The Dark Matter Scientific Assessment Group (DMSAG)
A Joint Sub-panel of HEPAP and AAAC

Report on the Direct Detection and Study of Dark Matter

July 5, 2007

Table of Contents

I. Executive Summary

DMSAG has been charged to make a detailed examination of the field of direct detection of dark matter and to consider it in the broader context of particle physics and astrophysics. Some specific guidance was provided in the Charge to DMSAG and includes questions such as these abstracted from the Charge Letter (see Appendix C) and listed immediately below.

The progress in experimental techniques in the field is in a state of rapid flux and new levels of sensitivity have been reached; many advances have been made during the course of the work of this sub-panel. From present evidence, further advances can be confidently expected in both the near and long term. The funding for the US direct detection program is currently severely limited and constraining relative to the new opportunities and importance of the field. Consequently, answers to many of the questions posed are often conditional on present and soon to be expected progress in funding and technology. The DMSAG response to the Charge questions are contained in a set of Findings and Recommendations summarized at the end of this Section and repeated in distribution through-out the relevant portions of the text. To aid the reader, we cite in the questions below those Findings, Recommendations and Sections most directly related to a particular question; each may appear more than once. For analyses leading to the Findings and Recommendations the reader is directed to the topical Sections indicated in the Table of Contents.

- *What are the most promising experimental approaches for the direct detection of dark matter using particle detectors in underground laboratories?*

Cryogenic techniques based on solid state (phonons and ionization in Ge and Si) and noble liquids (in two-phase systems of both liquid Xe and liquid Ar) are presently leading the field and showing the greatest promise for coherent scattering of WIMPs. Methods with single phase liquid argon and warm liquids or gases are showing significant promise for the future. (The leading axion search, ADMX, does not require underground siting.) See Findings #3, 4, and 5 and Recommendations #3, 4, 5 and 8 and Sec. II-2.

- *What are: the relative advantages, disadvantages, stages of development, realistic times to implementation, ultimate sensitivities, realistic limits of scalability, overburden requirements?*

The recommended program attempts to build in the near term on the complementarities (e.g., target compositions and background controls) among the presently leading techniques and --- to anticipate the future program needs --- provide intensive R&D on the other emerging techniques also mentioned above. The future program needs are interpreted to be: a) to provide the “standards of proof” in the case of a positive signal or b) to provide the ability to extend the sensitivity-reach to cover the range of well motivated theoretical models. The experimental evidence so far appears to show that present techniques will be sufficient to reach sensitivities of order 10^{-45} cm^2 and, that with additional R&D, 10^{-46} cm^2 or greater may be reached with adequately shielded detectors.

As this Charge question implies, in arriving at recommendations for choosing detector technologies for a comprehensive program there are many interconnected details to be considered; however, it is useful to keep in mind two principle ideas: a) background control is a key issue with new background issues developing as the detectors are scaled-up which may be found to be drastically different between any two choices of technique and b) while scalability of one technique may appear favorable over others for cost or simplicity, we do not yet have all the relevant data for exclusive choices for the long term. Each step in mass, for any technique aiming for improved sensitivity, may reveal new background issues and/or additional expense.
See Findings #2, 3, 4, 5, 6, 9, 10 and 11 (especially, Fig. 2) and Recommendations #1, 2, 3, 4, 5, 6, 7 and 8 and Sec. II-2, III, IV, V and Appendix A.

- *What is the optimum strategy to operate at the sensitivity frontier in the short and immediate term while making the investments required to reach the ultimate sensitivity by scaling up to some realistic size in the long term (5-10 year horizon)?*

It is compulsory for a program which wishes to establish a signal giving evidence for positive detection of WIMP's that *all* of the detectors meet certain strict criteria. Among these criteria are a full understanding and control of backgrounds, reliable calibrations of energy scales and stable operating performance. We have noted above complementarities of candidates for the U.S. program; *these complementarities are essential*. Assuming all meet our criteria, they can be exploited in a number of ways. Two aspects of a WIMP signature are the dependence of the WIMP interaction cross-section and recoil spectra on the atomic weight (A) of the target and of the rate dependence on expected annual and diurnal periodicities.

We imagine the first response to a statistically significant detection reported from any one of the detectors would require not only confirmation from others with the same reach but, most importantly, the rate dependence and recoil spectral shapes of all must confirm (or in the case of a large spin-dependent cross-section, deviate from) the expected dependence on A^2. The technology presently in operation or under development has this capability built into it via use of several target materials, (e.g., Ge, Si, Ne, Ar, Xe and CF_3I.) Various combinations of experiments based upon some of these materials could presently provide several essential pieces of information relating to the discovery of a WIMP signature: a measure of cross-sections, its A dependence and, from the spectral shape of the latter, an estimate of the WIMP mass. Any claims of periodicity could benefit from simultaneous operation of two or more detectors.

Establishing the periodicities is more difficult because of the constraints placed on the detectors. For the annual periodicity the effect on the rate is very small (<2%) and thus requires high statistics and long periods of stable operation. Observation of the diurnal periodicity would appear to somewhat relieve the stability and statistics issues but it imposes the requirement that the direction of the recoil nucleus must be reliably measured. Present detector technologies aiming for directionality have, of necessity, very low mass/volume ratios. We do not yet have detectors with this directional capability (i.e., event-by-event differentiation of leading from trailing end of recoil tracks); however, this constitutes one of the significant R&D goals among others. Seeing these periodicities will be a significant confirmation of the source of any signal as being due to WIMPs, for establishing other WIMP properties and for aiding in measuring properties of the WIMP relic distributions.

We suggest as an optimal strategy a near-term push to construct at least two experiments of differing target materials with a goal of improving sensitivity at least a factor 10 over present limits. The technologies to be chosen from those presently demonstrating the most promise to carry them out in a timely and cost effective manner. At the same time, aiming for the longer term and next level of sensitivity, R&D should be conducted on all techniques with potential for scalability to at least tonne-scale and/or background control (such as true directionality). (The R&D may still imply construction of a device with interesting reach in sensitivity or complementarity to the nearer term experiments.)

See Findings #1, 3, 4, 5, 7, 8 and 11 and Recommendations #1, 3, 4, 5, 6 and 8 and Sec.II, III, IV and V.

- *What is the present state of the worldwide program? Does the US program have the potential to make unique contributions in the future?*

In addition to the U.S.-led experiments, there are presently between 7-10 dark matter direct detection experiments principally in Europe, Canada and Japan. Those programs are also making significant progress and expect to field additional experiments. The U.S. experiments are presently leading the field in sensitivity in two or more of the major techniques (e.g., ADMX, CDMS, and XENON10). The U.S. program can, with prompt and increased funding, continue the lead and extend it to those other areas where there is new progress on ideas expected to lead to better background control and increased detector masses. Otherwise, the U.S. is likely to fall behind, especially if noble liquids assume a commanding leap in sensitivity and new funding is not forthcoming. An underground facility such as DUSEL is essential for these large detectors and could also serve as a cooperative center and shared infrastructure for the entire U.S. direct detection program.

See Findings #2, 3, 4, 5, 9, 10 and 11 (especially Fig. 2) and Recommendations #1-7 and Sec. II-2, III and IV.

- *What guidance and constraints for this program can be gained from other approaches to understanding dark matter? Consider approaches such as collider searches, astronomical observations as well as from astrophysical or particle theory.*

Direct searches for energy deposited by WIMPs passing through matter are the most straightforward way to discover WIMP dark matter. These interactions are extremely rare, and so this approach requires sensitive detectors with exquisite background rejection. Despite this formidable challenge, past investments are now paying dividends as current experiments are beginning to be sensitive to the rates predicted in well-motivated models.

More importantly, recent advances in detector technology imply that these sensitivities may increase by 3 orders of magnitude in the coming few years. Such rapid progress will revolutionize the field, and will lead to the discovery of dark matter for many of the most well-motivated WIMP candidates.

Evidence for WIMPs may also come from other sources. For example, WIMPs may be produced at particle colliders. The Large Hadron Collider will thoroughly explore the weak scale in the coming years, and it has excellent prospects for seeing the "missing energy" signals characteristic of WIMP production. WIMPs may also be discovered indirectly by finding evidence of WIMP pairs annihilating somewhere in the galactic neighborhood. These indirect signals are important targets for a vast array of experiments, including neutrino telescopes (such as IceCube and ANTARES), space-based anti-matter searches (PAMELA and AMS), and gamma ray telescopes (GLAST, HESS, MAGIC and VERITAS).

Collider and indirect searches for dark matter are complementary, but can be much less straightforward than direct searches. Colliders cannot definitively discover dark matter by themselves, because they cannot verify that the produced particles are sufficiently stable to be dark matter. Halo indirect search results are also subject to ambiguities. On the other hand, direct search experiments, in combination with colliders and indirect searches, may not only establish the identity of dark matter in the near future, but may also provide a wealth of additional cosmological information. The implications depend, of course, on what dark matter scenario is realized in nature.

These considerations imply the dark matter field is at a particularly auspicious moment. We will have simultaneously, for both the near and far term, the theoretical motivation and technical capability from the three directions --- direct and indirect detection and colliders --- to make major discoveries and inroads into understanding dark matter and its connections to particle and astrophysics.

See Findings #1, 7, 8 and 11 and Recommendations #1 and Sec. II-1, V and VI (especially VI-3 through VI-8).

Scientific Introduction

Evidence for the existence of dark matter in the Universe has steadily accrued since the 1930s, when the astronomer Fritz Zwicky found that additional matter, beyond that which is luminous, was needed to explain gravitational binding of clusters of galaxies. Stars and other bright astronomical objects were simply insufficient to understand the gravity in clusters; hence it was proposed that some new type of unidentified "dark matter" would be required to explain the discrepancy. Since then, evidence from galactic rotation curves, gravitational lensing, hot gas in galactic clusters, precision measurements of the cosmic microwave background and measurements of large scale structure in the Universe all support the existence of dark matter in the Universe. By combining these data sets with many others – including the density of baryons as deduced from Big Bang nucleosynthesis and various measurements of dark energy in the Universe - a simple cosmological model (the concordance or ΛCDM model) has emerged wherein the composition of the Universe is found to be about 21% cold dark matter, 75% dark energy, 4% baryonic/luminous matter (Figure 1) along with a tiny fraction of relic neutrinos.

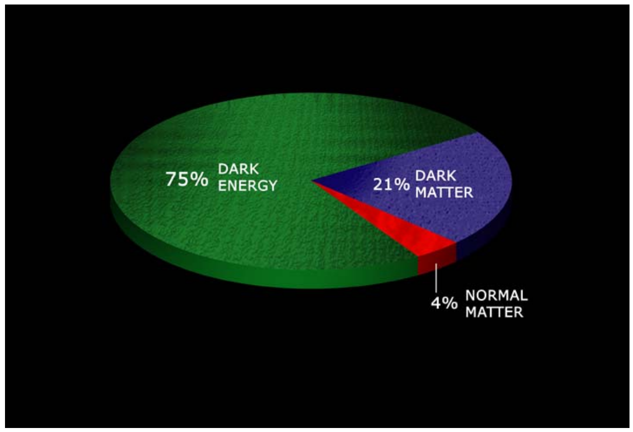

Figure 1: The Composition of the Universe

In short, only 4% of the universe consists of ordinary atomic matter, and the rest remains a mystery. Determining the composition of the rest of the Universe and the identification of its two main components, dark matter and dark energy, are among the most important goals in science today.

The local density of CDM is measured to be about 0.3 GeV/cm^3, which translates to about 1 particle per coffee cup volume for a 100 GeV dark matter candidate. While the local density of CDM might seem to be quite low, once one sums over the spherical volume surrounding the galaxies (and the space between galaxies) one finds that CDM can indeed be the dominant component of matter in the Universe.

While the density of dark matter in the Universe is becoming known to great precision, the identity of the CDM particle remains a complete mystery. No particle contained within the laws of physics as we know them has the right properties to be CDM. However, CDM particles do emerge quite naturally in a variety of well-motivated theories of physics beyond the Standard Model. Some of the possibilities have whimsical names such as black hole remnants, Q-balls, wimpzillas and fuzzy CDM (see Fig. 20 in Sec. VI.2).

The two most compelling candidates for dark matter are axions and weakly interacting massive particles (WIMPs). These particles are well motivated, not only because they resolve the dark matter puzzle, but also because they simultaneously solve longstanding problems associated with the standard model of particle physics.
Axions are elementary particles that arise naturally in theories that explain why large CP violating effects predicted by the standard model of particle physics have not been observed. Axions are expected to be both lighter and more weakly interacting than neutrinos, posing a great experimental challenge. Despite this, experiments have recently reached the extraordinary sensitivity required to detect them if they constitute all or much

of the dark matter. In promising experiments, a microwave cavity is placed in a high magnetic field. Axions passing through this cavity interact with the magnetic field and convert to photons, which are then detected.

WIMPs are particles that interact through the weak interactions of the standard model and have mass near the weak scale $M_{weak} \sim 100$ GeV – 1 TeV. They appear naturally in many model frameworks designed to understand the weak force, including supersymmetric theories, theories with extra spatial dimensions, and others. WIMPs may be searched for through a variety of techniques. Direct detection experiments are designed to find evidence for WIMPs interacting with ordinary matter. These experiments must be sensitive enough to observe the extremely small energy deposited in such interactions, while at the same time discriminating against other particle interactions that might simulate WIMP collisions.

To maximize the WIMP signal, high mass target nuclei are generally preferred, because the spin-independent WIMP-nucleus interaction rate is proportional to the square of the nuclear mass, and so should be greatly enhanced for large nuclei. In addition, the recoil energy of the recoiling nucleus is maximized when the mass of the nucleus is equal to the WIMP mass.

The proposed WIMP detectors use a variety of techniques to discriminate signal from background. The three most common experimental techniques that have been exploited for detection of this energy and background suppression are ionization, scintillation and phonon emission. The most sensitive of the detectors generally use a combination of two of these phenomena. By comparing information from two channels, it is possible to discriminate between nuclear recoils caused by WIMPs and neutrons and other backgrounds from electron recoils caused by gammas and betas. Further discrimination or more information is necessary to eliminate the neutron induced events.

The range of WIMP interaction strengths is model-dependent. In supersymmetric models, for example, spin-independent WIMP-proton scattering cross-sections typically range from 10^{-6} to 10^{-10} picobarn (10^{-42} to 10^{-46} cm^2). By comparison, the present CDMS sensitivity, until recently the world's best, is of the order of 2×10^{-7} pb (2×10^{-43} cm^2), representing an interaction rate of about 0.02 event/kg/day. (In a recent announcement the XENON10 Collaboration has reached twice this sensitivity for WIMPs of 100 GeV/c^2 and higher, and a factor of 6 better sensitivity for low mass WIMPs.) Therefore, to test a large fraction of supersymmetric predictions, the capability of isolating and identifying about 10 nuclear recoil events per ton of detector per year is required, a fantastic experimental challenge at the low energies -- a few tens of keV -- where a WIMP signal is expected.

The identification of dark matter will most likely not be immediately unambiguous, but will rather unfold gradually, and a complete experimental program must be sensitive to this possibility. As an example, a possible scenario for dark matter identification is the following:

In phase one, an experiment must identify a clear nuclear recoil signal and show that it cannot be reasonably be attributed to neutron background, radon chain disintegration products, or some other background.
In phase two, the interaction cross section, and WIMP mass if possible, of the reported signal must be confirmed by observations from at least one different target nuclei.
In phase three, if the cross-section is large enough to make this possible, the galactic nature of the signal would be confirmed by using a large statistics experiment sensitive to annual or, better, daily modulation, once the directionality of the signal has been determined. Corroborating evidence from indirect detection experiments and colliders will also provide essential confirmation.

U.S. groups are currently world leaders in direct searches with ADMX, an axion search experiment, CDMS, a cryogenic solid state WIMP detector and XENON10 a cryogenic noble liquid detector. Other noble liquid WIMP detectors such as WARP, and ZEPLIN-II - both European-lead but with U.S. participation - are also rapidly progressing. Additional innovative techniques are also being explored by a number of groups. Preliminary reports by the two most competitive of the noble liquid experiments appear to have results which are comparable or better than that of CDMS, pending confirmation of the preliminary results at the time of writing this report. The experimental program is therefore in a state of rapid transition and our Findings and Recommendations which follow immediately below reflect this. Our aim is to outline the requirements for a strong U.S. program. ***This includes the continued support for the on-going world-leading experiments and the very important increased support for the exciting new technologies that have the potential for a large increase in sensitivity.***

In the following sections we will first outline the theoretical motivation for the dark matter search, describe the current state of technology in the axion and WIMP searches and finally, give a detailed theoretical discussion examining the relationships between direct detection experiments, indirect detection experiments and the results that could be available from particle colliders such as the LHC and the ILC.

Findings & Recommendations

1. Findings

Finding 1: Timeliness of Dark Matter Science
Recent scientific breakthroughs have shown that most of the matter in the Universe is not made of atoms, but of something else, called dark matter. Although the amount of dark matter is becoming precisely known, its identity still remains a mystery. At the same time, well-motivated theories predict new particles that have all the properties required to be dark matter. These particles are expected to interact strongly enough to produce observable signals in detectors that exploit current and rapidly developing technologies. The confluence of cosmological observations, theoretical advances, and technological progress provides a timely opportunity to identify dark matter, with implications for some of the most important questions in science, such as how galaxies formed and what forces determine the behavior of fundamental particles.

Finding 2: Axion Detection
The ADMX experiment is the only experiment worldwide testing the possibility that an axion of mass 1-10 μeV is the dominant source of dark matter in the universe. The collaboration is starting to operate an improved detector based on low-noise SQUID electronics, which will allow them to improve the sensitivity compared to existing limits. They propose, in a second phase, to reduce the system temperature by an order of magnitude by adding a dilution refrigerator and making other improvements.

Finding 3: Cryogenic WIMP Detection
CDMS is the present world leader in cryogenic solid state WIMP detection technology and has demonstrated a clear strategy that should allow this experiment to almost certainly reach 10^{-8} pb (10^{-44} cm^2) sensitivity, and very probably 10^{-9} pb (10^{-45} cm^2) with the proposed 25 kg phase of SuperCDMS. On the other hand, it is not clear that this technique can be readily scaled to a cost-effective ton-scale experiment, which might be necessary to reach sensitivities down to 10^{-10} pb (10^{-46} cm^2).

Finding 4: Noble Liquid WIMP Detection
Experimental collaborations using noble liquid technology have made great strides in understanding their techniques and backgrounds. Prototype detectors operating with targets with masses less than 10 kg have recently shown preliminary unpublished results that are comparable to or better than the latest CDMS published results. This rapid development points to the possibility of large and relatively inexpensive detectors. The pace of progress is such that physics discoveries based on CDMS or these new detectors could occur as early as in the next two to five years.

Finding 5: Novel Directions in WIMP Detection
In the long term, it will be important that the global dark matter program include experiments and techniques that can incisively explore claimed signals, both to confirm discoveries and to provide additional information. This will require detectors sensitive to

the following: both spin-dependent and spin-independent interactions, detectors using different targets with correspondingly different recoil energy spectra, experiments that measure annual and/or diurnal variations of the signal as the Earth-Sun system moves through the galaxy, and detectors sensitive to the momentum direction of the incoming WIMPs. If WIMPs are convincingly observed, future detectors will map the local WIMP velocity and will usher in an era of WIMP astronomy.

In the last few years, there has been significant progress in exploiting low density gas detectors (DRIFT) and detectors based on room temperature bubble chambers (e.g. COUPP). Near-term COUPP upgrades to 50 kg scale prototypes may lead to limits competitive with the newest noble liquid and CDMS limits. Furthermore, a number of new techniques using high density gases also look promising (SIGN and HPGS), which could lead to very large masses at modest cost. Preliminary high pressure gas concepts show interesting potential but studies are not yet quantitative enough for a conclusion as to the limit achievable or the level of background to be overcome; with present knowledge, pursuit of further R&D on basic principles using modest prototypes is warranted.

Finding 6: Support and Funding Status

The funding for this very important area of physics has not kept up with the rapid experimental progress. It has been estimated that only about 2-3 M$/yr is currently being spent on direct detection dark matter experiments. This is not enough to sustain the current experiments and is certainly insufficient to support the strong program that is required to exploit the potential for important discoveries.

Finding 7: Complementarity with Indirect Searches

The indirect detection of dark matter in experiments such as GLAST, ICECUBE, PAMELA, HESS, MAGIC and VERITAS, offers many new dark matter detection possibilities that are complementary to direct detection. Typically, indirect detections are dependent on a different set of astrophysical uncertainties, but they offer the potential to probe regions of dark matter parameter space not accessible to direct detection. A direct detection signal for dark matter would help differentiate true signals of dark matter annihilation from astrophysical anomalies. At the same time, genuine signals in both types of experiments will provide a wealth of astrophysical information, constraining dark matter properties and halo profiles, with immediate implications for theories of structure formation.

Finding 8: Complementarity with Particle Colliders

If WIMPs are a significant component of dark matter, the properties that make them excellent dark matter candidates also imply that they are very likely to be produced at future colliders, such as the Large Hadron Collider and the proposed International Linear Collider. Direct detection of dark matter, in conjunction with detailed collider studies, will provide far more information than either approach alone, constraining the microscopic properties of WIMP particles, and their local distribution and velocity profile. This complementarity will also constrain the WIMP thermal relic density, opening a window onto the Universe at times just nanoseconds after the Big Bang.

Finding 9: Relation to Underground Laboratories and other Facilities
A strong program in direct dark matter detection requires a significant amount of underground space and facilities. Although direct detection experiments have made tremendous progress, the field is still in its infancy. Much larger experiments using several different targets and techniques will be necessary to fully understand the expected signal. While other countries have developed a number of underground sites, the total amount of deep experimental space is still far below that which will be required. The U.S. does not currently have an appropriate place to do this work. The proposed DUSEL program to develop a deep underground science and engineering laboratory would remedy this situation.

Finding 10: Material Scanning Facilities
To construct detectors with the extremely low radioactive contamination that is necessary to observe the rare nuclear recoil events, the construction materials must be carefully scanned and selected. The scanning facilities themselves must be located in a low background underground environment. Such facilities are in scarce supply and the increased experimental activity in this area will make this shortage critical.

Finding 11: Estimated Timescale for Detector Development and Results
The following Figure 2 gives the status and timescales projected by the various experimental groups for most of the existing and proposed experimental programs. The programs above the dashed line have significant U.S. group participation, while those below the line currently have none.

The figure shows that the next few years will be a time of great opportunity as new and relatively inexpensive techniques are rapidly developed.

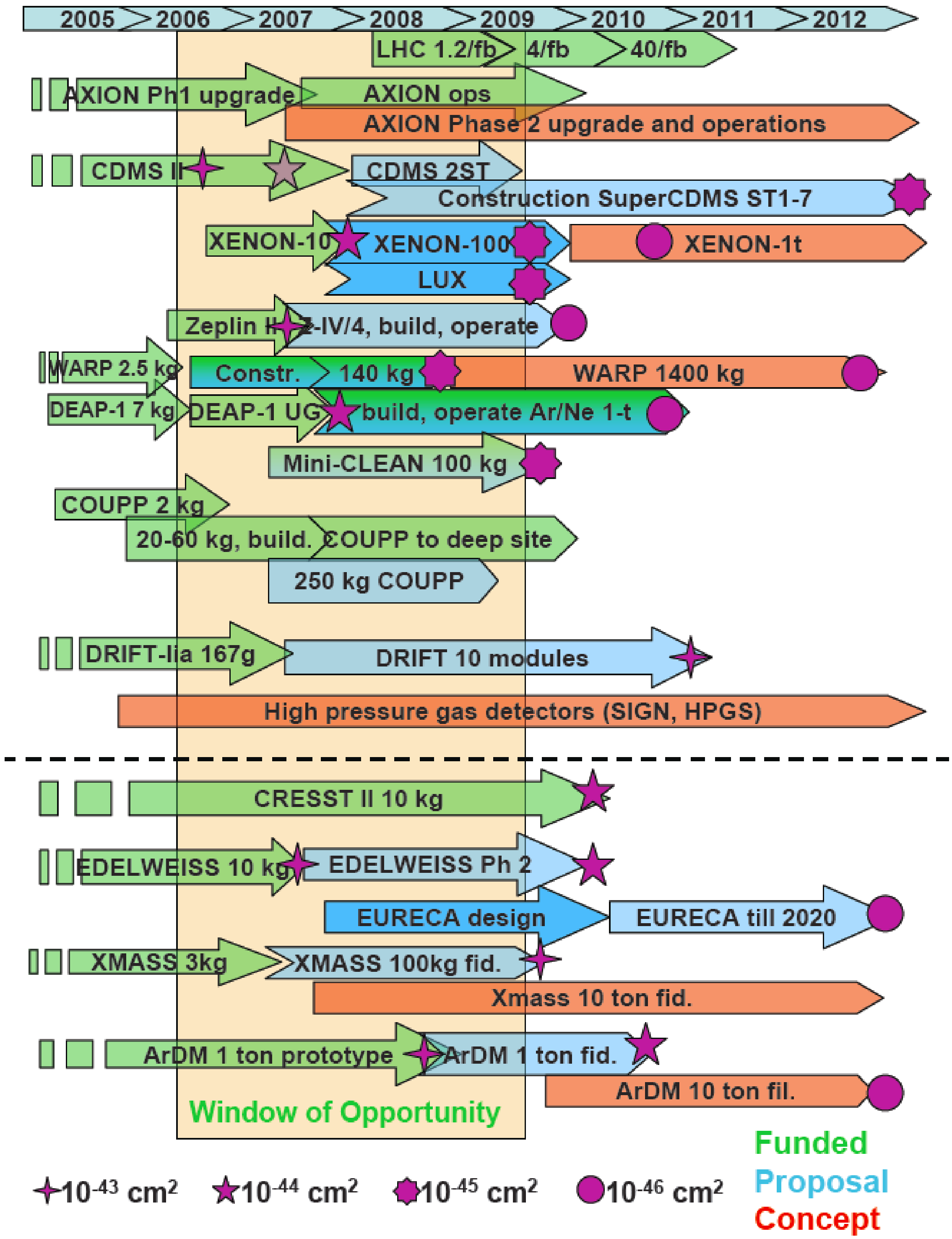

Figure 2: The status and timescales projected by the various experimental groups for most of the existing and proposed experimental programs. The programs above the dashed line have significant U.S. group participation, while those below the line currently have none.
The projected sensitivities are rounded to the nearest order of magnitude and are those estimated by the experimenters themselves. In some cases, especially for the longer term projections, a significant leap in background reduction is assumed, so the projections should be taken as possible but perhaps optimistic.

2. Recommendations

Recommendation 1: **Program and Funding**

The resolution of the mystery surrounding the dark matter in the universe is of exceptional scientific importance with implications well beyond particle physics. We recommend that the U.S. advance the direct search for dark matter using a variety of physical and technical approaches. U.S.-led experiments currently lead the world in sensitivity of the direct detection searches for both WIMPs and axions. We recommend that this leadership be preserved. This requires, in addition to supporting the running and improvement of existing detectors, that the R&D for the next stage of technology development be strongly supported with a goal of steady progress towards ton-scale and larger detectors.

To realize this program on an optimal time scale, the committee recommends that DOE and NSF increase funding for the direct detection of dark matter from the present ~$2-3M to ~$10M annually as soon as possible. The prospect of detecting dark matter while the LHC is operating amply justifies this increase. Such a figure is also consistent with the recommendations of P5 and EPP2010.

Recommendation 2: **ADMX**

The committee recommends that the ADMX collaboration be supported to operate the existing detector and, pending success of phase I, to take the necessary steps to reach greater sensitivity through lower system temperature.

Recommendation 3: **CDMS**

The sub-panel recommends that the CDMS Collaboration be supported to continue its outstanding direct-detection program. In order to accomplish this, we recommend the completion and operation of CDMS-II and the funding of two SuperCDMS supertowers at the Soudan site. Additionally, if dark matter funding is sufficient to permit the significant starts on the other portions of the U.S. program that we describe, and if the collaboration demonstrates the necessary control of the backgrounds, we support the completion and operation of the SuperCDMS detector with 7 supertowers at SNOLAB.
If funding is not sufficient for the rest of the program we have outlined, we recommend that the decision to go forward with supertowers 3-7 and installation of SuperCDMS in SNOLAB be considered in the broad context of a full evaluation of the field to be completed by mid-2009.

Recommendation 4: **Noble Liquid Detectors**

We recommend that the R&D required for the next stage of technology development for noble liquid detectors be strongly supported. In some cases, this means that demonstration projects need to be completed, while in others it means that the next-scale detector should be constructed. For the short-term program, the emphasis should be on developing detectors using larger target masses with decreased backgrounds to reach ever-greater sensitivity.

To capitalize on recent impressive results, the sub-panel recommends that a significant fraction of the total funding resources be devoted to noble liquid target experiments, successors of the present WARP, XENON10, and ZEPLIN-II prototypes. However, given the tight funding situation and the large range of new and promising ideas, the sub-panel also believes that it cannot support duplicate development programs in the U.S. using the same target and technique. Therefore:

a) The sub-panel supports the development of one two-phase xenon-based detector at the 100 kg scale and above.
b) The sub-panel supports the development of detectors using liquid argon and/or liquid neon technology. WARP and miniCLEAN/DEAP represent two quite different technologies in their application to liquid argon. Both of these techniques should be explored to discover which has greater potential.

Recommendation 5: **Superheated Liquids and Directional Sensitivity**
In addition to the above main lines of development,

a) The sub-panel recommends the development of superheated liquid detectors. The program proposed by COUPP appears to be well balanced and has recently been approved by the Fermilab PAC.
b) On the basis of the performance and background levels presented by the DRIFT collaboration, the sub-panel recommends the development of a single prototype detector module with the principal goal of demonstrating track reconstruction and directionality determination.

Recommendation 6: **DUSEL**
We strongly support the construction of a U.S. Deep Underground Science and Engineering Laboratory (DUSEL), which could host ton-size or greater direct dark matter detection experiments.

Recommendation 7: Scanning Facilities
We recommend additional underground scanning capability to alleviate the impending shortage, increase the sensitivity, and expedite the scanning of materials for the new generations of detectors. Ideally, a comprehensive facility, as described in the DUSEL S1 report, should be located in the DUSEL site.

