Right-Handed Sneutrino as the CDM

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Reference:

Asaka, Ishiwata & TM, PRD 73 (2006) 051301

Asaka, Ishiwata & TM, PRD 75 (2007) 065001

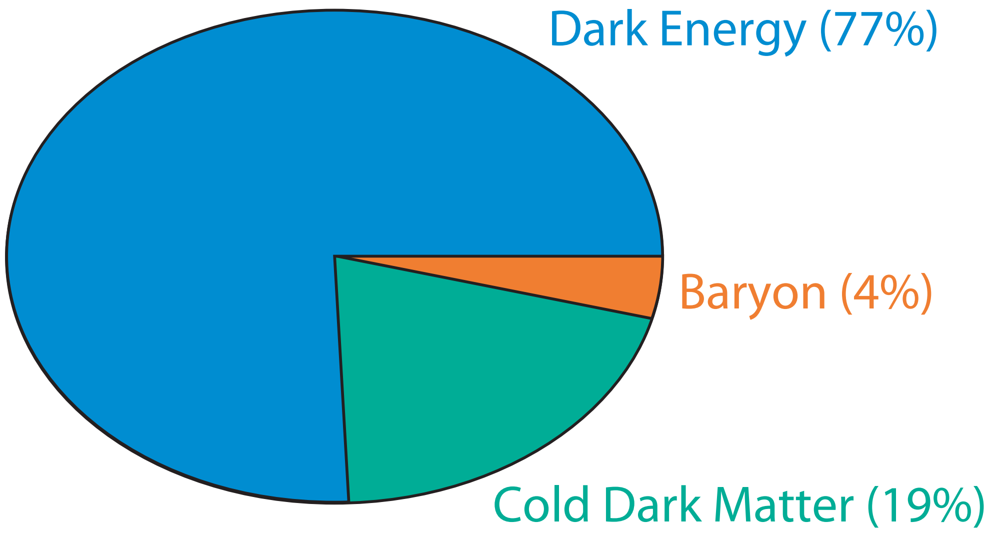
Ishiwata, Kawasaki, Kohri & TM, PLB 689 (2010) 163

Ishiwata, Matsumoto & TM, arXiv:1008.3636

1. Introduction

Dark matter (DM)

⇒ Dark matter should exist, but we don't know what it is



⇒ Well-motivated candidate: The lightest superparticle

⇒ It is often assumed that thermally-produced lightest neutralino is DM

Today, I consider a DM candidate with non-thermal origin

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

Seesaw scenario is usually adopted for small neutrino masses

[Minkowski; Yanagida; Gell-Mann, Ramond & Slansky]

$\Rightarrow$ Neutrino masses are Majorana-type

$\Rightarrow$ Right-handed (s)neutrinos are ultra-heavy, and are irrelevant for low-energy phenomenology

However, neutrino masses may be Dirac-type

$\Rightarrow$ Smallness of the neutrino mass is naturally explained by the (conserved) lepton-number symmetry

$\Rightarrow$ $\tilde{\nu}_R$ can be cold dark matter (CDM)

[Asaka, Ishiwata & TM; See also Gopalakrishna, de Gouvea & Porod]

Today, I consider SUSY cosmology with:

- Dirac-type neutrino mass
- Right-handed sneutrino LSP with $m_{\tilde{\nu}} \sim O(100 \text{ GeV})$

Outline

1. Introduction
2. Framework
3. Relic Density of $\tilde{\nu}_{\mathrm{R}}$-LSP
4. BBN Constraints
5. Implication to PAMELA Anomaly
6. Summary

2. Framework

Superpotential (for Dirac-type neutrino mass):

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

Yukawa coupling constant becomes very small:

$$y_\nu \sin\beta = 2.8 \times 10^{-13} \times \left(\frac{m_\nu^2}{2.4 \times 10^{-3}\ \text{eV}^2} \right)^{1/2}$$

In SUSY model with the Dirac-type neutrino masses

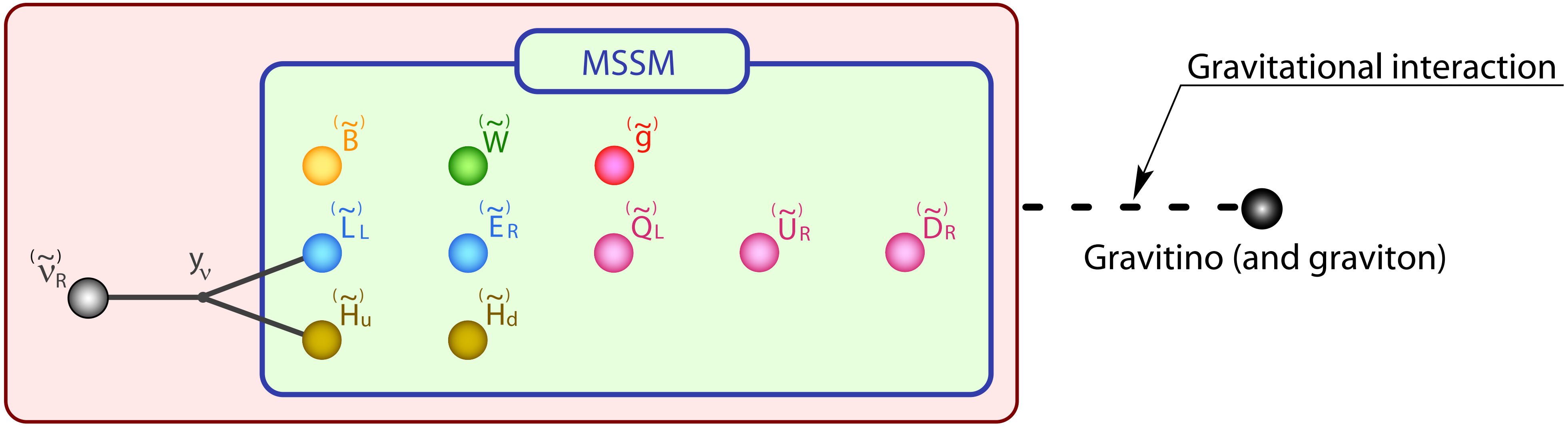
- Mass of $\tilde{\nu}_R$ is mainly from SUSY breaking effect

  $\Rightarrow m_{\tilde{\nu}_R} \sim O(100\ \text{GeV})$ (in gravity mediation)

