Thermal production of light Dirac RH sneutrino DM

based on 1808.00764 with Jongkuk Kim and Osamu Seto

Ki -Young Choi
Sungkyunkwan University

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Contents

Neutrino mass and Dark matter

Neutrino oscillation and non-vanishing masses [PDG]

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)

Stable, massive, cold dark matter with present abundance

$$\Omega_{\rm CDM} h^2 = 0.120 \pm 0.001.$$

[Planck 2018]

However standard model does not have solution for these.

Dirac Neutrino and RH sneutrino DM

[Asaka, Ishiwata, Moroi, 2006]

The super-potential includes

$$W \ni y_e L \cdot H_d E_R^c + y_\nu L \cdot H_u \nu_R^c + \mu H_u \cdot H_d + \text{H.c.},$$

three singlet right-handed neutrino super fields

After electroweak symmetry breaking, neutrinos get pure Dirac-type mass with the very small Yukawa coupling of

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

The RH sneutrinos as lightest SUSY particle (LSP) can be stable and a candidate for dark matter with R-parity.

Production of RH sneutrino DM

The Yukawa coupling is too small to make RH sneutrinos to be in the thermal equilibrium. However right amount can be produced thermally and/or non-thermally.

Thermal production (TP)

Production from the thermal particles by decay or scatterings

Non-thermal production (NTP)

Production from the non-thermal particles by out-of-equilibrium decay

Thermal Production

Boltzmann equation

$$\frac{dn_{\tilde{N}}}{dt} + 3Hn_{\tilde{N}} \simeq \sum_{i,j} \langle \sigma(i + j \to \tilde{N} + \cdots) v_{rel} \rangle n_i n_j + \sum_i \langle \Gamma(i \to \tilde{N} + \cdots) \rangle n_i,$$

Thermal production from scattering and decay

$$Y_{ij}^{\rm scat} = \int_{T_0}^{T_R} dT \frac{\langle \sigma(i + j \to \tilde{N} + \cdots) v_{rel} \rangle n_i n_j}{sHT},$$

$$Y_i^{\rm dec} = \int_{T_0}^{T_R} dT \frac{\langle \Gamma(i \to \tilde{N} + \cdots) \rangle n_i}{sHT}.$$

Thermal Production from decay

[Asaka, Ishiwata, Moroi, 2006]

$$\Gamma_{\tilde{H}^0 \to \tilde{\nu}_R \bar{\nu}_L} = \Gamma_{\tilde{H}^+ \to \tilde{\nu}_R l_L^+} = \frac{\beta_{\rm f}^2 y_\nu^2}{32\pi} \mu_H,$$

$$\Gamma_{\tilde{\nu}_L \to \tilde{\nu}_R h} = \frac{\beta_{\rm f}}{32\pi} \frac{A_\nu^2}{m_{\tilde{\nu}_L}},$$

$$\Gamma_{\tilde{\nu}_L \to \tilde{\nu}_R Z} = \frac{\beta_{\rm f}^3}{32\pi} \left[\frac{m_{\tilde{\nu}_L}^2}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \right]^2 \frac{A_\nu^2}{m_{\tilde{\nu}_L}},$$

$$\Gamma_{\tilde{l}_L \to \tilde{\nu}_R W^-} = \frac{\beta_{\rm f}^3}{16\pi} \left[\frac{m_{\tilde{l}_L}^2}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \right]^2 \frac{A_\nu^2}{m_{\tilde{l}_L}},$$

$$\Gamma_{\tilde{B} \to \tilde{\nu}_R \bar{\nu}_L} = \frac{\beta_{\rm f}^2 g_1^2}{64\pi} \left[\frac{A_\nu v_T}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \right]^2 m_{\tilde{B}},$$

$$\Gamma_{\tilde{W}^0 \to \tilde{\nu}_R \bar{\nu}_L} = \frac{\beta_{\rm f}^2 g_2^2}{64\pi} \left[\frac{A_\nu v_T}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \right]^2 m_{\tilde{W}},$$

$$\Gamma_{\tilde{W}^+ \to \tilde{\nu}_R l_L^+} = \frac{\beta_{\rm f}^2 g_2^2}{32\pi} \left[\frac{A_\nu v_T}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \right]^2 m_{\tilde{W}},$$

$$\beta_{\rm f}^2 = \frac{1}{m_x^4} [m_x^4 - 2(m_{\tilde{\nu}_R}^2 + m_y^2) m_x^2 + (m_{\tilde{\nu}_R}^2 - m_y^2)^2],$$

for the process $x \to \tilde{\nu}_R y$,

Enhancement in the mixing due to the degeneracy between LH and RH sneutrino masses.

