Neutralino Dark Matter in SUSY-SU(5) with RH neutrinos

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Abstract. In the context of low-energy Supersymmetry (SUSY), a model of Grand Unification (GUT) with right-handed (RH) neutrinos, based on the group SU(5), is discussed and its implications for neutralino dark matter (DM) are studied and compared with the constrained MSSM. RG effects in this model modify the sparticle spectrum such that the WMAP limit on the DM relic density cannot be satisfied for small values of tan $\beta$ ($\tan \beta \lesssim 35$) and the region of the parameter space allowed by efficient neutralino-stau coannihilation presents a peculiar phenomenology and an upper bound on the neutralino mass for most of the parameters choices.

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1 Introduction: neutralino DM in CMSSM

In the minimal supersymmetric extension of the Standard Model (MSSM), imposition of R-parity makes the lightest supersymmetric particle (LSP) stable. Therefore, a neutral and uncolored LSP would be a good candidate to explain dark matter in terms of WIMP (Weakly Interacting Massive Particle). This is the case of several SUSY models, where the LSP is the lightest neutralino ($\tilde{\chi}_1^0$).

Thanks to the recent WMAP results [1], the DM relic density is very well known and this translates into very strict constraints on the parameter space of the model. For instance in the Constrained MSSM (CMSSM), where the so-called universality condition is imposed at the GUT scale, $\tilde{\chi}_1^0$ is usually bino-like, thus very weakly interacting. This makes the annihilation cross-section of the LSP very small and the DM relic density $\Omega_{\text{DM}}$ easily exceed the WMAP limit (here at 3$\sigma$):

$$0.087 \lesssim \Omega_{\text{DM}} h^2 \lesssim 0.138$$

(1)

There are only three regions of the parameter space [2], which provide the correct relic density for neutralino DM and are not excluded by the LEP limits on the mass of the SUSY particles: (i) the $\tilde{\tau}$ coannihilation region [2], (ii) the A-pole funnel region [3] and (iii) the Focus point [4]. In such regions the (co)annihilation cross-section of $\tilde{\chi}_1^0$ is enhanced and the DM relic density doesn’t exceed the WMAP bound. The regions listed above respectively mean: (i) effective $\tilde{\tau}$-$\tilde{\chi}_1^0$ coannihilation when $m_{\tilde{\tau}} \simeq m_{\tilde{\chi}_1^0}$; (ii) resonant enhancement of the LSP annihilation via the s-channel mediation of the CP-odd Higgs $A$ for $m_A \simeq 2 m_{\tilde{\chi}_1^0}$ (which requires large values of $\tan \beta$); (iii) enhancement of the Higgsino component of $\tilde{\chi}_1^0$ (and so of the annihilation cross-section) for small values of $\mu$. As we can see, all these WMAP-allowed regions require very special relations among the parameters and moreover two of them, namely $\tilde{\tau}$ coannihilation and Focus Point, lie close to regions of the parameter space excluded by theoretical requirements: respectively, neutral LSP, i.e. $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}}$, and viable radiative electro-weak symmetry breaking (REWSB), i.e. $\mu^2 > 0$. This is an important point, as we’ll see in the following discussion.

In the present talk, we will consider the possibility that extensions of the CMSSM, namely an evolution of the parameters above the GUT scale $M_{\text{GUT}}$ and/or the presence of heavy sterile RH neutrinos, destabilize the critical relations among parameters needed to satisfy the WMAP constraint and thus modify the phenomenology of neutralino DM.

2 SUSY-SU(5)$_{\text{RN}}$: framework and parameter space

In this section, we will present a simple SUSY-GUT framework, based on $SU(5)$ with the addition of RH neutrino fields. The MSSM superfields are embedded in the 10 and 5 representation of $SU(5)$, while the Higgs doublets sit in two five-dimensional representations that we will call $5_u$ and $5_d$. RH neutrinos are singlets of $SU(5)$. The resulting superpotential, omitting generation indices, reads:
large positive contribution to the $\tilde{\tau}_R$ mass makes the stau heavier than $\tilde{\chi}_0^0$ for most of the parameter space.  

