*New Cosmological Data and the Values of the Fundamental Parameters*
*IAU Symposium, Vol. 201, 2005*
*Anthony Lasenby and Althea Wilkinson, eds.*

# Status of Experiments for Direct Detection of Galactic Dark Matter Particles

Peter F. Smith

*Rutherford Appleton Laboratory, Chilton, Oxon, OX11 0QX, UK*

**Abstract.** There is increasing evidence that the majority of dark matter is non-baryonic. Principal candidates are weakly interacting massive particles (WIMPS), axions, and neutrinos. There has been increasing effort on sensitive WIMP searches, motivated in particular by supersymmetry theory, which predicts a stable neutral particle in the mass range 10-1000 GeV. Interactions of these with normal matter would produce low energy nuclear recoils which could be observed by underground detectors capable of discriminating these from background. Current experimental progress is summarised, together with plans for more sensitive experiments. These include gaseous detectors with directional sensitivity, offering the prospect of a 'dark matter telescope' which would provide information on the dark matter velocity distribution. Axions could be detected by conversion to microwave photons, and experimental sensitivity is approaching the theoretically-required levels. Relic neutrinos could also form a component of the dark matter if any has a cosmologically significant mass, and the latter could be checked with a new detector able to detect the higher neutrino flavours from a Galactic supernova burst. More distant future possibilities are outlined for direct detection of relic neutrinos by coherent scattering.

## 1. Introduction

The nature of the non-luminous matter which constitutes 90% of the gravitating matter in our Galaxy has been the subject of considerable discussion for the past 20 years. An early speculation (1981) was that it might consist of a neutrino with cosmologically significant mass (10-50 eV) but these would have been relativistic at the time of galaxy formation and this 'hot dark matter' would appear to preclude Galaxy formation. A proposed alternative was the axion, a hypothetical light boson of mass $10^{-6} - 10^{-1}$ eV, which would have provided the required 'cold dark matter'. But by 1984 a more popular candidate was a hypothetical weakly interacting massive particle (WIMP), either a heavy neutrino or the 'neutralino' of supersymmetry theory, thought to have a mass 10-1000 GeV and which could have formed in the early universe and subsequently clustered in association with ordinary matter. Interactions of these heavy particles would be observable by the production of rare keV-range nuclear recoils in targets of ordi nary matter, and thus seemed the most experimentally accessible of the dark matter candidates. This was the position as reviewed in the late 1980s (Smith & Lewin, 1990; Primak et al. 1988) and has remained essentially unchanged to the present day. Figure 1 summarises some of the main dark matter explanations and detection methods. Limits on 'Machos' - non luminous stars or black holes (Lasserre et al., 2000)) have suggested that the dominant component of Galactic

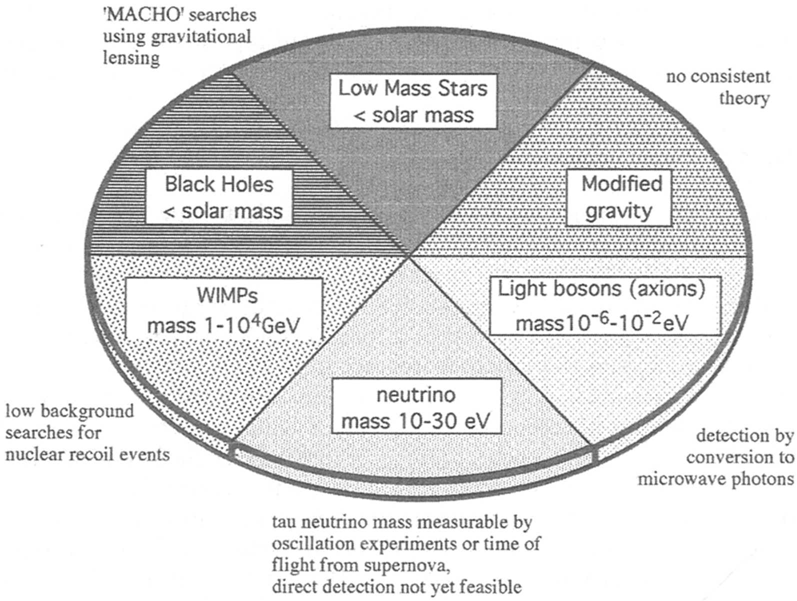


Figure 1. Principal Galactic dark matter candidates and detection methods.

dark matter is non-baryonic, and this is supported by other evidence that this is also the case at the cluster level (Birkinshaw, 2000).

