Comparison of coannihilation effects in low-energy MSSM

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Abstract. The neutralino relic density is calculated in the low-energy effective Minimal Supersymmetric extension of Standard Model (effMSSM). The slepton-neutralino, squark-neutralino and neutralino/chargino-neutralino coannihilation channels are taking into account. The comparative study of these coannihilations is performed and demonstrated that all of them give the sizable contributions to the reduction of the neutralino relic density. It is shown that the predictions for direct dark matter detection rates are not strongly affected by these coannihilation channels in the effMSSM.

1. Introduction

A variety of data ranging from galactic rotation curves to large scale structure formation and the cosmic microwave background radiation imply a significant density $0.1 < \Omega h^2 < 0.3$ [1] of so-called cold dark matter (CDM). Here $\Omega = \rho/\rho_c$ and $\rho_c$ is the critical closure density of the universe, and $h$ is the Hubble constant in units of 100 km/sec/Mpc. It is generally believed that most of the CDM is made of weakly-interacting massive particles (WIMPs) [2]. A commonly considered candidate for the WIMP is the lightest neutralino, provided it is the lightest supersymmetric particle (LSP) [3] in the Minimal Supersymmetric extension of Standard Model (MSSM). In most approaches the LSP is stable due to R-parity conservation [4]. The neutralino, being massive, neutral and stable, often provides a sizeable contribution to the relic density, which is strongly model-dependent and varies by several orders of magnitude over the whole allowed parameter space of the MSSM. The neutralino relic density then can impose stringent constraints on the parameters of the MSSM, and may have important consequences both for studies of SUSY at colliders and in astroparticle experiments. In light of this and taking into account the continuing improvements in determining the abundance of CDM, and other components of the Universe, which have now reached an unprecedented precision [5], one needs to be able to perform an accurate enough computation of the WIMP relic abundance, which would allow for a reliable comparison between theory and observation. On this way big progress in calculations of the relic density of neutralino in variety of supersymmetric models has been already achieved [6–41].

In the early universe neutralinos existed in thermal equilibrium with the cosmic thermal plasma. As the universe expanded and cooled, the thermal energy is no longer sufficient to produce neutralinos at an appreciable rate, they decouple and their number density scales with co-moving volume. The particles significantly heavier than the LSP decouple at the earlier time and decay into LSPs. Nevertheless there may exist some other next-to-lightest sparticles (NLSPs) which are not much heavier than the stable LSP. The number densities of the NLSPs have only slight Boltzmann suppressions with respect to the LSP number density when the LSP freezes out of chemical equilibrium with the thermal bath. Therefore they may still be present in the thermal plasma, and NLSP-LSP and NLSP-NLSP interactions hold LSP in thermal equilibrium resulting with significant reduction of the LSP number density.
These coannihilation processes can be particularly important when the LSP-LSP annihilation rate itself is suppressed [15, 14, 24]. In the coannihilation with the LSP can be involved any SUSY particle, provided its mass is almost degenerate with the mass of the LSP [15, 23]. In the low-energy effective MSSM (effMSSM), where one ignores restriction from unification assumptions and investigates the MSSM parameter space at the weak scale [24, 22, 42, 43] there is, in principle, no preference for the next-to-lightest SUSY particle.

The relativistic thermal averaging formalism [16] was extended to include coannihilation processes in [24], and was implemented in the DarkSusy code [25] for coannihilation of charginos and heavier neutralinos. In was found [24] that such a coannihilation significantly decreases the relic density. The importance of the neutralino coannihilation with sferinos, charginos and heavier neutralinos. In was found [24] that such a coannihilation significantly decreases the relic density. The importance of the neutralino coannihilation with sferinos was emphasized and investigated for sleptons [27, 29], stops [33, 35] and sbottoms [34] in the so-called constrained MSSM (cMSSM) [23, 7] or in supergravity (mSUGRA) models [44].

In [41], the comparative study of NCC and SLC channels, exploration of relevant changes in the relic density and investigation of their consequences for detection of CDM particles were performed in the effMSSM. This paper extends our investigations [41] to the neutralino-stop and neutralino-sbottom coannihilations and completes our consideration of the subject. Therefore the calculations of neutralino relic density with inclusion of the all relevant coannihilation channels (NCC, SLC, SQC) can be performed in the low-energy effMSSM.

