Right-Handed Sneutrinos as Thermal Dark Matter

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Abstract. We analyse the abundance of right-handed sneutrinos in the supersymmetric $F_D$-term model of hybrid inflation. As well as providing a natural solution to the $\mu$- and gravitino overabundance problems, the model offers the lightest right-handed sneutrino as a candidate for thermal dark matter. The $F_D$-term model predicts a new quartic coupling of purely right-handed sneutrinos to the Higgs doublets that thermalises the sneutrinos and makes them annihilate sufficiently fast to a level compatible with the current cosmic microwave background data. We discuss this scenario and identify favourable regions of the parameter space within mSUGRA.

1. $F_D$-Term Model of Hybrid Inflation

Hybrid inflation [1], along with its supersymmetric realisations [2], remains one of the most predictive models of inflation. In such a scenario, inflation terminates at some critical point when a so called waterfall field acquires a vacuum expectation value (VEV), thereby ending inflation. Recently, a new supersymmetric hybrid inflationary model was proposed [3], which realises $F$-term hybrid inflation and includes a subdominant non-anomalous Fayet-Iliopoulos $D$-term that arises from a U(1) gauge symmetry of the inflation waterfall sector. It has therefore been called the $F_D$-term model of hybrid inflation. The $F_D$-term model can naturally accommodate the currently favoured red-tilted spectrum, along with the actual value of the power spectrum of curvature perturbations, and the required number of $e$-folds.

The $F_D$-term model is defined through the superpotential

$$ W = \kappa \hat{S} \left( \hat{X}_1 \hat{X}_2 - M^2 \right) + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\rho_{ij}}{2} \hat{S} \hat{N}_i \hat{N}_j + h^{ij}_u \hat{L}_i \hat{H}_u \hat{N}_j + W_{\text{MSSM}}^{(\mu=0)} , $$

where $\hat{S}$ is the gauge-singlet inflaton superfield and $\hat{X}_{1,2}$ is a chiral multiplet pair of the so-called waterfall fields which have opposite charges under the U(1)$_X$ gauge group, i.e. $Q(\hat{X}_1) = -Q(\hat{X}_2) = 1$. In addition, $W_{\text{MSSM}}^{(\mu=0)}$ indicates the MSSM superpotential without the $\mu$-term. The model Lagrangian is supplemented by soft SUSY breaking terms, which contribute to the scalar potential, leading to an inflaton VEV naturally of $O$ (TeV).
Constraints on the model can be derived from cosmological inflation through the number of e-folds and the power spectrum and spectral index of curvature perturbations [3]. This implies the upper limit $\lambda(M_{\text{SUSY}}) \lesssim 1.14(1.82) \times 10^{-2}$ for an inflaton sector with a minimal (next-to-minimal) Kähler potential [5].

The presence of the Fayet-Iliopoulos term in the $F_D$-term model is necessary to approximately break a discrete symmetry in the waterfall sector. The late decays of the GUT-scale waterfall particles produce an enormous entropy that can reduce the gravitino abundance below the limits imposed by big bang nucleosynthesis (BBN), providing a viable solution to the gravitino overabundance problem [3].

In the $F_D$-term model the $\mu$-parameter of the MSSM can be generated effectively when the scalar inflaton receives a non-zero VEV, $\mu = \lambda(S)$. Moreover, the inflaton VEV will also produce an effective Majorana mass matrix as well, $M_N = \rho(S)$. As a consequence, the resulting heavy Majorana neutrinos are expected to have masses of order $\mu$. A possible explanation of the observed baryon asymmetry in the Universe may be obtained by thermal electroweak-scale resonant leptogenesis [4].

In this report, which summarizes the results of Ref. [5], we focus on the properties of the lightest right-handed sneutrino (LRHS) and identify favourable regions of the parameter space within mSUGRA, for which it becomes a viable candidate for thermal dark matter.

