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A Supersymmetric Solution to the Solar Neutrino and Dark Matter Problems

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Abstract

We show that the supersymmetric neutralino in presence of a $1 \div 2$ GeV Higgs is a good candidate for solving both the solar neutrino and dark matter problems. We also illustrate how the solution is achieved in the context of the minimal version of supergravity models.

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As it has been pointed out in ref. [1], a Weakly Interacting Massive Particle (WIMP) could simultaneously solve both the solar neutrino and dark matter problems. However, for this to be true, the WIMP should fulfil several restrictive requirements. First of all, the WIMP should be a (quasi)-stable particle with a sizable cosmological relic density in order to account for the missing mass. An efficient solar capture and energy transport requires the effective WIMP scattering cross section in the sun (σ_S) to be about:

$$\sigma_S \simeq 4 \cdot 10^{-36} cm^2 \ . \tag{1}$$

Moreover, the WIMP annihilation cross section in the sun (σ_A) must be suppressed according to

$$< \sigma_A \beta > \ \lesssim 10^{-4} \sigma_S \simeq 4 \cdot 10^{-40} cm^2 \ , \tag{2}$$

where β is the relative velocity of the annihilating particles. Finally, the WIMP should have a mass in the range of 4–10 GeV, so that it does not evaporate from the sun and leads to an efficient thermal transport. A particle satisfying all these constraints is generally called cosmion.

The elementary particle realization of this suggestive astrophysical scenario is not straightforward. The standard neutrino, photino, higgsino and sneutrino do not satisfy the above requirements[2]. In particular, $\sigma_S \simeq 4 \cdot 10^{-36} cm^2$ is difficult to be achieved, being about two orders of magnitude larger than a typical weak cross section. Moreover, for self charge-conjugate states, the inequality (2) seems problematic. Generally, a process contributing to σ_S leads also, in the crossed channel, to a contribution to σ_A of the same order of magnitude. Cosmions with a conserved quantum number and cosmic asymmetry between cosmions and anti-cosmions do not suffer from this problem.

Several explicit models have been proposed. The cosmion has been taken to be a spin 1/2 particle with a new interaction mediated either by a scalar color triplet[3] or by an extra neutral gauge boson lighter than the Z^0[4]. It has also been suggested that the cosmion is a fourth generation neutrino which interacts with matter either electromagnetically via a large anomalous magnetic moment[5] or through a very light Higgs boson[6].

In this paper, we aim at showing that the neutralino (a supersymmetric spin 1/2 neutral particle), in the presence of a light ($\simeq 1-2$ GeV) Higgs boson can behave as a cosmion, in spite of its Majorana nature. The light Higgs exchange provides the large neutralino capture cross section in the sun, eq. (1). The annihilation channels due to the Higgs couplings turn out to be p–wave suppressed. Because of the low neutralino velocity in the sun, this naturally accounts for eq. (2). With an appropriate choice of parameters, the neutralino annihilation due to the other interactions present in the theory can also be suppressed, and eq. (2) is then satisfied. We will show how the whole scheme can be consistently included in the minimal supersymmetric standard model (for a review, see ref. [7]). Although this is the model we have in mind, we will parameterize the couplings in such a way that our discussion can be extended to other versions of supersymmetric models.

In the minimal supersymmetric model, one finds four neutralinos, which are mass eigenstates, mixtures of b–ino, neutral w–ino and two higginos. Due to R–parity conservation, the lightest neutralino (χ) is stable and is a possible dark matter candidate. Its mass and its combination in terms of the four weak eigenstates,

$$\chi = \gamma_1 \tilde{b} + \gamma_2 \tilde{w} + \gamma_3 \tilde{h}_1 + \gamma_4 \tilde{h}_2 \ , \tag{3}$$

are functions of the following parameters of the theory: (i) the $SU(2)$ gaugino mass

M^1; (ii) the Higgs mixing mass μ; (iii) the ratio $v_2/v_1 \equiv \tan\beta$ of the vacuum expectation values of the two neutral Higgs bosons[2] (see ref. [7] for more details).