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

- ν_R and $\tilde{\nu}_R$ are very weakly interacting

$\tilde{\nu}_R$ is very weakly interacting: $y_\nu \sim O(10^{-13})$



- If $\tilde{\nu}_R$ is the LSP, the MSSM-LSP becomes long-lived

  MSSM-LSP: LSP in the MSSM sector

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

- Charged (or colored) particle may be the MSSM-LSP

3. Relic Density of $\tilde{\nu}_{\mathrm{R}}$-LSP

$\tilde{\nu}_R$ in the early universe

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

Possible production processes

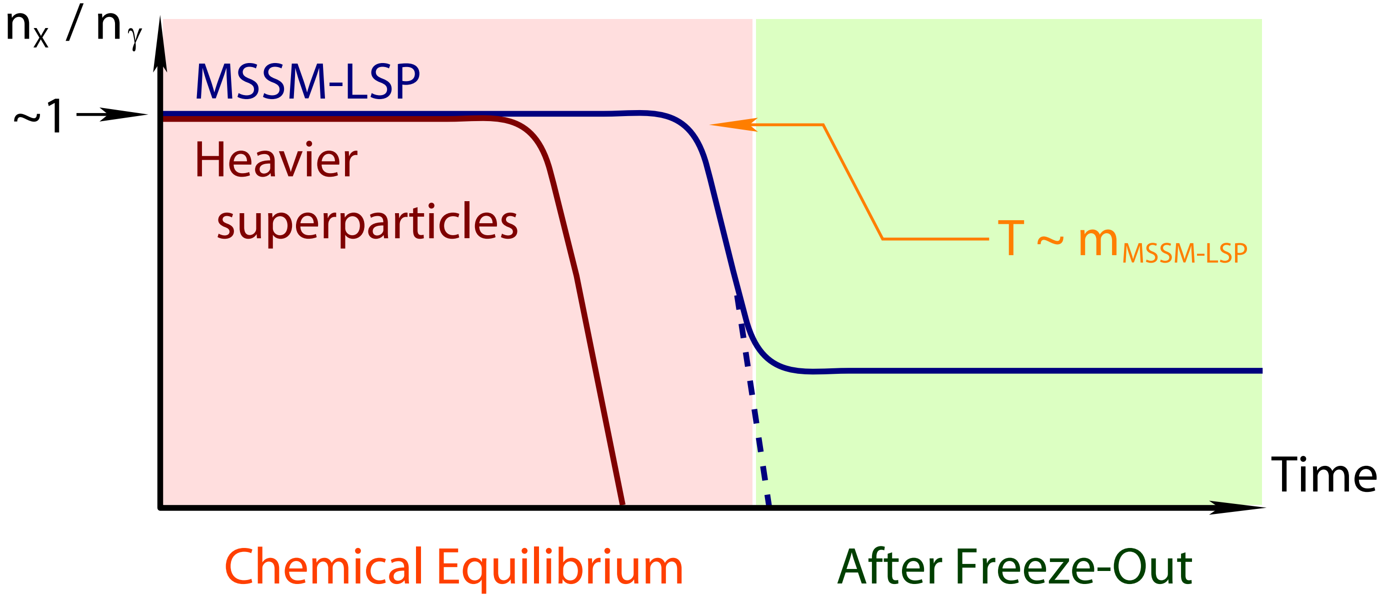
- Scattering and decay of MSSM particles in thermal bath
- Decay of the MSSM-LSP after freeze-out
- Decay of gravitino, axino, $\cdots$

I will show that $\Omega_{\tilde{\nu}_R} = \Omega_c$ is realized in wide parameter region

Production from MSSM particles: Boltzmann equation

$$\frac{dn_{\tilde{\nu}_R}}{dt} + 3Hn_{\tilde{\nu}_R} \simeq \sum_x n_x \langle \Gamma_{x\to\tilde{\nu}_R+\dots} \rangle + (\text{scattering})$$

n_x: number density of parent particles



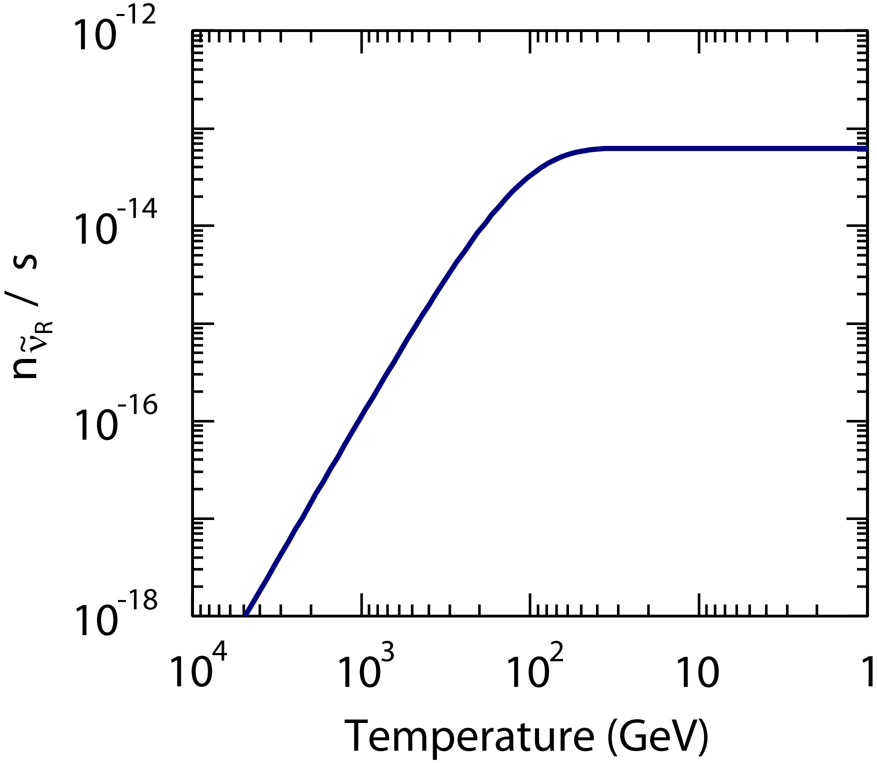
$$\Rightarrow n_{\tilde{\nu}_R} = n_{\tilde{\nu}_R}^{(\text{C.E.})} + n_{\tilde{\nu}_R}^{(\text{F.O.})}$$

$\tilde{\nu}_R$ from the decay of MSSM particles in thermal bath

$\tilde{\nu}_R$ production is dominated at lower temperature

[Asaka, Ishiwata & TM; See also Hall, Jedamzik, March-Russell & West]

