1. Introduction

The question of the nature of the dark matter in the Universe is getting more interesting than ever. As new observations are coming in, the possible candidates get more and more constrained. On the other hand, the picture which is emerging is to some extent puzzling, indicating that perhaps not all observations nor theoretical analyses are correct.

Let us first recall that from the particle physics point of view, the theoretically preferred (Einstein-De Sitter) Universe has the simple description

\[
\begin{align*}
\Omega & = 1 \\
\Lambda & = 0
\end{align*}
\]

(1)

where \( \Lambda \) is the cosmological constant, and

\[
\Omega \equiv \frac{\rho}{\rho_{\text{crit}}} = \frac{1.9 \cdot 10^{-29} h^2}{g \text{ cm}^{-3}},
\]

(2)

with \( h \) related to the Hubble constant \( H_0 \) by

\[
h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})
\]

(observationally, \( h \) lies between 0.4 and 0.8).

The cosmological model (1) has the attractive features that it is simple, avoids finetuning, and may be explained by a period of inflation in the earliest Universe.

Since Big Bang nucleosynthesis (BBN) puts an upper limit to the baryonic contribution \( \Omega_b \) of [1]

\[
\Omega_b h^2 \leq 0.026,
\]

(3)

non-baryonic dark matter dominates the energy density by a large factor in this type of model.

Staying in the particle physicist's favourite Universe, one of the prime candidates for the non-baryonic component is provided by the lightest neutralino \( \chi \) (see below).

Supersymmetry seems to be a necessity in superstring theory (or M-theory) which unites all the fundamental forces of nature, including gravity. In most versions of the low-energy theory there is a conserved multiplicative quantum number, R-parity, which makes the lightest supersymmetric particle stable. Thus, pair-produced neutralinos in the early Universe which left thermal equilibrium as the Universe expanded should have a non-zero relic abundance today. If the scale of supersymmetry breaking is related to that of electroweak breaking, \( \Omega_{\chi} \) comes out in the right order of magnitude to explain the non-baryonic dark matter. Maybe it is asking too much of Nature, but it would indeed appear as an economic solution if two of the most outstanding problems in fundamental science, that of dark matter and that of the unification of the basic forces, would have a common element of solution - supersymmetry.

The BBN limit (3) is important, since it implies
that if observations give a value of the total energy density above the BBN value, non-baryonic dark matter has to be present (or baryons have to be hidden in some non-standard way at the time of nucleosynthesis), even if the total $\Omega$ turns out to be less than unity. Indeed, there are several independent indications that $\Omega > 0.1$ (and hardly any estimates at all that fall below that limit). Of course, it has long been recognized that even the minimum value of $\Omega_b$ allowed by BBN is higher than the contribution from luminous baryons so that there also exists a dark matter problem for baryons - a lot of baryonic matter has to be hidden. Maybe the MACHO observations [2] have a bearing on that problem.

Perhaps the strongest argument in favour of non-baryonic dark matter comes from structure formation and the microwave background. The basic picture is very simple: the observation of the isotropy of the microwave background to a level of a few times $10^{-5}$ through the COBE measurements, coupled with the theory of growth of perturbations in the theoretically simple linear regime, makes it essentially impossible to create the non-linear structures we observe today with baryons only. In fact, the nice agreement between the COBE observations and the predictions from inflation of a nearly scale-invariant spectrum, may be taken as a piece of evidence in favour of inflation which could point to $\Omega = 1$ on the largest scales. Recently, there has been a flurry of balloon and ground-based CMBR experiments on smaller angular scales, which probe the interesting dynamics of the acoustic peaks in the primordial cosmic fluid [3]. Although we have to await longer duration balloon flights and the MAP and Planck satellite missions for precision measurements, it seems that the present data (interpreted with some courage) favour a critical universe of $\Omega = 1$ over an open Universe of, say, $\Omega = 0.3$ [4].

Still on very large scales, analyses of the peculiar velocity “flow” of large clusters and other structures seem to need a lot of gravitating matter for its explanation, at least $\Omega > 0.4$ [5]. The peculiar velocity field obeys the equation

$$\nabla \cdot \mathbf{v} = -\frac{\Omega_b^{0.6}}{b} \left( \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle} \right),$$

where $b = \frac{\delta \rho_{\text{Gal}}}{\delta \rho_{\text{M}}}$ is the “biassing” parameter which tells how light traces mass. The combination $\Omega_b^{0.6}/b$ is determined by the analysis of [5] to be $0.89 \pm 0.12$, which is consistent with $\Omega = 1$, $b = 1$. Using the theoretical limit $b > 0.75$, a 95% c.l. limit of $\Omega > 0.33$ can be given.

