Neutralino Dark Matter in View of Recent Cosmological Data

A.B. Lahanas
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Motivation

Evidence for Cold Dark Matter is one of the biggest mysteries in astrophysics and particle physics. SUSY provides a framework to understand the origin of the CDM. Latest data yield vaues for the relic CDM that may constrain SUSY. Our goal is to quantify the type of constraints in minimum supersymmetric extensions of the Standard Model.

[A. B. Lahanas, D. V. Nanopoulos and V. C. Spanos, Phys. Lett. B464 (1999) 213 and hep-ph/9909497 (to appear in Phys. Rev. D)]

Cosmological DATA

Last years measurements of the cosmological parameters are leading the way into the era of precision cosmology

CMB temperature	$\Rightarrow T_0 \;=\; 2.7277 \pm .002\ {}^0\mathrm{K}$
Hubble constant	$\Rightarrow H_0 \;=\; (65 \pm 5) Km/sec/Mpc$
Baryonic mass density	$\Rightarrow \Omega_M \;=\; (.019 \pm .001) h_0^{-2}$
Age of Universe	$\Rightarrow t_U \;=\; 14 \pm 1.5\ Gyr$

There is mounting evidence that Universe is flat and a significant fraction of Universe's total energy is vacuum energy which accelerates its expansion

- The anisotropy of CBR offers the best way to determine the curvature and through

$$R^2_{\mathrm{curv}} = \frac{H_0^{-2}}{\Omega_0 - 1}\,.$$

the ratio of the total matter/energy density to critical density,

$$\Omega_0 \;\equiv\; \rho_{\mathrm{total}}/\rho_c \;=\; 1.0 \pm 0.2$$

- There is supporting evidence that matter density is

$$\Omega_{\mathrm{M}} \;=\; .4 \pm .1$$

❑ We are confident that the radiaton component of the energy density is small (neutrinos and CBR contribute little) so that Ω_0 is decomposed as

$$\Omega_0 \;=\; \Omega_{\rm M} + \Omega_\Lambda .$$

• $\Omega_{\rm M,\Lambda}$ are constrained by the value of the Hubble constant and the age of the Universe through

$$t_U = \frac{1}{H_0}\int_0^1 dy\,\sqrt{\frac{y}{\Omega_{\rm M}(1-y)+\Omega_\Lambda(y^3-y)+y}}\,.$$

This is less restrictive than the limits put by Supernovae data which indicate that Ω_Λ is nonvanishing giving rise to an accelerating Universe.

Type-Ia supernovae (SNIa) data

Objects of known luminosities (standard candles) can be used to determine the relation between distance d and red shifts z . Type-Ia supernovae are the best candidates for standard candles. If standard candles are far away the relation between d, z is nonlinear and sensitive to $\Omega_{\mathrm{M},\Lambda}$

SCP (Supernovae Cosmology Project)
HZS (High Z - Supernovae Search)

Collected data on red shifts, luminosities, light curves of distant supernovae. Over 50 type-Ia SN were studied with $z = .3 \rightarrow .9$ and calibrated with a comparable number of nearby supenovae with $z \leq .1$

Distant supernovae are fainter, that is more distant than expected for a decelerated Universe $\Rightarrow$ *It appears that expansion rate is accelerating*

The acceleration is driven by a nonvanishing (although small) cosmological constant. The results are summarized in (Perlmutter et al. astro-ph/9904051.)

$$\Omega_\Lambda = \frac{4}{3}\Omega_\mathrm{M} + \frac{1}{3} \pm \frac{1}{6}$$

$$\Omega_\mathrm{M} = .4 \pm .1 \quad \Rightarrow \quad \Omega_\Lambda = .85 \pm .20$$

The full accounting of matter and energy in the Universe, as fractions of critical density, is :

Neutrinos	.3 % — 15. %
Stars	.3 % — .6 %
Baryons	5. % ± .5 %
Matter	40. % ± 10. %
Dark Energy	80. % ± 10. %

$$\Omega_{\rm M} \ = \ .4 \pm .1 \quad \text{and} \quad \Omega_{\rm Baryons} \ = \ .05 \pm .005 \quad \Rightarrow$$

$$\Omega_{\rm CDM} \ = \ .35 \pm .10$$

The CDM relic density is then

$$\boxed{\Omega_{\rm CDM} h_0^2 \ = \ .15 \pm .07}$$

($h_0 \ = \ 65. \pm 5.$ is the rescaled Hubble constant)

• Measurements of the baryonic to total mass in rich clusters yield $\Omega_{\rm B} / \Omega_{\rm M} \ \simeq \ .15$ resulting to even tighter values

$$\boxed{\Omega_{\rm CDM} h_0^2 \ = \ .12 \pm .04}$$

These limits on the CDM relic density put constraints on the supersymmetry breaking scale in versions of SUSY where R-parity is conserved and the LSP, if it is neutral with no strong interactions, emerges as candidate for CDM.

Evolution of Universe when $\Lambda \neq 0$

Einstein's eqs. $\Rightarrow$

$$\ddot{R}/R = -\frac{4\pi G}{3}(\bar{\rho} + 3\bar{p})$$
$$(\dot{R}/R)^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{k}{R^2}$$

Equation of state $\Rightarrow$

$$\dot{\rho} = -3(\rho + p)(\dot{R}/R)$$

with $\bar{\rho} = \rho + \Lambda \ , \ \bar{p} = p - \Lambda$

- Λ contributes negatively to pressure (for $\Lambda > 0$).
- For ordinary matter and radiation $(\rho + 3p) > 0$ and $\ddot{R}/R < 0$ (deceleration). "Exotic" component, like vacuum energy, may have sufficient negative pressure to make $(\bar{\rho} + 3\bar{p}) < 0$ (acceleration).

The deceleration parameter defined as $q \equiv -\frac{\ddot{R}R}{\dot{R}^2}$ is given by

$$q = \frac{1}{2}\Omega + \frac{3}{2}\sum_i \Omega_i w_i$$

The pressure of component i, $p_i \equiv w_i \rho_i$; e.g., for baryons $w_i = 0$, for radiation $w_i = 1/3$, and for vacuum energy $w_i = -1$.

