japan)</td>
<td>Scint. + ioniz. (~150 K)</td>
<td>2 kg LXe</td>
<td>2002–2004</td>
</tr>
<tr>
<td>XMASS-DM</td>
<td>Kamioka (Japan)</td>
<td>Scint. + ioniz. (~150 K)</td>
<td>14 kg LXe</td>
<td>2004–</td>
</tr>
<tr>
<td>DRIFT–I</td>
<td>Boulby (UK)</td>
<td>ioniz. NITPC (300 K)</td>
<td>0.167 kg CS$_2$</td>
<td>2002–2005</td>
</tr>
<tr>
<td>Bubble Chamber (Chicago)</td>
<td></td>
<td>Superheated liquid (~300 K)</td>
<td>1 kg Freons</td>
<td>2004–</td>
</tr>
<tr>
<td>(MACHe3)</td>
<td>Grenoble (France)—not underground</td>
<td>Exciton (~20 mK)</td>
<td>0.02 g He$_3$</td>
<td>1998–</td>
</tr>
</tbody>
</table>

Dark Matter Search Elements

The Elements
The Classical Approach
LIBRA

- Large sodium Iodide Bulk for RAre processes

- Target: Room Temp Scintillator
  - NaI crystals
  - Naturally abundant odd-spin isotopes allow for some sensitivity to both spin dependent and spin independent interactions

- Detection Mechanism
  - Photomultiplier tubes detect scintillation photons
  - \#scintillation photons proportional to recoil energy (roughly 6 photoelectrons per keV)
LIBRA

- **Background Discrimination**:  
  - Small difference in pulse shape between electron and nuclear recoils  
  - Insufficient for event by event discrimination, but can be used on a statistical basis

- **Mass / Exposure**:  
  - Operating 250 kg of detectors at the Gran Sasso underground laboratory (~3000 mwe) since 2003  
  - Recently finished operating 100 kg of detectors for 7 years (DAMA)  
  - Background rate ~ 1 evt/kg/keV/day
NaI Scintillator
Inside LIBRA

DAMA/LIBRA Collaboration
Libra Spectrum

![Graph showing the Libra Spectrum with Energy (keV) on the x-axis and Rate (cpd/kg/keV) on the y-axis. The graph includes data points at various energy levels.]
The Libra/DAMA Signal

- Observed a modulating signal in the lowest energy bins
- Amplitude and phase of modulation consistent with standard WIMP halo model

![Graph showing residuals (cpd/kg/keV) over time (day) for DAMA/NaI and DAMA/LIBRA experiments. The graph plots residuals against time with markers indicating data points and error bars. The x-axis represents time in days, ranging from 500 to 4500, and the y-axis represents residuals in units of cpd/kg/keV, ranging from -0.1 to 0.1. The graph includes annotations for DAMA/NaI (0.29 ton yr) with target mass 87.3 kg and DAMA/LIBRA (0.53 ton yr) with target mass 232.8 kg. The y-axis is labeled Residuals (cpd/kg/keV), and the x-axis is labeled Time (day).]
HDMS

- Heidelberg Dark Matter Search

- Target: Ge Crystals (cooled to liquid nitrogen temp.)
  - enriched Ge (A=72)
  - Largely sensitive to spin-independent interactions, although enriched presence $^{73}\text{Ge}$ allows for some spin-dependent sensitivity

- Detection Mechanism
  - Ionization signal: Electrons drifted through the crystal by an electric field result in a signal proportional to the recoil energy
  - #ionization electrons proportional to recoil energy
Insensitivity to Backgrounds
• **Chicagoland Observatory for Underground Particle Physics**

• **Target**: Halocarbon liquids
  - $\text{CF}_3\text{Br}$, $\text{CF}_3\text{l}$, ... (even Xe)
  - Sensitive to both spin-dependent AND spin-independent interactions

• **Detection Mechanism**
  - Bubble formation in superheated liquid
  - Pressure sensor detects formation of bubble, triggers imaging camera
  - Sensitive to events with recoil energy above a specific tunable threshold
COUPP

• Background Discrimination:
  • Insensitive to electron recoils (deposited energy density insufficient to create bubble)
  • By selecting operating pressure can reduce fraction of electron recoils resulting in bubble to $\sim 10^{-9}$