In the case of heavy weakly interacting particles, the key experimental challenge is to observe and identify the predicted rare nuclear recoil events in the presence of background rates typically a factor $10^3 - 10^4$ higher. Ideas have been developed for distinguishing nuclear recoil events from background, and a sensitivity about a factor 100 below background has been achieved, which could observe a signal level in the region 1 event/kg/day. The experiments currently running are outlined in §4 below, together with further ideas under development to gain a further two orders of magnitude in sensitivity which may be necessary to reach the most-favoured theoretical signal level.

Light bosons, including the axion, would not produce a detectable energy in a direct interaction, and were originally thought impossible to detect. However, a method was proposed (Sikivie,1983) for detection by conversion to microwave photons in a magnetic field, and this has led to several experiments which are approaching the theoretically predicted signal level (Rosenberg & Van Bibber, 2000). Latest results are summarised in Section 5.

Neutrinos would need to have a mass in the range 10-50 eV to contribute significantly to Galactic dark matter. This is currently disfavoured, but could be verified or definitively excluded by time-of-flight effects in the neutrino burst from a Galactic supernova, using a new detector for higher neutrino flavours described in Section 6. Direct detection of relic neutrinos presents a major challenge for the future. As with the axion, direct interaction produces neither a significant event rate or a detectable energy. However there is a possibility of detecting relic neutrinos through coherent optical-type reflection, with a consequent enhanced cross section for interaction with bulk matter (Smith & Lewin, 1983; Smith 1991). A conceptual experiment is outlined in Section 7 which could eventually become possible through foreseeable advances in nano-technology.

## 2. Underground laboratories

An essential requirement for WIMP searches is that they are carried out in sufficiently deep underground sites. This is because the nuclear recoil signal can also be produced by neutron scattering, and neutrons are produced by cosmic ray muons. The latter cannot be shielded except by large thicknesses of rock. Thus laboratories have been set up in mines, or under mountains, for a variety of particle astrophysics experiments requiring reduction of muon background. For dark matter searches, a depth of over 1000m is needed, as at Gran Sasso in Italy and the Boulby Mine in the UK, both of which reduce the muon flux by a factor $10^6$. The neutron background in a detector is then reduced to $< 0.01$ events/kg/d, lower than some predicted dark matter interaction rates. To reach even lower interaction rates, or to use slightly less deep sites, it will be necessary to surround the experiment with a muon veto system. All underground sites have a gamma background comparable to that at the surface. This does not directly simulate dark matter interactions, but is nevertheless shielded to as low a level as possible to reduce the absolute counting rate from which the expected dark matter signal (typically $< 1$ event/day in a 10-100 kg target) has to be extracted and identified.

## 3. Discrimination of nuclear recoils from background

Collision of neutral particles with nuclei results in recoil of the nucleus (or complete atom) which can be detected in a number of ways. The most important of these are ionisation, scintillation, and low temperature bolometric detection. The immediate problem is that these techniques also detect background events from photons and beta decay electrons. Thus additional information in the event signal is needed to identify those which are nuclear recoils. Figure 2(a) summarises some methods of discriminating between nuclear recoils and background. The first uses the fact that pulse decay times in crystal scintillators and liquid noble gases are 30-50% shorter for nuclear recoils, so that a population of shorter rise times can be identified statistically (Doll et al 1989; Smith et al,1996). A second scheme uses simultaneous scintillation and ionisation signals in liquid xenon (Benetti et al., 1993; Cline et al., 2000). The third method indicated is to use the ionisation signal in conjunction with low temperature bolometric detection (Booth et al, 1996). The fourth and most recent scheme is to use low temperature bolometry in conjunction with a scintillation signal, also measured bolometrically (Bravin et al, 1999).