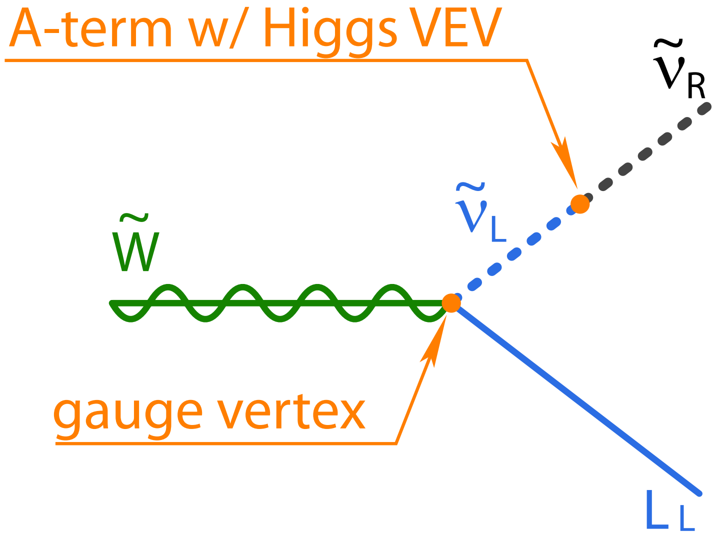
$\Leftrightarrow \langle \Gamma_{x \to \tilde{\nu}_R + \ldots} \rangle / H$ increases with time



$\Rightarrow$ Relic density is insensitive to the early thermal history

Important decay processes: $\tilde{W}^0 \rightarrow \tilde{\nu}_R \nu$ and $\tilde{W}^\pm \rightarrow \tilde{\nu}_R l^\pm$

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



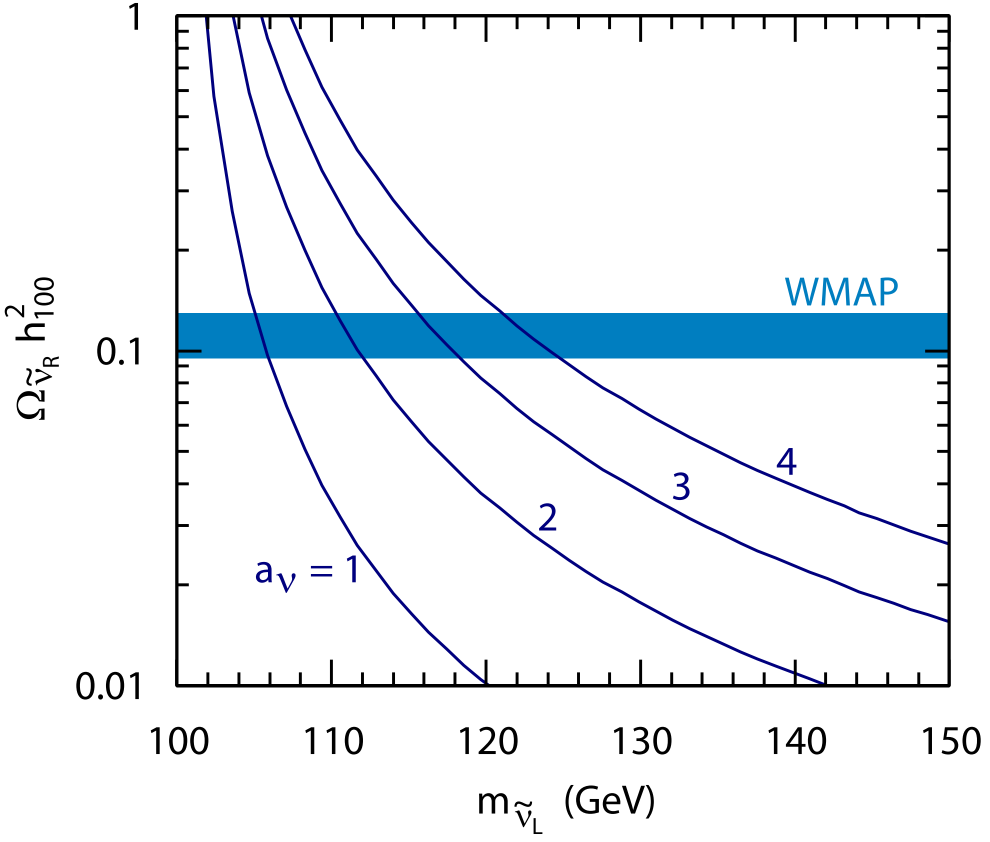
$$\Gamma_{\tilde{W}^0 \rightarrow \tilde{\nu}_R \nu} = \frac{\beta_{\rm f}^2 g_2^2}{64\pi} \left[\frac{A_\nu v_T}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \right]^2 m_{\tilde{W}}$$

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

Sneutrino production is enhanced with:

- Large A_ν-parameter
- Degenerate sneutrino masses

Relic density of $\tilde{\nu}_R$ (from MSSM particles in thermal bath)



