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Direct detection of dark matter in SU(5)×U(1) supergravity

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Abstract

We compute the scattering rates for the lightest neutralino χ_1^0 in the forthcoming germanium ($^{73}Ge+^{76}Ge$) detector and a proposed lead detector (^{207}Pb), within the framework of $SU(5)\times U(1)$ supergravity. We find that in only a small portion ($\lesssim 10\%$) of the parameter spaces of this class of models, are the rates in the germanium detector above the expected initial experimental sensitivity of 0.1 events/kg/day. However, a much larger portion ($\lesssim 40\%$) of the parameter spaces could be probed with an improved background rejection capability (0.01 events/kg/day) and/or a more sensitive detector (^{207}Pb).

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1 Introduction

The search for supersymmetry is being carried out in many ways. In high energy collider experiments, such as the Tevatron and LEP, various measurements have yielded lower bounds on the sparticle masses, although no signal has yet been observed. It is possible that we might need to wait for the next generation of colliders to further probe the spectrum of supersymmetric particles, although we may be able to get some interesting results through other types of experiments, such as the direct detection of dark matter particles. It is well-known that in supersymmetric theories where R–parity is conserved, the lightest supersymmetric particle (LSP) is stable, and it is a candidate for cold dark matter if neutral and colorless [1], as the lightest neutralino is ($\chi \equiv \chi_1^0$). According to astronomical observations, most notably from the refurbished Hubble Space Telescope, we know that most of the matter in the universe is invisible. If we define $\Omega_\chi = \rho_\chi/\rho_c$, where ρ_c is the critical density to "close" the universe and ρ_χ the neutralino dark matter density, it is known that $\Omega_\chi h^2 \sim 0.5$ where $h = H/(100km\, s^{-1}\, Mpc^{-1})$ and H is the Hubble parameter. Since recent Hubble Telescope observations indicate that $h \simeq 0.8$ [2], we see that $\Omega_\chi \sim 1$ is expected.

With this large amount of dark matter in the universe, it is expected that we should be able to detect the recoiling effect of the neutralino, as a dark matter particle, scattering off the target nuclei of certain types of detectors. Indeed, some experimental effort have been put into reality in this regard [3]. We consider two detectors $^{73}Ge(500g) +^{76} Ge(500g)$ and ^{207}Pb. The Ge detector is currently being set up at Stanford University, whereas the second one is still being discussed. There are two points regarding the detector dependence of the scattering processes which are worth mentioning: (i) There are two processes through which the χ_1^0 interacts with the partons in the protons and neutrons inside the target nucleus. The first one is the spin-dependent (S.D.) incoherent scattering, which is non–zero only when the target nucleus has non-zero spin. The second one is the spin-independent coherent scattering which increases with the mass of the target nucleus ($\propto m_N$). These two processes do not interfere with each other, thus the total rate is just the direct sum of these two rates. For the two detectors considered here the spin-dependent contribution (S.D.) is always negligible compared with the spin-independent (S.I.) contribution. (ii) Because of these features, a detector with the highest possible atomic number is prefered: ^{207}Pb is the superconducting material with highest atomic number. Concerning the size of the detector, one would naively think that since one wants to have the largest event rate, one should build the largest possible detector. However, this is not the case with the cryogenic experimental set up, whose operation is optimized for a 1kg detector mass.