Recommendation 8: Priorities
Following on the above recommendations, if the comprehensive program we have described above is not able to be fully funded, then we recommend that the funding priorities during the next few years be allocated as follows. In establishing these priorities, we have considered both the experimental evidence of promise in a particular technique and our estimation of its readiness for producing significant experimental results. In addition, all else being equal, predominantly US efforts are given somewhat higher priority.

1. Equal priorities between (A) and (B):
   A) Continuing the on-going CDMS and ADMX experiments and the initial construction of SuperCDMS in Soudan with two super-towers.
   B) Funding the expansion of the noble liquids with priorities i), ii) and iii):
      i) The expansion of the liquid Xenon experimental efforts to their next level.

ii) The U.S. participation in the WARP detector development.
iii) The next stage of the CLEAN Argon/Neon detector development.

(*Note on funding guidance: As we have noted elsewhere, we do not yet know which technique is the best route to the ton and larger scale. Consequently, there is a need to keep the three noble liquid techniques moving in parallel to that goal. As progress is achieved in each project, the levels of relative funding may need to change, independent of present priorities, in order to make fair evaluation of potential.***)**

2. The development of superheated liquid detectors and detectors capable of determining WIMP direction. Although these ideas have great promise, they still have significant R&D questions remaining to be answered.

We believe that many of the questions associated with the longer-term direction of the experimental efforts will be resolved during the next few years, provided that the current support continues and our recommendations are implemented, and that a program review in or around 2009 will be necessary.

II. Discussions

1. Theoretical Motivation

In the past decade, breakthroughs in cosmology have transformed our understanding of the Universe. A wide variety of observations now support a unified picture in which the known particles make up only one-fifth of the matter in the Universe, with the remaining four-fifths composed of dark matter. The evidence for dark matter is now overwhelming, and the required amount of dark matter is becoming precisely known.

Despite this progress, the identity of dark matter remains a mystery. Current constraints on dark matter properties show that the bulk of dark matter cannot be any of the known particles. The existence of dark matter is at present one of the strongest pieces of evidence that the current theory of fundamental particles and forces, summarized in the standard model of particle physics, is incomplete. At the same time, because dark matter is the dominant form of matter in the Universe, an understanding of its properties is essential to determine how galaxies formed and how the Universe evolved. Dark matter therefore plays a central role in both particle physics and cosmology, and the discovery of the identity of dark matter is among the most important goals in science today.

The theoretical study of dark matter is very well developed and has led to many concrete and attractive possibilities. Two leading candidates for dark matter are axions and weakly interacting massive particles (WIMPs). These are well motivated, not only because they resolve the dark matter puzzle, but also because they simultaneously solve longstanding problems associated with the standard model of particle physics.

Axions are predicted to be extremely light and feebly interacting particles. The theory of the strong interactions naturally predicts large CP violating effects that have not been observed. Axions resolve this problem by elegantly suppressing CP violation to experimentally allowed levels. In simple models, the axion's relic density Ω and mass m are related by $\Omega \sim m^{-7/6}$. The mass is constrained to the range 10^{-6} eV < m < 10^{-3} eV, where the lower limit follows from the requirement that axions not provide too much dark matter, and the upper limit is set by other astrophysical constraints. Although axions are extremely weakly interacting, experiments have recently reached the extraordinary sensitivity required to detect them as resonances in microwave cavities. The lowest decade of the allowed mass range, where axions are a significant component of dark matter, may be probed with current detectors. Future upgrades may provide sensitivity to the entire mass range.

WIMPs are particles that interact through the weak interactions of the standard model and have mass near the weak scale $M_{weak} \sim 100$ GeV – 1 TeV. Such particles have strong theoretical motivation. First, WIMPs appear in supersymmetric theories and many other model frameworks motivated by attempts to understand electroweak symmetry breaking. Second, these new particles are naturally produced by the Big Bang with the cosmological densities required for dark matter. This last property is a remarkable quantitative fact. In models containing thermal WIMPS, it implies that the weak scale is an especially promising mass scale for dark matter candidates, and experiments that probe the weak scale are required to determine if this possibility is realized in nature.

Direct searches for energy deposited by WIMPs passing through matter are the most straightforward way to discover WIMP dark matter. These interactions are extremely rare, and so this approach requires sensitive detectors with exquisite background rejection. Despite this formidable challenge, past investments are now paying dividends as current experiments are beginning to be sensitive to the rates predicted in well-motivated models. More importantly, recent advances in detector technology imply that these sensitivities may increase by 3 orders of magnitude in the coming few years. Such rapid progress will revolutionize the field, and will lead to the discovery of dark matter for many of the most well-motivated WIMP candidates.

Evidence for WIMPs may also come from other sources. For example, WIMPs may be produced at particle colliders. The Large Hadron Collider will thoroughly explore the weak scale in the coming years, and it has excellent prospects for seeing the missing energy signals characteristic of WIMP production. WIMPs may also be discovered indirectly by finding evidence of WIMP pairs annihilating somewhere in the galactic neighborhood. These indirect signals are important targets for a vast array of experiments, including neutrino telescopes (such as IceCube and ANTARES), space-based anti-matter searches (PAMELA and AMS), and gamma ray telescopes (GLAST, HESS, MAGIC and VERITAS).

Collider and indirect searches for dark matter are complementary, but can be much less straightforward than direct searches. Colliders cannot definitively discover dark matter by themselves, because they cannot verify that the produced particles are sufficiently stable to be dark matter. Halo indirect search results are also subject to ambiguities. In fact, tentative signals of WIMP dark matter annihilation have already been reported by many indirect search experiments, but their interpretation is clouded by astrophysical uncertainties.

On the other hand, direct search experiments, in combination with colliders and indirect searches, may not only establish the identity of dark matter in the near future, but may also provide a wealth of additional cosmological information. The implications depend, of course, on what dark matter scenario is realized in nature. Three of the many possibilities are:

(1) A current WIMP direct search experiment, such as CDMS, discovers a dark matter signal with spin-independent nucleon cross section $\sigma_{SI} \sim 10^{-8}$ pb (10^{-44} cm^2) in the next few years. With additional data, this signal constrains the dark matter particle's mass and also gives quantitative predictions for signal rates in other experiments. These results are confirmed by other direct search experiments using different target nuclei. At about the same time, the LHC discovers a new particle revealed through missing energy signals. Collider constraints on the missing particle's mass match those of the direct detection experiments, providing strong evidence that the particles produced at colliders do in fact

form dark matter. Follow-up studies at colliders determine that these particles are neutralinos, and that their thermal relic density is consistent with the amount required to explain dark matter, implying that dark matter is completely made of neutralinos. Colliders also determine the neutralino's couplings and other microscopic properties. The ILC may be crucial in these follow-up studies. Given these data, direct and indirect detection signal rates then constrain the spatial and velocity distributions of dark matter, providing essential information about dark matter halos now and how galaxies were formed.

(2) Current WIMP direct search experiments do not see signals in the coming few years. At the same time, the LHC discovers new particles revealed through missing energy and missing momentum. Further studies at the LHC determine that the new particles are Kaluza-Klein (KK) photons, particles predicted by extra dimensions. They also constrain the KK photon interaction cross section to be $\sigma_{SI} \sim 10^{-46}$ cm^2, providing a target for direct searches. Several direct detection experiments, exploiting new technologies now emerging, race to reach this level with 1 ton detectors and eventually find the predicted signal. Further studies at colliders and direct and indirect search experiments find consistent mass measurements, implying that KK photons contribute to dark matter.

(3) WIMP direct search experiments do not see signals in the coming years. The LHC discovers new particles through missing energy signals. Follow-up studies show that these particles are neutralinos, but that, if absolutely stable, the mass in neutralinos would be larger than the total mass of the Universe. The LHC further predicts interaction cross sections at levels accessible to direct search experiments, but signals in these experiments are not seen. These paradoxes are, however, resolved by the discovery of axions at the ADMX experiment. The axion mass is found to imply that some, but not all, of dark matter is in the form of axions. The simultaneous discovery of axions and supersymmetry, however, implies the existence of axinos, the supersymmetric partners of axions. The neutralinos produced in the early universe decay to axinos, which are too weakly interacting to be detected. Detailed studies later determine that the axino relic density is exactly sufficient to account for the remaining dark matter relic density, and establish a two-component theory of dark matter composed of a combination of axions and axinos. The axions form cold dark matter, but the axinos are warm, smoothing out structure on small scales and resolving discrepancies between numerical simulations and astrophysical observations.

The role of direct detection experiments varies widely in these scenarios. In all of these examples, however, a strong and multi-pronged program of direct searches for WIMPs and axions plays an essential role. A relatively modest investment in direct searches will maximize the cosmological information that may be extracted from the massive existing commitment to collider and indirect search experiments. Such an investment will lead to rapid improvements in our ability to detect and study dark matter and, in some cases, may even lead to a complete characterization of dark matter in the coming decade.

2. Current State of Technology and Issues to be Resolved

The past several years have brought tremendous progress in experimental techniques for direct detection of dark matter. Here we will survey them briefly, with emphasis on initiatives with strong U.S. participation. There is a single axion search initiative, and several WIMP detection programs. Among the existing WIMP detector programs, one (CDMS), based on solid-state detectors, is well-established and has already produced leading limits; a number of others are in various stages of development. Among those in the prototype/ R&D phase that are farthest along are detectors based on noble liquids such as Xe, Ar, and Ne. In fact two of these prototypes have produced competitive sensitivity limits. These latter seem very promising for scalability to large masses in the relatively near-term. Other ideas with promising scalability include warm liquids and high pressure gases. There are furthermore a number of detector-development programs which aim for the long term, for instance those which focus on directionality measurements, which will be vital in the case of WIMP detection.

This is a field of experimentation in which the development of technologies for extending the physics reach have been (and are) moving very rapidly. It is worth mentioning that, although the technologies may have tangential resemblances to more traditional particle and nuclear ones, they more often are a marriage of two or they incorporate new insights from condensed matter and astrophysics. This speaks well for the ingenuity, innovation and drive of the research community involved; it suggests further progress is to be expected.

In considering what technology issues still need to be resolved in the field we need to consider the twin goals of sensitivity/discovery and of "standards of proof" as well as the need to keep them moving along in tandem. *Consequently, at any given time it is not just a question of the next orders of magnitude in sensitivity but also having the right mix of target types and masses for signature tests.*

In this section we give a brief description of each technology, a picture of the current status (in the global context), and issues expected to be resolved in the next 2-5 years. *The reader should note that each technology section concludes with a part on "Further Plans and Issues to be Resolved" for that technique. In that section, even for the techniques currently most advanced or successful it should be kept in mind there are always R&D questions which unless addressed could under certain circumstances drastically change the relative competiveness.* In some cases, longer term issues are mentioned. With respect to the latter, it should be noted here that for all of these WIMP experiments underground siting at depth is a requirement. *Presently, there is no U.S. site or collection of sites suitable or capable of accommodating the evolving program; the DUSEL initiative presents a welcome prospect to resolve this particular issue.*

2.1 Axion searches

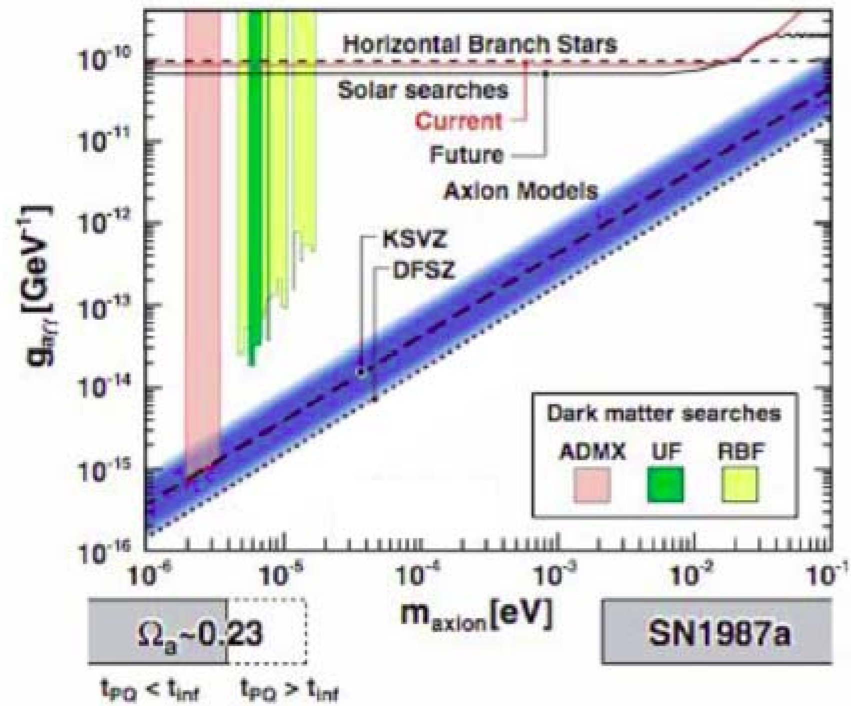

Figure 3: Axion limits in a particular parameter space of coupling strength vs. mass. The blue diagonal band represents the range of expectation from axion models, which predict coupling proportional to mass; "KSVZ" and "DFSZ" are particular models. Excluded regions from different experimental searches are shown as colored regions [1].

2.1.1 Microwave Cavity Searches

Description of technology and current status: In a static magnetic field, there is a small probability for halo axions (see theoretical description in sections VI-3.1 and VI-5) to be converted by virtual photons to a real microwave photon by the Primakoff effect. This would produce a faint monochromatic signal with a line width of $\Delta E/E$ of 10^{-6}. The Axion Dark Matter Experiment (ADMX) consists of a high-Q (Q=200,000) microwave cavity tunable over GHz frequencies[1, 2].

Around 1999 this collaboration (then called AXION) proposed a new round of experimentation based on GHz SQUID amplifier technology to replace a HEMT amplifier used earlier. In 2004, DOE funded the Phase I upgrade, which involved adding the SQUID amplifier. The collaboration is completing Phase I construction and is starting to commission the Phase I detector. They expect to reach sensitivity capable of seeing KSVZ axions (g_γ^2= 0.94) at the expected density over the mass range 1 to 10 μeV, which will require 1 to 2 years of scanning. In figure 3 this corresponds to a range of $g_{a\gamma\gamma}$ from ~4×10^{-16} to 4×10^{-15} GeV^{-1}.

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[1] K. van Bibber and L.J. Rosenberg, Phys. Today, **59N8**, 30 (2006).
[2] L.D. Duffy *et al.*, Phys. Rev. **D74**, 012006 (2006).

There is a single effort of this type in the U.S., and in fact this microwave cavity search is unique worldwide, although some other experiments are planned or in progress using other techniques e.g. the CAST solar axion search (with different sensitivity to masses and couplings[3]), and an experiment based on transitions in Rydberg atoms. The PVLAS group[4] has reported an apparent signal consistent with a 1-meV axion in an experiment looking for magnetically-induced dichroism in the vacuum. This experimental activity covers masses outside the present ADMX search range and would be inconsistent with stellar evolution in most models. The JLab photon regeneration experiment[5] is currently testing the PVLAS result.

Future plans and issues to be resolved: After completion of Phase I, the collaboration hopes to proceed to Phase II, which involves adding a dilution refrigerator to drop the system temperature, defined as the sum of the cavity and amplifier temperatures, from 1.7 to 0.2 K. Phase II would take 2 years of construction followed by 2 years of operation. This would reach the level expected for DFSZ axions ($g_\gamma^2 = 0.13$) over the same mass range (about a factor of three lower in $g_{a\gamma\gamma}$). Beyond this, they hope to develop, in an R&D phase, a high-frequency upgrade to reach higher mass that might result in construction in the period 2010 to 2013, with operation extending several years beyond that.

If a signal is seen, there are a number of tests that can be done to verify that it is actually due to an axion. The signal strength must go as B^2, it must behave as a psudoscalar and it should exhibit decoherence with increasing separation of test cavities. Once the axion is discovered and confirmed, the next experimental goal might involve a power-spectrum map of the resolved axion line and subsidiary lines. This contains the time history of our galaxy's evolution. The spatial pattern of decoherence in cavity pairs contains velocity information. Another experimental goal might involve looking for sidereal and annual modulations to study the velocity infall vectors of the axions.

Finding 2: Axion Detection

The ADMX experiment is the only experiment worldwide testing the possibility that an axion of mass 1-10 μeV is the dominant source of dark matter in the universe. The collaboration is starting to operate an improved detector based on low-noise SQUID electronics, which will allow them to improve the sensitivity compared to existing limits. They propose, in a second phase, to reduce the system temperature by an order of magnitude by adding a dilution refrigerator and making other improvements.

Recommendation 2: ADMX

The committee recommends that the ADMX collaboration be supported to operate the existing detector and, pending success of phase I, to take the necessary steps to reach greater sensitivity through lower system temperature.

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[3] K.Zioutas, *et al.* [CAST Collaboration], Phys. Rev. Lett. **94**, 121301 (2005).

[4] E.Zavattini et al. [PVLAS Collaboration], Phys. Rev. Lett. **96**, 110406 (2006).

[5] A.V.Afanasev, O.K.Baker and K.W.McFarlane, arXiv:hep-ph/0605250.

2.2 WIMP Searches

WIMP searches are based on detection of recoils induced by the scattering of WIMPS off nuclei. Recoil energies of tens of keV are expected, so very low threshold detectors are required. Because the expected rate is low, radioactive backgrounds must be minimized: an underground location, clean materials and extensive shielding are typically needed. Any remaining gamma and beta backgrounds (which produce electron recoils) must be discriminated from nuclear recoils, and detector technologies often employ multiple energy loss channels (scintillation, heat/phonons, ionization) to distinguish WIMP signal candidates from background.

2.2.1 Solid State Detectors

Description of technology and current status: The Cryogenic Dark Matter Search (CDMS) collaboration has pioneered the use of low temperature phonon-mediated Ge or Si crystals to detect the rare scattering of WIMPs on nuclei and distinguish them from backgrounds. With this powerful technology, operating deep underground in the Soudan

Figure 4: ZIP detectors

mine in Minnesota, the CDMS group has obtained data and published the most sensitive WIMP search in the world[6,7].

The CDMS technology based on the ZIP (Z-dependent Ionization and Phonon) detector uses simultaneous detection of phonons and ionization. The ZIP technology incorporates a novel use of tungsten-based transition edge sensors (TES). To make detailed use of the phonon signals, the TES are equipped with quasi-particle trapping arrays invented by this group. Together with their NIST collaborators, CDMS has also contributed the original development of SQUID series array amplifiers. Some of these new CDMS-related technologies are finding their way into other applications such as single photon detection in optical astronomy, x-ray detection and quantum computing.

In their CDMS application, ZIP detectors can incorporate either germanium or silicon as the target material. The ionization yield versus the recoil energy is used to reject

[6] D.S. Akerib *et al.* [CDMS Collaboration], Phys. Rev. Lett. **96**, 011302 (206).
[7] D.S. Akerib, *et al.* [CDMS Collaboration], Phys. Rev. D **73**, 011102 (2006).

background from gamma and beta decays: nuclear recoils have a smaller ratio of ionization to phonon yield than gamma or beta signals. Beta decays from surface contamination, that may mimic recoil signals due to partial loss of ionization, can be rejected using pulse risetime. Neutron backgrounds produce nuclear recoil signals, but can be rejected if they multiple-scatter. The collaboration states that measured rejection against gammas is 99.995% and against betas is 99.4%.

The experiment (CDMS-II) is housed in clean room conditions in the Soudan mine, and the detectors are enclosed within several layers of shielding, including active scintillator veto, and layers of polyethylene, copper and lead shielding. A central cryogenic chamber houses the detector "towers" cooled to 50 mK by a dilution refrigerator. Each tower accommodates six ZIP detectors. The first two towers were installed in 2003. The first tower, with 1 kg of Ge and 0.1 kg of Si, accumulated 53 live days of data in 2003 and 2004; the next two-tower configuration with 1.5 kg of Ge and 0.6 kg of Si accumulated 74 live days. The limits corresponding to the Ge data (1.6 x 10^{-43} cm^2) are shown in Figure 5 as "CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)" for spin-independent WIMP interactions.

CDMS-II is continuing to run at Soudan and expects to gain a factor of eight in sensitivity by the end of 2007. They are progressing along several fronts, e.g. improved data analysis techniques for better surface event rejection, and improved understanding of contamination. An additional three towers have been installed and operated, with a total of 4.5 kg Ge and 1.1 kg Si. They expect to maintain "zero background" through 2007 and into 2008 while new supertowers are being tested at Soudan. Once exposures are a factor of 10 higher, cosmic-ray induced neutrons will become the limiting factor.

EDELWEISS is a European project, also based on Ge detectors, at the Modane Underground Lab[8]. EDELWEISS makes use of heat and ionization signals for rejection of electronic recoils. A 1 kg-scale detector has produced competitive limits, and EDELWEISS-II (including some novel technologies) with 100 times the sensitivity, is currently in progress.
Another European project, CRESST-II at Gran Sasso, is also in progress. It makes use of heat and light signals from 10 kg of calcium tungstate[9].

Eureca (European Underground Rare Event Calorimeter Array) is a new project largely composed of the CRESST and EDELWEISS groups. The current CRESST and EDELWEISS experiments are providing the R&D for EURECA and technology decisions will be based on their results.

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[8] V. Sanglard, *et al*. [The EDELWEISS Collaboration], Phys. Rev. **D 71**, 122002 (2005).
[9] G. Angloher *et al.*, Astropart. Phys. **23**, 325 (2005).

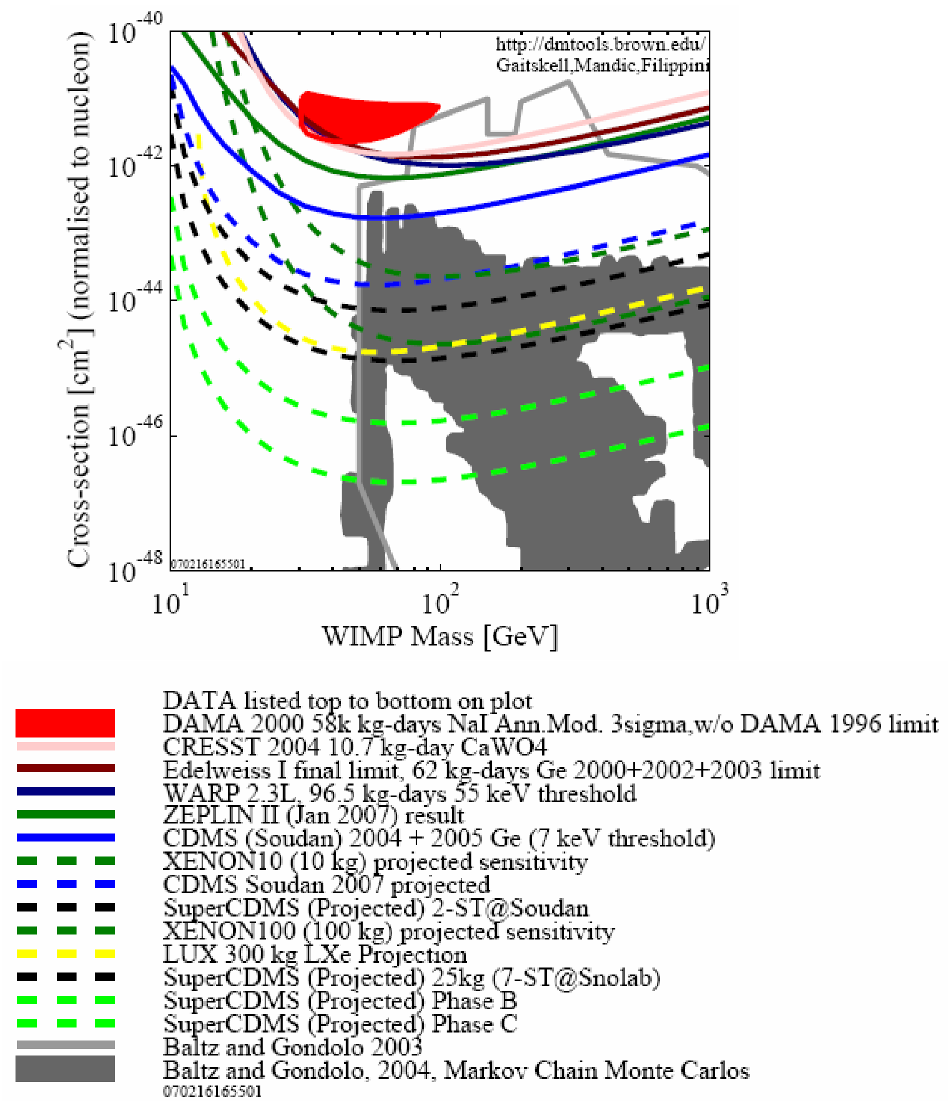


Figure 5: Sensitivity of various stages of CDMS and other detectors to spin-independent WIMPs. The shaded region are predictions for neutralino dark matter in the specific framework of minimal supergravity[10], and the gray band outlines the possible predictions for neutralino dark matter in a more general MSSM analysis[11].

Future plans and issues to be resolved: The proposed follow-up to CDMS-II is "SuperCDMS", which will consist of improved detectors, up to a total of 25 kg mass. New ZIP detectors with 2.5 times the mass (1 inch thick), and higher coverage Al-fin phonon sensors have been developed and successfully demonstrated. For the full 25 kg (and possibly larger) experiment, the CDMS collaboration (with the addition of new Canadian members) also proposes a move to SNOLAB, which offers a deeper site and lower cosmic ray-induced neutron background. They estimate overall a factor of about 40 background rejection and reduction for the new detectors, and more than a factor of 100 improvement in sensitivity over the current best limit with the full proposed

[10] Baltz and Gondolo, hep-ph/0407039.
[11] Baltz and Gondolo, Phys. Rev. **D67**, 063503 (2003).

SuperCDMS. The sensitivity for an enlarged SuperCDMS (phase B would be 150 kg and phase C 1000 kg) is also shown in Figure 5.

The shielding design for SuperCDMS 25 kg is patterned after the successful CDMS II shield, with modifications that take into account the much greater depth of SNOLAB compared with Soudan and the need to reduce conventional backgrounds sufficiently to meet their goal of improved sensitivity. Consequently for the SNOLAB installation, a significantly larger outer vacuum chamber and cryogenic system (or SNOBOX) is planned. This would allow placement of much of the shielding within the vacuum, where a much greater degree of cleanliness and radon exclusion could be maintained. Within the SNOBOX a graduated shield would be used consisting of ultra-clean polyethylene (sandwiched with thin layers of copper for thermal sinking) and of ultra low activity Pb to provide shielding against residual radioactivity of the SNOBOX materials. Outside of the inner vacuum cans, but contained within the outer vacuum chamber, are 18 cm of normal (Doe run) Pb intended to provide the main defense against gammas coming from the cavern. Surrounding would be 76 cm of polyethylene, to moderate low energy neutrons. At the depth of SNOLAB (6800'), the cosmic ray flux is expected to be ~1 muon/day interacting in the shielding, leading to an expected cosmic-induced neutron rate < 0.02 /(kg year), or 0.6 events for the full 25-kg exposure, prior to vetoing. Nonetheless they suggest it is advisable to build a veto because the calculated rate has some uncertainties. The veto might also provide information about the incoming flux of gammas. A plan-view of the SNOBOX and shield is shown in Figure 6.

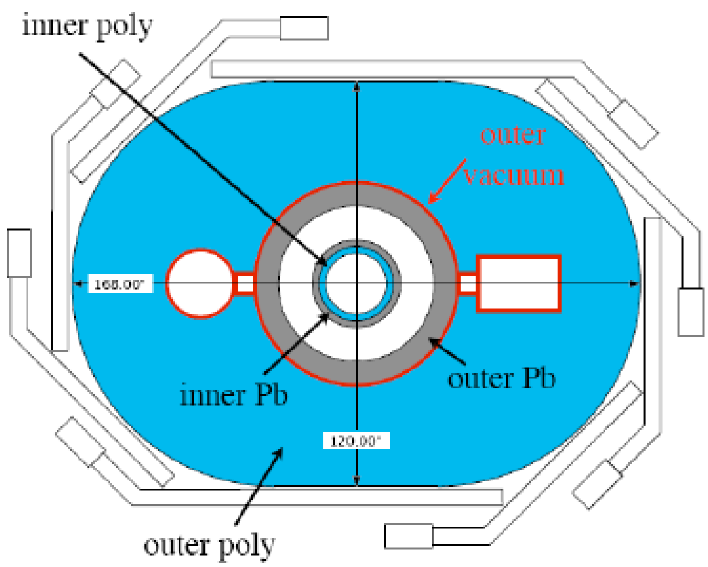


Figure 6: SuperCDMS SNOBOX with interior shield and veto (see text).

Three SuperCDMS scenarios were considered by the panel: (A) 2 super-towers at Soudan (corresponding to raw exposure 2800 kg-d), (B) 5 super-towers at Soudan (corresponding to raw exposure 15,000 kg-d), (C) 7 super-towers at SNOLAB (corresponding to raw exposure 18,000 kg-d). The CDMS collaboration's sensitivity estimates for these scenarios are shown in Figure 7.