Let us first parameterize the scalar Higgs interaction with fermionic matter (f) and the neutralino (χ) as follows:

$$\mathcal{L}_H = \frac{g}{2}\, a_H H^0 \bar{\chi}\chi - \frac{g}{2} a_f \,\frac{m_f}{m_W}\, H^0 \bar{f} f \;. \tag{4}$$

In the context of the minimal model, we find:

$$a_f = \begin{cases} \cos\alpha/\sin\beta & for\ f = up - type \\ -\sin\alpha/\cos\beta & for\ f = down - type \end{cases} \tag{5}$$

$$a_H = (\gamma_3 \sin\alpha + \gamma_4 \cos\alpha)(\gamma_2 - \gamma_1 \tan\theta_W) \tag{6}$$

$$\cos 2\alpha \equiv \cos 2\beta \left(\frac{\cos^2 2\beta + r^2 - 2r}{\cos^2 2\beta + r^2 - 2r\cos^2 2\beta} \right) \qquad r \equiv \frac{m_{H^0}^2}{m_Z^2} \;. \tag{7}$$

The scalar Higgs exchange[8] mediates a coherent interaction between the neutralino and matter[9], according to the graph of fig. 1. The neutralino capture cross section averaged in the sun, in the non-relativistic limit, is given by[9][3]:

$$\sigma_S = \frac{G_F^2}{2\pi}\, \alpha_H \left(\frac{8}{27}\, \frac{m_\chi m_W}{m_{H^0}^2} \right)^2 \sum_i \frac{m_i^4}{(m_\chi + m_i)^2}\, X_i \;, \tag{8}$$

where, assuming three generations of quarks:

$$\alpha_H \equiv a_H^2 \,(a_d + 2a_u)^2 \tag{9}$$

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[1]We assume the usual unification relation for gaugino masses.

[2]v_2 is proportional to the up quark mass, while v_1 is proportional to the down quark mass.

[3]We can safely ignore the invariant momentum transfer t, which is vanishingly small, due to the low neutralino velocity.

The sum in eq. (8) runs over the solar elements with mass m_i and abundance X_i. Taking the hydrogen and helium fractions $X_H = .94$ and $X_{He} = .06$, the cross section (8) satisfies the constraint (1) if,

$$m_{H^0} \simeq {\alpha_H}^{1/4}\, 1.4 \div 1.7\ GeV \tag{10}$$

for m_χ in the range 4–10 GeV. This Higgs is in general heavier than the one needed in ref. [6], since we have traded a Yukawa coupling with a gauge coupling in the cosmion–Higgs interaction. Then, the cross section (8) is about $\alpha_H \frac{m_W^2}{m_\chi^2}$ times larger than the analogous one obtained in ref. [6].

Given the large cross section (8), one might expect a correspondingly large annihilation rate for the Majorana neutralinos. Actually, the interactions (4) are sources of annihilation through the graphs shown in fig. 2. Nevertheless, the neutralino pair in the initial state is, in s–wave, CP odd, while H^0 is CP even. If CP is not violated, the processes of fig. 2 are forbidden in s–wave. Because of the low neutralino velocity in the sun ($\beta \simeq 10^{-3}$), this can provide an explanation for eq. (2).

The graphs of fig. 2 yield the following annihilation rates (in the non–relativistic approximation):

$$< \sigma_A \left(\chi\chi \to f\bar{f}\right) \beta >= \frac{g^4}{32\pi} \sum_f c_f \frac{a_H^2 a_f^2}{m_\chi^2} \frac{m_f^2}{m_W^2} \frac{\left(1 - \frac{m_f^2}{m_\chi^2}\right)^{3/2}}{(4-x)^2} \beta^2 \tag{11}$$

$$< \sigma_A \left(\chi\chi \to H^0 H^0\right) \beta >= \frac{g^4}{24\pi} \frac{a_H^4}{m_\chi^2} \frac{(9 - 8x + 2x^2)(1-x)^{1/2}}{(2-x)^4} \beta^2 , \tag{12}$$

where $x \equiv \frac{m_{H^0}^2}{m_\chi^2}$ and c_f is the fermion color factor. The β^2 factor in eqs. (11)–(12) is the signal of the above–mentioned p–wave suppression.

