Right-Handed Sneutrino as Cold Dark Matter

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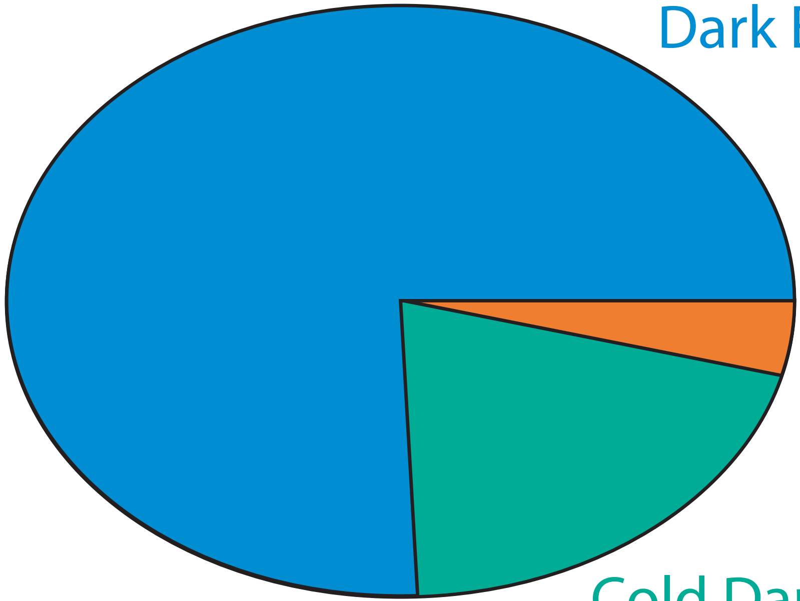
Reference:

Asaka, Ishiwata & Moroi, Phys. Rev. D73 (2006) 051301

Talk given at "SUSY 06"

1. Introduction

Density parameters are recently well determined



LSP dark matter: important motivation of SUSY

To realize LSP dark matter, the LSP should be neutral

$\Rightarrow$ Lightest neutralino, Gravitino, Axino, $\cdots$

A new candidate of the LSP (and CDM):

Right-handed scalar neutrino $\tilde{\nu}_R$

Seesaw scenario is usually assumed for the neutrino masses

[Yanagida; Gell-Mann, Ramond & Slansky]

$\Rightarrow$ However, neutrino masses may be Dirac-type

If the neutrino mass is Dirac-type, mass of $\tilde{\nu}_R$ originates from SUSY breaking

$\Rightarrow$ $\tilde{\nu}_R$ may be the LSP

Today's subject: possibility of $\tilde{\nu}_R$-CDM

- $\tilde{\nu}_R$ is assumed to be the LSP
- $\tilde{\nu}_R$-CDM (i.e., $\Omega_{\tilde{\nu}_R} \sim 0.1$) is realized in some case

2. Model

Superpotential:

$$W = y_\nu \hat{\nu}_R \hat{l}_L \hat{H}_u + W_{\mathrm{MSSM}} \quad \Rightarrow \quad m_\nu = y_\nu \langle H_u \rangle$$

Yukawa coupling constant becomes very small:

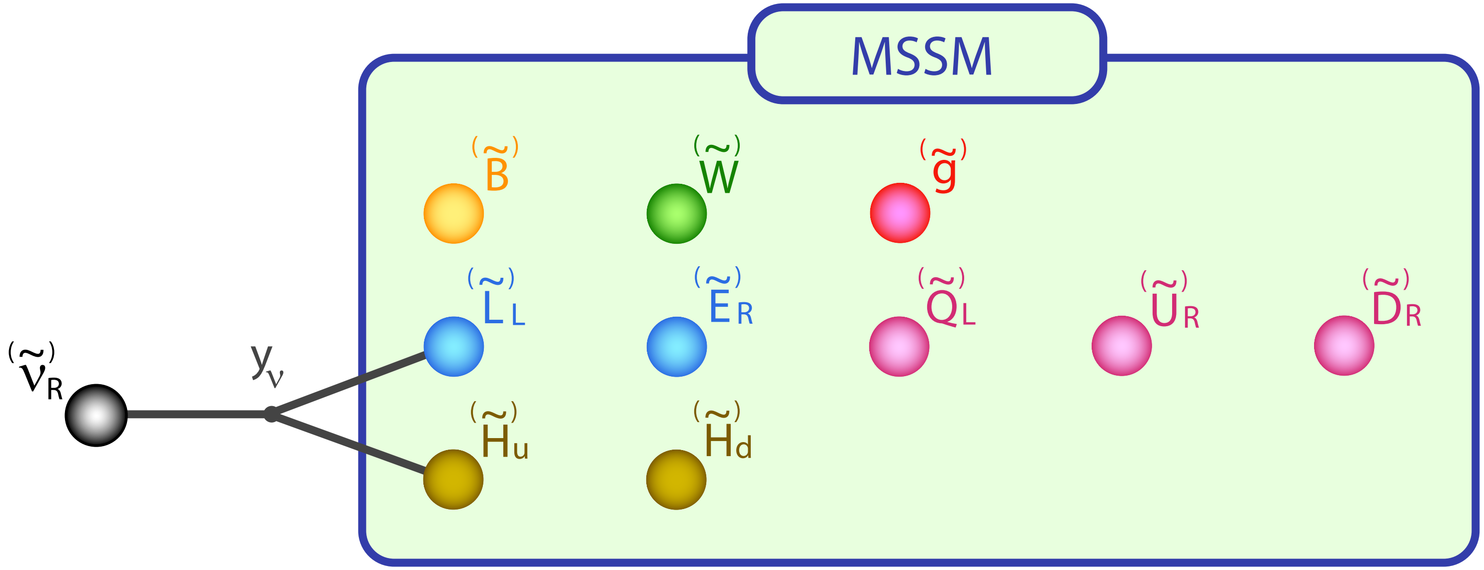
$$y_\nu \sin\beta = 3.0 \times 10^{-13} \times \left(\frac{m_\nu^2}{2.8 \times 10^{-3}\ \mathrm{eV}^2} \right)^{1/2}$$

C.f.: $\left[\Delta m_\nu^2\right]_{\mathrm{atom}} \simeq 2.8 \times 10^{-3}\ \mathrm{eV}^2$; $\left[\Delta m_\nu^2\right]_{\mathrm{solar}} \simeq 7.9 \times 10^{-5}\ \mathrm{eV}^2$

Small Yukawa coupling constant is natural (in 'tHooft's sense)

Chiral symmetry of ν_R is restored in the limit of $y_\nu \to 0$

Particle content



- $\tilde{\nu}_R$ is assumed to be the LSP (with $m_{\nu_R} \sim 100$ GeV)
- The NLSP (like χ_1^0 or $\tilde{\tau}$) becomes very long-lived

$$\Gamma^{-1}_{\tilde{H}_u \to \tilde{\nu}_R l_L} \simeq 100 \text{ sec} \left(\frac{y_\nu}{10^{-13}} \right)^2 \left(\frac{\mu_H}{100 \text{ GeV}} \right)$$

- Model (probably) looks like MSSM at collider experiments

3. Cosmology: relic density of $\tilde{\nu}_R$

$\tilde{\nu}_R$-LSP in early universe

- Production rate of $\tilde{\nu}_R$ is very small: $y_\nu \sim O(10^{-13})$
- $\tilde{\nu}_R$ cannot be thermalized

Typical production rate of $\tilde{\nu}_R$ in thermal bath

$$\langle \sigma v_{\text{rel}} \rangle \sim \frac{y_\nu^2}{T^2} \quad \Rightarrow \quad \Gamma_{\dots \to \tilde{\nu}_R} \sim n_{\text{MSSM}} \langle \sigma v_{\text{rel}} \rangle \sim y_\nu^2 T$$

Condition for thermalization: $\Gamma_{\dots \to \tilde{\nu}_R} \gg H \sim T^2 / M_{\text{Pl}}$

$$y_\nu \gg \sqrt{\frac{T}{M_{\text{Pl}}}} \sim 10^{-8} \times \left(\frac{T}{100\ \text{GeV}} \right)^{1/2}$$