• Mass / Exposure
  • Finished operating 2 kg of detector at Fermilab underground site ($\sim 300$ mwe)
  • Currently upgrading towards larger mass detectors: $\sim 60$ kg
  • Expect background rate $\sim 10^{-5}$ evt/kg/keV/day
COUPP in Action

A triple scatter neutron event
Bubble at the interface
 Recap  

• So far, we have discussed
  • The kinematics of Dark Matter / Nucleus scattering
  • General behavior of scattering cross-section with nuclear properties
  • Variety of detection techniques available for DM searches
  • Experimental reach (or sensitivity) of an experiment

• Today we will cover:
  • Finish the survey of direct detection experiments
  • Discuss the latest Dark Matter direct exclusion limits
  • Brief survey of indirect detection searches
  • If time allows, .... discussion of axion search experiments
Experimental Sensitivity vs Time

Zero Events

\[ S_{90} \propto \frac{2.3}{\alpha MT} \]

Discriminating Detector

\[ \sqrt{\frac{\beta (1 - \beta)}{(\alpha - \beta)^2}} \sqrt{\frac{B}{MT}} \]

Non-Discriminating

\[ \frac{B}{\alpha} + \frac{1.28}{\alpha} \sqrt{\frac{\beta B}{MT}} \]
Discriminating Variables

- Ideal behavior = Perfect discrimination between signal and event.
  - Place a cut at $\eta_0$ anywhere: We get the ideal detector behavior, i.e. $\beta = 0$, $\alpha = 1$
- Real detector resolution: Discrimination ability is somewhat degraded
  - There is now a preferred location for the cut $\eta_0$ with $\beta \neq 0$, $\alpha < 1$

![Graph showing Discriminating Variables]

- Background event
- Signal event

Generic Event Parameter: $\eta$
Discriminating Variables

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Insensitivity to Backgrounds
COUPP
(see also PICASSO / ORPHEUS)

• Chicagoland Observatory for Underground Particle Physics

• Target: Halocarbon liquids
  • CF$_3$Br, CF$_3$I, ... (even Xe)
  • Sensitive to both spin-dependent AND spin-independent interactions

• Detection Mechanism
  • Bubble formation in superheated liquid
  • Pressure sensor detects formation of bubble, triggers imaging camera
  • Sensitive to events with recoil energy above a specific tunable threshold
PICASSO

- Project In CAnada to Search for Supersymmetric Objects

- Target: Fluorinated Halocarbon liquids
  - CF$_4$
  - Sensitive to spin-dependent interactions

- Detection Mechanism
  - Bubble formation in superheated liquid
  - Acoustic sensors detect formation of bubble
  - Sensitive to events with recoil energy above a specific tunable threshold
PICASSO

• **Background Discrimination**:
  
  • Insensitive to electron recoils (deposited energy density insufficient to create bubble)
  
  • By selecting operating temperature can vary nuclear recoil energy thresholds
  
  • Sensitive to $\alpha$ interactions in the detectors

• **Mass / Exposure**

  • Currently operating 3 detectors with an active target mass of 19.4 g at SNOLab (~6060 mwe)
  
  • 1.98 kg day of exposure accumulated
PICASSO in Action

PICASSO Collaboration
PICASSO in Action
ULTIMA

- Ultra Low Temperature Instrumentation for Measurements in Astrophysics
- Target: $^3$He Superfluid
  - Sensitive to spin dependent interactions
  - Detection Mechanism
    - Recoil energy: Calorimetric measurement via quasiparticle induced damping of a vibrating wire resonator
- Background Performance:
  - Extreme purity of $^3$He results in an intrinsically low background detector
  - Scintillation photons can be absorbed/measured by a neighboring detector
  - Potential pulse shape based discrimination
ULTIMA in Action
Background Rejection
DRIFT
(see also DM-TPC / NEWAGE)

• Directional Recoil Identification From Tracks

• Target :
  • CS$_2$ gas
  • Sulfur : A=32
  • Sensitivity to spin-independent interactions

• Detection Mechanism
  • Time projection chamber
  • Length/shape of track dependent on energy density of recoiling particle
DRIFT

• Background Discrimination:
  • Track shape
  • Recoil directional

• Mass / Exposure
  • DRIFT-II : 10 kg-day data accumulated
  • DRIFT-III : 100 kg target mass