## 4. Experimental progress and prospects

Early limits to the dark matter counting rate were set by Ge detectors, already running underground as double beta decay searches (Smith & Lewin, 1983).

https://doi.org/10.1017/S0074180900216409 Published online by Cambridge University Press

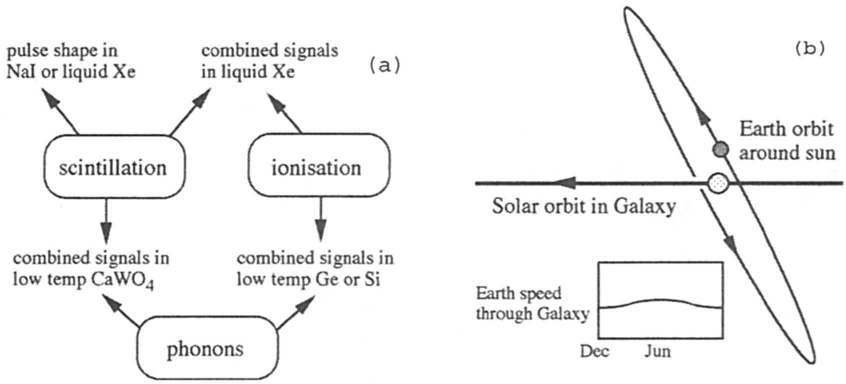


Figure 2. (a) Methods of discriminating nuclear recoils from electron recoils. (b) Directionality and seasonal modulation of dark matter flux arising from combined Earth and Sun motion.

The first limits using a discrimination technique were set in 1994-5 by pulse shape analysis of (background) events in NaI crystals (Smith, 1996; Bernabei et al, 1996). Subsequently improvements in sensitivity revealed two anomalous effects. The UK group encountered a systematic in the form of a population of short low energy pulses possibly due to surface alpha particles (Smith et al, 1998; Smith, Lewin & Smith, 2000). At the same time the Rome group reported an annual fluctuation of their total count rate over a period of 4 years (Bernabei et al., 1998; Belli et al., 2000), which they have interpreted as evidence of the expected annual modulation of the dark matter event rate, arising from the earth's varying speed relative to the Galaxy (Figure 2(b)). This is not generally accepted as a genuine signal because the nuclear recoil events are not separated and the total count rate contains various background events which could in principle be causing the modulation. Moreover the CDMS cryogenic experiment (method 3 of Section 3) although not yet located deep underground and needing to subtract neutron background, has now published results which appear to exclude the Rome result (Abusaidi et al., 2000).

This controversy is likely to be resolved by the next generation of experiments. Firstly the CDMS collaboration will be running in the Soudan Mine during 2001, thus reducing neutron background and improving their limit. Secondly a UK/UCLA/Torino/ITEP collaboration is constructing a series of liquid xenon experiments. The first of these, ZEPLIN I, is based on pulse shape discrimination and is now installed in the Boulby Mine. Two further detectors, ZEPLIN II and III, are being designed to use combined scintillation and ionisation signals in a two-phase Xe target (Figure 3) and should achieve at least one order of magnitude improvement using 10-30kg targets. A further factor 10 would be achievable by scaling up to a larger mass system. A similar sensitivity is also forecast for the CRESST cryogenic experiment to be installed in the Gran Sasso laboratory (Bravin et al., 1999). A summary of planned sensitivity improvements as a function of year is shown schematically in Figure 4.

