Dark Matter Searches

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1 Introduction

One of the most central problems in astronomy and cosmology is to understand the nature of the dark matter pervading the universe. And as we will see, the solution may involve particle physics. We review the current attempts to directly detect this dark matter. We have included in this written version the most recent results that were not available at the time of the Lepton Photon conference: the 5.7 year MACHO data [1], the 4 year modulation evidence for WIMPs claimed by DAMA [2], and the new WIMP results of CDMS [3].

Considerable evidence (see *e.g.*, [4]) gathered in the last fifteen years indicates that at least 90% of the mass in the universe is dark: it does not emit nor absorb any form of electromagnetic radiation. Once a subject of controversy among astronomers, the existence of dark matter 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. Figure 1 presents a map of the possibilities. A central question is whether this dark matter is made of ordinary baryonic matter or is non-baryonic. Note that the problem has become even more complex, because the recent measurement of supernovae at high redshift [5, 6] may indicate an additional diffuse component, possibly with negative pressure, such as a cosmological constant. We will review in Section 2 the astrophysical hints for the nature of dark matter. We need both dark baryons and non-baryonic dark matter. Section 3 will summarize searches for baryons. We review in Section 4 the various searches for non-baryonic dark matter before focusing in Section 5 on the detection efforts for Weakly Interacting Massive Particles (WIMPs).

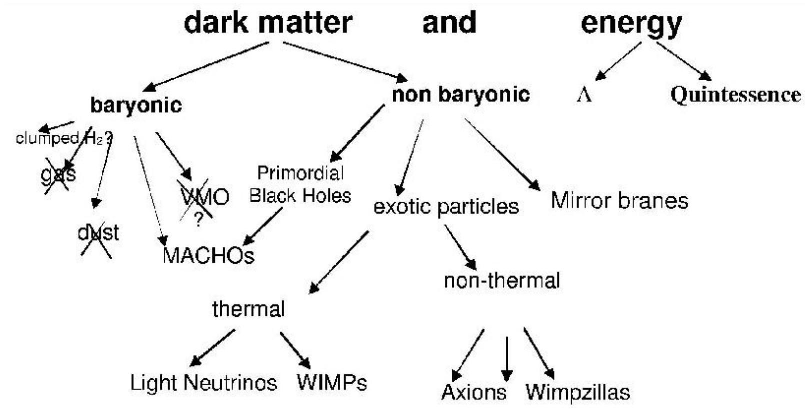

Figure 1: Dark matter and dark energy: a map of the territory.

2 Astrophysical hints on the dark matter nature

2.1 Evidence for dark matter

In large spiral galaxies, it is often possible (see, *e.g.*, [7]) to measure the rotation velocity of HII regions, atomic hydrogen clouds, or satellite galaxies [8], 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 such as DD0 154 which are totally dominated by dark matter [9]. 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 the 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 the 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 [10]. In many clusters, a large amount of gas is detected through its X-ray emission, and its high temperature (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 (see, *e.g.*, [11]) through the many arclets seen in a number of clusters indicates potential wells qualitatively similar to those observed with

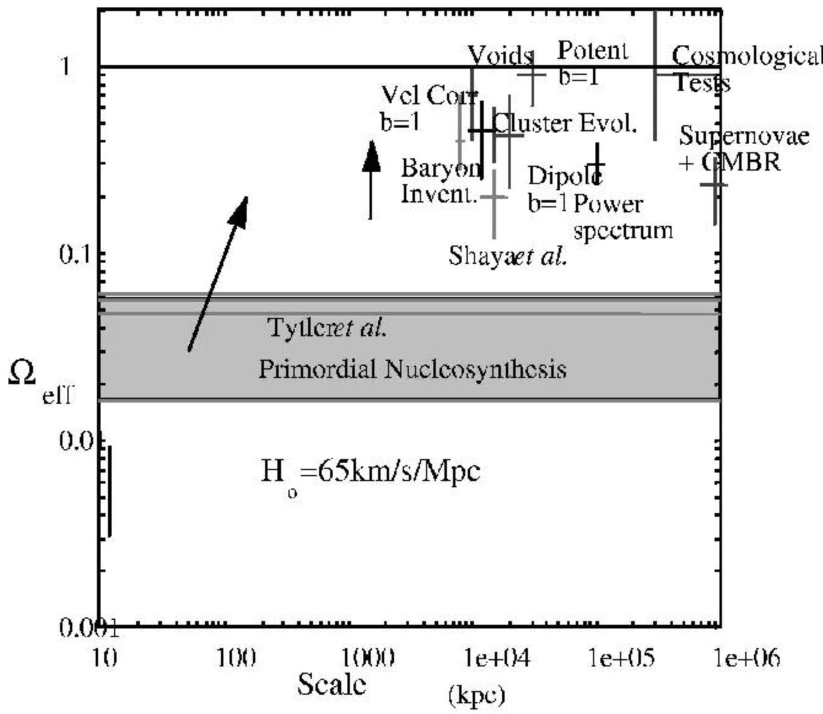

Figure 2: Measured effective density (measured in units of the critical density) as a function of scale.