From today's values for Ω_i it follows that $q_0 < 0$, due to the negative contribution of the cosmological constant.

Neutralino Dark Matter

In SUSY theories with R-parity conservation the LSP is stable and a candidate relic from Big Bang. A relic LSP should be neutral without strong interactions and the lightest of the neutralinos, $\tilde{\chi}$, is an appealing candidate for CDM. Their density today is calculated by solving the Boltzmann equation:

$$\frac{dn}{dt} = -3\frac{\dot{R}}{R}n - \langle \sigma v_{rel} \rangle \left(n^2(T) - n_{eq}^2(T)\right),$$

n is the # of $\tilde{\chi}$'s per unit volume, n_{eq} their density in thermal equilibrium and $\langle \sigma v_{rel} \rangle$ the thermally averaged $\tilde{\chi}$ annihilation cross section times their relative velocity.

• At very high T neutralinos were created and annihilated being in equilibrium with the cosmic soup. As the Universe expands the temperature drops and for $T \leq 2m_{\tilde{\chi}}$ can no longer be produced. They only annihilate $\tilde{\chi} + \tilde{\chi} \Rightarrow X + Y$ at a rate governed by σ_{annih}. As the temperature further drops the expansion rate outstrips the annihilation rate, at about $T_f \approx \frac{m_{\tilde{\chi}}}{20}$, freezing the remaining neutralino population locking in a $\tilde{\chi}$ relic density.

• *Caution should be taken in case some particle species have masses close to LSP's mass. In that case coannihilations of these with LSP may play an important role in keeping LSPs in chemical equilibrium with the bath and the number density of LSPs can be reduced.*

When coannihilations are of relevance Boltzman equation still holds with

$$n = \sum_i n^i \quad , \quad n_{eq} = \sum_i n_{eq}^i$$

$$\langle v_{rel}\sigma \rangle \Rightarrow \langle v_{rel}\sigma_{eff} \rangle = \sum_{i,j} \frac{n_{eq}^i n_{eq}^j}{n_{eq}^2} \langle v_{rel}\sigma_{ij} \rangle$$

The sum runs over all particles which are almost degenerate in mass.

Boltzmann transport equation can be brought into the form:

$$\frac{dq}{dx} = \lambda(x)\,(q^2 - q_0^2)$$

with $q \equiv \frac{n}{T^3\,h(T)}$, $x \equiv \frac{T}{m_{\tilde{\chi}}}$ and

$$\lambda(x) \equiv m_{\tilde{\chi}} \left(\frac{45}{4\pi^3 G_N g(T)} \right)^{1/2} \left(h(T) + \frac{m_{\tilde{\chi}}}{3} h'(T) \right) \langle \sigma v_{rel} \rangle \,.$$

The functions g(T) , h(T) are the effective energy / entropy degrees of freedom which determine Universe's energy $\rho(T)$ and entropy $s(T)$ density.

$$\rho(T) = \frac{\pi^2}{30}\, T^4\, g(T)\;,\;\; s(T) = \frac{2\pi^2}{45}\, T^3\, h(T)$$

♣ $g(T), h(T) \Longrightarrow$

Depending on temperature the content of particles in equilibrium is different. Special care should be taken in the regime $40 MeV < T < 2.5 GeV$ where the quark - hadron transition takes place. [M. Srednicki, R. Watkins and K.A. Olive Nucl. Phys. B310 (1988) 693.]

♣ $\langle \sigma v_{rel} \rangle \Longrightarrow$

The freeze out temperature is typically $T_f \approx \frac{m_{\tilde{\chi}}}{20}$ and thus need know the annihilation cross sections at their non-relativistic limits. Up to $\mathcal{O}(v^2)$, $v\sigma = a + \frac{b}{6} v^2$ entailing to

$$< v\sigma > = a + (b - \frac{3}{2} a) x$$

The coefficients a and b have been calculated for each annihilation channel $\tilde{\chi}\tilde{\chi} \rightarrow XY$. At low temperatures the final products can be ordinary fermions, gauge bosons or Higgses. [M. Drees and M. M. Nojiri, Phys. Rev. D47 (1993) 376]

Special care should be taken when we are close to either a threshold $2m_{\tilde{\chi}} = M_X + M_Y$ or a pole $2m_{\tilde{\chi}} = M_I$ (M_I = mass of particle into which $\tilde{\chi}$'s are fused to). In these cases the nonrelativistic expansion breaks down.

♣ $Solving Boltzmann \Longrightarrow$

The largeness of the prefactor $\lambda(x)$ can be used to find an approximate solution

$$q_{approx}(x) \;=\; q_0(x)\;(1\;+\;\frac{q_0'(x)}{2\lambda(x)q_0^2(x)})\;+\;\mathcal{O}(1/\lambda^2)$$

, in terms of the equilibrium density function $q_0(x)$, which is valid in the regime $x \equiv \frac{T}{m_{\tilde{\chi}}} > x_f \equiv \frac{T_f}{m_{\tilde{\chi}}}$. This method is reminiscent of the WKB approximation. This solution is used to integrate numerically Boltzmann equation by employing algorithms eligible to handle stiff differential equations. The codes used are very fast and the numerical solutions obtained are very accurate.

[A.B.L, D. V. Nanopoulos and V. C. Spanos, Phys. Lett. B464 (1999) 213 and hep-ph/9909497.]

Neutralino Relic Density in the CMSSM

We consider MSSM with universal boundary conditions for the soft scalar masses m_0, gaugino masses $M_{1/2}$ and trilinear couplings A_0. We do not enforce unification of couplings. Electroweak symmetry breaking is assumed and the 1-loop corrected effective potential is used in the minimization conditions. The inputs are

$$m_0 \; , \; M_{1/2} \; , \; A_0 \; , \; tan\beta \; , \; sign(\mu),$$

the values of gauge couplings at M_Z, and masses of SM particles. Two-loop RGE's are used to know all relevant quantities at a reference scale which is taken to be M_Z.

• We exclude points in the parameter space that are theoretically forbidden such as those for which EW radiative breaking is not implemented, or points for which the LSP is not a neutralino etc.

