SuperWIMP Dark Matter in Supergravity with a Gravitino LSP

Jonathan L. Feng\(^1\), Shufang Su\(^2\), Fumihiro Takayama\(^1\)

\(^1\)Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
\(^2\)Department of Physics, University of Arizona, Tucson, AZ 85721, USA

ABSTRACT

We investigate the superWIMP scenario in the framework of supersymmetry, in which the lightest supersymmetric particle (LSP) is a stable gravitino. We consider slepton, sneutrino or neutralino being the next-lightest supersymmetric particle (NLSP), and determine what superpartner masses are viable, applying cosmic-microwave background (CMB) and electromagnetic and hadronic Big-Bang Nucleosythesis (BBN) constraints.

1. Introduction

SuperWIMPs, superweakly interacting massive particles produced in the late decays of weakly-interacting massive particles (WIMPs): \( \text{WIMP} \rightarrow \text{superWIMP} + \text{SM particle} \), are promising non-baryonic dark matter candidates [1]. The relic density of superWIMP is related to the relic density of WIMP via

\[
\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}. \tag{1}
\]

For \( m_{\text{SWIMP}} \sim m_{\text{WIMP}} \sim \text{Electroweak scale} \), superWIMP inherits the relic density of WIMP, which is naturally of the right magnitude near the observed value. Well-motivated superWIMP candidates are the gravitinos in supersymmetric models [1,2,3,4] and the first excited gravitons in universal extra dimension models [1,5]. In this talk, I will focus on the gravitino LSP in the supersymmetric models as a concrete example.

In the supersymmetric framework with the gravitino LSP being the superWIMP, the NLSP, which is the WIMP, could be charged slepton \( \tilde{l} \), sneutrino \( \tilde{\nu} \), or neutralino/chargino \( \chi \). The dominate decay modes for the NLSPs are

\[ \tilde{l} \rightarrow \tilde{G} + l; \quad \tilde{\nu} \rightarrow \tilde{G} + \nu; \quad \chi \rightarrow \tilde{G} + \gamma/Z/W/h, \tag{2} \]

which occur at \( t \sim 10^4 - 10^8 \) sec, well after BBN. An immediate concern, therefore, is that they might destroy the successful light element abundance predictions of BBN. The constraints on the electromagnetic (EM) energy released in the decays of Eq. (2) exclude some of the weak scale parameter space, but leave much of it intact [1]. The BBN constraints on the hadronic energy release, however, is much stronger. For slepton and sneutrino, the hadronic decay could only occur via subdominant three or four body decay:

\[ \tilde{l} \rightarrow \tilde{G} + Z/W + l' \rightarrow \tilde{G} + q\bar{q} + l'; \quad \tilde{l} \rightarrow \tilde{G} + \gamma + l \rightarrow \tilde{G} + q\bar{q} + l. \tag{3} \]

The branching ratio is usually smaller than \( \mathcal{O}(10^{-3}) \) in most of the parameter space. For neutralino/chargino, however, the hadronic decay branching ratio is unsuppressed since

\(^a\)Presented by Shufang Su at SUSY2004, June 17-23, 2004, Tsukuba, Japan.
$Z/W/h$ in Eq. [2] could decay hadronically. Imposing the hadronic BBN constraints would disfavor much of the parameter spaces [2].

2. Late Time Decay and BBN Constraints

The overall success of standard BBN places severe constraints on energy produced by particles decaying after BBN. In our analysis, we use the BBN constraints on EM energy release in Ref. [6] and the latest analysis on both EM and hadronic energy releases in Ref. [7]. For time $t > 10^4$ sec, the BBN constraints are, to a good approximation, constraints on energy injection $\xi_i$: $\xi_i \equiv \epsilon_i B_i Y_{\text{NLSP}}$, where $i = \text{EM,had}$. Here $B_i$ is the branching fraction into EM/hadronic components, and $\epsilon_i$ is the EM/hadronic energy released in each NLSP decay. $Y_{\text{NLSP}} \equiv n_{\text{NLSP}}/n^{BG}_{\gamma}$ is the NLSP number density just before NLSP decay, normalized to the background photon number density $n^{BG}_{\gamma} = 2\zeta(3)T^3/\pi^2$.

In evaluating the constraints, we use two different approaches for $\Omega_{\text{SWIMP}}$:

- **Approach I:** SuperWIMP gravitinos make up all of the non-baryonic dark matter, with $\Omega_{\tilde{G}} \simeq 0.23$.

- **Approach II:** The NLSP freezes out with its thermal relic density $\Omega_{\text{NLSP}}^{th}$. The superWIMP gravitino density is then $\Omega_{\tilde{G}} = (m_{\tilde{G}}/m_{\text{NLSP}})\Omega_{\text{NLSP}}^{th}$. In this approach, the superWIMP gravitino density may be low and even insignificant cosmologically.

These approaches differ significantly. Low masses are excluded in the former case, while high masses are disfavored in the latter. This difference has obviously important implications for collider searches for new physics.

