

# Studies of a three-stage dark matter and neutrino observatory based on multi-ton combinations of liquid xenon and liquid argon detectors

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## Abstract

We study a three stage dark matter and neutrino observatory based on multi-ton two-phase liquid Xe and Ar detectors with sufficiently low backgrounds to be sensitive to WIMP dark matter interaction cross sections down to  $10^{-47}$  cm<sup>2</sup>, and to provide both identification and two independent measurements of the WIMP mass through the use of the two target elements in a 5:1 mass ratio, giving an expected similarity of event numbers. The same detection systems will also allow measurement of the pp solar neutrino spectrum, the neutrino flux and temperature from a Galactic supernova, and neutrinoless double beta decay of <sup>136</sup>Xe to the lifetime level of  $10^{27} - 10^{28}$  y corresponding to the Majorana mass predicted from current neutrino oscillation data. The proposed scheme would be operated in three Generic stages G2, G3, G4, beginning with fiducial masses 1-ton Xe + 5-ton Ar (G2), progressing to 10-ton Xe + 50-ton Ar (G3) then, dependent on results and performance of the latter, expandable to 100-ton Xe + 500-ton Ar (G4). This method of scale-up offers the advantage of utilizing the Ar vessel and ancillary systems of one stage for the Xe detector of the succeeding stage, requiring only one new detector vessel at each stage. Simulations show the feasibility of reducing or rejecting all external and internal background levels to a level <1 events per year for each succeeding mass level, by utilizing an increasing outer thickness of target material as self-shielding. The system would, with increasing mass scale, become increasingly sensitive to annual signal modulation, the agreement of Xe and Ar results confirming the Galactic origin of the signal. Dark matter sensitivities for spin-dependent and inelastic interactions are also included, and we conclude with a discussion of possible further gains from the use of Xe/Ar mixtures.

*Keywords:* dark matter, WIMP detection, solar neutrinos, supernova neutrinos, double beta decay, liquid Xe detectors, liquid Ar detectors, low backgrounds.

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## 1. Objectives and overview

Liquid noble gas detectors have proven capability to identify and distinguish both nuclear recoil and electron recoil events [1], and are shown in this paper to have the potential of achieving the ultra-low backgrounds needed to detect weakly interacting dark matter particles (WIMPs) with nucleon interaction cross sections down to  $10^{-47}$  cm<sup>2</sup> and with sufficient spectral precision to estimate their mass. With multi-ton target masses, these detectors could at the same time measure the spectra of pp solar and galactic supernova neutrinos, and detect neutrinoless double beta decay in <sup>136</sup>Xe at the lifetime level ( $10^{27} - 10^{28}$  y) predicted for Majorana neutrinos from neutrino oscillation data.

It is shown in Sec.2, that for unambiguous identification and mass measurement of dark matter particles, it is essential to have detectors observing signals in targets with two different atomic numbers, in particular to exploit the  $A^2$  dependence of the spin-independent cross section. For this, liquid Xe and liquid Ar provide an ideal pair of targets, having similar operating principles and construction, but having spectral and  $A^2$  differences giving approximately a factor 5 difference in event rates. Hence similar signal rates should be achievable for a liquid argon detector having five times the mass of a corresponding liquid xenon detector.

We study a dark matter and neutrino observatory of this type constructed in three progressively larger stages, with **Generic** designs referred to as G2, G3 and G4. The sizes and masses of each stage are shown in Tab.1.

	G2		G3		G4	
	Xe	Ar	Xe	Ar	Xe	Ar
Target dimensions, masses						
diameter × height (m)	1 × 1	2 × 2	2 × 2	4 × 4	4 × 4	8 × 8
total target mass (t)	2.2	9	18	73	146	580
nominal fiducial target mass (t)	1	5	10	50	100	500
No. of photodetectors						
top	120 (3'')	600 (3'')	600 (3'')	670 (6'')	670 (6'')	2000 (6'')
sides (if instrumented)	520 (3'')	670 (6'')	670 (6'')	2400 (6'')	2400 (6'')	8000 (6'')
bottom	120 (3'')	160 (6'')	160 (6'')	670 (6'')	670 (6'')	2000 (6'')

Table 1: Summary of sizes, masses and photodetector numbers for G2, G3 and G4 detectors

Each stage has the required 5:1 ratio of the Ar and Xe fiducial masses, beginning with 1 ton of Xe and 5 tons of Ar. After a period of data-taking with the G2 system, subsequent scale up can then be achieved by the following steps:

1. Replacing the 5-ton Ar with an equal volume of Xe, taking advantage of the factor 2 density ratio to give a G3 Xe target an order of magnitude larger in mass than G2 Xe.
2. Construction of one new vessel - a matching G3 Ar target, which would again have a mass 5 times that of the G3 Xe mass.
3. If warranted by the performance of the G3 system, replacing the G3 argon by 100 tons xenon to give the order of magnitude G4 scale up.
4. A final option of constructing a G4 Ar target with 5 times the G4 Xe fiducial mass.

The detectors will operate using the two-phase principle [2], yielding both scintillation and ionization signals whose ratio provides a factor  $\sim 10^2 - 10^3$  discrimination between nuclear recoils and background electron recoils. This has been demonstrated at the target mass level of 10 – 20 kg, both technically and operationally, by three collaborations ZEPLIN [3, 26, 4, 28], XENON [5, 6, 9] and WARP [7], the latter using liquid Ar and the others liquid Xe. Such devices have demonstrated

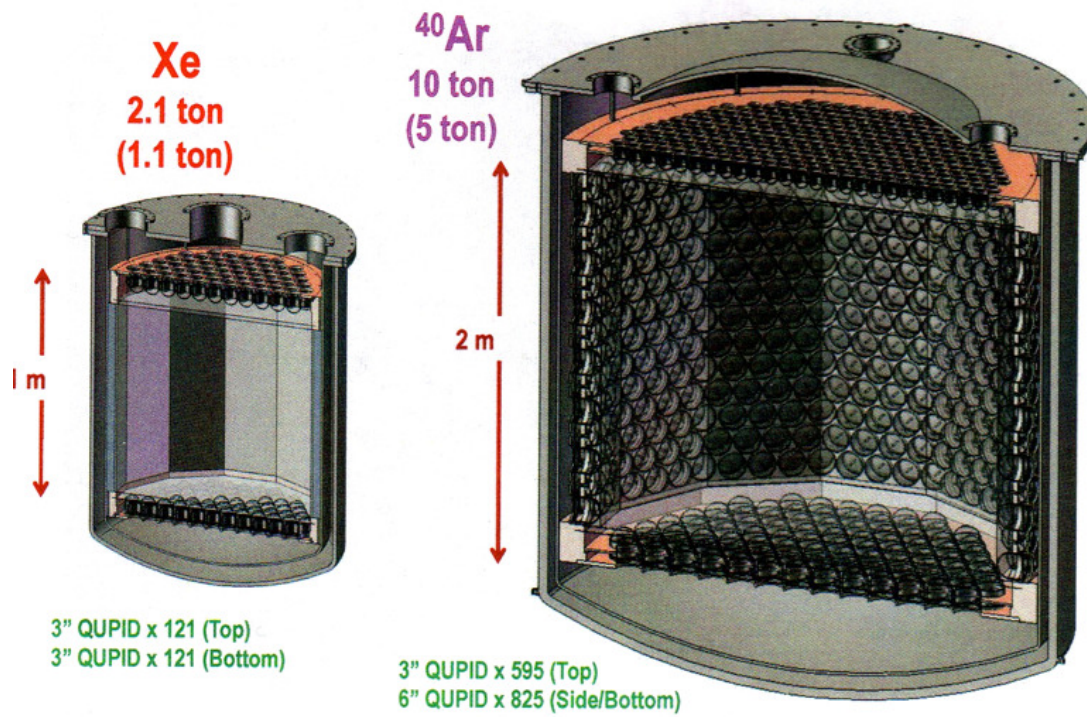


Figure 1: Main parameters of the 1 ton/5 ton (fiducial) G2 system

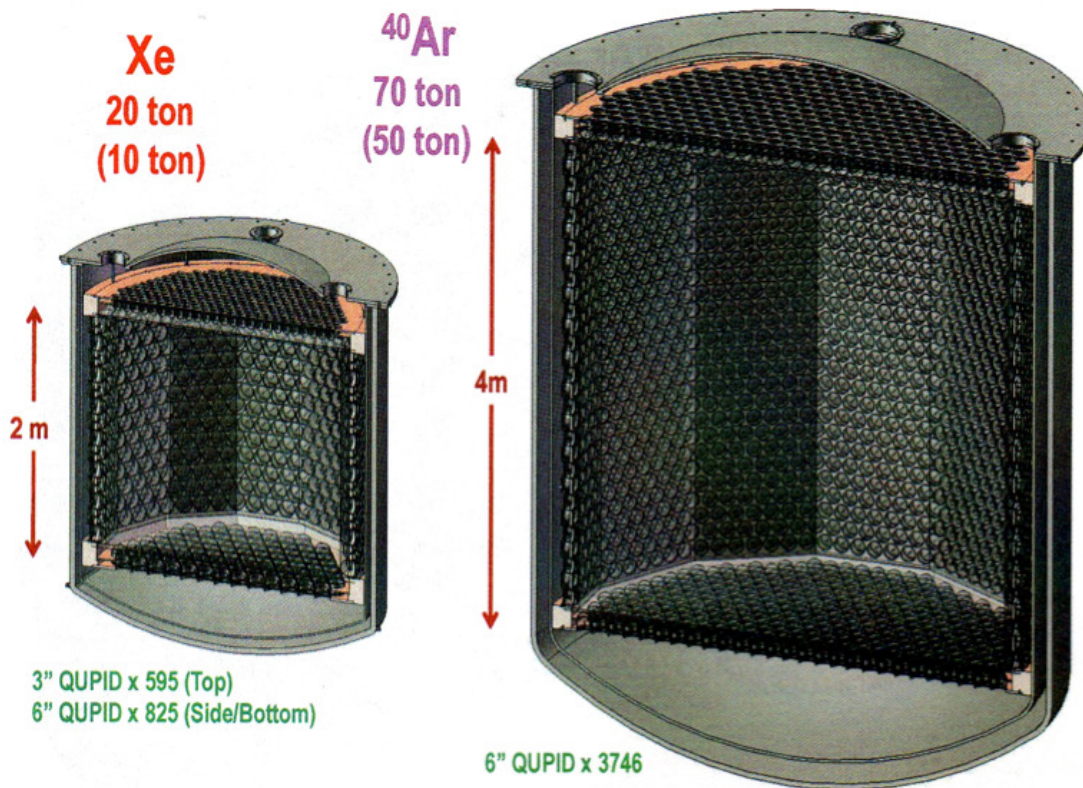


Figure 2: Main parameters of the 10 ton/50 ton (fiducial) G3 system

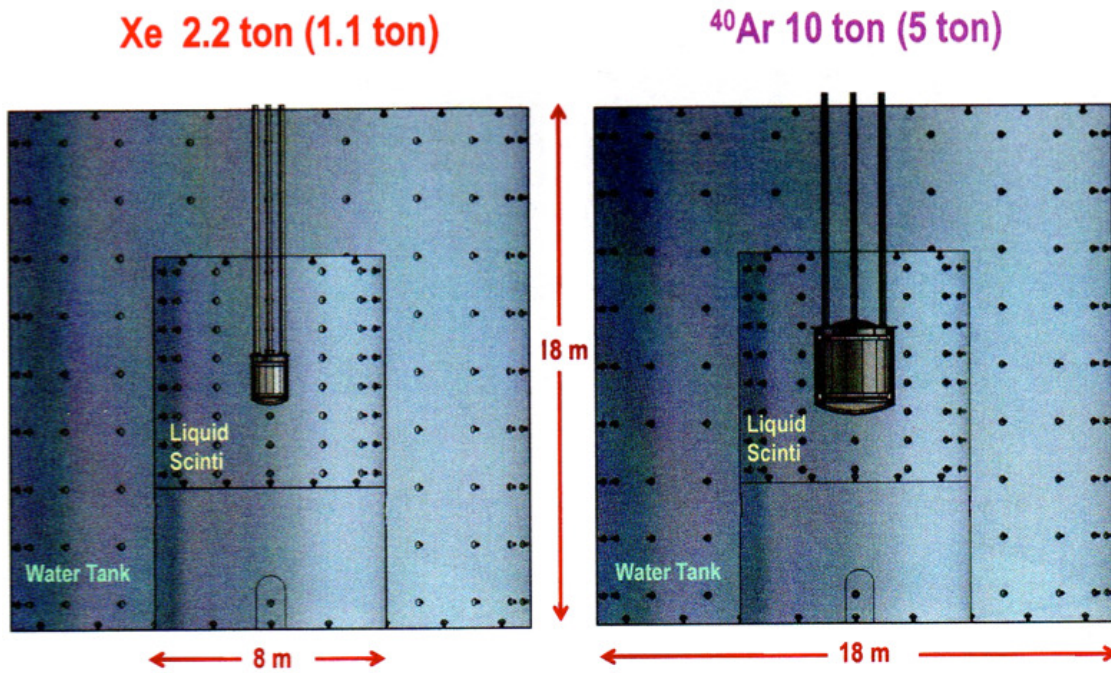


Figure 3: G2 system (1t Xe/5t Ar) in water and liquid scintillator shields

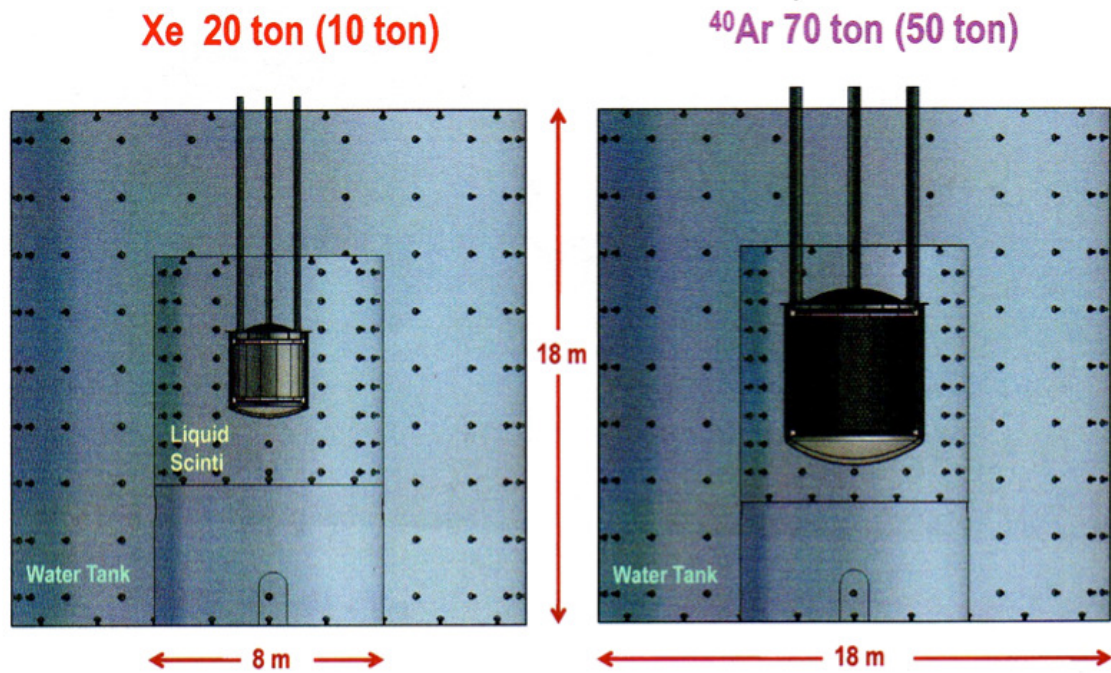


Figure 4: G3 system (10t Xe/50t Ar) in water and liquid scintillator shields

stable operation for periods in excess of a year. A 60 kg fiducial mass (48 kg fiducial mass) detector in the XENON series is now in successful operation [9]. In this paper we study the achievable backgrounds and potential physics sensitivity of the detection system in Tab.1, without further consideration of hardware design.

Illustrations of the basic internal structure of the G2 and G3 systems are shown in Fig.1 and Fig.2. Fig.3 and Fig.4 show the detectors immersed in water and liquid scintillator shields (to be discussed further in Appendix A). A constant water-shielding diameter is used to illustrate both systems, although smaller water shield thicknesses would be acceptable for the G2 system. The G4 Xe detector would be identical in configuration to the G3 Ar detector of Fig.2. The photodetectors shown in Fig.1 and Fig.2 register both the direct scintillation light from each event (referred to as S1) and also the simultaneous ionization which is drifted to the liquid surface by an electric field and then extracted and further drifted to produce proportional scintillation in the gas (referred to as S2). The electric drift field will be typically 0.5 - 1 kV/cm. XENON100 [10] operated at 0.5 kV/cm, while XENON1T [11] is designed at 1 kV/cm with a drift length of 100 cm, for which the total voltage 100 kV has been achieved in the R&D phase of that project. Thus the voltage requirements of the G2 stage are already demonstrated. The G3 stage would need a voltage of 200 kV for the xenon detector, which will also suffice for the argon detector at a field of 0.5 kV/cm, and a liquid argon TPC with this maximum voltage is already under development for the LBNE experiment [12]. A G4 xenon detector would require either a (foreseeable) factor 2 improvement over the LBNE value or a compensating reduction in the drift field.

The ratio S2/S1 provides a parameter which separates nuclear recoil and electron recoil events into two populations with less than 1% overlap. For the photodetectors we envisage the use of 3 inch or 6 inch QUPIDs (avalanche photodiodes within a quartz enclosure [13]), which are designed to have a factor 100 lower U/Th activity, per unit area of coverage, than the best photomultipliers. The required numbers of these are summarised in the lower half of Tab.1. The QUPIDs have a quantum efficiency  $\sim 35 - 37\%$  [82] for the 180 nm Xe wavelength, while for the liquid argon detectors, a TPB coating [84] would be used to wavelength-shift the argon scintillation light into the QUPID range, again with a QE  $\sim 35 - 37\%$  [83]. Development studies [82] show that the QUPID dynamic range is sufficient to cover both the low energy dark matter searches and the MeV-range neutrinoless double beta decay search.

Ideally the QUPIDs would fully surround the detector in a  $4\pi$  array, but a lower-cost option (at some sacrifice of light collection, energy threshold, and position resolution) would be to locate the QUPIDs at top and bottom only, using high-reflectivity ( $> 95\%$ ) PTFE on an array of 10 - 12 flat panels around the sides of the target volume (illustrated for the G2 Xe detector in Fig.1). Simulations below will show that, despite the greater simplicity and lower cost of these reflecting panels, the use of QUPIDs on the side walls would improve the light collection, and hence the energy threshold and detector sensitivity, by a factor 2 throughout most of the target volume.

In Sec.2 we use the basic expressions for WIMP nuclear recoil spectrum (on the assumption of a canonical velocity distribution), and spin-independence of the WIMP-nucleon cross section, to determine the sensitivity of each of these detector systems to WIMP-nucleus cross-section and WIMP mass, on the assumption that backgrounds (from neutron, gamma, and electron recoil events) can be reduced to the level  $\sim 0.1 - 0.5$  background events per year - i.e. signals or limits not background limited. We also show the sensitivity to the expected annual modulation arising from the Earth's orbital and Galactic motion, and the sensitivity to other types of WIMP-nucleus interaction, in particular spin-dependent and hypothetical inelastic interactions.

In Sec.3 we discuss in detail simulation results of both external water shielding and the reduction of detector backgrounds from local radioactivity, in the photodetectors and detector vessel, showing that a combination of a liquid scintillator veto and self-shielding by an outer thickness of target

material provides the key to achieving an essentially background-free fiducial target volume in all three of the G2, G3 and G4 systems. In addition we discuss the reduction of backgrounds from radioactive contaminants of liquid Xe and Ar.

In Sec.4 we calculate the sensitivity of these detectors to neutrinos from the solar pp chain and from a Galactic supernova. Finally in Sec.5 we show that sufficiently low backgrounds could be achieved in the G3 or G4 systems for the observation of neutrinoless double beta decay from  $^{136}\text{Xe}$  at the lifetime level  $10^{27} - 10^{28}$  y corresponding to the Majorana mass estimated from neutrino mixing data. Other possible configurations for this include a concentric target of enriched  $^{136}\text{Xe}$  shielded by  $^{136}\text{Xe}$ -depleted Xe (the “XAX” scheme, described in [13]) and the use of Xe/Ar mixtures.

## 2. Sensitivity to WIMP cross-section and mass

### 2.1. Nuclear recoil spectra from WIMP-nucleus collisions

The basic detector requirements, expected counting rates, and the dependence on target material and WIMP mass, can be seen from the expected form of the nuclear recoil energy spectrum. Adopting the “canonical” model of a Galactic dark matter velocity distribution similar in general shape to a Maxwell-Boltzman distribution, the resulting differential counting rate (events/keV/kg/day) with respect to recoil energy  $E_R$  (keV) is given by [14, 15]

$$dR/dE_R \text{ (events/keV/kg/d)} = c_1 [R_0/E_0 r] e^{-c_2 E_R/E_0 r} F^2(E_R) \quad (1)$$

where  $r = 4M_D A / (M_D + A)^2$  for target element  $A$  and incident particle mass  $M_D$  (both expressed in GeV),  $E_0 = 0.5 \times 10^6 M_D (v_0/c)^2$  ( $v_0 =$  Galactic velocity dispersion  $\approx 0.0007c$ ,  $E_0$  in keV) and  $F$  is a nuclear form factor correction. The coefficients  $0.5 < c_1, c_2 < 1$  provide an approximation for the motion of the Earth relative to the Galaxy. For a stationary Earth  $c_1 = c_2 = 1$ , giving a total event rate  $R_0$ . The orbital motion of the sun modifies this to  $c_1 = 0.78$ ,  $c_2 = 0.58$  with a further  $\pm 4\%$  seasonal variation arising from the orbital motion of the Earth [14, 15].

Thus an experimental limit on, or measurement of, the differential rate Eq.1 for a given range of  $E_R$  leads to a corresponding limit or value of  $R_0$  (events/kg/d) for each assumed value of  $M_D$ . This in turn can be converted [32] into a limit or value for the WIMP-nucleon cross section  $\sigma_{W-N}$  using the following relation, assuming a coherent spin-independent interaction and a detection efficiency and energy threshold capable of registering a fraction  $f$  (typically  $\sim 0.3 - 0.5$ ) of the total events in the spectrum of Eq.1:

$$\sigma_{W-N} \text{ (pb)} = 0.0091 \frac{R_0}{A^2 r f} \quad (2)$$

The above basic Eq.1 and Eq.2 reveal two key features:

1. Eq.2 shows that the total spin-independent normalized event rate  $R_0/r$  is proportional both to the interaction cross-section  $\sigma_{W-N}$  and to  $A^2$ , the square of the target atomic mass number.
2. Eq.1 shows a dependence on the dark matter particle mass  $M_D$  through the quantity  $E_0$ , so that a larger dark matter mass gives a more slowly falling spectrum. Thus, if a spectrum of events could be observed, the mass of particle responsible could be estimated as the maximum likelihood fit of  $M_D$  to Eq.1.

The above properties enable us to resolve the concern that it would be difficult to distinguish a genuine dark matter signal from a residual background of neutrons or spurious instrumental noise effects. A unique identification of a genuine dark matter signal could be obtained by two methods:

- a) The use of two target elements, to verify the rate dependence on  $A^2$ .

- b) Confirmation that the same value of  $M_D$  results, within experimental error, from the recoil spectrum of each target element.

It is of particular note that while method *a)* is based on comparing absolute counting rates for two different elements, method *b)* depends on the shape of the spectrum only, and not on the absolute counting rate. Thus the nuclear coherence of the interaction, and the mass determination, provide two mathematically independent methods of signal identification.

These comparisons ideally require that the two elements should be used in detectors with similar physical principles and technology. To achieve this, we can take advantage of the fact that detectors using similar principles have already been developed for the noble liquids Xe and Ar. Fig.5 compares the normalized nuclear recoil energy spectra for Xe and Ar (with other nuclei for comparison) for a dark matter particle mass of 100 GeV and interaction cross-section of  $10^{-44}$  cm<sup>2</sup>. This shows that a Xe target has a greater sensitivity than an Ar target at low energy, but that Ar is less affected by the form factor correction in Eq.1, so higher energy recoils can usefully contribute (up to a limit set by the Galactic escape velocity – see below). It is thus evident that the design and operation of two such detectors of similar design, one using Xe and the other Ar as the target element, and with similar operating conditions, provides a powerful combination for dark matter identification and particle mass estimation. It also follows by integrating the curves in Fig.5 that to achieve similar dark matter counting rates, and assuming experimental recoil energy thresholds 8 keV for Xe and 20 keV for Ar (discussed in detailed below) the Ar detector needs to have about 5 times the fiducial mass of the Xe detector, which gives rise to the choices of target mass values summarized above in Tab.1.

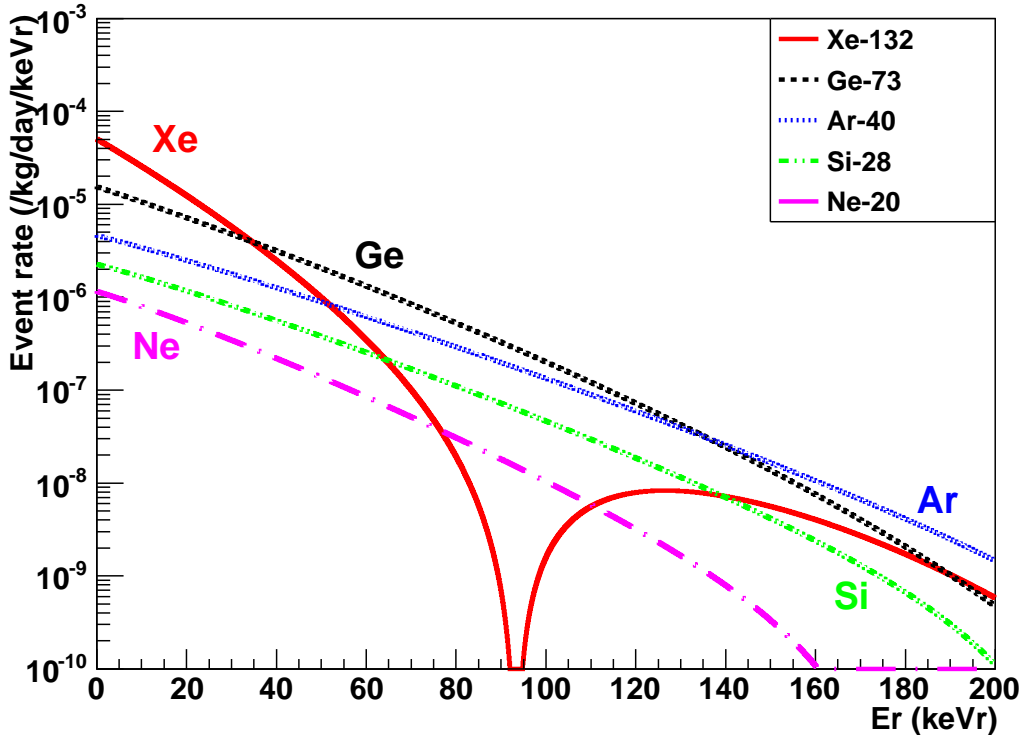


Figure 5: Differential nuclear recoil spectra for Xe and Ar and other nuclei, calculated from Eq.1 for a WIMP mass of 100 GeV.