$\tilde{\nu}_R$ is produced from particles in thermal bath

$\Rightarrow$ Decay processes are important

- $\tilde{H} \to \tilde{\nu}_R \nu_L$
- $\tilde{W} \to \tilde{\nu}_R l_L$
- $\cdots$

Boltzmann equation

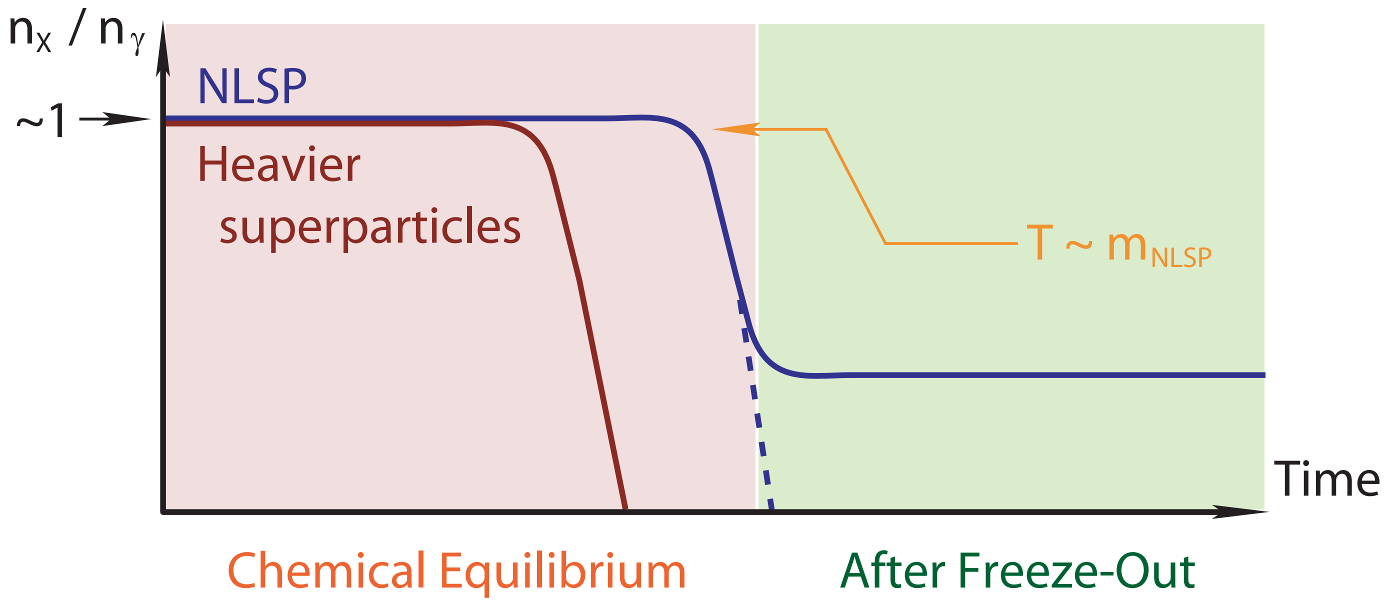
$$\frac{dn_{\tilde{\nu}_R}}{dt} + 3Hn_{\tilde{\nu}_R} \simeq \sum_x n_x \Gamma_{x \to \tilde{\nu}_R + \cdots}$$

n_x: number density of parent particle x

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_{\mathrm{Pl}}^2} \quad \text{with} \quad \rho_{\mathrm{rad}} = \frac{\pi^2}{30} g_* T^4$$

