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Non-Baryonic Dark Matter[1]

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Abstract

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Non-Baryonic Dark Matter †

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1. Introduction

The puzzle of the hypothetical dark matter (DM) in the Universe still remains unresolved [1]. While there may well be more than one type of DM, arguments from large structures suggest that a large, and presumably dominant, fraction of DM in the Universe is made of massive particles which at the time of entering the epoch of matter dominance would be already non-relativistic, or *cold*. From the particle physics point of view, cold DM (CDM) could most plausibly be made of so-called weakly interacting massive particles (WIMPs).

There exist several interesting WIMP candidates for CDM that are well-motivated by the underlying particle physics. The neutralino is considered by many a "front-runner" by being perhaps the most natural WIMP: it comes as an unavoidable prediction of supersymmetry (SUSY). The axion is another well-motivated candidate [2]. But by no means should one forget about some other contenders. While some old picks (sneutrinos and neutrinos with mass in the GeV range) have now been ruled out as cosmologically relevant CDM by LEP, axinos (SUSY partners of axions) have recently been revamped [3]. Another well-known candidate is the fermionic partner of the graviton, the gravitino. Most of the review will be devoted to the neutralino but I will also comment about recent results regarding axinos.

Neutrinos, the only WIMPs that are actually known to exist, do not seem particularly attractive as DM candidates. It has long been believed that their mass is probably very tiny, as suggested by favored solutions to the solar and atmospheric neutrino problems, which would make them hot, rather than cold DM. This picture has recently been given strong support by first direct evidence from Superkamiokande for neutrinos' mass [4]. While the new data only gives the $\mu - \tau$ neutrino mass-square difference of $2.2 \times 10^{-3}\,\mathrm{eV}^2$, it it very unlikely that there would exist two massive neutrinos with cosmologically relevant mass of 5 to 40 eV and such a tiny mass difference.

The strength with which the WIMP candidates listed above interact with ordinary matter spans many orders of magnitude. For the neutralinos it is a fraction ($\sim 10^{-2}$– $\sim 10^{-5}$) of the weak strength. Interactions of axions and axinos are suppressed by $(m_W/f_a)^2 \sim 10^{-16}$, where $f_a \sim 10^{10}\,\mathrm{GeV}$ is the scale at which the global Peccei-Quinn $U(1)$ symmetry is broken. Interactions of gravitinos and other relics with only gravitational interactions are typically suppressed by $(m_W/M_{\mathrm{Planck}})^2 \sim 10^{-33}$. One may wonder how such vastly different strengths can all give the relic abundance of the expected order of the critical density. The answer lies in the different ways they could be produced in the early Universe: the neutralinos are mainly produced "thermally": at some temperature they decouple from the ther-

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mal bath. But in addition there exist also several mechanisms of “non-thermal” production. This is how CDM axinos, gravitinos can be produced (in addition to “thermal” production), as well as Wimpzillas [5].

It is obvious that WIMPs do not necessarily have to interact only via weak interactions *per se*. WIMPs are generally required to be electrically neutral because of stringent observational constraints on the abundance of stable charged relics. On the other hand, they could in principle carry color charges. (For example, a stable gluino above $130-150\,\mathrm{GeV}$ [6], or in an experimentally allowed window $25-35\,\mathrm{GeV}$ [7], could still be the lightest SUSY particle (LSP) although its relic abundance would be very small [6].) In a halo they would exist as neutral states by forming composites with gluon or quarks. We can see that generally WIMPs are expected to have suppressed effective couplings with ordinary matter. Otherwise, they would dissipate their kinetic energy.

What is the WIMP relic abundance $\Omega_\chi h^2 = \rho_\chi/\rho_{crit}$ [8]? Current estimates of the lower bound on the age of the Universe lead to $\Omega_{\mathrm{TOTAL}} h^2 < 0.25$. Recent results from rich clusters of galaxies and high-redshift supernovae type Ia imply $\Omega_{\mathrm{matter}} \simeq 0.3$. The Hubble parameter is now constrained to 0.65 ± 0.1. Big Bang nucleosynthesis requires $\Omega_{\mathrm{baryon}} h^2 \lesssim 0.015$. Assuming that most matter in the Universe is made of CDM WIMPs, one therefore obtains

$$0.1 \lesssim \Omega_\chi h^2 \lesssim 0.15 \tag{1}$$

or so. At the very least, requiring that a dominant fraction of CDM is located only in galactic halos gives $\Omega_\chi h^2 \gtrsim 0.025$.

2. Neutralinos

The DM candidate that has attracted perhaps the most wide-spread attention from both the theoretical and experimental communities is the neutralino. It is a neutral Majorana particle, the lightest of the mass eigenstates of the fermionic partners of the gauge and Higgs bosons: the bino, wino and the two neutral higgsinos. If it is the lightest SUSY particle, it is massive and stable, due to assumed R-parity. A perfect candidate for a WIMP!

