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 ($\because$ small neutrino Yukawa coupling)
- Can be relatively light among superparticles

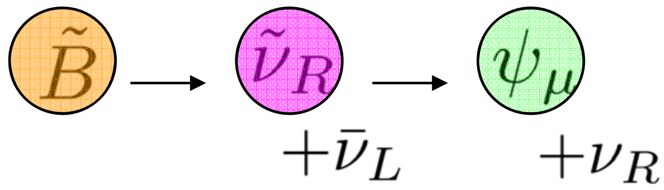
  ($\because$ no EW scale corrections for its mass)

$\longrightarrow$ 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

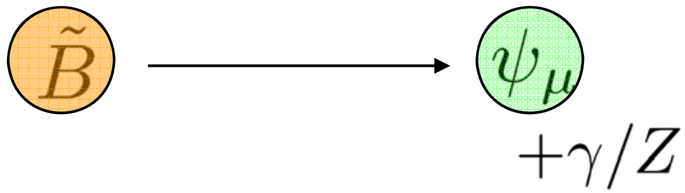
Gravitino-LSP scenario with right-handed sneutrino NLSP
- bino as NNLSP case $(m_{\tilde{B}} > m_{\tilde{\nu}_R} > m_{3/2})$ -

Bino :



- Freezes out, and decays
- Decay mode $\tilde{B} \to \tilde{\nu}_R \bar{\nu}_L$ competes with $\tilde{B} \to \psi_\mu \gamma/Z$, or dominates in total decay

Cf.) Without right-handed sneutrino



- $\tilde{B} \to \psi_\mu \gamma/Z$ dominates in total decay to emit more hadrons, which may spoil success of Big-Bang Nucleosynthesis (BBN)
- Gravitino mass is strictly constrained as $m_{3/2} \lesssim 0.1\ \mathrm{GeV}$ [J.L.Feng, S.Su, F.Takayama (2005)]

⟶ Constraints from BBN scenario is relaxed
A new parameter region $m_{3/2} \lesssim 40\ \mathrm{GeV}$ is allowed

2. Model

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

- Superpotential

$$W = W_{\rm MSSM} + y_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c$$

$$\longrightarrow \quad y_\nu \sin\beta = 3.0 \times 10^{-13} \times \left(\frac{m_\nu^2}{2.8\times10^{-3}\ \mathrm{eV}^2} \right)^{1/2}$$

(y_ν : neutrino Yukawa coupling
m_ν : neutrino mass)

- Soft SUSY breaking terms

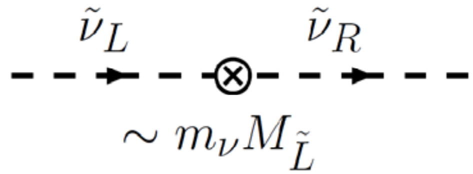
$$\mathcal{L}_{\rm soft} = -M^2_{\tilde{L}} \tilde{L}^\dagger \tilde{L} - m^2_{\tilde{\nu}_R} \tilde{\nu}^*_R \tilde{\nu}_R + (A_\nu H_u \tilde{L} \tilde{\nu}^c_R + \text{h.c.}) + \cdots$$

Assumptions :

- Three right-handed sneutrino masses are degenerate
- A_ν is parametrized as

$A_\nu = a_\nu y_\nu M_{\tilde{L}}$ where $a_\nu \sim O(1)$

→ $\tilde{\nu}_L$-$\tilde{\nu}_R$ mixing term



- Mass spectrum

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

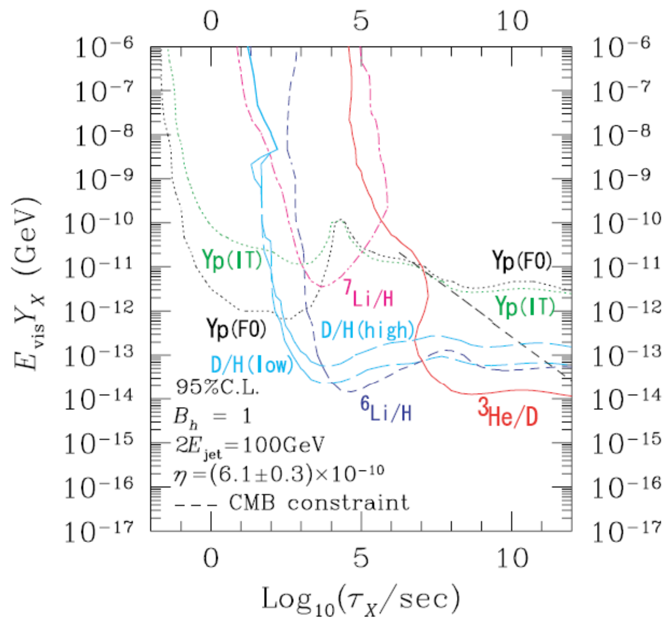
→ gravitino as LSP,
right-handed sneutrino as NLSP,
and bino as NNLSP(MSSM-LSP)