3. Results

**Approach I:** Fix $\Omega_{\tilde{G}} = 0.23$.

Fig. 1 shows the allowed and disfavored regions of the $(m_{\tilde{G}}, \delta m)$ plane for the two NLSP cases. The neutralino/chargino parameters are chosen to be $M_1 = 2m_{\text{NLSP}}$, $M_2 = \mu = 4m_{\text{NLSP}}$, and $\tan \beta = 10$. The CMB $\mu$ distortion constraint, the BBN constraint of Ref. [6] and Ref. [7] are included. For the $\tilde{\tau}_R$ case, the hadronic constraint is extremely important — it disfavors a large and natural part of parameter space that would otherwise be allowed. Even after all of these constraints, however, the unshaded area in the region $m_{\tilde{G}} \geq 200$ GeV and $200$ GeV $\leq \delta m \leq 1500$ GeV still remains viable. The $\tilde{\tau}_R$ mass must be above 500 GeV, which is within reach of the LHC.

The sneutrino NLSP case is also shown in Fig. 1. Hadronic BBN constraints from the D and $^4$He abundances only disfavor $\delta m \geq 100$ GeV. Even including the stronger but more speculative $^6$Li/H constraint, there is still a large region of $(m_{\tilde{G}}, \delta m)$ that is allowed.

The neutralino/chargino NLSP can not be realized in this approach, due to the unsuppressed hadronic decay branching ratio.

**Approach II:** $\Omega_{\tilde{G}} = (m_{\tilde{G}}/m_{\text{NLSP}})\Omega_{\text{NLSP}}$. 
Figure 1: Allowed and disfavored regions of the $(\tilde{m}_G, \delta m)$ plane, where $\delta m \equiv m_{NLSP} - m_\tilde{G} - m_Z$, for (left) $\tilde{\tau}_R$ and (right) $\tilde{\nu}$ NLSPs. The shaded regions are disfavored by CMB, EM BBN, and hadronic BBN constraints, as indicated. The lines correspond to EM constraints from $^3\text{He}/\text{D}$ (solid) and hadronic constraints from $^6\text{Li}/\text{H}$ (dashed). The circle indicates the best fit region where the $^7\text{Li}$ discrepancy is resolved. We have assumed $\Omega_{SWIMP} = 0.23$ and $\epsilon_{\text{had}} = \frac{1}{3}(m_{NLSP} - m_\tilde{G})$.

The results are presented in Fig. 2 for right-handed stau and sneutrino, where we have adopted a simple scaling behavior for the thermal relic density:

$$\Omega^\text{th}_{\tilde{\tau}_R} \approx 0.4 \left[ \frac{m_{\tilde{\tau}_R}}{\text{TeV}} \right]^2; \quad \Omega^\text{th}_{\tilde{\nu}} \approx 0.12 \left[ \frac{m_{\tilde{\nu}}}{\text{TeV}} \right]^2. \quad (4)$$

The shaded regions are excluded by the overclosure constraints and the absence of CMB $\mu$ distortions. The BBN sensitivity contours divided into those from Ref. [6] (EM1) and from Ref. [7] (EM2, had). The strength of the EM constraints in constraining gravitino LSP parameter space depends sensitively on how one interprets the BBN data. Adopting the more stringent EM2 contour, we find that bounds on $m_\tilde{G}$ are improved by about an order of magnitude. For relatively early decays, the hadronic constraint is the leading constraint, which covers the most natural parameter region for weak-scale supergravity.

Sneutrinos annihilate through $S$-wave processes even more efficiently than sleptons. The dark matter density bound is therefore weaker. The remaining constraints are therefore only the hadronic BBN constraints. These are stringent for early decays, that is, large $\delta m$. The more reliable D and $^4\text{He}$ constraints disfavor $\delta m \geq 300$ GeV, while $^6\text{Li}$ (had) is sensitive to $\delta m \geq 200$ GeV.

For neutralino NLSP, the strong BBN hadronic constrains exclude most of the parameter space except when the relic density of the gravitinos is insignificant. For a pure Bino, the viable parameter space is very limited, mostly for $m_\tilde{G}$ below about 100 MeV.

4. Summary and Outlook

In this work, we have determined the viability of superWIMP dark matter in the framework of supersymmetric scenarios in which the gravitino is the LSP. We found that
the hadronic BBN constraints, previously neglected, are extremely important, providing the most stringent limits in natural regions of parameter space [2].

The gravitino LSP scenario opens up many connections between particle physics and cosmology. The reduced Planck mass [8,9] could be measured by trapping a charged slepton and observe its consequent decay. A more detailed analysis of the trapping of sleptons at future colliders is now under study [10].

5. Acknowledgments

The work of JLF was supported in part by National Science Foundation CAREER Award PHY–0239817, and in part by the Alfred P. Sloan Foundation.

6. References

[1] J. L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. Lett. 91, 011302 (2003); Phys. Rev. D68, 063504 (2003).
[2] J. L. Feng, S. Su, and F. Takayama, hep-ph/0404198; hep-ph/0404231.
[3] J. R. Ellis, K. A. Olive, Y. Santoso and V. Spanos, Phys. Lett. B588, 7 (2004).
[4] F. Wang and J. M. Yang, hep-ph/0405186.
[5] J. L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. D68, 085018 (2003).
[6] R. H. Cyburt et. al., Phys. Rev. D67, 103521 (2003).
[7] M. Kawasaki, K. Kohri and T. Moroi, astro-ph/0402490.
[8] W. Buchmuller, K. Hamaguchi, M. Ratz and T. Yanagida, hep-ph/0402179.
[9] J. L. Feng, A. Rajaraman and F. Takayama, hep-th/0405248.
[10] J. L. Feng and B. T. Smith, in preparation.