2 The models and their parameter space

In what follows we investigate the parameter space of no-scale $SU(5) \times U(1)$ supergravity. For a recent review on the construction of these models see Ref. [4]. The effect of several other direct and indirect experimental constraints have been discussed in Refs. [5, 6]. These models have the features of universal soft-supersymmetry-breaking at the unification scale and radiative breaking of the electroweak symmetry, which is enforced by minimizing the one-loop effective potential. Generally speaking, there are four free parameters that describe these models, once the top-quark mass is fixed. They can be chosen to be: $m_{\chi_1^\pm}, \xi_0, \xi_A, \tan\beta$, where $m_{\chi_1^\pm}$ is the lightest chargino mass, $\tan\beta$ is the ratio of Higgs vacuum expectation values, and $\xi_0 \equiv m_0/m_{1/2}$ and $\xi_A \equiv A/m_{1/2}$ are ratios of the usual universal soft-supersymmetry-breaking parameters. In string-inspired supersymmetry breaking scenarios two parameters are eliminated: in the *moduli* scenario $m_0 = A = 0$, whereas in the *dilaton* scenario $m_0 = \frac{1}{\sqrt{3}} m_{\frac{1}{2}}, A = -m_{\frac{1}{2}}$. In either case there are only two free parameters left $(m_{\chi_1^\pm}, \tan\beta)$. We also consider the "strict" version of these scenarios where the bilinear scalar coupling B is also specified at the unification scale: in the (strict) moduli scenario $B(M_U) = 0$, and in the (strict) dilaton $B(M_U) = 2m_0$. In this case the value of $\tan\beta$ can also be determined, and we are left with one-parameter models. Compared with generic low-energy supersymmetric models like the Minimal Supersymmetric Standard Model (MSSM), these few-parameter models are better motivated and much more predictive.

The main inputs from these models to the dark matter detection calculation are: the lightest CP-even Higgs mass m_h, and the lightest neutralino mass $m_{\chi_1^0}$. The allowed ranges for these masses after all model constraints have been imposed are: $m_h \simeq (65 - 115)\, GeV$ and $m_{\chi_1^0} \simeq (23 - 145)\, GeV$. An important mass relation that one should keep in mind throughout our discussion is $m_{\chi_1^0} \approx \frac{1}{2} m_{\chi_1^\pm}$.

3 The scattering rate

The Feynman diagrams for the elastic scattering between the χ_1^0 and the partons inside the nucleons in the target nucleus ($\chi_1^0 + q \to \chi_1^0 + q$) are shown in Fig. 1. In order to calculate the scattering rate we need to write down the effective Lagrangian for this process. If we assume that most of the dark matter halo surrounding our galaxy is made of elementary particle dark matter, then the typical dark matter velocity is $v \approx 300 km/s = 10^{-3} c$, where c is the speed of light. At these velocities there is an energy transfer $\Delta E < m_{\chi_1^0} v^2 = 10 keV (m_{\chi_1^0}/10\, GeV)$ which is much smaller than the mass scale involved in the process $(m_{\chi_1^0})$. Therefore, we can use the effective Lagrangian approach to describe the low-energy χ_1^0-quark interaction,

$$L_{eff} = \bar{\chi}_1^0 \gamma_\mu \gamma_5 \chi_1^0 \cdot \bar{q} \gamma^\mu (A_q P_L + B_q P_R) q + \bar{\chi}_1^0 \chi_1^0 \cdot C_q m_q q \tag{1}$$

where $P_{R(L)} = \frac{1}{2}(1 \pm \gamma_5)$ and A_q, B_q $(q = u, d, s)$ are the coupling coefficients for the Z-exchange in the t-channel and the $\tilde{q}$-exchange in the s-channel; only light quarks contribute in this case. Also, C_q ($q = u, d, s, c, b, t$) are the coupling coefficients for the h, H-exchange t-channel and the $\tilde{q}$-exchange s-channel. Note that heavy quarks do not decouple in this case. Among the various contributions to the scattering amplitude, the squark contribution is negligible since $m_{\tilde{q}} > 200\,GeV$ in these models. The dominant contribution is from spin-independent coherent scattering due to (CP-even) Higgs boson exchange, mostly the lightest one (h) although the heavy Higgs (H) can have a significant sub-leading effect.

