Right-handed sneutrino as cold dark matter of the universe

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Refs: with Ishiwata and Moroi

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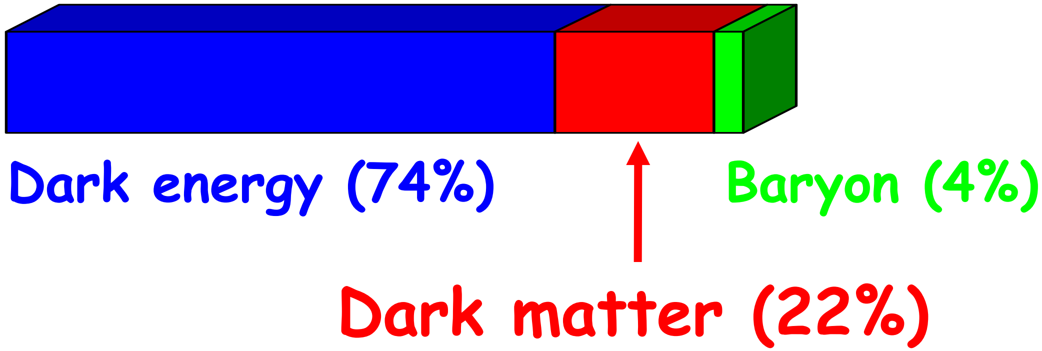
I. Introduction

Dark Matter

- Content of the universe



[WMAP '06]

$$\Omega_{\rm dm} h^2 = 0.105^{+0.007}_{-0.013}$$

$$\Omega_{\rm dm} = \rho^0_{\rm dm}/\rho_{\rm cr}$$

$h : H_0$ [100km/sec/Mpc]

- What is dark matter???
  - No candidate in SM $\Rightarrow$ New Physics !!!
  - One attractive candidate

LSP in supersymmetric theories

LSP Dark Matter

- R-parity: $R_p = (-1)^{3B+L+2s}$

  ordinary SM particles: R-parity even (+1)

  additional superparticles: R-parity odd (-1)

  - Lightest superparticle (LSP) is stable
  - LSP is a good candidate of DM if it is neutral

- What is the LSP DM?
  - Lightest neutralino

    (= combination of neutral gauginos and higgsinos)

Other candidates for LSP DM

- The lightest neutralino is NOT the unique candidate for the LSP DM
  - In supergravity, "gravitino"
  - In superstring, "modulino"
  - With Peccei-Quinn symmetry, "axino"
  - …

- Now, we know that the MSSM is incomplete accounting for neutrino oscillations

  → alternative candidate for the LSP DM

In this talk,

- Introduce RH neutrinos to explain neutrino masses
  - In supersymmetric theories,

    RH neutrino ν_R + RH sneutrino $\tilde{\nu}_R$

    fermion (Rp=+1) scalar (Rp=-1)

- If neutrino masses are purely Dirac-type,
  - Masses of RH sneutrinos come from SUSY breaking
    - $m_{\tilde{\nu}_R} = \mathcal{O}(10^2)\text{GeV}$
  - Lightest RH sneutrino can be LSP,

  - LSP RH sneutrino is a good candidate for CDM (i.e., $\Omega_{\tilde{\nu}_R} = \Omega_{\rm dm}$ can be realized)

II. Right-handed sneutrino as dark matter

Model

- **MSSM + three right-handed (s)neutrinos assuming neutrino masses are purely Dirac-type**

$$W = W_{\rm MSSM} + f_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c \quad \Rightarrow \quad m_\nu = f_\nu \langle H_u^0 \rangle$$

  - **Yukawa couplings are very small**

$$f_\nu \sin\beta = 3\times 10^{-13}\left(\frac{m_\nu^2}{2.5\times 10^{-3}\mathrm{eV}^2}\right)^{1/2}$$

$$\Delta m_{\rm atm}^2 \simeq 2.5\times 10^{-3}\,\mathrm{eV}^2$$
$$\Delta m_{\rm sol}^2 \simeq 8.0\times 10^{-5}\,\mathrm{eV}^2$$

  - **Small Yukawa couplings are natural in 'tHooft's sense**
    - chiral symmetry of neutrinos is restored in the limit of vanishing Yukawa couplings

Model (2)

- LSP = $\tilde{\nu}_R$ with $m_{\tilde{\nu}_R} \sim 100$ GeV
  - only suppressed interaction: $f_\nu = \mathcal{O}(10^{-13})$
- NLSP = MSSM-LSP
  - MSSM-LSP can be charged
  - rather long-lived: $f_\nu = \mathcal{O}(10^{-13})$
    - typically $\tau_{\rm NLSP} \sim 10^2 - 10^4$ sec

Our claim: LSP $\tilde{\nu}_R$ as CDM

$$\Omega_{\tilde{\nu}_R} h^2 = \Omega_{\rm dm} h^2 \simeq 0.1$$

Cf. $\Omega_{\tilde{\nu}_R} = \rho^0_{\tilde{\nu}_R}/\rho_{\rm cr}$

How are $\tilde{\nu}_R$ produced in the early universe???

