Cosmology of Gravitino LSP Scenario with Right-Handed Sneutrino NLSP

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1. Introduction

Supersymmetric model

• strongly motivated as a beyond standard model
• analyzed in detail from cosmological point of view recently

Supersymmetric model with right-handed (s)neutrinos where neutrino masses are purely Dirac type

Right-handed sneutrino $\tilde{\nu}_R$

• Never thermalized (very small neutrino Yukawa coupling)
• Can be relatively light among superparticles (no EW scale corrections for its mass)

$\longrightarrow$ Possibility to affect cosmology [T.Asaka,K.I.,T.Moroi(2005)]

$\longrightarrow$ Gravitino-LSP scenario with right-handed sneutrino NLSP changes usual gravitino-LSP scenario
Gravitino-LSP scenario with right-handed sneutrino NLSP
- bino as NNLSP case \( m_{\tilde{B}} > m_{\tilde{\nu}_R} > m_{3/2} \) -

**Bino:**
- Freezes out, and decays
- Decay mode \( \tilde{B} \rightarrow \tilde{\nu}_R \bar{\nu}_L \) competes with \( \tilde{B} \rightarrow \psi_\mu \gamma/Z \), or dominates in total decay

**Cf.) Without right-handed sneutrino**
- \( \tilde{B} \rightarrow \psi_\mu \gamma/Z \) dominates in total decay
- to emit more hadrons, which may spoil success of Big-Bang Nucleosynthesis (BBN)
- Gravitino mass is strictly constrained as
  \[ m_{3/2} \lesssim 0.1 \text{ GeV} \] [ J.L.Feng, S.Su, F.Takayama (2005) ]

→ Constraints from BBN scenario is relaxed
A new parameter region \( m_{3/2} \lesssim 40 \text{ GeV} \) is allowed
2. Model

MSSM with right-handed (s)neutrinos
where neutrino masses are *purely Dirac type*

• Superpotential

\[
W = W_{\text{MSSM}} + y_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c
\]

\[
\longrightarrow y_\nu \sin \beta = 3.0 \times 10^{-13} \times \left( \frac{m_\nu^2}{2.8 \times 10^{-3} \text{ eV}^2} \right)^{1/2}
\]

\[
\begin{cases}
    y_\nu & : \text{neutrino Yukawa coupling} \\
    m_\nu & : \text{neutrino mass}
\end{cases}
\]
• Soft SUSY breaking terms

\[ \mathcal{L}_{\text{soft}} = -M_L^2 \tilde{L}^\dagger \tilde{L} - m_{\tilde{\nu}_R}^2 \tilde{\nu}_R^* \tilde{\nu}_R + (A_\nu H_u \tilde{L} \tilde{\nu}_R^c + \text{h.c.}) + \cdots \]

Assumptions:

• Three right-handed sneutrino masses are degenerate

• \( A_\nu \) is parametrized as

\[ A_\nu = a_\nu y_\nu M_L \] where \( a_\nu \sim O(1) \)

\[ \rightarrow \tilde{\nu}_L - \tilde{\nu}_R \] mixing term

\[ \sim m_\nu M_L \]

• Mass spectrum

\[ m_{\tilde{B}} > m_{\tilde{\nu}_R} > m_{3/2} \]

→ gravitino as LSP,
  right-handed sneutrino as NLSP,
  and bino as NNLSP(MSSM-LSP)
3. Cosmological constraints

BBN constraints [ M.Kawasaki, K.Kohri, T.Moroi (2005)]

Upper bound of $Y_X E_{\text{vis}}$ as a function of $\tau_X$

$Y_X$ : yield variable of particle $X$
$E_{\text{vis}}$ : mean energy of hadrons emitted
$\tau_X$ : lifetime of particle $X$

- Calculating $B_{\text{had}} Y_{\tilde{B}} E_{\text{vis}}$ and $\tau_{\tilde{B}}$ and search for allowed parameter region

- Here, $Y_{\tilde{B}}$ is given by assuming $\Omega_{\tilde{B}} h^2 \sim 0.1 \left( \frac{m_{\tilde{B}}}{100 \text{ GeV}} \right)^2$

[ J.L.Feng, S.Su, F.Takayama (2005) ]
Bino decay

- After freezing out, bino decays to right-handed sneutrino or gravitino:
  \[ \tilde{B} \rightarrow \tilde{\nu}_R \tilde{\nu}_L, \text{ or } \tilde{B} \rightarrow \psi \mu \gamma / Z \]

The former mode competes with the latter one or dominates in total decay.

