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DARK MATTER PARTICLE CANDIDATES *

Graciela B. GELMINI

Department of Physics, University of California, Los Angeles, CA 90024

1. INTRODUCTION

Dark matter (D.M.) is the most abundant form of matter in the universe. Its density in units of the critical density, $\Omega_{D.M.}$, is known to be between 0.2 and 1 while the luminous regions in the universe account only for a fraction $\Omega_{\rm Lum.} \simeq 0.01$ of the critical density. The first requisite a D.M. particle candidate must fulfill is, therefore, to have at present a cosmological density in the range of $\Omega_{\rm D.M.}$. From the point of view of elementary particle physics there are some obvious ways to get $\Omega_{D.M.}$. The most obvious ones are to make nine out of ten baryons to end up in dark baryonic matter forms, to give specific masses to the light known neutrinos and to add neutral stable heavy particles with interactions of the weak order to the standard model. The bounds imposed by early universe nucleosynthesis on the total amount of baryonic matter, make it very difficult to have much more than $\Omega \simeq 0.1$ in baryonic matter [1]. To give the right mass to the light neutrinos seems easier. The present relic abundance in number of the three neutrino species of the standard model is fixed by their thermal history. Thus, non-relativistic standard neutrinos may have $\Omega_\nu \simeq 1$ only if the sum of the masses of all three neutrinos is of the order of 10 eV [2]. Baryons and light neutrinos are the only D.M. candidates known to exist, any other candidate is hypothetical. WIMP's (weakly interacting massive particles) are the next obvious choice. Heavy stable particles with masses in the range GeV - TeV and interactions of the weak order, have $\Omega \simeq 1$ [3]. This is an amazing coincidence, if nothing more, that allows for many extensions of the standard model to have "natural" D.M. candidates. Still another obvious way to get $\Omega_{D.M.}$ is to choose the right asymmetry in number in the early universe of candidates with a thermal history similar to that of baryons. The existence of an asymmetry ΔB of order 10^{-9} between baryons and antibaryons in the early universe is essential to get the present amount of nucleons. Without it baryons would account now for only $\Omega_B \simeq 10^{-11}$. With an asymmetry, many of the baryons cannot annihilate because of the lack of antibaryons. An asymmetry in number is defined as $\Delta = (n - \bar{n})/(n + \bar{n})$, where n and $\bar{n}$ are the number density of particles and antiparticles respectively. Let us assume a particle X, carrying a new conserved quantum number has an asymmetry ΔX the early universe comparable with that of baryons, $\Delta X \simeq \Delta B$. Then the present relic number density of X particles would be similar to that of baryons, $n_X \simeq n_B$. Therefore, the ratio of densities would be given by the ratio of masses $\Omega_X/\Omega_B = m_X/m_B$ and if $m_X \simeq 10 - 100\ m_B$, X would be a good D.M. candidate [4].

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Particle physics offers still other "well motivated" D.M. candidates whose density may easily account for $\Omega_{D.M.}$, even if in principle its value is arbitrary. By "well motivated" one understands that there are good reasons to proposed the existence of these particles, quite independently of the D. M. problem. Examples of these candidates are axions [5], associated to the solution of the strong CP problem, and particles in the "hidden sector" of supergravity or string models. These particles are "hidden" because, in principle, they interact only gravitationally with ordinary matter. This is the case of the gravitino in supergravity [6] models or of the "shadow matter" [7]. However, in some models those "hidden" particles may share some of the ordinary quantum numbers, such as in the case of "cryptons" [8].

Notice that "obvious" or "well motivated" or "natural" are tricky concepts when applied to D.M. candidates. How "well motivated" would protons and neutrons be if we did not know them? In order to account for the present density of baryons a particular asymmetry ΔB is needed, as mentioned above. In order to generate this ΔB in the early universe one has to assume baryon number B and C and CP violation (C is charge conjugation and P is parity) in processes out of equilibrium [9]. Still part or all of this ΔB may be erased before the electroweak phase transition [10] so that a very late generation of ΔB may be necessary. Thus, most proposed D.M. candidates are "more natural" than protons and neutrons! It may well be that Nature's mechanism to generate the D.M. is more sophisticated than the obvious ones we are trying now as a humble first approach to the problem.

This review concentrates in a few of the most obvious candidates: dark baryons, light neutrinos and, in particular, WIMP's. WIMP's are the candidates that direct and indirect dark matter searches are testing. Recent limits obtained at LEP have eliminated several of the WIMP candidates, but many remain, and several of them could soon be found or rejected in improved D.M. searches (for example, with a factor of improvement of one hundred in present experimental limits).

2. DARK BARYONS

The standard nucleosynthesis calculations seem to imply that some baryons must be dark and that as much as $\Omega_{\rm D.M.} \simeq 0.1$ could be accounted for by baryonic matter in non-shining condensed objects [1]. This amount of D.M. is enough to constitute all the dark haloes of galaxies, but not to account for the D.M. at larger scales. The baryonic condensed dark objects may be brown dwarfs or black holes or non-topological solitons, even if there is no hint of how they may have been formed and evolved. To account for $\Omega_{\rm D.M.} \simeq 1$, or any value much larger than 0.1, in dark baryons is difficult. It requires evading the standard nucleosynthesis bound. Moreover, the larger the density in dark baryons, the more difficult it becomes to "hide" those baryons. Modifications of the standard picture of nucleosynthesis, such as baryon inhomogeneities generated at the QCD phase transition [11] and a second late epoch of nucleosynthesis (due to late decaying particles [12] or black hole evaporation [13]) do not seem to provide viable scenarios where a large density (larger than 0.2) in baryonic matter can be obtained. Without modifying Ω_B during nucleosynthesys

An interesting idea is to increase Ω_B after nucleosynthesis. A mechanism recently proposed [14] increases the relic density of all decoupled species by decreasing the number of photons per comoving volume. This is obtained by decreasing the temperature of the photons. Because the number of baryons (or any other decoupled relics) per photon increases, given the

present measured density of photons in the universe the resulting present density in baryons is higher. The temperature of the photons is lowered when they enter into thermal contact with a plasma of cooler "shadow particles". These are particles belonging to a "hidden sector" that resembles the ordinary sector in some regards. They do not interact with ordinary particles until a time, after nucleosynthesis, when a mixing develops between the photons of both sectors. This mechanism is an example of how exotic the ideas that have to be invoked to obtain $\Omega_B \simeq 1$ may be.