## 2.2. Sensitivity to spin-independent cross section

We next use the above Eq.2 to estimate the cross section sensitivity for the systems described in Sec.1. The term “sensitivity” has two meanings in common use. The “limiting sensitivity” is the cross section corresponding to zero observed events (in a pre-selected background-free “event box”) and hence a statistical limit of 2 – 3 events. For larger detectors envisioning a non-zero signal, we need to define the “useful sensitivity” as the cross section for which the observed number of events would be sufficient to provide a fit to a recoil spectrum to allow an estimate of the particle mass. As an example, for typical WIMP-nucleon cross sections expected from supersymmetry ( $10^{-44}$   $\text{cm}^2$  to  $10^{-46}$   $\text{cm}^2$  or  $10^{-8}$  to  $10^{-10}$  pb), the corresponding interaction rates from Eq.1 and Eq.2 are expected to be in the range 0.1 – 10 per day per ton (fiducial) of Xe and a factor  $\sim 5$  lower for Ar. Net experimental efficiencies of  $\sim 30\% - 50\%$  are assumed (discussed further below) and already known to be achievable in detectors with target masses  $\sim 10 - 100$  kg [13, 31]. Thus a target mass of 1-ton (fiducial) Xe would provide a quantitatively useful signal of  $\sim 20 - 30$  events/y at  $10^{-46}$   $\text{cm}^2$ , or an upper limit of 2 – 3 events/y at  $10^{-47}$   $\text{cm}^2$ . Comparable signal rates would be achieved in 5 tons fiducial mass of Ar.

Fig.6 shows the spin-independent cross section limits for the G2, G3, G4, Xe and Ar detectors in one year of operation, compared with some existing limits. These are calculated for the case of zero observed signal (using 2.4 event 90% upper limit) and assuming all fiducial backgrounds reduced to  $< 0.2$  events/y. It is the purpose of this paper to show that such background levels can be achieved for each of the detector systems of Tab.1, and will be discussed in Sec.3.

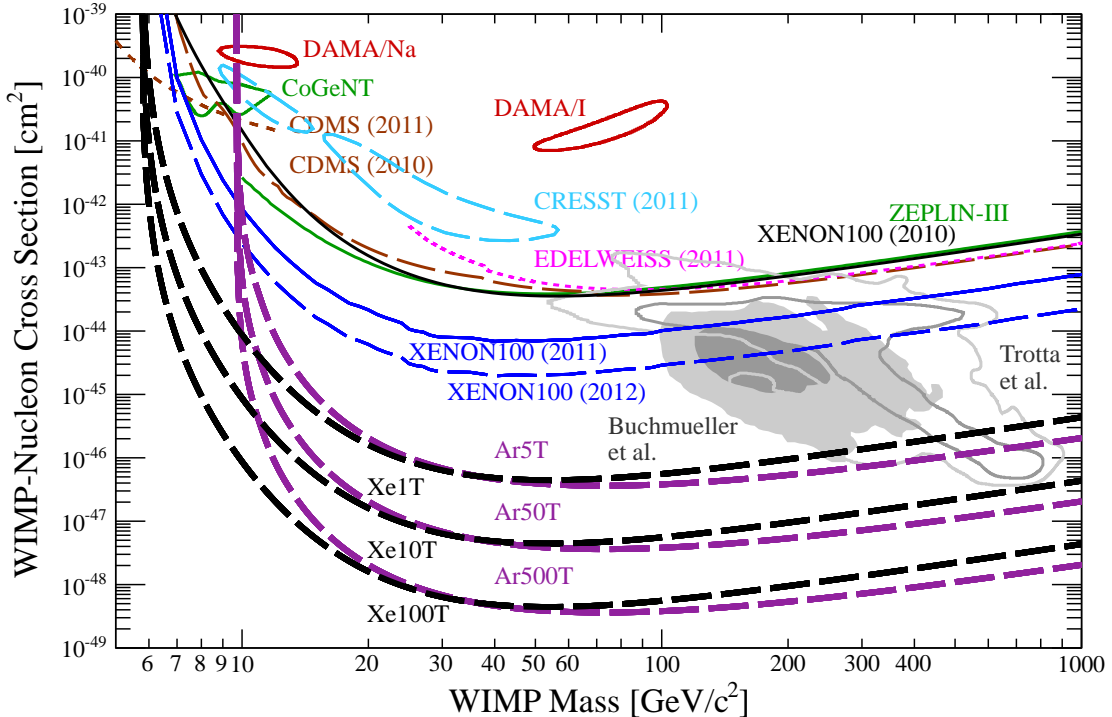


Figure 6: Spin-independent sensitivity plots for Xe and Ar detectors in G2, G3 and G4 systems, assuming future nuclear recoil energy thresholds  $\sim 8$  keVnr for Xe and  $\sim 20$  keVnr for Ar, as discussed in Appendix C. Curves show 90% confidence limits for WIMP-nucleus cross section ( $10^{-46}$   $\text{cm}^2 = 10^{-10}$  pb) for live time of 1 year, for zero background events in a signal region 50% of total nuclear recoil band and 80% cut efficiency. Some recent limits and hypothetical signal region are shown [18, 19, 20, 21, 22, 23, 24, 25, 26, 28], together. The shaded region shows the most favoured regions of parameter space from supersymmetry theory. above the  $\sim 40$  GeV mass limit from accelerator searches [29, 33], but could extend to lower cross sections in some variations of the theory.

### 2.3. Number of signal events

If a non-zero dark matter nuclear recoil signal exists at a cross section larger than the minimum sensitivity plotted in Fig.6, then the number of signal events available to form a recoil spectrum is calculable from Eq.1 of Sec.2.1 and plotted in Fig.7 against WIMP mass for 10 ton-y Xe and 50 ton-y Ar, the numbers for other running times and target masses being proportional.

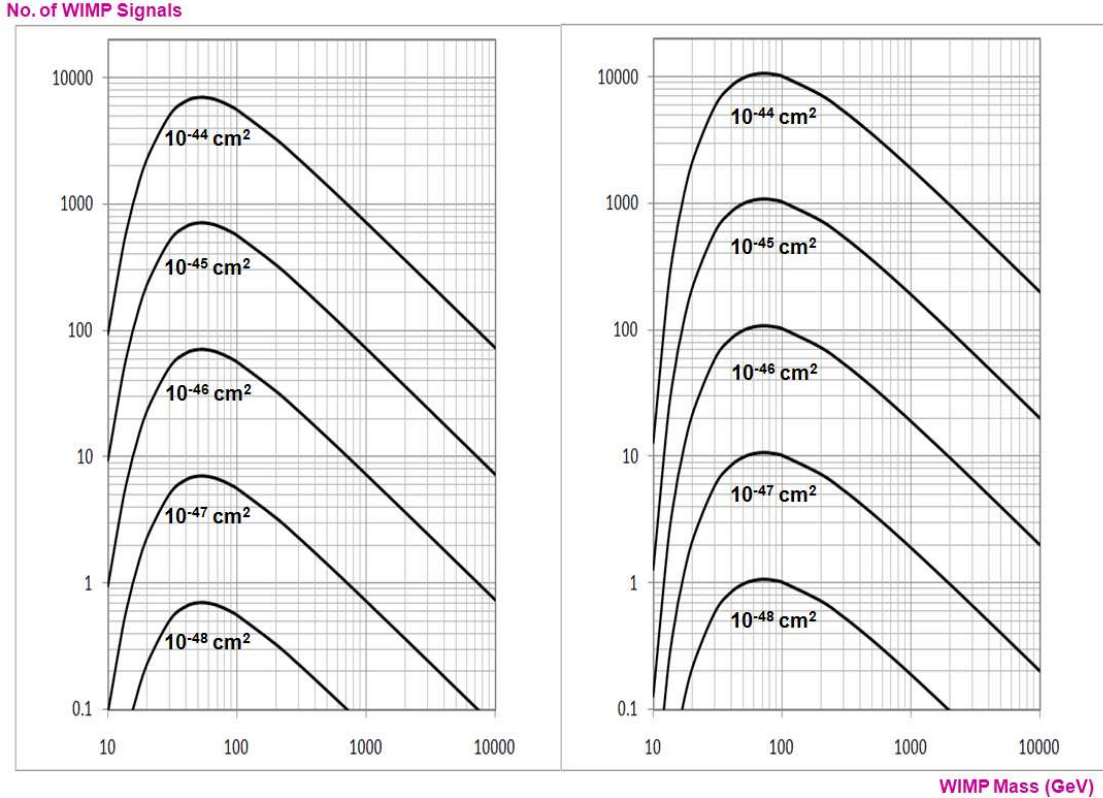


Figure 7: Number of events (vertical axis) in signal range versus WIMP mass for different WIMP-nucleon cross-sections, assuming the same efficiency factors used for Fig.6 and nuclear recoil energy thresholds  $\sim 8 \text{ keVnr}$  for Xe and  $\sim 20 \text{ keVnr}$  for Ar, as discussed in Appendix C. (Left plot) 10 ton-y (fiducial) liquid Xe in range 8 – 45 keVr. (Right plot) 50 ton-y (fiducial) liquid Ar in range 20-200 keVr.

### 2.4. Dependence on recoil energy threshold and Galactic escape velocity

The nuclear recoil energy scale is based on the LXe scintillation signal and thus requires knowledge of the relative scintillation efficiency of nuclear recoils, with recent direct measurements down to energies as low as 3 keV indicating a slow decrease from 15 keV [40], with Monte Carlo simulation techniques providing consistent results [41]. Here we have assumed a recoil threshold of 8.5 keV [9] for the purpose of calculating the Xe sensitivity estimates of Fig.6, although improved light collection (for example, from full photodetector coverage or higher quantum efficiency) would result in a lower effective threshold. In the case of Ar, the recoil energy threshold is dependent on the degree of success in reducing the low energy background from  $^{39}\text{Ar}$ , which restricted the energy threshold to  $\sim 40 - 55 \text{ keVnr}$  in the initial WARP experiment with natural Ar [7]. From the discussion and references in Appendix C.2, we adopt an expectation of 20 keV threshold for the purpose of calculating the limit curves in Fig.6. In addition we note, from the flatter Ar spectrum

in Fig.5, that the Ar limits will be less sensitive to energy threshold than the faster-falling spectrum for Xe.

To estimate the expected total count rate, the spectra of Fig.5 have to be integrated between a lower limit given by the detector nuclear recoil energy threshold, and an upper limit given by the Galactic escape velocity at the position of the sun (hence giving an upper limit on the energy of a dark matter particle in our vicinity). This escape velocity, although governed largely by the amount and distribution of the dark matter, can be estimated from the observed velocity distribution of the stellar population, the most recent detailed study concluding that the escape velocity lies in the range  $550 \pm 50$  km/s [34].

From this, and for simplicity treating the escape velocity ( $v_{esc}$ ) as a “cut-off” ( $E_{cut}$ ) rather than an additional attenuation of the velocity distribution, we can calculate from Eq.1 the observable percentage of the total events in the spectrum as function of the recoil energy threshold ( $E_{thr}$ ) and the escape velocity. The results are shown in Tab.2 (for a Xe target) and Tab.3 (for an Ar target) with those for the most probable escape velocity shown in bold.

These reduced collection figures, arising from the lower and upper cut-off in the spectrum, are in addition to the basic factor 5 difference in the total counts resulting from the form factor and  $A^2$  differences in Eq.1 and Eq.2. Tab.2 and Tab.3 also show that the Xe detector threshold needs to be about a factor 2 lower than the Ar detector threshold to achieve a similar event-collection efficiency. Assumed energy threshold values of 8.5 keVnr for Xe and 20 keVnr for Ar are used to calculate the G2, G3, and G4 sensitivity curves in Fig.6.

	Detector recoil threshold keV			
Escape Velocity km/s (energy cut-off)	5	10	15	20
600 (120 keV)	74	51	32	18
<b>550 (100 keV)</b>	<b>74</b>	<b>51</b>	<b>32</b>	<b>18</b>
500 (83 keV)	74	51	32	18
450 (67 keV)	73	50	31	17

Table 2: Percentage of total recoil spectrum registered in Xe target for  $M_D = 60$  GeV as a function of recoil energy threshold and escape velocity cut-off.

	Detector recoil threshold keV			
Escape Velocity km/s (energy cut-off)	10	20	30	40
600 (120 keV)	68	53	37	26
<b>550 (100 keV)</b>	<b>66</b>	<b>51</b>	<b>35</b>	<b>24</b>
500 (83 keV)	62	47	32	21
450 (67 keV)	57	42	27	16

Table 3: Percentage total recoil spectrum registered in Ar target for  $M_D = 60$  GeV as a function of recoil energy threshold and escape velocity cut-off.

It is of interest also to simulate the difference in light collection between the use of high reflectivity panels on the detector side-walls (see Xe detector illustration in Fig.1) and the replacement

of these by photodetectors. For Xe several mm PTFE inner walls, comparisons of simulated and observed detector performance are consistent with reflectivities 95-98% [86, 87] and for Ar comparable reflectivities appear to be achievable by coating inner wall with TPB wavelength shifter [88]. Fig.8 shows, for simulations in liquid Xe, that the (lower cost) reflecting panels give *i*) a less uniform light collection and *ii*) up to a factor 2 lower light output in photoelectrons/keV, creating a higher and position-dependent energy threshold.

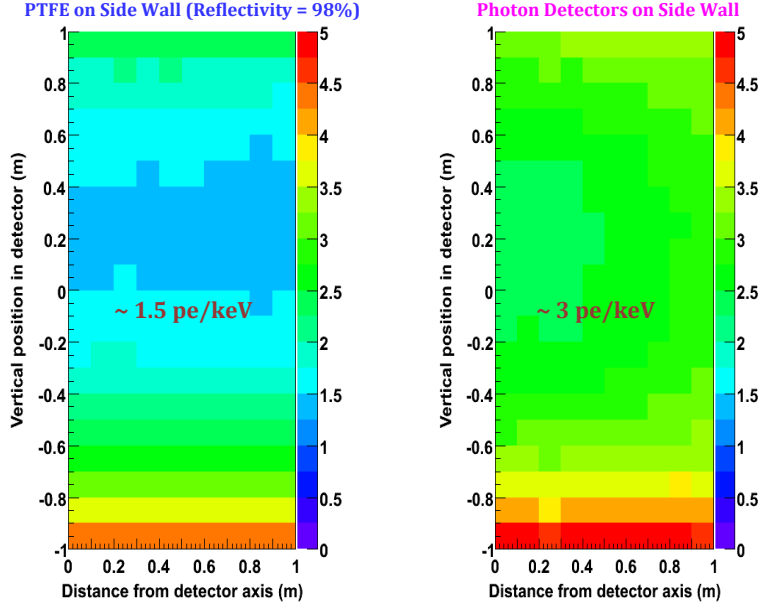


Figure 8: Comparison of light collection for sidewalls covered in QUPID photodetectors or 98% reflective PTFE panels for a  $2\text{ m} \times 2\text{ m}$  Xe target. The simulations used typical input parameters of Xe light output of 60 uv photons/keV, quenched to 30 photons by an assumed electric field of  $\sim 50 - 100\text{ kV/m}$ , with a 30% photocathode coverage, and 35% QUPID quantum efficiency.

### 2.5. WIMP mass determination – single detector

As discussed in Sec.2.1, a best fit of an observed spectrum of events to Eq.1 can yield a value for the WIMP mass with an accuracy dependent on target mass and running time.

Fig.9 (upper) illustrates this for the case of an interaction cross section  $10^{-45}\text{ cm}^2$  and the G2 1-ton Xe detector running for 1 year, showing  $1\sigma$  and  $2\sigma$  error contours for different WIMP mass values. Fig.9 (lower) shows the smaller errors resulting from the G3 10-ton detector running for the same time period. The same plots would apply for G3 and G4 detectors for an interaction cross-section  $10^{-46}\text{ cm}^2$ , the order of magnitude smaller cross section, with an order of magnitude greater mass, giving the same event numbers.

Fig.10 shows corresponding error contours for the G3 50-ton Ar detector, the higher mass of Ar providing event numbers comparable to those from the Xe detector, in accordance with the factor  $\sim 5$  lower yield of events/ton for Ar, as calculated above. Again the G4 Ar detector would provide a similar yield of events for a cross-section  $10^{-46}\text{ cm}^2$ . The one and two-sigma errors shown in these plots, and also in Figs. 11 and 12, are those arising specifically from statistical uncertainty in

the numbers of events, and assume no major departures from the “canonical” velocity distribution discussed in Sec.2.1 and the associated “standard” value of  $v_o$ .

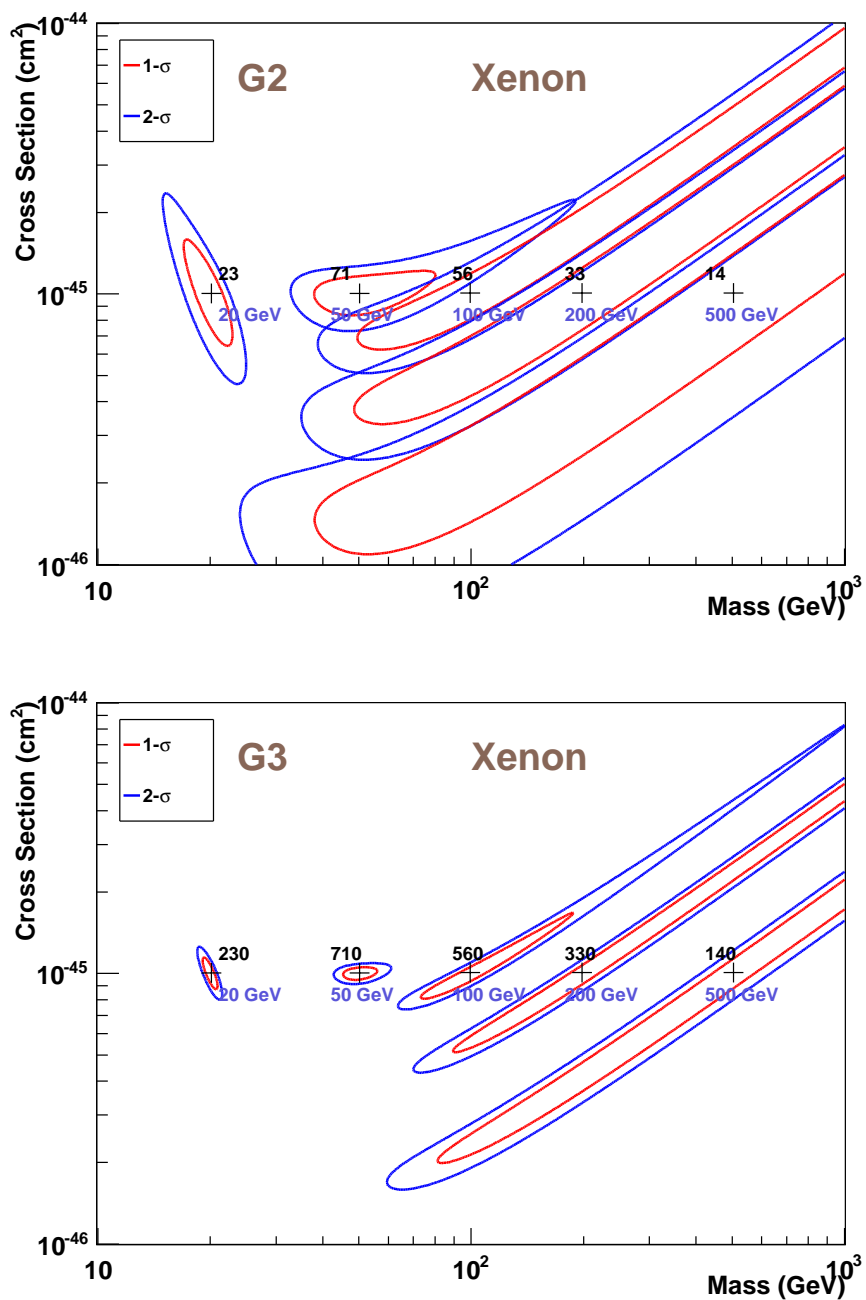


Figure 9: Examples of estimation of WIMP mass from spectrum of events in xenon detectors running for 1 year:  
*(upper plot)* G2 1-ton,  
*(lower plot)* G3 10-ton

Red and blue contours show  $1\sigma$  and  $2\sigma$  confidence spread for cross section  $10^{-45}$  cm<sup>2</sup> and mass values labelled in blue, event numbers in black.

The plots apply equally to G3 (upper) and G4 (lower) for cross section  $10^{-46}$  cm<sup>2</sup>.

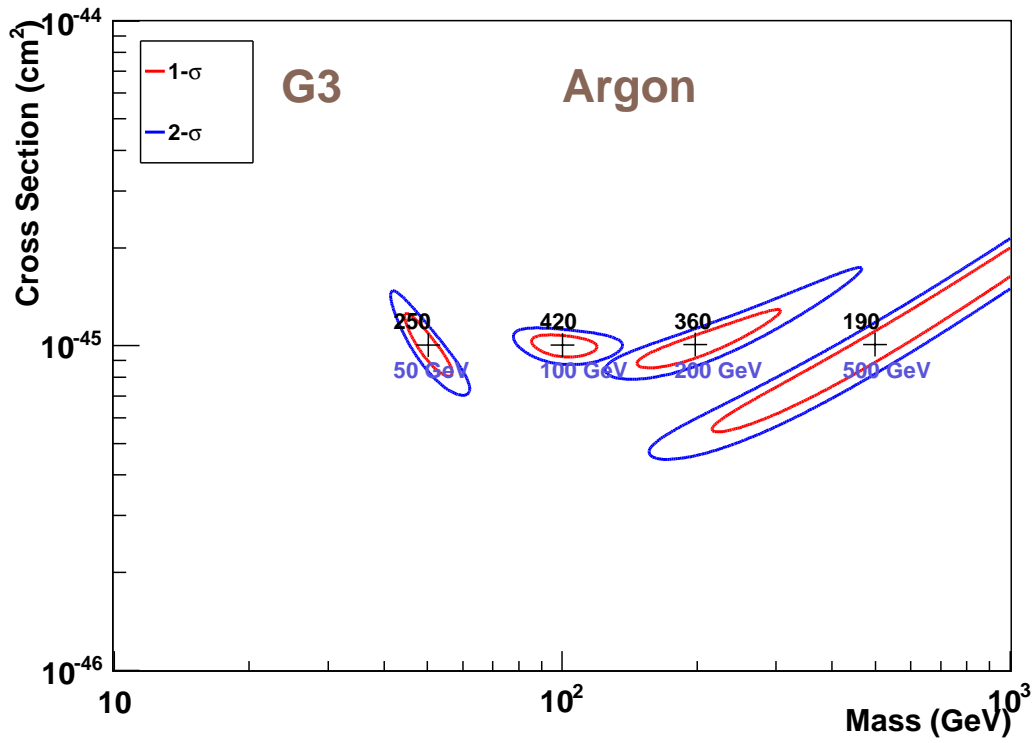


Figure 10:  $1\sigma$  and  $2\sigma$  contours of mass precision for cross-section  $10^{-45} \text{ cm}^2$  as in Fig.9, but for 50 ton-y G3 Ar detector. Numbers of events (in black) for each WIMP mass value are similar in order of magnitude to those in Fig.9, consistent with the requirement for an Ar/Xe target mass ratio  $\sim 5$  to obtain similar signals in each. The same plot, with the same event numbers, would apply to the G4 Ar detector for a cross-section  $10^{-46} \text{ cm}^2$ .

2.6. WIMP mass determination using combined Xe and Ar signals

As discussed in Sec.2.1, an important aspect of the use of two different elements is that they should provide independent signals that agree in the derived WIMP mass. Fig.11 gives an example of this, for the G2 system with a cross section  $10^{-45}$  cm<sup>2</sup> and a specific dark matter mass of 100 GeV, showing that the error contours for each will overlap and surround the same mass and cross-section values. The same plot applies to the G3 system for a cross-section  $10^{-46}$  cm<sup>2</sup>, and to the G4 system for a cross-section  $10^{-47}$  cm<sup>2</sup>.

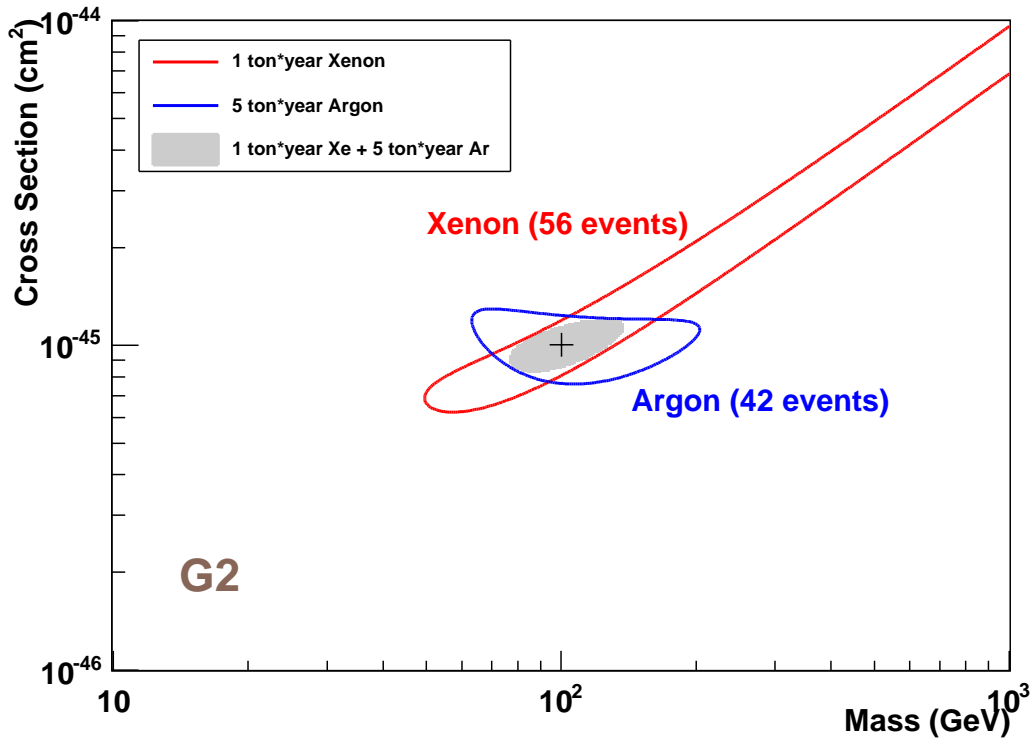


Figure 11: Overlaying Xe and Ar signals. Example of overlap of  $1\sigma$  contours from 1 ton-y Xe and 5 ton-y Ar for a specific WIMP Mass 100 GeV and WIMP-nucleus cross-section  $10^{-45}$  cm<sup>2</sup>, showing agreement of WIMP mass values and similar event numbers from Xe and Ar detectors with target mass ratio  $\sim 5$ . This plot applies also to the larger G3 system with a lower cross section  $10^{-46}$  cm<sup>2</sup> and to the G4 system with a cross section  $10^{-47}$  cm<sup>2</sup>.