2. The effMSSM approach

As free parameters in the effMSSM, we use the gaugino mass parameters $M_1, M_2$ the entries to the squark and slepton mixing matrices $m_{Q_1}^2, m_{U_1}^2, m_{D_1}^2, m_{R}^2, m_L^2$ for the 1st and 2nd generations and $m_{Q_3}^2, m_{T}^2, m_{B_1}^2, m_{R_3}^2, m_{L_3}^2$ for the 3rd generation, respectively; the 3rd generation trilinear soft couplings $A_t, A_b, A_{\tau}$; the mass $m_A$ of the pseudoscalar Higgs boson, the Higgs superpotential parameter $\mu$, and $\tan \beta$. To reasonably reduce the parameter space we assumed $m_{Q_1}^2 = m_{U_1}^2 = m_{D_1}^2 = m_{T}^2 = m_{B_1}^2 = m_{R_3}^2, m_{L_3}^2, m_{R_3}^2 = m_{L_3}^2$ and have fixed $A_b = A_{\tau} = 0$ [42]. The third gaugino mass parameter $M_3$ defines the mass of the gluino in the model and is determined by means of the GUT assumption $M_2 = 0.3 M_3$. The remaining parameters defined our effMSSM parameter space and were scanned randomly within the following intervals:

$$-1 \text{ TeV} < M_1 < 1 \text{ TeV}, \quad -2 \text{ TeV} < M_2, \mu, A_t < 2 \text{ TeV}, \quad 1.5 < \tan \beta < 50,$$

$$50 \text{ GeV} < M_A < 1 \text{ TeV}, \quad 10 \text{ GeV}^2 < m_{Q_1}^2, m_{L_3}^2, m_{Q_3}^2, m_{L_3}^2 < 10^6 \text{ GeV}^2.$$

We have included the current experimental upper limits on sparticle masses as given by the Particle Data Group [43]. The limits on the rare $b \rightarrow s\gamma$ decay [44] have also been imposed. The calculations of the neutralino-nucleon cross sections, and direct detection rates follow the description given in [3, 22]. The number density is governed by the Boltzmann equation [16, 24]

$$\frac{dn}{dt} + 3H n = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$$  \hspace{1cm} (1)

with $n$ either being the LSP number density if there are no other coannihilating sparticles, or the sum over the number densities of all coannihilation partners. The index “eq” denotes the corresponding equilibrium value. To solve the Boltzmann equation (1) one needs to evaluate the thermally averaged neutralino annihilation cross section $\langle \sigma v \rangle$. Without coannihilation processes $\langle \sigma v \rangle$ is given as the thermal average of the LSP annihilation cross-section $\sigma_{\chi\chi}$ times relative velocity $v$ of the annihilating LSPs $\langle \sigma v \rangle = \langle \sigma_{\chi\chi} v \rangle$, otherwise, it is determined
as \( \langle \sigma v \rangle = \langle \sigma_{\text{eff}} v \rangle \), where the effective thermally averaged cross-section is obtained by summation over coannihilating particles \([16, 24]\)

\[
\langle \sigma_{\text{eff}} v \rangle = \sum_{ij} \frac{n_i \, n_j}{n_{\text{eq}} \, n_{\text{eq}}} \langle \sigma_{ij} v_{ij} \rangle. \quad (2)
\]

The relic density is given by \( \Omega = \frac{m_{\chi} \, n_0}{\rho_c} \), where \( n_0 \) denotes the nowadays number density of the relics. For each point in the MSSM parameter space (MSSM model) we have evaluated the relic density of the LSP \( \Omega h^2 \) under the following assumptions: ignoring any possibility of coannihilation (IGC), taking into account only neutralino-chargino (NCC), slepton (SLC), or squark (SQC) coannihilations separately, as well as including all of the coannihilation channels (ACC). To this end in our former code \([42]\) DarkSusy procedures of \( \langle \sigma_{\text{eff}} v \rangle \) evaluation and solution of Boltzmann equation were implemented.

