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Review of dark matter direct detection experiments

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Abstract. Matter, as we know it, makes up less than 5% of the Universe. Various astrophysical observations have confirmed that one quarter of the Universe and most of the matter content in the Universe is made up of dark matter. The nature of dark matter is yet to be discovered and is one of the biggest questions in physics. Particle physics combined with astrophysical measurements of the abundance gives rise to a dark matter candidate called weakly interacting massive particle (WIMP). The low density of WIMPs in the galaxies and the extremely weak nature of the interaction with ordinary matter make detection of the WIMP an extraordinarily challenging task, with abundant fakes from various radioactive and cosmogenic backgrounds with much stronger electromagnetic interaction. The extremely weak nature of the WIMP interaction dictates detectors that have extremely low naturally occurring radioactive background, a large active volume (mass) of sensitive detector material to maximize statistics, a highly efficient detector-based rejection mechanism for the dominant electromagnetic background and sophisticated analysis techniques to reject any residual background. This paper reviews currently available major technologies being pursued by various collaborations, with special emphasis on the cryogenic Ge detector technology used by the Cryogenic Dark Matter Search Collaboration (CDMS).

Keywords. Dark matter; direct detection; phonon; ionization; scintillation; Ge; xenon; argon.

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1. Introduction

Never before have we had such a convergence of various astronomical measurements to provide us with a 'Standard Model' (SM) of the Universe. The last decade has brought about stunning measurements of the fluctuations in cosmic microwave background, expansion of the Universe as seen through supernovae, large and small-scale structure through lensing. The 'Standard Model' places us in the most awkward situation of being certain about the nature of less than 5% of the content of the Universe.

A variety of cosmological observations [1,2] indicate that 80% of the matter in the Universe is nonbaryonic and dark, presumably in the form of elementary particles produced in the early Universe. Because such particles have not yet been identified in particle accelerators, these observations require the knowledge of new fundamental particle physics. Weakly interacting massive particles (WIMPs) are a particularly interesting

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generic class of candidates for this dark matter [3,4] because independent arguments from cosmology and particle physics converge on the same conclusion. A WIMP is generically defined as a massive particle created in the early Universe that couples via a weak-scale interaction, allowing it to decouple and stop annihilating when non-relativistic. A weak-scale annihilation cross-section naturally results in the relic density required of non-baryonic dark matter. Simultaneously, new particle physics at the W and Z scale is required to solve the ‘hierarchy problem’ by cancelling radiative corrections that would push the Higgs mass higher than precision electroweak data indicate. The most popular solution, supersymmetry, naturally yields a WIMP in the form of the lightest superpartner (LSP). Thus, searches for astrophysical dark matter particles seek to solve fundamental problems in both cosmology and particle physics and complement accelerator searches for physics beyond the Standard Model.

2. Direct detection principles

The goal of all direct detection experiments is to detect the signature of WIMPs recoiling on their terrestial detectors. The expected rate of interaction of the WIMP on a terrestial detector is less than 1 per 10 kg-days [5]. The expected background rate from radioactivity in the surrounding material is expected to be more than a million times larger. Hence, this strategy is very challenging, due to the expected low rate of interaction from WIMPs, and the highly dominant radioactive background that can fake such WIMP signatures. Thus, the goals for all detector technologies is to employ various shielding technologies to block the radioactive background as well as install their detectors underground to block cosmic muons, which would otherwise produce neutrons that would be hard to distinguish from WIMPs. Beyond the shielding, the detectors are designed to take advantage of the nature of the recoil of electromagnetic background and the neutral WIMPs.

In addition, the WIMP recoil not only depends on the total mass of the detector, but may also depend on the exact nature of the nuclear composition of the detector target. The slow-moving WIMPs are expected to undergo coherent elastic scattering on the entire nucleus, which tremendously enhances the interaction rate, providing a boost to the rate that is proportional to the fourth power of the atomic number [5]. Depending on the type of signal being detected, one can have a wider range of statistics for a given recoil energy. As seen in figure 1, the energy of a quantum can be six orders of magnitude different in the three different signals types – light, ionization and phonon, with the phonon signal being the most sensitive with one quantum of energy of $\approx$1 meV, while the light signal being the least sensitive with one quantum of energy of $\approx$ 1 keV. In addition, the efficiency of the signal being produced and detected can be very different depending on the detector technology. For a nuclear recoil from a WIMP, the efficiency can be as high as 1 for the phonon signal to as low as less than 1% in the case of scintillation light.