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.*, [12]).

At a larger scale, measurements of velocity flows and correlations hint at even larger amounts of dark matter. At large scales such measurements give [13]

$$\Omega_M = \frac{\rho_M}{\rho_c} = 0.35 \pm 0.07 \text{ with } \rho_c = 1.88 \times 10^{-26}\ h^2 \text{ kg m}^{-3} \tag{1}$$

where as usual, Ω is the average density of the universe measured in units of the critical density and h is the Hubble expansion parameter in units of 100 km/s/Mpc ($h = 0.67 \pm 0.1$). Such a matter density is much greater than the visible matter density (which is less than 1% of the critical density).

These results are summarized in Fig. 2 where the measured effective density is plotted as a function of scale. While there is a broad consensus on the existence of such dark matter (unless Newton's laws are incorrect; see, *e.g.*, [14]), there is still an intense debate on its nature. Can it be formed of ordinary baryons or is it something new?

2.2 Need for baryonic dark matter

These measured densities should be compared with the baryon density

$$\Omega_b = (0.02 \pm 0.002)\ h^{-2}$$

inferred from the observations of ^{4}He, D, ^{3}He, and ^{7}Li in the very successful standard scenario of homogeneous primordial nucleosynthesis (see [15] 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. This will be discussed in Section 3.

2.3 Need for non-baryonic dark matter

Evidence from nucleosynthesis

It is also clear from Fig. 2 that it is 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—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 (see references in [15]).

Comparison of the fluctuations in microwave background and the large scale structure

A second argument for the non-baryonic 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 very large scale connects rather smoothly (Fig. 3) with the galaxy power spectrum measured at lower scale (see, *e.g.*, [16]), giving strong evidence for the formation of the observed structure by gravitational collapse. The observed spectral shape is natural with cold (that is, non-relativistivic) non-baryonic dark matter. It cannot be explained with baryons only; because they are locked in with the photons until recombination, they cannot by themselves grow large enough fluctuations to form the structure we see today.

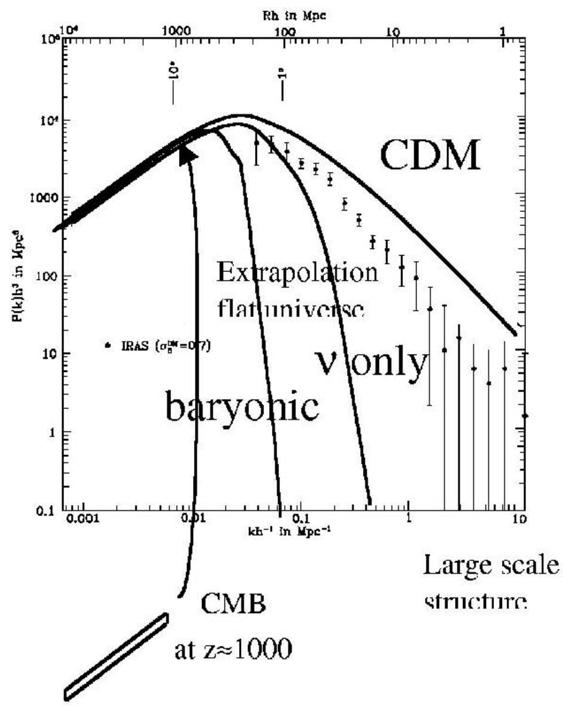

Figure 3: Comparison of estimates of density-fluctuation power spectrum from the COBE measurement of temperature fluctuations of the cosmic microwave background and the mapping of large scale structure. Curves sketch expectations from the Cold Dark Matter model, and scenarios with neutrinos only and baryons only.

Efficiency to form compact objects

A third general argument for non-baryonic dark matter comes from the implausibility of hiding a large amount of baryons in the form of compact objects (routinely called MACHOs, for Massive Compact Halo Objects). For instance, if the ratio of the mass in gas and stars to the total mass in clusters is of the order of 20% [17], 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 non-baryonic dark matter. We therefore need at least two components of the matter in the universe. The task of the observer is therefore clear: find the hidden baryon component and positively detect the non-baryonic dark matter.

3 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.