EGS4/Presta -13 keV e⁻ in 40 Torr Ar
SRIM97 - 15 keV He in 40 Torr Ar
SRIM97 - 40 keV Ar in 40 Torr Ar
Liquid Nobles
XENON
(see also WARP / CLEAN)

• Target : Liquid Xenon
  • A = 131
  • Large sensitivity to spin-independent interactions
  • Sensitive to spin-dependent interaction through $^{129}\text{Xe}$, $^{131}\text{Xe}$ isotopes

• Detection Mechanism
  • Scintillation in LXe : detected by photomultiplier tubes above the liquid (prompt signal)
  • Ionization in LXe : Electrons drifted through the liquid by an electric field. Result in scintillation in Xe vapor above the liquid (delayed signal ~ 150 μs)
  • #scintillation photons / ionization electrons proportional to recoil energy (roughly 200 photons for a 16 keV recoil)
**XENON: Detection Mechanism**

Excitation/Ionization depends on dE/dx!

⇒ discrimination of signal (WIMPs → NR) and (most of the) background (gammas → ER)!

Wavelength depends on gas (N: 85 nm, Ar: 128 nm, Xe: 175 nm)

Time constants depend on gas (Ne: few ns/15.4μs, Ar: 10ns/1.5μs, Xe: 3/27 ns)

\[
\begin{align*}
Xe^* + Xe & \rightarrow Xe_2^* \\
Xe_2^* & \rightarrow 2Xe + h\nu \\
Xe^* + Xe & \rightarrow Xe_2^+ \\
Xe_2^+ + e^- & \rightarrow Xe^{**} + Xe \\
Xe^{**} & \rightarrow Xe^* + \text{heat} \\
Xe^* + Xe & \rightarrow Xe_2^* \\
Xe_2^* & \rightarrow 2Xe + h\nu
\end{align*}
\]

Excitation mechanism in liquid xenon:

1. Electron excitation and ionization:
   - Electric excitation (ER):
     \[ E_R \rightarrow \text{Ionization} \rightarrow Xe^+ \]
   - Ionization:
     \[ Xe^+ + Xe \rightarrow Xe_2^* \]
     \[ Xe_2^* \rightarrow 2Xe + h\nu \]
   - Electron excitation:
     \[ Xe^{**} + Xe \rightarrow Xe_2^* \]
     \[ Xe_2^* \rightarrow 2Xe + h\nu \]

2. Excitation:
   - \[ Xe^* \rightarrow Xe_2^* \]
   - \[ Xe_2^* \rightarrow 2Xe + h\nu \]

3. Triplet and singlet states:
   - \[ 2Xe \rightarrow \text{triplet} \]
   - \[ 2Xe \rightarrow \text{singlet} \]

4. Light emission:
   - \[ h\nu \rightarrow \text{scintillation light} \]

5. Recombination:
   - \[ \text{Electron recombination} \]

6. Additional information and use for particle identification and improvement of detector performance.
XENON

• **Background Discrimination** :
  
  • Higher ratio of scintillation to ionization signal for nuclear recoils compared to electron recoils
  
  • Able to achieve event by event discrimination at 99%

• **Mass / Exposure**

  • Operated a 10 kg of detector at the Gran Sasso underground laboratory (~3000 mwe)
  
  • Exposure of 136 kg-day
  
  • Currently operating a 100 kg detector
The XENON Design

- Photomultipliers
- LXe
- GXe
- Primary
  - e^-
  - ~40 ns width
- Secondary
  - e^-
  - ~1 μs width
- WIMP

The XENON Design

Primary and secondary electrons are detected by the photomultipliers.

- LXe
- GXe
- Photomultipliers
- 5 μs/cm
- E_g
- E_d

The design is optimized for sensitivity to dark matter particles.
Self shielding in Liquid Xenon

- A big advantage of the liquid xenon detector is its self shielding ability
  - Xenon is a heavy nucleus, and LXe is a dense material --> excellent particle attenuation properties
  - Xenon liquifies at 166K, so most impurities will be frozen out outside the detector

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![Gamma rays from $^{238}$U chain](image)

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![Event position vs depth](image)

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![Drift time vs radius](image)
Event Signals in Liquid Xenon

Zooming in on S1 & S2
XENON Discrimination

- Rejection is > 99.6% for 50% Nuclear Recoil acceptance
  - Cuts: fiducial volume (remove events at teflon edge where poor charge collection)
  - Multiple scatters (more than one S2 pulse)
Signal Loss in Liquid Detectors