2. Sneutrino Mass Spectrum

Ignoring the terms proportional to the small neutrino-Yukawa couplings, the $6 \times 6$ right-handed sneutrino mass matrix $M^2_N$ is given in the weak basis $(\tilde{N}_{1,2,3}, \tilde{N}^*_{1,2,3})$ by

$$M^2_{N} = \frac{1}{2} \begin{pmatrix} \rho^2 v_S^2 + M^2_{N} & \rho A_\rho v_S + \rho \lambda v_u v_d \\ \rho A_\rho^* v_S + \rho \lambda v_u v_d & \rho^2 v_S^2 + M^2_{N} \end{pmatrix},$$

(2)

where $v_S = \langle S \rangle$, $v_u,d = \langle H_u,d \rangle$. Neglecting the possible flavor structure contained in the soft SUSY-breaking sneutrino mass matrix $M^2_{N}$ and trilinear coupling matrix $A_\rho$, the sneutrino spectrum will consist of 3 light (3 heavy) right-handed sneutrinos with masses

$$m^2_{N_{\text{LHS}}} = \rho^2 v_S^2 + M^2_{N} - (+) |\rho A_\rho v_S + \rho \lambda v_u v_d|.$$  

(3)

All mass terms in (3) are $\mathcal{O}(100-1000)$ GeV, so a proper choice of model parameters can accommodate a lightest right-handed sneutrino to act as LSP. Unless the trilinear coupling $A_\rho$ is small compared to $\mu$, the off-diagonal elements in (2) will induce a sizeable mixing between the heavy and light right-handed sneutrino states, suppressing the light masses to values smaller than $(\mu^2 + M^2_{N})^{1/2}$. In Figure 1 we plot the LHRS mass $m_{\tilde{N}_i}$ as contours in the mSUGRA parameter plane $(m_0, m_{1/2})$, $A_0 = 300$ GeV, $\mu > 0$ and two different values of $\tan \beta$. For the inflaton couplings $\lambda, \rho$ we simply choose $\lambda = \rho = 10^{-2}$, in accordance with the bounds derived from inflation. The connection between the LRHS mass $\tilde{N}_1$ and $\mu$ generally points towards a low-energy SUSY spectrum. This coincidentally includes the $H_1$-boson funnel region, where $m_{H_1} \approx 2m_{\tilde{N}_1}$. Very large and small values for $A_0$ and $\tan \beta$ are disfavoured as they exclude a sneutrino LSP. These correlations may be somewhat relaxed if non-universal inflaton couplings $\lambda$ and $\rho$ are considered.

3. Sneutrino Relic Density

As was first observed in [3], there exists a new quartic coupling between right-handed sneutrinos and Higgs fields in the $F_D$-term model described by the Lagrangian

$$\mathcal{L}^\text{LSP} = \frac{1}{2} \lambda \rho \tilde{N}_i^* \tilde{N}_j^* H_u H_d + \text{H.c.},$$

(4)
resulting from the $F$-term of the inflaton field. This leads to several channels of sneutrino annihilation into Higgses, gauge bosons and fermions via the direct quartic coupling as well as $s$-channel Higgs and $t/u$-channel sneutrino exchange once one of the Higgs fields in Eq. 4 acquires a VEV \cite{5}. The most effective annihilation process is $b\bar{b}$ production in the lightest Higgs boson resonance, $m_{\tilde{N}_1} = m_{H_1}/2$. In order to compute the sneutrino relic density remaining after the sneutrino freezes out of thermal equilibrium and to analyze the constraints on the effective annihilation coupling $\lambda \rho$, we adopt the mSUGRA scenario

$$m_0 = 125 \text{ GeV}, \quad m_{1/2} = 212 \text{ GeV}, \quad A_0 = 300 \text{ GeV}, \quad \tan \beta = 30, \quad \mu = 263 \text{ GeV},$$

while keeping the LRHS mass as a free parameter. The effective annihilation coupling $\lambda \rho$, Eq. 4, is then calculated so as to obtain a sneutrino relic density $\Omega_{\text{DM}} h^2 = 0.11$, consistent with observations. Numerical estimates of the allowed parameters in the $(m_{\tilde{N}_1}, \lambda \rho)$-plane are shown in Figure 2. In order to account for the observed DM relic abundance in the $H_1$-boson funnel region, where $m_{\tilde{N}_1} \approx m_{H_1}/2$, the effective coupling $\lambda \rho$ should be

