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Deep Underground Science and Engineering Lab
S1 Dark Matter Working Group

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1 Overview

The discovery of dark matter is of fundamental importance to cosmology, astrophysics, and elementary particle physics. A broad range of observations from the rotation speed of stars in ordinary galaxies to the gravitational lensing of superclusters tell us that 80–90% of the matter in the universe is in some new form, different from ordinary particles, that does not emit or absorb light. Cosmological observations, especially the Wilkinson Microwave Anisotropy Probe of the cosmic microwave background radiation, have provided spectacular confirmation of the astrophysical evidence. The resulting picture, the so-called "Standard Cosmology," finds that a quarter of the energy density of the universe is dark matter and most of the remainder is dark energy. A basic foundation of the model, Big Bang Nucleosynthesis (BBN), tells us that at most about 5% is made of ordinary matter, or baryons. The solution to this "dark matter problem" may therefore lie in the existence of some new form of non-baryonic matter. With ideas on these new forms coming from elementary particle physics, the solution is likely to have broad and profound implications for cosmology, astrophysics, and fundamental interactions. While non-baryonic dark matter is a key component of the cosmos and the most abundant form of matter in the Universe, so far it has revealed itself only through gravitational effects—determining its nature is one of the greatest scientific issues of our time.

Many potential new forms of matter that lie beyond the Standard Model of strong and electroweak interactions have been suggested as dark matter candidates, but none has yet been produced in the laboratory. One possibility is that the dark matter is comprised of Weakly Interacting Massive Particles, or WIMPs, that were produced moments after the Big Bang from collisions of ordinary matter. WIMPs refer to a general class of particles characterized primarily by a mass and annihilation cross section that would allow them to fall out of chemical and thermal equilibrium in the early universe at the dark matter density. Several extensions to the Standard Model lead to WIMP candidates. One that has received much attention is Supersymmetry (SUSY), which extends the Standard Model to include a new set of particles and interactions that solves the gauge hierarchy problem, leads to a unification of the coupling constants, and is required by string theory. The lightest neutral SUSY particle, or neutralino, is thought to be stable and is a natural dark matter candidate. Intriguingly, when SUSY was first developed it was in no way motivated by the existence of dark matter. This connection could be a mere coincidence—or a crucial hint that SUSY is responsible for dark matter.

The possibility that a new class of fundamental particles could be responsible for the dark matter makes the search for WIMPs in the galactic halo a very high scientific priority. In resolving this puzzle, it is intrinsically important to carefully search the parameter space defined by a WIMP signal in the galactic halo using terrestrial detectors. A direct detection of dark matter in the halo would be the most definitive way to determine that WIMPs make up the the missing

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mass. As we discuss further below, the study of WIMP candidates in accelerator experiments is critical in determining the relic density of these particles. The indirect detection of astrophysical signals due to WIMP-WIMP self-annihilation may also provide important clues but in many cases may be difficult to unambiguously separate from more mundane astrophysical sources. That leaves direct detection as playing a central role in establishing the presence of WIMPs in the universe today. Given both the technical challenge and fundamental importance of direct WIMP detection, it is vital to have the means to confirm a detection in more than one type of detector. In addition to giving a critical cross check on systematic errors that could fake a signal, detection of WIMPs in multiple nuclei will yield further information about the WIMP mass and couplings. Eventually, if WIMPs are discovered, then the ultimate cross check will be confirming their galactic origin by observing secondary signatures related to the motion of the earth and solar system.

Many accelerator-based experiments have searched for SUSY's predictions. Although no direct evidence has yet been found, the unexplored landscape on the energy frontier is still rich with candidates. Indeed, SUSY particles are the prime quarry of the large experiments at Fermilab's Tevatron and CERN's Large Hadron Collider (LHC), and the laboratory production of WIMP candidates would be a great help in solving the dark matter problem. However, accelerator experiments alone cannot offer a solution because it is impossible to determine whether the particles are sufficiently long-lived. Ultimately, only astrophysical observations can determine whether WIMPs exist in nature.

Astroparticle physics experiments worldwide are actively searching for WIMPs under the hypothesis that they make up the missing mass in the Galaxy. The two main approaches are direct detection of WIMP-nucleus scattering in laboratory experiments and indirect detection through the observation of WIMP-WIMP annihilation products. An astrophysical discovery of WIMPs would be a landmark event for cosmology and give new information on fundamental particle physics that may otherwise be inaccessible even to the LHC. In fact, if SUSY eludes the LHC, astrophysical evidence for new particles could provide the key guidance for the planned International Linear Collider (ILC). A solution to the dark matter puzzle will also address lingering questions about our understanding of gravity.

US scientists are in a world-leading position in direct detection, by having pioneered the development and deployment of several of the best technologies, and by engaging in an active R&D program that promises to continue this leadership. The detection of dark matter is an experimental challenge that requires the development of sophisticated detectors, suppression of radioactive contamination, and—most relevant to this report—siting in deep underground laboratories to shield from cosmic-ray-induced backgrounds. By building the world's premier deep laboratory, together with bringing the ongoing R&D efforts to fruition, the US will be in a very advantageous position internationally to attract and lead the major experiments in this field.

A number of recent reports have highlighted the importance of dark matter searches. Two NRC reports, "Connecting Quarks with the Cosmos," chaired by M. Turner [1], and "Neutrinos and Beyond," chaired by B. Barish [2]; and the HEPAP report "The Quantum Universe," chaired by P. Drell [3], have pointed out the high scientific priority of this enterprise. In reviewing these findings, the OSTP Interagency Working Group's "Physics of the Universe" report directed that in the area of dark matter "NSF and DOE will work together to identify a core suite of physics experiments. As stated in the report, this work will include research and development needs for specific experiments, associated technology needs, physical specifications, and preliminary cost estimates" [4]. The central role that dark matter plays at the intersection of cosmology and fundamental physics was highlighted most recently in the NRC report "Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics," chaired by H. Schapiro and S. Dawson [5]. In that report, the search for dark matter was included among the top three priorities of the long range US HEP program. These stated priorities and directives in these various reports are well-aligned with the DUSEL science program.

In Section 2 of this report we describe the cosmological and astrophysical evidence for dark matter and the deep connection to particle physics suggested by the WIMP hypothesis. A concordant picture of dark matter will require information from both astrophysical observations and laboratory measurements. On the one hand, accelerator experiments alone cannot establish a solution to the dark matter problem because of the question of particle stability. On the other hand, an astrophysical detection does not constrain the particle physics parameters well enough to determine their relic density.

In Section 3 we define the basic challenge of the direct detection of WIMPs, which is based on elastic scattering between WIMPs in the halo and atomic nuclei in a terrestrial detector. We examine there the general strategy, including the need to mitigate background sources by enhancing the sensitivity for nuclear recoil events relative to the predom-

inant electromagnetic backgrounds. We also discuss methods for comparing the sensitivity of different approaches, interpreting results within the framework of particle physics models, and conclude that section with a brief description of the present status of WIMP searches.

Following the general discussion of direct searches, we give an overview in Section 4 of indirect astrophysical methods to detect WIMPs. These methods are based on looking for WIMP annihilation products including gamma rays, neutrinos, and other particle species. The sources are based on enhanced concentrations of WIMPs that arise from scattering and clumping of the particles in astrophysical objects. Depending on the nature of the source and the annihilation channel, the sources range from broad-band to monoenergetic and include both directional and diffuse sources. While there are several interesting hints, the challenge remains to establish that these are not due to other astrophysical processes.

In Section 5, we take up in more detail the particle physics behind WIMP candidates. With the anticipated turn-on of the LHC at CERN and the high priority of the ILC to the US High Energy Physics program, it is particularly timely to examine the complementarity of the accelerator- and non-accelerator-based approaches to answering questions about the nature of both dark matter and fundamental interactions. Clearly, the laboratory production of WIMP candidates could provide important guidance to the astrophysical searches. By the same token, astrophysical measurements of WIMP properties can help to constrain physics beyond the Standard Model and provide knowledge that would otherwise be difficult to obtain at accelerators during a similar time frame.

The multi-decade scientific program at DUSEL will include dark matter searches at the ton-scale and beyond, with ultra-clean ultra-sensitive detectors. In this context, we examine in Section 6 some of the other physics that could also be pursued in combination with dark matter instruments. Specifically, we look at the related requirements of double-beta-decay experiments, which have in common the need for low-radioactive background and excellent energy resolution. Germanium, xenon and tellurium all have double-beta-decay nuclides and are being used as detection media in both fields. In Section 6, we also examine the prospects for detecting neutrinos from supernovae. These neutrinos, with energy in the 10-MeV range, would exhibit scattering rates in nuclei that are enhanced by coherent scattering and will give recoils above dark matter detection thresholds.

In the latter part of the report we focus on the specific experiments and technical requirements in Sections 7 and 8, respectively. The status of several candidate experiments for DUSEL are briefly reviewed, looking at both current status of progenitors and plans for the future. Infrastructure requirements are treated in subsections on depth, materials handling, and space and facility needs.

The report concludes with sections on the international context regarding experiments and laboratories outside the US, and our assessment of the long-range dark matter road map.

2 WIMP Dark Matter: Cosmology, Astrophysics, and Particle Physics

The evidence for dark matter is overwhelming, and arises from a wide range of self-consistent astrophysical and cosmological data. Dark matter appears to be ubiquitous in spiral galaxies, dating to observations from the 1970's by Rubin and Ford [6]. It is evident there in so-called "flat" rotation curves, in which the rotation speed of stars and gas as a function of galactic radius is larger than can be attributed to the centripetal force exerted by the luminous mass.

On larger scales, studies of clusters of galaxies show even larger fractions of dark matter relative to stars and intergalactic gas. Indeed, it was Zwicky's observation of the Coma cluster in 1933 that provided the first evidence for a missing-mass problem [7]. Independent studies of virial speeds of cluster-bound galaxies, gravitational-bound X-ray-emitting gas, and gravitational lensing of background objects by the cluster all reveal similar amounts of dark matter. A striking example, shown in Figure 1, is the gravitational lensing of a background galaxy into multiple images by a cluster in the foreground [8]. The mass of the cluster derived from its luminosity is insufficient to account for the strength of the lens, as indicated by the fit to a smooth distribution of matter underlying the galaxies, themselves [9]. The mean matter density of the Universe attributed to measurements of X-rays emitted from the gas finds that $\Omega_m = 0.26^{+0.06}_{-0.04}$ [10] in units of critical density.

On cosmological scales, detailed mapping of the anisotropy of the cosmic microwave background (CMB) and obser-

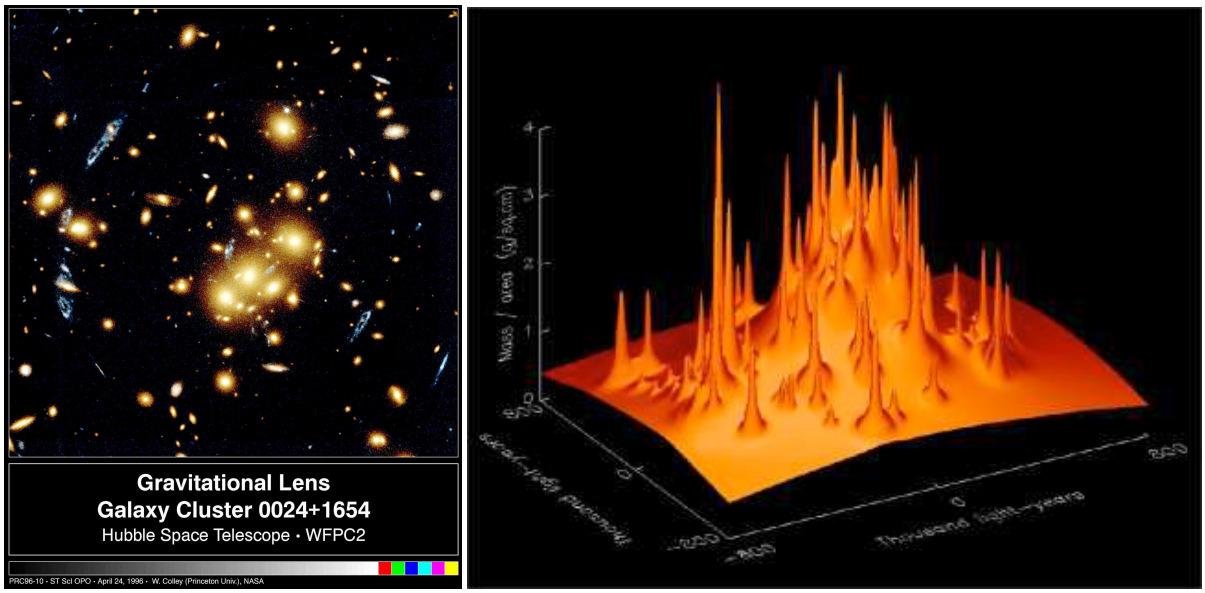

Figure 1: Left: The foreground cluster of galaxies gravitationally lenses the blue background galaxy into multiple images [8]. Right: A parametric inversion for the strength and shape of the lens shows a smooth background component not accounted for by the mass of the luminous objects [9].

vations of high-redshift supernovae and the large-scale distribution of galaxies have led to a concordance model of cosmology, which is consistent with the mean matter density of the universe inferred from clusters and the primordial light-element abundances from BBN. In this very successful model, the universe is made of $\sim$4% baryons which constitute the ordinary matter, $\sim$23% nonbaryonic dark matter and $\sim$73% dark energy (see, for example Refs. [11] or [12], for fits to cosmological parameters). From these observations we also know that the dark matter must have been nonrelativistic at the time that the energy density of radiation and matter were equal, and is thus generically referred to as "cold" dark matter. Modifications to gravity that can explain all the observations that indicate dark matter seem unlikely because the observations cover such a large distance scale.

Thermal production of WIMPs in the early Universe, followed by freeze-out, provides a natural mechanism for creation of dark matter with the observed relic density [13, 14]. This is a straight-forward extension of the standard BBN scenario, which successfully predicts the abundance of the light elements. The time and temperature at which the WIMPs decouple from ordinary matter is determined by their cross section for annihilation with themselves or other particles in the hot plasma, and the abundance at the decoupling time is determined by the temperature and the mass. Therefore, the relic density of dark matter today would depend principally on the WIMP's mass and annihilation cross section. Also, simple dimensional arguments relating the mass and cross section, along with the constraint that the relic density be equal to the dark matter density, naturally satisfy the criterion that the particles are non-relativistic at decoupling. Purely cosmological considerations lead to the conclusion that WIMPs should interact with a cross section similar to that of the Weak Interaction.