The neutralino is a well-motivated candidate. It is an inherent element of any phenomenologically relevant SUSY model. Being neutral, it is a natural candidate for the LSP (although one should remember that this is often only an assumption); it couples to ordinary matter with a weak-interaction strength (reduced by mixing angles) which is within the range of sensitivity of present-day high energy, as well as dark matter, detectors. Finally, as a bonus, it naturally gives $\Omega_\chi h^2 \sim 1$ for broad ranges of masses of SUSY particles below a few TeV and for natural ranges of other SUSY parameters.

Much literature has been devoted to the neutralino as DM, including a number of comprehensive and topical reviews (see, *e.g.*, Refs. [9,10]). Here I will only summarize the main results and comment on some recent developments and updates.

Neutralino properties as DM and ensuing implications for SUSY spectra are quite model dependent but certain general conclusions can be drawn. First, its cosmological properties are very different depending on a neutralino type. The relic abundance of gaugino-like (mostly bino-like) neutralinos is primarily determined by the (lightest) sfermion exchange in the LSP annihilation into $f\bar{f}$: $\Omega h^2 \propto m_{\tilde{f}}^4/m_\chi^2$. In order to have $\Omega_\chi \sim 1$, the lightest sfermion cannot be too light (below $\sim 100\,\mathrm{GeV}$) nor too heavy (heavier than a few hundred GeV) [11] which is a perfectly natural range of values.

On the other hand, higgsino-like χ's are strongly disfavored. Firstly, due to GUT relations among gaugino masses, higgsinos correspond to rather large gluino mass values, above 1 TeV, which may be considered as unnatural [11]. Furthermore, higgsino-like neutralinos have been shown to provide very little relic abundance. For $m_\chi > m_Z, m_W, m_t$ the χ pair-annihilation into those respective final states (ZZ, WW, $t\bar{t}$) is very strong. But both below and above those thresholds, there are additional co-annihilation [12] processes of the LSP with $\chi_1^\pm$ and χ_2^0, which are in this case almost mass-degenerate with the

LSP. Co-annihilation typically reduces $\Omega_\chi h^2$ below any interesting level although it has been recently argued that the effect of co-annihilation is not always as strong as previously claimed [13]. Higgsino-like LSPs are thus rather unattractive, although still possible DM candidates, especially in the large mass ($m_\chi \gtrsim 500\,\mathrm{GeV}$) regime. One also arrives at the same conclusions in the case of 'mixed' neutralinos composed of comparable fractions of gauginos and higgsinos. This is because, even without co-annihilation, in this case the neutralino pair-annihilation is less suppressed and one invariably finds very small Ω_χ there [11].

Remarkably, just such a cosmologically preferred gaugino type of neutralino typically *emerges* in a grand-unified scenario with additional assumptions that the mass parameters of all spin-zero particles are equal at the unification scale $\sim 10^{16}\,\mathrm{GeV}$. What one finds there is that the lightest bino-like neutralino emerges as essentially the only choice for a neutral LSP [14,15]. (It is still possible to find cases with a higgsino-like LSPs but they are relatively rare.) Furthermore, in order for $\Omega_\chi h^2$ not to exceed one or so, other (most notably sfermion) SUSY partner masses have to be typically less than 1 TeV [14,15]. Thus our phenomenological expectations for low-energy SUSY to be realized roughly below 1 TeV are nicely consistent with a bino-like neutralino as a dominant component of DM in the Universe.

What about the neutralino mass? In principle, it could be considered as a nearly free parameter. It would be constrained from below by the requirement $\Omega_\chi h^2 < 1$ to lie above some $2-3$ GeV [16] which is a neutralino version of the Lee-Weinberg bound [1]. This is because, in this mass range, the neutralino may be viewed as a massive neutrino with somewhat suppressed couplings. Much stronger bounds are in many cases provided by LEP. Unfortunately, collider bounds are rather model dependent and are no longer provided for the general SUSY model normally considered in DM studies. Nevertheless, one can reasonably expect that m_χ is now ruled out below roughly $30\,\mathrm{GeV}$, except in cases when the sneutrino is nearly degenerate with the LSP in which case the lower bound may disappear altogether.

A rough upper bound of 1 TeV follows from the theoretical criterion of naturalness: expecting that no SUSY masses should significantly exceed that value. Again, GUT relations among gaugino masses cause the above constraint to provide a much more stringent (although still only indicative) bound of about $150-200$ GeV. Remarkably, in the scenario with additional GUT unification of spin-zero mass parameters, just such a typical upper bound derives from the cosmological constraint $\Omega_\chi h^2 < 1$. Only in a relatively narrow range of parameters where the neutralino becomes nearly mass degenerate with a SUSY partner of the tau, $\widetilde{\tau}_R$, the effect of the neutralino's co-annihilation opens up the allowed range of m_χ up to about $600\,\mathrm{GeV}$ [17].