$$\lambda \rho \gtrsim 2 \times 10^{-4}. \quad (6)$$

This has to be compared with the upper limit derived from successful inflation \cite{5},

$$\lambda \rho \lesssim 2.3(5.8) \times 10^{-4}, \quad (7)$$

for a minimal (next-to-minimal) Kähler potential. In general, we find that LRHS masses larger than about 100 GeV are not possible within a mSUGRA realisation of the $F_D$-term model. This

Figure 1. Allowed $(m_0, m_{1/2})$ parameter space for $A_0 = 300 \text{ GeV}$, $\mu > 0$, $\lambda = \rho = 10^{-2}$ and $\tan \beta = 10$ (left), 30 (right). The black contours show the predicted LRHS mass, while a sneutrino $\tilde{N}_1$/neutralino $\tilde{\chi}_1^0$/stau $\tilde{\tau}_1$ LSP is present in the blue/green/orange area. The red area is excluded by direct SUSY mass searches. The white contour is defined by the condition $m_{\tilde{N}_1} = m_{H_1}/2$. 

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Figure 2. Effective annihilation coupling $\lambda_{\rho}$ as a function of the LRHS mass $m_{N_1}$ for a relic density $\Omega_{DM}h^2 = 0.11$ (blue curve) in the mSUGRA Scenario, Eq. 5. The actual sneutrino and neutralino masses in the scenario are indicated by vertical lines. The red curves denote the upper bound on $\lambda_{\rho}$ as obtained by the CDMS-II experiment and as expected by the projected sensitivities of SuperCDMS and Xenon1T.

is indicated by the value of the neutralino mass in the given mSUGRA scenario as displayed by vertical line in Figure 2.

Further constraints on the $(m_{N_1}, \lambda_{\rho})$-plane may be obtained by taking into account the limits from direct searches of experiments which look for scattering between Weakly Interacting Massive Particles and nuclei. Upper limits on $\lambda_{\rho}$ are derived by comparing the calculated elastic cross section between the sneutrino LSP and the nucleon with the current bound on the spin-independent nucleon cross section from the CDMS-II experiment and the expected sensitivities of the SuperCDMS extension [8] and the Xenon1T experiment [9]. These limits are included in Figure 2. The current bound already excludes large parts of the $(m_{N_1}, \lambda_{\rho})$-parameter plane. The upgraded experiment SuperCDMS and the proposed Xenon1T experiment will cover most of the parameter space, but will leave open the lightest Higgs-boson pole region which is theoretically favoured by inflation within the mSUGRA framework.

4. Conclusion
In this report we discussed the possibility of a right-handed sneutrino LSP as candidate for dark matter in the supersymmetric $F_D$-term model of hybrid inflation. By virtue of a new quartic coupling with the Higgs fields the sneutrino $N_{LSP}$ can efficiently annihilate via the lightest Higgs-boson resonance $H_1$ into pairs of $b$-quarks, in the kinematic region $m_{H_1} \approx 2m_{N_{LSP}}$, and so drastically reduce its relic density to the observed value $\Omega_{DM}h^2 \approx 0.11$. It might seem that to obtain this particular relation between the masses of the $H_1$ boson and $N_{LSP}$, a severe tuning of the model parameters is required. However, it is worth stressing here that such a mass relation may easily be achieved within a mSUGRA framework of the $F_D$-term model that successfully realizes hybrid inflation.

Relatively large couplings are required for the sneutrino DM scenario, that could make Higgs bosons decay invisibly, e.g. $H \rightarrow 2N_{LSP}$. Also, right-handed sneutrinos could be present in the
cascade decays of the heavier supersymmetric particles. The $F_D$-term hybrid inflationary model therefore gives rise to rich phenomenology which can be probed at high-energy colliders [10], as well as in low-energy experiments of lepton flavour and number violation [11].

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