On scales up to a redshift around unity, gravitational lensing [6] and deep supernova searches [7,8] provide interesting new methods which, however, still need to be improved as regards the systematic errors. Indeed, the first 7 supernovas analysed in [7] imply a large value for the matter density $\Omega_M$ (and a small value of the vacuum energy contribution $\Omega_\Lambda$), whereas the 4 supernovas of [8] favour a rather smaller $\Omega_M \sim 0.3$ (and is not incompatible with $\Omega_M + \Omega_\Lambda = 1$). This is a field of great potential which evolves rapidly, and the use of the infrared camera on the Hubble Space Telescope should make follow-up observations of high-$z$ objects easier.

The gravitational lensing analysis of [6] indicates that there is plenty of dark matter; the 95 % c.l. limits are $\Omega_M > 0.38$ and $\Omega_\Lambda < 0.66$. An analysis of the number of arcs from gravitational lensing of clusters expected in various cosmologies gives consistency for an open model with $\Omega \sim 0.3 - 0.4$, but failure for closed models with or without a cosmological constant [9].

The analysis of galaxy clusters has not yet converged to a universal value of $\Omega$. There are some indications [10] from the temperature-luminosity relation for rich clusters that a high value ($\Omega \sim 1$) might be needed. On the other hand [11,12] other dynamical estimates are more consistent with a lower value, $\Omega \sim 0.2 - 0.3$.

On galactic scales and smaller, the classical tests of the mass distribution provided by rotation curves continue to be refined. A recent compilation of almost 1000 rotation curves led to the conclusion that dark matter indeed is present in large amounts [13]. A very interesting class of objects is provided by low surface brightness galaxies and the dwarf spheroidal satellite galaxies to the Milky Way, which seem to be completely dom-
inated by dark matter [14]. A couple of these have unusual rotation curves which could perhaps be interpreted as being due to a combination of MACHOs and nonbaryonic dark matter [15].

The problem of how dark matter is distributed in halos of galaxies and galaxy clusters is an important one for the purpose of determining strategies for the detection of the various candidates, as we will see. Unfortunately, the available data on the structure of the Milky Way do not constrain the dark matter halo density profile very much [16].

A problem for high-Ω models without cosmological constant was until very recently the difficulty of reconciling the age of the Universe \( t_U \) based on the present expansion rate \( H_0 \) with the estimated age of the oldest globular clusters. The values \( \Omega_M = 1, \Omega_\Lambda = 0 \) give \( t_U = 2/(3H_0) \), which for \( h = 0.6 \) implies \( t_U \sim 10 - 11 \) Gyr. The determination of globular cluster ages on the other hand used to give \( 14 - 15 \) Gyr as best estimates. Besides some doubts that may still remain about the accuracy of these latter very indirect means of bounding the age of the Universe, it seems that the recalibration of the distance scale provided by the recent Hipparcos satellite parallax measurements brings the globular cluster age limit down by 2-3 Gyr [17], with the one-sided 95 % c.l. lower limit being 9.5 Gyr. This means that a critical universe is now allowed without cosmological constant, if \( h \leq 0.67 \), a value that is not far from the current best estimates.

To summarize at this point: A variety of independent estimates of the matter density in the Universe point to a value larger than the maximal value provided by baryons alone according to nucleosynthesis. The need for nonbaryonic dark matter is therefore striking. If the “natural” theoretical prediction \( \Omega_M = 1, \Omega_\Lambda = 0 \) is fulfilled is a different question, for which most of the observational data today do not yet give support, except maybe at the largest scales.

2. Dark Matter Candidates

Given that the total mass density of the universe seems to be higher than what is allowed by Big Bang nucleosynthesis, an important task of cosmology and particle physics is to produce viable non-baryonic candidates and to indicate how the various scenarios can be tested observationally.

2.1. Baryons

The “second” dark matter problem, to account for the baryons that have to hidden in order to get agreement with BBN, has not been fully solved. It is possible that a lot of the baryonic mass may be hidden in galactic halos in the form of sub-solar mass objects, MACHOS [2]. However, even with the surprisingly large optical depth for microlensing observed towards the LMC, the most likely fraction of the halo mass given by MACHOs is not larger than 50 % and could in fact be much smaller if debris from tidal stripping of the LMC itself or other dwarf satellites happens to lie in the line-of-sight, as indicated by some observations [18].

Probably, the main repository of baryons in the universe is the gas of rich clusters. These systems are large enough that the baryon fraction should be a good tracer of the total \( \Omega_b/\Omega_M \). Estimates [19] give a value of \( r_b \sim 0.1 - 0.2 \), which combined with the BBN determination of \( \Omega_b \) gives \( \Omega_M \sim 0.1 \) if the high deuterium measurement [20] is correct, \( \Omega_M \sim 0.5 \) for the low deuterium abundance case [21], with probably rather large systematic uncertainties related to the limited understanding of how clusters formed.