3. MASSIVE NEUTRINOS

The relic abundance of particles that were in equilibrium in the early universe can be reliably computed. Particles are in equilibrium when their interaction rate is larger than the expansion rate of the universe. At the moment of freeze out (or decoupling) and thereafter, the interaction rate becomes smaller than the expansion rate, interactions stop and the number of particles per comoving volume remains constant. The light standard left handed neutrinos are relativistic when they freeze out, at a temperature of a few MeV. After that the number of photons increases, due to the annihilation of electrons and positrons. The final number of left handed neutrinos, with g_ν=2 helicity states, of a given flavour is $n_{\nu_i} = (3/11)n_\gamma \simeq 114/cm^3$ [2, 3]. If these neutrinos are nonrelativistic at present, with masses m_{ν_i}, the present neutrino energy density is $\rho_\nu = \Omega_\nu \rho_c$, where ρ_c is the critical density $\rho_c = h^2 10.5\ keV/cm^3$ and h is the Hubble constant in units of 100 Km/Mpc sec., a number between 0.4 and 1. Thus,

$$\sum_i m_{\nu_i}(g_\nu/2) = 96\ eV \Omega_\nu h^2 \qquad (1)$$

where the sum runs over all neutrinos lighter than 1 MeV with full weak interactions (and no additional exotic interactions). The lower bound of $t_U > 1.\ 10^{10} y$ for the age of the universe requires that $\Omega_\nu h^2 < 0.3$ [15]. Only three neutrino species (actually 2.99 ± 0.05) are seen at LEP, in the decays of the Z^0 boson [16]. There could be more neutrinos only if they do not have full weak interactions or if they are heavier than half of the Z^0 boson mass, approximately 45 GeV. The experimental bounds on the neutrino masses are 9 eV, 250 KeV and 35 MeV for ν_e, ν_μ and ν_τ respectively [17]. Thus any of them may be cosmologically relevant. There may already be indications of non zero neutrino masses from solar neutrino observations made by the Homestake and Kamiokande experiments and preliminary by the SAGE experiment. Plausible and appealing particle models, such as the M.S.W. (Mikheyev-Smirnov-Wolfenstein) mechanism of matter enhanced neutrino oscillations, may explain the data. The M.S.W. solution, combined with the "see-saw" mechanism for neutrino mass generation, may favour the mass ranges $10^{-7} eV$, $10^{-3} eV$ and $100 eV$ for ν_e, ν_μ and ν_τ respectively, indicating ν_τ as a good D.M. candidate [18]. These exciting possibility may be confirmed or rejected within a few years.

Some recently proposed neutrino models for the D.M. do not seem to be viable. Sciama [19] revived recently the idea already proposed in 1980 [20] that a neutrino with a mass of 28 eV decaying into another lighter neutrino and a photon with a lifetime of 1.5 10^{23} sec. could explain the ionization of the galactic and intergalactic hydrogen. This lifetime is too short for most models of neutrino decay. However, suitable supersymmetric models with broken R-parity have been produced [21]. The problem with this candidate is that the monochromatic line expected at 14 eV has not been seen in the spectrum of a cluster (the Abell cluster A665) studied by the ASTRO-1 satellite [22]. Even if the absence of a line may be explained by absorb-

tion by intervening matter, this observational negative result makes the model dubious, if not rejected.

In 1985 Simpson claimed to have found indications for the existence of a neutrino of 17 KeV of mass [23]. Recent experiments supporting his claim have renewed an intense interest in this neutrino. Could it be the D.M.? The answer is provided again by the non-observation of a monochromatic line, this time at 8.5 KeV and coming from the D.M. halo of our galaxy. The standard model implies the decay of a 17 keV neutrino into a lighter neutrino and a photon with a lifetime of the order of 10^{24} sec. [24]. Let us assume that Simpson's neutrino constitutes a fraction f of the D.M. in the halo of our galaxy. The limit of the cosmic x-ray experiment A2 on the HEAO -1 mission against the existence of a line at 8.5 KeV imply that $f < 10^{-5}$ [25]. Thus, even if the Simpson neutrino exists it plays an insignificant role as D.M..

Giudice [26] has proposed a τ-neutrino with mass of a few MeV and a large magnetic moment, $\mu_{\nu_\tau} \simeq 10^{-6}\mu_B$ (μ_B is the Born magneton), as a D.M. candidate. This neutrino would have an annihilation cross section much larger than weak, due to electromagnetic interactions, and a consequent lower relic density that depends on the value of the magnetic moment. A reanalysis of old beam dump data has produced an upper bound $\mu_{\nu_\tau} < 5.6\ 10^{-7}$ that marginally rejects this candidate [27]. Rare meson decays may improve this bound [28].

4. HEAVY NEUTRAL RELICS

These are particles that, contrary to the case of light neutrinos, become non relativistic while in equilibrium in the early universe, before their freeze out. Their relic abundance depends on their interactions, mass and asymmetry in number, and on the entropy change (i.e. the change in the number of photons per comoving volume) after their freeze out [3, 29]. Only neutral weakly interacting particles, i.e. WIMP's, are good D. M. candidates. It has become clear, from the combined results of many different analyses of the issue, that neither charged particles [30] nor strongly interacting particles [31] are viable D.M. candidates.