• We respect all available experimental bounds. The most stringent one is the chargino mass bound $m_{\tilde{C}} > 95 \; GeV$. Only for very low $tan\beta$ the Higgs boson mass bound outstrips the chargino bound. Also the stop mass bound $m_{\tilde{t}_1} > 176 \; GeV$ excludes a small region of the parameter space which is allowed by chargino searches.

For each input we calculate the coefficients a , b and then we solve Boltzmann equation to get $\Omega_{\tilde{\chi}} \, h_0^2$.

The LSP's composition is

$$\tilde{\chi} \; = \; \alpha_B \, \tilde{B} \; + \; \alpha_W \, \tilde{W} \; + \; \alpha_u \, \tilde{H}_u \; + \; \alpha_d \, \tilde{H}_d$$

with $\sum_i |\alpha_i|^2 = 1$.

Higgsino like:	$|\alpha_u|^2 \; + \; |\alpha_d|^2 \; \simeq \; 1$
Gaugino like:	$|\alpha_B|^2 \; + \; |\alpha_W|^2 \; \simeq \; 1$

Remarks:

• In the CMSSM with universal boundary conditions for soft masses a Higgsino like LSP is not favored.

LSP is not slightly lighter than the lightest of charginos and the second - lightest neutralino. Coannihilations with these states are of no importance. Only coannihilations with $\tilde{\tau}_R$ *may be of relevance.*

• In most of the parameter space, $M_{1/2} > 120 \; GeV$, the LSP is mostly "Bino" with small contamination of Higgsinos. Only for $M_{1/2} < 120 \; GeV$ the Higgsino impurities become sizeable.

Light neutralinos can annihilate to a fermion-antifermion pair $\tilde{\chi}\tilde{\chi} \to f\bar{f}$, $(f \neq top)$ *and Z-exchange dominates in the limit of large* m_0 *. This puts a lower bound on* $\langle \sigma v_{rel} \rangle$ *and hence an upper limit on* $\Omega_{\tilde{\chi}} \, h_0^2$ *compatible with astrophysical data. These corridors of heavy* $\tilde{q}$, $\tilde{l}$ *and light LSP are excluded by chargino searches which put a lower bound* $M_{1/2} \; > \; 140 \; GeV$ *. In this region the LSP is mostly Bino and does not couple to Z - boson.*

We scan the parameter space for values

$$m_0\ ,\ M_{1/2}\ ,\ |A_0|\ <\ 1\,TeV\ ,\ \tan\beta\ <\ 40$$

$\tilde{\tau}_R - \tilde{\chi}$ coannihilations as well as $\tilde{\tau}_R - \tilde{\tau}_R$ annihilations are important in regions of the parameter space for which $\tilde{\tau}_R$ and $\tilde{\chi}$ are almost degenerate in mass.

[J. Ellis, T. Falk and K.A. Olive, Phys. Lett. B413 (1998) 355; J. Ellis, T. Falk, K.A. Olive and M. Srednicki, hep-ph/9905481;
M. Gomez,G. Lazarides and C. Pallis, hep-ph/990726;hep-ph/0004028.]

Depending on inputs we distinguish two cases both compatible with having the lightest of the neutralinos as the LSP:

- Coannihilation free region , $1.25\, m_{\tilde{\chi}}\ <\ m_{\tilde{\tau}_R}$
- Coannihilation region, $m_{\tilde{\chi}}\ <\ m_{\tilde{\tau}_R}\ <\ 1.25\, m_{\tilde{\chi}}$

Coannihilation free region

In this region the cosmological constraint $\Omega_{\tilde{\chi}}\, h_0^2\ =\ .15 \pm .07$ along with the bound $M_{1/2}\ >\ 140\ GeV$ imposed by chargino searches yields upper bounds on $m_0\ ,\ M_{1/2}$

$$m_0\ <\ 200\ GeV\ ,\ 140\ GeV\ <\ M_{1/2}\ <\ 340\ GeV$$

for $\tan\beta\ <\ 30$ and for all $|A_0|\ <\ 1\ TeV$ (see figures 1 and 2).

The bound on m_0 is correlated to $M_{1/2}$ ($m_0 = 200\ GeV$ for $M_{1/2}\ =\ 140\ GeV$ and $m_0\ \simeq\ 130\ GeV$ for $M_{1/2}\ =\ 340\ GeV$.)

Electroweak precision data

The EW precision data move to opposite direction, imposing lower bounds on the effective SUSY breaking scale, showing a preference towards large values of $M_{1/2}$. The higher the $M_{1/2}$ value the lower the χ^2 is and better agreement with the experimental data is obtained (SM limit). Studies of the effective weak mixing angle, if combined **SLD+LEP** data are used, dictate that $M_{1/2} > 300\ GeV$ ($> 500\ GeV$ if gauge coupling unification is enforced), although lower values $M_{1/2} \approx 200\ GeV$ are not totally excluded. If such lower bounds on $M_{1/2}$ are imposed the cosmologically allowed region is further restricted, especially for low values of $\tan\beta$ (see figure 3).

For $M_{1/2} > 300\ GeV$ and values of $\tan\beta < 10$, the mass bounds put on the LSP, the lightest of charginos, staus, stops and Higgs scalar are as:

$$
\begin{aligned}
m_{\mathrm{LSP}} &: \ 115\ (116)\mathrm{GeV} \ - \ 130\ (133)\mathrm{GeV}\,, \\
m_{\tilde{C}} &: \ 210\ (218)\mathrm{GeV} \ - \ 241\ (250)\mathrm{GeV}\,, \\
m_{\tilde{\tau}_R} &: \ 122\ (130)\mathrm{GeV} \ - \ 157\ (158)\mathrm{GeV}, \\
m_{\tilde{t}_1} &: \ 401\ (403)\mathrm{GeV} \ - \ 667\ (687)\mathrm{GeV}\,, \\
m_{h_0} &: \ 96\ (87)\mathrm{GeV} \ - \ 125\ (122)\mathrm{GeV}\,.
\end{aligned}
$$

These refer to the case $\mu > 0$ ($\mu < 0$).