Further examples of this overlap, illustrating the level of precision obtainable (for a one year exposure) by combining Xe and Ar signals, are shown in Fig.12 for the following cases:

1. (*upper plot*) G2 and (*lower plot*) G3, showing WIMP-nucleon mass measurement at cross-section  $10^{-45}$  cm<sup>2</sup> for WIMP masses 50 – 500 GeV. The plots also show the number of signal events from Xe and Ar in each case.
2. (*upper plot*) G3 and (*lower plot*) G4, allowing WIMP mass measurement at cross section  $10^{-46}$  cm<sup>2</sup>. The event numbers remain unaltered by this scaling.
3. (*upper plot*) G4, allowing the lower precision WIMP mass measurement at a cross section  $10^{-47}$  cm<sup>2</sup>.

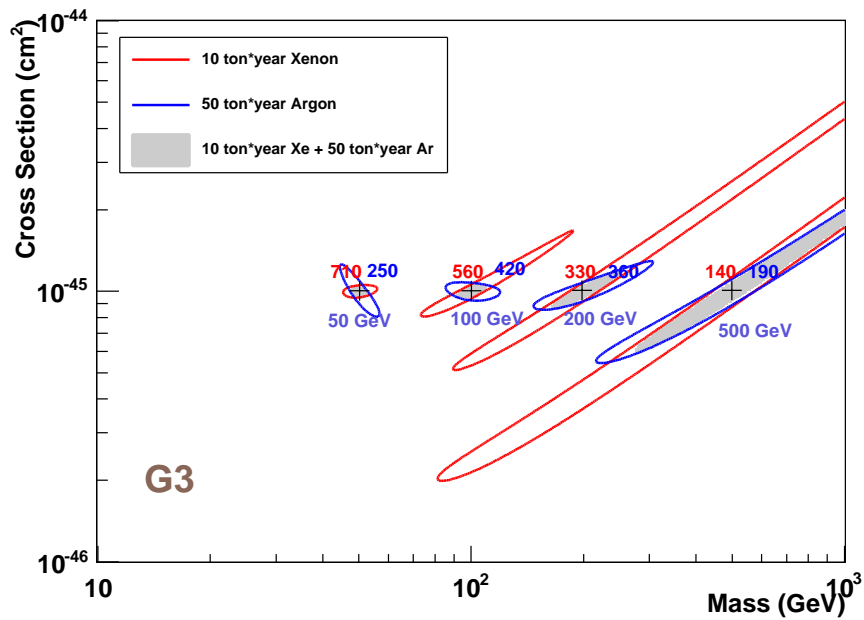
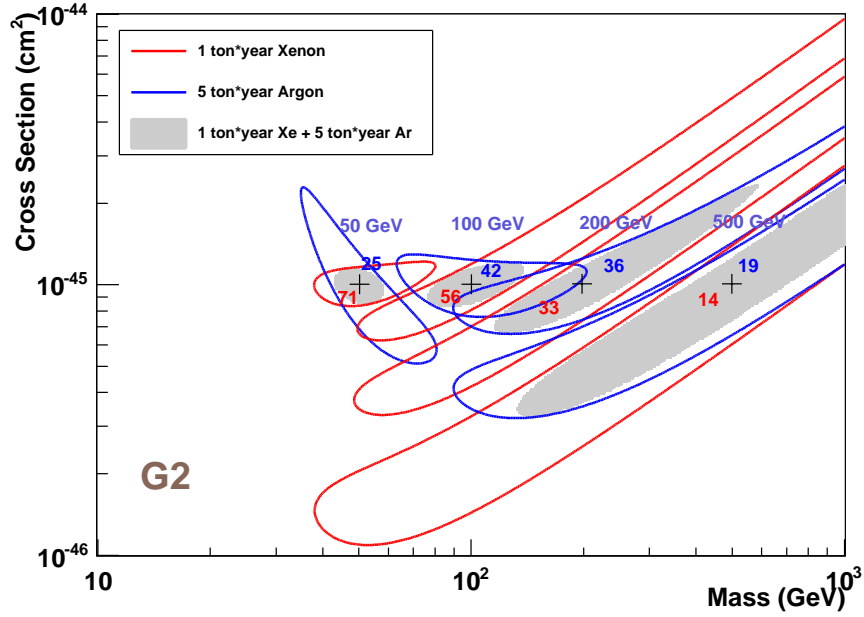


Figure 12: Examples of overlap of  $1\sigma$  Xe and Ar contours for WIMP masses 50 - 500 GeV  
*(upper)* cross-section  $10^{-45}$   $\text{cm}^2$  with G2 system: 1 ton-y Xe & 5 ton-y Ar  
 or cross-section  $10^{-46}$   $\text{cm}^2$  with G3 system: 10 ton-y Xe & 50 ton-y Ar  
 or cross-section  $10^{-47}$   $\text{cm}^2$  with G4 system: 100 ton-y Xe & 500 ton-y Ar.  
*(lower)* cross-section  $10^{-45}$   $\text{cm}^2$  with G3 system: 10 ton-y Xe & 50 ton-y Ar  
 or cross-section  $10^{-46}$   $\text{cm}^2$  with G4 system: 100 ton-y Xe & 500 ton-y Ar.



### 2.7. Annual signal modulation

With availability of a sufficiently large sample of signal events, an additional identifying signal would be the expected annual modulation arising from the motion of the Earth around the Sun, as the sun moves through the Galaxy. This can be conveniently parameterised as cyclic variations in the values of  $c_1$  and  $c_2$  in Eq.1 of Sec.2.1 (see [14, 15] for tables of values). The resulting difference in differential energy spectrum between June and December is shown, in dimensionless form, in Fig.13, which also shows, for comparison, a dashed curve for the spectrum that would result for an Earth stationary in the Galaxy.

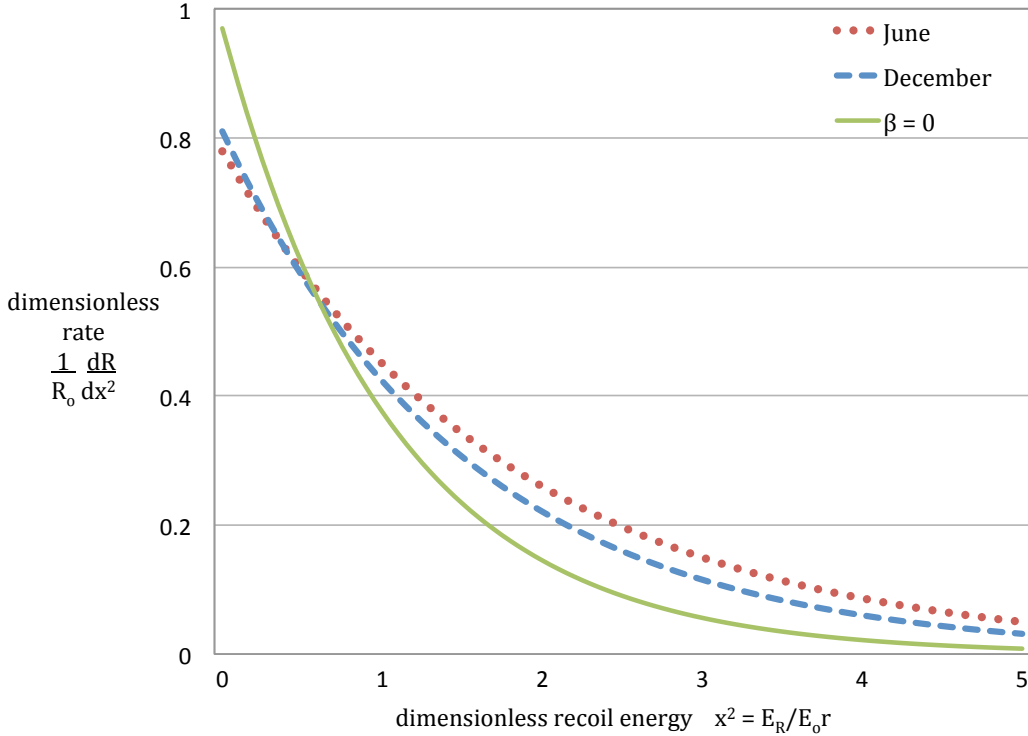


Figure 13: Predicted annual fluctuation of dimensionless recoil energy spectrum arising from orbital motion of the earth combined with Galactic motion of the sun (from [14]). The dashed line shows the spectrum expected for a stationary Earth.

The June and December curves cross at a recoil energy value  $\sim 0.7 E_0 r$ , where  $E_0$  and  $r$  are defined in Sec.2.1, which gives a mass-dependent crossover energy in the region 10 – 20 keV for WIMP masses 60 – 100 GeV. Of interest in the case of Xe and Ar detectors is the fact that, for that range of WIMP masses, the operating range of Xe lies predominantly below the crossover energy, while the operating range of Ar lies predominantly above the crossover energy. Thus the Ar detector may observe signal events which show a positive annual modulation – i.e. the June rate higher than the December rate, while at the same time the xenon detector may observe signal events showing a negative annual modulation – i.e. the June rate lower than December rate. This would provide an important confirmation of the Galactic origin of the signal. The fractional modulation of the total number of events as a function of WIMP mass is shown in Fig.14 (*upper plot*) for a cross section  $10^{-45} \text{ cm}^2$  and Fig.14 (*lower plot*) for a cross section  $10^{-44} \text{ cm}^2$ , with running times 10 ton-y Xe and 50 ton-y Ar, together with the  $1\sigma$  error contours. Thus these examples represent the G3 system running for one year or equivalently the same number of events from the G4 system running for 1 year with cross sections an order of magnitude smaller.

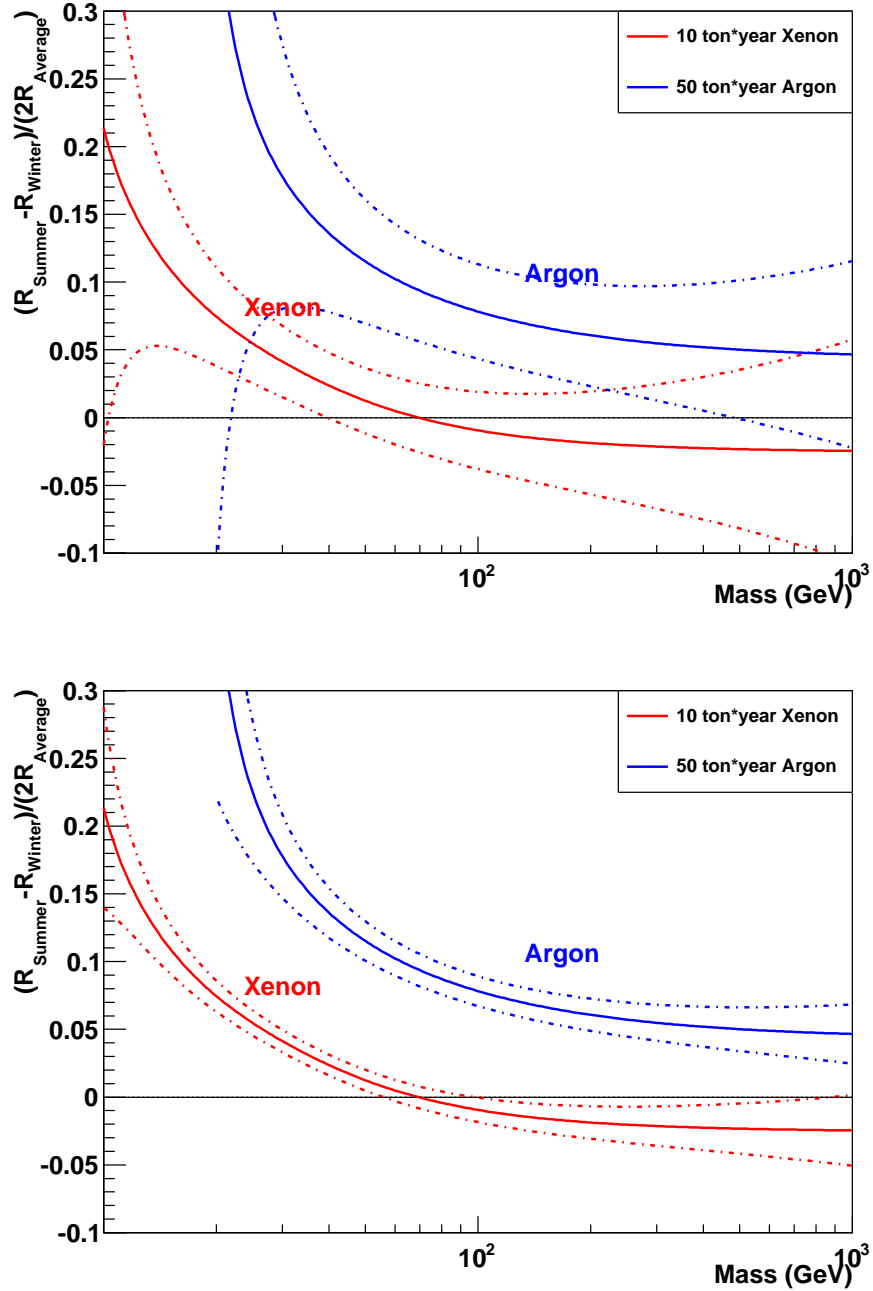


Figure 14: Fractional annual modulation versus WIMP mass, shown separately for 10 ton-y Xe and 50 ton-y Ar. Full lines show predicted mean. Dashed lines show  $1 - \sigma$  error bands.

(a) (*upper plot*) WIMP-nucleon cross section  $10^{-45} \text{ cm}^2$

(b) (*lower plot*) WIMP-nucleon cross section  $10^{-44} \text{ cm}^2$

The same plots will apply to 100 ton-y Xe and 500 ton-y Ar with cross sections a factor 10 smaller (i.e. giving the same event numbers)

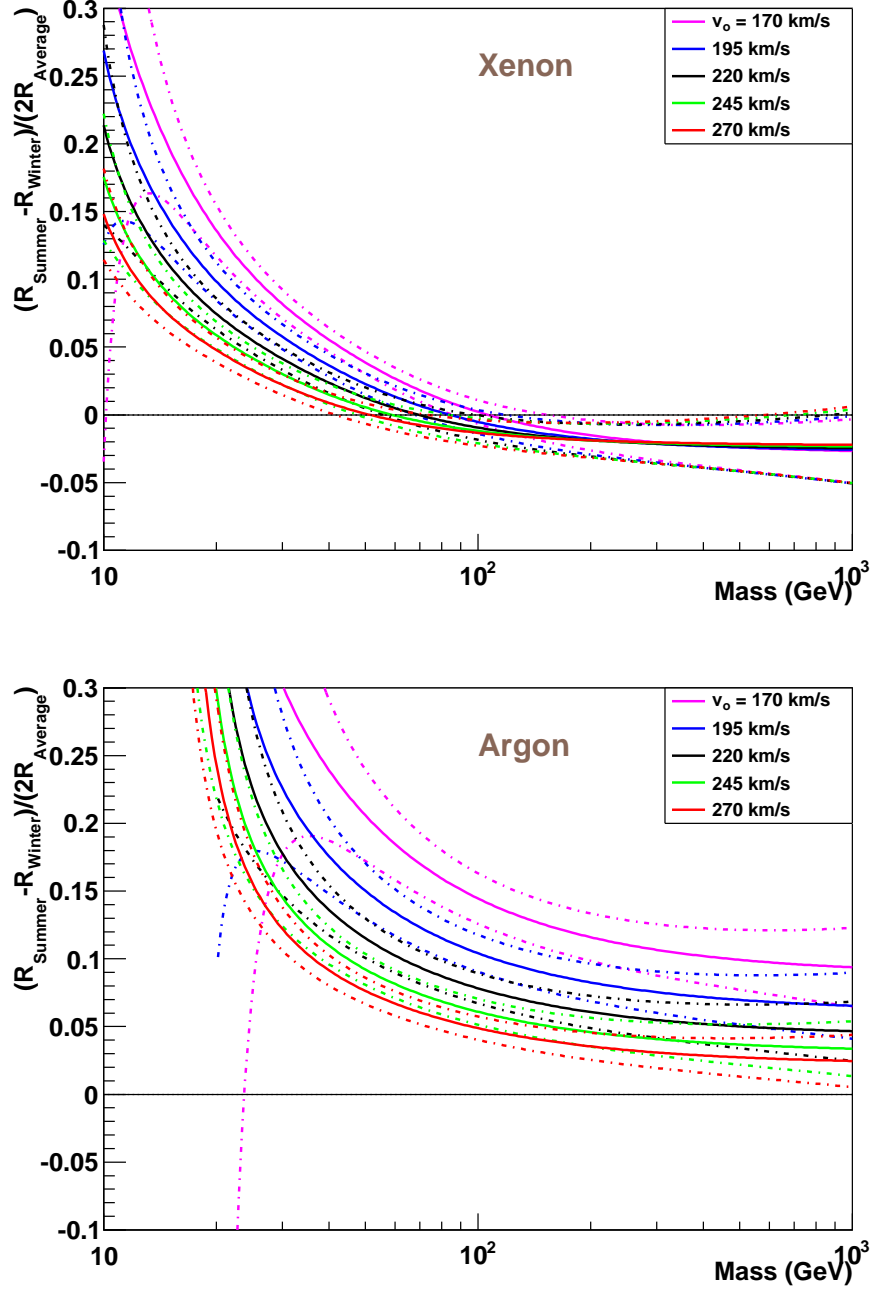


Figure 15: Example of the variation of annual modulation amplitude with WIMP mean velocity varied by  $\pm 50$  km/s about the “standard” assumption of 220 km/s. Dashed lines show  $1\sigma$  error bands for the illustrative case of 10 ton-y Xe, 50 ton-y Ar, for a WIMP-nucleon cross-section  $10^{-44}$  cm<sup>2</sup> (or equivalent numbers of events at  $10^{-45}$  cm<sup>2</sup> for 100 ton-y Xe and 500 ton-y Ar).

Following the difficulty of accounting for the persistent observed annual modulation of low energy events in the DAMA/LIBRA NaI arrays [16, 17] there has been interest in the effect of a possible uncertainty in the characteristic velocity  $v_0$  in the assumed WIMP velocity distribution [15], which is normally assumed to have the value  $v_0 \sim 220$  km/s (similar to that of the sun’s Galactic orbital velocity). We therefore illustrate in Fig.15 how the curves of annual modulation versus WIMP mass vary when the value of  $v_0$  is changed by  $\pm 50$  km/s. It is seen that modulation percentages may reach  $\sim 30\%$  at low WIMP masses if  $v_0$  is as low as 170 km/s. It is also apparent from the  $1\sigma$  error curves that the larger number of events provided by the G3 or G4 systems would be required for accurate investigation of annual modulation within a few-year time period.

### 2.8. Spin-dependent WIMP sensitivity

Because of the  $A^2$  multiplying factor for a coherent spin-independent interaction (i.e. involving the whole nucleus), it is usually believed that this will dominate over any spin-dependent interaction, which would involve interaction with usually a single unpaired nucleon in an odd- $A$  isotope. Nevertheless, spin-dependent interactions might dominate in some theoretical scenarios where the spin-independent term is suppressed. In addition, it has been suggested that the DAMA annual modulation [16, 17] might result from a low mass ( $< 15$  GeV) WIMP with spin-dependent interaction.

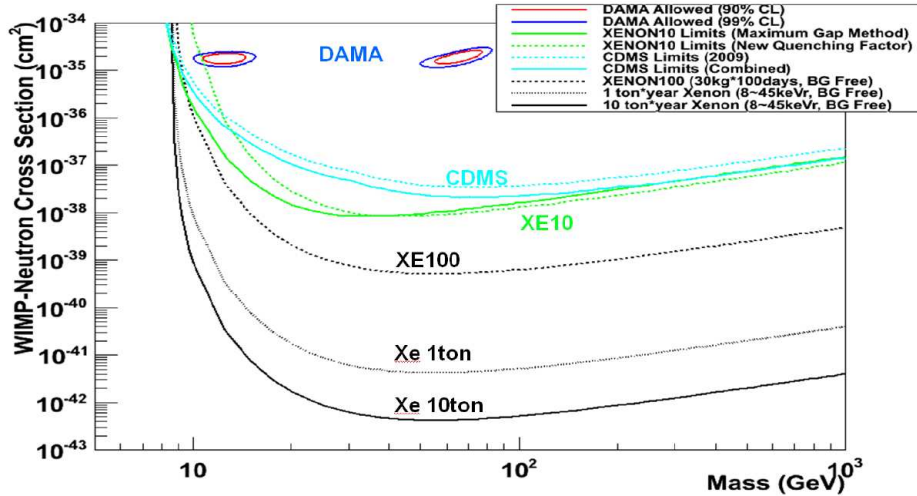


Figure 16: 90% limits for WIMP-neutron spin-dependent interactions for 1 ton-y and 10 ton-y Xe, also showing exclusion of DAMA limits by several previous experiments [16, 17, 39, 42, 43].

Xe has two stable odd isotopes,  $^{129}\text{Xe}$  (spin-1/2),  $^{131}\text{Xe}$  (spin-3/2), together constituting 47.6% of natural xenon, and is therefore able to observe signals from both spin-dependent and spin-independent interactions. Ar has only even- $A$  spin-0 stable isotopes, so that if WIMP-like signals were to be seen in liquid Xe but not in liquid Ar, this would be suggestive of a pure spin-dependent interaction (subsequently requiring confirmation by running with isotopically-enriched xenon to produce an enhanced odd- $A$  signal). Calculation of spin-dependent cross-section limits from the data is a more difficult process, requiring replacement of the spin-independent form factor in Eq.1 by a spin-dependent and nuclear structure-dependent form factor, and the replacement of the  $A^2$  factor in Eq.2 by a non-trivial combination of nuclear spin terms, which differ for neutrons and protons.

In the evaluation of spin-dependent limits for ZEPLIN III [26], the authors used the latest theoretical studies on the required nuclear spin terms and form factors, and concluded that the

limit curve (versus WIMP mass) for spin-dependent WIMP-neutron cross section lies close to a factor  $\sim 10^5$  higher than the limit curve for spin-independent interactions (Fig.6), while that for the WIMP-proton cross section lies close to a factor  $\sim 10^7$  higher. This factor  $\sim 100$  difference is consistent with the fact that both  $^{129}\text{Xe}$  and  $^{131}\text{Xe}$  nuclei contain unpaired neutrons, and hence are relatively insensitive to WIMP-proton scattering. These two scaling factors are almost independent of WIMP mass, so that the shapes of spin-dependent and spin-independent limit curves are essentially identical. Thus, for estimates of spin-dependent limits obtainable with the G2, G3, and G4 Xe detectors, it is necessary only to scale the Xe limit-curves in Fig.6 by the above factors  $10^5$  for WIMP-neutron and  $10^7$  for WIMP-proton interactions. The odd-isotopes of Xe provide the most sensitive experimental target element for detection of spin-dependent WIMP-neutron interactions [26].

### 2.9. Inelastic WIMP sensitivity

The concept of a dark matter particle that could exist in two mass levels, and thus recoil from a nucleus in an excited state, was introduced as a possible explanation of the DAMA annual modulation observations in a NaI detector [35, 36, 37]. The recoil spectrum differs from that of a single state particle, being suppressed at low energy, and peaking at a recoil energy of 40 – 50keV. For a hypothesised mass splitting  $\delta$  in the range 20 – 140 keV the spectrum can be consistent with the DAMA observations, while at the same time the annual modulation can be larger because one is sampling a higher velocity component of the WIMP velocity distribution [37] where the percentage seasonal fluctuations are larger [38].

Areas of inelastic cross section versus WIMP mass compatible with the DAMA annual modulation data for suitable choices of  $\delta$  are shown in Fig.17, together with published exclusion plots from XENON10 [39], XENON100 [42], CDMS [43], and ZEPLIN III [44]. It can be seen that the inelastic interpretation of the DAMA region appears now to be fully excluded. A limit curve for a 1 ton Xe detector (G2) is shown which will be capable of excluding the inelastic explanation of the DAMA modulation by a larger margin. Fig.17 is drawn for a galactic escape velocity of 550 km/s, and similar conclusions result from an assumption of the escape velocity anywhere in the range  $550 \pm 70$  km/s.

## 3. Backgrounds

### 3.1. Background categories and detector background discrimination

The cross-section sensitivity and target mass estimates discussed in Sec.2 depend on the reduction of the sum of all unrejected low energy ( $<50$  keV) backgrounds to below  $\sim 0.2$  events/y, in each of the detectors comprising the G2, G3 and G4 systems. Sources of background can be divided into three categories:

1. External backgrounds, i.e. gammas, neutrons from sources outside the detector.
2. Target backgrounds, i.e. gammas, neutrons and betas from isotopic contamination of the liquid xenon and argon and by contamination with other radioactive materials.
3. Internal backgrounds, i.e. gammas, neutrons, betas and other interactions from internal radioactive contamination of the detector vessel, photodetectors, and structural materials.

The detectors are two-phase Xe and Ar TPC configurations, which can discriminate nuclear recoils from electron recoils (gamma and beta interactions) by the ratio of primary (S1) and secondary (S2) scintillation signals. There is some overlap between the two distributions, and for an optimum “cut” between the two it is possible to remove all but 0.1 – 1% of the gamma background

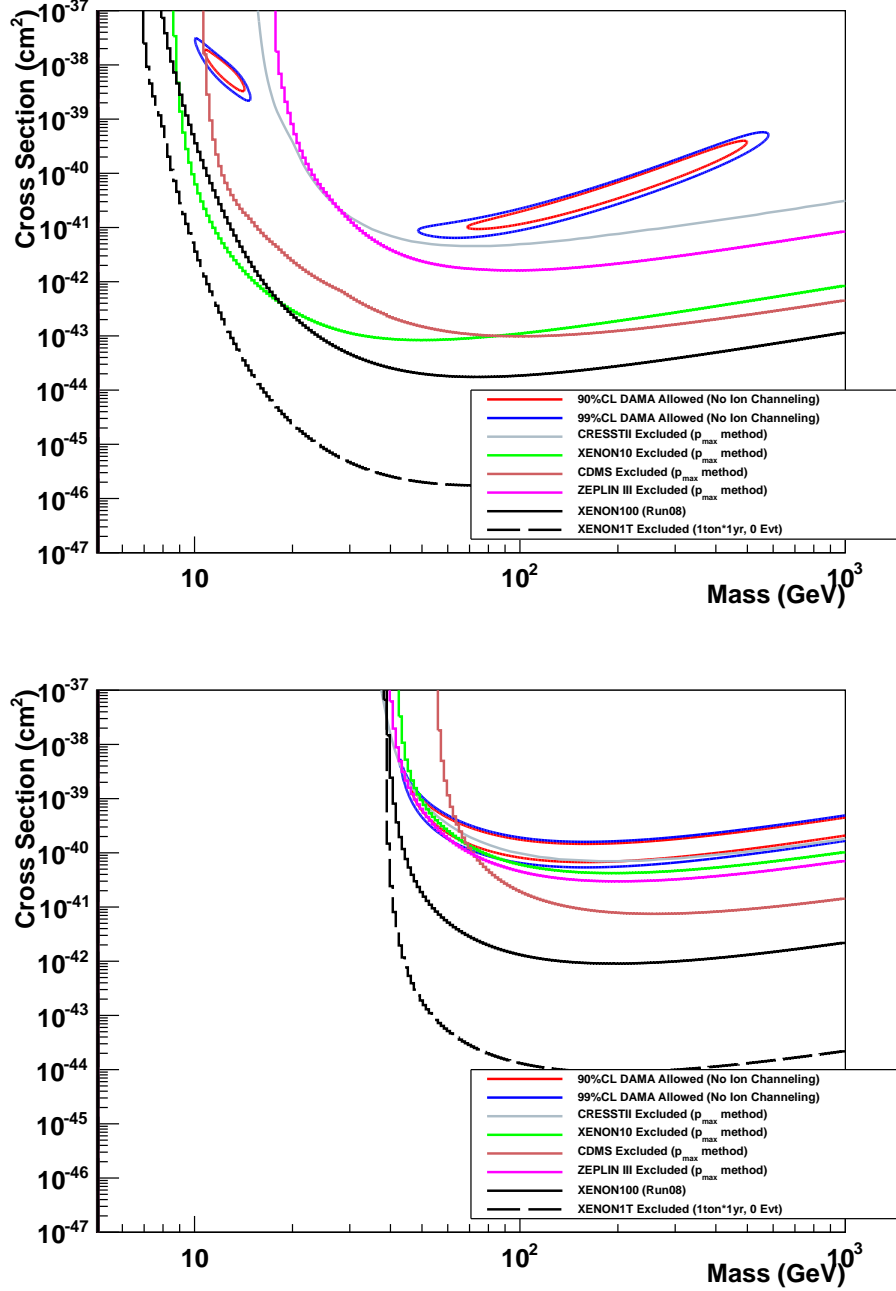


Figure 17: Inelastic WIMP-nucleon cross-section limits versus WIMP mass, showing DAMA [35, 36, 37] allowed regions and exclusion boundaries for CRESSTII [27], CDMS [43], XENON10 [39], XENON100 [42], ZEPLIN III [44], published limits, and projected 1 ton Xe limit, for Galactic escape velocity 550 km/s  
*(upper plot)* mass-splitting  $\delta = 20$  keV  
*(lower plot)* mass-splitting  $\delta = 100$  keV.

in a fiducial target region. We make the conservative assumption that this factor is  $\sim 1\%$ , so that it is sufficient to reduce low energy electron recoil background to  $< 20$  events/y, using the two-phase discrimination to reduce this to  $< 0.2$  events/y. For neutron interactions in the target, a basic multiple-scattering cut can be made, after which any remaining neutron-nucleus collisions will be indistinguishable from WIMP-nucleus collisions. For this reason the attenuation of neutron background to a negligible level, by shielding and veto techniques, is the prime requirement.

