Deciphering the nature of dark matter

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I. INTRODUCTION

The history of physics can be seen as the gradual discovery of structures invisible to the human eye and the instruments of the time. These structures are often hinted at first by indirect evidence, and new instrumentation has to be invented to fully establish their existence and to study their properties. The search for the dark matter in the universe represents an archetypal case study of such a process. It took nearly 60 years from the first evidence (Zwicki, 1933) for astronomers to reach a consensus that there is a dark component which dominates gravity but cannot be seen, as it neither emits nor absorbs light. As explained in Sec. II, the debate has now shifted to one about its nature, in particular whether dark matter is made of ordinary baryonic matter or whether new nonbaryonic components play a significant role. A number of innovative attempts to decipher this nature have been launched. Section III reviews the searches for baryonic forms of dark matter including the evidence for massive halo compact objects (MACHOs), and Sec. IV the nonbaryonic searches. As an example of the novel instruments necessary to make progress in this new field of astrophysics, Sec. V is devoted to the numerous attempts to detect weakly interactive massive particles (WIMPs). Because of space constraints, references are limited to recent reviews or representative works in each of the areas.

II. DARK MATTER: EVIDENCE AND NATURE

A. Dark matter

The existence of dark matter is now well established at a variety of scales (see, e.g., Trimble, 1987). In large spiral galaxies it is often possible to measure the rotation velocity of HII regions, atomic hydrogen clouds, or satellite galaxies out to large distances from the galactic centers. The constancy of these rotation velocities implies that the enclosed mass increases with radius well beyond the distance at which no more stars are observed. The effect is particularly spectacular for dwarf galaxies, which are totally dominated by dark matter. Similar evidence for dark matter is also observed in elliptical galaxies. The velocity dispersion of globular clusters and planetary nebulae, and the extended x-ray emission of the surrounding gas, show that most of the mass in outer parts of these galaxies is dark.

The dynamic effect of dark matter is even more pronounced in clusters of galaxies. It has been known for some time that dispersion velocities of the many hundreds of galaxies that constitute rich clusters are often in excess of 1500 km/s. Such large values indicate even deeper potential wells than for galaxies. In many clusters a large amount of gas is detected through its x-ray emission, and its high temperature ($\approx$5 keV) implies similar dark masses. In the last few years, a third piece of evidence has been gathered that also points to a very large amount of dark matter in clusters. Galaxy clusters gravitationally lens the light emitted by quasars and field galaxies in the background. The mapping of the mass distribution through the many arclets seen in a number of clusters indicates potential wells qualitatively similar to those observed with the two other methods. These dark matter density estimates are confirmed by the combination of measurements of the gas mass fraction in clusters (typically 20%) and estimates of the baryon density from primordial nucleosynthesis (see, e.g., White *et al.*, 1993).

At a larger scale, measurements of velocity flows and correlations hint at even larger amounts of dark matter. In this volume, Turner and Tyson summarize such measurements of the matter density in units of the critical density ρ_c as

$$\Omega_M=\frac{\rho_M}{\rho_c}=0.35\pm0.07$$

$$\text{with } \rho_c=1.88\times10^{-26}\ h^2\ \text{kg m}^{-3},$$

where h is the Hubble expansion parameter in units of $100\ \text{km s}^{-1}\,\text{Mpc}^{-1}$ $(h=0.67\pm0.1)$. Such a matter density is much greater than the visible matter density (less than 1% of the critical density).

While there is a broad consensus on the existence of such dark matter (unless Newton's laws are incorrect), there is still an intense debate on its nature. Can it be formed of ordinary baryons or is it something new?

B. Need for baryonic dark matter

An interesting element of this discussion is provided by the baryon density

$$\Omega_B=(0.02\pm0.002)h^{-2}$$

inferred from the observations of ^{4}He, D, ^{3}He, and ^{7}Li in the very successful standard scenario of homogeneous primordial nucleosynthesis (Schramm and Turner, 1998, and references therein). This is larger than the visible matter density, and we have to conclude that a component of the dark matter has to be baryonic. We need to understand where these dark baryons are hidden (Sec. III).

C. Need for nonbaryonic dark matter

It is clearly necessary to introduce a second type of dark matter to explain why measurements of Ω at large scales appear to be significantly higher than the baryonic density inferred from nucleosynthesis. Note that this argument is purely based on a set of converging observations, admittedly with large but different systematics, and not on inflation or the esthetic appeal of $\Omega=1$. Homogeneous Big Bang nucleosynthesis may be wrong, but all attempts to produce significantly different results, for instance through inhomogeneities induced by a first-order quark hadron phase transition, have been unsuccessful.