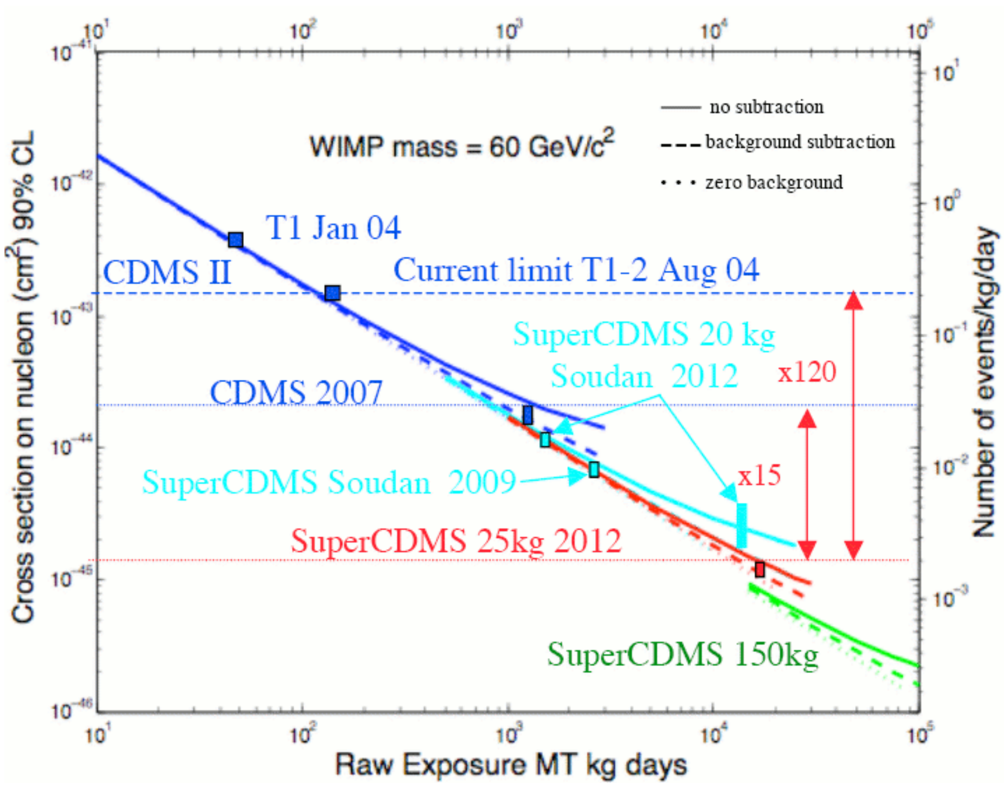


Figure 7: The blue lines show cross-section sensitivity as a function of exposure for CDMS-II. The cyan line represents a scenario corresponding to SuperCDMS at Soudan, and the red line corresponds to the proposed SuperCDMS detector at SNOLAB.

For the short term and in the run-up to 25 kg from the present CDMS-II, the principal issues being addressed concern the defeat of background beta events from detector surface events, neutrons from internal activity and development of a new cryogenic system (the large "SNO- or cold-box" and dilution refrigeration). The group has presented a plan of several stages with suitable possibilities for milestones along the way. Recent results on CDMS-II towers 3-5 now at Soudan appear to show an improving situation on surface cleanliness. Results from super-towers 1 and 2 could verify the expectations of improved background rejection and motivate the expansion to the full 7 super-towers. In the longer term, to go beyond 25 kg to say, 100 or 1000 kg and scaling from present understanding, will require new ideas for background control and major reduction in the cost and turn-around time for construction.

Finding 3: Cryogenic WIMP Detection

CDMS is the present world leader in cryogenic solid state WIMP detection technology and has demonstrated a clear strategy that should allow this experiment to almost certainly reach 10^{-8} pb (10^{-44} cm^2) sensitivity, and very probably 10^{-9} pb (10^{-45} cm^2) with the proposed 25 kg phase of SuperCDMS. On the other hand, it is not clear that this technique can be readily scaled to a cost-effective ton-scale experiment, which might be necessary to reach sensitivities down to 10^{-10} pb (10^{-46} cm^2).

Recommendation 3: CDMS
The sub-panel recommends that the CDMS Collaboration be supported to continue its outstanding direct-detection program. In order to accomplish this, we recommend the completion and operation of CDMS-II and the funding of two SuperCDMS supertowers at the Soudan site. Additionally, if dark matter funding is sufficient to permit the significant starts on the other portions of the U.S. program that we describe, and if the collaboration demonstrates the necessary control of the backgrounds, we support the completion and operation of the SuperCDMS detector with 7 supertowers at SNOLAB.
If funding is not sufficient for the rest of the program we have outlined, we recommend that the decision to go forward with supertowers 3-7 and installation of SuperCDMS in SNOLAB be considered in the broad context of a full evaluation of the field to be completed by mid-2009.

2.2.2 Noble Liquids

Description of the technology and current status: The noble elements xenon, argon and neon in the form of cryogenic liquids are all promising as WIMP detectors. The primary advantage of cryogenic noble liquid techniques with respect to solid state techniques is scalability: it appears likely that noble liquid detectors can be built at the ton scale, and at much lower cost. Detectors are relatively simple, and the liquids can be purified in situ. The higher operating temperatures of noble liquids allow more straightforward and less expensive cryogenic systems. With adequate position resolution the detectors can employ self-shielding to avoid the surface contamination problems that plague solid state detectors. Xenon, argon and neon all share these advantages and can be used with either single phase (liquid) or two-phase (liquid and gas) configurations.

Detectors employing these elements as a WIMP target can exploit scintillation light in the liquid, possibly using pulse shape discrimination to select nuclear recoils. They may also measure the ionization charge, using that as another handle on discrimination between nuclear recoils and other ionizing background particles (gamma-rays, betas), since the ratio of charge to scintillation light depends strongly on the rate of energy loss.

In a two-phase configuration when an ionizing event occurs, a prompt scintillation is produced by recombination of electron and ions in the liquid and the electrons that have not recombined are swept upward through the liquid by an electric field of ~1 kV/cm and then extracted through the surface to the gas with a field of ~5 kV/cm. The electrons can be accelerated in the gas and produce a second scintillation by gas ionization. The scintillation light in the gas phase, called S2, is delayed relative to the S1 (prompt scintillation) signal by the drift time of the electrons through the liquid.

Recoil ions produce a dense region of ionization whereas electrons produce a diffuse track. Because of the difference in ionization structure there is more recombination of electron-ion pairs in nuclear recoils compared to Compton or decay electrons. Consequently, compared to those electrons, nuclear recoils produce early scintillation light but have fewer un-recombined ionization electrons. Discrimination between recoils and β/γ events is therefore possible by measuring the ratio of scintillation light to collected (or sensed) ionization charge. The (ionization electrons)/(early scintillation) ratio is proportional to S2/S1, which is about 5 times bigger for electron events compared to recoil events. However, for reasons that are not well understood, the S2/S1 ratio for β/γ events has a non-statistical tail that extends into the recoil region. The tail of β/γ events in the recoil region, which is at a level of $\sim 10^{-2}$ in liquid xenon and liquid argon, limits the discrimination between recoils and β/γ events.

Because of the track structure there is also a difference in the scintillation pulse shape between recoils and electrons. Depending on the element used, this aspect can be exploited in either single or two-phase configurations The scintillation light has two components, a fast component due to the decay of singlet state and a slow component due to the decay of a triplet state. Heavily ionizing particles tend to have less of the slow component. For liquid argon the difference in pulse shapes is a very powerful discriminator between recoils and electrons, with estimates as high as 10^{-8}, or better for the leakage of β/γ events in the recoils region (see discussion of liquid argon detectors). However, in liquid xenon the much shorter triplet decay is quenched in both recoil and electron tracks and the pulse shapes are too similar for significant discrimination. We note that in gaseous xenon, pulse shape discrimination may be effective since quenching of the triplet state is less significant compared to liquids.

Xenon

With no pulse shape discrimination and/or limited suppression of β/γ events by S2/S1 discrimination, liquid xenon detectors rely on careful selection of low-background materials to suppress *internal* sources of background, "self-shielding" of a fiducial volume against gamma rays from *external* sources and good event position resolution to define fiducial volume. Self-shielding relies on the fact that it is unlikely that an external gamma ray can pass through the active buffer without scattering, deposit a small energy in the fiducial volume, and than pass out of the buffer again without scattering. Even a few centimeters of active buffer thickness can be quite effective in liquid xenon. In general, however, the need to employ self-shielding implies a sizable buffer and thus favors a detector with a large mass. External shielding is also required for β/γ and neutrons. Depending upon over-burden and the details of detector design the shield may require an active veto, particularly for neutrons.

The radioactivity in the photomultiplier tubes (PMTs) is a primary and unavoidable source of external γ-background (and neutrons) in the dual phase liquid xenon detectors. Two strategies are employed to deal with the PMT γ-background: first, development of low-background photon (or electron) detectors, and second, use of a thick buffer layer of liquid xenon between the PMTs and the fiducial volume. Both dual- and single-phase detectors can, depending on the details of the PMT array, provide excellent position reconstruction. In dual-phase the vertical position of the event in the liquid xenon has been shown to be measured to a few mm by the drift time of the electrons in the liquid, determined by the delay of S2 with respect to S1. The horizontal x-y position of the event is determined to ~ 1 cm or better from the relative intensity of light detected in the photo-detector array in the gas phase.

World-wide there are currently three liquid xenon detector programs in operation: Zeplin II in the Boulby Mine in the U.K., XENON10 in the Gran Sasso lab in Italy are both dual- phase, and XMASS in Japan is single-phase.

The XENON10 detector, illustrated in Figure 8, contains 22 kg of LXe and has a 10-kg fiducial mass out of a total active mass of 15 kg[12] . After detailed smaller scale tests in the U.S. it was installed at Gran Sasso in Italy in March 2006 and began operation in August 2006. The detector is two-phase and uses scintillation-ionization (S2/S1) and self-shielding to separate recoils from β/γ events. It is surrounded by a graded external shield of Pb and polyethylene. Preliminary results based on several weeks of running are quite positive. The liquid xenon is located in a cylindrical container 20 cm in diameter by 15 cm in height. The scintillation light is viewed by two arrays of small square photomultiplier tubes. One array is in the gas phase at the top of the cylinder, and one is in the liquid at the bottom of the cylinder. The prompt scintillation (S1) is detected by

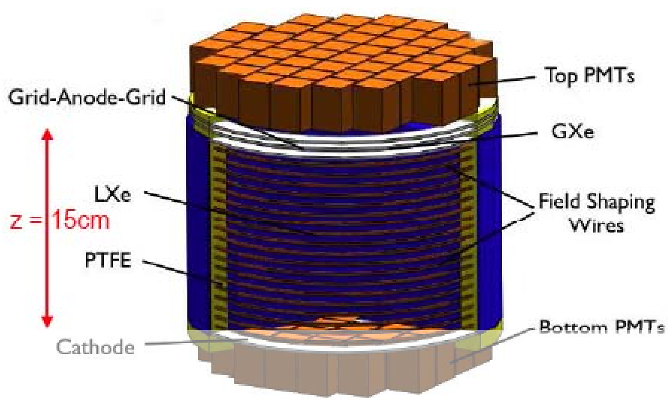


Figure 8: Left: The XENON 10 detector. Right: The ZEPLIN II detector

both arrays of PMTs. A negative high voltage is applied to the cathode at the bottom of the liquid; the anode in the gas phase is near ground potential resulting in an electric field of ~ 1 kV/cm in the liquid. Field shaping wires are arranged to produce a uniform electric field between the cathode and anode. Near the liquid surface there is an electric field sufficient to extract the electrons from the liquid to the gas phase. The electrons are further accelerated to excite the xenon gas and produce the second scintillation pulse (S2). The XENON10 detector has been acquiring data since August 24, 2006. The data have been used to measure backgrounds and to explore background suppression by the S2/S1 parameter and self-shielding. The data confirm earlier studies that the S2/S1 parameter suppresses β/γ events by a factor of $\sim 10^{-2}$. Self-shielding was also explored and demonstrated an additional suppression of $\sim 10^{-3}$ for external β/γ events; the suppression

[12] E. Aprile *et al*., Phys. Rev. Lett. **97**, 081302 (2006).

was achieved with a fiducial volume in which the top boundary is a few mm below the liquid surface and the horizontal boundary is 5 cm from the side of the container. A low threshold corresponding to a recoil energy of 10 keV was achieved and verified in-situ with an Am/Be neutron source. This result is consistent with their earlier small prototypes. The low threshold result is a very significant achievement. It is particularly important for xenon since the sensitivity to WIMP recoils depends strongly on the threshold energy.

Recently, the XENON10 collaboration presented[13] a new limit on coherent scattering of WIMPs. The result is based on 136 kg-days of data following in-situ calibrations and a "blind" analysis. It gives a value at 100 GeV WIMP mass of 5.5×10^{-44} cm^2 including known background. Presently this limit is the best obtained world-wide.

The ZEPLIN II[14] detector was commissioned in the Boulby mine in the U.K. in Fall 2005. Unlike its single-phase predecessor ZEPLIN I[15], ZEPLIN II is a two-phase liquid xenon detector operating with 32 kg total mass of Xe, contained within a tapered vessel made of PTFE. An electric field is applied between stainless steel meshes at the bottom of the basin and below the surface of the liquid; another mesh above the liquid surface provides a field for extraction and multiplication of the drifted electrons. Copper rings encircle the cylindrical body of the vessel for field uniformity. The scintillation light is detected by a single array of seven 5" PMTs located in the gas phase above the liquid. More than 3 photoelectrons per keV of primary (S1) scintillation light are collected, and the secondary scintillation (S2) provides about 250 photons (yielding more than 10 photoelectrons) per ionization electron. The interaction position can be determined using the drift time; however the large PMTs restrict the x-y position resolution to ~5 cm, resulting in a 50% radial cut and a fiducial mass of 8 kg. The detector is shielded by layers of lead, Gd-loaded wax, and polyethylene.

A 40 kg-day trial run took place in early 2006; following that, ZEPLIN II has collected >1200 kg-days of data About 10% of the data have been analyzed in preparation for a "blind" analysis of the total data sample. Calibrations with neutron and gamma sources were performed. The data indicate a level of S2/S1 discrimination between recoil and β/γ events which will yield a dark matter limit from the trial run data set at the level of 1.9×10^{-42} cm^2. The partial data set suggests that sensitivity at around the 10^{-43} cm^2 level will result from the full 1200 kg-day data set, and below that with continued operation of the present detector.

XMASS, a xenon detector under construction in Japan, differs in philosophy by using scintillation only in a single phase system, which allows a simpler design than the two-phase detectors, but leans more heavily on good fiducialization and self-shielding. A 3 kg fiducial mass prototype has been deployed at Kamioka[16], and the next planned upgrade (also for Kamioka) is at the 100 kg fiducial mass stage (XMASS-0.8). The

[13] Invited talks at American Physical Society Meeting by E. Aprile and R. Gaitskell for the XENON10 Collaboration (Jacksonville, FL, April 2007).
[14] G. J. Alner *et al.*, New Astron. Rev. **49**, 259 (2005).
[15] G.J.Alner *et al.* [UK Dark Matter Collaboration], Astropart. Phys. **23**, 444 (2005).
[16] Y. Takeuchi, *In 32nd International Conference on High-Energy Physics (ICHEP 04), Beijing, China, 16-22 Aug 2004.*

detector is submerged in a water tank for shielding against external backgrounds and the background level around the expected dark matter signal is below 10^{-4} /day/kg/keV. The sensitivity of the spin independent search is about 10^{-45}cm^2. There is also a plan to build 10 ton detector (XMASS-24) in the future.

Argon and Neon

Like Xe, both Ar and Ne have discrimination power between nuclear recoils and β/γ by means of the ratio of primary and secondary drifted charge scintillation (S2/S1) when used in a two-phase detector. However, because of the significantly longer lifetimes of their triplet dimers, Ar (1.6μsec) and Ne (20μsec) have an additional or alternate discrimination channel available through use of pulse shape discrimination (PSD). Regardless of technique but differing in detail, most of the noble liquid methods use PMT's and have similar issues related to control of backgrounds such as were outlined in the xenon section (self- and external-shield, position resolution, active veto, depth). Depending on the source, argon may contain varying amounts of the radioactive isotope ^{39}Ar whose effect must be considered in large detectors. There are now four projects making significant progress with argon, two with two-phase and two with single-phase: WARP, ArDM, miniCLEAN and DEAP.

a) Two-Phase Argon: the two-phase detector projects in operation or under construction are WARP and ArDM. Both are located and originated in Europe.

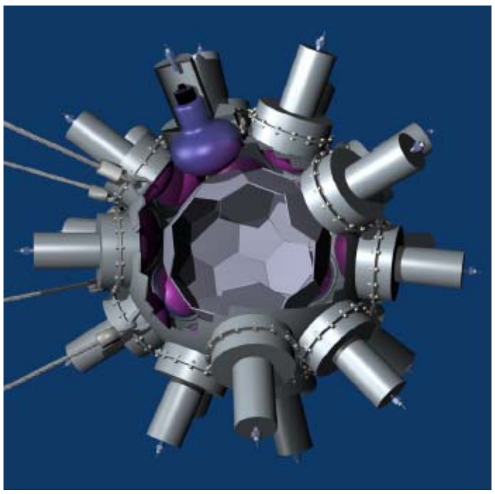
WARP is located in Gran Sasso and has U.S. collaborators participating[17]. The progress made by WARP has been very rapid and successful. Using a 3.2 kg (2.3 liter active) prototype detector viewed from above by 7 PMTs and shielded by Pb and polyethylene, they have accumulated ~110 kg-days of data. Both charge/scintillation and PSD have been employed. A depth resolution of ~1 mm was obtained by timing but the present PMT array did not permit x-y measurement. Following an upgrade of the PSD electronics, the latter 15 kg-days have allowed them to demonstrate the power of combining these two discrimination channels. A preliminary analysis of these data[18] suggests strong evidence for a PSD separation factor of ~10^{-7} and an apparently independent rejection factor of ~5×10^{-3} from S2/S1 scintillation ratio depending upon threshold cuts. Based on the experience gained from this prototype the collaboration has under construction a larger (140 kg) device expected to be capable of reaching a sensitivity of 10^{-45} cm^2 in one year of running. This 140 kg detector is expected to be commissioned in summer 2007. In parallel they are pursuing a number of studies related to establishing confidence in calibrations, background separation and thresholds; results from these studies are expected this year.

ArDM is a pilot project for an even larger two-phase device of one ton[19]. Presently under construction in CERN and Zurich, ArDM will be sited in the Canfranc tunnel laboratory. Differing from WARP, ArDM plans direct multiplication of the electrons drifted into the

[17] N. Ferrari [Warp Collaboration], J. Phys. Conf. Ser. **39**, 111 (2006).
[18] P. Benetti *et al.*, arXiv:astro-ph/0701286.
[19] L. Kaufmann and A. Rubbia, arXiv:hep-ph/0611288.

gas phase rather than by generation of scintillation in that phase. Preliminary testing at CERN is expected to begin in early 2007. There are no U.S. collaborators.

b) Single-Phase Argon or Neon:
Two collaborations, miniCLEAN (U.S.) and DEAP (U.S./Canada) have combined to pursue a single-phase noble liquid system in which argon or neon can be exchanged for the target. The ultimate goal is to achieve, in a phased way, a multi-ton capability with primary emphasis on $>10^9$ pulse shape discrimination for dark matter[20, 21]. In its very largest proposed version, CLEAN with neon, it might be used for low energy solar neutrinos. Relative to the WARP and ArDM two-phase approaches, this single-phase program is still in its early stages; however, these early stages are showing considerable promise.



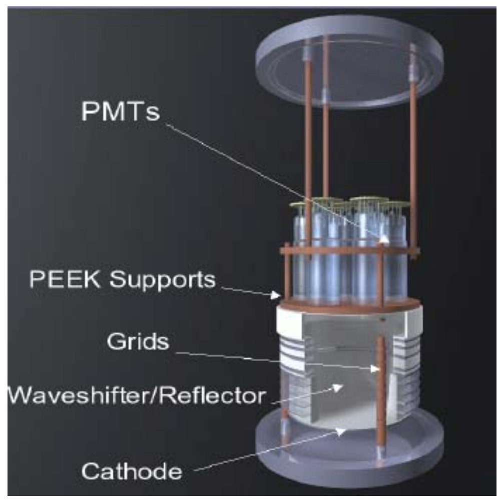


Figure 9: Left: Design of miniCLEAN **Right: WARP 3.2kg version**

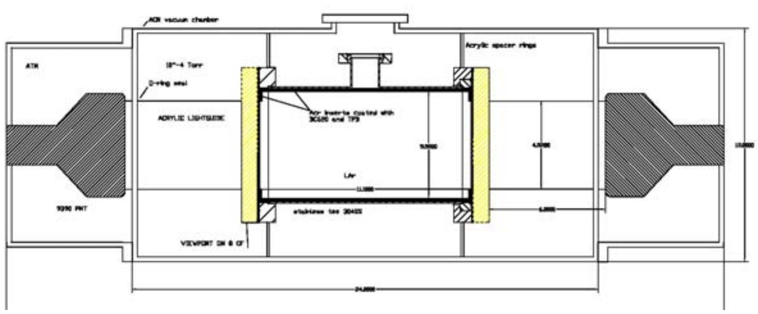


Figure 10: DEAP-I design

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[20] M. G. Boulay and A. Hime, Astropart. Phys. **25**, 179 (2006).
[21] D. N. McKinsey and K. J. Coakley, Astropart. Phys. **22**, 355 (2005).

Initially preparing separate prototypes with either cold (miniCLEAN) or warm (DEAP) phototubes, the two groups have accomplished several goals related to testing the potential for such a single-phase argon/neon device. The miniCLEAN group has been carrying out experiments in two small liquid cell prototypes to measure various scintillation properties of both Ar and Ne in response to incident gammas and neutrons with emphasis on the Ar. These projects are continuing. Studies are also being done on neon purification by charcoal filtering stages or recirculation. The DEAP group has performed simulations (a factor of better than 10^9 discrimination is projected) and prototype experiments directed toward evaluating the limits of the PSD method in Ar. Methods for improving the interior surface cleanliness from radioactive contamination are underway. The initial results are promising but not conclusive partly due to backgrounds caused from being above ground. A second version (DEAP-I; 7 kg of Ar) is preparing to go underground at SNOLAB and is expected winter 2007; if successful it could reach a sensitivity of 10^{-44} cm^2. These initial studies of both groups have so far been funded from institutional resources (such as “start-up” and LDRD funds).

Several next steps are being considered by the merged groups; initially, they have proposed to construct a 100kg detector for R&D and, if successful, to run it to reach a nearly background-free sensitivity of $\sim 10^{-45}$ cm^2 for a 100 GeV WIMP. This version, also called miniCLEAN, is described in a proposal to build and operate at Homestake Interim Lab, SNOLAB or DUSEL a 100kg initially argon-filled device equipped with the possibility of running with liquid neon alternately with argon. They argue that, although the neon WIMP coherent cross-section is a factor five lower than argon, the backgrounds are closely similar and can serve as a test of a positive signal or a confirmation of background understanding. This version of miniCLEAN envisions a spherical geometry in which the liquid is contained within a 25 cm radius quartz “sphere” whose interior surface is coated with wavelength shifter and whose outer surface is viewed by 32 cold, 20 cm photomultipliers through a 12 cm buffer layer of the same liquid. The buffer self-shielding layer is expected to perform an additional role as an active neutron veto. The device is to be contained in a vacuum cryostat and an external water shield is also planned. A significant, new LDRD grant has recently been awarded and other funding requests are pending for this work.

Future plans and issues to be resolved for noble liquids: A significant part of our ability to imagine a near-term comprehensive direct detection program results from the recent rapid progress made in creating operating noble liquid detectors and experiments. Aside from the intrinsic physical properties of the noble liquids, the rapidity in progress is due primarily to the relatively low cost of target materials and construction and to the apparent facility to scale-up quickly to multi-kg masses. (A word of caution: as appreciable multi-kg-scales are approached the requirements for control of neutron backgrounds by making use of increased self- and/or external-shielding may become a significant fraction of their overall cost.)
As a consequence these techniques present us with a somewhat unusual R&D style where each step in the R&D either results quickly in a new limit or reveals a new background to be dealt with. For examples of R&D projects either presently producing limits or soon expecting to do so, we might cite WARP, XENON10, ZEPLIN and DEAP-I. All are

serving to inspire and inform designs for the potential next larger versions. Collectively these projects address different ways of background discrimination in each of the liquids (Ar, Xe, and Ne). This gives us assurances that, as attempts for higher and higher sensitivity are made, direct comparison of effectiveness can occur. As noted for Ar (and Ne): WARP and ArDM have large versions under construction while DEAP and miniCLEAN aspire to larger versions pending success of the presently initiated DEAP-I and miniCLEAN. For xenon, studies of designs and funding proposals for significantly larger, two-phase xenon detectors are already underway by new collaborations formed out of combinations of the present XENON10 and ZEPLIN collaborations together with additional new groups. These are the two new projects referred to as LUX and XENON100.

Of the three noble liquids, the most experience with large volumes (albeit not yet for dark matter direct detection) has been with Ar and the least for Ne. We know from the ICARUS project that it is possible to construct and operate multi-ton volumes of LAr. So if control of other parameters important for dark matter discrimination can be maintained as the scale is increased, then it would appear that containment of several tons of liquid will not be a serious issue.

Among the other important parameters are:

- Calibration: a precise knowledge of the response, over a wide range of energies down to low thresholds, of β/γ and nuclear recoils not only under controlled laboratory conditions but subsequently in a running full scale detector. This must be done if the technique is to be competitive with the CDMS capability or to exceed it. Currently, excellent on-going work is in progress to obtain much of this knowledge.
- A related issue is to obtain as high as possible photo-electron number yield (pe/MeV). This is a goal for all the detectors in order to obtain good discrimination, low threshold control and also for effective fiducialization from inner surface contamination and/or radiation from PMTs, container and shield.
- Very high purity from activity of materials and cleanliness in all handling or construction of detector and shields is needed. Improved methods for reduction of activities particularly on surfaces interior to the detectors are under study.
- Suppressing neutron backgrounds to the low levels needed for the ultimate WIMP search will be challenging. The required suppression of backgrounds from internal and external sources of neutrons will likely require an external neutron detector, a muon detector, and a large passive shield, all of which could add significantly to the cost. A deep site will be beneficial. Techniques for active neutron vetoes are being tested. From the running experiments (WARP and XENON10 as well as in studies for their follow-on proposals) many of these questions will be addressed.
- Additional information on the cleaning procedures for electro-negative and other gases is proceeding. For Xe, Ne and Ar, ^{85}Kr has been successfully reduced by cold charcoal filtering and additional assay procedures are being studied. For the size of the Ar detectors now, or soon to be, under construction ^{39}Ar is not expected to be either a rate or a background problem; however, for much larger masses a study for isotopically purified or a search for geological sources of ^{39}Ar-poor gas is likely to be needed if the combination of data rate and

discrimination cannot be sustained. A funding proposal from the U.S. portion of WARP has been submitted to initiate this search.

As noted, all of these questions are being actively addressed by the community both by present efforts or proposed new R&D on them. Answers to many are expected in the coming year or two. A plan for a Consortium of U.S. scientists is forming to try to address several issues common to the different noble liquid techniques.

The analyzed results from the WARP, XENON10 and ZEPLIN-II experiments are providing an existence proof that the new techniques of scalable noble gas detectors, with reach at least that of CDMS-II, are reaching maturity. For the longer term, we do not yet know which if any of these present techniques will go to one ton or greater; however, the presently envisioned roadmap attempts to directly address that question.

Finding 4: Noble Liquid WIMP Detection
Experimental collaborations using noble liquid technology have made great strides in understanding their techniques and backgrounds. Prototype detectors operating with targets with masses less than 10 kg have recently shown preliminary unpublished results that are comparable to or better than the latest CDMS published results. This rapid development points to the possibility of large and relatively inexpensive detectors. The pace of progress is such that physics discoveries based on CDMS or these new detectors could occur as early as in the next two to five years.
Recommendation 4: Noble Liquid Detectors
We recommend that the R&D required for the next stage of technology development for noble liquid detectors be strongly supported. In some cases, this means that demonstration projects need to be completed, while in others it means that the next-scale detector should be constructed. For the short-term program, the emphasis should be on developing detectors using larger target masses with decreased backgrounds to reach ever-greater sensitivity.

To capitalize on recent impressive results, the sub-panel recommends that a significant fraction of the total funding resources be devoted to noble liquid target experiments, successors of the present WARP, XENON10, and ZEPLIN-II prototypes. However, given the tight funding situation and the large range of new and promising ideas, the sub-panel also believes that it cannot support duplicate development programs in the U.S. using the same target and technique. Therefore

a) The sub-panel supports the development of one two-phase xenon-based detector at the 100 kg scale and above.
b) The sub-panel supports the development of detectors using liquid argon and/or liquid neon technology. WARP and miniCLEAN/DEAP represent two quite different technologies in their application to liquid argon. Both of these techniques should be explored to discover which has greater potential.

2.2.3 Warm Bubble Detectors

Description of technology and current status: The Chicagoland Observatory for Underground Particle Astrophysics (COUPP) approach uses a new operating mode for a fifty-year old technology, the bubble chamber[22]. An energy deposit in a superheated liquid will nucleate boiling if it is sufficiently large and well localized. A COUPP chamber is operated at sufficiently low pressure that it is intrinsically insensitive to electrons, so does not see most forms of radiation. At the same time, a recoiling heavy target nucleus loses all of its energy in less than a micron, corresponding to very high dE/dx. Such a nucleus forms a single bubble above critical size if the energy deposit is greater than a tunable threshold. The bubbles are detected optically.

Large bubble chambers can be built and operated at moderate cost, as shown by long experience with those used in neutrino beams. COUPP chambers are effectively blind to beta and gamma radiation. Most neutron backgrounds can be rejected in a large chamber, and the level of the remaining neutron background should be measurable. Reconstruction of the bubble positions with sub-millimeter precision makes it possible to define a fiducial region that excludes a barrier layer near the wall of the vessel. Finally, the range of target nuclei makes it possible to vary the sensitivity to spin-dependent (see Figure 12) and spin-independent interactions.

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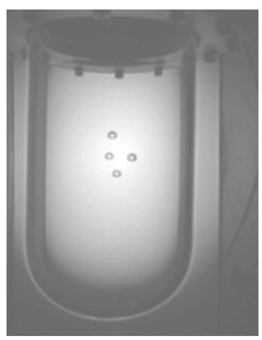

Figure 11: Multiple neutron interactions in COUPP prototype

These detectors have some disadvantages: they are vulnerable to α backgrounds, and one cannot measure the energy deposit of each event in a COUPP chamber, although it is possible to analyze the energy spectrum of the background by taking threshold scans.

Stable operation of a 1-liter COUPP chamber with 2 kg of CF_3I at a depth of 300 mwe has been established in the NuMI tunnel at Fermilab. Excellent γ rejection has been established.

A detector technology which has some features in common with COUPP is that employed by the PICASSO collaboration: this uses superheated droplets of carbofluoride

[22] W. J. Bolte *et al.*, J. Phys. Conf. Ser. **39**, 126 (2006).

target in a gel matrix[23,24]. Nuclear recoils are detected acoustically, and sensitivity is temperature-dependent. PICASSO is planned for SNOLAB; prototypes are at the 2 kg active mass scale, and the plan is to upgrade to 100 kg of active mass.