2.2. Neutrinos

Of the many candidates for non-baryonic dark matter proposed, neutrinos are often said to have the undisputed virtue of being known to exist. Actually, this is a statement which needs some qualification because neutrinos can only be dark matter candidates if they are massive. For this to be true, both left-handed and right-handed neutrino states are needed, and the latter are not known to exist (in the minimal Standard Model of particle physics the right-handed neutrino is simply absent). In principle, one can construct a mass term from only the left chirality neutrino field, but this give a Majorana type mass which violates lepton number by two units, and in the Standard Model \( B - L \) is exactly conserved.
Non-zero neutrino masses, if established, would thus be an indication of physics beyond the Standard Model. Since there exists a number of indications that the Standard Model cannot be the final theory, it would not be a big surprise if neutrinos are massive. As the direct experimental limits on neutrino mass show [27]:

\begin{align}
\nu_e &< 15 \text{ eV} \\
\nu_\mu &< 0.17 \text{ MeV} \\
\nu_\tau &< 24 \text{ MeV}
\end{align}

the neutrino masses have to be much smaller than the corresponding quark and charged-lepton masses. An intriguing explanation of this fact could be given by the so-called see-saw mechanism, where a right-handed Majorana mass $M$, at a large scale $\propto M_{\text{GUT}} \sim 10^{15-17} \text{ GeV}$ modifies through mixing the usual Dirac-type mass $m_D$ of the lightest state to $m_D^2/M \ll m_D$. In the simplest version of this scheme, the neutrino masses would scale as the square of the corresponding charged-lepton masses. There are variants (e.g. in models of loop-induced neutrino masses) where neutrino masses are instead linearly related to the charged-lepton masses.

Indeed, there are several indications that neutrinos are not massless. Although none of the direct kinematical measurements of neutrino masses has given a value inconsistent with zero, evidence from neutrino oscillation experiments is mounting that neutrinos oscillate in flavour and hence must possess non-zero masses. To give a cosmologically interesting contribution to $\Omega$, a relatively narrow range $m_\nu \sim 1 - 50 \text{ eV}$ is required. A neutrino heavier than that would overclose the universe (unless $m_\nu > 3 \text{ GeV}$, which for Dirac neutrinos is ruled out by accelerator and direct detection data up to the TeV range), whereas a lighter neutrino would only give a small and dynamically not very important contribution to $\Omega$.

Of the various experimental indications of neutrino oscillations, only the LSND results [22] seem to be in the cosmologically interesting range, with $\Delta m^2 \sim 1 - 6 \text{ eV}^2$. These results, however, need independent confirmation from other experiments.

The solar neutrino problem, which in view of new helioseismological data does not seem to be solvable by tampering with the solar model [23], and thus presents rather compelling evidence for oscillations, only gives solutions with very small $\Delta m^2$. The weak indications of an energy-dependence of the solar neutrino deficit seen so far in the Super-Kamiokande data [24] favour the small-angle MSW solution, which has $\sin^2 2\theta \sim 5 \cdot 10^{-3}$ and $\Delta m^2 \sim 10^{-5} \text{ eV}^2$. This would indicate small absolute values of neutrino masses unless there would be mass degeneracies of unknown origin between neutrinos.

Likewise, the atmospheric neutrino anomaly, recently confirmed by Super-Kamiokande data, has a preferred solution with a $\Delta m^2$ of only a few times $10^{-3} \text{ eV}^2$. Seen already in the smaller Kamiokande detector, as well as in IMB and Soudan-2 [25] as a deficit in the “ratio of ratios”, $r \equiv (\nu_\mu/\nu_e)_{\text{data}}/(\nu_\mu/\nu_e)_{\text{MC}} \sim 0.6$, the interpretation in terms of neutrino oscillations seems much stronger with the Super-Kamiokande data where a zenith-angle dependence of the ratio is indicated [24] with higher significance than in Kamiokande. Thus it seems plausible that neutrinos are indeed massive, but the mass is too small to be very significant for cosmology.

One should keep in mind, however, the need to check the LSND claims of a neutrino mass difference in the eV region, which if found correct could give a $10 - 20 \%$ contribution to $\Omega_M$. Such a mixture of hot and cold dark matter makes the galaxy and cluster large-scale structure power spectrum easier to connect to the COBE measurements of the Cosmic Microwave Background Radiation (CMBR). Also, even if the largest neutrino mass is of the order of only a few tenths of an eV, as indicated by the atmospheric neutrino anomaly, the effects on structure formation could still be large enough to be detected, e.g., by the Sloan Digital Sky Survey [26].

