LOOKING FOR DARK MATTER AT LOW THRESHOLDS: SEARCHING FOR ANNUAL MODULATION

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May 26, 2016
Today...

- Dark Matter in the Universe
- Searching for Dark Matter at Low Thresholds and the Search for Annual Modulation
- Background Subtraction in the CDMS II Search for Annual Modulation
DARK MATTER IN THE UNIVERSE
Astrophysical Observations

The Bullet Cluster. Image courtesy of NASA.

Galactic rotation curves.

M33 rotation curve

Corbelli & Salucci (2000); Bergstrom (2000). Photo by NASA.

Gravitational lensing.
Cosmological Constraints

CDM Halo Simulation, Frenkel and White, 2012

Image credit: ESA and the Planck Collaboration

Image credit: ESA and the Planck Collaboration
Particle Physics Puzzles

- The Hierarchy problem
  - Why is gravity $10^{32}$ times weaker than the weak nuclear force?

- The strong CP problem
  - Why haven’t we seen an experiment break charge-parity symmetry, since it’s allowed in QCD?
Quick Recap: Expected Properties of Dark Matter

- No photon coupling; little interaction with ordinary matter (weak-scale interactions)
- Cold at time of galaxy formation
- Non-baryonic
- Neutral
- Stable
- Massive
- Evidence on many scales; globally contributes ~27% of mass in the universe

Favored theory for incorporating these properties: \( \Lambda \)CDM (Cold Dark Matter with a cosmological constant)

Image credit: ESA and the Planck Collaboration

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Weakly Interacting Massive Particles (WIMPs)

**Properties Consistent with observation**

- Statistical Equilibrium + non-relativistic decoupling
- \( \Rightarrow \) weak-scale interactions

**Natural Candidate in SM extensions**

**Composition & Structure**

**ASTROPHYSICS**

**COSMOLOGY**

**PARTICLE PHYSICS**

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Searching for Dark Matter

- 3 main avenues
  + Production/Accounting
  + Indirect Detection
  + Direct Detection
Searching for Dark Matter: Collider Production

Collider Experiments

Look for missing energy in collision products

Two standard model (SM) particles collide

Two dark matter (X) particles are produced

*SM particles interact & annihilate*

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Searching for Dark Matter: Indirect Detection

Indirect Detection by annihilation products

Two dark matter ($X$) particles collide

$X$ particles interact & annihilate

Two standard model (SM) particles are produced

Detection by annihilation products
Searching for Dark Matter: Direct Detection

Direct Detection

- LHC Scattering on nuclei in particle detectors

A dark matter particle bumps into a standard model particle

$\bar{\chi} \rightarrow X \in SM$ particles interact

End up with a dark matter particle and a standard model particle

(consider either direction)

Scattering on nuclei in particle detectors

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Direct Detection Signatures: Rate Excess

Detector sensitive to interactions for particular ranges of recoil energy

\[ E_{\text{recoil}} = \frac{m^2 M}{(m + M)^2} v^2 (1 - \cos \theta) \]

\[ E_{\text{max}} = \frac{2m^2 M}{(m + M)^2} v^2 \]

\[ v_{\text{min}} = \sqrt{\frac{(m + M)^2 E_r}{2m^2 M}} \]

\[ R \propto \rho \int f(v)dv \]
Direct Detection Signatures: Annual Modulation

\[ \nu = \nu_{\text{Earth}} + \nu_{\text{Sun}} + \nu_{\text{rotation}} \]

Expected annual modulation of detector signal, peaking in June, troughing in December

SEARCHING FOR DARK MATTER
Roads to Direct Detection

Generally* 3 categories, often used in combination

- **Ionization**
- **Scintillation**
- **Phonons**

*Other technologies exist, such as the COUPP experiment, which uses bubble chambers

- CoGeNT
- MALBEK
- CDMSlite
- LUX
- XENON
- LZ
- ZEPLIN
- DAMA
- DM-Ice
- CDMS
- SuperCDMS
- EDELWEISS
- CRESST

... and more ...
Spin-Independent Direct Detection Limits, 2016
Regions of Interest: CRESST & CDMS II-
Silicon

- Collaborations have not claimed WIMP signal; have only reported inability to rule out WIMP hypothesis
- Experimental backgrounds believed to contribute to excess rates
- Each in strong tension with CDMS II-Germanium, Xenon, and EDELWEISS upper limits, as well as being mutually in tension
Regions of Interest: DAMA/LIBRA

- 9-sigma modulation signal reported, collected over 14 annual cycles
- Dark matter interpretation in strong tension with other direct detection results, but source of modulation remains unidentified
- Difficult to cross check with other experiments, particularly those with other target materials