With the availability of various detector media optimized to look for different signatures from the WIMP, there are many competing experiments all over the world. Figure 1 shows a few of the current experiments with the signal type they measure. Detectors typically measure more than one signal type, so that they can take advantage of the difference in the behaviour of the signal nuclear recoil and the background electron recoil. The nature of the recoil is usually significantly different in the ionization signal, since

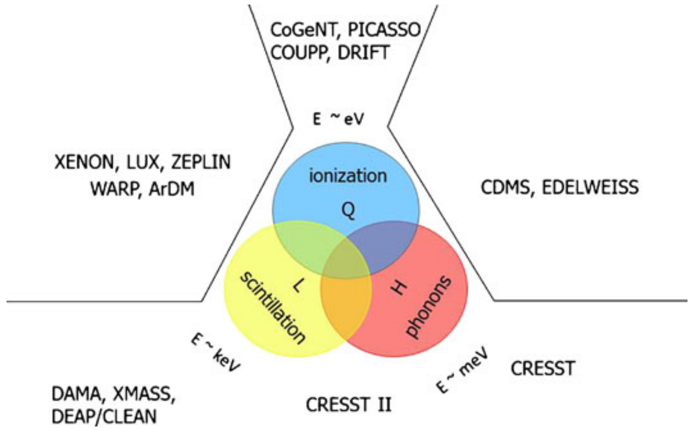

Figure 1. Various forms of energy dissipation from a particle recoil.

nuclear recoil from the signal WIMP or neutron deposits the recoil energy in a very small distance due to its collision with the nucleus, leading to very dense ionization density and low ionization efficiency. On the other hand, electron recoil from radioactive background leads to sparse ionization density, in which the collision is with orbital electron which causes very efficient ionization. Thus, measuring the ionization energy or its equivalent can allow separation of the background (excellent ionization efficiency) from the signal (poor ionization efficiency), provided an independent measure of a separate form of energy such as phonon or light is measured.

Figure 2 shows the principle of discrimination, for the Cryogenic Dark Matter Search (CDMS) detectors, which measures both ionization energy and phonon energy for every event. The phonon energy represents the true recoil energy, independent of the type of

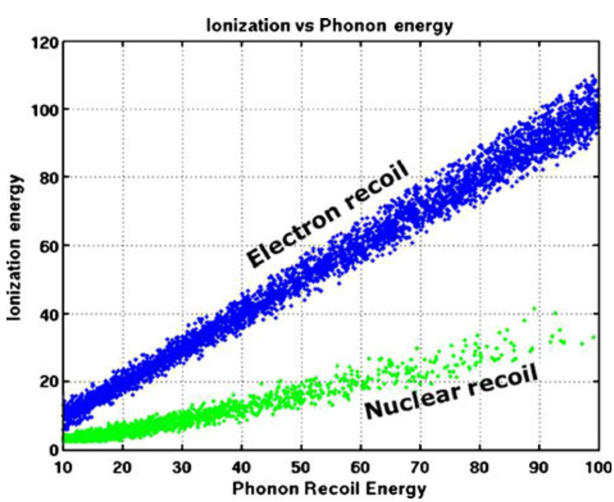

Figure 2. Various forms of energy dissipation from a particle recoil.

recoil, since the nature of the particle has no bearing on the mechanism of phonon creation. However, for the given true energy of recoil, the ionization energy is distinctly different depending on the type of particle. An electron recoil, such as from a photon or an electron, will yield total ionization energy equal to the phonon energy, since there is no loss in the ionization energy for electron recoil. On the other hand, due to the poor ionization efficiency resulting from nuclear recoil, the ionization energy collected is significantly lower for a given true energy of recoil (phonon energy), as shown by the green dots in figure 2. These responses were obtained by calibrating the detector with a gamma source (blue dots) and a neutron source (green dots).

