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SUPERSYMMETRIC DARK MATTER*

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ABSTRACT

If supersymmetry exists in Nature then it is quite plausible that the dark matter known to exist in the galactic halo is composed of the lightest supersymmetric particle (LSP) which in most models is the neutralino, a linear combination of the supersymmetric partners of the photon, Z^0 boson, and Higgs bosons. If so, neutralinos in the halo would accumulate in the Sun and Earth and annihilate therein producing high-energy neutrinos. Observation of such neutrinos from the Sun and/or Earth would provide a clear signature of particle dark matter in the halo.

1. Introduction

One of the biggest problems in cosmology is the nature of the dark matter.[1] Although it is not yet clear whether there is enough dark matter to "close" the Universe, the observed flat rotation curves of spiral galaxies imply a significant excess of dark matter over luminous matter. In particular, the *local* density of dark matter can be determined to be 0.3 GeV cm^{-3} to within a factor of about two (Ref. 2).

In particle physics, a very attractive idea for new physics beyond the Standard Model is supersymmetry (SUSY).[3] Simply stated, supersymmetry is the idea that for each fermion in Nature there is a boson (and *vice versa*) with similar quantum numbers. Some of the possible motivations for supersymmetry, aside from its intrinsic aesthetic appeal, are the preservation of the gauge hierarchy (*i.e.*, without SUSY, radiative corrections generally drive the mass of the

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Standard-Model Higgs boson to the GUT or Planck scale) and possible generation of the gauge hierarchy.[4] There is also evidence that SUSY may be an essential ingredient if the strong and electroweak coupling constants are to be unified at the GUT scale.[5] In addition, supersymmetry seems to be an essential ingredient in theories which unify gravity with the other three fundamental forces, and superstring theories are, of course, supersymmetric. As we will see below, another motivation for supersymmetry is that it provides an elegant solution to the dark-matter problem.[6,7]

In this talk I will discuss the dark-matter problem and its supersymmetric solution. I will then discuss the prospects for discovery of particle dark matter, should it exist in our halo, and focus on perhaps the most promising signature of supersymmetric dark matter: energetic neutrinos from annihilation of such particles in the Sun and Earth. It should be kept in mind that much of what I have to say of supersymmetric particles is also true of other stable weakly-interacting massive particles (WIMPs) such as heavy Dirac or Majorana neutrinos.

The outline of the talk is as follows: In the next Section, I will briefly review the evidence for dark matter in the halo and the evidence for a large (*i.e.*, near unity) value of Ω, and discuss some reasons for considering exotic dark matter candidates. In Section 3, I will review how to determine the relic abundance of a weakly-interacting massive particle. We will see that if a stable WIMP exists in Nature with roughly weak-scale interactions it will have a very interesting (*i.e.*, $\Omega \sim 1$) relic abundance. In Section 4, I will discuss supersymmetric dark matter, explain what a neutralino is, and we will see why it is a current frontrunning particle dark-matter candidate. In the penultimate Section we'll get down to the nitty-gritty and discuss prospects for discovery of dark matter via observation of energetic neutrinos from WIMP annihilation in the Sun and Earth, and in the last Section, I'll summarize and make some comments.

2. Why Exotic Dark Matter?

There are many reasons for believing most of the matter in the Universe is nonluminous. First of all, of the possible Robertson-Walker cosmologies, the flat ($\Omega = 1$) is by far the most theoretically attractive. Here are a few reasons: (1) Structure formation begins when the Universe becomes matter dominated and ends when it becomes curvature dominated. If the mass density contributed by the luminous matter ($\Omega_{LUM} \lesssim 0.01$) was all there was, the duration of the epoch of structure formation would be very short thereby requiring (in conventional theories of structure formation) fluctuations in the microwave background larger than those observed. (2) If the current value of Ω is of order unity today (to within an order of magnitude or so) then at the Planck time it must have been 1 ± 10^{-60}

leading us to believe that Ω is precisely 1 for aesthetic reasons. (3) Another reason is that inflationary scenarios reset the value of Ω to unity. The recent discovery of anisotropies in the microwave background[8] with a spectrum consistent with scale-invariant is in agreement with the predictions of inflation; furthermore, the observation of a quadrupole moment with roughly the same magnitude as the fluctuation on smaller scales suggests that the Universe is indeed flat. However, these are theoretical arguments that $\Omega = 1$; we would like some more concrete evidence for the existence of dark matter.

The most convincing evidence involves galactic dynamics. There is simply not enough luminous matter to account for the observed rotation curves of galaxies. From its gravitational effects one infers a galactic dark halo of mass 3-10 times that of the luminous component, and by applying Newton's laws to the motion of galaxies in clusters, one infers a universal mass density of $\Omega \simeq 0.1-0.3$. Therefore, even if we choose to neglect cosmological arguments, there is no way to avoid the fact that our galaxy is permeated by a dark halo contributing $\Omega \gtrsim 0.03-0.1$, and that dark matter outweighs the luminous component on larger scales by at least a factor of ten. Finally, recent attempts to measure the density of the Universe from observed peculiar velocities find values of Ω near unity.[9]