3.1 Gas

If the baryonic dark matter were today in the form of diffused non-ionized gas, there would be a strong absorption of the light from the quasars [18], 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 [19]. However, recent detailed measurements [20, 21] 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 a fraction (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:

1. It can still be in the form of ionized gas with a temperature of approximately one 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 [22].

2. 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 (see, *e.g.*, [23]) or in the halo of normal galaxies. In which form may these objects be?

   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 they could in principle be detected as sources of gamma rays from cosmic-ray interactions [24]. 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.

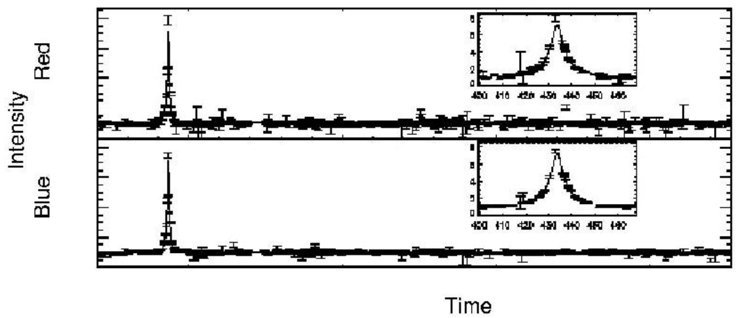

Figure 4: A typical microlensing event.

3.2 Massive compact halo objects

How do we detect such compact objects, which we will generically call Massive Compact Halo Objects (MACHOs)? Paczynski [25] 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 the star's intensity would increase. The MACHO, however, cannot be static, lest it fall into the potential well. Therefore it will soon move out of the line of sight. This leads to a temporary increase of the light intensity (Fig. 4) which, from the equivalence principle, should be totally achromatic. The duration of such a microlensing event is related to the mass m, the distance x, and transverse velocity $v_\perp$, of the lens, and the distance L of the source by

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

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, and OGLE) launched microlensing observations in 1992. Since then, they have been joined by some five other groups. The results of their five years of data can be summarized as follows:

1. The observation of more than two hundred events towards the bulge of the galaxy [26, 27] 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 that 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 the mass region between 10^{-7} and 10^{-1} solar masses [28] (Fig. 5). Our halo is not made of brown dwarfs!

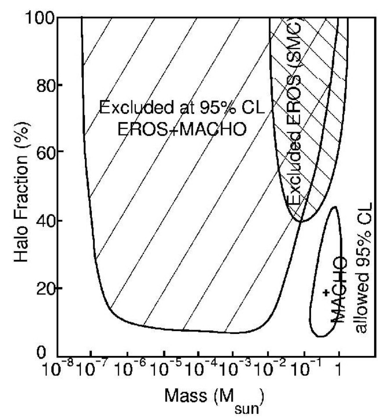

Figure 5: Current MACHO limits.

3. However, a number of long-duration LMC events have been observed. EROS [29] has detected 2 events in their original photographic plates and 2 new events with a CCD camera (EROS II [30]). OGLE [26] recently observed one event towards the Large Magellanic Cloud. In 5.7 years, the MACHO team has observed between 13 and 17 LMC lensing events depending on the selection

criteria [1]. Their duration ranges from 34 and 230 days (typically defined as the full width at 1.5 amplification, though the EROS group uses the half width). 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 earlier, 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, for instance, 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. The degeneracy between mass, distance, and velocity for most of the observed events limits in a fundamental way our capability to interpret the results.

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 typically of 20% with a 95% confidence interval of 8 to 50% (Fig. 5). Note that the 5.7 years data with more statistics and improved analysis, is no longer compatible with 100%. MACHOs do not form the bulk of dark matter in the halo! This interpretation is still problematic as the mass of individual lenses would be typically six tenth 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 [31]. They could be very old white dwarfs and there is tantalizing evidence for a population of such high proper motion white dwarfs in the Hubble Deep Field [32]. However, even if those observations are confirmed, making 20% of the halo with such objects requires an artificial initial mass function, an uncomfortable age, and a totally unknown formation mechanism [33]. 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 [34, 35].

4. The last model may be favored by the observations towards the Small Magellanic Cloud (SMC) which have so far detected two microlensing events [36, 37]. The first event is 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. The second SMC event is produced by a double lens clearly in the host galaxy. This result 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. Although the SMC is known to be thicker than the

LMC, these observations cast further doubt on a halo interpretation of the LMC events. The MACHO team acknowledges that their observations are marginally compatible with a thick LMC and no halo population [1]. A detailed mapping of the thickness of the LMC (for instance, by RR Lyrae stars) is an important task to prove or disprove this self-lensing hypothesis.