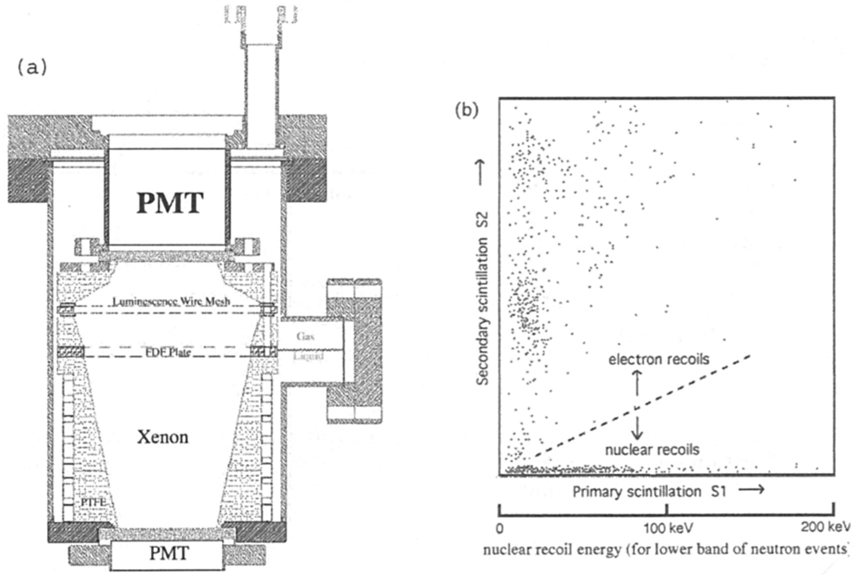


Figure 3. (a) Two phase liquid Xenon chamber giving primary scintillation signal and secondary scintillation signal from ionisation extracted into gas phase (Cline et al., 2000). (b) Separation of events into two populations by primary and secondary scintillation.

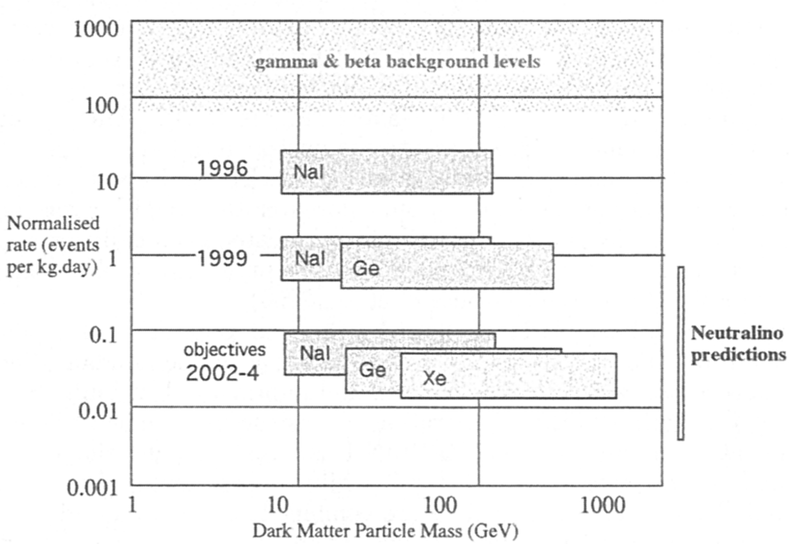


Figure 4. Improvement in sensitivity of dark matter searches as a function of time, showing (i) capabilities of techniques in Figure 2(a) to attain sensitivities below background levels; (ii) progress towards neutralino predicted sensitivity; (iii) objectives of planned experiments.

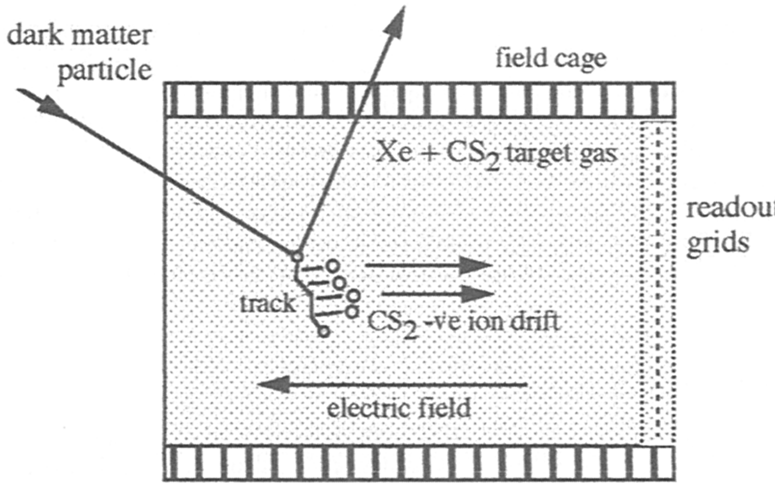


Figure 5. Principle of gaseous directional detector using negative ion drift to preserve track identity over long drift distances (Martoff et al., 2000).

