CERN-TH/96-171

Dark Matter in Theories of Gauge-Mediated Supersymmetry Breaking

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Abstract

In gauge-mediated theories supersymmetry breaking originates in a strongly interacting sector and is communicated to the ordinary sparticles via SU(3)×SU(2)×U(1) carrying "messenger" particles. Stable baryons of the strongly interacting supersymmetry breaking sector naturally weigh ~ 100 TeV and are viable cold dark matter candidates. They interact too weakly to be observed in dark matter detectors. The lightest messenger particle is a viable cold dark matter candidate under particular assumptions. It weighs less than 5 TeV, has zero spin and is easily observable in dark matter detectors.

CERN-TH/96-171
July 1996

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An attractive feature of the minimal supersymmetric theory is the existence of a stable particle, usually a neutralino, which can be the dark matter of the universe. Recently there has been a resurgence of interest in theories where the breaking of supersymmetry originates at low energies and is communicated to the ordinary sparticles via the usual gauge forces [1]–[4]. In these gauge-mediated theories the lightest sparticle is the gravitino and all other sparticles, including the neutralino, decay into it in a cosmologically short time. In theories where the supersymmetry-breaking scale $\sqrt{F}$ is low, less than 100 TeV, the gravitino mass $m_{3/2} \simeq 4$ eV $\times F/(100\ \text{TeV})^2$ is too small to give a significant contribution to the present energy density of the universe [1]. Such low values of F are favored in theories with only one mass scale; in addition, the interpretation of the Fermilab $e^+e^-\gamma\gamma + \not{E}_T$ event in the context of gauge-mediated theories requires $\sqrt{F} \lesssim 10^3$ TeV [3].

In gauge-mediated supersymmetric theories there are two new sectors with possibly stable particles which can act as cold dark matter candidates.

1) The secluded sector. This is the strongly interacting sector in which supersymmetry is dynamically broken.

2) The messenger sector. This contains fields charged under the $SU_3 \times SU_2 \times U_1$ gauge interactions which communicate supersymmetry breaking to the ordinary sparticles.

The secluded sector often has accidental global symmetries analogous to baryon number. The lightest secluded "baryon" B_φ is stable and a good candidate for cold dark matter, provided that the scale of supersymmetry breaking is in the range of $\sqrt{F} \sim 100$ TeV already favoured by both theory and the Fermilab event. The relic abundance of B_φ is determined from its annihilation cross section into "mesons" (*i.e.* other strongly interacting particles not carrying the conserved quantum number) lighter than B_φ. The B_φ annihilation occurs via the strong interactions and we can estimate an upper bound on the cross section using unitarity. This implies a bound on the B_φ relic abundance [7]

$$\Omega_{B_\varphi} h^2 \gtrsim (m_{B_\varphi}/300\ \text{TeV})^2\ . \tag{1}$$

Therefore a strongly-interacting particle with a mass in the 100 TeV range can be a good cold dark matter candidate. Direct detection of the B_φ is not possible. Particles in the secluded sector do not carry ordinary gauge quantum numbers, and therefore B_φ can only interact with nuclear matter via loop diagrams mediated by messenger fields. The resulting cross section is unobservable with present techniques.

The lightest messenger field is also a possible candidate for cold dark matter. Indeed, if the supersymmetry-breaking sector contains only singlets under the $SU_3 \times SU_2 \times U_1$ gauge interactions and if there are no direct couplings between the ordinary and messenger sectors, then the theory conserves a global quantum number carried only by messenger fields. These hypotheses are fairly generic in models with natural flavour conservation. The messenger quantum number is typically conserved also by the new interactions which generate the μ and B_μ parameters of

[1]The gravitino can be a warm dark matter candidate if $m_{3/2} \sim$ keV [5], corresponding to $\sqrt{F} \sim 2 \times 10^3$ TeV. A cold dark matter component can be obtained from non-thermal gravitinos produced in decay processes, but only at the price of unconventional choices of the relevant parameters [6].

the Higgs sector [4]. Therefore the lightest messenger is expected to be stable and can populate the present universe as a relic of the hot primordial era.