When T is high, MSSM particles are in chemical equilibrium

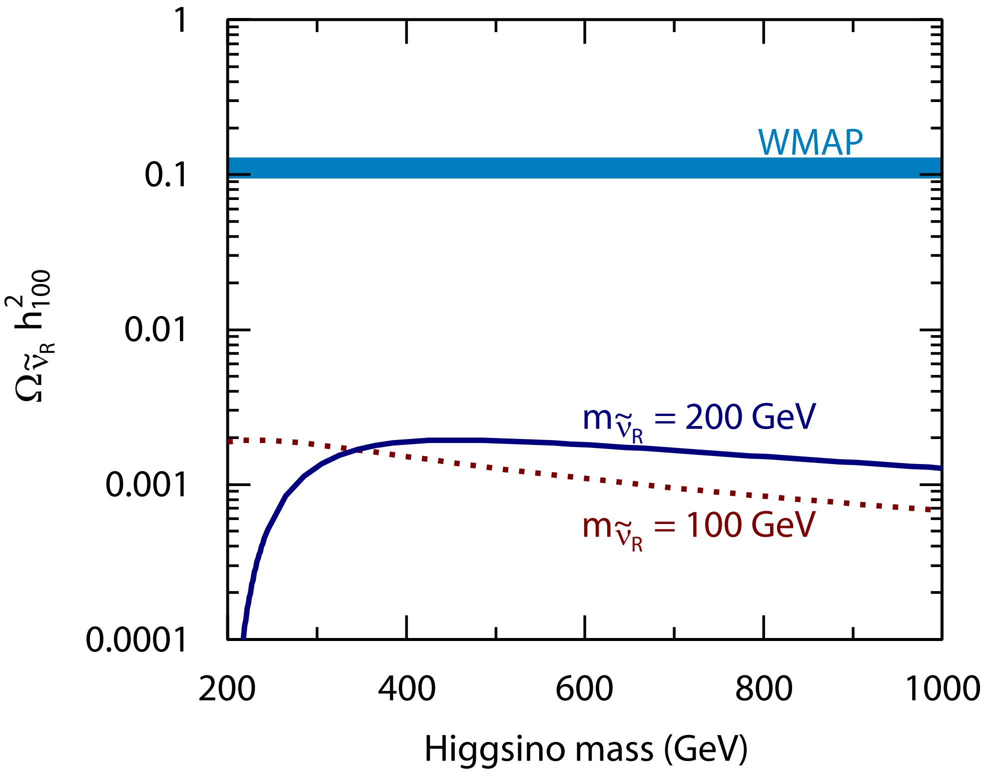
$\Rightarrow$ NLSP (like χ_1^0 or $\tilde{\tau}$) freezes out at low temperature



$$\Rightarrow n_{\tilde{\nu}_R} = n_{\tilde{\nu}_R}^{\text{(C.E.)}} + n_{\tilde{\nu}_R}^{\text{(F.O.)}}$$

- $n_{\tilde{\nu}_R}^{\text{(C.E.)}}$: $\tilde{\nu}_R$ produced when $T \gtrsim T_{\text{F}}$
- $n_{\tilde{\nu}_R}^{\text{(F.O.)}}$: $\tilde{\nu}_R$ produced when $T \lesssim T_{\text{F}}$

$\tilde{\nu}_R$ production before NLSP freeze-out: case with $\tilde{H} \to \tilde{\nu}_R l_L$



$$\Gamma_{\tilde{H} \to \tilde{\nu}_R l_L} = \frac{\beta_f^2 y_\nu^2}{32\pi} \mu_H$$