Other scenarios for particle cold dark matter exist, such as the very light axions [15] or the very heavy WIMPzillas [16]. Axions arise as a solution to the strong CP problem and arise in the early universe as a Goldstone boson from the QCD phase transition. Like WIMPs, they are also the subject of active dark matter search experiments but require a different set of experimental techniques (which are carried out in surface laboratories). Unlike axions and WIMPzillas, WIMPsare produced thermally and represent a generic class of Big Bang relic particles that are particularly interesting because of the convergence of independent arguments from cosmology and particle physics. That is, with the required ranges of mass and cross section characteristic of the Weak scale, WIMPs occur precisely where we expect to find physics beyond the Standard Model. Specifically, new physics appears to be needed at the Weak scale to solve the mass hierarchy problem. Namely, that precision electroweak data constrain the Higgs mass in the Standard Model to be less than 193 GeV/c^2 at 95% C.L. [17] in spite of the radiative corrections that tend to drive it to the much higher

scale of Grand Unified Theories (GUTs). These corrections tend to be cancelled in Supersymmetry, which naturally predicts that the Lightest Supersymmetric Partner (LSP) is stable and interacts at roughly the Weak-Interaction rate. More recently, compact extra dimensions have been proposed to solve this problem, also leading to WIMP candidates. The theoretical parameter space is very unconstrained so any empirical data that restrict it, both from dark matter detection and accelerator-based methods, are extremely valuable

If WIMPs are indeed the dark matter, their local density in the galactic halo inferred from the Milky Way's gravitational potential may allow them to be detected via elastic scattering from atomic nuclei in a suitable terrestrial target [18]. Owing to the WIMP-nucleus kinematics for halo-bound particles, the energy transferred to the recoiling nucleus is on the order of 10 keV. The expected rate of WIMP interactions, which is currently limited by observations to less than 0.1 events/kg/day [23], tends to be exceeded in this energy range by ambient radiation from radioisotopes and cosmic rays, and so sensitive high-radiopurity detectors and deep underground sites are required.

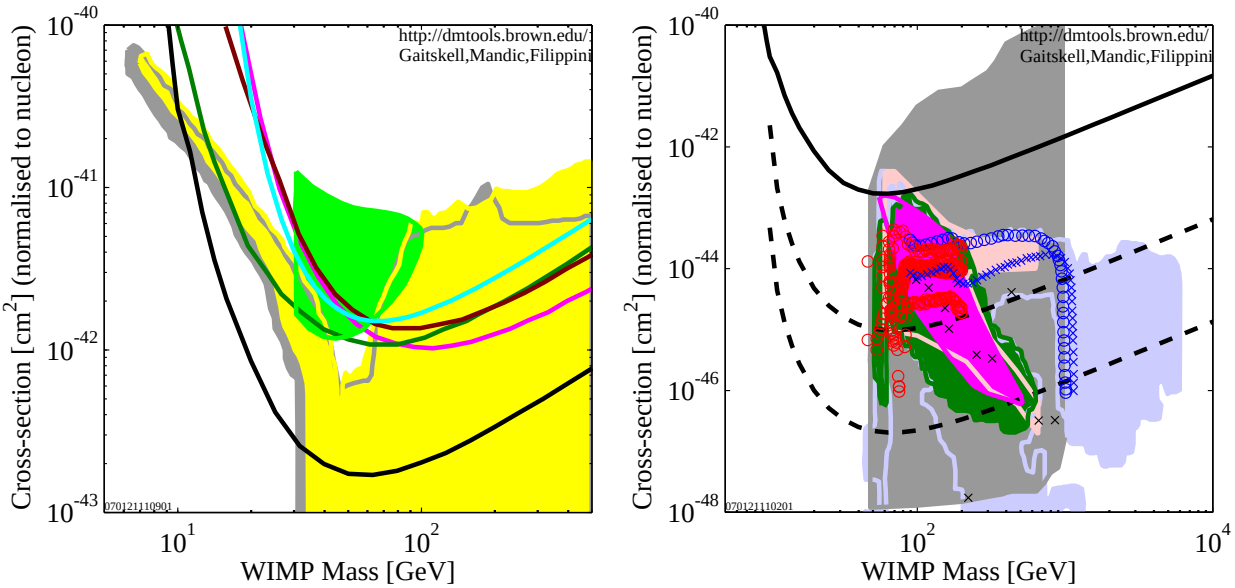

Figure 2: Plots of the elastic scattering cross section for spin-independent couplings versus WIMP mass. (a) The left panel shows the leading experimental results in which the solid curves represent experimental upper limits from the ZEPLIN-I single-phase liquid xenon detector (dark green) [19], the EDELWEISS thermal and ionization cryogenic detectors (dark red) [20], the CRESST thermal and scintillation cryogenic detectors (cyan) [21], the WARP two-phase liquid argon detector (magenta; 55 keV threshold) [22], and the CDMS-II athermal-phonons and ionization detectors (black) [23], in all cases assuming the standard halo model [24] and nuclear-mass-number A^2 scaling. The contested DAMA annual-modulation claim [25] is shown by the green region. The yellow and grey regions represent unconstrained Minimal Supersymmetric Standard Model (MSSM) predictions for low-mass WIMPs that result from relaxing the GUT-scale unification of gaugino masses [27]. (b) The right panel displays a broad range of models. The most unconstrained MSSM predictions are indicated by the large grey region [26]. Models within the minimal supergravity (mSUGRA) framework are shown in dark green [28], magenta [29] and pink [30]; the light blue region is from relaxing the constraint imposed by the SUSY interpretation of the muon "$g-2$" anomalous magnetic moment measurement [28]. More specific predictions are given by split Supersymmetry models shown by blue circles and crosses (for positive and negative values of the μ parameter, respectively) [31] and red circles [32]. The set of representative post-LEP LHC-benchmark models are shown by black crosses [33]. Experimental projections are shown as black-dashed curves and are representative of the sensitivity of next- and next-next-generation searches with detector masses in the range from several tens of kilograms up to the ton scale. The CDMS-II limit is shown again as a solid black curve for reference with the left panel.

Figure 2 illustrates the common landscape of direct WIMP searches and the theoretical parameter space in plots of the WIMP-nucleon cross section versus WIMP mass. The experimental bounds are represented by the U-shaped curves, above which cross sections are ruled out for a given experiment. Theoretical models that are constrained by the required relic density and all known accelerator bounds are differentiated by alternative theoretical ideas. In some of the theoretical cases, bounded regions indicate the remaining allowed parameter space. In other cases, the model is

fully specified and serves as a so-called benchmark, which is typical of a given class of models and provides for a more direct sensitivity comparison among different approaches, e.g., astrophysical searches or accelerator experiments. As is evident in the figure, some models of interest are already being constrained by direct detection methods.

In addition to the direct searches for WIMP dark matter, WIMPs are being sought by indirect means by looking for WIMP annihilation products. Since WIMPs would scatter and lose energy in astrophysical objects such as the Earth, Sun and in the galactic center, the number density could become high enough to detect annihilation or subsequent decay products such as neutrinos, gamma rays or charged particles. We describe the influence of these methods in Section 4.

3 Direct Detection of WIMPs

WIMP-search experiments seek to measure the interactions of dark matter particles bound in our galactic halo with the atomic nuclei of detector target materials on Earth. The calculation of the rate in terrestrial detectors depends on the WIMPs velocity distribution and density in the galaxy, the WIMP mass and elastic-scattering cross section on nucleons, and the nuclear structure of the target nuclei. Unfortunately, the relic density of WIMPs provides only a loose constraint on the scattering cross section because the relic density depends on the processes through which the particles annihilate. In the well-studied example of SUSY, model-dependent co-annihilation channels prevent the making of a simple crossing-symmetry argument to relate the density and the scattering rate [14]. Indeed, SUSY-based calculations for neutralinos show at least five orders of magnitude variation in the nucleon coupling, and can even vanish in finely-tuned cases. Covering the bulk of the SUSY parameter space for WIMPs will require an increase in sensitivity from the current rate limits of $\sim$0.1 event/kg/d to less than 1 event/ton/year, demanding increases in detector mass and exposure, and reduction in and/or improved rejection of radioactive and cosmogenic backgrounds.

Given the measured properties of the Milky Way galaxy and fairly generic assumptions about the spatial and velocity distribution of its dark matter halo, the spectrum of WIMP energy depositions in a detector can be calculated in terms of the unknown WIMP mass and total cross section for nuclear scattering. Because the WIMPs must be highly non-relativistic if they are to remain trapped in our galaxy, the shape of the spectrum has almost no dependence on the detailed particle physics model. As discussed in [24], the differential rate takes the form

$$\frac{dN}{dE_r} = \frac{\sigma_0 \rho_\chi}{2\mu^2 m_\chi} F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} dv, \tag{1}$$

where ρ_χ is the local WIMP density, μ is the WIMP-nucleus reduced mass $m_\chi m_N/(m_\chi + m_N)$ (assuming a target nucleus mass m_N, and WIMP mass m_χ), and the integral takes account of the velocity distribution $f(v)$ of WIMPs in the halo. The term v_{min} is the minimum WIMP velocity able to generate a recoil energy of E_r, and v_{esc} is the galactic escape velocity. $F^2(q)$ is the nuclear form factor as a function of the momentum transfer q and σ_0 is the total WIMP-nucleus interaction cross section.

The astrophysical uncertainties in Equation 1 are contained in ρ_χ and $f(v)$, which can be estimated by comparing our galaxy's measured rotation curve to dark matter halo models. Simple models of galactic structure indicate that the particles in the halo should be relaxed into a Maxwell-Boltzmann distribution with an RMS velocity related to the maximum velocity in the rotation curve. In the Milky Way, the value of the RMS velocity is estimated to be v_{RMS} $\sim$220 km/s. This will be assumed below in comparing direct detection experiments. However, the velocity structure of the dark halo may be more complex than a simple Maxwell-Boltzmann distribution. Current understanding of structure formation posits that a dark halo of galactic dimensions is built hierarchically from the merging of smaller dark halos. In the central parts of the galaxy, where many small halos have converged, the short orbital times and the strong tidal forces blend the halos together into a relaxed structure with a Maxwell-Boltzmann distribution. In the outer parts of the galaxy, where the orbital times are long (several Gyr), small halos are still falling into the galaxy at present. Matter is pulled out of the small halos by tidal forces and is redistributed into long arms in front and behind them. The capturing of a multitude of small halos renders the outer galaxy a crisscross of tidal streams. The crucial question for estimating direct detection rates is if the solar system lies in the outer or the inner part of the galactic halo,

i.e. where the halo velocity distribution is Maxwell-Boltzmann or where it is not. Recent data on the Sagittarius dwarf galaxy show that it may be one the "small halos" still falling into our Milky Way, and one of its tidal arms may pass very close, if not even across, the solar system [34]. The amount of matter in the Sagittarius arm seems however to be only a fraction of the local dark matter density [35, 36]. Theoretical calculations using N-body simulations and semi-analytic evaluations of the small halo tidal disruption rate are still too controversial to answer the question of how far from the galactic center small halos are well merged [37, 38]. The discovery of WIMPs in direct detection experiments and the subsequent measurement of the WIMP velocity distribution by means of directional detectors seems to be a primary route to provide an answer and inspire theoretical investigations.

The local dark matter density ρ_χ has significant uncertainty, since the local rotation velocity only constrains the total mass inside our solar system's radius while the matter distribution in the halo is not well-constrained by empirical data [39]. For example, deviations of the dark halo from a spherical shape to a flattened spheroid can produce an increase of the estimated local dark matter density from 0.3 to 2 GeV/c^2/cm^3 [40]. For the purpose of comparing the sensitivity of different dark matter experiments, it is conventional to use the value quoted by the Particle Data Group, ρ_χ=0.3 GeV/c^2/cm^3 [41], which is known to within a factor of two.

Integrating equation 1 over the sensitive recoil-energy range of the detector gives the expected rate for a calorimetric detector. Since the spectrum is featureless, using secondary signatures to distinguish a WIMP signal from the ambient backgrounds is desirable, such as the following two well-studied possibilities. First, the direction of the recoiling nucleus is correlated with the motion of the laboratory through the galactic rest frame. This manifests itself as a diurnal modulation in a terrestrial detector owing to the Earth's rotation. Second, the recoil-energy spectrum undergoes a seasonal kinematic variation owing to the Earth's orbit around the Sun.[†]

If the WIMP is a neutralino it couples to nucleons via neutral current reactions mediated by exchange of Z^0's, Higgs particles and squarks. In the non-relativistic limit, the most general possible interaction between a Majorana fermion such as the neutralino and the nucleon reduces to a simple form with only two terms, one of which is a spin-independent coupling and the other a coupling between the neutralino spin and the nucleon spin. Because the de Broglie wavelength of the momentum transfer is of nuclear dimensions (i.e., $\lambda = h/q \sim= 1$ fm for $m_\chi = 100$ GeV/c^2 and $v = 220$ km/s), the interaction is at least partially coherent over the target nucleus. For the spin-independent coupling, full coherence results in a cross section $\sigma_0 \propto A^2$ for a nucleus of atomic number A. For spin-dependent scattering, the coupling is dominated by the net nuclear spin, since the contribution from paired opposite-spin nucleons cancels. Corrections based on nuclear spin structure functions can spoil this cancellation, rendering odd-proton nuclei sensitive to WIMP-neutron couplings [14, 42], or vice versa.

In general, for a WIMP with equal spin-dependent and spin-independent couplings, detection via spin-independent scattering on a large-A nucleus is favored owing to the coherent enhancement. The majority of experiments performed to date have used heavy target materials to maximize sensitivity to this scattering mode. However, models exist (e.g., neutralinos that are pure gaugino or pure higgsino states) in which the spin-independent coupling is highly suppressed; a few experiments targeted at these models have been done with low-A high-spin target materials. Since the specific composition of WIMPs is not known, the long-term program should address this range of possibilities.

For large target nuclei and large recoil energies, the interaction between the WIMP and a nucleus loses coherence and the spin-independent cross section is suppressed for large q^2. Therefore, there are important tradeoffs to be made when designing experiments between the choice of target nucleus and the obtainable energy threshold. This point can be best illustrated by showing the results (Figure 3) of a full calculation assuming the spin-independent coupling dominates, using standard halo parameters and the formalism discussed in [24]. A WIMP mass of 100 GeV/c^2 is chosen with a cross section normalized to the nucleon, which is representative of the best current limits in direct detection experiments. Figure 3 shows both the differential and integrated (above the indicated threshold) WIMP event rate in keV$_r$ (which is the recoil energy imparted to the nucleus) expected for single isotope targets of ^{131}Xe (similar for ^{129}I), ^{73}Ge, and ^{40}Ar.

It can be seen that for a given elastic scattering cross section for WIMP-nucleon interactions, the smaller nuclei are penalized owing to a combination of smaller coherence enhancement ($\sim A^2$) and the less effective transfer of recoil

[†]This feature, which is the basis of a controversial detection claim by the DAMA Collaboration's NaI array, appears as an annual modulation in the scattering rate over a fixed recoil-energy range. Aside from the DAMA claim, which has been largely ruled by other experiments under standard assumptions, no other detections have been reported. See Section 7 for further details.

energy to a target that is lighter than the WIMP. The recoil spectrum for the heavier Xe nucleus is significantly suppressed by the loss of coherence for higher q^2 scattering events (form factor suppression). For a 100-GeV/c^2 WIMP, the integrated event rate drops by a factor of two for a threshold recoil energy increase of 13, 20, and 22 keV$_r$ for Xe, Ge, and Ar, respectively.