3. Cosmological constraints

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

Upper bound of $Y_X E_{\rm vis}$ as a function of τ_X

- Y_X : yield variable of particle X
- $E_{\rm vis}$: mean energy of hadrons emitted
- τ_X : lifetime of particle X



→
- Calculating $B_{\rm had} Y_{\tilde{B}} E_{\rm vis}$ and $\tau_{\tilde{B}}$ and search for allowed parameter region
- Here, $Y_{\tilde{B}}$ is given by assuming $\Omega_{\tilde{B}} h^2 \sim 0.1 \left[\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}}\right]^2$

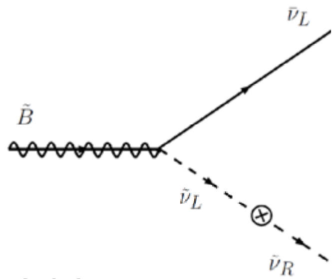
  [J.L.Feng, S.Su, F.Takayama (2005)]

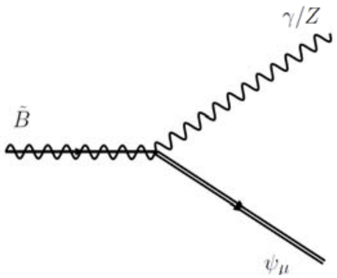
Bino decay

- After freezing out, bino decays to right-handed sneutrino or gravitino :

  $\tilde{B} \to \tilde{\nu}_R \bar{\nu}_L, \text{ or } \tilde{B} \to \psi_\mu \gamma/Z$

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

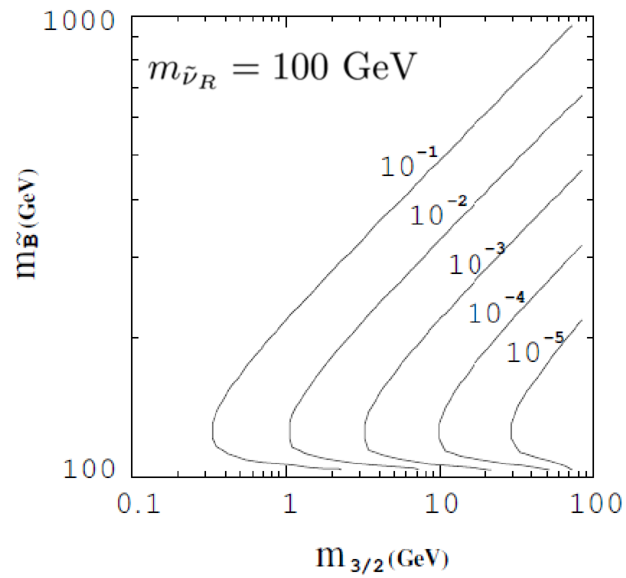




- Bino is long-lived : $\tau_{\tilde{B}} \sim 10^2$ sec

(Cf.) Without $\tilde{\nu}_R$, $\tilde{B} \to \psi_\mu \gamma/Z$ dominates in total decay to emit many hadrons and $m_{3/2}$ is strictly constrained from BBN)

$B(\tilde{B} \to \psi_\mu \gamma)$ Contour plot



→ 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 $B_{\rm had}$ and $E_{\rm vis}$, we consider

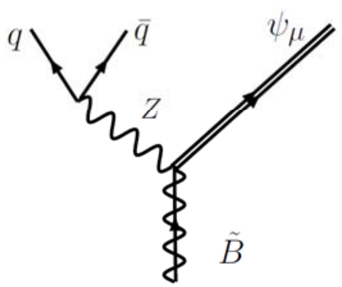
- Three- or four- body decays to produce hadrons :