Future plans and issues to be resolved: The collaboration is now constructing several modules in the range of 20-60 kg. The approach of building several modules in the 50 kg range allows the testing of new ideas and implementing the successful improvements in later modules. The goal of these larger modules would be to reach $3x10^{-4}$ pbarns for spin-dependent interactions (factor 1000 improvement over the present) and 10^{-8} pbarns for spin-independence. A scaling up to the ton scale is envisioned in the long term.

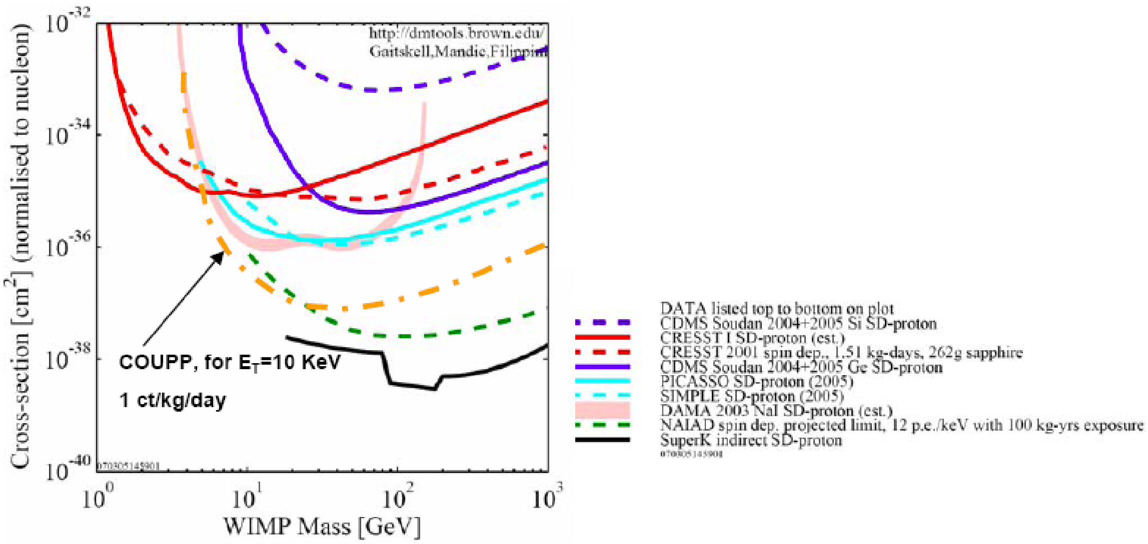

Figure 12 Although much of the DAMA allowed region, interpreted as a spin-dependent interaction, has already been ruled out by CRESST I and Super-Kamiokande, results from future experiments such as COUPP, PICASSO, SuperCDMS, and NAIAD will provide further limits on this observation.

The principal background issue is decays of radon and its products in the vessel and in the bulk liquid; this rate determines the length of live time possible and thus must be significantly reduced. Very low activities from U and Th in the bulk liquid must be established. The ability to tag neutron events at a level sufficient for signal extraction must still be shown. A well planned R&D program has been started combining several avenues to control these sources and progress can be expected in the next few years.

[23] M. Barnabe-Heider *et al.* [PICASSO Collaboration], Phys. Lett. **B 624**, 186 (2005).

[24] J. I. Collar, J. Puibasset, T. A. Girard, D. Limagne, H. S. Miley and G. Waysand, New J. Phys. **2**, 14 (2000).

2.2.4 Direction-Sensitive Detectors

Description of technology and current status: Several collaborations hope to exploit the predicted day/night modulation of a WIMP signal by using a detector with directional sensitivity. This will be a powerful advantage, especially in the case of a plausible WIMP signal and if true directionality ("head-to-tail" of recoil track) can be established.

The DRIFT detector is an example of technology with a Negative Ion Time Projection Chamber (NITPC), which operates at a low pressure (~1/20 - 1/3 atm) and thus extends the range of the recoil nucleus track to a few mm[25]. Electrons are captured by the electro-negative gas and the remaining CS_2 anion drifts in the electric field until it arrives at the read-out plane. The diffusion of the anion is very much reduced relative to that of an electron drift so the fine details of the recoil nucleus track are maintained. A module consists of two back-to-back TPCs sharing a common central cathode plane in a single vacuum vessel.

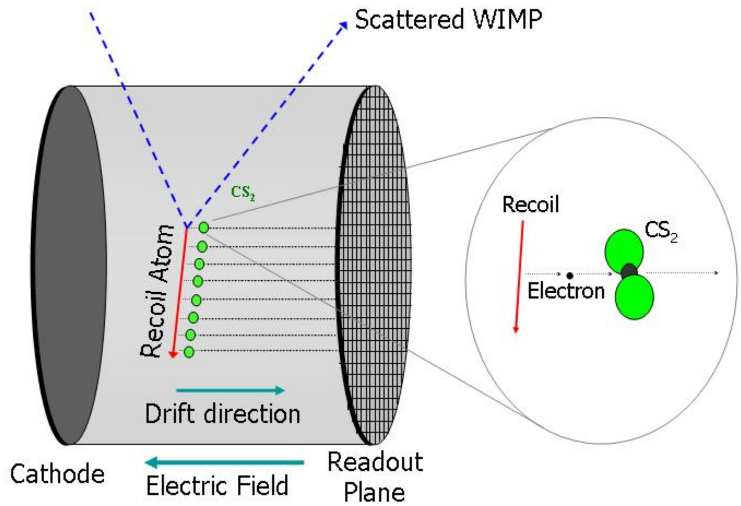

Figure 13: Left: NITPC idea. Right: DRIFT IIa detector.

Multi-wire proportional chambers 50 cm from the central cathode serve as the read-out planes. These employ a 2D readout plus timing to get 3D reconstruction with a spatial resolution of about 25 μm (2 MHz sample rate) in the drift direction and ~2 mm in the lateral plane. The background discrimination is based on excellent dE/dX determination. The target is necessarily low density and thus the experimental apparatus must be quite large to contain a significant target mass. The 1 m^3 DRIFT-IIa module contains less than 0.2 kg of target, but it is claimed that directional sensitivity will make this small mass as sensitive as a non-directional detector which is a factor of ~100 times as massive.

DRIFT-I was operated from 2002-2004 and demonstrated safe, stable, long-term operation underground along with event characterisation/discrimination. DRIFT II is planned to be a three or more detector system, each a NITPC with a 1 m^3 fiducial volume. It has an improved vessel design, improved (3D) track reconstruction (anode, grid and z-

[25] G. J. Alner *et al.*, Nucl. Instrum. Meth. **A 555**, 173 (2005).

drift), low noise and an improved gas system, all for an overall factor of 5 cost reduction per module relative to DRIFT-I. If successful, a single DRIFT-II module (167g target) is projected to have a sensitivity to 10^{-6}pb in one year. The first unshielded module, DRIFT IIa was installed in the Boulby mine (3300 mwe) in May 2005. A second module, DRIFT IIb, was completed in May 2006 and data has been collected continuously since then.

Directionality has not been fully established; to this end two new groups have joined the collaboration to explore alternative read-out methods. One group is exploring the use of GEMs and Micromegas to increase the gain in the read-out plane. This would have the great advantage of increasing the lateral resolution and lowering the energy threshold. These improvements could make it possible to determine the directional sense of the recoil tracks by observing the decrease in dE/dX as the track comes to an end. The second group is coordinating with the DRIFT collaboration and exploring the use of CF_4 as the target gas. The fluorine target would give the detector sensitivity to spin dependent interactions. The electrons that are produced as the recoiling fluorine nucleus moves through the gas are drifted to a wire mesh amplification region where the resultant electron cascade emits scintillation light. This light could be imaged with a CCD camera and the track direction determined.

Another group, independent of DRIFT group, is proposing an entirely new read-out scheme[26]. The concept is to use anode wires and cathode pads. The timing of the signal on the cathode pads provides the projected length of the track; when this is combined with the absolute length of the track given by the total ionization, the 2D features of the track are resolved. The third dimension is given by the TPC timing.

Future plans and issues to be resolved: The central issue for the development of detectors with recoil direction sensitivity is to achieve a full 3-D reconstruction for very short tracks (<2 mm) with ability to distinguish the leading from the trailing end of the track. A second issue, since the likely volume of a sufficiently massive device will be quite large, is shielding from external neutrons in an economical way. Immediate interest for all groups centers on seeking improvements in readouts sufficient for the achieving of full directionality. Among the alternative schemes being worked on involve GEMs, Micromegas[27], combinations of wires and scintillation optics or isochronous cells and time-resolved pads. These are important R&D efforts worthy of active support.

2.2.5 New Techniques

Several programs for novel detector development are in progress. These are all in fairly early stages and do not expect to be operating detectors that provide competitive limits in the short term. Nevertheless they offer some promising features that could be exploited in the long term.

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[26] J. Martoff, *In the Proceedings of International Symposium on Detector Development for Particle, Astroparticle and Synchrotron Radiation Experiments(SNIC 2006), Menlo Park, California, 3-6 Apr 2006, pp 0188.*

[27] I. Giomataris and G. Charpak, I. Giomataris, et al., Nucl. Instr. and Meth. **A 376,** 29 (1996).

Description of technology and current status:

High pressure gases

There are two new projects attempting to use high pressure noble gases at room temperature for WIMP detection: SIGN and HPGS. Although both are somewhat in a conceptual phase, they present interesting contrasting approaches. If successful in R&D, these methods would be candidates for several-ton-scale detectors at quite low cost by replication of a basic unit. Both methods aim for very low thresholds (~2 keV visible).

SIGN proposes very high pressure (100 to 300 bar) gaseous neon contained in cylindrical (50 cm diameter x 5 m length) commercial modules, typically with 100 kg of neon at 100 bar. The $\beta\gamma$ vs. neutron discrimination is primarily based upon prompt and delayed scintillation pulse height differences. Prompt scintillation produces both a PMT signal

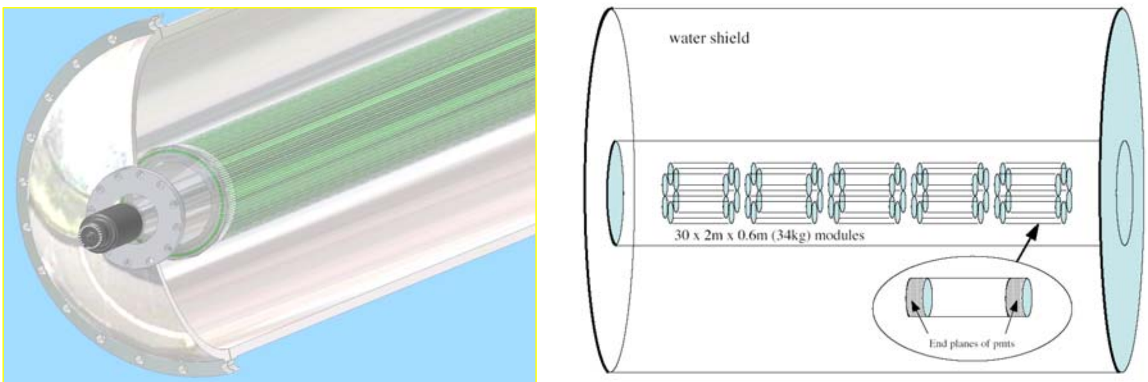

Figure 14: Left: SIGN conceptual design for a single high-pressure module; a photocathode lines the outside of the cylinder, wavelength-shifting fibers are shown in green, and phototubes are installed at the endcaps. Right: the idea foe HPGS: a water shield contains multiple high-pressure cylinders of Xe or Ar.

and photoelectrons produced from a CsI surface lining the cylinder and drifted into a high field region on the axis; secondary scintillation is also produced from drifted ionization charge. Wavelength-shifting fibers along the axis carry light to a single PMT mounted on each end. The preliminary data suggest that some pulse shape discrimination might be possible in addition to that provided by secondary (charge) to primary (scintillation) pulse height ratios.

HPGS proposes 10 bar gaseous xenon also contained within cylindrical modules (60 cm diameter x 2 m length) which typically might contain ~34 kg. The $\beta\gamma$ vs. neutron discrimination would be based entirely upon pulse shape discrimination with arrays of PMTs mounted on either end of the cylinder. Larger cylinders at lower pressure are also considered. Field wires or strips at low field strength are considered near the outer surface to suppress recoils from surface contamination.

Although each group has chosen to emphasize a particular gas, they both emphasize the ability to change the gas target. Initial R&D results carried out on small scale prototypes and some background modeling are quite interesting but we do not yet have have sufficient R&D results for a thorough analysis. A possible weakness is that the discrimination techniques envisioned do not initially appear to have much room for extra handles (e.g., no obvious fiducialization, little or no neutron tagging or veto).

Future plans and issues to be resolved: This is an area which in principle could lead to quite large devices; however the high pressure gas methods are in very early stages. Of the two programs we were presented both are modular and replicable; these features could lead to very large masses at modest cost. The SIGN group has been carrying out experiments in small, high pressure prototypes to test primary and secondary scintillation from β, γ and neutrons in neon and mixtures of neon with 0.5% xenon. The results are interesting but are not yet quantitative enough for a conclusion as to the limit achievable, nor is the level of background to be overcome yet quantified. The HPGS group, not yet at the prototype stage, has conducted an analysis of expected background rates for their approach. Although both high pressure gas detector cases appear feasible, with present knowledge it is too early to identify any specific potential issues other than to indicate that pursuit of further R&D on basic principles using modest prototypes would be appropriate.

In addition to the high pressure gas ideas, another preliminary technique, E-Bubble, was presented to the panel. The technique proposed by this project is to capitalize on these features of an electron trapped in a bubble of liquid helium or neon (e-bubbles) to create a detector with imaging properties for low energy deposits. The principal goal of the project was stated to be for low energy solar neutrinos, but with development it might be suitable for other low energy processes such as direct detection of dark matter. Which criteria would have to be developed for particle ID and discrimination for dark matter signal and backgrounds was not presented in any detail. No potential sensitivities were presented.

Finding 5: Novel Directions in WIMP Detection

In the long term, it will be important that the global dark matter program include experiments and techniques that can incisively explore claimed signals, both to confirm discoveries and to provide additional information. This will require detectors sensitive to both spin-dependent and spin-independent interactions; detectors using different targets with correspondingly different recoil energy spectra; experiments that measure annual and/or diurnal variations of the signal as the Earth-Sun system moves through the galaxy; and detectors sensitive to the momentum direction of the incoming WIMPs. If WIMPs are convincingly observed, future detectors will map the local WIMP velocity and will usher in an era of WIMP astronomy.

In the last few years, there has been significant progress in exploiting low density gas detectors (DRIFT) and detectors based on room temperature bubble chambers (e.g. COUPP). Near-term COUPP upgrades to 50 kg scale prototypes may lead to limits competitive with the newest noble liquid and CDMS limits. Furthermore, a number of new techniques using high density gases also look promising (SIGN and HPGS), which could lead to very large masses at modest cost. Preliminary high pressure gas concepts show interesting potential but studies are not yet quantitative enough for a conclusion as *to the limit achievable or the level of background to be overcome; with present knowledge, pursuit of further R&D on basic principles using modest prototypes is warranted.*

Recommendation 5: Superheated liquids and Directional sensitivity
In addition to the above main lines of development,

a) *The sub-panel recommends the development of superheated liquid detectors. The program proposed by COUPP appears to be well balanced and has recently been approved by the Fermilab PAC.*
b) *On the basis of the performance and background levels presented by the DRIFT collaboration, the sub-panel recommends the development of a single prototype detector module with the principal goal of demonstrating track reconstruction and directionality determination.*

III. Maintaining U. S. Leadership

There are two components to enabling leadership in a U.S. program of direct detection. The first is to provide support for the continuation of the present leading techniques and also for those with very promising new opportunities. The second is to insure that there are appropriate sites and facilities, such as a DUSEL, where these experiments can be carried out. We discuss these in turn in this section and the next.

Until recently, the only U.S.-led programs in the direct detection of dark matter have been the series of elegant experiments of the CDMS-I, II and ADMX groups; the former for WIMP detection and the latter for axions. While ADMX has been essentially a unique effort, the CDMS-series has had strong competition particularly from European groups. Together, CDMS, XENON10 and ADMX have established the most sensitive limits in the world up to the present.

Several developments have converged pointing to the next few years as providing the opportunity not only for discoveries but also for providing an understanding of the nature of particle dark matter. These include: further evidence for the existence of dark matter (e.g., observations of the separation of ordinary and dark matter in the "Bullet" galaxy clusters), the imminent initiation of LHC experimentation and the rapid emergence of new experimental tools for both direct and indirect detection of dark matter.

As we have noted elsewhere, it is these new tools and their capabilities which are a primary concern of this panel. Among these new tools are technical improvements on the now classic CDMS and ADMX methods and the emergence of noble liquid gases (argon, xenon, neon) in various detector configurations, as well as new ideas for use of warm liquids and various gases under high or low pressure. These quite complementary developments offer several things: most importantly they promise an increased reach in sensitivity by at least three orders of magnitude for WIMP's (one order for axions) but also the possibility of recoil particle direction measurement, increased sensitivity to spin-dependent interactions and detector sizes well beyond the ton scale. The complementarity of detector capabilities built into the roadmap includes a range of target types suitable for establishing WIMP signature as well as diverse background control methods (e.g., single phase vs. two-phase in noble liquids; various combinations of multiple signatures).

It is also important to realize that the pace of progress is such that physics discoveries based on these new detector developments could occur as early as the next 2 to 5 years. Many of these new initiatives are U.S.-led or have significant U.S. involvement; therefore, with appropriate investment in these technologies, the U.S. will be able to maintain a strong forefront role in direct detection science.

At this stage, it is difficult to know which of the techniques can best be extrapolated to the tonne-scale detectors which may be necessary. The vibrant competition currently taking place among the various experimental groups is an important and healthy way to quickly and reliably answer the various questions. Once the path is clear, we expect many of the groups may eventually consolidate into international collaborations pursuing two or more of the possible approaches.

There will be a need to site, simultaneously, several different devices in suitable ultra-low background space. Several reasons argue strongly to this: a) the variety of the techniques discussed above, b) the evolutionary nature of detectors (R&D stages through to increasing size experiments) and c) the "Standards of Proof for Dark Matter" (discussed in Sec. V). Additionally, all of the experiments share, to different degrees, needs for support facilities such as low background material fabrication underground, state-of-the-art low background counting facilities and cryogenic or hazardous material safety and containment procedures. Locating a majority of the U.S. program, as well as additional international experiments, in a single DUSEL site providing these superior facilities and program coherence will be a powerful addition to assuring the U.S. direct detection program the forefront role discussed above.

IV. Facilities and Space for the Direct Detection Program

What are the space and facility needs for a direct detection experiment? What do they imply for the program we envision which may well involve several experiments of different sizes over a period of time? We have argued above that a DUSEL would constitute a significant contribution to a forefront U.S. role in direct detection. In what follows we discuss, beginning with the quality of space needed for any single experiment, what a program would require and how it might be affected by constraints on space and facility availability with or without a DUSEL.

In considering the conditions necessary for carrying out a successful direct detection experiment it is important to appreciate that such experiments require extraordinarily low backgrounds and, as the mass (size) of the experiments increase, so does the severity of background control required. This is a requirement shared with other areas of physics such as neutrino-less double beta decay; together they may be considered as setting the ultimate standards of what is achievable. While there can be several types of background (beta decays, gamma conversions, neutrons, alphas), for WIMP detection the most dangerous background is by neutron scatters producing a nuclear recoil identical to a WIMP signal. This imposes severe restrictions for all; however, they may differ depending upon the type of detector employed.

In Appendix A we present in more detail considerations of neutron backgrounds; however, many of the points made there reflect directly upon the quality of space essential to an experiment and so we summarize them here. The sources of neutrons external to the detector are primarily from radioactivity of U and Th in the laboratory/rock walls, from cosmic-ray muon interactions in the surroundings or parts of the detector and radon decays from deposits on adjacent portions of the assembly. These backgrounds must be minimized or eliminated by a combination of strategies involving depth of overburden, passive and active neutron shielding, active muon vetoes and Ra-free atmosphere. Such precautions can add several meters beyond the dimensions of the detector itself in both vertical and lateral extent of the experiment. A large volume water tank surrounding the detector is considered as an inexpensive solution for either a passive or active shield. Implications from some background sources internal to the detector must also be considered as they impact upon construction or assembly of the detector itself underground. As examples, internal detector surfaces must be protected from Ra either by provision of Ra-free air or of an auxiliary and adjacent space where that can occur. Similarly, many experimenters, to reduce the content of cosmogenic and U, Th activity in copper prefer to electroform it underground implying additional and separate space requirements.

Installation, construction or assembly of any detector and its attendant shielding, vetoes and auxiliary apparatus (pumps, cryogenic storage, controls, etc) will require overhead crane access even for the existing <100 kg experiments. 24/7 personnel access to the apparatus, at least in the initial stages of assembly and shakedown, is important.

Cryogenic experiments of any size will need to have oxygen-deficiency apparatus and special safety procedures provided.

To estimate what these special requirements imply for volume of space for an individual experiment there is neither a universal rule-of-thumb nor a “generic” direct detection experiment; however, we do have guidance from existing experiments and some studies for possible future ones. It seems reasonable to take ~100 m^2 x 5m as a “standard” for the near-term and significantly larger volumes for multi-ton or low-density directional devices. R&D prototype installations would require significantly less space but of similar quality.

In the foregoing we have sketched the general space requirements for a “typical” near-term experiment. We have emphasized the importance of the quality and services required for that space. If there were to be more than a single experiment it is clear that several of the service/facility needs are common and could be shared if located at the same underground laboratory; however, they would have to be separately reproduced were they in a different site and not ordinarily provided by that site.

How many such experiments might be expected at a given time? We expect this will be driven by a combination of the rate of detector development, the extent of the reach in sensitivity achieved and, in the event of hoped for break-through, evidence for a detected signal. As evidenced by the discussions presented in Sec. II-2, summarized in Fig. 2 and in the Findings/Recommendations, in the near-term two to three experiments and some smaller R&D installations are to be expected. In the absence of a detected signal in that period it appears reasonable from present knowledge to speculate that the field might converge to much larger single experiments and several R&D installations. As discussed in Sec. V “Standards of Proof”, should a positive detection be presented then it may be expected that as many as three or more major experiments would be in operation; if not simultaneously then closely serially in order to fully exploit the dark matter science. There are clear advantages to locating as many of these experiments and installations as are appropriate into a single laboratory for economy of scale and coherence of the scientific effort over the expected long duration of the program. Although it would not be reasonable to construct a DUSEL solely for a direct detection program, the existence of a DUSEL would be a major opportunity and contribution by providing exactly the quality and quantity of space required for any direction the science of dark matter detection takes in the future.

In the absence of a DUSEL where is there suitable and available space for this program? The sub-panel did not conduct a first-hand survey of world underground facilities suitable for dark matter experiments; however, it depended on several reliable sources of information. These included the excellent S-1 study (Sadoulet et al) of the NSF DUSEL process, the desires for sites expressed by the various proponents of the larger present experiments, as well as considerations for some of the emerging technologies and, of course, the experience of several of the sub-panel members concerning sites and their capabilities. Our report’s Appendix A, which discusses neutron backgrounds, illuminates some of the potential and special considerations for future dark matter experiments that are not always generally available and for which a DUSEL could accommodate ab initio. A careful study of our Fig. 2, the details of those individual experiments and knowledge of the present North American sites make it clear that the existing sites could not handle the entire program either because of capacity or suitability. Further, there are other physics experiments in addition to dark matter which are, and will be, vying for many of the same spaces as dark matter. It seems clear that an integrated dark matter program in a single site satisfying common needs through shared facilities (e.g., low background scanning, cryogenics, special shielding) would serve to provide the US with a program in this leading science activity which is greater than the sum of its parts and, were they scattered world-wide, perhaps thereby stretched out in time.

This sub-panel does not have a specific recommendation for accommodating the direct detection program in the absence of a DUSEL; however, the outlines of some issues and obstacles which will have to be considered are apparent. The outline might be similar, but on a lesser financial scale, to that the agencies faced in agreeing to join CERN on the LHC. To handle the dark matter program, international agreements, among not just one but with several individual countries which possess labs, would have to be negotiated. Such agreements are likely to involve investments if not to expand space then at least to adapt it for the U.S. experiments and to share in expenses for installation, operation and removal. The space question is not just a question of square footage available beneath the surface somewhere but rather really suitable space for a field in transition. All this could no doubt be done over time and with appropriate planning, diplomacy and funds. It is clear, however, that a program compelled to be carried out with such ad hoc siting of experiments will likely result in a diminished set of experiments and on a presently unknowable time schedule.

Finding 9: Relation to Underground Laboratories and other Facilities
A strong program in direct dark matter detection requires a significant amount of underground space and facilities. Although direct detection experiments have made tremendous progress, the field is still in its infancy. Much larger experiments using several different targets and techniques will be necessary to fully understand the expected signal. While other countries have developed a number of underground sites, the total amount of deep experimental space is still far below that which will be required. The U.S. does not currently have an appropriate place to do this work. The proposed DUSEL program to develop a deep underground science and engineering laboratory would remedy this situation.

Recommendation 6: DUSEL
We strongly support the construction of a U.S. Deep Underground Science and Engineering Laboratory (DUSEL), which could host ton-size or greater direct dark matter detection experiments.

Finding 10: Material Scanning Facilities
To construct detectors with the extremely low radioactive contamination that is necessary to observe the rare nuclear recoil events, the construction materials must be carefully scanned and selected. The scanning facilities themselves must be located in a low background underground environment. Such facilities are in scarce supply and the increased experimental activity in this area will make this shortage critical.

Recommendation 7: Scanning Facilities

We recommend additional underground scanning capability to alleviate the impending shortage, increase the sensitivity, and expedite the scanning of materials for the new generations of detectors. Ideally, a comprehensive facility, as described in the DUSEL S1 report, should be located in the DUSEL site.

V. Standards of Proof for Dark Matter

Some descriptions of these new technologies and of the proposals presented to the panel are contained in the Current State of Technology Section II-2 of this report. In what follows we discuss how in combination they can satisfy some standards of proof and consistency for any claims of WIMP dark matter direct detection.

It is compulsory for a program which wishes to establish a signal giving evidence for positive detection of WIMP's that *all* of the detectors meet certain strict criteria. Among these criteria are a full understanding and control of backgrounds, reliable calibrations of energy scales and stable operating performance. We have noted the complementarities of candidates for the U.S. program; *these complementarities are essential*. Assuming all meet our criteria, they can be exploited in a number of ways. Two aspects of a WIMP signature are the dependence of the WIMP interaction cross-section and recoil spectra on the atomic weight (A) of the target and of the rate dependence on expected annual and diurnal periodicities.

We imagine the first response to a statistically significant detection reported from any one of the detectors would require not only confirmation from others with the same reach but, most importantly, the rate dependence and recoil spectral shapes of all must confirm (or in the case of a large spin-dependent cross-section, deviate from) the expected dependence on A^2. The technology in operation or under development has this capability built into it via use of atomic species, for example of Ge, Si, Ne, Ar, Xe and CF_3I. This combination of experiments would provide several essential pieces of information relating to the discovery of a WIMP signature: a measure of the coherent cross-section, its A dependence and, from the spectral shape of the latter, an estimate of the WIMP mass. Additionally, some of these detectors (as well as ones based on molecular compounds) will have sensitivity to test for spin-dependent interactions. Any claims of periodicity could benefit from simultaneous operation of two or more detectors.

Establishing the periodicities is more difficult because of the constraints placed on the detectors. For the annual periodicity the effect on the rate is very small (<2%) and thus requires high statistics and long periods of stable operation. Observation of the diurnal periodicity would appear to somewhat relieve the stability and statistics issues but it imposes the requirement that the direction of the recoil nucleus must be reliably measured. Present detector technologies aiming for directionality have, of necessity, very low mass/volume ratios. While a discovery or a new limit provides a guide as to how massive these directional detectors should be it is already clear that they will require very large volumes. As we have discussed, we do not yet have detectors with this directional capability; however, there are interesting ideas for reaching the directionality goal and they constitute one of the important R&D goals. Seeing these periodicities will be a significant confirmation of the source of any signal as being due to WIMPS, for establishing other WIMP properties and for aiding in measuring properties of the WIMP relic distributions.

To go further in identifying the properties of the dark matter, making the connections with the physics possibly “beyond the standard model” and with cosmology we need to establish the answers to questions such as: Can we identify the WIMP relationship with that of any other new particle discoveries? What is the precise mass(es) of the WIMP(s)? What is its spin? By its direct detection can we map details of the relic WIMP density and velocity distribution?

Here the new knowledge to be gained from the LHC (and eventually the ILC) will provide the other essential ingredients for finding answers to questions such as these. Section VI of this report provides discussion in more detail on the many complementarities between the accelerator and non-accelerator programs.

VI. Theory

1. Overview

In the past decade, breakthroughs in cosmology have transformed our understanding of the Universe. A wide variety of observations now support a unified picture in which the known particles make up only one-fifth of the matter of the Universe, with the remaining four-fifths composed of dark matter [28]. The evidence for dark matter is now overwhelming, and the required amount of dark matter is becoming precisely known.

Despite this progress, the identity of dark matter remains a mystery. Current constraints on dark matter properties show that the bulk of dark matter cannot be any of the known particles. The existence of dark matter is at present one of the strongest pieces of evidence that the current theory of fundamental particles and forces, summarized in the standard model (SM) of particle physics, is incomplete. At the same time, because dark matter is the dominant form of matter in the Universe, an understanding of its properties is essential to determine how galaxies formed and how the Universe evolved. Dark matter therefore plays a central role in both particle physics and cosmology, and the discovery of the identity of dark matter is among the most important goals in science today.

The identity of the dark matter particle (or particles) is an especially intriguing mystery, albeit a mystery whose solution may be close at hand. As discussed below, a variety of evidence now shows that the bulk of dark matter must be non-baryonic, cold or warm, and stable. These simple requirements exclude all SM explanations and have motivated a wealth of proposed candidates with diverse properties. At the same time, the most well-motivated candidates, WIMPs and axions, predict signals that are not far from current experimental sensitivities. Direct detection of these particles would not only be a spectacular achievement, but would also usher in a new era of synergy between particle physics, astro-particle physics, and cosmology.