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

$m_{\tilde{W}} = 300$ GeV

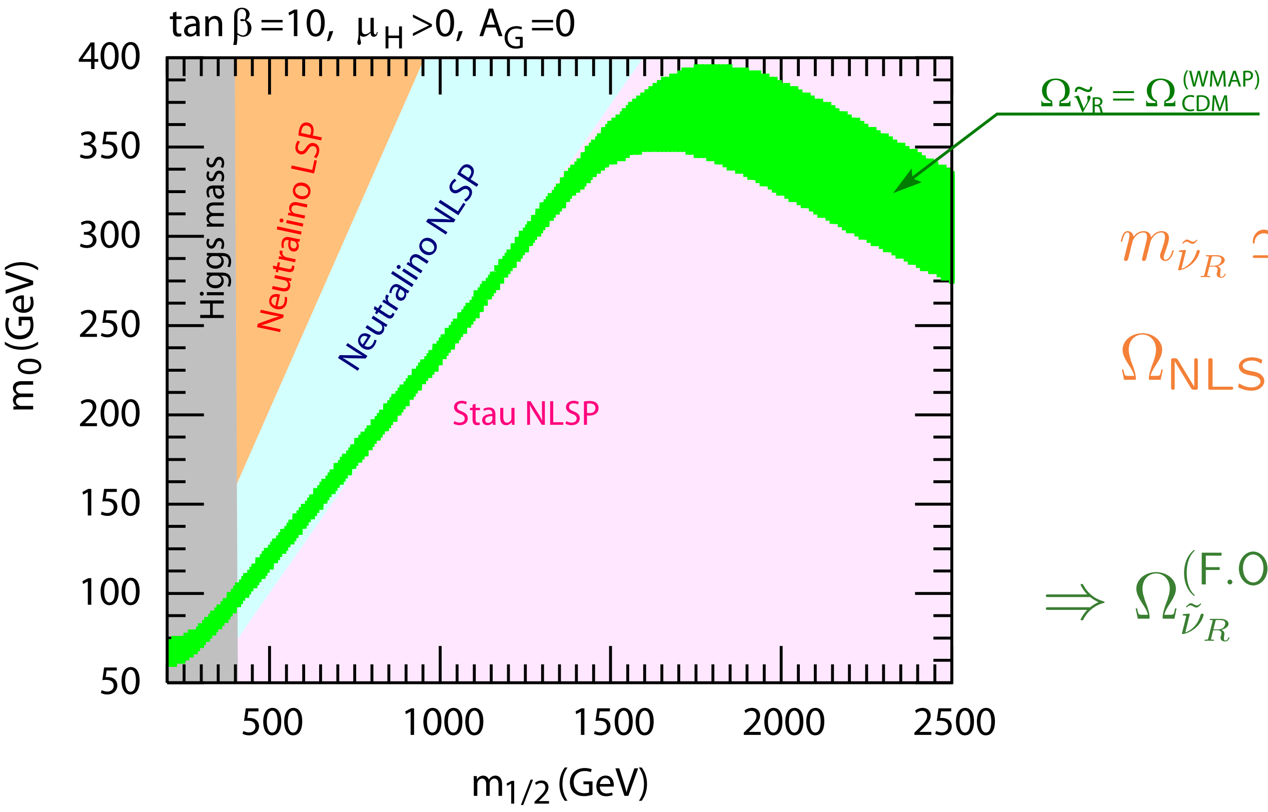
$A_\nu = a_\nu y_\nu m_{\tilde{l}_L}$

$\Rightarrow \Omega^{(\text{C.E.})}_{\tilde{\nu}_R} = \Omega_c$ is realized with a mild degeneracy

$\tilde{\nu}_R$ production after the freeze-out of MSSM-LSP

$$\Omega^{(\text{F.O.})}_{\tilde{\nu}_R} \simeq \frac{m_{\tilde{\nu}_R}}{m_{\text{MSSM-LSP}}} \Omega^{(\text{would-be})}_{\text{MSSM-LSP}}$$

CMSSM case: $m_{\tilde{\nu}_R} = m_0$ at the GUT scale



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

Ω_{NLSP} : w/ micrOMEGA

$\Rightarrow \Omega^{(\text{F.O.})}_{\tilde{\nu}_R} = \Omega_c$ can be realized

4. BBN Constraints

The MSSM-LSP decays into $\tilde{\nu}_R + X$ with very long lifetime

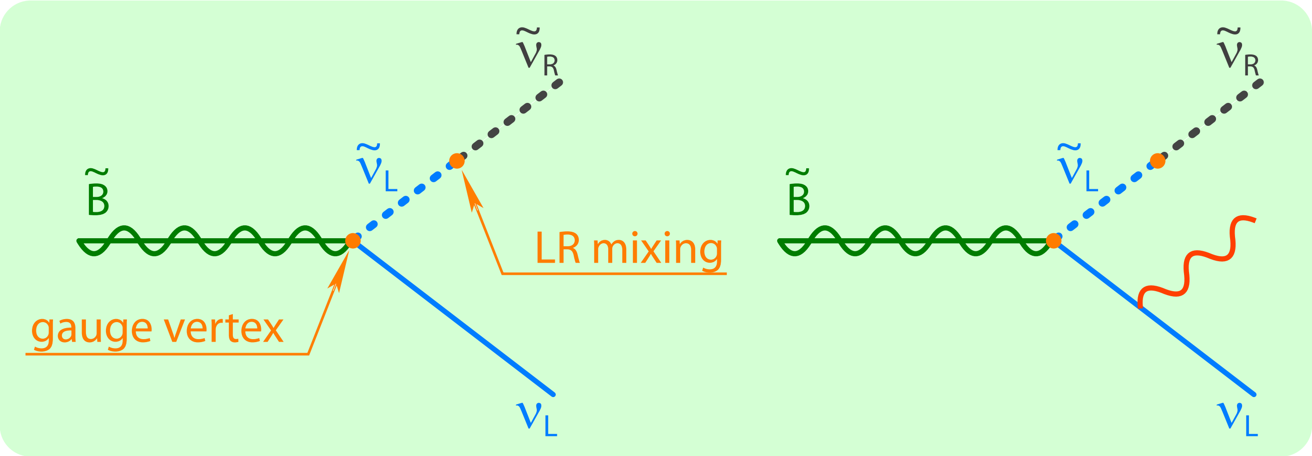
$\Rightarrow$ Decay products dissociate light elements produced by the BBN reactions, if $\tilde{\nu}_R$ decays after BBN epoch

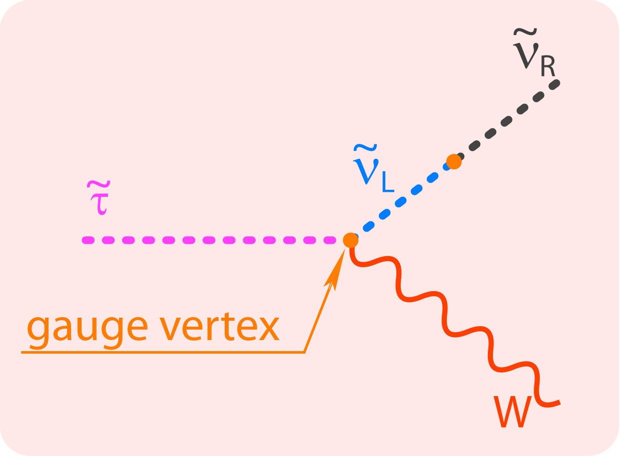
$\Rightarrow$ The light-element abundances may be significantly affected

Relevant processes:

- Hadrodissociation of ${}^4\mathrm{He}$
  $\Rightarrow$ ${}^4\mathrm{He} + p \rightarrow \mathrm{D} + X$ results in the overproduction of D
- Photodissociation
- $p \leftrightarrow n$ conversion
- $\tilde{\tau}^-$ catalyzed process (if $\tilde{\tau}$ is the MSSM-LSP)