The annihilation rates (11) and (12) have to satisfy eq. (2). However, a more stringent constraint comes from the requirement of a correct relic abundance of neutralinos as dark matter candidates. Their contribution to the present energy density of the universe if approximately given by

$$\Omega_\chi h^2 \simeq \frac{2 \cdot 10^{-37} cm^2}{< \sigma_A \beta >_f} , \tag{13}$$

where h is the Hubble constant in units of 100 km sec^{-1} Mpc^{-1}. The annihilation rate in eq. (13) is evaluated at the neutralino freeze–out temperature.

Now, we want the neutralino mass density to exceed the baryon cosmic density, without overclosing the universe, i.e.,

$$0.025 \lesssim \Omega_\chi h^2 \lesssim 1. \tag{14}$$

Because of the p–wave suppression, we can simply rescale the annihilation rate and, from eq. (13), obtain that (14) implies

$$2 \cdot 10^{-43} cm^2 \lesssim < \sigma_A \beta > \beta_f^2 \lesssim 8 \cdot 10^{-42} cm^2, \tag{15}$$

where $< \sigma_A \beta >$ has to be evaluated in the sun ($\beta \simeq 10^{-3}$) and β_f is the neutralino freeze–out velocity. Note that if eq. (15) holds, then eq. (2) is automatically satisfied. Using the expressions (11–12) for $< \sigma_A \beta >$, eq. (15) roughly corresponds to the bound:

$$10^{-3} \lesssim a_H^2 \lesssim 10^{-1}. \tag{16}$$

Therefore, we have shown that if the Higgs–neutralino coupling constant a_H lies in the range (16), then (i) a Higgs scalar with mass $m_{H^0} \simeq 1 - 2$ GeV mediates the correct solar capture cross section, eq. (1); (ii) the neutralino annihilation in the sun due to the presence of the light Higgs is safely suppressed; (iii) the neutralino has the correct relic density to account for dark matter.

Of course, the neutralino feels all the other interactions of the full supersymmetric theory, besides those in eq. (4). Then, we turn to discuss how the suppression of the annihilation rate, eq. (2), can be achieved in the complete model.

Squarks and sleptons can mediate the process $\chi\chi \to f\bar{f}$ through t-channel exchange. Eq. (2) is satisfied only if the sfermions are heavy enough. We derive the limit on their masses assuming that all squarks and sleptons are degenerate and taking the neutralino as a pure photino state[4]. This is a good approximation for our purpose, since the couplings of the higgsino components are suppressed by factors of $\frac{m_f}{m_W}$. In the non-relativistic limit, the exchange of sfermions with mass $\tilde{m}$ gives

$$< \sigma_A \left(\tilde{\gamma}\tilde{\gamma} \to f\bar{f}\right) \beta >= \frac{8\pi\alpha^2}{\tilde{m}^4} \sum_f c_f\, Q_f^4\, m_f^2 \sqrt{1 - \frac{m_f^2}{m_\chi^2}}\,. \qquad (17)$$

Q_f and c_f are respectively the electric charge and the color factor for the fermions allowed by phase space. The annihilation rate (17) satisfies the constraint (2) if:

$$\tilde{m} \gtrsim 280\ GeV. \qquad (18)$$

This is a fairly reasonable value for sfermion masses in standard supergravity models.