In this section, we review the evidence for dark matter and its implications for dark matter properties. We then discuss some of the best motivated dark matter candidates. We explain how they might be produced in the early Universe, and present predictions of several compelling scenarios for direct detection rates. Finally, we note that the discovery of remnant dark matter particles via their direct detection would be only the first step in a comprehensive dark matter research program. Additional data from particle colliders and indirect detection will provide strong supplementary information. By combining all such probes, the broad outlines of an answer to the question of what makes up dark matter may well be provided in the near future, after results from the LHC and ILC become available. In addition, such results will usher in a new era in which dark matter signals will not only identify the dominant matter content of the Universe, but also

[28] For a review, see e.g. O. Lahav and A. R. Liddle in *2006 Review of Particle Physics*, W.-M. Yao et al., J.Phys. **G33**, 1 (2006).

may provide information about its density and velocity profiles, as well as information on the past, present and future evolution of the contents of the Universe itself.

2. Evidence for the Existence of Dark Matter

A standard model of cosmology is emerging (often dubbed the *Concordance Model*), in which the universe consists of 4% ordinary baryonic matter, roughly 21% dark matter, and about 75% dark energy, with a tiny abundance of relic neutrinos. The baryonic content is well-known: both from element abundances produced in primordial nucleosynthesis roughly 100 seconds after the Big Bang, and from measurements of anisotropies in the cosmic microwave background (CMB). The evidence for the existence of dark matter is overwhelming, and comes from a wide variety of astrophysical measurements:

2.1 Clusters of galaxies

The first evidence for the existence of dark matter in the Universe was found by the pioneering astronomer Fritz Zwicky in the 1930s. Zwicky noticed that much more matter was needed to gravitationally bind clusters of galaxies together than was provided merely by the visible matter.

2.2 Rotation Curves

In the 1970's, Ford and Rubin first discovered to their surprise that rotation curves of galaxies are flat. The centripetal velocities of objects (stars or gas) orbiting the centers of galaxies, rather than decreasing as a function of the distance from the galactic centers, remain constant out to very large radii. Similar observations of flat rotation curves have now been found for all galaxies studied, including our Milky Way. The simplest explanation is that galaxies contain far more mass than can be explained by the bright stellar objects residing in galactic disks. This mass provides the force to speed up the orbits. To explain the data, galaxies must have enormous dark halos made of unknown "dark matter." Indeed, more than 95% of the mass of galaxies consists of dark matter.

This is illustrated in Figure 15, where the velocity profile of galaxy NGC 6503 is displayed as a function of radial distance from the galactic center. The baryonic matter which accounts for the gas and disk cannot alone explain the galactic rotation curve. However, adding a dark matter halo allows a good fit to data.

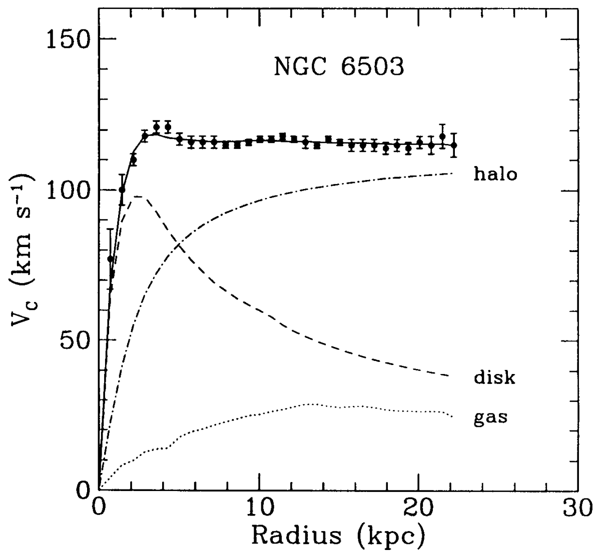

Figure 15: Galactic rotation curve[29] for NGC 6503 showing disk and gas contribution plus the dark matter halo contribution needed to match the data.

2.3 Lensing

Einstein's theory of General Relativity predicts that mass bends, or "lenses" light. This effect can be used to gravitationally ascertain the existence of mass even when it emits no light. Lensing measurements confirm the existence of enormous quantities of dark matter both in galaxies and in clusters of galaxies.

Observations are made of distant bright objects such as galaxies or quasars. As the result of intervening matter, the light from these distant objects is bent towards the regions of large mass. Hence there may be multiple images of the distant objects, or, if these images cannot be individually resolved, the background object may appear brighter. Some of these images may be distorted or sheared. The Sloan Digital Sky Survey used weak lensing (statistical studies of lensed galaxies) to conclude that galaxies, including the Milky Way, are even larger and more massive than previously thought, and require even more dark matter out to great distances. Again, the predominance of dark matter in galaxies is observed.

A beautiful example of a strong lens is shown in Figure 16. The panel on the right shows a computer reconstruction of a foreground cluster inferred by lensing observations made by Tyson et al. using the Hubble Space Telescope. This extremely rich cluster contains many galaxies, indicated by the peaks in the figure. In addition to these galaxies, there is clearly a smooth component, which is the dark matter contained in clusters in between the galaxies.

[29] V. Rubin, A. Waterman, J. Kenney, astro-ph/9904050.

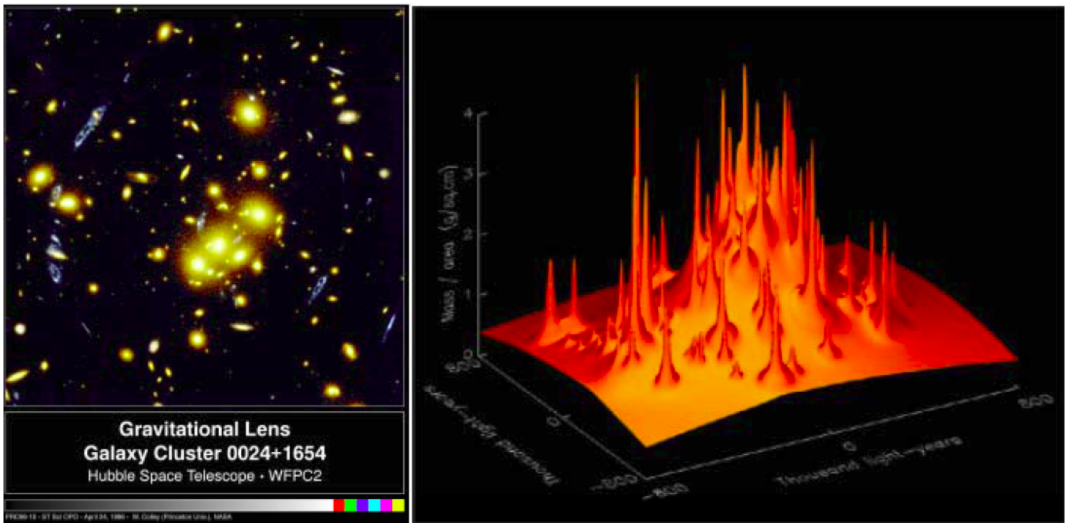

Figure 16: Left: The foreground cluster of galaxies gravitationally lenses the blue background galaxy into multiple images. Right: A parametric inversion of the strength and shape of the lens shows a smooth background component not accounted for by the mass of the luminous objects[30].

2.4 Hot Gas in Clusters

Another piece of gravitational evidence for dark matter is the hot gas in clusters. Figure 17 illustrates the Coma Cluster. The left panel is in the optical, while the right panel is emission in the x-ray (observed by ROSAT). (Note that these two images are not on the same scale.) The X-ray image indicates the presence of hot gas. The existence of this gas in the cluster can only be explained by a large dark matter component that provides the potential well to hold on to the gas.

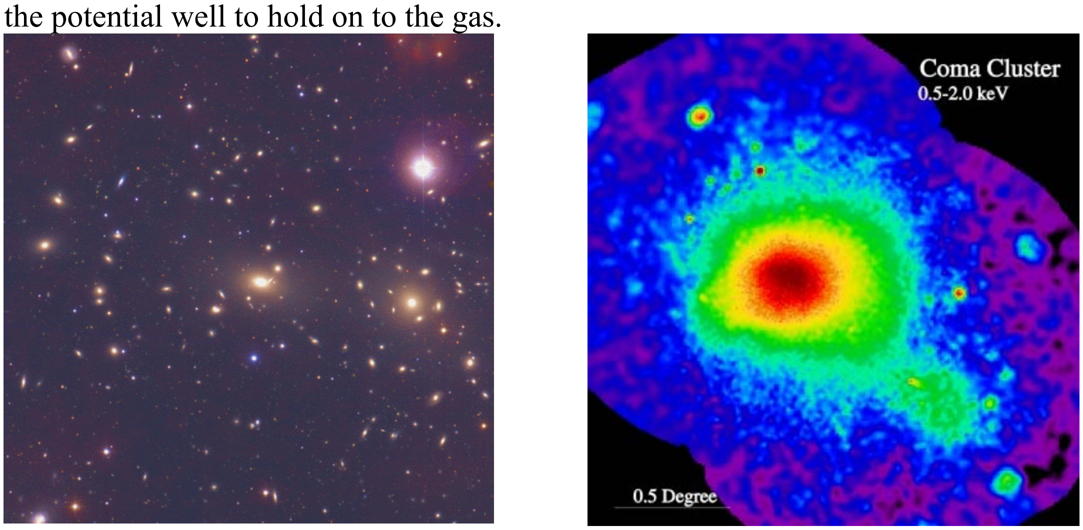

Figure 17: COMA Cluster: without dark matter, the hot gas would evaporate. Left panel: optical image. Right panel: X-ray image from ROSAT satellite[31].

[30] http://www.bell-labs.com/org/physicalsciences/projects/darkmatter/darkmatter1.html

[31] http://heasarc.gsfc.nasa.gov/docs/rosat/gallery/clus_coma.html ; Credit: S.L. Snowden USRA, NASA/GSFC.

2.5 The Cosmic Microwave Background and other Cosmological Measurements

Further evidence for dark matter comes from measurements on cosmological scales of anisotropies in the CMB[32]. This remnant radiation from the hot early days of the universe underwent oscillations that froze in just before it decoupled from the baryonic matter at a redshift of 1000. The angular scale and height of the peaks (and troughs) of these oscillations provide remarkable probes of cosmological parameters, including the total energy density, the baryonic fraction, and the dark matter component. Taken together with measurements of high-redshift supernovae and the large-scale distribution of galaxies, we now have a concordance model of the universe, in which roughly a quarter of its content consists of dark matter. In Figure 18, the allowed regions of dark matter and dark energy density are shown. The three disparate sets of data – CMB, large scale structure and distant supernovae – point to a Universe comprised of ~21% dark matter and ~75% dark energy.

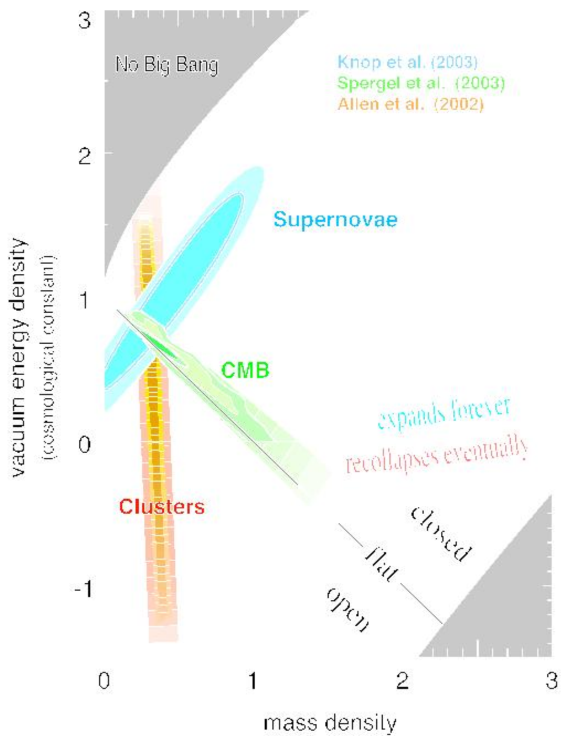

Figure 18: Dark matter and dark energy density allowed regions from measurements on CMB, large scale structure and distant supernovae.

From the above observations, along with computer simulations of the growth of structure in the Universe, it has been inferred that the dark matter must have been non-relativistic at the time of matter-radiation equality: i.e., it is some type of non-baryonic particle which makes up "cold'', or possibly ``warm,'' dark matter.

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[32] D. N. Spergel et al. (WMAP Collaboration), astro-ph/0603449 (2006).

2.6 Alternatives to Dark Matter

Alternative explanations for the flattening of galactic rotation curves have been proposed in which Newton's laws on large scales are modified in lieu of postulating the existence of dark matter[33]. While these theories of modified gravity can explain galactic rotation curves, they typically fail to explain the many additional pieces of evidence for dark matter that exist on a wide variety of length scales. As an example, a recent image (Figure 19) of the bullet cluster of galaxies (a cluster formed out of a collision of two smaller clusters) taken by the Chandra X-ray observatory shows in pink the baryonic matter; in blue is an image of the dark matter, deduced from gravitational lensing. The dark matter has passed through the collision point, while the baryonic matter has slowed due to friction. In modified gravity theories without dark matter, it is not likely that such an effect would take place. While these alternate theories have not been developed to the point where the resultant large scale structure can be computed, it is not likely that the many structures on a variety of scales could be successfully explained in these models. Taken together, the many pieces of evidence, while they do not exclude modified gravity, seem to require the existence of dark matter.

Figure 19: A collision of galactic clusters (the bullet cluster) shows baryonic matter (pink) as separate from dark matter (blue), whose distribution is deduced from gravitational lensing[34].

In summary: *the evidence for the existence of dark matter is overwhelming. The search for more than 95% of the content of galaxies including our Milky Way is an extremely important scientific endeavor*.

[33] Philip D. Mannheim, Prog.Part.Nucl.Phys. **56**, 340 (2006).

[34] http://chandra.harvard.edu/photo/2006/1e0657/ Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

3. Dark Matter Candidates

Although the evidence for dark matter presented in Sec. 2 is overwhelming, the constraints on its microscopic properties are weak. The particle or particles that make up the bulk of dark matter must be non-baryonic, cold or warm, and stable or metastable on 10 Gyr time scales. Such constraints leave open many possibilities, and there are numerous plausible dark matter candidates that have been discussed in the literature. The masses and interaction cross sections of these candidates span many orders of magnitude, as shown in Figure 20. Of the candidate dark matter particles displayed, axions and WIMPs are especially well-motivated from a particle physics perspective.

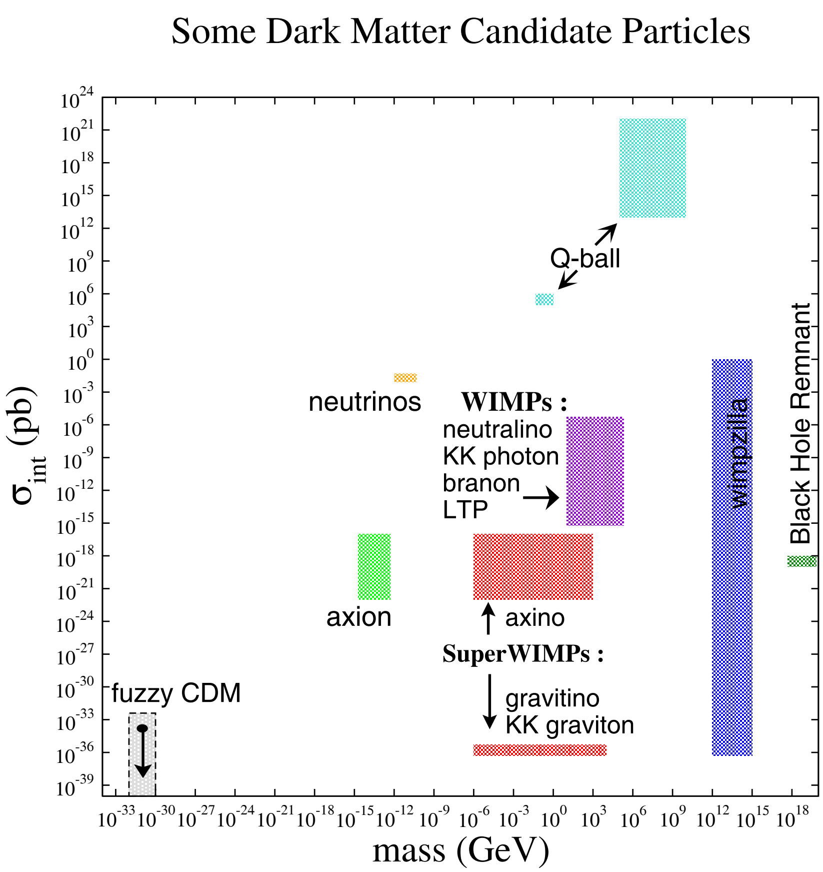

Figure 20: The locus of various dark matter candidate particles on a mass versus interaction cross-section plot[35]

3.1 Axion

The axion[36] is motivated by the strong CP problem, an unnatural property of the SM. The theory of the strong interactions allows a term $\theta/(32\pi^2)G_{\mu\nu}\widetilde{G}^{\mu\nu}$, which is explicitly CP-violating. A priori, one would assume θ to be ~1. However, current bounds from the electric dipole moment of the neutron impose the tight constraint that $\theta < 10^{-10}$. The axion solution to this problem is to make θ a dynamical field, which rolls to a potential

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[34] Figure courtesy of E.-K. Park.

[36] For a review, see e.g. P. Sikivie, astro-ph/0610440 (2006).

minimum that is CP-conserving. The fluctuations in this field are axions. Axions are extremely light and weakly coupled. In a wide class of models, their relic density is $\Omega \sim m^{-7/6}$, with $\Omega \sim 0.1$ for m ~ 0.1-1 μeV, and the induced axion-photon-photon coupling is suppressed by ~ 10^{-15} GeV^{-1} in the mass range of greatest interest.

3.2 WIMPs

Weakly-interacting massive particles (WIMPs) are among the most well-motivated dark matter candidates. WIMPs are particles with mass near the weak scale M_W ~ 100 GeV – 1 TeV. Their parton level interactions with standard matter, as well as their pair annihilation cross sections, are also determined by the same energy scale, and so are of the order of $\alpha^2/M_W^2 \sim 1$ pb. Such particles have several strong motivations. First, new particles at the electroweak scale are independently motivated by attempts to understand the gauge hierarchy of particle physics. Second, these new particles often naturally have all the right properties to be dark matter. Third, these new particles are naturally produced by the Big Bang with cosmological densities of the right order of magnitude required for dark matter. This last property is a remarkable quantitative fact and will be discussed further in Sec. 4.

The prototypical WIMP is the lightest neutralino, a Majorana spin ½ fermion predicted by supersymmetric theories[37]. In supersymmetric models designed to address the gauge hierarchy problem, every SM particle has a superpartner. There are 4 neutral superpartners with spin ½, all with mass ~ M_W: the gaugino superpartners of the U(1) B_μ gauge boson and the SU(2) W_μ^3 gauge boson, and the Higgsino superpartners of the two neutral Higgs bosons required by supersymmetry . These 4 gauge eigenstates mix to form mass eigenstates, the four neutralinos. In many models, the lightest neutralino is the lightest superpartner. Its stability is guaranteed by R-parity, a discrete symmetry posited to avoid too-fast proton decay. The neutralino, then, naturally emerges in these models as an excellent WIMP dark matter candidate. Its properties depend strongly on its mass and its composition, that is, whether it is Bino-like, Wino-like, Higgsino-like, or some mixture. Its interactions also depend on the properties of many other superpartners, which enter virtually in interaction processes. Detailed predictions for neutralino dark matter properties therefore are highly model-dependent.

Although the neutralino is by far the most studied WIMP candidate, there are many other possibilities. In theories with extra spatial dimensions, particles that propagate in the extra dimensions appear in 4 dimensions as Kaluza-Klein (KK) towers, a series of particles with masses ~ n/R, where n = 0, 1, 2, … , and R is the compactification radius of the extra dimension. In a subset of such theories with universal extra dimensions, all SM particles are assumed to propagate in extra dimensions with size $R \sim 1/M_W$. In explicit models, the first excited B_μ gauge boson state, B_μ^1, is the lightest excited state, and its stability is guaranteed by KK-parity, an extra-dimensional analogue of

[37] H. Goldberg, Phys. Rev. Lett. **50**, 1419 (1983) and J. Ellis, J. Hagelin, D. V. Nanopoulos and M. Srednicki, Phys. Lett. **B127**, 233 (1983).

supersymmetry's R-parity. The B^1_μ particle is therefore an excellent WIMP candidate[38], but differs from neutralinos in that it has spin 1, with interesting consequences.

WIMP dark matter candidates also exist in other models with extra spatial dimensions. For example, in models with large extra dimensions, where all SM particles are confined to a 3-dimensional hypersurface, or brane, the brane may fluctuate. These fluctuations, once quantized, correspond to particles, known as branons, and for certain masses and couplings, these particles are also excellent WIMP dark matter candidates[39]. Finally, WIMP candidates exist in models with neither supersymmetry nor extra dimensions. These include, for example, little Higgs models with T-parity, in which the WIMP candidate has spin 0[40].

3.3 SuperWIMPs

SuperWIMPs are proposed dark matter particles with weak scale masses, but with far smaller interaction strengths which are typically of gravitational scale[41]. SuperWIMP dark matter shares many of the virtues of WIMP dark matter. It is present in many of the same particle physics model frameworks, and is also naturally produced with the observed relic density. The prototypical superWIMP is the gravitino, a spin-3/2 particle with mass ~ M_W. Such gravitinos are predicted to exist in the same supersymmetric theories that support neutralino dark matter, that is, in theories with R-parity conservation and supersymmetry breaking mediated by gravitational interactions. If the neutralino is the lightest supersymmetric particle, these theories predict WIMP dark matter; if the gravitino is the lightest supersymmetric particle, they predict superWIMP dark matter.

In gravitino superWIMP scenarios, gravitinos are produced by late-decaying neutralinos, sleptons, or sneutrinos at 10^3 to 10^6 seconds after the Big Bang. Their interactions are, however, suppressed by the ratio of the weak to Planck scales $M_W/M_{Pl} \sim 10^{-16}$. Since these particles are superweakly interacting massive particles, they have been labeled as superWIMPs. Additional interesting superWIMP candidates include spin-1/2 axinos, the supersymmetric partners of axions, or weak-scale KK gravitons (spin-2), which occur in models of universal extra dimensions (UED). SuperWIMPs are impossible to detect in conventional direct and indirect dark matter searches. However, in the case that the particles that decay to superWIMPs are charged, these scenarios predict spectacular long-lived charged particles in collider detectors. They may also have cosmological signatures in structure formation, the CMB, and, possibly, Big Bang nucleosynthesis.

3.4 Exotic Candidates

Finally, there are many other dark matter possibilities, ranging from sterile neutrinos, to primordial black holes[42], to WIMPzillas[43], particles with masses ~ 10^{14} GeV. Typically,

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[38] H.-C. Cheng, J. L. Feng and K. Matchev, Phys. Rev. Lett. **89**, 211301 (2002) and G. Servant and T. Tait, Nucl. Phys. **B650**, 391 (2003).
[39] J. Cembranos, A. Dobado and A. Maroto, Phys. Rev. Lett. **90**, 241301 (2003).
[40] Hsin-Chia Chenh, Ian Low, Phys.Rev. **D70**, 115007 (2004); A. Birkedal, A. Noble, M. Perelstein and A. Spray, Phys. Rev. **D74**, 035002 (2006).
[41] J. Feng, A. Rajaraman and F. Takayama, Phys. Rev. Lett. **91**, 011302 (2003).
[42] P. Chen, New Astron. Rev. **49**, 233 (2005).

these particles are not naturally predicted in attempts to alleviate the strong CP or gauge hierarchy problems of the SM of particle physics, nor are they expected to be produced thermally in the early Universe. However, they do satisfy all current cosmological requirements for dark matter, and therefore remain open possibilities.

In addition, it was proposed years ago that dark matter may be ordinary baryons locked away in planetary objects (Jupiters), brown stars or black holes. Searches for such massive compact halo objects (MACHOs) have been made. A combination of experimental evidence, in particular microlensing data, as well as theoretical arguments, has shown that these baryonic candidates cannot be the predominant matter in the universe[44]. At most, white dwarfs can constitute up to 20% of the dark matter in galactic haloes, if one stretches all the bounds to their limits. Still, a preponderance of nonbaryonic dark matter is required as the dark matter in the universe.

Of course, in many cases, the possibilities discussed above are not mutually exclusive. Although it is currently reasonable to adopt the simple working assumption that dark matter is composed of one single type of particle, there remains the possibility that if the dark matter sector is as rich and varied as the observable universe is, there could be *several* types of dark matter particles contributing significantly to the observed matter density.

4. Dark Matter Relic Density

4.1 The WIMP miracle

WIMPs are, by definition, particles that participate in the weak interactions. Given this simple property, they should have been present in the thermal bath at early times in the Universe's history when temperatures $T >> M_{WIMP}$. Starting with this initial condition, their abundance in the Universe today can be calculated thermodynamically in the hot Big Bang picture[45]. It is a remarkable quantitative fact that their calculated relic abundance turns out to be in rather close accord with the actual measured abundance of cold dark matter in the Universe today provided that their *mass is also at the weak scale!* From a completely model-independent viewpoint, this implies that the weak scale is an especially promising mass scale for dark matter candidates, and experiments that probe the weak scale are required to determine if this possibility is realized in nature. Thus, cosmology alone tells us that there is likely new physics lurking at the weak scale.

4.2 Relic density of a thermal WIMP

If a relic particle's interactions with ordinary matter are strong enough that it is coupled to the thermal bath in the hot, early universe, its number density as a function of time is governed by the Boltzmann equation as formulated for a Friedmann-Robertson-Walker (FRW) universe:

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[43] D. Chung, E. Kolb and A. Riotto, Phys. Rev. Lett. **81**, 4048 (1998).
[44] C. Alcock et al. (MACHO Collaboration), Astrophys. J. **542**, 281 (2000).
[45] For a review, see *The Early Universe*, E. Kolb and M. Turner (Addison-Wesley, 1990).

$$\frac{dn}{dt} = -3Hn - \langle \sigma v_{rel} \rangle \left(n^2 - n_{eq}^2\right) ,$$

where n is the number density, t is time, H is the Hubble constant, n_{eq} is the equilibrium density, and $\langle \sigma v_{rel} \rangle$ is the thermally averaged WIMP annihilation cross section times relative velocity. The first term on the right represents a diminution of number density due to the expansion of the universe, while the second term on the right represents a change due to annihilation and creation of neutralinos in the thermal bath. At early times, the WIMPs are assumed to be in thermal equilibrium, and their distribution is Maxwellian: $n_{eq} = g\left(mT/2\pi\right)^{3/2} \exp\left(-m/T\right)$, where T is temperature, m is the WIMP mass and g is the number of WIMP degrees of freedom (e.g. $g = 2$ for a spin ½ fermion). If the WIMP remained in thermal equilibrium, its number density would decrease exponentially with time. However, at freeze-out temperature $T \sim m/20$, the WIMPs cease to annihilate and drop out of thermal equilibrium. Their number density at the present time is given by integrating the Boltzmann equation from freeze-out to the present time, and is

$$\Omega_\chi h^2 = \frac{mn}{\rho_c} h^2 \sim \frac{0.1 pb}{\langle \sigma v_{rel} \rangle} .$$

The number density as a function of time is displayed in Figure 21, wherein the solid curve indicates the equilibrium density, while the dashed curves indicate the number density after freeze-out, for different values of $\langle \sigma v_{rel} \rangle$.

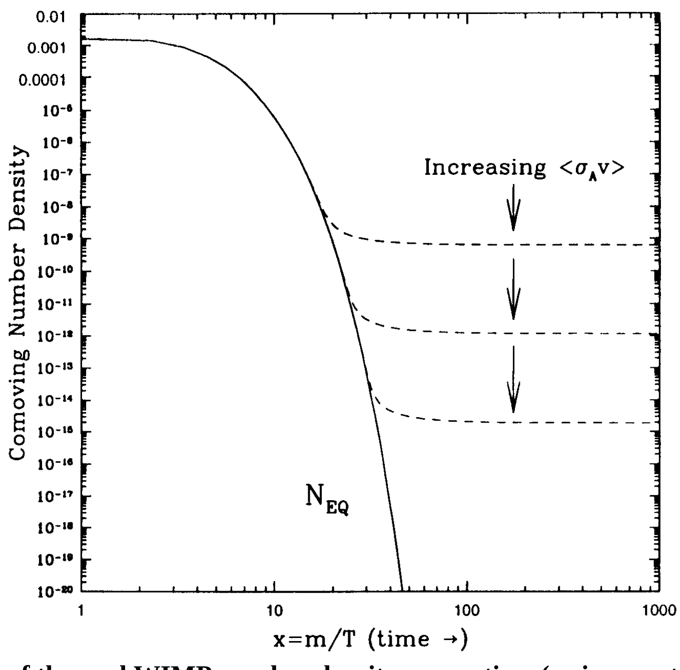

Figure 21: Evolution of thermal WIMP number density versus time (or inverse temperature) in the early Universe[46].

[46] Figure adapted from R. Kolb and M. Turner, *The Early Universe* (Addison-Wesley, 1990).

Thus, an evaluation of the thermally averaged neutralino annihilation cross section is central to the evaluation of the relic density. This may involve the evaluation of many hundreds or thousands of Feynman diagrams. Complicating the procedure is that if other particles with mass slightly greater than m_χ exist, the χ may also annihilate with them, and the so-called co-annihilation processes must also be evaluated.

4.3 Relic density of neutralinos in supersymmetric models

Several publicly available computer codes exist to evaluate the relic density in the case of the neutralino of supersymmetric theories. These include DarkSUSY, Micromegas and IsaReD (a part of Isajet). Thus, given a set of model parameters[47], the relic abundance can be calculated and compared to measured values. If the calculated abundance is greater than the upper bound deduced by the WMAP collaboration, $\Omega_{WIMP}h^2 > 0.122$ at the 2σ level, then the parameter choice is cosmologically disfavored.