The messenger sector consists of pairs of chiral supermultiplets $\Phi+\bar{\Phi}$, each pair describing a Dirac fermion with mass M and two complex scalar particles with mass squared $M^2 \pm F$. The cold dark matter candidate is the lightest of these scalars. Its gauge quantum numbers can be predicted if we assume that messengers belong to complete GUT representations, as to preserve the success of gauge coupling unification. The requirement of gauge-coupling perturbativity up to the GUT scale restricts the choice of messenger representations to $\mathbf{5}+\overline{\mathbf{5}}$ or $\mathbf{10}+\overline{\mathbf{10}}$ of SU_5 or $\mathbf{16}+\overline{\mathbf{16}}$ of SO_{10}. Gauge interactions split the mass spectrum of messengers belonging to the same GUT representation. For each irreducible $SU_3\times SU_2\times U_1$ representation a, the mass parameters M_a and $\sqrt{F_a}$ at the scale Q are related to the common value M and $\sqrt{F}$ of the GUT multiplet by a one-loop renormalization-group scaling

$$\frac{F_a(Q)}{F}=\frac{M_a(Q)}{M}=\prod_{i=1}^{3}\left[\frac{\alpha_i(Q)}{\alpha_i(M_{GUT})}\right]^{-2\frac{C_i}{b_i}} . \tag{2}$$

Here $C=\frac{N^2-1}{2N}$ for the N-dimensional representation of SU_N, and $C=Y^2$ ($Y=Q-T_3$) for the U_1 factor. Also b_i are the β-function coefficients $b_3=-3+n$, $b_2=1+n$, $b_1=11+5n/3$, and n counts the messenger contribution ($n=1,3,4$ for each $\mathbf{5}+\overline{\mathbf{5}}$, $\mathbf{10}+\overline{\mathbf{10}}$, and $\mathbf{16}+\overline{\mathbf{16}}$, respectively). Perturbativity of α_{GUT} at M_{GUT} implies $n\leq 4$.

Scalar particles within the same isospin multiplet are split at tree level by the SU_2 D-terms. Including these contributions, the mass eigenvalues of the two spin-zero messenger states are:

$$M^2\pm\sqrt{F^2+(T_3-Q\sin^2\theta_W)^2M_Z^4\cos^2 2\beta} , \tag{3}$$

where T_3 and Q are the corresponding third-component isospin and electric charge, and $\tan\beta$ is the usual ratio of Higgs vacuum expectation values. As the tree-level splitting inside the SU_2 multiplet is proportional to M_Z^4, it is important to include also one-loop corrections proportional to M_Z^2. In the limit $F,\ M^2-F\gg M_Z^2$, the correction to the mass difference between the lightest electric charged (φ^+) and neutral (φ^0) messenger is

$$\delta(m^2_{\varphi^+}-m^2_{\varphi^0})=\frac{\alpha}{4\pi}M_Z^2\left[4\ln\left(\frac{F}{M^2-F}\right)-\ln\left(\frac{M^2+F}{M^2-F}\right)+\frac{2F}{M^2-F}\ln\left(\frac{2F}{M^2+F}\right)-4\right] . \tag{4}$$

From this we find that the neutral component is lighter than the charged one only if F/M^2 is very close to one, where the one-loop correction in eq. (4) is positive and large, or if F/M^2 is very close to zero, where the tree-level result in eq. (3) dominates.

From eqs. (2)–(4) we conclude that in the three cases under consideration, *(i)* $\mathbf{5}+\overline{\mathbf{5}}$, *(ii)* $\mathbf{10}+\overline{\mathbf{10}}$, *(iii)* $\mathbf{16}+\overline{\mathbf{16}}$, the lightest scalar messenger is respectively: *(i)* the neutral or charged component of a weak doublet (depending on the value of F/M^2), *(ii)* a weak singlet with one unit of electric charge, *(iii)* an $SU_3\times SU_2\times U_1$ singlet [2].

[2]This conclusion can be evaded if messengers belonging to the same GUT multiplet have different masses at the unification scale. This can happen in non-minimal GUTs without spoiling gauge coupling unification [8].