More generally, it is clear that it is essential to break the degeneracy between mass, distance, and velocity. The data on 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 are beginning to be explored [38, 39], 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 so one is limited to pixel lensing whose interpretation depends on the good knowledge of the underlying star population. A satellite located one astronomical unit away would be a useful tool. It may allow a parallax measurement, because 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.

3.3 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 (see, *e.g.*, [40]). The microlensing result quoted above excludes the mass range between 10^{-7} and 10^{-1} solar masses also for 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. The Diffuse Infrared Background Experiment (DIRBE) severely constrains this possibility [41]. Even more massive black holes would disrupt galactic disks [42].

4 Searches for non-baryonic dark matter particles

The recent results therefore nearly rule out the last possibility for a substantial amount of baryonic dark matter. This increases the urgency of searches for a non-baryonic component! A large number of candidates have been proposed over the years. They range from shadow universes existing in some string models, strange quark nuggets formed at a first order quark-hadron phase transition [43, 44], Charged Massive Particles (CHAMPs [45]), 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.

4.1 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 [46] 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 [47]. 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 [48]. The first two searches [49, 50, 51] for cosmological axions, performed a decade ago, were lacking 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 [52] and will reach a cosmologically interesting sensitivity at least for one generic type of axion, the hadronic models of [53, 54] (see Fig. 6). By replacing their HEMT-based amplifiers by SQUID amplifiers, the collaboration hopes to improve their sensitivity down to the lowest couplings currently predicted (the DFZ model [55, 56]). Matsuka and his collaborators in Kyoto are developing a more ambitious scheme using Rydberg atoms, which 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 in frequency (and therefore axion mass) that can be explored with the present method is only one out of three which are presently allowed. Moreover, if the Peccei-Quinn symmetry has been broken after inflation, cosmic strings are formed. In that case, current calculations [57] disfavor this low mass region.

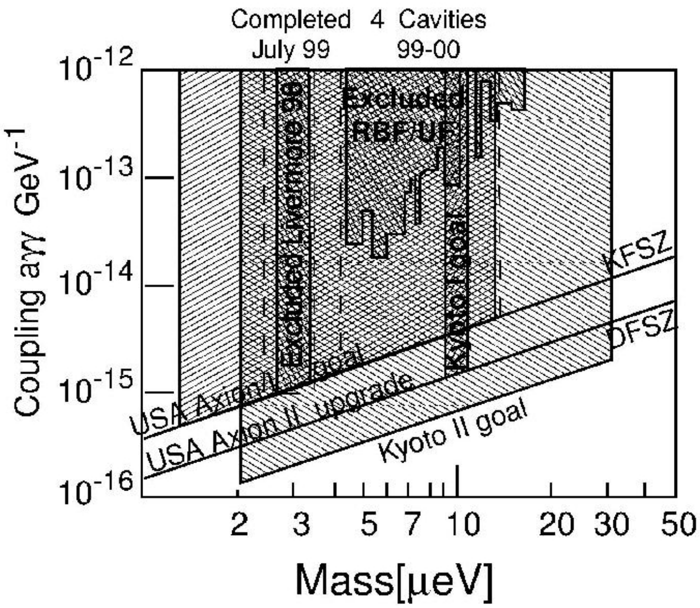

Figure 6: Current and future axion limits.

4.2 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 number density is basically equal to that of the photons in the universe. The relic particle density is therefore directly related to mass. A neutrino species of 25 eV would give Ω of the order of unity [58]. Note that neutrinos alone cannot lead to the observed large-scale structure, because fluctuations on scales greater than 40 h^{-1} Mpc are erased by neutrino streaming. They have to be mixed in with cold non-baryonic dark matter ([59] and references therein) or use structures seeded by topological defects. Both models however have serious difficulties with recent observations, the mixed dark model with the Lyman α forest and early formation of galaxies, the defects with the power spectrum of the large scale structure (Fig. 3). Moreover, because of phase space constraints, neutrinos cannot explain the dark matter halos observed around dwarf galaxies [60, 61]. So it is unlikely that neutrinos form the bulk of the dark matter. These neutrino models are now essentially abandoned.

We need, however, to measure the mass of the neutrinos to check what role they could have in cosmology. Unfortunately, no good ideas exist of possible ways to detect cosmological neutrinos (see, *e.g.*, [62]), 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 [63, 64] as follows: The direct mass measurement of the electron neutrino gives limits of the order of 2.5 eV, but the data show curious distortions near the end point. Model dependent limits of the order of 0.4 eV on the mass of Majorana neutrinos are given by neutrinoless double beta decay searches [65]. The claim by the LSND group [66] for muon to electron neutrino oscillation with relatively large $0.2 \leq \Delta m^2 \leq 2$ eV^2 is still controversial.

