

A Background-Subtracted Search for Annual Modulation in CDMS II

by

Danielle H. Speller

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Committee in charge:

Professor Bernard Sadoulet, Chair
Professor Marjorie Shapiro, Physics
Professor Chung-Pei Ma, Astronomy

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Abstract

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The identification of dark matter is one of the outstanding problems of our time. Cosmological and astrophysical clues such as structure formation and relic densities, anomalous galaxy rotation curves, and mass density profiles provide ample evidence of an undetected mass component of the universe. Meanwhile, recent advancements in particle physics point toward extensions to the Standard Model, many of which posit candidates for new particles and new physics at the weak scale and beyond. If, as expected, the confluence of the hints of new physics in particle physics, astrophysics, and cosmology at the weak scale is more than coincidence, the detection of dark matter will pave the way for a paradigm shift in our fundamental understanding of the universe.

Weakly interacting massive particles (WIMPs), in particular, are a well-motivated class of candidates for particle dark matter. Naturally predicted in supersymmetry (SUSY), WIMPs are stable, weakly-interacting, and produced in sufficient abundance to comprise the quantity of missing mass in a number of simple cases. Over the last two decades of experimentation, significant areas of the parameter space defined by the simplest SUSY theories have been ruled out, but WIMPs and related particles remain compelling candidates for dark matter searches.

Several avenues for the detection and identification of dark matter are currently being pursued. The present work is a description of the search for a direct detection of supersymmetric dark matter via scattering from standard model particles. The Cryogenic Dark Matter Search (CDMS) Experiment uses ionization and athermal phonon sensor technologies to achieve event-by-event discrimination of electron and nuclear recoils in cryogenic germanium crystal detectors. At low energies, where the the ability to discriminate individual nuclear recoil events from background is reduced, a periodic variation of the rate and crossover signatures in the energy spectrum can aid the identification of a WIMP signature in the presence of significant backgrounds. In general, the direct detection of dark matter is the first step toward the identification and classification of dark matter in the universe.

This work describes a background-subtracted search for annual modulation in the WIMP-search data acquired in the Cryogenic Dark Matter Search II (CDMS II) Experiment, which

was the second implementation of the highly successful CDMS technology. We observe no significant modulation in the $2.7 \text{ keV}_{\text{nr}}$ to $11.9 \text{ keV}_{\text{nr}}$ (nuclear-recoil-equivalent) energy range selected for this analysis. These results are not compatible with a WIMP dark matter interpretation of the signals reported by the DAMA/LIBRA and CoGeNT experiments, and provide complementary support to earlier CDMS low-threshold germanium analyses.

Psalm 19:1-2.
Soli Deo Gloria.

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With love to my parents and all glory to Christ.

Danielle H. Speller
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Part I

First Part

Chapter 1

Introduction

1.1 Overview

Nearly eighty years after the controversial Swiss astronomer Fritz Zwicky presented calculations pointing to the existence of “dark matter” [1], most cosmologists are now convinced that it comprises nearly twenty-seven percent of the universe - and almost 85% of the matter content ([2, 3]). One operational definition of dark matter is matter whose existence is inferred only through the gravitational interaction. Scores of experiments are now underway in an attempt to illuminate the nature of the unseen matter density that apparently permeates the natural universe on every scale([4]).

But what *is* dark matter? As mentioned previously, the identity and nature of dark matter are yet unknown. However, significant headway has been made in understanding what dark matter probably is *not*. Although the search continues, and the identity of dark matter remains a mystery, recent developments in particle physics, astrophysics, and cosmology all indicate that dark matter is nonbaryonic, and point enticingly to the possibility that dark matter may in fact be composed of elementary particles beyond the Standard Model of particle physics. The potential role of dark matter as a harbinger of new physics has secured its place as one of the most important questions of twenty-first century physics. In the following sections, we first discuss the astrophysical evidence for dark matter. Next, we examine the role of particle physics and the options that it provides in describing the characteristics of a suitable dark matter candidate, based on theory and recent observations. We mention several options for dark matter candidates before narrowing our discussion to focus on one long-standing class of candidates known as the weakly interacting massive particle (WIMP), which is the object of the Super Cryogenic Dark Matter Search (SuperCDMS) Experiment in which this thesis is contextualized. After motivating the strength of the candidacy of WIMPs, we discuss the properties that make the search for WIMPs feasible, and the hallmark signatures of a WIMP detection.

1.2 Evidence for the Existence of Dark Matter: Observational Indications from Astronomy and Astrophysics

Increases in the size and power of astrophysical instrumentation in recent decades have allowed astronomers to study the local universe at greater scales and in more detail than ever before, revealing puzzling discrepancies in the measured properties of astrophysical objects. In particular, calculations of the masses of galaxy clusters, the use of gravitational lensing, and the measurement of stellar rotation curves have all contributed to the growing body of evidence for a massive, but invisible, matter component of the universe. While the galaxy clusters are credited as being the first real indication for dark matter, there is accumulating evidence of dark matter on every observable scale, from galaxies to large scale flows. Below, we discuss the observational evidence for the existence of dark matter on length scales from large to small.

Galaxy Clusters

Galaxy clusters are among the largest scales providing observational evidence for dark matter. Early calculations by Swiss astronomer Fritz Zwicky [5] and, independently, Sinclair Smith [6] in the Coma and Virgo clusters, respectively, indicated discrepancies in cluster mass measurements. Such arguments on the cluster masses were among the first indications of dark matter.

More extensive work by Zwicky in 1937 demonstrated that contemporary techniques for determining the “masses of nebulae and clusters of nebulae” (with respect to the specific subset now known as “galaxies”) through measurements of the isophotal curves and internal rotations were inadequate, and that the results of such calculations, at best, represented lower limits on the masses of such systems [1]. By using data from the Coma Galaxy Cluster (Abell 1656, Figures 1.1, 1.2) and two alternative methods of calculation based on the virial theorem and statistical distributions, he established new order-of-magnitude estimates on the number of clusters and the average cluster mass ($N = 1500$ and $M \sim 4.5 \times 10^{10} M_{\odot}$ (solar masses), respectively) for a spherically symmetric, stationary system. These values were not only higher than those previously estimated, but also revealed an unexpected discrepancy with the measured average luminosity of a cluster galaxy (about 8.5×10^7 suns, with an additional mass-luminosity conversion factor of $\gamma \sim 500$). Furthermore, Zwicky showed that if the energy of the cluster was based solely upon the galaxies as a stationary gravitational system, the cluster would fly apart, and the constituent galaxies would be disrupted long before reaching stationary conditions. While he pointed out some uncertainty due to the unknown density of intergalactic matter resulting from the disrupted galaxies, which could significantly affect the estimates of the average mass of cluster galaxies, later observations have indicated that the intergalactic matter density in clusters is similar to the matter density in the general field [7], further establishing the presence of a mass discrepancy.



Figure 1.1: Wide star-field image of the region around the Coma Cluster (Abell 1656). The field-of-view is approximately 2.7×2.85 degrees. *Credit:* NASA, ESA, and the Digitized Sky Survey 2. *Acknowledgment:* Davide De Martin (ESA/Hubble). Image and caption from [8].

X-ray Temperatures in Galaxy Clusters

Measurements of the X-ray temperatures in galaxy clusters have provided two-fold support for the dark matter paradigm. First, X-ray studies allow detailed studies of the baryonic component of the cluster mass. The baryonic component is primarily in the form of gas. Gravitational squeezing of the gas in clusters leads to heating on the order of X-ray temperatures [9], the observation of which provides detailed information on the total mass of the cluster and can be used in the recovery of the cluster dark matter profile. Further more, the scale of galaxy clusters is large enough that the matter content and growth rates of clusters can be used to constrain the mass fraction of the universe [9]. X-ray measurements have also provided constraints on the self-interaction strength of dark matter by demonstrating that the dark matter distribution traces the collisionless behavior of stars (as opposed to gas) in the Bullet cluster (Figure 1.7) and by evincing the ellipticity of the dark matter halo NGC 720 [10]. X-ray measurements also constrain the annihilation signals of some dark matter candidates (such as sterile neutrinos) expected in indirect detection experiments [10].

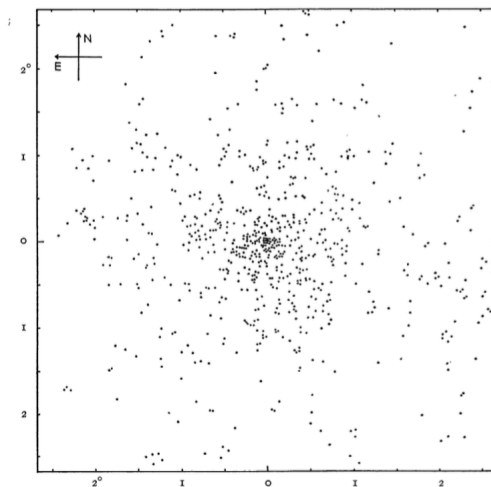


FIG. 3.—The Coma cluster of nebulae

Figure 1.2: Schematic diagram used in [1] to study the distribution of galaxies within the Coma Cluster. Dots represent nebulae which could be distinguished on 30-minute exposures on panchromatic films. Not all nebulae appearing on the original photographs were marked on the diagram to avoid crowding of points near the center of the cluster, though the ensuing calculations included all identifiable clusters. The original photographs were taken on Mount Palomar with the 18-inch Schmidt-type telescope of the California Institute of Technology. The faintest galaxies that can be distinguished from stars at the limiting exposures of this telescope (30-60 minutes) have an apparent magnitude of ~ 16.5 . (Image and caption adapted from description [1]).

Gravitational Lensing

Weak Gravitational Lensing Another indication of dark matter, also suggested in [1], is “gravitational lensing”: the lensing of distant bright objects by the bending of light in the deep gravitational potential wells surrounding massive objects. Weak gravitational lensing results in the production of partial or full false, duplicate images of the bright object in the sky, and can be used to estimate the mass of the lens (Figure 1.4). Weak gravitational lensing studies of the cosmic microwave background (CMB) [11] correlate with other tracers of large scale structure, and show lensing signals consistent with simulated dark matter halo profiles [11] (Figure 1.3).

Lensing by large objects such as galaxy clusters has developed rapidly. As observational techniques have advanced, so has the development of mass distribution maps from the gravitational lensing of quasars and field galaxies, which indicate large but invisible mass concentrations scattered across the sky ([12]). In contrast, lensing of distant objects by single galaxies, which would allow the direct determination of the galaxy mass, remains limited. Measurement of the absolute mass of a specific type of galaxy would allow the determination of the full mass distribution of the galaxies in the cluster, and the masses of the constituent

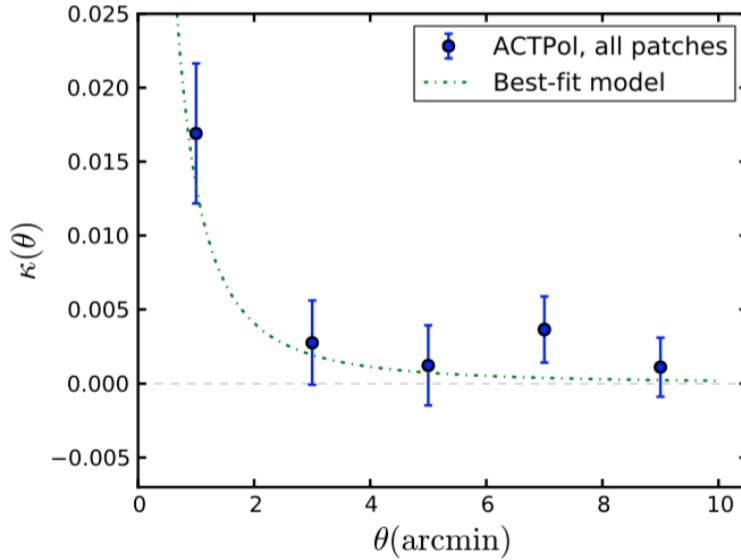


Figure 1.3: Figure 1 (left) from [11]. Convergence field of the CMB versus azimuthal angle (increasing distance from galaxy center) for thousands of stacked $\sim 70'$ deg-sq patches centered on known galaxy positions from the SDSS III/BOSS survey. The convergence is a measure of the amount of gravitational lensing, and this plot demonstrates that lensing of the CMB due to galaxy halos can be significantly detected. The dashed line is that of an NFW dark matter halo density profile fit to the data.

individual galaxies [1]. Due to the difficulty of measuring lensing by such relatively small objects, little information is currently available. Instead, there have been a number of works deriving the mass distribution on statistical and physical principles, which have subsequently been studied with extensive simulation [13, 14, 15, 16].

In addition to weak gravitational lensing, strong gravitational lensing from very massive objects can also be used for mass estimation.

Large-Scale Flows

Large scale cosmic flows are irregularities with respect to the Hubble flow caused by the gravitational interactions of astrophysical objects, and provide a more detailed picture of large scale structure than maps derived from redshift alone, including the density distribution of dark matter between galaxy clusters [18]. Discrepancies in the measurements derived from large-scale flows led to significant work in the area in the late 20th century, and implications for the mass fraction added to the evidence for dark matter [19, 20].

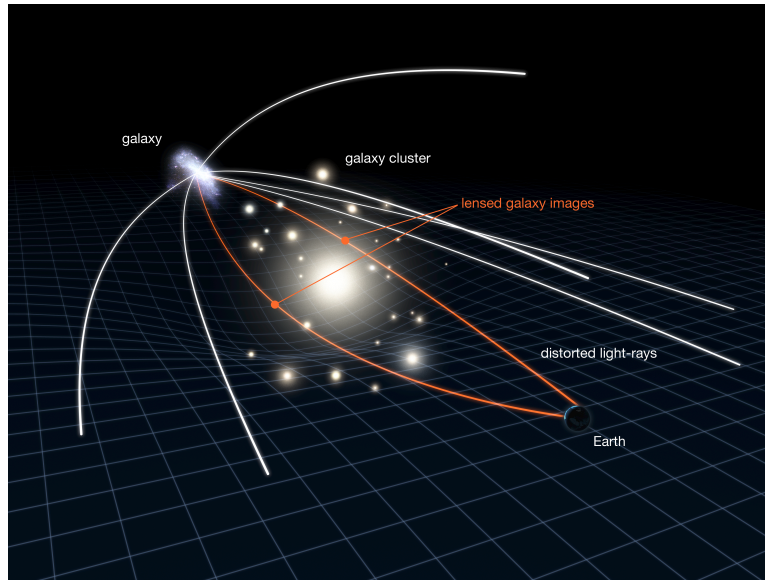


Figure 1.4: Gravitational lensing. Bending of light in the gravitational well of a massive object causes an observer to see multiple images of the same light source on the sky. *Credit:* NASA, ESA & L. Calçada [17]

Galaxy Rotation Curves

Figures 1.5 and 1.6 show the rotation curves for the Andromeda (M31) and Triangulum (M33) galaxies, respectively, as a function of the distance from their galactic centers. In Figure 1.6, two curves are shown, contrasting the expected and the measured rotational velocity curves as a function of radius. Measurements of the rotation curves of nearby galaxies have shown that the rotational velocity, when viewed as a function of the radius from the center of the galaxy, remains puzzlingly flat at very large distances, indicating that the mass density continues to rise linearly as a function of radius rather than decreasing as would be expected from the optical measurements. Measurements of several groups, including Babcock, Rubin, and Roberts, have indicated that some form of non-luminous matter is a major component of the masses of galaxies [21, 22].

Velocity Dispersions

The velocity dispersion of a galaxy is the root mean square (RMS) of the stellar radial (line-of-sight from Earth) velocities, often measured from the Doppler broadening of spectral lines [24].

Elliptical galaxies in particular can be modeled roughly as isothermal spheres (based upon a thermodynamical analogy of a gravitationally interacting cloud of gas [25]). Measurement of the velocity dispersion provides an estimate of the gas pressure of such a system, which in turn, allows estimation of the mass when stellar orbits are constrained by out-

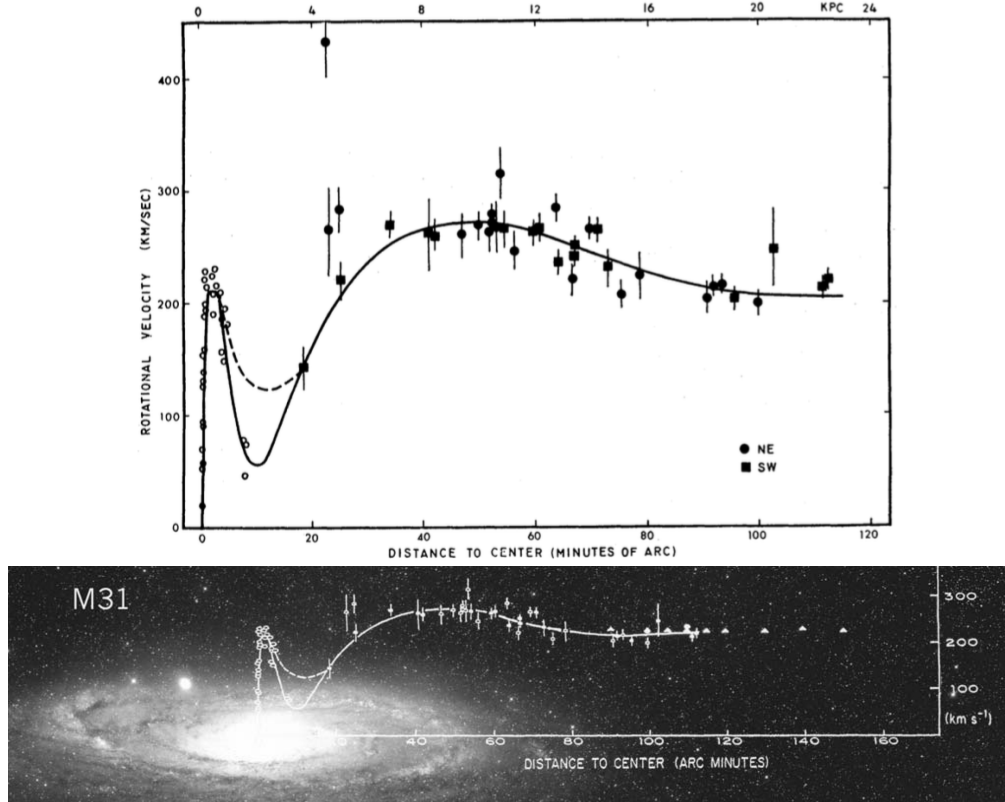


Figure 1.5: *Top*: Rotation curve of the Andromeda galaxy (M31) measured by [21]. Data points are based on spectroscopically measured velocities from [N II] emission lines across the galactic nucleus and from ionized gas in OB associations (loosely connected groups of hot, early, very bright, blue, massive stars) across the galaxy. The solid line is a piecewise polynomial rotation curve fitted to the data; the dashed curve is an alternative that maintains a positive mass density everywhere. Notice the flattening of the velocity curve at high radius. Image from [21]. *Bottom*: Rotation curve of the Andromeda galaxy (see top), shown superimposed on the optical image from the Palomar Sky Survey, with extended velocity measurements from radio observations [23]. The continuation of the flat rotation curve indicates the apparent extension of the mass density far beyond the optical edges of the galaxy. Image from [23].

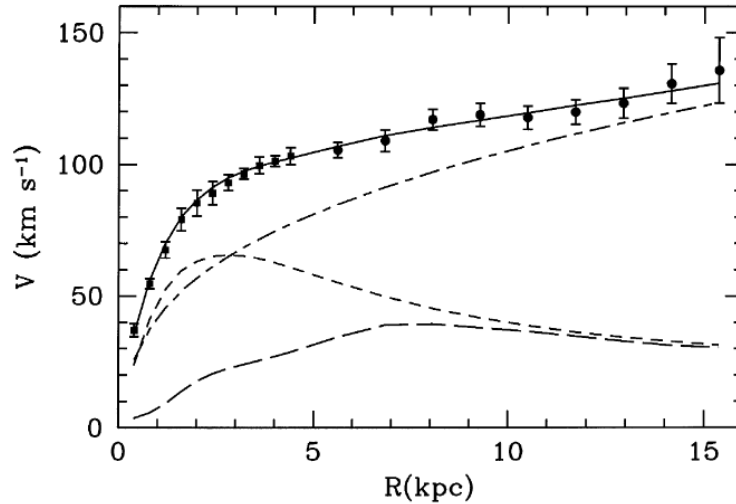


Figure 1.6: Rotation curve of M33 (the Triangulum galaxy) from [27]. The rotation curve is shown by the points, with the best-fit curve represented as a solid line. The visible components from the stellar disk and gas contribution are shown as short-dashed and long-dashed lines, respectively. The dark matter halo contribution is shown as the dot-dashed line. The flat, and slightly rising, shape of the rotation curve at large radii in contrast to the falling curve from the stellar and gas components indicate a mass density that extends far beyond the visible disk [27].

side measurements (using X-ray data). Measurements of the velocity dispersions of elliptical galaxies indicate the presence of dark halos extending well beyond the radius of the luminous component of the galaxy [26].

Dark matter in the Solar Neighborhood

Calculations of the minimum mass-to-light ratio for systems similar to that of the solar neighborhood are given in [24]. Comparisons of the measured mass-to-light ratio in the solar neighborhood with the expected minimum of the mass-to-light ratio indicates that roughly a third of the material in the solar neighborhood is dark matter [24]. Recent studies of stellar kinematics and mass-to-light ratios near the solar neighborhood and at radial distances 1 kpc to 4 kpc from the center of the Milky Way also indicate the presence of a dark matter component and provide measurements of the local dark matter density [28, 29].

Astrophysical Objects: The Bullet Cluster, Dwarf Galaxies, and Other Dark Objects

A few recent discoveries have provided additional phenomenological evidence for dark matter. The recent discovery of the Dragonfly galaxies [30, 31] adds a new dimension to the



Figure 1.7: The Bullet Cluster. Figure courtesy of NASA.

dark matter mystery. While small galaxies dominated by dark matter are known, the recent discovery of massive galaxies composed almost entirely of dark matter has added new evidence to the argument for dark matter.

The Bullet Cluster

One case study combining the use of gravitational lensing and the use of X-ray observations of 1E 0657-56 (the “the Bullet Cluster”, Figure 1.7) is cited by many as one of the most compelling arguments for the existence of dark matter to date. Using combined weak lensing and X-ray data, it was shown that while a clearly visible bow-shock was present in the Chandra images of the dust cloud of the colliding cluster system [32], the mass distribution of the system does not trace the baryonic matter, and the total center of mass is actually significantly ($\sim 8\sigma$) offset from the baryonic center of mass peaks[33]. The subsequent interpretation of two massive, non-interacting components passing through one another in spite of the intense interactions of the baryonic constituents of the merger, and the clear separation of dark matter and baryons, provides a strong argument for a nearly non-interacting dark matter component as a major contribution to the mass of galaxies.

1.3 Theoretical Implications from Cosmology

Developments in the understanding of dark matter occurred side-by-side with developments in fundamental cosmology. In the framework of general relativity (GR), the “standard cosmology” - the current model describing the origin, evolution, and fate of the universe - begins essentially from first principles with the Einstein field equations, which link the energy content of the universe with its geometry in a description of the gravitational interaction:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -\frac{8\pi G_N}{c^4}T_{\mu\nu} + g_{\mu\nu} \quad (1.1)$$

where $R_{\mu\nu}$ is the Ricci tensor, $g_{\mu\nu}$ is the spacetime metric, R is the Ricci scalar, G_N is Newton's gravitational constant, c is the speed of light in a vacuum, and $T_{\mu\nu}$ is the stress-energy tensor. (In traditional formulations, $g_{\mu\nu}$ is preceded by an as-yet-unidentified cosmological constant, Λ . For reasons which will be discussed, in particular the more intuitively physical interpretation of Λ as either a vacuum energy density, or some new field, our formulation incorporates Λ into $T_{\mu\nu}$.)

Using the framework of GR, modern cosmology rests on the assumption that there are “no special observers” in the universe (*The Copernican Principle*). In our context, this is taken to imply two major spatial symmetries: that the universe is rotationally invariant, or the same in every direction (*isotropic*), and that it is translationally invariant, so that there are no preferred locations (*homogeneous*). The assumption that the universe is both isotropic and homogeneous is known as the *cosmological principle*.

Measurements of the distribution of radio sources, the X-ray background (XRB), and the CMB strongly support the idea of an isotropic universe [34, 35] (Figure 1.8). Homogeneity is more difficult to establish experimentally, requiring measurements at different locations within the universe; however, isotropy and the Copernican principle together imply the homogeneity of the universe [34], since the universe will appear the same in any direction, for any observer (who may be located anywhere). While inhomogeneity (e.g. voids, clusters) is evident in the local universe below the scale of galaxy clusters ($\sim 10 h^{-1}$ Mpc), there are strong indications, most notably from measurements of the CMB, that the universe does appear homogeneous at scales larger than $\gtrsim 100 h^{-1}$ Mpc [35] (Figure 1.9).

The cosmological principle is encoded in the geometry through the spacetime metric, $g_{\mu\nu}$. In three space dimensions and one time dimension, the above assumptions lead to the Robertson-Walker metric,

$$ds^2 = c^2 dt^2 + a(t)^2 \left(\frac{dr^2}{1 - \kappa r^2} + r^2 d\Omega^2 \right), \quad (1.2)$$

to describe a spatially isotropic, homogeneous universe, in which distances between points are allowed to change as a function of time; here, ds^2 is the space-time separation between two events, t is cosmic time (the cosmological proper time), c is the speed of light in a vacuum, $d\Omega = \sin\theta d\theta d\phi$ is the differential element for the solid angle in spherical spatial coordinates (r, θ, ϕ) , $\kappa = \{-1, 0, 1\}$ is a parameter describing the curvature of the metric, and $a(t)$ is the scale parameter - a ratio of the cosmological distance at the present time to that at time $t = 0$ ($a(t) = \frac{R(t)}{R_0}$).

Combining the Robertson-Walker metric with the Einstein field equations leads to the Friedmann equation, which describes the expansion or subtraction of an isotropic, homogeneous universe (as described by the metric) as a function of time, and links the curvature with the energy density:

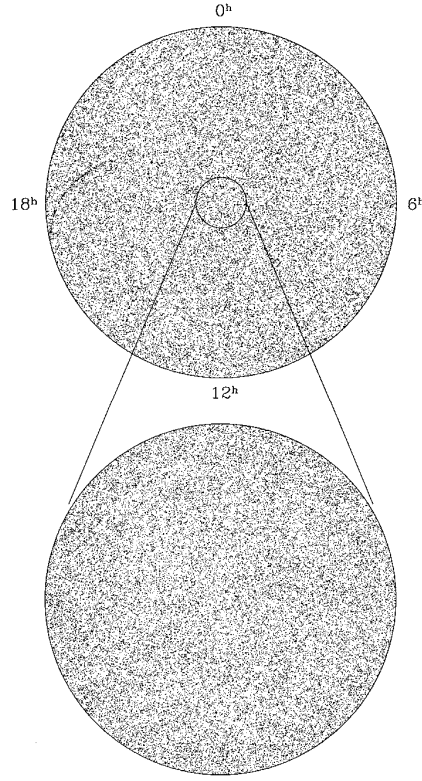


Figure 1.8: The distribution of radio sources on the sky. Figure from [34].

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2} \varepsilon(t) - \frac{\kappa c^2}{R_0^2} \frac{1}{a(t)^2} \quad (1.3)$$

Here again G is the gravitational constant, t is cosmic time, c is the speed of light in a vacuum, ε is the energy density, R_0 is a constant of integration which can be interpreted as the radius of curvature of the universe, and κ , the “curvature constant” (of modulus 1), gives the sign of the curvature.

While we defer a richer discussion of the interpretation of Equation 1.3 to works such as [37], we pointedly note that the Friedmann equation encodes the dynamical information for the evolution of the system.

A Specific Example: Matter-Dominated Universe

As a specific example, and in demonstration of analogy with Newtonian mechanics (following the example of [37]) for the special case of a universe dominated by non-relativistic [and conserved] matter (so that $\varepsilon = 3M/(4\pi R^3)$), if we replace the ratio of scale parameters on

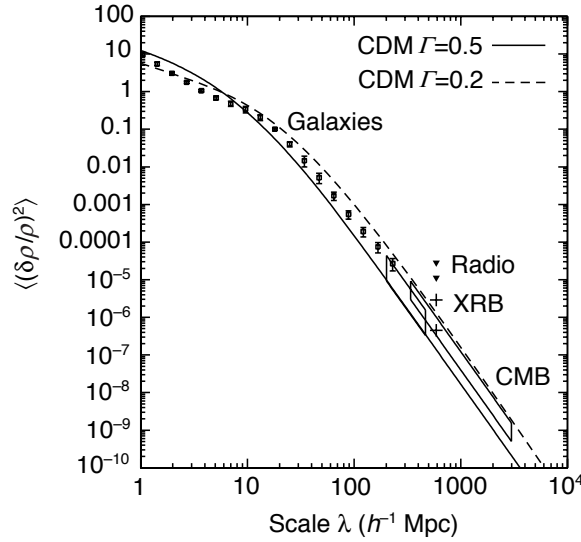


Figure 1.9: Relative density fluctuations as a function of scale (in h^{-1} Mpc), based upon several observations, including the clustering of optical galaxies and the CMB. The size of density fluctuations is less than $\sim 10\%$ on the scale of $\lambda = 100 h^{-1}$ Mpc, indicating large scale homogeneity. Although the mass distribution is a biased probe of the galaxy distribution [35], the bias is expected to be linear and scale independent [36], so that the galaxy distribution is a good tracer of the mass density. The data are compared to two popular cold dark matter (CDM) models (solid and dashed lines). The shape parameter of the CDM power spectrum for each model is given in the legend (Γ); the solid and dashed lines and associated parameters correspond to a standard and “low-density” CDM power spectrum, respectively. Figure from [35].

the left side of the equation with the equivalent ratio for cosmological distances ($\frac{\dot{R}(t)}{R(t)}$), and multiply both sides of Equation 1.3 by a factor $R^2/2$, we obtain the following,

$$\frac{\dot{R}}{2} - \frac{GM(R)}{R} = -\frac{\kappa c^2}{2} \quad (1.4)$$

In this non-relativistic case, we can immediately see that the terms on the left are essentially kinetic and potential energy terms, while the term on the right, a constant, represents their sum, the total energy. In short, the curvature of the universe is determined by the the total energy content.

There are three possibilities for κ ($\in \{-1, 0, +1\}$). A negative curvature ($\kappa = -1$) describes an “open” universe with positive energy and a hyperbolic geometry, expanding forever. A positive curvature ($\kappa = +1$) indicates a closed universe with negative energy that slows in expansion, eventually reaching a maximum radius and then contracting back upon itself. The final possibility, $\kappa = 0$, corresponds to a “flat” universe - one which is forever

expanding, but for which the rate of expansion continually slows, asymptotically approaching zero on long time scales and very large distances.

The General Case

In GR, non-relativistic matter is *not* the sole source of the energy density of the universe, which receives contributions from not only matter (relativistic and non-relativistic), but also from radiation and the vacuum state itself (denoted Λ) [37] (Equation 1.5).

$$\varepsilon_{\text{tot}} = \varepsilon_m + \varepsilon_r + \varepsilon_\Lambda \quad (1.5)$$

The contribution of the vacuum state, also known as the cosmological constant, is denoted Λ , and contributes a term $\frac{\Lambda}{8\pi G}$ to equation 1.3.

The critical density is defined as the density required for a flat universe, such that the curvature of the universe in Equation 1.3 is exactly zero:

$$\varepsilon_{\text{crit}} = \frac{3H^2 c^2}{8\pi G} \quad (1.6)$$

where $H = \frac{\dot{a}}{a}$ is Hubble's constant. The ratio of the density to the critical density is known as the closure parameter, and commonly denoted [37]

$$\Omega = \Omega_m + \Omega_r + \Omega_\Lambda = 1 - \frac{\kappa c^2}{R_0 a(t)^2} \quad (1.7)$$

When the curvature of the universe is zero, $\Omega = 1$ for all times t . Furthermore, it is conventional to express the curvature term itself as Ω_κ , so that

$$\Omega + \Omega_\kappa = \Omega_m + \Omega_r + \Omega_\Lambda + \Omega_\kappa = 1. \quad (1.8)$$

Measurement of the various components of the closure parameter and in the curvature term of Equation 1.8 yield important information for understanding the development of the universe and building a coherent picture of cosmology. From basic assumptions of large scale isotropy and homogeneity, and using the framework of GR to describe the relations between space-time, matter, and energy, we obtain a universe that expands or contracts (or is static, which was the original (now defunct) motivation for the introduction of the cosmological constant [38]), based on the energy density provided by matter, energy, and the vacuum state.

Measurements of the curvature term, most recently by the the Planck Collaboration [2, 3], indicate that the spatial curvature of the universe is very nearly zero, with $|\Omega_\kappa| < 0.005$. This indicates that the density of the universe is very nearly the critical density, and that Ω is very close to 1. Measurements of the matter, radiation, and vacuum terms of the closure parameter have also been performed - and it is here that we begin to encounter new puzzles that again point toward dark matter in the universe.

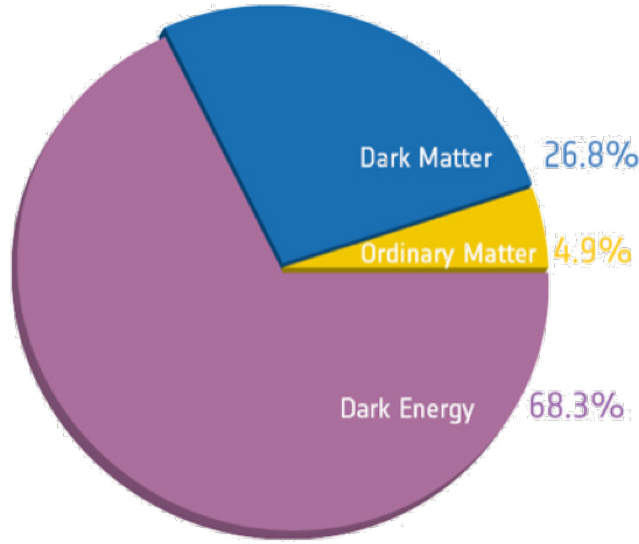


Figure 1.10: Pie chart of the mass/energy budget of the universe. Image credit: ESA and the Planck Collaboration.

Recent analyses of the 2015 Planck data set indicate that the matter content of the observable universe contributes about one-third of the energy density: $\Omega_m = 0.316 \pm 0.014$ [3] (Figure 1.10). Measurements of the baryon contribution, however (which includes stars, gas, planets, black holes, and all visible matter composed of the quarks and leptons discussed in Section 1.5), only seem to provide a fraction $\Omega_b = 0.0490 \pm 0.0015$, based upon nucleosynthesis and the CMB, [3]. The remnant, $\sim 27\%$ of the overall energy density of the universe, and approximately 84% of the expected matter contribution, has not been observed. This massive, missing matter component is a key indicator of the existence of dark matter.

A similar question exists regarding the makeup of what has now been termed “dark energy” [39]. The cosmological constant, Λ , was initially introduced to force a static universe. After Hubble’s observations [40] gained acceptance as evidence for the expansion of the universe, however, the constant was dropped [38]. Recently, the cosmological constant has been reinstated as a term describing the acceleration of the expansion of the universe due to an unknown energy component. This dark energy is believed to account for approximately 70% of the matter-energy content of the universe (Figure 1.10) and to be the impetus for the increasing acceleration of the expansion of the universe [41]. The source of this dark energy is not known, and further discussion of dark energy is beyond the scope of this work.

The present standard model of cosmology, known as the Concordance Model, incorporates the cosmological constant and cold dark matter with the dynamical universe described above to form a cohesive picture of the formation and evolution of the early universe known as lambda cold dark matter (Λ CDM). The paradigm features a non-baryonic particle remnant that was non-relativistic at the time of decoupling from thermal equilibrium with baryonic

matter (see Section 1.5) [42]. Among the key observations supporting this model are the CMB power spectrum, which contains small- (i.e., galaxy) scale structure contributions that would have been washed out had the dark matter been relativistic, as in many alternative models (known as “hot” dark matter) [43, 44, 45]. The potential wells caused by the aggregation of non-relativistic dark matter particles under the influence of gravity along density fluctuations in the early universe also provide a much earlier starting point for the formation of large-scale structure than would be possible in a universe consisting entirely of baryonic matter, and provides a better match to astrophysical observations [42].

