Neutralino as the lightest supersymmetric particle (LSP) is a candidate for supersymmetric dark matter. It is known that coannihilation effects could be important in neutralino relic density calculation. Here we present some results on neutralino-stop coannihilation in the CMSSM. In this model, the stop $\tilde{t}_1$ can be degenerate with the lightest neutralino $\chi$ when $|A_0| \neq 0$ and large, more specifically when the lighter stop mass is suppressed by large off-diagonal terms in the stop square mass matrix. In the region where $\tilde{t}_1$ is slightly heavier than $\chi$, the coannihilation effect brings the relic density into the range favored by cosmology. While the $\chi - \tilde{t}_1$ coannihilation channels do not increase the range of $m_\chi$, they do extend the cosmologically preferred region to larger values of $m_0$. 

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Neutralino-stop coannihilation in the CMSSM

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Neutralino as the lightest supersymmetric particle (LSP) is a candidate for supersymmetric dark matter. It is known that coannihilation effects could be important in neutralino relic density calculation. Here we present some results on neutralino-stop coannihilation in the CMSSM. In this model, the stop $\tilde{t}_1$ can be degenerate with the lightest neutralino $\chi$ when $|A_0| \neq 0$ and large, more specifically when the lighter stop mass is suppressed by large off-diagonal terms in the stop square mass matrix. In the region where $\tilde{t}_1$ is slightly heavier than $\chi$, the coannihilation effect brings the relic density into the range favored by cosmology. While the $\chi - \tilde{t}_1$ coannihilation channels do not increase the range of $m_\chi$, they do extend the cosmologically preferred region to larger values of $m_0$.

1. INTRODUCTION

A supersymmetric model with conserved $R$-parity provides a candidate for dark matter particle, i.e. the lightest supersymmetric particle (LSP) is stable and can sustain the time from the big bang to the current time. In the minimal supersymmetric standard model (MSSM), all fermion and gauge fields of the Standard Model are given supersymmetric partners and there are two Higgs multiplets. Furthermore, supersymmetry (SUSY) is broken and the breaking is represented by soft breaking terms. Assuming the most general MSSM, however, one has too many free parameters to deal with. The number of free parameters is reduced significantly when one assumes some kind of SUSY breaking mechanism. One such model is the constrained MSSM (CMSSM), or also known as the minimal supergravity (mSUGRA) model, where some universalities are imposed in the soft breaking terms, such that we have only five free parameters in this model: $m_0$ (the universal scalar mass at the GUT scale), $m_{1/2}$ (the universal gaugino mass at the GUT scale), $A_0$ (the universal trilinear couplings at the GUT scale), $\tan \beta$ (the ratio of the two Higgs vacuum expectation values), and $\text{sign}(\mu)$ where $\mu$ is the Higgs mixing parameter.

The best candidate for dark matter in the CMSSM is the lightest neutralino $\chi$. In our analysis, we take its relic density to be $0.1 \leq \Omega_\chi h^2 \leq 0.3$, where $\Omega = \rho/\rho_{\text{critical}}$ and $h$ is the Hubble constant in the unit of $100 \text{ km Mpc}^{-1} \text{ s}^{-1}$. The upper limit is imposed by the measurement of the age of the universe, while the lower limit is suggested by astrophysical observations. One can relax the lower limit if there are other sources of dark matter.

The cosmologically favored regions in the CMSSM have been studied intensively for more than a decade. This includes the bulk \textsuperscript{[2,3]}, the $H$ and $A$ pole rapid annihilation \textsuperscript{[2]}, the neutralino-stau ($\chi - \tilde{\tau}$) coannihilation \textsuperscript{[4]} and the focus point \textsuperscript{[5]} regions. It has also been realized that stop $\tilde{t}_1$ can be degenerate with $\chi$ when $|A_0|$ is large \textsuperscript{[6]}. Therefore we should also consider the neutralino-stop coannihilation \textsuperscript{[7,8]} to complete our study on the CMSSM parameter space \textsuperscript{[9,10]}.

2. NEUTRALINO-STOP COANNIHILA-

Neutralino relic density is calculated \textsuperscript{[11]} by assuming that in the early universe neutralino was in thermal equilibrium with other particles.

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When the expansion rate of the universe was greater than the scattering rate that keeps the neutralino in equilibrium, the neutralino froze out. The relic density is obtained by evolving the Boltzmann equation from the freeze out to the current time. Although, within $R$-parity conservation, the neutralino cannot decay, it can pair annihilate or coannihilate with other supersymmetric particles into Standard Model particles. Coannihilation effect is exponentially suppressed by Boltzmann factor, so it is only important when the mass difference between the particles involved is small [2].

To understand how the neutralino-stop degeneracy can occur, let us look at the mass spectrum. The lightest neutralino, in this model is mostly Bino with mass $\approx 0.4 m_{1/2}$. The stop square-mass matrix is

$$
\begin{pmatrix}
m^2_{\tilde{t}_L} & -m_t (A_t + \mu \cot \beta) \\
-m_t (A_t + \mu \cot \beta) & m^2_{\tilde{t}_R}
\end{pmatrix}
$$

(1)

Although $\tilde{t}_R$ is generally heavier than $\tilde{t}_L$, the off-diagonal terms can be very large due to the large top mass $m_t$, and this suppresses one of the eigenvalues, $m^2_{\tilde{t}_1}$. For a large $|A_t|$ with sign($A_t$) = sign($\mu$), we get a light $\tilde{t}_1$.

