TOWARDS ONE TONNE DIRECT WIMP DETECTORS: HAVE WE GOT WHAT IT TAKES?

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Experimentally have we got what it takes to pursue the direct observation of WIMP interactions down to a sensitivities of a few events /(100 kg)/year? For a Ge target with a low energy threshold (< 20 keVr) this corresponds to a WIMP-nucleon $\sigma \sim 10^{-46}$cm^2. A number of recent theoretical papers, making calculations in SUSY-based frameworks, show many (> 5) orders of magnitude spread in the possible interaction rates for models consistent with existing Cosmology and Accelerator bounds. Some theorists, but certainly not all, are able to generate models, that lead to interaction rates at the few /kg/day that would be implied by the current DAMA annual modulation signal. All theorists demonstrate models that generate much lower interaction rates. This paper takes an unashamed experimentalist's view of the issues that arise when looking forward to constructing 1 tonne WIMP detectors.

1 Pursuit of the Grail

It is very encouraging within the dark matter direct detection field to see so many of the technologies proposed over the last decade coming to fruition. It seems likely that next year will see a number of different experiments all vying to set the best sensitivity limits, and at the same time there will be an overall acceleration in the rate of progress of the field, as measured by space carved out in the log-log exclusion plots (see Fig. 6). We will shortly be able to test SUSY models that predict event rates in the 1/kg/week region. A common experimental challenge at present is how to run a few detector units reliably for periods of many months in order to collect statistically significant exposures. Of course, some collaborations are already taking long term running for granted.

It is also worth taking the time to look at the more distant road ahead, with an experimentalist's eye. The challenge for the next generation of experiments (for "First Dark" in 2005-7, say) will be to deploy these technologies at the 1 tonne scale.
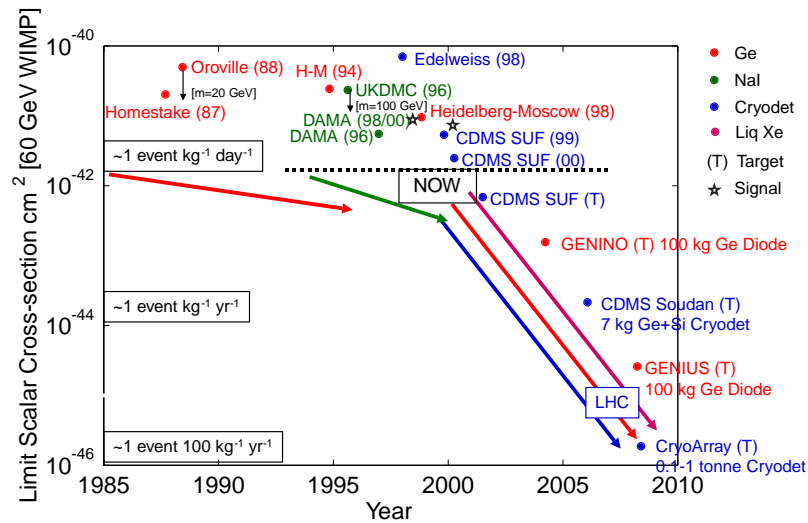
Figure 1. Experiments' 90% upper CL results for 60 GeV WIMP-nucleon scalar cross-section versus times of publications. (Not meant to be an exhaustive selection.) If an experiment performed significantly better for a different WIMP mass then this is indicated by the vertical arrows. The diagonal arrows are there to guide the eye: a gauge of the rate of improvement. The labels in the boxes give the equivalent event rates in Ge assuming a low recoil threshold > 10 keV.

1.1 The Rate of Change of the Rate of Progress of the Field.

We should review the past, in order to look at how robust our future predictions might be. Figure 1 shows the time development of the best scalar WIMP-nucleon σ limit from the mid 80's to date. The first decade was dominated by conventional HPGe (and Si) semiconductor detectors. The design of these detectors was to some extent 'off-the-shelf' and progress was achieved, for the most part, by improving the radioactive backgrounds around the detectors. In the mid-90's results from NaI scintillator detectors became competitive. They were able to employ pulse shape discrimination to make statistical distinctions between populations of electron recoil events, and nuclear recoil events. In principle, the intrinsic background of the detector and environment were no longer the limiting factors, since with sufficient exposure time and target mass the limits could be driven down. However, the relatively poor quality of the NaI discrimination meant that systematic effects rapidly dominate, halting any further improvement with mass×time. The NaI detector

technology could also be described as 'off-the-shelf', however, the low background and high light yield housing systems were very definitely novel. In the case of the DAMA experiment, the deployment of 100kg array of NaI also allowed the search for a WIMP annual modulation signal. At the end of 90's we finally saw results, from new detector technology that had been developed specifically for direct detection, take the lead in terms of sensitivity.