### 3.2. External backgrounds

Backgrounds from outside the detector arise from:

1. Neutrons produced by absorption and spallation of cosmic ray muons. These require operation in underground laboratories to reduce the muon flux by a factor  $10^6 - 10^8$ .
2. Neutrons from U/Th in surrounding materials, in particular the underground cavern rock, predominately from alpha-n reactions together with some U fission.
3. Gammas emitted by U/Th in surrounding materials, plus a smaller contribution from muon bremsstrahlung in the rock.

Typical neutron production rates and spectra from sources 1 and 2 have been tabulated by Bungau et al. [45] for several site depths. Neutrons from source 2 have energies  $< 10$  MeV, while those from source 1 have energies up to the region  $1 - 10$  GeV. The flux from source 1 is typically a factor 1000 less than that from source 2, but is more penetrating and could result in a higher target neutron background unless adequately shielded. In [45] simulation results are also shown of the attenuation of neutron flux by lead or iron outer shielding followed by inner passive hydrocarbon shielding (or an active scintillator veto) for detectors up to several hundred kilograms, and which are applicable to detectors of higher mass and larger surface area simply by increasing the thickness of the various shielding layers. However, for multi-ton detectors the required larger mass and higher cost of the metallic shielding, together with the availability of larger underground experimental volumes, is such that it is now thought to be simpler and more economical to use a several-meter thickness of water shielding, possibly also with an inner active scintillator veto.

A tabulation of total muon, neutron, and gamma fluxes for some typical underground laboratories is shown in Appendix A, together with the results of simulations of the attenuation of gamma and neutron fluxes by water shielding. The conclusion is that the water shielding radial thickness would need to be about 4 m for G2, increasing to 5.5 m for G3 and 7 m for G4, although self-shielding within the target volume can be used to provide some reduction in these figures.

### 3.3. Target material backgrounds

Significant concerns arise from target contamination by any of the following:

1. Contamination of liquid Xe with  $^{85}\text{Kr}$ , giving a population of low energy beta decay events and requiring Kr removal by distillation.
2. Contamination of liquid Ar with  $^{39}\text{Ar}$ , giving both data pile-up and a population of low energy beta decays, reducible by the use of  $^{39}\text{Ar}$ -depleted Ar gas from an underground source, possible further centrifuging, by anti-coincident position resolution and pulse shape discrimination (see Appendix C.2).
3. Contamination of Xe or Ar with Rn, the latter giving Po or Bi decay products on the detector walls, some of which alpha-decay into the wall and Po or Bi recoils into the liquid, with recoil energies  $< 100$  keVnr. These are known as “surface events” and can be rejected by a radial fiducial cut.

- Contamination of Xe or Ar with U/Th, giving a population of low energy gammas, betas, or neutrons, largely but not always vetoed by nearly-coincident higher energy events in the U/Th chain, together with purification to the 0.1 ppt level.

A more detailed and quantitative discussion of the above backgrounds is given in Appendix B.

### 3.4. Self-shielding of internal backgrounds from detector materials and photodetectors.

Shielding or rejection of low energy target events resulting from gamma and neutron activity in nearby materials (in particular vacuum vessels and photodetectors) can be achieved by a combination of the following methods:

- Rejection of  $\sim 99\%$  of electron recoil events by the S2/S1 discrimination analysis in the case of both xenon and argon.
- An additional factor  $> 100$  rejection of electron recoils by pulse shape discrimination in the case of argon.
- Rejection of neutrons multiply-scattered in the target, including tagging by gammas from neutron inelastic scattering.
- Additional use of a 0.1% Gd-loaded liquid scintillator (or Gd-interleaved plastic) around the detector, to register neutrons scattered out of the detector. A light attenuation length  $> 4$  m over a period of years can be achieved [89].
- Using an outer thickness of the target material as a region of passive/active shielding leaving an inner fiducial region of typically half the total mass.

		<b>G2</b>			<b>G3</b>			<b>G4</b>		
Xe	fiducial mass (nominal, tons)	1			10			100		
	diameter (cm)	100			200			400		
	passive outer zone (cm)	10			15			20		
	background particle		$\gamma/e$	n		$\gamma/e$	n		$\gamma/e$	n
	fiducial events per year		$\sim 0.1$	$\sim 0.1$		$\sim 0.1$	$\sim 0.1$		$\sim 0.2$	$\sim 0.2$
Ar	fiducial mass (nominal, tons)	5			50			500		
	diameter (cm)	200			400			800		
	passive outer zone (cm)	15			25			35		
	background particle		$\gamma/e$	n		$\gamma/e$	n		$\gamma/e$	n
	fiducial events per year		$<0.01$	$\sim 0.1$		$<0.01$	$\sim 0.3$		$<0.1$	$\sim 0.8$

Table 4: Summary of outer target zone passive thickness for G2, G3, G4, detectors, required to reduce gamma, electron & neutron events to  $< 1$  event/year in the fiducial target region.

To investigate the background levels achievable with these measures we have carried out a detailed program of simulations, the results of which are shown and discussed in Appendix C.

The overall conclusion is that the basic requirement of no more than 0.2 – 0.5 unrejected background events/year can be sustained for each order of magnitude increase in target mass through G2, G3 and G4, by using an increasing thickness of passive self-shielding, while nevertheless keeping to the fiducial volumes indicated in Tab.1 of Sec.1.

A summary of passive shielding thicknesses for G2,G3 and G4 xenon and argon detectors and corresponding residual gamma, beta, and neutron background events/y is given in Tab.4.



## 4. Low energy neutrino astrophysics

### 4.1. Solar neutrino p-p spectrum

The p-p solar neutrino spectrum produces in a Xe or Ar target a spectrum of electron recoils extending to 260 keV, and at low energies gives a flat background of  $10^{-5}$  electron recoil events/keV/kg/d. The S2/S1 discrimination reduces this by a factor  $\sim 100$  to  $10^{-7}$  electron recoil events/keV/kg/d (see Fig.C.1, Appendix C) at which it is below the background level required for a dark matter sensitivity of even  $10^{-47}$  cm<sup>2</sup>. However, above 20 keV (electron equivalent) the signal becomes observable in the S1 channel as a measurable signal.

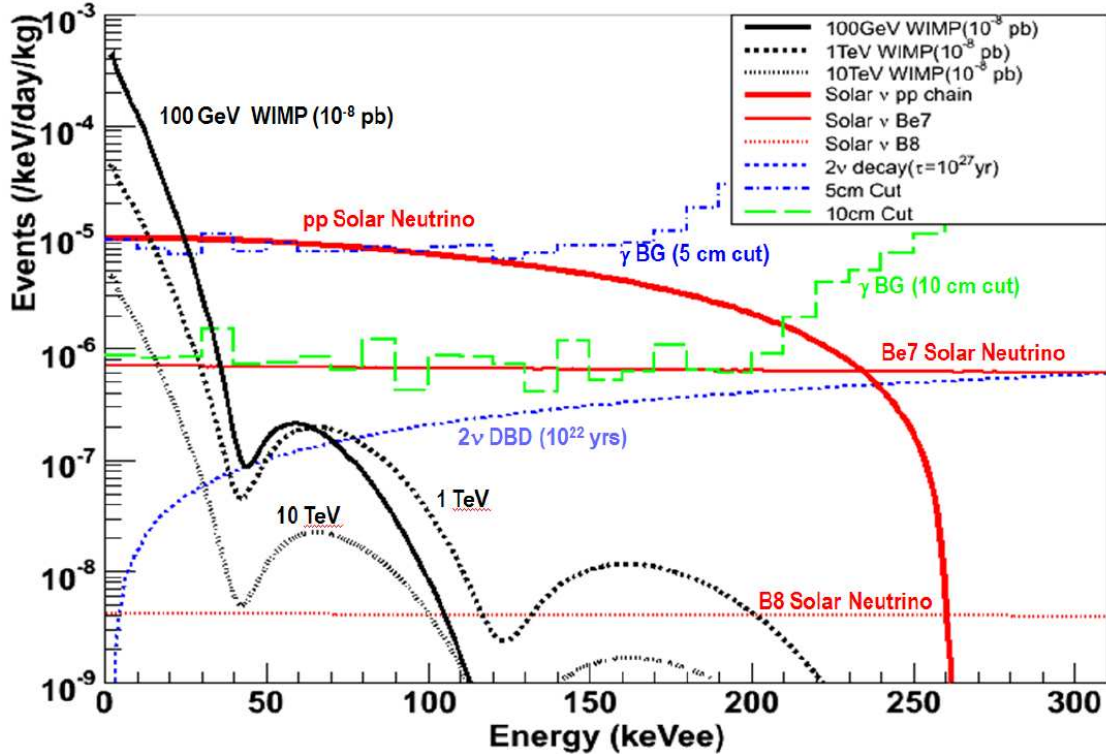


Figure 18: Spectra for p-p &  ${}^7\text{Be}$  solar neutrinos [90], depleted  ${}^{136}\text{Xe}$  two-neutrino double beta decay [91], and WIMP spectra for  $10^{-44}$  cm<sup>2</sup>, together with gamma background self-shielding cuts. No S1/S1 discrimination is used for the solar neutrino electron spectra.

However, as also shown in Fig.C.1 in natural Xe, the  $2\nu\beta\beta$  decay of the 8.9%  ${}^{136}\text{Xe}$  (using an assumed half life  $\sim 10^{22}$  years) exceeds the p-p solar neutrino signal above about 50 keV. Thus for accurate measurement of the solar neutrino spectrum it would be preferable to deplete the  ${}^{136}\text{Xe}$  component by a factor 10 -100 [56, 57]. Such depleted Xe may in fact become automatically available as a result of the simultaneous demand for enrichment of  ${}^{136}\text{Xe}$  for neutrinoless double beta decay experiments, as discussed in Sec.5, but even with a natural xenon target it would still be possible to extract a significant portion of the pp solar neutrino spectrum by a two-population fit to the overlapping  $2\nu\beta\beta$  and solar distributions. Fig.18 compares absolute rates and energy spectra of events from p-p and  ${}^7\text{Be}$  solar neutrinos, two neutrino double beta decay (with Xe depleted to 0.1%), and hypothetical dark matter fluxes for  $10^{-44}$  cm<sup>2</sup> WIMP-proton cross section (proportionally lower for  $10^{-45}$  cm<sup>2</sup> and  $10^{-46}$  cm<sup>2</sup>). The S2/S1 cut is not applicable for this plot since the required solar neutrino events are electron recoils. Fig.19 shows the progressive reduction of gamma background in a G3 detector to below the p-p (and  ${}^7\text{Be}$ ) solar neutrino rates

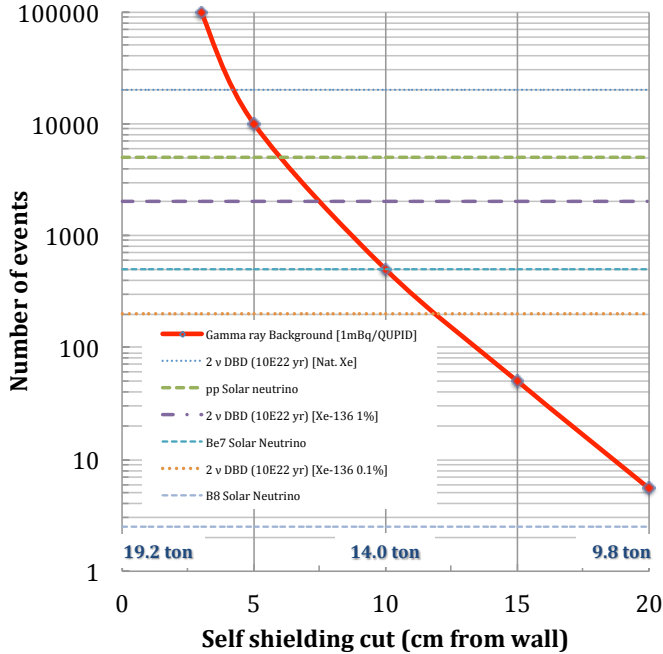


Figure 19: Number of solar neutrino events for 10 ton-y Xe and energy window 50-250 keV, showing reduction of electron recoil background to below solar neutrino signal by progressive increase of G3 Xe self-shielding cut, leaving 10-ton fiducial mass at 15 cm cut.  $2\nu\beta\beta$  levels are included for comparison, showing effect of  $^{136}\text{Xe}$  depletion.

by increasing the self-shielding cut, decreasing the 19-ton total Xe volume to leave a low background 10-ton fiducial mass. A similar gamma background reduction with self-shielding cut applies also to the 100-ton G4 Xe detector, which would provide ten times as many neutrino events per year but would require a correspondingly larger quantity of depleted Xe. Using a  $^{136}\text{Xe}$ -depleted target, the G3 Xe detector would provide sufficient events to measure the p-p neutrino spectrum with a few % precision.

In principle, the p-p solar neutrino signal would be observable also in the Ar detector (which has the same p-p neutrino event rate per ton) but the  $^{39}\text{Ar}$  beta background at a level (assuming the use of underground argon) of  $\sim 100$  events/keV/kg/d, and extending to 570 keV, would overwhelm the whole of the p-p neutrino spectrum even with several orders of magnitude further depletion of the  $^{39}\text{Ar}$ .

#### 4.2. Supernova neutrinos

Neutrino bursts from Galactic supernovae will be seen an order of magnitude more frequently than those near enough to the Earth to be visible optically, at a rate believed to be  $\sim 3 - 5$  per century [59]. All three types of neutrino will be emitted, and estimates of rates, fluxes, and spectra are summarised in Appendix D. Both vacuum and MSW mixing will occur after production, making detailed observation of these rare events using different types of detector a potentially important contribution to neutrino physics.

The G2, G3 and G4 detector systems can most efficiently detect these neutrinos through coherent neutral current elastic scattering from the Xe and Ar nuclei [60, 85], which will respond equally to all flavours. The relative fluxes of the different neutrino flavors will be affected by MSW mixing in the supernova environment, and by vacuum mixing between the supernova and Earth, but the total flux of all three types will remain constant. In addition, although the non-zero neutrino masses will propagate as mass eigenstates (mixtures of the three flavor eigenstates), the arrival

times will differ by less than 1 ms with neutrino masses all  $< 1$  eV, compared with the  $> 1$  s overall time duration of the neutrino burst. The typical distance of a Galactic supernova from the Earth is taken to be 10 kpc for the calculations in this section.

Both Xe and Ar detectors can independently determine both the total energy and the temperature of the neutrino burst. Fig.20a and Fig.20b show the yield/ton versus energy of Xe and Ar nuclear recoil events for a supernova at 10 kpc and several values of mean neutrino temperature  $T_\nu(= \langle E \rangle_\nu / 3)$  averaged over all neutrino types. Corresponding Monte Carlo simulations of G2, G3 and G4 data sets are shown in Fig.21, in turn leading to estimates of total energy and neutrino temperature, and with the typical precision shown in Fig.22 for G2 and G3 detectors. Figs.Fig.20 and 21 are plotted against recoil energy, so need to be considered in relation to the achievable future energy threshold in Xe and Ar detectors, estimated in this paper to be  $\sim 8$  keVnr for Xe and  $\sim 20$  keVnr for Ar, but in principle improvable in each case with sufficient gains in light collection.

## 5. Neutrinoless double beta decay

With the establishment, from neutrino mixing measurements, of a non-zero neutrino mass scale in the region  $0.01 - 0.1$  eV, the issue of the Dirac or Majorana nature of neutrinos has become of increased urgency for understanding the lepton family and the quark-lepton relationship. For Majorana neutrinos, the equivalence of neutrino and antineutrino would ensure that those nuclei that can undergo double beta decay with emission of two neutrinos must also undergo neutrinoless double beta decay. For the present study, we consider the Xe detectors in the G2, G3 and G4, stages, focusing on the isotope  $^{136}\text{Xe}$  which is present at 8.9% in natural Xe, and which could be enriched by an order of magnitude.

The rate for this process is a function of nuclear matrix elements multiplied by (the square of) a Majorana electron neutrino mass parameter  $m_{\beta\beta}$  which is expressible as a linear combination of the three neutrino mass eigenstates, but uncertain in the range  $0.01 - 0.1$  eV owing to the unknown absolute value of the lowest of the three mass eigenstates [61]. The resulting Majorana masses are shown in Fig.23 as a function of the unknown  $m_1$  for normal hierarchy, or the unknown  $m_3$  for inverted mass hierarchy [62]. The same figure gives corresponding half-lives for  $^{136}\text{Xe}$ , showing that sensitivity to  $10^{27} - 10^{28}$  y is likely to be necessary to provide a detection of  $0\nu\beta\beta$  decay for the first time, previous experiments having been sensitive to upper limits of  $10^{24} - 10^{25}$  y.

The signature for  $0\nu\beta\beta$  decay of  $^{136}\text{Xe}$  will be an electron recoil signal at the specific energy 2479 keV, which is at the end of the  $2\nu\beta\beta$  decay spectrum, mentioned previously as a background for pp solar neutrino detection. In this case the tail of the  $2\nu\beta\beta$  decay spectrum provides a background to the  $0\nu\beta\beta$  decay line, requiring the latter to be observed with good energy resolution. Scaling from the resolution achieved with 10 – 100 kg Xe detectors, we estimate a FWHM energy resolution of 50 keV at  $\sim 2.5$  MeV, giving the separation between the  $0\nu\beta\beta$  signal and  $2\nu\beta\beta$  spectrum tail shown on Fig.24. The superimposed gamma background versus self shielding, shown for the case of the 2 m diameter G3 Xe detector after rejection of multiple scattering events, arises mainly from the QUPID array, for which 1 mBq/QUPID is assumed. Consideration is also needed for possible contamination of the Xe by the  $^{232}\text{Th}$  chain, which includes a 100% intensity  $^{208}\text{Tl}$  2.61 MeV line, and by the  $^{238}\text{U}$  chain, which includes a 2% intensity  $^{214}\text{Bi}$  2.44 MeV line [72]. The peak/Compton ratios for these are  $\sim 10^{-5}$  so the majority of background comes from overlap with the Compton shoulder (at 2.38 MeV for  $^{208}\text{Tl}$ , and 2.32 MeV for  $^{214}\text{Bi}$ ). Reducing this background to an acceptable level thus depends firstly on ensuring U and Th contamination levels are below 1 ppt, and secondly on achieving sufficiently good energy resolution to fully separate the 2.48 MeV signal region from the above Compton shoulders.

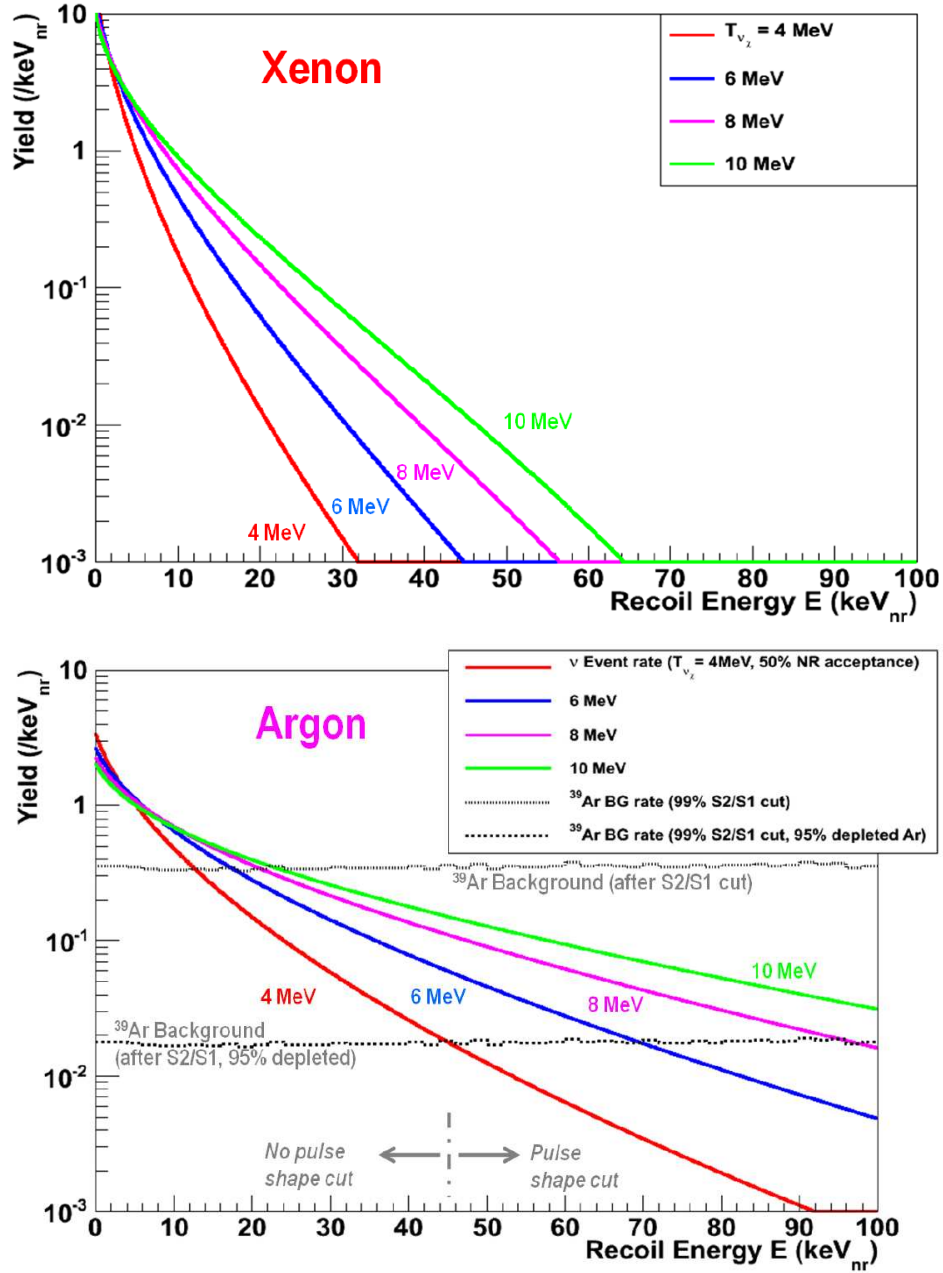


Figure 20: Energy spectrum of coherent nuclear scattering events from supernova neutrino burst at distance 10 kpc, for mean neutrino temperatures 4, 6, 8, 10 MeV.

(a) (upper) 1-ton Xe detector.

(b) (lower) 5-ton Ar detector, including 95% depletion of  $^{39}\text{Ar}$  and pulse shape cut.

Note that for a 20 second neutrino burst, the levels of continuous background for dark matter or solar neutrinos (see Fig. C.1) give 20 second event yields below the vertical scale of these plots.

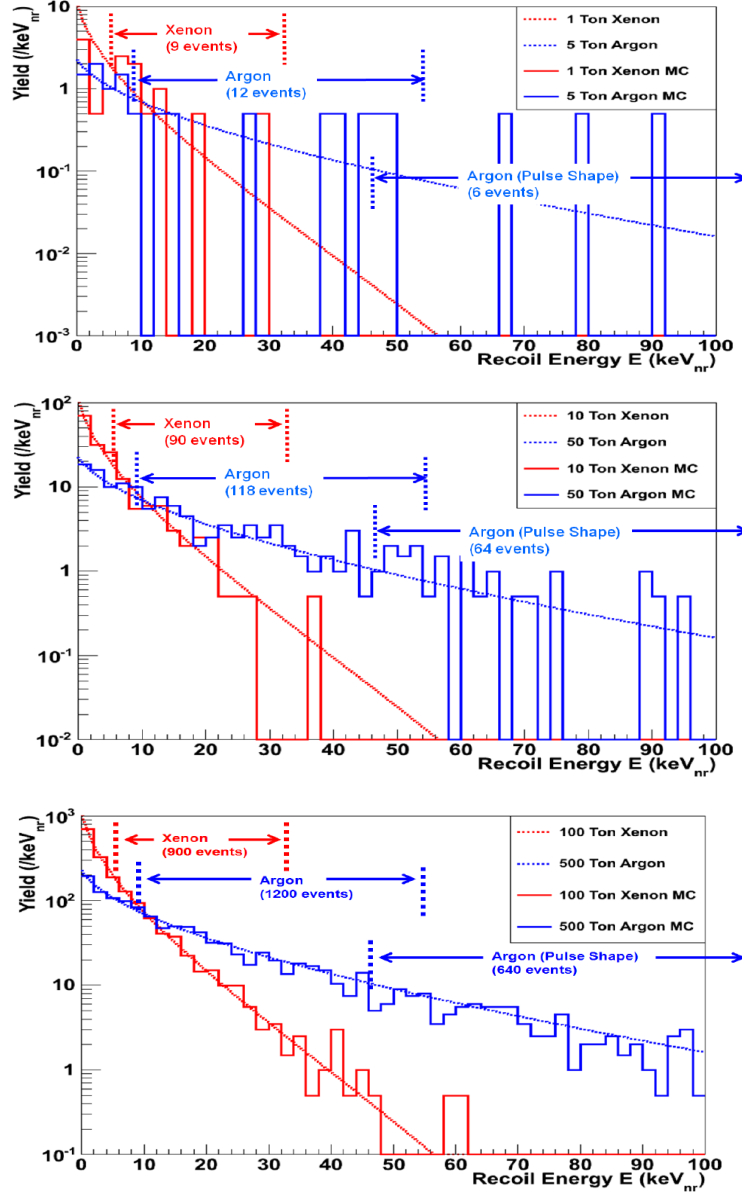


Figure 21: Simulated data for nuclear recoil spectra from supernova at 10 kpc  
*(upper plot)* G2: 1-ton Xe and 5-ton Ar  
*(middle plot)* G3: 10-ton Xe and 50-ton Ar  
*(lower plot)* G4: 100-ton Xe and 500-ton Ar.