The total scattering rate is given by [7]

$$R = (R_{S.I.} + R_{S.D.}) \frac{4 m_{\chi_1^0} m_N}{(m_{\chi_1^0} + m_N)^2} \frac{\rho_\chi}{0.3\,GeV\,cm^{-3}} \frac{|V_E|}{320 kms^{-1}} \frac{events}{kg \cdot day}\ , \qquad (2)$$

where m_N is the target nucleus mass, ρ_χ is the neutralino dark matter relic density, $|V_E|$ is the average velocity of the neutralinos that hit the detector (we take $|V_E| = 320\,km\,s^{-1}$), and

$$R_{S.I.} = 840 m_N^2 M_Z^4 \zeta \left[\hat{f}\, \frac{m_u C_u + m_d C_d}{m_u + m_d} + f C_s + \tfrac{2}{27}(1 - f - \hat{f})(C_c + C_b + C_t) \right]^2 . \qquad (3)$$

In the expression for $R_{S.I.}$, $\zeta = \frac{0.573}{b}[1 - \frac{e^{-b/(1+b)}}{\sqrt{1+b}} \frac{erf(\frac{1}{\sqrt{1+b}})}{erf(1)}]$ is a form factor with $b = \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{8}{9} \sigma^2 r_{charge}^2$, $\sigma = \frac{V_E}{1.2}$ the velocity dispersion, and the charge radius $r_{charge} = (0.30 + 0.89 A^{1/3})\,fm$. Also, $\hat{f} \approx 0.05$ and $f \approx 0.2$ are coefficients of proportionality in various hadronic matrix elements. Finally, the C_q parameters for the dominant Higgs exchange diagrams involve couplings of the Higgs to neutralinos and to quarks:

$$C_q = -\frac{g_2^2}{4 M_W^2} \left\{ \begin{array}{c} \frac{-\cos\alpha}{\sin\beta} \\ \frac{\sin\alpha}{\cos\beta} \end{array} \right\} \frac{F_h}{m_h^2} + \frac{g_2^2}{4 M_W^2} \left\{ \begin{array}{c} \frac{\sin\alpha}{\sin\beta} \\ \frac{\cos\alpha}{\cos\beta} \end{array} \right\} \frac{F_H}{m_H^2}\ ; \quad \left\{ \begin{array}{l} q = u, c, t \\ q = d, s, b \end{array} \right. , \qquad (4)$$

where α is the Higgs mixing angle, $F_h = (N_{11} - N_{12} \tan\theta_W)(N_{14} \cos\alpha + N_{13} \sin\alpha)$, $F_H = (N_{11} - N_{12} \tan\theta_W)(N_{14} \sin\alpha - N_{13} \cos\alpha)$, and the LSP is the admixture $\chi_1^0 = N_{11} \widetilde{W}^3 + N_{12} \widetilde{B} + N_{13} \widetilde{H}_1^0 + N_{14} \widetilde{H}_2^0$. It can be seen that $R_{S.I.} \propto m_N^2$, thus the reason for proposing the ^{207}Pb detector. Also, explicit calculations show that for both $^{73}Ge +^{76}Ge$ and ^{207}Pb detectors, the S.I. term is always much larger than the S.D. term (which we do not exhibit explicitly here).

4 Results and discussion

We have calculated the scattering rates for the neutralino dark matter particles in the two detectors mentioned above throughout the parameter space of the models. The results are shown in the Figs. 2, 3, 4 for the different scenarios. The following general features are noticed in all cases:

Table 1: The fraction of parameter space in $SU(5)\times U(1)$ supergravity which can be explored via direct detection of dark matter in Ge and Pb detectors with a sensitivity of 0.1 or 0.01 events/kg/day.

	Moduli		Dilaton		Strict Moduli	Strict Dilaton
	$\mu>0$	$\mu<0$	$\mu>0$	$\mu<0$	$\mu<0$	$\mu<0$
Ge(0.1)	2.1%	7.1%	10%	11%	10%	5.2%
Ge(0.01)	14%	30%	32%	39%	41%	29%
Pb(0.1)	3.6%	11%	18%	21%	17%	16%
Pb(0.01)	27%	49%	43%	53%	59%	45%

- The rates drop quickly with growing chargino masses. As mentioned above, the lightest neutralino is a linear combination of gaugino and higgsino gauge eigenstates. The intermediate states for the dominant spin-independent scattering process are the Higgs bosons, which couple to a product of the gaugino and higgsino components of the neutralino (see Eq. (4)). On the other hand, when the chargino mass grows the neutralino approaches the limit of a pure bino, thus greatly reducing its coupling to the Higgs bosons, and the scattering rate drops sharply.