BBN constraints depend on what the MSSM-LSP is





- Lifetime: $\tilde{B}$-NLSP case:

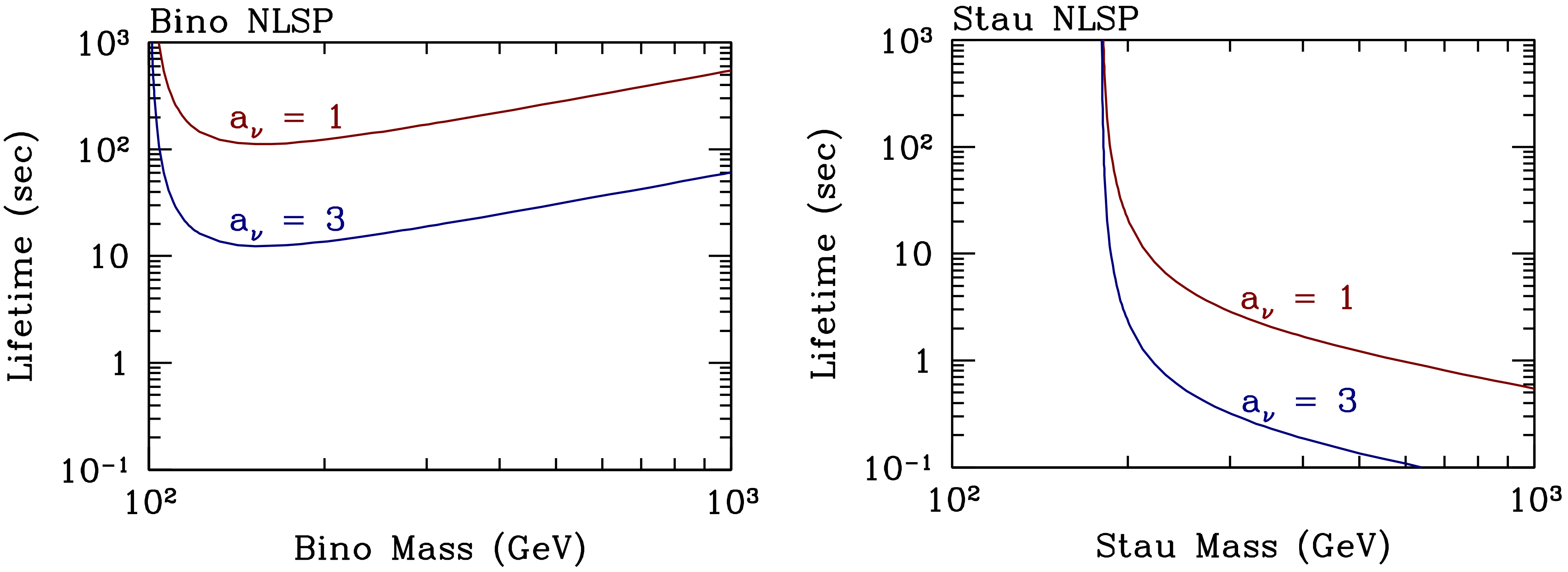
$$\Gamma_{\tilde{B}\to\tilde{\nu}_R\bar{\nu}} = \frac{\beta_{\rm f}^2 g_1^2}{64\pi}\left[\frac{A_\nu v}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2}\right]^2 m_{\tilde{B}}, \qquad B_{\rm had} \ll 1$$

- Lifetime: $\tilde{\tau}$-NLSP case (with $m_{\tilde{\tau}} > m_{\tilde{\nu}_R} + m_W$):

$$\Gamma_{\tilde{\tau}\to\tilde{\nu}_R W^-} = \frac{\beta_{\rm f}^3 \sin^2\theta_{\tilde{\tau}}}{16\pi}\left[\frac{m_{\tilde{\tau}}^2}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2}\right]^2 \frac{A_\nu^2}{m_{\tilde{\tau}}}, \qquad B_{\rm had} \sim 1$$