The CDMS II project with a 5-kg target mass has placed the best limits [6] on the WIMP-nucleon cross-section above half the Z-boson mass, with the most sensitive limit of 4×10^{-44} cm^2, at a WIMP mass of 60 GeV/c^2. The CDMS II project ended in 2010. The SuperCDMS experiment at Soudan implements a significantly larger detector $3'' \times 1''$ crystals weighing 640 g as well as significantly improved sensor design for better position information. The SuperCDMS@Soudan experiment will increase our sensitivity by an order of magnitude from our currently published values of 4×10^{-44} cm^2 to 2×10^{-45} cm^2. SuperCDMS, SNOLab with a 100-kg payload will be commissioned in the SNOLab in 2014 and will be highly complementary to the SUSY searches at the Large

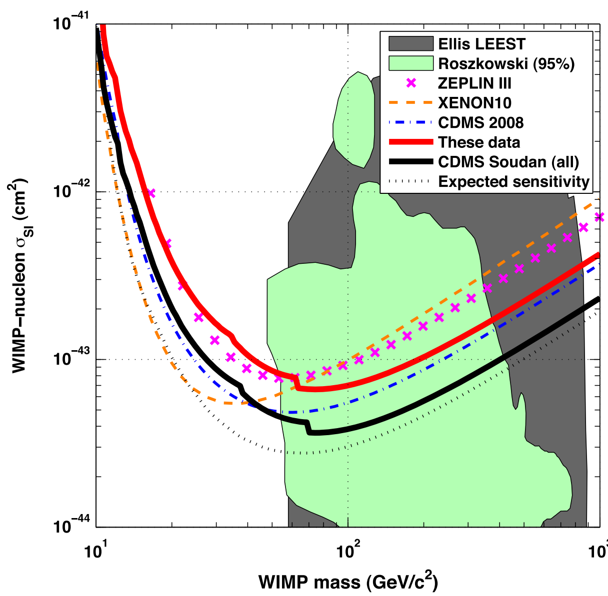

Figure 3. Experimental upper limits (90% confidence level) and theoretical allowed regions for the WIMP-nucleon spin-independent cross-section as a function of WIMP mass. The red (upper) solid line shows the limit obtained from the exposure analysed in this work. The solid black line shows the combined limit for the full dataset recorded at Soudan. The dotted line indicates the expected sensitivity for this exposure based on our estimated background combined with the observed sensitivity of past Soudan data. Prior results from CDMS, XENON10 and ZEPLIN III are shown for comparison. The shaded regions indicate allowed parameter space calculated from certain minimal supersymmetric models.

Hadron Collider (LHC). The collider will be able to produce SUSY particles up to a limit in mass around 300 GeV, but have no constraint as to how low the WIMP–nucleon interaction cross-section is. On the other hand, though the direct detection experiments such as SuperCDMS do not have any limit as to the mass of the WIMP for detection, they are all limited by the lowest cross-section that can be probed. The experiments are complementary since the discovery of a supersymmetric particle at the LHC does not guarantee that it is the dark matter and these should be direct detection for a closure of this mystery. With the advent of the LHC and the new-generation dark matter experiments, next few years are expected to be extremely exciting for SUSY in general and dark matter in particular (figure 3).

3. Cryogenic dark matter search

Current detector technology consists of 3-inch diameter high-purity Ge or Si crystals, with photolithographically fabricated phonon and charge sensors on opposite sides. The thickness of the detector has been increased from 1 cm in CDMS II to 1″ in SuperCDMS [7]. The CDMS II design has two concentric charge channels on the bottom and four phonon channels on the top. When a particle interaction takes place in the detector, electron–hole pairs and phonons are created. The phonons propagate through the crystal and get collected in the phonon sensors. To read out the charge signal, a constant field of 3 V/cm is applied between the two sides of the detector. The electrons and holes are formed during the event drift through the crystal after an electric field is applied. When they arrive at the surface they are collected by the charge electrodes and are read out using a capacitor-coupled FET amplifier.

Figure 4 shows a 3-inch diameter SuperCDMS detector in its copper housing. Each small sensor is a tungsten transition-edge sensor (W TES) in the middle surrounded by aluminium quasiparticle trapping fins. Phonons with energy larger than twice the gap of the aluminium break Cooper pairs and create quasiparticles, which diffuse to the W TES (getting trapped there because tungsten has a lower gap than aluminium) and deposit their

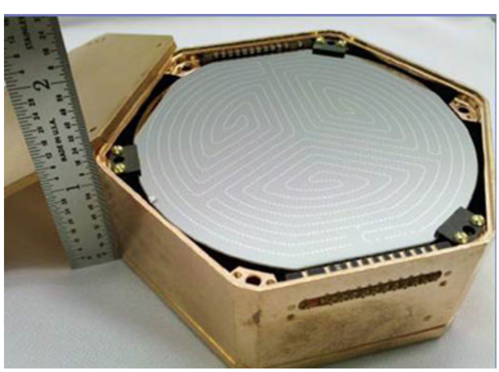

Figure 4. SuperCDMS iZIP detector in its copper housing. There are 4000 phonon sensors connected in parallel and readout as four channels (A, B, C and D) – three inner channels covering equal angles and an outer ring.

energy in the TES as heat (see figure 5). The phonon sensors are strung in parallel, 1000 per channel, and four channels are arranged on the detector, as shown in figure 4. Earlier sensor design in CDMS II had the four phonon quadrants divided into four equal quadrants and had significant degeneracies in position towards the outer radii, which resulted in some bulk recoils mis-reconstructed as surface events.