Case *(ii)* is unacceptable, as it corresponds to charged dark matter [9]. It also leads to overclosure of the universe for typical values of the messenger masses. In case *(iii)*, the singlet φ decouples when it is still relativistic and largely overpopulate the universe:

$$\Omega_\varphi h^2 \simeq 7 \times 10^{10} \left(\frac{m_\varphi}{100 \text{ TeV}} \right) . \tag{5}$$

As the singlet decouples at temperatures close to M_{GUT}, it can be diluted by a period of inflation occurring below the GUT scale. However the next-to-lightest messenger, which is a charged isosinglet with mass m and lifetime $\tau \sim 10^{10}$ yrs $(100 \text{ TeV}/m)^5$ gives rise to an unacceptable distortion of the diffuse cosmic ray background [10].

Case *(i)* is the most promising one and we discuss it in some detail. Let us consider values of F/M^2 such that the neutral component of the weak doublet is lighter than the charged one. The lightest messenger decouples from the thermal bath when it is non-relativistic and its relic abundance is determined by its annihilation cross section. As it is apparent from eqs. (3)–(4), the lightest messenger is almost degenerate in mass with its isodoublet companion. Also, if $F \ll M$, the mass splitting between the lightest messenger and the scalar or fermionic particles belonging to the same supermultiplet can be much smaller than the freeze-out temperature. In this case one should consider the simultaneous co-annihilation [11] of all quasi-degenerate species in the early universe. However, since all these particles have comparable annihilation cross sections, it is perfectly adequate to follow the cosmological fate of the lightest messenger alone (see discussions in ref. [11]).

The thermal average of the messenger annihilation cross section times the collision velocity v, in the non-relativistic limit, is given by

$$\begin{aligned}
\langle \sigma(\varphi\varphi^* \to Z^0 Z^0) v \rangle &= \frac{g^4}{128\pi \cos^4\theta_W m_\varphi^2} \left(1 - \frac{7}{2x}\right) , \\
\langle \sigma(\varphi\varphi^* \to W^+ W^-) v \rangle &= \frac{g^4}{64\pi m_\varphi^2} \left(1 + \frac{1 - 4\cos^2\theta_W - 44\cos^4\theta_W}{16\cos^4\theta_W x}\right) , \\
\sum_{i,j=1}^{3} \langle \sigma(\varphi\varphi^* \to H_i^0 H_j^0) v \rangle &= \frac{g^4}{1024\pi \cos^4\theta_W m_\varphi^2 x} , \\
\langle \sigma(\varphi\varphi^* \to H^+ H^-) v \rangle &= \frac{g^4 \cos^2 2\theta_W}{1024\pi \cos^4\theta_W m_\varphi^2 x} , \\
\sum_{i=1}^{3} \langle \sigma(\varphi\varphi^* \to H_i^0 Z^0) v \rangle &= \frac{g^4}{1024\pi \cos^4\theta_W m_\varphi^2 x} , \\
\sum_{i,j=1}^{4} \langle \sigma(\varphi\varphi^* \to \chi_i^0 \chi_j^0) v \rangle &= \frac{g^4}{32\pi \cos^4\theta_W m_\varphi^2} \left[\frac{r}{(1+r)^2} + \frac{1 - 12r - 42r^2 + 4r^3 + r^4}{8(1+r)^4 x}\right] , \\
\sum_{i,j=1}^{2} \langle \sigma(\varphi\varphi^* \to \chi_i^+ \chi_j^-) v \rangle &= \frac{g^4}{16\pi m_\varphi^2} \left[\frac{r}{(1+r)^2} + \frac{1 - 26r^2 + r^4}{4(1+r)^4 x} + \frac{\cos^2 2\theta_W}{16\cos^4\theta_W x}\right] , \\
\langle \sigma(\varphi\varphi^* \to f\bar{f}) v \rangle &= \frac{g^4}{128\pi \cos^4\theta_W m_\varphi^2} N_c \left[(Q\sin^2\theta_W - T_3)^2 + (Q\sin^2\theta_W)^2\right] \frac{1}{x} ,
\end{aligned}$$

$$\langle\sigma(\varphi\varphi^* \to \tilde{f}\tilde{f}^*)v\rangle \;\; = \;\; \frac{g^4}{256\pi\cos^4\theta_W m_\varphi^2} N_c(Q\sin^2\theta_W - T_3)^2 \frac{1}{x} \; . \tag{6}$$