DM Ice (2016)

- First results from new wave of NaI experiments
- Projected to provide direct cross-check of DAMA/LIBRA ROI

Other NaI experiments pending:
- ANAIS
- KIMS
- SABRE
Regions of Interest: CoGeNT (2011)
CDMS II WIMP-search Analyses (2010-2012)

- Dark matter search results, 2010 (*Science* 327, p. 1619-1621)
CDMS II WIMP-search Analyses (2010-2012)

- Dark matter search results, 2010 (Science 327, p. 1619-1621)

Phase: 106 days (CoGeNT best-fit phase, 2011)

Phase: 153 days (Standard Halo Model predicted phase)

Indication:
Tension with a WIMP interpretation of the CoGeNT modulation above 5.0 keV

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Search for Annual Modulation: Extension to 2.27 keV$_{\text{nr}}$

**Phases:**
- **Phase: 102 Days**
- **Phase: 152.5 Days**

**Data Points:**
- Recoil Energy [CoGeNT keV$_{\text{ee}}$]
- Recoil Energy [keV$_{\text{nr}}$]

**Graph:**
- $R_{\text{mod}}$ [kg day keV$_{\text{nr}}$]$^{-1}$
- $R_{\text{mod}}$ [kg day keV$_{\text{nr}}$]$^{-1}$

**Images & Analysis:**
- Courtesy of S. Hertel

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CDMS II: SEARCHING FOR ANNUAL MODULATION WITH BACKGROUND SUBTRACTION
The SuperCDMS Collaboration
The Cryogenic Dark Matter Search Experiment – Soudan, MN, USA

- 22 institutions, international collaboration
- Located in Soudan Underground Mine (MN)
- Data taking was completed in 2015; now decommissioned and moving to SNOLAB
Overview of the CDMS Concept

Ionization yield for nuclear recoils is lower than for electron recoils $\rightarrow$
Excellent discrimination

Nuclear Recoils

Electron Recoils

Dark Matter
(mass $\sim$ GeV - TeV)

E $\sim$ 3V

Observation

133Ba
252Cf
CDMS II – the Z-sensitive Ionization and Phonon (ZIP) Detectors

Collection of:
- Ionization (Charge electrodes)
- Athermal phonons (TESs)

→ Event by event discrimination
CDMS II: The Cryogenic Dark Matter Search Experiment

- Ionization + phonon collection
- Discrimination of electronic and nuclear recoil events
- Germanium & silicon payload; low-threshold searches primarily employ germanium detectors

Search for Annual Modulation

<table>
<thead>
<tr>
<th>Exposure</th>
<th>240 kg-d</th>
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<td>Total Number of Detectors</td>
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<td>Time Span</td>
<td>Oct '06 - Nov '08</td>
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<tr>
<td>Number of Runs</td>
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<tr>
<td>Number of detectors used for WIMP search (low threshold)</td>
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<th>Energy Range</th>
<th>Detector Selection</th>
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<td>5.0-11.9 keV$_{nr}$</td>
<td>T1Z2, T1Z5, T2Z3, T2Z5, T3Z2, T3Z4, T3Z5, T3Z6</td>
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<tr>
<td>Below 5 keV$_{nr}$</td>
<td>Subset varies; eligible detectors include: T1Z2, T1Z5, T3Z2, T3Z4, T3Z5, T3Z6</td>
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The Z-sensitive Ionization and Phonon (ZIP) Detector (CDMS II)
CDMS II (2012)

Above: Candidate event selection for detector T1Z2, one of the low threshold detectors used in the modulation analysis.

Right: Trigger threshold and detector selection versus recoil energy. Analysis at the lowest energies was limited to detectors with trigger efficiencies $\sim 1$.

Figure courtesy of S. Hertel
Active Detectors

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<th>Bin #</th>
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<th>T2Z5</th>
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Detector-Specific Live Periods
Excluded Due to Cf Calibration

- Run 123
- Run 124
- Run 125
- Run 126
- Run 127
- Run 128

01/2007 07/2007 01/2008 07/2008
Challenges to Low Energy Searches

- Noise & trigger thresholds
- No Timing Cut
- Backgrounds
  - Cosmogenics
  - Radiogenics
- More Problematic events:
  - Surface events
  - Zero charge events
Example Systematics in the Search for Modulation

- Noise trends
- Trigger Efficiency Stability
- Fiducial Volume & Signal Region Efficiency Stability
- Zero Charge Band Contribution
- Electron Recoil Leakage Contribution
- Multiples contamination
- Helium Film cut coverage
- Glitch events
Systematics could mask or mimic a WIMP signal. Understanding and subtracting backgrounds improves the estimate of the modulation amplitude.
Systematics: Cut Efficiency Stability

Nuclear recoil band defined for each of 6 runs spanning October ‘06 – September ‘08

Run to run changes in band definitions may introduce time dependent changes.