If we now look forward at some of the predicted goals of a few experiments over the next decade, it is immediately apparent that the forecast rate of progress appears to be rapidly accelerating. The question is whether this is simply a 'triumph of hope over expectation', or represents a genuinely improved rate of progress that stems from applying detector technologies (2-phase Xe, semiconductor and scintillator cryogenic detectors, naked HPGe) that were 'birthed' with this specific application in mind.

2 Radioactive Background and Discrimination Goals

	Event Rate [mdru]	Expose [1000 kg-day]	Raw Events [counts]	Reject [%]	Post rejection [counts]	Subtract 90% CL [counts]	Sys'tic 90% CL [counts]
GAMMA							
CDMS I *	800	0.011	254	99.85%	0.4	-	-
CDMS II	260	2.50	19,500	99.50%	98	16	5
Heidelberg-M *	40	0.25	0	n/a			
CryoArray	13	500	195,000	99.95%	97	16	5
BETAS							
CDMS I *	300	0.011	95	95.00%	5	-	-
CDMS II	20	2.50	1,500	95.00%	75	14	4
CryoArray	1	500	15,000	99.50%	75	14	4
NEUTRONS							
CDMS I*(Shield)	2201	0.011	700	99.90%	1	-	-
CDMS I*(Rock)	22	0.011	7	(multi)	n/a	4	-
CDMS II (Sh)	0.5	2.50	38	99.00%	0.4	-	-
CDMS II (Rk)	0.11	2.50	8	(multi)	n/a	6	1
CryoArray (Sh)	0.5	500	7,500	99.90%	8	-	-
CryoArray (Rk)	0.0055	500	83	(multi)	n/a	21	8

Site (Multiple levels given in ft)	Relative Muon Flux	Relative Neutron Flux T>10 MeV
WIPP (2130 ft) (1500 mwe)	x 65	x 45
Soudan (2070 mwe)	x 30	x 25
Kamioke	x 12	x 11
Boulby	x 4	x 4
Gran Sasso (3700 mwe) Frejus (4000 mwe), Homestake (4860 ft)	x 1	x 1
Mont Blanc	x 6^{-1}	x 6^{-1}
Sudbury	x 25^{-1}	x 25^{-1}
Homestake (8200 ft)	x 50^{-1}	x 50^{-1}

Figure 2. (**a**) Table summarising the event rates seen, or projected, for CDMS I, CDMS II , Heidelberg-Moscow and CryoArray (see text). This is the event rate after multiple detector events are vetoed. The detector material is Ge, and the energy region is 15-45 keVee for H-M and 15-45 keVr in other cases. "-" means term is negligible, or unimportant for the discussion in this paper. For gamma and beta backgrounds the spectra are usually flat ($< 2\times$) in the energy range considered. For neutrons and WIMPs the spectra fall exponentially with slope $\sim 10's$ keV. In both cases we quote the mean value in the range. mdru is 10^{-3} /keV/kg/day. The rows marked with "*" are results from actual runs; the rest are target performances. (**b**) Table summarising the relative cosmic-ray muon flux, and high energy ($T > 10$ MeV) neutron flux at a number of deep sites. Gran Sasso, normalised to 1, is taken at average effective depth of 3.7 kmwe (equiv. to 6.37 10^{-5} muons m^{-2} s^{-1}).

Figure 2a shows a tabulation of gamma, beta and neutron background

levels and event rates in the energy range 15-45 keV [a] for actual, or projected exposures of the CDMS I [1,2], CDMS II[3], Heidelberg-Moscow [6] and CryoArray experiments. CryoArray is the working title for a 1 tonne deployment of semiconductor cryogenic detectors, of a type similar to that in use in CDMS II. The reason for breaking up gamma and beta interactions is because the CDMS detectors have been shown to have different responses to electron-recoils in the bulk and near the surface.