So what *is* the dark matter? Could it be baryons? In the standard model of big-bang nucleosynthesis (BBN), concordance of the observed abundances of light nuclei requires a baryon density of $\Omega h_{50}^2 = 0.05 \pm 0.01$[10] where h_{50} is the Hubble constant in units of 50 km/sec/Mpc. In recent years many people have proposed that the observed abundances of light elements could be produced with a larger baryon density if inhomogeneities were produced during a first-order QCD phase transition; however, results from recent lattice simulations showing a smooth transition make this possible loophole increasingly unlikely.[11] We should mention that even with standard BBN there is the possibility that some baryons are dark (jupiters, white dwarfs, neutron stars, black holes?), perhaps even enough to account for the dark matter in the halo. Still, there is no good reason why these baryons should remain dark and why they wind up in the halo, and even if they do, there is no way that dark baryons can account for dynamics of clusters of galaxies and peculiar velocity flows, and no easily imaginable way they could contribute values of Ω near unity.

If not baryons, perhaps a neutrino species of mass $\mathcal{O}(30\text{eV})$? Although possible, N-body simulations of structure formation in a neutrino-dominated Universe do a poor job of reproducing the observed structure of the Universe. Furthermore, it is difficult to see (essentially from the Pauli principle) how such a neutrino could make up the dark matter in the halos of galaxies.[12]

Thus we are lead to consider the possibility that the dark matter consists of

some new exotic particle species. The two candidates that have received the most attention from both theorists and experimentalists are WIMPs and axions.[13] Axions are very light and weakly interacting particles associated with the Peccei-Quinn solution to the strong-CP problem, and several promising terrestrial experiments to detect axions in our halo are currently underway.[14] I will not discuss axions further. The other frontrunners are WIMPs, weakly-interacting particles with masses typically in the GeV-TeV range. The first WIMPs proposed in the literature were massive Dirac and Majorana neutrinos. Null results from direct detection experiments coupled with LEP measurements of the Z^0 width have ruled out Dirac neutrinos, and non-observation of energetic neutrinos from the Sun coupled with the Z^0 width have recently ruled out Majorana neutrinos as the primary component of the halo. This leaves the neutralino, a linear combination of the supersymmetric partners of the photon, Z^0, and Higgs bosons, as the most promising WIMP. In the next section, we will see what determines the cosmological abundance of a WIMP and then afterwards I will discuss the neutralino in more detail and we will see that if SUSY exists in Nature, we should not at all be surprised to find that the dark matter is composed of SUSY particles.

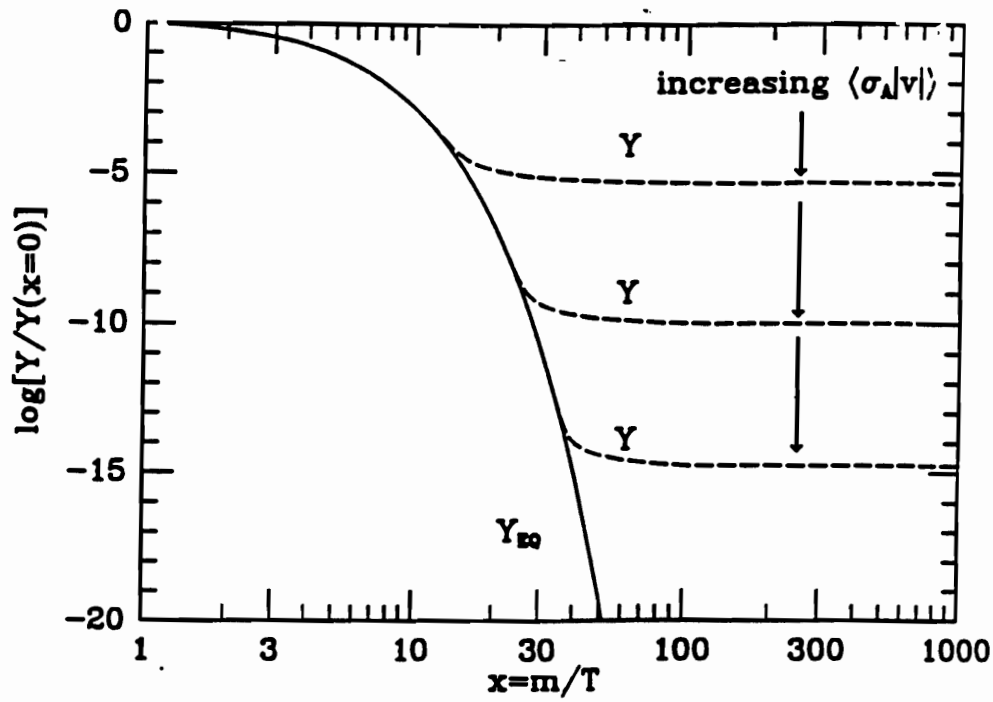
3. Freezeout

Suppose that in addition to the known particles of the Standard Model there exists a new, yet undiscovered, stable weakly-interacting massive particle, X. In a thermal bath, the number density of X particles is