For WIMP's with no cosmic asymmetry and if there is no change of entropy after their freeze out, the relic density Ω turns out to be

$$\Omega h^2 \simeq 1 \cdot 10^{-37} cm^2 < \sigma_a v >^{-1} \qquad (2)$$

where $< \sigma_a v >$ is the thermal average of the annihilation cross section by the relative velocity of the WIMP's [3]. Using order of magnitude and dimensional arguments on the annihilation cross section, it is easy to obtain the dependence of the density on the mass, and the range of masses for which WIMP's could have the abundance adequate to be D.M. candidates. For non-relativistic particles lighter than the Z and W weak gauge bosons (or other exchanged particles of similar mass), the annihilation cross section is roughly $\sigma_a \simeq G_F^2 m^2 N_a$. Here G_F is the Fermi coupling constant, m is the mass of the WIMP, and N_a is the number of annihilation channels. Thus,
$\sigma_a \simeq 0.4 N_a 10^{-37} cm^2 (m/1\ GeV)^2$ and

$$\Omega h^2 \simeq 0(1-10)(m/1\ GeV)^{-2} \qquad (3)$$

the density decreases with increasing mass. WIMP's with these interactions must have masses of the order of 1 to 100 GeV to account for $\Omega_{D.M.}$. WIMP's much heavier than the weak gauge bosons (or any other exchanged particles) have "electromagnetic like" cross sections (since the mass of the exchanged particle can be neglected). Thus,
$\sigma_a \simeq \alpha^2 N_a/m^2 \simeq 0.2 N_a 10^{-37} cm^2 (m/1\ TeV)^{-2}$, with

α the electromagnetic coupling constant. Therefore,

$$\Omega h^2 \simeq 0(1-10)(m/1TeV)^2 \qquad (4)$$

the density increases with increasing mass. D.M. candidates with these interactions must have masses or order of 1 to 100 TeV.

For $m > 300\ TeV$, entropy generation after the freeze out becomes necessary. Usually one partial wave σ_J, corresponding to one value of the angular momentum $J = 0, 1 \cdots$, dominates the annihilation cross section. Partial wave unitarity imposes $\sigma_a v \simeq \sigma_J\ v < 10^{-32} cm^2 (2J+1)(TeV/m)^2$ what in turn means $\Omega > 10^{-5}(m/TeV)^2$. Thus for $m > 300\ TeV$ the relic density would be unacceptably large, $\Omega > 1$, unless the relic number of particles is diluted after freeze out [32]. Any mechanism that effectively increases the number of particles in equilibrium per comoving volume, decreases the number of non-interacting particles per photon. Thus, given the present density of photons, the present density of heavy particles decreases. The effect of an asymmetry between the number of heavy particles and antiparticles is the opposite. It increases the density of the most abundant of the two, the majoritary component, since those particles in excess cannot annihilate. The larger the asymmetry, the larger is the relic abundance of the majoritary component. Both, asymmetries and entropy increase, affect the density values stated above. Thus, when they are incorporated in a model, D.M. candidates may have practically any mass (up to the Planck mass).

Recent results from LEP combined with other bounds on D.M., have rejected several of the neutral WIMP D.M. candidates proposed up to now [33]. Even if many old candidates remain viable, the negative results have, in turn, provided the motivation for a new generation of D.M. candidates compatible with the LEP results and, in several cases, detectable in future experiments.

Heavy Dirac neutrinos have been rejected by the combination of LEP results and bounds from direct D.M. searches with Ge-spectrometers. Heavy Majorana neutrinos are forced by LEP bounds to be too heavy to have a non-negligible relic abundance. This abundance cannot be increased by an asymmetry since particles and antiparticles coincide. "Cosmions" are the D.M. candidates that were proposed to solve simultaneously the solar neutrino problem, by improving the heat conduction in the core of the sun, with the result of lowering its central temperatures [34]. Most candidates for cosmions have been rejected by direct searches with Ge and Si spectrometers [35], but some particular candidates have been eliminated by LEP. Only cosmions with spin- dependent interactions with nuclei are still allowed. Giudice and Raby [36] have produced a model for cosmions of this type. This model shows the difficulty to account for such cosmions, and its only appeal is to be still allowed. New helioseismological analysis provide further arguments against cosmions [37].

One of the preferred D.M. candidates is still the LSP, the lightest supersymmetric particle, in supersymmetric models where the conservation of a particular quantum number, usually the R-parity, insures the stability of the LSP. Sneutrinos, the supersymmetric partners of the neutrinos, may be the LSP in some models, but they have been rejected by LEP and bounds from direct as well as indirect searches. The gravitino, the supersymmetric partners of the graviton, cannot be excluded as the LSP, but it is essentially undetectable in searches, since it have only gravitational interactions with ordinary matter [6]. The lightest neutralino, i. e. the lightest supersymmetric partner of the neutral bosons, to which the last section of this review

is dedicated, either lighter or heavier that the weak gauge bosons is still alive as a D.M. candidate, even if LEP has reduced the allowed regions in the parameter space of many models.

Some recent extensions of the standard model provide D.M. candidates that evade the LEP bounds. One type of models proposes the existence of an additional neutrino N that is not coupled to the Z^0 and, therefore, is not produced at LEP. This neutrino has a gauge invariant mass term in the lagrangian, $M\bar{N}N$, thus its mass is not generated in a Higgs mechanism, and a new lepton number L_N. There are two particular models, one with $M \simeq 1\ TeV$ [38] and the other with $M \simeq 30 - 80\ GeV$ [39]. Another model proposes the addition of a new $U(1)'$ symmetry group, with a new gauge vector known Z' that mediates the interactions of a new fermion, the D.M. candidate, with baryons and leptons [40]. This candidate can be immediately tested in direct searches. It is most likely to be observed for the mass ranges of 10 GeV to 100 GeV or 400 GeV to 40 TeV.