The Super-Kamiokande group [67] 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} eV^2 and a large mixing angle. A muon to electron neutrino oscillation is disfavored, both by CHOOZ [68] and internally by Super-Kamiokande. This very important result will be fully checked by long baseline neutrino experiments, by K2K in the next year or two and at Fermilab and CERN in the next five years.

The combination of the chlorine, water Cerenkov and gallium solar neutrino experiments have indicated for some time now a depletion of solar neutrinos with respect to the standard solar model [69]. The most natural explanation is an MSW [70, 71] or vacuum oscillation with Δm^2 of 10^{-6} eV^2 or 10^{-10} eV^2, respectively. However, the distortion of the energy distribution observed by Super-Kamiokande is not fully understood. The key measurements of neutral current events by SNO and of the ^{7}Be neutrino flux depletion by Borexino should be available in the next few years.

Note that these oscillation experiments do not give in themselves a definite mass as there could be near mass degeneracy between the neutrino families [63]. Independently of whether LSND is correct or not, the neutrino masses may well be in the electron volt range, and it is important for cosmology to keep pushing the resolution of the direct electron neutrino mass measurement. We can, however, put a lower limit on one of the neutrino masses by assuming that the muon neutrino mass is negligible. In this case, the atmospheric neutrino result would imply a minimum cosmic density of neutrinos comparable with the cosmic density of stars!

4.3 Weakly interacting massive particles

A generic class of candidates for dark matter consists of particles that 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 [72, 73]. 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^0 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/c^2 mass range. In particular, the lightest supersymmetric particle could well constitute the dark matter. This class of particles is usually called Weakly Interacting Massive Particles (WIMPs). We review in the next section the experimental challenge to detect them.

5 WIMPs searches

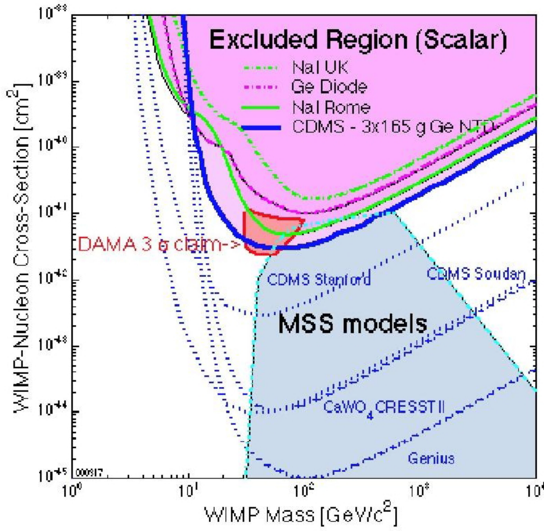

Figure 7: Currently achieved limits for spin-independent couplings as a function of the WIMP mass.

The most direct method to detect these WIMPs is by elastic scattering on a suitable target in the laboratory [74, 75, 76]. We devote most of this section to such "direct detection" methods before briefly commenting on indirect detection. In direct detection (elastic scattering) experiments, WIMPs are expected to produce a roughly exponential energy spectrum with a mean dependent on the WIMP and target nucleus masses. 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 which would lead to differential rates larger than observation.

5.1 Experimental challenges of direct detection of WIMPs

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 Fig. 7, as the lower hatched region, the range of cross sections (rescaled to a proton target) expected [77] 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 for low radioactivity background. They barely skirt the supersymmetric region, although relaxing the unification assumptions enlarges this region somewhat [78, 79]. Unfortunately, the expected rates can be very small for specific combinations of parameters where axial ("spin dependent") couplings dominate. In this case, the interaction couples to the spin of the nucleus, which limits the number of possible targets, and the current limits are very far above the supersymmetric region [77].

It is therefore essential to construct experiments in which radioactive backgrounds are kept very low or even actively rejected. The main tool for this purpose is the recognition of the nature of the recoil. 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. One also should be careful to distinguish between true and electron equivalent energy which may differ by a factor 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 [80], 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 the time of the year [81, 82].

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. If we except interesting attempts to use mica, which integrates for billions of years [83], and superheated microdots [84] which should be only sensitive to nuclear recoil, three main experimental strategies are being pursued.