Acceptance of the Concordance Model and its incorporation of Λ CDM is bolstered by the consistency between the model’s predictions and current measurements of cosmological parameters, including light element abundances [46], baryon acoustic oscillations [47], and the power spectrum of the CMB [48], despite some tension with the recent data of Planck [49]. Discussions of these predictions are available in many references, including [3, 37, 50].

1.4 Generally Expected Properties of Dark Matter

Multiple schemes for dark matter have been proposed, but the Λ CDM paradigm currently remains the standard, due to its explanatory power and consistency with most current observations. Λ CDM relies upon a non-baryonic, particle-based solution to the dark matter problem. Alternative measures, such as dynamical modifications, have been proposed. The most prominent of these solutions is MOdified Newtonian Dynamics (MOND), which modifies Newtonian dynamics for small accelerations [51].

MOND provides an interesting alternative to particle dark matter, though historically, most discussions have pointed to a number of apparent conflicts with observation [33, 52, 53]. Recent work has attempted to address these conflicts and focus on MOND as an effective theory manifestation of a more fundamental framework [51, 54]. Nevertheless, the prevailing evidence is for a particle solution to dark matter, and the necessity of new particle physics beyond the Standard Model remains. Extensions to the Standard Model generally predict a number of new particles that serve as interesting possibilities for dark matter candidates. In this work, we focus on the particle candidates for dark matter, as described below.

Properties of Particle Dark Matter

Based on the astrophysical and cosmological considerations, a particle-based solution to the dark matter problem is generally expected to have the following characteristics.

- *Neutral.* WIMP dark matter does not carry an electromagnetic charge, and has no coupling to ordinary photons.
- *Weak-scale interaction strength; No strong nuclear interaction, weak self-interactions.* The strength of WIMP interactions with Standard Model particles are expected to be on the weak-scale. WIMPs are not expected to carry a quantum chromodynamics

(QCD) charge, and do not carry a strong nuclear interaction. WIMPs are also not expected to interact strongly with each other. While some models for strong self-interactions exist, observations of the Bullet Cluster (see Section 1.2) using weak-lensing and X-ray measurements indicate that the primary components of two large mass concentrations associated with colliding galaxy clusters passed through each other with little interference, while the baryonic gas components of each collided. This is largely taken as evidence of the lack of self-interaction of halo dark matter.

- *Stable.* One of the primary qualifications of a dark matter candidate (such as the lightest supersymmetric particle (LSP)) is its stability against decay. Candidates formed in the early universe that do not annihilate before freeze-out can then be expected to remain as a thermal relic (see also Section 1.3).
- *Massive.* Dark matter candidates are expected to be massive. Even the lighter particle candidates are expected to be produced in large numbers, such that the relic density of dark matter forms a substantial fraction of the matter density of the universe ($\sim 27\%$) (see also Section 1.3).
- *Non-baryonic, exotic.* No Standard Model particle fulfills all of the requirements of a dark matter candidate. Astrophysical observations indicate that the dark matter in galaxy halos only weakly couples to ordinary matter (see, for example, Section 1.2; see also [33]).

As discussed in Sections 1.5 and 1.6, extensions to the Standard Model provide a number of compelling candidates for a particle solution to the nature dark matter. After briefly reviewing the basic contents of the Standard Model, we describe two of the most prominent particle classes, which are each the objectives of a number of ongoing dark matter search experiments: axions and WIMPs.

1.5 Theoretical Implications from Particle Physics

The observational evidence from astrophysics and the constraints required for a consistent cosmology provide compelling arguments for the existence of a dark matter component of the universe. Particle physics, in turn, contributes to the field by providing a number of viable candidates.

The Standard Model of Particle Physics

The Standard Model is the current theory of fundamental particles and interactions. Its success has been demonstrated by its explanation of the observed spectrum of particles. In general, the Standard Model provides a nearly complete description of the constitution and interactions of “normal” (i.e. *baryonic* - see below) matter. Several questions, however,

either remain unaddressed by the Standard Model or point to hints of departure from its predictions. It is in the attempt to address these open questions with extensions to the Standard Model that dark matter plays a role.

The formulation of the Standard Model is largely based on symmetry, which, throughout physics, manifests as the correspondence or equivalence of a system's behavior or appearance even after undergoing some type of transformation. In Section 1.3, for example, we briefly discussed the apparent symmetry of the observable universe under rotation (isotropy) and translation (homogeneity). The presence of these symmetries, in this case described mathematically via the metric, constrain the possible solutions of Einstein's field equations to those most closely describing the physical universe, enabling a better understanding of the general behavior of the system and providing greater predictive power for seeking out and interpreting new phenomena (Section 1.3).

Noether's theorem [37, 55] summarizes a deep connection between the presence of symmetry and the behavior of physical systems: the invariance of the Lagrangian density under transformation generally leads to a conserved quantity of the system. This idea forms the basis for the use of gauge symmetries in particle physics, which results in a number of conserved charges by which particle interactions can be classified.

The Standard Model is described by the symmetry groups of the strong and electroweak interactions:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \quad (1.9)$$

where C represents the “color” charge of the strong interaction, described by QCD [56]; L denotes that the symmetry acts on left-handed leptons (right-handed leptons do not appear in the Standard Model), and Y is the generator for the electroweak hypercharge. Each of the symmetry groups corresponds to a conserved charge. The model spontaneously breaks down into $SU(3)_C \otimes U(1)_Q$, where Q is the familiar electromagnetic charge. The mechanism of the spontaneous symmetry breaking, known as the Higgs mechanism, results in the weak-force carrying, massive bosons $W^\pm$ and Z , and in the Higgs boson [4].

The basic elementary particle components of the Standard Model are shown in Figure 1.11.

The Particles

The first major division of the elementary particles is determined by internal spin. Particles with half-integer spin multiples ($\pm 1/2, \pm 3/2, \dots$, etc.) are known as *fermions*, with the distinguishing characteristic of waveforms that are antisymmetric under particle exchange. As a result, fermions obey the Pauli exclusion principle: no two identical fermions can occupy the same state. Particles with integer-multiples of spin (e.g. $0, \pm 1$, etc.) are bosons. Bosonic waveforms are symmetric under the exchange of identical particles, and multiple particles can occupy the same state. (The connection between the spin and the type of particle is known as the spin-statistics theorem.)

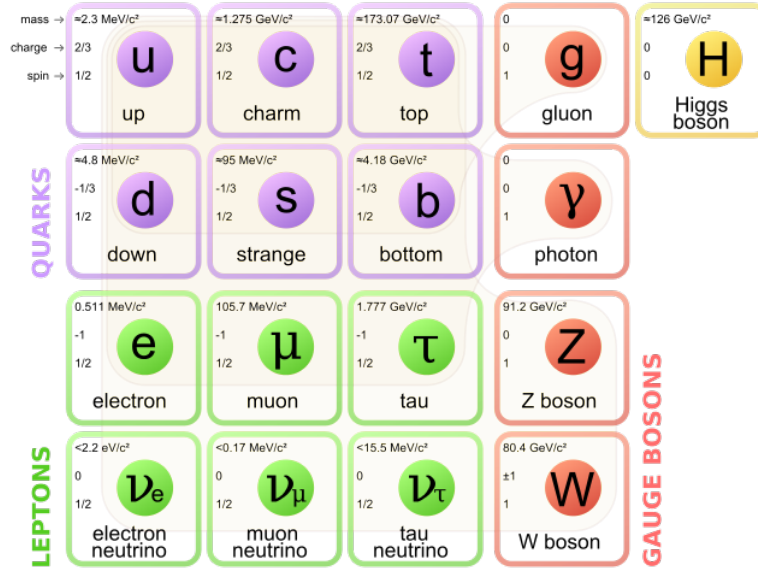


Figure 1.11: (Color online) Elementary particle constituents of the Standard Model of particle physics, with the 12 fermions in the first three columns, the four gauge bosons in the fourth column, and the Higgs boson in the fifth column. Brown loops indicate which bosons (red) couple to which fermions (purple and green). Figure and description from [57].

In the standard model, matter is composed primarily of spin- $\frac{1}{2}$ fermions. These fermions can be further divided into two basic groups, quarks and leptons, based upon the forces by which they interact. The interactions between particles are primarily mediated by the gauge boson “force carriers” (Figure 1.11; Table 1.1).

Quarks possess color charge, electromagnetic charge, and weak charge. The color charge is the source of the strong nuclear force. There are three types of color charge, along with associated anti-charges (called “red”, “green”, and “blue”; these terms, however, bear no relation to the usual visual colors). Quarks are exclusively found in colorless bound states (typically quark-antiquark *mesons* or 3-quark *baryons*, such as the nucleons that form the basis of atomic nuclei - i.e. *baryonic* matter). Quarks and *gluons* (discussed below) interacting via the strong nuclear force exhibit confinement and asymptotic freedom, where the particles behave essentially freely at very small distances (much less than the radius of a nucleon), but where binding forces are stronger at distances on the order of the nucleon radius. The theory governing the strong nuclear interaction, QCD, is based on the symmetry group $SU(3)$.

Leptons do not possess color charge, but are sensitive to one or both of electromagnetic and weak charge.

There are three generations of the quark and lepton families, with each generation composed of a quark doublet and a lepton doublet, and successive generations increasing in mass (Figure 1.11) while sharing the charge and spin quantum numbers of their counterparts of

Table 1.1: The known fundamental forces (Gravity, electromagnetism (EM), weak nuclear force, strong nuclear force) with their particle mediators. Relative coupling constants have been normalized with respect to the strong nuclear force [37].

Force	Rel. Coupl.	Range (m)	Carrier	Carrier Mass	Particles
gravity	10^{-39}	infinite	graviton	massless	all massive
EM	10^{-2}	infinite	γ	massless	quarks, some leptons
weak	10^{-7}	10^{-18}	$W^\pm, Z^0$	$M_W = 80.2 \text{ GeV}/c^2$, $M_Z = 91.2 \text{ GeV}/c^2$	quarks, leptons
strong	1	10^{-15}	gluons	massless	quarks

the previous generations. The first - and lightest - generation consists of an up quark (u), a down quark (d), an electron (e), and the electron neutrino (ν_e). This generation, being the lightest, is stable, and forms the basis of the baryonic matter content of the observable universe. The second generation consists of the charm (c) and strange (s) quarks, the muon (μ), and the muon neutrino (ν_μ). The third generation consists of the top (t) and bottom (b) quarks, the tau (τ), and the tau neutrino (ν_τ). The heavier generations are short lived and quickly decay to their lighter counterparts.

The Forces

The inter-particle interactions described in the Standard Model arise from one or more of three fundamental forces: the electromagnetic force, the weak nuclear force, and the strong nuclear force [58]. Each of the three fundamental forces of the Standard Model interact through the exchange of bosons between particles that carry the corresponding charge (Table 1.1). The electromagnetic force is mediated by the photon (γ); the weak force is mediated through the exchange of $W^\pm$ and Z bosons; and the strong nuclear force is mediated between particles with color charge through the exchange of “gluons”. There are eight gluons, which in addition to mediating force and color changes in quark interactions, also carry color charge, and can interact with one another.

While gravity is also considered to be a fundamental force, it has not been incorporated into the Standard Model because of incompatibilities between general relativity and quantum field theory at the short length scales and high energy scales required. Furthermore, because gravity is so much weaker (at least 32 orders of magnitude) than the other forces, its strength is primarily seen with massive astrophysical objects on large distance scales, beyond the range of the weak and strong nuclear forces, and where the net electromagnetic neutrality of most aggregations of matter leaves the gravitational effects dominant. At the length scales and at the sub-Planckian energy ranges probed by current high energy physics experiments, however, the gravitational effect is negligible.

The Higgs Boson

Unique among the elementary particles of the Standard Model is the Higgs boson. This elementary boson appears due to spontaneous symmetry breaking of global gauge symmetries of the Higgs field [59], which results in an associated massive scalar boson. Particles that interact with the Higgs field experience a “drag” that manifests as mass. This includes all quarks and leptons. Only massless particles such as the photon and graviton are uncoupled to the Higgs, although the interaction with the nearly massless neutrinos is also very weak. The Higgs provides the symmetry-breaking mechanism to produce mass in the standard model. So far, one Higgs-like boson has been discovered by the ATLAS (ATLAS) collaboration (and by the Compact Muon Solenoid (CMS) collaboration), although the number of possible bosons could be more. Moreover, as of this writing, analyses of the properties of the boson and its status as a single or composite Higgs are still underway.

Successes of the Standard Model

The Standard Model of particle physics describes the spectrum of elementary particles and their interactions: It provides a framework for the calculation of those interactions, and in most cases, provides an excellent description of particle properties. In many cases, it has predicted the existence and properties of particles before their discovery.

Outstanding questions in particle physics

While the Standard Model has provided a very successful framework for particle physics, there are several notable outstanding questions and exceptions to agreement between theory and experiment. A selection of these outstanding puzzles are described below. Detailed descriptions of the work done on each of these problems is beyond our scope; however, a few words on the naturalness and hierarchy problems, and their solutions in a few select models and supersymmetry, in particular, will assist in the contextualization of our dark matter search.

Naturalness and the Hierarchy Problem

The Standard Model contains a sizable number of free parameters that are not determined by any internal aspect of the model. Furthermore, the values of some of these parameters are not arbitrary; some of these values must be “tuned” to a high degree of precision to maintain compatibility between the predictions of the model and observation. This “fine-tuning” is qualitatively debated in discussions regarding the “naturalness” of the Standard Model [60].

In a complete and “natural” model, it is expected that any parameters not described or constrained internally by the model should have little bearing on the overall behavior of the model - in other words, it should be robust against changes in input not modeled within its scope. Because the Standard Model depends closely on parameters that are not naturally

included, and even diverges, it is generally regarded as incomplete. High levels of fine-tuning may also point toward higher degrees of symmetry or new physics [61].

In the Standard Model, the Higgs mechanism provides the means of electroweak symmetry breaking, and results in the generation of masses for the $W^\pm$ and Z bosons and other particle through interaction with the Higgs field. Higher-order terms in the Feynman loops, however, diverge, driving the Higgs mass—and through it, the masses of the other particles—to infinity. These divergences point to missing elements of the model that prevent or cancel the contributions of these higher-order terms.

The strong CP problem

While symmetries leading to the conservation of electromagnetic charge (C), conservation of parity (or “handedness”, P), and conservation of the combination of charge and parity (CP) play an important role in the Standard Model, the formalism of the Standard Model breaks this symmetry, and is explicitly (and strongly) CP-violating. This non-conservation leads to predictions such as a neutron electric dipole moment (EDM). Measurements of the neutron EDM and other searches for CP violation, however, indicate that within current experimental limits, CP is conserved to a high degree [62, 63].

Gravity and Beyond

The Standard Model does not incorporate the gravitational force. The three Standard Model gauge couplings (for the electromagnetic, weak, and strong forces), all have manifestly different strengths in the low energy limit, but at high energy scales, the couplings approach the same strength [64]. Extensions of the Standard Model seek to unify these three forces at high energies, as accomplished for the electroweak force. Finally, the Standard Model is also silent on the origins of dark matter and dark energy. Theories seeking to address these phenomena will require an extension of the standard model of particle physics.

Extensions to the Standard Model

Each of these primary challenges is being addressed by the particle physics community. In light of the outstanding questions of the Standard Model, a number of extensions have been proposed. Several of these extensions involve the prediction of new, stable, weakly-coupled particle species that could be candidates for dark matter.

The Peccei-Quinn Mechanism and Axions

Axions are a dark matter candidate arising naturally from a solution to the strong charge and parity (CP) problem. As stated above, in the strong CP problem, the Lagrangian for QCD contains a term that violates the CP symmetry, but this symmetry is highly conserved in experimental measurements. One solution, known as the Peccei-Quinn mechanism [65], is the introduction of a new symmetry, $U(1)_{\text{PQ}}$, which is spontaneously broken at some higher

energy scale, allowing the coupling in the QCD CP-violating term, now interpreted as a dynamical field minimized at zero, to be very small. Soon afterward, it was emphasized ([66, 67]) that this new field results in the existence of a new light boson - the axion.

Experimentally, the original axion, which (somewhat arbitrarily) assumed symmetry breaking at the electroweak scale [68] has been ruled out, but variations on the “invisible axion” are now the objects of various searches [69]. Limits on the axion from cosmology (avoiding overclosure of the universe) and astrophysics (stellar evolution effects and supernova measurements - for example, 1987A) provide bounds on the properties of the axion. The very weak coupling of axions requires sensitive experiments for laboratory observation. Most of the current experiments take advantage of the Primakoff effect arising from the coupling of axions to photons, particularly in strong magnetic fields.

If the axion exists, there are two populations of cosmic axions: a thermal population produced by quark and gluon scattering in the very early universe, and a nonthermal population. Thermal axions are typically still relativistic at the time of galaxy formation and unable to form galactic halos. This population is expected to have energies similar to the CMB radiation and cosmic neutrinos. Nonthermal axions, however, are much colder, nonrelativistic, and provide good candidates for the galactic dark matter [69].

Laboratory experiments have attempted to detect axions through the coupling with photons by “shining light through walls” and through changes in the polarization of light in a magnetic region[69]. Current and future searches for galactic halo axions include Axion Dark Matter eXperiment (ADMX) and ADMX-High Frequency (ADMX-HF), using microwave cavities to search for resonant axion frequencies, and Cosmic Axion Spin Precession Experiment (CASPEr), using NMR techniques [68].

Meanwhile, if the axion exists, it can also be produced in stars, including the Sun. The axions could then interact with the strong magnetic fields in the vicinity of the sun, or with matter, resulting in the production of detectable X-ray signatures [70, 71]. Axion helioscopes (for example, [72]) and the CERN axion solar telescope (CAST) [73] have conducted searches for solar axions; dark matter experiments such as CDMS have also placed limits on solar axions [74] in their detectors. To date, however, the positive detection of axion dark matter has remained elusive [68].

Supersymmetry

The supersymmetry (SUSY) framework has been advanced among extensions to the Standard Model as a potential solution to the hierarchy problem and provides a natural, stable class of candidates for dark matter known as the weakly interacting massive particle (WIMP). We will discuss SUSY in more detail in Section 1.6.

Further Extensions

Extensions to the standard model of particle physics are discussed in [75, 76], which also provides an extensive list of references for the discussion. Dark sector theories are also

gaining popularity as the parameter space for the simplest models is ruled out by current experiments. Results of searches for dark matter in direct, indirect, and collider searches are discussed in later sections.

1.6 Supersymmetry

Supersymmetry (SUSY) is the most prominent framework for the extension of the Standard Model. Furthermore, it is a core feature of the even more generalized theories of everything (TOEs). Both SUSY and axions appear in string theories. Some paradigms combine SUSY and the Pecci-Quinn mechanism in the extension of the Standard Model.

Main Ideas

SUSY goes beyond the gauge theories of quantum field theory to establish a relationship between internal particle spins and space-time translations. Under this symmetry, particles that obey the Pauli exclusion principle and thus Fermi-Dirac statistics are connected to particles that obey Bose-Einstein statistics, which are not subject to the exclusion principle. Particles of integral and half-integral spin are thus related, and SUSY establishes a connection between fermions and bosons [77, 78, 79]. Each boson has a fermionic superpartner, and in turn, each fermion, a bosonic counterpart.

SUSY is a broken symmetry, evidenced by the lack of mass degeneracy between particles and their sparticle superpartners. Depending on whether SUSY is a global or a local symmetry and the means by which SUSY breaking is mediated, the symmetry-breaking process can result in a LSP that impacts the manifestation of SUSY in collider experiments [79].

For supersymmetric theories to remain consistent with experimental constraints, they must observe (within constraints) the conservation of baryon-lepton number, which has been tested to very high precision. As a result, an additional new symmetry, R-parity, is introduced. For a particle of spin S ,

$$R = (-1)^{3(B-L)+2S} \quad (1.10)$$

where B is baryon number and L is lepton number. Particles of the Standard Model have R-parity 1, while supersymmetric partners have R-parity equal to (-1).

One of the phenomenological consequences of R-parity is that SUSY particles must be produced in pairs. Most of the particles produced will be unstable and decay to lighter states. However, a second consequence of R-parity is that because it is conserved, the LSP must be stable, generally produced at the end of a decay chain initiated by the decay of some heavier, unstable SUSY particle.

The model for incorporating SUSY with the smallest possible number of additional fields and extensions is known as the Minimal Supersymmetric Standard Model (MSSM). The Minimal Supersymmetric Standard Model (MSSM) [80] provides the minimal extension to

the Standard Model necessary to incorporate the general framework for the implementation of SUSY. The Lagrangian for the model includes all of the possible supersymmetric terms with 4 or fewer dimensions that satisfy Standard Model gauge invariance and conservation of baryon-lepton number, along with the most general soft-SUSY-breaking terms consistent with the required symmetries. As summarized in [79], this model consists of the two-Higgs-doublet extension to the Standard Model, all of the associated SUSY partners for the fermions, gluons, and gauge bosons (and their antiparticles), two complex Higgs doublets, their higgsinos, and their antiparticles. In fact, the Minimal Supersymmetric Standard Model (MSSM) contains over 100 free parameters, which makes it prohibitively challenging to meaningfully explore the entire parameter space. Modified versions of the MSSM constrain the number of parameters and establish regions of the parameter space that can be probed by experiment. Modified versions of the MSSM that have been explored in some detail include minimal Super Gravity (mSUGRA) or the constrained MSSM (cMSSM) [81], p(henomenological) MSSM (pMSSM) [82, 83], and the NUHM models [84], among others. Most of these models differ by the types and number of parameter constraints used to make predictions. The simplest of these theories have largely been ruled out by recent experiment, but since the models are highly constrained, they do not allow a full exploration of the rich phenomenology of the full MSSM. Such constraints, however, are necessary to obtain models that can be meaningfully compared with experimental data. Recent work has shifted to the 19-parameter pMSSM. A summary of recent results from the Run I data from the LHC interpreted in light of the pMSSM is described in some detail in [85]. Some of these results are mentioned briefly in section 1.9.

Advantages of Supersymmetry

One of the major advantages of supersymmetry is the resolution of the hierarchy problem. The terms leading to the “ultraviolet divergence” of the runaway Higgs mass are cancelled by contributions from the particle superpartners. Weak-scale SUSY also provides a natural explanation of the large gap between the electroweak symmetry-breaking scale (around 100 GeV) and the Planck scale ($M_p \sim 10^{19}$ GeV). Supersymmetry also provides a framework for the incorporation of gravity, and for unification at the Planck scale, as well as a framework for addressing the question of matter-antimatter asymmetry.

Finally, the stable, massive LSP predicted by SUSY provides a viable - and attractive - candidate for particle dark matter: the weakly interacting massive particle (WIMP).

1.7 A Favored Candidate: The Weakly Interacting Massive Particle

Based on the properties described in Section 1.4, no particle from the Standard Model satisfies the requirements for dark matter [86, 87]. The observational evidence for dark matter from astrophysics and the prediction of new particles beyond the Standard Model

become increasingly powerful when considered in light of the implications for cosmology. The weak-scale interaction cross sections predicted for WIMPs in supersymmetry results in a thermal relic of WIMPs of the correct density to account for all of the dark matter. This correspondence, known as the “WIMP miracle”, is a compelling case for WIMP dark matter [88].

Low Mass WIMPs

As discussed in 1.9 and subsequent sections, constraints from collider experiments such as ATLAS and CMS at the LHC place strong but model dependent constraints on the existence of WIMP dark matter candidates of mass greater than $\sim 30 \text{ GeV}/c^2$. The absence of a positive direct detection of more massive WIMPs, however, and the resulting resurgence of interest in more complex dark matter models has also renewed interest in the possible existence of less massive dark matter, and in particular, the “low-mass WIMPs”; that is, WIMPs of mass on the order of $\sim 10 \text{ GeV}$.

In this work, we will concentrate on the direct search for SUSY WIMPs in the halo of the Milky Way galaxy.

Galactic WIMPs and the Standard Halo Model

Evidence that the Milky Way galaxy is surrounded by a large dark matter halo includes motions of satellite objects [89, 90] and other objects outside of the disk, which indicate a spherical aggregation of mass surrounding the disk. The spherical shape of the dark matter halo in contrast the spiral disk occupied by baryonic matter is believed to be a result of the inability of dark matter to release energy in the form of radiation [42, 91]. Nevertheless, the dark matter velocity distribution within the halo is assumed, in its simplest form, to be isotropic and to follow a Maxwell-Boltzman distribution. The violent relaxation [92, 93] of the halo early in its formation leads to thermalization of the dark matter velocities from fluctuations in the gravitational potential. This leads, to first order, to the expectation that the velocities follow a Maxwell-Boltzmann distribution [94]. The halo is generally assumed to be smooth. Although contributions from substructure (streams, etc.) are not unexpected, they are generally omitted from first order analyses using the simple halo model. In order for dark matter to clump together to form potential wells, we generally assume that the dark matter was cold (non-relativistic) at the time of galaxy formation. The velocity distribution is generally truncated at the escape velocity, either with a sharp cutoff, or using a smoother but still somewhat arbitrary terminal exponential distribution. The rms velocity for the standard halo model is 270 km s^{-1} . These parameters are summarized in Table 1.2.

Table 1.2: Commonly used astrophysical parameters for the standard halo model.

Parameter	Value
RMS Velocity	$v_{\text{rms}} = 270 \text{ km s}^{-1}$
Escape Velocity	$v_{\text{esc}} = 540 \text{ km s}^{-1}$
Local Density	$\rho = 0.4 \text{ GeV}/c^2$

1.8 Searching for WIMPs

Three main avenues are employed in the search for dark matter: production via particle accelerators, indirect astrophysical searches, and direct-detection experiments.

Figure 1.12 shows a Feynman diagram of the interaction between dark matter and the Standard Model. This diagram can be interpreted in three ways, each of which is reflected by a dark matter search strategy. First, reading the time axis from right to left, the annihilation of particles of the Standard Model and the production of dark matter among the interaction products can arise from high energy collisions at particle colliders. The resulting dark matter particles escape the detector. Although the particles will not be detected, such an interaction can result in missing transverse energy that can be identified during analysis. The diagram can also be read from left to right. In this case, the annihilation of dark matter particles and antiparticles can result in the production of Standard Model particles, which can produce excess rates in terrestrial and satellite detectors during indirect dark matter searches. Finally, one can symmetrically consider the time axis as pointing either from top to bottom or from bottom to top. Here, the scattering of a dark matter particle from a Standard Model target will produce an observable recoil in the target atom. This is the paradigm for dark matter direct detection. Direct detection is discussed in more detail in Section 1.11.

1.9 Particle Physics Constraints on Supersymmetry

Production-Colliders

Large particle experiments such as those at the LHC accelerate standard model particles to sufficient energy to create new particles and excited states upon collision. Some of the short-lived collision products subsequently decay into lower-energy stable configurations. Carefully analyzing the particles, jets, and energy released in the collision allows searches to identify missing energy in the final products, which could be a signature of the production of dark matter particles, which, being only weakly interacting, subsequently escape the detector. Major experiments include the ATLAS [96] and CMS experiments, both stationed at collision points of the beam at the LHC. Many works, including [97], have used constraints

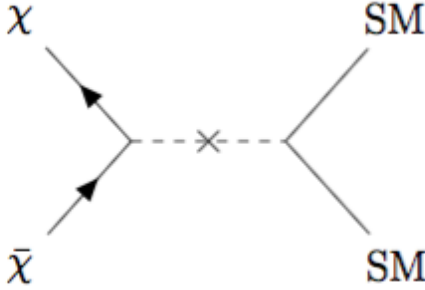


Figure 1.12: Representative Feynman diagram for the interaction between a dark matter WIMP candidate and a Standard Model target. For a time axis pointing from left to right, annihilation of a dark matter particle-antiparticle pair in the initial state results in the production of Standard Model particles (final state) which can subsequently be detected, as in the case of indirect detection; from right to left, the annihilation of Standard Model particles from the initial state results in the production of dark matter (final state), as in the case of production in particle colliders such as the LHC; while a vertical time axis (pointing either from top to bottom or from bottom to top) represents a direct scattering interaction between a dark matter candidate and the Standard Model, with both particles appearing in both the initial and final states. Feynman diagram produced via [95].

from both experiments to place constraints on the WIMP-nucleon cross section for various dark matter production channels.

Constraints on SUSY dark matter from colliders

Recent studies of the constraints on SUSY following Run I of the LHC have devoted large-scale computing resources to simulate and analyze the parameter space of the pMSSM (see Section 1.6) and distinguish between excluded and remaining models, based upon the combined results of SUSY searches in a variety of decay channels [85]. A specialized study dedicated to $\sim 10.2 \times 10^3$ “natural” models with a neutralino LSP and satisfying additional constraints on the Higgs mass, WMAP relic density, and low fine-tuning demonstrated that application of the constraints from recent global precision, flavor, dark matter, and collider experiments indicates that the LSP mass should be greater than $\sim 30 \text{ GeV}/c^2$ and less than $\sim 400 \text{ GeV}/c^2$. The lower constraint, in particular, arises from experimental constraints on the invisible decay width of the Z-boson.

While many dark matter searches, including CDMS and SuperCDMS analyses, probe the parameter space for lower-mass WIMPs, and scan ranges allow for lighter versions of the LSP, these constraints are fairly strong. According to [85], based on both the specialized study discussed above and a broader study of the parameter space for a neutralino LSP in the pMSSM, LSP masses greater than $\sim 30 \text{ GeV}/c^2$ are required for consistency with a) experimental and dark matter search constraints, b) a Higgs mass of $126 \pm 3 \text{ GeV}/c^2$, c) the

invisible Z-decay width ($\Gamma(Z \rightarrow \chi\chi) < 2 \text{ MeV}$), d) the WMAP thermal relic density, e) and trivial satisfaction of the Large Electron-Positron Collider (LEP) constraints on charged sparticles. Discovery of a lighter mass LSP, while satisfying all of these conditions, would strongly disfavor the pMSSM and potentially exclude the full MSSM [85]. Nevertheless, strong motivations for continuing low-mass WIMP searches are discussed in Section 1.7, with additional details provided in [98, 99, 87].

1.10 Indirect Detection Efforts

Annihilation- Indirect detection

Although weakly interacting, WIMPs may lose energy and slow down as they pass through other concentrations of matter (e.g., the Sun, the Earth, or the galactic center), and through gravitational interactions become more concentrated in the vicinity of these objects. As more and more WIMPs thermalize inside large bodies of matter, the frequency of interaction increases and the particles may begin to annihilate one another [94]. Many of the annihilation channels of WIMPs result in the pair-production of Standard Model particles such as high-energy neutrinos, gamma-rays, and positrons, which can be detected in ground-and space based observatories. Numerous constraints on the WIMP dark matter annihilation flux from indirect detection experiments have been set, for specific channels of annihilation [100]. Searches for the Standard Model products of dark matter annihilation comprise the field of “indirect detection” of dark matter. Major indirect experiments include IceCube Neutrino Observatory (IceCube)/DeepCore, Fermi Gamma-ray Space Telescope, Veritas, AMS-02, HESS, PAMELA, ANTARES, MAGIC, and the Cherenkov Telescope Array (CTA) [101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111]. In 2012 the IceCube collaboration reported on the detection of high energy neutrinos (coming from Earth). However, the diffuse distribution provided little indication of a dark matter source, instead correlating weakly to maps of known gamma ray sources. IceCube also placed limits on dark matter annihilations in the sun, as well as for annihilations in the Milky Way galaxy.

1.11 Direct Detection

Direct Detection

The final means by which we search for the interaction of WIMP dark matter with constituents of the Standard Model is by direct scattering, where both the initial and final states consist of a dark matter particle and a baryonic target with some interaction between them in the interim.

In section 1.8, the means of WIMP interaction with baryonic matter was through pair annihilation or pair production, coupling to baryonic matter only in its creation or destruction. Direct detection experiments look for interactions of WIMPs directly scattering from

baryonic targets, with both the target and WIMP existing in the initial and final states of the interaction. Although the dark matter particle generally continues to travel after scattering in the target, we observe the recoil of atoms within the target because of the transfer of momentum and energy during the interaction.

When a WIMP interacts with a target, the energy and momentum transferred to the target nucleus is shortly released in various ways, depending upon how the particle interacts and the type of target. This energy may be subsequently released as heat, light, or the ejection of particles in spallation or ionization. These products can be picked up by detectors and used for the measurement of the desired signals. At the weak-scale interactions characterizing WIMP direct searches, the detected signals are light, heat (usually as phonon signals), and ionization (or charge collection).

The observed effects from a WIMP-target interaction also depend upon whether the incident particle interacts primarily with the nucleus or the electron cloud of a target. While both electronic and nuclear recoils of the target atom result in the release of energy, the ratios of energy deposited as different forms will in general differ between the two. For example, in a germanium detector, the incidence of a particle causing the recoil of electrons in an atom releases more ionization than an interaction resulting in the recoil of the nucleus, for the same amount of deposited energy (which can be measured by the phonon signal in both interactions). While some direct detection experiments focus exclusively on one type of signal, many experiments are specifically designed to look for a combination of signals in order to take advantage of this ability to discriminate between different types of recoils (Section 1.11 and Chapter 2).

Because WIMPs interact through the weak interaction, recoils of detectable energy resulting from WIMP scattering events will primarily be the result of interaction with the target nuclei, rather than electrons. The expected energy of WIMP-scatter from electrons is much smaller than the expected strength of WIMP-nucleus [112, 113, 114, 43]. Furthermore, most known backgrounds resulting in the production of beta or gamma radiation will interact primarily with the target electrons, producing an electron recoil. As a result, most experiments search for the nuclear recoil interaction, and experiments with discrimination between electron and nuclear recoils have an important handle on the removal of backgrounds from the set of candidate events [115] with minimal effect on the efficiency of the nuclear recoil signature expected from WIMPs.

The hallmarks of a WIMP signature include an excess (above backgrounds) of the (nuclear) recoil event rate, the presence of an annual modulation of the recoil event rate, and a cross over of the phase of the modulation at low-energy thresholds. In addition, this crossover, if detected, can be used to place additional constraints on the mass of the incident WIMPs. Much of this information is reviewed and summarized in [22] and [116].

Direct Detection Experiments

There are now many direct-detection experiments searching for an excess event rate or a modulating signal. Most of these detectors rely on the interaction of WIMPs with nuclear tar-

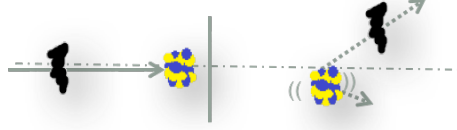


Figure 1.13: Dark matter particle scattering from target nucleus.

gets to produce one or more detectable signals, such as ionization, phonons (heat/vibrations), scintillation, or bubble nucleation. These signals are generally detected by carefully designed sensor and electronics systems, and analyzed to produce the measurements of the physical quantities of interest. A list of select current and recent experiments, tabulated in large part in [22], are listed in Table 1.3.

Directional Detection

In addition to the annually modulating signal, a true WIMP signature is expected to bear an diurnal signature due to the daily rotation of Earth about its axis and the change in orientation of the terrestrial detector with respect to the WIMP wind. While such a signal is currently beyond the sensitivity of most direct detection experiments, development of directional detectors has continued, with the potential to provide important contributions to the verification and further study of any dark matter discovery. Further discussion of directional detection is beyond the scope of this thesis, but [116, 117, 118, 119] provide detailed discussions of the concept and status of current directional experiments. Much progress has been made in recent years; we will, not, however, discuss it further.

WIMP signatures in Direct Detection Experiments

WIMPs interacting in a detector are expected to transfer energy (and momentum) to the atoms of the target material. The amount and spectrum of deposited energy, the means by which the transferred energy is released and measured, and the rate at which energy depositions occur all depend on properties of the WIMP and the nature of the WIMP-target interaction. As a result, measurements of the rate and magnitude of energy depositions above a particular detection threshold are studied for specific signatures (recoil rate excess, time-variation (modulation), and modulation phase reversal), which can be used to infer the values of parameters such as the interaction cross section and WIMP mass.