![Figure 1. Effects of squark-neutralino (SQC), slepton-neutralino (SLC), and neutralino-chargino(neutralino) (NCC) coannihilations in effMSSM. Panels a)–d) display ratios \( \Omega h^2_{\text{SQC}}/\Omega h^2_{\text{IGC}} \), \( \Omega h^2_{\text{SLC}}/\Omega h^2_{\text{IGC}} \), \( \Omega h^2_{\text{NCC}}/\Omega h^2_{\text{IGC}} \), and \( \Omega h^2_{\text{ACC}}/\Omega h^2_{\text{SLC}} \) for the case when all coannihilations are included. The maximal reduction factors for all channels (NCC, SQC, and SLC) are of the order of \( 10^{-3} \). Points in circles mark cosmologically interesting relic density \( 0.1 < \Omega h^2_{\text{COA}} < 0.3 \). In panel a) up-going triangles correspond to stop coannihilations and down-going triangles correspond to sbottom coannihilations. One can see that stop and sbottom equally contribute.](image-url)
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[27], and [35] in a way that guarantees the correct inclusion of SLC and SQC. We assume
$0.1 < \Omega h^2 < 0.3$ for the cosmologically interesting region [1].

3. Coannihilation effects in the relic density

The general view of the reduction effect on the relic density (RD) due to SQC, SLC, NCC and
ACC are shown in Fig. 1 as ratios $\Omega h^2_{COA}/\Omega h^2_{IGC}$. Here $\Omega h^2_{COA}$ is a common notation for
$\Omega h^2_{ACC}$, $\Omega h^2_{NCC}$, $\Omega h^2_{SQC}$ or $\Omega h^2_{SLC}$. On the basis of our sampling (20000 models tested)
the maximum RD suppression factor for NCC and SLC channels is of the same order of about
$10^{-3}$. Almost the same maximal suppression is also for squark coannihilation channels. These
results depend on the applied experimental limits on the second-lightest neutralino, chargino
and slepton stop and sbottom masses. The current experimental limits for $m_{\tilde{\tau}}, m_{\tilde{\mu}}, m_{\tilde{\chi}^{\pm}}, m_{\tilde{t}}$, and
$m_{\tilde{b}}$ are 80–90 GeV [45], and therefore the critical LSP mass that enables non-negligible
NCC, SLC, and SQC contributions is also of the same order ($m_{\chi} \geq 80$ GeV). From panel a) of the figure one can conclude that stop (up-going triangles) and sbottom (down-going triangles) equally contribute to reduction of RD due to coannihilations.

Figure 2. The same as in Fig. 1, but plotted together. Here $\Omega h^2_{SQC}/\Omega h^2_{IGC}$,
$\Omega h^2_{SLC}/\Omega h^2_{IGC}$, $\Omega h^2_{NCC}/\Omega h^2_{IGC}$, and $\Omega h^2_{ACC}/\Omega h^2_{SLC}$ are marked with crosses, circles,
dots and squares, respectively. Therefore, a square filled with a cross, circle, or dot depicts a
model that is affected only by SQC, SLC, or NCC, respectively, and any other coannihilation
channel gives negligible contribution. Such a situation takes place for the majority of models,
but there are some (quite few) models, given by empty squares, for which at least two
coannihilation channels are relevant. For example, arrows in the right side of the figure
demonstrate how reduction of RD proceeds: SLC gives no effect ($\Omega h^2_{SLC}/\Omega h^2_{IGC} = 1$),
SQC reduces RD with factor $\Omega h^2_{SQC}/\Omega h^2_{IGC} \approx 0.4$, and finally NCC gives main
contribution to RD suppression $\Omega h^2_{ACC}/\Omega h^2_{SLC} \approx \Omega h^2_{NCC}/\Omega h^2_{IGC} \approx 0.04$ (the square
nearly coincides with the dot).

The circles with symbols inside depict a some kind of “constructive” reduction, when
due to the coannihilations the relic density falls into cosmologically interesting region $0.1 < \Omega h^2_{COA} < 0.3$. Other points present the cases when coannihilations too strongly reduce the
relic density. One can see that NCC plays the main role in “destructive” reduction of RD, these
channels reduce maximal number of models form cosmologically interesting region [24, 1].
Despite the fact, in “constructive” reduction of RD all coannihilation channels contribute at the same strength (there are almost the same number of circled points in a)–c) panels).

