Direct searches for dark matter

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After briefly recalling the evidence which suggests that the dark matter pervading the universe is nonbaryonic, we review the present searches for the best motivated particle candidates: axions, light neutrinos and Weakly Interacting Massive Particles (WIMPs).

1. INTRODUCTION

In the last decade considerable additional evidence[1] has been gathered supporting the hypothesis that at least 90% of the mass in the universe is dark: it does not emit or absorb any form of electromagnetic radiation. Understanding this dark matter has become one of the more central problems in astronomy and cosmology. Once a subject of controversy among astronomers, its existence is now well established at a variety of scales.

The debate has shifted to measuring the amount of dark matter in the universe, studying its distribution and unraveling its nature. A central question is whether this dark matter is made of ordinary baryonic matter or is nonbaryonic. A number of cosmological observations, reviewed in section 2, indicate that it may indeed be nonbaryonic. This case is not undermined by the current observations of Massive Compact Halo Objects (MACHOs), as there is a fundamental ambiguity in the distance of the lensing objects.

Following our conclusion that the searches for nonbaryonic dark matter remain essential, we review the current detection efforts for axions (section 3), massive neutrinos (section 4), and Weakly Interacting Massive Particles (WIMPs – section 5).

2. THE CASE FOR NONBARYONIC DARK MATTER

2.1. Comparison of Ω and Ω_b

Figure 1 summarizes the current attempts of measuring the average density Ω of the universe in units of the critical density

$$\Omega = \frac{\rho}{\rho_c} \text{ with } \rho_c = 1.88 \times 10^{-26}\, h^2 \text{ kg m}^{-3}$$

where h is the Hubble expansion parameter in units of 100 km/s/Mpc (h = 0.65±0.1). Ω can be determined through an inventory of the masses of the various objects in the universe, for instance using the virial velocities in galaxy clusters. This intrinsically can give only a lower limit of Ω, as these methods only measure local density inhomogeneities. Dynamic methods attempt to relate the observed velocity deviations from the Hubble flow to the density concentrations and deduce from it an effective Ω, which unfortunately depends on the way the number density of galaxies tracks the mass density fluctuations. Cosmology tests can also be used to directly probe the geometry but, as this involves very distant objects, it is difficult to correct the measured quantities for evolution. This fundamental difficulty, which foiled the earlier attempts,[2] is still a cause for concern in the interpretation of high redshift supernovae.[3] Taken at face value, these exciting observations indicate that the universe is accelerating. They provide an approximate measurement of the difference between the vacuum energy density and matter density, $\Omega_\Lambda-\Omega_m$. The sum between these quantities, $\Omega_\Lambda+\Omega_m$,, can be obtained from the acoustic ("Doppler") peak in the microwave background power spectrum indicated by the Saskatoon and CAT data. Together these observations give Ω_m = 0.25 (+0.18-0.12, 95%CL interval).[4]

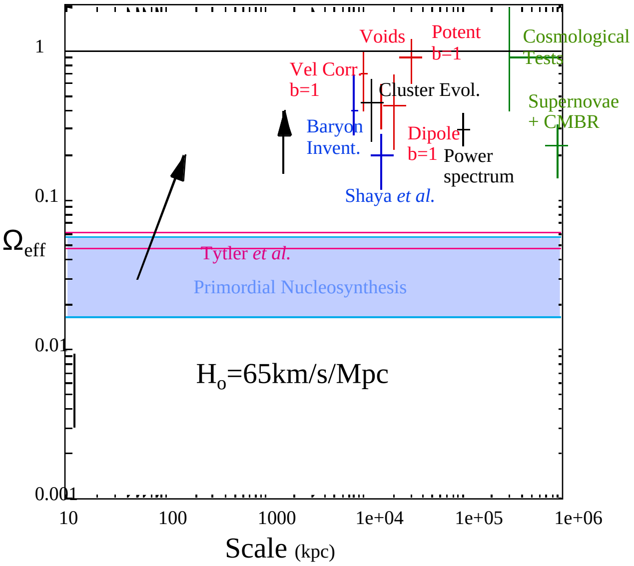


Figure 1. Effective Ω as a function of scale of measurement for H_O = 65 km/s/Mpc. The bands give the Ω in baryons expected from primordial nucleosynthesis.