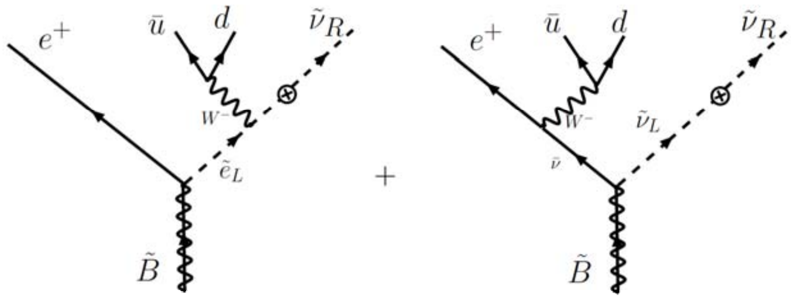
$$\tilde{B} \to \psi_\mu q\bar{q}$$

$$\tilde{B} \to \tilde{\nu}_R e_L^+ q\bar{q}'$$

$$\tilde{B} \to \tilde{\nu}_R \bar{\nu}_L q\bar{q}$$

(and CP conjugate final states for last two)

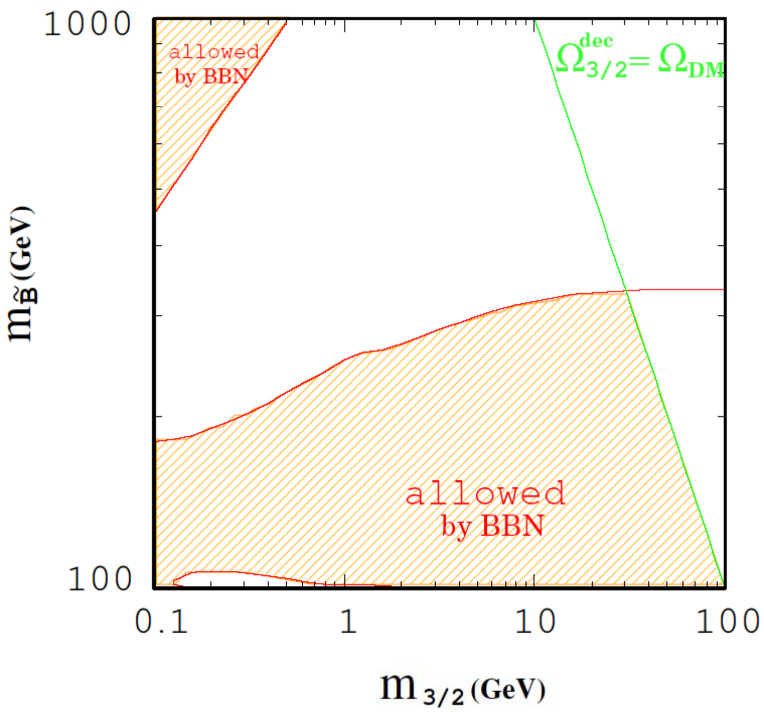




Results (from BBN constraints)

Constraints from BBN scenario is drastically relaxed

$\longrightarrow$ $m_{3/2} < 100\ \mathrm{GeV}$



$m_{\tilde{\nu}_R} = 100\ \mathrm{GeV}$

For a new allowed region,

- Upper bound of $m_{\tilde{B}}$ (given by BBN constraints)

  Mainly comes from four-body decay modes,

  $\tilde{B} \to \tilde{\nu}_R e_L^+ q\bar{q}', \tilde{B} \to \tilde{\nu}_R \bar{\nu}_L q\bar{q}$

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

- $\Omega_{3/2}^{\rm dec} < \Omega_{\rm DM}$ (not to overclose universe)

Constraints from structure formation

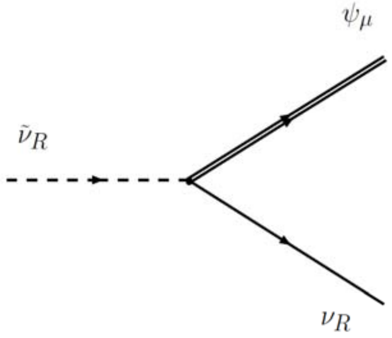
Right-handed sneutrino decay

- Right-handed sneutrino is long-lived :

$$\tau_{\tilde{\nu}_R} \sim 10^{5-8} \text{ sec}$$

- Emitted gravitino is relativistic :