![Figure 3. Ratio $\Omega h^2_{NCC}/\Omega h^2_{SLC}$, $\Omega h^2_{NCC}/\Omega h^2_{SQC}$ and $\Omega h^2_{SLC}/\Omega h^2_{SQC}$ versus $m_{NLSP} - m_{\chi}$. Open circle indicates that the $\tilde{\tau}$ is the NLSP, star means that the light chargino $\tilde{\chi}^\pm$ is the NLSP, small filled square marks the model where the second-lightest neutralino $\tilde{\chi}_2$ is the NLSP. Up-going (down-going) triangles indicates that $\tilde{t}$ ($\tilde{b}$) is the NLSP.](image)

From Fig. 2 one can see that the reduction of RD is mainly due to the only one dominant coannihilation channel NCC, SQC, or SLC. The other channels of coannihilation in general play no role or lead only to a much smaller further reduction \[41\]. Figure 3 shows that for all coannihilation channels maximal RD reduction factors (less than 0.01) occur for mass differences $m_{NLSP} - m_{LSP} \leq 20$ GeV. In contrast with NCC and SLC, SQC can produce the same reduction effect with larger mass difference between squark and the LSP ($m_{\tilde{q}} - m_{LSP} \approx 150$ GeV) due to the possibility of coannihilation via strong interactions. For NCC and SLC channels of coannihilation, relevant effects occur if the mass difference between the coannihilation partner and the LSP is within 15%. It was obtained that for SQC the relevant effects occur if the mass difference between the coannihilating squark and the LSP is within 50%.

Although other coannihilation processes (including LSP annihilation with the next-to-NLSP (NNLSP) and next-to-NNLSP, etc), can in principal be also open from Fig. 3 one can conclude that dominant coannihilation channel is defined by the type of the NLSP. If next neutralino $\tilde{\chi}_2$ or chargino $\tilde{\chi}^\pm$ is the NLSP, then NCC indeed dominates. Stau $\tilde{\tau}$ (or another slepton) being the NLSP indeed entails a dominant SLC effect \[41\]. The SQC dominates when NLSP is the stop or the sbottom.

In Fig. 4 all calculated relic densities ($\Omega h^2_{IGC}$, $\Omega h^2_{SQC}$, $\Omega h^2_{SLC}$, $\Omega h^2_{NCC}$ and $\Omega h^2_{ACC}$) are depicted in the cosmologically interesting region $0.1 < \Omega h^2_{COA} < 0.3$. There is a quite big amount of models (mostly with $m_{\chi} \leq 250$ GeV) which are completely unaffected by any kind of coannihilation. When at least one of coannihilation channels is relevant, the RD decreases and some cosmologically unviable models with $\Omega h^2_{IGC} > 0.3$ enter the cosmologically interesting range $0.1 < \Omega h^2_{COA} < 0.3$, due to NCC (squares with a dot inside), SLC (squares with circles inside), SQC (squares with crosses inside), or due to joint...
Figure 4. Illustration of the shifting of effMSSM models inside and outside the cosmologically interesting range $0.1 < \Omega h^2_{\text{COA}} < 0.3$ due to NCC, SQC and SLC. RD $\Omega h^2_{\text{IGC}}$, $\Omega h^2_{\text{SQC}}$, $\Omega h^2_{\text{SLC}}$, $\Omega h^2_{\text{NCC}}$ and $\Omega h^2_{\text{ACC}}$ are marked with stars, crosses, circles, small dots, and squares, respectively. Therefore, a superposition of all symbols corresponds to a model which is totally untouched by coannihilation. A star-crossed circle marks a model which is untouched by SLC and SQC ($\Omega h^2_{\text{SLC}} = \Omega h^2_{\text{SQC}} = \Omega h^2_{\text{IGC}}$), but shifted down due to NCC. If the corresponding $\Omega h^2_{\text{ACC}}$ (which is equal to $\Omega h^2_{\text{NCC}}$) remains within this range, it still presents in the figure below this star-crossed circle as an empty square with a black dot inside (see short arrow). By analogy, an square with a circle inside gives a model which is shifted into the region due to SLC only ($\Omega h^2_{\text{ACC}} = \Omega h^2_{\text{SLC}}$), and if the corresponding $\Omega h^2_{\text{IGC}} = \Omega h^2_{\text{NCC}} = \Omega h^2_{\text{SQC}}$ is also in the cosmologically viable range, it is located above the symbol as an crossed star with a dot inside (see long arrow). A quite big amount of models is shifted out of $0.1 < \Omega h^2 < 0.3$ due to NCC (star-crossed circles).