As an example, in Figure 22 we show regions of allowed and disfavored relic abundance in the parameter space of the minimal supergravity (mSUGRA) model. The parameter space of the model is given by

$$m_0, m_{1/2}, A_{0,} \tan\beta, sign(\mu),$$

where m_0 is the universal scalar mass, $m_{1/2}$ is the common gaugino mass, A_0 is the universal trilinear coupling, $\tan\beta$ is the weak scale ratio of Higgs vacuum expectation values, and sign(μ) is the sign of the superpotential Higgsino mass term. The first 3 parameters are given at the scale $Q = M_{GUT}$, and the magnitude of μ is determined by the constraint of appropriate electroweak symmetry breaking. The results are for a χ^2 value formed from the neutralino relic abundance, the branching ratio $BF(b \to s\gamma)$ and the muon $g-2$. The χ^2 is everywhere dominated by the relic abundance. The results are plotted in the m_0 vs. $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 54$ and $\mu > 0$. The gray regions are excluded by the requirements that the DM particle not be charged and that electroweak symmetry be broken appropriately. The blue-shaded region gives a chargino mass below LEP2 bounds. Most of the parameter space (the red-shaded region) is excluded by having too high a relic abundance. The allowed regions have neutralino annihilation enhanced by some mechanism, and include

1. The *bulk region* given by the yellow shaded region at low m_0 and low $m_{1/2}$, where neutralino annihilation to lepton pairs is enhanced by light slepton exchange in the t-channel.
2. The *focus point region* at large m_0 adjacent to the right-most excluded region, where the neutralino develops a significant higgsino component, enhancing its annihilation rate to vector bosons.
3. The *stau co-annihilation region*, the green shaded strip adjacent to the left-most excluded region where neutralinos co-annihilate with light tau sleptons in the early universe.

[47] P. Gondolo, J. Edsjo, hep-ph/9804459.

4. The *A-funnel region*, the triangular band in the left-middle of the plot, where neutralino annihilation to SM particles is enhanced by s-channel resonance annihilation through he pseudoscalar Higgs boson A. (This region only occurs at large values of the parameter $\tan\beta$ in the mSUGRA model.)

The regions below the black contours are potentially accessible to various direct dark matter search experiments.

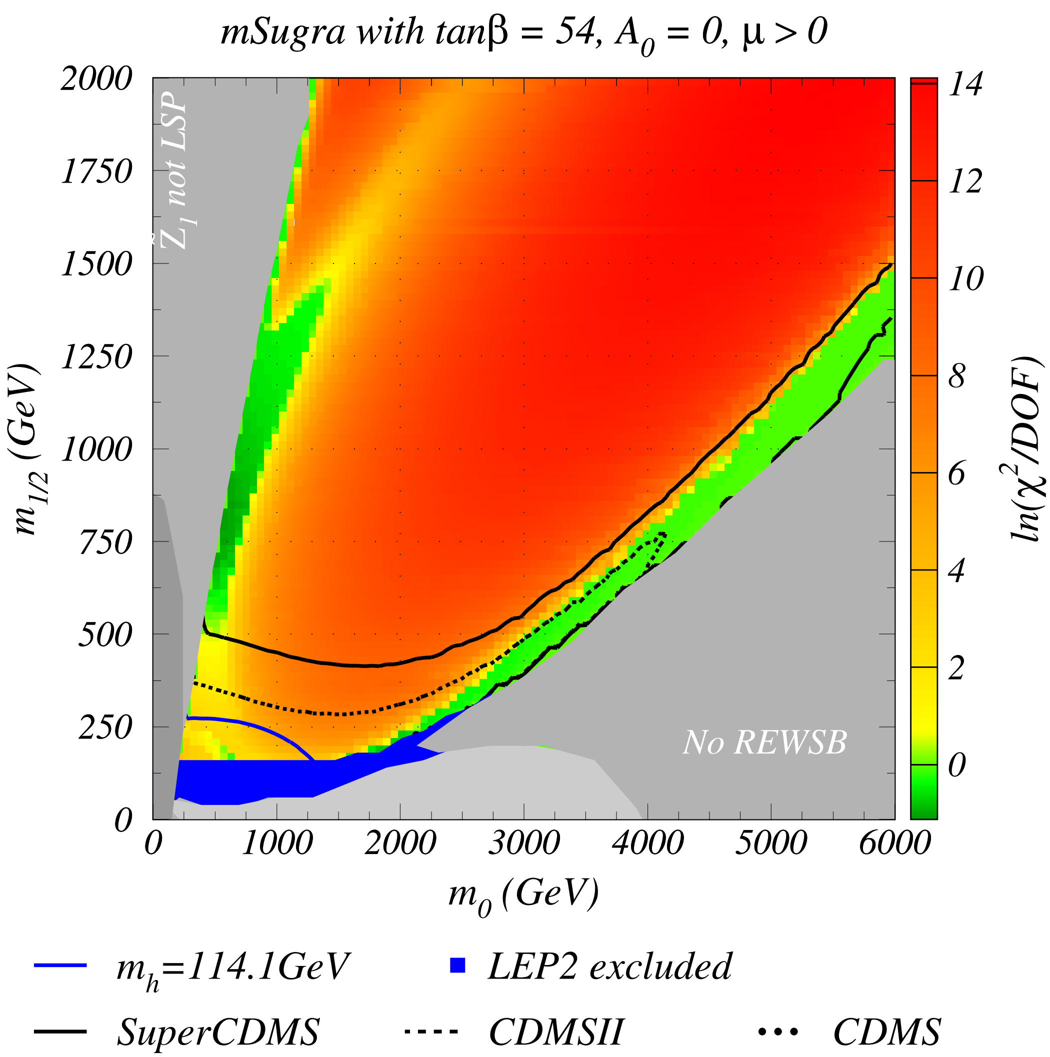

Figure 22: Dark matter allowed and dis-allowed regions[48] of the m_0 vs. $m_{1/2}$ plane of the mSUGRA model for $A_0 = 0$, $\tan\beta = 54$ and $\mu>0$.

While most of the parameter space of the mSUGRA model is excluded in a standard cosmology due to too high a neutralino relic density, it must be pointed out that distinct regions survive and give exactly the right relic abundance of CDM. Each of these regions gives rise to distinct predictions for dark matter detection via direct, indirect and collider searches. Regions with heavy third generation scalars seem favored by constraints from

[48] Figure adapted from H. Baer and C. Balazs, JCAP **0305**, 006 (2003).

b→ γ decay, while a match of theory to data on the muon anomalous magnetic moment seems to favor light second generation scalars. Arguments from naturalness seem to favor models with low values of $m_{1/2}$. However, at this time all CDM allowed regions remain essentially equally viable.

In addition, it is easy to move towards models with more parameter freedom than mSUGRA. For instance, if Higgs soft masses are distinct from matter scalar masses (as seems likely in SUSY GUT models), then any point in m_0 vs. $m_{1/2}$ space can be dark matter allowed by dialing in an appropriate value of μ to give mixed higgsino dark matter or an appropriate value of m_A to yield A funnel annihilation dark matter.

Alternatively, if the SU(3), SU(2) and U(1) gaugino masses (M_3, M_2 and M_1 respectively) are not chosen to unify at M_{GUT}, then relic density constraints can be accommodated by parameter choices which lead to mixed wino dark matter ($M_1 \sim M_2$) or bino-wino co-annihilation dark matter ($M_1 \sim -M_2$), or again mixed higgsino dark matter ($M_3 \ll M_1 \sim M_2$).

4.4 Relic density of a superWIMP

While superWIMPs would likely be too weakly coupled to be an element of the thermal bath in the hot Big Bang universe, they nonetheless may inherit part of the relic density of a thermal WIMP. For instance, in the case of supersymmetry, the neutralino may be produced as usual as a thermal relic. However, if the neutralino decays to a superWIMP such as the gravitino with a rather long lifetime, then the relic density of gravitinos would be simply

$$\Omega_{superWIMP} h^2 = \frac{m_{superWIMP}}{m_{WIMP}} \Omega_{WIMP} h^2 .$$

4.5 Relic density of axions

Axions can be produced in the early universe via four mechanisms: 1. thermal production, 2. production via vacuum re-alignment, 3. production via decays of axionic cosmic strings and 4. production via decays of axion domain walls. Thermal production gives a significant contribution to the mass density of the universe only if $m_{axion} \sim 130h^2$ eV. In this case, the axion lifetime would be shorter than the age of the universe, so that this mechanism is essentially excluded. The second mechanism, production via vacuum re-alignment, is highly non-thermal, and takes place at temperatures $T \sim \Lambda_{QCD} \sim 0.2$ GeV, giving rise to non-relativistic axions, which would form cold dark matter. The relic density from vacuum re-alignment is estimated to be

$$\Omega_{axion} h^2 \sim \frac{1}{2}\left(\frac{6\times 10^{-6}\,eV}{m_a}\right)^{\frac{7}{6}}\left(\frac{0.7}{h}\right)^2 h^2 ,$$

where m_a is the axion mass and h is the scaled Hubble constant with $h \sim 0.7$. Note that if the entire axion relic density comes from the vacuum re-alignment mechanism and is to saturate the WMAP measurement of CDM in the universe, this implies $m_a >\sim 10\,\mu\text{eV}$, which provides an approximate lower bound on the axion mass. Axion domain wall decay is usually thought to be less important than axion string decays. Computer simulations of axionic string decays in the early universe estimate that these sources might yield an axion relic abundance comparable to or even an order of magnitude greater than the abundance due to vacuum re-alignment.

5. Direct detection of WIMPs and axions

5.1 WIMP-nucleon scattering cross sections

The WIMP dark matter hypothesis suggests that the universe is filled with a gas of non-relativistic, weakly interacting massive particles with mass of order $0.1-1$ TeV. An essential test of this hypothesis is to actually detect relic WIMPs left over from the Big Bang. As discussed in this report, a large variety of direct dark matter detection experiments have been deployed or are in the formative or planning stages. The idea behind these experiments is to detect the relatively rare WIMP-nucleus collisions, wherein the WIMP elastically scatters off of nuclei, depositing of order $10-100\,\text{keV}$ of energy[49]. The deposited energy may then be detected via 1. ionization along the path of the recoiling nucleus, 2. phonons resulting from the WIMP-nucleus collision in cryogenic detectors and/or 3. detection of light from excited atoms along the path of the nuclear recoil.

The WIMP-nucleus collision rate can be calculated from fundamental theory, starting with WIMP-quark interactions. For non-relativistic WIMPs, the calculation simplifies considerably, in that many terms of the scattering amplitude turn out to be proportional to the WIMP velocity, and hence may be neglected. One class of non-negligible terms resolves themselves into a WIMP-quark scalar interaction. In the case of supersymmetric models where the WIMP is the lightest neutralino, WIMP-quark scattering takes place via Feynman diagrams involving either squark or Higgs boson exchange. The scalar interaction also receives contributions from WIMP-gluon scattering processes which occur via heavy squark and quark loops; these latter contributions can be large when the quark Yukawa coupling is large, as in the case of the top quark. The WIMP-quark and WIMP-gluon interactions can be recast as WIMP-nucleon interactions, using appropriate nucleon scattering matrix elements. Finally, the WIMP-nucleon interactions can be converted to WIMP-nucleus interactions by convoluting with appropriate nuclear form factors. It should be noted here that the WIMP-nucleon scalar interaction ends up coupling to the *mass* of the nucleus, so that using a heavy nuclear target increases the interaction cross section accordingly: thus, the spin-independent WIMP-nucleon scattering rate is proportional to A^2, where A is the number of nucleons in the target nuclei.

The other important contribution to WIMP-quark scattering comes from axial vector interactions, which resolve themselves into an interaction which couples the WIMP spin to the nucleon spin. In this case, the WIMP-quark interactions have to be convoluted with

[49] For a review, see C. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267**, 195 (1996).

appropriate nuclear *spin* form factors. For many targets in use, the WIMP-nucleus scalar interaction gives more sensitivity than the spin interaction. Exceptions occur in the case of high spin nuclear targets (such as Ge^{73}, which has $J = 9/2$), or in targets with light nuclei, such as the sun itself, where WIMP-hydrogen spin interactions allow the sun to gravitationally capture WIMPs.

Once the WIMP-nucleus scattering cross section is known, detection rates can be computed if the local density and velocity distribution of WIMPs in the galaxy is known. The local density is generally inferred from galactic modeling and rotation curves, but may vary depending perhaps on WIMP clumping or voids. The WIMP velocity distribution is most simply taken to be Maxwellian, but may depend as well on dark matter streams or bulk motion. The velocity of the earth on its path through the galaxy can also affect the relative velocity distribution, and in fact should give rise to seasonal effects depending on whether the earth's motion is aligned or anti-aligned with the motion of the sun about the galactic center. The seasonal effect is calculated to be of the order of ten percent. Indeed, the DAMA experiment has claimed to see a WIMP signal based upon a seasonal variation in their detection rates. There also may be a WIMP detection day-night effect depending again on the earth's relative velocity.

It is traditional now amongst various dark matter detection groups to plot their WIMP detection sensitivity as the WIMP-proton spin-independent scattering cross section as a function of WIMP mass[50]. By de-convoluting the effects of various target materials, such plots allow many different types of experiments to be compared on the same plot.

While most experiments are currently focused first on just detecting a WIMP signal, we note here that once a signal is detected, interest will shift to such questions as
1. the identity of the WIMP candidate, 2. determining the mass of the WIMP, 3. determining the spin of the WIMP and 4. mapping out details of the relic WIMP density and velocity distributions. In this latter capacity, detectors with directional information will be very useful.

5.2 Target detection rates for various supersymmetric models

As an example, we show in Figure 23 a variety of predicted direct detection rates for the lightest neutralino χ of the paradigm mSUGRA model in the m_χ vs. $\sigma(\chi p)$ plane. The model parameter space has been scanned over, and only solutions with $0.094 < \Omega_\chi h^2 < 0.129$ (i.e. consistent with the WMAP1 CDM density measurement) have been plotted. Points in the stau co-annihilation region can have very low direct detection rates, especially when $\mu < 0$, for which destructive interference occurs between various contributions to the scattering processes. However, in the focus point region, where the neutralino is a mixed higgsino-bino state, the direct detection rates are typically in the 10^{-8} pb range, which might be within the capabilities of experiments in the next

[50] See e.g. webpage by R. Gaitskell, V. Mandic and J. Filippini, http://dendera.berkeley.edu/plotter/entryform.html .

several years! We note here that the focus point region of the mSUGRA model is one of the most difficult regions of mSUGRA parameter space for CERN LHC to discover supersymmetry.

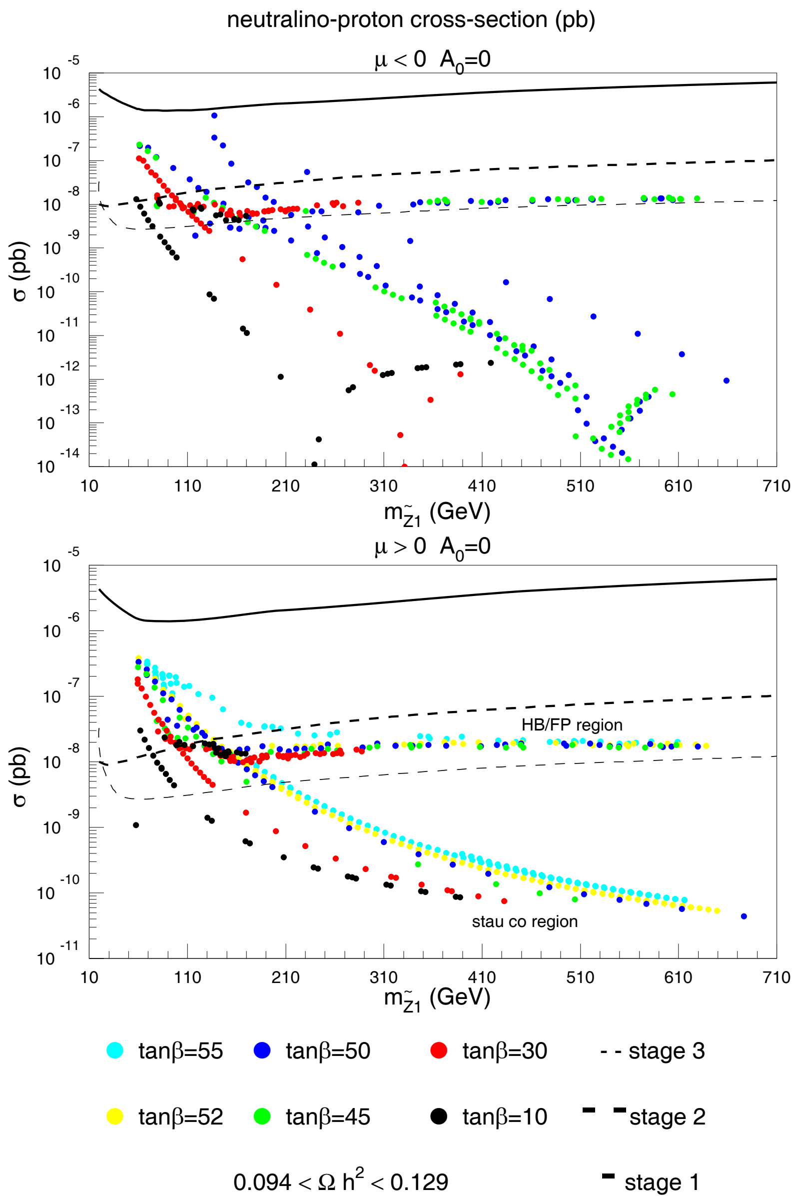

Figure 23: Plot[51] of spin-independent neutralino proton scattering cross-section versus neutralino mass in the mSUGRA model. Only WMAP-allowed points are plotted.

In Figure 24, we show an analogous plot based on GUT scale boundary conditions known as mixed modulus-anomaly mediated SUSY breaking. These models are inspired by the Kachru et al. (KKLT) construction of type IIB superstring models with flux

[51] Figure adapted from H. Baer, C. Balazs, A. Belyaev and J. O'Farrill, JCAP **0309**, 007 (2003).

compactifications. These models stabilize all moduli and lead to a de Sitter vacuum in accord with cosmological observations of a small positive cosmological constant. The theory is characterized by a mass hierarchy $m_{\mathrm{moduli}} >> m_{gravitino} >> m_{SUSY}$, which induces soft SUSY breaking terms with a comparable mixture of moduli-mediated and anomaly-mediated contributions. Models are characterized by whether matter or Higgs fields live on D3 branes, D7 branes or brane intersections, and these are determined by the matter (n_M) and Higgs field (n_H) modular weights, which can be 0, 1 or ½, respectively. A plot of $\sigma($

$\sigma(\chi_1$

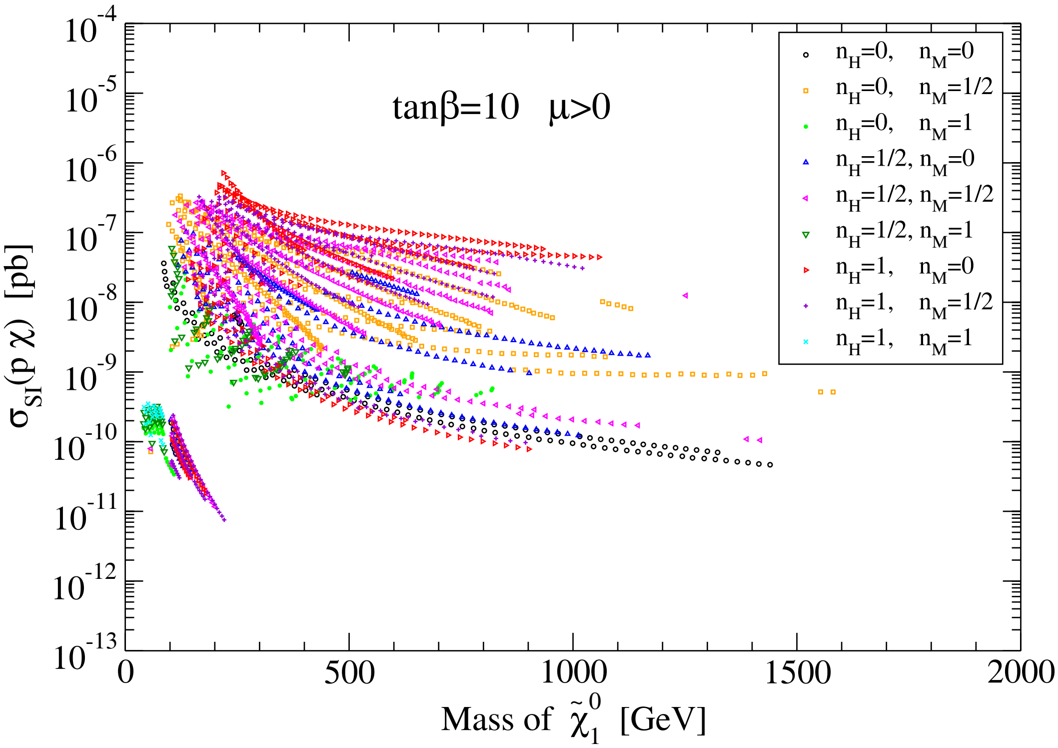

Figure 24: Spin-independent neutralino-proton scattering cross-section versus neutralino mass for mixed modulus-anomaly-mediated SUSY breaking models, with various choices of matter and Higgs field modular weights. Only WMAP allowed points are plotted[52].

5.3 Results from DAMA and spin-dependent direct detection

The DAMA/NaI experiment was located in the Grand Sasso laboratory, and used NaI crystals as target nuclei for WIMP direct detection. The strategy was to look for an annual modulation signal in their event rate. In fact, their final results, collected over seven years, did seem to indicate an annual modulation signal which could be characterized by a 40-100 GeV WIMP scattering with a spin-independent cross section of around 10^{-6} pb[53]. This mass and cross section range has since been ruled out by many other direct search experiments, for instance, by the recent CDMS II results.

[52] Figure courtesy of T. Wang

[53] R. Bernabei et al. (DAMA Collaboration), Int. J. Mod. Phys. **D13**, 2127 (2004)

However, we see from Figure 23 that the spin-independent neutralino direct detection cross section can fall to extremely low values in some regions of parameter space, while the spin-dependent cross section remains high.
Savage, Gondolo, and Freese[54] examined whether the annual modulation found by the DAMA dark matter experiment can be explained by WIMPs with spin-dependent (axial vector, SD) couplings of WIMPs to nuclei, in light of null results from other experiments. They considered the general case of coupling to both protons and neutrons. They found CMDS II places one of the strongest bounds on the WIMP-neutron cross-section, and showed that SD WIMP-neutron scattering alone is excluded. SD WIMP-proton scattering alone is allowed only for WIMP masses in the 5-13 GeV range. For the general case of coupling to both protons and neutrons, for WIMP masses above 13 GeV and below 5 GeV, there is no region of parameter space that is compatible with DAMA and all other experiments. The overall result is that, in the range (5-13) GeV, a small acceptable region of parameter space does remain for WIMPS with spin-dependent couplings as explanations of DAMA and in agreement with all other experiments (see Figure 1 in ref. 48 and Figure 12 this report).

5.4 WIMP mass determination

Once a WIMP signal is detected, the era of WIMP astronomy will begin. One of the next steps will be to focus on ascertaining WIMP characteristics, such as its mass. Direct detection experiments do have some sensitivity to WIMP mass via measuring the energy spectrum of the nuclear recoils. The average nuclear recoil energy is given roughly by

$$\langle E_R \rangle \approx \frac{2v^2 m_T}{\left(1 + m_T / m_{wimp}\right)^2}$$

where v is the WIMP velocity, m_T is the target nuclei mass and m_{wimp} is the WIMP mass. The average recoil energy is plotted versus WIMP mass in Figure 25 for several different target nuclei.

The value of $\langle E_R \rangle$ increases rapidly for WIMPs in the mass range of 10-100 GeV, so here mass measurements will have their best sensitivity. For higher mass WIMPs, the recoil spectra changes slowly, and so mass measurements are correspondingly more difficult.

A study has been performed by the CDMS group of Schnee et al. on how well the WIMP mass can be measured with various data sets and target nuclei. A variety of difficulties can arise in such an analysis that can affect the final result. These include knowledge of the local WIMP velocity distribution, the presence of various isotopes in the target medium, experimental energy resolution and backgrounds and annual[55] and diurnal modulation of the WIMP profile, plus the possibility of dark matter streams or other

[54] C. Savage, P. Gondolo and K. Freese, Phys. Rev. **D70**, 123513 (2004).
[55] A.K. Drukier, K. Freese, D.N. Spergel, Phys. Rev. **D33,** 3495 (1986); K. Freese, J. A. Frieman, A. Gould, Phys. Rev. **D37**, 3388 (1988).

irregularities. Nonetheless, assuming these can be controlled at some level, an analysis

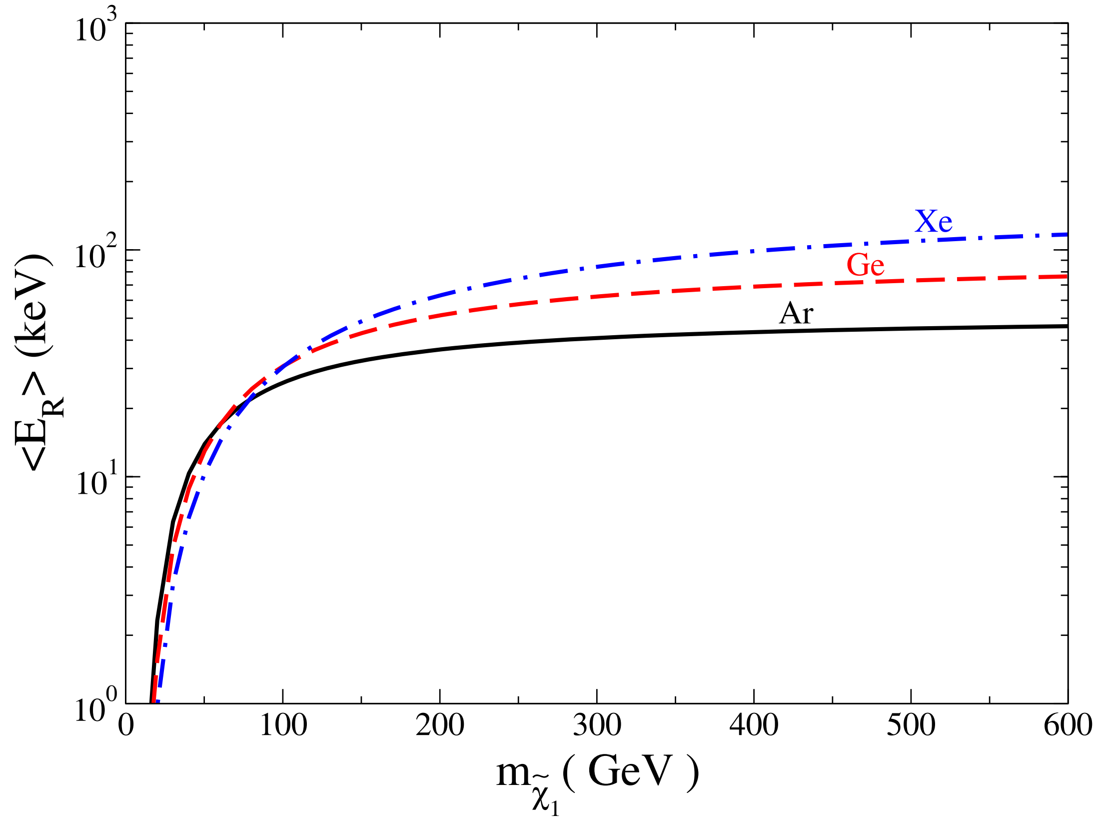

Figure 25: Average nuclear recoil energy versus WIMP mass for several choices of target nuclei[56].

has been performed by the CDMS group, with results shown in Figure 26 under the assumption that the mass determination is dominated by statistical uncertainties. Here, it can be seen that, with a data set including 100 signal events, a WIMP mass determination is possible to $\sim 10-20\%$ for a 60 GeV WIMP, while the uncertainty is much greater for more massive WIMPs, and in particular no upper bound on the WIMP mass can be achieved for a 250 GeV WIMP. Of course, with higher statistics, the mass measurements can be made correspondingly more precise.

[56] Figure courtesy of E-K. Park.

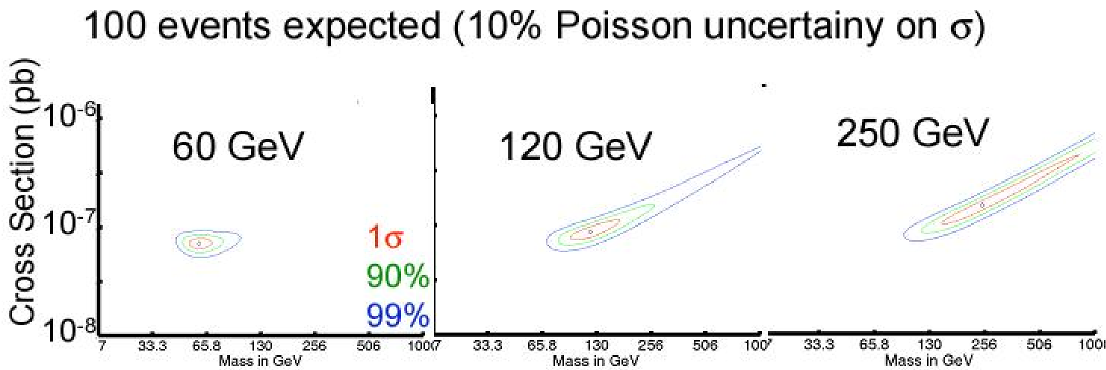

Figure 26: Error ellipses in the cross-section versus WIMP mass plane from an assumed signal of 100 events, for three different WIMP masses[57].

5.5 Direct detection of axion dark matter

Axion interactions with SM particles are extremely weak, but still non-negligible. Of particular importance for direct detection of axions is the axion-photon-photon coupling which has the form $L_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{a(x)}{f_a} \vec{E} \cdot \vec{B}$, where α is the fine structure constant, f_a is the axion decay constant, related to its mass via $m_a \cong 6eV \frac{10^6 GeV}{f_a}$, and g_γ is a model dependent co-efficient of order 1: it takes values of $g_\gamma = 0.36$ in the Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) model, and $g_\gamma = -0.97$ in the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model. Also, $a(x)$ is the axion field, and $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields.

In a static magnetic field, there is thus a small probability for halo axions to be converted by virtual photons into a real microwave photon via the Primakov effect. The energy spread of the halo axions would lead to a faint monochromatic signal with line width $\frac{\Delta E}{E} \sim 10^{-6}$. Thus, a microwave cavity such as in the ADMX experiment with a magnetic field and high Q value can search for halo axion conversion to real photons with energy nearly equal to the axion mass.