The first columns of the table show the radioactivity goals and the total number of events that will be observed during the tabulated exposures for CDMS I (10.6 kg-days); CDMS II (6.8 kg-years); and CryoArray (1.4 tonne-years). Heidelberg-Moscow is shown as an example of currently achievable low gamma backgrounds. The later columns show how the application of detector event by event discrimination can be used first simply to reject most of the background, but then also to subtract part of the residual background if the detector response is well enough understood. [7] The final column shows the systematic error in background counts associated with a 5% error in the detector discrimination calibration. For the case of neutrons the rejection parameter listed represents the local muon veto efficiency (see below). However, the subtraction is performed based on the observed population of multiple nuclear recoil (NR) events.

The WIMP NR event sensitivity (upper 90% CL) of CDMS I in this limited energy range is $\lesssim 4$ events. More details of the background levels observed, and the discrimination performance of the detectors *in situ*, can be found elsewhere [2] and refs. therein.

We will discuss the goals for CDMS II, as an introduction to the CryoArray 1 tonne goals. For CDMS II the WIMP sensitivity goal is around 1 WIMP event/100 kg/day. The exposure goal is 2500 kg-days and so $\lesssim 25$ events total would be present in the background channels. In the original event budget this was to be achieved by lowering the gamma background by 3 compared to current CDMS I performance with a discrimination goal of 99.5%. Notably, the gamma discrimination performance goal for CDMS II has already been exceeded by CDMS I. In addition, studies are underway to identify the current dominant sources of gamma activity. The beta electron background represents a greater challenge. Current levels of observed background are at 300 mdru, whereas the CDMS II goal is 20 mdru. We believe we have identified the source of some of the beta contamination in CDMS I as due to exposure to a leaking calibration source during detector testing. Again, the discrimination

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[a]We use 15 keV rather than 10 keV to avoid the additional contribution of the cosmogenic activation peaks in Ge $\sim$ 10 keV when considering this simple measure of gamma activity.

performance of the new ZIP detectors (99.7% [3]) has exceeded the original CDMS II targets, which will provides some buffer if CDMS II doesn't reach the absolute beta background level. The neutrons causing NR events arise from muons interacting inside the Pb/Poly/Cu shielding, and also muons interacting in the cavern rock. [b] The former can be tagged using a local active muon veto directly around the passive shielding. 80% veto performance will be adequate at this depth to ensure that this type of neutron does not make a significant contribution. In fact, a veto efficiency of 99% is the stated CDMS II goal, and 99.9% has been achieved in the CDMS I veto, so it is unlikely this neutron source will be a limitation. [c] In addition, a high energy neutron flux is generated in the cavern rock by spallation processes of >TeV muons, and is proportional to the muon flux. For the shallower sites [d] the hardening of the muon spectrum with depth leads to an additional factor for the neutron flux which can be approximated by $(depth/2.5kmwe)^{0.75}$. Figure 2b records the relative muon and neutron fluxes at a number of underground sites, and Fig. 3a shows the calculated high energy neutron flux in a cavern at 2000 mwe. [4]

The high energy neutrons from the rock are a more difficult rejection problem, because of the difficulty in stopping them (see latter in this section). With the polyethylene and Pb configuration for CDMS II (cylindrical geometry 5 cm plastic scin. veto, 40 cm poly, 22 cm Pb, 10 cm poly, then the Cu icebox and detectors) the residual signal due to "punch-through" neutrons, after vetoing multiple NR events using 42 detectors, is expected to be 8 during the 2500 kg-day exposure, based on extensive Monte Carlo studies.[4,5]

In order to reach down a further 2-3 orders of magnitude in WIMP event rate it will be necessary to instrument 1 tonne target masses. This detector would be sensitive to WIMP-nucleon σ 10^{-46}cm^2, which in low threshold Ge detectors corresponds to a few events /100 kg/year. A set of possible background contamination and discrimination goals are shown in the CryoArray entries of Fig. 2a. These are obviously meant to aid discussion and are not set in stone. Broadly, these numbers would reflect a factor 20 improvement in backgrounds, and a factor 10 improvement in discrimination, over the goals for CDMS II.