Summarizing, we can see that, despite the complexity of the neutralino parameter space and a large number of neutralino annihilation channels, one can, remarkably, select *the gaugino-like neutralino in the mass range between roughly 30 and 150 GeV as a natural and attractive DM candidate*. Furthermore, one is able to derive relatively stringent conditions on the mass range of some sfermions, which are consistent with our basic expectations for where SUSY might be realized.

3. Neutralino WIMP Detection

3.1. Predictions

The local halo density of our Milky Way is estimated at $0.3\,\mathrm{GeV/cm^3}$ with a factor of two or so uncertainty [9]. For neutralino WIMPs as a dominant component of the halo this translates to about 3000 LSPs with mass $m_\chi = 100\,\mathrm{GeV}$ per cubic meter. With typical velocities in the range of a few hundred km/s, the resulting flux of WIMPs is actually quite large

$$\Phi = v\rho_\chi/m_\chi \approx 10^9\,(100\,\mathrm{GeV}/m_\chi)\,\chi'\mathrm{s}/m^2/s. \quad (2)$$

A massive experimental WIMP search programme has been developed during the last few years. Although a variety of techniques have been explored, most of them follow one of the two basic strategies. One can look for DM neutralinos *directly*, through the halo WIMP elastic scattering off nuclei, $\chi N \to \chi N$, in a detector. *Indirect* searches look for traces of decays of WIMP pair-annihilation products. One promising way is to look for multi-GeV energy neutrinos coming from the Sun and/or the core of the Earth. One can also look for monochromatic photons, positrons or antiprotons produced in WIMP pair-annihilation in a Galactic halo. I will not discuss these indirect methods here. Perhaps I should only mention about an interesting new way of looking for WIMPs at the Galactic center [20]. If there is a super-massive black hole there (for which there is now some evidence), it will accrete WIMPs and thus increase their density in the core. They will then be annihilating much more effectively and the resulting flux of neutrinos, photons and other products from the center of the Milky Way may be strongly enhanced, even up to a factor of 10^5 in halo models with central spikes in their profiles. Such spiked halo models have been obtained in recent N-body simulations [18].

In the following I would like to make several comments about direct detection and in particular about an intriguing claim made by the DAMA Collaboration regarding a possible evidence for a WIMP signal in their data. For a more detailed review, see Ref. [19]. First, I will briefly summarize the theoretical aspects and predictions.

In direct searches one of the most significant quantities is the event rate $R \sim \sigma(\chi N)\,(\rho_\chi/m_\chi v)\,(1/m_N)$ - the product of the elastic cross section $\sigma(\chi N)$ of neutralinos from nuclei, their flux $\rho_\chi/m_\chi v$ and the density of target nuclei with mass m_N.

The elastic cross section $\sigma(\chi N)$ of relic WIMPs scattering off nuclei in the detector depends on the individual cross sections of the WIMP scattering off constituent quarks and gluons. For non-relativistic Majorana particles, these can be divided into two separate types. The coherent part described by an effective scalar coupling between the WIMP and the nucleus is proportional to the number of nucleons in the nucleus. It receives a tree-level contribution from scattering off quarks, $\chi q \to \chi q$, as described by a Lagrangian $\mathcal{L} \sim (\chi\chi)\,(\bar{q}q)$. The incoherent component of the WIMP-nucleus cross section results from an axial current interaction of a WIMP with constituent quarks, given by $\mathcal{L} \sim (\chi\gamma^\mu\gamma_5\chi)\,(\bar{q}\gamma_\mu\gamma_5 q)$, and couples the spin of the WIMP to the total spin of the nucleus.

The differential cross section for a WIMP scattering off a nucleus X_Z^A with mass m_A is therefore given by

$$\frac{d\sigma}{d|\vec{q}|^2} = \frac{d\sigma^{scalar}}{d|\vec{q}|^2} + \frac{d\sigma^{axial}}{d|\vec{q}|^2}, \tag{3}$$

where the transferred momentum $\vec{q} = \frac{m_A m_\chi}{m_A + m_\chi}\vec{v}$ depends on the velocity $\vec{v}$ of the incident WIMP. The effective WIMP-nucleon cross sections σ^{scalar} and σ^{axial} are computed by evaluating nucleonic matrix elements of corresponding WIMP-quark and WIMP-gluon interaction operators.