Note that for a 20 second neutrino burst, the levels of continuous background for dark matter or solar neutrinos (see Fig. C.1) give 20 second event yields below the vertical scale of these plots.

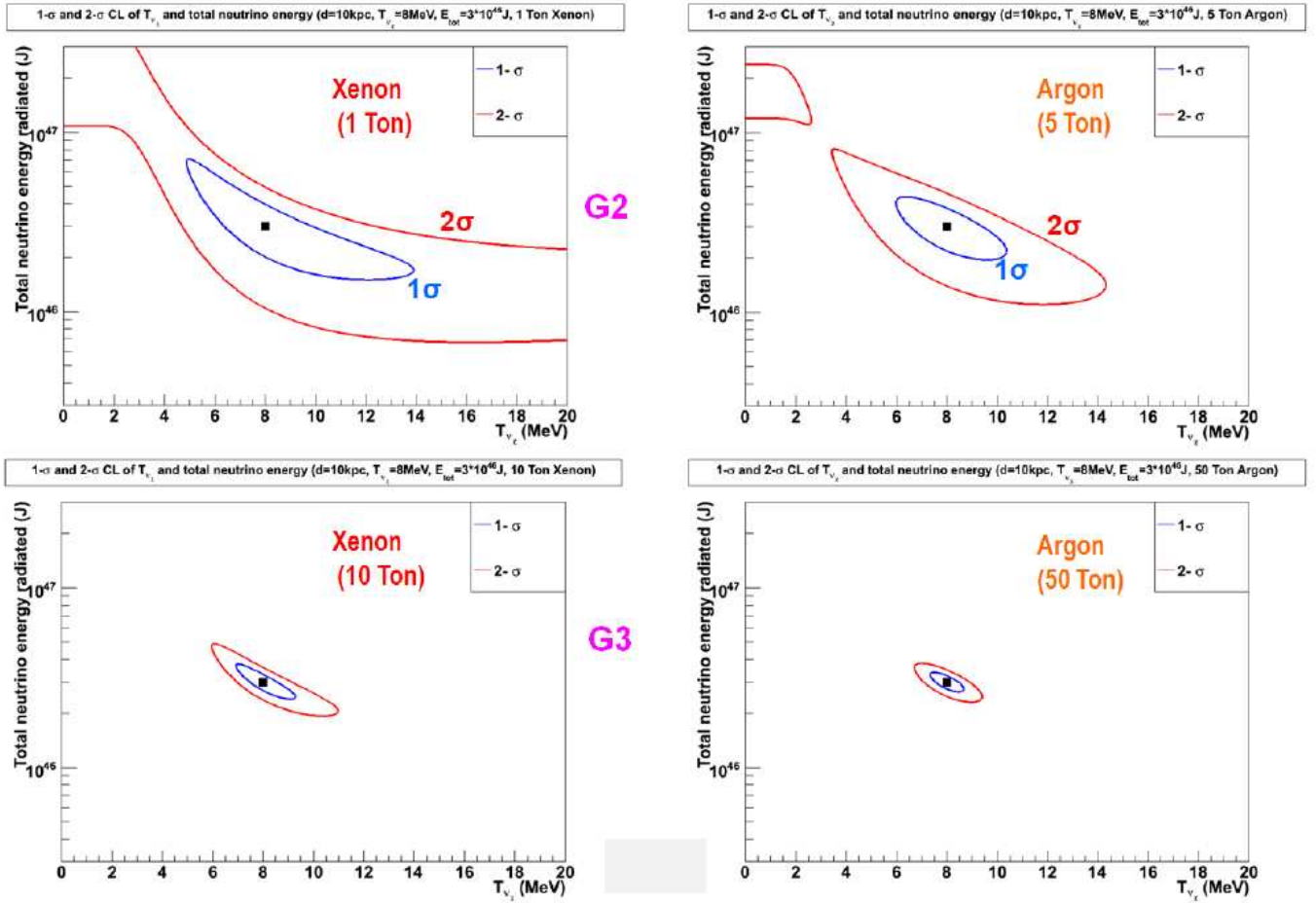


Figure 22: Examples of combined precision of Supernova neutrino total energy and mean temperature, derivable from the spectrum of coherent nuclear recoil events shown in Fig21.

(upper plots) Predicted precision of the G2 system with fiducial 1-ton Xe, 5-ton Ar.

(lower plots) Predicted precision of the G3 system, with fiducial 10-ton Xe, 50-ton Ar.

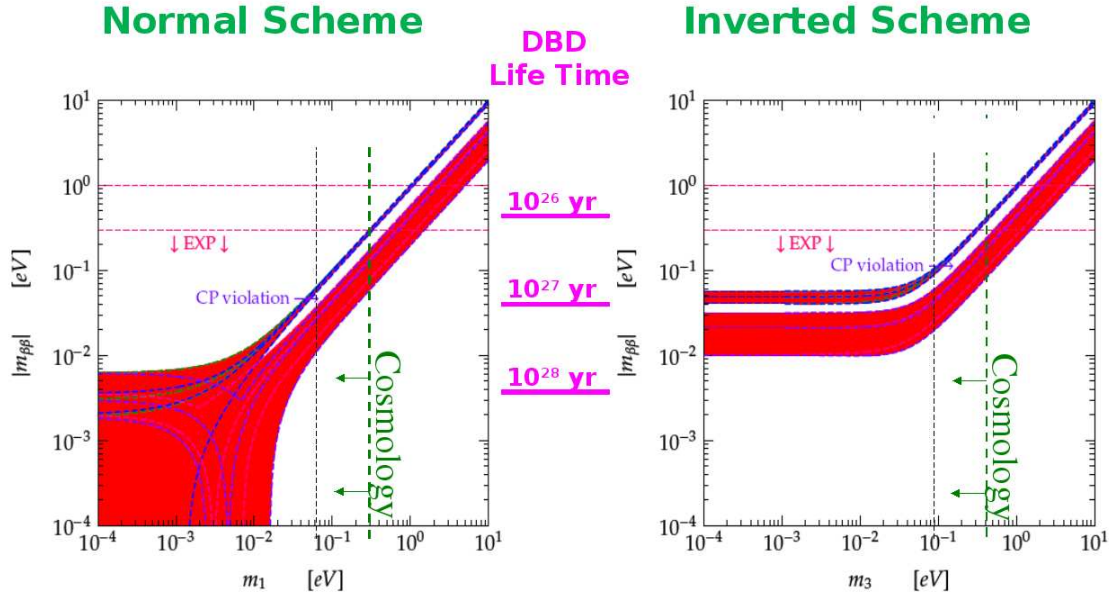


Figure 23: Plots of Majorana neutrino mass versus unknown lowest mass eigenstate [60], together with corresponding neutrinoless double beta decay half-lives.

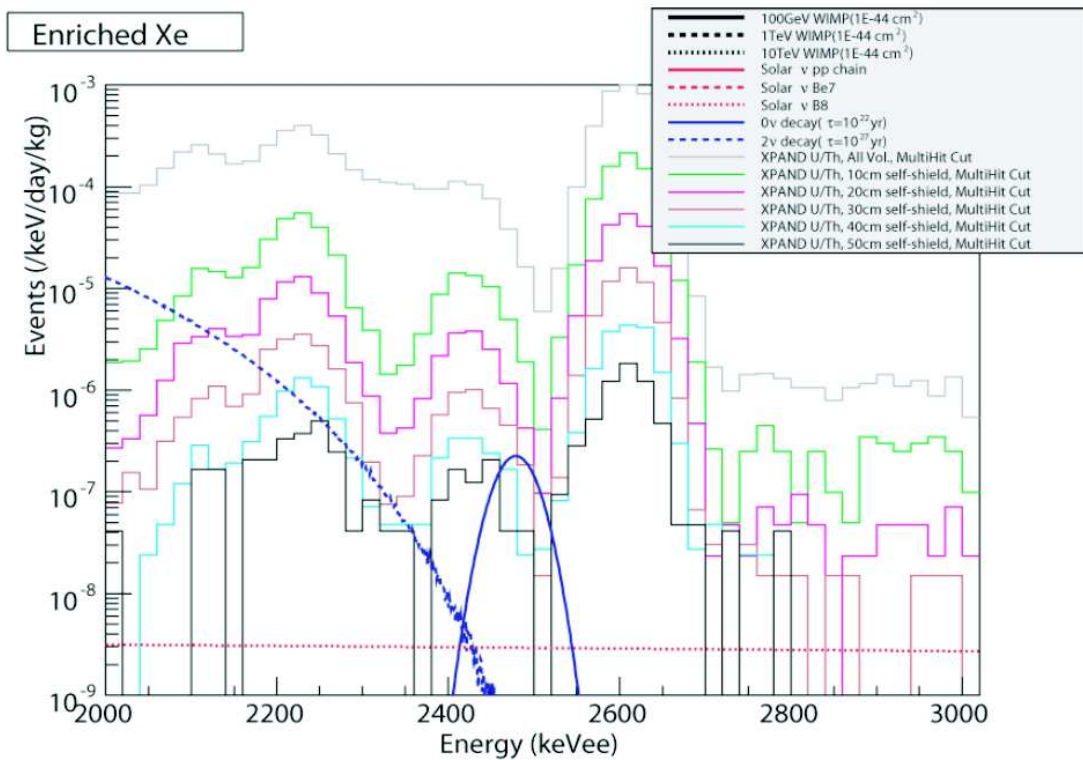


Figure 24: Plot showing  $0\nu\beta\beta$  signal (half-life  $10^{27}$  y) and  $2\nu\beta\beta$  tail in a 2 m diam. detector with 90%  $^{136}\text{Xe}$ , together with simulated gamma background after progressively increasing self-shielding cuts. The largest background is from the QUPID array, for which 1 mBq/QUPID is assumed.

Fig.25 shows the spatial distribution of gamma background events in the  $0\nu\beta\beta$  energy range 2450 – 2500 keV (including energy resolution) requiring a larger self-shielding cut ( $\sim 40$  cm) than in the case of the dark matter background discussed in Sec.3, because the S2/S1 cut is not relevant to the electron recoil signal. This would reduce the G3 fiducial target mass to  $\sim 8$  tons, but a foreseeable reduction of QUPID activity from 1 mBq to 0.1 mBq/QUPID would reduce the required cut to 15cm and restore the fiducial mass to  $\sim 10$  tons. Fig.26a summarizes background number per year versus self-shielding cut, and Fig.26b plots  $0\nu\beta\beta$  signal in events per 10 ton-y operation versus  $0\nu\beta\beta$  lifetime, for both natural Xe, and Xe enriched by a factor 10 to  $\sim 90\%$   $^{136}\text{Xe}$ . The calculation for a unit of 10 ton-y enables the plots to be scaled for G2, G3 and G4 detectors with corresponding fiducial masses and running times.

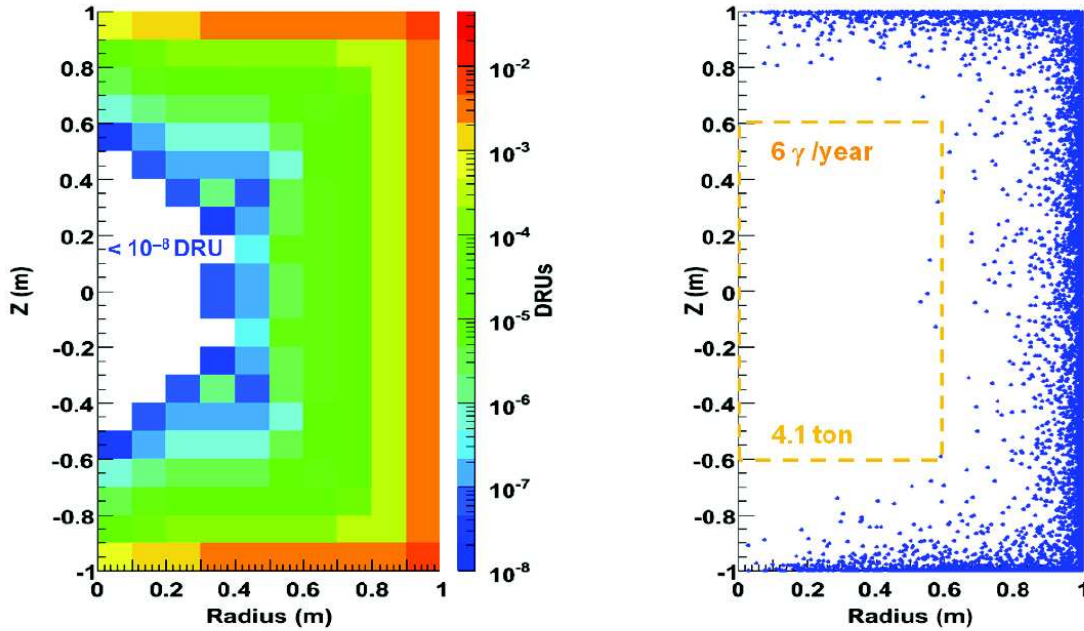


Figure 25: Spatial distribution of 1-y gamma background from QUPID array surrounding 2 m diameter Xe detector, after rejection of multiple scattering events and showing need for a 40 – 45 cm radial cut for observation of a small (i.e.  $<10$  event) electron signal from  $0\nu\beta\beta$ .

Tab.5 summarizes the estimated  $0\nu\beta\beta$  lifetime sensitivity for most of the currently proposed world experiments aimed at reaching  $> 10^{26}$  years (reviewed in [61, 63, 64, 65]). For comparison, the approximate sensitivity levels that would be achievable by the G2, G3 and G4 detectors in this paper are also shown, estimated from Fig.26(a) and 26(b) assuming sufficient events to give a non-zero 90% Poisson (Feldman-Cousins) lower signal limit, together with a conservative 50% energy resolution and detection efficiency. The table also shows the ultimate sensitivity obtainable using enriched  $^{136}\text{Xe}$  in the 10 ton G3 detector. In the latter case, it would be preferable to restrict the scarcer  $^{136}\text{Xe}$  specifically to the fiducial region, using the concentric XAX configuration proposed previously [13]. In all cases the detector design and component activity need to be chosen to keep the background in the  $0\nu\beta\beta$  peak within the 1 – 10 events/y level, in turn arising from the need to constrain this below a potential signal  $\sim 5 - 10$  events/y. In each project this is believed by the proposing groups to be an attainable objective, but subject to further R&D.

As concluded in [13], if the estimated energy resolution and backgrounds for a 10-ton Xe detector can be matched in practice, it will be possible to achieve a half-life sensitivity  $>10^{28}$  y without the



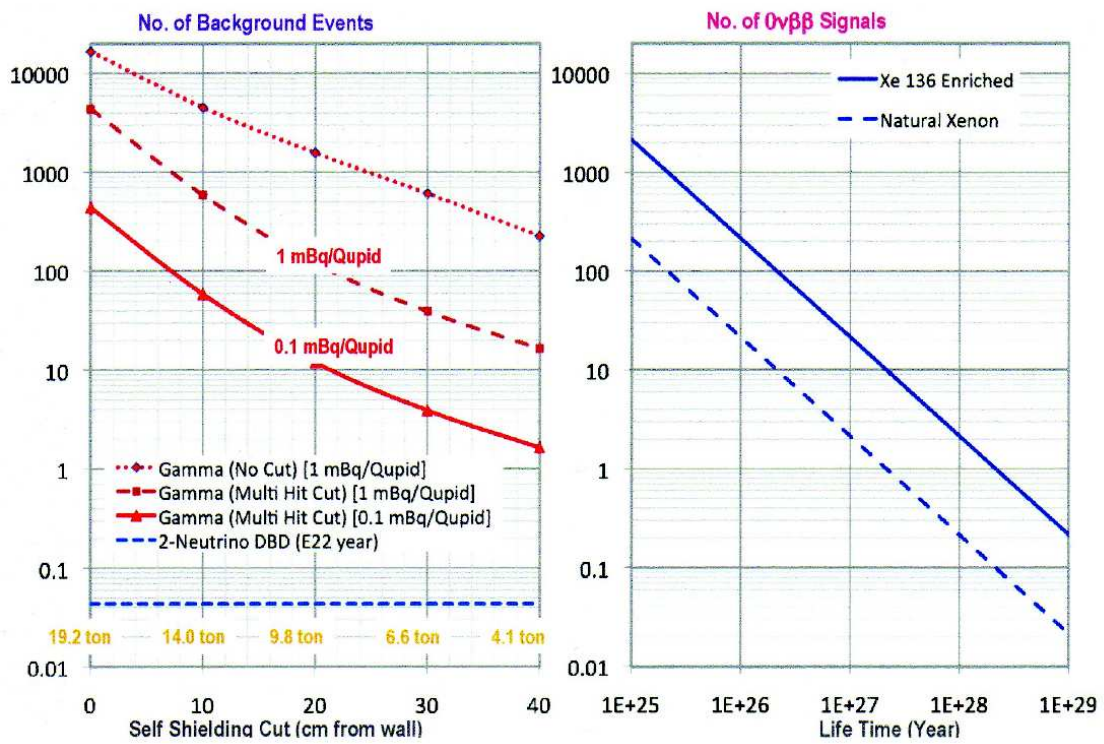


Figure 26: (a) (left) Gamma background events remaining in Xe fiducial region versus self-shielding cut, for 10 ton-y operation and photodetector activity of 1 or 0.1 mBq/QUPID  
 (b) (right) Number of  $0\nu\beta\beta$  events for 10 ton-y operation in enriched and unenriched  $^{136}\text{Xe}$  versus  $0\nu\beta\beta$  half-life.

needing to tag the Ba nucleus as proposed by the EXO project [70]. It is at present premature to include in Tab.5 specific figures for an enriched version of G4, but it is evident that if it proves realistic to produce 60 – 80 tons enriched  $^{136}\text{Xe}$ , then this could achieve a sensitivity  $> 10^{28}$  y in only 1 year of operation.

Future Project	ref	Isotope	Fid. isotopic mass (tons)	Exp. bkg in peak (evts/y)	$0\nu\beta\beta$ $\tau_{1/2}$ (y) 1y run	$0\nu\beta\beta$ $\tau_{1/2}$ (y) 5y run
MAJORANA	[64]	$^{76}\text{Ge}$ en.	0.5	2 – 5	$6 \times 10^{26}$	$2 \times 10^{27}$
COBRA	[64]	$^{113}\text{Cd}$ en.	0.4	10 – 20	$1 \times 10^{26}$	$3 \times 10^{26}$
CUORE	[64]	$^{130}\text{Te}$ nat.	0.2	4 – 20	$2 \times 10^{26}$	$6 \times 10^{26}$
NEXT	[66, 67]	$^{136}\text{Xe}$ en.	0.1	2 – 5	$6 \times 10^{25}$	$2 \times 10^{26}$
GERDA	[64]	$^{76}\text{Ge}$ en.	0.05	2 – 10	$4 \times 10^{25}$	$1 \times 10^{26}$
SuperNEMO	[64, 68]	$^{82}\text{Se}$ en.	0.1	2 – 10	$1 \times 10^{26}$	$3 \times 10^{26}$
MOON III	[69]	$^{100}\text{Mo}$ , $^{82}\text{Se}$ , en.	0.5	10 – 20	$1 \times 10^{26}$	$3 \times 10^{26}$
CANDLES III	[64, 70]	$^{48}\text{Ca}$ nat.	0.1	5 – 10	$1 \times 10^{26}$	$3 \times 10^{26}$
EXO200	[64, 71]	$^{136}\text{Xe}$ en.	0.2	4 – 8	$3 \times 10^{25}$	$1 \times 10^{26}$
EXO 1T	[71]	$^{136}\text{Xe}$ en.	1	4 – 8	$4 \times 10^{26}$	$1 \times 10^{27}$
EXO 10T + Ba tag	[71]	$^{136}\text{Xe}$ en.	8	1 – 2	$6 \times 10^{27}$	$2 \times 10^{28}$
Xe G2 1T	this work	$^{136}\text{Xe}$ nat.	0.04	3 – 6	$2 \times 10^{25}$	$6 \times 10^{26}$
Xe G2 1T	this work	$^{136}\text{Xe}$ en.	0.32	3 – 6	$1 \times 10^{26}$	$4 \times 10^{26}$
Xe G3 10T	this work	$^{136}\text{Xe}$ nat.	0.4	4 – 8	$2 \times 10^{26}$	$6 \times 10^{26}$
XAX 10T	[13]	$^{136}\text{Xe}$ en.	8	4 – 8	$4 \times 10^{27}$	$1 \times 10^{28}$
Xe G4 100T	this work	$^{136}\text{Xe}$ nat.	9	2 – 4	$7 \times 10^{27}$	$2 \times 10^{28}$
Xe G4 100T	this work	$^{136}\text{Xe}$ en.	see text			see text

Table 5: Summary of projected  $0\nu\beta\beta$  performance of G2,G3,G4, Xe detectors, and other planned world projects to reach half-lives  $10^{26} - 10^{28}$  y (all background estimates are approximate and subject to further R&D). In the table “en.” stands for enriched, while “nat.” for natural.

## 6. Xe/Ar mixtures

In addition to the above possibilities for separate liquid Xe and Ar detectors, it is of interest to consider possibilities for combining the two elements in one detector, for example using a low concentration of Xe as a dopant for Ar, or single detectors containing higher percentage mixture of the two.

A number of papers have reported measurements of scintillation light output and wavelength, electron mobility, and pulse shape, in liquid Ar doped with Xe at the 10 – 100 ppm level [73, 74, 75, 76, 77]. It was also found that measurements could be extended to much larger Xe concentrations, up to 5 – 20% (Mol fraction). By visual tests in transparent vessels, it was found that there was settling out of frozen Xe at 20% mol fraction, but that the mixture remained apparently stable up to 5%, and possibly 10% [73]. Mol fractions 5 – 10% correspond to mass fractions 14 – 26%. This unexpectedly high solubility was suggested to be the result of the formation of clusters and compounds. More recently Peifer et al. [73] found possible evidence of inhomogeneous mixing, or stratification, which could impair the performance of detectors utilising such mixtures, and thus needs further investigation.

Some key features of the published results are

1. an admixture of 100 ppm Xe was found to produce complete wavelength shifting of the scintillation light from 128 nm to 178 nm [76].
2. Adding Xe to Ar resulted in a progressive increase of scintillation light output, by up to a factor 2, for Xe concentrations up to 1%, in zero electric field, this increase being suppressed by electric fields  $\sim 1 - 8$  kV/cm [73].
3. The addition of only 100 ppm Xe produces considerable changes in scintillation pulse shape, including a small improvement in neutron/gamma pulse shape discrimination for only 300 ppm Xe [77] suggesting further investigation of pulse shape discrimination at larger Xe fractions.

These observations suggest several possible applications to the Xe and Ar detectors:

- a) ability to use Xe-wavelength photodetectors for both Xe and Ar detectors;
- b) prospects for improved energy threshold and resolution in Ar detectors, from the increased scintillation light per keV.
- c) possibility of detectors combining Xe and Ar targets in the same vessel, if separate identification of Xe and Ar recoils proves feasible, for example by pulse shape. In particular, a 7% molar ( $\sim 20\%$  by weight) Xe concentration would provide the 5:1 Ar/Xe ratio required in the G2 and G3 two-vessel detector systems, but in the single Ar vessel;
- d) an alternative possibility of determining the Xe/Ar signal ratio (and verifying an  $A^2$  signal dependence) by comparison of signals before and after the addition of Xe to an Ar detector;
- e) A G3-level  $0\nu\beta\beta$  detector, using the (4 m diameter) G3 Ar detector but with a target consisting of a 20% Xe/Ar mass ratio (13 tons  $^{136}\text{Xe}$ , 65 tons Ar). This could provide a  $0\nu\beta\beta$  experiment with a majority of self-shielding from the Ar, to give a lower background and higher resolution than the use of the enriched  $^{136}\text{Xe}$  in the G3 Xe detector (and without requiring the two concentric vessels of the XAX configuration). This offers the additional possibility that some of the track pairs (range  $\sim 8$  mm for the factor  $\sim 2$  lower mixture density) might be identifiable by timing in the vertical direction. This is part way towards the high pressure (5 –10 bar) Xe gas TPC detectors proposed by Nygren et al. [78, 79, 80] with a factor 10 lower density than that of the Xe/Ar mixture and allowing more complete reconstruction of the two  $\beta$  tracks.

## 7. Conclusions

We have studied the capabilities of a several stage program of construction and operation of multi-ton liquid Xe and liquid Ar two-phase TPC detectors. The principal objective is to measure the energy spectrum of nuclear recoils from weakly interacting massive particles that may constitute the Galactic dark matter, with sufficiently low background to reach WIMPnucleon cross-sections  $\sim 10^{-46}$  cm<sup>2</sup> and lower, with sufficient events to allow determination of the shape of the recoil energy spectrum and from this to estimate the WIMP mass. As previously proposed [81] it is important to measure this signal in two detectors with different target elements, to confirm the expected  $A^2$ -dependence of the signal from a coherent spin-independent cross-section, and to provide agreement between two independent determinations of the incident particle mass.

The first stage of this program, referred to as G2, would consist of a liquid Xe detector of 1-ton fiducial mass, paired with a liquid Ar detector with a 5-ton fiducial mass. The second stage, referred to as G3, would use the G2 argon vessel as a 10-ton fiducial Xe detector, then paired with a 50-ton fiducial Ar detector. A further order of magnitude scale-up, referred to as G4, could be achieved by using the G3 argon vessel for a 100 ton Xe detector, and adding if required, a 500 ton argon

detector. It has been shown in this paper that sufficiently low gamma and neutron backgrounds can be achieved by combining the following methods:

- a) by the now proven two-phase discrimination of nuclear recoils from gamma/beta events;
- b) by using in each case a total target mass approximately twice the fiducial mass and using the outer half of the mass as self-shielding;
- c) by the development, now in progress, of a new high quantum efficiency QUPID photodetector, with a radioactivity level lower by 1 – 2 orders than the current best photomultipliers. This would allow for the first time the use of full  $4\pi$  photodetector arrays with improved light collection, energy resolution, and event position resolution.

Other internal backgrounds, from radioactive impurities in structural materials, have been shown to be reducible to negligible levels. In addition to achieving the best sensitivity for measurement of signals from spin-independent interactions, the data will at the same time provide the best limits on spin-dependent or inelastic WIMP scattering, again with independent data from Xe and Ar detectors.

The two detectors of the G3 system are further capable of observing the annual WIMP-spectrum modulation arising from the combined Earth-Sun motion in the Galaxy. The Xe and Ar detectors will provide two independent measurements of this, confirming the Galactic origin of the signal.

The sensitivity of liquid noble gas detectors to signals below 100 keV provides the opportunity to measure signals from two sources of astrophysical neutrinos: solar and supernova. The excellent position resolution of the two-phase design and light collection system allows the gamma background to be reduced sufficiently to allow pp solar neutrinos to be clearly seen as a neutrino-electron scattering spectrum up to 250 keV and, with a Xe target depleted in  $^{136}\text{Xe}$ , sufficient events could be obtained to measure the spectrum to a precision of a few percent. The total neutrino burst from a Galactic supernova could be observed as a coherent neutral current nuclear recoil spectrum, in both the Ar and Xe detectors, with sufficient accuracy to measure both the total flux and mean energy (temperature) of the neutrino source. At a distance  $\sim 10$  kpc, the precision would be  $\sim 10\%$  with the G3 detection system.