The detectors are designed to provide event-by-event discrimination between nuclear recoils from signal and electron recoils from radioactive background. Nuclear recoils interact primarily with the nucleus and produce approximately one-third electron–hole pairs compared to electron recoils, where the particle loses energy through interaction with the valence electrons. Thus measuring both ionization and phonon energies provide a strong rejection of the electron recoils, mostly dominated by radioactive γs. To quantify this, we define the ionization yield of the event as the ratio of the charge signal to the phonon signal. There is no loss of the phonon energy specific to the type of recoil and hence it provides a true measure of the recoil energy irrespective of the type of recoil.

Figure 6 shows the discrimination between electron and nuclear recoils from calibration sources for CDMS II [6]. Yield is normalized to 1 for electron recoils, thus nuclear recoils have a yield of $\sim 1/3$. The difference in yield allows these detectors to detect nuclear recoils down to 5 keV of deposited energy while rejecting 99.9998% of electron recoils in the bulk of the detectors [6]. WIMPs and neutrons will interact primarily through nuclear recoils, and cannot be discriminated event-by-event. This is the primary reason for locating the dark matter experiment as deep as possible to avoid cosmogenic neutrons. High-energy neutrons will typically have multiple scatters in one detector or

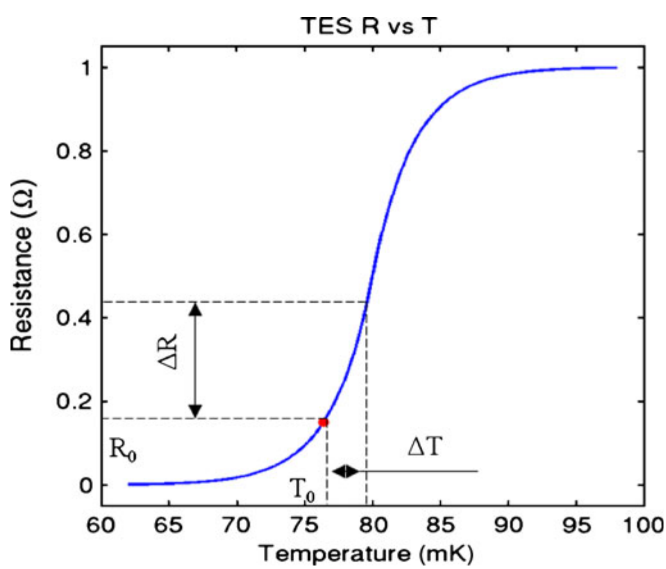

Figure 5. Small depositions of energy can be converted into large signals with low noise, utilizing a transition edge sensor (TES), which is held in equilibrium between superconducting and normal temperatures with a sharp transition curve. Heat trapped from the recoil drives the temperature up, leading to a sharp change in the resistance and hence current flowing through the sensor circuit.

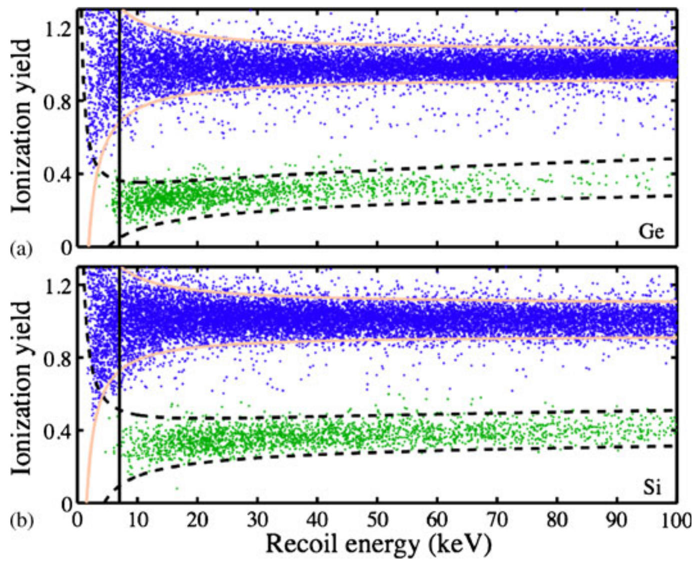

Figure 6. Ionization yield vs. recoil energy for photon and neutron calibration data with $\pm 2\sigma$ bulk electron-recoil band (solid) and nuclear-recoil band (dashed) for (**a**) Ge and (**b**) Si detectors. Events with ionization yield < 0.6 (green) are shown only if they pass the phonon-timing cuts. A 7-keV analysis threshold is indicated.