A second argument for the nonbaryonic character of dark matter is 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 inferred from the COBE measurement of the temperature fluctuations of the cosmic microwave background. The deduced power spectrum of the (curvature) mass fluctuations at a very large scale connects rather smoothly with the galaxy power spectrum measured at lower scale, giving strong evidence for the formation of the observed structure by gravitational collapse. The observed spectral shape is natural with cold (that is, nonrelativistic) nonbaryonic dark matter but cannot be explained with baryons only; since they are locked in with the photons until recombination, they cannot by themselves grow large enough fluctuations to form the structure we see today.

A third general argument comes from the implausibility of hiding a large amount of baryons in the form of compact objects (routinely called MACHOs). For instance, if 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 cooling and star formation scenarios. The same argument applies to galactic halos.

In conclusion, it seems very difficult to construct a self consistent cosmology without nonbaryonic dark matter. We therefore need at least two components of the matter in the universe. In addition, as explained by Turner and Tyson in this volume, there may be a third diffuse component, possibly with negative pressure, such as a cosmological constant. The fact that their densities are similar ($\Omega_B \approx 0.05$, $\Omega_{DM} \approx 0.3$, $\Omega_\Lambda \approx 0.65$) is somewhat disturbing, since they arise from *a priori* distinct physical phenomena and components with different equations of state evolve differently with time (e.g., if there is a sizable cosmological constant we live in a special time). This may indicate that our theoretical framework is incomplete. The task of the observer is clear however: to convincingly establish the existence of these three components and their equations of state. In addition to the confirmation of the recent indications for an accelerating universe provided by supernovae observations at high redshift, it is therefore important to solve the two dark matter problems: find the hidden baryon component and positively detect the nonbaryonic dark matter.

III. SEARCHES FOR BARYONIC DARK MATTER

Where are the dark baryons? It is difficult to prevent baryons from emitting or absorbing light, and a large number of constraints obtained at various wavelengths considerably restrict the possibilities.

A. Gas

If the baryonic dark matter were today in the form of diffused nonionized gas, there would be a strong absorption of the light from the quasars, while if it were ionized gas, the x-ray background flux would be too large and the spectrum of the microwave background too much distorted by upward Compton scattering on the hot electrons. However, recent detailed measurements of the absorption lines in the spectrum of high redshift quasars (the so-called Lyman α forest) indicate that, at a redshift of three or so, the Lyman α gas clouds contain (0.01–0.02) h^{-2} $(h/0.67)^{1/2}$ of the critical density in ionized baryons, enough to account for all the baryons indicated by the primordial abundance of light elements.

The problem then shifts to explain what became of this ionized high redshift component. Two general answers are proposed:

(i) It can still be in the form of ionized gas with a temperature of approximately 1 keV. Such a component would be difficult to observe as it would be masked by the x-ray background from active galactic nuclei. This is the most natural solution, as it is difficult for ionized gas to cool off and clump significantly, as shown by hydrodynamical codes.

(ii) However, it has also been argued that our simulations are still too uncertain to believe these cooling arguments: this gas could have somehow condensed into poorly visible objects either in the numerous low surface brightness galaxies or in the halo of normal galaxies.

Atomic gas would be visible at 21 cm. Dust is excluded as it would strongly radiate in the infrared. Clumped molecular hydrogen regions are difficult to exclude but could in principle be detected as sources of gamma rays from cosmic-ray interactions. However, the most likely possibility, if this gas has been able to cool, is that it has formed compact objects. In particular, objects with masses below 0.08 solar masses, often called brown dwarfs, cannot start thermonuclear reactions and would naturally be dark. Black holes without companions would also qualify.