Coming to the REWSB issue, let us consider the standard (tree-level) relation coming from the minimization of the Higgs potential [5]:

$$
\mu^2 = -m_{H_u}^2 \tan^2 \beta + m_{H_d}^2 \tan^2 \beta - \frac{1}{2} M_Z^2
$$

(4)

where $m_{H_u}$ and $m_{H_d}$ are the soft masses of the up-type and down-type Higgs doublets. Eq. (4) is usually used to fix $\mu^2$ letting $\tan \beta$ as a free parameter. If $\mu^2$ turns out to be negative, the corresponding point of the parameter space cannot give a viable vacuum. It’s clear that a sufficient condition for REWSB to take place is that $m_{H_u}^2$ (which is equal to $m_0^2$ at $M_X$) gets a negative value at low energy as an effect of the RG evolution. In CMSSM this is achieved thanks to the large negative corrections driven by the $O(1)$ top Yukawa coupling, $y_t$. In presence of RH neutrinos, the RGE for $m_{H_u}^2$ reads (neglecting gaugino contributions) [9]:

$$
(4\pi)^2 \frac{\partial m_{H_u}^2}{\partial \ln(\mu/M_X)} \approx 6 y_t^2 (m_{H_u}^2 + m_{H_d}^2 + m_{Q_3}^2 + A_1^2) + 2 y_t^2 (m_{H_u}^2 + m_{N_e}^2 + m_{L_3}^2 + A_2^2)
$$

(5)

where $m_{Q_3}^2$ and $m_{L_3}^2$ are the $\tilde{t}_L$ and $\tilde{t}_R$ soft masses, while $m_{L_3}^2$, $m_{N_e}^2$ are the same for the LH and RH sneutrinos respectively. As we can see, our assumption of a top-like neutrino Yukawa $y_{\nu}$ adds a further large negative contribution to the renormalization of $m_{H_u}^2$. Moreover in $SU(5)$ the squark masses $m_{U_3}^2$ and $m_{Q_3}^2$ are increased by the unified gauge sector running, such as $m_{2\tilde{t}_R}$ in Eq. (3). These two effects of $SU(5)_{RN}$ contribute to make easier to achieve $m_{H_u}^2 < 0$ and thus a correct REWSB, getting rid to the ‘no-REWSB’ region usually present in the CMSSM parameter space.

In the next section, we will discuss the phenomenology of neutralino DM in $SU(5)_{RN}$, presenting the results published in Ref. [7].

## 3 Neutralino DM in $SU(5)_{RN}$

The modifications of the $SU(5)_{RN}$ parameter space with respect to CMSSM are sufficient to offset the conditions which give viable dark matter in CMSSM at low $\tan\beta$. In Fig.2 we plot all the points which satisfy the available direct/indirect constraints and give viable relic density as a function of $\tan\beta$ and LSP mass. From the figure we see that viable DM is only possible for values of:

$$
\tan \beta \gtrsim 34 ; \quad m_{\chi_0^0} \gtrsim 160 \text{ GeV}
$$

(6)

These are quite strong lower bounds on the neutralino mass and $\tan \beta$ and will be useful in distinguishing this model compared to the standard CMSSM parameter space. A remarkable point is that such lower bounds remain valid even choosing non-vanishing values of $A_0$, 

In the following, we will consider just one RH neutrino, while for a consistent generation of neutrino masses at least two are needed.
up to $|A_0| \simeq 3 m_0$ (larger values are excluded by the arising of tachyonic $\tilde{\tau}$ in most of the parameter space).

Looking at the peculiar $SU(5)_{\text{RN}}$ phenomenology of coannihilation, it is possible to understand the reason why there are no regions of the $SU(5)_{\text{RN}}$ parameter space which give a neutralino relic density compatible with WMAP for low values of $\tan \beta$. In Fig. 3 the plane $(m_0, M_{1/2})$ is plotted in the case of both CMSSM and $SU(5)_{\text{RN}}$, for $\tan \beta = 40$ and $A_0 = 0$. The WMAP allowed region is due to efficient $\tilde{\tau}$ coannihilation in both cases. Two features are evident from such a comparison between the CMSSM and the $SU(5)_{\text{RN}}$: in the case of $SU(5)_{\text{RN}}$, (i) the WMAP compatible region is much smaller and (ii) the shape of the allowed region is quite different. In fact, the allowed region cuts-off for a value of $M_{1/2} \simeq 520$ GeV. This would correspond to a LSP mass of around 240 GeV; this corresponds to an upper bound on the LSP mass. Therefore, in the considered case of $\tan \beta = 40$, $A_0 = 0$, the LSP mass can achieve a very limited range of values ($160 \text{ GeV} \lesssim m_{\tilde{\chi}_1^0} \lesssim 240 \text{ GeV}$) which could be useful in distinguishing the model at colliders.