- Primary: ~40 ns width
- Secondary: ~1 μs width

Photomultipliers:
- P.M.T. P.M.T. P.M.T. P.M.T.
- GXe
- LXe

E

e

5 μs/cm

WIMP
XENON Data
Cryogenic Experiments
CDMS
(see also CRESST / Edelweiss)

• Cryogenic Dark Matter Search

• Target: Semiconductor crystals
  • Ge (A=72) / Si (A=28)
  • Largely sensitive to spin-independent interactions, although presence of some naturally abundant odd spin isotopes allows for some spin-dependent sensitivity

• Detection Mechanism
  • Athermal phonons in crystal: provide a calorimetric measure of the recoil energy
  • Ionization signal: Electrons drifted through the crystal by an electric field result in a signal proportional to the recoil energy
CDMS

• Background Discrimination:
  • Higher ratio of ionization to athermal signals for electron recoils
  • Able to reject bulk electron recoils at the $1 \text{ in } 10^6$ level

• Mass / Exposure
  • Operated 5 kg of detectors at the Soudan underground laboratory (~2000 mwe)
  • Background rate $\sim 1 \text{ evt/kg/keV/day}$
  • Planning upgrade in detector mass to 25 kg (SuperCDMS)
CDMS Detectors

Consider the following electrical/thermal circuit
CDMS Detectors

Consider the following electrical/thermal circuit

\[ V_{\text{bias}} \]

\[ R_{\text{bias}} \]

\[ R_{\text{sensor}} = R(T) \]

Heat Capacity

\[ "C" \]

Thermal conductance

\[ "G" \]

\[ R \]

\[ T \]

Current

\[ \text{Time} \]
Getting the Energy to the Sensors

Athermal Phonons and Quasiparticles
Anatomy of a CDMS Detector

These are the Aluminum collection fins

This is the superconducting thermometer

Si or Ge Crystal

phonons

Tungsten TES

qp diffusion

qp trap
Electrons and holes are drifted across the crystal by an electric field of a few V/cm.
Anatomy of a CDMS Detector

Aluminum fins double as ground electrode

Ionization electrode

holes

electrons

Vbias

Ionization electrode
This is the superconducting thermometer 1x250 μm.
CDMS Shields Outside-In

- Surround detectors with active muon
- Use passive shielding to reduce gamma/Neutrons
- Overburden reduces muon-induced Neutrons
- Polyethylene for low-energy neutron
- Lead and Copper for photon
- Neutron background small in Soudan, for recent runs
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- Polyethylene for low-energy neutron
- Lead and Copper for photon
- Neutron background small in Soudan, for recent runs
Box it all up and go to Northern Minnesota

4 hours drive North of Minneapolis
CDMS Collaboration

CDMS Institutions
- Fermilab
- NIST

University
- CalTech
- Case Western
- Colorado (Denver)
- Florida
- Queen's
- Minnesota
- MIT
- Stanford
- Santa Clara
- Syracuse
- UC Berkeley
- UC Santa Barbara
- Zurich
CDMS Background Discrimination in Action

- Calibration with $^{60}$Co ($\gamma$) source results in the **blue** (high yield) electron recoils

- Calibration with $^{252}$Cf (n) source results in the **red** (low yield) nuclear recoils

- Can identify/eliminate the electron recoils better than 1 in $10^6$

- ... BUT ...
CDMS Background  Achilles' Heel

- Calibration with $^{60}\text{Co}$ ($\gamma$) source also results in the green (mid yield) electron recoils

- Events are due to electrons that interact near the surface (dead layer) of the detector

- Can be mis-identified as nuclear recoils
Timing to The Rescue

- Analysis of pulse shapes / timing parameters further separates the event populations.
Applying the Timing Cut
Net CDMS Rejection

Yield + Timing Provide Excellent (>10^6:1) rejection of EM Backgrounds
WIMP Candidate: Blind Analysis

All cuts set blind, without looking at the signal. i.e. we do not look at events which are:

- Inside the good fiducial volume
- In the Nuclear Recoil Band
- Single Scatter
- Not a surface event: phonon timing cut
Efficiencies