For the annihilation channels into neutral Higgs bosons (H^0), neutralinos (χ^0), and charginos ($\chi^\pm$), we have summed over all possible final states. Here f ($\tilde{f}$) denote a generic (s)quark ($N_c = 3$) or (s)lepton ($N_c = 1$) with electric charge Q and third isospin component T_3. Finally m_φ is the mass of the lightest scalar messenger, $r = M^2/m_\varphi^2$, $x = m_\varphi/T$, and T is the temperature of the annihilating particle.

The freeze-out temperature T_f is defined as the temperature at which the annihilation rate is equal to the expansion rate, and it is given by ($x_f = m_\varphi/T_f$)

$$x_f = \ln\left[\frac{0.076}{\sqrt{g_*}}\frac{M_{Pl}}{m_\varphi}\left(A + \frac{B}{x_f}\right)\frac{\sqrt{x_f}}{x_f - \frac{3}{2}}\right] \; , \tag{7}$$

where the total annihilation cross section has been parametrized as

$$\langle\sigma(\varphi\varphi^* \to \text{anything})v\rangle = \frac{1}{m_\varphi^2}\left(A + \frac{B}{x}\right) \; . \tag{8}$$

We find that x_f varies between 24 and 20, as we vary m_φ between 1 and 100 TeV.

The messenger relic abundance in units of the critical density is

$$\Omega_\varphi h^2 = \frac{8.5\times 10^{-5}}{\sqrt{g_*}}\left(\frac{m_\varphi}{\text{TeV}}\right)^2 \frac{x_f}{A + \frac{B}{2x_f}}, \tag{9}$$

where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. Here g_* is the effective number of degrees of freedom in thermal equilibrium at the decoupling temperature and it is equal to 228.75, if we sum over the complete spectrum of the minimal supersymmetric model.

If we require $\Omega_\varphi h^2 < 1$, we obtain from eq. (9) an upper bound on m_φ of about 5 TeV. If the messenger sector consists of n families of $\mathbf{5} + \overline{\mathbf{5}}$ that do not mix with each other, we have a conserved quantum number for each family and then n stable particles. In this case, $\Omega_\varphi h^2 < 1$ leads to the constraint

$$\sum_{i=1}^{n} m_{\varphi_i}^2 \lesssim (5 \text{ TeV})^2 \; . \tag{10}$$

However if there are mixing terms between the n families of messengers, the heavy families will decay to the lightest one. The 5 TeV upper bound will only apply to the mass of the lightest scalar.

The mass difference $m_{\varphi^+}^2 - m_{\varphi^0}^2$ between the charged and neutral components of the SU_2 doublet is so small that the φ^+ decay width is strongly suppressed by phase space:

$$\Gamma(\varphi^+ \to \varphi^0 e^+ \nu) = \frac{G_F^2}{15\pi^3}\left(m_{\varphi^+} - m_{\varphi^0}\right)^5 \; . \tag{11}$$

A late φ^+ decay will inject energetic particles in the primordial thermal bath, potentially destroying the successful predictions from nucleosynthesis. We therefore require that the φ^+ lifetime is shorter than about a second; eq. (11) then implies

$$m_{\varphi^+} - m_{\varphi^0} \gtrsim 5 \text{ MeV} . \tag{12}$$

This constraint singles out only two small regions of F where the lightest neutral messenger can be the dark matter. The first one corresponds to $\sqrt{F} \lesssim 350$ GeV, where the tree-level splitting in eq. (3) is large enough to satisfy eq. (12). The second one corresponds to $F/M^2 \gtrsim 0.95$, where the one-loop correction in eq. (4) is enhanced by a large logarithm. We recall that the stability of the messenger vacuum requires $F/M^2 < 1$. In the whole intermediate range of F/M^2, either φ^+ is lighter than φ^0, or its lifetime is too long.