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[b]The low energy neutrons $T < 10$ MeV coming from radioactivity in the rock are trivially stopped by hydrogenous shielding, and will not be considered in this analysis

[c]At deeper sites than Soudan 2000 mwe the requirements for local muon veto performance would be even more relaxed

[d]For the sites < 2.5 kmwe the differential muon flux is typically flat up to an energy 250GeV/1kmwe, and then falls at higher energies. (WIPP is 1.5 kmwe, Soudan 2.0 kmwe.) For sites deeper than 2.5 kmwe the muon spectral shape remains constant, only the flux varies. [8]
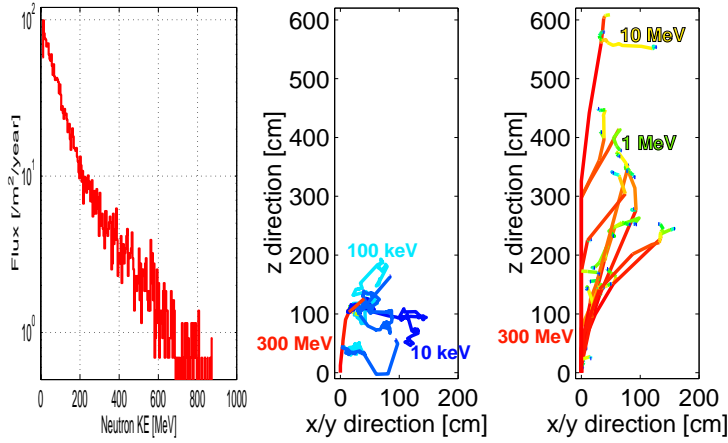
Figure 3. (**a**) Monte Carlo prediction of high energy neutron flux from the rock walls arising from muons at a depth of 2000 mwe. Also shown in plots on the right are tracks from a Monte Carlo simulation of 300 MeV Neutron(s) entering shielding material vertically upwards on the plots. (**b**) Fe Shield (similar to Pb): only 1 event is shown for clarity. (**c**) Water (similar to polyethylene): 10 separate events are shown.

In CryoArray the gamma background goal would be 13 mdru. This is only $3\times$ lower than that currently achieved by Heidelberg in HPGe detectors in the same energy range. The discrimination would need to be 99.95% which again is only factor $3\times$ better than that which is already demonstrated in CDMS I.

The situation for beta background is more difficult to make reliable projections for. Ideally, by the time the semiconductor cryogenic detectors would be deployed for the CryoArray, the performance for gamma and beta discrimination would be very similar. The best ZIP beta discrimination to date is >99.7%, and we look forward to further improvements as the signal-to-noise of the detectors improves further. A beta discrimination of 99.5% would still require ~ 1 mdru which is over two orders of magnitude better than current levels of beta contamination. A significant reduction of this type is a much tougher promise to keep, and so we would realistically expect to beat this by some mixture of improved discrimination (comparable to that for gammas) and background reduction.

The neutron situation for CryoArray is interesting. The NR signal for the neutrons from the shield would now require veto performance comparable to that for CDMS I at 99.9%, if this experiment was sited at Soudan (2000 mwe).

A move to Gran Sasso (or equiv at 4 kmwe) would provide a neutron reduction of 25x (see Fig 2b) and the active muon veto requirement would then become very modest. The 'punch-through' neutrons at the Soudan site would be more of an issue. Figure 2a assumes a factor 20 reduction in the raw rate of these neutrons for CryoArray in order to meet the target. This could be achieve in a number of ways. Firstly, the probability of multiple scattering and therefore vetoing neutrons is higher in a 1 tonne detector vs $\sim$ 10 kg. This factor needs to be Monte Carlo'd in detail since it will depend on the detailed composition of the detector region. Secondly, a move to a depth of 4 kmwe would seem to achieve a suitable reduction. Lastly, if the goal was to perform the experiment at a site at $\lesssim$ 2000 mwe (e.g. WIPP, or Soudan) then either, a much thicker liquid scintillator buffer would be required around the detector in order to tag high energy neutrons, or the cavern rock itself (or an outer heavy shield) would need to be instrumented with additional veto detectors in order to catch some part of the shower associated with the muon that generated the neutron. Studies in this direction are being pursued. [4]