Temperature-dependent Higgs vev. and mixing between LH and RH sneutrinos.

$$\tan 2\Theta(T) \simeq \frac{2 m_\nu(T) |\cot\beta \mu - A_\nu^*|}{m_{\tilde{\nu}}^2(T) - m_{\tilde{N}}^2}.$$

which vanishes for T > 150 GeV.

$$v(T) = v_0 \sqrt{1 - T^2/T_c^2}$$

Non-thermal Production of RH sneutrino DM

[Asaka, Ishiwata, Moroi, 2007]
[Page, 2007]

Production from the decay of the MSSM LSP after its freeze-out time.

$$\Omega^{\rm FO}_{\tilde{\nu}_R} = \frac{m_{\tilde{\nu}_R}}{m_{\rm MSSM\text{-}LSP}} \Omega_{\rm MSSM\text{-}LSP},$$

The MSSM LSP can be neutralino or stau.

Constraints from big bang nucleosynthesis for stau.

[Ishiwata, Kawasaki, Kohri, Moroi, 2010]

Possible collider signatures.

[Banerjee, Belanger, Mukhopadhyaya, Serpico, 2016]
[Banerjee, Belanger, Ghosh, Mukhopadhyaya, 2018]

Thermal Production from Scatterings

[KYC, Jongkuk Kim, Osamu Seto, 2018]

2-body scatterings can produce RH sneutrinos from thermal particles.

The production rate of RH sneutrinos from scatterings are sub-dominant compared to the production from decay and it has been ignored.

However the recent low-bound on the mass of SUSY particles > TeV.

Some of the decay production are suppressed due to the heavy mass and T-dependence of mixing.

$$Y^{\rm decay} \simeq \sum_i \frac{3\zeta(5)\bar{g} M_P g_i \Gamma_i}{4\pi m_i^2} \qquad \tan 2\Theta(T) \simeq \frac{2 m_\nu(T) |\cot\beta\mu - A_\nu^*|}{m_{\tilde{\nu}}^2(T) - m_{\tilde{N}}^2}.$$

Thermal Production from Scatterings

[KYC, Jongkuk Kim, Osamu Seto, 2018]

Our set-up:

SUSY particles are heavy >> TeV

Except slepton and sneutrino are light around a few100 GeV

LH and RH sneutrinos masses are similar

➡ thermal production from scatterings can be important or comparable to the production from decay and NTP