The combination of all these observations makes it rather convincing that dark matter does indeed exist, as the value obtained over large scales (≈ 0.3) is much greater than the contribution of stars (0.003-0.01).

It also provides a convincing argument for the nonbaryonic nature of dark matter. The shaded band displays the relatively narrow limits ($0.007 \leq \Omega_b h^2 \leq 0.024$) inferred from the observations of ^{4}He, D, ^{3}He and ^{7}Li in the very successful standard scenario of homogeneous primordial nucleosynthesis.[5] It is definitely below most measurements of Ω at large scale. If we believe the recent measurement of the D fraction in Lyman alpha systems by Tytler,[6] Ω_b may be close to the upper boundary of this band but our conclusion is not significantly affected.

2.2. Formation of the large-scale structure

A second argument for nonbaryonic dark matter is based on the fact that it provides the most natural explanation of the large-scale structure of the galaxies in the universe in terms of collapse of initial density fluctuations. They can be inferred from the COBE measurement of the temperature fluctuations of the cosmic microwave background. The deduced power spectrum of the (adiabatic) mass fluctuations at very large scale connects rather smoothly with the galaxy power spectrum measured at lower scale,[7] giving strong evidence for the formation of the observed structure by gravitational collapse. The observed spectral shape is natural with cold nonbaryonic dark matter but cannot be explained with baryons only, since they are locked in with the photons until recombination and cannot grow enough fluctuations to form the structure we see today.

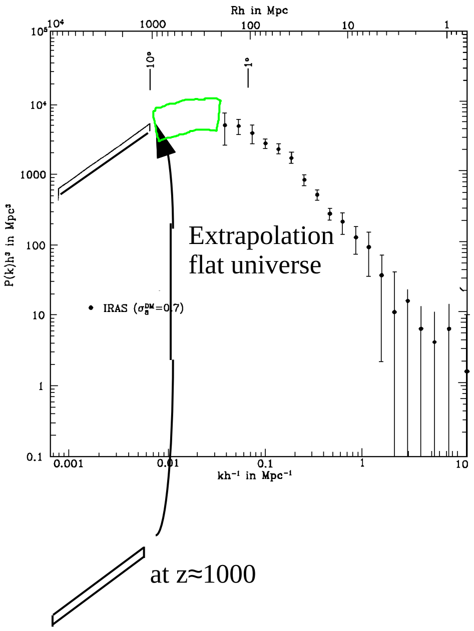


Figure 2. Measured power spectrum measured for IRAS galaxies and extrapolation of the COBE result assuming nonbaryonic dark matter and a flat universe (after Fisher et al., 1992). The contour in the middle gives a rough estimate of the power spectrum inferred from the measurement of the acoustic peak of the cosmic microwave background (after Scott et al., 1995).

Although their interpretation is more model-dependent, the recent measurements of temperature fluctuations at the degree scale of the cosmic microwave background appear to support this conclusion.[8] They are smoothly bridging the gap between the COBE extrapolation and large-scale structure.

2.3. Inefficiency of the formation of compact objects

A third general argument comes from the implausibility of hiding a large amount of baryons in the form of MACHOs. For instance, as the ratio of the mass in gas and stars to the total mass in clusters is of the order of 20%, this would require 80% of the initial gas to have condensed into invisible MACHOs. This is very difficult to understand within the standard scenarios of star formation. The same argument applies to galactic halos.