There is an additional fundamental objection to having neutrinos as the dominant constituent of dark matter on all scales where it is observationally needed. This has to do with the fact that neutrinos are spin-1/2 particles obeying the
Pauli exclusion principle. To make up the dark matter in dwarf galaxies (which in fact are seen to be completely dominated by the dark matter component), neutrinos would have to be stacked together so tightly in phase-space that it seems difficult to evade the Pauli principle. Quantitatively, Tremaine and Gunn found [28] that to explain the dark matter of a dwarf galaxy of velocity dispersion $\sigma$ and core radius $r_c$, the neutrino mass has to fulfil

$$m_\nu \geq 120 \text{ eV} \left( \frac{100 \text{ km/s}}{\sigma} \right)^{\frac{1}{2}} \left( \frac{1 \text{ kpc}}{r_c} \right).$$

This high value is, however, not consistent with the requirement $\Omega_\nu h^2 \leq 1$, which requires $\sum_i m_{\nu_i} < 90 \text{ eV}$.

### 2.3. Axions

Axions are hypothetical particles, spinless light pseudoscalar bosons, which appear in models which explain the smallness of the CP violating $\theta$ parameter of QCD by the existence of a global symmetry, $U(1)_{PQ}$, which is spontaneously broken. The Goldstone boson of this symmetry breakdown is the axion, which however gets a non-zero mass from the QCD anomaly (which can be interpreted as a mixing of the axion field with the $\pi$ and $\eta$ mesons). The phenomenology of the axion is determined, up to numerical factors, by one number only - the scale $f_a$ of symmetry breaking. In particular, the mass is given by

$$m_a = 0.62 \text{ eV} \left( \frac{10^7}{f_a} \right),$$

and the experimentally important coupling to two photons is due to the effective Lagrangian term

$$\mathcal{L}_{a\gamma\gamma} = \left( \frac{\alpha}{2 \pi f_a} \right) \kappa \mathbf{E} \cdot \mathbf{B} a,$$

where $\kappa$ is a model-dependent parameter of order unity.

The axion, constrained by laboratory searches, stellar cooling and the dynamics of supernova 1987A to be very light, $m_a < \text{(few eV)}$ [29], couples so weakly to other matter that it would behave today as Cold Dark Matter. The window where axions are viable DM candidates is progressively getting smaller, but still there is an acceptable range between around $10^{-5}$ and $10^{-2}$ eV where they pass all observational constraints and would not overclose the Universe. Fortunately, there are now two experiments [30,31] which have the experimental sensitivity of probing much of the remaining window within the next few years.

### 2.4. Other Solutions to the Dark Matter Problem

Axions share with massive neutrinos and the supersymmetric candidates to be discussed next the attractive feature of having other, particle-physics motivated, reasons to exist besides giving a possible explanation of dark matter. Of course there are other proposed candidates which, although not yet generally accepted, could finally turn out to give the correct explanation.

It has turned out to be very difficult to modify gravity on the various length scales where the dark matter problem resides, but one cannot logically exclude the possibility that this could be finally achieved.

The three classes of non-baryonic dark matter we discuss here have the additional virtue of lending themselves to experimental investigations at a level that is already starting to probe relevant regions of parameter space.

The next class of models, supersymmetric (susy) dark matter, should be seen at one particular realization of a generic type of models, sometimes named WIMPs (weakly interacting massive particles). Here weakly interacting, electrically neutral massive (GeV to TeV range) particles are assumed to carry a conserved quantum number ($R$-parity in the case of susy) which suppresses or forbids the decay into lighter particles. Such particles should have been copiously produced in the early universe through their weak interactions with other forms of matter and radiation. As the universe expanded and cooled, the number density of the WIMPs successively became too low for the annihilation processes to keep up with the Hubble expansion rate. A relic population of WIMPs should thus exist, and it is very suggestive that the canonical weak interaction strength is, according to detailed calculations, just right to make the relic density fall in the required range to contribute substantially to $\Omega$.

In addition, WIMPs are generically found
to decouple at a temperature that is roughly $m_{\text{WIMP}}/20$, which means that they are non-relativistic already at decoupling and certainly behave as CDM by the time of matter dominance and structure formation.

Although the details of structure formation probably will remain unclear until the next generation of microwave background measurements and digital sky surveys are available, the formerly so popular “Standard CDM” (SCDM) model with $\Omega_{\text{CDM}} = 0.95$, $\Omega_b = 0.05$, the slope parameter of the scale invariant primordial power spectrum $n = 1$, $h = 0.5$ seems to be more or less ruled out by observations. The main problem is that normalization to the COBE spectrum at the largest scales causes by a factor of 2 or so too much power on the smaller scales probed by galaxy and cluster surveys. However, with only small modifications such as adding an HDM component, tilting the primordial spectrum to $0.8 - 0.9$, decreasing $h$ or a combination thereof one can get a very satisfactory description of essentially all the data. As these are all very reasonable modifications (and indeed SCDM an oversimplified model), the case for a large component of the CDM type appears as strong as ever.