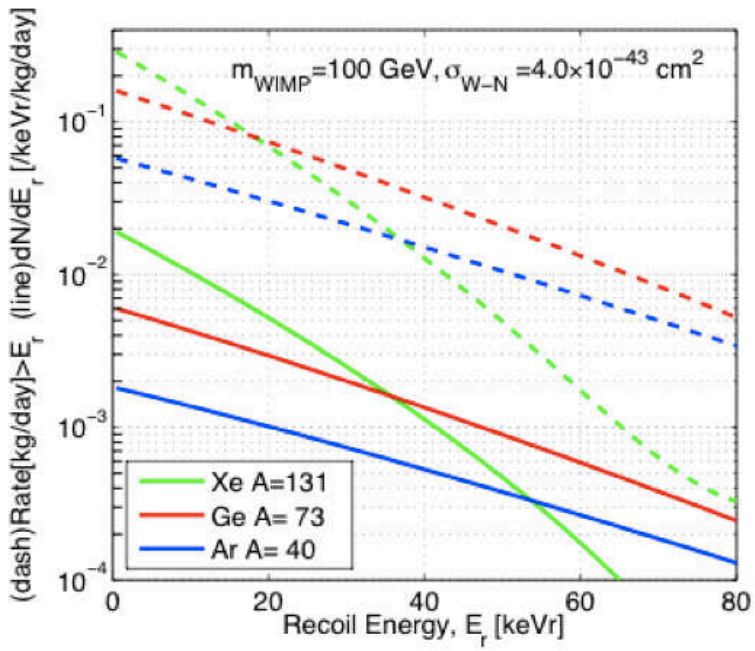

Figure 3: Calculated differential spectrum in evts/keV/kg/day (solid lines), and the integrated rate evts/kg/day (dashed lines) above a given threshold energy (keV$_r$) for Xe, Ge and Ar targets. A 100-GeV/c^2 WIMP with a WIMP-nucleon spin-independent cross section of $\sigma = 4 \times 10^{-43}$ cm^2 has been used. The plot shows that the total event rate per mass in a Xe detector with a threshold of 16 keV$_r$ is identical to that of a Ge detector with a lower threshold of 10 keV$_r$. An Ar detector with a threshold of 16 (30) keV$_r$ would have a total event rate per mass which is 1/3 (1/5) of Ge and Xe at the stated thresholds.

The scattering of WIMPs on nuclei would produce signals in many types of conventional radiation detectors. For example, scintillation counters, semiconductor detectors and gas counters are all capable of detecting nuclear recoils of a few keV. Unfortunately, these instruments are also efficient detectors of environmental radiation, such as cosmic rays and gamma rays from trace radioisotopes present in construction materials. Detectors exposed to environmental radiation in an unshielded room typically register about 10^7 events a day per kg of detector mass, while WIMPs are known to produce less than 0.1 count per kg-day (approximately the current limit) and significant SUSY parameter space exists down to 10^{-6} per kg-day. Exploring this parameter space will require ton-scale detectors with nearly vanishing backgrounds.

Background reduction in WIMP detectors can be approached with two basic strategies: reduction in the background radiation level by careful screening and purification of shielding and detector components, and development of detectors that can discriminate between signal and background events. Most experiments employ a combination of the two strategies.

Technologies for producing ultra-pure low-radioactivity materials have been pursued by many groups, and materials have been produced or identified with levels of radioisotope contamination three to six orders of magnitude below typical environmental contamination levels. For example, ^{238}U is typically present at 10^{-6}-g/g but levels in the 10^{-9}–10^{-12} g/g range have been achieved [43]. This progress has gone hand-in-hand with the development of ever more sensitive instruments for the detection of contamination. After the common environmental radioisotopes have been minimized by purification, the dominant source of radioactivity in materials is often "cosmogenic," i.e., originating from isotopes that are produced in the material by cosmic-ray-induced secondaries during the above-ground manufacturing process. Since purification and assembly of all but a few types of detector materials in an underground

cosmic-ray-free environment poses a logistical challenge, additional work is required to reduce activity below the lower limit imposed by cosmogenic activation (see Section 8.2 for further discussion). Most recent experiments emphasize improving the sensitivity using a background discrimination mechanism.

The development of new background discrimination mechanisms is a very active field and many innovative techniques are being studied at the kilogram scale. The most sensitive proven technique, which is used by the CDMS and EDELWEISS experiments, exploits the difference in charge yield in semiconducting crystal targets for nuclear-scattering compared to background electron-scattering processes. The target crystals, which are made of silicon or germanium, are cooled below 100 mK and instrumented with both charge and phonon sensors. The ratio of the amplitudes of the charge and phonon pulses (or simply the ratio of charge to temperature rise in some versions of the technology) is used as a discrimination parameter. The detailed shape and timing of the pulses contains additional information which can be exploited to separate nuclear-scattering events from events with imperfectly-collected charge.

Other background discrimination technologies include low-temperature detectors with phonon and scintillation readout, cryogenic noble liquid targets with pulse shape discrimination and/or simultaneous measurement of charge and light, low-pressure gas with sensitivity to the energy density and direction of nuclear recoils, and heavy-liquid bubble chambers with bubble nucleation conditions fine tuned to avoid backgrounds. Demonstrated discrimination factors for gamma rays from these techniques (i.e., fraction of unrejected background events) range down to 10^{-9} and some of them are plausibly scalable to greater than one ton of target mass. Details and status reports on several of the technologies are given in Section 7.

The problem of reducing the background from neutron scattering in dark matter detectors requires special mention. Neutrons interact exclusively by nuclear scattering, so the discrimination methods mentioned above are not effective. Discrimination is possible based on the propensity for neutrons to multiple-scatter in a detector, while WIMPs would only scatter once. However, discrimination mechanisms based on multiple scattering only become effective for very large detectors with excellent spatial resolution or high granularity. Neutrons up to 8 MeV are produced by (α,n) reactions and spontaneous fission in rock and common construction materials, and cosmic rays produce non-negligible fluxes up to 1 GeV, even at substantial depths underground. The low-energy neutrons can be shielded by practical thicknesses of hydrogenous moderating materials and minimized by material selection, but the high-energy neutrons are very difficult to attenuate by shielding. This problem, which is discussed in detail in Section 8.1, strongly influences the choice of appropriate underground laboratory depth.

We conclude this section with a description of the current results for both spin-independent and spin-dependent scattering. The limits on the spin-independent cross section, in particular from CDMS II [23], EDELWEISS [20], WARP [22] and ZEPLIN I [19], are beginning to significantly constrain the WIMP-nucleon scattering cross section in some SUSY models, as shown earlier in Figure 2. As that figure shows, it is difficult to reconcile the DAMA claim of a WIMP signal based on annual modulation of the rate of iodine recoils [25] with the current limits on the spin-independent scattering cross section from other experiments. A recent reinterpretation of DAMA's data as an annual modulation on the rate of the lighter sodium nuclei [44] is sensitive to lower-mass WIMPs. Such WIMPs are possible in SUSY if gauge unification is relaxed [27], although these investigators predict a cross section ten times lower than the corresponding DAMA interpretation. The recent result from CDMS II rules out most of this parameter space [23].

Limits on the spin-dependent cross section on neutrons and protons are shown in Figure 4. Since sensitivity is dominated by the unpaired nucleon, different experiments tend to provide the best limits in only one or the other case. The DAMA signal on the odd-proton sodium and iodine nuclei for neutron couplings has been ruled out by other experiments under standard halo assumptions [24]. The corresponding case for proton couplings has been ruled out by other experiments except in the mass range from about 5–15 GeV/c^2. In addition to the limit curves in the proton graph, a spin-dependent proton interpretation is excluded above a WIMP mass of 18 GeV/c^2 by the SuperKamiokande search [45] for high-energy neutrinos resulting from WIMP annihilation in the sun.

4 Indirect Detection of WIMPs

WIMP dark matter can be searched for not only directly with low-background detectors, but also indirectly through WIMP annihilation products. For example, Supersymmetric WIMPs like the neutralino are identical to their antiparti-

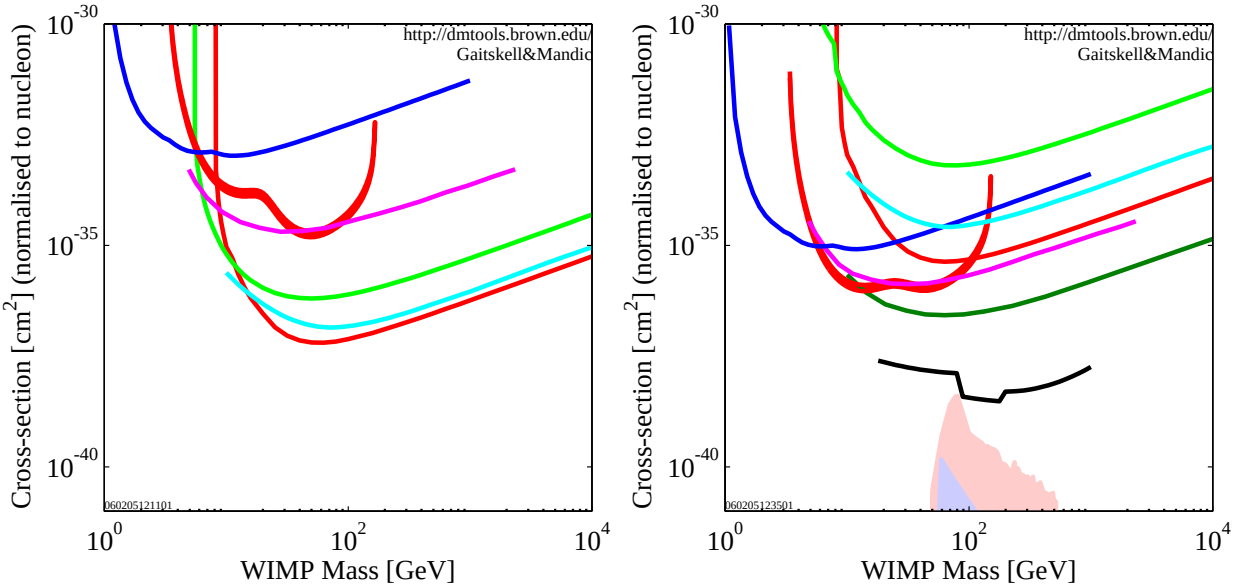

Figure 4: Current limits on the WIMP-nucleon cross section for spin-dependent neutron (left) and proton (right) scattering. The filled red contours are from DAMA [46, 47]. The limit curves are from CRESST-I (blue) [48, 47], PICASSO (magenta) [49], CDMS-II silicon (green) and germanium (red) [50], and ZEPLIN-I (cyan) [51]. The proton case also includes limits from NAIAD (dark green) [52] and the indirect detection limit from Super-Kamiokande (black) [45], as well as theoretical predictions from the Minimal Supersymmetric Standard Model (MSSM) (pink) [53] and the constrained MSSM (light blue) [54].

cles, and can mutually annihilate and produce standard model particles. If the neutralino density is large enough, the annihilation rate may be sufficient to produce detectable signals in the form of neutrinos, gamma-rays, and cosmic rays. Detectable neutrinos would be produced in the center of the Sun [55] or of the Earth [56, 57]; gamma-rays, positrons, anti-protons, and anti-deuterons would be produced in the galactic halo [58, 59, 60, 61], at the galactic center [62], or in the halos of external galaxies [63].

Typically, the annihilation products have an energy equal to a fraction of the neutralino mass, with the notable exception of gamma-ray lines at an energy equal to the mass of the neutralino. The number density of WIMPs is higher inside compact celestial bodies such as the Sun, the Earth, and the Galactic center. In addition to a mono-energetic energy signal in some annihilation channels, a directional signal pointing back to a celestial body may also provide a distinguishing observable.

We examine here the relationship of indirect searches to direct searches in deep underground laboratories. The extent of Supersymmetric parameter space that can be probed by the next generation of direct detectors (one order of magnitude improvement in the current limits) is illustrated in Figure 5(a) for spin-independent scattering cross sections. The figure represents a projection of a 7-parameter Supersymmetric space onto the neutralino mass-composition diagram [64]. Green full dots indicate that all models projected onto that point can be reached by direct detection searches, blue triangles indicate that some but not all models can be reached, and red open circles that no model can be reached. The horizontal axis is the neutralino mass m_χ in GeV/c^2, while the vertical axis is the ratio of gaugino-to-higgsino fractions Z_g/Z_h: neutralinos which are prevalently gauginos are at the top of the diagram, and neutralinos which are prevalently higgsinos at the bottom. Neutralinos of mixed type fall around $Z_g/Z_h \sim 1$. Since the spin-independent neutralino-nucleon scattering cross section is chirality-suppressed for pure gauginos and pure higgsinos, spin-independent direct searches are mainly sensitive to the mixed-type region. However, the sensitivity of direct searches has been greatly improving, and the next generation detector will be able to probe higgsino purity of the order of 1%, and gaugino purity of the order of 0.1% (the latter at relatively low neutralino masses, below 100 GeV/c^2, say). We will see that indirect searches by means of gamma-rays and cosmic antideuterons are sensitive to the complementary higgsino and gaugino regions.

Searches for WIMP annihilation products from the centers of the Sun and Earth are sensitive to regions of parameter space similar to those reached by direct searches. Of the annihilation products produced inside the Sun and the Earth, only the neutrinos interact weakly enough to escape. These high-energy neutrinos from WIMPs have been searched for in deep underground neutrino detectors originally built to search for proton decay. Currently the best upper bounds on neutrinos from WIMPs come from the SuperKamiokande and Baksan detectors; the currently-running AMANDA experiment and the future IceCube detector will be able to improve on these limits. The WIMP annihilation rate in the Sun and the Earth generally depends on the scattering cross section of neutralinos with nuclei, which is the same cross section probed by direct detection. This is so because for all but very massive WIMPs the annihilation rate in the Sun and Earth equals the rate at which they capture neutralinos. Capture occurs when repeated scattering off nuclei makes the neutralino lose so much of its kinetic energy that it becomes gravitationally bound and sinks to the center of the object. Thus the annihilation rate is governed by the capture rate, in turn proportional to the scattering cross section. For this reason, direct searches and indirect searches via neutrinos from the Sun or Earth probe similar regions in Supersymmetric parameter space. The region reached by indirect searches for neutrinos from the Sun is shown by dots and triangles in Figure 5(b). The reach of this kind of indirect search is similar to direct searches, i.e., they probe mixed-type neutralinos, although they do not extend so much into the pure gaugino and higgsino regions. (One must also distinguish the cases of spin-dependent and spin-independent scattering cross sections: the spin-dependent cross section contributes to scattering from hydrogen in the Sun while several, but not all, direct detection experiments are mainly sensitive to the spin-independent cross section.)