2.4. Impact of the MACHO observations

The intrinsic degeneracy arising in the interpretation of microlensing observations prevents the fascinating MACHO results from seriously undermining the case for nonbaryonic dark matter. As explained by Spiro in these proceedings,[9] the lensing duration is a degenerate function of the mass, distance and transverse velocity of the lens, and we do know where the lenses responsible for the observed events are. The location of the two observed double lenses in the host galaxies, the large mass implied by a halo distribution hypothesis, and the low event rate towards the Small Magellanic Cloud cast considerable doubt about the MACHOs forming the totality of the halo.

In any case, if a nonbaryonic component exists, it is difficult to prevent it from accreting (unless it is hot) and, even in the presence of MACHOs in the halos, it should constitute a significant portion of the halo and be present locally for detection. In fact, taking into account all kinematic information on the galaxy and the MACHO observations, the most likely density for a nonbaryonic component is close[10] to the canonical 0.3 GeV/cm^3 inferred from the velocity curves of our galaxy.[11]

2.5 Conclusion

In conclusion, it seems very difficult to construct a self-consistent cosmology without nonbaryonic dark matter and the MACHOs results do not so far undermine those arguments. Thus, it remains urgent to search for nonbaryonic dark matter.

A large number of candidates have been proposed over the years for such a nonbaryonic component. They range from shadow universes existing in some string models, strange quark nuggets formed at a first order quark-hadron phase transition,[12] Charged Massive Particles (CHAMPs),[13] and a long list of usually massive particles with very weak interactions. We should probably search first for particles that would also solve major questions in particle physics. According to this criterion, three candidates appear particularly well motivated.

3. SEARCHES FOR AXIONS

3.1. Cosmological axions

Axions are an example of relic particles produced out of thermal equilibrium, a case where we depend totally on the specific model considered to predict their abundance. These particles have been postulated[14] in order to dynamically prevent the violation of CP in strong interactions in the otherwise extremely successful theory of quantum chromodynamics. Of course, there is no guarantee that such particles exist, but the present laboratory and astrophysical limits on their parameters are such that if they exist, they would form a significant portion of cold dark matter.[15] Such low-mass cosmological axions could be detected by interactions with a magnetic field, which produce a faint microwave radiation detectable in a tunable cavity.[16] The first two searches[17] for cosmological axions performed a decade ago were missing a factor of 1000 in sensitivity.

This is no longer the case; Livermore, MIT, Florida and Chicago are currently performing an experiment which has published preliminary limits[18] and will reach (Fig. 3) a cosmologically interesting sensitivity at least for one generic type of axion (hadronic models[19]). By replacing their HEMT-based amplifiers by SQUID amplifiers, the collaboration hopes to improve their sensitivity down to the lowest couplings currently predicted (DFZ model[20]). Matsuka and his collaborators in Kyoto are developing a more ambitious scheme using Rydberg atoms, which are very sensitive photon detectors and should be able to directly reach the DFZ limit.

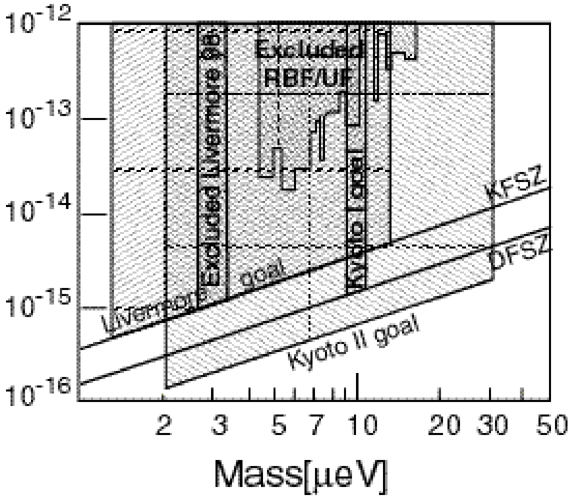


Figure 3. Expected sensitivity of the Livermore and Kyoto experiments. The lines labeled KSVZ and DFSZ refer to two generic species of axions. The shaded regions in the upper right are the previous experimental limits.

Although these experiments are very impressive, it should be noted that the decade of frequency (and therefore of mass) which can be explored with the present method is only one out of three which are presently allowed.