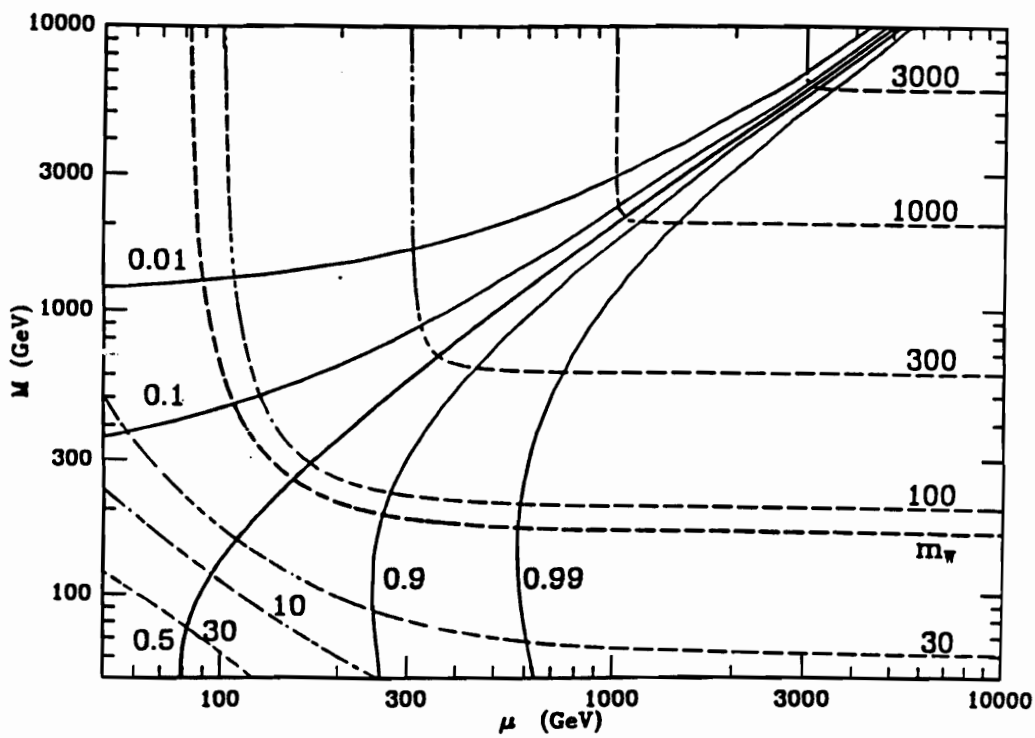
$$n_X = \frac{g}{(2\pi)^3} \int f(\mathbf{p}) d^3\mathbf{p}, \tag{1}$$

where g is the number of internal degrees of freedom and $f(\mathbf{p})$ is the familiar Fermi-Dirac or Bose-Einstein distribution. At high temperatures ($T \gg m_X$, where m_X is the mass of X), $n_X \propto T^3$ (*i.e.*, there are roughly as many X particles as photons), while at low temperatures ($T \ll m_X$), $n_X \propto (m_x T)^{3/2} \exp(-m_X/T)$. If the expansion of the Universe was so slow that thermal equilibrium was maintained, the number of WIMPs today would be exponentially suppressed (essentially, there would be no WIMPs); however, due to the expansion of the Universe, at some point the interactions of the WIMPs "freeze out" and a relic abundance of X persists.

At high temperatures ($T \gg m_X$) X's are abundant and rapidly converting to lighter particles and *vice versa* ($XX \leftrightarrow l\bar{l}$, where $l\bar{l}$ are quark-antiquark and lepton-antilepton pairs and, if m_X is greater than the mass of the gauge and/or Higgs bosons, $l\bar{l}$ could be gauge and/or Higgs bosons pairs as well). Shortly after



1. Fig. 1. Freeze out of a massive-particle species. The dashed line is the actual abundance per comoving volume and the solid line is the equilibrium abundance per comoving volume. Taken from *The Early Universe* (Ref. 15).



2. Fig. 2. Lightest neutralino composition and mass for $\tan\beta = 2$. The broken curves are contours of constant neutralino mass $m_{\tilde{\chi}}$, and the solid curves are contours of constant gaugino fraction $(Z_{n1}^2 + Z_{n2}^2)$. Only $\mu > 0$ is shown here; the graph for $\mu < 0$ is similar.

T drops below m_X the number density of X's drops exponentially and the rate for annihilation of X's, $\Gamma = \langle \sigma_A v \rangle \, n_X^2$ (where $\langle \sigma_A v \rangle$ is the thermally averaged total cross section for annihilation of XX into ligher particles times relative velocity), drops below the expansion rate H, the X's cease to annihilate and fall out of equilibrium, and a relic abundance remains. In Fig. 1, the equilibrium (solid line) and actual (dashed lines) abundances per comoving volume are plotted as a function of $x \equiv m_X/T$ (which increases with increasing time). As shown in the graph, as the annihilation cross section is *increased* the WIMPs stay in equilibrium longer, and we are left with a *smaller* relic abundance. Given the annihilation cross section, the relic abundance can be determined quite accurately by solving the Boltzmann equation.[15] The result is roughly

$$\Omega_X h^2 \simeq \left(\frac{\langle \sigma_A v \rangle}{3 \times 10^{-27} \, \mathrm{cm}^3 \, \mathrm{sec}^{-1}} \right)^{-1}, \tag{2}$$

where h is the Hubble parameter in units of 100 km/sec/Mpc. The result is roughly independent of the mass of the WIMP and is inversely proportional to the annihilation cross section of the WIMP; furthermore, it interesting to note that a cross section that gives $\Omega \sim 1$ is roughly a weak-scale cross section.