Figure 3a shows a Monte Carlo simulation of the high energy neutron flux from the walls of the Soudan cavern at 2000 mwe. Figures 3b and 3c show simulations of 300 MeV neutron(s) entering Fe and water, respectively, from the bottom of the plot, in a +ve $z-$direction. For Fe only 1 event is shown for clarity. The multiplicity of neutrons generated from the initial scatters is high, typically $\sim$ 20, as these processes are predominantly inelastic. The resulting neutrons have T$\sim$ 1MeV and then 'diffuse' within the Fe with only small energy losses per elastic scatter. Based on Monte Carlo simulations, 100(200) cm of Fe is required to reduce the flux of neutrons by a factor 10, counting those left above 1 MeV(100 keV). For water 10 separate events are shown. In this case the typical neutron multiplicity of the event is lower, being from 1 to a few. 460 cm of water is required to reduce the flux of initial neutrons by factor 10 ($T > 10$ keV). Given the topology of the interactions discussed above it should be apparent why a shield containing interleaving Pb and poly would be most effective at stopping high energy neutrons from ultimately creating lower energy nuclear recoils (10-100 keV) at the detectors.

According to the Monte Carlo simulations, neutrons in the range $T = 50-600$MeV make equal contributions to the "punch-through" neutron population within the poly/Pb shield of CDMS II. This is because although the muon-induced neutron flux falls at higher energies, the effective penetration length of the more energetic neutrons rises almost exactly to compensate. Below 20 MeV the neutrons are very successfully moderated by the polyethylene.
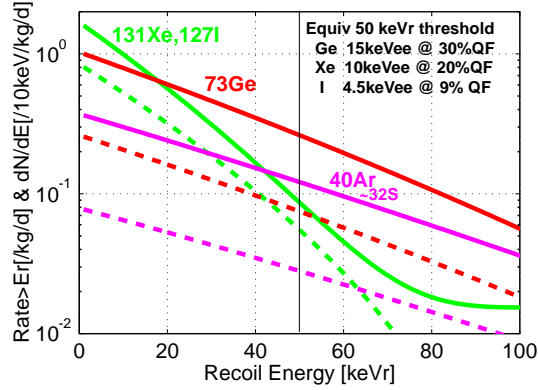
Figure 4. Expected rates in both integrated (*solid*) above threshold, and differential (*dashed*) for 300 GeV WIMP with a WIMP-nucleon $\sigma = 5 \ 10^{-42} \ cm^2$ The effect of both nuclear coherence $\sim A^2$ and the Form Factor suppression for $q^2 > 0$, as well as kinematics are taken into account.

3 Comparison of Detector Technologies and Threshold Behaviour

It is not possible in the space of this paper to comprehensively discuss the technology of the possible detectors for 1 tonne experiments. These proceedings will contain a myriad of technical details. However a few observations are appropriate here.

The use of naked HPGe detectors in liquid N_2 for the GENIUS/GENINO experiment is innovative, and they may be relatively simple to deploy. However, if such a system is to be used to probe $\sigma \sim 10^{-45} cm^2$ this would require $\sim 3 \ 10^3$ reduction in the low energy gamma/beta backgrounds of the detector assembly compared to the current Heidelberg-Moscow levels, since the detector has no background discrimination. Low energy (E< 100 keV) backgrounds are very difficult to Monte Carlo reliably since the observed rate will probably be limited by small localized contamination rather than distributed levels of U/Th/K. It is also worth noting that the activity from cosmogenically produced ^{3}H in Ge, would begin to exceed the GENIUS target background (0.03 mdru) in the range 0-19 keVee (0-60 keVrecoil) after only a few hours exposure at sea level. This activity would take too long to cool, subsequently, when underground.

The three main technologies, in use at kg scales, that exploit nuclear recoil

(NR) discrimination are 2-phase Xe and two types of cryogenic detectors. [e]

The favoured mode of operation for liquid Xe based detectors involves measuring both primary scintillation light and drifted ionisation signal from the interaction. Amplification of the latter signal in the gas phase means that the main signal-to-noise limitation is in detecting the light from the primary scintillation. This is likely to determine the effective energy threshold for the detector. It is too early in the prototype development of the 2-phase Xe to get an accurate indication of this threshold value. The importance of the threshold on the observed rate of interactions is shown in Fig. 4. Clearly the liquid Xe target will scale relatively quickly, since large liquid noble element calorimeters are already deployed in a number of particle physics applications, albeit with much higher energy thresholds.