6. Distribution of dark matter in the galaxy

The local density of dark matter in our galaxy is measured to be around $0.1 - 0.7\,\mathrm{GeV/cm^3}$ from measurements of stellar velocities about the galactic center.
While the local dark matter density is relatively well-known, the halo density near the galactic center is rather poorly known. The situation is illustrated in Figure 27Figure 27 where we show several models of the halo density profile vs. distance from the galactic center.

[57] Figure courtesy of R. Schnee.

The location of Earth lies at about 8.5 kpc from the galactic center.

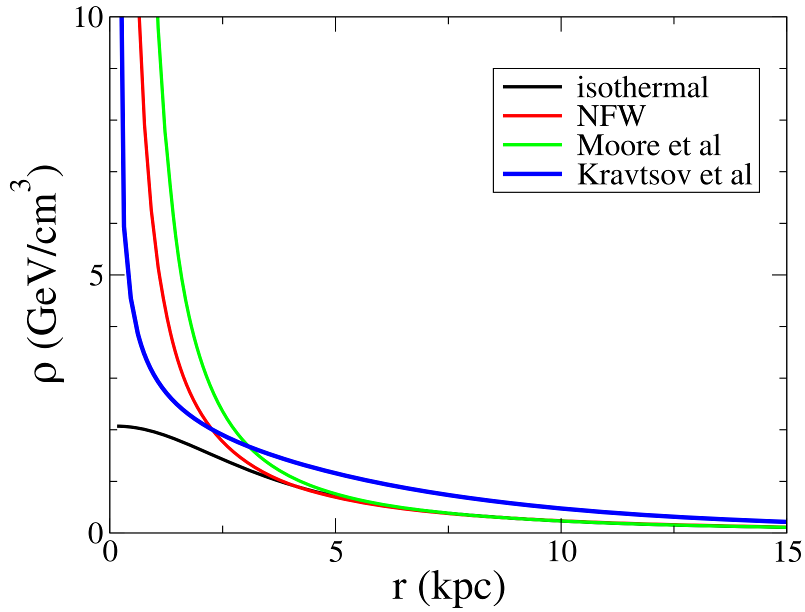

Figure 27: Various model predictions for the dark matter density profile of the Milky Way galaxy.

Predictions for WIMP direct detection experiments are often computed with the simplifying assumption that our galactic halo can be treated as a standard isothermal sphere. However, observations and numerical simulations indicate that this assumption is too crude. In fact, galaxy halos appear to be triaxial and anisotropic, and in addition contain substructure. These modifications to the halo distribution may affect detection strategies.

The differential elastic scattering rate depends on the local WIMP density ρ_χ and the normalized speed distribution in the frame of the detector, f_v, as $dR/dE \sim \rho_\chi \int_{v_{\min}}^{\infty} \frac{f_v}{v} dv$, where $v_{\min}$ is the minimum WIMP velocity which can kinematically produce a nuclear recoil of energy E. Typical analyses assume an isotropic Maxwellian distribution for the halo WIMPS, $f_v \sim \exp(-3v^2/2\sigma_v^2)$, characterized by a velocity dispersion σ_v. However, observations of galaxies, as well as numerical simulations in which galaxies form by mergers of substructures, indicate anisotropic triaxial halos. Figure 28 shows the speed distributions for the standard halo model as well as that from an anisotropic model by Osipkov and Merritt where β is the anisotropy parameter. Other groups have considered the effect of non-spherical halos on exclusion limits in existing detectors, which depend on time-averaged speed distribution, and found that they vary by of order tens of percent. However, future experiments with better energy resolution may be more sensitive to the difference. In addition, the annual modulation signal is far more sensitive to the WIMP velocity distribution, so that experiments (such as DAMA) which rely on the annual modulation signal may find an increase in the size of the $m_\chi - \sigma$ parameter space when “non-standard” models are taken into account. The phase and shape of the annual modulation may also change.

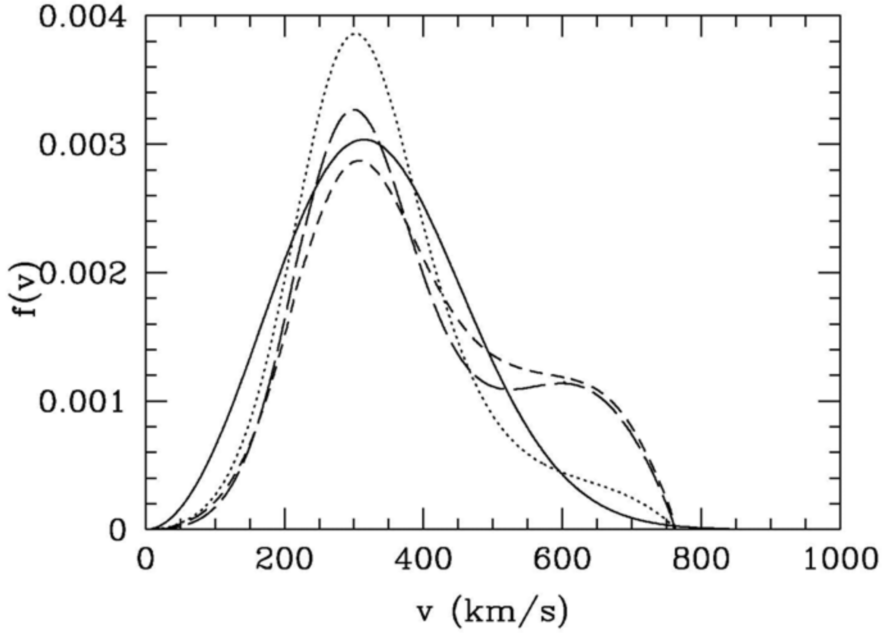

Figure 28: The speed distributions for the standard halo model (solid line), and the OM anisotropy model with b=0.13, 0.31 and 0.4 (dotted, short-dashed and long-dashed, respectively)[58].

Another important effect is due to the fact that galaxy formation is a continual process, with new material still being accreted through mergers of smaller structures. The result is that the halo can contain a non-trivial amount of substructure such as clumps and tidal streams of material. The presence of such substructure is supported by N-body simulations of galaxy formation. Unlike the virialized component of the halo, a clump or stream of material would result in a ``cold'' flow of WIMPs through a detector: the velocity dispersion is small relative to the typical speed with respect to the Earth, so that the WIMPs are incident from nearly the same direction and with nearly the same speed. Alternative models of halo formation, such as the late-infall model recently examined by Sikivie and others also predict cold flows of dark matter.

An illustrative example is the Sagittarius stream. On the other side of the Galactic Center is a dwarf galaxy named Sagittarius which is currently being shredded apart by the Milky Way. There are two tidal streams of material being pulled out of the Sagittarius Galaxy, one of them streaming towards the Solar System (a stream of stars is seen within a few kpc of the Sun). Though the contribution to the local dark matter density is likely to be small, perhaps a few percent increase over the standard halo component, it can still have observable effects in detectors. As shown in Figure 29, there is an increased count rate in the energy recoil spectrum at energies above a cutoff energy E_c; some experiments might be able to find this cutoff. In particular, the location of the cutoff moves with the time of year, with a modulation different from the annual modulation of the overall signal.

[58] Figure courtesy of A. Green.

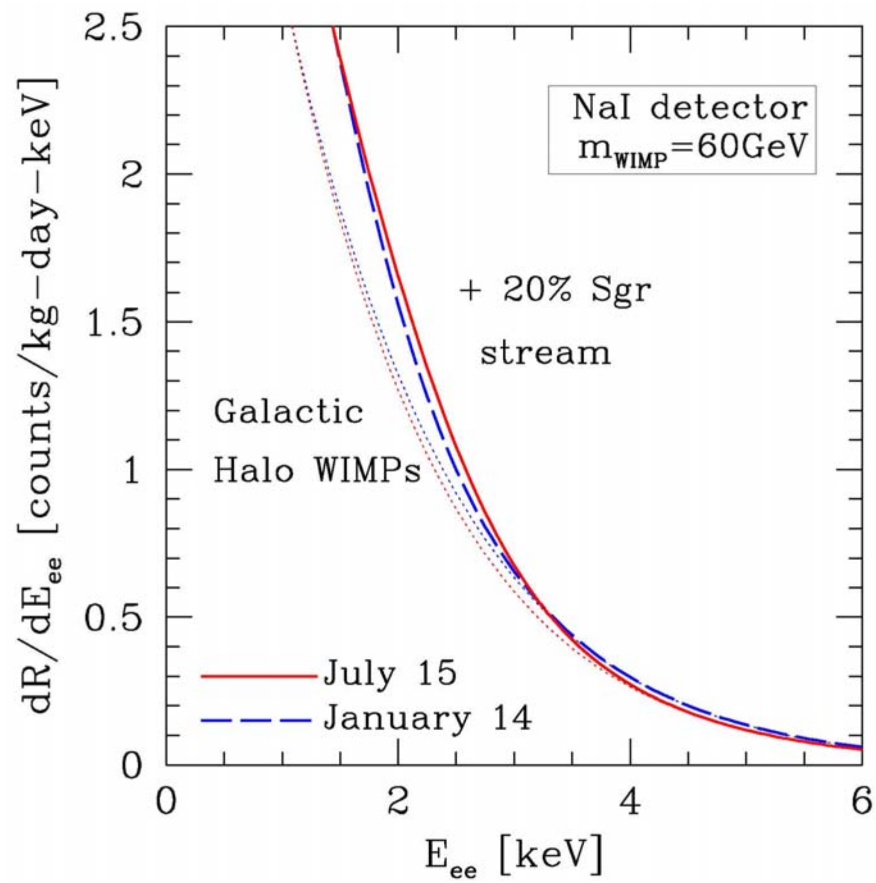

Figure 29: Count rate of 60 GeV WIMPs in a NaI detector such as DAMA vs. recoil energy. The dotted lines show the count rate from galactic (isothermal) halo WIMPs alone. The solid and dashed lines show the step in count rate if one includes the Sgr stream WIMPs. The plot assumes that the stream contributes an additional 20% of the local galactic halo density and comes from our reference direction. The solid and dashed lines are for July 15 and January 14, respectively, the dates of maximum and minimum count rate for the stream[59].

Any such streaming of WIMPs will yield a significantly different modulation effect than that due to a smooth halo. A stream actually provides two types of modulation: a modulation in the overall signal and a modulation in some cutoff energy above which counts due to the stream are not observed. Together, these two types of modulation can yield a ``smoking gun'' for WIMPs. Savage, Freese, and Gondolo examined how various parameters describing a stream affect the modulation signal, and showed that even for a small stream density of a few percent that of the isothermal Halo, the stream can have significant effects on the annual modulation.

In summary the Milky Way is a more complex object than previously thought, and has formed out of mergers of smaller objects. Consequently anisotropy, triaxiality, and substructures such as streams must be considered when computing detection rates in WIMP detectors or analyzing data.

[59] Figure from K. Freese et al., Phys. Rev. Lett. **92**, 111301 (2004).

7. Indirect detection of WIMP dark matter

7.1 Neutrino Telescopes

If a gas of WIMPs forms a galactic halo, then it might be possible to detect WIMPs by a variety of indirect methods. One method is through WIMP annihilation in the center of the sun[60] or earth[61]. As WIMPs pass through the Sun or Earth, they occasionally scatter off of nuclei in these objects and lose enough energy to be captured in the core. In the case of the Sun, WIMPs scatter from hydrogen and helium nuclei and lose energy, thus becoming gravitationally bound to the sun. The WIMPs may then collect in the solar core at a high density, and thus pair annihilate into SM particles. Most of the SM particles will be absorbed by material in the solar core. However, high energy neutrinos from direct WIMP annihilation, or from the decays of heavy quarks, leptons or vector bosons that have been produced in WIMP annihilation, will escape the solar core. These neutrinos will typically have many GeV of energy, and so energetically are quite distinct from solar neutrinos. The same process may happen in the Earth.

Neutrino telescopes that are operating or under construction may be able to detect these high energy neutrinos emanating from dark matter annihilations in the core of the Earth or the Sun. For instance, inspired by the successful construction of the Amanda neutrino telescope at the South Pole, IceCube, a neutrino telescope with 1 km^3 of volume is now being constructed. Muon neutrinos coming from space may convert to muons within the earth, and the muons, as they pass through the south polar ice, will release a characteristic signal of Cerenkov radiation. The array of phototubes sunk deep in the polar ice can detect the light signals, and reconstruct the muon path, which at high energies follows roughly along the original neutrino direction. The IceCube experiment expects to be able to see neutrinos with energy threshold $E_\nu > 50-100$ GeV. The Antares neutrino telescope is also being constructed in the Mediterranean Sea, where it will also search for neutrino-to-muon conversions in deep sea water.

If the WIMPs are the neutralinos of supersymmetric theories, then their annihilation rate in the solar core is actually found to depend mainly on their scattering rate with nuclei in the sun (which governs how well the sun can trap the neutralinos), and depends more weakly on the neutralino annihilation rate in the solar core. The neutralino annihilation rate in the solar core is given by

$$\Gamma = \frac{1}{2} C \tanh^2(\sqrt{CA} t_{sun}) \, ,$$

where C is the solar capture rate, A is the total neutralino annihilation rate times relative velocity per unit volume, and t_{sun} is the present age of the sun. For the sun, the age of the solar system exceeds the equilibration time, so $\Gamma \sim C/2$. Thus, the highest rate for neutrino detection via WIMP annihilation in the solar core occurs in regions of model parameter space where the neutralino-nucleus scattering cross section is highest. In the

[60] J. Silk, K. A. Olive, M. Srednicki, Phys.Rev.Lett. **55**, 257 (1985).

[61] K. Freese, Phys.Lett. **B167**, 295 (1986); L. M. Krauss, M. Srednicki, F. Wilczek, Phys.Rev. **D33**, 2079(1986).

case of the mSUGRA model, this occurs in either the bulk annihilation region, or in the focus point region, where the neutralino is a mixed higgsino-bino state.

7.2 Gamma-ray and Cosmic-ray Telescopes

WIMPs may also annihilate with one another to produce SM particles that would lead to signals detectable by high-energy gamma-ray and cosmic-ray instruments. There are a variety of potential astrophysical sources, including the Galactic Center, the Galactic Halo, satellite galaxies, and extragalactic sources.

A specific example is annihilation in the Galactic Halo. WIMP annihilation leads to quarks and gluons, which hadronize to various mesons and baryons. Any $\pi^0 s$ produced will decay via $\pi^0 \to \gamma\gamma$, and the photons can be detected via gamma ray telescopes, either ground-based atmospheric Cerenkov telescopes, such as HESS, MAGIC, or VERITAS, or spaced-based telescopes, such as GLAST. Ordinarily, these γ 's will provide a continuum signal upon a continuum background. Distinctive characteristics occur in that $E_\gamma < m_\chi$, so that given enough signal rate, a cut-off depending on m_χ might be seen. It is also possible to have WIMP-WIMP annihilations directly to gamma ray pairs. Atmospheric-Cherenkov telescopes and GLAST may be sensitive to such line signals.

Since gamma rays may easily propagate through the galaxy, and are not deflected by magnetic fields, they are expected to point back to their source. Thus, a good place to look for dark matter annihilations to gamma rays is in the direction of the galactic center, where a high density of WIMPs is expected to occur. Different models predict significantly different densities of WIMPs at the galactic center. Thus, the predicted signal rates vary by several orders of magnitude. Interestingly, the galactic center is now firmly established as a strong source of VHE gamma rays, having been detected by four different Cherenkov telescopes in the energy range from 100 GeV to 10 TeV. The spatial extent of the detected source is consistent with a point source at the position of SGR A* and a halo contribution. Understanding the origin of the gamma-rays will require additional measurements to pin down the relative contribution of the astrophysical sources to determine if a signal for dark matter annihilations does in fact exist.

WIMPs may also annihilate to particle-antiparticle pairs. Since antiparticles are relatively rare in cosmic ray events, detection of cosmic antimatter above expected rates may signal WIMP annihilation in the galactic halo. The space-based PAMELA experiment, and possibly also AMS aboard the International Space Station, will be able to look for e^+ s and $\overline{p}$ s. The e^+ s would have to originate relatively nearby in the galaxy, since they lose most of their energy during their propagation. The $\overline{p}$ s can propagate to longer distances than e^+ s. Currently the HEAT experiment[62] reports an anomalously high signal of positrons at 10 GeV, though a neutralino explanation of this signal would require a boost

[62] M.A. DuVernois et al., Astrophys.J. **559**, 296 (2001).

factor[63] of at least 30 of the local dark matter density over that predicted by an isothermal sphere. Finally, experiments are underway to detect anti-deuterons via WIMP annihilation to quarks and gluons. The advantage here is that $\overline{D}$s are quite rare in the cosmos, but they can be detected with a high degree of certainty. For instance, the GAPS experiment intends to slow down and then capture cosmic $\overline{D}$ s and detect them via emissions from the exotic atoms they can form. The GAPS experiment can be either space-based, or launched on high altitude balloon missions.

7.3 Relation between direct and indirect dark matter detection

Indirect detection of dark matter offers many new dark matter detection possibilities which are complementary to direct detection. The situation can be illustrated for the case of neutralinos in supersymmetric models. In the mSUGRA model, direct detection of dark matter is largest when squark masses are light (the bulk region) or when scattering via Higgs exchange is enhanced (mixed Higgsino dark matter in the focus point region). These regions are also where DM annihilation to neutrino signals is expected to be largest, since they depend on the WIMP-nucleon scattering rate in the sun. Neutralino halo annihilation signals are expected to occur in regions of parameter space where the neutralino annihilation rate is large. This includes the bulk annihilation region, the focus point region and the A -annihilation funnel. Meanwhile, if co-annihilation is the dominant neutralino annihilation mechanism in the early Universe, then there is not likely to be any enhancement in the direct or indirect dark matter detection rates.

Thus, depending on the various direct and indirect detection signals ultimately seen, one might be able to identify the neutralino annihilation mechanism in the early universe: in co-annihilation regions of parameter space, very low direct and indirect DM detection rates are expected, while in the focus point region, all direct and indirect DM signals are expected to occur at significant rates. Meanwhile, in the A-annihilation funnel, halo annihilation signals can occur at large rates, while direct DM detection and detection via neutrino telescopes is typically expected to be quite low.

The situation is illustrated in Figure 30. Here, we plot for the case of the mSUGRA model the common GUT scale scalar mass m_0 on the x-axis, and the common gaugino mass $m_{1/2}$ on the y-axis. We also take $A_0 = 0$ (the various signal rates typically depend only very weakly on variations in A_0), $\tan\beta = 45$ and $\mu < 0$ with $m_t = 175$ GeV. The red-shaded regions are excluded either by the lack of appropriate EWSB (right-hand side) or by the presence of a charged (stau) LSP (left-hand side).
The yellow-shaded region is already excluded by null searches for supersymmetry carried out at the CERN LEP2 e^+e^- collider. Most of the remaining parameter space shown has a relic density $\Omega_\chi h^2 > 0.129$, and would be excluded by the WMAP determination of the relic abundance of cold dark matter. However, the green shaded regions have $\Omega_\chi h^2 < 0.129$, and so are WMAP allowed. The magenta contour denotes the projected

[63] E. A. Baltz, J. Edsjo , K. Freese , P. Gondolo, Phys.Rev. **D65**, 063511 (2002).

reach of IceCube to indirectly detect DM via neutralino annihilation to neutrinos in the core of the sun. The reach is largest in the focus point region, where the mixed higgsino-bino LSP has a large rate to scatter and be captured by solar material, and also in the bulk region where squarks are light. We also show some projected reach contours for detection of gamma rays by the GLAST experiment with $E_\gamma > 1$ GeV (dark blue contour), and the detection of positrons (turquoise contour) and antiprotons (gray contour) by PAMELA or AMS. These projections depend sensitively on the assumed galactic DM halo profile — in this case, the rather pessimistic DarkSUSY default isothermal profile was used. It is useful to note that the reach of these contours is maximal in the focus point region and also in the A annihilation funnel where the neutralino annihilation cross section is largest.

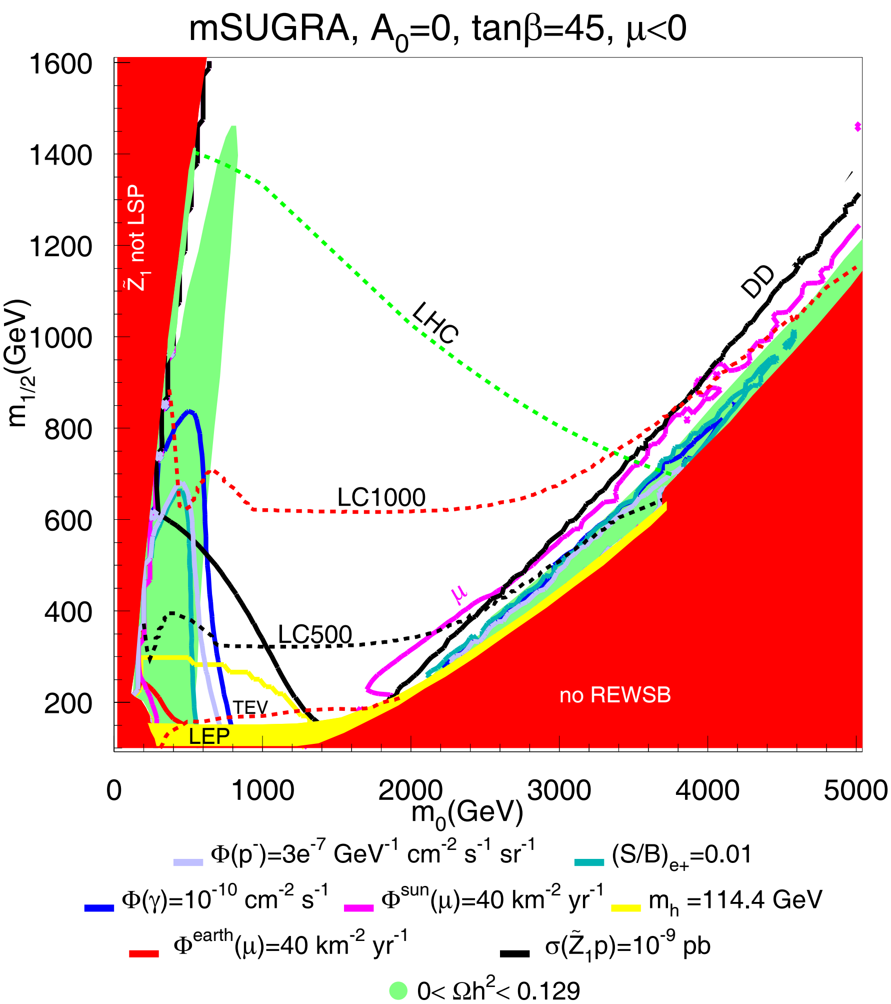

Figure 30: Contours of projected direct, indirect and collider detection of supersymmetric dark matter in the mSUGRA model64. The dark blue contour, for example, is the reach for GLAST.

It is important to realize at this stage that the various indirect detection rates are highly dependent on astrophysical uncertainties. For instance, projections on dark matter

[64] Figure from H. Baer, A.Belyaev, T. Krupovnickas and J. O'Farrill, JCAP **0408**, 005 (2004).

detection rates from neutralino annihilation to gamma rays at the galactic center can vary by several orders of magnitude depending on the assumed halo density profile.
Indeed, already several different and mutually exclusive signal anomalies are seen in cosmic ray data. A direct detection signal for dark matter would help pin down which of these might be due to dark matter annihilations, and which are just astrophysical anomalies. While indirect dark matter detection can yield important complementary information on relic WIMP dark matter, it is no substitute for direct detection.

8. Dark Matter at Colliders

8.1 WIMPs at colliders

If dark matter is indeed composed of WIMPs, then the dark matter particles ought to couple via weak nuclear interactions to ordinary matter. This means not only that direct and indirect detection of dark matter is possible, but also that it may be possible to produce dark matter particles — either directly or via decays of other new matter states – at high energy colliders. In some theories of beyond the SM physics with a DM particle, direct production of DM particles is not noteworthy because the DM production cross section is quite small, and the DM particle escapes unseen from the detector. (An exception occurs in e^+e^- annihilation to DM particles, where the events might be tagged if a hard photon is radiated as well.)

However, in theories such as supersymmetry, universal extra dimensions, and little Higgs models, in addition to the new DM candidate particle, there are additional heavy exotic states that can be produced at colliders, and which decay (usually through a cascade) into the DM particle plus a variety of other SM particles. In these cases, the signal for DM production is the existence of collider events with visible particles, but also with an apparent imbalance of energy-momentum, namely that carried off by the DM particles. For specificity, we will focus on the well-studied case of production of SUSY particles at colliders, with the lightest neutralino acting as the dark matter WIMP candidate.

8.2 SUSY at colliders

In supersymmetric models, it is expected that TeV scale supersymmetric matter should be produced with observable cross sections at colliders like the CERN LHC, a pp collider with $\sqrt{s} = 14$ TeV in the CM system, which is expected to take data starting in 2008. At the LHC, strongly interacting particles like the squarks and gluinos should be produced at large rates, and should subsequently cascade decay to the expected lightest neutralino, plus a variety of quarks, charged leptons and neutrinos. Thus, production of SUSY particles will be characterized by collider events containing multiple jets, multiple isolated and non-isolated leptons and missing transverse energy.

By stipulating a SUSY model along with allowable input parameters, the weak scale sparticle mass spectrum and mixings may be computed, along with the sparticle production cross sections and decay rates. Event generator programs such as Isajet, Pythia and Herwig can then calculate the various collider events expected from supersymmetric models. A comparison of signal rates to expected SM background rates, after suitable signal selection cuts, should allow a determination of whether a signal can be seen above SM background for an assumed value of the collider integrated luminosity.

The calculated reach of the CERN LHC, assuming 100 fb^{-1} of integrated luminosity, is shown in Figure 30. A signal should be discoverable below the green dashed contour marked "LHC". At low m_0, it extends to $m_{1/2} \sim 1400$ GeV (corresponding to $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 3000\,\mathrm{GeV}$), and at large m_0 where squarks and sleptons have masses in the multi-TeV range, it extends to $m_{1/2} \sim 700$ GeV (corresponding to a gluino mass of ~1800 GeV).

For comparison, we also show the reach of a $\sqrt{s} = 500$ and $\sqrt{s} = 1000\,\mathrm{GeV}$ linear e^+e^- collider. The right side of the LC reach plots is largely determined by the kinematic reach for chargino pair production, while the left-side contour is determined by the kinematic reach for slepton pair production. The intermediate bulge gives an extra reach due to $\chi_1^0\chi_2^0$ production. Note that the LC reach extends well up the focus point region. In this case, the superpotential μ parameter becomes small, so charginos become light, and should be accessible to LC searches, even though this class of events is extremely difficult to see at the CERN LHC.

The region below the black contour denotes the spin-independent neutralino-proton scattering cross section of 10^{-9} pb. The reach is substantial when squarks are quite light (the bulk region at low m_0 and low $m_{1/2}$) and also in the focus point region where the χ is a mixed higgsino-bino state with enhanced cross section due to Higgs exchange diagrams. We note especially the region at large m_0 where $\Omega_\chi h^2 < 0.129$ within the WMAP bound where dark matter might be discovered by direct detection experiments even while SUSY particles are too heavy to be detected by the LHC!

8.3 Extracting astrophysical results from collider measurements.

A key feature of collider experiments lies in their ability to provide measurements of important astrophysical quantities based on microscopic physics measurements. This program of study has been investigated in several recent studies, but most comprehensively in the recent work of Baltz et al.[65]. To provide detail, they adopted four case study points in the mSUGRA model, labeled LCC1-4, for investigation. Point 1 was in the bulk annihilation region, point 2 was in the focus point region, point 3 in the stau co-annihilation region and point 4 was in the A-annihilation funnel, with spectra generated by Isajet 7.69. The first step was to assemble for each point a list of projected sparticle mass and scattering cross section measurements plus error bars for the LHC,

[65] E. Baltz, M. Battaglia, M. Peskin and T. Wizansky, Phys. Rev. **D74**, 103521 (2006).

ILC ($\sqrt{s} = 500$ GeV) and ILC ($\sqrt{s} = 1000$ GeV). Next, using a general model of the MSSM with 24 free weak scale parameters (CP violating and flavor changing parameters were ignored), they scanned the 24 dimensional parameter space via a Markov Chain Monte Carlo to try to fit all the so-called ``observables''. Of course, each parameter space point also gave rise to predictions of important astrophysical quantities, including the dark matter relic density, the thermally averaged neutralino annihilation cross section times velocity and the neutralino-proton spin-independent scattering rate. By measuring the goodness-to-fit of the observables, these authors showed that collider experiments could provide a ``measurement'' of these three properties of the dark matter particles.

An example of collider measurement of the neutralino relic density is provided in Figure 31 for point LCC2. In this case, the LHC is found to be able to provide a measurement of $\Omega_\chi h^2$ to ~82%. While the LHC is a rather broad band discovery machine, and is able to make many precision measurements of sparticle mass differences, its ultimate resolution is limited by the well known issue that protons are not fundamental particles, and so the parton-parton initial state is not well known. If sparticle pair production is accessible to the ILC500 machine, then kinematic and threshold measurements allow much more precise measurements of sparticle masses, and beam polarization and event cleanliness allow detailed cross section measurements. The additional information gained by the ILC500 translates into a much more precise collider measurement of the relic density. The collider measurement may then be compared against astrophysical measurements to determine consistency, and to check whether the collider WIMP candidate is really the cosmological dark matter particle, or whether a possibility of ``mixed dark matter'' occurs. The situation improves even more if ILC1000 is used, since typically more sparticles and Higgs bosons are accessible to a higher energy machine. In this case, an ILC1000 measurement of $\Omega_\chi h^2$ is at the 8% level!

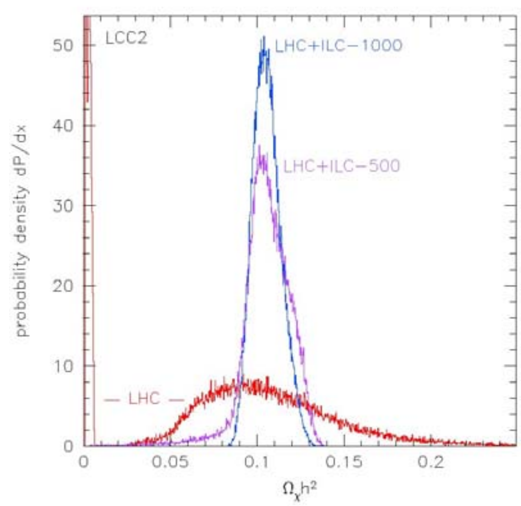

Figure 31: Collider measurements of neutralino relic density (see footnote 26).