B. Massive halo compact objects

How do we detect such compact objects? Paczynski (1986) made the seminal suggestion of using gravitational lensing to detect such objects. Suppose that we observe a star, say in the Large Magellanic Cloud (LMC), a small galaxy in the halo of the Milky Way. If one MACHO assumed to be in the halo were to come close to the line of sight, it would gravitationally lens the light of the star and its intensity would increase. This object, however, cannot be static, lest it fall into the potential well. Therefore it will soon move out of the line of sight, and one would expect a temporary increase of the light intensity that, from the equivalence principle, should be totally achromatic. The duration of such a microlensing event is related to the mass m, distance x, and transverse velocity $v_\perp$ of the lens, and the distance L of the source by

$$\Delta t \propto \sqrt{mx(L-x)/v_\perp^2 L}.$$

The probability of lensing at a given time (the optical depth τ) is given by a weighted integral of the mass density $\rho(x)$ of MACHOs along the line of sight:

$$\tau \propto \int \rho(x) \frac{x(L-x)}{L} dx.$$

The maximum amplification unfortunately does not bring any additional information as it depends in addition on the random impact parameters.

To be sensitive enough, such a microlensing search for MACHOs in the halo should monitor at least a few million stars every night in the LMC. Following Alcock's observation that this was within the reach of modern instrumentation and computers, three groups (MACHO, EROS, OGLE) launched microlensing observations in 1992. Since then they have been joined by five other groups. The results of these five years can be summarized as follows:

(1) The observation of some 300 events towards the bulge of the galaxy has clearly established gravitational microlensing. The distribution of amplifications and the independence from the star population confirm this explanation. Microlensing has opened a new branch of astronomy which can now probe the mass distribution of condensed objects. It is even hoped that it will allow the detection of planets around lensing stars, as they would produce sharp amplification spikes.

(2) Probably the most important result of the microlensing experiments is that there is no evidence for short lensing events (corresponding to low-mass MACHOs) in the direction of the LMC. A combination of the EROS and MACHO results excludes (Fig. 1) the mass region between 10^{-7} and 10^{-1} solar masses (Alcock *et al.*, 1998). Our halo is not made of brown dwarfs!

(3) However, a number of long-duration LMC events have been observed. EROS has detected two events and in five years the MACHO team has observed some 18 LMC lensing events of duration (defined as the full width at 1.5 amplification—the EROS group uses the half width) between 35 and 150 days. This cannot be explained in the standard picture of a rather thin Milky Way disk and a thin LMC. The main problem in interpreting this interesting result is that we usually do not know where the lenses are along the line of sight. As explained above, for each event we have only two experimental observables, the duration of the microlensing event and its probability, an insufficient amount of information to unravel the distance of the lens, its mass, and its transverse velocity. Only in specific events can we give the distance of the lens. One LMC event corresponds to a double lens that creates two amplification spikes at caustic crossing. This double lens is clearly in the LMC. One other event is produced by a disk star that we can see. For most of the observed events, the degeneracy between mass, distance, and velocity limits in a fundamental way our capability to interpret the results.

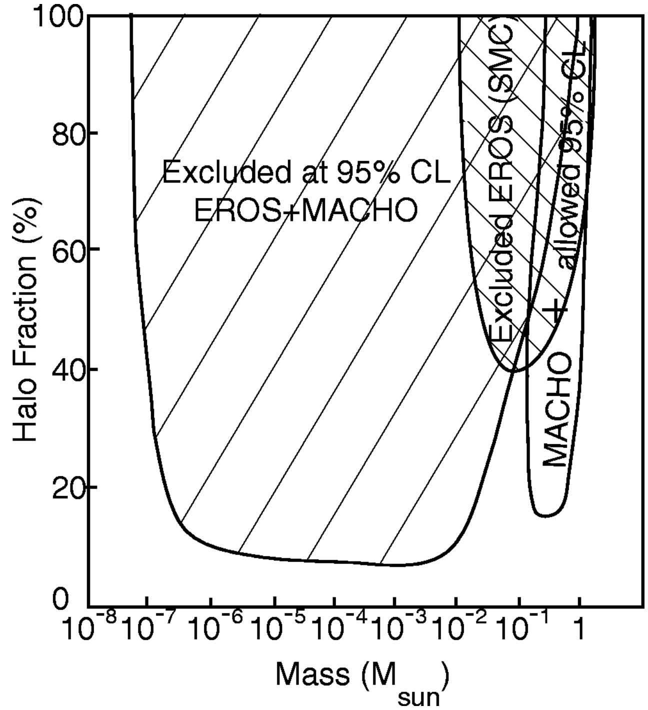

FIG. 1. Excluded region (at 95% confidence level) of the halo fraction in MACHOs as a function of their mass in a standard halo model. The ellipse on the right is the 95% confidence level range allowed by the two year data of the MACHO collaboration.