$$\lambda_{\rm FS} \sim 6 \text{ Mpc}$$



→ 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

$$\rho_{3/2} = \rho_{3/2}^{\rm dec} + \rho_{3/2}^{\rm th}$$

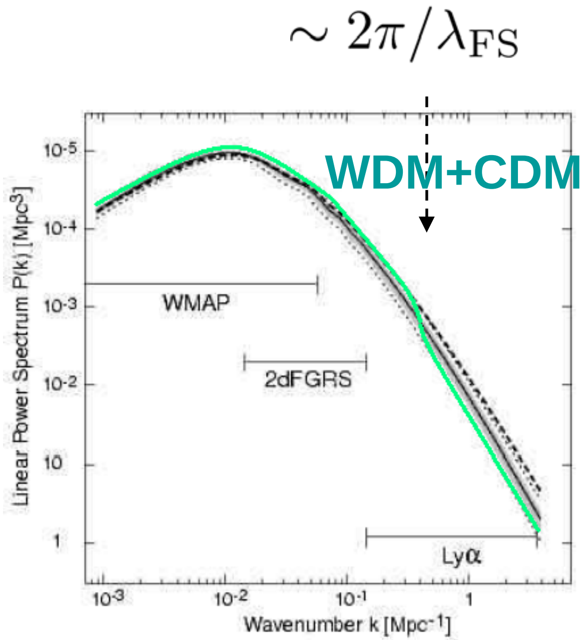
[$\rho_{3/2}^{\rm dec}$, $\rho_{3/2}^{\rm th}$: energy density of gravitino produced by decays, or by thermal scattering respectively]

A step-like decrease in power spectrum where
$k \sim 2\pi/\lambda_{\rm FS}$
(∵ Only power spectrum of WDM component dumps)

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

$$f \lesssim 0.4 \qquad (f \equiv \rho_{3/2}^{\rm dec}/\rho_{3/2})$$

$$\longrightarrow \quad \Omega_{3/2}^{\rm dec} \lesssim 0.4\Omega_{\rm DM}$$

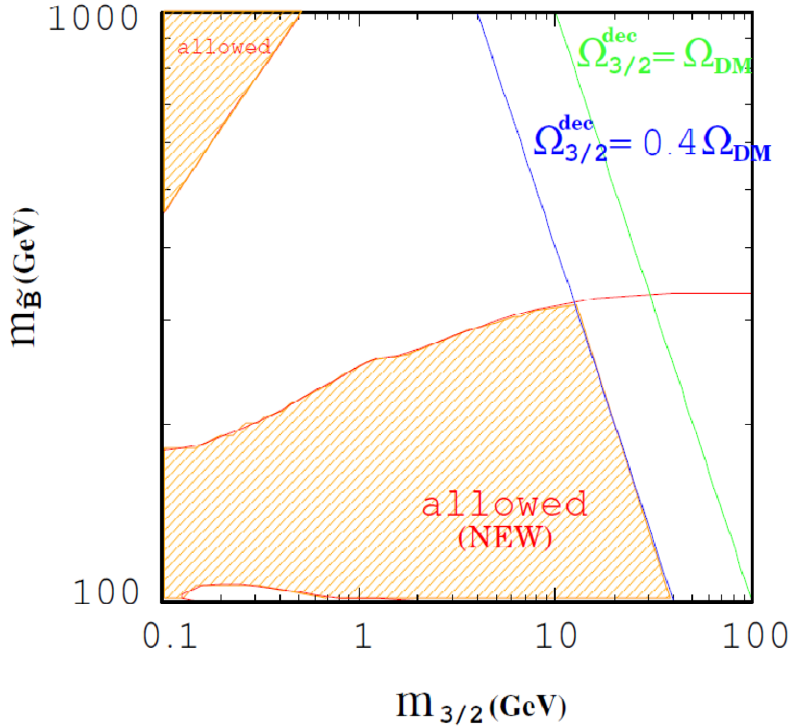


[D.N.Spergel (2003)]

Results
(including constraints from structure formation)

Parameter region allowed by BBN is cut a little bit as

$$m_{3/2} \lesssim 40 \text{ GeV}$$



$m_{\tilde{\nu}_R} = 100$ GeV

For a new allowed region,

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

$$\Omega^{dec}_{3/2} = \frac{m_{3/2}}{m_{\tilde{B}}}\Omega_{\tilde{B}} \quad \text{with} \quad \Omega_{\tilde{B}}h^2 \sim 0.1\left[\frac{m_{\tilde{B}}}{100 \text{ GeV}}\right]^2$$

$$\Omega_{DM}h^2 \simeq 0.105$$ [D. N. Spergel (2006)]

$$\longrightarrow \; m_{\tilde{B}} m_{3/2} < 0.4 \times 10^4 \text{ GeV}^2$$

4. Conclusion

Model :

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

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

Cosmological constraints

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

⟶ Constraints from BBN is drastically relaxed as

$m_{3/2} \lesssim 40 \text{ GeV}$ (Cf.) $m_{3/2} \lesssim 0.1 \text{ GeV}$ without $\tilde{\nu}_R$)

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