To summarize, given a particle-physics theory with a stable WIMP, the prescription for determining the abundance of the WIMP is straightforward: (1) calculate the cross section for annihilation of the WIMP into lighter particles, and (2) solve the Boltzmann equation, which then gives you a result in the ballpark of Eq. (2).

4. Supersymmetric Dark Matter

Although supersymmetry is a very promising idea for new physics, the practical problem is that theorists still cannot make accurate predictions (with too much confidence) about the superparticle spectrum. This should come as no surprise: although we know that Nature has an $SU(3) \times SU(2) \times U(1)$ gauge symmetry we still have no idea what the top-quark mass is. Similarly, the simple hypothesis that supersymmetry exists tells us little about the masses of the superpartners. Therefore, our goal here will be to enumerate the parameters that specify a supersymmetric theory, discuss the range of values these parameters may assume, calculate the relic abundance of the lightest superpartner (LSP) in each model, see how the abundances depend on the parameters of the model, and then try to assess how "likely" it is that the LSP makes up the dark matter in galactic halos.

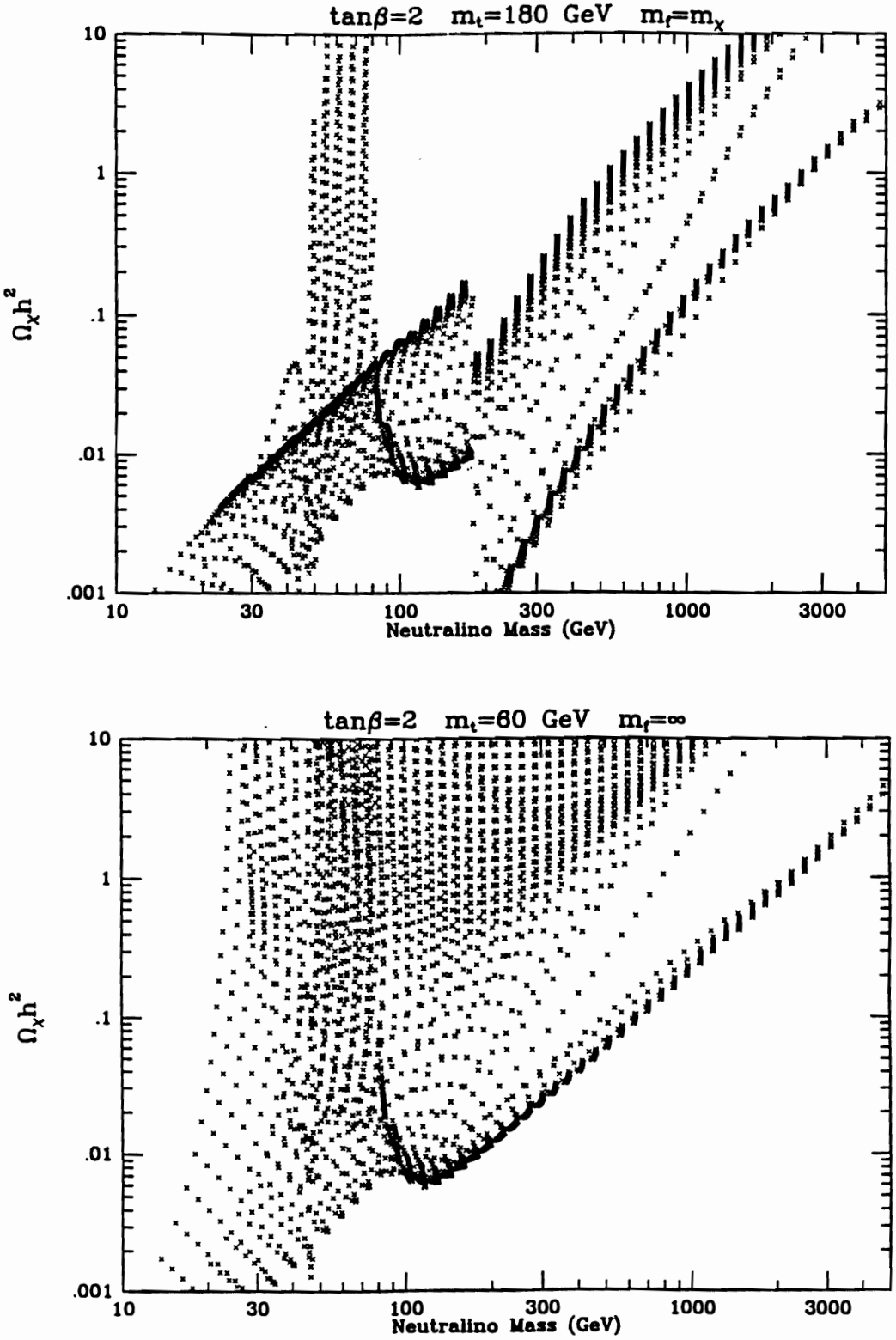
In most supersymmetric models, the lightest supersymmetric particle is the neutralino,[6] a linear combination of the photon, Z^0 and Higgs bosons. The neutralino field may be written