Nuclear Recoil Excess

Kinematically, the energy of a recoiling nucleus after elastic scattering by a WIMP (Figure 1.13) is given by Equation 1.11:

Table 1.3: Partial list of WIMP dark matter direct-detection experiments with target isotope and signal type.

Experiment	Material	Signal
ANAIS	NaI	scintillation
ArDM	Ar	ionization, scintillation
CDEX	Ge	ionization
CDMS	Ge, Si	ionization, phonon
CDMSlite	Ge	ionization (with Luke-Neganov amplification)
CoGeNT	Ge	ionization
COSINE - 100	NaI	scintillation
COUPP	CF ₃ I	bubble chamber
CRESST	CaWO ₄	scintillation, phonon
DAMA/LIBRA	NaI	scintillation
DAMA/NaI	NaI	scintillation
DAMIC	Si CCD	scintillation
DEAP/CLEAN	Ar	scintillation
DM-Ice17	NaI	scintillation
DRIFT	CS ₂ , CF ₄	ionization
EDELWEISS	Ge	ionization, phonon
KIMS	NaI	scintillation
LUX	Xe	scintillation, ionization
LZ	Xe	scintillation, ionization
MALBEK	Ge	ionization
PandaX	Xe	scintillation, ionization
PICO	C ₃ F ₈	bubble chamber
PICASSO	C ₄ F ₁₀	bubble chamber
ROSEBUD	Al ₂ O ₃	scintillation, phonon
SIMPLE	C ₂ ClF ₅	bubble chamber
TEXONO	Ge	ionization
WArP	Ar	scintillation, ionization
XENON10	Xe	scintillation, ionization
XENON100	Xe	scintillation, ionization
XENON1T	Xe	scintillation, ionization
XMASS	Xe	scintillation, ionization
ZEPLIN	Xe	scintillation, ionization

$$E_{\text{nr}} = \frac{\mu^2 \nu^2}{M} (1 - \cos \theta) \quad (1.11)$$

where $\mu = \frac{m_\chi M}{m_\chi + M}$ is the the WIMP-nucleus reduced mass.

Assuming separable equations for the differential recoil rate per unit detector mass [22], we can write

$$\frac{dR}{dE_{\text{nr}}} = \frac{1}{2m_\chi \mu^2} \sigma(q) \rho_\chi \eta(\nu_{\text{min}}(E_{\text{nr}})) \quad (1.12)$$

where, in equation 1.12,

$$\eta(\nu_{\text{min}}, t) = \int_{\nu > \nu_{\text{min}}} d^3\nu \frac{f(\mathbf{v}, t)}{\nu} \quad (1.13)$$

is the mean inverse speed [22]. The velocity distribution, $f(\mathbf{v}, t)$, is the velocity distribution of dark matter particles in the galactic halo. In the simplest models, the velocity distribution is taken to be a Maxwell-Boltzman velocity distribution obtained from a smooth, virialized, isothermal sphere in the dark matter rest frame, $\tilde{f}(\mathbf{v})$, and transformed into the laboratory frame through a Galileian transformation [22]. Meanwhile, $\sigma(q)$ is an effective scattering cross section, and ν_{min} is the minimum WIMP velocity that can result in a recoil energy E_{nr} for the case of elastic scattering:

$$\nu_{\text{min}} = \sqrt{\frac{ME_{\text{nr}}}{2\mu^2}}. \quad (1.14)$$

As a result, a detector is sensitive to interactions for particular ranges of the recoil energy. Generally, the case considered in direct detection studies is that of a spin-independent recoil from elastic scattering of a WIMP from the target nucleus, with a simple smooth, isothermal, spherical halo configuration.

The effective scattering cross section is often defined as

$$\sigma(q) \equiv \sigma_0 F^2(q)$$

The zero-momentum-transfer limit is denoted σ_0 , while the form factor encodes the nuclear effects [22]. Throughout the history of dark matter direct searches this cross-section has been assumed to be primarily the sum of contributions from the spin-independent (σ_{SI}) and spin-dependent (σ_{SD}) interactions as the dominant interactions. Recent work on the effective field theory of WIMP-nucleon interactions, however, [120] has shown that in some cases several other operators can contribute significantly, and even dominantly, to the interaction cross section. Further discussion of the effective field theory is beyond the scope of this thesis, but details of the effect on the interpretation of direct detection results, particularly in the context of the CDMS experiment, can be found in [120, 121, 122].

Most direct detection experiments are most sensitive to the coherent spin-independent cross section, which is essentially an interaction with the entire nucleus, and as a result, scales as A^2 . In addition, the ratio of reduced masses is on the order of another factor of A^2 , further enhancing the scattering cross section and, giving experiments with heavier targets an advantage in sensitivity [22]. While this is somewhat modified by the form factor, which has a stronger suppression effect for more massive nuclei, in most cases considered, and certainly in the simplest paradigm of WIMP searches, the SI interaction is considered to be the primary case.

If the the WIMP-proton and WIMP-neutron interactions are identical (i.e., isospin is conserved), the spin-independent cross section simplifies to the following:

$$\sigma_{\text{SI}} = \frac{\mu^2}{\mu_p^2} A^2 \sigma_{p,\text{SI}}$$

where $\sigma_{p,\text{SI}}$ is the cross section of WIMP interaction with a single nucleon [22].

The form factor can be written

$$F(q) = 3 \exp(-q^2 s^2/2) \frac{\sin(qr_n) - qr_n \cos(qr_n)}{(qr_n)^3} \quad (1.15)$$

In equation 1.15, r_n is an effective nuclear radius.

There are also model-independent form factors obtained from fits to electron scattering data [123]; however, most experiments continue to rely on the Helm form factor shown in Equation 1.15, as described in [116].

For the case of spin-dependent scattering, the interaction does not scale as strongly in proportion to the size of the nucleus, and there is no extra factor of A^2 from the coherent scattering of the nucleus. Spin-dependent (SD) scattering only occurs in nuclei with unpaired nucleons (unpaired n or p) and is further reduced when the target material only contains a small number of isotopes with these unpaired nuclear configurations. As a result, experimental sensitivity to SD scattering is more limited than in the SI case.

There are a number of other WIMP-nuclear couplings that are generally subdominant but may become important in cases where there is significant suppression of the SI and SD terms [22].

With the form factor and astrophysics shown above, the differential event rate for the scattering of WIMPs from detector nuclei is

$$\frac{dR}{dE_{\text{nr}}} = \frac{1}{2m_\chi \mu^2} \sigma_0 F^2(q) \rho_\chi \eta (nu_{\text{min}}(E_{\text{nr}})) \quad (1.16)$$

The differential event rate (Equation 1.12) obtained from the astrophysics, nuclear physics, and kinematics equations described above for specific values of the WIMP mass and WIMP-proton scattering cross section can be integrated over the energy range of interest to produce the expected event rate in a detector sensitive to recoil energies above some threshold. This detection rate will be in excess to any nuclear recoil event rates caused by Standard Model

backgrounds. With the astrophysical assumptions described in Section 1.7 and the effective form factor shown in Equation 1.15, we can use measurements of the actual rate of events incident in a dark matter detector to estimate and set limits on the WIMP mass and interaction cross section parameters (m_χ , μ , and σ_{SI}) in Equation 1.16.

The nuclear recoil excess rate due to incident WIMPs needs to be identifiable in the presence of backgrounds such as radioactivity, noise and cosmogenic events. As a result, experiments need background discrimination in order to unambiguously identify a WIMP signal through a nuclear recoil excess.

Annual Modulation

In a simple halo model, the recoil event rate as a function of time in a detector can be described as

$$S \approx S_0 + S_m \cos(\omega(t - t_0)) \quad (1.17)$$

where S_0 is the unmodulated signal, S_m is the maximum amplitude of modulation, and t_0 is the phase, i.e., the time of year when the amplitude is at its peak.

Figure 1.15 illustrates the motion of the Earth through the galactic halo, resulting in a WIMP wind streaming against the earth. Because of the earth's motion about the sun, the relative velocity of a WIMP incident on a detector changes annually, resulting in an annual modulation of the recoil event rate (Figure 1.14). For the simplest astrophysical assumptions (standard halo model), the modulation will be a simple sinusoid, peaking in June (when the relative velocity between the Earth and the “WIMP wind” is largest) and reaching a minimum in December.

The phase and the amplitude of a modulation signal can be significantly altered by the presence of substructure (e.g. streams) in the dark matter halo. In some cases, the signal can cease to be sinusoidal or even symmetric. Furthermore, the effects of the annual modulation signal or changes thereof usually most strongly apply to the high-speed tail of the velocity distribution, which can be altered in significant departures of the velocity distribution from that of the standard halo model. Nevertheless, an annual modulation of the rate can be used for WIMP detection even in the presence of significant backgrounds, as most known backgrounds due to known sources are unlikely to cause a modulation with the same phase and period as the WIMP signal. As for the above discussion of the nuclear recoil excess, much of this information is reviewed and summarized in [22] and [116].

In Chapter 5, we use as our most basic model (without background subtraction) the equivalent parameterization

$$\begin{aligned} N_{\text{expected}} &= N_{\text{DC}} + N_1 \cos \omega t + N_2 \sin \omega t \\ &= \xi (M_0 + M_1 \cos \omega t + M_2 \sin \omega t) \end{aligned} \quad (1.18)$$

where in general, ξ is some efficiency-weighted, energy-integrated exposure ($\xi = m\tau_{\text{live}}\varepsilon\Delta E$), M_0 is the unmodulated rate of events, and M_1 and M_2 are rate coefficients, related to the

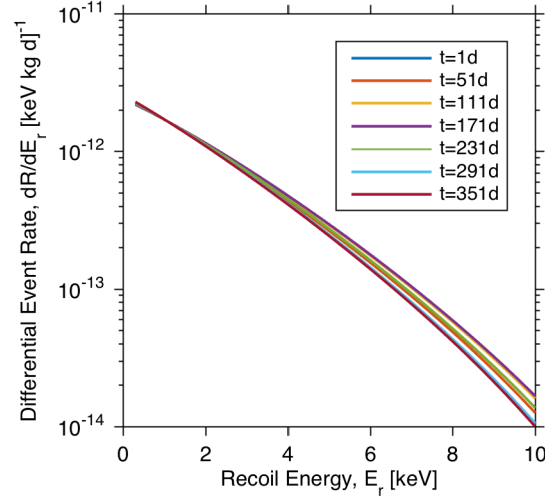


Figure 1.14: Differential event rates shown for a 60 GeV WIMP incident on a target nucleus of ^{73}Ge , with an assumed phase of 150 d based on the standard halo model. The rates are shown for varying times of the year. Note the cross over at low energies.

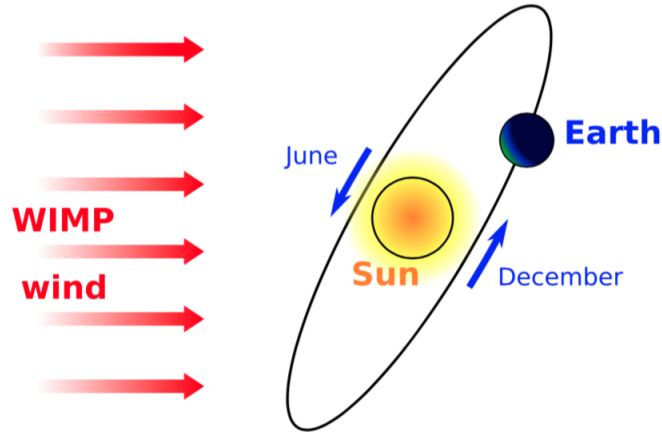


Figure 1.15: Figure 1 from [22]. Schematic illustration of Earth's annual motion relative to the WIMP wind arising from motion through the galactic halo.

overall amplitude (R_{mod}) and phase (ϕ) by

$$\begin{aligned} R_{\text{mod}} &= \sqrt{M_1^2 + M_2^2} \\ \tan(\phi) &= M_2/M_1 \end{aligned} \tag{1.19}$$

With this model, measurements of the time-variation of the nuclear recoil event rate allow us to estimate the parameters (M_0 , M_1 and M_2) for the unmodulated and modulated components of the rate, and to set bounds on the amplitude and phase of any annually modulating signal. Subtraction of backgrounds involves extension of the models to incorporate the contribution of background event rates, as discussed in Chapter 5.

Phase reversal

At low energies, the phase of the modulation is reversed: when the WIMP velocity distribution increases in June (based on the standard halo model), WIMPs are able to deposit a higher fraction of their kinetic energy in a detector, compared with that deposited in December. As a result, the differential rate spectrum crosses at specific energies that depend on the WIMP mass, as well as the halo dispersion velocity [124]. When the differential rate is integrated over recoil energy (depending on the energy interval), the crossing can alter the amplitude of the modulation.

Because the crossover energy is particular to the incident WIMP mass, if detected, it can be used to constrain the WIMP mass [125]. Measurements of the modulation parameters taken with respect to energy can be used to create a spectrum to determine this crossover energy. The crossover energy is also a monotonically rising function of the WIMP mass, as well, so that a upper limit on the crossover energy (such as an excess but no turnover observed at the low-energy threshold of an experiment) also establishes an upper limit the allowed WIMP mass.

Model-Independent Signatures

Most of the signatures of a WIMP signal described above rely upon various assumptions on the astrophysical model and on models of the nuclear interactions. Several approaches emphasizing model independence in some respect [126, 127, 128] seek to remove dependence upon astrophysics by integrating over the velocity distribution. This astrophysics-independent approach allows the comparison of experiments with different target nuclei.

1.12 Excluded Regions in WIMP Detection, This Work, & Next Steps

Recent results in dark matter direct detection experiments form a puzzling view of the WIMP parameter space. The XENON100 [129] and LUX [130, 131] collaborations report no

signal, and LUX has set upper limits on the spin-independent cross-section of interaction at $\sim 2.2 \times 10^{-46} \text{ cm}^2$ for a $50 \text{ GeV}/c^2$ WIMP. The CDMSlite [132, 133, 134] and SuperCDMS low-threshold [135] analyses have set new limits on WIMP-mass interactions below $10 \text{ GeV}/c^2$. Meanwhile, several experiments, including CoGeNT [136, 137, 138, 139], CRESST [140], and CDMS II - Si [141], have reported excess events within the signal regions of their detectors (CDMS II not at discovery significance). The increase in interest surrounding low-energy, low-threshold interactions has led to an increase in the concentration on searches for low-mass WIMP interactions, including the analysis of low threshold data from CDMS II for annual modulation in an attempt to provide further insight into the reconciliation of direct detection results in this low-mass regime. Recently, MAJORANA Low-Background BEGe at Kimballton (MALBEK), a point-contact germanium experiment modeled after CoGeNT, and PandaX, a 500-kg liquid Xe experiment at China Jinping Underground Laboratory, have confirmed null results that rule out the CoGeNT and DAMA/LIBRA, CRESST, and CDMS II - Si regions of interest.

Figure 1.16 shows the current state of the field for WIMP masses ranging from $< 1 \text{ GeV}/c^2$ to $10^4 \text{ GeV}/c^2$. The orange band, representing the “neutrino floor”, represents the interaction cross-section at which detectors become sensitive to neutrino interactions as an irreducible background, so that experiments will no longer be able to operate generally as “background-free” [156].

Next Steps in Direct Detection

Increases in the scale and complexity of dark matter direct search experiments have ultimately led to a concentration of effort behind two major strategies: increased exposures, to enhance the sensitivity to high-mass WIMP interactions, and lowering the energy thresholds, to increase sensitivity to low-mass wimp interactions. LUX-ZEPLIN (LZ) and SuperCDMS (SNOLAB) are the two primarily North American experiments selected by the U.S. Department of Energy and the National Science Foundation to target these goals as second-generation (G2) dark matter search experiments. LZ, a joint effort of the LUX and ZonEd Proportional scintillation in LIquid Noble gases (ZEPLIN) collaborations, is a a ton-scale experiment using liquid Xe focusing on the high-mass WIMP search. SuperCDMS SNOLAB Experiment, with the sensitivity advantage of semiconducting crystals, will use a combination of IZIP and a special operating mode of high-voltage detectors to search for low-mass WIMPs.

Figure 1.17 shows the projected sensitivity of the SuperCDMS experiment operated at SNOLAB.

1.13 Disentangling the Low Mass Region

While most experiments searching in the high WIMP-mass region for the SI interaction have established upper-limits on the WIMP-nucleon cross section, at low masses, the dif-

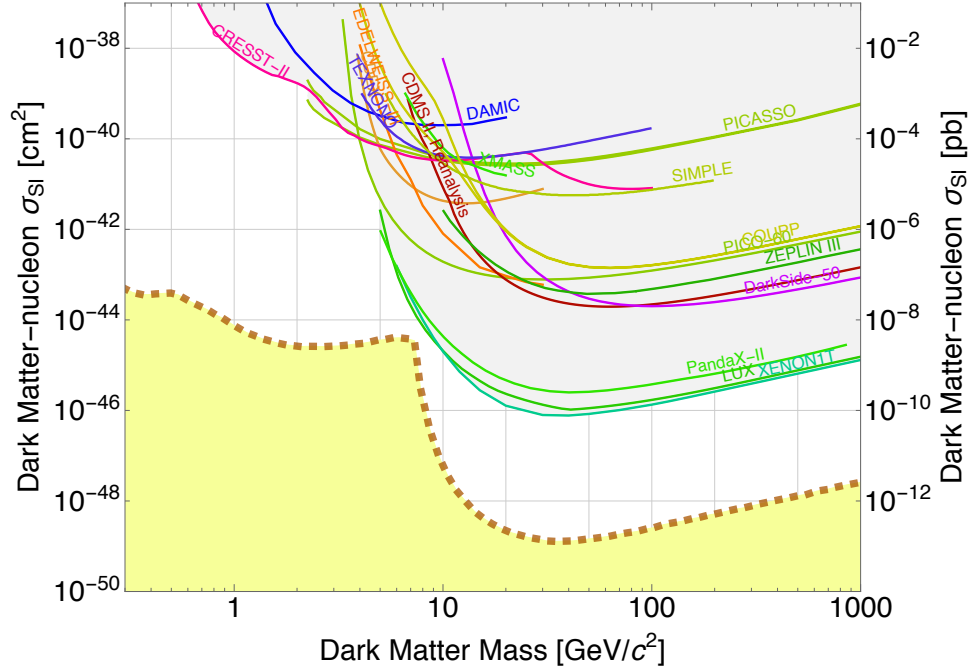


Figure 1.16: All-mass WIMP-nucleon exclusion limits and regions of interest. Featured are the 2015 reanalysis of CDMS II Runs 125-128 [142] (deep red); EDELWEISS-III [143] (2016; orange); CDEX-1 [144] (2016; goldenrod); COUPP [145] (2012; yellow); SIMPLE [146] (2012; yellow-green); PICASSO [147] (2017; light green); PICO-60 [148] (2017; pale green); PandaX [149] (2016; neon green); XMASS (no citation available) (2013; bright green); LUX [131] (2011, green); ZEPLIN-III [150] (2011; forest green); XENON1T [151] (2017, teal); DAMIC I [152] (2016, blue); TEXONO [153] (2013, purple); DarkSide-50 (from [154]) (2015, magenta); and CRESST-II [155] (2015, pink). The level at which detection rates due to neutrino coherent scattering become significant (shown for an Ar target) is indicated as a function of WIMP mass by the thick dashed orange curve [156]. Figure from the WIMP Limit Plotter v3.00 [157].

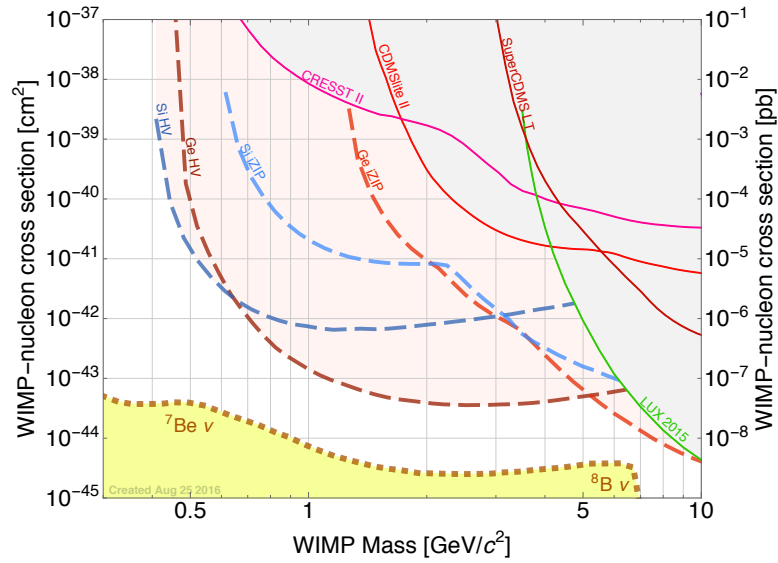


Figure 1.17: SuperCDMS sensitivity projections using an optimal-interval analysis. The vertical axis is the SI WIMP-nucleon interaction cross section, using the standard halo assumptions, while the horizontal axis is the WIMP mass. Blue dashed curves are the expected sensitivities for the silicon high-voltage (HV) and IZIP detectors, while the red curves are the expected sensitivities of the germanium HV and IZIP detectors. The solid lines are experimental exclusion limits from CRESST-II, SuperCDMS, and LUX, while the dotted orange line is the cross-section at which the interaction rate from dark matter particles becomes comparable to the solar neutrino coherent elastic scattering rate. Figure from [158].

fering target nuclei and experimental sensitivities have produced a tangle of puzzling results. Among the more prominently known experiments, non-detections by such as CDMS, CDMSlite, SuperCDMS, LUX, and XENON10 (XENON10) stand in tension with claimed or WIMP-interpretable detection signals by CoGeNT, DAMA/LIBRA, CRESST, and even CDMS II - Si.

DAMA, CoGeNT, CRESST, CDMS II, LUX, & CDMS-lite

DAMA/LIBRA

Dark Matter (DAMA) is a sodium iodide experiment doped with Thallium scintillator (NaI(Tl)) located in the Laboratori Nazionali del Gran Sasso (LNGS) in Gran Sasso, Italy. The earliest phase began taking data in 1996, with the intent of directly detecting WIMP dark matter signal. DAMA/LIBRA-phase 1 completed data collection in 2010. The data collected corresponded to 7 annual cycles [160]. Phase II began in January of 2011. The combined results of DAMA/LIBRA and its predecessor, the DAMA/NaI experiment, report a cumulative signal of $\sim 9.3\sigma$, with an combined exposure of 1.33 ton-year and correspond-

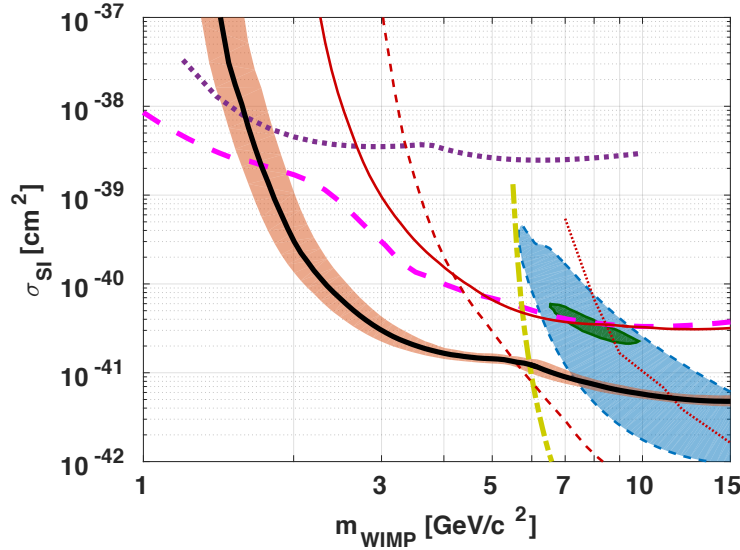


Figure 1.18: SI cross-section versus WIMP mass for the low-mass search region. Black limit is the median limit of CDMSlite Run 2 from Monte Carlo sampling, with the salmon band as the 95% confidence interval. Also shown are CDMSlite Run 1 (red thin solid), SuperCDMS LT (red thin dashed), CRESST 2016 (magenta thick dashed), LUX 2014 (yellow thick dot-dashed), DAMIC 2012 (purple thick dotted), and EDELWEISS 2012 (red thin dotted). The filled regions are CDMS II - Si 2013, 90% confidence level (blue dashed) and CoGeNT 2013, 90% confidence level (green solid). Figure from [159].

ing to 14 annual cycles. Although the experiment by far represents the most significant and longest continual data collection, lack of background discrimination and a failure to reproduce the detection in any other experiment has resulted in widespread skepticism over the interpretation of the result as a true dark-matter signal.

While a dark matter interpretation of the signal is in strong tension with several other direct detection experiments, a viable explanation from known backgrounds has not been established. Muons have been ruled out as the source of the modulation, and while speculation over contamination from the radioactive isotope ^{40}K has been explored, that interpretation is also still in question. Few other backgrounds are expected to produce an annually modulating signal, so the question of origin remains open for debate. Because of the persistence of the signal, the unreproduced signal, and the lack of conclusive evidence for a particular background, new experiments using the same detector substrate have been developed and are expected to come online in the next few years. One experiment which has already set limits and demonstrated proof of principle is DMice-17, a NaI experiment in the Southern Hemisphere in the IceCube array made from the same detector substrate (NaI(Tl)) substrate as the DAMA. Other upcoming experiments of a similar nature include SABRE, NAIAD, and the combined efforts of the COSINE collaboration [161, 162].

CoGeNT

The CoGeNT experiment is a point-contact germanium detector located in Soudan. While the detector only collects ionization and does not possess the same type of nuclear recoil/electron recoildiscrimination capabilities as a CDMS detector, the ultra high purity, low background experiment is sensitive to very low energy thresholds. One of the original motivations of the CoGeNT experiment was as a test of the DAMA experiment. In 2011 the CoGeNT experiment reported both an excess in the recoil event rates measured by the detector and an annually modulating signal, though neither approached discovery significance [136]. In 2014, the collaboration released an extended data set with over 3 years of data and a reanalysis of modulation. The collaboration reported the persistence of the modulation signal, though somewhat reduced in significance [139]. The MALBEK collaboration, however, in large part a replication of the CoGeNT experiment, reported no excess beyond expected backgrounds, in strong tension with the CoGeNT result. Furthermore, the regions of interest reported by the CoGeNT collaboration from the observed excess and modulating signals were in tension with the results from DAMA/LIBRA, making it unlikely (in the simple WIMP hypothesis) that the two reported results were of the same origin.

CRESST-II

The CRESST experiment, designed to collect phonons and scintillation for the discrimination of nuclear and electronic recoils, reported an excess of the event rates above expected backgrounds. Subsequent investigation and reanalysis revealed an unforeseen population of backgrounds arising from radioactivity.

CDMS II-Si

The Silicon-32 detectors of the CDMS II experiment were analyzed and reported three events in the signal region. The significance did not rise to the level of discovery. All three events were located close to the detector thresholds. Nevertheless, a dark matter interpretation of the excess events could not be ruled out.

XENON10

The XENON10 experiment conducted low-threshold searches for light dark matter using the S2-only signal. In addition, the collaboration searched for annual modulation in both the nuclear and electronic recoil events.

CDMS II-Ge and SuperCDMS-LT Soudan

The CDMS II low-energy germanium analysis and more recently, the analysis of the low-threshold SuperCDMS Soudan data, reported no excess above expected backgrounds, in strong tension with signals of both the DAMA/LIBRA and CoGeNT collaborations.

CDMS-lite

The CDMSlite experiment is an alternative operation mode of the CDMS detection technology which uses a relatively high voltage to enhance the Luke-Neganov gain to the phonon signal from ionization. Several iterations of the CDMSlite experiment have achieved very low thresholds of sensitivity and explored new parameter space. Both CDMSlite Run I and CDMSlite Run II have reported no excess above expected backgrounds.

LUX

The LUX experiment [163, 164] was a large scale liquid xenon experiment based at the Sanford Lab in Lead, South Dakota. As a dual-phase time projection chamber, LUX used both scintillation and ionization to discriminate against backgrounds in the search for WIMPs. The large mass of liquid xe provided high exposures. LUX has reported no signal above expected backgrounds [131].

Theoretical Attempts at Reconciliation

Work on the reconciliation of the dark matter question has been approached from both astro- and particle physics. Recent attempts at reconciliation of the tension between high- and low-redshift parameter values includes a model in which a small fraction of the primordial dark matter decays at late times [165]. Several theoretical attempts to reconcile the conflicting low energy results have been advanced, including inelastic dark matter (2001), magnetic inelastic dark matter, (2010), asymmetric dark matter, and “forbidden” dark matter, among others. In addition, variations to halo assumptions and alternative effective field theory operators have been explored for parameter space in which all of the experimental results could coexist. Many of the alternative theories have largely been ruled out, and alternative halo models have been unable to reconcile the differences between experiments. A few of the effective field theory (EFT) operators have shown cases where dependence upon particle momentum and spin have caused important differences between the WIMP-nucleus interactions of various targets, but have also been unable to fully resolve the tension, although in many cases or scenarios the tension can be reduced [166].

In this context, we now discuss the search for a modulating signal in the CDMS II data with the incorporation of background subtraction.

Part II

Second Part

Chapter 2

The Cryogenic Dark Matter Search Experiment

2.1 CDMS & CDMS II

In Chapter 1, we discussed the evidence for the existence of dark matter in the universe and strongly motivate the weakly interacting massive particle (WIMP) as an interesting class of particle candidates for its nature. We also briefly discussed the physics of interactions between WIMPs and baryonic matter, the primary measurable signals that would be expected from such interactions, and the physical data required to search for and detect these signals. In this chapter, we overview the structure and operation of one experiment designed to search for these signals: the Cryogenic Dark Matter Search Experiment.

CDMS

The first Cryogenic Dark Matter Search (CDMS) Experiment was a low-background, direct-detection experiment designed to simultaneously measure ionization and phonons from particle interactions within the detector. The detector was specifically designed for the identification of nuclear recoil events and the discrimination of backgrounds [115]. The experiment began running in 1996 in a shallow underground site (~ 17 meters water-equivalent (mwe)) at Stanford University. After moving to Soudan Underground Laboratory (Soudan), the experiment was recommissioned with the same six detectors as the new Cryogenic Dark Matter Search II (CDMS II), and continued operation well into 2004. The detectors were upgraded in 2005, and resumed low-background WIMP-search data collection in 2006.

CDMS used (and continues to use) ultra-high purity ^{29}Si and ^{73}Ge crystals as the target material for its detectors. Small energy deposits from incident particles can be detected in cryogenic (~ 10 mK) semiconducting crystals, even in relatively large amounts of mass [167]. An energy deposition from an incident particle results in both the production of vibrational modes (that is, heat) known as *phonons* within the crystal, and in the displacement of charged particles (*ionization*). When energy is deposited, the (very) low specific heat and

fast thermal response of the semiconducting crystals (when cooled to $\sim$ mK temperatures) result in measurable changes in temperature throughout the crystal, which can be picked up by sensors on the crystal surface with relatively fast recovery times. In CDMS, the crystals were maintained at approximately 20 mK. The ionization is simultaneously collected by electrodes at the top and bottom of the detector, which are also patterned on the crystal surface.

Phonon Sensors

The early CDMS detectors featured one of two types of phonon sensors, each of which used a different method to measure the recoil energy of an interaction. The first detectors used neutron-transmutation-doped (NTD) germanium thermistors to detect the temperature rise from the deposited energy [115]. These bolometers, known as Berkeley Large Ionization- and Phonon-based (BLIP) detectors, were generally implemented on Ge targets, and actually used two NTDs per detector in order to reject events originating in an NTD that might otherwise mimic nuclear recoil events because of low ionization.

The second method of phonon detection used in the early CDMS experiment was based on the Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge sensor (QET). Rather than measuring the rise in temperature (essentially the collection of thermal phonons) as with the use of NTDs, QET technology focuses on the collection of non-equilibrium phonons before thermalization (athermal phonons) [168].

In a QET, voltage-biased tungsten Transition Edge Sensors (TESes) are maintained near the bottom of their superconducting transition by negative electrothermal feedback. Each TES consists of a tungsten line with aluminum fins to facilitate the rapid capture and concentration of the quasiparticles produced when an event occurs in the detector, depositing energy and breaking Cooper pairs [169]. These quasiparticles are absorbed by the aluminum and trapped in the deposited layer between, releasing energy in the form of phonons. As the energy from these initial (“prompt” or athermal) phonons is absorbed, the temperature of the TES rises and the sensor changes from superconducting to normal, with the accompanying rise in resistance. This change in resistance is measured by the electronics [170] as the change in the flux from the inductor is picked up by superconducting quantum interference device (SQUID) amplifiers and measured as a pulse. The time integral of the signal produced is proportional to the energy deposited in the detector. The QET is the combination of SQUID readout and TES phonon sensor array. The Si detectors on which the QET technology was first implemented were known as Fast Large Ionization- and Phonon-based (FLIP) detectors [171, 172].

The major advantage of the FLIP detectors was the ability to exploit the timing information encoded in the signals from the athermal phonon collection. Each detector was patterned on one side with four phonon sensors. Fast collection times for the athermal phonons provided relative timing information between the sensors that allowed 2-dimensional position reconstruction of events to within a few millimeters [115]. In addition, differences in the pulse rise times between events originating in the dead layer near the surface - where charge

trapping led to incomplete ionization collection - and events arising from interactions in the bulk of the detector provided the ability to reject surface events, resulting in a tremendous improvement in sensitivity. Subsequent CDMS detector designs have all adopted the QET-based technology; some are further discussed in Section 2.1.

Ionization Sensors

Both BLIPs and FLIPs were patterned with ionization electrodes on both sides of the detector, with the bottom surface contact (opposite the phonon sensors) split into an inner region and an outer guard ring separated by approximately 1 mm. This configuration provided radial position information and identification of events occurring near the outer cylindrical wall of the detector, where charge trapping on the wall could again result in incomplete ionization collection. A small bias voltage ($\mathcal{O}(1 \text{ V cm}^{-1})$) was applied across the bulk of each detector to assist in the efficient collection of ionization [115].

CDMS II

The background-subtracted search for annual modulation described in this work uses data collected during the CDMS II experiment. Much of the infrastructure (Section 2.1) and detector technology established in CDMS were subsequently carried over into CDMS II and later implementations of the experiment. While the first run of CDMS II was conducted using the same six detectors as were run at the original shallow site, in 2005, a full complement of TES-based detectors (now known as Z-sensitive Ionization and Phonon (ZIP) detectors) were implemented to further reduce the impact of the dead layer of material prone to incomplete charge collection near the surface of the detectors (see also Section 4.2).

Z-sensitive Ionization and Phonon-mediated (ZIP) Detectors

As discussed in Section 2.1 the CDMS detection paradigm depends upon the collection of two signals: ionization and phonons. The designs of the detectors by which these signals are collected has evolved significantly over the course of the experiment, but the general principles remain the same.

The ZIP detectors developed for use in CDMS II were patterned with four phonon channels on top (Figure 2.1) and two ionization channels on the bottom, and as in CDMS, were read out using a SQUID array [170]. Each detector was a 250 g ^{73}Ge or 100 g ^{29}Si crystal, 1 cm thick, with 7.5 cm diameter [173]. The design of the detector allowed for radial positioning of events, as well as pulse-shape discrimination of surface and bulk events based on rise time (surface events have faster rising edges than bulk events) [174]. The cryogenics, infrastructure, and shielding setup of CDMS II are described in section 2.1.