In Figure 32, we show the Baltz et al. determination of the neutralino annihilation cross section. It is determined by ILC1000 to an accuracy of 9%. Once this quantity is known from fundamental collider measurements, it can be combined with possible astrophysical indirect DM detection signals, such as neutralino annihilation to gamma rays, to extract information on the galactic distribution of dark matter essentially performing galactic dark matter tomography.

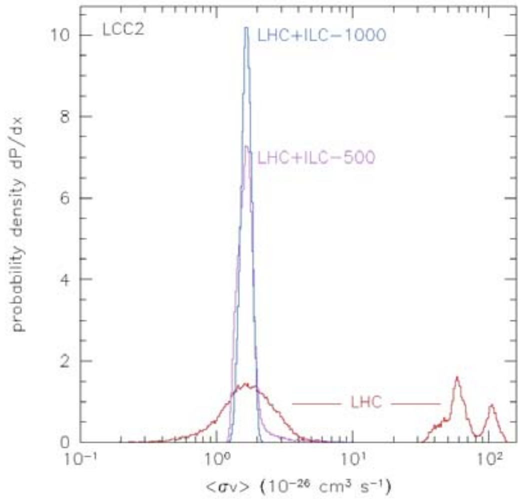

Figure 32: Collider measurements of thermally averaged neutralino annihilation cross section times velocity (see footnote 26).

Finally, in Figure 33 we show the Baltz et al. determination of the neutralino-proton spin-independent scattering cross section. The measurement by ILC500 is to 60% and by ILC1000 to 22%. In this case, the scattering cross section can be compared with the event rate which is measured directly by DM detection experiments. The difference between the two measurements yields the local number flux of dark matter particles- another crucial astrophysical quantity.

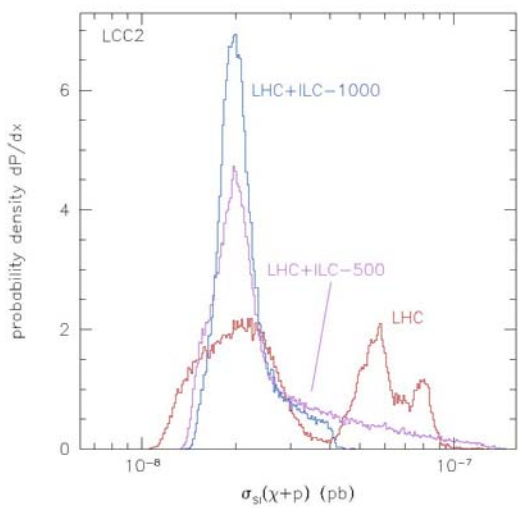

Figure 33: Collider measurements of spin-independent neutralino-nucleon scattering cross section (see footnote 26).

In all these examples, it is clear that the combined efforts of direct DM detection, indirect DM detection, and DM detection at collider experiments is extremely complementary, and provides a variety of different measurements which, when combined, could serve to provide us with a solid portrayal of dark matter in the galaxy and in the Universe.

8.4 SuperWIMPs at Colliders

In the event that the DM in the universe consists of superWIMPs rather than WIMPs, then direct and indirect DM detection experiments will likely give null results. In this case, however, collider searches for DM can still give much information. In the case that the DM particle is a TeV scale gravitino of supersymmetric theories, then sparticles can still be produced at collider experiments, with many signatures similar to those of SUSY theories with neutralino dark matter. In the superWIMP case, however, the lightest MSSM particle (now the next-to-lightest SUSY particle or NLSP) will be unstable, and will likely decay to SM particles plus the gravitino with a lifetime which depends sensitively on the fundamental scale of supersymmetry breaking. If the lifetime is of order $10^{-13} - 10^{-8}$ seconds, then delayed decays resulting in displaced vertices will likely be seen in collider detectors. If the lifetime is even longer, then the NLSP will escape detection, and decay much later outside of the detector. The collider signatures will be similar to those of models with stable neutralinos. The superWIMP scenario also provides the possibility that the NLSP might be charged or colored. In this case, highly ionizing tracks from massive charged or colored exotic particles will be seen at colliders, possibly ending in a decay vertex. In cases such as a metastable tau slepton, scenarios are envisioned where the NLSP can be trapped and collected, for example, in water tanks surrounding the detector[66]. The collected NLSPs can then be monitored to measure their decay lifetime and decay products, yielding important information on the superWIMP identity and the fundamental scale of SUSY breaking.

[66] J. L. Feng and B. Smith, Phys. Rev. **D71**, 015004 (2005) ; K. Hamaguchi, Y. Kuno, T. Nakaya, M. Nojiri, Phys. Rev. **D70**, 115007 (2007).

APPENDIX A – Review of Neutron Backgrounds

The search for dark matter WIMPs by direct detection consists of searching for low energy nuclear recoils that are produced by WIMP-nuclear collisions. The low recoil energy (< 100 keV) and the low rate (1-100 c/ton/yr) are demanding and unprecedented requirements for the detector. Increasing the sensitivity of WIMP searches will require detectors of larger mass and, equally important, lower backgrounds per unit mass. Even with careful selection of low background materials for the internal parts of the detector and careful shielding against external backgrounds, natural sources of radioactivity pose a serious challenge, especially for neutron-induced backgrounds. As one evaluates the long range plan for WIMP searches it is important to recognize that the requirements for improving neutron suppression will drive the size, cost, and complexity of the experiments upward, and could also favor some technologies over others. The purpose of this note is to outline possible strategies that future detectors could employ for reducing the background per unit mass due to neutrons.

To suppress β/γ backgrounds the experiments generally exploit differences in the signal between recoils and β/γ events to separate recoil events from β/γ events. A combination of external shielding and "self-shielding" is also employed to suppress gamma rays. Self-shielding is used to suppress external gamma rays by defining a central "fiducial" volume that is surrounded by an active outer buffer of the detector. The outer buffer is chosen to be thick enough to absorb or scatter the external gamma rays before they reach the fiducial volume. Self-shielding requires that the position of the event be measured.

Neutrons that scatter off target nuclei in the detector will produce signals from the recoiling nucleus that are essentially identical to signals due to WIMP collisions. Pulse shape and other discrimination methods used for β/γ suppression are therefore of no use for distinguishing neutron events from WIMP events. Also, self-shielding with a central fiducial volume, which works well to suppress external γ-background, is less effective for neutrons. Unlike γ-ray Compton scattering in which gamma rays lose a large fraction of their energy with each collision, neutrons lose little energy in elastic collisions with a heavy nucleus. A 1-MeV neutron can scatter multiple times within an argon or xenon detector resulting in a distribution of nuclear recoil events throughout the active volume. Thus, selection of events within a central fiducial volume will not be as effective at suppressing neutrons as compared to gamma rays. However, detectors that can distinguish multiple-hit events from single-hit events enable the multi-hit neutron events to be identified. Since multi-hit detection does help to distinguish a single-hit neutron event from a WIMP collision some detector designs feature an external neutron veto detector.

Suppressing neutron backgrounds to the low levels needed for the ultimate WIMP search will be challenging. The required suppression of backgrounds from internal and external sources of neutrons will likely require an external neutron detector, a muon detector, and a large passive shield. Some of the strategies to be employed in future detectors are summarized below.

1) Muon-induced neutron background.

The muons can interact with the detector materials, with the local shielding, or with the surrounding rock to produce neutrons. Strategies to reduce this source of background include the following.

a) Deep underground site.

b) Efficient muon veto detector (but this will not veto muons that hit the surrounding rock and are not detected.)

c) Efficient external neutron veto detector

d) External shielding.

- Passive shield to absorb and/or thermalize neutrons (polyethylene, paraffin, etc.)
- Water tank with Cerenkov detector for muons. (shields against neutrons produced in rock and also serves as a muon veto detector.)
- High energy neutrons produced by muons in the rock are difficult to shield since they are highly penetrating.

Since the muon flux decreases with depth, it is desirable to be as deep as possible. However, with an efficient muon veto operating also as an active shield (e.g., 2 to 3 m thick water shield) background from muon-induced neutrons may be tolerable at modest depths of a few thousand meters water equivalent[67]. Without a thick local active shield against muon-induced neutrons from the rock, a deep site is required to reach a sensitivity of 10^{-46} cm^2. Modest depths may be sufficient, however, with thick local shielding[68].

2) Neutrons from U and Th activity in rock or external detector parts.

Neutrons are produced by (α, n) reactions initiated by alpha decays in the radioactive chains of U and Th. Spontaneous fission of ^{238}U is a comparable source of neutrons. Strategies for suppressing neutrons from natural radioactivity in the rock are similar to the case of muon-induced background in the rock.

a) External passive shielding to thermalize the neutrons. (Shielding must be relatively free of U and Th.)

b) External active water shield is better as it can be used to detect the muons.

The active shield can be used to veto any event in the central detector.

Neutrons from radioactivity in the rock are lower in energy and are easier to shield than the high energy neutrons produced by muons in the rock. If the neutron shield is passive it can be a source of muon-induced neutrons.

3) Neutrons from U and Th radioactivity in the internal detector parts.

This source includes radioactivity in the active medium of the detector (Ge, Ar, Xe, etc.), the photo-detectors (if employed), the internal electronic components, the containment vessel, etc. Since the potential sources and rates depend on details of the detector design we do not attempt to make a detailed analysis, but give only a general outline of the problem and strategies to suppress the background.

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[67] Bungau, et al., Astropart. Phys. **23**, 97 (2005).

[68] D.M. Mei and A. Hime, Phys. Rev. **D73**, 053004 (2006).

Rate of Neutron Emission in materials containing U and Th:
All materials contain trace levels of U and Th. Rock dust, glass, and common materials have U and Th concentrations of ~ 1 ppm, which is typical of the earth's crust. Typical values for quartz, steel, and aluminum parts are ~ 1 ppb, while plastics without inorganic additives are typically ~ 0.01 ppb. Other synthetic materials such as organic solvents used for liquid scintillators can be ~ 10^{-15} g/g, or lower. Copper is quite pure with U levels of 10^{-12} g/g, or lower. Purified water and liquid scintillator can be produced with U less than 10^{-15} g/g.

At a concentration of 1 ppm, the decay rate of each member of the normal U and Th chains is 12 Bq/kg and 4 Bq/kg, respectively. The branching ratio for fission of ^{238}U is 5.45×10^{-7}, which leads to a fission rate of 6×10^{-6} fissions/s/kg of material containing 1 ppm U, with ~2 neutrons emitted per fission. The alphas in the decay chains can produce neutrons through the (α, n) reaction on light nuclei. The neutron yield depends on the alpha energy and the target material. Typical neutron yield for the higher energy alphas in the U and Th decay chains is 10^{-6} neutrons per alpha. At ~ 1 ppm the neutron emission rate would be ~ $10^{-4\text{-}5}$ n/s/kg. Thus, a rough estimate for the neutron yield of materials with 1 ppm U, Th is ~ 1 to 10 neutrons/day/kg.

Plate-out of Radon Daughters:
The radioactive daughters of airborne ^{222}Rn are typically ionized and attached themselves to aerosols that settle out onto surfaces. As a result of this process all surfaces become slightly radioactive. As a rough estimate of the surface radioactivity one may assume that all the radon daughters in column of air of height one meter, or so, above a surface will collect on the surface in a one day period. By this estimate one finds that a one-day exposure of surfaces to air containing 20 Bq/m^3 of ^{222}Rn will result in ~0.01 Bq/m^2 of the 22-year beta emitter ^{210}Pb and its daughters, ^{210}Bi and ^{210}Po. The alpha-emitting daughter ^{210}Po (E_α = 5.3 MeV) can produce neutrons through the (α,n) reaction on light nuclei in the surface.

If we take the neutron yield on the contaminated surfaces to be 10^{-6} n/α, the neutron emission rate would be 0.3 n/m^2/year for a one-day exposure. Surfaces that are exposed to ambient radon for one year would result in ~100 n/m^2/yr, if the yield is 10^{-6} n/α. Since removing ^{210}Pb from radon-contaminated surfaces by cleaning procedures can be difficult (only about half can be removed from many materials), this could be a long-term source of neutrons. For a detector of 1 m^3 volume and surface area of 6 m^2 exposed to radon for a year, a neutron emission rate of 100 to 600 n/yr is quite possible.

The neutron yield for 5.3 MeV alphas varies strongly with the target material, and is generally less than 10^{-6} n/α. But fluorine, a major component of Teflon that is used as a photon reflector, has a yield of 8×10^{-6} n/α[69]. The estimate of neutron background from radon daughter contamination is very rough but should be kept in mind as a potential source of internal neutrons.

[69] Heaton, et al., NIM **A276**, 529 (1989).

Containment vessels:

The sensitive media of most of the detectors is contained in a vessel of some sort. The vessel might be stainless steel, copper, quartz, or a high purity synthetic material such as fused silica. The U and Th concentrations in the materials can range from 10^{-6} g/g for a worst case to 10^{-12} g/g for some of the best materials. Taking the value of 10^{-12} g/g for an estimate of the best one can do (e.g. high purity copper or synthetic quartz), and assuming that a 100-kg vessel is needed to contain a 1000-kg detector, one finds a neutron emission rate of 0.4 n/yr. This is a tolerable rate, but it could easily be 1000 times larger, or a few hundred counts per year, if one is forced to use less pure materials such as stainless steel.

Lead and Polyethylene shielding:

Lead is used in some designs to absorb external gamma rays. Polyethylene or other materials of high hydrogen content are used to thermalize external neutrons. Several tons of these materials are planned for some of the future detectors. Taking a U, Th concentration of 10^{-12} g/g as typical of a very good shield, one finds a neutron emission rate of ~4 n/yr /ton. The background rate will depend strongly on the layout of the shielding, but it will not be difficult to have a source of hundreds of neutrons per year from shielding with these materials. The neutrons that arise from fission have coincident gamma rays which if detected can be used to veto the event. Most of the gammas will be absorbed by the lead making the possibility of a veto inefficient. A large water shield offers a significant advantage since the purity of water can be 1000 times better than lead and polyethylene materials used for shielding.

Photomultiplier tubes:

The dark matter detectors that employ the rare gases Xe, Ar, Ne will rely on detection of scintillation light for the detection of the recoil events. A high light-collection efficiency is needed to obtain the best signal. The radioactivity of the photo-detectors depends on the materials used in the construction. In general, unless special materials are employed the photomultiplier detectors will be the dominant background source near the detector. Photomultiplier tubes made of normal glass are quite radioactive (~1 ppm U ~12 Bq/kg). Low radioactivity glass has a uranium content of ~ 0.02 ppm and is much better than normal glass, but even these PMTs are still likely to be a dominant source of internal neutrons. Progress on producing low radioactivity PMTs is being made: PMTs with ~1 ppb U are rare but are becoming available. PMTs with ~1 ppt U (e.g., synthetic fused silica) would be highly desirable.

Considering a cubic detector with volume of 1 m^3 (~ 1 ton detector) and a modest PMT coverage of $4\pi/3$, the area to be covered with PMTs is ~ 2 m^2. The total mass of the 4 mm thick (two sides) PMTs is ~ 25 kg. For materials with 1 ppb U, the neutron emission rate by (n/α) reactions would be ~ 4 n/kg/yr, yielding a total of ~100 n/yr. PMTs of low radioactivity glass would produce ~2000 n/yr.

Summary of potential internal neutron sources:
For a 1-ton detector the estimated rate of neutron emission from various sources is given in the table below. The combination of all the sources will be somewhere between 100 and 1000 n/year.

Source	**Neutron emission rate (n/yr)**
^{210}Po on surfaces due to ^{222}Rn in air (1yr-6 m^2)	~ 100
Containment Vessel and Miscellaneous parts	~ 0.4-400
PMT Radioactivity	~ 100-2000

The chance that an emitted neutron will produce a signal in the recoil spectrum between 10 keV and 100 keV depends on the location of the source with respect to the active detector. For sources close to the active detector an estimate of 10% is not unreasonable for the fraction of emitted neutrons that produce a WIMP background signal. This would result in 10-100 neutron background events per year for a 1000 kg detector.

Expected Rate for WIMP-Nuclear Collisions:
The neutron background will limit the ultimate sensitivity that can be achieved in direct searches for WIMP dark matter. The rate of WIMP elastic scattering events depends on a number of factors. For a WIMP of mass 100 GeV, a spin-independent nucleon cross section of 10^{-46} cm^2, and the usual assumptions on the WIMP density and velocity distribution, the rate for a 1-ton Ge or Xe detector with a threshold for recoils of ~10 keV, is ~ 20 events/year[70]. A neutron background rate of 10-100 events per year would pose a serious problem for future detectors that attempt to achieve such sensitivity.

External Neutron Veto Detector:
One way to suppress the internal neutron background is to employ an external neutron detector that can be used to veto an internal event if a signal is simultaneously detected in the internal and the external detectors. The external neutron veto detector should completely surround the central detector and have a high efficiency for detecting a neutron that originates inside the detector, scatters in the active medium, and then enters the external detector. Depending on the internal neutron emission rate, the external veto detector should have an efficiency for detecting neutrons of 99%, or possibly greater, to achieve a background rate of 1 event per year in a 1-ton detector. Employing an active neutron veto could be crucial for the next generation of experiments that will attempt to establish a positive detection of dark matter with possibly a small number of candidate events.

[70] R.J. Gaitskell, Ann. Rev. Nucl. Part. Sci. **54**, 315 (2004).

APPENDIX B – Glossary of Experiments

Experiment	Location	Discrimination Technique	Target	Status	Discussed on Page:
Direct detection					
ADMX	Livermore	Microwave cavity	Magnetic field	running	4,6,10,11,15,16,20,**22**,23,45,73
AXION	Livermore	Microwave cavity	Magnetic field	stopped	
ArDM	CERN/Canfranc	Ionization + Light	2-phase Ar	proposal	**33**,34,36
CDMS-I	Stanford	Heat + Ionization	1 kg Ge + 0.2 kg Si	stopped	45
CDMS-II	Soudan mine	Heat + Ionization	5 kg Ge + 1 kg Si	running	15,**25**,26,27,28,29,37,70
COUPP	Fermilab	Bubble chamber	Freon-type liquids	prototype	12,16,**38**,39,43,44
CRESST-II	Gran Sasso	Heat + Light	10 kg CaWO4	starting	25
CUORICINO	Gran Sasso	Heat	41 kg TeO2	running	
DAMA	Gran Sasso	Light	100 kg NaI	stopped	39,68,**70**,71,74,76
DEAP		Light	various kg Ar	proposal	16,**33,34**,35,36,37
DRIFT	Boulby mine	Low pressure TPC	CS2	running	12,16,**40**,41,43,44
EDELWEISS-I	Modane	Heat + Ionization	1 kg Ge	stopped	25
EDELWEISS-II	Modane	Heat + Ionization	10-30 kg Ge	starting	25
EURECA	Europe	Heat + Ionization/Light	100 kg - 1 ton	R&D	
GENIUS-TF	Gran Sasso	Ionization	42 kg Ge in liq. N2	running	
HDMS	Gran Sasso	Ionization	0.2 kg Ge diode	stopped	
HPGS		Hi pressure gas	various	proposal	12,**42**,43
IGEX	Canfranc	Ionization	2 kg Ge Diodes	stopped	
LIBRA	Gran Sasso	Light	250 kg NaI	running	
LUX		Ionization + Light	300 kg Xe	proposal	36
miniCLEAN		Light	100 kg Ar/Ne	proposal	16,33,**34**,35,36,37
NaIAD	Boulby mine	Light	65 kg NaI	stopped	39
PICASSO	SNO	Metastable gel	Fluorine-loaded	running	**38**,39
PVLAS	CERN	Optical rotation	Laser + magnetic field	running	23
SIGN		Hi pressure gas	Ne, various	proposal	12,**42**,43
SIMPLE	Rustrel	Metastable gel	Fluorine-loaded	running	
superCDMS		Heat + Ionization	Ge (various kg)	proposal	11,15,16,**26**,27,28,29,39
WARP	Gran Sasso	Ionization + Light	2-phase Ar	running	10,16,17,**33**,34,35,36,37
XENON-10	Gran Sasso	Ionization + Light	10 kg Xe	running	6,9,10,16,**31**,32,35,36,37,45
XENON-100		Ionization + Light	100 kg Xe	proposal	36
XMASS	Kamioka	Light	100 kg Xe	running	31,**32**,33
ZEPLIN-I	Boulby mine	Light	4 kg Liquid Xe	stopped	32
ZEPLIN-II	Boulby mine	Ionization + Light	2-phase Xe	starting	10,16,31,**32**,37
Indirect detection					
AMS	Space Station	Magnetic spectrom	particle-antiparticle	prototype	7,19,78,80
ANTARES	Mediterranean	Water Cherenkov	HE neutrinos	prototype	7,19,77
GAPS	Balloon	Calorimeter	particle-antiparticle	prototype	79
GLAST	Earth orbit	Calorimeter	HE gamma rays	ready	7,12,19,78,80
HEAT	Balloon	Magnetic spectrom	particle-antiparticle	stopped	79
HESS	Namibia	Atmos. Cherenkov	HE gamma rays	running	7,12,19,78
ICECUBE	South Pole	Ice Cherenkov	HE neutrinos	running	7,12,19,77,80
MAGIC	Canary Is.	Atmos. Cherenkov	LE gamma rays	running	7,12,19,78
PAMELA	Earth orbit	Magnetic spectrom	particle-antiparticle	running	7,12,19,78,80
VERITAS	Arizona	Atmos. Cherenkov	HE gamma rays	running	7,12,19,78

APPENDIX C – DMSAG Panel Charge

JOINT DOE AND NSF LETTERHEAD

Deadlines for Interim Report and Final Report Changed on May 8, 2006

Professor Melvyn J. Shochet	Professor Garth Illingworth
Chair, HEPAP	Chair, AAAC
Enrico Fermi Institute	Department of Astronomy and Astrophysics
University of Chicago	University of California, Santa Cruz
5630 S. Ellis Ave.	1156 High St.
Chicago, IL 60637	Santa Cruz, CA 95064

Dear Professors Shochet and Illingworth:

We are requesting that the High Energy Physics Advisory Panel (HEPAP) and the Astronomy and Astrophysics Advisory Committee (AAAC) form a joint subpanel to provide advice on priorities and strategies for the direct detection and study of the dark matter that dominates the mass of the universe. This request is made within the context of the report of the interagency working group, entitled "The Physics of the Universe—A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy," produced under the auspices of the Office of Science and Technology Policy. Specifically, we ask that HEPAP and AAAC establish a Dark Matter Scientific Assessment Group (DMSAG) to advise the National Science Foundation Divisions of Physics and Astronomical Sciences and the Department of Energy's Office of High Energy Physics on matters concerning the U.S. dark matter research program.

There has been a growing recognition of the compelling scientific opportunities emerging at the interface between physics and astronomy. In particular, great importance has been assigned to the detection and understanding of the mysterious dark matter that dominates the mass of the universe, a scientific area that is of central importance to both particle physics and astronomy. A number of studies over the last few years (*Quarks to the Cosmos, Quantum Universe, The Physics of the Universe, etc.*) have all identified the compelling discovery opportunities in the area of dark matter, and the physics and astronomy communities have put forward numerous projects designed to directly detect or systematically map the effects of dark matter in the cosmos.

The time has come for the science agencies to develop a coherent plan of specific steps to be taken to address this important scientific theme; and it is for this purpose that we seek advice from your two committees.

DMSAG will be established as a joint subpanel of HEPAP and AAAC. It will report to HEPAP and AAAC, which will consider its recommendations for approval and transmittal to the agencies. DMSAG will proceed within the context of the extant reports and long-range plans directly impacting on dark matter, and it will conduct meetings at which spokespersons for different approaches present their ideas, as well as closed meetings to deliberate and develop recommendations. To be most useful, we ask that DMSAG provide an interim report by October 15, 2006 and a final report by December 15, 2006.

More specifically, DMSAG is charged to address the following questions:

- What are the most promising experimental approaches for the direct detection of dark matter using particle detectors in underground laboratories? DMSAG should consider technologies such as Ge/Si crystals, liquid Xe, two-phase Xe, liquid Ar, and any other promising technology. Thus the scope of this charge will make it necessary to address techniques that are in very different stages of development.
- The analysis of each approach should address topics such as: relative advantages and disadvantages, stage of development, realistic time to implementation, ultimate sensitivity, realistic limit of scalability, overburden requirements.
- What is the optimum strategy to operate at the sensitivity frontier in the short and intermediate term, while making the investments required to reach the ultimate sensitivity achievable by scaling up to some realistic size in the long term (5-10 year horizon)?
- What is the present state of the worldwide dark matter program, and how would the candidate approaches advance the field in the international context? Does the US program have the potential to make unique contributions to direct dark matter searches in the future?
- What guidance and constraints for this program can be gained from other approaches to understanding dark matter? What implications for this program are likely to come from astronomical observations or theoretical astrophysics and particle physics? How would direct detection by the proposed approaches complement the observation of new elementary particles at TeV-scale colliders? What new understanding would be possible from the combination of these approaches compared to any one of them alone?

We thank you for your help in establishing this joint subpanel. Its deliberations and recommendations will contribute very significantly to the national program in dark matter over the next decade. We look forward to working with you in the endeavor.

Sincerely,

(Original Signed by)
Michael S. Turner

(Original Signed by)
Robin Staffin

APPENDIX D – DMSAG Panel Members

Hank Sobel, Chair (University of California at Irvine)

Howard Baer (Florida State University)

Frank Calaprice (Princeton University)

Gabriel Chardin (SACLAY)

Steve Elliott (Los Alamos National Laboratory)

Jonathan Feng (University of California at Irvine)

Bonnie Fleming (Yale University)

Katie Freese (University of Michigan)

Robert Lanou (Brown University)

Charles Prescott (Stanford Linear Accelerator Center)

Hamish Robertson (University of Washington)

Andre Rubbia (ETH-Zurich)

Kate Scholberg (Duke University)

Yoichiro Suzuki (University of Tokyo)

Michael Witherell (University of California at Santa Barbara)

Jonathan Bagger, Ex-Officio (Johns Hopkins University)

Garth Illingworth, Ex-Officio (University of California at Santa Cruz)

APPENDIX E – Schedule of Panel Meetings

The panel had two, two-day meetings where presentations were given by the various experimental collaborations, one two-day closed meeting, and several video conferences. The agendas of the first two meetings are given below.

THURSDAY 29 June			
8:30 AM	9:00 AM	CLOSED SESSION	
9:00 AM	9:30 AM	8:30 - 9:30	
9:30 AM	10:00 AM	Theory talk	Jonathan Feng
10:00 AM	10:30 AM	9:30 - 10:30	
10:30 AM	11:00 AM	Direct Detection Review Talk	Gabriel Chardin
11:00 AM	11:30 AM	10:30 - 12:00	
11:30 AM	12:00 PM		
12:00 PM	12:30 PM	LUNCH	
12:30 PM	1:00 PM		
1:00 PM	1:30 PM	Indirect Detection Review Talk	Lawrence Wai
1:30 PM	2:00 PM	1:00 - 2:00	
2:00 PM	2:30 PM	BREAK	
2:30 PM	3:00 PM	CDMS	
3:00 PM	3:30 PM	2:30 - 4:00	
3:30 PM	4:00 PM		
4:00 PM	4:30 PM	BREAK	
4:30 PM	5:00 PM	XENON	
5:00 PM	5:30 PM	4:30 - 6:00	
5:30 PM	6:00 PM		

FRIDAY 30 June		
9:00 AM	9:30 AM	ZEPLIN
9:30 AM	10:00 AM	9:00 - 10:30
10:00 AM	10:30 AM	
10:30 AM	11:00 AM	BREAK
11:00 AM	11:30 AM	MINI-CLEAN
11:30 AM	12:00 PM	11:00 - 12:30
12:00 PM	12:30 PM	
12:30 PM	1:00 PM	LUNCH
1:00 PM	1:30 PM	
1:30 PM	2:00 PM	DISCUSSION - CLOSED SESSION
2:00 PM	2:30 PM	1:30 - 4:00
2:30 PM	3:00 PM	
3:00 PM	3:30 PM	
3:30 PM	4:00 PM	

MONDAY 14th August

8:30 AM	9:00 AM	Discussion
9:00 AM	9:30 AM	Closed Session
9:30 AM	10:00 AM	8:30 - 10:00
10:00 AM	10:30 AM	
10:30 AM	11:00 AM	ADMX - AXION
11:00 AM	11:30 AM	10:30 -- 11:30
11:30 AM	12:00 PM	LUNCH
12:00 PM	12:30 PM	11:30 - 1:00
12:30 PM	1:00 PM	
1:00 PM	1:30 PM	DEAP
1:30 PM	2:00 PM	1:00 - 2:00
2:00 PM	2:30 PM	
2:30 PM	3:00 PM	WARP
3:00 PM	3:30 PM	2:30 - 3:30
3:30 PM	4:00 PM	
4:00 PM	4:30 PM	Large Noble dark Matter Consortium
4:30 PM	5:00 PM	
5:00 PM	5:30 PM	DRIFT
5:30 PM	6:10 PM	5:00 - 6:10
6:15 PM	6:30 PM	Large Direction Sensitive Detectors

TUESDAY 15th August

8:30 AM	9:00 AM	Discussion
9:00 AM	9:30 AM	Closed Session
9:30 AM	10:00 AM	8:30 - 10:00
10:00 AM	10:30 AM	
10:30 AM	11:00 AM	COUPP
11:00 AM	11:30 AM	10:30 - 11:30
11:30 AM	12:00 PM	LUNCH
12:00 PM	12:30 PM	11:30 - 1:00
12:30 PM	1:00 PM	
1:00 PM	1:30 PM	e-bubble
1:30 PM	2:00 PM	1:00 - 2:00
2:00 PM	2:30 PM	
2:30 PM	3:00 PM	SIGN
3:00 PM	3:30 PM	2:30 - 3:30
3:30 PM	4:15 PM	HPGS 3:30 - 4:15
4:15 PM	4:30 PM	Discussion
4:30 PM	5:00 PM	Closed Session
5:00 PM	5:30 PM	4:15 - 5:30