### 2.5. Supersymmetric particles

One of the favoured particle dark matter candidates is the lightest supersymmetric particle $\chi$, assumed to be a neutralino, i.e. a mixture of the supersymmetric partners of the photon, the Z and the two neutral CP-even Higgs bosons present in the minimal extension of the supersymmetric standard model (see, e.g. [32]). The attractiveness of this candidate stems from the fact that its generic couplings and mass range naturally gives a relic density in the required range to explain halo dark matter. Besides, its motivation from particle physics has recently become stronger due to the apparent need for 100 GeV - 10 TeV scale supersymmetry to achieve unification of the gauge couplings in view of LEP results [33]. (For a recent review of supersymmetric dark matter, see Ref. [34].)

Thanks to new exciting developments in string theory [35], supersymmetry has become an even more attractive feature to be expected at the doorstop beyond the Standard Model. At a more phenomenological level, supersymmetry gives a nice solution to the so-called hierarchy problem, which is to understand why the electroweak scale is so much smaller than the Planck scale despite the fact that there is nothing in non-supersymmetric theories to cancel the severe quadratic divergences of loop-induced mass terms. In supersymmetric theories, the partners of differing spin would exactly cancel those divergences (if supersymmetry were unbroken).

#### 2.5.1. MSSM: The minimal supersymmetric extension of the standard model

The minimal $N = 1$ supersymmetric extension of the standard model is defined by the the particle content and gauge couplings required by supersymmetry and a gauge-invariant superpotential. The only addition to the obvious doubling of the particle spectrum of the Standard Model concerns the Higgs sector. It turns out that the single scalar Higgs doublet is not enough to give masses to both the u- and d-like fermions and their superpartners. Thus, two complex Higgs doublets have to be introduced. After the usual Higgs mechanism, three of these states disappear as the longitudinal components of the weak gauge bosons leaving 5 physical states: two neutral scalar Higgs particles $H_1$ and $H_2$ (where by convention $H_2$ is the lighter state), one neutral pseudoscalar state $A$, and two charged scalars $H^\pm$. The Z boson mass gets a contribution from the vacuum expectation values (VEVs) of both of the doublets, but the way this division is done between the VEV $v_1$ of $H_1$ and $v_2$ of $H_2$ is not fixed a priori.

Electroweak symmetry breaking is thus caused by both $H_1$ and $H_2$ acquiring vacuum expectation values,

$$\langle H_1 \rangle = v_1, \quad \langle H_2 \rangle = v_2,$$

with $g^2(v_1^2 + v_2^2) = 2m^2_W$, with the further assumption that vacuum expectation values of all other scalar fields (in particular, squark and sleptons) vanish. This avoids color and/ or charge breaking vacua. The ratio of VEVs

$$\tan \beta \equiv \frac{v_2}{v_1}$$

always enters as a free parameter in the MSSM,
although it seems unlikely to be outside the range between 1.1 and 45 [34].

After supersymmetrization, the theory also has to contain the supersymmetric partners of these spin-0 Higgs fields. In particular, two Majorana fermion states, higgsinos, are the supersymmetric partners of the photon (the photino) and the $Z$ (the zino). When diagonalizing the mass matrix of these four neutral Majorana spinor fields (neutralinos), the lightest physical state becomes an excellent candidate for Cold Dark Matter.

The non-minimal character of the Higgs sector may well be the first experimental hint at accelerators of supersymmetry. At tree level, the $H_2$ mass is smaller than $m_Z$, and even after allowing for radiative corrections it can hardly be larger than around 140 GeV.

2.5.2. Supersymmetry Breaking

Supersymmetry is a mathematically beautiful theory, and would give rise to a very predictive scenario, if it were not broken in an unknown way which unfortunately introduces a large number of unknown parameters.

Breaking of supersymmetry has of course to be present since no supersymmetric particle has as yet been detected, and supersymmetry requires particles and sparticles to have the same mass. This breaking can be achieved in the MSSM by a soft supersymmetry-breaking potential which does not re-introduce large radiative mass-shifts (and which strongly indicates that the lightest supersymmetric particles should not be too much heavier than the 250 GeV electroweak breaking scale). The origin of this effective low-energy potential need not be specified, but it is natural to believe that it is induced through explicit breaking in a hidden sector of the theory at a high mass scale. The susy breaking terms are then transmitted to the visible sector through gravitational interactions.

Another possibility, of recent resurging interest, is that supersymmetry breaking is achieved through gauge interactions at relatively low energy in the hidden sector [36]. This is then transferred to the visible sector through some messenger fields which transform non-trivially under the Standard Model gauge group. Although this scenario has some nice features, it does not seem to give as natural a candidate for the dark matter as the “canonical” scenario, which is the one we shall assume in most of the following. See, however, [37] for some possibilities of dark matter candidates in gauge-mediated models.