If we assume that the MACHOs are distributed in the same way as the galactic halo, they may represent a fraction of the halo density between 10 and 100% (Fig. 1). Although the compatibility with 100% may superficially indicate that the dark matter problem is solved, this interpretation encounters the serious difficulty that the mass of individual lenses would be typically one third of a solar mass. These objects are not brown dwarfs. They cannot be ordinary stars as this is incompatible with the Hubble Space Telescope surveys. The hypothesis that they could be very old white dwarfs requires an artificial initial mass function, an uncomfortable age of more than 18 billion years, and a totally unknown formation mechanism.

We are then led to question the assumed distance and velocity distributions. Four types of models have been proposed: an additional component of our galaxy such as a thick or warped disk, an extended spheroid, an intervening dwarf galaxy, or a tidally elongated LMC.

(4) The last model may be favored by the observations towards the Small Magellanic Cloud (SMC) that have so far detected two microlensing events. The first

event is much longer (250 days) than all the LMC events and the absence of parallax due to the movement of the earth constrains it to be close to the SMC. While this result is unlikely for a halo-like distribution (some four events of duration similar to LMC events would have been expected), it is quite natural if the lenses are in the observed galaxies: the longer duration of the SMC event is due to the lower SMC dispersion velocity. The second SMC event is produced by a double lens clearly in the host galaxy. Although the SMC is known to be thicker than the LMC, these observations cast further doubt on a halo interpretation of the LMC events. A detailed mapping of the thickness of the LMC (for instance, by R. R. Lyrae's) is an important task to prove or disprove this self-lensing hypothesis. Note that lensing by a low-density extended component of the LMC would not produce a quadratic dependence on the lensing rate with respect to the star density on the sky. The apparent absence of such a dependence cannot be used as an argument against a self-lensing explanation. Note that the lack of events observed towards SMC excludes, as shown in Fig. 1, the possibility that MACHOs of mass smaller than a solar mass form a large fraction of the halo (Palanque Delabrouille *et al.*, 1998).

It is clear that it is essential to break the degeneracy between mass, distance and velocity. The data of double lenses, or the precise photometry of very long events, partially break this degeneracy. The different lines of sight such as the SMC or M31, which is beginning to be explored, are very important to test the assumption of a halo-like distribution. Unfortunately in the case of M31 one cannot see individual stars from the ground and one is limited to pixel lensing, in which interpretation depends on the good knowledge of the underlying star population. A satellite located one astronomical unit away would be a useful tool, as it may allow a parallax measurement as the lensing will be observed at a different time. The Space Interferometric Mission satellite to be launched in 2006 can also help break the degeneracy.

C. Dark matter black holes

Although black holes may not be initially formed by the collapse of baryonic objects and in any case have technically lost any information about their baryonic content, we summarize at the end of this baryonic section their possible contribution to dark matter.

Very low-mass black holes cannot form the bulk of dark matter, as they would evaporate through Hawking radiation and give rise to high energy gamma-ray flashes, which are not observed.

The quoted microlensing result exclusion of the mass range between 10^{-7} and 10^{-1} solar masses also applies to black holes. Note that primordial black holes of a solar mass or so could explain the MACHO observations towards the LMC and would otherwise behave as cold dark matter. One solar mass happens to be the mass inside the causal horizon at the quark hadron phase transition, and a strongly first-order transition may indeed induce density fluctuations large enough to produce these black holes. However, the needed abundance appears to require fine-tuning of parameters.

Very massive objects (VMOs), an early star population of at least a hundred solar masses, could have rapidly formed black holes without contaminating the interstellar medium with metals. However, we should now see the radiation of the progenitor stars in the far infrared and the diffuse infrared background experiment (DIRBE) severely constrains this possibility. Even more massive ones would disrupt galactic disks.

IV. SEARCHES FOR NONBARYONIC DARK MATTER

The intrinsic degeneracy arising in the interpretation of microlensing observations prevents the fascinating MACHO results from seriously undermining the case for nonbaryonic dark matter. Moreover, if such a nonbaryonic component exists, as hinted by the cosmological arguments of Sec. II, it is difficult to prevent it from accreting (unless it is relativistic); 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 to the canonical 0.3 GeV/cm^3 inferred from the velocity curves of our galaxy.

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 (Witten, 1984), charged massive particles (CHAMPs) (De Rujula, Glashow, and Sarid, 1990), and a long list of usually massive particles with very weak interactions. We should probably first search for particles that would also solve major questions in particle physics. According to this criterion, three candidates appear particularly well motivated.