- There are two noticeable dips in the rates for $m_{\chi^\pm}\sim 70-90\,GeV$. For $m_{\chi^0_1}\approx \frac{1}{2}m_Z, \frac{1}{2}m_h$, in the calculation of the relic density of the neutralinos (which we perform following the methods of Ref. [8]), the Z or h-pole is encountered in the neutralino pair-annihilation, and the resulting neutralino relic density is highly suppressed. This implies that little neutralino dark matter is expected in the halo. To account for this possibility, in Eq. (2) we take

$$\rho_\chi = min\,[1,(\Omega_\chi h^2)/0.05]\,0.3\,GeV\,cm^{-3}\ , \tag{5}$$

  since one expects that $\Omega_{halo}\gtrsim 0.1$ [9]. In the figures, the ordering of the poles with increasing $m_{\chi^\pm_1}$ is h,Z for $\tan\beta=2$, and Z,h for $\tan\beta=10$ (and in Fig. 4).

- The rates have a non-trivial $\tan\beta$ dependence (only $\tan\beta=2,10$ are shown in the figures). The C_q coefficients in Eq. (4) depend on $\tan\beta$, and so does m_h, which increases with $\tan\beta$.

For the Ge detector, which is the one being set up right now and should start producing data in the near future, with the realistic experimental sensitivity of 0.1 event/kg/day, only a small portion ($\sim 2-10\%$) of the parameter space would be probed in all scenarios (see Table 1). These fractions have been determined by computing the rates for *all* points in parameter space; only selected values of $\tan\beta$ are shown in the figures. There are two ways to improve the reach into parameter space. First, one could improve the sensitivity by reducing the background. If the sensitivity of the Ge detector could be enhanced to 0.01 event/kg/day, a larger fraction of the parameter space could be probed ($\sim 15-40\%$), as seen in the figures and quantified in Table 1.

There has also been some discussions about the possibility of building a ^{207}Pb detector, which is an improvement over the Ge detector because the scattering rate scales about linearly ($R \propto m_N/(1+m_\chi/m_N)^2$) with the atomic number of the target nucleus, *i.e.*, an improved sensitivity by increasing the signal in the detector. With the 0.1 event/kg/day sensitivity the Pb detector should probe a larger ($\sim \times 2$) fraction of the parameter space, compared to the Ge detector with the same sensitivity (see Table 1). Of course the best experimental scenario would be a ^{207}Pb detector with the better sensitivity (0.01 events/kg/day). In such best case scenario, for $\tan\beta = 2$ and $\mu < 0$, chargino masses as high as $180\,(160)\,GeV$ could be probed in the moduli (dilaton) scenario. The reach is somewhat lower for larger values of $\tan\beta$. Note also that in strict no-scale $SU(5)\times U(1)$ – dilaton scenario, an experimental upper bound on R would immediately provide a lower bound on $m_{\chi_1^\pm}$.

It has been recently pointed out [10] that experimental limits on $B(b\to s\gamma)$ may disfavor some regions of parameter space where R is particularly enhanced. The computations of $B(b\to s\gamma)$ in supergravity models in Ref. [11], in particular for no-scale $SU(5)\times U(1)$ supergravity, indicate that $b\to s\gamma$ is an important constraint only for $\mu > 0$, and even in that case only for $\tan\beta \gtrsim 4$. Therefore, even assuming that the $b\to s\gamma$ constraints are rigorous, there should still be a large portion of the parameter space accessible to direct searches of dark matter.

We conclude with the following comment. At LEPII, chargino masses as high as 100 GeV should be readily detectable in all the scenarios which we have considered here [5, 6], and yet, direct detection of the LSP with $m_{\chi_1^0} \approx \frac{1}{2} m_{\chi_1^\pm} \lesssim 50\,GeV$ may take a while to occur. Indirect detection of dark matter via upwardly moving muon fluxes in neutrino telescopes may taken even longer to happen, as explicit calculations show in the models we considere here [12] and more generally in model-independent analyses [13].