We have discussed the further gains to be achieved with the G4 100-ton (fiducial) Xe scale-up, with or without a corresponding 500-ton (fiducial) Ar detector. These include order of magnitude gains in dark matter event numbers and mass determination, more precise annual modulation signal, and increased numbers of neutrino events from a supernova burst, giving sensitivity to more remote Galactic supernovae.

An important application of the G3 and/or G4 systems would be a high level of sensitivity to neutrinoless double beta decay from  $^{136}\text{Xe}$ . This would be achievable with the 10-ton G3 Xe detector, using either natural or enriched  $^{136}\text{Xe}$ , reaching a lifetime sensitivity  $10^{27} - 10^{28}$  y which, for Majorana neutrinos, lies within the 0.1 – 0.01 eV majorana mass range expected from existing neutrino mixing data, and hence an expectation of a positive  $0\nu\beta\beta$  signal for the first time. We consider also the option of using Xe/Ar mixtures for this and/or dark matter detection, for potentially higher resolution and improved self shielding.

This study concludes that the ultra-low backgrounds needed for these searches are achievable with existing techniques, and that combinations of multi-ton Xe and Ar detectors provide the most sensitive method of identifying dark matter signals, providing at the same time new high sensitivity measurements at the frontier of neutrino physics.

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## Appendix A. Underground background fluxes and water shielding simulation

A comparison of the orders of magnitude of muon, neutron and gamma fluxes for several underground sites is shown in Tab. A.1.

	LNGS Hall B/C 3600 mwe	LSM 4800 mwe	DUSEL 4800 mwe
$\mu$ flux (0.1 MeV – 10 GeV) $\text{cm}^{-2}\text{s}^{-1}$	$3 \times 10^{-8}$ (meas.)	$3 - 4 \times 10^{-9}$ (meas.)	$3 - 4 \times 10^{-9}$ (meas.)
n flux from $\mu$ in rock (1 MeV – 1 GeV) $\text{cm}^{-2}\text{s}^{-1}$	$3 \times 10^{-9}$ (sim.)	$3 \times 10^{-10}$ (sim.)	$3 \times 10^{-10}$ (sim.)
n flux from rock activity (1 MeV – 6 MeV) $\text{cm}^{-2}\text{s}^{-1}$	$4 \times 10^{-6}$ (sim.) (50% from concrete)	$4 \times 10^{-6}$ (meas.)	$6 - 10 \times 10^{-6}$ (scaled from $\gamma$ flux)
$\gamma$ flux from rock activity (0 – 3 MeV) $\text{cm}^{-2}\text{s}^{-1}$	0.2 (sim.) (80% from concrete)	0.2 – 0.3 (activity similar to LNGS)	0.3 – 0.5 (sim.)

Table A.1: Comparison of muon, neutron, and gamma fluxes for some underground sites

To provide a suitable external background for the detectors discussed in this paper, we need to reduce the external neutron and gamma fluxes to below the level  $10^{-10}$  events/ $\text{cm}^2/\text{s}$ . Although this could be achieved by sufficient thicknesses of conventional outer metallic and inner hydrocarbon shielding, which provide the most compact shielding solution, the potential availability of larger underground experimental volumes has increased preference for an all-water shield, 3 – 4 m thick, with the innermost 50 – 60 cm instrumented as an active veto or replaced by liquid scintillator. This offers the additional possibility of instrumenting the scintillator with photomultipliers placed outside the water volume, and hence with their activity shielded by the water. The latter can at the same time function as a muon veto by detecting Cerenkov signals in the water.

We simulate the performance of this by tracking first a typical cavern gamma flux from rock U/Th/K activity (using the example of the LNGS activity given by Wulandari et al. [46]) through successive 1 m thicknesses of water, then through 50 g/ $\text{cm}^2$  liquid scintillator, and through an outer 10 cm passive layer of liquid Xe to an internal fiducial target 80 cm diameter, finally assuming a 2-phase detector discrimination factor of 100. The results of these steps are summarized in the right hand path of Fig. A.1, which traces the decrease in total gamma flux through the shielding. The simulations also keeps track of the gamma energy spectrum after each stage, allowing the final number of low energy events in the fiducial Xe region to be counted. The horizontal dashed line

at  $2 \times 10^{-10}$  events/cm<sup>2</sup>/s is the level corresponding to an unrejected background of 0.2 events/y ( $< 40$  keV) in an inner 1-ton (fiducial) Xe target.

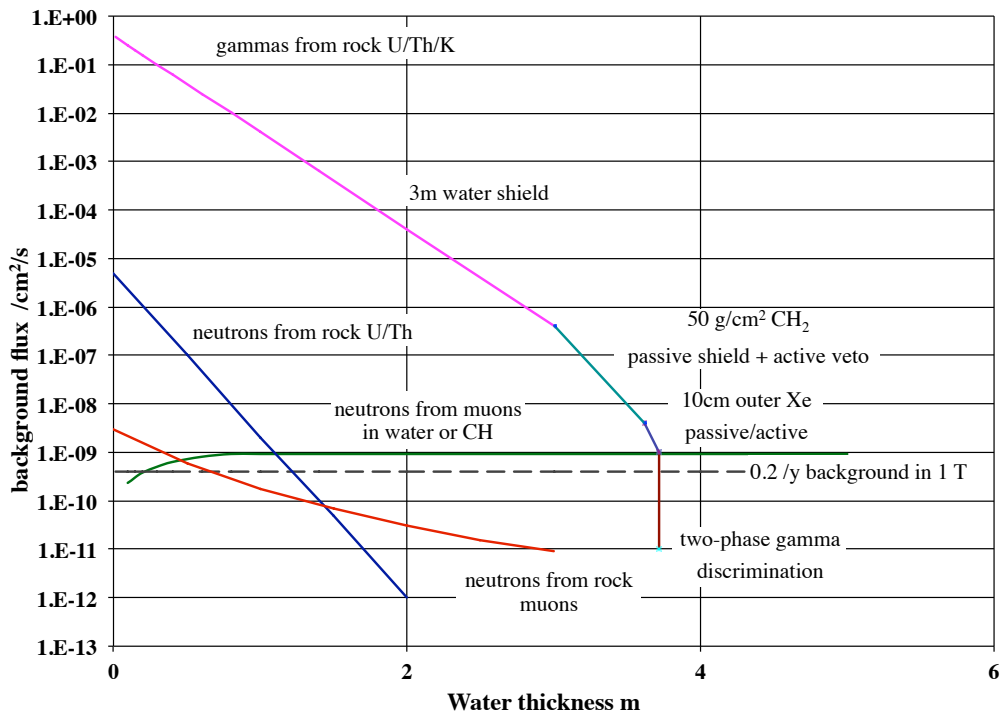


Figure A.1: Chart showing progressive attenuation of external gamma and neutron fluxes through 3 m water shielding, an active and/or passive hydrocarbon veto, and a 10 cm passive outer layer of the target. An additional factor  $\sim 100$  two-phase detector discrimination for gammas is also shown. The dashed line shows the level required for sensitivity to a signal at WIMP-nucleon cross-section  $10^{-46}$  cm<sup>2</sup> with a fiducial one ton Xe target. These simulations used RAL-developed shielding code FAUST (1992, unpublished) using cross-section data files identical to MCNP and GEANT4, cross checked against MCNP in [92], and subsequently against GEANT4 (ZEPLIN III internal notes, unpublished)

The corresponding attenuation of the principal neutron sources is shown by the three curves on the left hand side of the plot, again each needing to fall below the horizontal dashed line to achieve a 0.1 – 0.2 event/y background. The one source that remains above this level is that of neutrons from muons interacting in the metre of water closest to the detector. However, this can be rejected by using the water itself as a Cerenkov veto, or by means of additional scintillating muon veto panels above the water shield. For these calculations, the muon flux at 3600 m.w.e. depth (the LNGS site depth) has been used as an example, together with the typical gamma flux from LNGS rock activity.

The shielding requirement for other target masses and materials, can be estimated by scaling of fiducial surface area, and noting the approximate linearity of the water attenuation, as follows:

1. For G2 detector combination  $\sim 1$ -ton Xe &  $\sim 5$ -ton Ar.

Fig. A.1 applies to a 1 m diameter, 1 m high, Xe detector volume with 0.8 m diameter fiducial

region (density 2.9 g/cc). Thus for an Ar detector of 5 times the fiducial mass (and density 1.45 g/cc) the fiducial diameter is a factor 2 larger and the fiducial surface area a factor 4 larger. At the same time the required background/ton is reduced by a factor 5 (to achieve the same signal sensitivity in Ar). Hence the dashed line in Fig A.1 is lower by a factor 20 for Ar, which nevertheless remains within the attenuation curves and hence requires no additional shielding.

2. For G3 detector combination  $\sim 10$ -ton Xe &  $\sim 50$ -ton Ar.

To achieve all of the physics objectives of a factor 10 increase in Xe and Ar masses, one will require a factor 10 gain in background/ton for both detectors. At the same time, the fiducial surface areas would increase by a factor  $\sim 4$ . Thus the combined drop in the dashed curve of Fig A.1 becomes a factor 40 for 10 T Xe, and (taking account also of the size factor in (a)) a factor  $\sim 800$  for a 50-ton Ar detector. The former remains within the attenuation curves of Fig.A.1, but for the 50-ton Ar this would require extending the water shielding by an additional 1.5 m radially to lower by a factor 1000 the end point of the gamma-shielding curve. It is also apparent that the slower attenuation of neutron events from high-energy muons in rock (red curve) may be marginal for a 50-ton Ar detector, and would benefit from a deeper site (see Tab. A.1) to gain a factor 10 in muon flux.

3. For G4 detector combination  $\sim 100$ -ton Xe &  $\sim 500$ -ton Ar.

For the G4 Xe detector, a further factor 40 gain over G3 is already covered by the increased water radius specified in (b) for the G3 50 ton Ar detector. A further 1.5 m radial increase is needed to gain an additional reduction factor 800 for the 500 ton G4 Ar detector, now increasing the overall water radius to 7 m, and the overall G4 water tank diameter to over 22 m. However, this would be significantly reduced by the increasing thickness of the target self-shielding layer outside the fiducial volumes, in progressing from G2 to G3, and from G3 to G4, to reduce backgrounds from detector vessel and photodetectors (see Sec.3, Tab.4).

It is important to keep in mind that the above water shielding discussion applies to continuous ( $4\pi$ ) coverage of the shield around the detector. Electrical, cryogenic, and mechanical feed-throughs will provide channels along which external gamma and neutron fluxes can reach the target. Since the external fluxes can be 6-8 orders greater than the shielded flux, even small areas of such channels could substantially increase the target background. The solution to this is to ensure that all such channels have two or three 90 degree bends, the scattering at each decreasing the flux (reaching the detector) by typically a factor  $10^3$ . This will be straightforward for cryogenic pipes and electrical connections, but will need novel design for the metallic structures that support the detector within the water shield.

## Appendix B. Radioactive contamination of target elements

### Appendix B.1. $^{85}\text{Kr}$ background in natural Xe

Natural Kr is present as an impurity in commercial Xe, at a level typically 50 ppb, and in turn contains  $\sim 10^{-11}$  cosmogenic  $^{85}\text{Kr}$ , which emits a continuous beta decay spectrum with maximum energy 690 keV and a 10.7 y half-life. This would contribute a low energy beta background  $\sim 1$  events/keV/kg/d to be added to the gamma population and, at this contamination level, limiting the dark matter sensitivity to  $10^{-44}$  cm<sup>2</sup>. The need to remove this, to reach lower cross sections, has led to the development of reflux distillation columns that will reduce the level of Kr in Xe by a factor  $10^3$  per pass [47]. Thus, using several passes, it will be possible to reduce the  $^{85}\text{Kr}$  content to a negligible level.

### *Appendix B.2. $^{39}\text{Ar}$ background in natural Ar*

In the case of the Ar target, natural (atmospheric)  $^{40}\text{Ar}$  contains a fraction  $\sim 10^{-15}$  of cosmogenically produced  $^{39}\text{Ar}$ , which beta-decays with a half-life 269 y and a continuous spectrum with maximum energy 570 keV. This gives a total background rate  $\sim 1.2$  events/kg/s, a low energy differential rate  $\sim 3 \times 10^2$  events/kg/d/keV, and thus a total event rate  $\sim 6000$  events/kg/d in the 5 - 25 keVee electron equivalent dark matter energy range. This is too high a starting point for the two-phase discrimination technique alone, and can also produce “pile-up” in the data acquisition system. However, using argon depleted in  $^{39}\text{Ar}$  from an underground source, this can be immediately reduced by a factor  $> 100$  [48, 49, 50] and then by a further factor  $\sim 10^8$  using pulse shape discrimination. By means of these factors it becomes possible to reduce the  $^{39}\text{Ar}$  background to  $< 1$  event/5 tons/year for a nuclear recoil energy threshold of 20 keVnr. This is calculated in detail in Appendix C.2 below. We note in addition that if the 5 ton and 50 ton argon detectors can be instrumented with a  $4\pi$  photodetector array, this provides a position resolution  $\sim 1\%$  of the detector volume, permitting rejection of events that do not correspond to a position coincidence of S1 and S2 in the same 1% of detector volume, also reducing  $^{39}\text{Ar}$  “pile-up” by a factor 100.

### *Appendix B.3. Rn-related background*

Radon in the air ( $^{222}\text{Rn}$ ) has a lifetime  $\sim 4$  days, continuously replenished from uranium in the ground and neighboring materials. Hence it does not survive in stored xenon or argon gas, but has been seen to cause background problems in the Xe detectors [3, 26, 5], by contaminating the target or gas systems during assembly and/or transfer and depositing its decay products (for example  $^{210}\text{Po}$ , lifetime 138 days) on the detector walls where it further decays by alpha emission. The alphas themselves are in the MeV range, and hence do not result in low energy signals if emitted into the liquid. But if emitted into the wall, the Po nucleus recoils into the liquid, with (by momentum conservation)  $< 100$  keV recoil energy and thus can produce a signal comparable to that of a recoil Xe or Ar nucleus. These “wall-events” can be eliminated from the data set by using the S2 position sensitivity to make a radial cut, but a 10 cm – 20 cm cut is already envisaged as an essential part of the target shielding and included in the estimates in Sec.3.4 and Appendix C. Thus for large volume detectors the fiducial target is already protected from this source of background.

### *Appendix B.4. U & Th contamination of liquid Xe or Ar*

Contamination of the target material with radioactive isotopes might in principle occur during production and purification, or during recirculation through getters if used in the detector cryogenic system, so we need to estimate some permissible limits on the tolerable U or Th content in the target material. The presence of U/Th chains would give rise to both gamma emission, alpha emission, and beta decay, the latter being the sum of  $> 100$  different beta spectra in the U/Th chains. Summing these contributions, we estimate that to reduce the absolute level of electron recoil events (after the S2/S1 cut) to  $< 1$  events/ton/y below 20 keV would require a stringent U/Th concentration level no more than  $\sim 10^{-3} - 10^{-4}$  ppt. However, the majority of these events will be automatically vetoed by near-simultaneous higher energy events in the chain (gammas, electrons, alphas). Within a time window range of, say,  $\pm 1$  ms to  $\pm 1000$  ms (dependent on overall trigger rate), we estimate that 99.9% of U/Th events  $< 20$  keV will be in coincidence with a higher energy decay in the chain, thus automatically reducing this background by a factor 1000. On this basis it would appear that the permissible upper limit on the contamination of Xe or Ar by U/Th is eased to about 0.1 – 1 ppt. If the levels of U/Th in liquid Xe or Ar are found to be higher than this, some additional purification would be necessary.



## Appendix C. Self-shielding of radioactivity in detector components

For simulations of detector background from radioactive impurities in the detector vessels and photodetectors, the assumed limits on U/Th/K contamination, based on recent sample selection and testing, are summarized in Tab.C.1.

material	unit	U (mBq/unit)	Th (mBq/unit)	K (mBq/unit)
Copper	kg	$\leq 0.07$	$\leq 0.03$	$\leq 0.5$
Titanium	kg	$\leq 0.25$	$\leq 0.20$	$\leq 1.3$
PTFE	kg	$\leq 0.31$	$\leq 0.16$	$\leq 2.2$
QUPID (3")	single QUPID	$\leq 0.5$	$\leq 0.4$	$\leq 2.4$
QUPID (6")	single QUPID	$\leq 4.0$	$\leq 3.2$	$\leq 20$
Conversion	1 mBq (0.001 parent decays/s)	0.08 ppb	0.25 ppb	.03 ppm

Table C.1: Assumed radioactivity levels in detector materials and components

We need estimates of both gamma and neutron backgrounds from these sources. Gammas are emitted directly by U/Th chains, and by K, with a known energy spectrum extending up to  $\sim 3$  MeV (tabulated, for example, in [14]). Neutrons are produced by the MeV-range alpha emission from U/Th, interacting with the host nuclei to produce an MeV-range neutron spectrum with a total material-dependent rate calculated by Heaton et al [52], also incorporated in the **SOURCES** program [93]. The latter also provides a prediction the emitted neutron energy spectrum, but which appears not to be consistent with underground measurements [45, 46, 53]. We therefore consider it safer to use, for background simulations, a more conservative (higher mean energy) generic neutron spectrum shape as proposed in [45]. We consider in turn gamma and neutron backgrounds for each of the four detectors illustrated in Fig.1 (G2) and Fig.2 (G3).

### Appendix C.1. G2 system: backgrounds for 1 ton Xe detector

For the 1 ton Xe detector, Fig.C.1(*upper*) shows the results of a **GEANT4** simulation [94] of the energy spectrum of single scatter gamma events in the fiducial region, assuming 99% rejection by the two-phase S2/S1 discrimination and various Xe thicknesses from zero to 30cm used as an outer passive shield. Position sensitivity also allows events in the latter region to be identified and used as an active Xe veto. The results are shown as a rate in unrejected events/kg/day/keVee (electron equivalent) sometimes abbreviated to dru (differential rate unit [15]). Superimposed on these results are spectra for WIMPs of various masses, a WIMP-nucleon cross section of  $10^{-45}$  cm<sup>2</sup>, also, for later discussion, pp and <sup>7</sup>Be solar neutrinos, and a two-neutrino double beta decay spectrum (emitting 2.6 MeV electron recoil energy). Fig.C.1(*lower*) shows the same results for the expanded energy region  $<50$  keVee showing also the  $\sim 2 - 20$  keVee range most relevant to WIMP detection with the liquid Xe TPC. For a 1-ton target, the results show that a 10 cm outer passive Xe layer is sufficient to reduce the unrejected gamma background to 0.1 events/y.

Fig.C.2 shows the spatial distribution of single scatter gammas for a simulated 1 year running, without an S2/S1 cut. Removing an outer 10 cm leaves only 7 events/y in the fiducial region, which then reduces to  $<0.1$  events/y after the two-phase S2/S1 cut. The electron recoil spectrum from pp-chain solar neutrinos, shown in Fig.C.1(*upper*), is about a factor 10 higher and thus represents an additional known background (constant with energy below 50 keVee and hence fully subtractable)  $\sim 0.7$  event/y, or lower if foreseeable improvements in the S2/S1 cut are made.

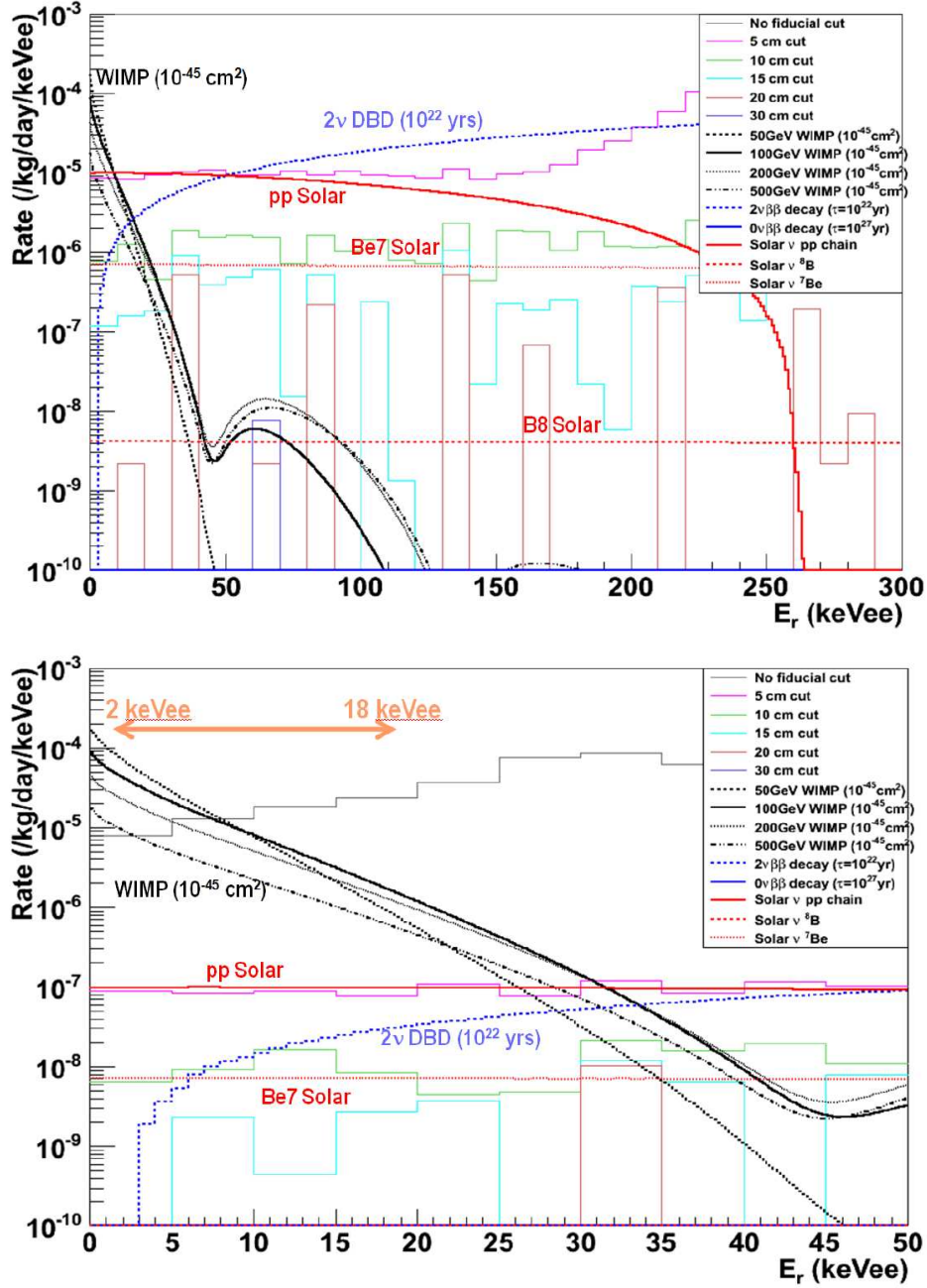


Figure C.1: (*upper plot*) Gamma rates from cryostat and QUPID radioactivity for 1 m diameter Xe detector (2.2 tons total Xe mass) with 0, 5, 10, 15, 20, 30 cm outer Xe shield, with multiple scattering cut, and no factor S2/S1 cut. Superimposed spectra show nuclear recoils from WIMPs at  $10^{-45} \text{ cm}^2$  cross section, electron scattering from pp and  $^7\text{Be}$  solar neutrinos, and a  $2\nu\beta\beta$  spectrum.  
 (*lower plot*) Same as upper plot but expanded low energy scale and S2/S1 cut.

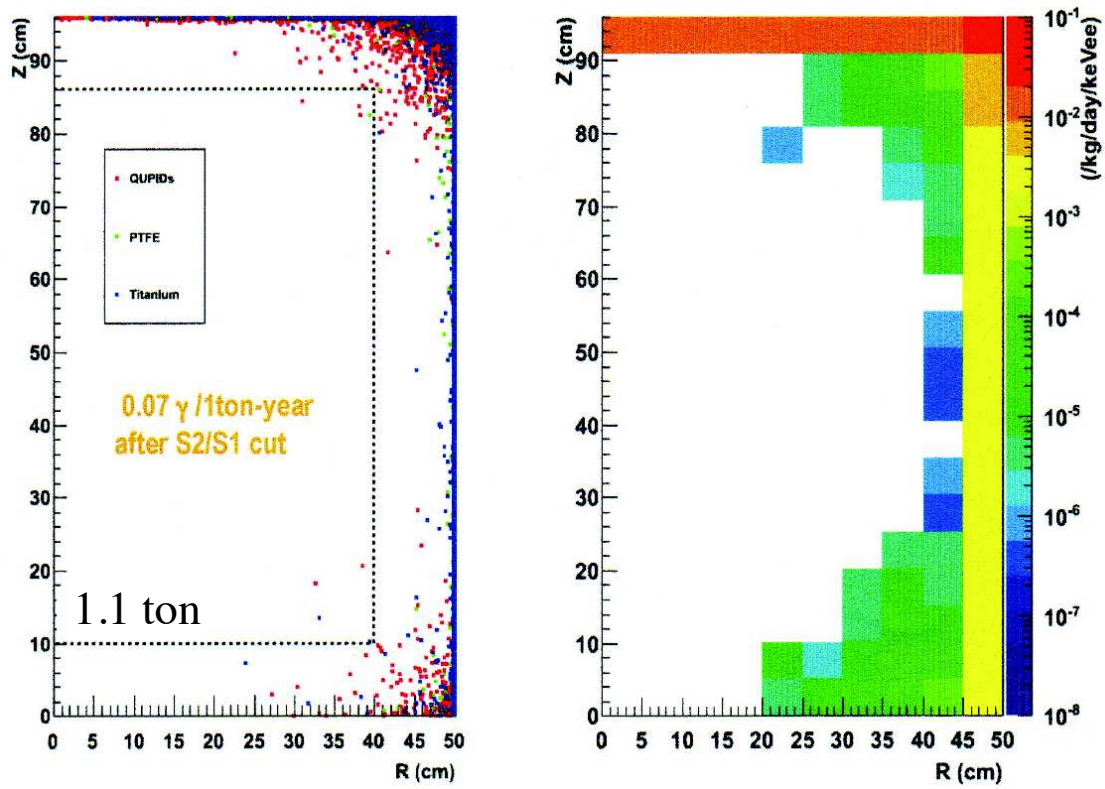


Figure C.2: Simulated spatial distribution of gamma background in 2.2 ton (total) Xe detector after 1 year, with multiple scattering cut but without S2/S1 discrimination.

An outer cut of 10 cm leaves a fiducial mass 1.1 ton and removes all but 7 events which, after a factor 100 S2/S1 discrimination, leaves 0.07 events/ton/y unrejected.

Results of simulations of the corresponding single scatter neutron backgrounds in 1 ton Xe are shown in Fig.C.3 and Fig.C.4. The production of neutrons from U and Th is material-dependent but typically a factor  $10^5$  lower in absolute rate than the production of gammas. However, neutrons are less attenuated than gammas by the outer 10 cm passive Xe and not discriminated at all by the S2/S1 cut. Fig.C.3(*upper*) shows the total single scatter neutron background spectrum in the Xe fiducial region after outer cuts of various thicknesses. Fig.C.3(*lower*) uses a fixed 10 cm outer cut, and plots the individual contributions from QUPIDs and the different nearby detector materials. This shows the largest contributions come from the QUPIDs and the PTFE (if used on the side walls as a reflector in place of a full array of QUPIDs). Thus in the absence of the PTFE, the QUPIDs are the dominant source of background, a conclusion utilised below to simplify the estimates for larger detectors.