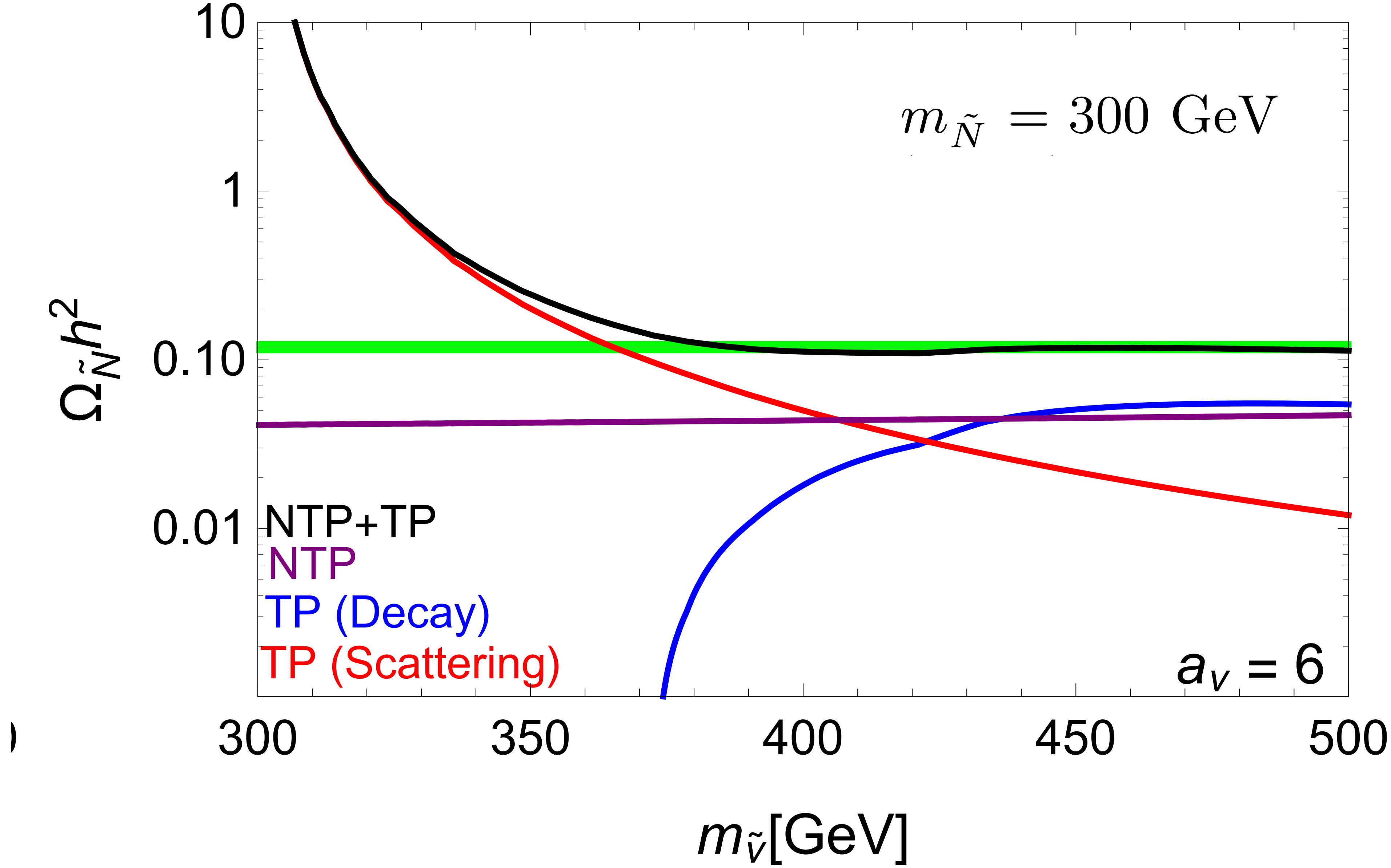
Thermal Production from Scatterings

There are many scattering modes for the production of RH sneutrinos.

Scattering Process	Number of modes
$Z + \tilde{\ell}_j \to W^- + \tilde{N}_j$	$3 \times 3_g$
$W^\pm + \tilde{\nu}_j \to W^\pm + \tilde{N}_j$	$2 \times 3_g \times 2_\pm$
$u_i(\nu_i) + \tilde{\ell}_j \to d_k(\ell_i) + \tilde{N}_j$	$3 \times 3_g^2 (3 \times 3_g^2 \times 3_{susy})$
$q_i(\ell_i, \nu_i) + \tilde{\nu}_j \to q_i(\ell_i, \nu_i) + \tilde{N}_j$	$3 \times 3_g^2 (3 \times 3_g^2 \times 3_{susy} \times 2_{l,\nu})$
$W^+ + \tilde{\ell}_j \to h(\gamma) + \tilde{N}_j$	$3 \times 3_g \times 2_{h,\gamma}$
$Z + \tilde{\nu}_j \to h(\gamma) + \tilde{N}_j$	$3 \times 3_g \times 2_{h,\gamma}$

* with light slepton and sneutrinos

Thermal Production from Scattering



$a_\nu = A_\nu / m_{\tilde{L}}$

Ki-Young Choi, Sungkyunkwan University, Korea

Non-thermal Production from Scattering

LH sneutrino decay to RH sneutrino after freeze-out

$$\Gamma_{\tilde{\nu}}^{2-body} \simeq \Gamma(\tilde{\nu} \to \tilde{N}\, Z)$$

$$\Gamma_{\tilde{\nu}}^{3-body} \simeq \sum_f \Gamma(\tilde{\nu} \to \tilde{N} + \bar{f} + f)$$