Acknowledgments

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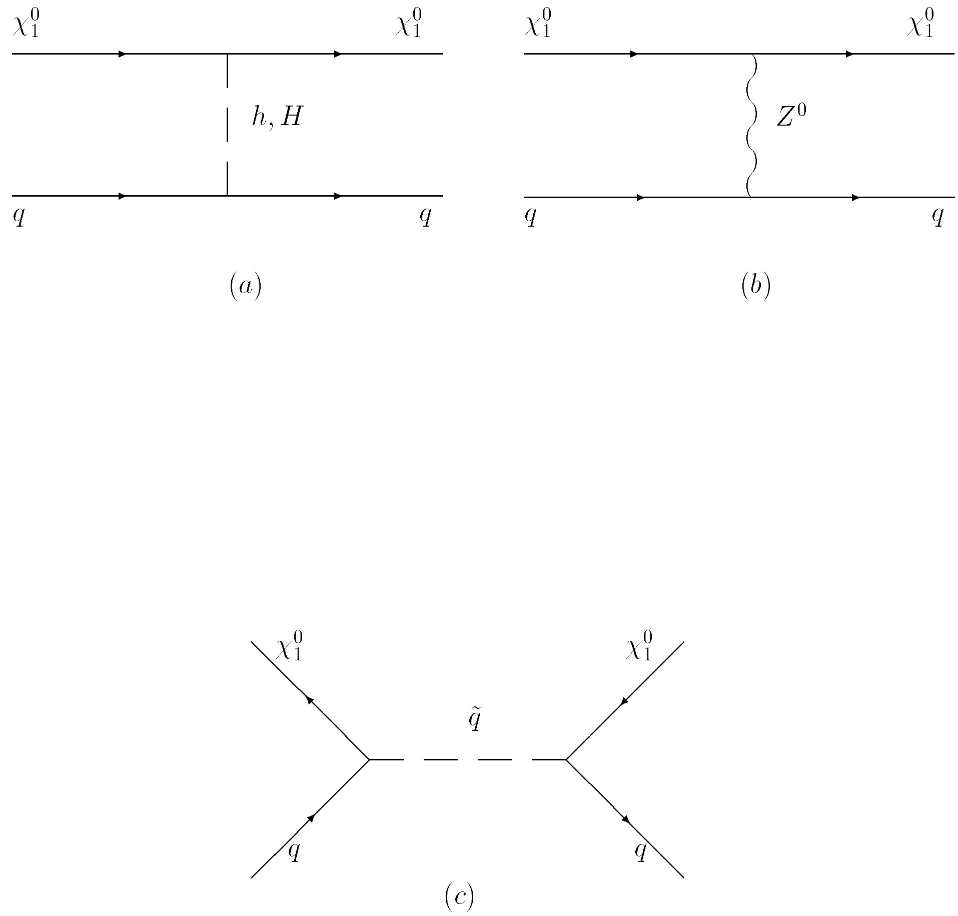

Figure 1: The Feynman diagrams for the elastic χ_1^0-quark scattering process, which occurs via t-channel h, H- and Z-boson exchange (a, b) and via s-channel $\tilde{q}$-exchange (c).