Aggressive reduction of the radioactive background

A first approach is to attempt to decrease the radioactive background as much as possible. Germanium is the detector of choice because it is very pure. The first limits [85, 86, 87] were obtained by decreasing the threshold of double beta experiments. The most impressive results have been obtained by the Heidelberg-Moscow group [88] with a background of 0.05 events/kg/day/equivalent electron 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 [89] and Baksan-USC-PNL [90] collaborations have achieved slightly worse levels (0.25 events/kg/day/equivalent electron keV), but have reached lower thresholds. The current combined exclusion plot is given in Fig. 7. GENIUS [91], an ambitious proposal 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 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 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 [92].

Statistical rejection of the background

When the active background rejection is imperfect, one may use statistical arguments to distinguish between the signal and the background. Three main methods have been proposed:

1. **Multiple scattering events.** The WIMPs are so weakly interacting that they have an exceedingly low probability to interact. Thus, multiple interactions are signatures of photons, surface electrons, or neutrons. Incidentally, this method would be available to GENIUS.

2. **Pulse shape discrimination.** Scintillators tend to have slightly shorter pulses for high energy density deposition. Therefore, pulse shape could be used on a statistical basis to distinguish between electronic recoils and nuclear recoils.

3. **Annual modulation.** As explained above, the WIMP signal is expected to have a small annual modulation, while in a carefully controlled experiment, it may be possible to guarantee that the background remains stable.

Such techniques can be used with scintillators and, because this is a relatively simple technology, large masses can be assembled. The DAMA group [93] has installed 100 kg of sodium iodide in Gran Sasso, and the UK Dark Matter group [94, 95] has similar plans in Boubly. The most impressive (and somewhat surprising) result so far has been obtained by DAMA, which has published slightly better limits than those obtained with conventional germanium detectors.

Even more controversial is the claim by the DAMA of the observation [96, 2] of a nearly 4 σ yearly modulation over 4 years. This modulation of ± 2% appears to have the right period and the right phase (Fig. 8) and the team has so far not found any other explanation than a significant WIMP interaction rate. The corresponding WIMP scalar nucleon cross section is constrained to be at the 3 σ confidence level in the heart-shaped region of Fig. 7. However a number of questions remain so far unanswered:

1. Even before addressing the more difficult questions of behavior close to threshold and stability, there seems to be some incompatibility between the observations and the WIMP hypothesis. As indicated by the curve in Fig. 8, the global fit of the modulations and rates observed in each of the nine detectors and each of the energy bins is unable to reproduce the full modulation! It appears that either the energy dependence of the modulation or the low energy rate in some detectors (or both) do not allow one to raise the WIMP cross section enough to fully fit the modulation. Only half of the effect (± 1%) is accounted for! In order to understand the statistical significance of such incompatibility, it would be important to have access to both the individual detector rates and the unfitted modulation as a function of the energy.

2. The signal appears mainly in the lowest energy bins in a region of rapidly varying efficiency, and the resulting energy spectrum has surprisingly a dip at low energy instead of the peak expected on general grounds. The DAMA team has not yet published the original spectrum before they apply stringent cuts to distinguish scintillation signals from phototube noise and has not shown how their results change as a function of the applied threshold.

3. The most difficult aspect in a modulation experiment is to demonstrate the required stability which in this case should be better than ±0.25% if a 4 σ effect is claimed on the fitted value. A number of experimental effects could generate a summer/winter modulation at that level and the arguments presented so far do not fully address these concerns. It would be interesting for

instance to show that the events excluded by the noise cut or the multiple interactions do not display modulation.

Given the importance of such a result if it is correct, the scientific community is eagerly awaiting more details from the experimental team.

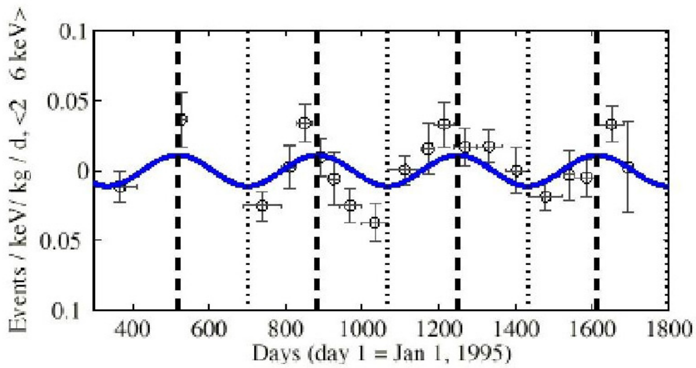

Figure 8: The DAMA modulation signal. The curve is the result of the global fit of modulation and rates shown in Table I of [2].