Cryogenic detectors use the phonon signal combined with either electron-hole signal in semiconductor crystals, or photon signal in scintillating crystals. In contrast to Xe, the signal-to-noise in the cryogenic detectors is extremely favourable for WIMP detection. In CDMS the resolution in the ZIP phonon and charge channels is $\lesssim 1$ keV. This means that high quality event-by-event discrimination occurs above a low threshold of 10 keVr. However, the challenge in constructing a 1 tonne array will be to establish the necessary mass production techniques for ~ 1000 detectors. The infrastructure build for CDMS II (42 detectors, ~ 10 kg) has lead to the development of cold and warm electronics systems that already lend themselves well to mass production. Other cryogenic detector groups are also looking at the same scaling issues.

While it is the case that gas TPCs provide elegant methods for background discrimination, the effective target mass for 1 m^3 of gas at 40 torr is 2.3 g×RMM, so $\sim 10,000$ m^3 of chambers are required to achieve 1 tonne. The possibility of increasing the gas operating pressure is being investigated although this may come at the expense of discrimination quality.

Figure 5a shows a threshold effect of the "first kind", which arises because the difference in the x_2/x_1 ratio for background and signal is relatively small. A region of confusion occurs for the event by event discrimination as the signal-to-noise falls where the distributions start to overlap. For CDMS x_1 is recoil energy and x_2 ionisation energy. In Ge (Si) if x_2/x_1 for gamma events is 1, then x_2/x_1 for NR is $\sim 1/3$ (1/2). The confusion threshold in CDMS I was below 10 keVr and did not have a significant impact on the sensitivity

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[e] Obviously, NaI scintillators have been very successful to date. However, the intrinsically weak power of discrimination means that even based on improvements to 12 p.e./keV, (DAMA currently have 5-7 p.e./keV, UKDM previously at around half this, but this has improved significantly with new unencapsulated crystals) systematics would still dominate exposures with sensitivities below $\sigma \sim 10^{-43}$cm^2.
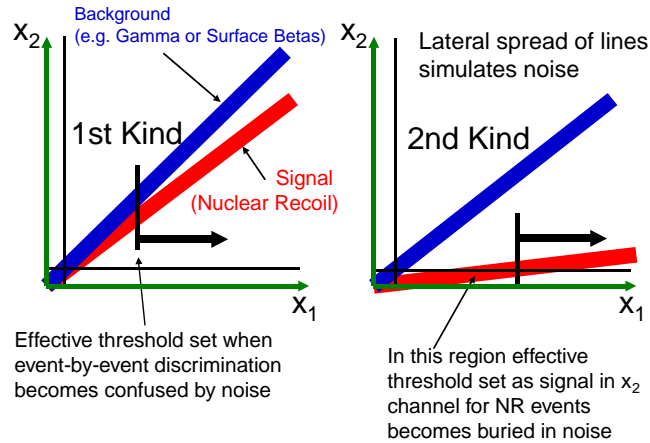
Figure 5. The plots represent background and signal event distributions in discriminating detectors, which use the ratio of parameters x_1 and x_2 to characterise the event. The threshold effect arising from the relative ratios of the discrimination parameters are shown in (**a**) Threshold of First Kind: Signal and background distributions become confused. (**b**) Threshold of Second Kind: x_2 falls into noise for signal events.

analyses of the latest results.

The CRESST experiment helps illustrate the "second kind" of threshold in Fig. 5b. The intrinsic separation of lines for electron recoil and signal (NR) events is significantly greater at 1/7.4, (compared to 1/3 for Ge, in CDMS). In this case x_2 is the amount of scintillation light from the events, with x_1 as the recoil energy in phonons. This threshold is more subtle, since for smaller signal-to-noise, the problem is not one of confusion of NR signal with conventional background events. The small NR events now contain information in only the x_1 (phonon) channel with x_2 (scintillation) lost in noise. This category of x_1 only events could be subject to other forms of fake background such as the "crack-o-phonics" that have been seen to emanate from crystal mounts. The current numbers for the 300 g $CaWO_4$ set up (given that 0.68% of gamma event signal is collected as scintillation energy) are such that a 25 keVr neutron(gamma) would deposit 23 eV(170 eV) in the scintillation light detector. Such a neutron scintillation signal would likely to be in the noise.[f]