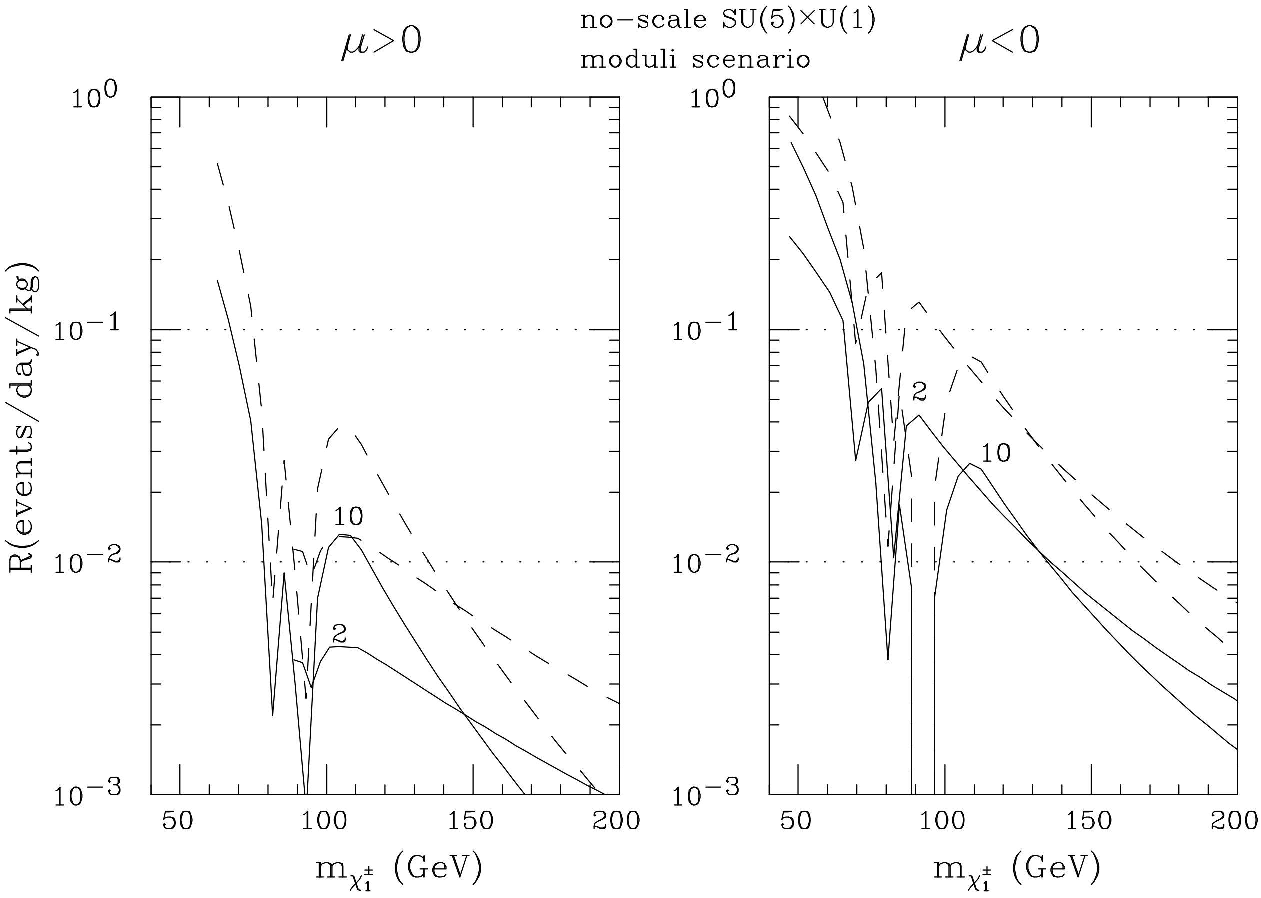

Figure 2: The calculated scattering rates for the Ge (solid lines) and Pb (dashed lines) dark matter detectors in no-scale $SU(5) \times U(1)$ supergravity – moduli scenario for $\tan\beta = 2, 10$. The horizontal dotted lines represent the detector sensitivities of 0.1 and 0.01 events/kg/day. The dips in the rates correspond to a suppressed neutralino relic density when the Z and h poles in the neutralino pair annihilation are encountered.