One of the most important properties of WIMP's as D.M. candidates is that many of them may be tested in direct or indirect D.M. searches designed to detect D.M. particles in the halo of our galaxy. Direct searches look for the energy deposited by a halo D.M. particle in a collision with a nucleus within a detector [41, 42]. Existing detectors look for ionization in Ge or Si crystals, and the background rate is of the order of 1 (event/keV Kg day) [43]. Future cryogenic detectors, bolometers or detectors of both ionization and phonons, may reach a background rate of the order of 10^{-2}(events/ KeV Kg day) [42]. Indirect searches [44, 42] look for the products of the annihilation of the D.M. candidates. The best results come from the search for neutrinos above the atmospheric background,coming from the sun or the earth. They would be produced in the annihilation of halo D.M. particles trapped in the sun and the earth. These neutrinos could be seen as contained events or through going muons in proton decay detectors, such as IBM, Kamiokande and Frejus, or in future neutrino observatories. For D.M. candidates with $m < 100\ GeV$ the best bounds come from the search for neutrinos from the earth. This is because the annihilation rate in the sun and earth equals the capture rate and this is enhanced when the halo particles have a mass close to that of the heavy nuclei present in the earth, in particular F_e nuclei. When this happens the halo particle energy loss in a collision with the particular nucleus may be large and, consequently, the capture of the D.M. particle in the earth is more efficient than the capture in the sun [45]. Heavy particles are trapped within a small core in the earth of radius $r \simeq 0.12R_e(20GeV/m)^{1/2}$ [45],thus the bounds have been recently improved by more than one order of magnitude, by the analysis of the angular dependence of muons from the earth seen by Kamiokande [46] (R_e above is the radius of the earth). For heavier WIMP's, because the capture in the earth is not kinematically enhanced, the capture in the sun turns out to be more efficient than in the earth.

The search for very high energy neutrinos has yielded good bounds on very heavy unstable relic, such as neutralinos in models with broken R-parity or cryptons [47], that may be part of the D.M. for lifetimes longer than the age of the universe.

The annihilation of D.M. particles in the dark halo of our galaxy may provide a signature of charged particles, such as positrons or antiprotons, or photons in cosmic rays. Due to the uncertainties in the propagation of cosmic rays, these indirect detection methods has not yielded any useful constraints on D.M. so far [48].

However, it is not excluded that a distinctive signature may originate from specific channels of annihilation, as the one recently suggested of heavy neutralinos annihilating into a pair of W bosons that decay into electron-positron pairs [49].

5. THE LIGHTEST NEUTRALINO

It is still one of the theoretically better motivated D.M. candidates. The lightest neutralino, either light or heavy as compared with the weak gauge bosons is still good D.M. candidate. Its phenomenology has been studied in detail not only in the M.S.S.M. (Minimal Supersymmetric Standard Model) but also in some M.N. M.S.S.M. (Minimally Non-Minimal Supersymmetric Standard Models). Non-minimal models modify one or more of the several assumptions incorporated in the minimal model. The M.S.S.M. [50] is the simplest phenomenologically acceptable supersymmetric version of the standard model. The model has $N = 1$ supergravity spontaneously broken at a large scale, close to the Planck scale M_P by a "super Higgs" or "hidden" sector, itself a potential source of D.M. candidates with only gravitational interactions. At lower energy scales (in the limit $M_P \rightarrow \infty$, with the gravitino and gaugino masses, $m_{3/2}$ and $m1/2$, fixed), what remains is a theory with supersymmetry broken explicitly by soft breaking terms, in which all supersymmetric partners are heavier than the known particles. The mass of the supersymmetric partners cannot be higher than a few TeV, if supersymmetry is to provide the solution to the gauge hierarchy problem, i. e. to explain that radiative corrections to the masses of Higgs fields are not much larger than the Fermi scale, 100 GeV.

The M.S.S.M. has several additional defining properties [50]. At the TeV energy scale the symmetry group is that of the standard model, $SU(3) \times SU(2) \times U(1)$ (models with additional symmetries, such as an extra $U(1)$ for example, are non minimal) There are no new matter fields besides the standard quarks and leptons and their corresponding supersymmetric partners, the sleptons and squarks. The Higgs sector contains just two doublets H_1, and H_2, the first coupled to the down fermions and the second coupled to the up ones (therefore there are three neutral and two charged physical Higgs bosons in the model, after the electroweak symmetry breaking; models with more Higgs fields are non minimal). The values of the constants appearing in the Lagrangian depend on the "hidden sector". The usual assumptions leave only five parameters at the scale of Grand Unification in addition to those of the standard model. They are m_0, a common mass for the scalars, $m_{1/2}$, a common mass for the gauginos (the partners of the gauge bosons), μ, a supersymmetric mass term for the Higgs fields, and two adimentional parameters, A and B. Many times there is a further reduction of the number of parameters. Two of the most used choices are either $B = A - 1$, an older choice [50], or $m_{1/2}^2 >> m_0^2$, $A_0^2 \simeq 0$ and $B_0^2 \simeq 0$, a "string inspired" choice [51]. The theory has to be scaled down from the GUT scale to low energies, according to the renormalization group equations. Through radiative corrections the Higgs masses become negative, thus the Higgs fields develop non-zero vacuum expectation values $< H_1 >= v_1$ and $< H_2 >= v_2$. A correct spontaneous breaking of the standard model implies two minimization conditions that reduce the five parameters mentioned above to just three independent parameters. They can be chosen to be a gaugino mass M_2, the Higgs mass parameter μ and the mass of the lightest scalar Higgs field, m_h. M_1, M_2 and M_3 are the masses of the three gauginos, the supersymmetric partners of the $U(1)$, $SU(2)$ and $SU(3)$ gauge bosons respectively. The gaugino masses, assumed in

the M.S.S.M. to be all identical to $m_{1/2}$ at the GUT scale, get renormalized to

$$M_3 = (\alpha_s/\alpha)\sin^2\theta_w M_2 = (3\alpha_s/5\alpha)\cos^2\theta_w M_1 \quad (5)$$

i.e. $M_3 \simeq 4M_2 \simeq 8M_1$, at the weak scale ($\alpha_s$ is the strong coupling constant, α the electromagnetic coupling constant, and θ_w is the weak mixing angle).

It is the assumption of equal gaugino masses at the GUT scale, that allows to translate the CDF lower bound on the gluino mass M_3, into a lower bound of $10 - 20$ GeV for the lightest neutralino mass, since this mass depends on M_1, and M_2. Not making this assumption leads to a non-minimal model [52] where the neutralino may be lighter than 10 GeV.

