Deep Underground Science and Engineering Lab
Dark Matter Working Group 2007 White Paper

D.S. Akerib and R.J. Gaitskell, Working Group Co-chairs

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This whitepaper is the result of discussions and presentations initiated at the DUSEL Town Meeting held in Washington in November 2007. The essential elements of this report are:

- The quest to detect dark matter is a science goal of the very highest priority, and is flagship science for DUSEL.
- The dark matter community presents here a Roadmap for a set of proposals for the Initial Suite of Experiments. The science goals will be reached in two phases of experiments, at the 4850 and 7400 ft levels, respectively.
- The US is currently the world leader in the search for WIMP dark matter. Constructing DUSEL will ensure that the US will continue its leading role and attract international collaborators to DUSEL.

1 Science Overview

The discovery of dark matter is of fundamental importance to cosmology, astrophysics, and elementary particle physics [1, 2, 3, 4, 5].[1] A broad range of observations from the rotation speed of stars in ordinary galaxies to the gravitational lensing of superclusters tell us that 80–90% of the matter in the universe is in some new form, different from ordinary particles, that does not emit or absorb light. Cosmological observations, especially the Wilkinson Anisotropy Probe of the cosmic microwave background radiation, have provided spectacular confirmation of the astrophysical evidence. The resulting picture, the so-called "Standard Cosmology," finds that a quarter of the energy density of the universe is dark matter and most of the remainder is dark energy. A basic foundation of the model, Big Bang Nucleosynthesis (BBN), tells us that at most about 5% is made of ordinary matter, or baryons. The solution to this "dark matter problem" may therefore lie in the existence of some new form of non-baryonic matter. With ideas on these new forms coming from elementary particle physics, the solution is likely to have broad and profound implications for cosmology, astrophysics, and fundamental interactions. While non-baryonic dark matter is a key component of the cosmos and the most abundant form of matter in the Universe, so far it has revealed itself only through gravitational effects—determining its nature is one of the greatest scientific issues of our time, making the potential for its discovery and study a key program at DUSEL.

Many potential new forms of matter have been suggested as dark matter candidates in theories that go beyond the Standard Model of strong and electroweak interactions, but none has yet been produced in the laboratory. One possibility is that the dark matter is comprised of Weakly Interacting Massive Particles, or WIMPs, that were produced moments after the Big Bang from collisions of ordinary matter. WIMPs denote a general class of particles characterized by a mass and annihilation cross section such that they would fall out of chemical and thermal equilibrium in the early universe at the dark matter density. Several extensions to the Standard Model lead to WIMP candidates. One of them is Supersymmetry (SUSY), which extends the Standard Model to include a new set of particles and interactions that

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[1] This section is adapted from the S1 DM working group report [6]

solves the gauge hierarchy problem, leads to a unification of the coupling constants, and is required by string theory. The lightest neutral SUSY particle, the neutralino, is thought to be stable and is a natural dark matter candidate. Intriguingly, when SUSY was first developed it was in no way motivated by the existence of dark matter. This connection could be a mere coincidence—or a crucial hint that SUSY is responsible for dark matter.

The possibility that a new class of fundamental particles could be responsible for the dark matter makes the search for WIMPs in the galactic halo a very high scientific priority. This will require the use of low-background detectors in a deep underground location, with excellent sensitivity to nuclear recoils and high rejection power for betas and gammas. A direct detection of dark matter in the halo would be the most definitive way to demonstrate that WIMPs make up the the missing mass. The study of WIMP candidates in accelerator experiments will play a crucial role in determining the relic density of these particles, and extensions to the Standard Model that lead to WIMP candidates are among the primary motivations for current and next-generation accelerators. The indirect detection of astrophysical signals due to WIMP-WIMP self-annihilation may also provide important clues but in many cases may be difficult to unambiguously separate from more mundane astrophysical sources. That leaves direct detection as playing a central role in establishing the presence of WIMPs in the universe today. Given both the technical challenge and fundamental importance of direct WIMP detection, it is vital to have the means to confirm a detection in more than one type of detector. In addition to giving a critical cross check on systematic errors that could fake a signal, detection of WIMPs in multiple nuclei will yield further information about the WIMP mass and couplings. If eventually WIMPs are discovered, the ultimate cross check will be confirming their galactic origin by observing secondary signatures related to the motion of the earth and solar system, and the velocity distribution of the WIMPs. Further development of detectors sensitive to the WIMP direction is important to the long-term program to achieve a state of readiness to vigorously follow up on an initial detection.