contribution of NCC, SQC, or/and SLC (empty squares). There are also models which enter the less interesting region for LSP to be CDM ($\Omega h^2_{\text{COA}} < 0.1$). The largest amount of models is shifted out due to NCC (star-crossed circles), and a relatively small amount of models is shifted out due to SLC (crossed stars with a dot inside), SQC (circles with a star and a dot inside), both NCC and SLC (crossed stars). There are cosmologically interesting LSPs within the full mass range $20\text{ GeV} < m_\chi < 720\text{ GeV}$ (Fig. 4) accessible in our scan whether or not coannihilation channels are included.

4. Coannihilation effects in the detection rates

Now we consider the influence of all coannihilation channels in question (NCC, SQC and SLC) on prospects for direct detection of CDM neutralinos. We compare the rate predictions for cosmologically interesting LSPs when the RD is evaluated with or without any of coannihilation channel taken into account. We have seen (Fig. 4) that the RD in most
models with $m_\chi \leq 250$ GeV is untouched by SQC, SLC and NCC, mostly because the difference $m_{\text{NLSP}} - m_\chi$ is too large to yield significant effects, therefore the corresponding detection rates are not influenced (depicted in the figures as square filled with a star, a cross and a dot simultaneously). Figure 5 shows neutralino-proton scattering cross sections for the scalar (spin-independent) and the axial (spin-dependent) interactions. The models with $m_\chi \leq 250$ GeV are hardly affected by coannihilation, and for the majority of those models both neutralino-proton and neutralino-neutron scattering cross sections reach values
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$\sigma_{\chi p} \leq 10^{-17}$ GeV$^{-2}$ with the maximal cross section of order $10^{-15}$ GeV$^{-2}$. Cosmologically interesting models with $m_\chi \geq 250$ GeV were influenced by coannihilations, and the maximal value of the neutralino-nucleon cross-section decreases from $10^{-15}$ GeV$^{-2}$ to $5 \cdot 10^{-16}$ GeV$^{-2}$ for the models with $m_\chi > 500$ GeV. In total, independently of neglection or inclusion of NCC, SQC and SLC the maximal scalar scattering neutralino-nucleon cross section reaches $10^{-16}$–$10^{-15}$ GeV$^{-2}$. The spin-dependent neutralino-nucleon cross sections are typically higher than the spin-independent ones, and we have found the maximal values at $10^{-10}$ GeV$^{-2}$ for the axial neutralino-proton and $10^{-11}$ GeV$^{-2}$ for the axial neutralino-neutron scattering for the models which are untouched by the coannihilations. The majority of cosmologically interesting models yields axial neutralino-proton scattering cross sections in the range $5 \cdot 10^{-16}$ GeV$^{-2} < \sigma_{\chi p} < 2 \cdot 10^{-12}$ GeV$^{-2}$ and axial neutralino-neutron scattering cross sections in the range $2 \cdot 10^{-16}$ GeV$^{-2} < \sigma_{\chi n} < 8 \cdot 10^{-13}$ GeV$^{-2}$ \cite{41}. The SQC contribute in reduction of the cross sections, but again not significantly. Figure 6 shows the expected direct detection event rates calculated for a $^{73}$Ge detector when NCC, SQC, SLC, and ACC are taken into account. For models with $m_\chi \leq 250$ GeV coannihilations of any kind play no role. The estimations of the event rate for models with $m_\chi \geq 400$ GeV are decreased mainly due to NCC \cite{41}.

![Figure 7. Neutralino-proton scattering cross sections for scalar (spin-independent) interaction. Expectations for GENIUS detector \cite{47} and the annual-modulation region of DAMA (shaded region) \cite{48} are also given. The maximal sensitivity of GENIUS and the region of DAMA are located at $40 \leq m_\chi \leq 300$ GeV.](image)