Figure 2(b) shows that motion through the dark matter (unless co-rotating) would give a directional component to the particle flux through the earth - expected to be on average similar to the motion of the Sun through the Galaxy. There would also be expected a near-radial infall component from non-baryonic dark matter in the cluster. Clearly the most convincing demonstration of detection would be the demonstration of this directionality in the signal, which would give a forward-back asymmetry in the nuclear recoil direction. The methods outlined above do not reveal this, because of the very short range ($0.01\mu$m) of the nuclei in a solid or liquid target. Directionality can be achieved in several ways, the most promising of which is the use of low pressure gas target, forming short particle tracks and using the TPC (track projection chamber) principle well-established in particle physics to drift the tracks to an observation plane (Figure 5). An initial obstacle to this was the loss of track information by diffusion of the charge, but this can be solved by attaching the charge to a heavier ion such as $CS_2$ (Martoff et al., 2000). A UK/US collaboration to develop this DRIFT experiment is now in progress and such a technique offers the prospect of a 'dark matter telescope' to determine separately the solar-orbital velocity component and any infall component at near escape velocity.

## 5. Axion searches

Although the hypothetical axion would have too low an energy to register by interactions in any conventional detector, it does couple to two photons via intermediate quark states. As a result, if an axion enters a magnetic field it will annihilate by absorbing one photon and emitting the second with energy equal to the axion mass (Sikivie, 1983). Cosmological and stellar considerations restrict the mass to the range $\sim 10^{-6} - 10^{-3}$ eV, resulting in microwave photons. The appropriate experiment consists of a volume of high magnetic field containing microwave cavities which can be tuned to scan continuously through the hypothetical axion mass range. The number of groups attempting axion searches is considerably less than in the case of WIMP searches, but several experiments have reached a sensitivity, for parts of the above mass range, approaching the predicted coupling strength for the two principal theoretical models (Rosenberg & Van Bibber, 2000) and can achieve these with further upgrades and longer running time. Studies have also been made of detecting axions produced in the sun and laboratory-made axion beams (Smith & Lewin, 1990; Rosenberg & Van Bibber, 2000).

## 6. Cosmologically-significant neutrino mass

Stable neutrinos are required to have masses totalling $< 100$ eV to avoid overclosing the universe. Masses $> 10$ eV would play a major role in cosmology and could from all or part of the dark matter. Recent observations of neutrino mixing appear to suggest sub-eV mass differences between all three neutrino types, apparently precluding masses $> 10$ eV unless nearly degenerate. However, it remains the case that a neutrino of mass 20-30 eV would simultaneously fit the observed dark matter density and the phase space density at decoupling - and has the advantage over WIMPs of being a known particle. One would like, therefore, to have a definitive means of establishing whether or not a neutrino mass $> 10$ eV exists. An opportunity for this arises from a Galactic supernova burst, which releases all three neutrino types, and the typical distance $\sim 8/pm4$ kpc is ideal for measuring the time-of-flight delay (1-2s) for a 20-30 eV neutrino compared with a neutrino $< 10$ eV in mass. Visible type II/Ib Supernova bursts have occurred on average every 240 years in the local 4 kpc (6% sample) of the Galaxy, which suggests a 15 year interval for neutrino bursts from the whole Galaxy. It is therefore proposed that an inexpensive multiflavour supernova detector (OMNIS) could be set up to run continuously in an automated mode and resolve this question when the next galactic supernova occurs. This would record the higher flavour (and higher energy) neutrinos by nuclear exciation of Pb and Fe targets, releasing neutrons which can be detected within 0.1ms and hence accurately replicate the arrival time profile of the neutrinos (Smith, 1997). This detector will also observe mixing between flavours (Fuller et al., 1999). A typical configuration is shown in Figure 6.

## 7. Relic neutrino detection

Neutrinos clustered in the Galaxy would have a density $\sim 10^7$/cc, momentum $\sim 10^{-2}$ eV/c and energy $\sim 10^{-5}$ eV. With these parameters the low interaction cross section gives an event rate $\sim$ 1/year/ton and a recoil energy $\sim 10^{-9}$ eV. Hence these relic neutrinos are not detectable by single particle interactions. However the low momentum transfer in an interaction between the neutrino and an atomic particle (electron, proton, neutron) has a relatively large quantum mechanical wavelength (10 $\mu$m for $10^{-2}$ eV/c, 1 mm for $10^{-4}$ eV/c) so that the interaction amplitude is coherent over very large numbers of atoms. This results