US scientists are in a world-leading position in direct detection by having pioneered the development and deployment of several of the best technologies, and by engaging in an active R&D program that continues this leadership.

The detection of dark matter is an experimental challenge that requires the development of sophisticated detectors, suppression of radioactive contamination, and—most relevant to this report—siting in deep underground laboratories to shield from cosmic-ray-induced backgrounds. By building the world's premier deep laboratory, together with bringing the ongoing R&D efforts to fruition, the US will be in a very advantageous position to attract international collaborations and lead the major experiments in this field. Furthermore, given the technical demands of the required scale-up to larger detectors, the establishment of the laboratory and of strong technical and engineering support are essential to the success of these experiments.

The fundamental challenge of the direct detection of WIMPs is based on elastic scattering between WIMPs in the halo and atomic nuclei in a terrestrial detector. The energy range for WIMP-induced nuclear recoils is of order 10 keV, an energy range in which the rate from electromagnetic backgrounds are dominant by many orders of magnitude. It is therefore essential that WIMP detectors combine low-radioactivity materials and environments with background rejection of electron recoil events to keep spurious signals at bay. The dark matter community has developed a broad range of techniques to address these challenges. At present the upper limit on the WIMP-nucleon cross section is below 10^{-43} cm^2, which is well into the region of parameter space where SUSY particles could account for the dark matter, as is illustrated in Fig. 1. The next 2-3 orders of magnitude represent a particularly rich region of electroweak-scale physics (see [6] for a full discussion). The combination of what we may learn from astrophysical searches combined with accelerators is truly profound. Thus, as we describe in the following section, the priority for the dark matter community is to press ahead with a pre-DUSEL round of experiments to further explore this parameter space and hone the technological approaches. Then, by building DUSEL and preparing more sensitive dark matter experiments for the ISE we will position ourselves to either follow up and study a dark matter detection in the coming few years or to search completely the remaining parameter space in a discovery mode.

2 Priority for initial suite of experiments

The scientific priority of the DUSEL dark matter ISE is to either detect and confirm an initial signal that can be confidently attributed to WIMPs, or if a signal (or hint thereof) is observed in the pre-DUSEL era, to move rapidly into an exploitation and study phase. That study would open an era of "WIMP" astronomy that would reduce the