- Bino is long-lived: \( \tau_{\tilde{B}} \sim 10^2 \text{ sec} \)

\[ \text{Cf.) Without } \tilde{\nu}_R, \text{ the decay } \tilde{B} \rightarrow \psi \mu \gamma / Z \text{ dominates in total decay to emit many hadrons and } m_{3/2} \text{ is strictly constrained from BBN} \]

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Although bino is long-lived, less hadrons are emitted in its decay compared to no \( \tilde{\nu}_R \) case.

Thus constraints from BBN is relaxed.
No hadrons are produced in two-body decays
In order to calculate $B_{\text{had}}$ and $E_{\text{vis}}$, we consider

- Three- or four- body decays to produce hadrons:
  
  \[ \tilde{B} \to \psi_\mu, q\bar{q} \]
  
  \[ \tilde{B} \to \tilde{\nu}_R e^+_L q\bar{q}' \]
  
  \[ \tilde{B} \to \tilde{\nu}_R \bar{\nu}_L q\bar{q} \]

  (and CP conjugate final states for last two)
Results (from BBN constraints)

Constraints from BBN scenario is drastically relaxed

\[ m_{3/2} < 100 \text{ GeV} \]

For a new allowed region,

- **Upper bound of** $m_{\tilde{B}}$ (given by BBN constraints)
  
  Mainly comes from four-body decay modes,
  
  $\tilde{B} \rightarrow \tilde{\nu}_R e^+_L q \bar{q}'$, $\tilde{B} \rightarrow \tilde{\nu}_R \tilde{\nu}_L q \bar{q}$

  Large $m_{\tilde{B}}$ region is excluded because $B_{\text{had}}, E_{\text{vis}}$ are enhanced

- $\Omega_{3/2}^{\text{dec}} < \Omega_{\text{DM}}$ (not to overclose universe)
Constraints from structure formation

Right-handed sneutrino decay

• Right-handed sneutrino is long-lived:
  \[ \tau_{\tilde{\nu}_R} \sim 10^{5-8} \text{ sec} \]

• Emitted gravitino is relativistic:
  \[ \lambda_{FS} \sim 6 \text{ Mpc} \]

→ Emitted gravitino acts as warm dark matter

On the other hand, gravitino is also produced by thermal scattering processes and acts as cold dark matter

→ We consider constraints on WDM+CDM scenario from structure formation
WDM+CDM scenario

\[ \rho_{3/2} = \rho_{3/2}^{\text{dec}} + \rho_{3/2}^{\text{th}} \]

\[ \rho_{3/2}^{\text{dec}}, \rho_{3/2}^{\text{th}} : \text{energy density of gravitino produced by decays, or} \]

\[ \text{by thermal scattering respectively} \]

A step-like decrease in power spectrum where

\[ k \sim \frac{2\pi}{\lambda_{FS}} \]

\( \ast \ast \text{Only power spectrum of WDM component dumps} \)

In a condition that power spectrum is in 95% C.L. region of observation data,

\[ f \lesssim 0.4 \quad (f \equiv \rho_{3/2}^{\text{dec}}/\rho_{3/2}) \]

\[ \longrightarrow \quad \Omega_{3/2}^{\text{dec}} \lesssim 0.4\Omega_{DM} \]

[ D.N.Spergel (2003) ]
Results
(including constraints from structure formation)

Parameter region allowed by BBN is cut a little bit as

\[ m_{3/2} \lesssim 40 \text{ GeV} \]

For a new allowed region,

- \( \Omega_{3/2}^{\text{dec}} < 0.4 \Omega_{\text{DM}} \) (from structure formation)

\[
\begin{align*}
\Omega_{3/2}^{\text{dec}} &= \frac{m_{3/2}}{m_{\tilde{B}}} \Omega_{\tilde{B}} \\
&\text{with } \Omega_{\tilde{B}} h^2 \sim 0.1 \left[ \frac{m_{\tilde{B}}}{100 \text{ GeV}} \right]^2 \\
\Omega_{\text{DM}} h^2 &\sim 0.105 \quad [ \text{D. N. Spergel (2006)} ]
\end{align*}
\]

\[ m_{\tilde{B}} m_{3/2} < 0.4 \times 10^4 \text{ GeV}^2 \]
4. Conclusion

Model:
MSSM with right-handed (s)neutrinos
where neutrino masses are purely Dirac type

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Cosmological constraints

- Bino decay mode \( \tilde{B} \to \tilde{\nu}_R \tilde{\nu}_L \) competes \( \tilde{B} \to \psi_{\mu} \gamma/Z \) or dominates in total decay
  Less hadrons are emitted than in no right-handed sneutrino case

\[ m_{3/2} \lesssim 40 \text{ GeV} \]

\[ \text{(Cf.) } m_{3/2} \lesssim 0.1 \text{ GeV} \text{ without } \tilde{\nu}_R \]

- Upper bound of \( m_{3/2} \) is given by constraints from structure formation