Fig.C.4 is the neutron counterpart to Fig C.2, and shows the individual single scatter events in the 1-ton fiducial region for the equivalent of 100-year data, and for the specific case of a 10 cm passive Xe thickness. In this simulation the fiducial region contains 10 neutron events for 100 years, thus achieving the desired background of  $\sim 0.1$  events/ton/y.

#### *Appendix C.2. G2 system: backgrounds for 5-ton Ar detector*

As discussed in Sec.1, the G2 system consists of a  $\sim 1$ -ton fiducial Xe detector partnered by a  $\sim 5$ -ton fiducial Ar detector. The liquid argon detector will also be constructed in a two-phase TPC configuration, but operated at a higher nuclear recoil threshold than liquid xenon, typically  $\sim 20$  keVnr compared with  $\sim 8$  keVnr for Xe. This is to achieve separation from the  $^{39}\text{Ar}$  beta decay background discussed in Appendix B, and calculated numerically in the next paragraph. The upper recoil energy range remains higher than that for Xe owing to the lower form factor correction as shown in Fig.5 (subject to the Galactic escape velocity cut-off in Tab.3).

The nuclear recoil energy threshold for argon arises from an interplay between the scintillation light output and the pulse shape discrimination between electron and nuclear recoils. But for the presence of  $^{39}\text{Ar}$  it would be trivial to obtain a nuclear recoil threshold even as low as a few keV. With a measured light output of 40 photons/keV, 75% photodetector coverage, and a  $> 36\%$  quantum efficiency for wavelength-shifted argon QUPIDs [83] the scintillation output is  $> 10.8$  photoelectrons/keVee, and 9 pe/keVee even with conventional PMTs. Thus, with a trigger  $\sim 5$  pe this high pe/keVee output could give a nuclear recoil threshold as low as 2 - 3 keVnr, were it not for the presence of a  $^{39}\text{Ar}$  flat background at low energy. We now show that the latter can be reduced to  $< 1/\text{y}$  in detectors containing 5 - 50 tons argon, for an energy threshold of 20 keVnr.

Using a quenching factor of 25% [54] the required electron recoil threshold is 5 keVee. We assume an analysis energy span of 5 - 25 keVee, corresponding to 54 - 270 photoelectrons in the case of the QE already achieved for argon QUPID photodetectors. From Appendix B.2 the  $^{39}\text{Ar}$  background in this energy span is 6000 events/kg/d =  $10^{10}$  events/5 ton/y, reduced to  $10^8$  events/5 ton/y by the use of argon from an underground source. Simulations of pulse shape discrimination based on measured pulse time constants have been presented as a function of photoelectron number by A. Hime [51]. These give an average psd of  $6 \times 10^{-9}$  over the (flat) energy range 5 - 25 keVee (54 - 270 photoelectrons), which reduces the background to 0.6 events/5 ton/y.

Hence, even without any additional low energy two-phase discrimination, the  $^{39}\text{Ar}$  background in a 5 ton detector is reduced by psd to  $< 1/\text{year}$  with a 20 keVnr threshold. For the case of detectors larger than 5 tons, we can utilize the additional discrimination available from the two-phase S2/S1 ratio. From the measurements of [7] the measured ratio of the quantity S2/S1, for electron and nuclear recoils, averages 8 in the range 5 - 25 keVee, giving a further discrimination

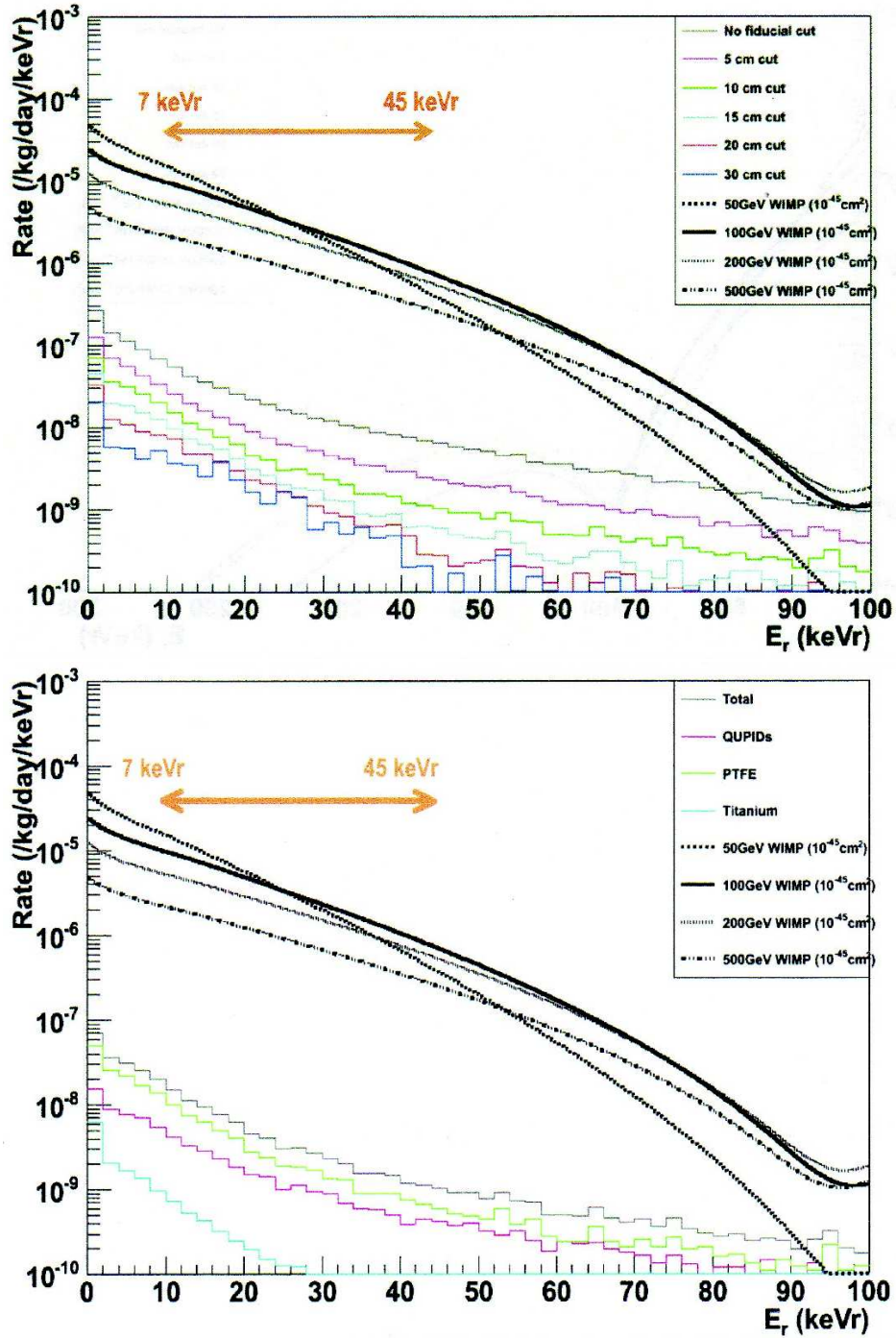


Figure C.3: Neutron single-scatter spectra in 1.1 ton fiducial Xe. Energy axis (keVr) is nuclear recoil energy (*upper plots*) Showing several thicknesses of passive Xe. (*lower plots*) Fixed 10 cm thickness passive Xe, but the showing individual contributions from QUPIDs and different nearby detector materials. Dark matter spectra for WIMP-nucleon  $\sigma = 10^{-45} \text{ cm}^2$  shown for several WIMP masses.

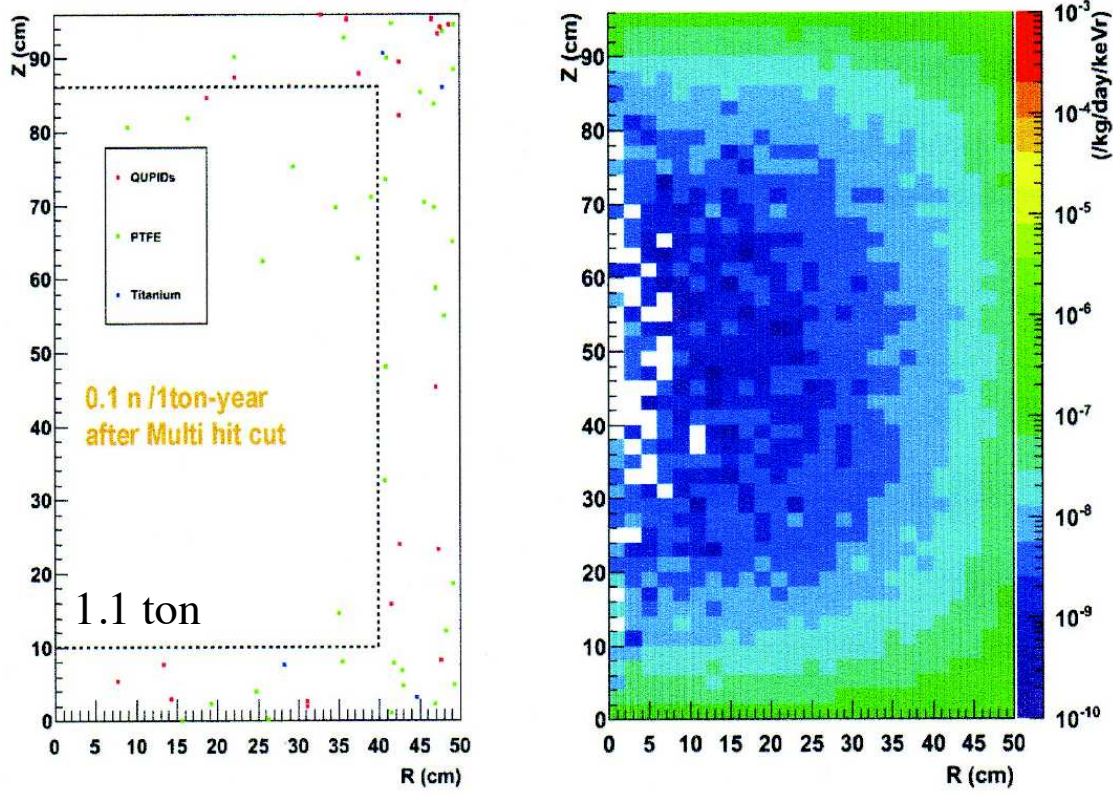


Figure C.4: Simulated spatial distribution of single scatter neutron events in 2.3 ton (total) Xe detector for 100 years. An outer cut of 10 cm leaves 10 events in a fiducial mass of 1 ton giving 0.1 events/ton/y unrejected.

factor conservatively 50 - 100, which further reduces the background in both 5 and 50 ton detectors below 0.1 event/year. The electric field requirement for this modest additional discrimination can be adjusted to minimize reduction in light output by suppression of recombination [8]. There is also likely to be an additional gain of an order of magnitude or more from underground argon, since the latest measurements have not yet seen any  $^{39}\text{Ar}$  in underground samples.

From the preceding estimates of electron recoil background, we can assume that in the case of two-phase argon detectors, the residual neutron background rate will dominate in the fiducial target zone, and this will now be discussed.

As mentioned previously, Fig.C.3(*lower*) shows that the dominant contributions to fiducial neutron background arise from the QUPIDs and the PTFE, the latter providing an optional reflector on the detector sides in place of a full array of QUPIDs. However, the G2 Ar design under consideration here would utilize a full array of QUPIDs, and no PTFE reflecting walls, so that only the neutron background from U/Th in the QUPIDs need be included in the simulations. Figs C.5(*upper*) and C.5(*lower*) show the resulting spectrum of nuclear recoils, with a multiple scattering cut, for various thicknesses of outer liquid Ar cut, and with or without the use of signals from a 0.5% Gd-loaded liquid scintillator veto outside the detector. Without the Gd, neutrons are slowed and absorbed by H releasing a 2.2 MeV gamma. With 0.5% Gd loading, > 95% of neutrons are absorbed on Gd nuclei releasing 4 gammas totalling 8 MeV. The veto rejects two types of event:

1. neutrons emitted from the QUPIDs into the outer shield, then scattered into the target;
2. neutrons emitted first into the target, then scattered out into the scintillator.

Fig.C.6 is the Ar counterpart to Fig.C.4 for Xe, and shows the spatial distribution of individual single scatter events in the 5 ton fiducial region for 100 years data, and for the specific case of a 15 cm outer passive Ar cut, and in this case shown with or without rejection of events by a liquid scintillator veto surrounding the detector. With both the multiple scattering cut and veto cut, about 10 events (in the dark matter recoil range) remain in the fiducial region in 100 years equivalent running time, thus achieving the background objective of  $\sim 0.1$  events/y. Fig.C.7 provides a further illustration of the stages of neutron background reduction, showing that the multiple scattering cut and veto cut each produce about an order of magnitude reduction in the events remaining in the fiducial region. Thus from the simulations for the Xe and Ar detectors constituting the G2 system, we conclude that a neutron background  $\sim 0.1$  events/y can be achieved in both detectors, but the additional use of the liquid scintillator veto appears essential in the larger argon detector, unless a sensitivity limited by  $\sim 1$  neutrons/y background is judged acceptable.

### *Appendix C.3. G3 system: backgrounds for 10-ton Xe detector*

Using the same assumptions for materials radioactivity levels as for the 1-ton Xe detector, Fig.C.8 shows GEANT4 simulation results for the spectrum of electron recoils in the fiducial region, after a multiple scattering cut and the two-phase S2/S1 cut, shown for different outer radial cuts ranging from 0 to 30 cm.

An outer cut of  $\sim 15$  cm reduces the 18 tons total mass to a 10-ton fiducial mass, in which, after multiple scattering cut and S2/S1 cut of a factor 100, the residual gamma rate is reduced to  $< 0.1$  events/y. As in the G2 1-ton Xe detector, there is, below 20 keVee, a spatially uniform and energy independent background of electron recoils from pp solar neutrinos, at the level  $\sim 8$  events/y, which is acceptable (compared with the  $\sim 1000$  events for dark matter at  $10^{-45}$  cm<sup>2</sup> or  $\sim 100$  events at  $10^{-46}$  cm<sup>2</sup>) since it has a subtractable spectrum of known shape and magnitude.

For the neutron backgrounds, we utilize again the preceding conclusion that the principal contribution comes from U/Th in the QUPID photodetectors. Fig.C.9(*upper*) and Fig.C.9(*lower*) show the simulated spectra of single-scatter events, for different outer cuts in the range 0 – 30 cm,

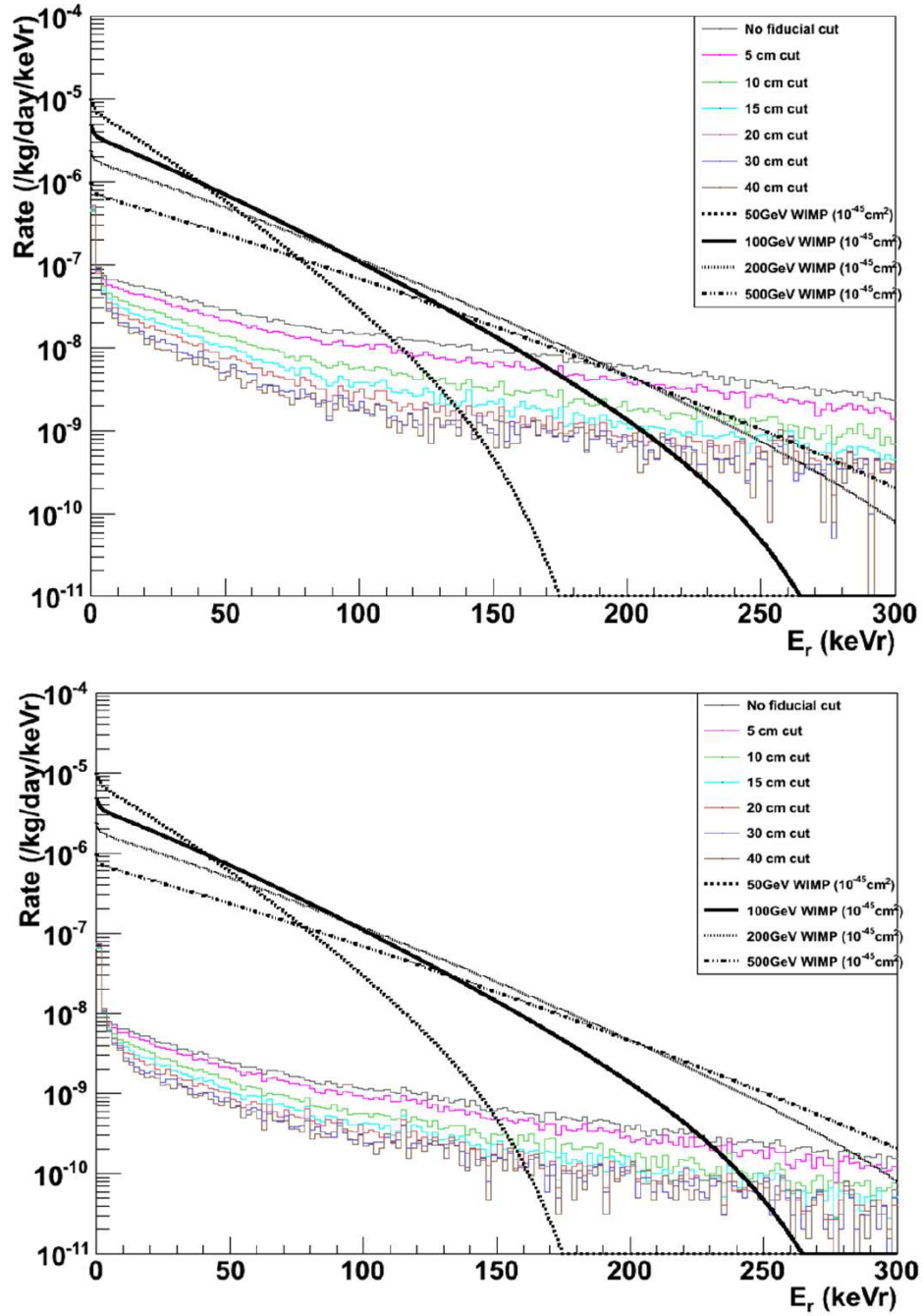


Figure C.5: Neutron single scatter spectra in 5-ton (fiducial) liquid Ar, assuming dominant contribution from residual U/Th in QUPIDs, and showing mass-dependent DM spectra for WIMP-nucleon  $\sigma = 10^{-45} \text{cm}^2$ .

(upper plots) No outer liquid scintillator veto

(lower plots) 0.5% Gd-loaded liquid scintillator with veto threshold 300 keV.



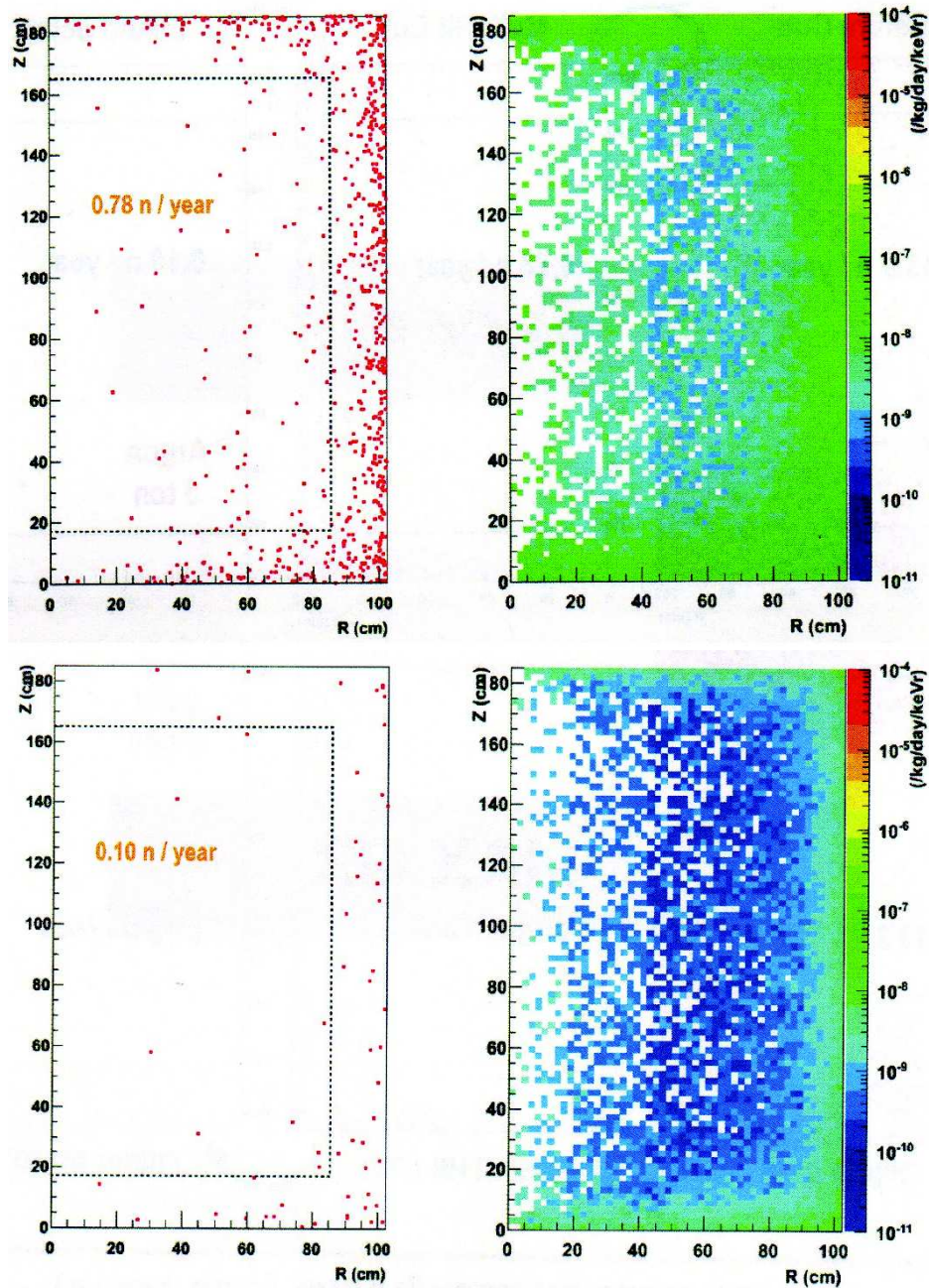


Figure C.6: Simulated spatial distribution of single scatter neutron events in 100 years from U/Th in full QUPID array around 9-ton (total) Ar detector for 100 years, *(upper)* with no outer liquid scintillator veto. An outer cut of 15 cm leaves 78 events in a fiducial mass of 5 ton giving  $\sim 0.8$  events/y (in the dark matter recoil energy range). *(lower)* using 0.5% Gd-loaded liquid scintillator veto with 300 keV signal threshold. An outer cut of 15 cm leaves 10 events in a fiducial mass of 5 tons, giving  $\sim 0.1$  events/y (in the dark matter nuclear recoil energy range).

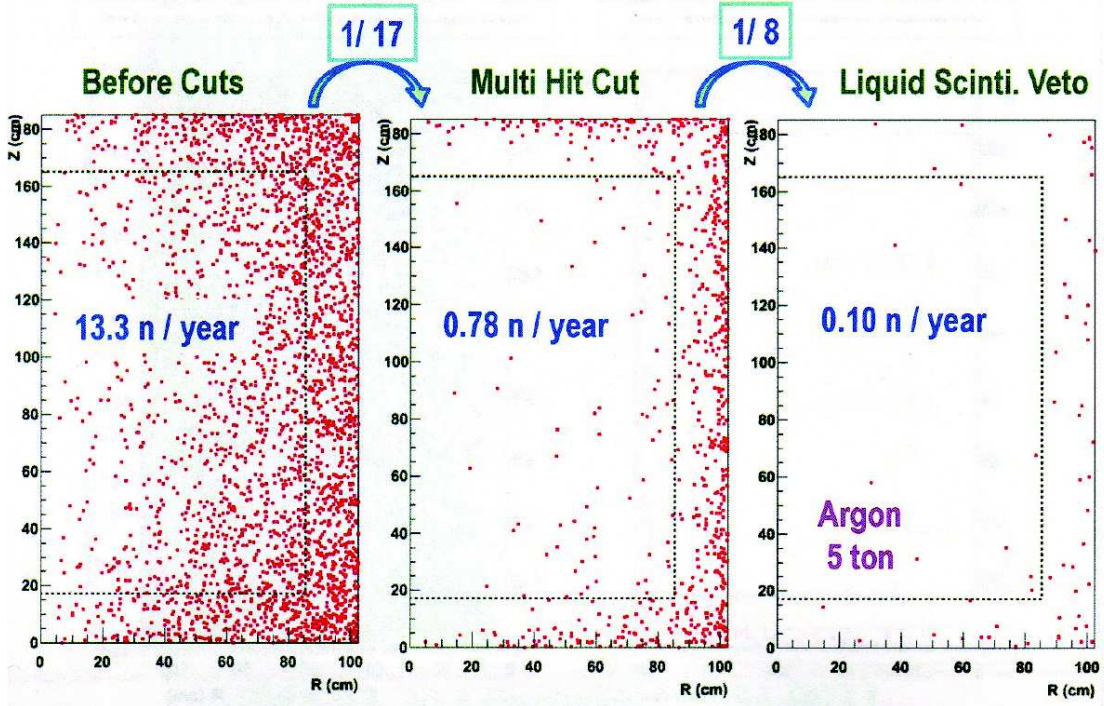


Figure C.7: Summary of neutron background reduction in 5 ton Ar fiducial region. The multiple scattering cut and the liquid scintillator veto each produce a factor  $\sim 10$  reduction to leave the desired level of  $\sim 0.1$  neutrons/y (in the dark matter recoil energy range).

and with or without the liquid scintillator veto surrounding the detector vessel. Fig.C.10 is the counterpart to Fig.C.7, showing the progressive reduction of neutron background, firstly to  $\sim 0.1$  neutrons/y by a multiple scattering cut, and secondly to  $\sim 0.03$  events/y by the liquid scintillator veto operating at a threshold of 300 keV. The latter rejects neutrons by simultaneous scattering in the liquid scintillator either before or after scattering in the xenon, providing also an important diagnostic tool in the event of unpredicted additional background in the target.

#### Appendix C.4. G3 system: backgrounds for 50-ton Ar detector

For the 50-ton (fiducial) Ar detector, which partners the 10 ton Xe detector, we adopt the simplifications concluded in Appendix C.2 for the 5-ton Ar detector:

1. that the unrejected neutron background will dominate over the unrejected gamma background.
2. that neutrons from the QUPIDs will provide the dominant contribution to target background.

Fig.C.11(*upper*) and Fig.C.11(*lower*) show the simulated spectrum of nuclear recoils from QUPID neutrons, for various thicknesses of outer cut in the liquid Ar, with a multiple scattering cut, and without or with a liquid scintillator outer veto. The comments in Appendix C.2 on the type of events rejected by the veto apply here also, but the assumed veto energy threshold of 300 keV may be more difficult to achieve in this larger detector. Repeating the simulation of Fig.C.11(*lower*) with 1000 keV veto threshold increased the absolute background numbers by a factor  $\sim 1.5$ .