$$\widetilde{\chi} = Z_{n1}\widetilde{B} + Z_{n2}\widetilde{W}^3 + Z_{n3}\widetilde{H}_1 + Z_{n4}\widetilde{H}_2, \tag{3}$$

where $(Z)_{ij}$ is a real orthogonal matrix that diagonalizes the neutralino mass matrix and depends only on the gaugino and Higgsino mass parameters M and μ which are constrained only to be less than a few TeV, and on a parameter $\tan\beta$, the ratio of Higgs vacuum expectation values which lies in the range $1 < \tan\beta < m_t/m_b$ (where m_t and m_b are the top and bottom quark masses). In Fig. 2 we plot neutralino mass contours (broken curves) and contours of $Z_{n1}^2 + Z_{n2}^2$ (solid curves), the gaugino fraction, for $\tan\beta = 2$ (plots for other values of $\tan\beta$ are similar). As noted originally by Olive and Srednicki[7] in much of parameter space where the neutralino is heavier than the W, the gaugino fraction is greater than 0.99 and the neutralino is almost pure B-ino, and in much of parameter space, the gaugino fraction is less than 0.01 and the neutralino is almost pure Higgsino.

In addition to $\tan\beta$ and the gaugino and Higgsino mass parameters M and μ, in order to specify a supersymmetric model the mass of the lightest Higgs boson $m_{H_2^0}$ and the masses of the squarks, sleptons, and sneutrinos must be given resulting in a rather large parameter space to study (there is also the top-quark mass which is still undetermined); however, in order to survey the range of possible relic abundances of the neutralino we can take all the squark and slepton masses to be the same and then consider first the extreme case where the squark mass is equal to the neutralino mass (which *minimizes* the relic abundances since it *maximizes* the cross sections) and then we consider the other extreme case where the squark mass is infinite (which maximizes the relic abundances).

In Fig. 3 we plot the relic abundance $\Omega_{\tilde{\chi}}h^2$ of the neutralino versus the neutralino mass $m_{\tilde{\chi}}$. Each $\times$ represents a supersymmetric model as specified by values of M and μ taken from the regions of parameter space shown in Fig. 2. In (a) we have taken the top-quark mass $m_t = 180$ GeV near its maximum possible value and taken the squark masses to be equal to the neutralino mass; this combination yields the *minimum* relic abundance for a given M and μ. On the other hand in (b) we have taken $m_t = 60$ GeV (now below the experimentally allowed range) and the squark mass to be infinite which yields a *maximum* abundance for a given M and μ. Therefore, the relic abundance of any neutralino would lie somewhere between the values shown in (a) and (b) [and probably closer to (a)]. If we had taken a value of $\tan\beta$ larger than the value $\tan\beta = 2$ taken here our results would have been qualitatively similar, although numerically, the



3. Fig. 3. Scatter plots of $\Omega_{\tilde{\chi}} h^2$ vs neutralino mass for a wide range of models. In (a) $m_t = 180$ GeV and the squark mass is taken to be equal to the neutralino mass. In (b) $m_t = 60$ GeV and we have taken the squark mass to be infinite.

corresponding abundance for a given M and μ would generally be slightly lower. The results are highly insensitive to the value of $m_{H_2^0}$.[7]

Two important conclusions may be drawn from Fig. 3. First, if the Universe is older than 10 billion years (a conservative lower limit) then $\Omega_{\tilde{\chi}} h^2 \lesssim 1$;[15] therefore, models in which a value of $\Omega_{\tilde{\chi}} h^2$ greater than unity arise "overclose" the Universe and are therefore cosmologically inconsistent. As can be seen in Fig. 3 (and confirmed by a careful search of parameter space), neutralinos heavier than about 3 TeV are cosmologically inconsistent.[7] It is interesting to note that in order to preserve the gauge hierarchy, superparticle masses are expected to be less than a few TeV; whether this is more than a coincidence between cosmology and fundamental physics remains to be seen.

The other thing to note is that if a neutralino is to be considered a candidate for the halo dark matter it should have an abundance in the range $0.01 \lesssim \Omega_{\tilde{\chi}} h^2 \lesssim 1$, the lower limit coming from a low estimate for the fraction of closure density contributed by halos. (If $\Omega_{\tilde{\chi}} h^2 \lesssim 0.01$ it would be cosmologically consistent although too scarce to account for the dark matter in halos.) Although we cannot say anything really definite (how do you put a measure on parameter space?) looking at Fig. 3, we see that $0.01 \lesssim \Omega_{\tilde{\chi}} h^2 \lesssim 1$ arises in many (if not most) models which seems to suggest that if low-energy supersymmetry exists in Nature, then the dark matter known to exist in galactic halos is probably composed of neutralinos.

5. Energetic Neutrinos from WIMP Annihilation

Since supersymmetry may not be easily accessible in traditional accelerator experiments, whereas neutralinos may populate the halo, we are offered the intriguing prospect that supersymmetry may be discovered from astrophysical sources before it is observed terrestrially. A variety of complementary experiments to detect neutralinos in our galactic halo are currently being pursued. Some seek to observe neutralinos by detecting the energy deposited in an ultra-low background detector when a neutralino elastically scatters off of a nucleus therein.[16] Such experiments have already been used to rule out Dirac neutrinos as the primary component of the galactic halo.[17] Unfortunately, neutralino-nucleus interactions are generally much weaker than Dirac-neutrino–nucleus interactions so improvements in detector sensitivity by several orders of magnitude are required before such experiments can address supersymmetric dark matter.