Z^0-exchange in the s-channel can also contribute to $\chi\chi \to f\bar{f}$. In the non-relativistic limit, the annihilation rate is:

$$< \sigma_A \left(\chi\chi \to f\bar{f}\right) \beta >= \frac{G_F^2}{4\pi}\, a_Z^2 \sum_f c_f\, m_f^2 \sqrt{1 - \frac{m_f^2}{m_\chi^2}}\,. \qquad (19)$$

a_Z is the coupling constant of the $Z^0\chi\chi$ interaction term:

$$\frac{g}{4\cos\theta_W}\, a_Z\, Z_\mu\, \bar{\chi}\, \gamma^\mu\, \gamma_5\, \chi \qquad (20)$$

[4]For more general formulae, see ref. [10].

and, in the minimal model, is given by

$$a_Z = \gamma_3^2 - \gamma_4^2, \tag{21}$$

where the parameters γ_i have been defined in eq. (3).

Eq. (19) shows the well-known p-wave suppression for the annihilation into massless fermions, due to the Majorana nature of neutralinos[11]. However, this suppression is, for heavy fermions, not sufficient to accomplish eq. (2). It is then necessary to require

$$a_Z^2 \lesssim 10^{-3} \,. \tag{22}$$

We want to show now that, even in the minimal supersymmetric model, the proposed scheme is consistent. In other words, we check that the existence of a neutralino with mass 4–10 GeV is compatible with conditions (16) and (22). This is true in two different situations.

1^0 Solution: The neutralino is a "quasi-photino" state. Then, the mass parameter M is small with respect to μ and m_Z, leading automatically to a light neutralino. The higgsino components γ_3, γ_4 are small and a_Z is suppressed, see eq. (21). As a_H and a_Z vanish respectively linearly and quadratically with γ_3, γ_4 (see eqs. (6),(21)), eqs. (16) and (22) can be simultaneously satisfied. Large values of v_2/v_1 are needed, in agreement with the expectation of the radiative electroweak symmetry breaking in supergravity models with a heavy top quark. Since the second factor of eq. (9) grows about quadratically with v_2/v_1, even if a_H is small, α_H is of order one, and we expect $m_{H^0} = 1 \div 2$ GeV from eq. (10). Under these conditions, the main annihilation channel for primordial neutralinos is $\chi\chi \to b\bar{b}$ through Higgs exchange, which correctly leads to $\Omega_\chi \simeq 0.1 \div 1$.

2^0 Solution: The neutralino parameters are close to the condition

$$\mu = \left(\frac{\cos^2 \theta_W}{M} + \frac{\sin^2 \theta_W}{M'} \right) \sin 2\beta \, m_Z^2 \, , \tag{23}$$

where M' is the $U(1)$ gaugino mass. When this relation holds, the neutralino mass matrix becomes singular[12]. In the vicinity of equality (23), one neutralino state is light. Now, the higgsino components are not necessarily small, but they are related by

$$\gamma_3 \simeq -\gamma_4 \tan \beta \, . \tag{24}$$

If $v_2/v_1 \simeq 1$, eq. (24) entails the suppression of a_Z. a_H is not suppressed and turns out to be much larger than in the previous case. Therefore, $\chi\chi \rightarrow H^0 H^0$ is the main annihilation channel of primordial neutralinos. We find that this rate can be rather large but, due to the uncertainty on h, can still lead to a sizeable neutralino relic density. Again, α_H is of order one and we obtain $m_{H^0} \simeq 1 \div 2$ GeV.

We have checked numerically that both previous solutions provide the expected suppression of a_Z in the correct range for m_χ and a_H. In table 1, we show a sample of neutralino parameters that fulfil these requirements. The values in the table reflect the main features of the two different solutions we have just illustrated.

Next, we examine the annihilation processes due to light pseudoscalars. These particles have the right CP quantum number for contributing to the annihilation of neutralinos in s-wave. The relevant processes are $\chi\chi \rightarrow f\bar{f}$ through pseudoscalar exchange or scalar–pseudoscalar pair production via Z^0 or neutralino exchange.

The minimal supersymmetric model contains one pseudoscalar. Since its coupling with the neutralino is deeply connected to the $H^0\chi\chi$ coupling, the only way to get rid of the pseudoscalar contribution is by taking it sufficiently heavy. From $\chi\chi \rightarrow f\bar{f}$

mediated by the pseudoscalar, we find that its mass should be larger than about 200 $\div$ 300 GeV.