3.2. Solar axions

For large enough masses, axions can also be produced in the sun. Such axions would produce x-rays in germanium detectors by conversion in the field of the nucleus and it was suggested that a characteristic Braggs modulation could be observed. The Zaragoza and USC-PNL groups have searched for such effects, but the limits are still much above the required level of sensitivity.

4. LIGHT NEUTRINOS

4.1. Neutrinos in cosmology

Neutrinos of mass much smaller than 2 MeV/c fall in the generic category of particles which have been in thermal equilibrium in the early universe and decoupled when they were relativistic. Their current number density is approximately equal to that of the photons in the universe. The relic particle density is therefore directly related to its mass, and a neutrino species of 25 eV would give an Ω of the order of unity.[21] Note that neutrinos alone cannot lead to the observed large-scale structure, as fluctuations on scales greater than 40 h^{-1} Mpc are erased by neutrino streaming. They have to be mixed in with cold nonbaryonic dark matter[22] or seeded by topological defects. Moreover, because of phase space constraints, they cannot explain the dark matter halos observed around dwarf galaxies.[23]

Unfortunately, no good ideas exist of possible ways to detect cosmological neutrinos,[24] and one can only rely on the mass measurements of neutrinos in the laboratory through the study of beta spectra, neutrinoless double beta decay, and oscillation experiments.

4.2. Neutrino mass measurements

A large fraction of these proceedings is devoted to the neutrino mass measurements. For the sake of completeness, one may summarize the situation as follows: The direct mass measurement of the electron neutrino gives limits of 5 eV.[25] Model dependent limits of the order of 1 eV on the mass of Majorana neutrinos are given by neutrinoless double beta decay searches. The claim by the LSND group[26] for muon to electron neutrino oscillation with relatively large $\Delta m^2 \approx 6$ eV^2 oscillation is now challenged by the Karmen experiment.[27]

At this conference, the SuperKamiokande group has presented statistically significant results[28] demonstrating the disappearance of atmospheric muon neutrinos which points to an oscillation with Δm^2 of a few 10^{-3} eV^2 and a large mixing angle. A muon to electron neutrino oscillation is disfavored, both by Chooz[29] and internally by SuperKamiokande.

At the date of this writing, the situation of solar neutrinos is less clear. The combination of the chlorine, water Cerenkov and gallium experiments have now indicated for some time a depletion of solar neutrinos with respect to the standard solar model.[30] The most natural explanation is an MSW[31] or vacuum oscillation with Δm^2 of 10^{-6} eV^2 or 10^{-10} eV^2 respectively.[32] However, the distortion of the energy distribution observed by SuperKamiokande, which would be a direct confirmation independently of the solar model, is not fully understood. The essential measurements of neutral current events by SNO and of the ^{7}Be neutrino flux depletion by Borexino will not be available before 2000 and 2001 respectively.

If the oscillation interpretation of both atmospheric and solar neutrinos is correct, we are led to nearly degenerate masses of the three types of neutrinos (unless we have a light sterile neutrino), without any direct indication of the mass which may well be in the electron volt range if we do not invoke the see-saw mechanism. It is therefore important for cosmology to keep pushing the resolution of direct electron neutrino mass measurement.

5. WEAKLY INTERACTIVE PARTICLES

A generic class of candidates is constituted by particles which were in thermal equilibrium in the early universe and decoupled when they were non-relativistic. In this case, it can be shown that their present density is inversely proportional to their annihilation rate.[33] For these particles to have the critical density, this rate has to be roughly the value expected from weak interactions (if they have masses in the GeV/c^2 to TeV/c^2 range). This may be a numerical coincidence, or a precious hint that physics at the W and Z scale is important for the problem of dark matter. Inversely, physics at the W and Z^o scale leads naturally to particles whose relic density is close to the critical density. In order to stabilize the mass of the vector intermediate bosons, one is led to assume the existence of new families of particles such as supersymmetry in the 100 GeV mass range. In particular, the lightest supersymmetric particle could well constitute the dark matter. This class of particles is usually called Weakly Interactive Massive Particles (WIMPs).