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[f] It should be noted that the calibration provided by a radioactive neutron source is dominated by O recoils (of the $CaWO_4$ target) for events $E_r > 10$keV. This is a consequence of the kinematic factor $4(m_1 m_2)/(m_1 + m_2)^2$ in the recoil energy expression, which pushes W recoils to very low energies. In the case of a WIMP search with $CaWO_4$ the interaction

4   Conclusion

Part of the recent need to consider larger dark matter detectors has arisen because more sophisticated SUSY based calculations [g] are being performed, [9] many of which have driven possible cross-sections down significantly relative to current sensitivities (see Fig. 6). The other factor being improvements in current experimental limits, of course!

Experimentalists are often urged to ignore the predictions of theoreticians, and to hunt for new particles regardless, by the means that are at hand. While precedent indicates that it may be prudent not to put too much weight on many theoretical machinations, it is an important feature of WIMPs that they are motivated by both Particle Physics and Cosmology. Unfortunately, within SUSY the link between the WIMP annihilation σ and the WIMP-quark σ is fairly loose, and while the former is determined within ~ 10 by comological bounds (Ω_m) the latter ranges over many orders of magnitude. If the correlation becomes extremely soft then one could argue that direct detection is the wrong method to use to look for Cold Dark Matter (CDM) WIMPs and that a technique more closely dependent directly on the annihilation σ should be preferred. (However, beware of suppressed branching ratios if one is detecting a specific decay product.)

If we see SUSY at accelerators within this decade then it is hoped that enough parameters will be determined to allow calculation of the LSP properties to see if it can be CDM and, if so, what the quark interaction rate will be. If we fail to observe SUSY at LHC at the end of this decade it would seem reasonable to abandon direct detection searches in the absence of any new compelling framework in which to calculate the WIMP interaction rate.

In the meantime, it remains a tantalizing possibility that one (or more) of the current experiments may observe an unequivocal signature for SUSY WIMPs (corresponding to an interaction rate that is at the upper end of the theoretically allowed range), and thereby provide a single answer to two of the more entertaining riddles in Particle Physics and Cosmology.

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rate will be dominated by W. The WIMP mass is better matched to the nuclear mass, and the prospect of significant A^2 enhancement (A=184 for W) seems attractive. However, for WIMP scattering at a threshold of say, > 32keVr, the loss of coherence, reflected in the form factor, is such that the observed rate will be 1/10 th of that for a zero threshold. In addition, the W (and Ca) quenching factors for NR have not yet been measured directly, and so it is not known whether they are the same as that for O nuclei. This is an important parameter to determine in order to estimate the ultimate threshold and so effective mass of the experiment.

[g]The simple crossing symmetry argument, for evaluating nucleon cross-section, from the annihilation cross-section, is not satisfactory
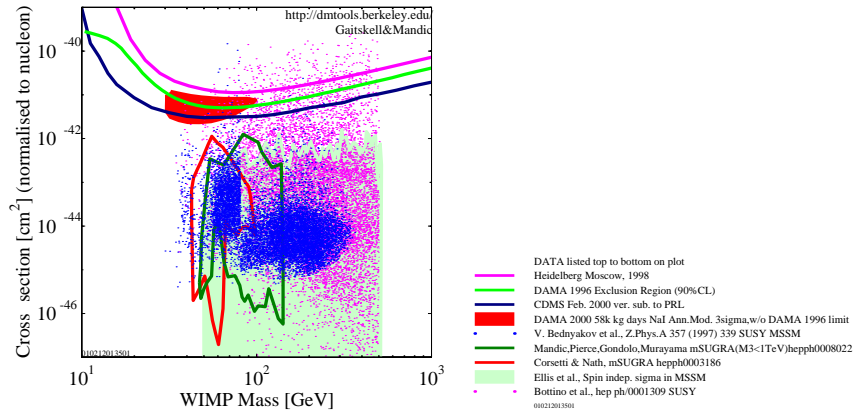
Figure 6. Spin-independent WIMP-nucleon cross section vs WIMP mass. The legend on the right contains labels identifying data sets. Further data can be obtained at http://dmtools.berkeley.edu/.

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