In the case of Solution 1, the large v_2/v_1 and the small m_{H^0} necessarily imply that the pseudoscalar is approximately degenerate with the scalar and therefore very light. If one insists in large values of v_2/v_1, one has to enlarge the Higgs sector (extra gauge singlet, more Higgs doublets,...) in order to avoid the relation between scalar and pseudoscalar masses. On the contrary, the scenario envisaged in solution 2 predicts exactly the correct Higgs mass spectrum. If $v_2/v_1 \simeq 1$, one Higgs scalar is forced to be very light (few GeV), while the pseudoscalar gets very heavy (hundreds GeV).

The last remark concerns the limits on light Higgs bosons. Theoretically, there is no lower bound on the Higgs mass in a two doublet model. As discussed in ref. [13], due to theoretical uncertainties, experimental data on B decays are not able to rule out a Higgs of 1–2 GeV. It is also premature to exclude such a Higgs from the unsuccessful search for $\Upsilon \to H^0\gamma$[14], since higher order QCD corrections can easily affect the result. However, if $v_2/v_1 \gg 1$, the light Higgs has an enhanced coupling with down-type quarks and thus it can certainly be excluded by CUSB experiment[14]. Therefore, Solution 1 has to be discarded, while Solution 2 is fully consistent.

We should also stress that the "quasi–photino" solution has the potential problem of having a too light chargino (10–20 GeV) and, assuming the usual unification relation for gaugino masses, a too light gluino (40–60 GeV). On the contrary, Solution 2 predicts a heavy gluino ($\simeq$ 300 GeV) and a chargino in the interesting mass range of 30–40 GeV. Therefore, since squarks, sleptons and gluinos are rather heavy and the lightest neutralino is mostly decoupled from the Z^0, we expect chargino pair production at LEP to be one of the crucial tests for the model.

In conclusion, we have described a scenario in which the supersymmetric neutralino is a good dark matter candidate and simultaneously solves the solar neutrino problem. The scheme works as follows.

If the neutralinos are sufficiently concentrated in the sun, they affect the solar core temperature and reduce the flux of the observed ^8B neutrinos. In order to do so, the neutralino should have a mass of 4–10 GeV, large cross section and small annihilation rate in the sun.

The exchange of a Higgs scalar with mass 1–2 GeV yields a capture cross section in the correct range. Such a light Higgs lies within an experimentally allowed window. The contribution to the annihilation from the same Higgs interaction vanishes in s–wave and thus it is strongly suppressed.

This p–wave suppression is less effective for primordial neutralinos which are much hotter than the neutralinos captured by the sun. Then, the annihilation from Higgs interaction leads to a neutralino relic density which correctly accounts for dark matter.

The contributions to the annihilation coming from forces mediated by squarks, sleptons and Higgs pseudoscalars are small enough if these particles are heavier than few hundreds GeV. The Z^0–exchange is suppressed by inhibiting the $Z^0\chi\chi$ coupling.

This scheme can be implemented in the minimal supersymmetric standard model if the neutralino mass parameters approximately satisfy eq. (23) with $v_2/v_1 \simeq 1$. Then, the neutralino is light and has suppressed couplings with the Z^0. The appropriate Higgs mass spectrum is also automatically predicted.

Experiments looking for dark matter, light Higgs bosons and supersymmetric particles can all very well test the validity of the scenario we have proposed.

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Table 1: Values of the neutralino parameters $M, \mu, v_2/v_1$ which lead to a possible cosmion solution.