The most direct method to detect these WIMPs is by elastic scattering on a suitable target in the laboratory[34] (indirect methods are reviewed by B. Barish in this volume[35]). Elastic WIMP scattering would produce a roughly exponential spectrum with a mean energy dependent on their mass. The hope is to identify such a contribution in the differential energy spectrum measured by an ultra-low background detector, or at least to exclude cross sections that would lead to differential rates larger than observation.

5.1. Experimental challenges

In specific models such as supersymmetry, the knowledge of the order of magnitude of the annihilation cross section allows an estimation of their elastic scattering, taking into account the coherence over the nucleus. Typically, if scalar (or "spin independent") couplings dominate, the interaction rate of WIMPs from the halo is expected to be of the order of a few events per kilogram of target per week for large nuclei like germanium. We display in Figure 4, as the lower shaded region, the range of cross sections (rescaled to a proton target) expected[36] in grand unified theory inspired supersymmetric models, where scalar interactions usually dominate.

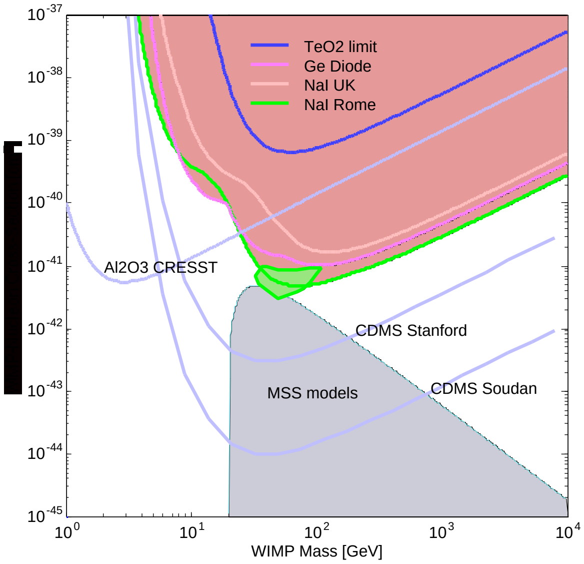


Figure 4. Current achieved limits for spin independent couplings as a function of the WIMP mass. This figure includes the results of the Rome[37] NaI, UK[38] NaI, Milan[39] TeO_2, Modane[40] Al_2O_3, and the Ge diode experiments: PNL-USC,[41] Oroville,[42] Neuchâtel-Caltech,[43] Heidelberg-Moscow,[44] and IGEX.[45] All the results have been converted to WIMP-nucleon cross sections assuming scalar interactions scaling as the square of the atomic number. The shaded region at the top is excluded by these experiments. The heart shaped in the middle is the region corresponding to the modulation signal claimed by Bernabei et al.[46] The shaded region at the bottom is the rate predicted by minimal supersymmetric models including the constraints from LEP and CDF.

The upper shaded regions summarize the current limits achieved with state of the art techniques for low radioactivity background. These limits barely skirt the supersymmetric region, although relaxing the unification assumptions enlarges it somewhat.[47]

Unfortunately, the expected rates can be very small for specific combinations of parameters where axial ("spin dependent") couplings dominate. In this case, the interaction takes place with the spin of the nucleus, which limits the number of possible targets, and the current limits are very far above the supersymmetry expectation.[36]

It is therefore essential to construct experiments with very low radioactive backgrounds or, even better, with active background rejection. The main tool for this purpose is to use the fact that WIMP interactions produce nuclear recoils, while the radioactive background is dominated by electron recoils (if neutrons are eliminated).

A second challenge faced by the experimentalist comes from the fact that the energy deposition is quite small, typically 10 keV for the mass range of interest. For detectors based only on ionization or scintillation light, this difficulty is compounded by the fact that the nuclear recoils are much less efficient in ionizing or giving light than electrons of the same energy. This increases the recoil energy threshold of such detectors, and one should be careful to distinguish between true and "electron-equivalent" energy, which may differ by a factor three (Ge) to twelve (I).