In CDMS II detectors, the ionization and phonons are primarily collected on opposite sides of the detector. The bottom surface of the detector is photolithographically patterned with two concentric charge electrodes, designated as an inner charge electrode and an outer

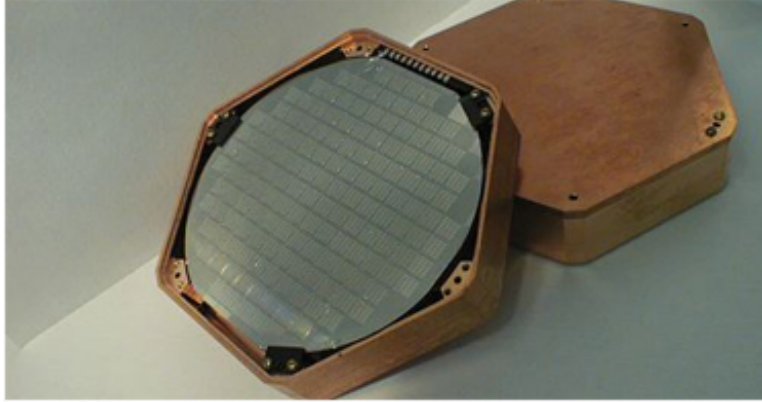


Figure 2.1: A Z-sensitive Ionization and Phonon (ZIP) detector from the installation of CDMS II at Soudan Underground Laboratory (Soudan) in Soudan, Minnesota. Photo courtesy of the Super Cryogenic Dark Matter Search (SuperCDMS) Collaboration.

guard ring (Figure 2.3) [174]. Separation of the two electrodes provides radial information on the location of an event and a means of fiducialization of the detector volume. During operation, a voltage bias is placed across the bulk of the detector by placing both the inner and outer charge electrodes at -3 V , and grounding all of the phonon channels. Ionization released during an event in the detector drifts across the detector due to the electric field and is collected at the charge electrodes. Events that are collected primarily on the inner charge electrode, with ionization signals consistent with noise on the outer guard ring, are considered to occur within the interior bulk region of the detector. For these events, complete ionization collection can be assumed. Events for which a large fraction of the ionization is collected on the outer guard ring are designated as shared or outer charge events. Because of trapping and weak electric fields near the cylindrical wall of the detector, there is a high probability of incomplete ionization collection for events occurring at high radius. As a result, shared and outer charge events are generally rejected from WIMP search data. Such events are, however, reserved and instead used, when possible, to study detector behavior and when searching for possible sources of systematic error. Each charge channel is instrumented with a charge amplifier (Figure 2.3), the details of which are thoroughly described in [175, 170], and read out via the detector readout chain as described in [170].

The top surface of the ZIP detector is patterned with four phonon collection channels, labeled A through D (Figure 2.3). Measurement of the relative amount of phonon energy collected by each channel allows the reconstruction of the position of an event within the detector. Each phonon channel is comprised of several hundred voltage-biased TESes [174]. As in the case of the FLIP detectors, during operation, the tungsten TES is maintained near the bottom of its transition from superconducting to normal. A voltage bias is applied to all sensors in parallel, and permits the stable tuning of many sensors at once through electrothermal feedback [176, 174, 175]. The concept is quickly demonstrated with the application of Ohm's law: when the temperature of the TES is raised, the resistance increases,

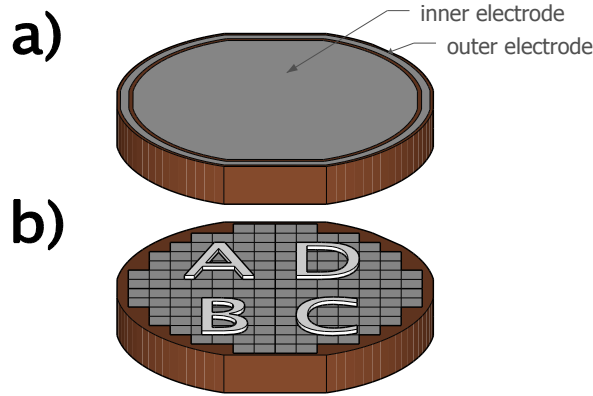


Figure 2.2: Diagram of patterned germanium ZIP detector faces. Figure by A. Villano (SuperCDMS Collaboration).

and the current through the circuit decreases, which reduces the load and pushes the system back toward a lower temperature. When the temperature of the TES decreases, the resistance decreases, and the current through the circuit increases, with the accompanying increase in power and the tendency of the system to push the circuitry back toward higher temperatures due to Joule heating [115, 175]. This negative electrothermal feedback results in a stable equilibrium for the operation of the sensors. A separate SQUID array is used for each of the four independent phonon channels of the detector (Figure 2.3).

Apparatus

The CDMS II experiment was assembled into five towers, each housing six detectors. This payload was housed in a cryostat cooled to approximately 50 mK for WIMP search operations. A layer of ancient roman lead surrounded the icebox to provide shielding from neutrons. A layer of polyethylene shielding surrounded the ancient lead, while another layer of lead surrounded the polyethylene shielding. The entire assembly was surrounded by an active muon veto of scintillator paddles to signal the incidence of charged high energy muons that would otherwise provide an additional background to the experiment [174].

2.2 SuperCDMS

The third implementation of the CDMS technology was SuperCDMS.

The recently concluded SuperCDMS Experiment was run in the same experimental configuration as CDMS II, replacing the CDMS II detectors with a new payload of 15 double-sided Interleaved Z-sensitive Ionization and Phonon (IZIP) detectors. These detectors featured an updated mask design in which the phonon sensors and ionization electrodes were patterned together in an interleaved design on both the top and bottom surfaces of the de-

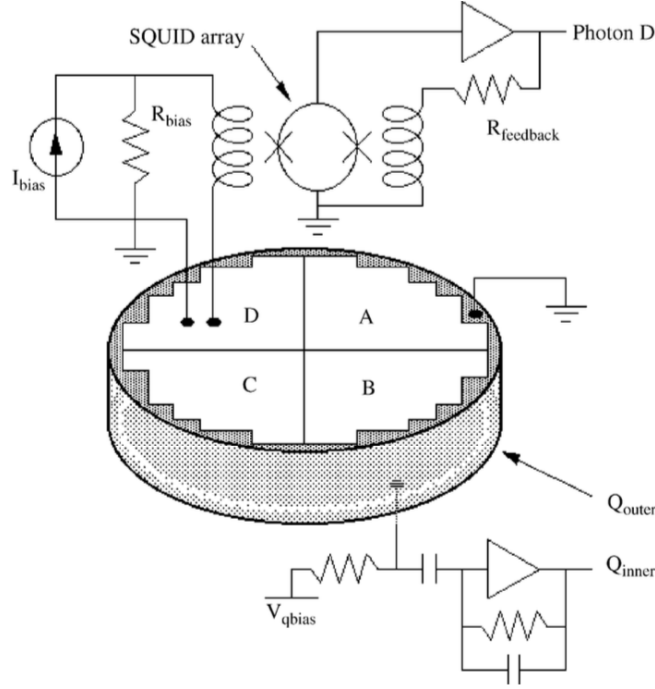


Figure 2.3: Schematic diagram of a CDMS II ZIP detector and readout electronics. Diagram from [173].

tector. When a voltage was placed across the crystal, this configuration created a uniform electric field in the bulk of the detector, and high fields near the flat surfaces, resulting a dramatic improvement in ionization collection and the discrimination of bulk and surface events over the performance of previous detectors [177].

The next implementation of CDMS: SuperCDMS (SNOLAB). This is the generation 2 project selected to look for low-mass dark matter, supported by DOE, NSF, CFI, and NSERC, and located at SNOLAB, the deepest laboratory in North America [158, 178, 179].

While the IZIP represented a significant advancement in detector technology, the germanium ZIP detectors used in CDMS II provided nearly background-free discrimination of nuclear recoil events to thresholds as low as $10 \text{ keV}_{\text{nr}}$ (keV, assuming a nuclear recoil event), and discrimination against backgrounds to energy thresholds as low as $2.27 \text{ keV}_{\text{nr}}$. This thesis describes a background-subtracted modulation analysis of the low-energy germanium data collected during the six five-tower runs of CDMS II between October 2006 and November 2008.

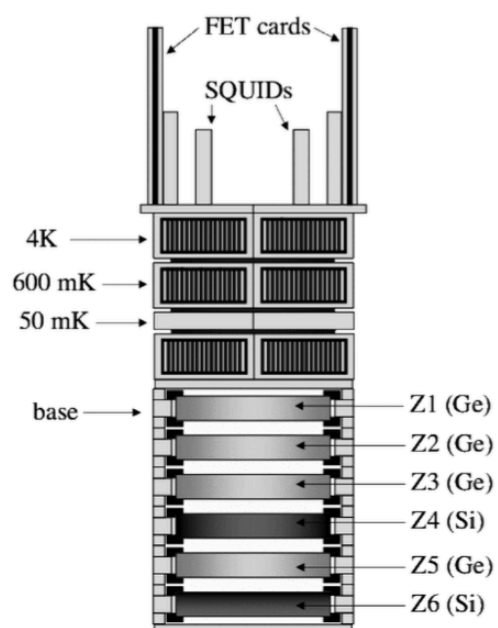


Figure 2.4: Tower Diagram. Figure from [174].

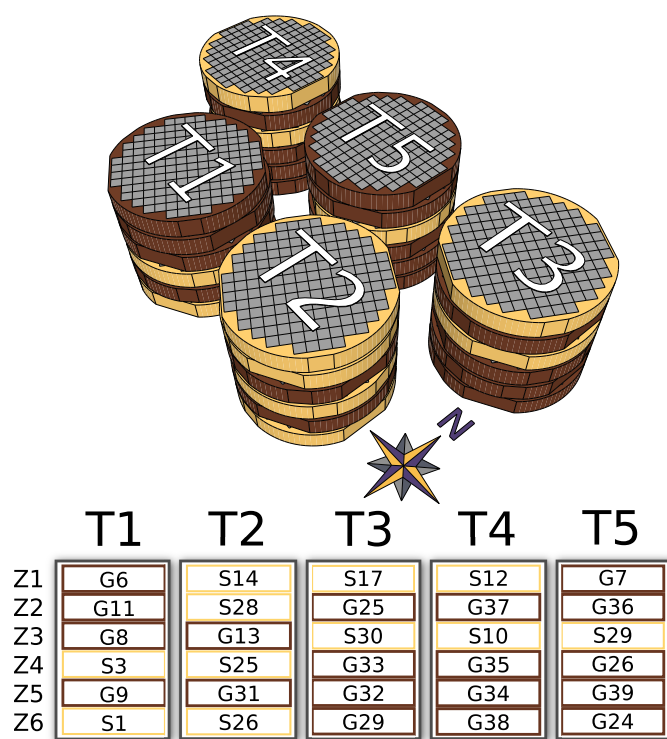


Figure 2.5: CDMS II tower array. Figure from [142].

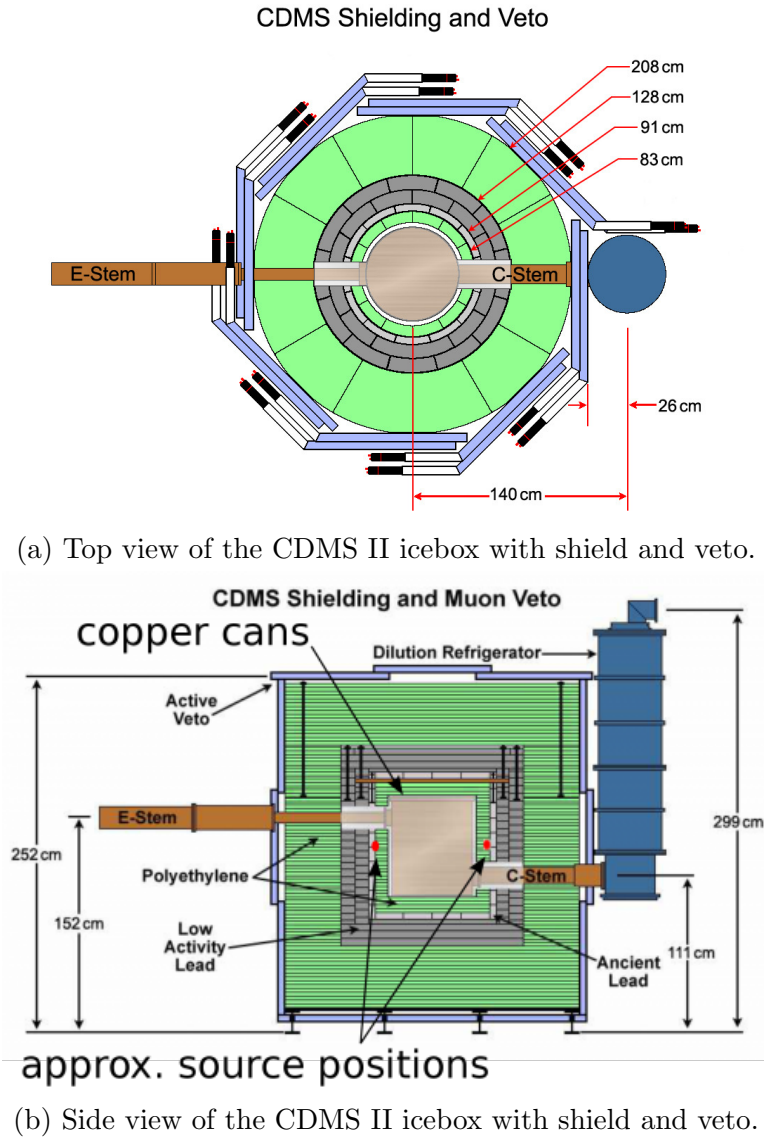


Figure 2.6: Top (*left*) and side (*right*) view diagrams of the CDMS icebox, shield and veto. Figures by R. Bunker and J. Sander, SuperCDMS Collaboration.

Chapter 3

Science Results of the Cryogenic Dark Matter Search Experiment

3.1 WIMP-search Overview: Results from CDMS and CDMS II

The CDMS family of experiments has placed world-leading limits on the strength of the spin-independent interaction between WIMPs and standard model nucleons, for a wide range of WIMP masses [135, 141, 159, 180, 181]. With the exclusion of large amounts of parameter space for the most general WIMP candidates, and further reduction of the high-WIMP-mass landscape by more recent experiments with very large exposures (see Chapter 1), the CDMS experiment and its subsequent generations have become increasingly attentive to the low-energy frontier, at which the detector sensitivity and low-background performance of CDMS provide a unique edge in the search for low-energy interactions and light-mass WIMPs.

High-Energy Threshold Searches for High-Mass WIMPs

Exclusion limits on the WIMP-Nucleon Cross Section from the Cryogenic Dark Matter Search (2000)

The CDMS experiment reported first exclusion limits [180] from a search for WIMPs at the Stanford Underground Facility (SUF), based on the results from two sets of data: an initial data set collected by a 100 g Si ZIP detector, and a second data set collected using three 165 g Ge BLIPs (for a description of BLIP and ZIP detectors, see Chapter 2), with net exposures (after cuts) of 1.6 kg d and 10.6 kg d, respectively. The analysis threshold was 10 keV to 100 keV. Only single-scatter nuclear recoil events were considered as candidates, because of the negligible rate of interaction of a single WIMP in more than one detector. Four single-scatter nuclear recoil events were observed from the Si exposure. The Ge exposure yielded 13 single-scatter events, along with 4 multiple-scatter nuclear recoil events.

A WIMP interpretation of the nuclear recoil events observed in CDMS was disfavored for several reasons. First, a WIMP interpretation of the 4 Si events, assuming the conventional spin-independent (SI) interaction, would require a larger rate of single-scatter nuclear recoil interactions than those observed in the Ge exposure. The topology of the events also precluded their explanation as low-energy electronic recoils from surface electron scatters, indicating that the Si events were instead a measurement of the unvetted neutron background [180]. Second, the 4 Ge multiple-scatter events were readily identifiable as nuclear recoil events, being well-separated from the region of potentially mis-identified electronic recoils. Third, with the inability to interpret the Si events as arising from anything other than the neutron background, the observed numbers of events provided “reasonable agreement” with the relative expected rates of Si single-scatter and Ge single- and multiple-scatter rates from neutron interactions, as predicted by a Monte Carlo study normalized to the number of expected events. The number of nuclear recoils in Si and the number of multiple scatters in Ge were used as constraints on the unvetted neutron flux in an analysis to determine the 90% CL on the excluded region for the WIMP mass and SI elastic scattering cross section.

The experiment excluded new parameter space with an upper limit on the WIMP-nucleon SI cross section. The experiment also excluded the 3σ allowed region for the WIMP signal reported by DArk MATter (DAMA) (DAMA/NaI from years 1 to 4) at 84%, though remaining potentially compatible with the exclusion limits set by DAMA/NaI-0 [182] and dark matter interpretations based on alternative WIMP-nucleon interaction scalings. Additional details of this analysis are provided in [180] and references therein.

Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory (2009)

The exposure and sensitivity of the CDMS experiment were greatly enhanced with an increased detector mass and relocation to a new deep underground site at Soudan, where an increased rock overburden provided additional protection from the muonic cosmic ray background event rate.

Following an initial run with the original CDMS tower at the new site [174], thirty detectors were employed at Soudan, divided into five towers of six detectors, with each detector constructed from a high-purity Ge or Si crystal substrate. After conducting a blind analysis of the first data from the full five-tower complement of ZIP detectors, CDMS II reported an upper limit on the WIMP-nucleon spin independent cross-section of $\sigma_{\text{SI}} = 6.6 \times 10^{-44} \text{ cm}^2$ for a WIMP of mass $60 \text{ GeV}/c^2$, for recoil energy depositions in the range 10 keV to 100 keV. Additional details of the analysis are discussed in [183].

Dark Matter Search Results from the CDMS II Experiment (2010)

A second search for WIMP dark matter with CDMS II significantly increased the exposure reported in [183]. Again using a blind analysis to search for high-mass WIMP interactions in

the recoil energy range 10 keV to 100 keV, two events were observed after unblinding, with an expected background of 0.9 ± 0.2 events. The experiment reported an upper limit on the WIMP-nucleon interaction cross section of less than $70 \times 10^{-44} \text{ cm}^2$ for a WIMP of mass $70 \text{ GeV}/c^2$.

With both sets of five-tower data, the combined upper limit on the spin-independent WIMP-nucleon cross section was reduced to $3.8 \times 10^{-44} \text{ cm}^2$ for a $70 \text{ GeV}/c^2$ WIMP. Additional details of this analysis are discussed in [184]. An extended analysis of reprocessed CDMS II data is discussed in [142].

Low-Threshold Germanium WIMP Searches

Lowering the energy threshold of CDMS II analyses increases sensitivity to low-mass WIMP interactions at the expense of weaker discrimination between nuclear and electronic recoils. Even with reduced background discrimination, however, several analyses of the low-energy data collected during the CDMS II experiment place strong upper limits on the interaction cross section of low-mass WIMPs with standard model nucleons, and set the stage for the annual modulation searches discussed throughout Chapters 4 and 5. The low-energy germanium analyses were conducted on data collected from the eight detectors with the lowest thresholds, using the remaining 22 detectors to veto multiple-scatter events. For low-WIMP-mass searches, the low energy thresholds achievable in the high-purity germanium detectors results in a better sensitivity than that generally achieved in the Si detectors [185]. As a result, only germanium detectors are used to search for low-mass WIMPs.

Analysis of the Low-Energy Germanium data from Stanford shallow-site (2010)

Low-energy germanium analyses from Soudan (2011)

CDMS II reported results from low-energy germanium analyses conducted in a shallow-site laboratory at Stanford University and at Soudan. The 2011 Soudan study on nuclear recoil candidate events in the range $2.27 \text{ keV}_{\text{nr}}$ to $11.9 \text{ keV}_{\text{nr}}$ [186] established a SI upper limit of $\sim 4 \times 10^{-41} \text{ cm}^2$ for a WIMP mass of $8 \text{ GeV}/c^2$. The experiment reported no excess above the expected backgrounds.

CDMS II-Silicon Results (2013)

Other Searches

Search for Inelastic Dark Matter with the CDMS II Experiment (2011)

Beyond the assumption of elastic scattering (Chapter 1), the standard WIMP paradigm can be extended to consider inelastic dark matter [187], in which the scattering of WIMPs from target nuclei only if it induces an excited state of the WIMP of some specific minimum energy, with elastic scattering either highly suppressed or forbidden. This alters the expected

recoil energy spectrum of the target nuclei, and varies with the mass splitting (δ_χ) between the ground and excited states of the WIMP.

Extending the energy range of analysis to 150 keV, CDMS II searched for signs of inelastic dark matter collisions in the high-threshold analysis data [188]. The entire set of germanium data from CDMS II was reanalyzed to optimize the rejection of surface event backgrounds and increase the sensitivity to inelastic dark matter.

Between 25 keV to 100 keV, three candidate events were observed (in the specified range, the probability of observing 3 or more events is 11%). The limits set by the inelastic dark matter analysis were, in general, slightly weaker than those of the standard analysis for all mass splittings to which CDMS II was sensitive. For the case $\delta_\chi = 0$, the weaker limit was because the redefined surface-event cut was more loosely defined than in the standard analysis (by design): the inelastic dark matter recoil energy spectrum actually significantly decreases below 25 keV and becomes negligible, and the looser cut yields the benefit of higher efficiency and increased sensitivity to inelastic scattering events. For the case of elastic scattering, however, the recoil energy spectrum due to WIMPs increases with decreasing energy. The increase in the number of background events from the looser cut in the energy region below 25 keV weakens the limit in the case of elastic scattering. For higher mass splittings ($\delta_\chi = 120$), the observation of the three candidate events above 25 keV also weakened the limits on inelastic scattering in comparison to the projected sensitivity of the experiment. Nevertheless, both analyses exclude the vast majority of the region of $m_\chi - \delta_\chi$ parameter space allowed by an inelastic dark matter interpretation of the second generation DAMA (DAMA/LIBRA) signal [188].

With these limits on the WIMP-nucleon spin-independent interaction cross section, and those described for many other experiments as described in Chapter 1, we turn our attention to the low-energy threshold, and discuss searches for the less standard but increasingly interesting scenario of low-mass ($\mathcal{O}(10)\text{GeV}/c^2$) WIMPs (for a brief description of “low mass WIMPs”, see Chapter 1).

Search for Annual Modulation (2012)

While the primary search mode of current direct detection experiments is to search for an excess of nuclear recoils, an expected hallmark of a true WIMP signal is the presence of both an excess and modulation in the nuclear recoil event rate. Even the absence of one or the other of these components, the detection of either signature may provide an important clue for the elimination of previously unexpected backgrounds at low thresholds, and help to provide some resolution of the tension between conflicting direct detection results.

Overview of the Search for Annual Modulation to 5 keV_{nr} (2012)

Using the low-energy data set defined during the low-threshold germanium analysis, the CDMS collaboration searched for an annually modulating signal in CDMS II in the data covering the low-energy range from 5 keV_{nr} to 11.9 keV_{nr}. The modulation amplitude was

constrained to less than $0.06 \text{ [keVkgd]}^{-1}$ at the 99% confidence level. The results of the search for annual modulation were reported in [189]. Work on extending the analysis to lower thresholds was performed by S. Hertel and discussed in internal CDMS documentation.

Summary

The CDMS WIMP search results have established upper limits on both the spin-dependent (SD) and SI cross sections of interaction for WIMPs. So far, no detection or unambiguous rate excess has been reported. The focus of this dissertation is the background-subtraction of the search for annual modulation and selected systematics studies, as discussed in Chapters 4, 5 and 6.

Chapter 4

Introduction to the Search for Annual Modulation in CDMS II

Chapters 1, 2, and 3 described the motivation for WIMP dark matter searches, a description of detectable signals, CDMS detector technology designed to search for such signals, and results of searches so far conducted by the CDMS and SuperCDMS experiments, primarily for the excess rate signal in nuclear recoil events. We now shift to the focus of the present work, which is a background-subtracted search for an annual modulation in the rate of nuclear recoil events collected during CDMS II. We begin in this chapter by briefly describing the data selection process and the measurement of selection efficiencies, focusing in particular on those not shared with the previous CDMS low-energy germanium analyses. We describe a search for annual modulation in the low energy data without the use of background subtraction, to set the stage for the background-subtracted analysis. The unsubtracted modulation search described here is a modified reproduction of the search described in [190], originally reported in [189]. For this work, we use an alternative model and have implemented several changes to facilitate more robust performance and better estimation of the modulation parameters. The unsubtracted results presented in this chapter are consistent with those reported in [190], and provide a useful framework for expansion of the analysis to include subtraction of backgrounds.

4.1 The Low-Energy Data Set

The full CDMS II experiment was run at Soudan Underground Laboratory (Soudan) from October 2006 until November 2008 with a complement of 19 Ge and 11 Si detectors. The CDMS II low-energy dataset consists of the data collected during low-background WIMP-search Runs 123-128, spanning the entire period of operation at Soudan.

As described in [185], only Ge detectors were selected for the low-energy analysis due to the higher relative background rate of the Si detectors, which were only approximately 50% as massive as the Ge detectors. Furthermore, the detectors in Towers 4 and 5 possessed poorer

Detector	Mass
T1Z2	0.2276 kg
T1Z5	0.2193 kg
T2Z3	0.2193 kg
T2Z5	0.2389 kg
T3Z2	0.2312 kg
T3Z4	0.2389 kg
T3Z5	0.2389 kg
T3Z6	0.2317 kg

Table 4.1: Detector selection for the search for modulation in CDMS II

phonon energy resolution due to smaller pulse amplitudes, so only detectors from Towers 1, 2, and 3 were selected. Detectors 1 and 3 in Tower 1 (T1Z1 and T1Z3) were excluded from the analysis because of malfunctions that prevented the readout of all channels on these detectors. The eight remaining germanium detectors from Towers 1, 2, and 3, however, were all used for the low-threshold analysis (Table 4.1). Because of the need for detector stability in the search for annual modulation, the energy threshold for each of the eight detectors was selected by using the range over which the trigger efficiency for the detector was essentially ~ 1 . The low-energy detectors and the thresholds of each as applied for the annual modulation analysis are listed in Table 5.2 of Chapter 5.

Data collected during WIMP-search operations are processed according to the description in [185, 175]. Raw detector data are collected and converted to *reduced quantities (RQs)* which include measurement baselines, pulse amplitudes, rise times, trigger information, and experimental run-mode. The RQs are then taken through a second level of processing and calibration to calculate and produce the relational reduced quantities (RRQs), which consist largely of physical quantities such as phonon and charge sensor energies, sensor delays, yields, timing, and position information. The second-tier RRQ data are then used in higher level analysis tasks to define cuts, study backgrounds, calculate efficiencies, and ultimately, in the estimation of the physical parameters under study.

For most CDMS and CDMS II analyses, the phonon-based timing quantities are important for position information and the discrimination of surface events. For the energies less than ~ 10 keV, however - almost the entire range of the low-threshold analyses - poor signal-to-noise and the rising domination of electronic noise results in poor estimation of the delay quantities, so that the charge position correction is no longer effective and the phonon position correction no longer improves the resolution (see chapter 3 of [185]). An energy-dependent calibration is still applied in order to address energy-dependent nonlinearities in the phonon response [185]. One consequence of these limitations, in addition to a decrease in the ability to discriminate via ionization yield, is a reduction in the ability to

discriminate against surface backgrounds known as zero charge or zero yield events, believed to be caused by incomplete collection of ionization from high radius events near the surface of the detector. These events are further described in Section 4.3.

The initial CDMS II germanium detector analyses employed a data blinding strategy to remove the region where a signal could appear from consideration until the final analysis in order to avoid bias. The general blinding strategy is described in [191]. The CDMS II low-threshold germanium analysis, low-threshold germanium likelihood analysis, and the annual modulation searches, including the search described in Chapter 5, were first performed post-unblinding of the CDMS II germanium detectors. These are not considered blind analyses in the traditional sense. The signal region was not hidden from the analyzers, but a small fraction of the data were separated and reserved for the re-optimization of cuts and efficiency measurements prior to analysis.

4.2 Backgrounds

Low-level counting experiments in general, and CDMS II in particular, face unique challenges in mitigating background radiation levels to reach required experimental sensitivities.

There are numerous background event sources for CDMS II, many of which are common to any rare event search. Most known background sources are not anticipated to significantly modulate with an annual period of the phase and properties expected from a dark matter signal. However, all can contribute to the overall unmodulated event rate, and seasonal effects in some backgrounds may in a few instances potentially mimic or hide a true modulation. Several sources of backgrounds and the steps taken for mitigation in CDMS II are detailed in [174]. Where possible, steps are taken for mitigation prior to the experiment; where contamination exists, simulation and characterization allow estimation of the expected backgrounds.

Backgrounds in CDMS II

Trace amounts of U, Th, and ^{40}K , in most natural materials results in low levels of radiation throughout the laboratory environment. Products from the U and Th decay chains, such as Rn and Pb, which are themselves radioactive, are major sources of contamination on surfaces and during fabrication of detector materials. Shielding, high-purity fabrication techniques, and cleaning are all used to mitigate environmental sources of radioactivity. Beyond this, characterization and accounting of remaining sources of radioactivity is needed to understanding the background spectrum of the experiment.

In the search for WIMPs, the annual modulation of the event rate is believed to be an unambiguous characteristic allowing discrimination of a genuine signal in the presence of significant backgrounds. Recently, however, measurements of the incident gamma rates in Soudan using a scintillation detector revealed an annual modulation in the gamma rate that

could potentially mimic a dark matter signature [192], and so should be understood as a systematic.

In addition to environmental radiation, cosmic rays—often high energy muons—incident on a germanium detector result in activation of the detector observed in the gamma spectrum. Expérience pour DEtecter Les WIMPs En Site Souterrain (EDELWEISS) III [143] has recently produced measurements of the cosmogenic activation of germanium detectors, including the production of tritium [193]. Furthermore, the cosmic ray muons penetrating the rock overburden can interact within the rock, and produce “cosmogenic” neutrons that add to the background radiation. Fusion of heavy radioactive impurities within the experiment and α -n interactions also produce “radiogenic” neutrons [194]. Since a neutron signal is essentially indistinguishable from that of a WIMP, characterization of the neutron signal is also required to understand the experimental background.

4.3 Event Selection

Analysis of CDMS II data exploits the event-by-event discrimination of the ZIP detector for the removal of backgrounds. At low energies, where this discrimination is degraded by the reduction of the signal-to-noise ratio, general discrimination of background and signal regions is still possible. In addition to the removal of particle backgrounds, selection criteria are applied for the removal of periods of poor data quality and detector stability.

General CDMS II Data Quality Cuts

The data quality cuts used in the analysis of CDMS-II data are designed to remove bad data periods, poor hardware performance, and poor quality pulses from the event pool. Most of these data quality cuts are also detailed in [185]. Basic data quality cuts were applied generally during all CDMS II analyses (according to run); those particularly applicable to the annual modulation analysis are described below.

Bad Times

“Bad times” are periods of data collection in which environmental factors or detector instability compromises the quality of data for analysis. A reliable measurement of modulation requires a stable detector. Several cuts were applied for the removal of bad times. These cuts ensured that selected for analysis met the following criteria:

- Voltage bias of the Ge detectors was set to 3 ± 0.1 V on both the inner and outer electrodes.
- Trigger rates of the detector remained below 0.7 Hz.
- Periods with abnormally high ionization noise were excluded.

- The QET bias tuning was stable, following initial commissioning of the detectors.
- In ^{133}Ba calibration data, a cut was applied to ensure that the low-yield fraction was within 2σ of the mean value, to reduce the occurrence of outlier events and ensure proper neutralization of the detectors.
- WIMP-search datasets taken without re-establishing the neutralization of the detector after long periods of time (> 20 hours) or following the collection of ^{252}Cf or ^{133}Ba calibration data were removed.
- Periods in which the optimal filter (OF) start time resolutions and pulse amplitudes were more than 25-35% above the means of their respective distributions (depending on the cut) for one or more channels were removed.
- Periods during power outages or other environmental interruptions were removed.
- Data with inconsistent variable distributions, determined by comparison with benchmark data sets through Kolmogorov-Smirnov tests, were removed.
- Periods in which detectors observed to be affected by helium films were removed.
- We remove periods in which trigger modes were not properly enabled and working.
- Periods with high levels of electronic noise were removed.
- Data taken within the 20 days following exposure to a ^{252}Cf calibration source were removed.

Poor Hardware Performance

Additional cuts were applied to remove periods of poor hardware performance:

- Events in detector regions with large amounts of cross-talk between detectors caused by floating grid sections of the detector phonon channels on some detectors were removed.
- Data demonstrating periods of detector instability were removed.
- Data with poor phonon reconstruction on some detectors were removed.
- All events originating in a specific quadrant of T3Z2 indicating origin in regions of poor hardware performance were removed.

Bad Pulses

Finally, analysis of the pulse shape provides an important handle in discriminating against noise events in the analysis. Events with pulse shapes inconsistent with signal pulses are identified as “bad pulses” and removed from the analysis. Several cuts defined on the quality of the collected pulses are applied for the selection of good data:

- Glitch events, which are abnormally shaped and result in a large number of phonon triggers with respect to the number of charge triggers. These are believed to actually be coherent noise on the phonon QET lines, and are removed.
- Cryocooler noise is identified by outliers ($> 4\sigma_{\text{rms}}$) of the pre-pulse charge baseline, and is removed.
- Outliers to the pre-trigger phonon and charge baseline distributions are rejected.
- Events coincident with the veto are excluded from the analysis.

Event Selection Cuts

Beyond the basic data quality cuts described above, we define additional event selection cuts during the analysis to distinguish event multiplicity and select candidate events. The following cuts were specifically used for event selection in the background-subtracted annual modulation analysis to identify the nuclear recoil signal region and identify electron recoil and zero charge events.

- All events to be considered in the low-energy analysis were subject to a raw energy cut of 0.6 to 20keV_{nr} . This cut is wider than the analysis thresholds.
- *cBlindLowE* - Although the search for annual modulation was not blind, the analysis uses the same dataset as that of the low-energy germanium analysis, in which 1/4 of the data was reserved for the calibration of low-energy cuts. This portion was not used for WIMP search.
- *cChiSq_XXX* - χ^2 cuts were defined for each run using the goodness-of-fit parameters from the charge optimal filter to remove outliers from the charge distribution.
- *cBad_XXX* - A run-based umbrella cut was defined to apply the data quality cuts described above. This cut was also used in the calculation of the experiment livetime.
- *cPsat*, *cNegPhononPulse_XXX*, *cQsat* - Events with saturated or negative phonon pulses were removed from the analysis, as were events with saturated charge pulses.
- *cMultGlitch** - Additional glitch cut based on the phonon energy was developed, particularly for use in studies involving multiple-scatter events.

- *cVTStrict_XXX*, *cVTrig*, *cNuMi_XXX* - Veto-coincident and veto-triggered events were removed, as were events received coincident with the operation of the nearby Main Injector Neutrino Oscillation Search (MINOS) detector.
- *cRTrig* - Randomly triggered events were taken throughout the experiment and used in the study of noise baselines. These events were removed from WIMP search analysis.
- *cSingle_XXX* - Selects events triggering in only 1 detector above a specified ionization energy threshold.
- *cQinle_c38* - This cut selects events primarily occurring on inner charge electrodes and consistent with the 2-sigma noise in the outer charge electrode; extended to fit a decay at low charge energies and a linear tail at high charge energies.
- *cNRle_c38* - Selects events within the 2-sigma nuclear recoil band, refit at low energies.
- *cERle_c38* - Selects events within the 2-sigma gamma (electron recoil) band, refit at low energies.
- *cZCle_const_c38* - Selects zero charge events in the 2-sigma time invariant zero charge band.

Figure 4.1 displays the selected events classified as electron recoil (red crosses), nuclear recoil (blue filled circles), and zero charge (black triangles) as a function of the recoil energy in runs 123-128 for T1Z2, while Figure 4.2 shows the rates of all selected single-scattered events in c38, divided by detector and run.

A Note on Zero Charge Events

The origin of zero charge events in CDMS II has been the object of some study. A full discussion is beyond the scope of this work. In general, these events are believed to be the results of high-radius events collected near the phonon side of the detector, where the electric field is relatively weak and trapping occurs on or near the sidewalls before the ionization generated in an event can be completely collected. Careful study may reveal a more complex morphology for these events than assumed by the cut described above, but as a good approximation and for consistency with the low-threshold analysis, any event that passes all data quality cuts (including the removal of random-trigger events) and is selected by the 2σ zero charge band defined above is considered a zero charge event.