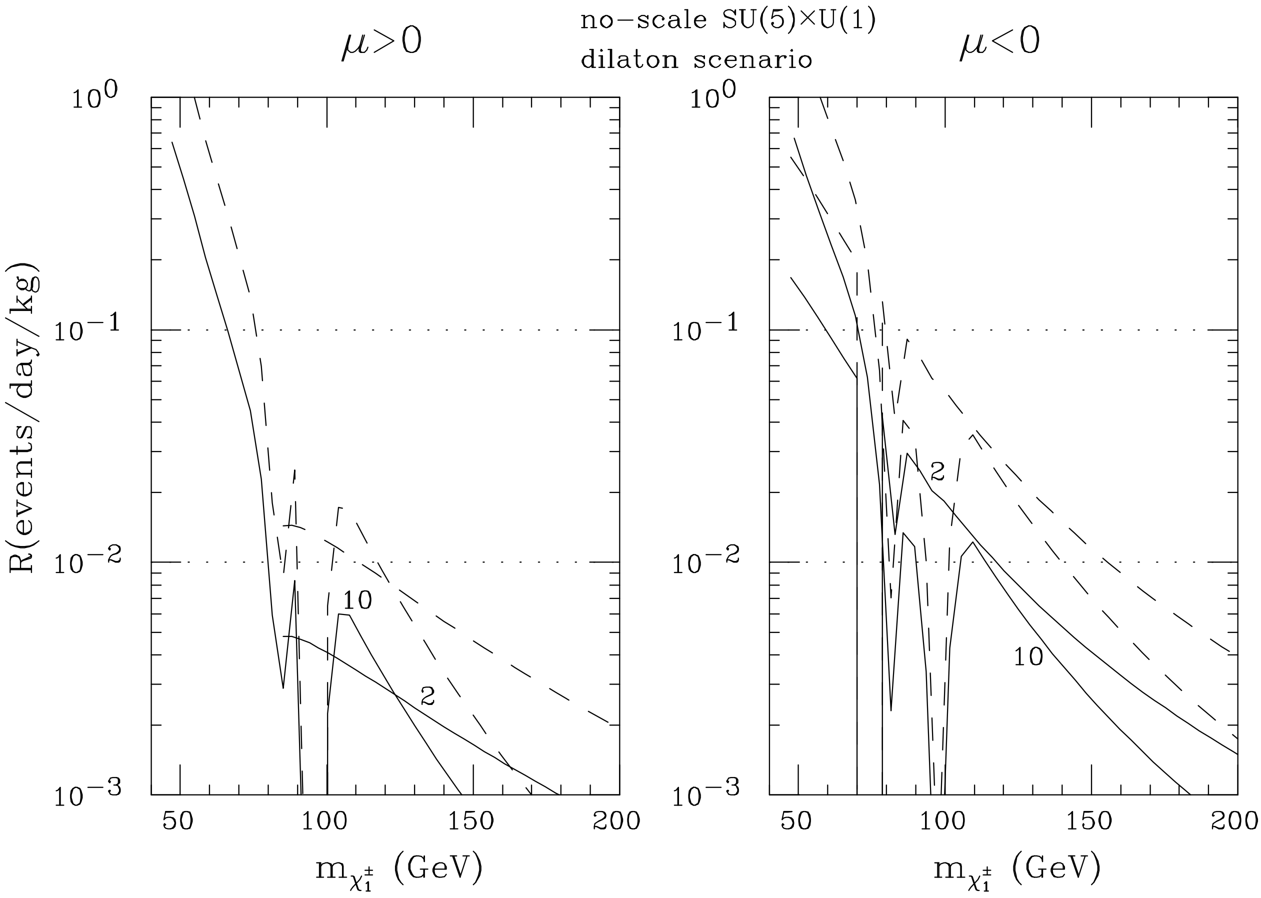

Figure 3: The calculated scattering rates for the Ge (solid lines) and Pb (dashed lines) dark matter detectors in no-scale $SU(5)\times U(1)$ supergravity – dilaton scenario for $\tan\beta\, =\, 2, 10$. The horizontal dotted lines represent the detector sensitivities of 0.1 and 0.01 events/kg/day. The dips in the rates correspond to a suppressed neutralino relic density when the Z and h poles in the neutralino pair annihilation are encountered.