Since one of the virtues of supersymmetry is that it resurrects the hope for a grand unification at a common mass scale, a simplifying unification assumption is often used for the gaugino mass parameters,

$$M_1 = \frac{5}{3} \tan^2 \theta \omega M_2 \simeq 0.5 M_2,$$

$$M_2 = \frac{\alpha_{\omega}}{\sin^2 \theta \omega} M_3 \simeq 0.3 M_3.$$  \hfill (10)

As mentioned, the one-loop effective potential for the Higgs fields has to be used used to obtain realistic mass estimates. The minimization conditions of the potential allow one to trade two of the Higgs potential parameters for the $Z$ boson mass $m_Z^2 = \frac{1}{2} (g^2 + g'^2) (v_1^2 + v_2^2)$ and the ratio of VEVs $\tan \beta$. The third parameter can further be reexpressed in terms of the mass of one of the physical Higgs bosons, for example $m_A$.

The neutralinos $\tilde{\chi}_i^0$ are linear combination of the neutral gauge bosons $\tilde{B}, \tilde{W}_3$ (or equivalently $\tilde{\gamma}, \tilde{Z}$) and of the neutral higgsinos $\tilde{H}_1^0, \tilde{H}_2^0$. In this basis, their mass matrix

$$\mathcal{M} = \begin{pmatrix}
M_1 & 0 & -\frac{g_1 \alpha}{\sqrt{2}} & +\frac{g_2 \alpha}{\sqrt{2}} \\
0 & M_2 & +\frac{g_1 \alpha}{\sqrt{2}} & -\frac{g_2 \alpha}{\sqrt{2}} \\
-\frac{g_1 \alpha}{\sqrt{2}} & +\frac{g_2 \alpha}{\sqrt{2}} & 0 & -\mu \\
+\frac{g_1 \alpha}{\sqrt{2}} & -\frac{g_2 \alpha}{\sqrt{2}} & -\mu & 0
\end{pmatrix}$$  \hfill (11)

can be diagonalized to give four neutral Majorana states,

$$\tilde{\chi}_i^0 = a_{i1} \tilde{B} + a_{i2} \tilde{W}_3 + a_{i3} \tilde{H}_1^0 + a_{i4} \tilde{H}_2^0$$  \hfill (12)

the lightest of which, $\chi_1$, is then the candidate for the particle making up (at least some of) the dark matter in the universe.

For simplicity, one often makes a diagonal ansatz for the soft supersymmetry-breaking parameters in the sfermion sector. This allows the squark mass matrices to be diagonalized analytically. Such an ansatz implies the absence of tree-level flavor changing neutral currents (FCNC) in
all sectors of the model. In models inspired by low-energy supergravity with a universal scalar mass at the grand-unification (or Planck) scale the running of the scalar masses down to the electroweak scale generates off-diagonal terms and tree-level FCNC’s in the squark sector. For a discussion of this class of models, and of effects related to relaxing the assumption of universal scalar masses, see [38]. In most of the estimates of detection rates given below, we will adhere to a purely phenomenological approach, where the simplest unification and scalar sector constraints are assumed, but no supergravity relations are used.

When using the minimal supersymmetric standard model in calculations of relic dark matter density, one should make sure that all accelerator constraints on supersymmetric particles and couplings are imposed. In addition to significant restrictions on parameters given by LEP [40], the measurement of the $b \rightarrow s \gamma$ process is providing important bounds.

The relic density calculation in the MSSM for a given set of parameters is nowadays accurate to 10 % or so. A recent important improvement is the inclusion of coannihilations, which can change the relic abundance by a large factor in some instances [41].

2.5.3. Detection methods

If neutralinos are indeed the CDM needed on galaxy scales and larger, there should be a substantial flux of these particles in the Milky Way halo. Since the interaction strength is essentially given by the same weak couplings as, e.g., for neutrinos there is a non-negligible chance of detecting them in low-background counting experiments. Due to the large parameter space of MSSM, even with the simplifying assumptions above, there is a rather wide span of predictions for the event rate in detectors of various types. It is interesting, however, that the models giving the largest rates are already starting to be ruled out by present direct detection experiments [39,42].

Besides these possibilities of direct detection of supersymmetric dark matter, discussed extensively at this Workshop [22] (indeed even with a weak indication of a positive signal [43,44]), one also has the possibility of indirect detection through neutralino annihilation in the galactic halo. This is becoming a promising method thanks to very powerful new detectors for cosmic gamma rays and neutrinos planned and under construction.