In both the low-threshold germanium analysis and the search for annual modulation, the zero charge band is defined independently of recoil energy for each detector, and is livetime-averaged over all runs, so that the definition is also time-independent.

Because of the positive bias introduced by the optimal filter in CDMS II [185], the baseline noise, and thus the zero charge band, will in general be centered above zero. These zero charge events are among the primary backgrounds for the background-subtracted annual modulation analysis.

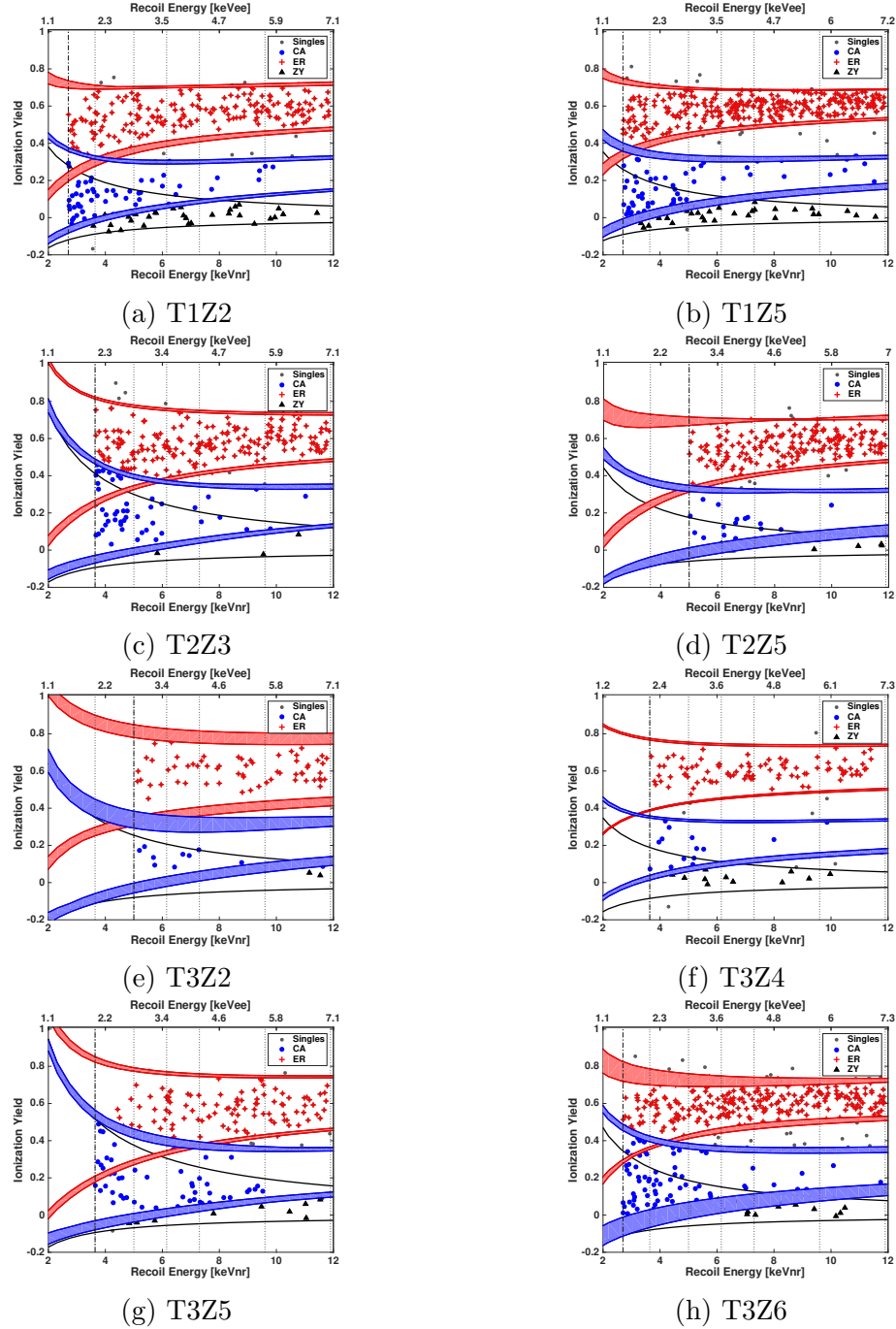


Figure 4.1: Event classification for detectors T1Z2, T1Z5, T2Z3, T2Z5, T3Z2, T3Z4, T3Z5, and T2Z6. For each region, the width of the selection bands represents the variation of the cut width over the course of runs 123-128.

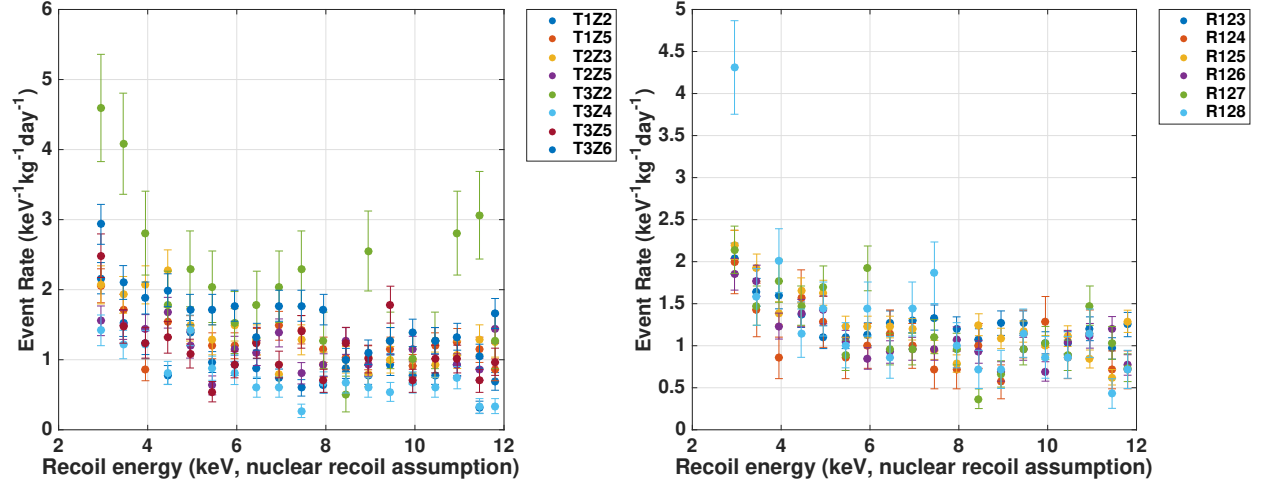


Figure 4.2: Rates of all selected single-scattered events in c38, divided by detector (*left*) and by run (*right*). Detector T3Z2 contributes a higher event rate, but with larger uncertainty, due to the reduced exposure on this detector.

4.4 Efficiencies

The final livetimes and efficiencies for the low threshold analysis were calculated by D. Moore [185]. Most of the data quality and event selection efficiencies used in this background-subtracted search for annual modulation were the same as those used for the low-threshold germanium analysis, and details are discussed in [185]. Below, we highlight details of a few specific efficiency measurements that were either originally from the low-threshold analysis but of particular importance to the modulation search, or performed specifically for use in background subtraction.

Electron Recoil Event Efficiencies

Selection Efficiency

The selection efficiencies for the electron recoil events were measured on ^{133}Ba calibration data for the low-threshold germanium analysis. The γ 's emitted in the decay of ^{133}Ba incident on the detector produce a distinct band (alternatively referred to as the gamma band or the electron recoil band) that is used to calibrate the selection cuts for electron recoils in the plane of ionization yield versus phonon energy. (The plane of ionization yield versus phonon energy is not preferred in this analysis because of the broadening of the ionization yield band at low energies.) To avoid unnecessarily skewing the efficiency measurements by considering regions far from the electron recoil band, the efficiency is measured on the pool of events falling within 3σ of the mean of the electron recoil band (see Section 4.4 and [185]). The selection efficiencies are defined as the ratio of the number of events that pass the 2σ

electron recoil acceptance cut to the number of events within 3σ of the mean of the electron recoil band (Equation 4.1).

$$\varepsilon_{\text{ER}} = \frac{(\text{ER}_{2\sigma})}{(\text{ER}_{3\sigma})} \quad (4.1)$$

The efficiencies were measured on a series of narrowly binned energy ranges and fitted to a linear form. For this analysis, measurements of the efficiencies were provided by [195]. Details on the electron recoil selection efficiency are available in [185].

Exclusion Efficiency

The electron recoil exclusion efficiencies were defined and measured specifically for the purpose of background subtraction. Consider first the events that are selected by the 2σ electron recoil band (see Section 4.3 and [185]). We define the exclusion efficiency as the efficiency with which events selected by the electron recoil band are *rejected* by the nuclear recoil band (Equation 4.2).

$$\varepsilon_{\text{ERexcl}} = \frac{(\text{ER}_{2\sigma})\text{and}(\overline{\text{NR}}_{2\sigma})}{(\text{ER}_{2\sigma})} \quad (4.2)$$

The exclusion efficiency of the electron recoil events was measured as a function of energy (E_{pt}) for each detector, for each of runs 123-128, and fitted to a logistic function via maximum likelihood, for best fit parameters a and b . Because of the large number of events in the ^{133}Ba calibration data, contamination from either of nuclear recoil or zero charge events in the electron recoil band was considered negligible for the efficiency measurement.

Zero Charge Event Efficiencies

Because the overlap of the zero charge and nuclear recoil bands is so great at low energies, and because of the potential contamination of the zero charge band with the general electron recoil band and the possible introduction of bias by over-counting low-yield events, the zero charge band selection efficiency was measured by simulated events. For the zero charge events, both the selection and exclusion efficiency measurements described below were performed specifically for the background-subtracted analysis.

Event Simulation

Throughout CDMS II, random-triggered events were collected during WIMP-search data collection, providing a means to measure the baseline noise on each detector during each 3-hour data collection series of each of Runs 123-128. Creating the scatter plot of the inner (qi) and outer (qo) ionization measurements of the random-triggered events for each detector and series produces a roughly uncorrelated binormal distribution in qi and qo for the detector-series. This distribution is known colloquially as the noise-blob distribution.

Fitting a Gaussian along the q_i direction at the center of the distribution of the random-trigger events provides the mean and standard deviation of the noise expected on the inner ionization channel of the detector. True events should register much higher; anything falling within 2σ of the mean of this distribution comprises the bulk ($\sim 95\%$) of the noise distribution. By definition, zero charge events fall within the bulk of this distribution.

Using the measured means and standard deviations from the noise and assuming a Gaussian ionization distribution as implied by the q_i - q_o distribution of the random-trigger events, we create a simulated set of zero charge events, drawing from each 3-hour series in proportion to the exposure of a given detector during that series. This allows us to recover some of the expected variation of the event distribution on a given detector that occurs from changes in the baseline noise as a function of time.

Although the definition of the zero charge band is itself time- and energy-independent, the band is applied separately to each of Runs 125-128, and the efficiency of the cut varies slightly as it is applied to simulated data from each run. This procedure was designed so that ionization distribution of the simulated zero charge events on which the efficiency is measured imitates that of the population of zero charge events collected during the course of Runs 125-128, by accounting for the time-varying shifts in the ionization noise of each run.

Selection Efficiency

The zero charge band cut defines one set of cut parameters, independent of energy and time, unique to each low-threshold detector but covering all runs of R123-128 (Section 4.3). The cut efficiency is defined as the ratio of the number of simulated events that pass the 2σ acceptance cut to the number of simulated events within 3σ of the mean of the zero charge band (Equation 4.3).

$$\varepsilon_{ZC} = \frac{(ZC_{2\sigma})}{(ZC_{3\sigma})} \quad (4.3)$$

The efficiency of the events generated from one run passing this cut will be slightly different from the efficiency of events generated in another run (e.g. R123 versus R125) passing the same cut, due to differences in exposure, livetime, and the ionization noise distribution from run to run. As a result, the run-to-run efficiencies given for even a single detector vary slightly (see Table 4.2). On average, however, the total efficiency measured on the simulated events is near the expected average efficiency of $\sim 95\%$. In Table 4.2, $\varepsilon = 0$ indicates that the specified detector was not active during a run.

Exclusion Efficiency

The exclusion efficiency of the zero charge events is measured on the simulated events in a procedure similar to that for the electron recoils, and is the efficiency of being accepted by the zero charge band cut but rejected by the nuclear recoil selection cut (Equation 4.4).

Table 4.2: Zero charge selection cut efficiencies for the low-threshold detectors, CDMS II Runs 123-128 (rounded).

Run	T1Z2	T1Z5	T2Z3	T2Z5	T3Z2	T3Z4	T3Z5	T3Z6
123	0.97	0.95	0.95	0.92	0.96	0	0.96	0.96
124	0.97	0.95	0	0	0	0	0	0
125	0.96	0.96	0.96	0.97	0.96	0.96	0.96	0.96
126	0.95	0.96	0.96	0.96	0.96	0.96	0.96	0.95
127	0.94	0	0.96	0.97	0.95	0.96	0.95	0.95
128	0.94	0	0	0	0.96	0.95	0.95	0.96

$$\varepsilon_{\text{ZCexcl}} = \frac{(\text{ZC}_{2\sigma})\text{and}(\overline{\text{NR}}_{2\sigma})}{(\text{ZC}_{2\sigma})} \quad (4.4)$$

The efficiency was measured on large samples of simulated data binned in very fine energy ranges, so that no functional fit to the final form was necessary.

Chapter 5

Background Subtraction of the CDMS II Search for Annual Modulation

5.1 Background Subtraction in CDMS II

As discussed in Chapter 4, both the electron recoil and zero charge event bands substantially overlap the nuclear recoil band at low energies, potentially contributing a significant number of background events to the set of candidate events. The energy at which the overlap between the electron recoil, zero charge, and nuclear recoil bands becomes important varies significantly from detector to detector and from run to run. Figure 5.1 demonstrates the relative positions of the nuclear recoil, electron recoil, and zero charge yield bands (see Section 4.3) for detector T1Z2, during Run 123 (see Section 4.1).

Background subtraction accounts for this by including background contributions in the modeling and likelihood estimation of the candidate event rates, and therefore by incorporating the error on the measurements of the backgrounds directly into the estimation of the confidence intervals on the maximum-likelihood estimates. The procedure described in this work simultaneously fits the likelihoods for the total background event rates and the rates of the nuclear recoil events, using efficiency-corrected estimates of the backgrounds based on their event rates outside of the signal region.

Data

The data used in the background-subtracted search for annual modulation were collected during CDMS II runs 123-128 (collectively referred to as c38; see section 4.1). For this analysis, data are separated by detector and separated into 16 time and 6 energy bins. The 16 time bins are each approximately 25 days long, with eleven ^{252}Cf neutron calibration periods interspersed between (see Figure ??). The 20 days following each neutron calibration

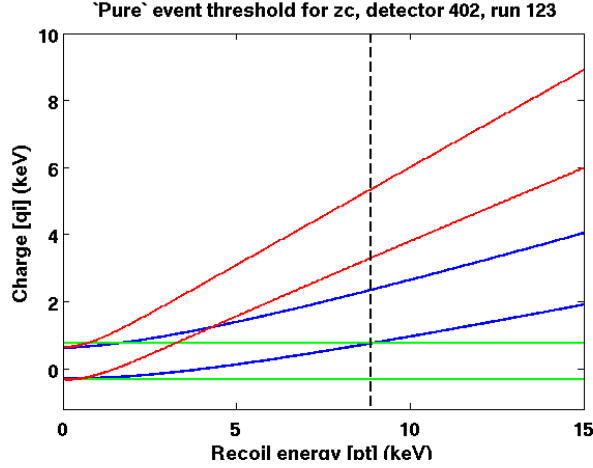


Figure 5.1: Overlap of the electron recoil (red), nuclear recoil (blue), and zero charge (green) bands shown for T1Z2 in the plane of total phonon energy versus charge, with threshold of overlap between the zero charge and nuclear recoil bands (dashed).

are removed from the low threshold data used in this analysis, due to activation of the ^{73}Ge (resulting in the enhancement of the 1.3 keV line). The start and end times of each time period are listed in Table 5.1. The detector cuts and efficiencies described in Chapter 4 are generally defined and measured on a run-by-run basis; Table 5.1 also lists the mapping of the run corresponding to each time bin.

Table 5.2 summarizes the energy ranges used for the analysis. While above $5 \text{ keV}_{\text{nr}}$, the trigger efficiencies of the eight low-threshold detectors are all essentially unity, below $5 \text{ keV}_{\text{nr}}$, this is no longer the case, and the threshold of stability varies by detector. As a result, the subset of detectors used for the modulation search becomes increasingly restricted at low energies. Table 5.2 also lists the CDMS II low-threshold germanium detectors included in each range of the analysis.

The live times during runs 123-128 - the amount of time that the detector was active to trigger on an incident event - were calculated by summing the live time of the detector in each time bin remaining after the application of cuts removing bad time periods, bad detector regions, poor detector performance, and the $\sim 1/4$ of WIMP-search data reserved for low-energy cut calibration (see Section 4.3). The live times for each time bin are shown in Table 5.3.

Table 5.1: Start and end times for each time division in the modulation analysis.

Time bin	Run	Dates
1	123	Oct. 21, 2006-Nov. 9, 2006
2	123	Nov. 29, 2006-Jan. 12, 2007
3	123	Feb. 1, 2007-Mar. 7, 2007
4	124	Mar. 27, 2007-Apr. 30, 2007
5	124	May 20, 2007-Jun. 14, 2007
6	124	June 14, 2007-Jul. 13, 2007
7	125	Aug. 2, 2007-Aug. 27, 2007
8	125	Aug. 27, 2007-Sep. 27, 2007
9	125	Oct. 17, 2007-Nov. 11, 2007
10	125	Nov. 11, 2007-Dec.18, 2007
11	126	Jan. 17, 2008-Feb. 8, 2008
12	126	Feb. 28, 2008-Mar. 24, 2008
13	126	Mar. 24, 2008-Apr. 25, 2008
14	127	May 15, 2008-Jun. 9, 2008
15	127	Jun. 9, 2008-Jul. 21, 2008
16	128	Aug. 12-2008 Sep. 15, 2008

Table 5.2: Energy bins and ranges used in the annual modulation analysis, with detectors used for WIMP search in each range.

Energy Range	Detector Selection
2.7 keV _{nr} to 3.64 keV _{nr}	T1Z2, T1Z5, T3Z6
3.64 keV _{nr} to 5.0 keV _{nr}	T1Z2, T1Z5, T2Z3, T3Z4, T3Z5, T3Z6
5.0 keV _{nr} to 6.15 keV _{nr}	T1Z2, T1Z5, T2Z3, T2Z5, T3Z2, T3Z4, T3Z5, T3Z6
6.15 keV _{nr} to 7.3 keV _{nr}	T1Z2, T1Z5, T2Z3, T2Z5, T3Z2, T3Z4, T3Z5, T3Z6
7.3 keV _{nr} to 9.6 keV _{nr}	T1Z2, T1Z5, T2Z3, T2Z5, T3Z2, T3Z4, T3Z5, T3Z6
9.6 keV _{nr} to 11.9 keV _{nr}	T1Z2, T1Z5, T2Z3, T2Z5, T3Z2, T3Z4, T3Z5, T3Z6

Table 5.3: Detector live times during the annual modulation analysis, following application of data quality cuts.

Timebin	T1Z2	T1Z5	T2Z3	T2Z5	T3Z2	T3Z4	T3Z5	T3Z6
1	6.66	8.25	6.69	8.8	2.12	0	6	0
2	23.46	20.72	20.6	22.13	5.45	0	14.61	19.03
3	14.9	14.08	15.77	18.54	4.52	0	11.08	18.09
4	1.48	4.9	0	0	0	0	0	0
5	13.74	14.83	0	0	0	0	0	0
6	13.76	14.18	0	0	0	0	0	0
7	12.21	12.2	11.63	12.1	2.33	12.65	8.45	11.67
8	15.95	15.44	12.86	14.12	3.09	15.84	10.18	13.9
9	11.04	9.98	9.59	11.3	2.23	11.68	8.4	11.75
10	8.17	8.37	7.82	8.85	1.59	8.99	6.39	8.51
11	5.43	5.86	3.85	5	0.94	5.84	3.25	5.36
12	13.45	13.65	10.05	11.21	2.15	14.31	7.96	13.85
13	15.37	16.9	12.54	14.75	3.26	15.02	9.3	15.9
14	8.78	0	6.38	8.47	1.8	9.74	5.22	9.24
15	11.33	0	10.05	10.03	1.74	13.34	7.9	12.41
16	15.16	0	0	0	2.67	16.41	9.04	16.29

5.2 Background Subtraction Scheme for the CDMS II Search for Annual Modulation

A Background Subtraction Scheme for the CDMS II Search for Annual Modulation

At low energies in CDMS II (energy thresholds less than ~ 5 keV), the misidentification of electron recoils and zero charge events as nuclear recoil candidates becomes a significant source of backgrounds to a WIMP signal. The following scheme, originally based on suggestions and discussion with B. Sadoulet and S. Yellin, provides a way to explicitly subtract the electron recoil and zero charge event backgrounds from the measured modulation amplitude of WIMP candidate events in the low-energy data, in the context of a binned maximum likelihood analysis.

Throughout the following discussion, the subscript indices i , j , and l are used to represent the time, detector, and energy binning, respectively.

Defining the Background Subtraction Model

In a model for CDMS II event collection assuming the presence of true nuclear recoil events (denoted NR), zero charge events (ZC), and electron recoil events (ER) occurring in the signal region, and with negligible contributions from neutron backgrounds, the number of events expected to be incident on detector j during the time bin starting at t_i , in energy bin E_l , can be written as in 5.1:

$$n_{\text{tot}_{ijl}} = n_{\text{NR}_{ijl}} + n_{\text{ZC}_{\text{leak}_{ijl}}} + n_{\text{ER}_{\text{leak}_{ijl}}} \quad (5.1)$$

where $n_{\text{tot}_{ijl}}$ is the total expected number of events during time bin i , on detector j , and in energy bin l , as predicted by a model; $n_{\text{NR}_{ijl}}$ is the expected number of true nuclear recoils, $n_{\text{ZC}_{\text{leak}_{ijl}}}$ is the number of zero charge events leaking into the signal region, and $n_{\text{ER}_{\text{leak}_{ijl}}}$ is the number of electron recoil events leaking into the signal region.

To simplify the analysis, we assume that the energy intervals we have chosen are small enough that the signal amplitude and modulation do not vary significantly in a given interval. As a result, the rate of events with recoil energies within the range covered by E_l is approximately energy-independent. In this case, the event rate can be treated as the sum of an unmodulated mean rate and a modulating component as described in Chapter 1. We also assume that the signal in each energy bin is independent of the signal at higher and lower energies.

Each of the seven energy ranges searched for annual modulation was analyzed independently. In general, the following discussion applies within a specific energy bin E_l (and the subscript l will be dropped).

Candidate Event Models with a Single Modulation Signal

In considering a model for candidate event modulation, we first qualitatively consider the expected time variation of the event rates between detectors, for both the unmodulated and modulating components of the rate. Background contributions to the event rate will primarily affect the unmodulated component—for example, individual detectors may have varying amounts of surface contamination. As a result, we can expect the unmodulated component of the nuclear recoil rate to vary between detectors.

With the modulating component, this expectation is somewhat altered. First, there are very few background sources for which the event rate can be expected to vary with a period of one year, so the presence of modulation in the nuclear recoil event rate is already considered a hallmark of a WIMP signal. Furthermore, the weak interaction rate of WIMPs should be the same on all detectors.

Although an annual modulating contribution to the event rate from backgrounds is unlikely, the recent measurement of an annually modulating gamma rate at Soudan [192], demonstrates that it is not impossible, and is in fact present in the lab environment. Even so, the higher interaction rate of gammas in matter, coupled with the geometry of the

CDMS II detector, would likely again result in contributions of varying amounts on individual detectors, with more shielded detectors experiencing less of a rate contribution than their unshielded neighbors. Meanwhile, a true WIMP signal, with the very low interaction rate in matter, can still be expected to remain constant across detectors.

For this model, we assume a single, small-amplitude modulation signal common across all detectors, described by the set of coefficients M_1 and M_2 . Then for any particular (pure) event type, the expected number of events can be written

$$n_{ij} = \xi_{ij} [M_{\text{DC}_j} + M_{1_j} \cos \omega t_i + M_{2_j} \sin \omega t_i] \quad (5.2)$$

where n_{ij} is the expected number of events, M_{DC_j} is the unmodulated rate of events on detector j , and M_{1_j} and M_{2_j} are the cosine and sine amplitude coefficients, respectively, of the modulating component of the differential rate (taken to be the same value on every detector). As mentioned, the modulation amplitude is assumed to be the same on all detectors, so that

$$M_{1_j} = M_1 \text{ and } M_{2_j} = M_2, \forall j = 1, \dots, N_{\text{dets}}. \quad (5.3)$$

Because of this, from this point forward we will simply write M_1 and M_2 . Finally, $\omega = \frac{2\pi}{365.24} \text{d}^{-1}$ is the angular speed, t_i is the time at which time bin i begins, and ξ_{ij} is an efficiency-weighted, energy-integrated exposure, such that

$$\xi_{ij} = m_j \times \tau_{\text{live}_{ij}} \times \varepsilon_{ij} \times \Delta E. \quad (5.4)$$

with detector mass m , livetime τ_{live} , efficiency ε , and with ΔE as the width of the energy bin under analysis. This efficiency-weighted, energy-integrated exposure will be referred to as the “bin exposure”.

Each background term $n_{\text{XX leak}}$ in Equation 5.1 is estimated by the application of some set of scaling factors (discussed below) to the number of events expected of a “pure” sample of the background taken from outside of the signal region (Equation 5.5).

$$\begin{aligned} n_{\text{tot}_{ij}} &= n_{\text{NR}_{ij}} + n_{\text{ZC leak}_{ij}} + n_{\text{ER leak}_{ij}} \\ &= n_{\text{NR}_{ij}} + \alpha_{\text{ZC}_{ij}} n_{\text{ZC}_{ij}} + \alpha_{\text{ER}_{ij}} n_{\text{ER}_{ij}} \end{aligned} \quad (5.5)$$

The definitions of the scale factors, α_{ZC} and α_{ER} , are discussed below. First, we describe the models for the expected number of events, $n_{\text{NR}_{ij}}$, $n_{\text{ER}_{ij}}$ and $n_{\text{ZC}_{ij}}$, for the “true” nuclear recoil events within the nuclear recoil band and for each background in the selection region excluding overlap with other bands ((ZC, NR ER) and (ER, NR, ZC), respectively).

The Nuclear Recoil Event Count Model

For a simple case (without backgrounds) of pure nuclear recoil events, based upon Equation 5.2, the model is the following (Equation 5.6):

$$n_{\text{NR}_{ij}} = \left(m_j \tau_{\text{live}_{ij}} \varepsilon_{\text{DQ}_{ij}} \varepsilon_{\text{NR}_{ij}} \Delta E \right) \left[M_{\text{DC}_j} + M_1 \cos \omega t_i + M_2 \sin \omega t_i \right] \quad (5.6)$$

where $\xi_{ij,\text{NR}} = (m_j \tau_{\text{live}_{ij}} \varepsilon_{\text{DQ}_{ij}} \varepsilon_{\text{NR}_{ij}} \Delta E)$ is the bin exposure for the nuclear recoil events (because of the included efficiency on the nuclear recoil band cut), M_{DC_j} is the efficiency-corrected unmodulated event rate on detector j , and M_1 and M_2 are the amplitude coefficients for the modulation of nuclear recoil events.

The Zero Charge Event Count Model

Since we are searching for a detector-independent, sinusoidal modulation rate in the nuclear recoil region, we again consider a common modulation of zero charge events across all detectors. For a pure sample of zero charge events, the model for the number of zero charge events in the zero charge-only region is

$$n_{\text{ZC}_{ij}} = \left(m_j \tau_{\text{live}_{ij}} \varepsilon_{\text{DQ}_{ij}} \varepsilon_{\text{ZC}_{ij}} \varepsilon_{\text{ZC},\overline{\text{NRER}_{ij}}} \Delta E \right) \left[M_{\text{DC,ZC}_j} + M_{1,\text{ZC}} \cos \omega t_i + M_{2,\text{ZC}} \sin \omega t_i \right] \quad (5.7)$$

The bracketed term ($[M_{\text{DC,ZC}_j} \dots]$) on the right side of Equation 5.7 corresponds to the *efficiency-corrected* rate of pure zero charge events, so that

$$R_{\text{XXeffcorr}} = \frac{R_{\text{measured(outside)}}}{\varepsilon_{\text{XX}} \varepsilon_{\text{XXNR}}}. \quad (5.8)$$

The efficiencies (ε) described in Equation 5.7 are as follows.

- $\varepsilon_{\text{DQ}_{ij}}$, the efficiency of the WIMP-search data quality cuts.
- $\varepsilon_{\text{ZC}_{ij}}$, the efficiency of the 2σ zero charge band, as measured on simulated zero charge event data (see Section 4.4).
- $\varepsilon_{\text{ZC}\overline{\text{NRER}_{ij}}}$, the efficiency of events selected as zero charge events passing only the 2σ zero charge band, and not the 2σ electron recoil or 2σ nuclear recoil bands, from simulated zero charge event data (see Section 4.4).

The Electron Recoil Event Count Model

Our treatment of the electron recoil events follows a similar pattern to that described for the zero charge events above. We adopt the following model for the number of electron recoil events in the electron recoil only region (Equation 5.9):

$$n_{\text{ER}_{ij}} = \left(m_j \tau_{\text{live}_{ij}} \varepsilon_{\text{DQ}_{ij}} \varepsilon_{\text{ER}_{ij}} \varepsilon_{\text{ER}\overline{\text{NRZC}_{ij}}} \Delta E \right) \left[M_{\text{DC,ER}_j} + M_{1\text{ER}} \cos \omega t_i + M_{2\text{ER}} \sin \omega t_i \right] \quad (5.9)$$

The efficiencies for the selection of the electron recoil events are as follows.

- $\varepsilon_{\text{DQ}_{ij}}$, the efficiency of the WIMP-search data quality cuts for candidate events.
- $\varepsilon_{\text{ER}_{ij}}$, the efficiency of the 2σ electron recoil band, as measured on ^{133}Ba calibration data (see Section 4.4).
- $\varepsilon_{\text{ERNRZC}_{ij}}$, the efficiency of events passing only the 2σ electron recoil band, and not the 2σ zero charge or 2σ nuclear recoil bands, measured on ^{133}Ba calibration data (see Section 4.4).

In the case of both the zero charge and electron recoil event models, the unmodulated (M_{DC}) and modulation rates (M) are efficiency-corrected, as a result of including the selection cut efficiencies and the exclusion efficiencies $\varepsilon_{\text{ZCNRER}_{ij}}$ and $\varepsilon_{\text{ERNRZC}_{ij}}$ in the bin exposure (Equations 5.7 and 5.9).

The Leakage Event Count Models

Similar to the expressions above, we can write the zero charge event leakage as the fraction of zero charge events expected to leach into the signal region:

$$n_{\text{ZCleak}} = \left(m_j \tau_{\text{live}_{ij}} \varepsilon_{\text{DQ}_{ij}} \Delta E \right) \alpha_{\text{ZC}_{ij}} \left[M_{\text{DC,ZC}_j} + M_{1,\text{ZC}} \cos \omega t_i + M_{2,\text{ZC}} \sin \omega t_i \right] \quad (5.10)$$

where the M 's (as in Equation 5.7) are the efficiency-corrected rates and α is a leakage fraction describing the amount of overlap of the zero charge and nuclear recoil signal regions. Similarly, the expected number of electron recoil events leaking into the signal region is

$$n_{\text{ERleak}} = \left(m_j \tau_{\text{live}_{ij}} \varepsilon_{\text{DQ}_{ij}} \Delta E \right) \alpha_{\text{ER}_{ij}} \left[M_{\text{DC,ER}_j} + M_{1,\text{ER}} \cos \omega t_i + M_{2,\text{ER}} \sin \omega t_i \right]. \quad (5.11)$$

The calculation of the leakage fractions α_{ER} and α_{ZC} is discussed in more detail in Section 5.3.

The Candidate Event Count Model

Finally, for the specific case of single-scatter, nuclear recoil candidate events which may include backgrounds, the model is a combination of true nuclear recoil events and leakage from electron recoil and zero charge events (Equation 5.12).

$$n_{\text{tot}_{ij}} = \left(m_j \tau_{\text{live}_{ij}} \varepsilon_{\text{DQ}_{ij}} \Delta E \right) \cdot \left[\varepsilon_{\text{NR}_{ij}} \left(M_{\text{DC,NR}_j} + M_{1,\text{NR}} \cos \omega t_i + M_{2,\text{NR}} \sin \omega t_i \right) \right. \\ \left. + \alpha_{\text{ZC}_{ij}} \left(M_{\text{DC,ZC}_j} + M_{1,\text{ZC}} \cos \omega t_i + M_{2,\text{ZC}} \sin \omega t_i \right) \right. \\ \left. + \alpha_{\text{ER}_{ij}} \left(M_{\text{DC,ER}_j} + M_{1,\text{ER}} \cos \omega t_i + M_{2,\text{ER}} \sin \omega t_i \right) \right] \quad (5.12)$$

where $M_{DC,ZC}$, $M_{DC,ER}$, $M_{1,2ZC}$, and $M_{1,2ER}$ are the efficiency-corrected amplitudes measured for the zero charge and electron recoil event populations, and $\alpha_{\chi\chi,ij}$ is a scaling defined from the ionization and recoil energy distributions of the background, defined as

$$\alpha_{\chi\chi,ij} \int_{E_r=E_{l_1}}^{E_r=E_{l_2}} \int_{E_q=\mu_{NR,ij}-2\sigma_{NR,ij}}^{E_q=\mu_{NR,ij}} f_{\chi\chi,ij}(E_q|E_r) g_{\chi\chi,ij}(E_r) dE_q dE_r \quad (5.13)$$

(see Section 5.3) and used to estimate the rates of the backgrounds inside of the signal region from the measured rates (modulated and unmodulated) of backgrounds outside of the signal region. In the expression for α , f is the distribution in ionization energy and g is a probability density function based upon the recoil energy spectrum for the background events (see Section 5.3).

Since the rates are all efficiency-corrected by the efficiency-weighted exposure (see, for example, equation 5.7), the scaling factor does not contain such a correction. The models in equations 5.12, 5.7, and 5.9 above are all used in the total likelihood function for the background subtraction analysis as discussed in section 5.2.

The likelihood function

The number of events observed in a CDMS II detector in an interval (such as [keVkgd]⁻¹) will be distributed according to a Poisson distribution,

$$P(k; \lambda) = \frac{\exp(-\lambda)\lambda^k}{k!} \quad (5.14)$$

where k is the number of events observed and λ is the expected number of events.

On a detector j during each time interval t_i , k_{ij} events are collected by the experiment. The expected number of events for a given interval of exposure is predicted by the model expressed in Section 5.2, such that $\lambda_{ij} = n_{ij}$ events for detector j in time bin i . The likelihood of the model over all times, given the observed data, based on our Poisson probability distribution for k , then becomes

$$\mathcal{L}_{\text{tot}} = \prod \mathcal{L}_{ij}(\lambda_{ij}|k_{ij}) = \prod_{j=1}^{N_{\text{detectors}}} \prod_{i=1}^{N_{\text{tbins}}} \frac{e^{-\lambda_{ij}} \lambda_{ij}^{k_{ij}}}{k_{ij}!} \quad (5.15)$$

where N_{tbins} is the total number of time bins and $N_{\text{detectors}}$ is the number of detectors active during that time.

For simplicity of calculation, it is common to consider instead the logarithm of the likelihood:

$$\ln \mathcal{L}_{\text{tot}} = \sum_{ij} -\lambda_{ij} + k_{ij} \log \lambda_{ij} - \log k_{ij}! \quad (5.16)$$

In either expression of 5.15 or 5.16, $\lambda = n = n(M_{\text{DC}}, M_1, M_2)$. Finally, we maximize the likelihood over all physically relevant values of the modulation parameters.