In the scalar part contributions from individual nucleons in the nucleus add coherently and the finite size effects are accounted for by including the scalar nuclear form factor $F(q)$. (The effective interaction in general also includes tensor components but the relevant nucleonic matrix elements can be expanded in the low momentum-transfer limit in terms of the nucleon four-momentum and the quark (gluon) parton distribution function. As a result, the non-relativistic WIMP-nucleon Lagrangian contains only scalar interaction terms.) The differential cross section for the scalar part then takes the form [9]

$$\frac{d\sigma^{scalar}}{d|\vec{q}|^2} = \frac{1}{\pi v^2}[Zf_p + (A-Z)f_n]^2 F^2(q), \tag{4}$$

where f_p and f_n are the effective WIMP couplings to protons and neutrons, respectively, and typically $f_n \approx f_p$. Explicit expressions for the case of the supersymmetric neutralino can be found, *e.g.*, in the Appendix of Ref. [21].

The effective axial WIMP coupling to the nucleus depends on the spin content of the nucleon $\Delta q_{p,n}$ and the overall expectation value of the nucleon group spin in the nucleus $< S_{p,n} >$. For a nucleus with a total angular momentum J we have

$$\frac{d\sigma^{axial}}{d|\vec{q}|^2} = \frac{8}{\pi v^2}\Lambda^2 J(J+1)S(q), \tag{5}$$

with $\Lambda = \frac{1}{J}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]$. The axial couplings

$$a_p = \frac{1}{\sqrt{2}}\sum_{u,d,s} d_q \Delta q^{(p)}, \quad a_n = \frac{1}{\sqrt{2}}\sum_{u,d,s} d_q \Delta q^{(n)} \tag{6}$$

are determined by the experimental values of the spin constants $\Delta u^{(p)} = \Delta d^{(n)} = 0.78$, $\Delta d^{(p)} = \Delta u^{(n)} = -0.5$ and $\Delta s^{(p)} = \Delta s^{(n)} = -0.16$. The effective couplings d_q depend on the WIMP properties and for the neutralino they can be found, *e.g.*, in the Appendix of Ref. [21].

In translating $\sigma(\chi q)$ and $\sigma(\chi g)$ into the WIMP-nucleon cross section in Eq. (3) several uncertainties arise. The nucleonic matrix element coefficients for the scalar interaction are not precisely known. Also, the spin content of the nucleon and the expectation values of the proton (neutron) group spin in a particular nucleus are fraught with significant uncertainty and nuclear model dependence. These ambiguities have to be considered in numerical calculations. Finally, in order to obtain $\sigma(\chi N)$, models of nuclear wave functions must be used. The scalar nuclear form factor reflects the mass density distribution in the nucleus [9].

The resulting cross section for scalar (or coherent) interactions is

$$\sigma^{scalar}(\chi N) \sim G_F^2 \frac{m_\chi^2 m_N^2}{(m_N + m_\chi)^2} A^2 \tag{7}$$

and is proportional to the mass of the nucleus.

For axial (or incoherent) interactions one finds

$$\sigma^{axial}(\chi N) \sim G_F^2 \frac{m_\chi^2 m_N^2}{(m_N + m_\chi)^2} \tag{8}$$

which can be shown to be proportional to the spin of the nucleus. (G_F is the Fermi constant.)

Unfortunately, in supersymmetric models actual calculations produce a rather broad range of values, $R \sim 10^{-5} - 10$ events/kg/day. The rates are also very small. The reason why this is so is clear: this is because of smallness of $\sigma(\chi N)$. The elastic cross section is related by crossing symmetry to the neutralino annihilation cross section $\sigma_{\rm ann}$ which is of weak interaction strength and such as to give $\Omega_\chi h^2 \sim 1$, and therefore very small.

Such small event rates are clearly an enormous challenge to experimentalists aiming to search for dark matter. One may realistically expect that continuing SUSY searches in high energy accelerators and improving measurements of $\Omega_{\rm CDM}$ and the Hubble parameter will cause those broad ranges of R to gradually shrink.

The not so good news is that the choices of SUSY parameters for which one finds the favored range of the relic abundance, $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.15$, correspond to rather low values of the event rate $R \lesssim 10^{-2}$ events/kg/day or so, typically about an order of magnitude below the reach of today's detectors.

3.2. Annual Modulation

One promising way of detecting a WIMP is to look for yearly time variation in the measured energy spectrum. It has been pointed out [22,23] that a halo WIMP signal should show a periodic effect due to the Sun's motion through the Galactic halo, combined with the Earth's rotation around the Sun. The peaks of the effect are on the 2nd of June and half a year later.

The effect, called "annual modulation", would provide a convincing halo WIMP signal. Unfortunately, in SUSY models the effect is usually small, $\Delta R \lesssim 5\%$ [9,21]. With the absolute event rates being already very small, it is going to be a great challenge to detect the effect.