There has recently been a new balloon-borne detection experiment [45], with increased sensitivity to eventual positrons from neutralino annihilation, where an excess of positrons over that expected from ordinary sources has been found. However, since there are many other possibilities to create positrons by astrophysical sources, e.g. near the centre of the Milky Way, the interpretation is not yet conclusive.

Antiprotons could for some supersymmetric parameters constitute a useful signal [46], but probably the upcoming space experiments [47] will be needed to disentangle a low-energy signal from the smooth cosmic-ray induced background. For kinematical reasons, antiprotons created by pair-production in cosmic ray collisions with interstellar gas and dust are born with relatively high energy, whereas antiprotons from neutralino annihilation populate also the sub-100 MeV energy band. A problem that plagues estimates of the signal strength of both positrons and antiprotons is, however, the uncertainty of the galactic propagation model and solar wind modulation.

Even allowing for large such systematic effects, the measured antiproton flux gives, however, rather stringent limits on the lifetime of hypothetical $R$-parity violating decaying neutralinos [48].

2.5.4. Methods with distinct experimental signature

With these problems of positrons and antiprotons, one would expect that problems of gamma rays and neutrinos are similar, if they only arise from secondary decays in the annihilation process. For instance, the gamma ray spectrum arising from the fragmentation of fermion and gauge boson final states is quite featureless and gives the bulk of the gammas at low energy where the cosmic gamma ray background is severe. Also, the density of neutralinos in the halo is not large enough to give a measurable flux of secondary
neutrinos, unless the dark matter halo is very clumpy. However, neutrinos can escape from the centre of the Sun or Earth, where neutralinos may have been gravitationally trapped and therefore their density enhanced. Gamma rays may result from loop-induced annihilations \( \chi \chi \rightarrow \gamma \gamma [49] \) or \( \chi \chi \rightarrow Z \gamma [50] \).

The rates of these processes are difficult to estimate because of uncertainties in the supersymmetric parameters, cross sections and halo density profile. However, in contrast to the other proposed detection methods they have the virtue of giving very distinct, “smoking gun” signals: high-energy neutrinos from the centre of the Earth or Sun, or monoenergetic photons with \( E_\gamma = m_\chi \) or \( E_\gamma = m_\chi (1 - m_Z^2/4m_\chi^2) \) from the halo.

### 2.5.5. Gamma ray lines

The detection probability of a gamma line signal depends on the very poorly known density profile of the dark matter halo.

To illustrate this point, let us consider the characteristic angular dependence of the gamma-ray intensity from neutralino annihilation in the galactic halo. Annihilation of neutralinos in an isothermal halo with core radius \( a \) leads to a gamma-ray flux of

\[
\frac{dF}{d\Omega} \simeq \left( 2 \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right) \times \\
\frac{(\sigma_{\gamma\gamma} v)_{29}(\rho_{\chi}^{0.3})^2}{(m_\chi/10 \text{GeV})^2} \left( \frac{R}{8.5 \text{kpc}} \right) J(\Psi)
\]

where \( (\sigma_{\gamma\gamma} v)_{29} \) is the annihilation rate in units of \( 10^{-29} \text{cm}^3 \text{s}^{-1} \), \( \rho_{\chi}^{0.3} \) is the local neutralino halo density in units of \( 0.3 \text{ GeV cm}^{-3} \) and \( R \) is the distance to the galactic center. The integral \( J(\Psi) \) is given by

\[
J(\Psi) = \frac{1}{R\rho_0^2} \int_{\text{line-of-sight}} \rho^2(\ell) d\ell(\Psi),
\]

and is evidently very sensitive to local density variations along the line-of-sight path of integration.

We remind of the fact that since the neutralino velocities in the halo are of the order of \( 10^{-5} \) of the velocity of light, the annihilation can be considered to be at rest. The resulting gamma ray spectrum is a line at \( E_\gamma = m_\chi \) of relative linewidth \( 10^{-3} \) which in favourable cases will stand out against background. The process \( \chi \chi \rightarrow Z \gamma \) is treated analogously and has a similar rate [50].

To compute \( J(\Psi) \), a model of the dark matter halo has to be chosen. Recently, N-body simulations have given a clue to the final halo profile obtained by hierarchical clustering in a CDM scenario [51]. It turns out that the universal halo profile found in these simulations has a rather significant enhancement \( \propto 1/r \) near the halo centre.

If applicable to the Milky Way, this would lead to a much enhanced annihilation rate towards the galactic centre, and also to a very characteristic angular dependence of the line signal. This would be very beneficial when discriminating against the galactic and extragalactic gamma ray background, and Air Cherenkov Telescopes (ACTs) would be eminently suited to look for these signals, if the energy resolution is at the 10–20% level.