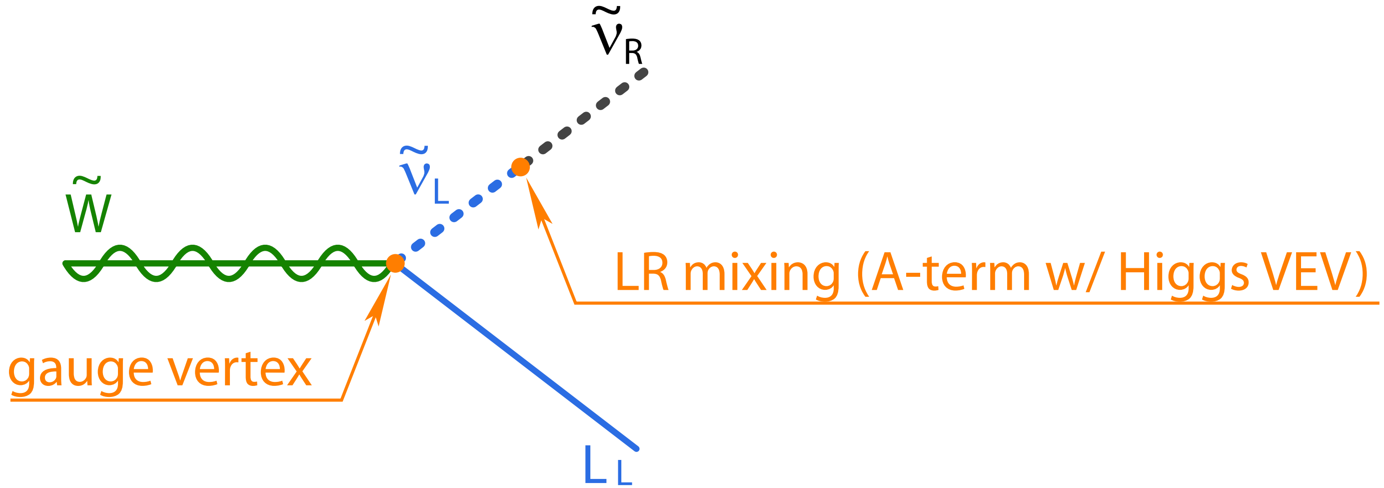
$$y_\nu = 3 \times 10^{-13}$$

In this case, $\Omega_{\tilde{\nu}_R}$ is too small to realize $\tilde{\nu}_R$-CDM

$\Rightarrow$ However, there are several possibilities to enhance $\Omega_{\tilde{\nu}_R}$

Possibility 1: Mixing enhancement (via left-right mixing)

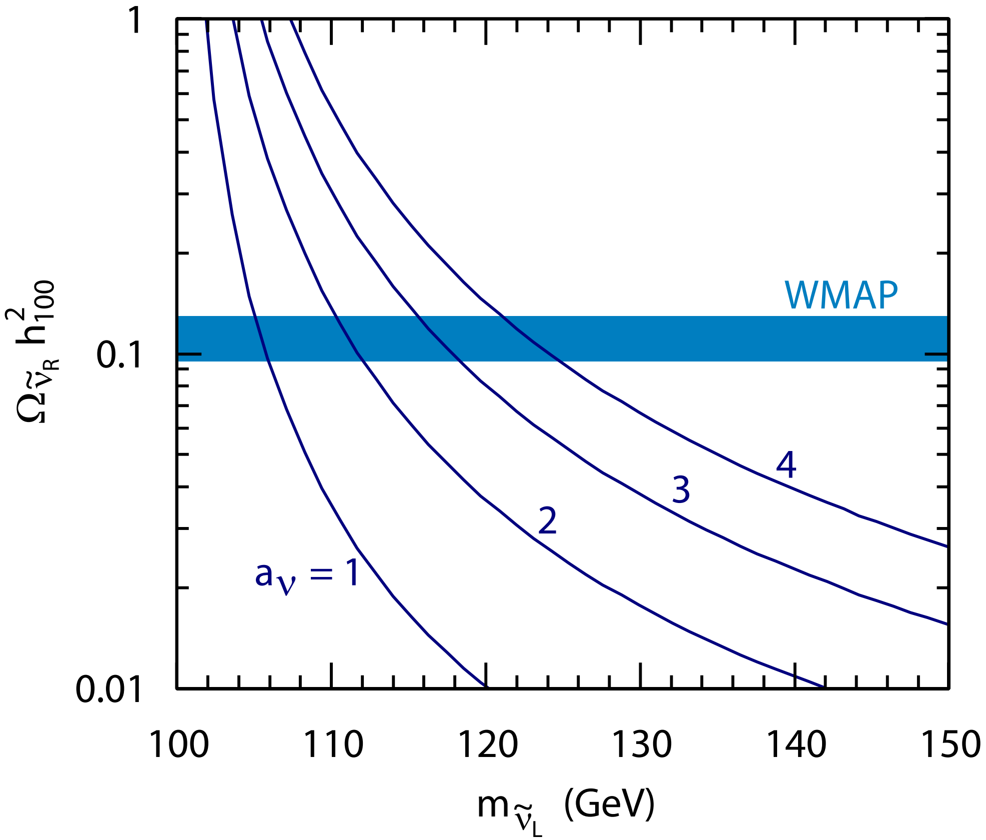
$$\mathcal{L}_A = A_\nu H_u \tilde{L} \tilde{\nu}_R + \text{h.c.}$$