Solution	M	μ	v_2/v_1	m_χ	a_H^2	a_Z^2	α_H
1^0	10	-150	20	5	3.10^{-3}	9.10^{-4}	1.2
	15	-120	10	8	2.10^{-3}	8.10^{-4}	0.2
2^0	80	150	1.1	4	2.10^{-1}	5.10^{-4}	1.8
	105	130	1.1	10	2.10^{-1}	7.10^{-4}	2.0

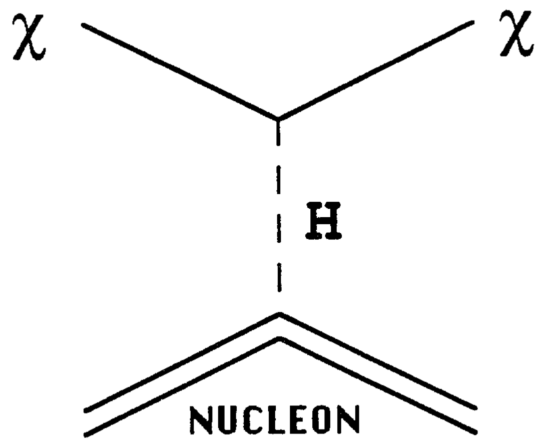

FIG. 1

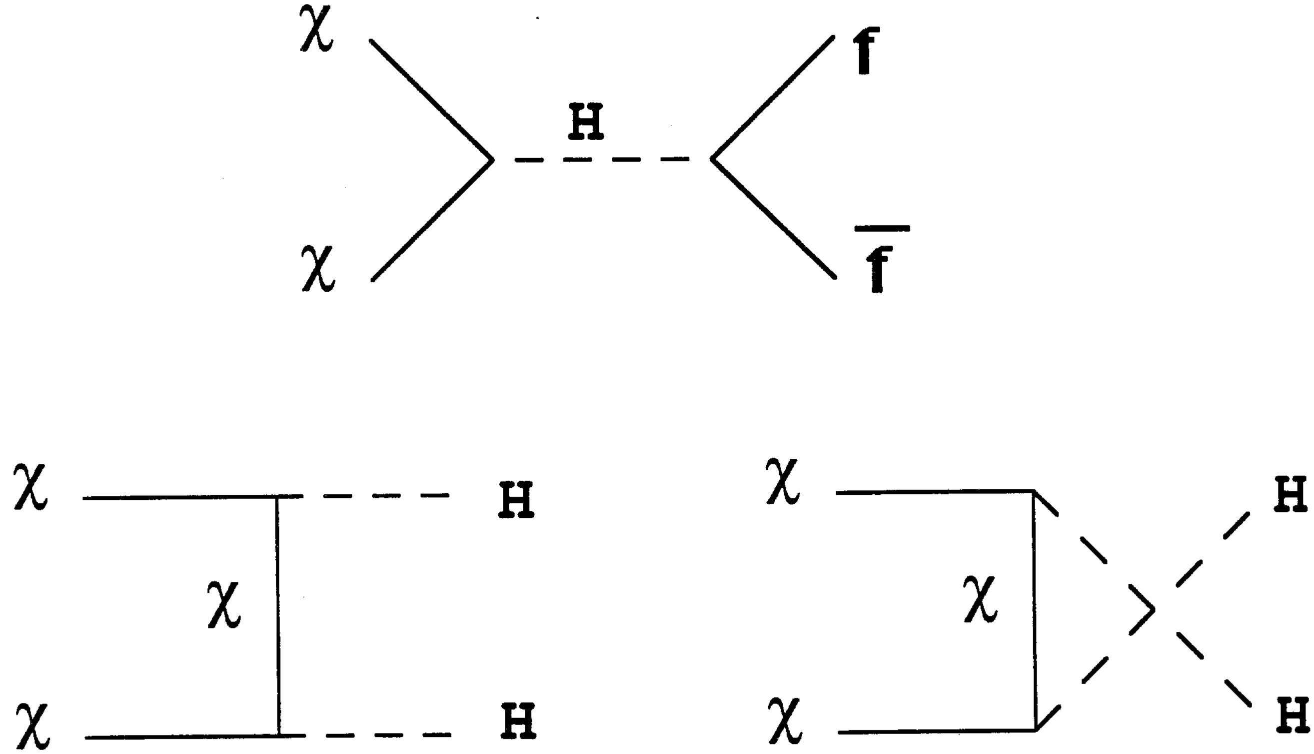

FIG. 2