Cumulative Detector Efficiencies

Total Efficiency with Respect to Full Detector Mass

Recoil energy (keV)
CDMS Dark Matter Data

- A complete blind analysis was performed
- No events passing the background rejection cuts!!
CDMS Dark Matter Data

- A complete blind analysis was performed
- No events passing the background rejection cuts!!
CDMS Dark Matter Data

- A complete blind analysis was performed
- No events passing the background rejection cuts!!
CRESST

• Cryogenic Rare Event Search using Superconducting Thermometer

• Target : Scintillating crystals
  • CaWO$_4$ : W has $A = 184$, Ca has $A = 40$
  • Largely sensitive to spin-independent interactions

• Detection Mechanism
  • Superconducting phase thermometer provides calorimetric measurement of the recoil energy
  • Scintillation photons absorbed/measured by neighboring detector
CRESST

- **Background Discrimination:**
  - Higher ratio of scintillation to thermal signals for electron recoils
  - Able to reject bulk electron recoils better than 99%

- **Mass / Exposure**
  - Ran 2 0.3 kg detectors at the Gran Sasso laboratory (~2000 mwe) for 20.5 kg-days
  - Background rate ~ 6 evt/kg/keV/day
  - Planning upgrade in detector mass to 10 kg in 2005
Dark Matter data
- No events seen that are consistent with W nuclear recoils

Electron Recoil Band

Nuclear Recoil Band from Oxygen

Nuclear Recoil Band from Tungsten

CRESST in Action
Experimental Limits
WIMP exclusion plots

- Two WIMP parameters experimentally determined by direct detection searches: $M_X$, $\sigma_{X-N}$
Spin-Independent Limits

http://dmtools.brown.edu/

Gaitskell, Mandic, Filippini

CDMS: 2008
XENON10 2007
DAMA 2000
Ruiz et al. 2007
Spin Indep Limits at low mass

DAMA is getting squeezed out
Spin Indep Limits at low mass

DAMA is getting squeezed out
Spin-Dependent Limits

Wimp-Neutron $\sigma$

Wimp-Proton $\sigma$

Cross-section [cm$^2$] (normalised to nucleon)

WIMP Mass [GeV/c$^2$]

http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini

http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Indirect Detection Searches
A couple of places to look: Photons

- Galactic and extra-galactic x-rays, gammas
  - EGRET, GLAST, Imaging Atmospheric Cherenkov Counters

- Advantages/Disadvantages:
  - Direct line of travel from source
  - Many “background” astrophysical continuum sources
A couple of places to look: Photons

- A closer look at the energy scale of the photon final states
  - All the range is readily covered with modern instrumentation
  - “Mundane” galactic backgrounds dominate in most wavelengths
EGRET: Diffuse Galactic Gammas

- Diffuse galactic gamma component $\sim 2x$ larger than the expected background

- Can be interpreted as arising from Dark Matter annihilation in the halo with $m_X \sim 60\text{ GeV/c}^2$

A couple of places to look: Charged Cosmic Rays

- Galactic and extra-galactic charged particles (positrons/anti-protons)
  - PAMELA, ATIC, HEAT

- Advantages/Disadvantages:
  - Slightly fewer “background” astrophysical sources
  - Diffusive travel from source
    - does not point back to origin
• Electron / proton spectrometer in orbit for >2 yrs

• Detects an excess of positrons above 10 GeV

• Possibly from DM with m_X~150 eV, but require very large densities
Hot of the Presses
Hot of the Presses

- Recent FERMI data inconsistent with ATIC electron peak
A couple of places to look: Neutrinos

- Neutrinos from the Earth’s & Sun’s center
  - Super-K, Antares
  - AMANDA, IceCube:
    - Looking for WIMPs in Antarctica
WIMP Annihilation into Neutrinos

- Looking for excess μ’s from the Sun’s direction, above atmospheric background
- Upper limit on μ flux translates into WIMP-proton cross section
Final Words

• What if there aren’t WIMPs or Axions?

• The techniques presented here describe the detection of ANY particles that couples with either a photon, electron, or nucleus (our three favorite, and most manipulable tools)

• As the couplings get weaker, or the densities smaller, we have to keep up by reducing the backgrounds

The truth is

• If it is out there, ... we will see it

Fox Mulder, X-Files
Dark Matter Searches in the 21st Century

Tarek Saab

Oran School on Particle Physics and Cosmology
May 2009