Production of RH sneutrino

- $\tilde{\nu}_R$ is not thermalized in the early universe!!!
  - Interaction rate of $\tilde{\nu}_R$ is very small: $f_\nu = O(10^{-13})$
    - Typically, $\Gamma_{\rm int} \sim f_\nu^2 T$

$$\Gamma_{\rm int} > H \sim T^2/M_{\rm pl} \Rightarrow \; f_\nu \gtrsim \sqrt{\frac{T}{M_{\rm pl}}} \sim 10^{-8}\left(\frac{T}{100\mathrm{GeV}}\right)^{1/2}$$

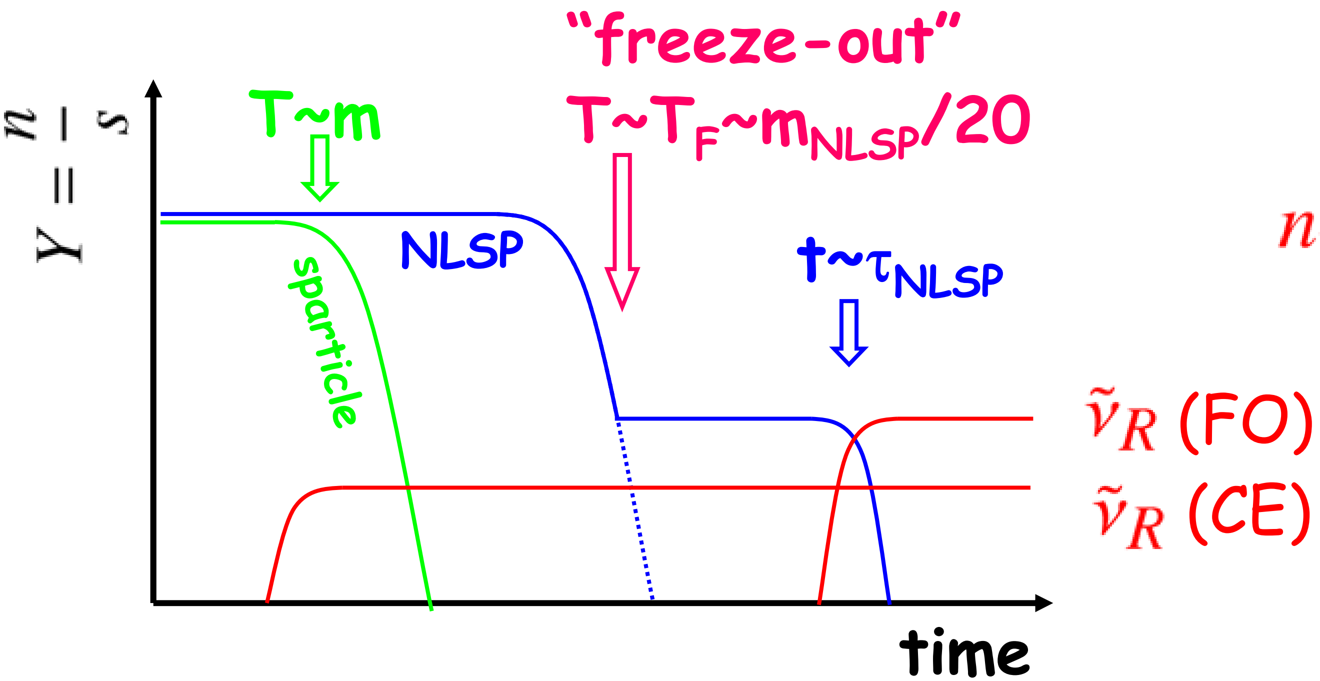
- How are $\tilde{\nu}_R$ produced in the early universe???

A.

$\tilde{\nu}_R$ is effectively produced by superparticle decay

Production by superparticle decay

- Two distinct contributions:
  - decay of superparticle in chemical equilibrium (CE)
  - decay of NLSP after freeze-out (FO)



$$n_{\tilde{\nu}_R} = n_{\tilde{\nu}_R}^{\text{CE}} + n_{\tilde{\nu}_R}^{\text{FO}}$$

Relic density from sparticle in CE

- Boltzmann equation

$$\frac{dn_{\tilde{\nu}_R}}{dt} + 3\,H\,n_{\tilde{\nu}_R} = \sum_{x\to\tilde{\nu}_R\,y} \int \frac{d^3k_x}{(2\pi)^3} \frac{m_x}{\sqrt{k_x^2+m_x^2}} (2s_x+1)\Gamma_{x\to\tilde{\nu}_R y} f_x \langle 1 \pm f_y \rangle$$