Alternatively, neutralino dark matter in the galactic halo may be indirectly detected by its annihilation products. A continuum spectrum of cosmic-ray antiprotons,[18] γ rays,[19] and positrons,[20] are produced in the cascade resulting

from the annihilation products of the neutralinos; however, astrophysical uncertainties involving the propagation of cosmic rays from conventional sources are so great that it seems unlikely that WIMP-induced continuum cosmic rays could ever be distinguished from those from standard sources. Another possibility is that annihilation of WIMPs in the galactic halo could produce either γ-ray[21] or positron[22,23] line radiation which could be readily distinguished from background. While such a signal would provide unambiguous evidence for particle dark matter, because of astrophysical uncertainties an observable signal of this kind is not guaranteed even if suitable WIMPs *do* reside in the galactic halo.

Perhaps the most promising experimental route is indirect detection of heavy neutralinos by observation of yet another annihilation product: high-energy neutrinos.[24,25] WIMPs in the galactic halo will be captured in the body of the Sun or the Earth[26] and annihilate therein producing high-energy neutrinos that may be observable in underground neutrino detectors. This method of detection has several advantages over cosmic-ray signatures: First of all, whereas cosmic rays are expected to be isotropically distributed, the neutrino signal comes from a fixed direction and is therefore much more easily distinguished from background. The number density $n_{\tilde{\chi}}$ of neutralinos in the halo is inversely proportional to the neutralino mass and, as we shall see, the annihilation rate in the Sun is $\propto n_{\tilde{\chi}}$ while the annihilation rate in the halo is $\propto n_{\tilde{\chi}}{}^2$, making the neutrino signal favored for higher neutralino masses. In addition, the uncertainties in the predicted rates for neutrino events are smaller than those in the predicted cosmic-ray fluxes (roughly factors of about two for neutrino events and orders of magnitude for cosmic-ray fluxes). Basically this is because the local halo density is known better than the dark-matter distribution throughout the galaxy, and propagation of neutrinos through the Sun is more easily modeled than cosmic-ray propagation through the galaxy. We should also mention that null results of searches for energetic neutrinos from the Sun have been used to rule out Majorana neutrinos (with standard electroweak interactions), and several light supersymmetric candidates as the primary component of the galactic halo.[27]

Although determination of the rate for energetic neutrino events is relatively straightforward, it is quite lengthy and depends on a variety of input physics such as solar physics, neutrino physics, hadronization of quarks, underground detectors, and, of course, the interactions of neutralinos with ordinary matter. The flux of high-energy neutrinos of type i (*e.g.*, $i = \nu_\mu, \bar{\nu}_\mu$, etc.) from neutralino annihilation in the Sun is simply

$$\left(\frac{d\phi}{dE}\right)_i = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \left(\frac{dN}{dE}\right)_{Fi} . \tag{4}$$

The quantity Γ_A is the rate of neutralino-neutralino annihilations in the Sun, and R is simply the distance of the Earth from the Sun. Neutralinos from the galactic halo are accreted onto the Sun and their number in the Sun is depleted by annihilation. In most cases of interest these two processes come to equilibrium on a time scale much shorter than the solar age in which case $\Gamma_A = C/2$ where C is the rate for capture of neutralinos from the halo. As one might imagine, the capture rate is basically determined by the flux of neutralinos incident on the Sun and a probability for capture which in turn depends on kinematic factors and the cross sections for elastic scattering of the neutralino off of the elements in the Sun. The sum is over all annihilation channels F (*e.g.*, pairs of gauge or Higgs bosons or fermion-antifermion pairs), B_F is the annihilation branch for channel F, and $(dN/dE)_{Fi}$ is the differential energy flux of neutrino type i at the ***surface*** of the Sun expected from injection of the particles in channel F in the ***core*** of the Sun. The flux $(dN/dE)_{Fi}$ is a function of the energy of the neutrino and of the energy of the injected particles. Determination of these fluxes is quite complicated as it involves hadronization of the annihilation products, interaction of the particles in the resulting cascade with the solar medium and the subsequent interaction of high-energy neutrinos with the solar medium as they propagate from the core to the surface of the Sun.[28]

The experimental signature on which we focus is the number of upward-moving muons induced by high-energy neutrinos from the Sun that are observed in underground detectors. Given the fluxes $(d\phi/dE)_i$ the final result for the rate (per unit detector area) for neutrino-induced upward moving muons may be written simply as

$$\Gamma_{\text{detector}} = \sum_i D_i \int \left(\frac{d\phi}{dE}\right)_i E^2 dE, \tag{5}$$