through several detectors in the detector array, and can thus be identified and screened out. Low-energy neutrons are shielded against, by the passive layers of polyethylene in our apparatus and the active veto made of plastic scintillators. Extensive simulation, and comparison with data is performed to estimate the neutron background.

Surface events, especially from βs, pose a serious challenge to our detectors. When a β hits the detector, it is absorbed within the first few μm of the surface, and the initial energetic electrons and holes have enough energy to diffuse against the voltage bias and a significant fraction ges collected on the 'wrong' electrode, resulting in a lower charge signal. Since the charge to phonon ratio is our main discriminator between electron and nuclear recoils, these events can look like nuclear recoils, and thus contaminate our dark matter signal. In our current detectors, surface rejection is done through a timing parameter, as shown in figure 7. Some electron events (crosses in the figure) still contaminate the neutron signal at low timing parameters. Thus a smaller region (black rectangular box) is defined as the WIMP search region, to screen out these low-yield surface electrons. Using this timing parameter, a rejection of 99.79% of surface events is achieved. As can be seen in figure 7, the main loss of signal efficiency stems from this timing cut.

The new iZIP detectors developed by the CDMS Collaboration contains interleaved ionization and phonon channels on both faces of the detector. The primary reason for the surface event background in the CDMS II detector was the low electric field at the surface, which sometimes allowed the electrons and holes to travel to the wrong electrode, thus reducing the collected ionization and allowing the surface events to pollute the low yield nuclear recoil signal region (figure 7). The iZIP design provides a strong electric field on

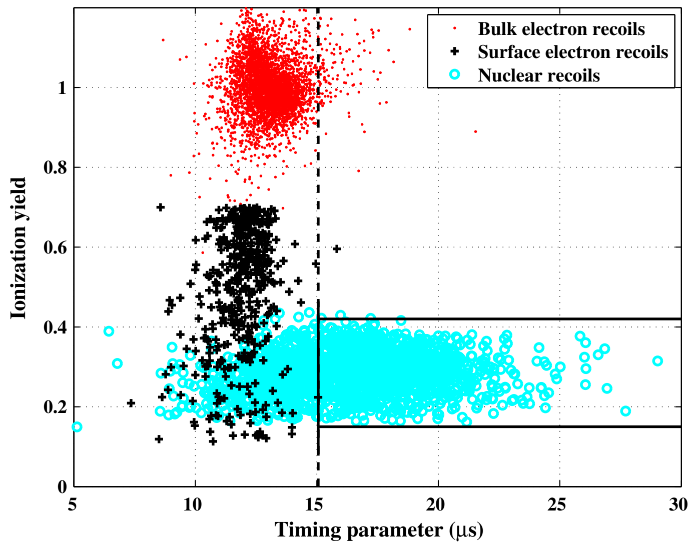

Figure 7. Ionization yield vs. phonon-timing parameter for neutron-calibration data (light blue circles) and bulk (red dots) and surface (black crosses) electron-recoil events from a photon calibration, for recoil energies 10–100 keV, in a Ge detector. The approximate timing-parameter cut and acceptance region are indicated with the vertical dashed line and the box.

the surface, by biasing the alternating ionization electrode (figure 9) at negative 2 V and holding the phonon sensors at the ground. The surface event rejection provided by the iZIPs is more than 100 times better than the previous generation CDMS II detectors, thus