Another well studied non-minimal model provides a neutralino, called $\tilde{D}$, that in the mass range of 5 to 20 GeV has a cosmological density close to critical [53]. The model is non-minimal because it contains an additional singlet Higgs field, besides the two doublet H_1 and H_2 of the M.S.S.M. [54]. The $\tilde{D}$ field is a linear combination of five neutralinos, two neutral gauginos and three neutral Higgsinos (instead of the two gauginos and two Higgsinos of the M.S.S.M.). The rates for elastic scattering of $\tilde{D}$ neutralinos constituting the galactic halo would be from 0.1 to a few per (Kg day) in proposed cryogenic detectors, well within the range of their discovery limits.

The best studied neutralino is that of the M.S.S.M. It remains a good D.M. candidate whose existence in the halo may be tested in the near future in both direct and indirect searches, in some regions of the parameter space of the model. These regions are usually shown in a $\mu - M_2$ plane for given values of v_2/v_1 and other determining parameters.

Several recent studies have been made of the combined bounds imposed on neutralinos lighter than the W boson, by LEP and direct and indirect D.M. searches taking into account the relic density of neutralinos [55 - 57]. For these "light" neutralinos the mass m_h of the lightest physical scalar Higgs field is very important. The exchange of this field induces spin independent coherent interactions with nuclei, that dominate the scattering of neutralinos with nuclei within a detector (in direct D.M. searches) or the scattering with heavy nuclei in the earth (in indirect D.M. searches). For a heavy top, 100 GeV or more, there are important radiative corrections to the mass of the lightest scalar Higgs, that have been taken into account only very recently [58]. Different evaluations of the Higgs-nucleon coupling provide an estimate of the theoretical uncertainties involved in them. A new evaluation [59] yields cross sections lower by factors close to three [57,58] than previous ones [60]. These evaluations include the contribution of the sea of strange quarks in the nucleon, that had been neglected at first [61] and increases by itself the cross sections by at least a factor of three [55].

Unless a very odd origin of the neutralino relic density, such as a late decay of gravitinos, for example, is invoked, the relic density of neutralinos is determined by the same parameters ($M_2, \mu, v_2/v_1, m_h$, etc) that determine the experimental bounds. Neutralinos with $\Omega h^2 < 0.05$ cannot account for the whole dark halo of our galaxy. If the halo consist of cold D.M., it is reasonable to expect that the cosmological fraction of neutralinos will be maintained in the halo, and this fraction could not be larger than $\Omega h^2/0.05$.

The figures 1 and 2 show some of the results of Bottino et al. [57], where all the new elements mentioned above were incorporated. These figures show present bounds, and future discovery regions with a realizable factor of improvement in present direct and indirect D.M. searches. Thus, the goodness of both searching

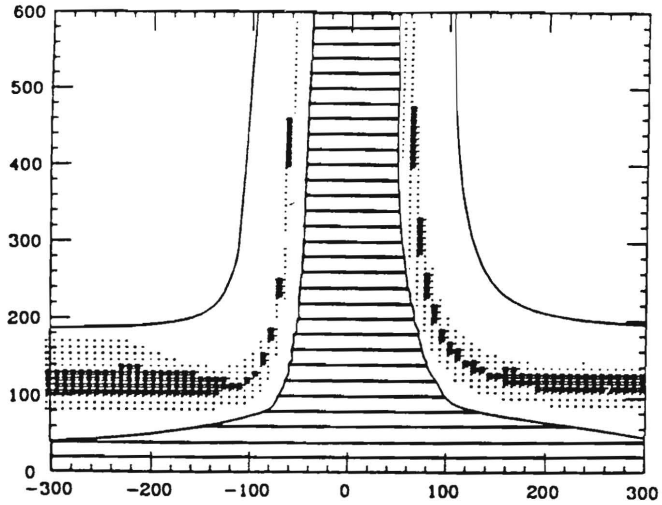

FIGURE 1.a

Fig. 3.a of Ref. [27].Vertical axis: M_2 (GeV); horizontal axis:μ (GeV); parameters: $(v_2/v_1) = 8$,$m_h = 50$ GeV, $m_{top} = 100$ GeV, $m_{stop} = 1$ TeV, with density rescaled. Higgs - nucleon coupling from Ref. [60]. Indirect searches (up-going muons).

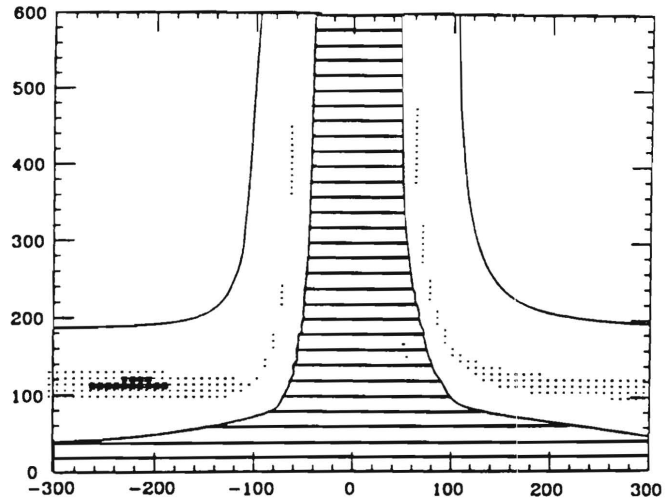

FIGURE 1.b

Fig. 3.b of Ref. [27]. Same axes and parameters as in 1.a. Higgs - nucleon coupling from Ref. [59]. Indirect searches (up-going muons).