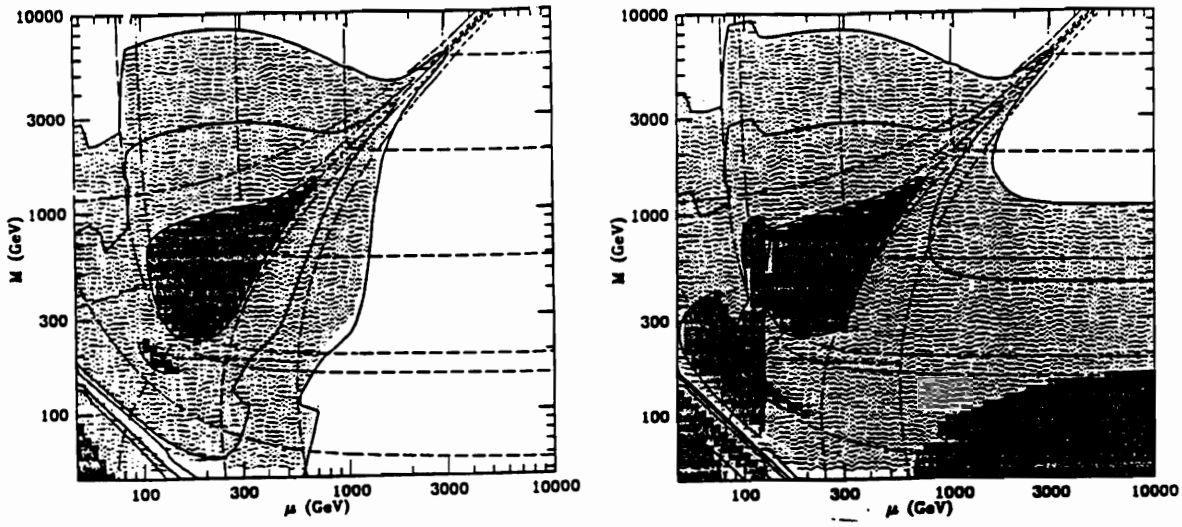
where the sum is over ν_μ, which produce muons, and $\bar{\nu}_\mu$, which produce antimuons. Since the cross section for the neutrino to produce a muon in the rock below the detector is proportional to the neutrino energy E and the range of the muon is roughly proportional to its energy, the probability a neutrino of energy E produces a muon which traverses the detector is E^2 times a constant D_i; hence the integral in Eq. (5). Neutrinos may also be detected by contained events in which a charged lepton is produced within the detector, but because this process is proportional only to the neutrino energy E (as opposed to E^2 for throughgoing events), the throughgoing muons should provide a more promising signature for heavy neutralinos.

The results we use here for purposes of illustration are from those from the IMB collaboration.[29] They obtain an upper limit on the flux of upward-moving muons induced by neutrinos from the Sun with energy larger than 2 GeV of

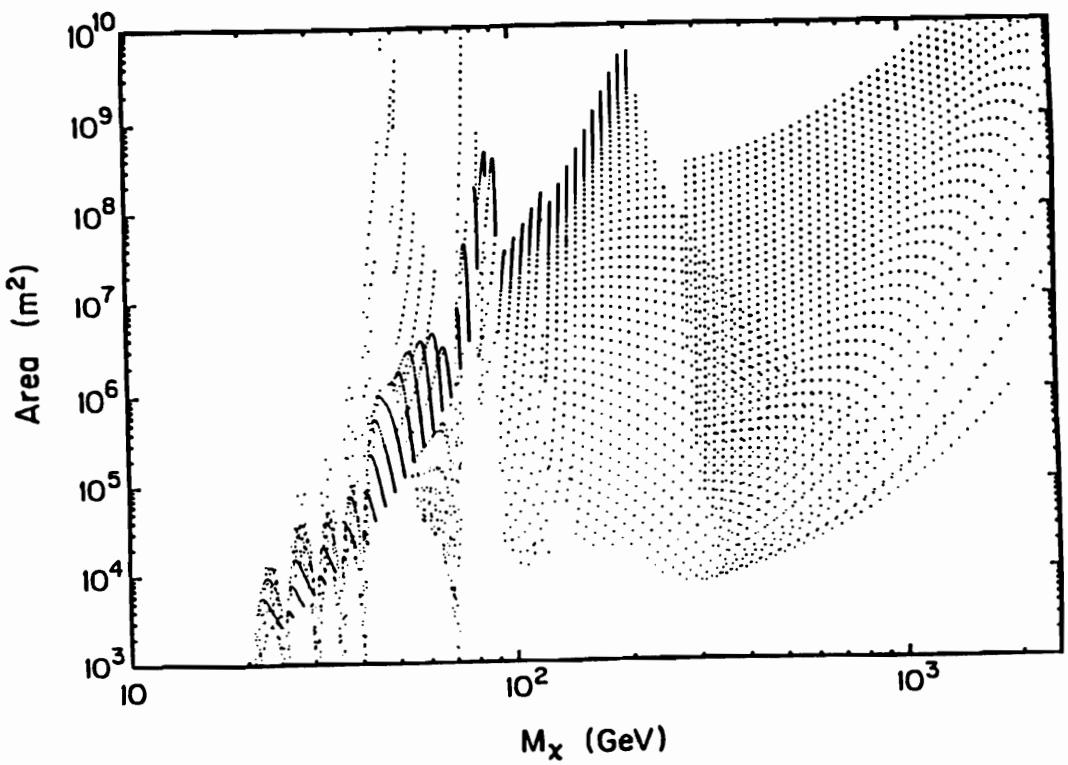
2.65×10^{-2} m^{-2} yr^{-1}. Supersymmetric models which result in larger fluxes are inconsistent candidates for the primary component of the galactic halo.[25,30] In Fig. 4 the dark shading denotes the regions of parameter space excluded by this constraint. The light shaded regions are those that would be excluded if the observational flux limits were to be improved by a factor of 100. The curve inside the light shaded areas encloses regions of parameter space that would be excluded if current observational limits were improved by a factor of 10. To indicate the sensitivity of these results to uncertainties in the calculation, the dashed curve inside the excluded region indicates the region excluded if the true neutrino rate is only 1/5 as large as our calculations indicate. In (a) $\tan\beta = 2$, $m_{H_2^0} = 35$ GeV, $m_t = 120$ GeV, the squark mass is taken to be infinite and $\mu > 0$, and (b) is similar except that we take the squark mass to be 20 GeV greater than the neutralino mass. Larger values of $m_{H_2^0}$ result in lower event rates for mixed-state neutralinos, and larger values of $\tan\beta$ or m_t result in higher event rates.