Large tanβ

In the coannihilation free region, these upper limits set on $M_{1/2}, m_0$ can be evaded in certain cases where $\tan\beta$ takes large values and μ is positive. This happens when the pseudoscalar Higgs A has a mass approaching $2\ m_{\tilde{\chi}}$. This along with the fact that the couplings $A\tau\bar{\tau}$, $Ab\bar{b}$ are proportional to $\tan\beta$, and hence large, make the pseudoscalar Higgs exchange dominate the reactions $\tilde{\chi}\ \tilde{\chi} \to \tau\ \bar{\tau}$ and $\tilde{\chi}\ \tilde{\chi} \to b\ \bar{b}$. This enhances the corresponding cross sections resulting to acceptable relic densities. Note the important role the pseudoscalar Higgs boson plays in this case since it dominates the $\tilde{\chi}\ \tilde{\chi} \to \tau\tilde{\tau}, b\tilde{b}$ reactions even when the LSP's composition involves a small $(\ 10\ \%)$ Higgsino component. Such points of the parameter space allow for $M_{1/2}, m_0$ as large as $\simeq 450\ GeV$ and stay comfortably well with the process $b \to s\ \gamma$ which is not in conflict with large $\tan\beta$ and $\mu > 0$. Since large values of $\tan\beta$ are compatible with Yukawa coupling unification, the possibility of obtaining acceptable $\tilde{\chi}$ relic densities in the coannihilation free region may feasible in such scenarios (see figure 4).

Coannihilation region

In this region $\tilde{\tau}_R - \tilde{\chi}$ coannihilations, and to a lesser extend $\tilde{\tau}_R - \tilde{\tau}_R$ annihilations, play an important role. If $\Omega_{\tilde{\chi}}\, h_0^2$ is the actual relic desity, and $\Omega^0_{\tilde{\chi}}\, h_0^2$ that calculated ignoring these effects an empirical formula connecting these is $\Rightarrow$

$$\Omega_{\tilde{\chi}} = R(\Delta M)\, \Omega^0_{\tilde{\chi}}$$

The reduction factor $R(\Delta M)$, which depends on $\Delta M = (m_{\tilde{\tau}_R} - m_{\tilde{\chi}})/m_{\tilde{\chi}}$, smoothly interpolates between ≈ 0.1 and 1.0 for values of ΔM in the range $0.00 - 0.25$, (see figure 5), and can be extracted using the results of reference

[J. Ellis, T. Falk, K.A. Olive and M. Srednicki, hep-ph/9905481.]

The above equation is a handy device to find the actual relic density from $\Omega^0_{\tilde{\chi}}\ h_0^2$, in cases where coannihilations are important. See for instance how 1 is modified when the above equation is used to find the actual relic density in regions where coannihilation effects are of relevance. Also the part of figure 3 which lies below the line marking the boundary of the coannihilation region, has been drawn using the above formula.

Conclusions

We have calculated the relic neutralino abundance in the framework of the CMSSM, using the recent cosmological data which support evidence for a flat and accelerating Universe

- Although the recent cosmological data do not rule out corridors in the $(m_0, M_{1/2})$ plane in which the LSP is light, with unbounded sfermion masses, however such regions are excluded by experimental data from chargino searches.
- In the cosmologically interesting domain, $M_{1/2} \lesssim 340\mathrm{GeV}$ and $m_0 \lesssim 200\mathrm{GeV}$, provided $1.25\ m_{\tilde{\chi}} \leq m_{\tilde{\tau}_R}$ where coannihilation processes do not play any significant role. If we put a lower bound on $M_{1/2}$, as EW precision data suggest, the allowed $m_0, M_{1/2}$ domain is severely reduced constraining the masses of SUSY particles.
- Within CMSSM there are two ways to reconcile the experimental information from EW and cosmological data with values of m_0 and $M_{1/2}$ that lie outside the strict bounds quoted above $\Longrightarrow$
  a) Move to the large $\tan\beta$ and $\mu > 0$ region, while staying within the domain $1.25\ m_{\tilde{\chi}} \leq m_{\tilde{\tau}_R}$.
  In this case the pseudoscalar Higgs boson A plays an

essential role since its exchange may dominate the reactions $\tilde{\chi}\tilde{\chi} \to \tau\bar{\tau}, b\bar{b}$, enhancing the corresponding cross sections. Large $\tan\beta$ values, for $\mu > 0$, are compatible with the CLEO data for the process $b \to s\gamma$. Moreover this mechanism may offer the possibility of obtaining cosmologically acceptable $\tilde{\chi}$ relic densities in the coannihilation free region $1.25\, m_{\tilde{\chi}} \leq m_{\tilde{\tau}_R}$, in Yukawa coupling unification scenarios.

b) Move into the narrow band $m_{\tilde{\chi}} < m_{\tilde{\tau}_R} \lesssim 1.25 m_{\tilde{\chi}}$ in which case $\tilde{\tau}_R$, the next to LSP sparticle, is almost degenerate in mass with the LSP and $\tilde{\tau}_R - \tilde{\chi}$ coannihilation processes are of relevance. In this region the upper limit on the parameter $M_{1/2}$ is pushed to $> 1\, TeV$, approaching the boundary of the CMSSM parameter space in which LHC searches will be sensitive.