A. Axions

Axions are an example of relic particles produced out of thermal equilibrium, a case in which we depend totally upon the specific model considered to predict their abundances. These particles have been postulated 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 (Turner, 1990). Such low-mass cosmological axions could be detected by interaction with a magnetic field that produces a faint microwave radiation detectable in a tunable cavity. The first two searches 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 that has published preliminary limits (Hagmann *et al.*, 1998).

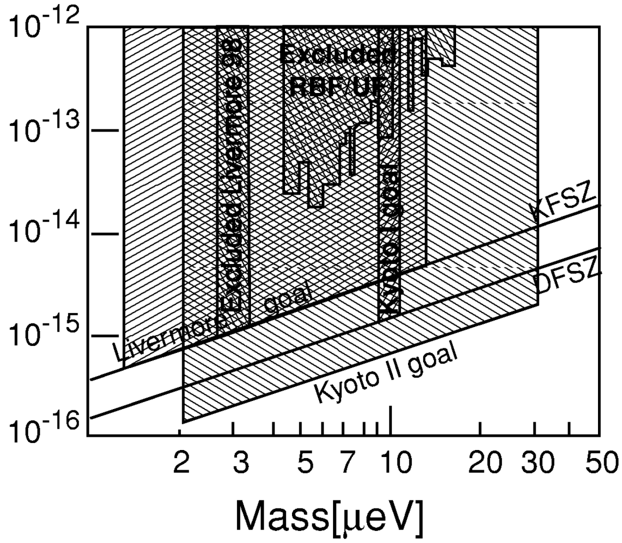

FIG. 2. Expected sensitivity of the Livermore experiment. The lines labeled KSVZ and DFSZ refer to two generic species of axions. The shaded regions in the upper right are the previous experimental limits.

It will reach (Fig. 2) a cosmologically interesting sensitivity at least for one generic type of axion (the so-called hadronic model; see Turner, 1990). The collaboration hopes to improve their sensitivity down to the lowest couplings currently predicted (the DFZ model; see Turner, 1990). Matsuka and his collaborators in Kyoto are developing a more ambitious scheme using Rydberg atoms that are very sensitive photon detectors and should immediately reach the DFZ limit. Although these experiments are very impressive, it should be noted that the decade of frequency (and therefore of mass) that can be explored with the present method is only one out of three that is presently allowed.

B. Light massive neutrinos

Neutrinos of mass much smaller than 2 MeV/c fall in the generic category of particles that have been in thermal equilibrium in the early universe and decoupled when they were relativistic. Their current density is basically 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. 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 relativistic neutrino streaming. They have to be mixed in with cold nonbaryonic dark matter (Klypin, Nolthenius and Primack, 1997, and references therein) or seeded by topological defects. Moreover, because of phase space constraints, they cannot explain the dark matter halos observed around dwarf galaxies.

Unfortunately no good ideas have yet been put forward of possible ways to detect cosmological neutrinos (see, e.g., Smith and Lewin, 1990) 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. One may summarize the situation (see accompanying review of Wolfenstein for details and references) as follows: The direct mass measurement of the electron neutrino gives limits of 5 eV. Model-dependent limits of the order of 1 eV on the mass of Majorana neutrinos are given by neutrinoless double beta decay searches (Heidelberg-Moscow). The claim by the LSND group for muon to electron neutrino oscillation with relatively large $\Delta m^2 \approx 6\ \mathrm{eV}^2$ oscillation is now challenged by the Karmen experiment.

The best indication that neutrinos have a nonzero mass comes from atmospheric and solar neutrinos. The SuperKamiokande group has recently presented statistically significant results demonstrating the disappearance of atmospheric muon neutrinos that points to an oscillation with Δm^2 of a few $10^{-3}\,\mathrm{eV}^2$ and a large mixing angle. The combination of the chlorine, water Cerenkov, and gallium experiments has been indicating for some time a depletion of solar neutrinos with respect to the standard solar model. The most natural explanation is a MSW (Mikheyev-Smirnov-Wolfenstein) or vacuum oscillation with Δm^2 of $10^{-6}\,\mathrm{eV}^2$ or $10^{-10}\,\mathrm{eV}^2$ respectively (Hata and Langacker, 1997).