Here I would like to make some comments about possible evidence for a WIMP signal in annual modulation that has been claimed by the DAMA Collaboration. Based on the statistics of $14,962$ kg×day of data collected in a NaI detector over a period from November '96 to July '97 (part of run II), the Collaboration has reported [24] a statistically significant effect which could be caused by an annual modulation signal due to a WIMP with mass m_χ and WIMP-proton cross section σ_p given as

$$m_\chi = 59\,{\rm GeV}^{+22}_{-14}\,{\rm GeV}, \tag{9}$$

$$\xi_{0.3}\sigma_p = 7.0^{+0.4}_{-1.7} \times 10^{-6}\,{\rm pb} \tag{10}$$

at 99.6% CL, where $\xi_{0.3} = \rho_\chi/\rho_{0.3}$ stands for the local WIMP mass density ρ_χ normalized to $\rho_{0.3} = 0.3\,{\rm GeV/cm^3}$. (See also Figure 6 in Ref. [24] for a 2σ signal region in the $(m_\chi, \xi_{0.3}\sigma_p)$ plane.) According to DAMA, the new analysis is consistent with and confirms the Collaboration's earlier hint [25] for the presence of the signal based on $4,549$ kg×day of data.

The claimed effect comes from a few lowest bins of the scintillation light energy, just above the software threshold of 2 keV, and predominantly from the first bin ($2-3$ keV). This is indeed what *in principle* one should expect from the annual modulation effect. DAMA appears confident about the presence of the effect in their data, and claims to have ruled out other possible explanations, like temperature effects, radon contamination or nitrogen impurities. According to DAMA, the effect is caused by single hit events (characteristic of WIMPs unlike neutron or gamma background) with proper modulation of about one year, peak around June, and small enough amplitude of the time dependent part of the signal.

Nevertheless, several experimental questions remain and cast much doubt on the validity of the claim. Here I will quote some which I find particularly important to clarify. First, as stated above, the claimed effect comes from the lowest one or two energy bins. This is indeed what one should expect from an annual modulation signal. But is the effect caused by just one or two energy bins statistically significant? This is especially important in light of the fact that the shape of the differential energy spectrum dR/dE in the crucial lowest energy bins as measured by DAMA is very different from the one measured by Gerbier, *et al.* [26] for the same detector material (NaI). In Ref. [26] the corrected-for-efficiency dR/dE is about 10 events/$kg/keV/$day at 3 keV, decreasing monotonically down to about 2 events/$kg/keV/$day at 6 keV. (See Fig. 15 in Ref. [26].) In contrast, DAMA's spectrum shows a dip down to 1 events/$kg/keV/$day at 2 keV, above which it increases to nearly 2 events/$kg/keV/$day at 4 keV [24,27]. It is absolutely essential for the controversy of the shape of dR/dE in the lowest energy bins to be resolved. Furthermore, DAMA's data from the second run (~ 15000 kg$\times$day) shows that the background in the crucial lowest bin ([2,3] keV) is only about half or less of that in the next bins [27]. One may wonder why this would be the case. Examining more closely the data in the constituent nine NaI crystals, one finds a rather big spread in the event rates [27]. In detector 8, in the lowest energy bin one finds no contribution from the background whatsoever!

Two other groups which have also used NaI have reported [26,28] robust evidence of events of unexpected characteristics and unknown origin. The data of both teams has been analyzed using a pulse shape analysis (PSA). A small but statistically significant component was found with the decay time even shorter than the one expected from WIMPs or neutrons. While the population of those events appears to be too small to explain DAMA's effect, a question remains not only about their origin (contamination?, external effect?) but also how they contribute to the energy spectrum in the crucial lowest bins. DAMA claims not to have seen such events.

DAMA has not yet published the data over a full annual cycle.[3] In particular, no evidence has been published of the signal going down with time. So far, the claimed signal has been based on two periods of data taking. Ref. [25] was based on two relatively short runs, one in winter and one in summer. The second analysis [24] used the data collected between November and July. Much more data has been collected and will soon be published. One should hope that a full and clear analysis of statistical and systematic errors will also be performed.

In Ref. [29] annual modulation was reanalyzed for germanium and NaI. It was concluded that the effect would be too small to be seen with current sensitivity. Particularly illuminating is Fig. 6.a where DAMA's data from Ref. [25] (run one) was re-plotted along with an expected signal for the modulated part of the spectrum for the central values of the ranges of the WIMP mass and cross section (σ_p) selected by DAMA. One can hardly see any correlation between the data and the expected signal.

A controversy over DAMA's alleged signal is of experimental nature. One may therefore hope that it will be definitively resolved. It would be of particular importance for another experiment using different detector material to put DAMA's claim to test. The CDMS cryogenic detection experiment using germanium and silicon crystals at Stanford has now reached an adequate sensitivity and has already ruled out about a half of the re-

[3]See Note Added.