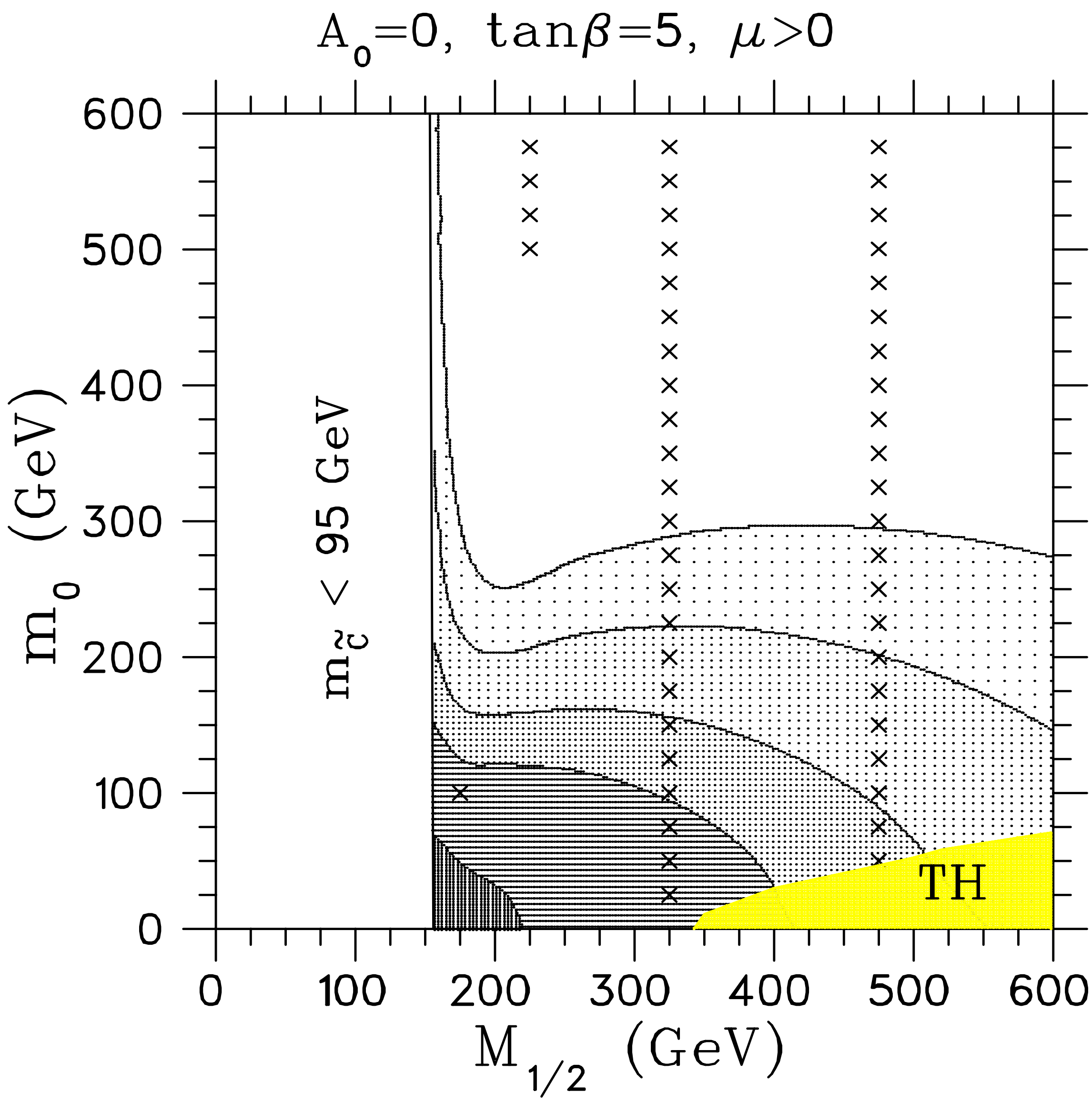


Figure 1: The LSP relic density $\Omega_{\tilde{\chi}}\, h_0^2$ in the $(m_0, M_{1/2})$ plane for given values of A_0, $\tan\beta$ and sign of μ. Grey tone regions, from darker to lighter, designate areas in which the LSP relic density takes values in the intervals: $0.00 - 0.08$, $0.08 - 0.22$, $0.22 - 0.35$, $0.35 - 0.60$ and $0.60 - 1.00$ respectively. In the blanc area $\Omega_{\tilde{\chi}}\, h_0^2 > 1.0$. The area marked by "TH" is theoretically excluded . The area labelled by $m_{\tilde{C}} <$ 95GeV is excluded by chargino searches. Crosses denote points for which thresholds or poles are encountered.