A third challenge is to find convincing signatures linking detected events to particles in the halo of the galaxy. The best one would be the measurement of the direction of the scattered nucleus,[48] a very difficult task. Short of this directionality signature, it is in principle possible to look for a change in the event rate and the spectrum of energy deposition with the time of the year.[49]

5.2. Prominent direct search strategies

In spite of these experimental challenges, low expected rates and low energy depositions, a number of experimental teams are actively attempting to directly detect WIMPs. A number of interesting attempts have been made to use mica which integrates for billions of years,[50] superheated microdots[51] which should be only sensitive to nuclear recoil, and low pressure time projection chambers which could give the directionality.[52] However, the main developments occurred along three main experimental strategies.

1. A first approach is to attempt to decrease the radioactive background as much as possible. Germanium is the detector of choice as it is very pure, and the first limits[41,42,43] were obtained by decreasing the threshold of double beta experiments. The most impressive results have been obtained by

the Heidelberg-Moscow group[44] with a background of 0.05 events/kg/day/electron-equivalent-keV around 20 keV (equivalent electron energy). This impressive performance comes from a careful screening of surrounding material, the large size of their crystal (2.5 kg), and signal shape discrimination. The IGEX and Baksan-USC-PNL[53] collaborations have achieved somewhat worse levels (0.25 events /kg/day/electron-equivalent-keV), but reached lower thresholds. The current combined exclusion plot is given in Fig. 4. GENIUS, an ambitious proposal[54] to immerse one ton of germanium detectors in an ultra-pure liquid nitrogen bath, pushes this strategy to the extreme.