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

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

$\tilde{\nu}_R$ production is enhanced when $\tilde{\nu}_R$ and $\tilde{\nu}_L$ are degenerate



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

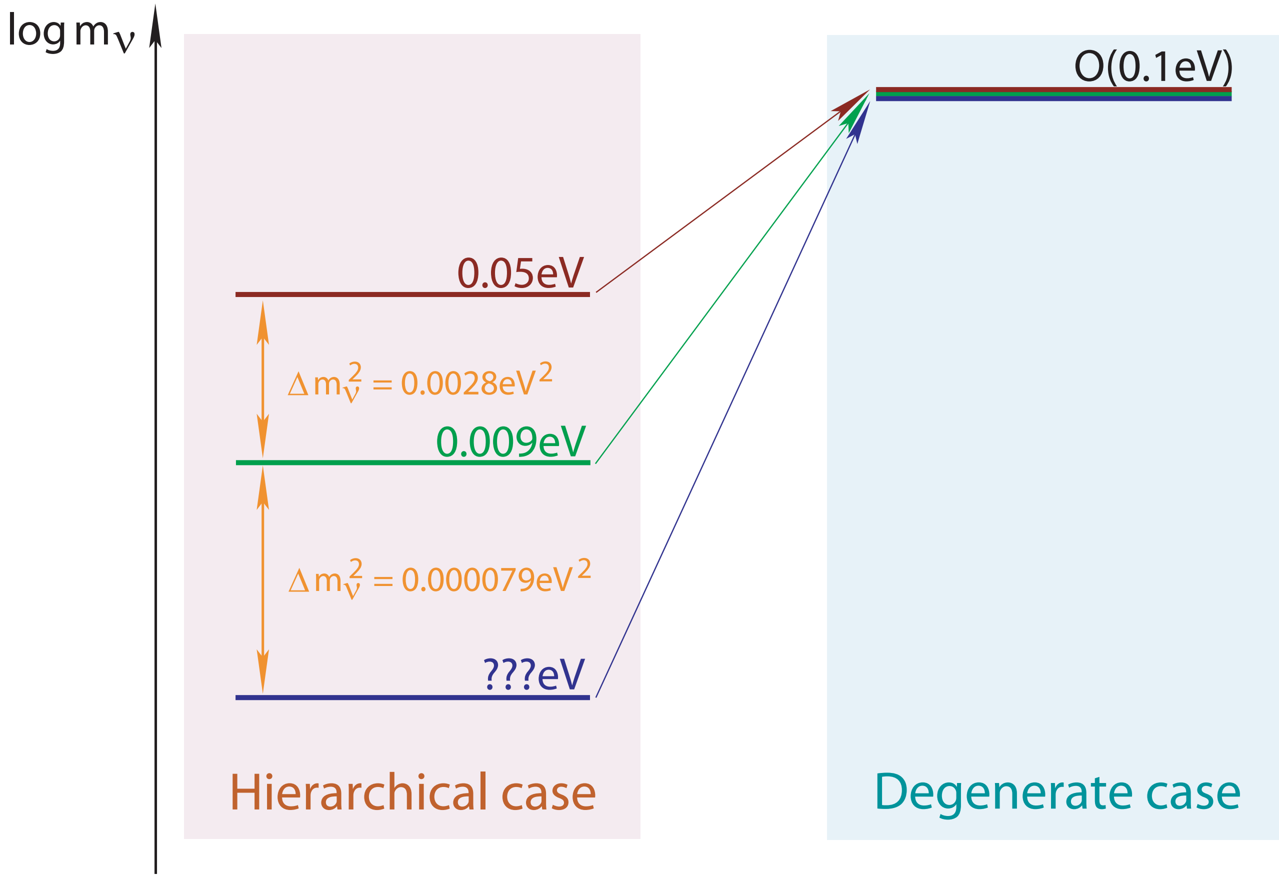
$$y_\nu = 3 \times 10^{-13}$$

$$A_\nu = a_\nu y_\nu m_{\tilde{l}_L}$$

- $\tilde{\nu}_R$-CDM is realized with a mild degeneracy
- In this case, light sleptons are likely to be found at colliders