The calculation of the \( \chi \chi \rightarrow \gamma \gamma \) cross section is technically quite involved with a large number of loop diagrams contributing. In fact, only very recently a full calculation in the MSSM was performed [52]. Since the different contributions all have to be added coherently, there may be cancellations or enhancements, depending on the supersymmetric parameters.

An important contribution, especially for neutralinos that contain a fair fraction of Higgsino components, is from \( W^+W^- \) intermediate states. This is also true for the \( Z \gamma \) final state for very massive neutralinos [50]. In fact, thanks to the effects of coannihilations [41], neutralinos as heavy as several TeV are allowed without giving a too large \( \Omega \). These extremely heavy dark matter candidates (which would require quite a degree of finetuning in most susy models) are predominantly higgsinos and have a remarkably large branching ratio into the loop-induced \( \gamma \gamma \) and \( Z \gamma \) final states (the sum of these can be as large as 30%). Recently, there has been some interest in TeV neutralinos due to a claim of a possible structure in existing data [53]. It seems, however, that this claim was based on an erroneous estimate of the acceptance of the experiments. Also, the purported rate is at least 3 or 4 orders of magnitude larger than what can be obtained in susy models.
In Fig. 1, we show the gamma ray line flux given in a scan of supersymmetric models consistent with all experimental bounds (including $b \rightarrow s\gamma$), assuming an effective value of $10^3$ for the average of $J(\Psi)$ over the $10^{-3}$ steradians that typically an Air Cherenkov Telescope (ACT) would cover. (See [55] for details.)

![Figure 1. Results for the gamma ray line flux in an extensive scan of supersymmetric parameter space in the MSSM [55]. Shown is the number of events versus photon energy in an Air Cherenkov Telescope of area $5 \times 10^4$ m$^2$ viewing the galactic centre for one year. The halo profile of [51] for the dark matter has been assumed. The different colours represent different values of the gaugino (photino plus zino) fraction $Z_g$.](image)

It can be seen that the models which give the highest rates should be within reach of the new generation of ACTs presently being constructed. These will have an effective area of almost $10^5$ m$^2$, a threshold of some tens of GeV and an energy resolution approaching 10%. In favourable cases, especially at the low $m_\chi$ end, also a smaller area detector with better energy resolution and wider angular acceptance such as the proposed GLAST satellite could reach discovery potential.

### 2.5.6. Indirect detection through neutrinos

Another promising indirect detection method is to use neutrinos from annihilations of neutralinos accumulated in the centre of the Sun or Earth. This will be a field of extensive experimental investigations in view of the new neutrino telescopes (AMANDA, Baikal, NESTOR, ANTARES) planned or under construction [56].

The capture rate induced by scalar (spin-independent) interactions between the neutralinos and the nuclei in the interior of the Earth or Sun is the most difficult one to compute, since it depends sensitively on Higgs mass, form factors, and other poorly known quantities. For the Sun, the axial cross section is relatively easy to compute, a good approximation is given by [34]

$$C_{ax}^\odot = (1.3 \times 10^{25} \text{s}^{-1}) \frac{\rho_\odot \sigma_{0 \text{ spin}}^{H(40)}}{(m_\chi/(1\text{GeV}) \bar v_{270})}$$

where $\sigma_{0 \text{ spin}}^{H(40)}$ is the cross section for neutralino-proton elastic scattering via the axial-vector interaction in units of $10^{-40}$ cm$^2$, $\bar v_{270}$ is the dark-matter velocity dispersion in units of 270 km s$^{-1}$, and $\rho_\odot$ is the local halo mass density in units of 0.3 GeV cm$^{-3}$. The capture rate in the Earth is dominated by scalar interactions, where there may be kinematic and other enhancements, in particular if the mass of the neutralino almost matches one of the heavy elements in the Earth. For this case, a more detailed analysis is called for, but convenient approximations are available [34].

To illustrate the potential of neutrino telescopes for discovery of dark matter through neutrinos from the Earth or Sun, we present the results of a full calculation [57]. In Fig. 2 it can be seen that a neutrino telescope of area around 1 km$^2$, which is a size currently being discussed, would have discovery potential for a range of supersymmetric models.
If a signal were established, one can use the angular spread caused by the radial distribution of neutralinos (in the Earth) and by the energy-dependent mismatch between the direction of the muon and that of the neutrino (for both the Sun and the Earth) to get a rather good estimate of the neutralino mass [59]. If muon energy can also be measured, one can do even better [60].

3. Conclusions

To conclude, indirect detection methods have the potential to be very useful complements to direct detection of supersymmetric dark matter candidates. In particular, new air Cherenkov and neutrino telescopes may have the sensitivity to rule out or confirm the supersymmetry solution of the dark matter problem.

Since also the experimental situation concerning massive neutrinos and axions is getting clearer, there is a chance to reach the goal of explaining the nature of the dark matter in the not too distant future.

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