Lifetime of $\tilde{B}$ / $\tilde{\tau}$

$\Leftrightarrow$ BBN epoch: $\sim 1 - 1000$ sec

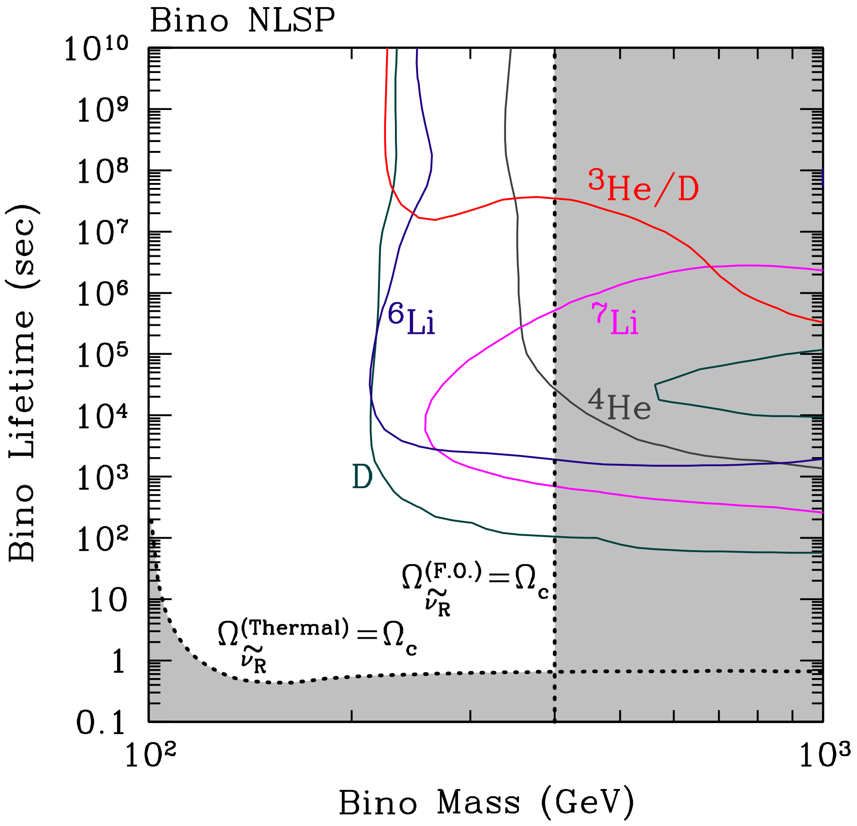


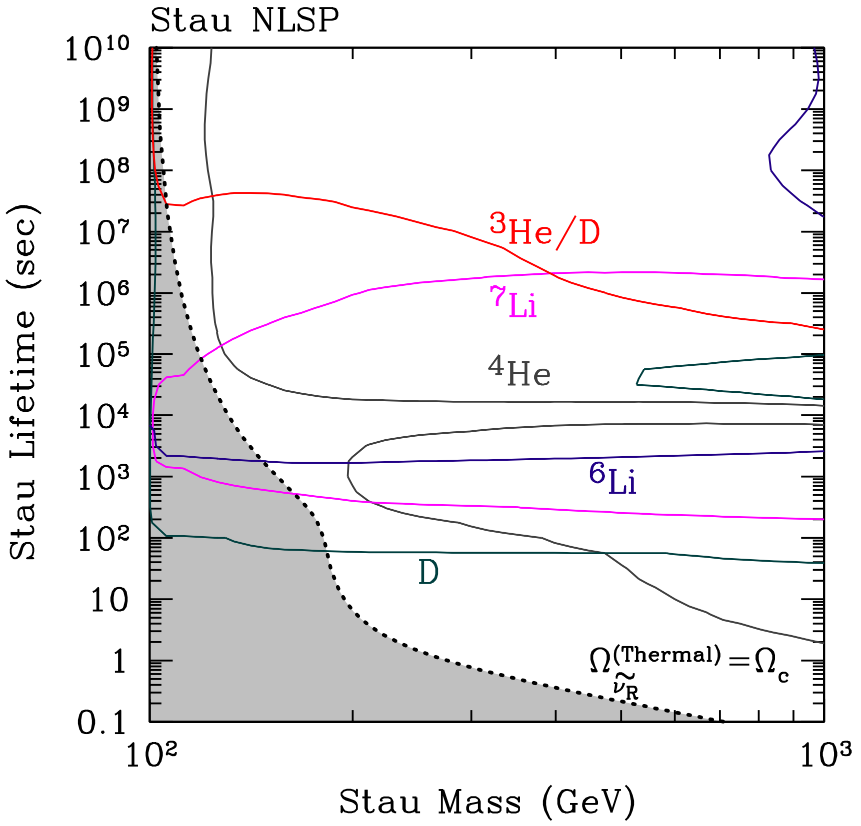
$m_{\tilde{\nu}_L} = 1.2 m_{\text{MSSM-LSP}}$

$\sin\theta_\tau = 0.3$ (for the $\tilde{\tau}$-NLSP case)

BBN constraints with $\tilde{\nu}_R$-LSP (with $m_{\tilde{\nu}_R} = 100$ GeV, $\cdots$)

"Typical" relic abundance of the MSSM-LSP is used





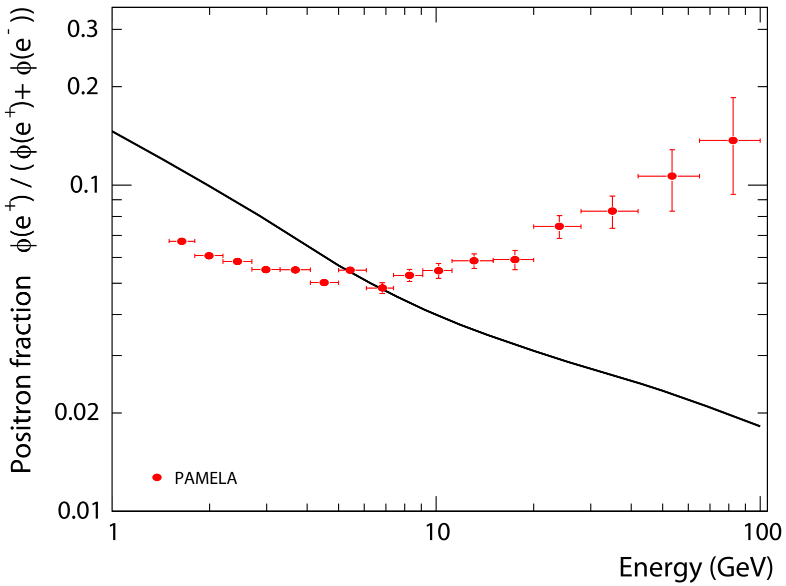
$\Rightarrow$ BBN constraints can be avoided (with $\Omega_{\tilde{\nu}_R} = \Omega_c$)

Notice: $\Gamma_{\tilde{\nu}}$ and $\Omega_{\tilde{\nu}_R}$ are both proportional to A_ν^2

5. Implication to PAMELA Anomaly

PAMELA anomaly

⇒ Observed $e^+/(e^- + e^+)$ ratio is larger than expectation



[PAMELA collaboration]

Possible solutions:

- Decaying dark matter
- Annihilating dark matter
- Pulser

PAMELA anomaly may be due to the decay of $\tilde{\nu}_R$-DM

[Ishiwata, Matsumoto & TM; See also Chen & Takahashi]

- $\tilde{\nu}_R$ can be dark matter, because $\tau_{\tilde{\nu}_R} \sim O(10^{26}\ \text{sec})$
- $\tilde{\nu}_R$ may decay via a very weak R-parity violation (RPV)

For $\tilde{\nu}_R$-LSP case, let me introduce:

$$W_{\text{RPV}} = \lambda_{ijk} L_i L_j E_k^c$$

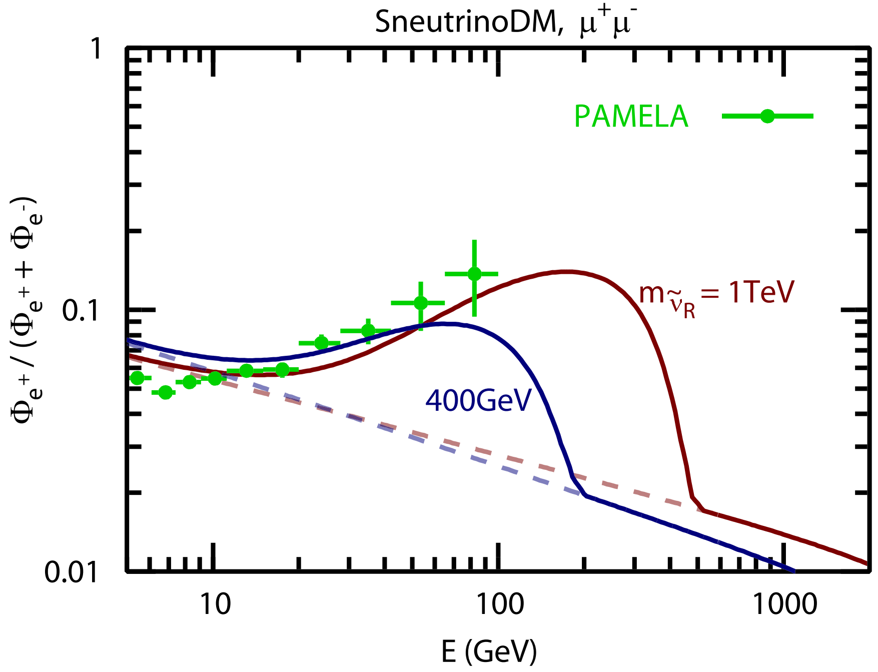
Then, $\tilde{\nu}_R$ decays (using LR mixing):

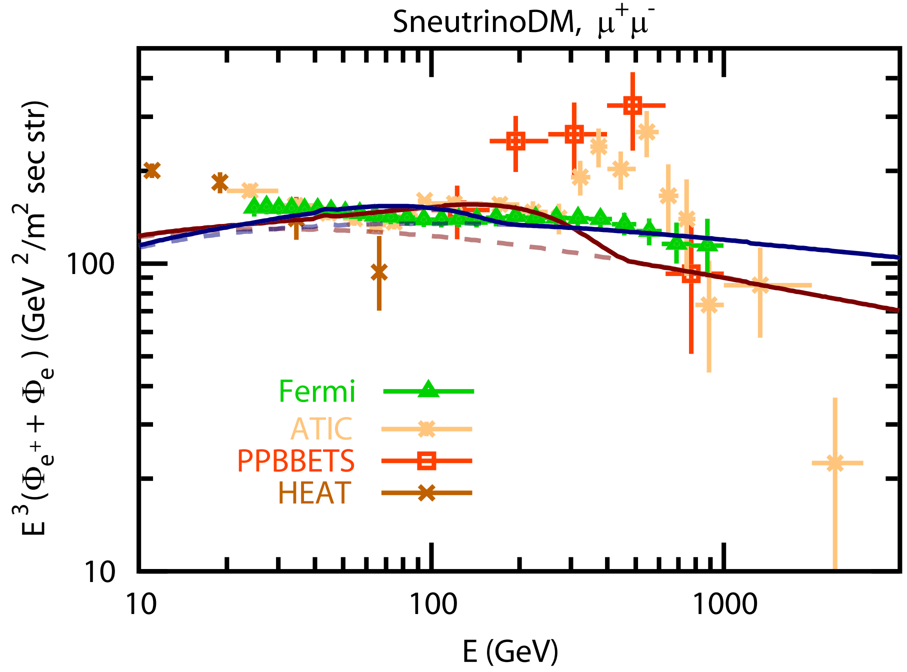
- $\tilde{\nu}_R \to l^+ l^-$

  ⇒ Enhancement of positron fraction
- Hadronic branching ratio is negligible

  ⇒ Anti-proton constraint can be avoided

Cosmic-ray fluxes with decaying $\tilde{\nu}_R$-DM: $\tau_{\tilde{\nu}_R} \sim O(10^{26}$ sec)



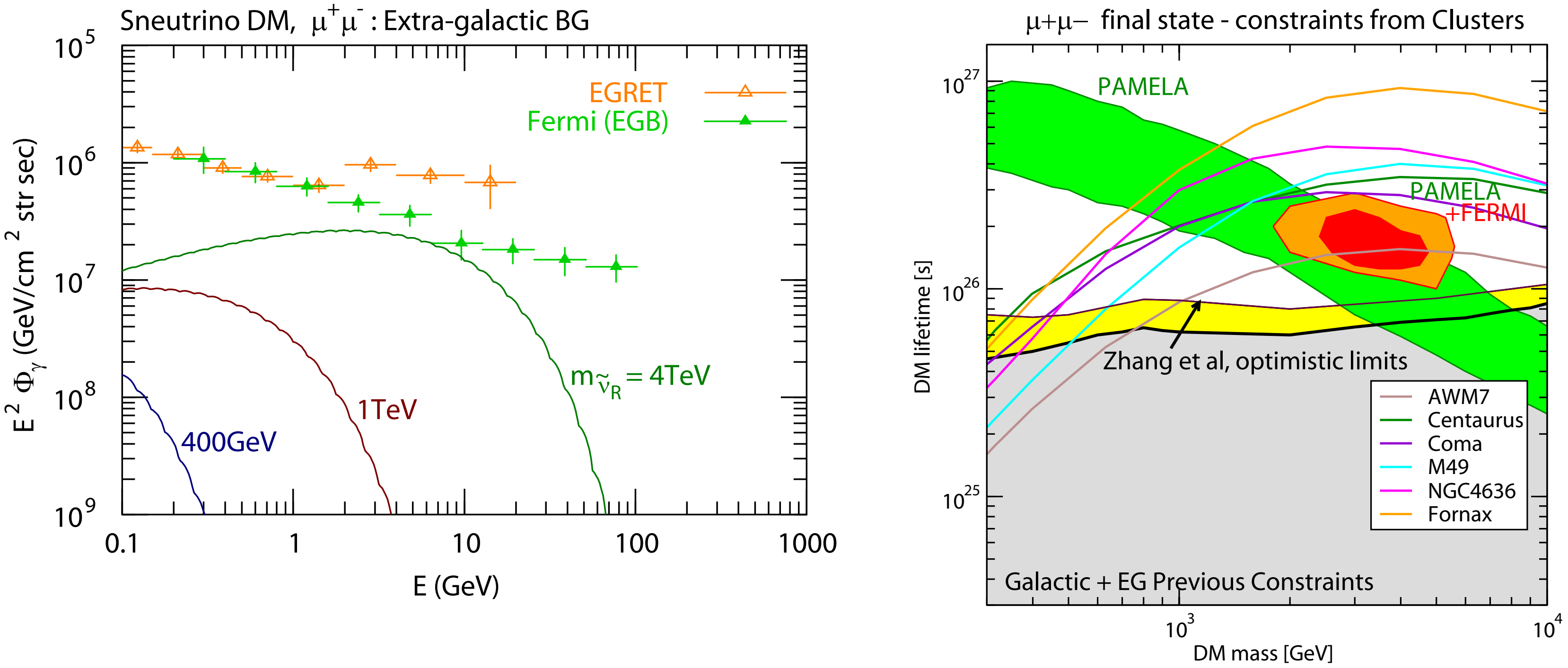


$m_{\tilde{\nu}_R} = 400$ GeV and 1 TeV

BG-parameters and lifetime: best-fit values

$\Rightarrow e^{\pm}$ fluxes can be consistent with the PAMELA and FERMI results if 300 GeV $\lesssim m_{\tilde{\nu}_R} \lesssim 1$ TeV