5. Conclusion

The neutralino relic density (RD) is calculated taking into account slepton-neutralino (SLC), neutralino-chargino/neutralino (NCC), and squark-neutralino (SQC) coannihilation channels within the low-energy effective MSSM. The maximum factors of RD decrease due to NCC as well as due to SQC and SLC can reach $10^{-3}$, as long as the lower experimental limits for $m_\tilde{\tau}$, $m_\tilde{t}$, $m_\tilde{b}$, and $m_\tilde{\chi}^\pm$, are of the order of 80 GeV. SQC, NCC, SLC produce comparable RD reduction effects in the effMSSM. For the majority of models affected by coannihilations it was observed that either NCC, SQC or SLC alone produces significant reduction of RD while the other coannihilation channels can give considerably smaller further
reduction. Contrary to NCC and SLC, which produce non-negligible effect only if the NLSP mass is smaller than $1.15m_\chi$, for SQC the relevant NLSP mass could reach $1.50m_\chi$. The type of the NLSP determines the dominant coannihilation channel. In the effMSSM all coannihilations do not imply new cosmological limits on the mass of the LSP. The optimistic predictions for neutralino-nucleon cross sections and LSP direct detection rates for cosmologically interesting models are almost untouched by these coannihilations. Only for large $m_\chi \geq 400$ GeV, the respectively high values are reduced, because of corresponding models are ruled out from the cosmological interesting region $0.1 < \Omega h^2_{IGC} < 0.3$.

From Fig. 7 one can see that the field of maximal sensitivity of the best new-generation CDM detectors, like GENIUS [47], as well as the annual-modulation region of DAMA [48] are located at $40 \leq m_\chi \leq 300$ GeV, where coannihilation effects are almost invisible. Therefore despite of obvious importance of sophisticated RD calculations including complete set of coannihilation channels it may happen that coannihilations will play no any role at least for direct detection of cold dark matter.

This work was performed in collaboration with prof. H.V. Klapdor-Kleingrothaus and V.Gronewold. Author thanks Yudi Santoso for making his code available, I.V. Krivosheina for permanent interest to the work, the Max Planck Institut fuer Kernphysik for the hospitality and RFBR (Grants 00–02–17587 and 02–02–04009) for support.

References

[1] Balbi A 2000 astro-ph/0005124, de Bernardis P 2000 astro-ph/0004404
[2] Kolb E W and Turner M S 1990 The Early Universe (Redwood City: Addison-Wesley), Turner M S 2001 astro-ph/0108103
[3] Jungman G, Kamionkowski M and Griest K 1996 Phys. Rep. 267 195
[4] Nilles H P 1984 Phys. Rept. 110 1, Haber H E and Kane G 1985 Phys. Rept. 117 75, Martin S 1997 hep-ph/9709356
[5] Lee A T et al. 2001 Astrophys. J. 561 L1, Netterfield C B et al. 2001 astro-ph/0104460, Halverson N W et al. 2001 astro-ph/0104489, de Bernardis P et al. 2001 astro-ph/0105296, Melchiorri A 2002 astro-ph/0201237
[6] Goldberg H 1983 Phys. Rev. Lett. 50 1419
[7] Ellis J et al. 1983 Phys. Lett. B 127 233, Ellis J et al. 1984 Nucl. Phys. B 238 453
[8] Krauss L M 1983 Nucl. Phys. B 27 556
[9] Griest K 1988 Phys. Rev. D 38 2357, Erratum 1989 39 3802
[10] Griest K, Kamionkowski M and Turner M 1990 Phys. Rev. D 41 3565
[11] Ellis J, Roszkowski L and Lalak Z 1990 Phys. Lett. B 245 545
[12] Olive K A and Srednicki M 1989 Phys. Lett. B 230 78, 1991 Nucl. Phys. B 355 208
[13] Drees M and Nojiri M 1993 Phys. Rev. D 47 376
[14] Mizuta S and Yamaguchi M 1993 Phys. Lett. B 298 120
[15] Griest K and Seckel D 1991 Phys. Rev. D 43 3191
[16] Gondolo P and Gelmini G 1991 Nucl. Phys. B 360 145
[17] Nath P and Arnovitt R 1992 Phys. Rev. Lett. 69 725, 1993 70 3696, 1998 Phys. Lett. B 437 344
[18] Lopez L J, Nanopoulos D V and Yuan K 1993 Phys. Rev. D 48 2766
[19] Srednicki M, Watkins R and Olive K 1988 Nucl. Phys. B 310 693
[20] Baer H and Brhlik M 1996 Phys. Rev. D 53 597, 1998 57 567, Baer H et al. 2001 Phys. Rev. D 63 015007
[21] Barbieri R, Frigeni M and Giudice G F 1989 Nucl. Phys. B 313 725
[22] Bottino A et al. 1992 Astropart. Phys. 1 61, Bottino A et al. 1994 Astropart. Phys. 2 67,
Comparison of coannihilation effects in low-energy MSSM