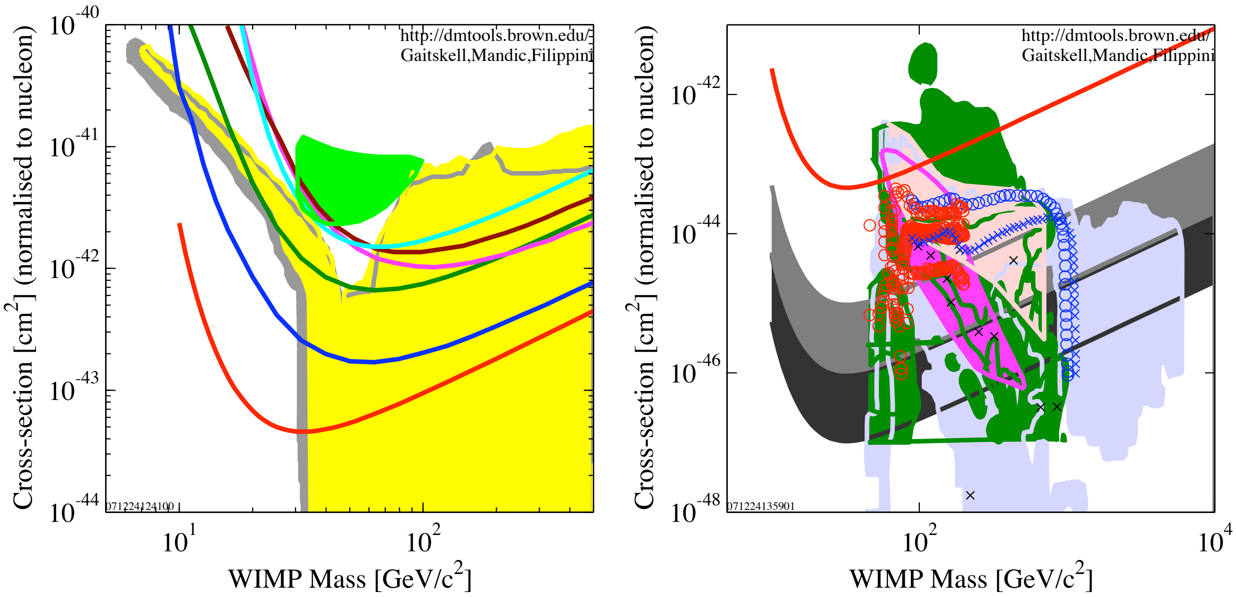

Figure 1: Plots of the elastic scattering cross section for spin-independent couplings versus WIMP mass. (a) The left panel shows the leading experimental results in which the solid curves represent experimental upper limits from the CRESST thermal and scintillation cryogenic detectors (cyan) [7], the EDELWEISS thermal and ionization cryogenic detectors (dark red) [8], the WARP two-phase liquid argon detector (magenta; 55 keV threshold) [9], the ZEPLIN-II two-phase liquid xenon detector (dark green) [10], the CDMS-II athermal-phonons and ionization detectors (blue) [11], and the XENON-10 two-phase liquid xenon detector (red) [12], in all cases assuming the standard halo model [13] and nuclear-mass-number A^2 scaling. The contested DAMA annual-modulation claim [14] is shown by the green region. The yellow and grey regions represent unconstrained Minimal Supersymmetric Standard Model (MSSM) predictions for low-mass WIMPs that result from relaxing the GUT-scale unification of gaugino masses [15]. (b) The right panel displays a broad range of models. CMSSM models from [16] are shown in dark green. Well-tempered neutralinos from [17] are shown in light red. Models within the minimal supergravity (mSUGRA) framework are shown in magenta [18] and light blue [19]. More specific predictions are given by split Supersymmetry models shown by blue circles and crosses (for positive and negative values of the μ parameter, respectively) [20] and red circles [21]. The set of representative post-LEP LHC-benchmark models are shown by black crosses [22]. Experimental projections are shown as grey and black regions for the two ISE phases discussed in the Roadmap section of this report, at the 4850- and 7400-foot levels, respectively. The XENON-10 limit is shown again as a solid red curve for reference with the left panel.

astrophysical uncertainties, deduce the nature of the WIMP-nuclear coupling, measure the WIMP mass, and together with accelerator measurements determine if WIMPs are the full explanation of non-baryonic dark matter. The results of this grand accomplishment would achieve nothing less than confirming our understanding of gravity on a broad range of heretofore-untested distance scales and give us insight into a new form of matter.

Detection in more than one detector using different target nuclei is essential to gain confidence to eliminate systematic effects, or misidentified backgrounds. Data from additional detectors would permit consistency checks regarding how the cross section scales with nuclear mass and/or spin, and would better exploit kinematic determination of the WIMP mass. Constraining the WIMP properties and couplings will allow for comparison with accelerator-based experiments. Determination of the interaction rate will provide a foundation for designing the follow up experiments to confirm the galactic origin of the signal and the reduction of astrophysical uncertainties.

The current sensitivity of WIMP search experiments is at $\sigma_{SI} \sim 10^{-43}\,\mathrm{cm}^2$. It is likely that in the pre-DUSEL period the sensitivity level will reach down to about the 10^{-45} level. In addition, the LHC may give an indication of new physics that informs WIMP searches, although tight constraints on the elastic cross section are unlikely. This is discussed in the S1 report [6]. Whether we are still in a search mode or in an exploitation phase, the experiments for the DUSEL ISE will aim for sensitivity of $10^{-46}\,\mathrm{cm}^2$ – $10^{-47}\,\mathrm{cm}^2$/nucleon. Depending on the target nucleus, this goal will require a minimum fiducial mass of $\sim$1 tonne, with 1–10 tonne fiducial likely.

Improvement factors of about a 1000 in detector-mass scale up and in background reduction, compared to currently operating detectors, appear in reach but will be challenging. Achieving them will rely on maintaining a robust program in the pre-DUSEL period that continues to improve the sensitivity to WIMPs while also providing key technical demonstrations that will inform the ISE. Oriented toward the possibility of galactic-origin confirmation, this would come most definitively from a detector sensitive to the direction of the recoiling nucleus, so R&D on such technologies should proceed in parallel with scaling up the more conventional calorimetric detectors. While DUSEL planning may be focused on defining and planning for the ISE, we emphasize that the dark matter program requires additional space and support for building and deploying prototype detectors for future generations of experiments.