$$\simeq \sum_{x\to\tilde{\nu}_R\,y} n_x \Gamma_{x\to\tilde{\nu}_R y}$$

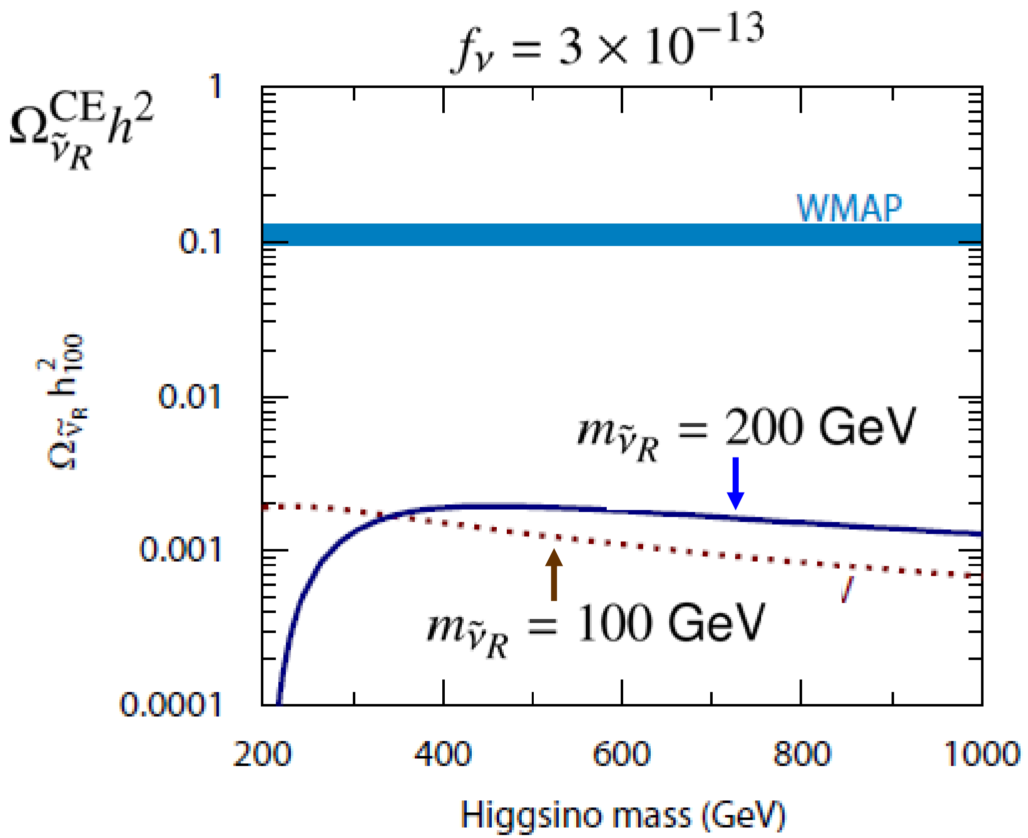
$n_{\tilde{\nu}_R}$: number density of $\tilde{\nu}_R$

n_x : number density of parent particle

- $\Omega^{\rm CE}_{\tilde{\nu}_R} = \dfrac{m_{\tilde{\nu}_R}\, n_{\tilde{\nu}^0_R}}{\rho_{\rm cr}}$ $\quad\quad \Gamma_{x\to\tilde{\nu}_R y} \propto f_\nu^2 \Rightarrow \Omega^{\rm CE}_{\tilde{\nu}_R} \propto f_\nu^2$

- **Dominant production occurs at T~mx**
  - Present abundance is insensitive to thermal history for T >> 100GeV

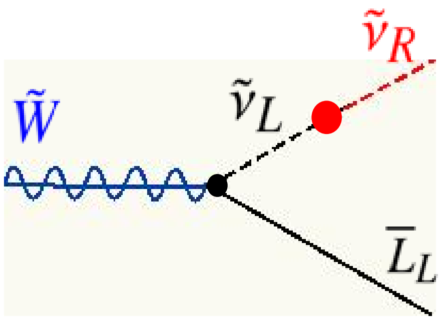
Higgsino decay $\tilde{H}^0 \to \tilde{\nu}_R \bar{\nu}_L, \;\; \tilde{H}^+ \to \tilde{\nu}_R \bar{\ell}_L^+$



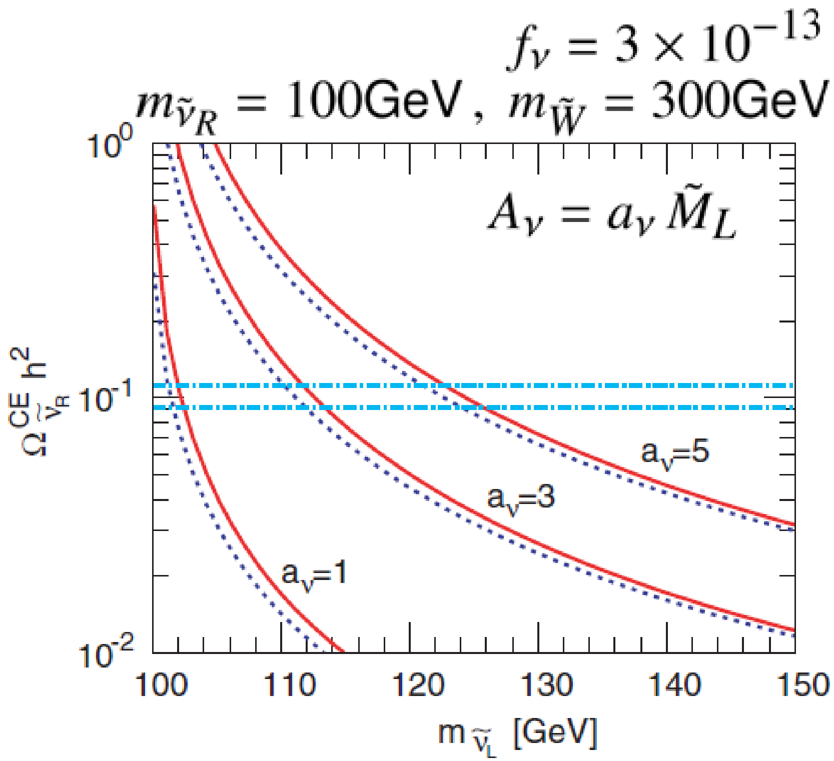
- **In this case, the abundance is too small:** $\Omega_{\tilde{\nu}_R}^{CE} \sim 10^{-2} \Omega_{dm}$
- **But, the production is enhanced in some cases !**

(1) Enhance left-right mixing

- Wino decays



$$\tan 2\Theta = \frac{2m_\nu|\cot\beta\mu_H - A_\nu^*|}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2}$$



- $\tilde{\nu}_R$ DM can be realized with a mild degeneracy between $\tilde{\nu}_R$ and $\tilde{\nu}_L$
- Light $\tilde{\nu}_L$ will be a good target of collider exp.