Berezinsky V et al., 1996 Astropart. Phys. 5 1, Bottino A et al. 1999 Phys. Rev. D 59 095004

[23] Ellis J and Roszkowski L 1992 Phys. Lett. B 283 252, Roszkowski L and Roberts R 1993 Phys. Lett. B 309 329, Kane G et al. 1994 Phys. Rev. D 49 6173

[24] Edsjo J and Gondolo P 1997 Phys. Rev. D 56 1879, 1998 Phys. Atom. Nucl. 61 1181, Gondolo P and Edsjo J 1998 hep-ph/9804459, Edsjo J 1997 hep-ph/9704384

[25] Gondolo P et al. 2000 astro-ph/0012234, http://www.physto.se/~edsjo/darksusy/

[26] Ellis J et al. 2001 Phys. Lett. B 510, 236

[27] Ellis J R, Falk T and Olive K A 1998 Phys. Lett. B 444 367, Ellis J R et al. 2000 Astropart. Phys. 13 181, Erratum-ibid. 2000 15, 413

[28] Belanger G et al. 2001 hep-ph/0112278

[29] Gomez M E, Lazarides G and Pallis C 2000 Phys. Lett. B 487 313, 2000 Phys. Rev. D 61 125312

[30] Gomez M E and Vergados J D 2001 Phys. Lett. B 512 252

[31] Lahanas A B, Nanopoulos D V and Spanos V C 2000 Phys. Rev. D 62 023515

[32] Arnowitt R, Dutta B and Santos Y 2001 Nucl. Phys. B 606 59, Arnowitt R and Dutta B 2001 hep-ph/0112157

[33] Corsetti A and Nath P 2001 Phys. Rev. D 64 125010, 2000 hep-ph/0005234

[34] Boehm C, Djouadi A and Drees M 2000 Phys. Rev. D 62 035012

[35] Ellis J R, Olive K A and Santos Y 2001 hep-ph/0112113

[36] Belanger G et al. 2001 Phys. Lett. B 519 93

[37] Baer H, Balazs C and Belyaev A 2002 hep-ph/0202076

[38] Nihei T, Roszkowski L and Ruiz de Austri R 2002 hep-ph/0202009

[39] Nihei T, Roszkowski L and Ruiz de Austri R 2002 JHEP 0207 024

[40] Santos Y 2002 hep-ph/0205026

[41] Bednyakov V A, Klapdor-Kleingrothaus H V and Zaiti E 2002 Phys. Rev. D 66 015010

[42] Bednyakov V A and Klapdor-Kleingrothaus H V 2001 Phys. Rev. D 62 043524, Bednyakov V A, Klapdor-Kleingrothaus H V and Tu H 2001 Phys. Rev. D 64 075004

[43] Kim Y G et al. 2002 hep-ph/0208069

[44] Chamseddine A, Arnowitt R and Nath P 1982 Phys. Rev. Lett. 49 970, Barbieri R, Ferrara S and Savoy C 1982 Phys. Lett. B 119 343, Hall L J, Lykken J and Weinberg S 1983 Phys. Rev. D 27 2359

[45] Hagiwara K et al. 2002 Phys. Rev. D 66 010001, http://pdg.web.cern.ch/pdg

[46] Alam M S et al. 1995 Phys. Rev. Lett. 74 2885, Abe K et al. 2001 hep-ex/0107065

[47] Klapdor-Kleingrothaus H V 1998 Int. J. of Modern Phys. A 13 3953, Klapdor-Kleingrothaus H V et al., 1999 GENIUS: A Supersensitive Germanium Detector System for Rare Events hep-ph/9910205, Klapdor-Kleingrothaus H V 2002 “GENIUS: A new underground observatory for non-accelerator particle physics” hep-ph/0206249

[48] Bernabei R et al. 2000 Phys. Lett. B 480 23, 2000 Eur. Phys. J. C 18 283.