In summary, the science priorities are to scan with at least two target types both SD and SI couplings with large enough detectors to discover WIMPs at the $\sigma_{SI} \sim 10^{-46}$ cm^2 level, i.e., on the order of 10 or more events, and a post-discovery phase that exploit multiple targets to determine WIMP mass and couplings (i.e., SI couplings that scale with A^2 or SP couplings to odd-n or odd-p nuclei). Following discovery, and continued R&D on directional detection, that approach to galactic confirmation will be defined. To carry out this program the targets will likely chosen from F, Ar, Xe, Ge, Ne, and I.

Achieving the sensitivity level will require sufficient depth (overburden) and local shielding to bring unvetoed neutron interactions in the detector material to well below 10^{-5} events/kg/day. A combination of very effective local shielding and muon vetoes, high radiopurity, event discrimination, and accessible well-planned deep laboratory space are needed to reach this physics-driven goal. The 7400 level at DUSEL will be important to insure that the dark matter detectors can reliably reach to 10^{-46} cm^2 – 10^{-47} cm^2/nucleon, and beyond.

3 Roadmap

The science priorities for the dark matter field in the next 10+ years are clear. Arriving, immediately, at a **detailed** technical roadmap covering this entire period to pursue those goals is challenging. For example, our field has seen a rapid evolution of new technologies using noble liquids with a variety of approaches that have a realistic potential to reach the requisite target mass /background levels/WIMP sensitivity at reasonable cost. At the same time, there are clear cost and engineering challenges to scaling up the well-understood solid-state low temperature germanium detectors. Bubble chamber experiments are advancing in sensitivity, and major scale ups are being considered. Low-pressure gas detectors have the unique capability of sensitivity to recoil direction, but further R&D is required before major scale ups can be proposed.

The opportunity presented by the MREFC process is highly significant in the context of historical funding profiles for dark matter, and there is a strong argument for organizing our community to take best advantage of it. Fully exploring the science program to achieve a robust discovery will require multiple experiments. To evaluate the candidate experiments, and stage them in a way that is well matched to the laboratory schedule, we propose the following process to arrive at a proposal for the MREFC dark matter ISE.

A roadmap for the period 2008–2011 (Pre-DUSEL) has been well studied by the DMSAG committee. However, that committee was not asked to consider the direct impact of the MREFC ISE, as discussed here. The DMSAG recommendations for the field should be followed. However, it is clear that the MREFC ISE selection/submission process (2008–9) will exist in parallel, and will modify the former plans some. For the health of the field it will be important that a strong potential program continues to exist outside the umbrella of the MREFC. Once the funding under MREFC is guaranteed this will clearly lead to some modification of the DMSAG plan, in so far as certain technologies will be being funded directly by the DUSEL program.

For the ISE selection, an *ad hoc*, or an existing panel (Homestake PAC or DMSAG), or combination thereof, would solicit Letters of Intent for submitting a PDR. These Letters (of order 10 pages) would describe and justify technical plans, sensitivity, cost estimate, make up of collaboration, and schedule, and generally give a preview of plans that would be expanded into a PDR. The community would agree to “binding arbitration” of the panel’s recommendation for the experiments to be included in the MREFC. We understand that a recommended panel and timetable for this type of process is being studied by the S1 panel. We would recommend that the panel assess submissions in March 2008, to permit enough time for the subsequent MREFC proposals to be written.

Selected programs would make a good faith effort to incorporate new members which would anyway be in their interest given the large scope of the ISE projects.

Those technologies that are not selected for the MREFC can be maintained at an R&D scale providing the potential for future DUSEL experiments. They will pursue pre-DUSEL goals through the usual peer-review regular program process.

Realistic cost and schedule estimates are required. To date, we have relied on self-reporting of these profiles for the ISE, and as a field are just at the point where pre-DUSEL experiments are entering detailed stages of review. As the MREFC ISE is defined, it is essential to build in an independent oversight process to assess these estimates. The DMSAG chaired by Hank Sobel reported in 2007 primarily on the pre-DUSEL era with the recommendation for further review in 2009 to prioritize the different approaches. ISE proponents will prepare for detailed reviews that address:

- Cost and FTE estimates of progenitor experiment to serve as baseline
- R&D needed to finalize detector design and demonstrate sensitivity reach
- Development required for construction start (subject of S4 proposals but too late to affect a late 2008 MREFC selection process)
- Estimated cost, schedule, manpower and sensitivity (signal and background) with as detailed justification as possible
- Estimate of DOE/International component

The evolution of experiments under the ISE would follow a phased construction matched to the two main campuses at DUSEL, with a milestone review of each experiment after their first phases. For example, using the CTF/Borexino experiment as a model, the MREFC would contain a detailed PDR for the first phase, which would start construction in 2011 for installation at the 4850 level. The second phase, for construction in 2015 at the 7400 level, would be described at a less detailed level in the MREFC and release of funds would require that technical milestones from phase I be reached. This approach has the benefit of mitigating risk and allowing the more expensive larger phase to derive considerable technical benefit from its progenitor. In addition, the larger more sensitive detector requires greater depth for background suppression and is built and deployed on a time frame commensurate with laboratory construction.