A clear signature of WIMP annihilation would be the detection of a gamma-ray line at an energy equal to the WIMP mass. The line is produced by the two-body annihilation of a pair of WIMPs into a pair of photons, which can occur in the galactic halo, in nearby external galaxies, and in the large scale structure at high redshift. A similar annihilation into a Z boson and a photon produces a gamma-ray line which for heavy WIMPs is close in energy to the $\gamma\gamma$ line. For neutralinos, the highest cross section for annihilation into $\gamma\gamma$ occurs in the higgsino region, due to the similar masses of (heavy) higgsino-like neutralinos and charginos, and the possibility of forming short-lived bound states among them. Searches for gamma-ray lines from neutralino annihilation are thus mainly sensitive to the higgsino region, as shown in Figure 5(c). Thus they probe a region of Supersymmetric parameter space different from that probed in direct searches. In this sense, direct searches and searches for a gamma-ray line are complementary.

Antideuterons ($\overline{\mathrm{d}}$) are a very rare product of astrophysical processes, and detection of antideuterons could constitute evidence for WIMP annihilation in our Galactic halo [65]. Current searches are still an order of magnitude away from the theoretical predictions for neutralinos [66], but proposals such as the General Anti-Particle Spectrometer (GAPS) [67] should be able to reach into the Supersymmetric parameter space. Antiparticle detection is achieved by collecting low-energy $\overline{\mathrm{d}}$ and observing the de-excitation ladder x-rays and pion burst following annihilation of the exotic atom. While considerable work remains to clarify near-Earth $\overline{\mathrm{d}}$ backgrounds [68], these backgrounds are far more favorable than the case of anti-protons, which are relatively more abundant in the cosmic rays compared with the signal rate from annihilation of Supersymmetric WIMPs. The expected antideuteron flux decreases rapidly with increasing neutralino mass and is sensitive to relatively light neutralinos. In addition, due to the specifics of antideuteron production, $\overline{\mathrm{d}}$ searches are mainly sensitive to gaugino-like neutralinos, more so than indirect searches through gamma-ray lines, as shown by comparing Figures 5(c) and (d). They also provide better sensitivity than direct searches in some of the gaugino-higgsino parameter space.

There are other indirect searches for WIMP annihilation products beyond those illustrated above, such as searches for antiprotons, positrons, and continuum gamma-rays from pion decay. Detection of WIMP signals has been claimed using these probes. For example, an excess in the cosmic ray positron flux observed in the HEAT detector [69] has been attributed to WIMP annihilation in the halo [70, 71, 72]; an excess of gamma-ray flux in the EGRET data has been construed as emission from an unusually-shaped WIMP halo [73]; the detection of a TeV gamma-ray source at the Galactic Center by the HESS collaboration [74] (after tentative detections by VERITAS [75] and CANGAROO [76]) has been interpreted as due to heavy WIMPs [77, 78, 79, 80]. Unfortunately, these kinds of searches share a problem of interpretation when ascertaining the origin of a claimed signal: the energy spectrum from WIMP annihilation does not show unequivocal signatures of its origin, and anomalies can be difficult to isolate from modifications to other astrophysical inputs, such as cosmic ray fluxes. Whether these modifications are reasonable is largely still a matter of taste, although further data (for example from GLAST, HESS, VERITAS, etc.) may be able to shed some light on the issue.

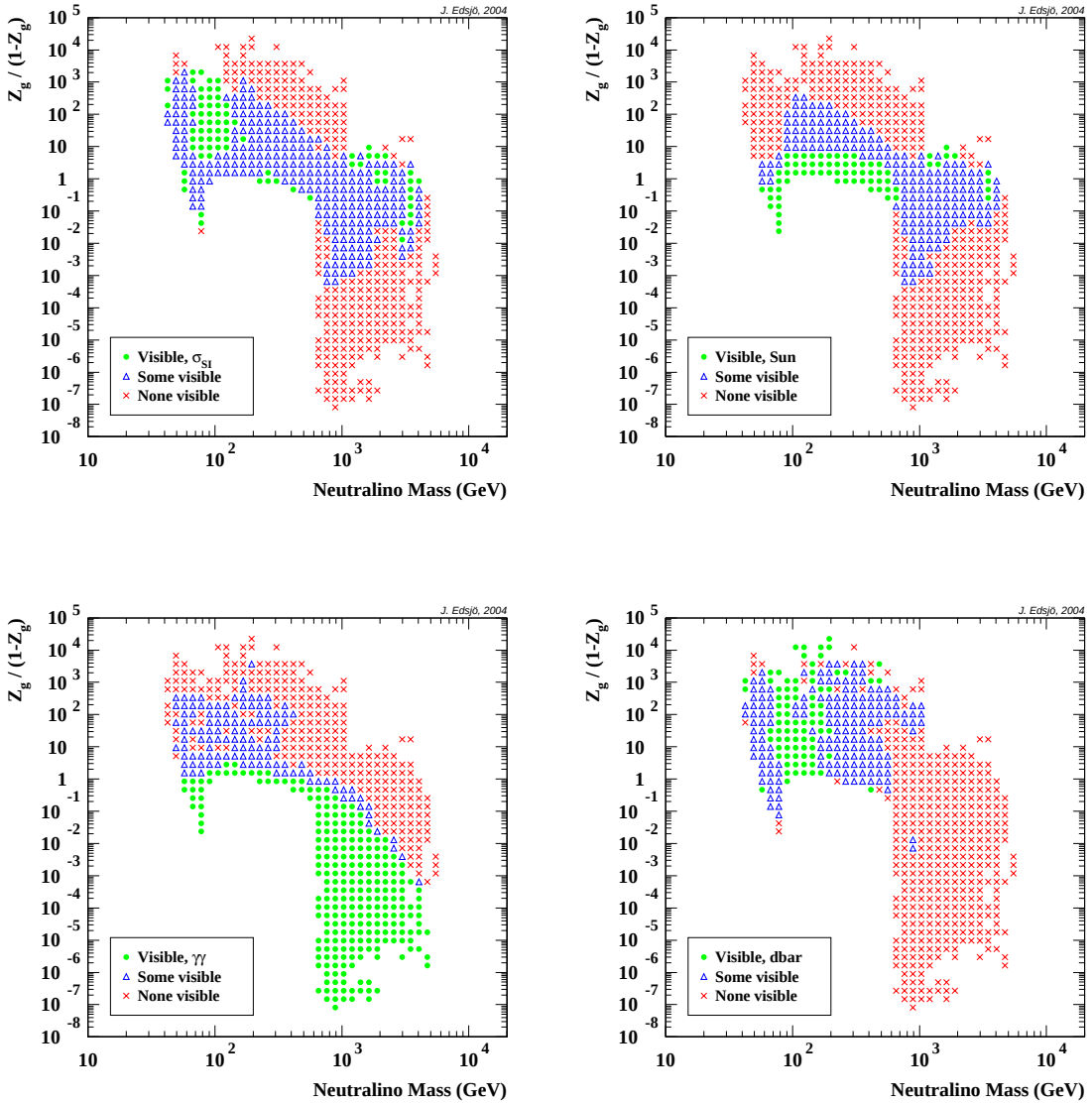

Figure 5: Reach of next generation searches for neutralino dark matter: (a) Top left: direct searches, (b) Top right: indirect searches via high-energy neutrinos from the Sun, (c) Bottom left: searches for a gamma-ray line in the Galactic halo, (d) Bottom right: searches for antideuteron in cosmic rays. The figures show a projection of a 7-parameter space onto the neutralino mass-composition diagram. The neutralino composition is represented by $Z_g/(1-Z_g) = Z_g/Z_h$, i.e., the ratio of gaugino and higgsino fractions. Green full dots indicate that all points in the projection can be reached in the respective search, blue triangles that some but not all projected points can be reached, red open circles that none can be reached. (All from [64].)

In summary, indirect searches provide better sensitivity than direct searches in some regions of parameter space, and comparable sensitivity in others. While there may be the challenge of systematic errors from assessing background of non-WIMP astrophysical sources for some modes, indirect searches could play an equally important role as direct searches in establishing the presence of particle dark matter. On the one hand, laboratory approach offers more control over systematic effects, but it is also possible that the actual physical parameters of WIMPs may lead to stronger evidence through the observation of annihilation products, e.g., in the case of a directional mono-energetic feature.

5 Dark Matter Candidates and New Physics in the Laboratory

A longstanding goal of the particle-physics community has been to find evidence of Supersymmetry. As noted in Section 2, this extension to the Standard Model promises to stabilize the Higgs mass and unify the coupling constants at the GUT scale, and is required by string theory. The currently best-motivated WIMP candidate is the Lightest Super Partner (LSP), which would be stable in SUSY models with R-parity conservation. SUSY particles, in addition to the Higgs boson itself, are the prime quarry for discovery at the LHC and precision studies at the ILC. A detection of new particles at the LHC beyond the Higgs would indicate new physics at the electroweak scale, possibly related to dark matter. While laboratory results cannot independently establish a solution to the dark matter problem, the production of a compelling dark matter candidate is of critical importance. To identify such a particle as the dark matter, a consistent astrophysical observation would be needed to demonstrate that the same particle is found in the cosmos and that it is stable compared with the age of the Universe. The precision in particle properties necessary to determine the relic density with precision comparable to astrophysical and cosmological measurements would likely require the ILC.

Supersymmetry has over a hundred free parameters, and so the study of its phenomenology spans a broad continuum of approaches. At one end of the spectrum, constraints may be imposed that favor a particular theoretical idea, such as minimal Supergravity (mSUGRA) or Split Supersymmetry, in order to gain predictive power. In some cases, fully-specified models are defined that are representative of a characteristic region of parameter space, which serve as useful benchmarks for scoping experiments or comparing the sensitivity of different approaches. At the other end of the spectrum is the exploration of the available parameter space imposing only known empirical constraints and minimum theoretical bias. This approach serves to define the range of experiments necessary to fully explore the SUSY/WIMP hypothesis. Interestingly, a wide variety of models, even including the maximally constrained ones, can lead to interesting dark matter candidates, as illustrated earlier in Figure 2.

Examples of unconstrained models include those calculated by Baltz and Gondolo [81], and by Kim et al. [26]. These modelers only use minimal unification assumptions, empirical constraints from accelerator experiments and the WIMP relic-density requirement. Bottino et al. [27] may represent the most extreme form of such a model, in which unification assumptions are relaxed and result in candidates with masses down to a few GeV/c^2.[‡]

Examples of theoretically-constrained models, which serve as a useful benchmark for LHC searches, also show the complementarity of WIMP and accelerator experiments. For example, consider the Constrained Minimal Supersymmetric model [33, 82] or the mSUGRA model [28], which impose unification of the SUSY parameters. Some of the regions within the parameter space, such as the focus-point region, which tends to large scalar masses, are inaccessible at the LHC but could be easily seen in the next generation of dark matter experiments in the 10–100 kg scale at a WIMP-nucleon cross section of 10^{-44} cm^2. On the other hand, in the "co-annihilation" region, the LHC has a good chance of seeing the 5 Higgs particles, as well as gaugino decays into identifiable squarks and neutralinos. However, the WIMP-nucleon cross section could be anywhere in the range 10^{-46}–10^{-44} cm^2, which requires a ton-scale detector for a full exploration.

More highly-specified models, such as the recently-proposed Split Supersymmetry model of Arkani-Hamed and Dimopolous [83], lead to the WIMP-nucleon cross-section range of 10^{-45}–10^{-44} cm^2 [31, 32]. This model, inspired by the large number of vacua in string theory and the difficulty of accounting for the apparent small value of the cosmological constant, further decreases the effective number of parameters by allowing the scalars to be very massive. An anthropic argument is used to pay the price of fine-tuning the Higgs mass to account for the dark matter—otherwise galaxies (and observers) would not have formed. In addition to the narrow range of predicted elastic cross sections, there are also testable consequences in accelerator experiments. The LHC would detect only one Higgs, the neutralino (if it is light enough), and a long-lived gluino [84]. Meanwhile, direct searches would check that indeed the neutralino constitutes the dark matter, providing the justification of the Split-Supersymmetry scheme, and fixing the remaining parameters of the model. According to [83], the long life of the gluino would then be a signature for fine tuning.

In recent years, there has been much excitement about compact extra dimensions of order 1 TeV^{-1} as an alternative explanation of the hierarchy problem. In a broad class of such models, the lightest Kaluza Klein excitation is stable

[‡] As shown in Figure 2, CDMS II has ruled out the low-mass branch of this model down to 10 GeV/c^2. The region from 5–10 GeV/c^2 could accommodate the DAMA result for sodium recoils, however the halo velocity distribution would need to be altered to enhance the modulation amplitude since the predicted cross section is too low by an order of magnitude under standard assumptions (see also Figure 4 of Ref. [23]).

and could be the dark matter [85], with a mass of order 1 TeV/c^2. Interestingly, the elastic scattering cross section covers the range from 10^{-46} to 10^{-42} cm^2 per nucleon.

A new benchmark study is well underway to look at connections between cosmology and the ILC. Because the actual parameters of SUSY are numerous and their values unknown, these benchmarks help to define measurement scenarios for specific experimental signatures at the LHC, ILC, and direct searches, as well as how a set of actual measurements could, in turn, constrain the theoretical parameter space.