Background Subtraction via Maximum Likelihood Estimation

While equation 5.16 gives the simplest form of the likelihood function, the background subtraction is performed by simultaneously determining the likelihood of the measured background rates with the rate of candidate events, so that the full log-likelihood function becomes

$$\begin{aligned} \ln \mathcal{L}_{\text{bgSub}_{ij}} &= \ln \mathcal{L}_{\text{tot}_{ij}} + \ln \mathcal{L}_{\text{ZC}_{ij}} + \ln \mathcal{L}_{\text{ER}_{ij}} \\ &= \sum_i^{N_{\text{tbins}}} \sum_j^{N_{\text{detectors}}} \left(-n_{\text{tot}_{ij}} + k_{\text{tot}_{ij}} \ln(n_{\text{tot}_{ij}}) - \ln(k_{\text{tot}_{ij}}!) - n_{\text{ZC}_{ij}} \right. \\ &\quad \left. + k_{\text{ZC}_{ij}} \ln(n_{\text{ZC}_{ij}}) - \ln(k_{\text{ZC}_{ij}}!) - n_{\text{ER}_{ij}} + k_{\text{ER}_{ij}} \ln(n_{\text{ER}_{ij}}) - \ln(k_{\text{ER}_{ij}}!) \right) \end{aligned} \quad (5.17)$$

where n_{tot} , n_{ZC} , and n_{ER} are the models described in section 5.2 for the expected total number of candidate events, the number of zero charge events, and the number of electron recoil events, respectively; and where k_{tot} is the number of nuclear recoil candidate events passing all cuts, k_{ZC} is the number of zero charge events not overlapping the nuclear recoil and electron recoil bands, and k_{ER} is the number of electron recoil events that do not fall into the region overlapping the nuclear recoil and zero charge bands.

The full log-likelihood function used to simultaneously fit the rate parameters of the electron-recoil and zero-charge backgrounds with the rates of the true nuclear recoils among the candidate events is the sum of the individual log-likelihoods. Summation over the indices i and j produces the total log-likelihood for the full set of parameters ($M_{\text{DC,NR}}$, $M_{1,\text{NR}}$, $M_{2,\text{NR}}$, $M_{\text{DC,ZC}}$, $M_{1,\text{ZC}}$, $M_{2,\text{ZC}}$, $M_{\text{DC,ER}}$, $M_{1,\text{ER}}$, $M_{2,\text{ER}}$), given the data collected in the experiment on all detectors, at all times, within the specified range of energy.

The maximum likelihood is fitted for a range of values in $M_{1,\text{NR}}$ and $M_{2,\text{NR}}$, with all other parameters taken as nuisance parameters. The error is estimated as an asymptotic approximation of Feldman-Cousins confidence intervals, assuming a χ^2 distribution with two degrees of freedom of the test statistic $\chi^2 = -2 \ln R$, where $R = \mathcal{L}_{\text{fixed}}/\mathcal{L}_0$, and $\mathcal{L}_0$ is the null hypothesis (no modulation).

5.3 Leakage Estimates

We now discuss the calculation of the leakage fractions α_{ZC} and α_{ER} used for the candidate events model described in Equation 5.12.

Calculating the leakage fractions, α_{ER} and α_{ZC}

Each scaling factor $\alpha_{\text{XX}_{ijl}}$ is estimated as the fraction of the background ionization distribution falling into the signal region for a specified range of energy. Because of the rapid change of some of the event selection efficiencies across the energy bin, the overlap fraction

is corrected by weighting by the portion of the probability distribution function of the background event recoil energy spectrum across the given energy bin, so that the full expression for α becomes:

$$\alpha_{XX_{ij}} = \int_{E_r=E_{l_1}}^{E_r=E_{l_2}} \int_{E_q=\mu_{NR_{ij}}-2\sigma_{NR_{ij}}}^{E_q=\mu_{NR_{ij}}+2\sigma_{NR_{ij}}} f_{XX_{ij}}(E_q|E_r) g_{XX_{ij}}(E_r) dE_q dE_r \quad (5.18)$$

For both electronic recoils and zero charge events, the ionization energy at a fixed recoil energy E_r is assumed to follow a normal distribution $f_{XX_{ij}}$, with mean $\mu_{ij}(E_r)$ and standard deviation $\sigma_{ij}(E_r)$ taken from the definition of the ionization bands for the given event type “XX” (ER or ZC) during timebin i on detector j :

$$f_{XX_{ij}}(E_q|E_r) = \frac{1}{\sqrt{2\pi}\sigma_{XX_{ij}}} \exp\left(-\frac{1}{2}\left(\frac{E_q - \mu_{XX_{ij}}(E_r)}{\sigma_{XX_{ij}}(E_r)}\right)^2\right). \quad (5.19)$$

Integration over the Gaussian ionization distribution of the zero charge events from the upper edge of the zero charge event band to the lower edge of the nuclear recoil band, accounting for the amount of overlap falling within the nuclear recoil band, then takes the form

$$\int f = 0.5 * (\text{erf}(E_{qZC,upper}/\sqrt{2}) - \text{erf}(E_{qNR,lower}/\sqrt{2})); \quad (5.20)$$

This assumption of a normally-distributed ionization band is empirically justified for the zero charge events, and provides a simplifying approximation for the distribution of the electron recoil events. For the zero charge events, the recoil energy distribution, g_{ZC} , is a falling exponential distribution, normalized to the width of the current energy bin (E_l):

$$g_{ZC,ij}(E_r) = \frac{\exp\left(-\frac{E_r}{E_{0,ij}}\right)}{-E_{0,ij} \left[\exp\left(-\frac{E_{l,2}}{E_{0,ij}}\right) - \exp\left(-\frac{E_{l,1}}{E_{0,ij}}\right) \right]}. \quad (5.21)$$

Here E_{l_1} and E_{l_2} are the lower and upper bounds of energy bin E_l , respectively, and E_0 is a characteristic energy parameter defining the steepness of the exponential curve.

In order to define g_{ZC} for each detector, a single characteristic energy $E_{0,j}$ for the zero charge event distribution is estimated via maximum likelihood using WIMP-search data which 1) fall into the 2σ zero charge event band and 2) are excluded from both the electronic and nuclear recoil bands, from all runs. The best fit value of E_0 for each detector is used to define g_{ZC} for all times and the full energy range.

For the electron recoil events, the recoil energy spectrum is essentially flat across our range of interest, and g_{ER} is assumed to follow a uniform distribution.

The scaling factors $\alpha_{ZC_{ijl}}$ and $\alpha_{ER_{ijl}}$ are calculated for each run and detector within each of the seven energy regions of the search for annual modulation, and used to compute the candidate events model for the background subtraction described in Equation 5.12 of Section 5.2. Figures 5.2 and 5.3 show the electron recoil and zero charge event leakage factors

obtained for Runs 123-124 of the eight low threshold germanium detectors in the modulation analysis.

The leakage fractions of each detector-run combination are included as constants in the up to 30-parameter simultaneous fit of the nuclear recoil and background event rates for the background subtracted analysis. Fits to the modulation amplitude are considered independently in each of the six energy ranges of the analysis.

In Chapter 6, we discuss the results of background-subtraction in the search for annual modulation in CDMS II.

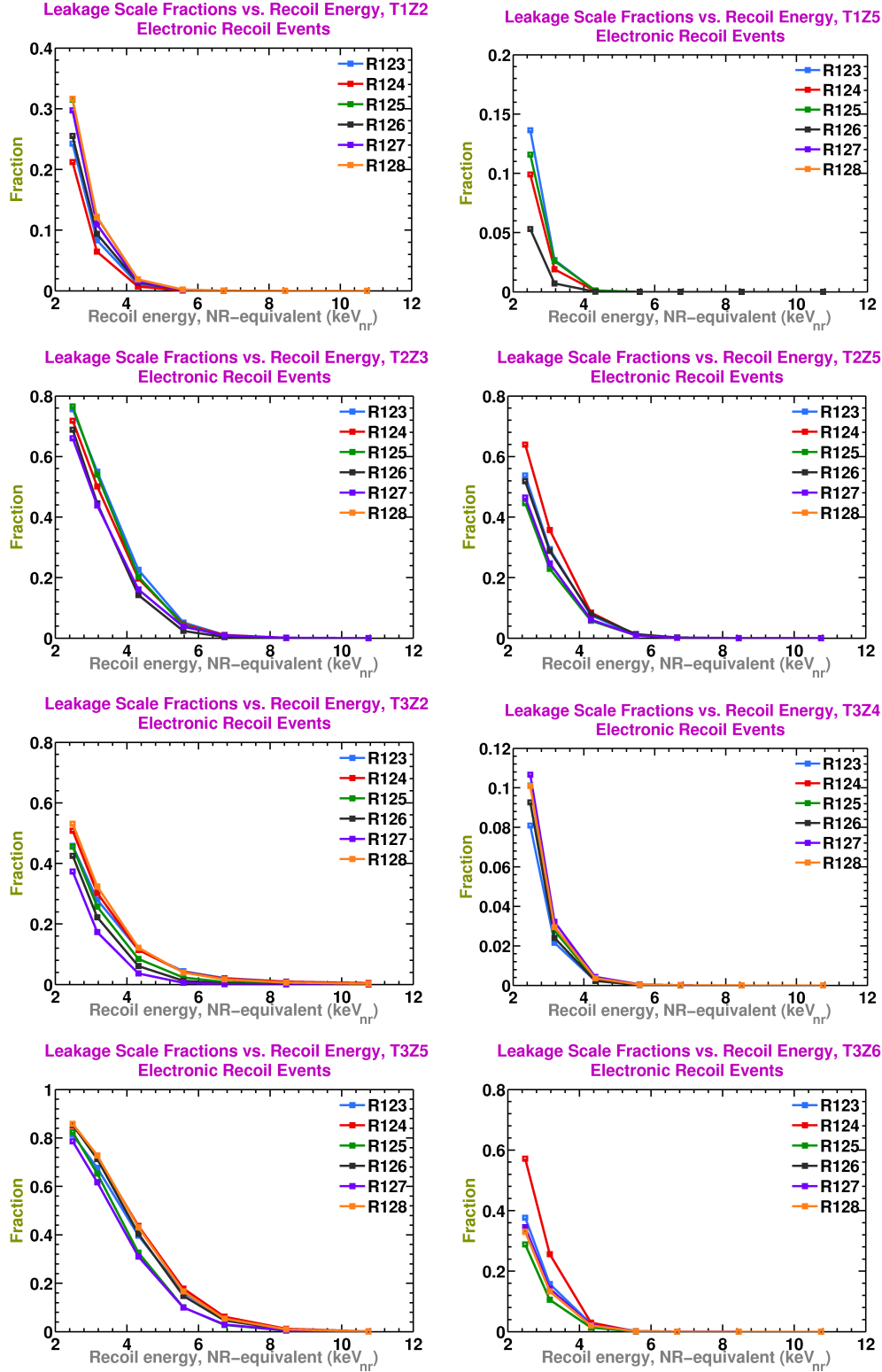


Figure 5.2: Leakage fractions for electron recoil events.

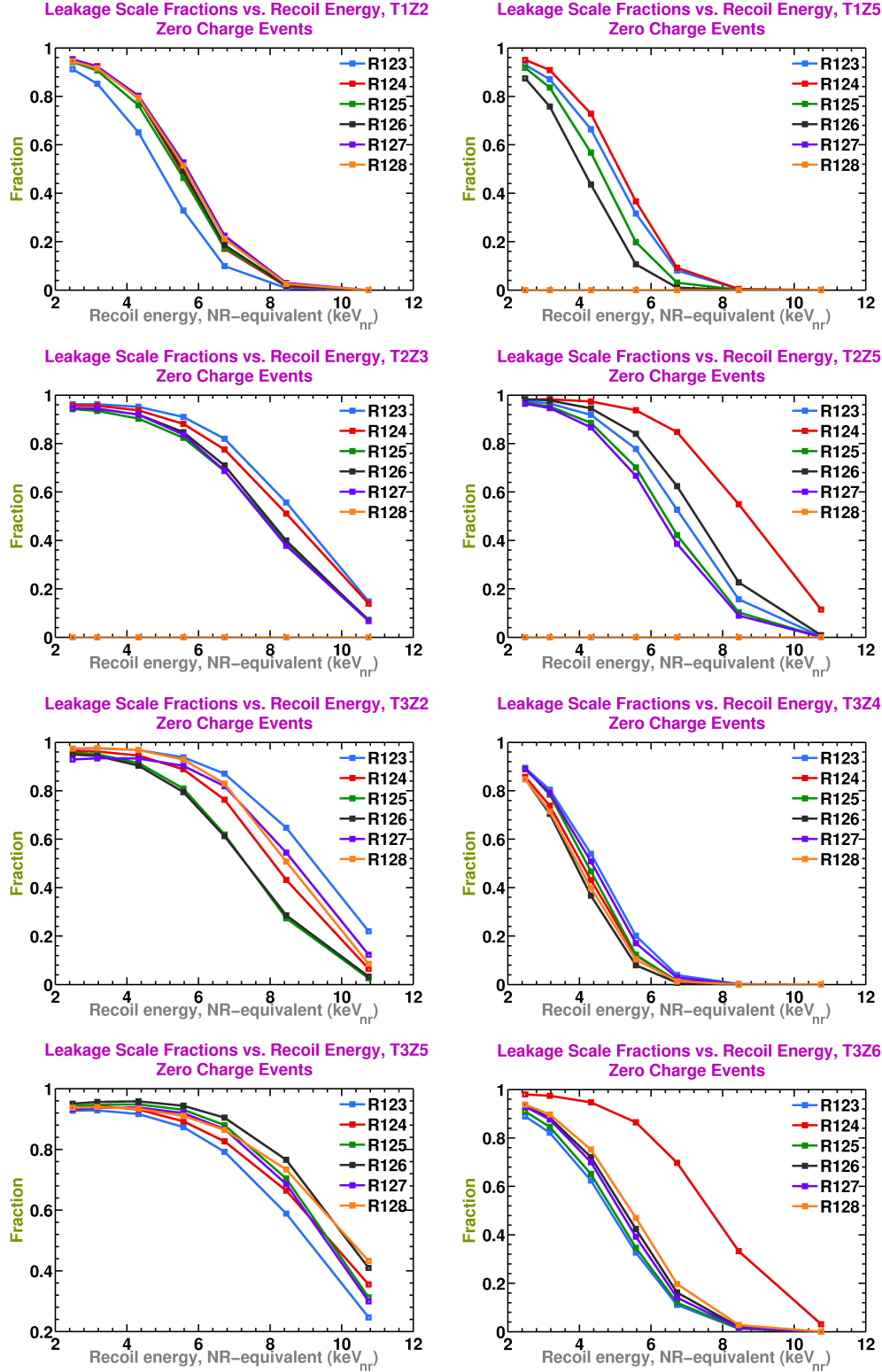


Figure 5.3: Leakage fractions for zero charge events.

Chapter 6

Results of the Background Subtracted CDMS II Search for Annual Modulation

6.1 Results

We have now traced the development of our measurement from its context in the dark matter framework, through the development of the required experimental apparatus, and described the analysis of the collected data. In this chapter, we present the results of the analysis.

As discussed in Section 5.1, this analysis spans approximately 2 years of CDMS II operations. The data collected during that time are divided into sixteen time periods of WIMP-search data collection, each of ~ 25 d. Because of neutron activation following ^{252}Cf calibrations, the twenty days immediately following each of the 11 neutron calibration runs were removed from the analysis.

The selection of nuclear recoil candidate events for this modulation analysis mirrors the events selections used in [185] and [189]. In both [189] and this work, the nuclear recoil selection band was widened to accept events within a symmetric region within 2σ of the mean of the nuclear recoil ionization yield band.

We express the results of the analysis in two formats. First, we present a set of confidence intervals for the sine and cosine coefficients of the modulation amplitude, for each of the seven subsets of the energy range spanned by the analysis. We then show the modulation spectrum, in which the maximum likelihood estimate of the amplitude (assuming an unconstrained phase) is shown as a function of energy. The second format, in particular, shows the region of the spectrum at which any modulation occurs most strongly, and provides an astrophysics-independent means of comparison between experiments.

We first discuss the the measured amplitudes without background subtraction, demonstrating results compatible with the analysis of [190, 189]. We also show the expected modulation amplitudes of electron recoils and zero charge events within the signal region.

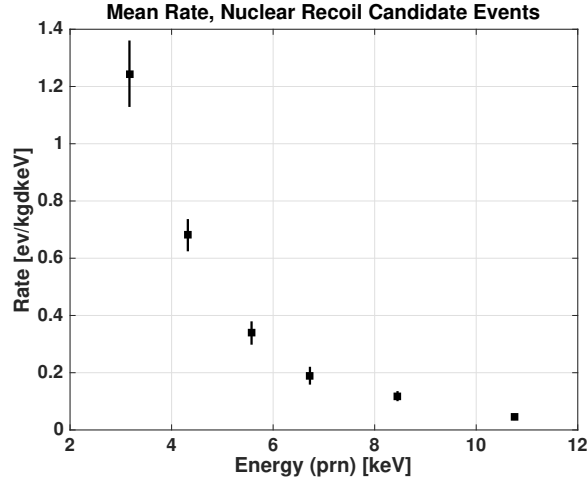


Figure 6.1: Mean event rate from eight detectors as a function of energy, prior to background subtraction.

6.2 Annual Modulation of Nuclear Recoil Events without Background Subtraction

The mean total unmodulated event rate over all detectors as a function of energy, prior to background subtraction, is shown in Figure 6.1. Figure 6.2 shows the residual rates versus time of the CDMS II nuclear recoil band events before subtraction of backgrounds, after subtracting the total best-fit unmodulated rate, with statistical uncertainties in the residual count rates shown as asymmetric Poisson errors (vertical) for each time bin. In each plot of Figure 6.2, the width of the horizontal bar indicates the length of the respective time bin. At the lowest energies (2.7 keV_{nr} to 5.0 keV_{nr}), subtraction of the unmodulated rate removes most of events, resulting in large statistical errors on the residual rate. The very short duration of the fourth time block results in larger uncertainties throughout the entire energy range.

We estimate the modulation rate coefficients M_1 and M_2 using a maximum likelihood analysis as discussed in 5.2. The confidence intervals are determined through an asymptotic approximation of the Feldman-Cousins method, in which the distribution of the log-likelihood ratio test statistic is treated as a χ^2 distribution with two degrees of freedom. All of the unmodulated rates on the 3, 6, or 8 detectors analyzed in a given energy range are maximized and treated as nuisance parameters. In the case of background subtraction, both modulation amplitude coefficients of each of the background zero charge and electron recoil event rates are also treated as nuisance parameters. The allowed regions for the modulation amplitude of the nuclear recoil candidate events prior to background subtraction are shown in Figure 6.3.

Figure 6.3 shows the 68%, 95%, and 99% confidence intervals for the modulation amplitude of the nuclear recoil candidate events without background subtraction, displayed on

Residual Rates versus time, nuclear recoil candidate events (before background subtraction)

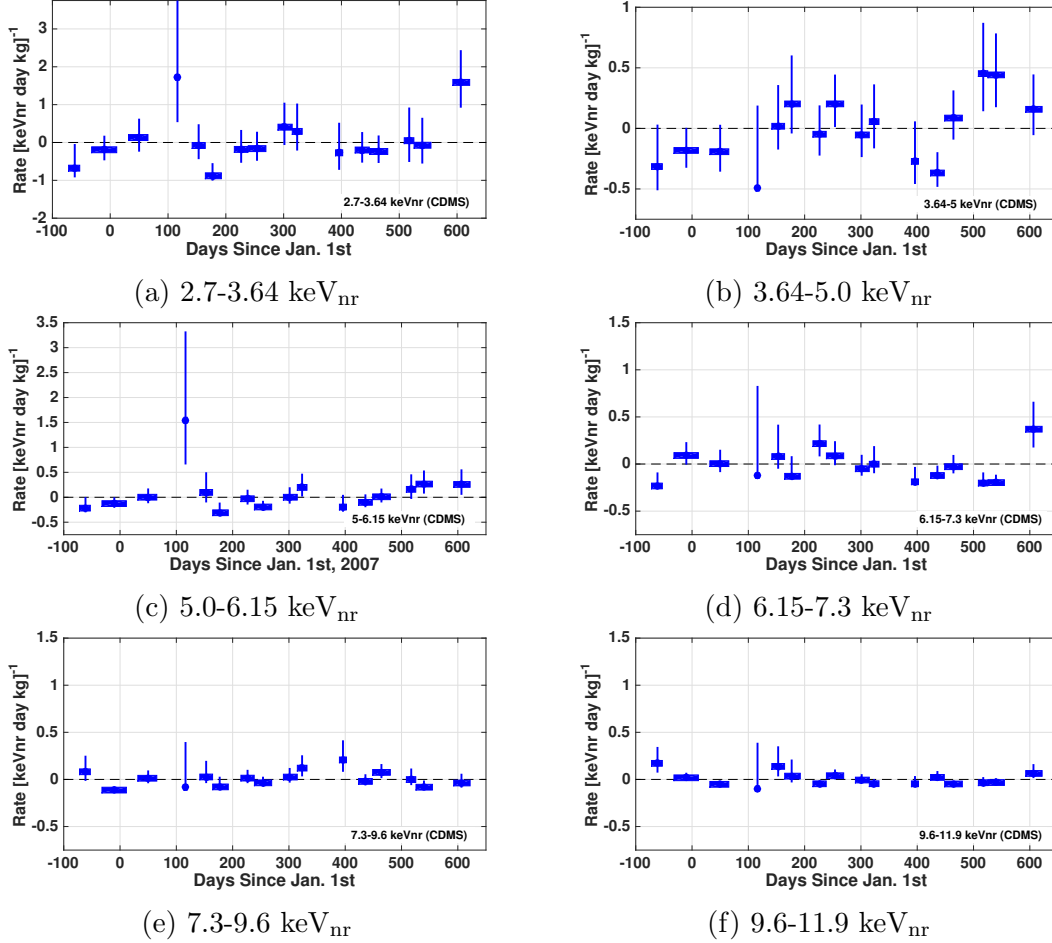


Figure 6.2: Residual (best-fit unmodulated rate removed) rates versus time before background-subtraction for the CDMS II low threshold detectors.

a set of polar axes with the amplitude corresponding to the radius and with the preferred phase of modulation shown as the angle. On each figure, the black dashed line at 150 days (around June 1) represents the preferred phase of modulation in the SHM (standard halo model) (see Section 1.7).

In the nuclear-recoil-equivalent recoil energy range from 2.7 keV_{nr} to 3.64 keV_{nr} (Figure 6.3, a and b), the measured amplitudes of CDMS II nuclear recoil candidate events are consistent with no modulation. In the range 3.64 keV_{nr} to 5 keV_{nr}, there is a preferred region of interest at greater than $\sim 3\sigma$ significance. Above 5 keV_{nr}, to the maximum range of the analysis (11.9 keV_{nr}), the measured amplitudes are consistent with no modulation.

This region of interest is notable for several reasons.

1. It is directly below the threshold where all eight detectors have full trigger efficiency,

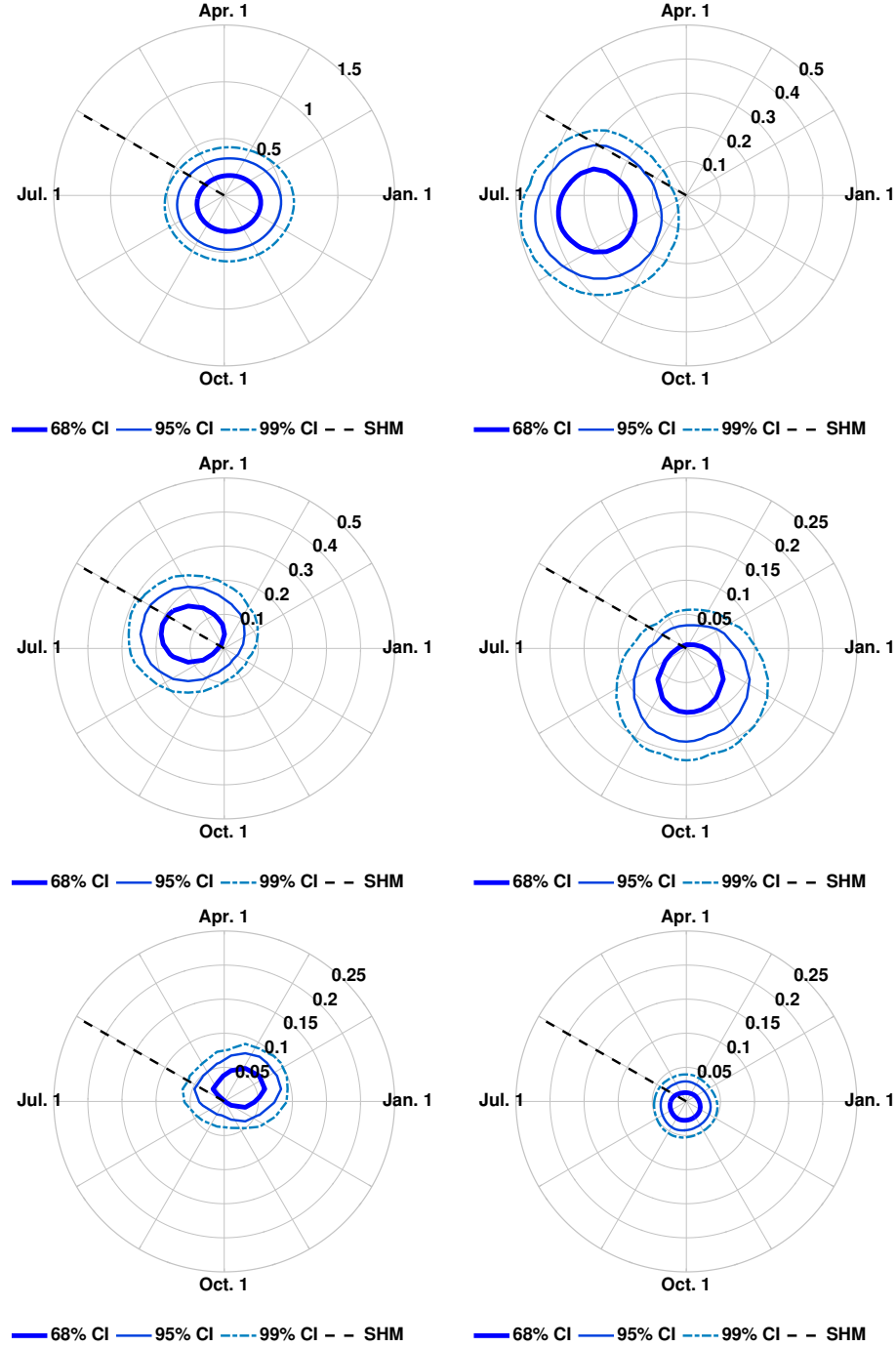


Figure 6.3: (color online) Allowed regions for annual modulation of nuclear recoil candidate events, before subtraction of electron recoil and zero charge backgrounds, for the 2.7–3.64 keV_{nr} (top left), 3.64–5.0 keV_{nr} (top right), 5.0–6.15 keV_{nr} (middle left), 6.15–7.3 keV_{nr} (middle right), 7.3–9.6 keV_{nr} (bottom left), and 9.6–11.9 keV_{nr} (bottom right) intervals. Modulation amplitude is measured along the radial axis, while the phase is represented by the counter-clockwise angle from the polar axis. A phase of 0 corresponds to January 1st. The phase of a modulation signal predicted by the standard halo model is shown by a black dashed line. The 68%, 95%, and 99% C.L. contours are shown, with an apparent modulation of $\sim 3\sigma$ significance in the 3.64–5.0 keV_{nr} energy range.

and close to the analysis thresholds.

2. *Heavy overlap with the zero-yield event band.* As discussed in previous chapters, the inability to discriminate on an event-by-event basis at low thresholds results in the acceptance of background events, with the nuclear recoil, electron recoil and zero charge bands overlapping heavily in the lowest energy ranges.
3. *Reduced understanding of background contributions at low energies, and the possibility of systematic contributions to the recoil event rate.* Systematics for this analysis are studied in more detail in Section 6.4.

Because of the potential contribution of background events, and to obtain an estimate of modulation amplitude of true nuclear recoil candidate events, we analyze and subtract the electron recoil and zero charge contributions.

Modulation of Backgrounds

Figure 6.4 shows, from top to bottom, the 1) gamma band, 2) surface events (gray points beneath gamma band), 3) nuclear recoil band (signal region), 4)(corner, left) overlap of the signal and zero charge bands, and 5) the zero charge band. For the background subtraction, the contribution of surface events is negligible, and we concentrate on contributions from the electron recoil and zero charge bands.

In order to quantify the maximum expected contribution of backgrounds, in particular the zero-yield events, to a modulation in the signal rate, we estimate the amount of modulation present in the yield regions of the WIMP-search data outside of the signal region using the same technique as for the nuclear recoil candidate events. Figure 6.5 shows the 68%, 95%, and 99% confidence intervals on the amplitude of modulation of electronic recoils in CDMS II WIMP-search data, while Figure 6.6 shows the 68%, 95%, and 99% confidence intervals on the modulation of zero charge events. Using data measured outside of the signal region (see Chapter 5), the measured rates are efficiency-corrected with the exclusion efficiencies discussed in Section 5.3 to give the total expected modulated rates.

As discussed in Chapter 5, the modulation amplitudes of the electronic and zero charge events are fit simultaneously with the model of the candidate events as the combined contribution of nuclear recoil and background event leakage, and are treated as nuisance parameters in the fit for the modulation amplitudes of true nuclear recoil events. The resulting nuclear recoil event rates are the background-subtracted rates shown and discussed in Section 6.3.

6.3 Background-Subtracted Nuclear Recoil Event Rates

The calculations of the expected leakage of the electronic recoils and zero charge events into the nuclear recoil (signal) region were discussed in Chapter 5. For each background, the

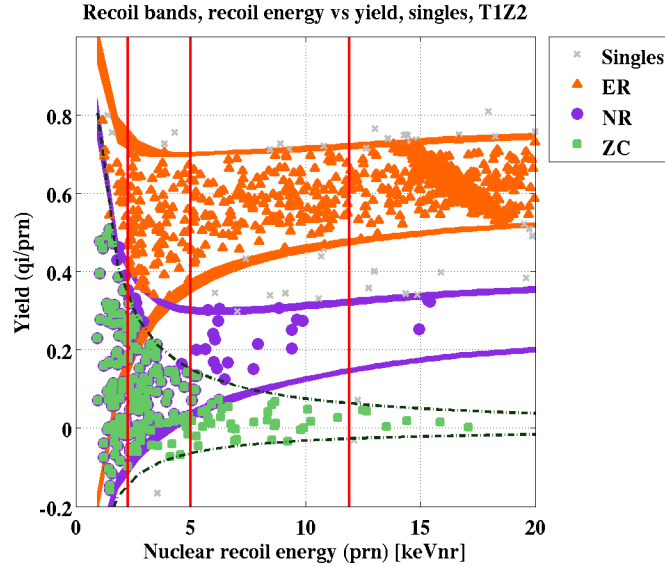


Figure 6.4: Background yield regions in the CDMS II WIMP-search data for detector T1Z2, shown for single-scatter (“singles”, triggering in only one detector). Events falling into each band region are highlighted with the color of the band. Band widths are representative of varying band definitions from CDMS II. From the top: Gammas (orange triangles), nuclear recoils (purple circles), and zero-yield background events (green squares). Note the heavy overlap of the zero-yield band with the signal region below 5 keV_{nr}. The red lines show, from left to right, the lower edge of the low threshold germanium analysis (2.27 keV_{nr}) and the 5 and 11.9 keV_{nr} thresholds used in the background-subtracted analysis.

expected leakage fractions were determined as functions of time and energy, and applied to the event rates of the background measured outside of the signal region to form the model for the candidate events discussed in Chapter 5. Finally, simultaneously fitting the candidate events with the background rates outside of the signal region, and maximizing over all other modulated and unmodulated rates as nuisance parameters, we obtain the background-subtracted maximum likelihood estimates of the modulation parameters for true nuclear recoil events (Figure 6.7). The best fit MLE estimates for the modulation parameters M_1 and M_2 are shown in Table 6.1, while the errors are indicated by the confidence intervals in Figures 6.7 and ??

Recoil Energy Dependence of the Modulation Amplitude

The cosine and sine amplitude coefficients described in the analysis of Chapter 5 are essentially projections along the primary axes of a circle of radius R , where R is the maximum amplitude of the modulation. These can be re-expressed in polar coordinates as the ampli-

Modulation of electron recoil background amplitudes

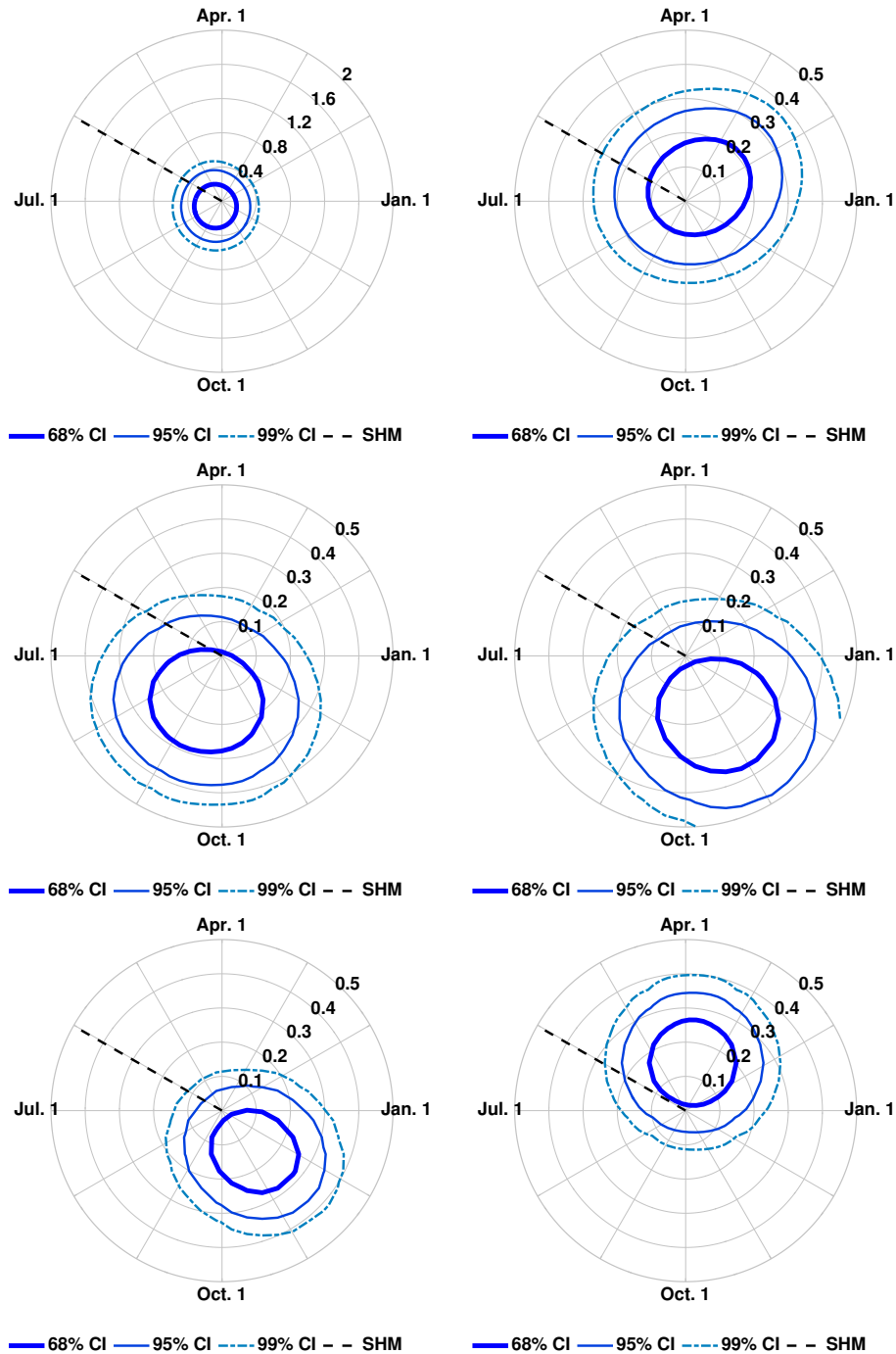


Figure 6.5: The 68% (solid), 95% (dashed), and 99% (thin, dashed) confidence intervals on the modulation amplitude of electron recoil event rates.