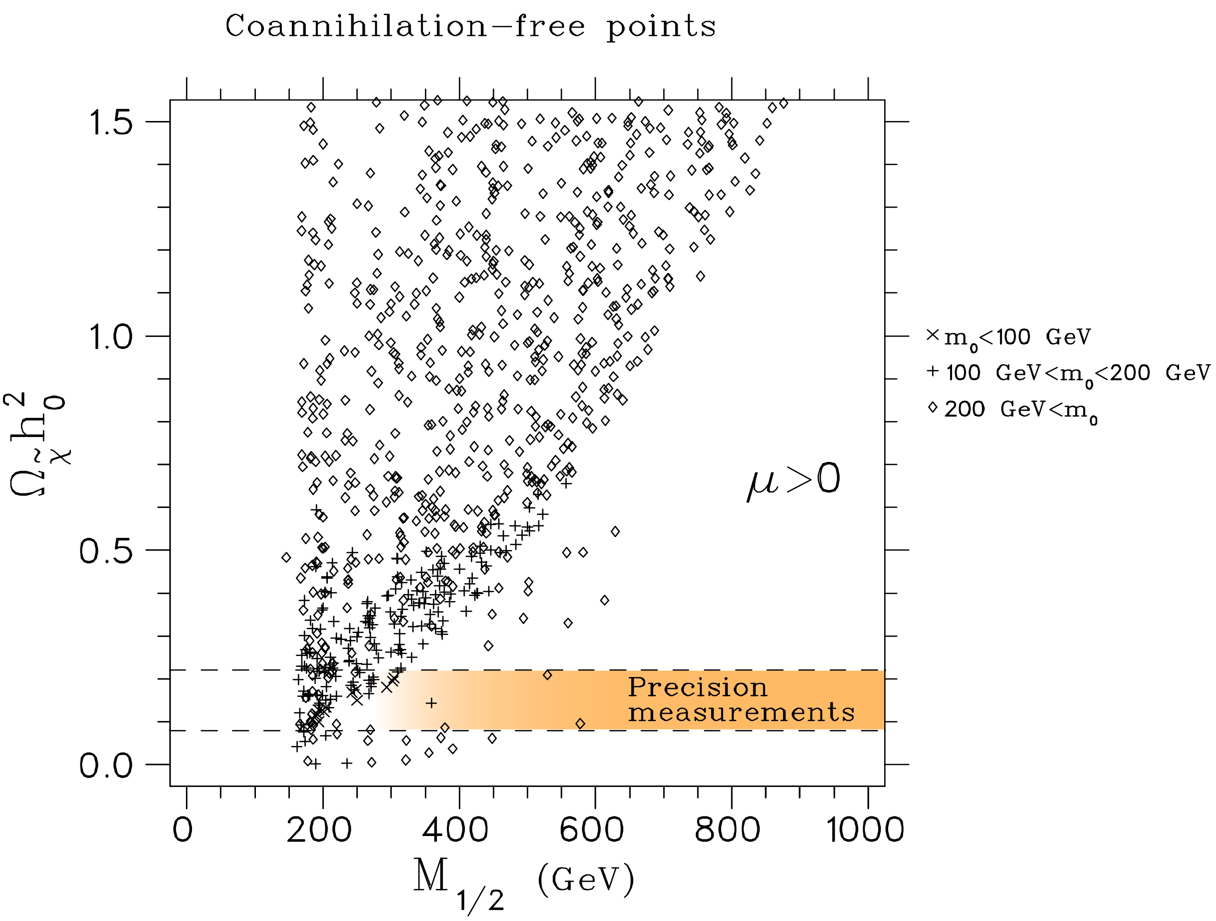
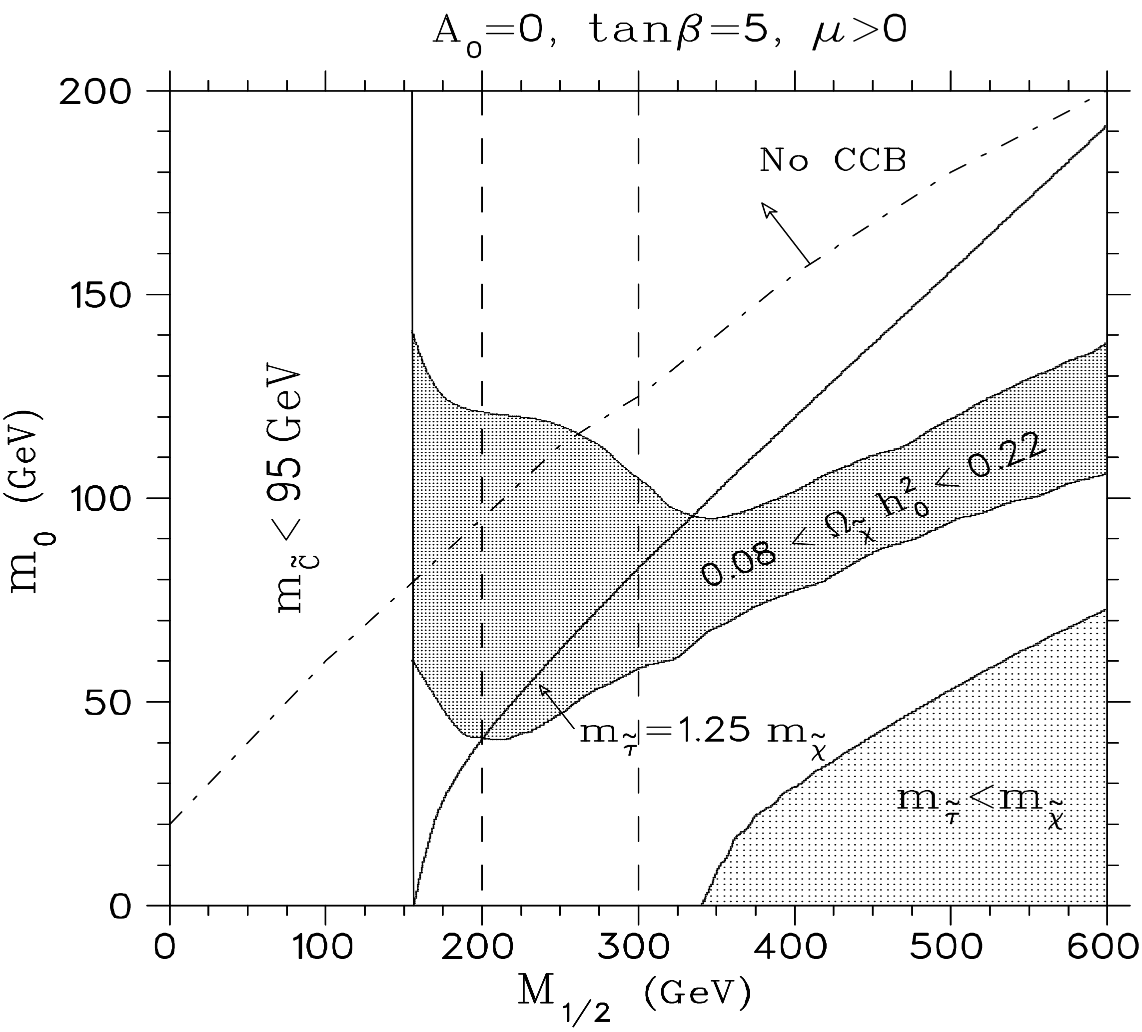


Figure 2: Scattered plot of the relic density versus $M_{1/2}$ from a sample of 4000 random points in the parameter space. Low $M_{1/2}$ values are excluded by chargino searches. All points shown are in the coannihilation free region. Only the points with relic density less than 1.5 are shown. The grey tone region within the cosmologically allowed stripe designates the region which agrees with EW precision data. The horizontal dashed lines mark the limits $0.08 < \Omega_{\tilde\chi} h_0^2 < 0.22$.



(a)

Figure 3: The dark-shaded area designates the cosmologically allowed region $\Omega_{\tilde{\chi}} h_0^2 = 0.15 \pm 0.07$. The boundary of the coannihilation free region is labelled by $m_{\tilde{\tau}} = 1.25\ m_{\tilde{\chi}}$. Also shown is the region in which $m_{\tilde{\tau}} < m_{\tilde{\chi}}$, shaded in light-grey tone. The boundary of the region which is free of color and charged breaking minima, marked as "No CCB", is also shown. The vertical dashed lines represent the boundaries of the regions $M_{1/2} > 200$GeV and $M_{1/2} > 300$GeV.