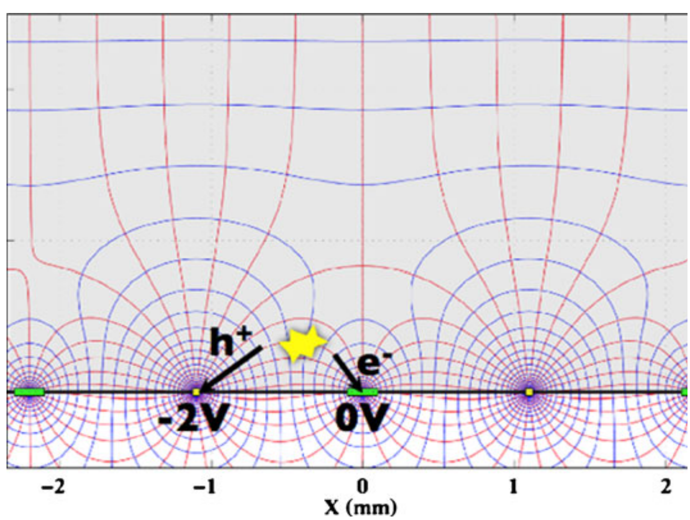

Figure 8. Interleaved ionization electrodes biased at 2 V and phonon sensors held at ground, provide strong electric field at the faces of the detector to efficiently collect ionization from surface event recoils.

Figure 9. New dedicated detector fabrication facility at the Texas A&M University.

making it a negligible background for the SuperCDMS runs. The iZIP technology will allow the SuperCDMS experiment to continue as a world leader in search for the WIMPs, since it has one of the lowest total expected background events among current generation technologies.

3.1 *Improved dedicated fabrication facility at Texas A&M University*

Even though the CDMS detector technology has been the pioneer in low background WIMP searches, its progress towards more total mass is hampered by the slow and expensive fabrication and testing of the detectors. CDMS II detectors were fabricated at the Stanford Nano Fabrication Facility, a shared facility with resources to fabricate CDMS detectors. The average yield of science quality detectors was only about 20% and the rate of fabrication of detectors was about 1 detector/2 months, including testing time. The dominant drivers for the cost and time was the high failure rate of the detectors, coupled with the highly non-uniform distribution of the superconducting W film on the detector surface. To fix the latter problem, first a detector had to get cryogenically tested to map out the T_c distribution of its four channels. This would be followed by ion implantation, where ^{56}Fe ion would be implanted into the detector surface to modify the T_cs so that the four channels have similar T_cs, as well as change the mean T_c to a desirable range of 80–110 mK. This would then be followed by another round of cryogenic testing to verify if the detector is working properly with the desired T_cs. Coupled with the 20% average yield of good detectors, the cost per kilogram for the CDMS II project was very high (350,000 USD/kg). This cost had to come down significantly for the SuperCDMS 100 kg and the ton-scale GEODM project.

A dedicated fabrication facility (figure 9) was established at the Texas A&M University over the last 3 years, with state-of-the-art semiconductor instruments either purchased or acquired from various semiconductor industries closing their fabrication facilities in the US. The set of instruments include a fully automated deposition system capable of simultaneously depositing thin films on eight crystals at a time, with a very fast turn-around time from crystal loading to deposition due to a high-quality load lock system. This allows the deposition chamber to be under vacuum at all points of time, leading to very little contamination of the chamber. The chamber is additionally monitored through a residual gas analyser using *in situ* gas. This set-up guarantees that the deposited crystals have identical thin film properties from crystal to crystal. This is crucial for a high yield of science-quality detectors. In addition, we also obtained T_c values of the W thin film that could be tuned to be in the desired range, thus making the ion implantation and the follow-up cryogenic testing redundant. The T_cs are similar from crystal to crystal and also have a much smaller spread among the four channels of the detector, leading to much more uniform detector response within and across the crystals.

These improvements have led to dramatically better detectors at a significantly reduced cost. The exact cost per kilogram will be firmly established when we move on to the SuperCDMS, SNOLab project phase.

4. Noble liquid detectors

A recent detector technology which is leading the world in WIMP search sensitivity utilizes liquid Xe as the detector medium. The general principle behind noble liquid detectors is that most of the noble gases such as He, Ne, Ar, Kr, Xe, scintillate from particle interaction. The medium does not absorb its own scintillation light, which provides for signal extraction for large volumes of the liquid. Additionally, a large volume of liquid scintillator will provide self-shielding, in which the outer volume of the liquid scintillator bath will be able to contain most of the external radioactive contamination such as gammas, electrons and alphas. Finally, the required cryogenics to cool down the noble gases to liquid state is easy, since it is above the liquid nitrogen temperature for most of the noble gases. In combination, these traits provide for very powerful detector technology, which satisfies all the requirements for a low-count dark matter search. The innner volume of the liquid noble detector is almost entirely background-free and such detectors can be built at a lower cost compared to the cryogenic Ge detectors, and in principle can be scaled up more easily.