Based on the current understanding of the capability of technologies within the field it seems likely that the Pre-DUSEL experiments (2008–2010) will deploy gross masses of 25–500 kg with a physics reach of 10^{-44}–10^{-45} cm^2. The ISE proposal would contain details of a phased construction of the order of 3-tonne (gross) detectors (reach 10^{-45}–10^{-46} cm^2) at 4850 level (2011–2013) and 10+ tonne (gross) detectors (reach 10^{-46}–10^{-47} cm^2) at the 7400 level (2015–). The MREFC would contain the full PDR for the 4850-level ISE phase, with more limited technical description of the 7400-level ISE phase. Development work under the first phase would be used to establish full feasibility of the second phase.

The cost estimates plus contingency for the second phase experiments would need to be used to define an likely experiment cost envelope for the period 2015– which would be used in the MREFC. The development of PDR level specification of the second phase experiments would occur in 2012. Technologies not selected for the ISE first phase could be considered for the second phase.

In defining the road map above, given the speed at which some of the technologies have been improving there is the possible risk that the science associated with a reach of 10^{-45}–10^{-46} cm^2 gets done earlier than 2011 at another non-US underground laboratories.

A broad summary of estimates relating to proposed experiments are shown in the Table 1.

As this process is carried out, the S4 proposals will serve as additional “markers” for MREFC-bound bids. However, the current timeline for the MREFC submission itself appears sufficiently rapid that S4-supported work will not directly impact it. However, S4 support will be critical to developing full-scale construction-ready plans for the

Experiment Type	Fiducial (Gross) Mass [tonne]	DM Reach c-s cm^2	Depth (ft Level) / Shielding	Proj. Cost ($M)	Comments including readiness for PDR
LXe TPC	1.5 (3)	0.7×10^{-46}	4850 w/3-m water	10-15	Costs based on existing technologies
LXe TPC	8 (10)	1×10^{-47}	7400	20-35	
LAr TPC	1 (3)	5×10^{-46}	4850 w/3-m water	7	Requires reduced ^{39}Ar
LAr TPC	5 (10)	5×10^{-47}	7400	20	Requires reduced ^{39}Ar
LAr Single	10 (40)	2×10^{-47}	7400	55	CLEAN
LNe Single	10 (40)	1×10^{-46}	7400	55	CLEAN
Cryo Ge	0.9 (1)	1×10^{-46}	7400	Goal 50	SuperCDMS - R&D required for industrialization
Bubble Ch.	1 (1)	4×10^{-46}	4850 w/3-m water	2	
LP Xe Gas					CS_2, CF_4 promising. At R&D phase for large mass.
HP Xe Gas					Still at R&D phase

Table 1: Future candidate experiments for dark matter searches at DUSEL. The Project Cost is equipment and engineering costs, and does not include operations, cavity cost, or basic outfitting. HP - High pressure > 1 atm. LP - Low pressure < 1 atm. In the depth column, 4850 and 7400 refer to the depth level in feet of the to primary physics labs at DUSEL

anticipated MREFC construction start. In some cases, the PDR will detail some options for a technology choice, e.g., readout method for a target type, which could facilitate cooperation in the near term.

The technical roadmap is aligned with the science program goals. The primary science goal is initially extending the sensitivity to WIMPs with spin-independent (SI) couplings since these are expected to dominate in most models. A secondary priority is to push sensitivity for spin-dependent (SD) couplings, which for some nuclei and couplings (xenon and germanium for odd-neutron) are included in the “SI” searches; for odd-proton couplings other nuclei (e.g., fluorine or iodine) are required. At present it does not appear that these experiments can match the physics sensitivity reach of SI couplings, which reduces their relative merit, during the period when a WIMP signal has yet to be observed.