Zero yield events
Systematics: Cut Efficiency Stability

- Shown: 68%, 95%, and 99% confidence levels of efficiency modulation.
- Contribution to signal amplitude is negligible.
Systematics: Leakage of Bulk Electronic Recoil and Zero Charge Events

Event selection regions overlap at low energies.

Zero yield events
Systematics: Zero Charge Event Leakage

- Measured on Barium-133 calibration data

*2.27-2.7 keVnr is omitted because of very small sample size.*
Systematics: Bulk Electron Recoil Event Leakage

Sample Bands: T1Z2, Run 123

- Measured on Barium-133 calibration data

*6.15-11.9 keVnr is not background subtracted for electron recoils.
Background subtraction incorporates an estimate of the background contributions to provide a better estimate of the true signal.
Background Subtraction (2015)

Blue/Gray: With/ Without Background Subtraction.

2.27 – 2.7 keVnr
5 – 6.15 keVnr

2.7 – 3.64 keVnr

3.64 – 5 keVnr

5 – 6.15 keVnr

6.15 – 7.3 keVnr

7.3 – 9.6 keVnr

9.6 – 11.9 keVnr

*2.27-2.7 keVnr: Electron Recoil Subtraction-Only
Inferred modulation in the range 2.7-3.64 keV$_{nr}$ slightly increases
Inferred modulation in the range 3.64-5.0 keV$_{nr}$ slightly decreases - drops to approximately ~2 sigma
Possible correlation between energy bins
Background Subtraction (2015)

- Rise in amplitude toward low energies
- The addition of background-subtraction to the analysis uses information about the low-energy behavior of detectors and backgrounds to improve sensitivity to low-energy signals.
- Subtraction of zero charge background reduces the significance of modulation for the range 3.64-5.0 keV\(_{nr}\), slightly raises significance for energy range 2.27-2.7 keV\(_{nr}\) (~1 sigma)
- Both results are excluded by 100% modulation of results from SuperCDMS low threshold analysis (2014)
Background Subtraction (Preliminary, APS 2015): CDMS II-Ge vs. CoGENT (2014 data)

- “In the range 2.27-5.0 keV$_{nr}$, background subtraction reduces the significance of modulation in CDMS II from 97% to 87% (less than 2 sigma).”

- “In the range 5.0-11.9 keV$_{nr}$, CDMS remains consistent with a null result. Although some tension remains with the new analysis of CoGeNT data, both experiments are compatible with no modulation.”

Orange: CoGeNT (2014). Blue: CDMS II.
Recent Work (2016)

- Previous background subtraction relied on background selection efficiencies from Ba-133; known differences in zero charge event spectrum when compared to WIMP search data. Switch to simulated events based on measured ionization distributions

- Corrections to calculation, updated leakages, and updated efficiency measurements in updated background subtraction
Low Energy Backgrounds: Zero-Charge Events

- **Zero Charge Events**: Low-ionization events passing all data quality and event selection cuts, but which fall within 2-sigma of the mean of the ionization noise of a detector.

- Most believed to originate from incomplete collection of ionization.

- Modeling over the recoil energy range, but outside of the ionization band defining the signal region, provides a better understanding of the shape of the spectrum at low energies.

Recoil energy spectrum of zero charge events excluded from the signal and gamma selection regions. Fits shown include efficiency corrected exponential spectrum and assumed exponential PDF.
Background Subtraction: Leakage Fractions ("alpha_zc") for Low-Ionization ("Zero-Charge") Events
Low Energy Backgrounds: Electronic Recoil Events

- Spectrum for “pure” sample of electronic recoil events essentially flat

- 1.3 keV (activation line from K-shell electron capture in Ge-71) line appears below range of interest for this analysis

- 10.3 keV (activation line from K-shell electron capture in Ge-71) line appears above range of interest for this analysis (~15 keVnr; not shown)

- No other significant cosmogenic peaks appear in data
Background Subtraction: Leakage Fractions ("alpha_er") for Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T122
Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T125
Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T223
Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T225
Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T322
Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T324
Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T323
Electronic Recoil Events

Leakage Scale Fractions vs. Recoil Energy, T326
Electronic Recoil Events

5/19/16
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Conclusions

- Now implementing updated leakages, efficiencies, and corrections to background subtraction analysis. Improved modeling of zero charge and electronic recoil event backgrounds.
- Updated calculation of leakage factors for zero charge and electronic recoil events.
- New background-subtracted results pending.
- Stay tuned!