A lower bound on the messenger mass scale can be derived from the negative experimental searches on supersymmetric particles. It is therefore necessary to check whether this bound is consistent with the cosmological constraint. For our purpose, the most relevant limits come from sneutrino and right-handed selectron searches at LEP1[3]. Their masses can be expressed as a function of M and F, assuming that all n messengers carry the same value of F and M:

$$\tilde{m}^2_{e_R} = \frac{10}{3}\left(\frac{\alpha}{4\pi\cos^2\theta_W}\right)^2 n\frac{F^2}{M^2} f(F/M^2) - M_Z^2 \sin^2\theta_W \cos 2\beta \,, \tag{13}$$

$$\tilde{m}^2_{\nu_L} = \frac{1}{6}\left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{9}{\sin^4\theta_W} + \frac{5}{\cos^4\theta_W}\right) n\frac{F^2}{M^2} f(F/M^2) + \frac{M_Z^2}{2}\cos 2\beta \,. \tag{14}$$

Here $f(F/M^2)$ describes the exact result of the two-loop integration

$$f(x) = \left\{\frac{(1+x)}{x^2}\left[\ln(1+x) - 2Li\left(\frac{x}{1+x}\right) + \frac{1}{2}Li\left(\frac{2x}{1+x}\right)\right] + (x \to -x)\right\} , \tag{15}$$

and it is normalized such that $f(0) = 1$. The requirement that eqs. (13) and (14) simultaneously satisfy $\tilde{m}_{e_R}, \tilde{m}_{\nu_L} > M_Z/2$ implies

$$\frac{F}{M}\sqrt{nf(F/M^2)} > 20 \text{ TeV} . \tag{16}$$

For $n \leq 4$ (which is the maximum allowed by perturbativity of α_{GUT}), this bound is inconsistent with the cosmological condition $\Omega_\varphi h^2 < 1$, unless $F/M^2 \gtrsim 0.87$. It is interesting to notice that the experimental limit in eq. (16) selects the same region of parameters allowed by the constraint on the φ^+ lifetime. Indeed for $M \gtrsim 10$ TeV (with $n = 4$) or $M \gtrsim 20$ TeV (with $n = 1$) and $F/M^2 \gtrsim 0.95$, all constraints can be simultaneously satisfied and the lightest messenger is an acceptable dark matter candidate.

The constraint in eq. (16) can be relaxed if the messengers have different masses M_i ($i = 1, ..., n$), splittings F_i and small mixings to each other. The dark matter candidate can be

[3] The limit on the right-handed selectron mass from LEP1.5 critically depends on the nature of the neutralino and therefore it is not of general validity.

the lightest of these messengers into which the rest can decay via their small mixings. If the lightest messenger has a ratio F/M which is significantly smaller than the corresponding ratios for the other messengers, then it does not sizeably contribute to sparticle masses and is not constrained by eq. (16). Conversely, the contribution to the sparticle masses depend on messengers with large F/M that are unstable and, consequently, are not directly constrained from cosmology. This scenario seems quite generic and decouples the relic abundance and spectroscopic constraints, allowing for the possibility that a messenger with $\sqrt{F} < 350$ GeV forms the dark matter. Such small values of F are not unnatural and do not require any fine tunings. Generic superpotentials often result in singlets with vanishing F-terms.

We have seen that the lightest messenger in the $\mathbf{5}+\overline{\mathbf{5}}$ SU$_5$ representation is a viable cold dark matter particle if the mass parameters satisfy the requirements described above. This possibility can be tested in halo particle detection experiments. Because of its coupling to the Z^0 boson, the lightest messenger φ scatters off nuclei with mass m_N, atomic number Z, and atomic mass A with non-relativistic cross section [12]

$$\sigma = \frac{G_F^2}{2\pi}\frac{m_\varphi^2 m_N^2}{(m_\varphi+m_N)^2}\left[A+2(2\sin^2\theta_W-1)Z\right]^2 \ . \tag{17}$$

This is four times larger than the scattering cross section of a Dirac neutrino with corresponding mass. Present limits [13] from direct dark matter searches exclude that a particle with 5 TeV mass and cross section given by eq. (17) could contribute to more than about 25 % of a standard galactic halo with local density 0.3 GeV/cm^3. Given the uncertainty in the halo determination, it is still possible that the lightest messenger with mass parameters as specified above can play some role in the dynamics of our galaxy, maybe in conjunction with the dark baryonic matter which has been identified by the observations of gravitational microlensing in the Large Magellanic Cloud [14]. We should also recall that for large values of m_φ, the momentum transfer is no longer negligible, and unknown nuclear form factors may reduce the cross section in eq. (17).