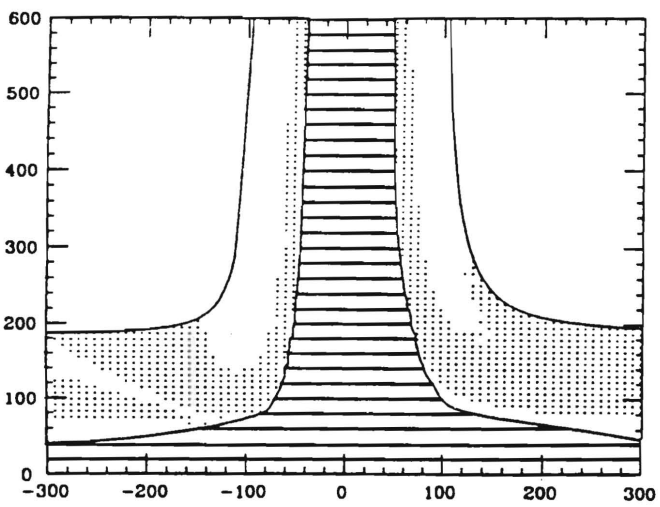

FIGURE 2.a

Fig. 4.a of Ref. [27]. Same axes and parameters as in 1.a. Higgs - nucleon coupling from Ref. [60]. Direct search (Ge- spectrometer) with a factor 10 of improvement over the present sensitivity.

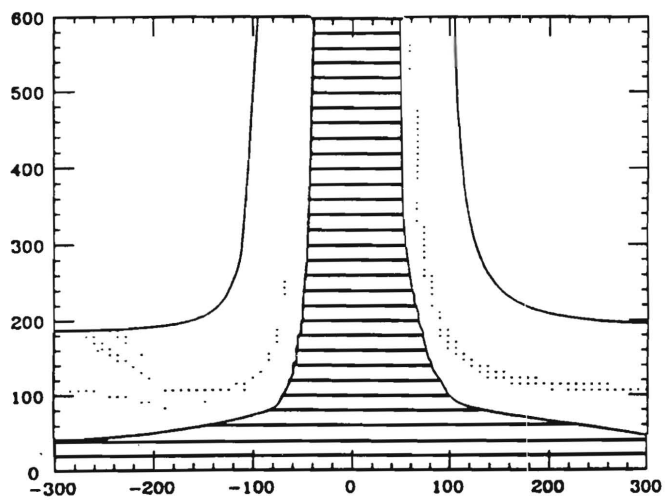

FIGURE 2.b

Fig. 4.b of Ref. [27] Same axes and parameters as in 1.a. Higgs - nucleon coupling from Ref. [59]. Direct search (Ge- spectrometer) with a factor 10 of improvement over the present sensitivity.

methods can be compared. Both figures show areas in a $M_2 - \mu$ parameter space with $v_2/v_1 = 8$, 50 GeV for the mass of the lightest scalar Higgs field and radiative corrections with $m_{\rm top} = 100$ GeV and $m_{\rm stop} = 1$ TeV.

The local neutralino density is rescaled according to the factor $\Omega h^2/0.05$, wherever $\Omega h^2 < 0.05$. The horizontally hatched regions are excluded by LEP and the regions above the solid line on both sides correspond

to neutralinos heavier than the W boson mass, not considered in this analysis. The figures 1.a and 1.b refer to the indirect searches through up-going muons in proton decay detectors. Muon neutrinos produced in the annihilations of neutralinos trapped in the earth would interact in the rock surrounding the proton decay detectors. The regions denoted by stars are excluded (at 95% c.l.) by the experimental results of Kamiokande, recently improved by the analysis of the angular dependence of the expected signal [46]. The dotted regions show the discovery area with a factor of improvement of about 300 in the signal. This factor corresponds to a $4-\sigma$ effect in a neutrino telescope of the size $10^5 m^2$ in two years (with a muon threshold energy of 2 GeV). The figures 2.a and 2.b refer to direct searches with a Ge - spectrometer. No bounds are obtained at present but a detector with a sensitivity improved by a factor of 10 could see a signal in the dotted regions. In both cases, the figures a and b use, the previous [60] and the new [59] evaluation of the Higgs - nucleon coupling strength respectively.

The elastic scattering rates of light neutralinos in proposed cryogenic detectors has been reanalysed recently by Ellis and Flores [62], for different parameters in the M.S.S.M. that give a critical relic densities of neutralinos at present. They found interesting rates for neutralino masses in the range 20 to 60 GeV.

Neutralinos heavier than the W boson in the M.S.S.M. can also be good D. M. candidates for masses not larger than 3.2 TeV, heavier neutralinos would be too abundant to be acceptable [63]. Those heavy neutralinos are almost purely bino (the supersymmetric partner of the $U(1)$ gauge boson) or almost purely Higssino for most (M_2, μ) values, for $M_2 < \mu$ and $M_2 > \mu$ respectively. The heavy neutralinos are a Higgsino/gaugino combination only for $M_2 \simeq \mu$.

The neutrino signal from annihilation of these heavy WIMP's in the sun are stronger than that for annihilations in the earth, as mentioned above. Neutralinos that are either nearly pure Higgsino or a Higgsino/gaugino admixture are generally captured in the sun by coherent scattering off nuclei due to the exchange of the lightest scalar Higgs field. Neutralinos that are nearly pure gaugino are captured mainly due to spin dependent scattering off hydrogen in the sun, due to the exchange of squarks. Kamionkowski [64] found that in some regions of the (M_2, μ) plane, mainly around $M_2 \simeq \mu$, the neutralino is excluded as the primary component of the dark halo of our galaxy by the current IMB limits on the flux of upwards-going neutrino induced muons from the sun. He analysed also the discovery regions with factors 10 and 100 of improvements in the IMB experimental limits on muons. Notice that no reduction of the signal was considered when the computed relic abundance was too low to account for the haloes of galaxies, what requires non standard scenarios to increase (or decreased) the relic abundance to the desired value.