(2) Degenerate neutrinos

- Larger neutrino mass enhances the production of $\tilde{\nu}_R$ since $\Omega_{\tilde{\nu}_R} \propto f_\nu^2 \propto m_\nu^2$
- Neutrino mass bound:
  - From CMBR
    - $\Sigma m_\nu < 1.8\text{eV} \rightarrow m_\nu < 0.60\text{eV}$ [WMAP '06]

      CF. if we include other data from large scale structure/Ly-alpha, the bound becomes severer
- DM can be realized when $m_\nu \sim O(0.1)$ eV
  - Scenario with degenerate neutrino masses will be tested in future astrophysical observations

NLSP decay after freeze-out

- NLSP (=MSSM-LSP) decays into $\tilde{\nu}_R$ after freeze-out

$$\Omega_{\tilde{\nu}_R} = \Omega_{\tilde{\nu}_R}^{\rm CE} + \Omega_{\tilde{\nu}_R}^{\rm FO} = \Omega_{\tilde{\nu}_R}^{\rm CE} + \frac{m_{\tilde{\nu}_R}}{m_{\rm NLSP}} \Omega_{\rm NLSP}$$

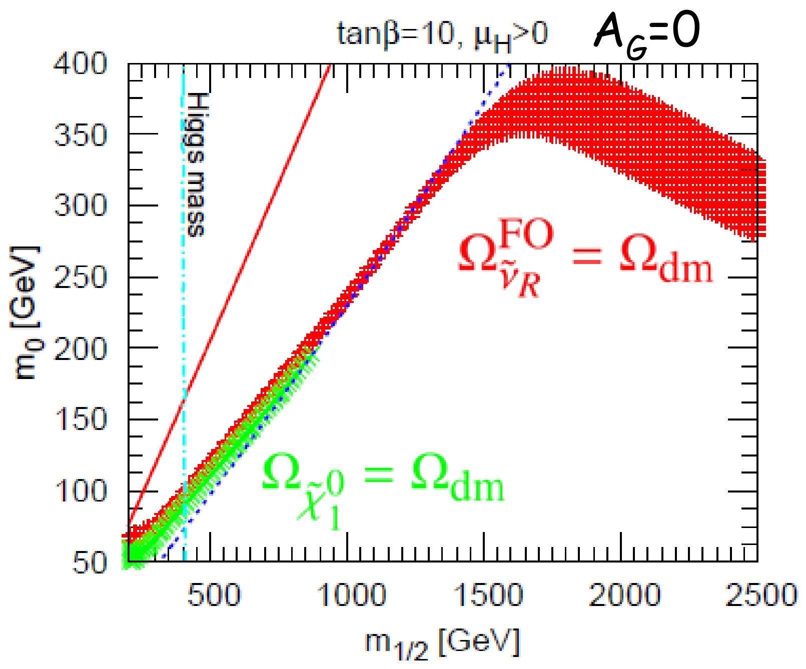
$\Omega_{\rm NLSP}$ is "would-be" relic density of NLSP

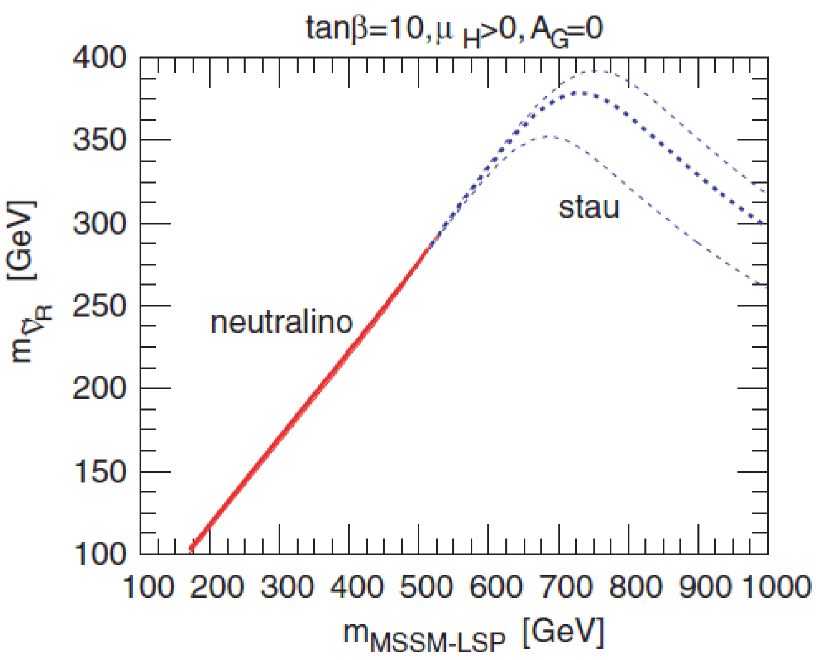
- When $\Omega_{\tilde{\nu}_R} \simeq \Omega_{\tilde{\nu}_R}^{\rm FO} \simeq \Omega_{\rm dm}$, $\tilde{\nu}_R$ DM can be realized
  - different parameter space from the standard neutralino DM since $\Omega_{\rm NLSP} > \Omega_{\rm dm}$
  - Present abundance is insensitive to thermal history for T >> 100GeV
  - $\Omega_{\rm NLSP}$ (and $\Omega_{\tilde{\nu}_R}$) depends strongly on MSSM params