Possibility 2: Degenerate neutrinos

Neutrino-oscillation experiments determine only difference of mass squared



Required enhancement of $\Omega_{\tilde{\nu}_R}$: factor of ~ 100

$\Rightarrow$ This is realized when $m_\nu \sim O(0.1 \text{ eV})$

Notice: $\Omega_{\tilde{\nu}_R} \propto y_\nu^2 \propto m_\nu^2$

Upper bound on m_ν from large-scale structure

[Seljek et al. (SDSS collaboration)]

$\sum m_\nu < 1.54$ eV : without Ly-α forest data

$\sum m_\nu < 0.42$ eV : with Ly-α forest data

Systematic uncertainties (probably) remain in the current study of Ly-α forest

$\Rightarrow$ With a better understanding of Ly-α forest, scenario with degenerate neutrinos will be more precisely tested

Possibility 3: $\tilde{\nu}_R$ production after freeze-out of the NLSP

$\Rightarrow$ $\tilde{\nu}_R$ production after NLSP freeze-out may be significant

$$\Omega_{\tilde{\nu}_R}^{(\mathrm{tot})} = \Omega_{\tilde{\nu}_R}^{(\mathrm{C.E.})} + \Omega_{\tilde{\nu}_R}^{(\mathrm{F.O.})} = \Omega_{\tilde{\nu}_R}^{(\mathrm{C.E.})} + \frac{m_{\tilde{\nu}_R}}{m_{\mathrm{NLSP}}} \Omega_{\mathrm{NLSP}}$$

Ω_{NLSP}: "would-be" density parameter of the NLSP

- Ω_{NLSP} strongly depends on MSSM parameters

  $\Rightarrow$ Ω_{NLSP} becomes larger than $O(0.1)$ in some case

- Ω_{NLSP} is (in principle) calculable once MSSM parameters are measured at collider experiments

Comment 1: $\tilde{\nu}_R$ may be even produced by inflaton decay

$\Rightarrow \Omega_{\text{NLSP}}$ depends on physics at very high energy

Comment 2: Case with Majorana neutrino mass

[Yanagida; Gell-Mann, Ramond & Slansky]

$$W = y_\nu \hat{\nu}_R \hat{l}_L \hat{H}_u + \frac{1}{2} M_{\nu_R} \hat{\nu}_R \hat{\nu}_R + W_{\text{MSSM}} \quad \Rightarrow \quad m_\nu = \frac{y_\nu^2 \langle H_u \rangle^2}{M_{\nu_R}}$$

$y_\nu \gg 10^{-13}$ when $M_{\nu_R} \gg m_\nu$

$\Rightarrow \Omega_{\tilde{\nu}_R} \sim \Omega_{\text{WMAP}}$ when $M_{\nu_R} \sim 1\text{eV}$

$\Rightarrow \Omega_{\tilde{\nu}_R} \gg \Omega_{\text{WMAP}}$ when $M_{\nu_R} \gg 1\text{eV}$

4. Conclusions

I discussed the possibility of $\tilde{\nu}_R$-CDM

- $\tilde{\nu}_R$-LSP may be CDM (with some enhancement of $\Omega_{\tilde{\nu}_R}$)
- $\Omega_{\tilde{\nu}_R}$ is insensitive to the thermal history of $T \gg m_{\text{SUSY}}$

Probably, rich phenomenology with $\tilde{\nu}_R$-LSP:

- Detailed study of the effects of NLSP decay
- $\tilde{\nu}_R$ at colliders: possibility of $\tilde{l}^{\pm}$-NLSP (with long lifetime)

  $\Rightarrow$ Charged-slepton trapping

  [Feng & Smith; Buchmuller, Hamaguchi, Ratz & Yanagida]
- Baryogenesis (probably, by Affleck-Dine mechanism?)
- $\cdots$