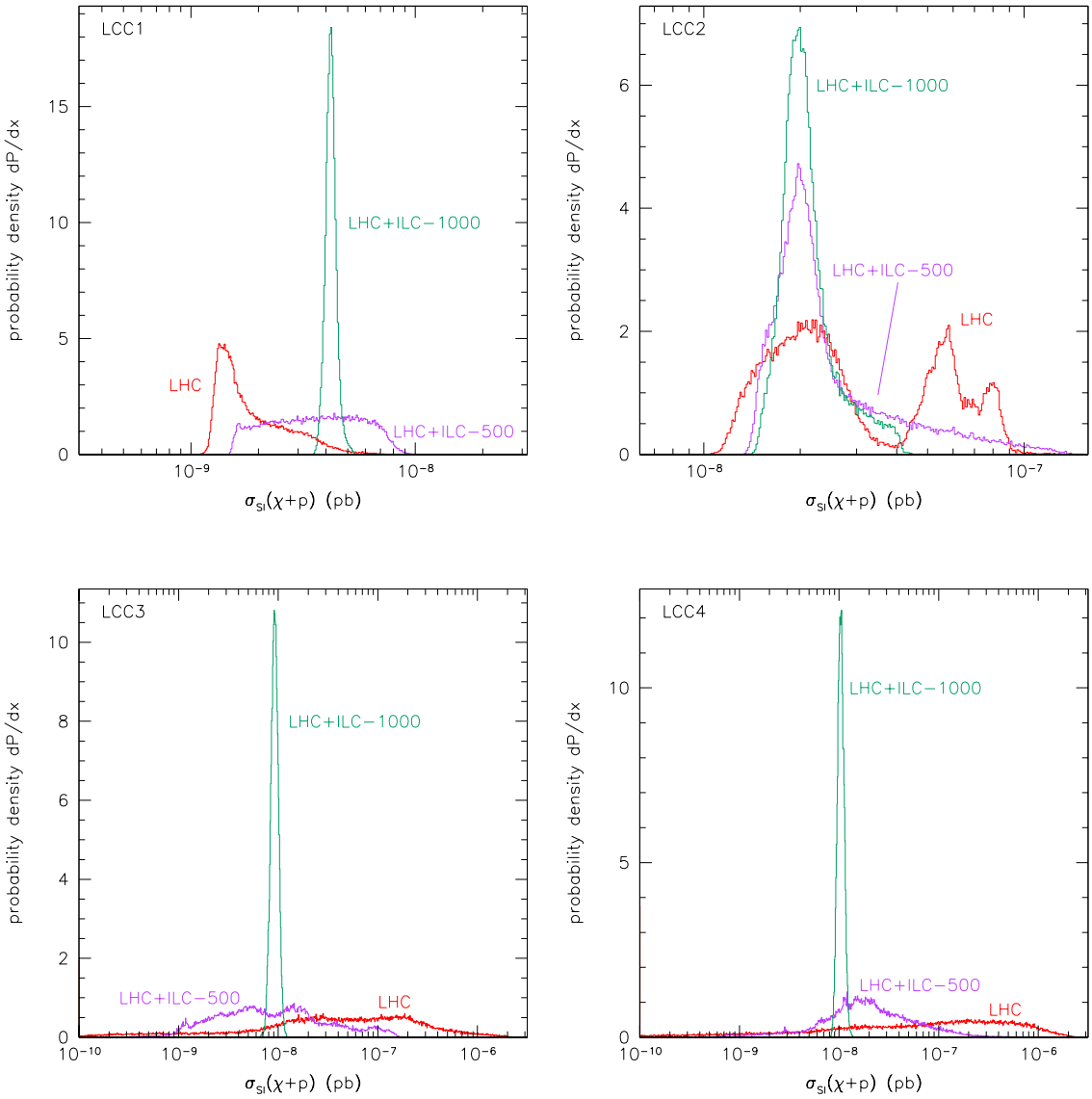

Figure 6: Allowed range of the WIMP-proton elastic cross section for LHC and ILC measurements of the benchmark models LCC1 (top left), LCC2 (top right), LCC3 (bottom left), and LCC4 (bottom right). The three curves in each graph correspond to measurements of these models at the LHC, ILC 500-on-500 GeV and ILC 1000-on-1000 GeV. See text for details [86].

Detailed calculations are being performed for each benchmark model by computing a set of measured physical quantities, including experimental uncertainties, and then examining the full range of SUSY parameter space that would be allowed by these measurements. From this range of allowed parameters, specific derived quantities of interest can be constrained. For example, to inform dark matter searches the mass of the LSP and its elastic cross section on nucleons

could be constrained. In particular, a set of benchmark points accessible to both the LHC and ILC, and interesting for cosmology, has been proposed. Labeled LCC1–4, each has a relic density broadly similar to that required to explain the dark matter. While each is accessible to direct dark matter searches, the aim of this study is to the examine and compare what can be learned about the benchmark models from the different approaches.

For benchmark point LCC1 (in the bulk region where coannihilations are not necessary), Baltz, Battaglia, Peskin and Wizansky [86] determined that if that model is the actual model in nature, and the LHC measured accessible masses (three of the neutralinos, sleptons except the heavy stau, squarks except for the stops, the gluino, and the light Higgs), then the range of models consistent with those measurements would allow the neutralino-proton cross section to vary over an order of magnitude, as illustrated in Figure 6. In fact, the central value is off by more than a factor of two. Also shown is the allowed range for what would be measured for ILC center-of-mass energies of both 500 GeV and 1 TeV. The 500-GeV ILC offers some improvement, but the TeV ILC is required for a solid measurement. This is because the important quantity for direct detection in this model is the mass of the *heavy* Higgs boson, which at 395 GeV is accessible only to the TeV ILC. The non-detection at LHC or ILC-500 gives the wide range of possibilities, limited only by the artificial upper limit (taken to be 5 TeV) put on this mass. Figure 7 illustrates specifically what a direct-detection constraint can do for particle physics. In particular, the mass of the heavy Higgs bosons is usually unconstrained until a TeV ILC, unless $\tan\beta$ is large. For point LCC1, the mass distribution for the CP-odd Higgs improves significantly for LHC and even ILC-500 measurements. This shows that direct detection would strongly constrain this part of the Higgs sector before a TeV ILC was available, and again relates dark matter and electroweak symmetry breaking!

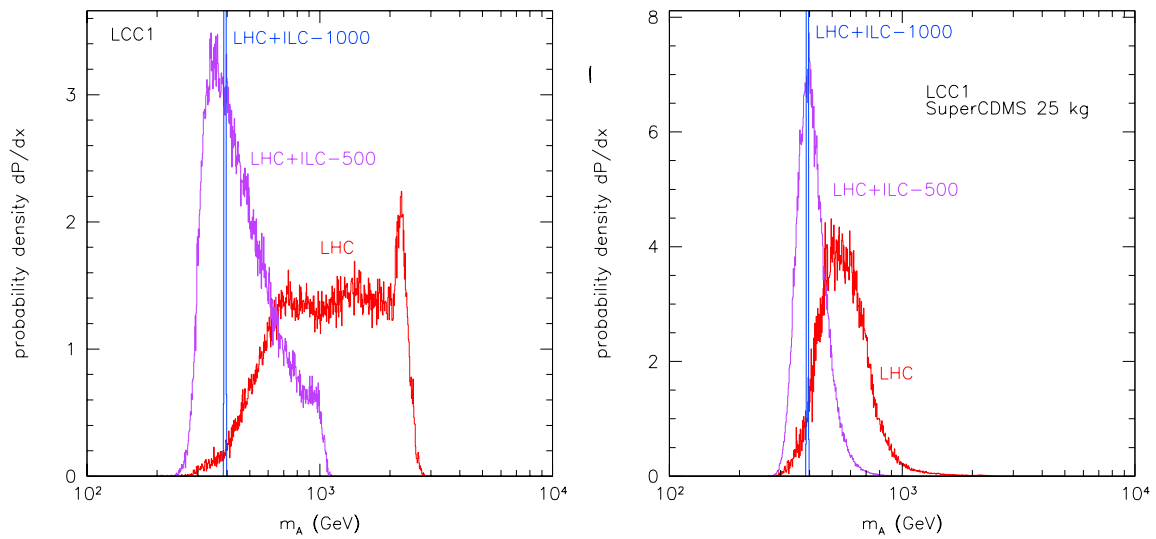

Figure 7: Allowed range of the mass of the heavy CP-odd Higgs in the LCC1 model is shown for accelerator-based measurements (left) and combined accelerator and direct detection (right) with a per-nucleon cross-section sensitivity of $10^{-45}\mathrm{cm}^2$, such as the SuperCDMS 25 kg experiment [86].

For the benchmark model LCC2, (in the focus-point region where neutralinos can annihilate to gauge bosons, and coannihilations with charginos can be important), colliders can do a better job of constraining the direct-detection cross section. This model has a "mixed" neutralino giving larger elastic cross section, and it depends on the light Higgs, easily constrained by the LHC. The usually dominant heavy Higgs is more than 3 TeV/c^2 in mass, and thus irrelevant to direct detection. At the LHC, there is a complication in that the data can not distinguish between the discrete possibilities that the lightest neutralino is Bino, Wino, or Higgsino. Assuming a standard halo, a few dozen events in a direct detection experiment would serve to completely eliminate the incorrect solutions. The ILC would be required to eliminate the incorrect solutions without astrophysical input.

For the benchmark model LCC3 (with stau coannihilations important), again colliders give little information before a TeV ILC, though in this case, the heavy Higgs bosons are visible even to the LHC. Here, the important uncertainty is

the gaugino-higgsino mixing angle that can only be readily constrained by a TeV ILC, which can observe most of the neutralinos and charginos. Furthermore, the TeV ILC could also measure the width of the pseudoscalar Higgs, which constrains $\tan\beta$ and thus the neutralino mass matrix.

The point LCC4 is an interesting case. This model has a large resonant annihilation cross section (through the pseudoscalar Higgs, which is closely tied in mass to the heavy Higgs). Again, these heavy Higgs particles are visible to the LHC, but the neutralino mixing angles can only be measured at a TeV ILC. As with LCC3, measuring the width of the pseudoscalar Higgs at a TeV ILC gives $\tan\beta$, but for this point, the measurement is crucial for determining the relic density.

So we see that for all of these benchmarks, which have been chosen to illustrate the power that colliders would have, direct detection would make significant contributions to fundamental physics, in advance of a TeV linear collider. While such LHC/ILC measurements could help to constrain the astrophysical searches, a WIMP detection in the Galaxy leading to a determination of the elastic cross section would place a significant constraint on SUSY, otherwise absent from the accelerator experiments. Since a WIMP detection could constrain the elastic cross section to better than a factor of a few, the neutralino mass matrix becomes better defined because the mixing angles are constrained by including the elastic cross section measurement. The uncertainties are dominated by halo uncertainties and the strange content of the nucleon for SI interactions. SD interactions suffer, in addition, from uncertainty in the spin structure of the nucleus. From the direct-search viewpoint, it is important and attainable that the long-term program address the sensitivity requirements for both SI and SD interactions. Sorting out this physics will require a variety of target nuclei with different masses and spins, and the present R&D program is headed in that direction (see Section 7 for further details).

As for the LHC/ILC informing the solution to the dark matter problem in the absence of halo searches, the best they can do is refine the candidates but can say nothing relevant about the stability on the Hubble time scale. In fact, if LHC/ILC measurements result in a robust prediction that astrophysical searches should have seen something *but didn't* then we may arrive at the very interesting conclusion that the particles are unstable and that R-parity is not conserved. This result could not be obtained from accelerator experiments, alone. Thus the question of particle stability, the province of dark matter searches, is of fundamental importance to both cosmology and particle physics. Moreover, the WMAP measurement of the relic density is broadly recognized as a powerful, though hypothetical constraint on SUSY parameters—that constraint is only realized once it is demonstrated that the neutralino is stable on the Hubble time scale and the particle mass is consistent between the halo and accelerator measurements. It remains that an astrophysical detection of WIMPs is the essential link between early-universe physics and fundamental particle physics in this sector.

* * *

In summarizing sections 3, 4 and 5, we see that detecting WIMP scatters in terrestrial detectors, observing astrophysical sources of WIMP annihilation products, and producing WIMPs and related particles in the laboratory can each play an important role in resolving the dark matter problem and elucidating the new fundamental physics that could be behind it. Direct detection remains the clearest and most promising means for establishing that WIMPs exist in the galaxy. If WIMPs are comparable in mass that that of detector target nucleus, then the WIMP mass can be determined well enough to cross check against accelerator-produced candidates, and even if WIMPs are heavier, the target mass serves as a strong lower-bound. With detection in multiple targets, the nature of the WIMP coupling to nuclei can be constrained. A measurement of the elastic cross section also has the potential to provide information about the underlying particle model, e.g., the neutralino mixing angles. Indirect searches have the challenge of discriminating against astrophysical backgrounds in most channels, but the possibility of a "smoking gun" signal remains, for example, from a mono-energetic and/or directional signal. Together, either the direct or indirect techniques are needed to establish particle stability comparable to the age of the universe—and could also inform us on the nature of R-parity. While indirect means will inform the annihilation cross section, it remains with the accelerator-based experiments to work out the full phenomenology of the WIMP sector and to permit a sufficiently robust calculation of the relic density. Naturally, we stand to learn the most if WIMPs are observed in all three regimes, in terms of both overall confidence and consistency, and through reducing uncertainties of both the particle properties and the astrophysical parameters (such as halo density and velocity distribution). If we are unfortunate in that the observation of WIMPs proves elusive, then it is equally important to push on all fronts since there are substantial regions of parameter space that are searched

uniquely by only one method. Unless and until new information arrives, say, a detection of dark matter axions, WIMPs remain an excellent hunting ground.

6 Synergies with Other Sub-Fields

Dark matter searches push the frontier on low-background low-threshold high-energy-resolution particle detection. These capabilities are similar to some of the requirements for double-beta decay experiments, and not surprisingly there has historically been a strong connection between these fields. Despite the great differences in the characteristics of the rare decays sought, background concerns for the two experiments are very similar and result in many of the same shielding and cleanliness requirements. However, the demands on both types of experiments have become so strict that it is extremely difficult for a single experiment to be competitive in both sub-fields. For double-beta decay, discrimination of electron recoils from nuclear recoils is not important, but excellent energy resolution at relatively high energies ($\sim$MeV) and rejection of multiple-site events are critical. While it is very unlikely that a single experiment can pursue both dark matter and double-beta decay without compromising the sensitivity for either process, technological advances driven by a dark matter experiment could benefit a double-beta decay experiment based on the same target material. This synergy will become especially relevant as experiments move to larger scale and cost. We discuss in more detail below the requirements and opportunities for a multi-purpose experiment, in some specific target material.

Following that, we examine the prospects for the detection of supernova neutrinos in dark matter experiments. As the experiments reach the ton scale, supernova neutrinos become interesting quarry because, like WIMPs, the scattering rate from nuclei is enhanced by coherence effects.

6.1 Double-Beta Decay

Dark matter experiments using Ge detectors could also, if enriched in ^{76}Ge, be useful for searching for neutrinoless double-beta decay. Cryogenic detectors based on NTD thermistors or athermal-phonon sensors could result in better energy resolution than the ~ 4 keV of Ge ionization detectors alone, resulting in improved background rejection, especially of the important $\beta\beta2\nu$ background. The intrinsic energy resolution of athermal-phonon sensors can be better than 200 eV (FWHM), but better correction for the position dependence of the collected energy will be necessary in order to achieve resolution better than 5 keV at energies of 2 MeV. Furthermore, athermal-phonon sensors may provide sufficient position reconstruction to allow improved rejection of multiple-site events from Compton backgrounds and inelastic neutron interactions. At a scale of 500 kg to a ton, a single experiment combining the technologies of current dark matter and double-beta decay experiments may be able to achieve both goals, with sensitivity to effective Majorana neutrino mass of 20 meV.