These peculiar features of $SU(5)_{\text{RN}}$ DM can be traced to the enhancement of the $\tilde{\tau}_R$ mass discussed above. A rough approximation for the lightest $\tilde{\tau}$ mass is:

$$m_{\tilde{\tau}_R}^2 \approx m_{\tilde{\tau}_R}^2 - m_{\tau} \mu \tan \beta$$  \hspace{1cm} (7)

From here we can see that the term $m_{\tau} \mu \tan \beta$, which corresponds to the L-R mixing term of the $\tilde{\tau}$ mass matrix, is crucial in setting the condition $m_{\tilde{\tau}_R} \simeq m_{\tilde{\chi}_1^0}$ for an efficient neutralino-stau coannihilation. As a consequence of the GUT enhancement of $m_{\tilde{\tau}_R}^2$ in Eq. 8, higher values of $\tan \beta$ are needed to lower the $\tilde{\tau}_R$ mass at the level of $m_{\tilde{\chi}_1^0}$. This explains the lower limit for $\tan \beta$ of Eq. 6. Moreover, being the enhancement directly dependent on $M_{1/2}$, there is a value of $M_{1/2}$ such that the L-R mixing term is no more able to lower sufficiently $m_{\tilde{\tau}_R}$, and the resultant coannihilation cross-section results too low to give the correct relic density.

From another point of view, the very peculiar shape of the $\tilde{\tau}$ coannihilation region in $SU(5)_{\text{RN}}$ is related to the fact that the $\tilde{\tau}$-LSP region, along which the allowed region runs, is consistently reduced and bounded from above in $M_{1/2}$. This is again due to the GUT enhancement of $m_{\tilde{\tau}_R}^2$.

Let’s now consider what happens to the other two DM branches of CMSSM listed in the introduction. The A-pole funnel region makes its appearance for $\tan \beta \simeq 45 - 50$, as in CMSSM. In Fig. 3 the funnel region is plotted for $\tan \beta = 50$, $A_0 = 0$. We can also see large regions of the parameter space where the lightest stau is the LSP and thus regions of coannihilation also which are fused with the funnel region. As a consequence, the upper bound on the LSP mass is no longer present for $\tan \beta = 50$, as it is also evident from Fig. 2.

As discussed above, the REWSB is very easy to be achieved due to the presence of additional GUT effects and top-like Yukawa contribution from the neutrino Yukawa coupling to the up type Higgs between $M_X$ and $M_R$. The same effect induces an increasing of $\mu \simeq -m_{H_u}^2 - M_Z^2/2$. As a result, there is no focus-point region (at least up to $(m_0, M_{1/2}) \simeq 5 \text{ TeV}$).

The enhancement of $m_{\tilde{\tau}_R}^2$ in Eq. 7, being the L-R term suppressed by the small $\tau$ mass.
Finally, it is worth to mention that large values of $A_0$ can open an additional coannihilation branch with respect to the one of Fig. 3. The reason is that $m_{\chi}^2$ is suppressed, even to negative values, by an additional A-term running effect. This effect is showed in Fig. 5 for $A_0 = 3 m_0$ and $\tan \beta = 40$. Here a further thin line where coannihilation provides the correct relic density is present and, as a consequence, there is no upper bound on $m_{\chi}^2$.

4 Conclusions

We have seen how GUT running effects and/or the presence of RH neutrinos can destabilize the peculiar relations among parameters, which are needed in the CMSSM in order to provide a DM relic density in accord with WMAP. In $SU(5)_{RN}$, a major consequence is a severe constraint on the allowed range of $\tan \beta$ ($\gtrsim 35$). Moreover, the peculiar phenomenology of $\tau$ coannihilation region determines an upper bound on the LSP mass (around 250-350 GeV) for some regions of the parameter space. Finally, the A-pole funnel branch appears for very large $\tan \beta$, such as in CMSSM, while focus point is absent.

An interesting point to address is the possibility of distinguishing $SU(5)_{RN}$ from CMSSM at colliders. The direct measurements of the LSP mass and $\tan \beta$, maybe possible at the LHC, can test the constrained ranges of such parameters allowed in $SU(5)_{RN}$. Another interesting possibility is the study of the average polarization of $\tau$ leptons coming from $\tau$ decays, which is possible with good accuracy at an International Linear Collider (ILC) [10]. $\tau$-polarization gives a deep insight of the mixing structure of stauas and neutralinos and should be able to distinguish $SU(5)_{RN}$ from CMSSM as long as SUSY spectrum lies in the stau coannihilation region [11].

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