Active rejection of the background

More powerful discrimination methods need to be devised. 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, four large setups are currently being routinely operated—Milano [97], CDMS [98], CRESST [99], and EDELWEISS [100]—with total detector masses ranging from 70 g to 7 kg. For dark matter searches this technology appears to have three advantages:

1. There is a much lower threshold, because 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. The CRESST group has demonstrated a FWHM of 133 eV at 1.5 keV in a 262 g crystal of sapphire. CDMS is now routinely getting a resolution of better than 1 keV FWHM both in (thermal or athermal) phonons and in ionization with detectors of the order of 200 g.

2. With the simultaneous measurement of ionization and phonons in crystals of germanium or silicon [101, 102], it is possible to distinguish between nuclear recoils and electron recoils. This approach is used by both the CDMS

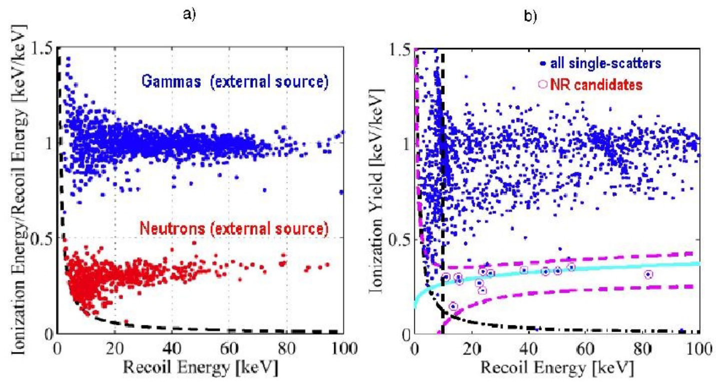

Figure 9: CDMS ionization yield as a function of full recoil energy: a) with radioactive sources, b) in the low background conditions of CDMS I.

and the EDELWEISS collaborations. Figure 9a demonstrates how the ionization yield (*i.e.*, the ratio of ionization to recoil energy, normalized to unity for gamma interactions) can be used to discriminate between electron recoils and nuclear recoils generated by radioactive sources. The CDMS team has demonstrated greater than 99% rejection of gamma interactions with thermal (and athermal phonon) plus ionization technology down to 10 keV recoil energy. In the first generation of ionization collection contacts used by CDMS, there was a significant surface dead layer due to back diffusion of the carriers to the contacts. For soft electrons incident on the surface, this led to ionization losses and a significant contamination of the nuclear recoil region. Replacing the implanted contacts by a larger-gap amorphous silicon contact, CDMS was able to completely circumvent this problem.

Figure 9b demonstrates the situation obtained in a low background environment [3]. In addition to the gamma band, one can identify an electron band at slightly lower ionization yield. Note that there is also a nuclear recoil band: 13 events for some 10.6 kg days! Is this a confirmation of the DAMA claim for a WIMP signal? Unfortunately, it is not, as 4 multiple events are observed in the same exposure. This clearly indicates that these events are neutrons, due to muon interaction in the rock at the shallow Stanford site currently used by CDMS. The team has a number of arguments supporting this conclusion, including the observation of 4 nuclear recoil events in a silicon detector exposed for 1.6 kg days. Subtracting this neutron contribution, CDMS gives the 90% confidence limit indicated in Fig. 7. For scalar interactions, this is incompatible with the DAMA modulation at more than 99% confidence level! Note that, because they are using different targets, the two experiments could in principle be both right. However, this would require WIMP interactions in strong disagreement with Minimal Supersymmetry. With athermal phonon technology and an internal neutron moderator, CDMS is hoping to improve its sensitivity at the Stanford site to the dashed line in Fig. 7. CDMS has recently been approved to install 10 kg of target with athermal phonon technology in the Soudan underground site. This should provide a factor 100 improvement with respect to the current exclusion limit.

An interesting development along the same line is the demonstration by the CRESST team of a photons + phonons discrimination scheme in $CaWO_4$. An excellent rejection of electron recoils, without detrimental surface effect, has been obtained for a 6 gram detector, and a reasonable photon collection has been achieved for a 300 g crystal (60% of that of the 6 g prototype). Installing 10kg of such detectors would yield a sensitivity similar to that of CDMS at Soudan (Fig. 7).

3. 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: CDMS has recently demonstrated that geometrical fiducial cuts can be imposed using the phonon information and that its problematic soft electrons could be eliminated by a phonon rise time cut [103]. 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 as the most promising technology to explore in the next few years a significant portion of the supersymmetric WIMP space.

   In addition to cryogenic detectors, we should mention two other discrimination techniques that also are promising, albeit with relatively high thresholds. Although these techniques may be simpler than cryogenic detectors, there has not been enough development so far to fully judge their real potential. Liquid xenon would allow the simultaneous measurement of scintillation and ionization, in particular, with amplification in a gas phase above the liquid. Low pressure time projection chambers should have excellent discrimination against electron recoils [104, 105, 106] and should give directionality information. However it is difficult to have large target masses, and the ratio of active to passive mass is worrisome from the point of view of radioactivity.