Processes involved in the neutralino-stop coannihilation are listed in Table 1. The most dominant contribution comes from $\tilde{t}_1 \tilde{t}_1 \rightarrow gg$. The $\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}$, $\tilde{t}_1 \tilde{t}_1 \rightarrow tt$ and $\tilde{\chi}_1 \rightarrow tg$ are also dominant when the final states are kinematically available. Processes that have only electroweak couplings, i.e. $\tilde{t}_1 \tilde{t}_1 \rightarrow \ell\bar{\ell}, W^+W^-, Z\gamma, ZZ$ and $\chi \tilde{t}_1 \rightarrow t\gamma$, contribute only $\approx 1\%$ and therefore can be neglected.

To see the significant of this annihilation, we plot the separate contribution to the annihilation cross section $\sigma_{\text{eff}}$ versus $\Delta M \equiv (m_{\tilde{t}_1} - m_{\chi})/m_{\chi}$. Fig. 1 shows such a plot with $\tan \beta = 10$, $A_0 = 1000$ GeV and $m_0 = 300$ GeV. For small $\Delta M$, $\sigma_{\text{eff}}$ is dominated by stop-stop ($\tilde{t}_1 - \tilde{t}_1$, $\tilde{t}_1 - \tilde{t}_1^*$ and $\tilde{t}_1^* - \tilde{t}_1^*$) annihilation. Notice that, had we neglected the coannihilation effect, we would get a $\sigma_{\text{eff}}$ up to four order of magnitude less. Passing over the $tg$ production threshold at $\Delta M \approx 0.2$, the $\tilde{t}_1 - \chi$ coannihilation becomes dominant. The coannihilation effect is suppressed when $\Delta M$ is large and, in this case, can be neglected for $\Delta M \gtrsim 0.4$.

### 3. THE CMSSM PARAMETER SPACE

For $A_0 = 0$ the stop mass is much heavier than the neutralino mass. We start seeing the neutralino-stop coannihilation tail at $A_0 \approx 500$ GeV for $\tan \beta = 10$. Here we show an example of CMSSM region with neutralino-stop coannihilation tail.

Fig. 2 is a contour plot on the $(m_{1/2}, m_0)$ plane with $\tan \beta = 10$, $A_0 = 2000$ GeV and $\mu > 0$. The red shaded region is excluded because it has charged LSP, either stau for small $m_0$ or stop for small $m_{1/2}$. The light (turquoise) shaded region is the one that has $0.1 \leq \Omega h^2 \leq 0.3$. We still see the neutralino-stau coannihilation tail extending to larger $m_{1/2}$. The bulk region, common in the CMSSM, is hidden inside the red shading on the left-bottom corner. Extending to higher $m_0$ is the neutralino-stop coannihilation tail.
Figure 1. The separate contributions to the total effective cross sections $\hat{\sigma}_{\text{eff}}$ for $x = T/m_\chi = 1/23$, as functions of $\Delta M \equiv (m_{\tilde{t}} - m_\chi)/m_\chi$, obtained by varying $m_{1/2}$, with $A_0 = 1000$ GeV, $\tan \beta = 10$, $\mu > 0$ and $m_0 = 300$ GeV. The dark (black) solid line is the total $\sigma_{\text{eff}}$. The (blue) dot-dashed line is the contribution from $\tilde{t}_1 - \tilde{t}_1$ and $\tilde{t}_1 - \tilde{t}_1^*$. The (green) dashed line is the contribution from $\tilde{t}_1 - \chi$. The (red) dotted line is the contribution from $\chi - \chi$. The pale (blue) solid line is the $\chi - \chi$ annihilation cross section if we neglect the coannihilation effect.

Figure 2. The $(m_{1/2}, m_0)$ plane for $\tan \beta = 10$, $\mu > 0$ and $A_0 = 2000$ GeV. The very dark (red) shaded regions are excluded because the LSP is the $\tilde{t}_1$ or the $\tilde{\tau}_1$. The light (turquoise) shaded regions are those favored by cosmology, with $0.1 \leq \Omega h^2 \leq 0.3$ after the inclusion of coannihilation effects.

Around $m_{1/2} \approx 440$ GeV there is top production threshold, and there the region favored by cosmology is broader. This can be understood as the following. Beyond the threshold, neutralino can pair annihilates into $t\bar{t}$ through channels shown in Fig. 3. Because of the large $m_t$, a small Higgsino content in the neutralino is enough to make this channels significant. Furthermore, near the neutralino-stop degeneracy line, $\tilde{t}_1$ is relatively light, and this enhances the cross section to the level needed to bring the relic density into the preferred range.

In doing this analysis we also consider experimental constraints, such as the LEP Higgs, chargino and selectron mass limits, the $b \to s\gamma$ branching ratio and the muon anomalous magnetic moment. (Please see Ref. [8] for more details on these constraints.) At this moment the cosmological region shown in Fig. 2 is not yet excluded by any of these constraints. Thus a complete proposal for the future accelerator search for supersymmetry should also consider the neutralino-stop coannihilation region.

Higher $m_0$ suppresses the neutralino-proton cross section. Thus the neutralino-stop coannihilation predicts the possibility of a lower neutralino direct detection rate. However this reduction should be less than about one order of magnitude, as the tail extending not to a very high $m_0$. 
Figure 3. Neutralino pair annihilation diagram to $t\bar{t}$ through t- and u-channel stop exchange.

4. CONCLUSION

We have presented the neutralino-stop coannihilation in the CMSSM. This coannihilation is important when $|A_0| \neq 0$ and large. It opens up higher $m_0$ in the parameter space. There are now five generic cosmological regions recognized in this model, i.e. the bulk region, the neutralino-stau coannihilation tail, the $H$ and $A$ rapid annihilation funnel, the focus point channel and the neutralino-stop coannihilation tail. Future experiments will exclude more parameter space and we will see which region will survive. We hope that, ultimately supersymmetry will be discovered and its parameters will be measured. Before that happens, however, we should include all possibilities in our consideration.

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