An important aspect of the sensitivity goal is to go beyond limit-setting and make a robust discovery. Therefore we have placed significant importance in pursuing at least two experiments that are sensitive to the higher-priority SI couplings.

4 R&D needs

Current WIMP search experiments employ a range of technologies to shield or reject background sources, and these form the basis from which to draw the first dark matter experiments at DUSEL. These technologies include noble liquids and cryogenic detectors, which together define the forefront of this field, along with the different and unique capabilities of bubble chambers and gaseous detectors. The critical aspects of these technologies required to provide the sensitivity reach of the DUSEL era of dark matter experiments depends on cost/scalability, radiopurity, background rejection, and stability — as well as sensitivity, which depends primarily on low energy threshold, instrumented fiducial mass, and the properties of the target nucleus. Carrying out the pre-DUSEL experiments which will continue to substantially advance the sensitivity frontier are the primary foundation on which the DUSEL program will be built. In that sense, they are a key *development* stage. In addition, specific needs for R&D to ensure a vigorous and flexible program include:

- Background assay and benchmarking tools (see white paper from that cross-cutting working group
- Advanced low-background PMTs and/or alternative scintillation readout schemes
- Industrialization of cryogenic detector production and production of higher-mass modules
- Gas detector readout to address head-tail discrimination and higher pressure operation

It needs to be established whether R&D costs can be included in the MREFC ISE, and/or appear in DUSEL Laboratory operations costs, or whether they will to continue to come only from the agencies. The funding levels for R&D will need to be increased substantially to ensure the resulting technologies have been demonstrated at a level of proficiency consistent with their deployment at the multi-tonne scale.

5 Other considerations

In defining the dark matter ISE within the overall MREFC cost profile, a mitigating factor is the potential for multi-purpose science across other sub-disciplines addressed by the double-beta decay and solar neutrino working groups. Specifically, if large Xe or Ge targets are pursued then added value accrues in the context of the overall ISE if double beta decay science goals can be met; at least a process to "join forces" must be considered, although we must be wary of distraction — it will not serve the science interests of either program if compromises are made in trying to oversell a given approach. A 10 tonne Xe dark matter experiment, even containing natural isotopes, would have significant sensitivity to the neutrinoless double beta decay (DBD) mode. The energy resolution of a Xe TPC could be sufficiently good to separate the 2ν and 0ν modes. However, for the unambiguous discrimination of a very weak gamma line from the 0ν mode would require Ba tagging which may be a significant complication of the detector. A purchasing program for accumulating target materials over a period of time for multi tonne experiments should be considered, especially if isotopically-enriched material is needed. (e.g., Xe rich in ^{136}Xe, Ar low in ^{39}Ar) Also, as experiments reach to the 10^{-46}–10^{-47} cm^2/nucleon level, sensitivity to astrophysical neutrino sources is also of interest. Cross-fertilization of the working groups should be nurtured to explore these possibilities.

6 E&O

The dark matter community has had a strong record of education and outreach programs that have capitalized on the public's fascination with cosmological questions. The accessibility of the subject owing to the non-specialists familiarity with gravity presents us with the opportunity to draw them in with the surprising statement that if gravity behaves as we understand it according to the household names of Newton and Einstein, then we have a profound mystery on our hand of not being able to describe or locate most of the matter in the universe, starting right here at home in our own Milky Way galaxy.

Building on this exciting question, there is also the opportunity to draw in the public with the interesting "gadgets" that we are compelled to develop to carry out the search for these ghost-like particles.

The subject of dark matter searches is a fertile source of material for drawing in, informing and educating the public about a specific profound lack of understanding about nature — and how we set ourselves about to answer it. It touches on the questions of the origin, formation and fate of the astrophysical structures that appear necessary for our existence. The search for answers is a dynamic illustration of the scientific method itself: how we construct and test hypotheses, what assumptions those hypotheses rest on, and the limitations of empirical evidence that we will find, be it for or against the existence of WIMPs.

The dark matter community at Dusel will be an excellent resource for the E&O team, and will offer numerous opportunities for visiting K-12 teachers, college teachers, and students of all ages to learn about astro-particle physics. Longer term programs, such as summer teacher training or research experiences for undergraduates from area schools, will also will be an important component of the program. It has also been suggested that university groups consider hosting summer programs in which South Dakota students spend time in summer school programs at the home institutions which can be broadening and formative experiences.[2]

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[2] Frank Calaprice's group at Princeton University has developed and carried out a very successful summer program with Italian high-school students from the Gran Sasso area.

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