The noble liquid detectors are available in many flavours, for each type of noble gases, such as He, Ne, Ar, Kr and Xe. However, the fundamental technology has only two variants – single and dual phases. Figure 10 shows a single-phase liquid Xe detector, as developed by the XMASS Collaboration [8]. Such single-phase noble liquid detectors work by having a large spherical volume of noble liquid medium, with the scintillation light being monitored by photomultiplier tubes with as high a solid angle coverage as possible. The outer part of the detector volume acts as self-shielding, by absorbing external particles. This allows a clean inner volume – called as good fiducial region – which is used for the WIMP search. These single-phase detectors act as counters with position reconstruction abilities, since they cannot discriminate nuclear recoil (signal) and electron recoil (background) on an event-by-event basis.

There are several single phase detectors in the world either currently operating or being commissioned. Using liquid Xe as the target nucleus, XMASS [8] is operating a 800 kg

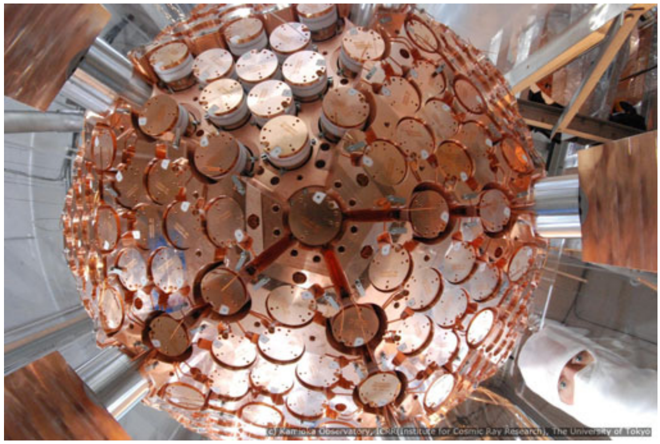

Figure 10. XMASS single-phase liquid Xe detector.

detector in Kamioka lab. The fidual mass – effective clean mass – is $\sim$ 100 kg. The threshold achieved by the collaboration is $\sim$ 25 keV for nuclear recoil events. A large single-phase noble liquid detector utilizing liquid Ar as the detector medium is being set up by the DEAP Collaboration in SNOLab. The DEAP detector has a total Ar mass of 3600 kg, out of which the good fiducial mass is $\sim$ 1 t. The experiment is being commissioned now and will begin collecting science data in 2014 or early 2015. Argon has a unique property which allows for some possible event-by-event discrimination of nuclear recoil and electron recoil events, based on the pulse shape. The ratio of the signal obtained in the first 150 ns and the entire 9 μs time window provides the discrimination, since

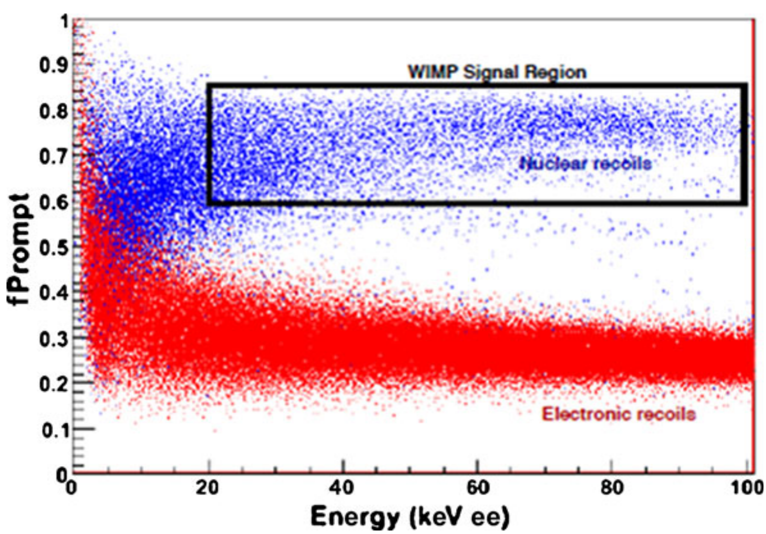

Figure 11. Pulse-shape-based discrimination for nuclear recoil and electron recoil induced events in liquid argon.

nuclear recoils have been found to cause most of their signals in the first 150 ns, whereas the electron recoil-induced pulses take longer to develop, as shown in figure 11. There are other possible target materials being explored for single-phase detectors, such as the mini-CLEAN detector, which will use liquid Ar as the target.