Note, however, that these oscillation experiments do not give a direct measurement of the neutrino masses that may well be in the electron volt range (for nearly degenerate masses). It thus remains important for cosmology to improve the electron neutrino mass limit.

C. Weakly interactive massive particles

A generic class of candidates is constituted by particles that were in thermal equilibrium in the early universe and decoupled when they were nonrelativistic. In this case it can be shown that their present density is inversely proportional to their annihilation rate (Lee and Weinberg, 1977). 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^0 scale is important for the problem of dark matter. Inversely, physics at such a 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. We review in the next section the experimental challenge to detect them.

V. SEARCHES FOR WEAKLY INTERACTIVE PARTICLES

The most direct method to detect these WIMPs is by elastic scattering on a suitable target in the laboratory (Goodman and Witten, 1985; Primack, Seckel, and Sadoulet, 1988). WIMPs interaction with the nuclei in the

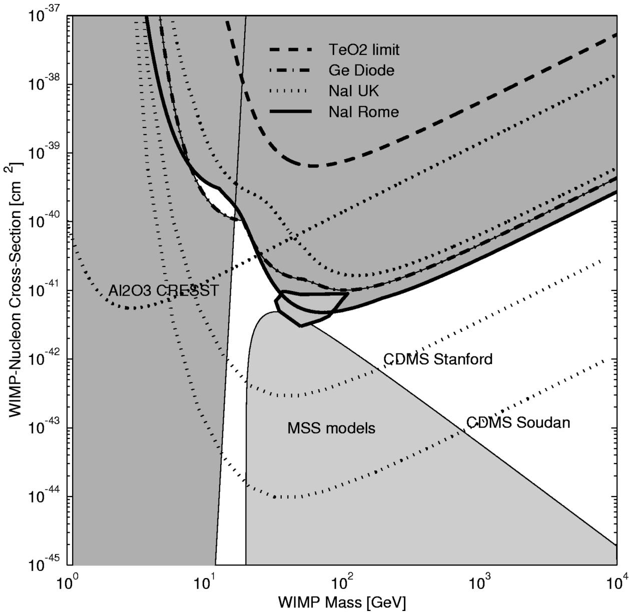

FIG. 3. Current achieved limits for spin-independent couplings as a function of the WIMP mass. All the results have been converted to WIMP-nucleon cross sections assuming scalar interactions scaling as the square of the atomic number. The hatched region at the top is excluded by these experiments. The shaded regions at the bottom are the rates predicted by minimal supersymmetric models including the constraints from LEP and CDF experiments. The curves labeled CRESST and CDMS are goals of these experiments.

target would produce a roughly exponential distribution of the recoil energy with a mean 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.

A. Experimental challenges

In specific models such as supersymmetry, the knowledge of the order of magnitude of the annihilation cross section allows an estimation of the WIMP 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 Fig. 3, as the lower hatched region, the range of cross sections (rescaled to a proton target) expected (Jungman *et al.*, 1996) in grand-unified-theory-inspired supersymmetric models, where scalar interactions usually dominate. The upper hatched regions summarize the current limits achieved with state-of-the-art techniques to achieve low radioactivity background. They barely skirt the supersymmetric region.

Unfortunately, the expected rates can be very small for specific combinations of parameters in which 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 supersymmetric region (Jungman *et al.*, 1996).

It is therefore essential to construct experiments with very low radioactive backgrounds and, if possible, with the instrumental capability to recognize nuclear recoils (only produced by WIMPs, if neutrons are eliminated) and actively reject the electron recoils produced by gamma rays and electrons from radioactivity. Note that, without this discrimination, the background is not measured independently of the signal. The experimental sensitivity to a small signal then ceases to improve with exposure, once the background level is measured with sufficient statistical accuracy. In contrast, with discrimination the combination of background rejection and subtraction of the remaining contamination allows a sensitivity increase as the square root of the target mass and the running time, until the subtraction becomes limited by systematics.

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 that may differ by a factor of 3 (Ge) to 12 (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, a very difficult task. Short of that directionality signature, it is, in principle, possible to look for a change in the event rate and the spectrum of energy deposition with a change in the time of the year.

B. 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. The detection techniques are very diverse, ranging from mica, which integrates for billions of years over minute target masses, and superheated microdots, which should be only sensitive to nuclear recoil, to low pressure time projection chambers, which could give the directionality. However, we can identify 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 were obtained by decreasing the threshold of double-beta experiments. The most impressive results have been obtained by the Heidelberg-Moscow group (Baudis *et al.*, 1998) with a background of 0.05 events/kg/day/(equivalent electron keV) around 20 keV

(equivalent electron energy). The current combined exclusion plot is given in Fig. 3.