Xenon is another element that is being used for both dark matter detection and double-beta decay, where the latter exploits the isotope ^{136}Xe. However, the operating principle and the readout of a liquid xenon TPC for dark matter and for double-beta decay are quite different and, at present, exclude the possibility of a single experiment for both processes. The poor energy resolution of a dual-phase xenon TPC as currently implemented for dark matter detection, where the emphasis is rather very low energy threshold and recoil discrimination, is incompatible with a double-beta decay search which has to emphasize energy resolution to distinguish the two-neutrino process at the continuum endpoint from the mono-energetic zero-neutrino process. In the long term, the goal of building a directional gaseous TPC for dark matter may offer a unique opportunity for double-beta decay detection if xenon enriched in ^{136}Xe is a component of the chamber. Preliminary studies are underway to assess the background-rejection capability and the physics content that would result from a measure of the opening angle of the two mono-energetic electrons emitted by the zero-neutrino decay process.

Also notable is the element tellurium, which has a double-beta decay nucleus in ^{130}Te. This element is being pursued primarily for double-beta-decay studies by instrumenting TeO_2 with NTD thermistors in a cryogenic array known as Cuore. Owing to the very low radioactive background and an energy threshold of 10 keV, this experiment will also have sensitivity to dark matter signals.

Thus, while the emphasis of the dark matter and double-beta decay studies are different in several respects, these differences tend not to be mutually exclusive, especially in the case of cryogenic crystals with very fine spectroscopy. For these, as well as for other materials such as liquid xenon, many technology developments, such as radio-purification, low-background assays, ways to improve energy resolution, ways to fabricate large arrays, etc., are common to both efforts, and there has been much positive exchange between the fields. It is possible that a particular experiment could be well-suited to performing frontier studies on both counts. However, as the needs for each become more restrictive and the experiments become more complicated, it is critical to optimize each experiment's design to ensure obtaining its primary measurement of interest.

6.2 Supernova Neutrino Detection

The core-collapse of a massive star, and the subsequent Type-II supernova event, releases a burst of $\sim 10^{58}$ neutrinos of all flavors at of order 10 MeV energy. Neutrinos with these energies have an enhanced rate for scattering from nuclei due to coherent interactions, producing nuclear recoils of order 10 keV—above dark matter detection thresholds. As detectors reach the ton scale and beyond within the dark matter program at DUSEL, the detection of these neutrinos, in particular from a supernova in our galaxy, becomes possible. Here we summarize the rates and prospects for detecting supernova neutrinos.

The condition for coherent nuclear scattering is $\Delta R_A < 1$, where Δ is the three-momentum transferred to the nucleus, and R_A is the radius of the nucleus. For all nuclei of interest up to germanium, this condition is satisfied for neutrinos up to energies of about 50 MeV. Supernova neutrinos emerge with nearly thermal spectra, with mean energies of 13, 15, and 24 MeV for electron-neutrino, electron anti-neutrino, and muon/tau neutrino flavors, respectively. The average energy of the recoiling nucleus is $2/(3A)(E_\nu/\mathrm{MeV})^2$, where A is the mass number of the nucleus, making the coherent-scattering channel sensitive to the high-energy tail of the thermal spectrum. Heavier target nuclei have an A^2 enhancement of the total cross section, but the energy of the recoils is smaller than for lighter nuclei.

As an example of expected yields from a Galactic supernova at 10 kpc, there will be 18 events in 1 ton of germanium from muon and tau neutrinos, with 10 events above 10 keV recoil energy [87]. Electron neutrinos contribute a total yield of 4 events. For lighter nuclei, in particular for the case of a neon target, there will be a total yield of about 4 events, including all neutrino flavors. For lighter nuclei there is a larger probability that all of the recoils will be above 10 keV. In some cases, the intrinsic threshold for neutrino scatters may be substantially lower than for dark matter. Ordinarily, the threshold for dark matter detectors that rely on a dual measurement for gamma and beta rejection is determined by optimizing efficiency versus background rejection. Since the neutrino events occur in a burst coincident with an externally-defined time window, background rejection is not needed and so the intrinsic lower energy-threshold of the device can be used. In the case of cryogenic detectors, their intrinsic 1 keV threshold allows the full recoil-energy spectrum to be detected. With burst-detection thresholds of a few keV, nearly the full spectrum would be accessible to scintillation detection, e.g., in noble liquids.

The yield from a Galactic burst is clearly small compared with the expected yields in much larger neutrino detectors, such as Super-Kamiokande, KamLAND, and SNO [88]. However, even a few events in a 1-ton dark matter detector could be the first detection of neutrino-nucleus coherent scattering. This is very promising if we consider that larger neutrino detectors will accurately determine the average energies of the different flavors. From just a few recoil events, we can make the first measurement of the coherent cross section, and look for deviations from the expected standard model result.

In addition to the yield from a Galactic supernova, potential 100-ton detectors may have sensitivity to the Diffuse Supernova Neutrino Background (DSNB). Modern predictions indicate that the DSNB flux is approximately $6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, including contributions from all neutrino flavors [89]. In a 100-ton germanium detector, this corresponds to about 2 events per year. In addition to this low event rate, a hindrance for DSNB detection is that the mean DSNB neutrino energy is lower relative to the spectrum of neutrinos from a galactic supernova burst, due to cosmological redshifting of neutrino energies. However, this flux may be detectable if the WIMP-nucleus cross section is at the lower end of the theoretical models.

7 Direct Detection Experiments: Status and Future Prospects

The initial goal of direct dark matter searches is to detect a signal that can be confidently attributed to elastic scatters of galactic halo WIMPs from the nuclei in an earthbound detector. It would be essential to follow up an initial detection by confirming the signal and its galactic-halo origin in several ways:

- Detect again using a different target nucleus, to confirm that the cross section scales with nuclear mass or spin as expected for scattering of WIMPs rather than neutrons or other background.
- Constrain the WIMP mass to the greatest extent possible by measuring the recoil spectrum in a well-matched target nucleus to test whether it is compatible with candidates resulting from accelerator-based experiments.
- Confirm the galactic origin of the signal by detecting the expected annual modulation effect, which would require increased statistics, and the diurnal modulation effect, which would require a directionally-sensitive detector.
- Ultimately, refine our understanding of the galactic halo by accumulating larger statistics in both recoil energy and directional measurements to exploit information in spectrum and modulation signals.

With these broad goals in mind, we review in this section the present status of the direct detection experiments and of the R&D programs underway for future experiments.

The following subsections, listed alphabetically, detail the status and prospects of specific experiments, with an emphasis on those that are included in the infrastructure matrix assembled in the context of the "Solicitation 1" process. (For a more comprehensive review of dark matter searches, see, for example, the recent review by Gaitskell [90].)

7.1 CLEAN and DEAP

The CLEAN experiment, or Cryogenic Low Energy Astrophysics with Neon, is a large cryogenic scintillation detector with 130 tons of liquid neon as the active material. The central dewar is to be approximately 6 m on a side, located within a 10-m-diameter by 12-m-tall water shielding tank. The combination of water shielding, self-shielding by a layer of neon outside the central fiducial volume, and the radiopurity of neon, results in very low backgrounds. The scintillation light output has a time structure that allows discrimination between electron recoils and nuclear recoils. The design sensitivity is 10^{-46} cm^2 per nucleon for WIMP-nucleus spin-independent scattering. Other physics goals include a 1% measurement of p-p solar neutrinos, supernova neutrino detection, and $10^{-11}\mu_b$ neutrino magnetic moment detection. The collaborators describe CLEAN as an R&D collaboration at this time with emphasis on the development of smaller-scale prototypes to realize the technical requirements of a large LNe detector. The program has evolved to enable such smaller-scale prototypes to be exploited in a dedicated WIMP search using LAr in place of LNe based upon recent developments to exploit LAr in a detector dubbed DEAP (Dark matter Experiment with Argon and Pulse shape discrimination).

7.2 Chicagoland Observatory For Underground Particle Physics (COUPP)

A heavy liquid bubble chamber (CF_3I) sensitive to nuclear recoil events has been operated in a thermodynamic regime in which it is insensitive to minimum-ionizing radiation and electron recoils from gamma and beta backgrounds. It thus affords a high degree of background discrimination. The critical challenge of long-term stable operation of the chamber has been met, which requires a glass-walled vessel to minimize surface-induced nucleation events. The high content of nonzero spin nuclei is noteworthy for this target material. The present 2-kg room-temperature prototype, which is expected to have a sensitivity of approximately of 10^{-42} and 10^{-40} cm^2 per nucleon for spin-independent and spin-dependent WIMP scattering, respectively, would be scaled up in phases to 250 kg, 1000 kg, then several tons. This prototype is now running in a 300 m.w.e.-depth site at Fermilab.

7.3 Time Projection Chambers (Directional-TPC group and DRIFT III)

Two collaborations, Directional-TPC group and the DRIFT-III (Directional Recoil Identification from Tracking) collaboration, are proposing Time Projection Chambers (TPC's) with total mass in the hundreds of kilograms, to initiate the study of WIMP astronomy by tracking nuclear recoils in low-pressure gas at room temperature. The solar system orbits around the galactic center with tangential speed similar to that expected for halo WIMPs, and presently directed toward the constellation Cygnus. Combined with the Earth's rotation on its axis, this will result in a sidereal-day modulation of the *direction* of WIMPs in an earthbound lab, as the apparent source of the WIMP wind rises and sets. A large low-pressure negative-ion TPC can measure the orientation of WIMP-recoil tracks, as was shown by the 0.2 kg DRIFT-I and DRIFT-II prototypes in the Boulby Mine. While such detectors also have very good discrimination properties, work is ongoing to demonstrate this at sufficiently low thershold. These devices presently rely on use of a toxic flammable chemical dopant (CS_2) for the negative-ion drift. Although DRIFT underwent a thorough safety review to operate in Boulby and has had no accidents of any sort in roughly five years of operation, R&D is underway to identify alternative dopants.

7.4 European Underground Rare Event Calorimeter Array (EURECA)

The CRESST and EDELWEISS collaborations have developed extremely sensitive cryogenic solid detectors operating at milliKelvin temperatures. Electron- versus nuclear-recoil discrimination is achieved by combining heat detection with a secondary signal that has a different response for the two recoil types. The CRESST detectors augment the thermal signal with a scintillation signal in $CaWO_4$ targets which is detected thermally in a second adjacent device. Two 300-g detectors were successfully operated in Gran Sasso and were limited by nuclear recoils consistent with that expected from neutron-background (and the limited shielding deployed in this early run). The EDELWEISS detectors augment the thermal signal in germanium targets with an ionization signal. Their 2002 and 2003 data sets from an array of three 300-g detectors were a then world-best upper limit. The sensitivity was limited by a low-energy beta background that suffers ionization-signal loss near the detector surface. Improved designs are being developed, some of which include a highly-resistive metal-film readout that should offer additional information for discriminating surface events from bulk nuclear recoils. The EURECA program is the joint effort of these two collaborations to plan a ton-scale recoil-discriminating cryogenic array to achieve sensitivity in the 10^{-46} cm^2/nucleon range.

7.5 Scintillation and Ionization in Gaseous Neon (SIGN)

The SIGN (Scintillation and Ionization in Gaseous Neon) concept is a modular room-temperature nuclear-recoil-discriminating pressurized neon target for dark matter and neutrino detection. A detector module would consist of a cylindrical vessel with a diameter of $\sim$50 cm and a length of $\sim$5 m. An array of 100 modules at 100 atm would result in a 10-ton target mass and occupy a detector space of less than 1000 m^3, including a 2-m-thick shield. The signal would be read out from both ends of the cylinder either as charge or as light via wavelength-shifting fibers, and would provide position information along the cylinder. Timing between the ionization and scintillation signals would provide radial positioning. The primary scintillation signal would be detected using a photocathode on the inside diameter of the cylinder. Nuclear-recoil discrimination is achieved by the ratio of ionization to scintillation. Measurements have recently been completed that confirm excellent discrimination between gammas and nuclear recoils. The physics reach for WIMPs is 10^{-45} cm^2/nucleon per ton of detector assuming zero background. Such a detector would also see $\sim$2.5 nuclear-recoil events per ton from a supernova at a distance of 10 kpc (center of galaxy). Low energy nuclear recoils ($<$3 keV) would also be observable from coherent scattering with solar neutrinos with energies above 10 MeV.

7.6 SuperCDMS

The CDMS collaboration has developed semiconductor detectors of both silicon and germanium which operate at milliKelvin temperatures. Recoil discrimination is achieved by combining ionization and athermal-phonon readout. While the ionization signal suffers the same tendency with regard to low-energy betas as the EDELWEISS detectors,

the athermal technology provides phonon-pulse shape information that allows event localization. This information permits surface-versus-bulk discrimination to reject surface betas, which would otherwise be the dominant internal background. CDMS has set world-leading limits in the mid-10^{-43} cm^2/nucleon range using several 0.25 kg detectors in the Soudan Mine, and expects to improve the sensitivity by a factor of 10 in 2006–2007. SuperCDMS would further develop this technology to larger detector modules with improved performance to further reject surface betas, and to engage industrial partners to eventually reach an array of total mass of about one ton. Sensitivity is anticipated to reach 10^{-46} cm^2/nucleon.

7.7 XENON

The XENON collaboration is currently developing a discriminating liquid-xenon 15-kg prototype detector with an expected sensitivity of mid-10^{-44} cm^2/nucleon, coupled with advanced R&D to develop a ton-scale experiment. Signals from primary scintillation in the liquid and proportional scintillation by electrons extracted into the gas phase are being shown to allow both electron-nuclear recoil discrimination and 3-D localization of events. The prototype is currently being installed in a shielded setup at Gran Sasso. Based on what is learned there, along with detailed laboratory studies of various readout schemes to maximize light-collection, the collaboration anticipates fielding a set of 100-kg modules to reach one ton of active mass and sensitivity to a WIMP-nucleon cross section of 10^{-46} cm^2/nucleon.

7.8 ZEPLIN IV-Max

The ZEPLIN collaboration has used several kilograms of liquid xenon in a scintillation detector with pulse-shape discrimination (ZEPLIN-I) to set limits vying with the world's best. In addition to self shielding, the detectors have external liquid-scintillator vetoes. Currently the group is commissioning detectors with tens of kilograms of active mass, which derive signals from both primary scintillation and ionization in the liquid to discriminate electron from nuclear recoils and to localize events within the sensitive volume. These systems use liquid-plus-gas "two-phase" detection employing two different readout schemes in the ZEPLIN-II and ZEPLIN-III detectors. ZEPLIN-IV (also referred to as ZEPLIN-Max) would scale up the two-phase technique to a ton of active mass with sensitivity in the range of 10^{-46} cm^2/nucleon.

7.9 Summary

The direct detection of dark matter is a vital, growing field with a number of well-developed plans for developing ton-scale experiments. The goal of all such experiments is to reach deep into the SUSY-predicted WIMP-nucleon cross-section range of $\sim 10^{-46}$ cm^2/nucleon for spin-independent couplings. While most SUSY models have stronger spin-independent couplings, the sensitivity of these same experiments to spin-dependent couplings, e.g., through the presence of isotopes such as ^{17}F, ^{73}Ge, and ^{129}Xe, is also of great interest. Achieving this sensitivity level will require sufficient depth and local shielding to bring unvetoed neutron interactions in the detector material to well below 3×10^{-5} events/kg/day. A combination of very effective local shielding and muon vetoes, high radiopurity, event discrimination, and accessible well-planned deep laboratory space are needed to reach this physics-driven goal.