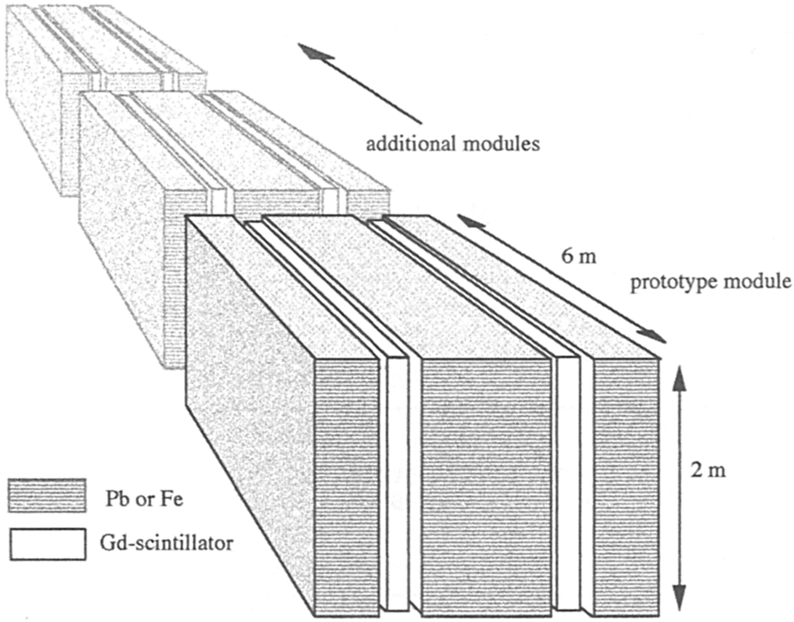


Figure 6. Proposed arrangement of OMNIS modules along underground tunnel.

in an enhanced cross section for interaction with bulk matter (Figure 7) giving rise to an effective 'optical' refractive index and a substantial reflection coefficient at a material interface (Smith & Lewin, 1990). A range of detection schemes based on this has been considered, some fallacious, but others conceptually possible (Smith, 1990).

Two classes of experiment appear feasible in principle. One is analogous to gravitational wave detection: a multi-ton target mass suspended within a reference enclosure in a zero gravity environment, with SQUID systems to measure small displacements ($10^{-12} - 10^{-14}$ cm) due to the coherent momentum transfer from the reflected component of the 'neutrino wind'. This is subject to serious problems of 'tidal noise' from the earth, moon and sun, which may exceed the neutrino force by many orders. An alternative approach would be to use an array of levitated microgranules (each $< 0.1\mu$m, $< 10^{-14}$ g), and search for individual motions due to coherent collision of relic neutrinos with individual granules (Figure 8). This, like the large mass option, can be designed to satisfy the quantum measurement limit, and foreseeable non-invasive quantum interference techniques might be used to monitor the entire (pseudo-crystalline) array for individual displacements. Linear arrays of levitated 10-100 $\mu$m spheres have been previ ously created for laser fusion research, so that it may not be unreasonable to envisage a factor 100-1000 reduction in scale, and extension to large 2- and 3-dimensional arrays, with future advances in nanotechnology. This would remain a challenging experiment to develop, but we can hopefully

https://doi.org/10.1017/S0074180900216409 Published online by Cambridge University Press

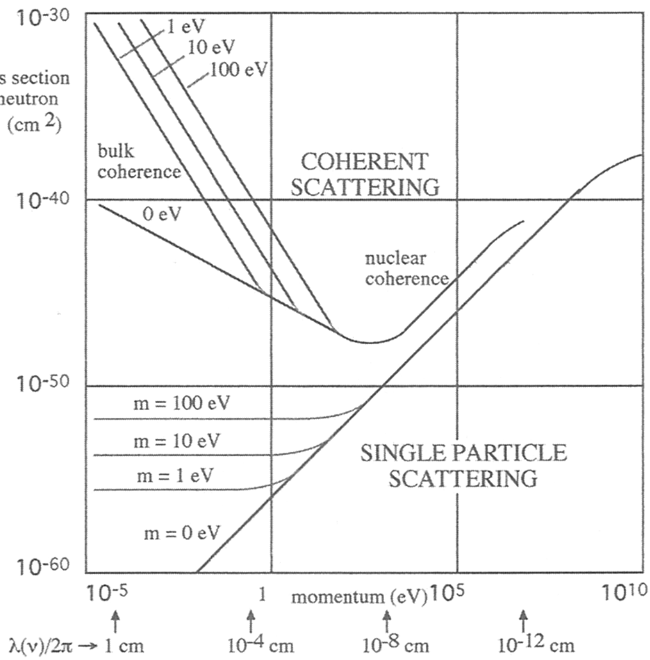


Figure 7. Coherent bulk neutrino scattering cross section versus momentum, compared with single particle scattering cross section.