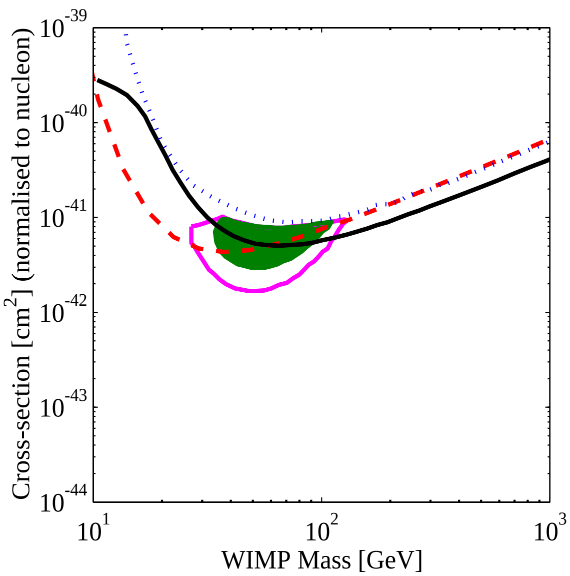

Figure 1. The current and some recent limits on the WIMP-proton spin-independent (scalar) cross-section. The legend is as follows: dot: Heidelberg-Moscow Ge [30], solid: DAMA NaI [31], dash: CDMS 1999 4 kg×day Ge with neutron background subtraction [27]. Marked also are the $2-\sigma$ DAMA regions: solid closed curve: $15,000$ kg×day, filled region: $20,000$ kg×day [24].

gion selected by DAMA [27].[4] Let us hope that DAMA's claim will be falsified soon.

Figure 1 shows the current status of WIMP searches in the plane of the WIMP-proton scalar cross-section σ_p versus the WIMP mass.[5] A claimed DAMA region is also indicated.

It is worth pointing out that the claimed signal region selected by DAMA [24] was too restrictive as it did not include astrophysical uncertainties. The effect is rather sensitive to assumptions about a model of the Galactic halo. In the DAMA analysis the peak of the WIMP (Maxwellian) velocity distribution was fixed at $v_0 = 220\,km/s$. Since the Galactic halo has not been directly observed and there still is a considerable disagreement about a correct halo model, quoted error bars for v_0 and the local halo density should, in my opinion, be treated with much caution. Varying v_0 within a reasonable range leads to a significant enlargement of the region selected by DAMA, [24] as first shown in Ref. [32]. This is so because of the significant dependence on v_0 of the differential event rate spectrum, as can be seen in Fig. 1 in Ref. [32].

As a result, the upper limit of m_χ corresponding to the claimed signal region increases considerably, from about 100 GeV for the initially assumed value $v_0 = 220\,km/s$ up to over 180 GeV at $v_0 = 170\,km/s$ [33] (at 2σ CL). On the other hand the range of $\xi_{0.3}\sigma_p$ is not much affected.

Assuming that the effect claimed by DAMA were indeed caused by DM WIMPs, it is interesting to ask what ranges of SUSY parameters and LSP relic abundance it would correspond to. This issue was addressed by three groups, each using their own code for computing the direct detection rate and the relic abundance [34–36]. While there is some difference in approach (somewhat different ranges of input parameters, techniques and assumptions, *etc.*) the overall outcome is that it is indeed possible to find such SUSY configurations which could reproduce the signal but only for large enough $\tan\beta$ (typically above 10 although SUSY points with smaller values can also sometimes be found). More importantly, the corresponding values of $\Omega_\chi h^2$ are rather small, typically below 0.06 [34–36] although somewhat larger values can also sometimes be found. These are clearly small values, well below the favored range $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.15$. This is illustrated in Figure 2 [36].

However, one should remember that these results have been obtained using commonly used but often rather uncertain values of several input parameters. In addition to astrophysical ones, the nuclear physics and quark mass inputs in calculating the scalar cross-section for the neutralino-nucleus elastic scattering are rather poorly determined, as mentioned above. The effect of the latter has been recently re-analyzed in Ref. [37]

[4] See Note Added.

[5] The figure has been produced with the help of a particularly useful plotting facility of Gaitskell & Mandic which is now available on the Web: http://cdms.berkeley.edu/limitplots/.