5. CONCLUDING REMARKS

The main conclusion regarding underground experiments is that, even after LEP, there are many WIMP D.M. candidates to be found or rejected with the improvements expected soon in D.M. searches techniques. Some "old" candidates, such as the lightest neutralino of the Minimal Supersymmetric extension of the Standard Model, will still be tested by D.M. searches in large interesting regions of the parameter space of the model. Also "new" candidates have been proposed, inspired by previously rejected models, such as Non Minimal Supersymmetric extensions of the Standard Model or heavy neutrinos not coupled to the Z-boson. One can forsee a cycle of rejected candidates leading to

the proposal of new particle candidates for the D.M. The challenge to experimental physicists is to finish the cycle by detecting particles in the dark halo of our galaxy and thereby uncover one of the major mysteries of modern science.

REFERENCES

[1] D. Schramm, these proceedings and references therein.

[2] R. Cowsik and J. McClelland, Phys. Lett. 29 (1972) 669 (however they used $g_\nu = 4$).

[3] E. Kolb and M. Turner, the Early Universe (Addison-Wesley, Reading MA 1990) and references therein.

[4] S. Nussinov, Phys. Lett. B165 (1985) 55 and Phys. Lett. B 179 (1986) 103; S. M. Barr, R. S. Chivukula and E. Fahri; Phys. Lett. B 241 (1990); 387; S. M. Barr, Phys. Rev. D 44 (1991) 3062.

[5] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38 (1977) 1440; F. Wilczek, Phys. Rev. Lett. 40 (1978) 279; S. Weinberg, Phys. Rev. Lett. 48 (1978) 223; for reviews see M. Turner, Phys. Rep 197 (1990) 67 and G. Raffelt, ibid. 198 (1990) 1.

[6] For example J. Frieman and G. F. Giudice, Phys. Lett. B 224 (1989) 125.

[7] E. W. Kolb, D. Seckel and M. S. Turner, Nature 314 (1985) 415.

[8] J. Ellis, J. L. Lopez and D. V. Nanopoulos, Phys. Lett. B247 (1990) 257.

[9] A. D. Sakharov, JETP Letters 5 (1967) 24.

[10] V. Kuzmin, V. Rubakov and M. Shaposhnikov, Phys. Lett. B 155 (1985) 36.

[11] J. Applegate, C. Hogan and R. Scherrer; Phys. Rev. D 35(1987) 1151; C. Alcock, G. Fuller and G. Mathews, Ap. J. 320 (1987) 439; W. A. Fowler and R. Malaney, Ap. J. 333 (1988) 14; H. Kurki - Suonio, R. Matzner, K. Olive and D. Schramm, Phys. Rev. D 38 (1988) 1091 and Ap. J. 353 (1990) 406; K. Sato and N. Terazawa, Phys. Rev. D 39 (1989) 2893.

[12] S. Dimopoulos, R. Esmailzadeh, L. Hall and G. Starkman, Ap. J. 330, 545 (1988).

[13] E. Carlson, R. Esmailzadeh, L. Hall and S. Hsu, Phys. Rev. Lett. 65 (1990) 2225.

[14] J. Bartlett and L. Hall, Phys. Rev. Lett. 66 (1991) 541.

[15] P. B. Pal, Nucl. Phys. B 227 (1983) 237.

[16] Proceedings "Lepton-Photon and High Energy Physics Symposium", Geneva, 1991.

[17] Review of Particle Properties, Phys. Lett. B 239 (1990) J. F. Wilkerson and M. Roos, Proceeding of the 14th Int. Conference on Neutrino Physics and Astrophysics, "Neutrino 90" (CERN, Geneva 1990).

[18] See for example, S. Bludman, D. Kennedy and Langacker CFPA-TH-91-003-Rev (1991) and UPP-0443T (1991).

[19] D. W. Sciama, Comm. Astrophys. 15 (1990) 71.

[20] A. De Rujula and S. Glashow, Phys. Rev. Lett. 45 (1980) 942; D. W. Sciama and A. Melott, Phys. Rev. D25 (1982) 2214; A Melott, D. McKay and J. Ralston, Ap. J. 324 (1988) L43.

[21] E. Roulet and D. Tommasini, Phys. Lett. B256 (1991) 218; F. Gabbiani, A. Masiero and D. Sciama, Phys. Lett. B. 259 (1991) 323.

[22] A. C. Fabian, T. W. Maylor, D. W. Sciama, Mon. Not. R. Astr. Soc. 249 (1990) 29.

[23] J. J. Simpson, Phys. Rev. Lett. 54 (1985) 1891.

[24] S. T. Petcov, Yad. Fiz 25 (1977) 641 [Sov. J. Nucl. Phys. 25 (1977) 340; 25 (1977) 698 E]; T. Goldman and J. Stephenson, Phys. Rev. D16 (1977) 2256; P. B. Pal and L. Wolfenstein, Phys. Rev. D25 (1982) 766.

[25] G. Gelmini, S. Nussinov and R. Peccei, UCLA-91-TEP-15 (1991); E. Carlson, D. Land and L. Randall, Phys. Lett. B264 (1991) 132.

[26] G. F. Giudice, Phys. Lett. B251 (1990) 460.

[27] A. M. Cooper-Sarkar, P. 0. Hulth, K. Hultqvist and S. Sarkar Oxford preprint (1991).

[28] L. Berngström and H. R. Rubinstein, Phys. Lett. B253 (1991), 168.

[29] M. Kamionkowski and M. Turner, Phys., Rev. D42 (1990), 3310.

[30] J. L. Basdevant, R. Mochkovitch, J. Rich, M. Spiro and A. Vidal-Madjar, Phys. Lett. B 234 (1990), 395; S. Dimopoulos, D. Eichler, R. Esmailzadeh and G. Starkman, Phys. Rev. D41 (1990) 2388; A Gould, B. Draine, R. Romani and S. Nussinov, Phys. Lett. B 238 (1990) 337; S. Chivukula, A.

Cohen, S. Dimopoulos and T. Walker, Phys. Rev. Lett. 65 (1990) 957; S. Barwick, P. Price and D. Snowden-Ifft, Phys. Rev. Lett. 64 (1990) 2859.