This strategy is pushed to the extreme by GENIUS, an ambitious proposal to immerse one ton of germanium detectors in an ultra-pure liquid nitrogen bath. However, this approach is fundamentally limited by the absence of discrimination against the radioactive background.

(2) A second approach has been to use large scintillators with pulse-shape discrimination of nuclear and electronic recoils, unfortunately with energy thresholds difficult to bring below 50 keV ($\approx$4 keV equivalent electron energy on iodine). The technique is simple and large masses can be assembled to search for modulation effects. The most impressive result so far has been obtained by NaI. The groups using NaI have published limits that are slightly better than those obtained with conventional germanium detectors. The Rome group has recently announced (Bernabei *et al.*, 1998) a close to 3σ detection of a signal using the annual modulation expected for a WIMP spectrum (heart-shaped region in Fig. 3). Note that because Na has a spin, these experiments so far give the best limits for spin-dependent couplings. It is too early to conclude, but 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) Thus 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 very low temperature operation, two large setups are currently being routinely operated (Milano: Alessandro *et al.*, 1986; CDMS: Nam *et al.*, in Cooper, 1997; CRESST: Sisti *et al.*, in Cooper, 1997) with total detector mass ranging from 1 kg to 7 kg. For dark matter searches this technology appears to possess significant advantages.

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

C. Indirect detection methods

Let us note finally that several methods have been proposed for detecting WIMPs through their annihilation products (Primack, Seckel, and Sadoulet, 1988 and references therein). They of course assume dark matter exists in the form of both particles and antiparticles (or is self conjugate) as otherwise no annihilation would occur.

The detection of gamma-ray lines from their annihilation into two photons will require the resolution of the next generation of satellites and may be masked by the galactic background, especially if the dark matter density does not strongly peak at the galactic center. The first measurements of the energy spectra of antiprotons and antielectrons offered tantalizing hints of dark matter particle annihilations, but they turned out to be inaccurate. The interpretation of such spectra would in any case be very uncertain because of the uncertainty on the confinement time of these antiparticles in the halo of our galaxy.

A much more promising method is to search for high energy neutrinos coming from the centers of the earth and the sun. Since they can lose energy by elastic interactions, some dark matter particles would be captured by these objects, settle in their centers, and annihilate with each other producing, among other products, high energy neutrinos that can then be detected in underground detectors, especially through the muons produced by their interactions in the rock. The current generation of such detectors (Baksan, MACRO, and SuperKamiokande) of roughly 1000 m^2 area set a limit of the order of 10^{-14} muon $cm^{-2}\,s^{-1}$ above 3 GeV. Such results exclude any charge-symmetric Dirac neutrino or scalar sneutrino and put limits on supersymmetric models that are generally in agreement but less restrictive than direct detection experiments. Fairly model-independent arguments (Kamionkowski *et al.*, 1995) show that such an advantage of direct detection should be maintained for the next generation of detectors (cryogenic WIMP searches and $10^4\,m^2$ detectors such as AMANDA II), especially for scalar interactions. However, the very large neutrino detectors currently being studied ($10^6\,m^2$) may be more sensitive than direct searches for large-mass WIMPs.

VI. CONCLUSION

In the past decade astrophysicists have clearly confirmed the earlier indications that there is much more mass in the universe than we can see. This dark matter dominates gravity over a variety of scales, from dwarf galaxies to the larger structures and velocity flows that we can see. Representing more than 99% of the mass density, it is an essential component of any cosmology and appears responsible for the formation of structure, galaxies, stars, and planets. Ultimately, in spite of being totally inert, it may be an essential element for the appearance of life as planets would not exist without dark matter.

Elucidating the nature of this dark matter has therefore become a central question in astrophysics and probably one of the most fundamental and multidisciplinary quests in science today. Are we observing a new form of matter (and energy) in the universe? We have reviewed the large number of projects devoted to this question. They require long term efforts and highly sophisticated instrumentation, but after a decade of development, a number of searches are beginning to reach the necessary level of sensitivity. As often remarked, a positive answer would lead to another Copernican revolution; not only are we not the center of the universe, but we are not even made of what most of the universe is made of!

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