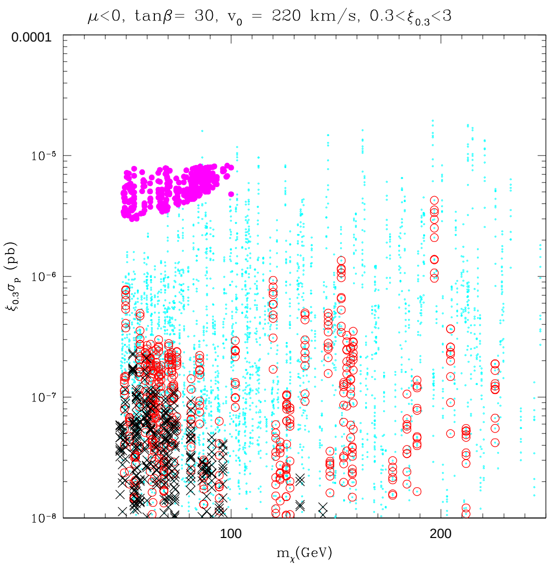

Figure 2. A scan of SUSY points in the plane $(m_\chi, \xi_{0.3}\sigma_p)$ where $\xi_{0.3} = \rho_\chi/(0.3\,\mathrm{GeV}/cm^3)$. The legend: circles: $0.1 < \Omega_\chi h^2 < 0.15$ (cosmologically favored range), crosses: $\Omega_\chi h^2 > 0.25$ (excluded), small points: $0.02 < \Omega_\chi h^2 < 0.25$ (conservative range). The $2-\sigma$ region (upper left) of DAMA is marked with full thick dots.

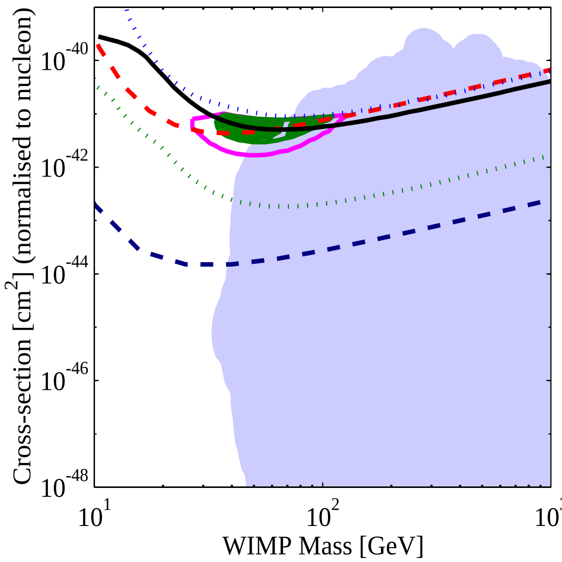

Figure 3. The current and some future reach limits on the WIMP-proton spin-independent (scalar) cross-section compared with conservative predictions from minimal SUSY (large shaded region). The legend is as follows: upper dot: Heidelberg-Moscow Ge [30], solid: DAMA NaI [31], upper dash: CDMS 1999 4 kg×day Ge with neutron background subtraction [27]. Marked also are the $2-\sigma$ DAMA regions: solid: $15,000$ kg×day, filled: $20,000$ kg×day [24]. Future reach of some experiments (as claimed by the respective groups): lower dash: CDMS at Soudan, lower dot: CRESST. Some other experiments (*e.g.*, Edelweiss, UKDMC-Xe, GENIUS) expect to reach roughly similar sensitivities. (Source: http://cdms.berkeley.edu/limitplots/).

and found to affect the overall scalar cross-section by a factor of ten or so.

It is worth presenting Figure 3 again with an outlook for some expected limits (as claimed by the respective groups) and compare them with predictions of minimal SUSY obtained for very broad ranges of SUSY parameters and neglecting nuclear input uncertainties mentioned above. The SUSY region is bounded from above by a somewhat arbitrary requirement $\Omega_\chi h^2 > 0.025$. From below it is limited by a generous bound $\Omega_\chi h^2 < 1$. The SUSY points falling into the currently expected range $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.15$ (not indicated in the plane) form a sub-region reaching up to roughly a few times 10^{-6} pb.

It is clear that today's experiments are now only reaching the sensitivity required to begin testing predictions coming from SUSY. What I find promising is that several experiments using different detector materials and often different methods of [attempts at] distinguishing signal from background will explore a large fraction of the SUSY parameter space within the next few years. Especially reassuring would be an observation of a positive signal in more than type of DM detector, although many experimentalists would probably remark that I am asking for too much.

Time will tell.

4. Axinos

Axinos are a natural prediction of the Peccei-Quinn solution to the strong CP-problem and SUSY. The axino is the fermionic partner of the axion. Similarly to the axion, the axino couples to ordinary matter with a very tiny coupling proportional to $1/f_a$ where $10^9 - 10^{10}\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$.

It is plausible to consider the axino as the LSP since its mass is basically a free parameter which can only be determined in specific models. As we have seen above, the neutralino has been accepted in the literature as a "canonical" candidate for the LSP and dark matter. But with current LEP bounds between about 30 and 60 GeV (depending on a SUSY model), it becomes increasingly plausible that there may well be another SUSY particle which will be lighter than the neutralino, and therefore a candidate for the LSP and dark matter.