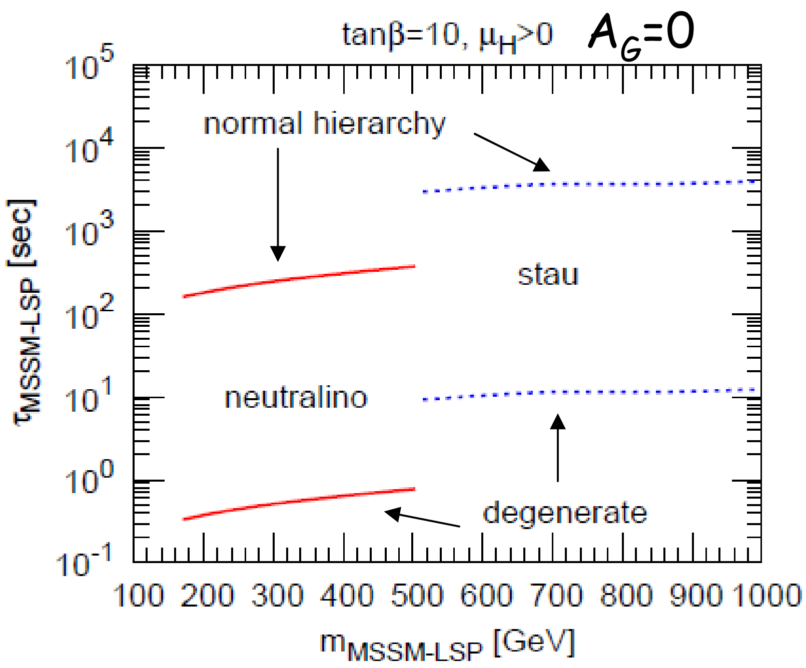
Example

- **mSUGRA:**

$$m_{\tilde{\nu}_R} = m_0$$







III. Summary

Summary

- We discussed MSSM with three RH (s)neutrinos assuming neutrino masses are purely Dirac-type
  - Lightest RH sneutrino can be LSP
  - LSP RH sneutrino can be a good candidate for DM
    - $\Omega_{\tilde{\nu}_R} = \Omega_{\mathrm{dm}}$ can be realized
  - $\Omega_{\tilde{\nu}_R}$ is insensitive to physics at T >> 100 GeV
  - MSSM-LSP can be charged

- The list of LSP DM
  - Neutralino, Gravitino, Axino, … , RH sneutrino

Comments:

- Other production mechanism:
  - by inflaton decay / as coherent oscillation
    - depends on physics at high energy
  - by new interaction
    - extra U(1)' [Lee, Matchev, Nasri]
- When Majorana masses are present,

$$W = W_{\rm MSSM} + f_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c + \frac{M_R}{2} \hat{\nu}_R^c \hat{\nu}_R^c \quad \Rightarrow m_\nu = \frac{(f_\nu \langle H_u^0 \rangle)^2}{M_R}$$

  - Yukawa couplings become larger:

$$\Omega_{\tilde{\nu}_R} > \Omega_{\rm dm} \ \text{for} \ M_R \gtrsim 1\text{eV}$$

[See also Gopalakrishna, de Gouvea, Porod]

Sneutrinos

- **Mass squared matrix of sneutrinos** $(\tilde{\nu}_L, \tilde{\nu}_R)$

$$-\mathcal{L}_{\rm soft} = \tilde{M}_L^2 |\tilde{L}|^2 + \tilde{M}_{\nu_R}^2 |\tilde{\nu}_R|^2 + (f_\nu A_\nu H_u \tilde{L} \tilde{\nu}_R^c + h.c.)$$

$$m_{\tilde{\nu}}^2 = \begin{pmatrix} \tilde{M}_L^2 + \frac{1}{2}\cos 2\beta m_Z^2 + m_\nu^2 & m_\nu (A_\nu^* \sin\beta - \mu_H \cos\beta) \\ m_\nu (A_\nu \sin\beta - \mu_H \cos\beta) & \tilde{M}_{\nu_R}^2 + m_\nu^2 \end{pmatrix}$$

- **Very small left-right mixing of sneutrinos** $(\tilde{\nu}_L, \tilde{\nu}_R)$

$$\tan 2\Theta = \frac{2 m_\nu |\cot\beta \mu_H - A_\nu^*|}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2}$$