8 Infrastructure

In this section we describe infrastructure and technical support that is generally required for dark matter experiments aimed at ton-scale detectors. Depth, which is a particularly important requirement because it is the primary method of suppressing the cosmogenic neutron background, is treated in Section 8.1. Following that discussion, we describe in Section 8.2 the materials handling methods that are needed. Section 8 concludes with an itemized list of the space and facilities needs defined by the envelope of possible experiments, and a second list of experiment-specific items that the lab needs to be prepared to provide depending on which experiments are staged there.

Since a separate working group is devoted to low-background counting, we do not discuss that here. Of course, such facilities are critical to the preparation of dark matter experiments, and access to state-of-the-art low-background assaying and cleaning methods developed at the laboratory will be vital to the success of virtually the full range of dark matter detection strategies.

8.1 Depth Requirements

The most important cosmic-ray-muon background for direct dark matter detection experiments is due to fast neutrons (20–500 MeV) produced outside the detector shielding. These high-energy "punch-through" neutrons are difficult to tag with a conventional local muon-veto system, as they can originate several meters within the cavern's rock walls. They create secondaries in the surrounding shielding materials, which can scatter in the detector target and generate signals quite similar to those of WIMPs. While a variety of countermeasures are possible, such as thick active shields and wide umbrella vetoes deployed in the cavern, an extensive earthen overburden remains the most reliable means to reduce the muon flux and its accompanying cosmogenic-neutron background. Moreover, as the mass and sensitivity of dark matter searches grows to the ton-scale and beyond, as expected on the time-scale of the 30-plus year DUSEL program, the combination of depth and active shields may be called for. Therefore siting the laboratory at the greatest depth possible is critical to a successful long-term program.

Estimates of the size of the punch-through neutron background depend on the muon flux, material composition of a specific underground site, neutron-production cross sections, and the details of the subsequent hadronic cascades. The muon flux is the best measured of these, and at the earth's surface is about 170/m^2/s with a mean energy of about 4 GeV. The attenuation at 4500 m.w.e. is nearly a factor of 10^7 with a flux of 800/m^2/y and a much harder spectrum with mean energy of about 350 GeV. For comparison, the flux at 1700 m.w.e. is 100 times higher, while at 6000 m.w.e. it is 15 times lower. The neutron flux in the energy range of interest does not decrease as quickly with increasing depth because the neutron production rate and yield (per muon) increase with muon energy.

The neutron cross sections are far more uncertain than the muon flux and spectrum. Energetic muons produce neutrons in rock through quasielastic scattering, evaporation of neutrons following nuclear excitation, photonuclear reactions associated with the electromagnetic showers generated by muons, muon capture, and secondary neutron production in the subsequent electromagnetic showers and hadronic cascades. The neutron yield as a function of the mean muon energy is approximately a power law, $N \propto \langle E_\mu \rangle^{0.75}$. While various theoretical estimates of the high-energy neutron spectrum at depth have been made, few experiments have been done.

A recent and comprehensive study of the cosmic-ray muon flux and the activity induced as a function of overburden has been made for a suite of underground laboratories ranging in depth from $\sim$1000 to 8000 m.w.e. [91] derived from the Monte Carlo muon-shower propagation code FLUKA. The FLUKA code works reasonably well, with deviations from measurements being about 50%. This study also develops a Depth-Sensitivity-Relation (DSR) in an attempt to characterize the depth requirements of next-generation experiments searching for neutrinoless double-beta decay and WIMP dark matter.

Figure 8a shows the total flux of cosmic-ray muons as a function of overburden and for a selected set of underground laboratories. Depth is defined in terms of the total muon flux that has been experimentally determined and that would be present in a laboratory with flat overburden. Figure 8b shows the total neutron flux that is induced by the muons and that emerge at the rock-cavern boundary of an underground site. Roughly speaking these fluxes are attenuated by about one order of magnitude for every increase in depth of 1500 m.w.e.

The effect of this muon-induced background will depend upon the details of a specific detector geometry and its scientific goal. In ref. [91], the DSR was developed for germanium detectors specific to the direct search for WIMP dark matter (CDMS II) and that under development to search for neutrinoless double beta decay (Majorana). As can be seen in Figure 9, elastic scattering of fast neutrons produced by cosmic-ray muons represent an important background for direct dark matter searches, while Figure 10 demonstrates the sensitivity to these fast neutrons in neutrinoless double-beta decay experiments owing primarily to inelastic scattering processes.

Next-generation dark matter experiments will either require depths in the range of 4000–5000 m.w.e. or greater, or significant steps to actively shield or veto the fast neutrons produced through cosmic-ray muon interactions to reach

the desired sensitivity levels. Which option is more cost-effective will depend on the available of space at depth, and the nature of the central detector hardware. For example, some classes of experiments, such as noble liquids may lend themselves to submersion in large water-filled cavities. Although the focus here is on depth requirements to defeat fast neutron backgrounds, the experiments will also need to address internal sources of neutrons from (α,n) reactions and nuclear fission in the residual contamination in detector and shielding components, which should also be sufficiently thick to shield against similar neutron sources in the surrounding rock.

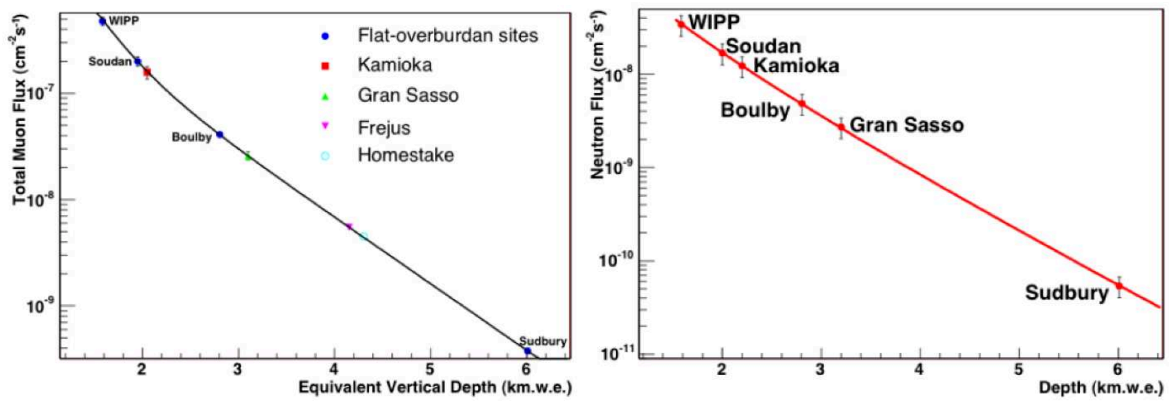

Figure 8: (a) Left: The total muon flux measured for the various underground sites as a function of the equivalent vertical depth relative to a flat overburden. The smooth curve is a global fit function to those data taken from sites with flat overburden. (b) Right: The total muon-induced neutron flux deduced for the various underground sites displayed. Uncertainties on each point reflect those added in quadrature from uncertainties in knowledge of the absolute muon fluxes and neutron production rates based upon simulations constrained by the available experimental data. (All from [91].)

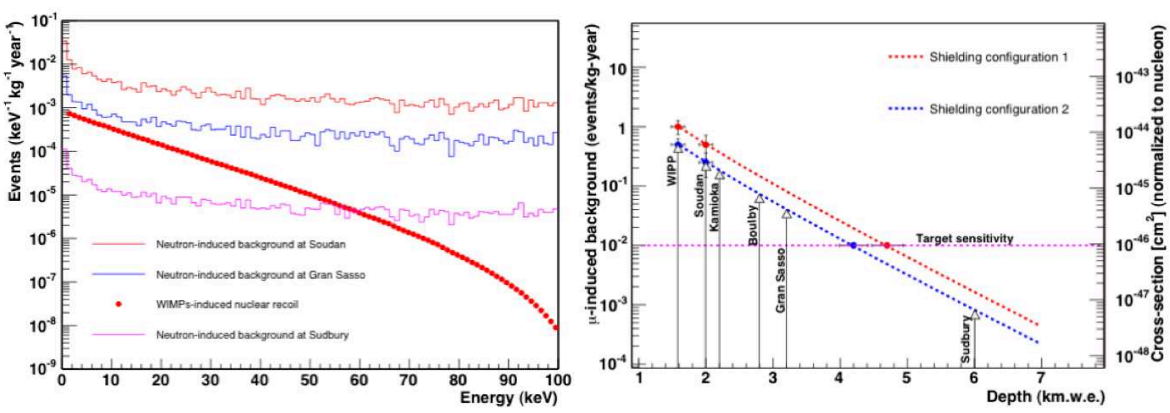

Figure 9: (a) Left: The predicted event rates for spin-independent WIMP-nucleon scattering (dotted-line) in Ge assuming a WIMP-nucleon cross-section of $\sigma_p = 10^{-46}$ cm^2 and a 100-GeV/c^2 WIMP mass. Muon-induced neutron backgrounds are also displayed for comparison, indicating the need for greater and greater depth as experiments evolve in scale and sensitivity. (b) Right: The Depth-Sensitivity-Relation (DSR) derived for the actual CDMS-II detector geometry (upper curve) and for a reconfigured shield in which all the lead gamma shield is exterior to the polyethylene moderator. The muon-induced background is dominated by elastic scattering of neutrons depositing visible recoil energy in a 10 to 100 keV window. Specific points are shown, for example, at the depth of the Soudan mine where the CDMS-II detector has been operating. Uncertainties reflect those present due to uncertainties in the rock composition and in generating the muon-induced fast neutron flux. (All from [91].)

For example, simulations carried out by the CDMS II collaboration [23] at the Soudan Mine depth of 2080 m.w.e. using Geant3 to propagate cosmogenic neutrons from the rock predict that this Ge-based experiment would detect single-scatter nuclear-recoil events from punch-through neutrons at a rate about one per 400 kg-d exposure. With an

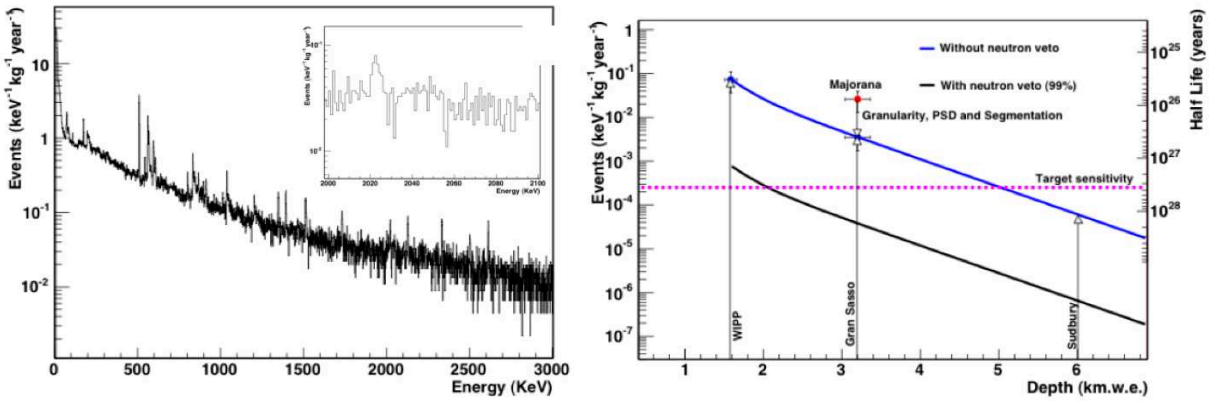

Figure 10: (a) Left: A simulation of the muon-induced background for a Majorana-like experiment operating at an equivalent overburden provided by the Gran Sasso Laboratory, showing the full spectrum and an expanded profile (inset) spanning the Region-of-Interest (ROI) around the Q-value for neutrinoless double beta decay at 2039 keV. The peak at 2023 keV is characteristic of that produced via the $^{76}Ge(n, n'\gamma)$ reaction. (b) Right: The Depth-Sensitivity-Relation (DSR) applied to a Majorana-like experiment. The raw event rate in the energy region of interest of 0.026 events/keV/kg/year can be reduced by a factor of 7.4 by exploiting the detector granularity, pulse-shape discrimination, and detector segmentation. The upper curve displays the background simulated in the case that no active neutron veto is present and the lower curve indicates the reduction that would result from an active neutron veto that is 99% efficient. (All from [91].)

additional factor of two reduction from a scintillator veto system, the estimated rate of unvetoed neutrons becomes 0.5 events/kg/year. An exposure of 3 kg-years, which corresponds to a WIMP-nucleon sensitivity of 10^{-44} cm^2 in the absence of background, would contain 1.5 background events at this rate. More detailed simulatons that include correlations of the parent muon, as well as all charged and neutral secondaries, were done with FLUKA and MCNPX that simulate energy depositions in the surrounding scintillator and in the dark matter detectors [92]. These simulations predict a rate of 0.05 events/kg/year $\pm$ 0.01 (stat.) $\pm$ 0.03 (sys.), where the reduction compared with the previous simulations is in part attributed to improved tracking of signals in the scintillator, and a larger fraction of multiple-scatters (these latter simulations were done for a 10-times larger array). At the higher rate, which is very likely an overestimate, a factor of 300 improvement to reach 10^{-46} cm^2 sensitivity would require, according to the DSR derived in [91], a depth of 6000 m.w.e. in the absence of additional shielding measures. At the lower rate a depth of 4200 m.w.e. would suffice for a factor of 30 reduction.

While the absolute rate of unvetoed nuclear recoils estimated with Monte Carlos lacks direct validation with experimental data for the specific mechanisms that lead to background events in dark matter experiments, detecting events correlated with unvetoed nuclear recoils can be used to predict their rate. For example, in the CDMS experiments performed at shallow depth, neutrons that multiple scattered were combined with simulations to estimate the number of single scatters associated with the same ambient neutron population. New simulations underway based on FLUKA and MCNPX show that an 60-cm-thick outer shield of liquid scintillator loaded with 0.5% Gd could efficiently detect a majority of the spallation events that produce neutrons that could interact with the dark matter detectors inside the shield [92]. The efficient detection of such events would simultaneously provide a cross check on the background simulations and higher-statistics measure of the in situ background compared with the multiple-scatter technique.