5.3 Indirect detection methods

Let us note finally that several methods have been proposed for detecting WIMPs through their annihilation products [75]. These methods 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 annihilation into two photons [107] 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 positrons offered tantalizing hints of dark matter particle annihilations [73], 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 [108, 109, 110, 111, 112] is to search for high energy neutrinos coming from the centers of the earth and the sun. Because dark matter particles can lose energy by elastic interactions, some of them would be captured by these objects, settle in their centers and annihilate with one. The annihilation would produce, among other products, high energy neutrinos which can then be detected in underground detectors, especially through the muons produced by their interactions in the rock. The current generation of detectors (Baksan, MACRO and Super-Kamiokande), with roughly 1000 m^2 area, put a limit of the order of 10^{-14} muon/cm^2/s 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 [113] show that such an advantage of direct detection should be maintained for the next generation of detectors (cryogenic WIMP searches versus 10^5 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 [114, 115].

6 Conclusions

In the past decade, astrophysicists have clearly confirmed the earlier indications that there is much more mass in the universe than we can see. There is increasing evidence that this dark matter is non-baryonic. In particular, in spite of the fundamental degeneracy between mass, velocity, and distance present in microlensing experiments, the recent results exclude that the halo is made of MACHOs. Rapid progress is made with the search for non-baryonic dark matter particles. Two axion experiments are underway which should give us a definite answer for axion masses over a mass range of one order of magnitude (out of three which are still allowed). Oscillation neutrino experiments are convincingly pointing to massive neutrinos. However, although atmospheric neutrino oscillation implies a minimum neutrino mass density in the universe similar to that of stars, the exact mass scale is as yet too poorly defined to establish their role in cosmology. The WIMPs search is very active with germanium setups of unprecedented radioactive purity, the installation of very large NaI scintillators, and the development of totally new cryogenic sensors providing excellent background discrimination. In spite of the fact that the claim by DAMA for a WIMP detection may be premature, current experiments are decisively entering the supersymmetric territory and a number of second generation experiments (CDMS II, CRESST II, and GENIUS) will explore a significant amount of the parameter space. Through the combination of all these efforts, we may soon be able to solve a central puzzle of cosmology and astrophysics.

At the same time, with the evidence for an accelerating universe, we may be establishing that the equation of state of the dark component is more complex than we thought. The dark energy density is apparently similar in magnitude to that of dark matter, baryons, and even neutrinos. This fine tuning of parameters may imply, as the Ptolemaic epicycles did, that we are lacking a deep enough understanding of fundamental physics. The direct detection of dark matter, the observational confirmation of the acceleration of the universe and the experimental investigation of gravity are exciting goals that may well lead to a fundamental revision of the conceptual framework of particle physics and gravity!

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Discussion

David Saxon (University of Glasgow): Could you comment on the prospects for liquid xenon detectors?

Sadoulet: As I said in my talk, the recognition of nuclear recoils in liquid xenon through the simultaneous use of scintillation and ionization is a promising method. It is currently being pursued by the UK dark matter group and at UCLA. However, my personal feeling is that not enough development work has be performed so far to judge the full potential of this technology.

Wim de Boer (University of Karlsruhe): Could you explain again what is the problem with mixed dark matter?

Sadoulet: The original motivation of the mixed dark matter models was to fit the power spectrum of the large-scale structure (Fig. 3) by combining the cold dark matter and neutrino predictions. And, indeed, a good fit could be achieved and a number of interesting features were reproduced. The main problem with this approach is that galaxies are forming too late compared to observations: It is incompatible with the star formation history and the red shift dependence of Lyman alpha clouds. This is serious enough for the main proponents of the mixed dark matter model to have stopped working on it!

Anthony Mann (Tufts University): Any attempt to detect WIMPs by annual modulation in the Northern Hemisphere is looking for trouble, since the radon level tends to be higher in the summer than in the winter. Could you comment on this effect?

Sadoulet: The DAMA team is well aware of this problem and has been specifically looking for that effect. They have not seen any correlation with the proper phase. However there could be lags! More generally, they are performing a very difficult experiment. In order to be able to assert the existence of a one percent modulation effect, it is necessary to control systematics to better than a fraction of a percent and we all know that this is very challenging. A number of spurious effects can lead to such a weak modulation. DAMA has not yet provided the community with complete enough information for it to be convinced. In particular it would be nice to see the stability very close to threshold of the detection efficiency measured over the whole crystals.