suppressed by m_ν

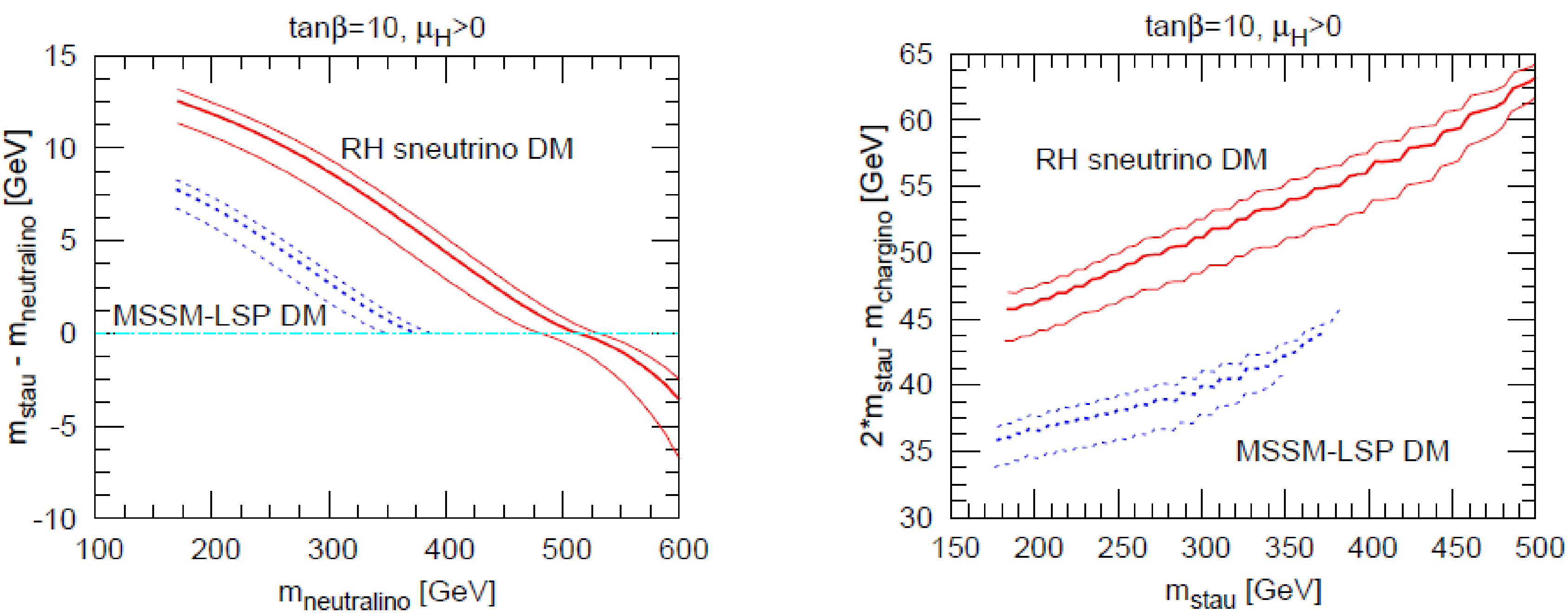
- **RH sneutrino masses come from SUSY breaking**

$$m_{\tilde{\nu}_R}^2 \simeq \tilde{M}_{\nu_R}^2 \qquad m_{\tilde{\nu}_L}^2 \simeq \tilde{M}_L^2 + \frac{1}{2}\cos 2\beta\, m_Z^2$$

→ **LSP can be the lightest RH sneutrino**

Implication of RH sneutrino DM

- **Parameter space of RH sneutrino DM is different from the standard neutralino DM**
  - $\Omega_{\tilde{\nu}_R}^{FO} = \frac{m_{\tilde{\nu}_R}}{m_{NLSP}} \Omega_{NLSP} \Rightarrow \Omega_{NLSP} = \frac{m_{NLSP}}{m_{\tilde{\nu}_R}} \Omega_{dm} > \Omega_{dm}$



3. Cosmological constraints

- NLSP (=MSSM-LSP) decays around or after the BBN
  - would spoil success of BBN
  - put constraints on