If the messenger parameters do not satisfy the constraints identified above, a stable messenger generally leads to relic overabundance. The problem can be solved by a late stage of inflation with a reheating temperature not much higher than the weak scale. Another possibility is to allow the decay of the messenger. In this case we have to introduce in the theory new couplings between the messengers and the ordinary matter, which break the conserved messenger quantum number. If these couplings correspond to renormalizable interactions, they are dangerous, as they presumably introduce flavour violations, spoiling the main motivation for considering supersymmetry breaking at low energies. However such couplings are likely to be generated by Planckean physics and may then correspond to higher dimensional operators. Here is a list of all the dimension-five operators which violate messenger number by one unit:

$$\begin{aligned}
&\frac{1}{M_{Pl}}\int d\theta^2\left\{\bar{5}_M 10_F^3 \quad , \quad 5_M^2\bar{5}_M\bar{5}_F\right\}, \\
&\frac{1}{M_{Pl}}\int d\theta^4\left\{\bar{5}_M^\dagger 10_F^2 \quad , \quad 5_M^\dagger\bar{5}_F 10_F\right\}+h.c.\,,
\end{aligned} \tag{18}$$

where 5_M, $\bar{5}_M$ and $\bar{5}_F$, 10_F are respectively the messenger and ordinary family SU$_5$ superfields.

The latter operators induce messenger decays with a lifetime of $\sim 5 \times 10^{-2}$ s. Furthermore, they do not introduce flavour violations or, more important, proton decay. The reason is that all these operators violate messenger number by one unit; so proton decay requires two such operators and, consequently, it can be adequately suppressed. In general, operators of dimensionality m cause lightest messenger decays with a lifetime $\tau \sim (M_{Pl}/m_\varphi)^{2m-8}\ 10^{-28}$ s. It is clear that only dimension-five operators can allow for the messengers to decay before the time of nucleosynthesis. Of course, both the cases of late inflation and late decay do not allow for messengers to be the dark matter.

In conclusion, we have analysed here the different possibilities for dark matter candidates in theories with gauge-mediated supersymmetry breaking.

(i) The gravitino can have a significant abundance if we choose a rather large value of the supersymmetry-breaking scale $\sqrt{F} \sim 10^6$–10^7 GeV, which is not favored by either theory or the Fermilab event. The gravitino gives rise to warm dark matter scenario and it is invisible in halo detection experiments.

(ii) The secluded sector can contain a dark matter candidate which feels the strong interactions responsible for supersymmetry breaking. Particles up to about 300 TeV are allowed. Direct detection is impossible, as the dark matter particle does not carry ordinary gauge quantum numbers.

(iii) The messenger sector can naturally have a conserved quantum number corresponding to an accidental global symmetry. In this case the lightest messenger is a stable scalar particle. It is neutral and satisfies the appropriate cosmological constraints only in specific cases. It must belong to the $\mathbf{5} + \overline{\mathbf{5}}$ SU_5 representation, be lighter than about 5 TeV, and either correspond to values of F/M^2 very close to one ($F/M^2 \gtrsim 0.95$) or to values of F/M much smaller than those which correspond to other messenger fields ($\sqrt{F} < 350$ GeV). The former option appears fine tuned whereas the latter is quite generic. Direct detection experiments already constrain the contribution of such particles to the standard local halo density to less than about 25 %. If the lightest messenger particle does not satisfy the specific criteria described above, then it leads to overclosure of the universe. The simplest solution to this problem is to introduce dimension-five Planck suppressed operators which violate the messenger number and allow the lightest messenger to decay before the time of nucleosynthesis.

It is a pleasure to thank Michael Dine, Gia Dvali, Scott Thomas and Jim Wells for very valuable conversations.

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