From Fig. 4, we see that limits on energetic neutrino fluxes from the Sun already exclude many supersymmetric models with heavy mixed-state neutralinos lighter than about a TeV, and models where the neutralino is a light B-ino. This is because mixed-state neutralinos have relatively strong couplings to heavy nuclei and B-inos can scatter off hydrogen in the Sun (provided the squark is not too heavy) whereas Higgsinos do not really couple to any nuclei with any appreciable strength. We see that if current flux limits are improved by factors of ten or 100 either by improved data analysis and/or increased exposure[31,32,33,34] many more models will become observable, although realistically, such experiments will never be able to probe the entire parameter space. When we note that a B-ino more massive than about 550 GeV is cosmologically inconsistent,[7] Fig. 4 suggests that if the dark matter is a B-ino, that it will most likely be discovered by the next generation of energetic-neutrino telescopes.

In order to further assess the experimental effort required to make progress in indirect detection of supersymmetric dark matter, we plot in Fig. 5 the detector size versus neutralino mass required to observe a 4σ signal in one year.[35] Each dot gives the detector size required to observe a 4σ signal in one year for a point in the M-μ plane in which the neutralino is a good dark matter candidate ($0.02 \lesssim \Omega_{\tilde{\chi}} h^2 \lesssim 1$) and in each case we have taken $\tan\beta = 2$, $m_{H_2^0} = 50$ GeV, and $m_t = 120$ GeV. The background is from from atmospheric neutrinos arriving within a 5 deg cone of the Sun. If the detector has some energy resolution then the sensitivity of the detector can be improved.[35]



4. Fig. 4. Regions where the neutralino is excluded as the primary component of the galactic halo by limits on the flux of upward-moving muons induced by energetic neutrinos from the Sun. The dark shaded regions are those excluded by current IMB limits. The light shaded regions are those those that would be excluded if the current observational limits were improved by a factor of 100, and the curve inside the the light shaded region encloses the regions is current observational limits were to be improved by a factor of ten. The curve inside the currently excluded region encloses the region that would be excluded if the true neutrino flux was actually 1/5 the result of our calculation. In (a) $\tan\beta = 2$, $m_{H_2^0} = 35$ GeV, $m_t = 120$ GeV, the squark mass is taken to be infinite, and $\mu > 0$, and (b) is similar except we take the squark mass to be 20 GeV greater than the neutralino



5. Fig. 5. Detector area required to show a 4σ signal in one year. Each dot gives the detector area required to observe a σ signal in one year for a point in the M-mu plane in which the neutralino is a good dark-matter candidate ($0.02 \lesssim \Omega_{\tilde{\chi}} h^2 \lesssim 1.0$).

6. Concluding Remarks

In this talk I have hopefully convinced you that a variety of cosmological arguments involving our current understanding of the dark-matter problem, big-bang nucleosynthesis, and notions of large-scale structure formation lead us to consider exotic dark-matter candidates. I have tried to convince you furthermore, that if a stable weakly-interacting massive particle exists, as predicted by supersymmetric theories, that an interesting cosmological relic abundance of the WIMP would arise and that it is eminently reasonable that it could account for the dark matter. I finally pointed out that if such WIMPs *do* populate the halo, there is the possibility that they could be observed via detection of energetic neutrinos from WIMP annihilation in the Sun and/or Earth.

A careful analysis shows that the properties of the heavy neutralino in many models are such that their capture and annihilation in the Sun yields an observable flux of energetic neutrinos. We should also point out that in many models, a heavy neutralino may easily make up the primary component of the galactic halo while remaining invisible to neutrino detectors, so null results from energetic neutrino searches are not likely to rule out supersymmetric dark matter. As shown in Fig. 5, detectors of scale greater than about 10^5 m^2 are required to study a significant portion of the neutralino parameter space.

It goes without saying that discovery of particle dark matter would be revolutionary to both cosmology and particle physics. I have tried to convince you that a search for energetic neutrinos from the Sun or Earth—although not guaranteed even if WIMPs *do* make up the dark matter—holds considerable promise for discovery. Certainly the rewards in case of discovery would be so overwhelming to physics that even the skeptic, given a neutrino telescope, should be eager to look for these "smoking-gun" dark-matter signatures.

7. Acknowledgements

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