Modulation of zero charge event background amplitudes

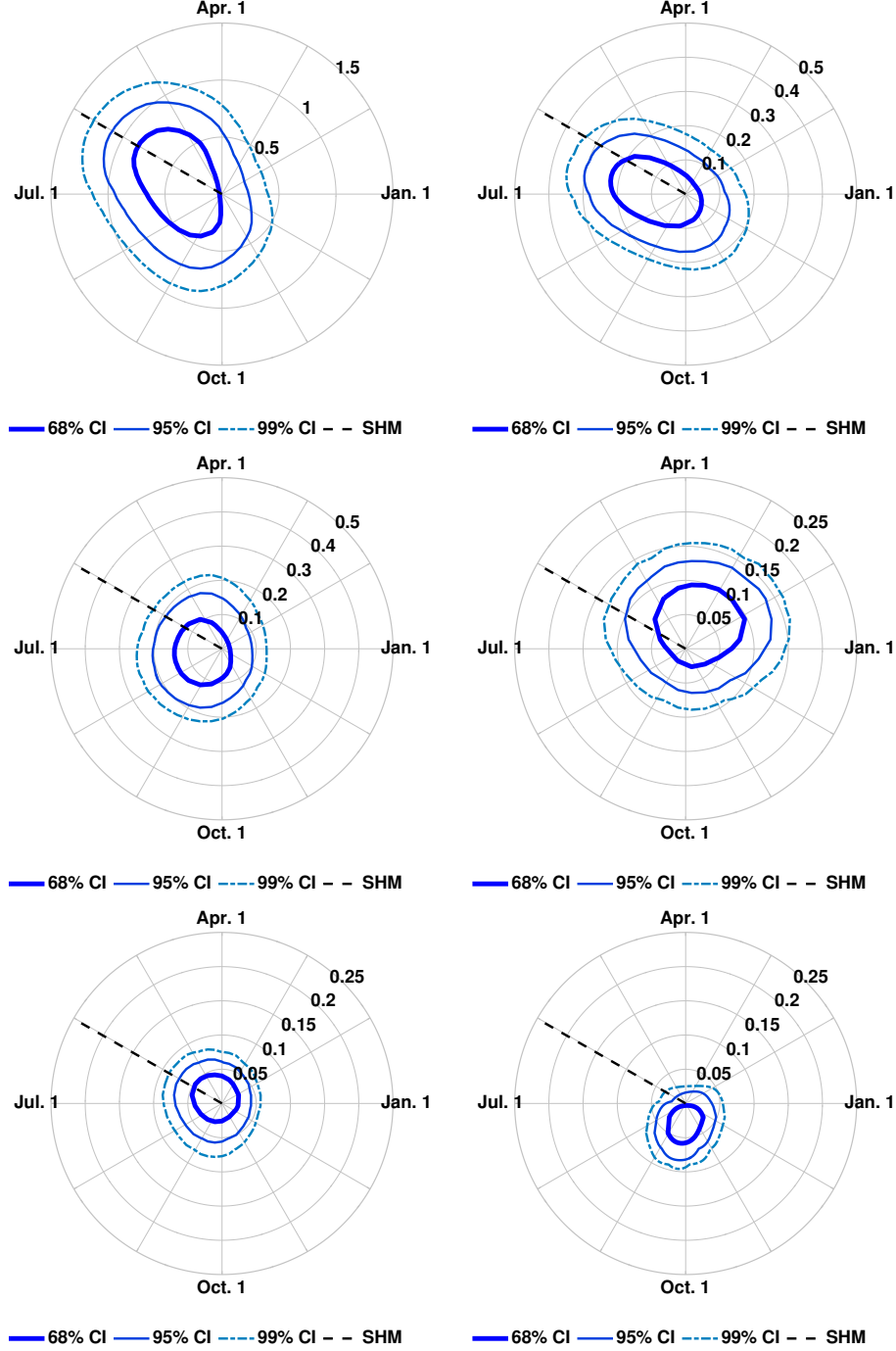


Figure 6.6: The 68% (solid), 95% (dashed), and 99% (thin, dashed) confidence intervals on the modulation amplitude of zero charge event rates. Above $7.3 \text{ keV}_{\text{nr}}$, the leakage of the zero charge band into the signal region becomes small.

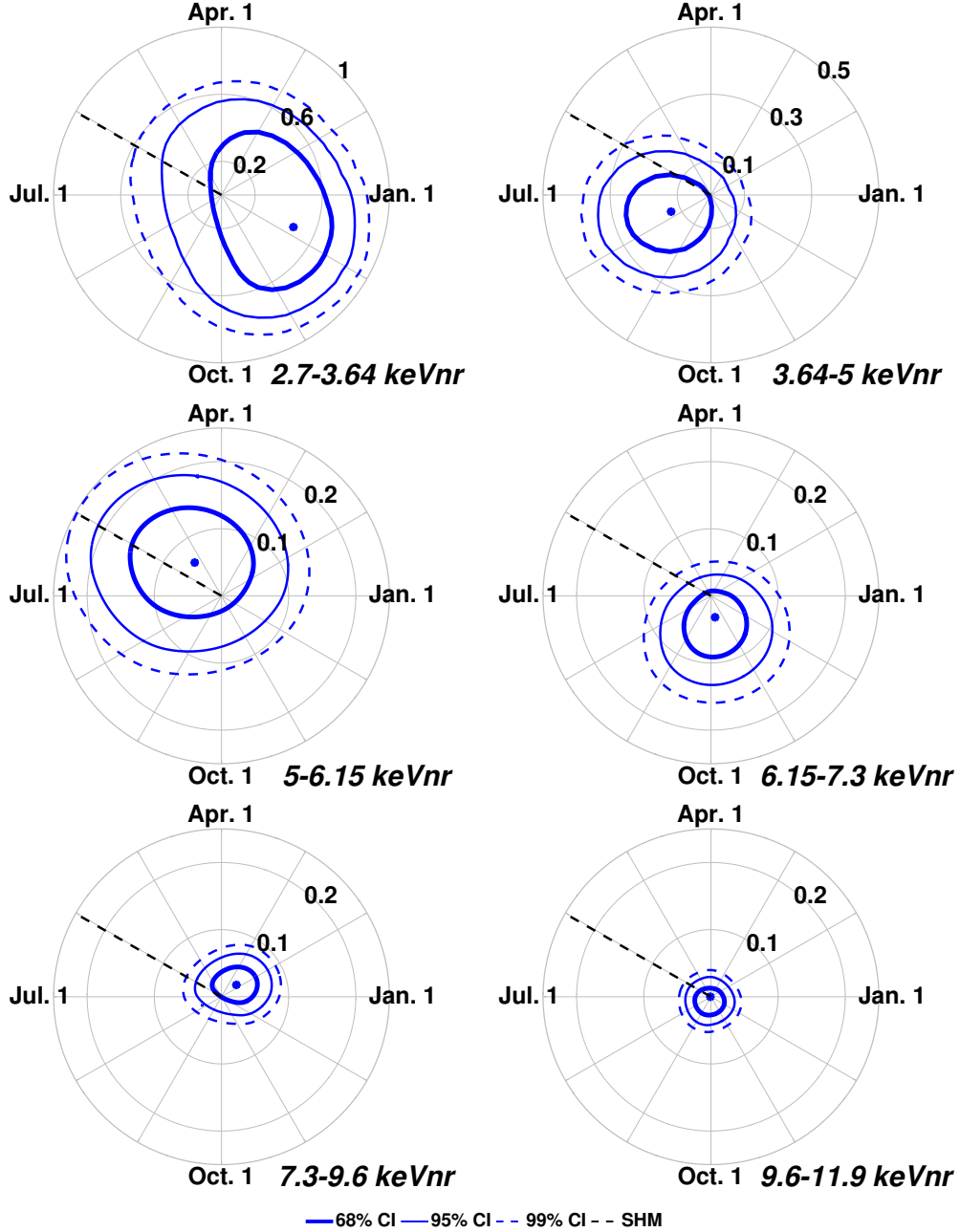


Figure 6.7: (color online) Allowed regions for annual modulation of the background-subtracted nuclear-recoil sample (dark blue), for the 2.7–3.64 keV_{nr} (top left), 3.64–5.0 keV_{nr} (top right), 5.0–6.15 keV_{nr} (middle left), 6.15–7.3 keV_{nr} (middle right), 7.3–9.6 keV_{nr} (bottom left), and 9.6–11.9 keV_{nr} (bottom right) intervals. Full modulation amplitude in $[\text{keVkgd}]^{-1}$ is measured along the radial axis, while the modulation phase is represented (in days) by the counter-clockwise angle from the polar axis. A phase of 0 corresponds to January 1st, and the phase of a modulation signal predicted by the standard halo model (152.5 days) is highlighted by a black dashed line. The 68% (thickest), 95% (thinnest), and 99% (dashed contour, outside) C.L. contours are shown. All regions are consistent with no modulation.

Energy	Unsubtracted, M_1	Unsubtracted, M_2	Bg. Sub., M_1	Bg. Sub., M_2
2.7-3.64keV _{nr}	0.039568	-0.067521	0.42515	-0.19407
3.64-5.0keV _{nr}	-0.26897	-0.040438	-0.11759	-0.050832
5.0-6.15keV _{nr}	-0.091432	0.041607	-0.040643	0.049398
6.15-7.3keV _{nr}	0.0058238	-0.036462	0.0054969	-0.032665
7.3-9.6keV _{nr}	0.020554	0.018198	0.021362	0.016865
9.6-11.9keV _{nr}	-9.4075e-05	-0.0011506	-5.0221e-05	-0.00044398

Table 6.1: Maximum likelihood estimates for the modulation amplitude parameters M_1 and M_2 for the nuclear recoil candidates, before and after background-subtraction.

Unsub			Bgsub	
Energy	M (keVkgd ⁻¹)	Days since Jan 1	M (keVkgd ⁻¹)	Days since Jan 1
2.7-3.64keV _{nr}	0.078	304	0.45	340
3.64-5.0keV _{nr}	0.27	191	0.13	206
5.0-6.15keV _{nr}	0.10	158	0.064	131
6.15-7.3keV _{nr}	0.037	283	0.033	283
7.3-9.6keV _{nr}	0.027	42	0.027	39
9.6-11.9keV _{nr}	0.0012	269	0.00045	267

Table 6.2: Amplitude and phase conversions for the best-fit modulation parameters for nuclear recoil candidate events, before and after background-subtraction.

tude and phase of the modulation, such that

$$M_{\text{tot}} = \sqrt{M_1^2 + M_2^2} \quad (6.1)$$

$$\phi = \tan^{-1} \left(\frac{M_2}{M_1} \right) \quad (6.2)$$

Table 6.2 gives the best fit phases and the absolute value of the amplitude for each energy range, based on the values from Table 6.1.

To obtain an estimate of the unconstrained modulation spectrum while accounting for the correlation of the errors on M_1 and M_2 , we determined the 68% confidence intervals on the maximum modulation amplitude for each of the six energy sub-ranges of the analysis by fitting a quadratic surface to the log-likelihood function of each energy range in the M_1 , M_2 parameter space. Using the maximum of the surface as an estimate of the maximum of the log-likelihood and taking the asymptotic approximation of the resulting likelihood ratio, we can obtain the 1-dimensional errors on the sine and cosine components of the amplitude

and use them to determine confidence intervals for the maximum amplitude in each energy range allowed. In this case, each energy range is treated as a separate analysis in which the phase is allowed to float, and the maximum of the best-fit signal within each bin may occur at any time of year.

By assuming and constraining the phase of the modulation signal for the entire energy range, however, we can gain information about the shape of the modulation spectrum for the specified model, rather than only considering the absolute values of the maximum amplitudes. The standard halo model predicts a phase peaking in early June, at 152.5 days [22]. In some cases, alternative models predict detectable shifts in the phase. Experiments may also report a best-fit phase different from that of the standard halo model. For example, the best-fit minimum for the annually modulating signal reported by the CoGeNT experiment in 2011 [137] was 16 ± 12 d, so the maximum would be expected to occur at ~ 106 days. An external analysis of the Coherent Germanium Neutrino Technology (CoGeNT) 2014 data release indicated a best-fit phase for the maximum near 102 days [196]. Meanwhile, in CDMS II, the best-fit phase of the nuclear recoil $\sim 3\sigma$ modulation in the energy range 3.64 keV_{nr} to 5.0 keV_{nr} before background subtraction is close to 190 days.

To fix the phases, we modified the analysis to perform a maximum likelihood fit to one of the modulation amplitude parameters of the nuclear recoil event rate, M_1 , constraining the second parameter to be $M_2 = M_1 * \tan(\omega\phi)$, where ω is the angular frequency for a period of 1 year, and ϕ is the desired modulation phase in days. All of the modulation parameters of the backgrounds, and all of the unmodulated rates of the nuclear recoil, electron recoil, and zero charge events are treated as nuisance parameters. The confidence intervals were again determined based on the asymptotic approximation of the Feldman-Cousins confidence intervals. The MLE and confidence intervals on the total amplitude of modulation M in this 1-dimensional fit were then obtained by transforming the fitted amplitudes by $M = M_1 / \cos(\omega\phi)$. The results of this fixed-phase analysis of the background-subtracted CDMS II data are shown in Figure 6.8 for 30, 60, 106 (CoGeNT), 120, 152.5 (standard halo model), and 190 days (CDMS II, before background-subtraction), respectively. Comparisons for the cases of 152.5 and of 102 days are shown in Figures 6.18, 6.19 and 6.20.

6.4 Systematics in the search for annual modulation

Beyond the contribution of background events to the nuclear recoil candidate modulation rate, several additional systematics were studied in conjunction with the search for annual modulation.

Signal efficiencies

Events selected for the modulation analysis were required to have ionization energies consistent with noise in the outer charge electrode (fiducial volume cut), and an ionization yield within 2-sigma of the mean of the nuclear recoil band (signal region cut) [174].

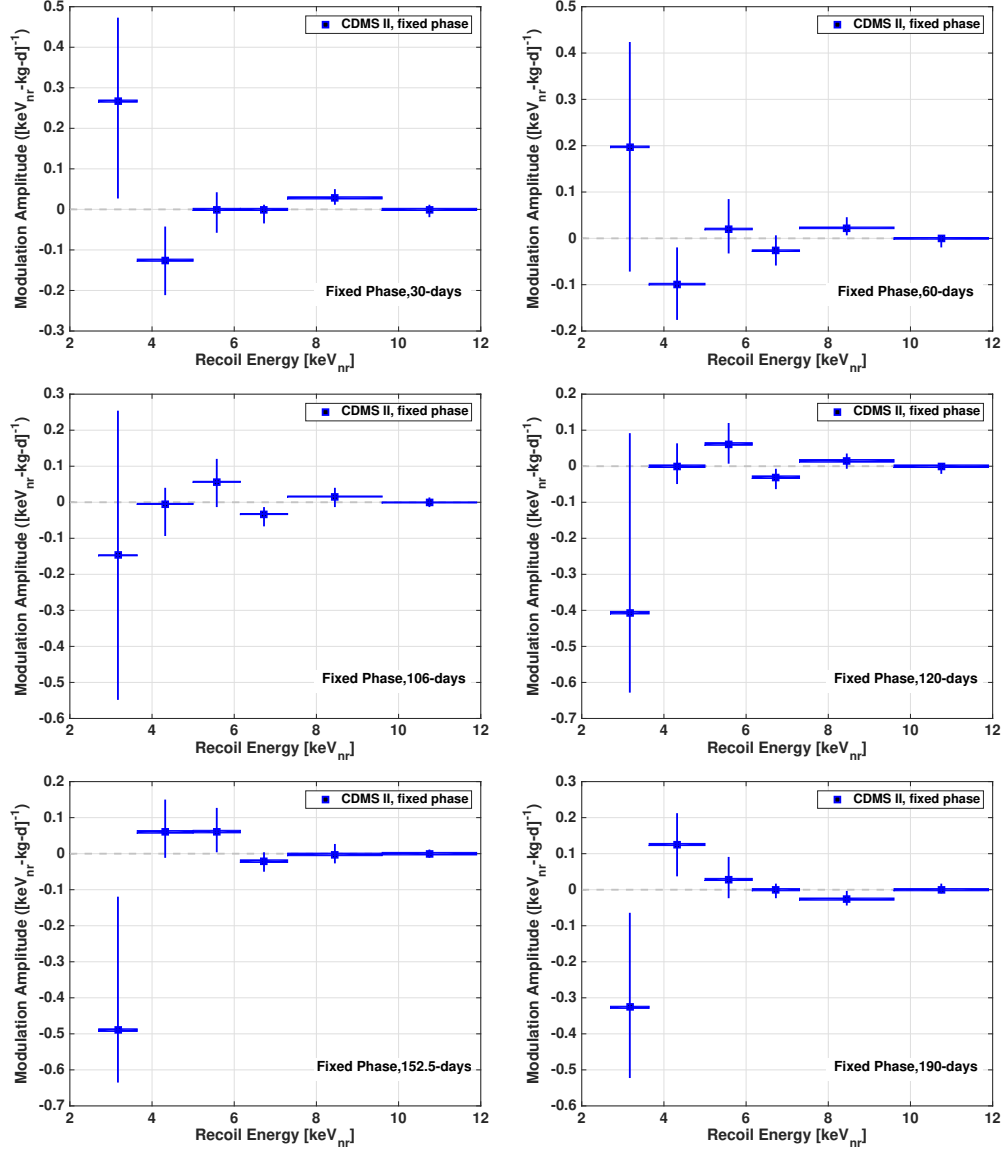


Figure 6.8: Background-subtracted modulation amplitudes at fixed phase values of 30 days, 60 days, 106 days (corresponding to the best-fit phase of CoGeNT), 120 days, 152.5 days (corresponding to the standard halo model), and 190 days.

As discussed in Chapter 4, each applied cut results in an efficiency. In reality, each efficiency $\varepsilon(t, E, d)$ depends on the time, t , the deposited energy, E , and the detector d . The data quality cuts possess negligible time dependence. For the cuts defining the detector fiducial volume and the signal region, we performed an analysis of the modulation in the efficiency assuming a binomial likelihood function. We determined upper limits on any contribution to a modulating signal using an asymptotic approximation to the Feldman-Cousins approach [197] for two degrees of freedom, and found their contributions to be small. In the energy range 2.7-11.9 keV_{nr}, the efficiency modulation is less than 7% at the 99% confidence interval, and less than 5% in each of the other ranges, and is not sufficient to mask the modulation of CoGeNT above 5keV_{nr}.

Cut acceptance of backgrounds

For each of the six runs included in the CDMS II search for annual modulation, the signal region (nuclear recoil band cut) was defined based on nuclear recoils from Cf-252 calibration data taken over the course of the run. In this study, we examine fluctuations in the acceptance of background events by the nuclear recoil yield band cut due to run-varying band definitions. Using the ionization distributions of “random” triggered events throughout CDMS II, and the measured recoil energy spectrum of zero charge events in the detectors, we generate a set of simulated “zero-yield” (i.e., ionization signal consistent with noise) events and study the acceptance rates of this background as a function of time. The simulation showed that the relative modulation rate of any time variance introduced by fluctuations in the definition of the nuclear recoil band cut is not large enough to be the source of modulation observed in the analysis before background subtraction. Contributions from this systematic were found to be consistent with no modulation, with the largest relative modulation amplitudes (relative to the unmodulated rate) on the order of $\sim 10\%$.

Zero charge event model

The model for the zero charge event distribution is based the assumptions that the number of events observed in the recoil energy range E_{r1} to E_{r2} follows a Poisson distribution, and that the recoil energy distribution of zero charge events over the entire energy range follows an exponential function, so that in the range E_1 to E_2 , the distribution can be described by a truncated exponential function. Based on these assumptions, the likelihood function for the zero charge event distribution is given as

$$\mathcal{L} = \frac{\lambda^k \exp -\lambda}{k!} \prod_{\eta}^k \frac{\epsilon(E_{r\eta}) \exp(-E_{r\eta}/E_0)}{\int_{E_{\min}}^{E_{\max}} \epsilon(E_r) \exp(-E_r/E_0) dE_r} \quad (6.3)$$

so that the log-likelihood function is

$$\ln \mathcal{L} = k \ln \lambda - \lambda - \ln k! - k \ln \left(\int_{E_{min}}^{E_{max}} \epsilon(E_r) \exp(-E_r/E_0) dE_r \right) + \sum_{\eta}^k [\ln(\epsilon(E_{r\eta})) - E_{r\eta}/E_0]. \quad (6.4)$$

The log-likelihood function is shown in Figure 6.9, along with 1σ errors from an asymptotic approximation to the ratio of the log-likelihood to its maximum. Using the $\pm 1\sigma$ values of E_0 , we recalculate the leakage fractions discussed in Section 5.3. The impact of variations in the estimates of E_0 on the leakage fractions used in the modulation analysis were shown to be negligible (Figure 6.10).

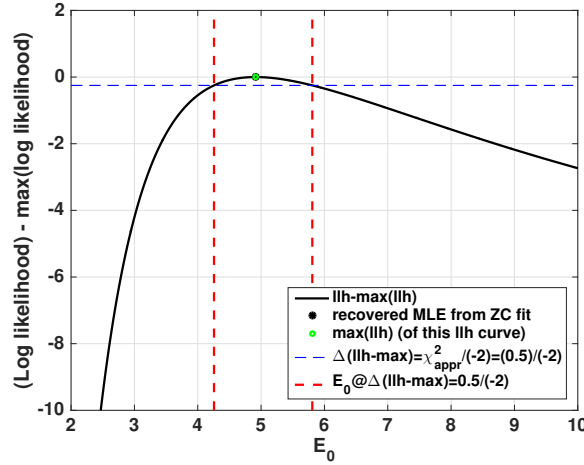


Figure 6.9: Log-likelihood of the estimate of E_0 with 1σ errors. The $\pm 1\sigma$ values of E_0 are used to estimate the error in the systematic error in the leakage fraction.

6.5 Verification

Estimating the Variance

To obtain order-of-magnitude estimates of the variance as a check on the results of Chapter 6, we assume uniform exposure and an integer number of periods of modulation, so that $\sigma_{M_{1,2}} = \sqrt{2N}/mT\varepsilon$, where ε is efficiency and N is the number of events. The confidence intervals on the modulation amplitudes presented in Chapter 6 can be checked by comparison with the variance on the estimators of M_0 , M_1 , and M_2 .

Bias

The background-subtracted search for annual modulation is designed to detect a modulating signal in the low-threshold germanium data from the CDMS II experiment, while accounting

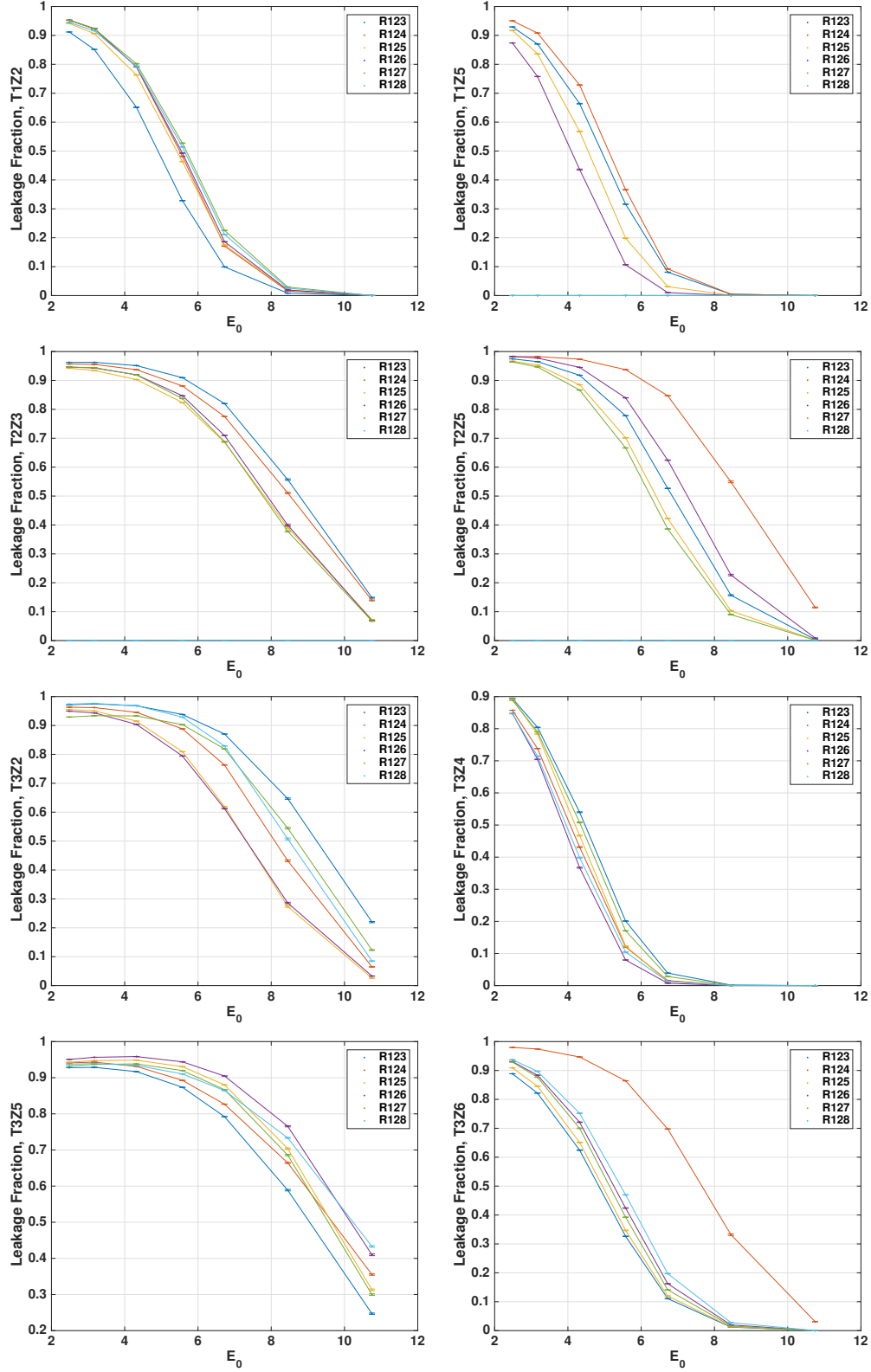


Figure 6.10: Estimates of the zero charge event leakage fractions with errors based on $\pm 1\sigma$ values of E_0 . Vertical error bars indicate the estimated error on the leakage fraction.

Comparison of Asymptotic Feldman-Cousins Confidence Intervals with
Estimates of Error, Nuclear Recoil Candidate Events (without Background
Subtraction)

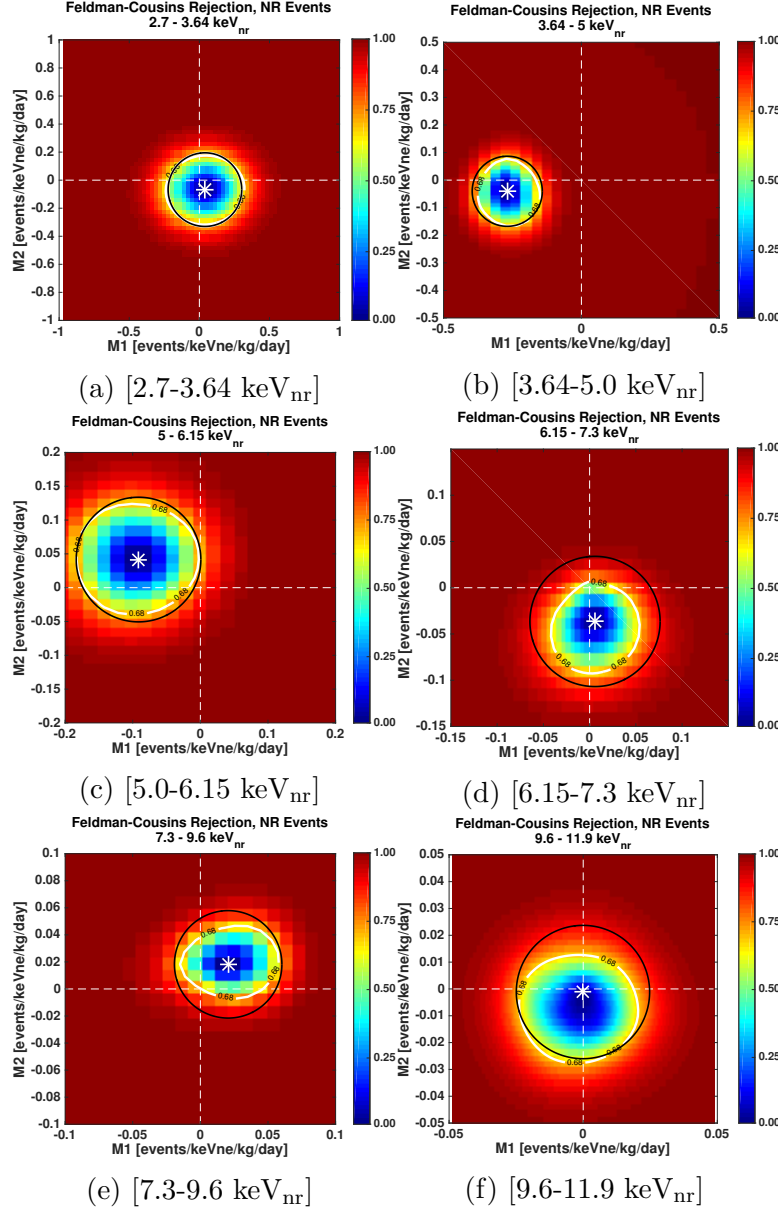


Figure 6.11: 68%, 95%, 99% Comparison of asymptotic confidence intervals to estimates of the variance for the nuclear recoil candidate events (without background subtraction). The white star (*) is the maximum-likelihood estimate of the best-fit set of modulation parameters, M_1 and M_2 ; the white dashed lines mark the origin [0, 0] and axes for M_1 and M_2 ; the labeled white contour represents the 68% confidence level for the estimate of the modulation parameters, and the color map shows increasing levels of rejection from 0 (blue) to 1 (dark red, rejection - 1). Analytical estimates of the error (σ) on the modulation amplitudes (black circles) are also shown. Note the change in scale with increasing energy.

Comparison of Asymptotic Feldman-Cousins Confidence Intervals with Estimates of Error, Electron Recoil Events

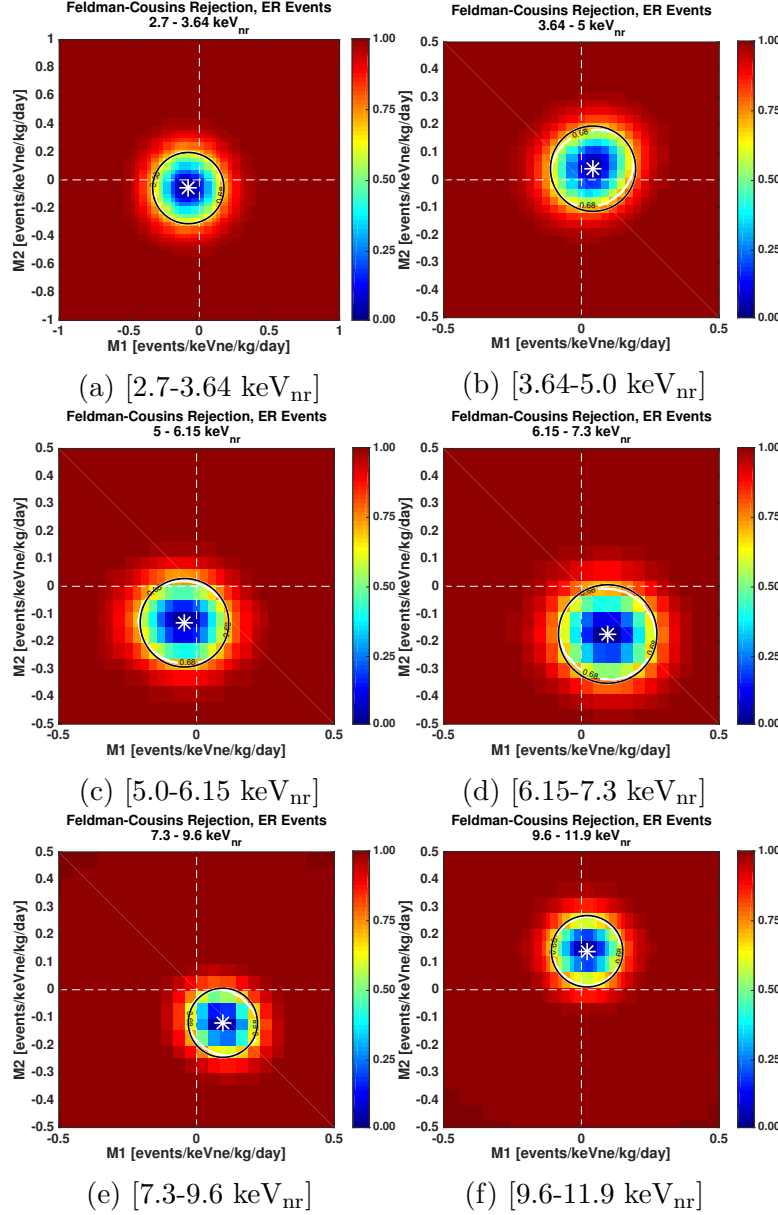


Figure 6.12: 68%, 95%, 99% Comparison of asymptotic confidence intervals to estimates of the variance, for electron recoil events. The white star (*) is the maximum-likelihood estimate of the best-fit set of modulation parameters, M_1 and M_2 ; the white dashed lines mark the origin [0, 0] and axes for M_1 and M_2 ; the labeled white contour represents the 68% confidence level for the estimate of the modulation parameters, and the color map shows increasing levels of rejection from 0 (blue) to 1 (dark red, rejection - 1). Analytical estimates of the error (σ) on the modulation amplitudes (black circles) are also shown. Note the change in scale with increasing energy.