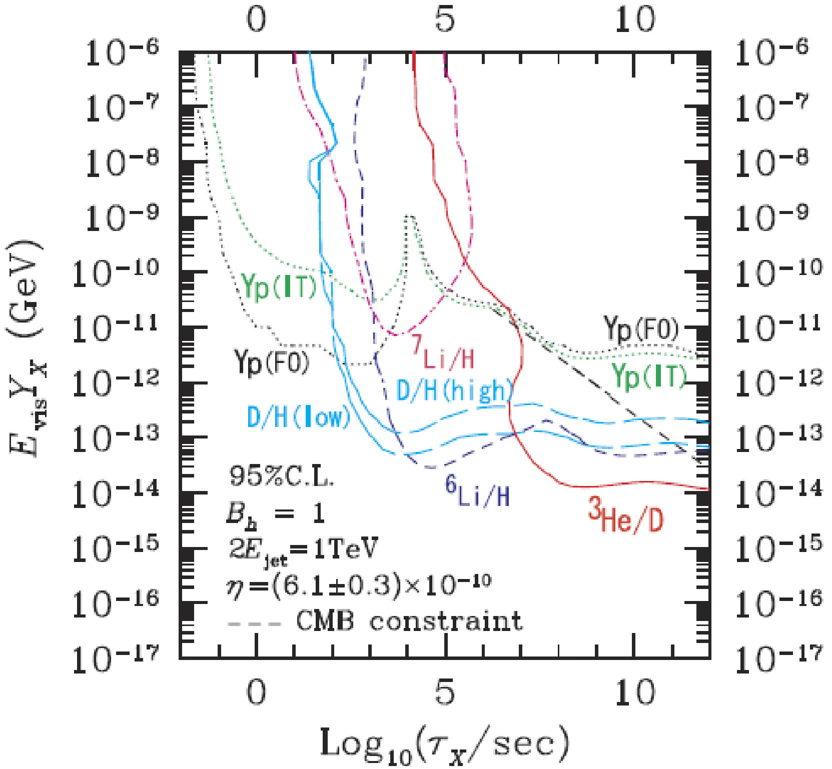
$\tau_{\rm NSLP}$

lifetime of NLSP

$B_h \, E_{\rm vis} \, Y_{\rm NLSP}$

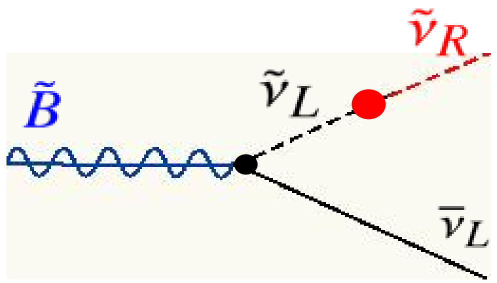
- hadronic branching ratio
- visibile energy of decay products
- yield of NLSP

$$Y_{\rm NLSP} = n_{\rm NLSP}/s$$



[Kawasaki, Kohri, Moroi]

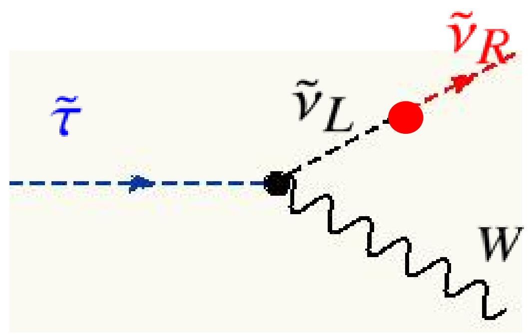
NLSP decays



- Bino-like neutralino
  - Main decay mode: $\tilde{B} \to \tilde{\nu}_R \overline{\nu}_L$
    - no visible energy
  - Subdominant modes: $\tilde{B} \to \tilde{\nu}_R \overline{\nu}_L Z^{(*)}$, $\to \tilde{\nu}_R \ell_L^{+} W^{(*)}$

→ hadronic branching ratio is small

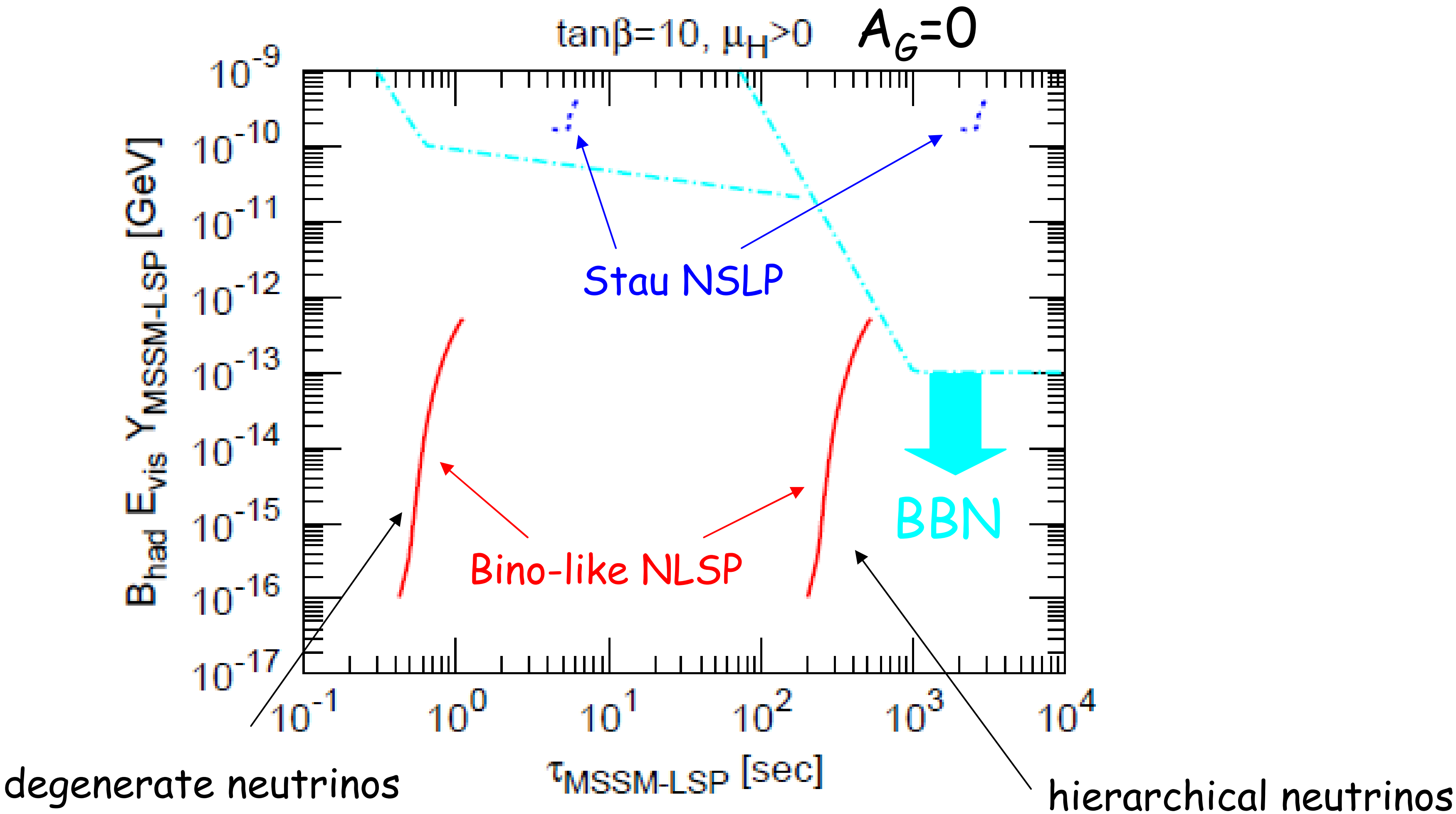
- Stau
  - Main decay mode: $\tilde{\tau}_1 \to \tilde{\nu}_R W^{(*)}$