Primordial axinos decouple from the thermal soup very early, around $T \simeq f_a$, similarly to the axions. The early study of Ragagopal, *et al.* [38] concluded that, in order to satisfy $\Omega h^2 < 1$, the primordial axinos had to be light ($\lesssim 2$ keV), corresponding to warm dark matter, unless inflation would be invoked to dilute their abundance. In either case, one did not end up with axino as cold DM.

However, it has recently been shown [3] that the axino can be a plausible *cold* dark matter candidate, and that its relic density can naturally be of order the critical density. The axino can be produced as a non-thermal relic in the decays of heavier SUSY particles. Because its coupling is so much weaker, superparticles first cascade decay to the next lightest SUSY partner (NLSP) for which the most natural candidate would be the neutralino. The neutralino then freezes out from thermal equilibrium at $T_f \simeq m_\chi/20$. If it were the LSP, its co-moving number density after freeze-out would remain nearly constant. In the scenario of Covi *et al.* (CKR) [3], the neutralino, after decoupling from the thermal equilibrium, subsequently decays into the axino via, *e.g.*, the process

$$\chi \to \widetilde{a}\gamma \tag{11}$$

as shown in Fig. 1 in Ref. [3]. This process was already considered early on in Ref. [39] (see also Ref. [38]) in the limit of a photino NLSP and only for both the photino and axino masses assumed to be very low, $m_{\widetilde{\gamma}} \leq 1\,\mathrm{GeV}$ and $m_{\widetilde{a}} \leq 300\,\mathrm{eV}$, the former case now excluded by experiment. In that case, the photino lifetime was typically much larger than 1 second thus normally causing destruction of primordial deuterium from Big Bang nucleosynthesis (BBN) by the energetic photon. Avoiding this led to lower bounds on the mass of the photino, as a function of f_a, in the MeV range [39].

Because both the NLSP neutralino and the CKR axino are both massive (GeV mass range), the decay (11) is now typically very fast. In the theoretically most favored case of a nearly pure bino, [11,15] the neutralino lifetime can be written as

$$\tau \simeq 3.3\times10^{-2}\mathrm{s}\left(\frac{f_a/(NC_{aYY})}{10^{11}\,\mathrm{GeV}}\right)^2\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^3 \tag{12}$$

where the factor NC_{aYY} is of order one. One can see that it is not difficult to ensure that the decay takes place well before 1 second in order for avoid problems with destroying successful predictions of Big Bang nucleosynthesis. The axino number density is equal to that of the NLSP neutralino. Therefore its relic abundance is $\Omega_{\widetilde{a}}h^2 = \left(m_{\widetilde{a}}/m_\chi\right)\Omega_\chi h^2$. The axinos are initially relativistic but, by the time of matter dominance they become red-shifted by the expansion and become cold DM.

There are other possible production mechanisms and cosmological scenarios for massive axinos.[6] Even if the primordial population of axinos is inflated away (which would happen if the reheating temperature $T_{\mathrm{reh}} \ll f_a$), they can be regenerated from thermal background processes at high enough T_{reh}.

[6]For a recent comprehensive study, see [40].

5. Conclusions

Looking for the invisible is not easy but is certainly worthwhile. The discovery of dark matter will not only resolve the mystery of its nature but is also likely to provide us with much information about the particle physics beyond the Standard Model. What I find most encouraging is that we have a very good chance of fully testing the neutralino as a WIMP by the end of the decade. Detecting other candidates, like the axino, will be the task for the more distant future.

Note Added:

After the Conference both the DAMA and CDMS Collaborations published new results. Based on the combined statistics of $57,986$ kg$\times$day of data collected in a NaI detector since November '96, the DAMA Collaboration reported [41] a statistically significant ($4\,\sigma$ CL) effect which it interprets as being caused by a WIMP annual modulation signal.

The CDMS experiment using germanium and silicon crystals at Stanford published [42] a new limit on scalar WIMP-proton cross section. The new result is based on the total of 10.6 kg$\times$day of data collected a current shallow site (17 mwe) at Stanford during 1999. A powerful event-by-event discrimination method allows CDMS to reach a sensitivity matching that of DAMA with only less than 0.2% of DAMA's statistics.

The new 90% CL CDMS limit excludes most of the signal region claimed by DAMA. In particular, it fully rules out the previous $2\,\sigma$ region based on the combined data of $19,511$ kg$\times$day from runs I and II [24] and the new $3\,\sigma$ region at more than 84% CL.

An updated compilation of these and other data can be found on the Web: http://cdms.berkeley.edu/limitplots/.)

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