The second and more successful variant of the technology is the dual-phase detector, as shown in figure 12. This detector technology utilizes both the scintillation as well the ionization of the medium. When a particle strikes the liquid, it produces both primary scintillation and electron–hole pairs. A strong electric field (≈ 1 kV/cm) is applied along the cylindrical volume, which drifts the electrons to the top of the detector, where the gaseous phase of Xe is held in equilibrium. The electron produces secondary ionization in the gaseous Xe phase that leads to secondary scintillation, thus dramatically multiplying the signal quanta. Similar to the Ge technology and due to the same reason, the ionization signal and thus the secondary light is highly suppressed for nuclear recoil events, compared to electron recoil events. This is utilized as a basis for the discrimination of the signal and the background, as shown in figure 13.

Xenon100 [9], utilizing the dual phase liquid Xe technology, leads the world in WIMP search sensitivity. It has a fiducial mass of $\sim$ 30–40 kg, where the rate of the background particle is extremely low and can be used for the WIMP search. A similar dual-phase liquid Xe experiment, called LUX, is being commissioned in the Homestake mines in USA. The LUX experiment has a significantly larger fiducial mass than the Xenon100 experiment, at approximately 100 kg. LUX has improved background monitoring of the liquid Xe bath, so as to detect possible deterioration of the liquid radiopurity. Krypton is the most worriesome radioactive isotope for the liquid Xe experiments. Major dual-phase liquid Ar detectors are being commissioned in Europe – WARP in LNGS and

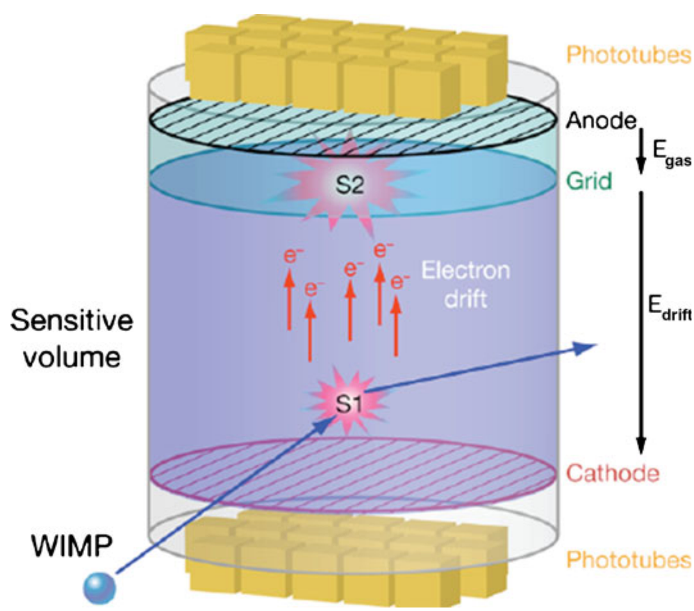

Figure 12. Xenon100 dual phase liquid Xe detector.

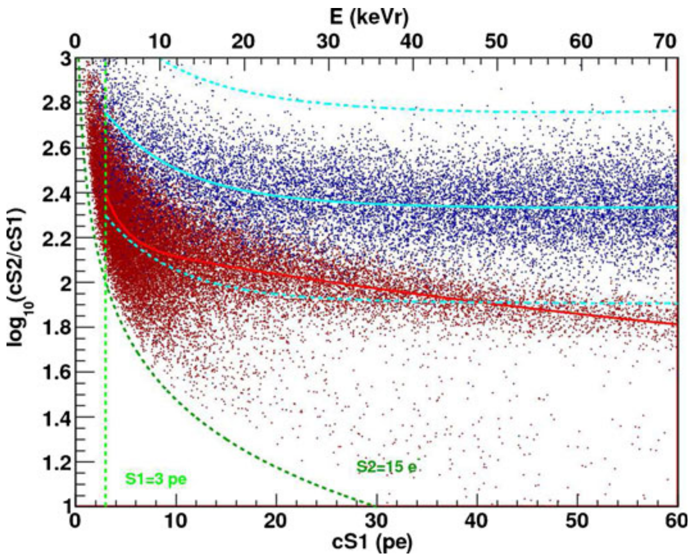

Figure 13. Xenon100 dual-phase discrimination between nuclear recoil and electron recoil events, based on the ratio of the secondary light (S2) and primary light (S1).

ArDM at CERN. The most worrisome background for the Ar detectors is the radioactive ^{39}Ar isotope.

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