Although depth is the simplest and most certain solution to the fast-neutron background, several more ideas have been suggested that could make sites shallower than about 4000 m.w.e. acceptable. Sophisticated shielding and vetoing could reduce this background by one to two orders of magnitude. A thick (1–2 m) scintillator active veto around the detectors could tag high-energy neutrons as they penetrate inward. If instrumented as a Gd-loaded neutron multiplicity meter, as described above, a thickness of 60–80 cm would provide an order of magnitude reduction as predicted by simulations done for CDMS II [93]. In addition the cavern rock, or an outer heavy passive shield, could be instrumented with additional veto detectors in order to catch some part of the shower associated with the initial muon. Work is also ongoing to investigate very thick passive high-purity water shields, which could economically shield both gammas and

neutrons. Simulations of a 4-m-thick water shield have shown a factor of 20 reduction in the recoil rate due to punch-through neutron compared with the conventional external-lead internal-polyethylene shield configuration referred to in Figure 9 [94].

Increased granularity in detectors will enhance the multiple-scatter rejection rate (primarily for inner detector at some cost of fiducial mass), but would nonetheless serve as a cross check on systematics. Along these lines, measuring the neutron multiplicity in the energy range 100 keV–10 MeV in which neutrons produce WIMP-like recoils would also be helpful for benchmarking Monte Carlo simulations and quantifying systematic errors. The focus here has been on the depth-related fast-neutron background, but it is worth noting that its suppression through the use of depth and passive and/or active shielding must be accompanied by sufficient control of neutron sources from radioactivity. Primary sources are (α,n) processes from uranium- and thorium-series contamination and from spontaneous fission of uranium. Sufficiently thick moderator will adequately shield (α,n) sources from the rock (e.g., 1–2-m thick), but radiopurity of internal components will require continued vigilance. With regard to fission, one source that has been considered is from Pb shielding. G. Heusser and co-workers have observed upper limits of 20 ppt gram of uranium per gram of lead, with no positive measurements in any samples counted [95]. That level would produce on the order if 1 event per ton-year in a dark matter detector, but as noted by Heusser it may be that the chemistry of these heavy metals tends to make lead intrinsically pure.

In summary, next generation experiments, for example, those aiming for sensitivity in the 10^{-45} cm^2 range, could be performed at depths on the order of 4000 m.w.e. As experiments aim for greater sensitivity, such as those that could occur in the first suite of DUSEL experiments, depths of 6000 m.w.e. become very desirable. Ultimately, we find that these depths should be available at a laboratory that is aimed at a long-duration program. Surely, if WIMPs are discovered with cross sections anywhere in the range between present limits and 10^{-46} cm^2, a DUSEL at 6000 m.w.e. would be needed, possibly along with active vetoes, to study WIMPs with greater statistics and without contamination from depth-related backgrounds.

8.2 Materials Handling

Underground storage, handling, and fabrication facilities are important for dark matter experiments. Materials exposed to cosmic rays at the Earth's surface become radioactive through inelastic interactions, primarily due to air-shower neutrons. Even a 30-day exposure of an initially-pure sample of a medium-mass element will result in long-lived low-energy activity due to ^{3}H at several tens of disintegrations per kg per year. Other radionuclides within 10–20 mass units lighter than the target are also produced, with specific activities in some cases a hundred times higher than for ^{3}H. These effects have been seen in experiments, and computer programs such as COSMO and SIGMA have provided estimates of the activation and decay processes, in reasonable agreement with measurements.

The activation rate is reduced by a factor $\sim$100 at a depth of just 10–20 m.w.e. Current and past experiments have taken effective measures to shield or limit exposure times for critical components during processing at the surface. Underground storage for several halflives of the most critical radionuclides is also effective at reducing this background. However, the event rates to be sought in next-generation dark matter experiments are predicted by Supersymmetry to be exceedingly low, of order 10 per ton per year. Even experiments proposed to have excellent electron-recoil rejection efficiency would benefit significantly from eliminating the cosmogenics by conducting final purification and fabrication of critical components at least in a shallow underground facility.

Exposure to radon during these final operations must also be limited, to avoid deposition or incorporation of radon or its daughters (including long-lived ^{210}Pb) into critical components. The extent of radon mitigation required will be highly dependent on the particular experiment and component involved. It would be prudent to provide at least a section of the facility with radon significantly below the surface air level of $\sim$16 Bq/m^3. The Borexino collaboration built an assembly area at Princeton with radon concentration reduced by a factor of 100 from the local surface level.

Based on these considerations, DUSEL should have a 100–200 m^2 clean shop and storage area at least 20 m.w.e. underground, equipped with radon and particulate mitigation infrastructure. Cleaning stations, chemical hoods, and machine tools should be present from opening day. More materials processing equipment such as copper electroforming and semiconductor crystal growing may be incorporated as specific experiments are staged in, so provision for these capabilities brings potential benefits.

8.3 Facility Needs and Space

Most dark matter experiments have modest-size footprints (typically 200 m^2, or less) for the actual experiment. Additional space is of course needed for staging, DAQ, and control rooms. The environments must be able to be maintained at modest, e.g., Class 1000 clean room conditions with some mitigation of radon backgrounds. These needs are similar to those of double-beta decay experiments.

An initial suite of experiments would therefore be accommodated by one or two full-size caverns of 2000 cubic meters each, plus an additional 50 square meters for equipment staging, storage, control rooms, and R&D projects. The lab should also have the capability for further expansions that can be excavated for new experiments with minimal disruption to existing projects.

The more specific basic facility needs of dark matter experiments are itemized below:

- The space required to set up any one of the next-generation detectors is typically a 10 m high by 200 m^2 footprint. Several such experiments would be mounted in a single large hall. The hall should have crane(s) up to 30 tons with trained riggers available by arrangement. An overall muon veto and possibly water shielding for the entire hall would be cost-effective solutions to the needs of nearly all experiments. Water shields for individual experiments might require a sunk-in pit of 10-m depth below floor level to accommodate the shield base section.
- Experimental rooms must be cleanable, that is, upgradeable to clean-room standards during initial assembly and later operations. Soft-wall clean room systems are available commercially to allow flexible configuration of the underground space.
- Radon underground is a critical problem for sensitive low energy experiments. Experimental requirements are typically specified in the 10–100 mBq/m^3 range. Either each experiment will need its own radon-scrubbing micro-environment, or the entire cavern wall should be sealed and the hall continuously supplied with air scrubbed to reduce radon levels. Some experiments require constant radon purging for experiment interiors, so a compressor system for old-air storage and filtration, or cover gas derived from a liquid-nitrogen boiloff source will be required.
- Each experiment requires additional underground laboratory floor space to house data acquisition and experiment control rooms of typically 50 m^2.
- Because stability during extended periods of data-taking is critical, temperature control to at least office-building standards ($\pm 1°$C) is necessary in all underground areas.
- Average power requirements per experiment are typically 100 kW or less, with peak power no more than a factor of two higher. Critical subsystems such as control computers and cryogenics will require uninterruptable power supplies which should be provided by the individual experiments.
- The typical size of underground experimental crews during installation and commissioning is 10–20 people. Standard running requires only two to four people accessing experimental areas, with larger numbers during upgrade periods and run commissioning. The principal laboratory requirement is 24/7 access in case of emergency. During commissioning and detector start-up sequences, extended access (e.g., two shifts per day) is beneficial. None of the experiments as envisioned requires continuous underground presence.
- Provision for radioactive calibration sources is required for all experiments, including the necessary licensing, safety, and storage protocols.
- A 100–200 m^2 clean shop, staging and storage area should be provided at least 20 m.w.e. underground, equipped with radon and particulate mitigation infrastructure. This facility could be shared with non-dark matter users. Cleaning stations, chemical hoods, and machine tools should be present from opening day. More elaborate materials processing equipment such as copper electroforming and Ge detector re-processing could benefit nearly all dark matter experiments. The infrastructure should allow these to be incorporated as specific experiments are staged in.

- A surface facility with laboratory space and experiment control rooms providing computer links to the underground laboratory is also needed. This would amount to roughly 30 m^2 per experiment.

Special facility needs (experiment specific): Each experiment has specific additional needs not discussed above, but which are listed in the Infrastructure Table. These tend to fall into groupings as follows.

- Large inventories of liquid cryogen are used in several experiments. Safety systems must be included to minimize the possibility of large accidental releases, and to mitigate the oxygen-deficiency hazard which could develop with accidental release or accumulation of boiloff gas. Oxygen deficiency alarms, standby ventilation, and/or personnel escape/refuge facilities would be needed.
- EURECA is calling for a helium liquefier located near their experiment. This would have to be engineered to allow safe operation or shutdown in case of a power outage.
- As presently configured, the TPC experiments use flammable, toxic gases for the negative-ion drift. The detectors themselves operate below atmospheric pressure so catastrophic releases are unlikely. However, appropriate procedures must be in place for safe storage, transfer and disposal of these materials. COUPP presently plans to use several hundred kilograms or more of a non-flammable heavy liquid (CF_3I) which is much less toxic than the CS_2 negative-ion capture agent but is used under several bar pressure. Release prevention and management systems will still be required for this material.
- Water shielding tanks are planned for COUPP, CLEAN, and possibly others. These require personnel safeguards to prevent injury and equipment damage.
- Power outages of duration longer than 30 minutes can be disruptive for cryogenic experiments that plan to use cryocoolers, such as XENON and SuperCDMS. Since battery-type Uninterruptable Power Supplies UPSs are not practical for long outages, the provision for experiment-run backup generators may be called for.

9 International Context

As we have discussed in section 8.1, it is best to perform dark matter experiments as deep as possible. For ton-scale experiments, the neutron background can be eliminated at depths of 6000 m.w.e., or at shallower depths if adequate active shielding is used and systematic effects are well studied. Several current efforts that are building or performing experiments are developing next-generation plans. These plans were quite evident through the recent series of workshops held at SNOLAB, the site of the Sudbury Neutrino Observatory, or SNO.

SNOLAB is located at a depth of 6000 m.w.e. and, using funds provided by the Canadian Fund for Innovation, is constructing a laboratory to house a suite of four to six new experiments as early as 2007. A call to the physics community for Letters of Interest yielded 18 responses, 7 of which were for experiments aimed at detecting WIMPs. While it is unlikely that all 18 of these experiments will be funded and built (e.g., some represent similar competing technologies), it is likely that the capacity of SNOLAB will be exceeded by approximately a factor of two, though such an estimate is inherently uncertain and depends on many factors.

In addition to SNOLAB, other major laboratories that will host next-generation dark matter experiments include Boulby, Gran Sasso, Modane, Canfranc, and Kamioka. None of these is as deep as SNOLAB, but several dark matter experiments which are already operating at these locations are likely to remain there, to take advantage of the existing infrastructure and proximity to home institutions. For example, the Italian-led WARP and the Swiss-led ArDM liquid-argon experiments (which follow on the developments for ICARUS) and the Japanese-led XMASS liquid-xenon experiment, are likely to remain at Gran Sasso, Canfranc and Kamioka, respectively. Strong candidates for DUSEL from the international community are the UK program and Eureca, in addition of course to the various US efforts and others discussed in Section 7, including CLEAN, Coupp, DEAP, DRIFT, SuperCDMS, XENON, and ZEPLIN. Given the strong demand for deep space for dark matter experiments, the larger scale of "next-next" generation experiments timed for, say, a 2012 opening of DUSEL, and the capacity limitations of SNOLAB, it is clear that a robust and exciting dark matter program will be part of the initial DUSEL program.

10 Summary and Outlook

In this report we have described the broad and compelling range of astrophysical and cosmological evidence that defines the dark matter problem, and the WIMP hypothesis, which offers a solution rooted in applying fundamental physics to the dynamics of the early universe. The WIMP hypothesis is being vigorously pursued, with a steady march of sensitivity improvements coming both from astrophysical searches and laboratory efforts. The connections between these approaches are profound and will reveal new information from physics at the smallest scales to the origin and workings of the entire universe.

Direct searches for WIMP dark matter require sensitive detectors that have immunity to electromagnetic backgrounds, and are located in deep underground laboratories to reduce the flux from fast cosmic-ray-muon-induced neutrons which is a common background to all detection methods. With US leadership in dark matter searches and detector R&D, a new national laboratory will lay the foundation of technical support and facilities for the next generation of scientists and experiments in this field, and act as magnet for international cooperation and continued US leadership.

The requirements of depth, space and technical support for the laboratory are fairly generic, regardless of the approach. Current experiments and upgraded versions that run within the next few years will probe cross sections on the 10^{-45}–$10^{-44}\,\mathrm{cm}^2$ scale, where depths of 3000–4000 m.w.e. are sufficient to suppress the neutron background. On the longer term, greater depths on the 5000–6000 level are desirable as cross sections down to $10^{-46}\,\mathrm{cm}^2$ are probed, and of course, if WIMPs are discovered then building up a statistical sample free of neutron backgrounds will be essential to extracting model parameters and providing a robust solution to the dark matter problem.

While most of the detector technologies are of comparable physical scale, i.e., the various liquid and solid-state detector media under consideration have comparable density, a notable exception is the low-pressure gaseous detectors. These detectors are very likely to play a critical role in establishing the galactic origin of a signal if the remaining challenges of background rejection and low threshold can be demonstrated, and so it is important to design the lab with this capability in mind. For example, for a WIMP-nucleon cross section of $10^{-43}\,\mathrm{cm}^2$ (just below the present limit [23]), 100 modules of the size and pressure currently being investigated by the DRIFT-II collaboration ($1\,\mathrm{m}^3$ at 40 torr CS_2 [96]) would require a two-year exposure [90] to get the approximately 200 events [97] required to establish the signal's galactic origin. While detector improvements are under investigation, a simple scaling for the bottom of the MSSM region at $10^{-46}\,\mathrm{cm}^2$ would require a $100{,}000\,\mathrm{m}^3$ detector volume. If a factor of 10 reduction in required volume is achieved (e.g., higher pressure operation, more detailed track reconstruction, etc.) then an experimental hall of $(50\,\mathrm{m})^3$ could accommodate the experiment.

Because the WIMP-nucleon cross section is unknown, it is impossible to make a definitive statement as to the ultimate requirements for a directional gaseous dark matter detector, or any other device, for that matter. What is clear, however, is that whatever confidence one gives to specific theoretical considerations, the foregoing discussion clearly indicates the high scientific priority of, broad intellectual interest in, and expanding technical capabilities for increasing the ultimate reach of direct searches for WIMP dark matter. Upcoming experiments will advance into the low-mass Supersymmetric region and explore the most favored models in a complementary way to the LHC, and on a similar time scale. The combination of astrophysical searches and accelerator experiments stands to check the consistency of the solution to the dark matter problem and provide powerful constraints on the model parameters. Knowledge of the particle properties from laboratory measurements will help to isolate and reduce the astrophysical uncertainties, which will allow a more complete picture of the galactic halo and could eventually differentiate between, say, infall versus isothermal models of galaxy formation.

The scientific landscape of dark matter, which spans particle physics, astrophysics and cosmology, is very rich and interwoven. Exploring this exciting program following an initial detection will need many observables and hence a range of capabilities for follow-up experiments including different targets to sort out the mass and coupling of the WIMP, and directional sensitivity to confirm its galactic origin and open the age of WIMP astronomy. Clearly, this broad and fascinating program is ideally suited to the multi-decade span of DUSEL.

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