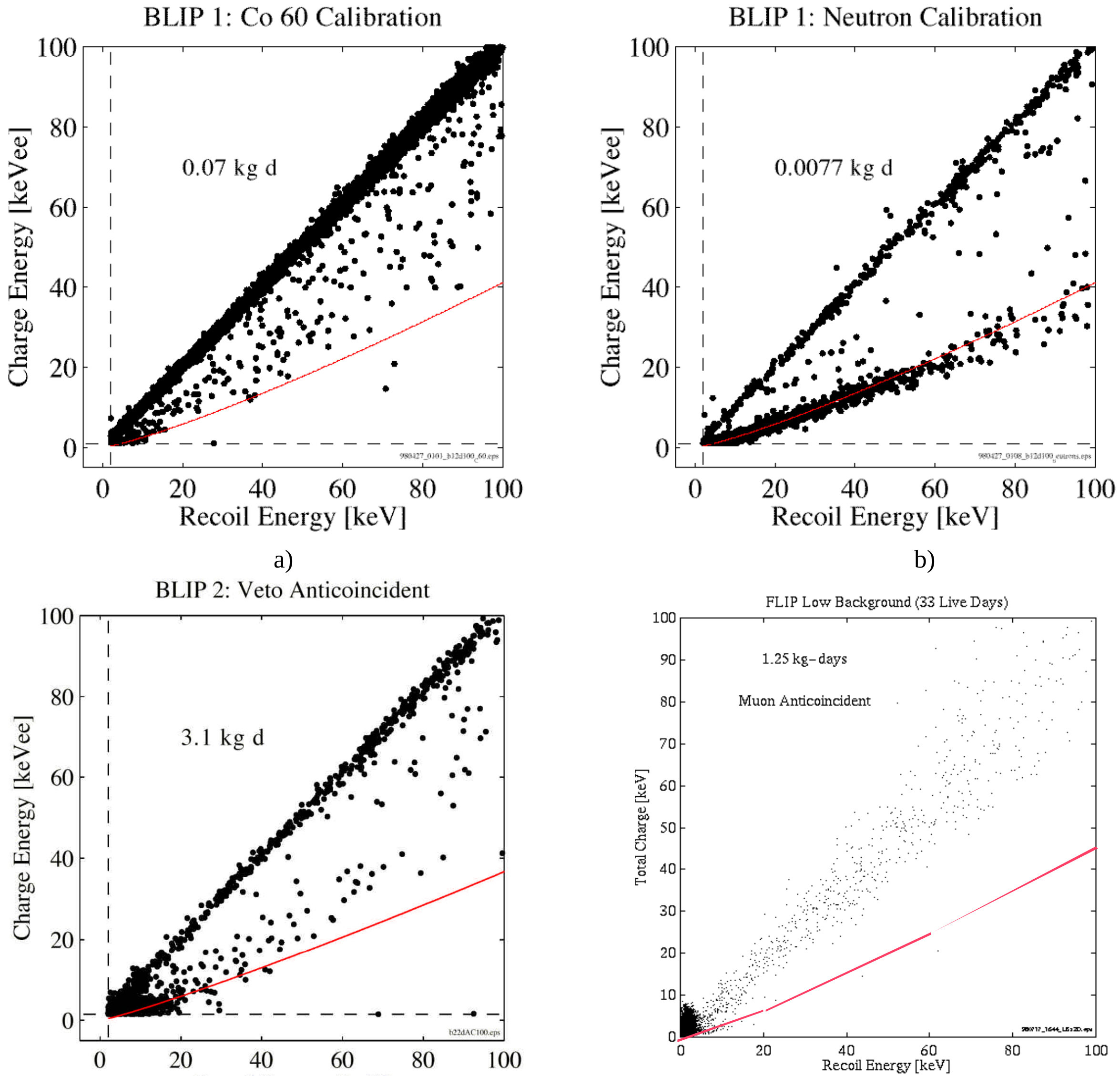
However, this approach is fundamentally limited by the absence of discrimination against the radioactive background. Not only can this background not be partially rejected, but it also cannot be measured independently of the signal and subtracted. Once the background level is measured with sufficient statistical accuracy, the sensitivity of the experiment does not improve with exposure. In contrast, the combination of an active background rejection and subtraction allows a sensitivity increase as the square root of the target mass and the running time, until the subtraction becomes limited by systematics.[55]

2. A second approach has been to use large scintillators with pulse shape discrimination of nuclear and electronic recoils. The technique is simple and large masses can be assembled to search for modulation effects. The most impressive result so far has been obtained with NaI. The NaI groups[37,38] have published limits that claim to be slightly better than those obtained with conventional germanium detectors. However, these limits remain controversial, as they may not fully take into account systematics in the efficiency close to the threshold or in the rejection power from pulse shape discrimination. In any case, because sodium has a spin, these experiments so far give the best limits for spin dependent couplings. The Rome group has recently announced[46] a nearly three σ detection of a signal using the annual modulation expected for a WIMP spectrum (heart-shaped region in Fig. 4). This modulation signal represents less than 1% of the observed background and it is not yet clear that the systematics have been controlled at the required level. Overall, it is unlikely that NaI could make significant additional progress, as the small number of photoelectrons at the energies of interest and the lack of power of the pulse shape discrimination make it highly susceptible to systematics.

3. Therefore, more powerful discrimination methods need to be devised. Liquid xenon with simultaneous measurement of scintillation and ionization is a promising approach, albeit with relatively high thresholds, and not enough development so far to fully judge its potential. In contrast, the active development of novel "cryogenic" detectors based on the detection of phonons produced by particle interactions is beginning to bear fruit. In spite of the complexity of the very low temperature operation, four large setups are currently being routinely operated (Milano,[39] CDMS,[56] CRESST[57] and EDELWEISS[58]), with total detector mass ranging from 70 g to 7 kg.