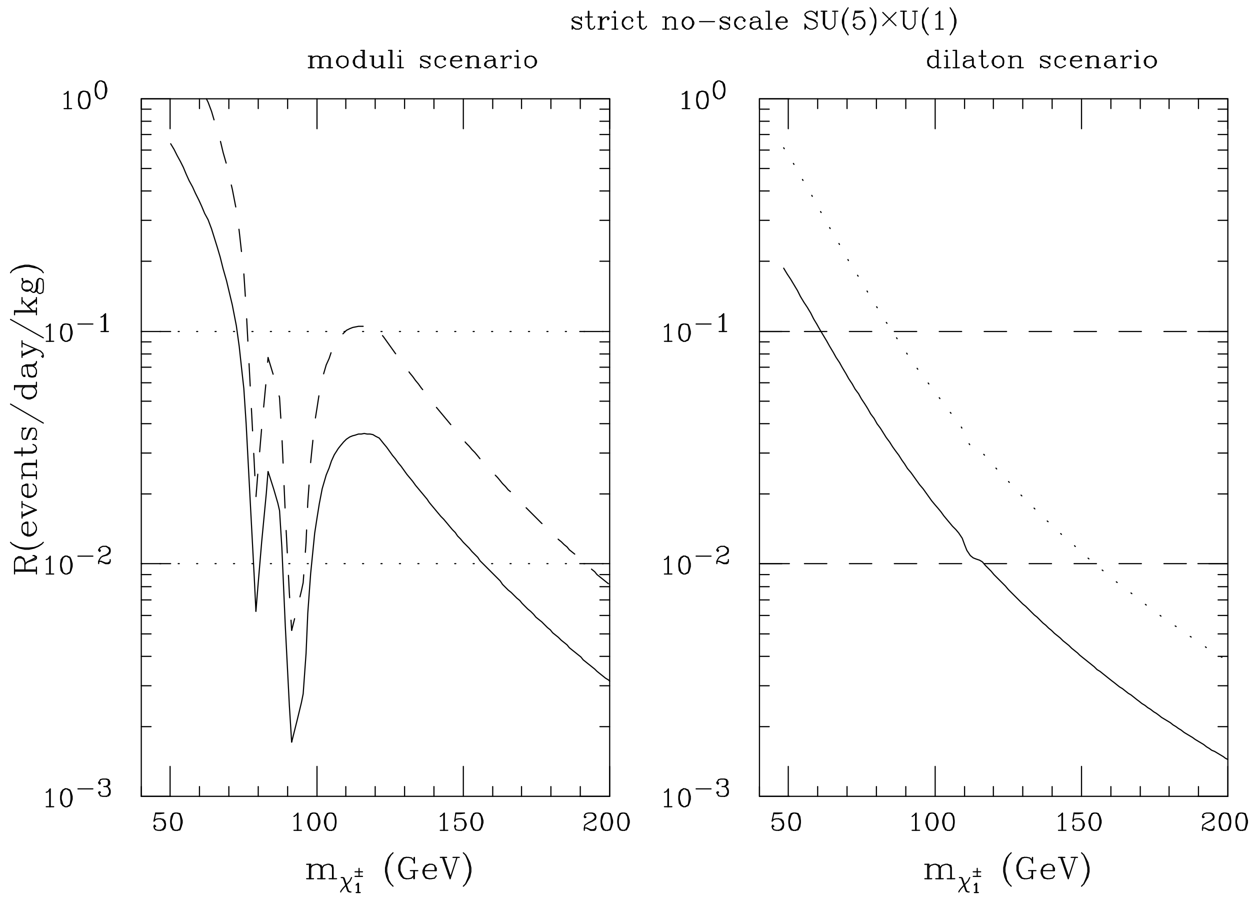

Figure 4: The calculated scattering rates for the Ge (solid line) and Pb (dashed line) dark matter detectors in strict no-scale $SU(5) \times U(1)$ supergravity – moduli and dilaton scenarios. The dotted lines represent the detector sensitivities of 0.1 and 0.01 events/kg/day. The dips in the rates correspond to a suppressed neutralino relic density when the Z and h poles in the neutralino pair annihilation are encountered.