[31] J. Rich, R. Rocchia and M. Spiro, Phys. Lett. B194 (1987) 173; G. Starkman, A. Gould, R. Esmailzadeh and S. Dimopoulos, Phys. Rev. D41 (1990) 3594; E. Nardi, E. Roulet and D. Tommasini, Fermilab-pub-91-207-A (1991); D. Caldwell UCSB-HEP-91-04, lecture at Int. School of Astroparticle Physics, The Woodlands TX (1991).

[32] K. Griest and M. Kamionkowki, Phys. Rev. Lett. 64, (1990) 615; L. Hall, Proc. 16th SLAC Summer Institute on Particle Physics (ed. Brennan, E.C., 1988) 85.

[33] J. Ellis, D. Nanopoulos, L. Roszkowski and D. N. Schramm, Phys. Lett. B245 (1990) 251; L. Krauss YCTP-P4-91 (1991); L. Roszkowski CERN-TH-6264-91 (1991).

[34] W. H. Press and D. N. Spergel Ap. J. 296 (1985) 679; J. Faulkner and R. L. Gilliland, Ap. J. 299 (1985) 994.

[35] D. O. Caldwell, B. Magnusson, M. S. Witherell et al., Phys. Rev. Lett. 65 (1990) 1305.

[36] G. F. Giudice and S. Raby, Phys. Lett. B247 (1990) 423.

[37] Th. Toutain and C. Fröhlich, to be published in Astronom Astrophys. 1992.

[38] S. Dimopoulos, R. Esmailzadeh, L. Hall and N. Tetradis, Nucl. Phys. B 349 (1991) 714.

[39] P. Salati, Phys. Lett. B 253 (1991) 173.

[40] D. Brahm and L. Hall, Phys. Rev. D41 (1990) 1067; D. Brahm UMI-91-03634 (1990).

[41] M. Goodman and E. Witten, Phys. Rev. D31 (1985) 3059; I. Wasserman, Phys. Rev.D33 (1986) 2071, A. K. Drukier, K. Freese and D. N. Spergel, Phys. Rev. D33 (1986) 3495.

[42] For reviews see J. Primack, D. Seckel and B. Sadoulet, Ann. Rev. Nucl. Part. Sci. 38 (1988) 751 and P. Smith and J. Lewin, Physics Reports 187 (1990) 203.

[43] S. P. Ahlen et al., Phys. Lett. B195 (1987) 603; D. O. Caldwell et al., Phys. Rev. Lett. 61 (1988) 510; D. Reusser et al., Phys. Lett. B255 (1991) 143; E. Garcia, et. al., IFNAE preprint, presented at TAUP91, 1991.

[44] J. Silk, K. A. Olive and M. Srednicki, Phys. Rew Lett.55 (1985)257 and Nucl. Phys. B279 (1987) 804; K. Freese, Phys. Lett.167B (1986)295; L. Krauss, M. Srednicki and F. Wilczek, Phys. Rev. D33 (1986) 2079.

[45] A. Gould, Ap. J. 321 (1987) 571.

[46] M. Mori et al. (Kamiokande Collaboration), Phys. Lett. B 270 (1991) 89.

[47] J. Ellis, G. B. Gelmini, J. Lopez, D. Nanopoulos and S. Sarkar, CERN-TH-5853-90; P. Gondolo, G. Gelmini and S. Sarkar, UCLA-91-TEP-31 (1991); V. S. Berezinskii BA-90-87, (Bartol Research Inst. preprint, 1990) and LNGS-91-02 (L. N. Gran Sasso preprint, 1991).

[48] J. Ellis, R. Flores, K. Freese, S. Ritz, D. Seckel and J. Silk, Phys. Lett. B 214 (1988) 403; G. F. Giudice and K. Griest, Phys. Rev. D40 (1989) 2549.

[49] M. Kamionkowski and M. Turner, Phys. Rev. D43 (1991) 1774.

[50] H. E. Haber and G. L. Kane, Phys. Rep. 117 (1985) 75; J. F. Gunion and H. E. Haber, Nucl. Phys. B272 (1986) 1; R. Barbieri, Riv. Nuovo Cim. 11, No. 4 (1988).

[51] J. Ellis and F. Zwirner, Nucl. Phys. B 338 (1990) 317.

[52] K. Griest and L. Roszkowski, CFPA-TH-91-013 (1991).

[53] R. Flores, K. Olive and D. Thomas, Phys. Lett. B245 (1990) 509 and Phys. Lett. B 263 (1991) 263.

[54] J. Ellis, J. Gunion, H. Haber, L. Roszkowski and F. Swirner, Phys. Rev. D39 (1989) 844.

[55] G. B. Gelmini, P. Gondolo and E. Roulet, Nucl. Phys. B 351 (1991) 623.

[56] A. Bottino, V. de Alfaro, N. Fornengo, G. Mignola, M. Pignone, Phys. Lett. B 265 (1991) 57.

[57] A. Bottino, V. de Alfaro, N. Fornengo, A. Morales, J. Puimedon and S. Scopel, DFTT-35-91 (University of Torino preprint, 1991).

[58] See, for example, J. Ellis, G., Ridolfi and F. Zwirner, Phys. Lett. B 257 (1991) 83.

[59] J. Gasser, H. Leutwyler and M. E. Sainio, Phys. Lett. B 253 (1991) 252.

[60] T. P. Cheng, Phys. Rev. D38 (1988) 2869 and H. Y. Cheng, Phys. Lett. B219 (1989) 347.

[61] M. A. Shifman, A. I. Vainshtein and V. I. Zacharov, Phys. Lett. 78B (1978) 443 and JETP Lett. 22 (1975) 55.

[62] J. Ellis and R. Flores, Phys. Lett. B 263 (1991) 259.

[63] K. Griest, M. Kamionkowski and M. Turner, Phys. Rev. D41 (1990) 3565; see also K. Olive and M. Srednicki, Nucl. Phys. B555 (1991) 208 and Phys Lett. B230 (1989) 78.

[64] M. Kaminkowski, Phys. Rev. D44 (1991) 3021; A. Gould, IASSNS-AST-91-34, Princeton Inst. for Advanced Study preprint,1991.