For dark matter searches, this technology appears to have three advantages:

- It can lead to a much smaller threshold, as phonons measure the total energy of nuclear recoil without any loss. Already the performance of thermal phonon detectors in the laboratory exceeds that of ionization detectors. Berkeley[59] is now routinely getting a resolution of better than 900 eV and 450 eV FWHM in phonons and ionization respectively with 165 g detectors. The CRESST group has also demonstrated a FWHM of 235 eV at 1.5 keV in a 250 g crystal of sapphire. Four of these detectors are now installed in the CRESST experiment, which hopes to obtain without discrimination the limits shown in Fig. 4. Stanford[60] has recently shown that it is even possible to detect athermal phonons after very few bounces on the surface and get similar baseline resolution (1 keV).
- With the simultaneous measurement[61] of ionization and phonons in crystals of germanium or silicon, it is possible to distinguish between nuclear recoils and electron recoils. This approach is used by both the CDMS and the EDELWEISS collaborations. CDMS has demonstrated greater than 99% rejection with thermal and athermal phonon plus ionization technology down to 20 keV recoil energy (Figure 5 a and b). This allows them to reach at a shallower site an effective gamma contamination better than Heidelberg-Moscow, with much lower thresholds. Unfortunately, as often in such situations, a new background was uncovered: soft electrons incident on the surface suffer from ionization losses in a micron-thick dead layer and partially simulate nuclear recoils (Figure 5 c). This dead layer is due to back diffusion of the carriers and can be decreased by suitable modification of the contacts. Combining these improvements with better shielding, the team has recently be able to drastically reduce this problem and hopes to reach at its present Stanford site the limit displayed in Fig. 4. A second line indicates the expected sensitivity at a deep underground facility (the Soudan mine).
- A third advantage of phonon-mediated detectors is the greater amount of information obtained about very rare events. Already the simultaneous measurement of phonons and ionization gives two pieces of information instead of one, and allows a more efficient rejection of microphonics and spurious instrumental effects. The detailed measurement of out-of-equilibrium phonons is even more promising.



a) b)

c) d)

Figure 5. CDMS scatter plots of the ionization measurement versus the recoil energy measurement for (a, b, c) a 165 g Ge detector with thermal phonon readout (BLIP), and (d) a 100 g Si detector with athermal phonon sensing (FLIP) obtained at the Stanford Underground Facility Icebox. The ionization measurements are normalized to electron equivalent energy. Panels (a) and (b) show results of calibration runs with a ^{60}Co photon source (a) and a ^{252}Cf source producing neutrons (and photons). The line represents a fit to the region of nuclear recoil events. Panels (c) and (d) are obtained in low background running conditions. Note in (a) and (c) the soft electron component, intermediate between the diagonal photon line and the nuclear recoil line. In panel (c), after an athermal phonon signal rise time cut, only two events are left in the nuclear recoil region.

CDMS has recently demonstrated that geometrical fiducial cuts can be imposed using the phonon information and that the problematic surface electrons can be eliminated by a phonon rise time cut (Figure 5 d). In the long run, athermal phonons may allow a determination of the directionality for isotopically pure targets.

To summarize, cryogenic detectors are making fast progress and currently appear the best promise to explore a significant portion of the supersymmetric WIMP space in the next few years.

6. CONCLUSION

The case for nonbaryonic dark matter remains very strong and it is important to aggressively continue the current particle searches. An axion experiment is underway which should give us a definite answer about axions over a mass range of one order of magnitude (out of three that are still allowed).

Oscillation neutrino experiments are in progress, which cover the mass range of cosmological interest. The WIMPs search is very active with the installation of very large NaI scintillators, liquid xenon detectors, and phonon-mediated detectors that are beginning to be operational.

The combination of all these efforts may well give us the solution of a central puzzle of cosmology and astrophysics. It may even give us important information about particle physics, with perhaps the discovery of the long sought-for axions or supersymmetric particles.

ACKNOWLEDGMENTS

This work was supported by the Center for Particle Astrophysics, a National Science Foundation Science and Technology Center operated by the University of California under Cooperative Agreement no. AST-912005, and by the Department of Energy under the contract DE-AC03-76SF00098.

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