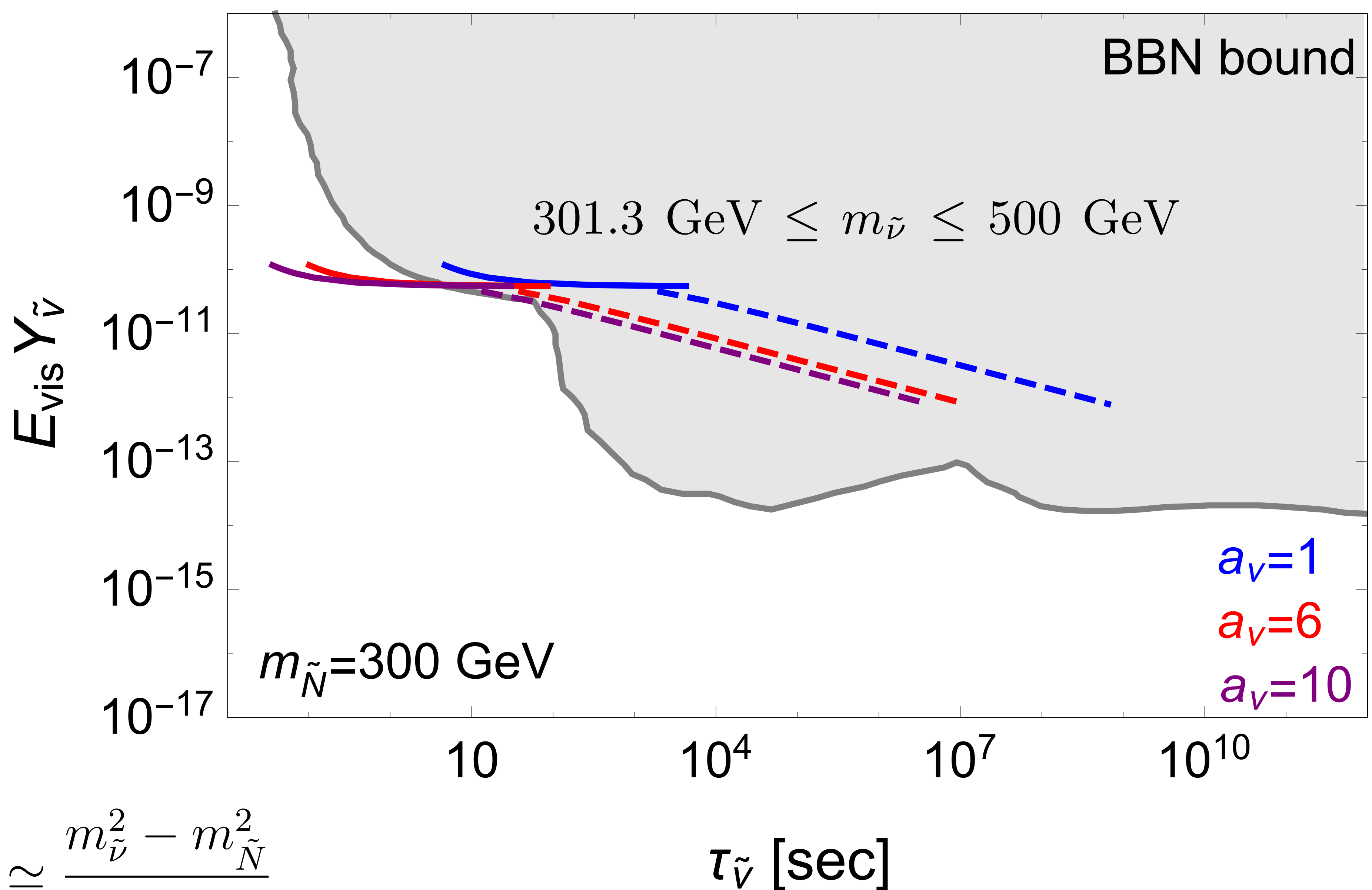
For three-body decay (when 2-body is disallowed),

$$\tau_{\tilde{\nu}} \simeq 10^3 \,\mathrm{sec} \left(\frac{300\,\mathrm{GeV}}{m_{\tilde{N}}}\right) \left(\frac{0.1\,\mathrm{eV}}{m_\nu}\right)^2 \left(\frac{0.1}{\delta}\right)^3 \left(\frac{1\,\mathrm{TeV}}{|\cot\beta\mu - A^*|}\right)^2,$$

$$\delta = (m_{\tilde{\nu}} - m_{\tilde{N}})/m_{\tilde{N}} \ll 1$$

Constraints from Big Bang Nucleosynthesis

[Kawasaki, Kohri, Moroi, 2005]



$$E_{\rm vis} \simeq \frac{m_{\tilde{\nu}}^2 - m_{\tilde{N}}^2}{2m_{\tilde{\nu}}}$$

Summary

- Neutrino mass and dark matter

  : pure Dirac-type neutrino mass and RH sneutrino as dark matter

- Production of RH sneutrino dark matter

  : thermal (decay+ scattering) + non-thermal

- For light slepton, sneutrino and heavy SUSY spectrum

  : thermal scatterings of RH sneutrino DM can be important

Thank You!