Important check point: γ-ray spectrum



[Left: Ishiwata, Matsumoto & TM; Right: Dugger, Jeltema & Profumo]

$\Rightarrow$ γ-ray flux is small enough, if $m_{\tilde{\nu}_R} \lesssim 1$ TeV

6. Summary

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

$\Rightarrow$ Implications to cosmology (dark matter, BBN, $\cdots$)

$\Rightarrow$ $\tilde{\nu}_R$ is a viable candidate of dark matter

Rich phenomenology with $\tilde{\nu}_R$-LSP:

- Baryogenesis (Affleck-Dine mechanism?)
- $\tilde{\nu}_R$ at colliders: MSSM-LSP becomes unstable

  $\Rightarrow$ Decay in the detector

  [Ishiwata, Ito & TM]

  $\Rightarrow$ Charged-slepton trapping (if $\tilde{\tau}$ is the MSSM-LSP)

  [Buchmuller et al.; Feng & Smith; Asai, Hamaguchi & Shirai]
- $\cdots$

Back Up

^{7}Li problem:

SBBN value of $^7\mathrm{Li}$ abundance may have an inconsistency with observation

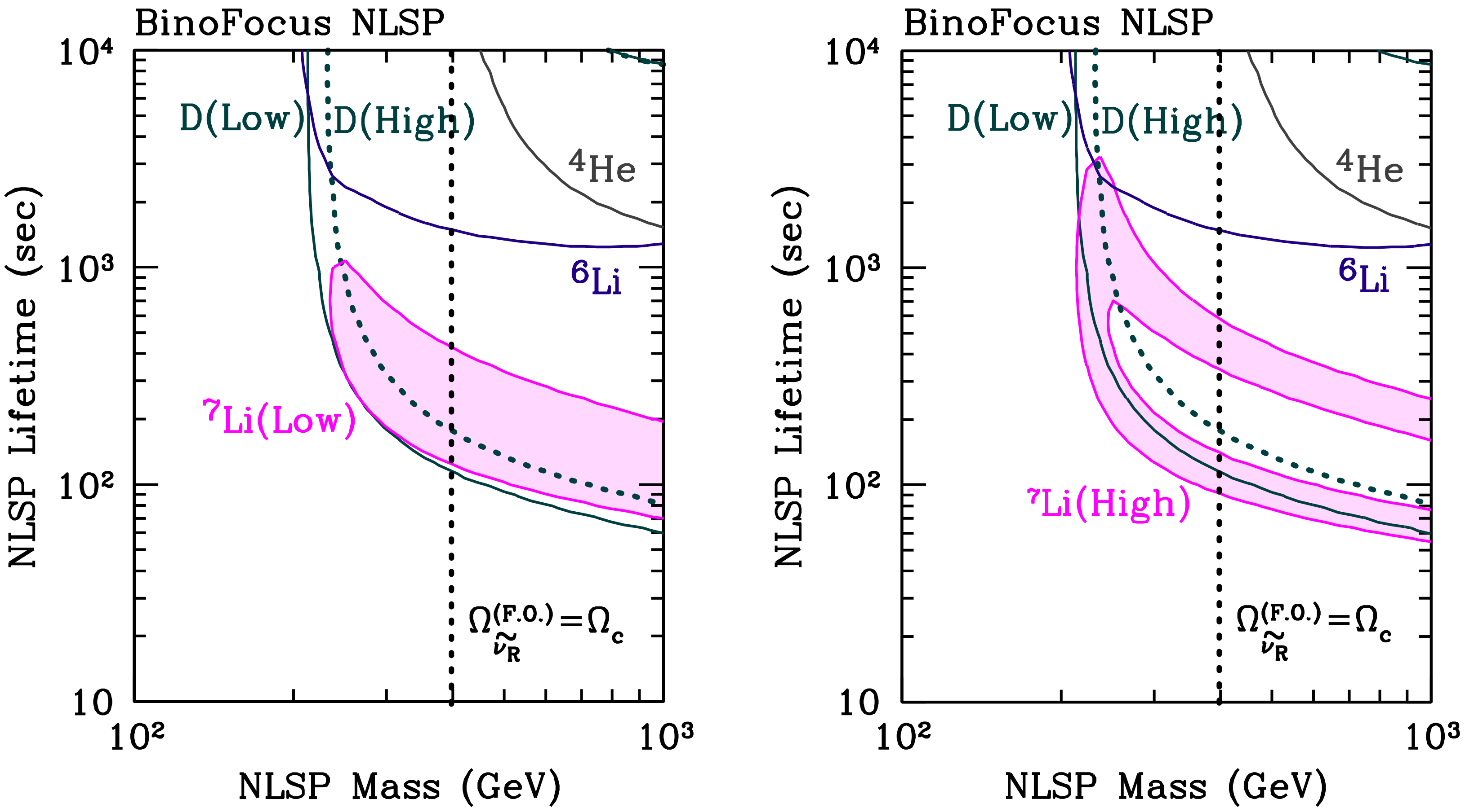
Observational constraints on $^7\mathrm{Li}$ abundance

- Low $^7\mathrm{Li}$: $\log_{10}(n_{^7\mathrm{Li}}/n_\mathrm{H})_\mathrm{p} = -9.90 \pm 0.09\ (+0.35)$
  [Bonifacio et al.]
- High $^7\mathrm{Li}$: $\log_{10}(n_{^7\mathrm{Li}}/n_\mathrm{H})_\mathrm{p} = -9.63 \pm 0.06\ (+0.35)$
  [Melendez et al.]

$+0.35$: systematic error

- This error may be due to depletion in stars or diffusion
- Without this error, the SBBN is inconsistent with observation at 4-σ level (with the low value)

With no systematic error in ^{7}Li abundance



[Kawasaki, Kohri, Ishiwata & TM]

⇒ Allowed region shows up without systematic error