→ hadronic branching ratio is large

BBN constraint

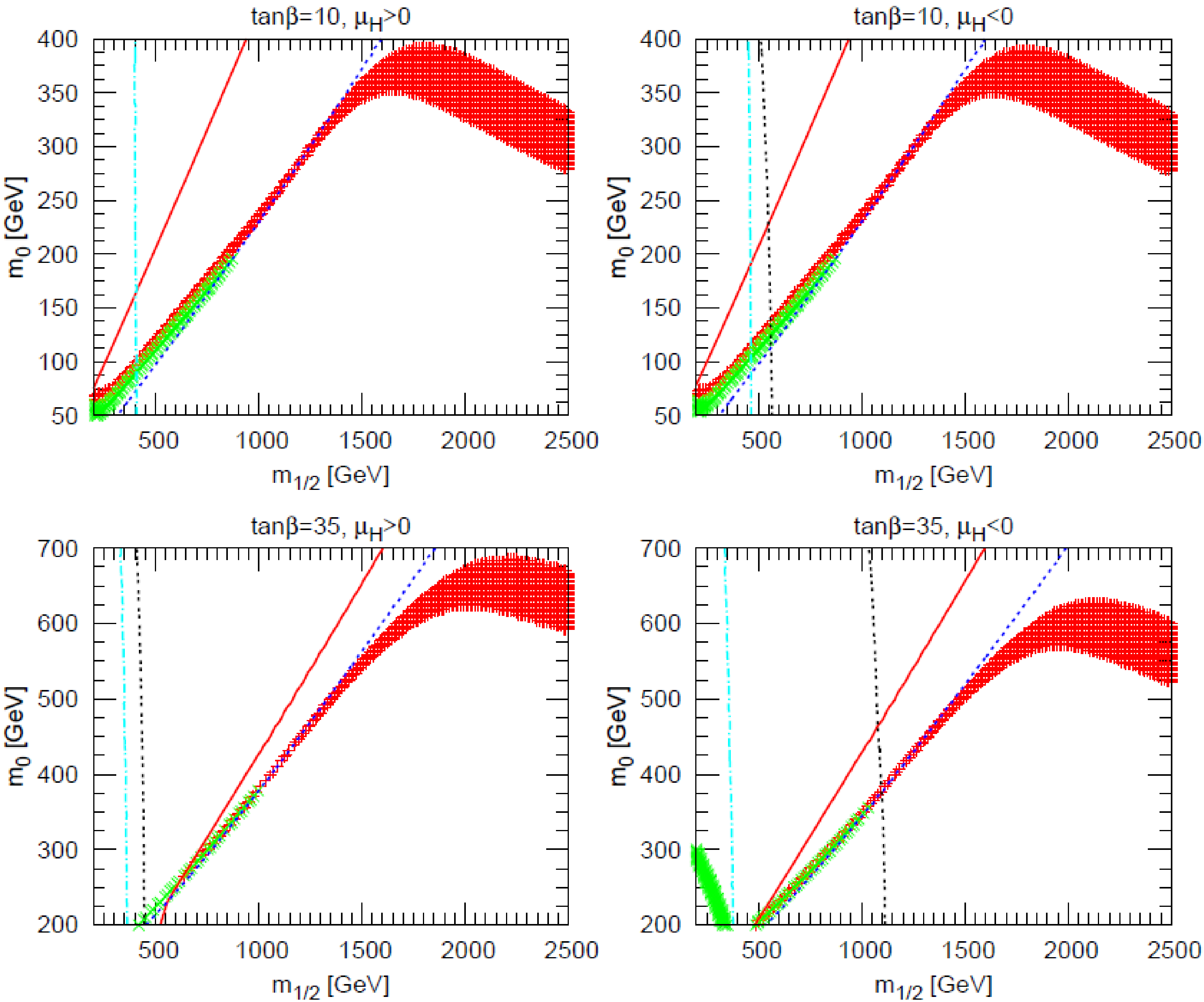
- **mSUGRA point**



BBN constraints on NLSP decay

- Bino-like NLSP
  - almost harmless
- Stau NLSP
  - severely restricted
    - even more stringent from recent obs.
      - ^{6}Li production is enhanced
        [Pospelov / Hamaguchi et al]
  - → lifetime should be shorter
    - degenerate neutrinos
    - large left-right mixing of sneutrino

$$\tan 2\Theta = \frac{2m_\nu |\cot\beta \mu_H - A_\nu^*|}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2}$$


tanβ=10, μ_H>0
tanβ=10, μ_H<0
tanβ=35, μ_H>0
tanβ=35, μ_H<0
m_0 [GeV]
m_1/2 [GeV]
50
100
150
200
250
300
350
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500
600
700
1000
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2000
2500