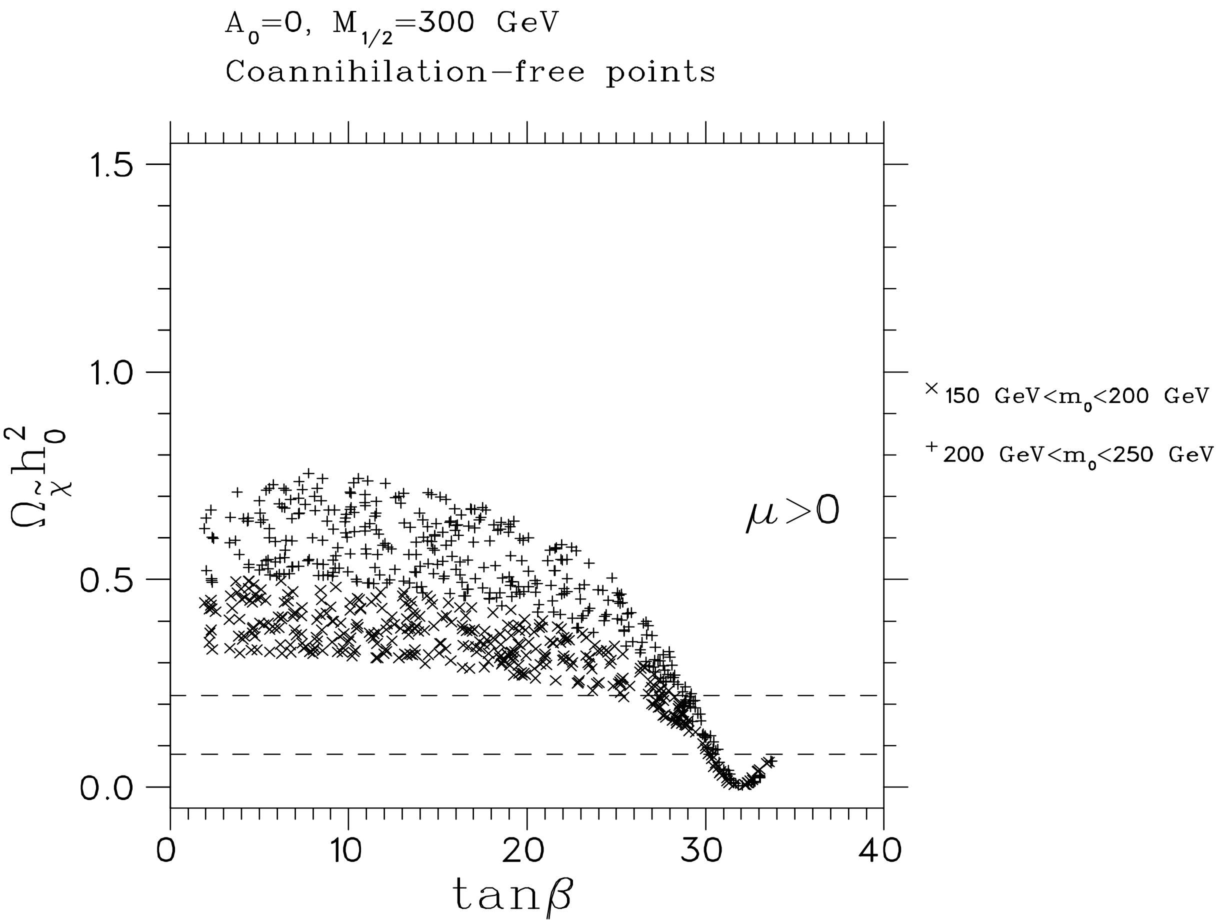


Figure 4: Scattered plots of the relic density versus $\tan\beta$ from a sample of random points with fixed $A_0 = 0\text{GeV}$, $M_{1/2} = 300\text{GeV}$. and $\mu > 0$. The points shown fall within the coannihilation free region. The two horizontal dashed lines mark the cosmologically allowed stripe.