Fig.C.12 is the counterpart to Fig.C.10, again showing two orders of magnitude gain from applying both the multiple scattering cut and the veto cut, this time leaving a final background of 0.4 neutrons/y for a 300 keV veto threshold, or 50% higher at 0.6 neutrons/y for a more conservative

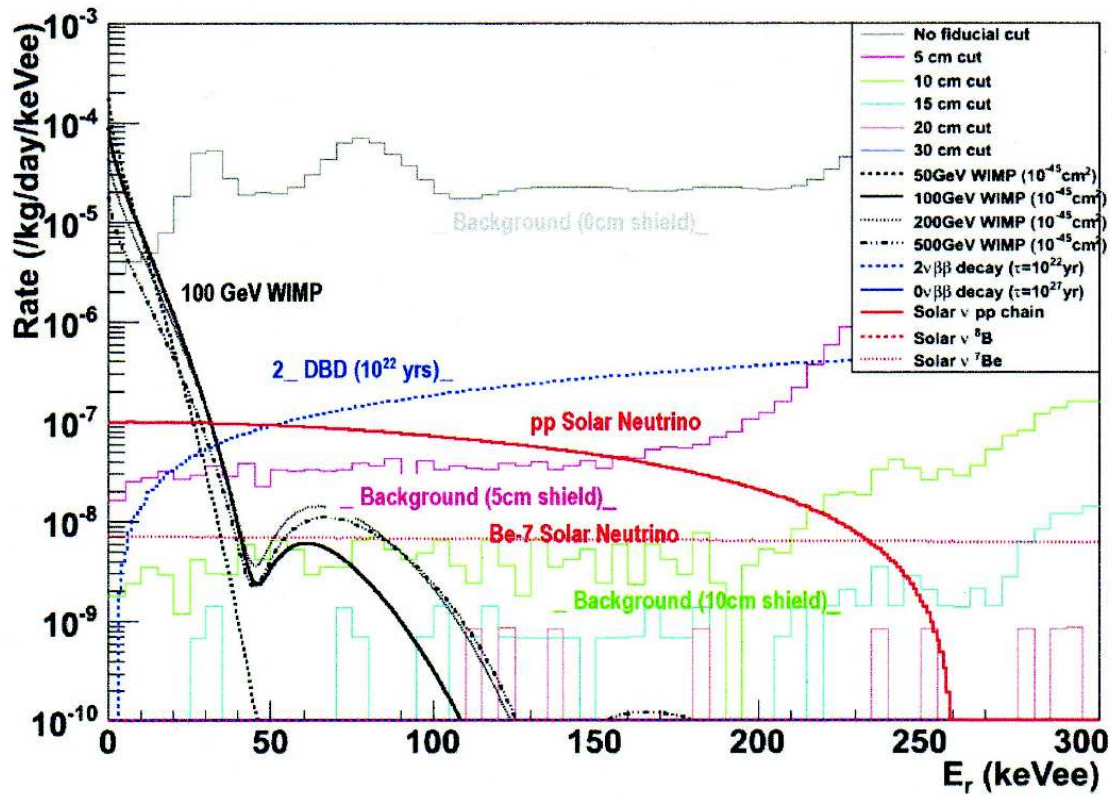


Figure C.8: Gamma rates from cryostat and QUPID radioactivity for 2 m diameter Xe detector (18 tons total Xe) using multiple scattering cut, S2/S1 cut, and 0, 5, 10, 15, 20, 30 cm outer Xe shield. Superimposed spectra show nuclear recoils from WIMPs at  $10^{-45} \text{ cm}^2$  cross section, electron scattering from pp and  $^7\text{Be}$  solar neutrinos, and a  $2\nu\beta\beta$  spectrum.

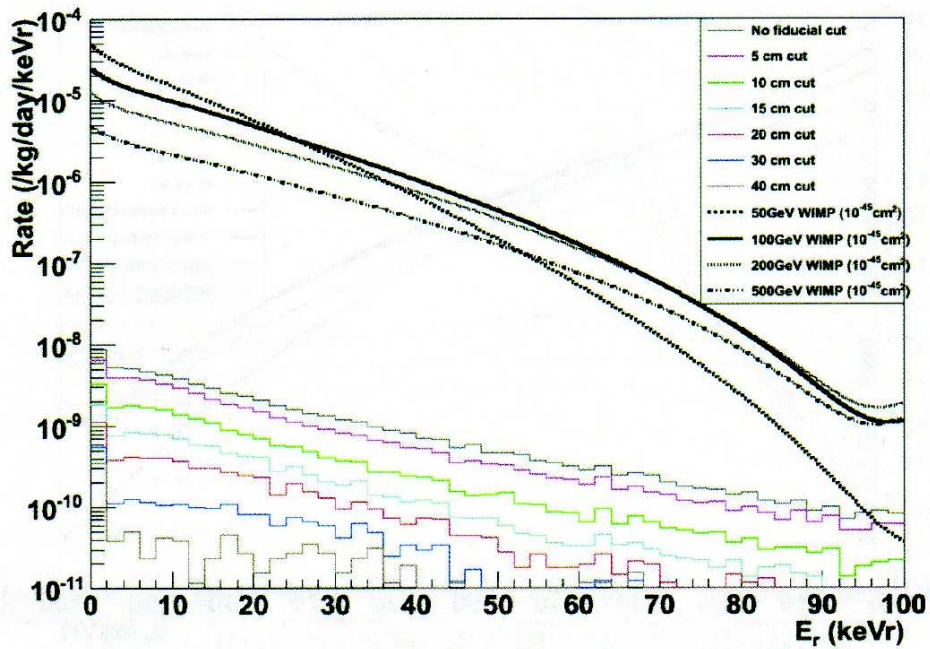
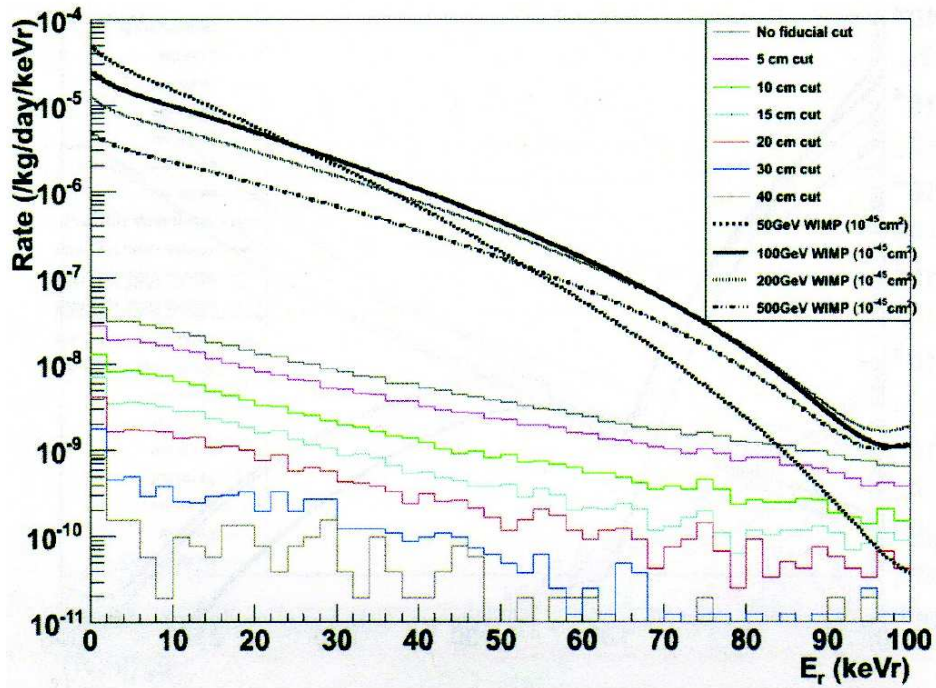


Figure C.9: Neutron single scatter spectra in fiducial 10-ton Xe (versus keVr) for outer Xe cuts of 0, 5, 10, 15, 20, 30 cm, compared with dark matter spectra (black curves) for WIMP-nucleon  $\sigma = 10^{-45} \text{ cm}^2$  shown for several WIMP masses.

(upper plots) No outer liquid scintillator veto

(lower plots) 0.5% Gd-loaded liquid scintillator with veto threshold 300 keV.

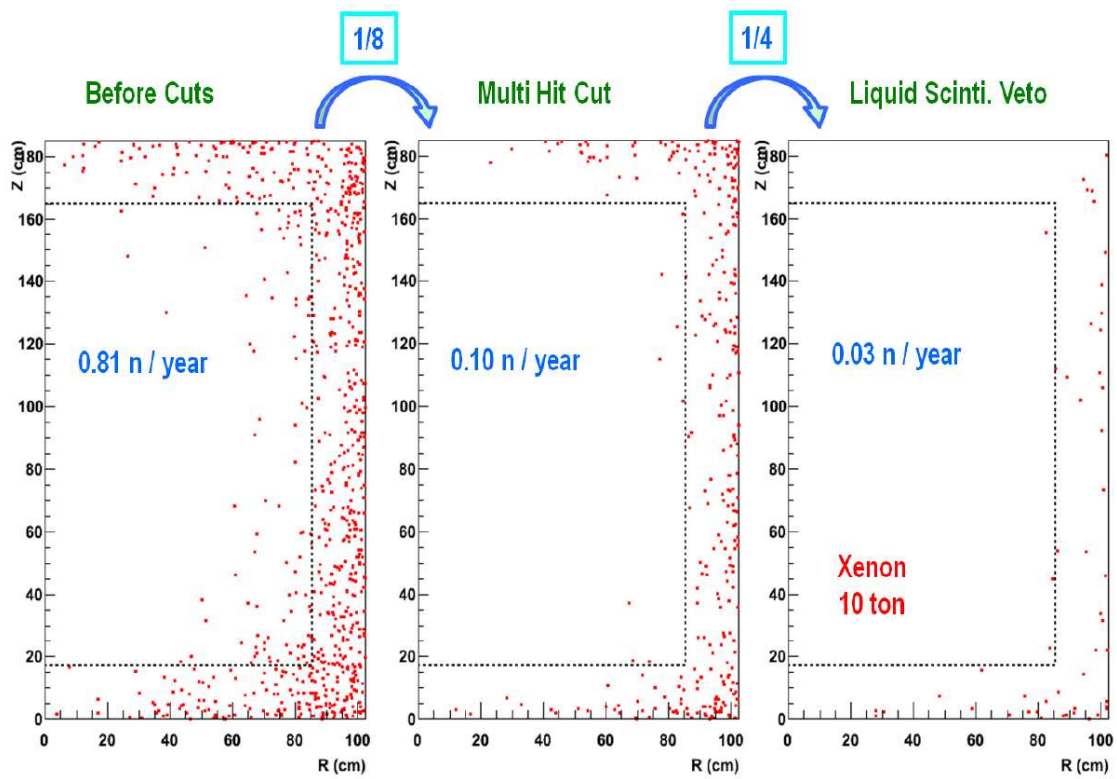


Figure C.10: Summary of neutron background reduction in 10-ton Xe fiducial region, using a 15 cm outer cut and a 100 y simulation. The multiple scattering cut is sufficient to reach the background level  $\sim 0.1$  events/y, with a further factor 4 gain from the veto signal.

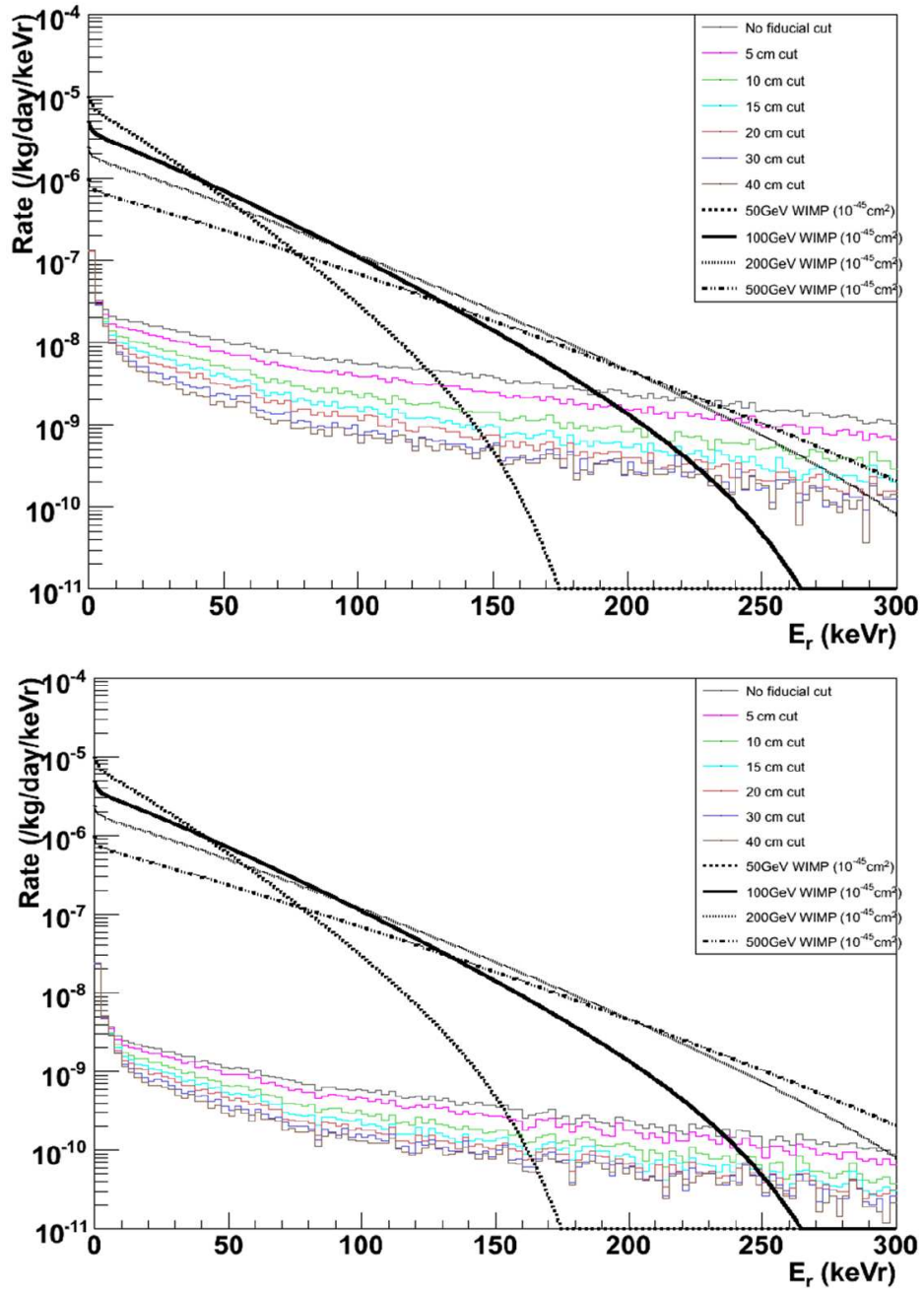


Figure C.11: Neutron single scatter spectra in fiducial 50-ton Ar (versus keVr) for outer Ar cuts of 0, 5, 10, 15, 20, 30, 40 cm, compared with dark matter spectra (black curves) for WIMP-nucleon  $\sigma = 10^{-45} \text{ cm}^2$ , shown for several WIMP masses.

(upper plots) No outer liquid scintillator veto

(lower plots) Using veto signal with threshold 300 keV (spectra  $\times 1.5$  for 1000 keV.)

veto threshold of 1 MeV. This could be reduced to  $<0.3$  events/y by increasing the self-shielding cut to 25 cm (with  $\sim 7\%$  loss of fiducial volume).

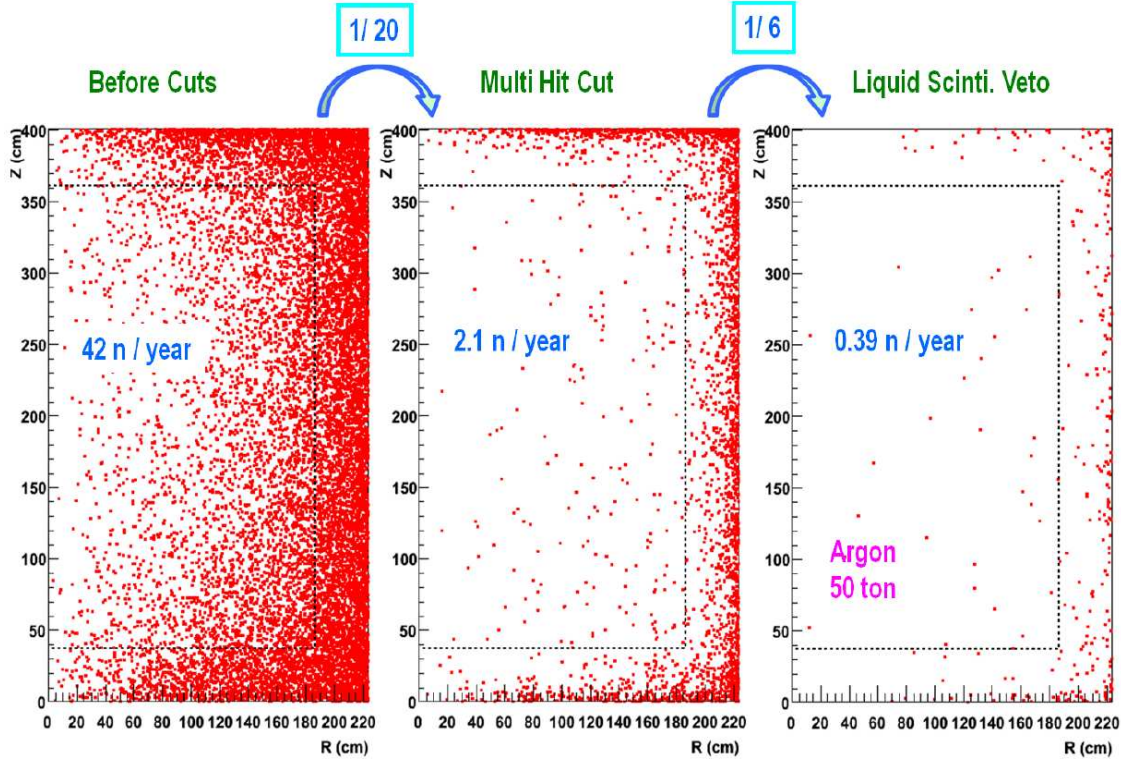


Figure C.12: Summary of neutron background reduction in 50-ton Ar fiducial region, using a 15cm outer cut. The multiple scattering cut is sufficient to reach a background level  $\sim 2$  events/y with a further factor 5 gain from the veto signal. A larger outer cut gains relatively slowly, reducing to 0.3 n/y for a 25 cm cut.

#### Appendix C.5. G4 system: backgrounds for 100-ton Xe and 500-ton Ar

To obtain a gain in detector sensitivity for G4 corresponding to the factor 10 increase in fiducial mass, it is necessary that the unrejected backgrounds (in absolute event numbers per year) are not significantly greater than those in G3, i.e. remaining below the 0.5 – 1 events/y level. For this, one can take advantage of the fact that greater thicknesses of passive outer layer can be used for larger detectors, without significant loss of the fiducial volume.

Low energy gamma and neutron backgrounds for G4 can be extrapolated immediately from the principles established by G2 and G3 simulations above. Total gamma emission from detector components will be approximately proportional to detector surface area. This would have increased the simulated absolute background numbers in the G3 Xe detector, calculated above in C.4, by a factor 4 over those in G2, but they were kept at a similar level ( $\leq 0.1$  events/y) by increasing the thickness of the outer layer of Xe used as passive shielding from 10cm to 15cm.

For the G2 to G3 argon scale-up different considerations applied to gamma and neutron rejection, as discussed in Appendix C.1 and Appendix C.3. In argon the electron/gamma pulse shape discrimination, combined with the two phase discrimination, enabled gamma and electron background to be reduced to a negligible level in both G2 and G3, and a 15 cm passive layer is needed to achieve a level 0.1 neutrons/y in the G2 argon detector. A similar 15 cm passive thickness then

gives the expected area factor 4 higher background in G3 Ar, of 0.4 events/y. As seen in Fig.C.12, this can be reduced to 0.2 – 0.3 events/y by increasing the passive thickness to 25 cm.

Applying these principles to the G3 to G4 Xe scale up the factor 4 increase in gamma and neutron background, arising from the increased surface area, can again be offset by an increase in the (software-adjustable) outer passive shielding thickness from 15 cm to 20 cm, retaining 100-ton fiducial mass while reducing both backgrounds to  $\sim 0.2$  events/y. In the case of the G3 to G4 argon scale up, the unrejected gamma background is again negligible (owing to the additional pulse shape discrimination discussed above) and for neutron events the expected area scaling factor  $\sim 4$  increase in the absolute number per year can again be offset by an increase in the non-fiducial passive argon thickness, in this case from 25 cm to  $\sim 35$  cm, keeping the fiducial neutron background events to below 1 event/y for the loss of only 8% of the fiducial mass.

## Appendix D. Galactic supernovae

A type II or 1b supernova explosion releases typically  $3 \times 10^{53}$  ergs of energy, mostly as a burst of neutrinos and antineutrinos of all flavours, lasting 10 – 20 seconds and with the neutrino time profiles shown in Fig.D.1 [58]. With detectors of currently foreseeable size, these neutrinos are detectable only for supernovae in our own Galaxy. The frequency of supernovae in our Galaxy is uncertain, a common estimate being  $3 \pm 1$  /century. A slightly higher rate  $4 \pm 1$  events/century can be estimated from the historical record of visible supernovae in our Galaxy [59], shown for the past 2000 years in Fig.D.2.

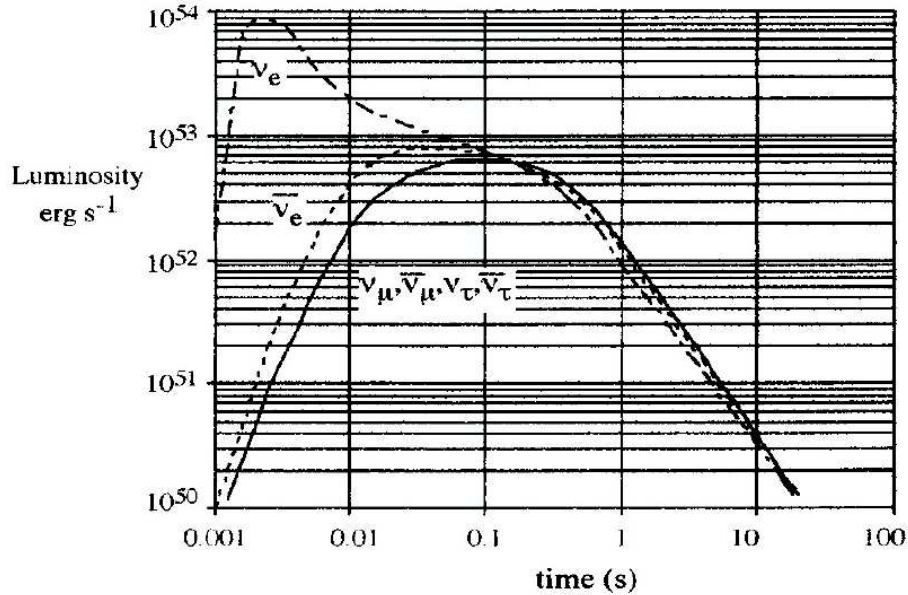


Figure D.1: Generic form of supernova neutrino burst, showing luminosity versus time for different neutrino and antineutrino flavours (from [57]).

It is evident from these recorded SN locations that supernovae are not usually seen by visible light beyond a distance from the Earth of 4 – 5 kpc, due to obscuration by material in the Galactic plane, so the visible record covers less than 10% of the whole Galaxy. Hence using neutrino detection we would be able to see at least an order of magnitude more than the number observed visibly. Allowing for some identification uncertainties, there have been  $7 \pm 1$  type II/Ib supernova in 2000 years in a region  $8 \pm 2\%$  of the Galaxy, or  $\sim 4 \pm 1$  /century, on the assumption that the local 5 kpc



(which in fact crosses two spiral arms) represents a random sample of stellar SN progenitors. From this it appears likely that another Galactic supernova, visible as a neutrino burst, will occur within the lifetime of current and foreseeable detectors, which should therefore all be designed with data acquisition buffers able to collect and record a high flux of incident neutrinos from this source.

	$\nu_e$	$\bar{\nu}_e$	$\nu_\mu$	$\bar{\nu}_\mu$	$\nu_\tau$	$\bar{\nu}_\tau$
Total energy (ergs)	$5 \cdot 10^{52}$	$5 \cdot 10^{52}$	$5 \cdot 10^{52}$	$5 \cdot 10^{52}$	$5 \cdot 10^{52}$	$5 \cdot 10^{52}$
Mean energy $\langle E \rangle$ (MeV)	10 – 12	14 – 17	24 – 27	24 – 27	24 – 27	24 – 27
Temperature (MeV)	3 – 4	4 – 6	7 – 9	7 – 9	7 – 9	7 – 9
Time-integrated flux ( $\nu/\text{cm}^2$ )	$2.4 \times 10^{11}$	$1.6 \times 10^{11}$	$1.0 \times 10^{11}$	$1.0 \times 10^{11}$	$1.0 \times 10^{11}$	$1.0 \times 10^{11}$

Table D.1: Mean energy and time-integrated flux for the three neutrino flavours from a Galactic SN at a distance 10 kpc from Earth.

Tab.D.1 summarises the total energy, mean energy and time-integrated flux for the three neutrino types, for a supernova at 10 kpc from Earth [58]. For a Maxwell-Boltzman spectrum the temperature is 1/3 of the mean energy  $\langle E \rangle$ , and for a Fermi-Dirac spectrum the temperature is  $0.83 \times (1/3) \langle E \rangle$  giving the temperature ranges shown in Tab.D.1.

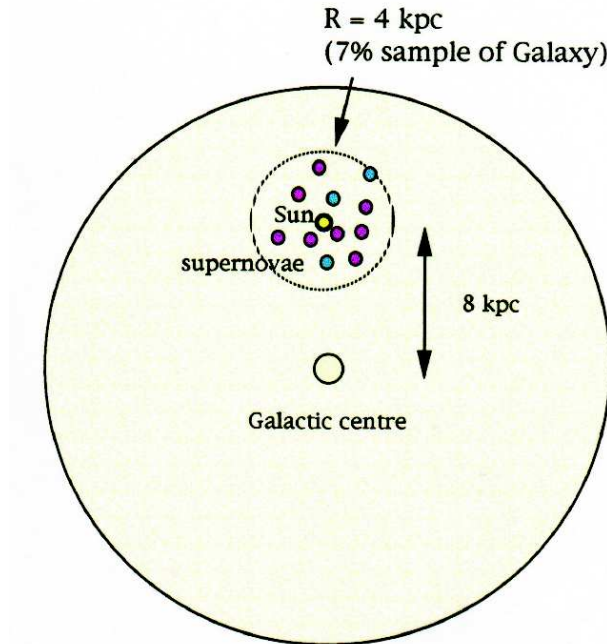


Figure D.2: Sketch of Milky Way Galaxy, showing positions of observed Galactic supernovae from the historical visible record for the past 2000 years (omitting 1987a, in the Large Magellanic Cloud at 51 kpc from Sun). (blue points) SN type Ia, (purple points) SN type II and Ib, (yellow point) Sun.

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