Comparison of Asymptotic Feldman-Cousins Confidence Intervals with Estimates of Error, Zero Charge Events

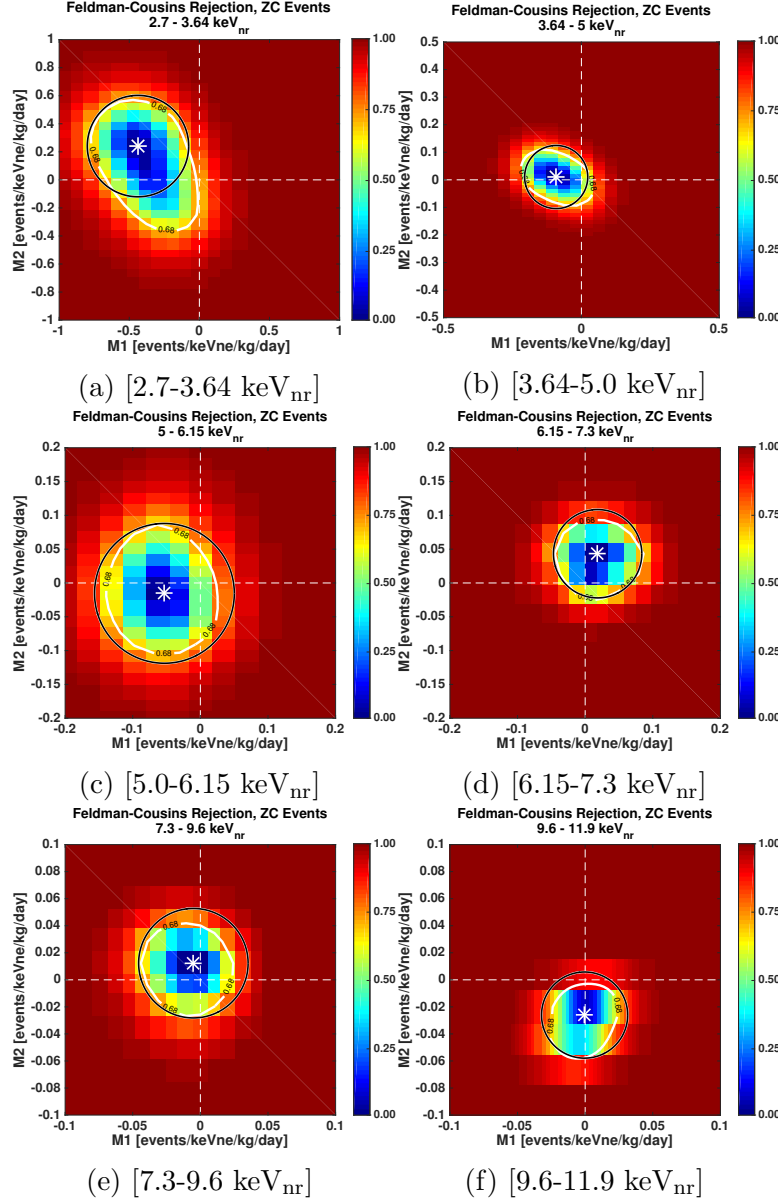


Figure 6.13: 68%, 95%, 99% Comparison of asymptotic confidence intervals to estimates of the variance, for zero charge events. The white star (*) is the maximum-likelihood estimate of the best-fit set of modulation parameters, M_1 and M_2 ; the white dashed lines mark the origin $[0, 0]$ and axes for M_1 and M_2 ; the labeled white contour represents the 68% confidence level for the estimate of the modulation parameters, and the color map shows increasing levels of rejection from 0 (blue) to 1 (dark red, rejection - 1). Analytical estimates of the error (σ) on the modulation amplitudes (black circles) are also shown. Note the change in scale with increasing energy.

Comparison of Asymptotic Feldman-Cousins Confidence Intervals with Estimates of Error; Nuclear Recoils with Background Subtraction

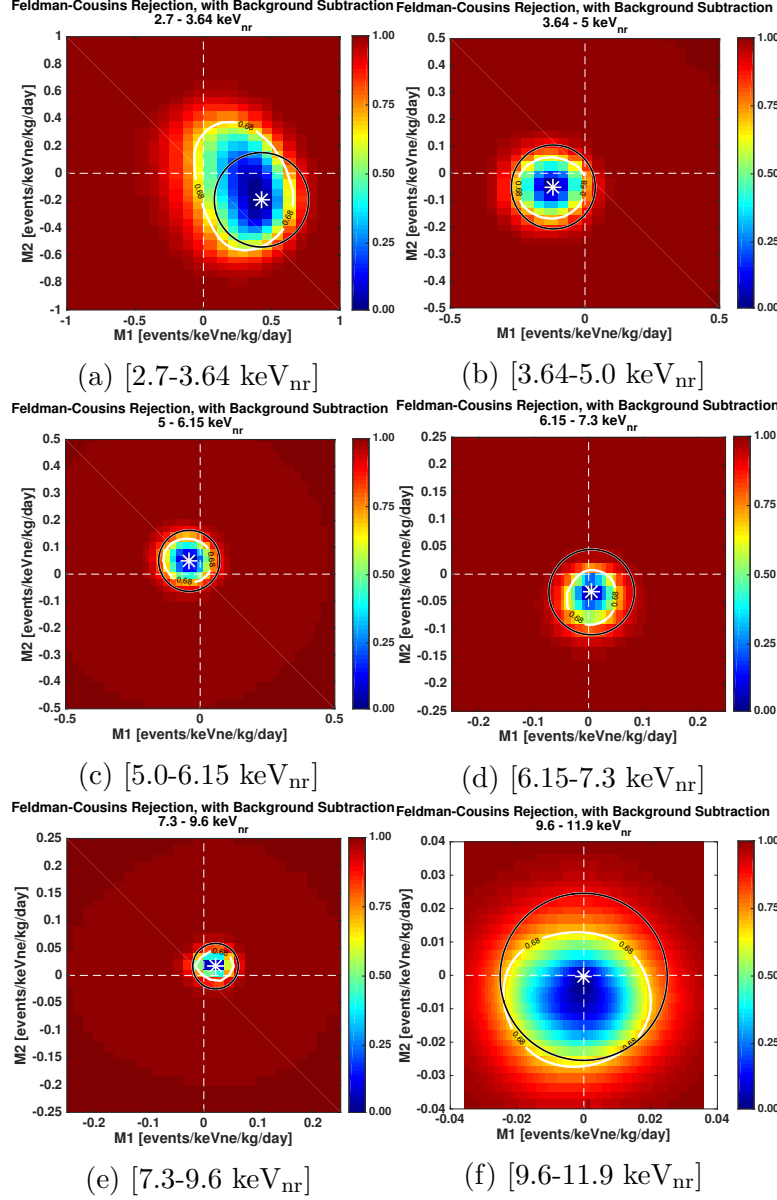


Figure 6.14: Comparison of the 68%, 95%, and 99% asymptotic confidence intervals to estimates of the variance, now for the background-subtracted nuclear recoil candidate events. As before the white star (*) is the maximum-likelihood estimate for the best-fit set of modulation parameters, M_1 and M_2 ; the labeled white contour represents the 68% confidence level for the estimate of the modulation parameters, and the color map shows increasing levels of rejection from 0 (blue) to 1 (dark red). Analytical estimates of the error (σ) on the modulation amplitudes (black circles) are also shown. In the range 2.7 keV_{nr} to 3.64 keV_{nr}, the shape of the confidence intervals deviates from the norm, likely due to the limits of the asymptotic approximation. Again, note the change in scale with increasing energy.

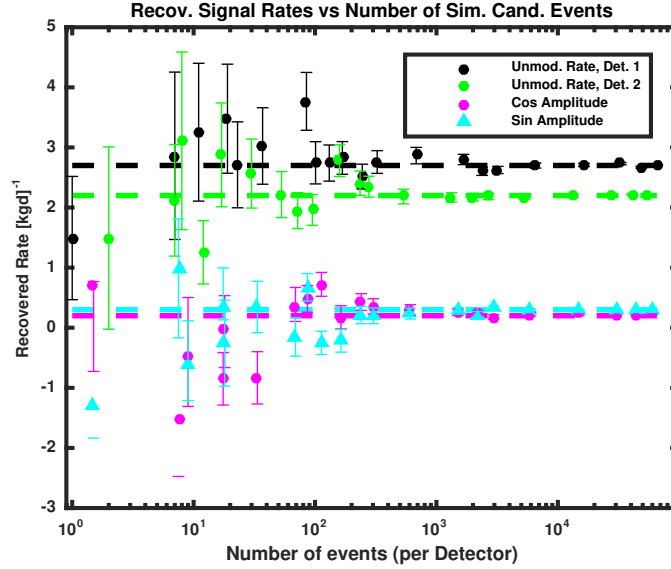


Figure 6.15: Recovered event rate versus number of events (each detector) for simulated set of candidate events with contamination from 2 backgrounds. Likelihood maximization with background subtraction successfully recovers the signal rates.

for the uncertainty in the time dependence of the electronic recoil and zero charge event background rates. The analysis is based on a maximum likelihood technique which simultaneously fits the modulated and the mean unmodulated event rates for signal and backgrounds. In order to demonstrate the reliability of the developed technique, we describe several tests using simulated sets of signal and background events.

Figure 6.15 shows the given and recovered rate of “true signal” events per detector, versus the number of simulated events, for maximization of the likelihood with background subtraction in a single test simulation. The simulated set of candidates includes contributions from a primary signal and two backgrounds, each with an overlap fraction of 20%. The experiment is comprised of two detectors, each given a slightly different unmodulated event rate, with both sharing a common small modulation amplitude. Figure 6.15 shows the recovered values of the unmodulated event rates for each of the two detectors, and common modulation parameters M_1 and M_2 corresponding to the cosine and sine components of the modulation amplitude.

Figures 6.16 and 6.17 show the given and recovered rate of “background” events per detector for each of the two simulated background populations (“background 1” and “background 2”, respectively). The backgrounds are fit in a region considered outside of the signal region. Here, both backgrounds were generated with a leakage efficiency of 80%. The unmodulated rates and modulation amplitudes used to generate each background are shown in Table 6.3. The resulting efficiency-corrected background rates are used to determine the expected contribution to the signal region.

At large numbers of events, there is no bias in the estimate of the recovered event rate.

Event Type	Leakage Frac.	Unmod.(keV kg d ⁻¹)	M_1	M_2
Nuclear Recoils	n/a	[2.7, 2.2]	0.2	0.3
Background 1	0.80	[1.7, 1.5]	0.1	0.1
Background 2	0.80	[1.5, 1.2]	0.2	0.1

Table 6.3: Leakage fractions and event rates used for simulation of nuclear recoil events and backgrounds. The unmodulated event rates are shown for each of the two simulated detectors. Both detectors share a common modulation amplitude, the cosine and sine components of which are given as M_1 and M_2 .

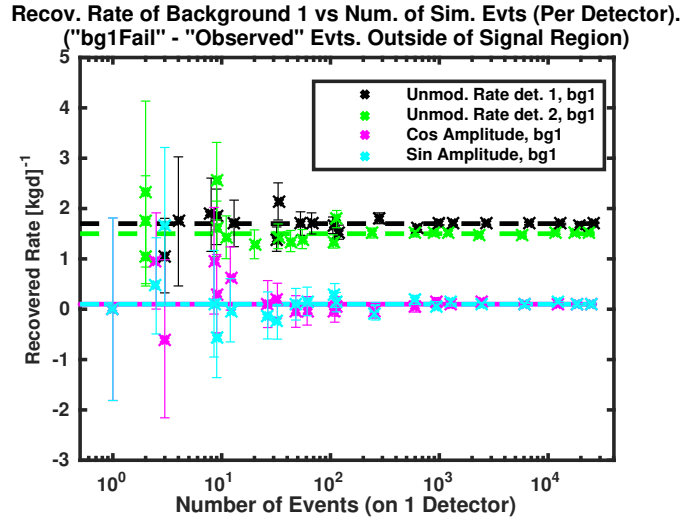


Figure 6.16: “Background 1” recovered event rate versus the number of events (each detector) for a simulated set of background events generated to model events “outside” of the signal region. The likelihood for these events is maximized simultaneously with that of the candidate events as a measurement of the background event rates to estimate the amount of leakage for background subtraction. This figure shows “background 1”. The expected event rate given is for each detector in Table 6.3. Both backgrounds were generated with leakage fractions of 0.8. The likelihood maximization recovers the background rates.

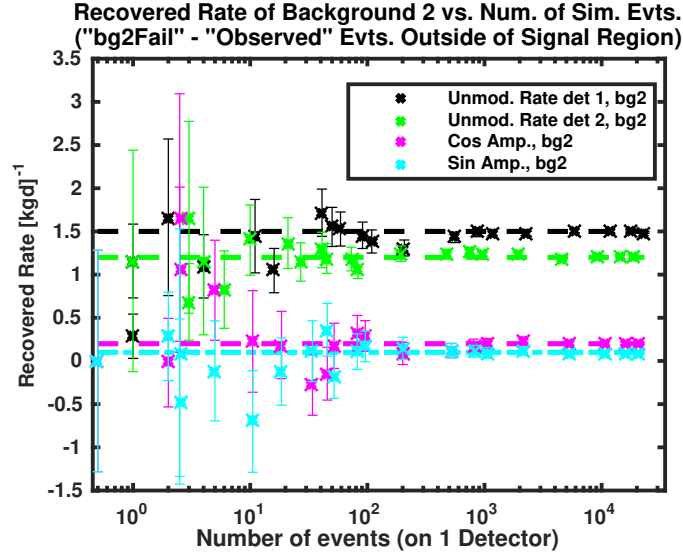


Figure 6.17: Recovered event rate versus the number of events (each detector) for a simulated set of background events generated to model events “outside” of the signal region. The likelihood for these events is maximized simultaneously with that of the candidate events as a measurement of the background event rates to estimate the amount of leakage for background subtraction. Here, “background 2” is shown. The expected rates are given in Table 6.3. The likelihood maximization recovers the background rates.

For smaller samples, corresponding to lower exposures, the errors are larger but consistent with the known modulation amplitudes. However, a test of the likelihood maximization without background subtraction showed indications of a downward bias for small numbers of events, and is still under study.

6.6 Comparisons with DAMA/LIBRA and CoGeNT

The original motivation for this analysis was to serve as a comparison to the contemporary results of the CoGeNT experiment, which reported an annually modulating signal from several years of data [136, 139]. This analysis is also in comparison to the long-standing and somewhat controversial results of the DAMA/LIBRA experiment, a $\sim 9\sigma$ annually modulating signal of unknown origin [198, 160, 199]. Here we compare these results to those of CoGeNT and DAMA/LIBRA.

CDMS II and the DAMA/LIBRA Experiment

In Figure 6.18, we compare the CDMS II results for a modulation peaking at 152.5 days with the results from the DAMA/LIBRA experiment, assuming a 10 GeV WIMP and a NaI

quenching factor of 0.3. The excess and rise reported by the DAMA/LIBRA experiment is not seen in the background-subtracted CDMS II modulation spectrum.

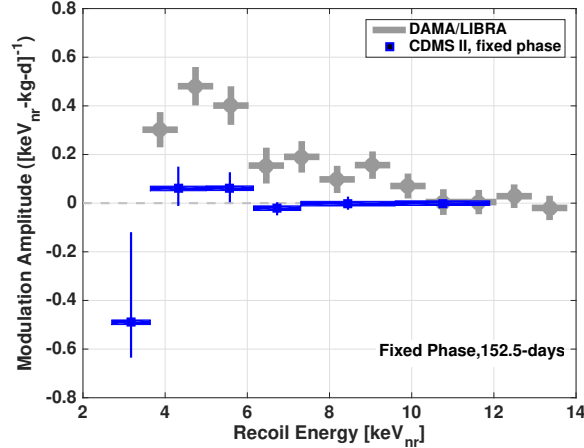


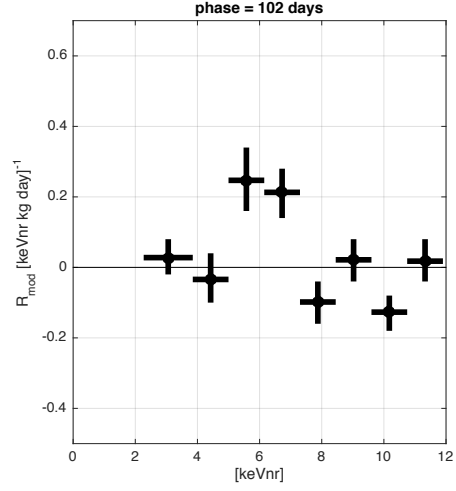
Figure 6.18: The CDMS II modulation amplitude versus energy, compared with DAMA/LIBRA, both for an assumed phase of 152.5 days (based on the standard halo model). The DAMA/LIBRA spectrum assumes a 10 GeV WIMP and a quenching factor of 0.3.

CDMS II and CoGeNT

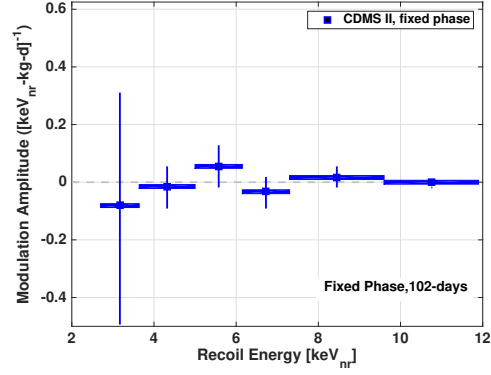
In 2014, the CoGeNT collaboration reported an annually modulating signal in a dataset spanning 3.4 years of operation [139], after previously reporting an “exponential excess of unknown origin” in an earlier analysis, and explored the scenario in which the signal originated from WIMP interactions from non-standard halo configurations. Because both CDMS II and CoGeNT are both germanium experiments, a comparison of the energy spectra is more straightforward than for other target materials. However, because CoGeNT relies only on the ionization signal, recoil energies are typically reported under the assumption of an electron recoil, whereas the results of CDMS II are reported as nuclear recoil-equivalent energy. Comparisons of the energy scales must therefore account for the differences in ionization yield between electron recoil and nuclear recoil events. More details on the conversion between the nuclear recoil- and electron recoil energy scales can be found in [185].

Figure 6.19 shows a comparison of the CDMS II modulation spectrum with that of CoGeNT for a fixed phase of 102-days, based on an internal analysis by S. Hertel [196] of the CoGeNT 2014 data release [139].

Figure 6.20 shows a comparison for both experiments at a fixed phase of 152.5 days. At both phases of the modulation, the CDMS II experiment does not see the CoGeNT modulation. In addition, the significance of modulation in the extended CoGeNT data set in the Hertel analysis is reduced from the original signal reported in 2012 [136].

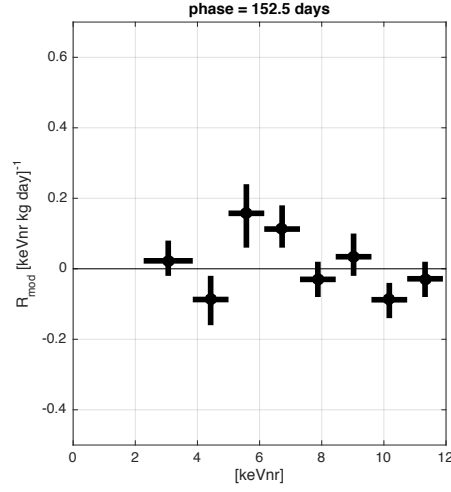


(a) CoGeNT modulation spectrum, for the best-fit phase of 102-days. Figure courtesy of S. Hertel [196].

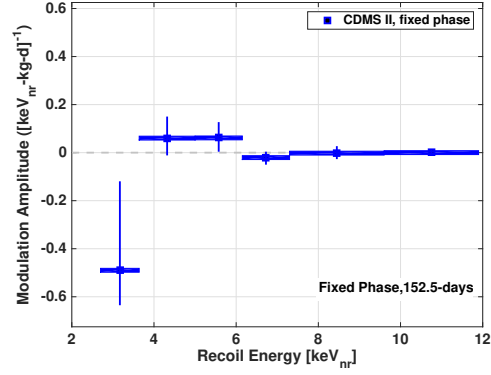


(b) CDMS II background-subtracted modulation spectrum for a fixed phase of 102 days, corresponding to the best-fit CoGeNT phase.

Figure 6.19: CDMS II vs. CoGeNT, 102-day phase.



(a) Modulation amplitude versus nuclear recoil energy for the CoGeNT experiment, for a fixed phase of 152.5 days. Figure courtesy of S. Hertel [196].



(b) Modulation amplitude versus nuclear recoil energy for the CDMS II experiment for a fixed phase of 152.5 days, using the background-subtracted analysis.

Figure 6.20: CDMS II vs. CoGeNT, 152.5-day phase.

New experiments to directly check the results of DAMA/LIBRA are now online. The DMIce-17 collaboration recently released first results from 17 kg of NaI(Tl). While the sensitivity of DM-Ice (17 kg) (DM-Ice17) was not yet sufficient to exclude the DAMA/LIBRA result, it has now joined with several other NaI experiments to form the COSINE-100 collaboration, located in South Korea. COSINE-100 is currently collecting data [162].

Several subsequent analyses of the CoGeNT data have produced strong indications of surface contamination contributing to the excess in the low-energy recoil spectrum. A second experimental search for low mass WIMPs using a point-contact Ge detector, MAJORANA Low-Background BEGe at Kimballton (MALBEK), now excludes the CoGeNT region of interest [200]. Furthermore, the recent reports of modulation of the gamma signal from radon in Soudan Underground Laboratory demonstrate the need for careful evaluation of backgrounds [192]. Recent results from the large liquid noble gas experiments Large Underground Xenon (LUX) and XENON100 (XENON100) have also strengthened the exclusion limits on a low-mass WIMP [201] with reports of no excess.

Remarks on the CDMS II Analysis and Future Recommendations

Future constraints on the annual modulation in a CDMS-style detector can be made stronger by several considerations. A dedicated search, with better calibration for the low energy scale, could provide a more consistent measurement of the background rates on each detector at low energy. A more specific background model for low energy background rates would provide a better estimate of the leakage for background subtraction. A more detailed modeling of the zero yield and gamma events and a more quantitative description of their origin is necessary to improve the modeling of backgrounds for subtraction. In addition, limits on the SI WIMP-nucleon interaction cross section corresponding to the maximum amplitude of modulation consistent with these results, not included in this work, could serve as a useful cross check of the analysis, along with the SNR sensitivity.

Understanding correlations between the event rates in different populations of background events and energy regions could also shed light on the specific origin of the potential increase in the rate of CDMS II at low energies. A correlation of the event rates with the radon fluctuations at Soudan National Laboratory would be informative. Finally, in preliminary studies of the amplitude of modulation in multiple scatter events without background subtraction, as also suggested by [185], we found indications of an excess in modulation in the multiple scatter events at similar energies. Additional studies of the multiply-scattering events would yield more insight on the nature and origin of the CDMS II backgrounds, and provide a firmer basis for the next search for an annually modulating signal from low-mass WIMPs.

Additional work should be done on the measurement of the standard error to determine the bias in the annual modulation analysis, for both the unsubtracted and background subtracted searches. As briefly discussed in Section 6.5 a test of the likelihood maximization without background subtraction showed indications of a downward bias for small numbers of events, and is still under study. In addition, at a phase of 90%, the errors on the 1-D fixed-phase analysis become vanishingly small for energies above 3.64 keV_{nr}. Verification

of the confidence intervals for the fixed-phase analysis indicates that while this is not an indication of strong issues within the analysis, a finer scanning of the modulation parameter range is required for a more accurate determination of the errors at this phase.

Finally, the asymptotic approximation routine that we developed for this analysis was verified by comparison with a full Feldman-Cousins analysis of the unsubtracted data, and found to be in excellent agreement. As hinted in Figure 6.14, however, at low energies in the background-subtracted analysis, we approach a regime in which the number of events is sufficiently small that the approximation may no longer hold. Performing the background-subtraction analysis using the full Feldman Cousins method would provide more robust confidence intervals in the lowest energy range of 2.7-3.64 keV_{nr}.

An alternative approach to that which we presented above, but which we have not done, is to perform a model-independent analysis. In order to more effectively compare results between experiments, a number of authors developed model-independent analyses of detection rates [128, 202, 203, 127, 204]. The modulation spectrum discussed in Section 6.3, which provides the modulation amplitude as a function of the recoil energy, is especially useful for adaptation to the comparison of results from different target materials. Although a Maxwell-Boltzmann distribution is usually assumed as a first-order approximation of the velocity distribution, the resulting model-dependence makes it more difficult to compare experiments of different target materials. Furthermore, sensitivity to the high energy tails of the velocity distribution is important in searches for signal modulation [13]. This has become increasingly important as more experiments have reported signals just above detection thresholds and in regions excluded by other searches. In [128] the comparable energy ranges of two experiments can be deduced by mapping the energy range of the first experiment into the space of minimum velocities required for a WIMP interaction at those energies, and then mapping from that minimum velocity space into the equivalent energy range of the second experiment. Future analyses can check the compatibility of reported results by examining the two experiments in the same region of phase space.

Chapter 7

Conclusions

7.1 Conclusions

With the subtraction of the electron recoil and zero charge event backgrounds, we find no statistically significant modulation of the nuclear recoil candidate events in the energy range $2.7 \text{ keV}_{\text{nr}}$ to $11.9 \text{ keV}_{\text{nr}}$ (Figure 7.1).

Low-threshold analyses of CDMS II germanium data found no excess signal in the energy ranges $2.27 \text{ keV}_{\text{nr}}$ to $11.9 \text{ keV}_{\text{nr}}$ [186]. Furthermore, any attempt to interpret the the amplitude of modulation in CDMS II prior to background subtraction in light of a WIMP signal is excluded by the results of SuperCDMS-LT and several generations of the CDMS low ionization threshold experiment (CDMSlite) [135, 132, 159, 134], and would require a modulation of 100% of the rate observed in SuperCDMS-LT.

The best fit absolute values of the modulation amplitudes for the unsubtracted and background-subtracted nuclear recoil candidates of CDMS II are summarized in Table 6.2. After background subtraction, the maximum amplitude of modulation in any energy range was found to be less than $0.5 [\text{keVkgd}]^{-1}$, with the highest rate in the lowest energy bin, $2.7 \text{ keV}_{\text{nr}}$ to $3.64 \text{ keV}_{\text{nr}}$. In the energy range $3.64 \text{ keV}_{\text{nr}}$ to $5.0 \text{ keV}_{\text{nr}}$, a $2.7 [\text{keVkgd}]^{-1}$ modulation amplitude at 3σ significance before background subtraction, was reduced to $0.13 [\text{keVkgd}]^{-1}$ after the subtraction of electron recoil and zero charge backgrounds, and found to be consistent with a hypothesis of no modulation. Because of the lack of statistical significance of any modulating signal, the small deviations of the best-fit modulation amplitude from zero in the energy range $2.7 \text{ keV}_{\text{nr}}$ to $3.64 \text{ keV}_{\text{nr}}$ cannot be taken as evidence of a WIMP signal.

Our analysis of the CDMS II low energy data set places strong constraints on an annually modulating signal in the $2.7 \text{ keV}_{\text{nr}}$ to $11.9 \text{ keV}_{\text{nr}}$, and is incompatible with claims by CoGeNT and DAMA of a modulating signal for low mass WIMPs, suggesting that neither of the modulations seen by either experiment is of WIMP origin.

Background-subtracted versus unsubtracted nuclear recoil event rates

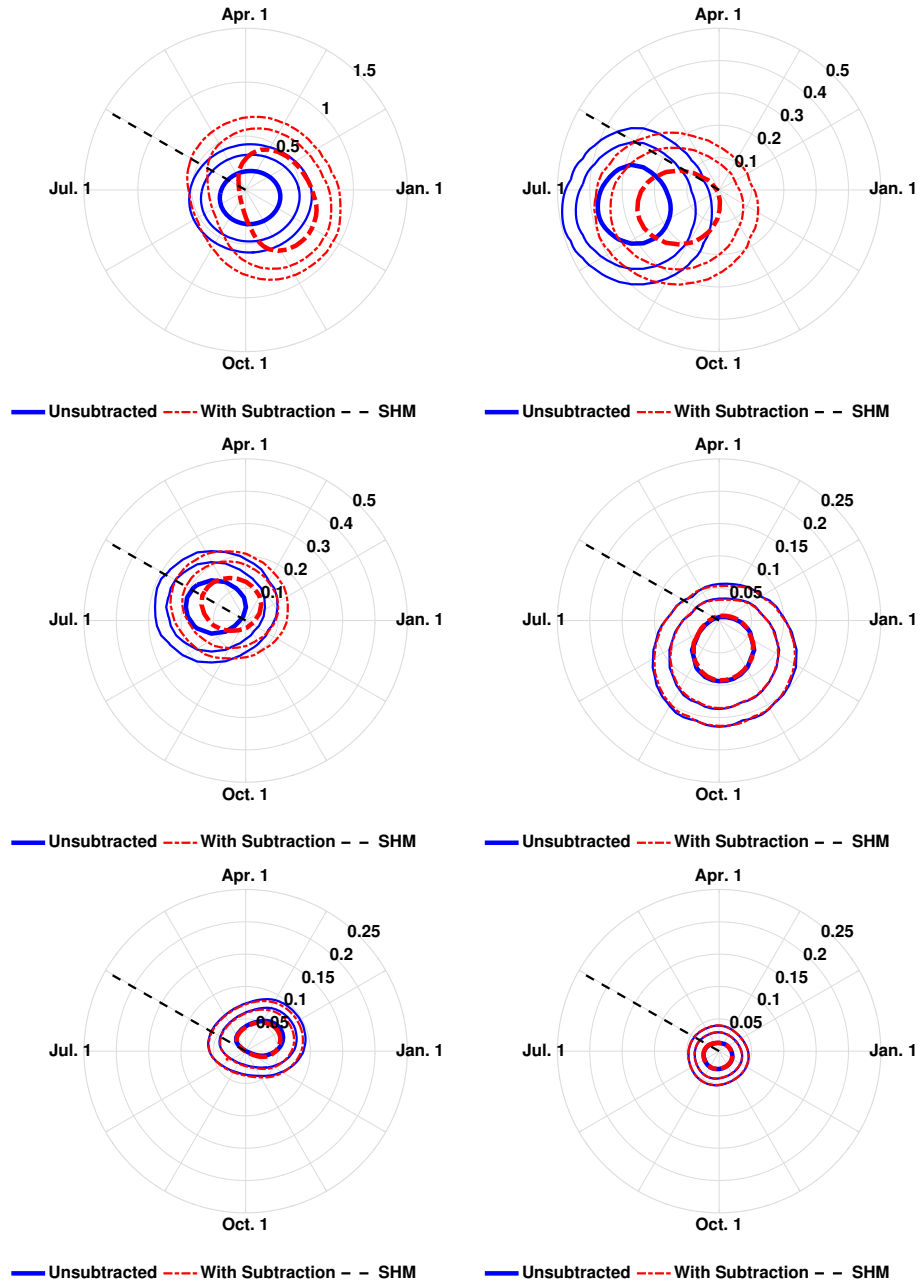


Figure 7.1: 68%, 95%, and 99% Confidence intervals on the modulation amplitude of nuclear recoil event rates, background-subtracted.

Acronyms

Λ CDM lambda cold dark matter. 15, 16

ADMX Axion Dark Matter eXperiment. 23

ADMX-HF ADMX-High Frequency. 23

ANAIS Annual modulation with NAI Scintillators. 32

ArDM Argon Dark Matter. 32

ATLAS A Toroidal LHC ApparatuS. 21, 26, 27

BLIP Berkeley Large Ionization- and Phonon-based. 46, 47, 54

BOSS Baryon Oscillation Spectroscopic Survey. iv, 6

CASPEr Cosmic Axion Spin Precession Experiment. 23

CAST CERN axion solar telescope. 23

CDEX China Dark Matter EXperiment. 32

CDM cold dark matter. v, 13

CDMS Cryogenic Dark Matter Search. iii, vii, 1, 2, 23, 28, 32, 33, 38, 41, 42, 45–47, 49, 50, 53–55, 58–60, 110

CDMSlite CDMS low ionization threshold experiment. vii, 32, 38, 39, 41, 42, 112

CDMS II Cryogenic Dark Matter Search II. iii, vi–viii, x, xi, 1, 38, 39, 42, 43, 45, 47–50, 52–57, 59–62, 65, 68, 70–72, 74–76, 79, 82, 85–87, 89, 90, 95, 97, 106–110, 112

CDMS II - Si CDMS II Silicon. 38, 39

CLEAN Cryogenic Low-Energy Astrophysics with Nobles. 32

CMB cosmic microwave background. iv, v, 5, 6, 11, 13, 15, 16, 23

CMS Compact Muon Solenoid. 21, 26, 27

cMSSM constrained MSSM. 25

CoGeNT Coherent Germanium Neutrino Technology. viii, x, 32, 38, 39, 41, 42, 95–97, 106–110, 112

COSINE - 100 COSINE - 100. 32

COUPP Chicagoland Observatory for Underground Particle Physics. vi, 32, 39

CP charge and parity. 22, 23

CRESST Cryogenic Rare Event Search with Superconducting Thermometers. vii, 32, 38–42

CTA Cherenkov Telescope Array. 29

DAMA DArk MAtter. 32, 39–41, 55, 112

DAMA/LIBRA second generation DAMA. x, 32, 38–40, 42, 57, 106, 107, 110

DAMIC Dark Matter in CCDs. vii, 32, 39, 41

DEAP Dark Matter Experiment using Argon Pulse-shape. 32

DM-Ice17 DM-Ice (17 kg). 32, 110

DRIFT Directional Recoil Identification from Tracks. 32

EDELWEISS Expérience pour DEtecter Les WIMPs En Site Souterrain. vi, vii, 32, 39, 41, 62

EDM electric dipole moment. 22

EFT effective field theory. 43

FLIP Fast Large Ionization- and Phonon-based. 46–48

G2 second-generation. 38

GR general relativity. 10, 11, 14

IceCube IceCube Neutrino Observatory. 29, 41

IZIP Interleaved Z-sensitive Ionization and Phonon. vii, 38, 40, 49, 50

- KIMS** Korea Invisible Mass Search. 32
- LEP** Large Electron-Positron Collider. 29
- LHC** Large Hadron Collider. vi, 25–28
- LNGS** Laboratori Nazionali del Gran Sasso. 39
- LSP** lightest supersymmetric particle. 17, 24, 25, 28, 29
- LUX** Large Underground Xenon. vi, vii, 32, 37–42, 110
- LZ** LUX-ZEPLIN. 32, 38
- MALBEK** MAJORANA Low-Background BEGe at Kimballton. 32, 38, 41, 110
- MINOS** Main Injector Neutrino Oscillation Search. 65
- MOND** MOdified Newtonian Dynamics. 16
- MSSM** Minimal Supersymmetric Standard Model. 24, 25, 29
- mSUGRA** minimal Super Gravity. 25
- mwe** meters water-equivalent. 45
- NFW** Navarro-Frenk-White. iv, 6
- NTD** neutron-transmutation-doped. 46
- OF** optimal filter. 63
- PandaX** Particle and Astrophysical Xenon Detector. vi, 32, 38, 39
- PICASSO** Project In CANada to Search for Supersymmetric Objects. vi, 32, 39
- PICO** from PICASSO and COUPP. vi, 32, 39
- pMSSM** p(henomenological) MSSM. 25, 28, 29
- QCD** quantum chromodynamics. 16, 18, 19, 22, 23
- QET** Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge sensor. 46, 47, 63, 64
- RMS** root mean square. 7

- ROSEBUD** Rare Objects SEArch with Bolometers UndergrounD. 32
- RQ** reduced quantity. 60
- RRQ** relational reduced quantity. 60
- SD** spin-dependent. 34, 58
- SDSS III** Sloan Digital Sky Survey III. iv, 6
- SI** spin-independent. vii, 34, 38, 40, 41, 55, 56, 58, 110
- SIMPLE** Superheated Instrument for Massive ParticLe Experiments. vi, 32, 39
- SNOLAB** . 38, 50
- Soudan** Soudan Underground Laboratory. vii, 41, 45, 48, 55, 56, 59, 61, 75
- SQUID** superconducting quantum interference device. 46, 47, 49
- standard halo model** SHM. vi, viii, 35–37, 87, 88, 96
- Standard Model** Standard Model of particle physics. vi, 16–18, 20–25, 27–29, 34
- SUF** Stanford Underground Facility. 54
- SuperCDMS** Super Cryogenic Dark Matter Search. ii, vi, vii, 2, 28, 38–41, 48–50, 53, 59, 112
- SUSY** supersymmetry. 1, 23–26, 28
- TES** transition edge sensor. 46–49
- TEXONO** Taiwan EXperiment On Neutrino. vi, 32, 39
- TOE** theory of everything. 24
- WArP** WIMP Argon Programme. 32
- WIMP** weakly interacting massive particle. iii, vi, vii, x, xi, 1, 2, 16, 17, 23, 25, 26, 28–43, 45, 48, 49, 54–64, 68, 72–78, 85, 89, 106, 107, 110–112
- WMAP** Wilkinson Microwave Anisotropy Probe. 28, 29
- XENON10** XENON10. 32, 39, 42
- XENON100** XENON100. 32, 110

XENON1T XENON1T. 32, 39

XMASS Xenon detector for weakly interacting MASSive particles. vi, 32, 39

XRB X-ray background. 11

ZEPLIN ZonEd Proportional scintillation in LIquid Noble gases. vi, 32, 38, 39

ZIP Z-sensitive Ionization and Phonon. vii, 47–50, 54, 55, 62

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