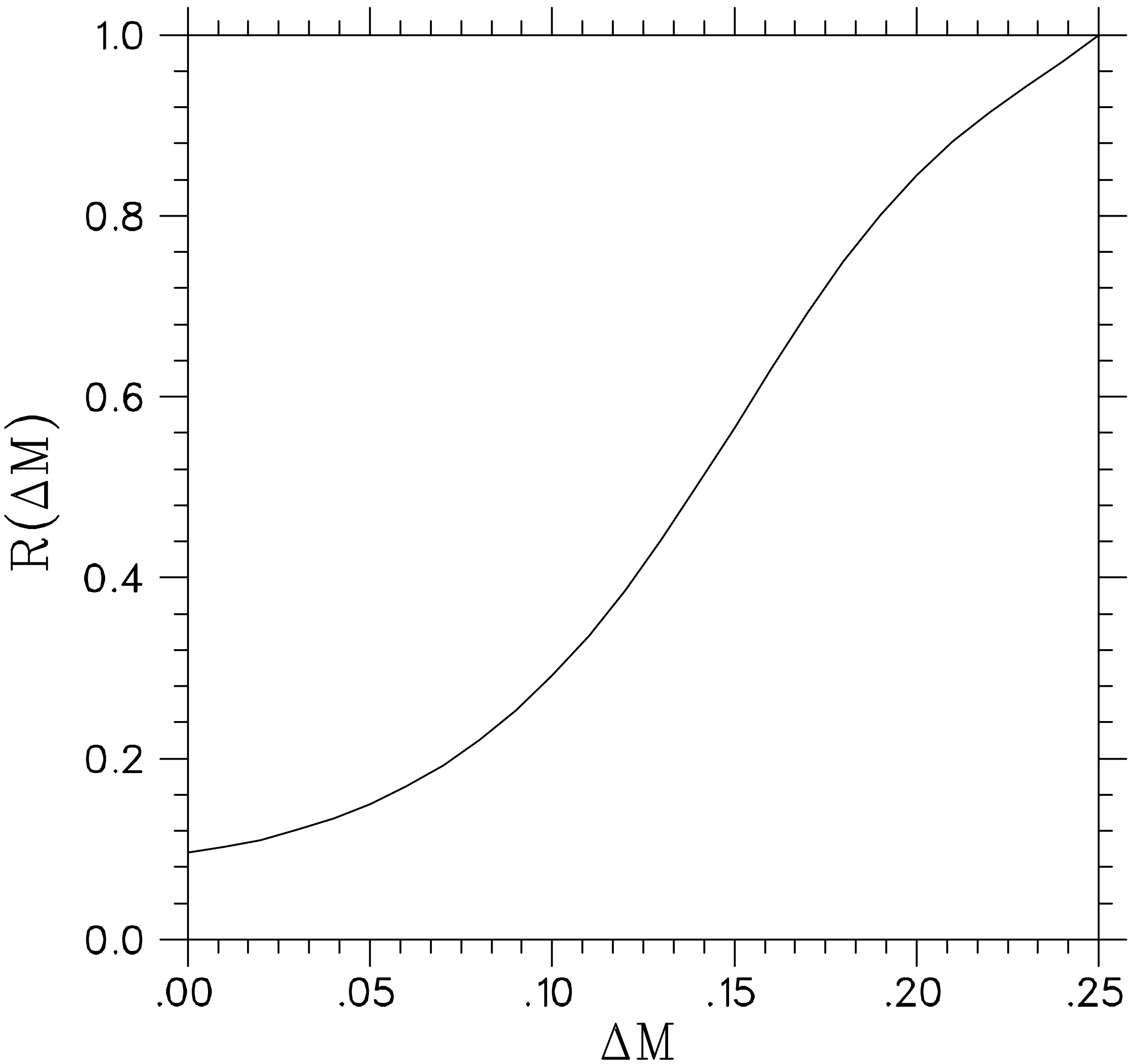


Figure 5: The reduction factor $R(\Delta M)$ as function of $\Delta M = (m_{\tilde{\tau}_R} - m_{\tilde{\chi}})/m_{\tilde{\chi}}$.

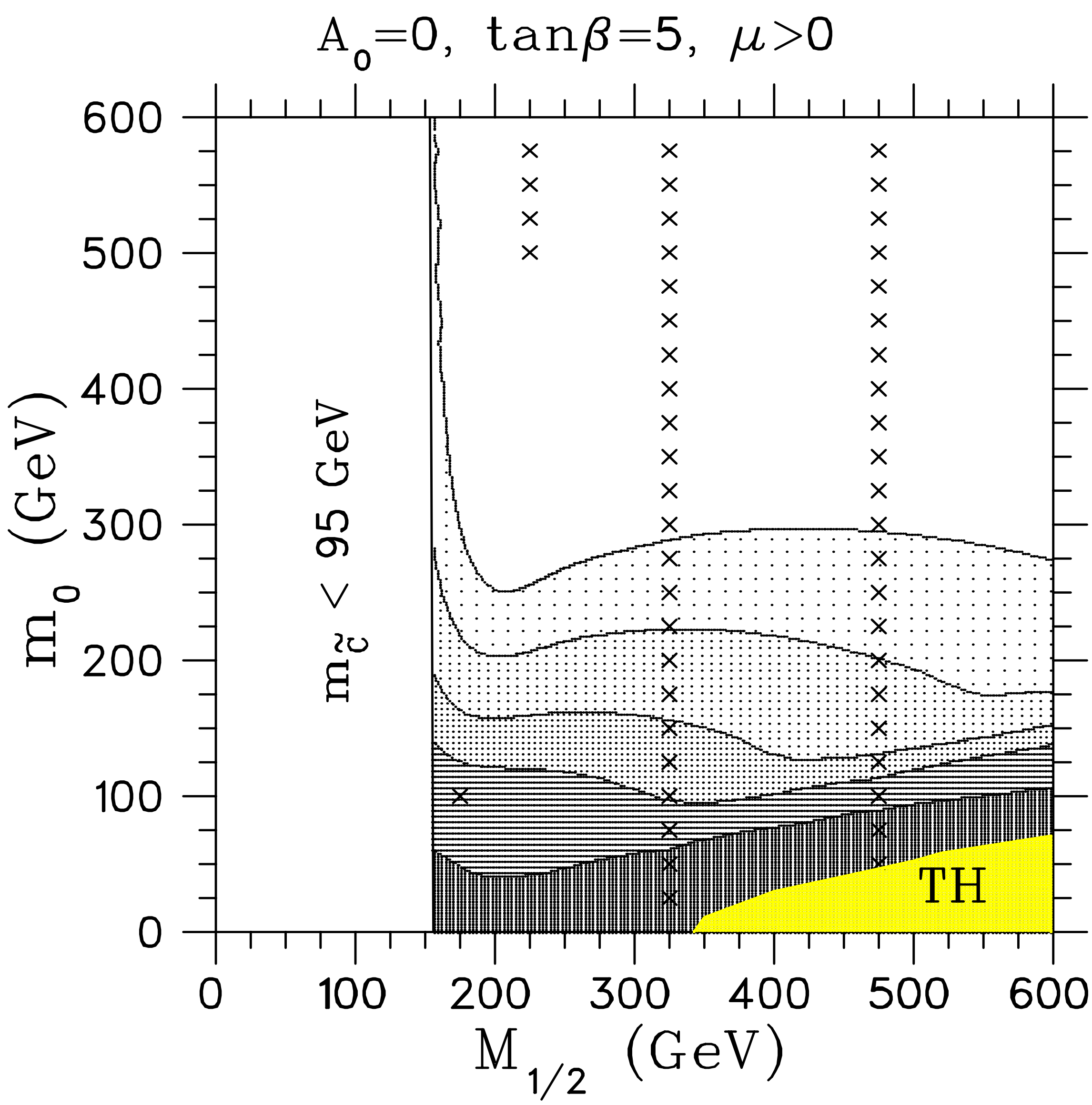


Figure 6: The LSP relic density $\Omega_{\tilde{\chi}}\, h_0^2$ in the $(m_0,M_{1/2})$ plane for given values of A_0, $\tan\beta$ and sign of μ when coannihilation effects are taken into account.