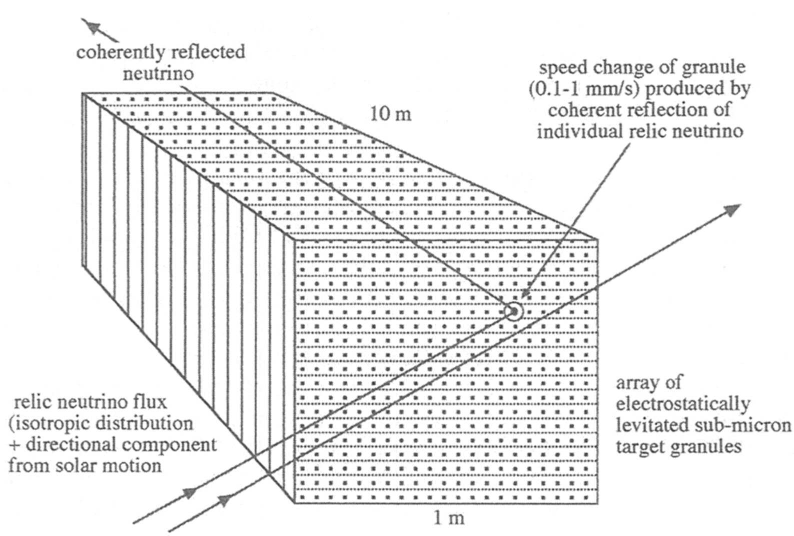


Figure 8. Conceptual design of a future relic neutrino detector, based on coherent reflection from levitated sub-micron targets. A full detector would require 10-100 modules of this size.

https://doi.org/10.1017/S0074180900216409 Published online by Cambridge University Press

anticipate parallel medical advances which will provide the necessary extended lifespan for the experimenters!

## References

Abusaidi, R. et al. 2000, Phys.Rev. Letters 84 5699

Belli, P. et al. 2000, Proc. Conf. Sources of Dark Matter (D. Cline, ed., Marina del Rey, to be published

Benetti, P. et al. 1993 Nucl. Instrum. Methods A 327 203

Bernabei, R. et al. 1996, Phys. Lett. B 389 757

Bernabei, R. et al. 1998, Phys. Lett. B424 195

Birkinshaw, M. 2000, these proceedings

Booth, N. E., Cabrera, B. & Fiorini, E. 1996, Ann. Rev. Nucl. Part. Sci, 46 471

Bravin, M. et al. 1999, Astropart. Phys. 12 107

Cline, D. et al. 2000, Astropart. Phys. 12 373

Doll, P. et al. 1989, Nucl. Instrum. Methods A285 46

Fuller, G. M., Haxton, W. C. & McLaughlin, G. C. 1999 Phys.Rev. D59 085005

Lasserre, T. et al. 2000, Astron. Astrophys. 355 L39

Martoff, C. J et al. 2000, Nucl. Instrum. Methods A 440 355

Primak, J. R., Seckel, D. Sadoulet, B. 1988 Ann. Rev. Nucl. Part. Sci. 38 751

Rosenberg, L. J. & Van Bibber, K. A. 2000 Physics Reports 325 1

Sikivie, P. 1983 Phys. Rev. Letters 51 1415

Smith, N. J. T., Lewin, J. D. & Smith, P. F. 2000 Phys.Lett. B 485 9

Smith, P. F. 1990 Proc. Texas/ESO-CERN Symposium 4 (Brighton) 425

Smith, P. F. 1991 Texas/ESO-CERN conference, Ann. NY Acad. Sci. 647 425 4

Smith, P. F. 1997 Astropart. Phys. 8 27

Smith, P. F. & Lewin, J. D. 1983, Phys. Lett. B 127 185

Smith, P. F. & Lewin, J. D. 1990 Physics Reports 187 203

Smith, P. F. et al. 1996, Phys. Lett. B 379 299

Smith, P. F. et al. 1998, Physics Reports 307 275

https://doi.org/10.1017/S0074180900216409 Published online by Cambridge University Press