SuperWIMP Dark Matter

Takeo Moroi (Tokyo)

1. Introduction

Popular candidate of dark matter: thermal relic of a WIMP

$\Rightarrow$ Important alternative: SuperWIMP dark matter

[Feng, Rajaraman & Takayama]

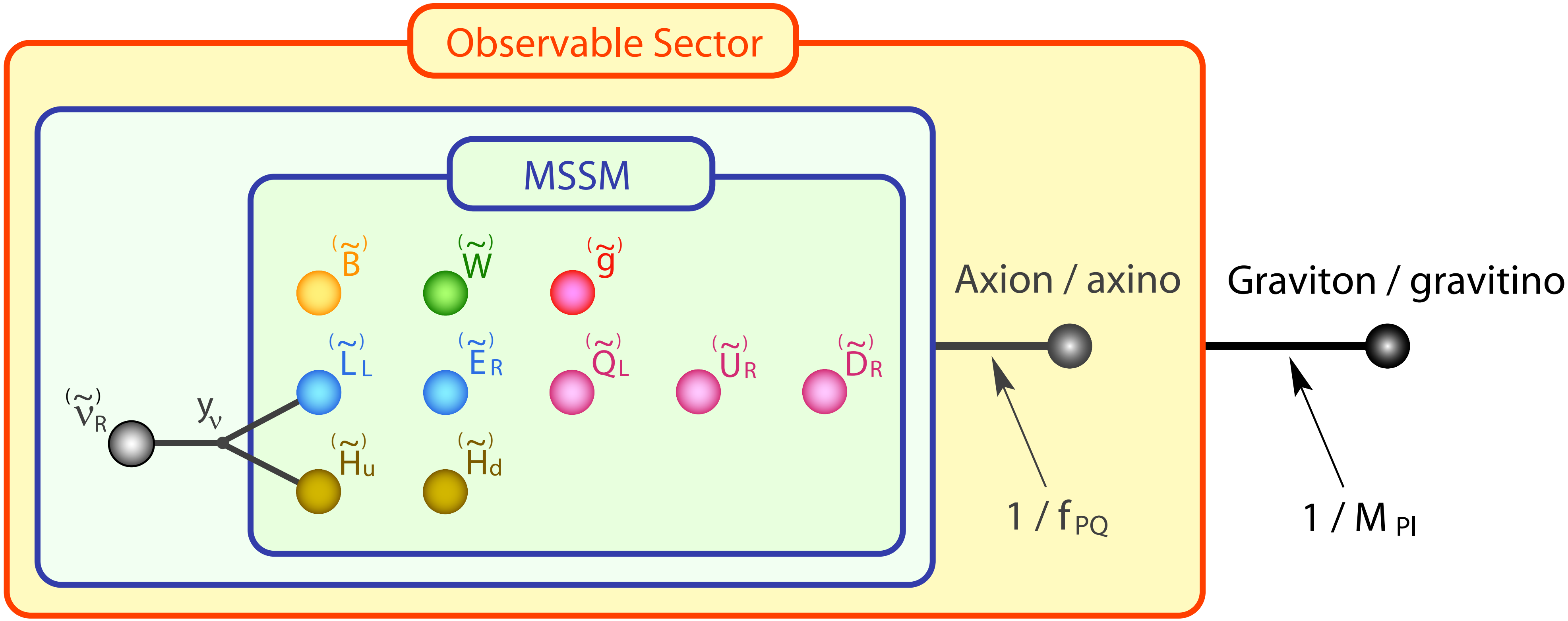
SuperWIMP: super-weakly interacting massive particle

There are many candidates of SuperWIMP

- Gravitino, axino, $\cdots$ (SUSY)
- KK-graviton (UED)
- $\cdots$

Today, I focus on candidates in SUSY model

⇒ Otherwise, too many possibilities...



⇒ One of the SuperWIMPs may be the LSP

Today's subject: SuperWIMP dark matter (in SUSY model)

- Production processes of SuperWIMP dark matter
- Phenomenology

Outline

1. Introduction
2. Candidates
3. Production Mechanisms
4. Big-Bang Nucleosynthesis (BBN) Constraints
5. High Energy Cosmic Ray
6. Summary

2. Candidates

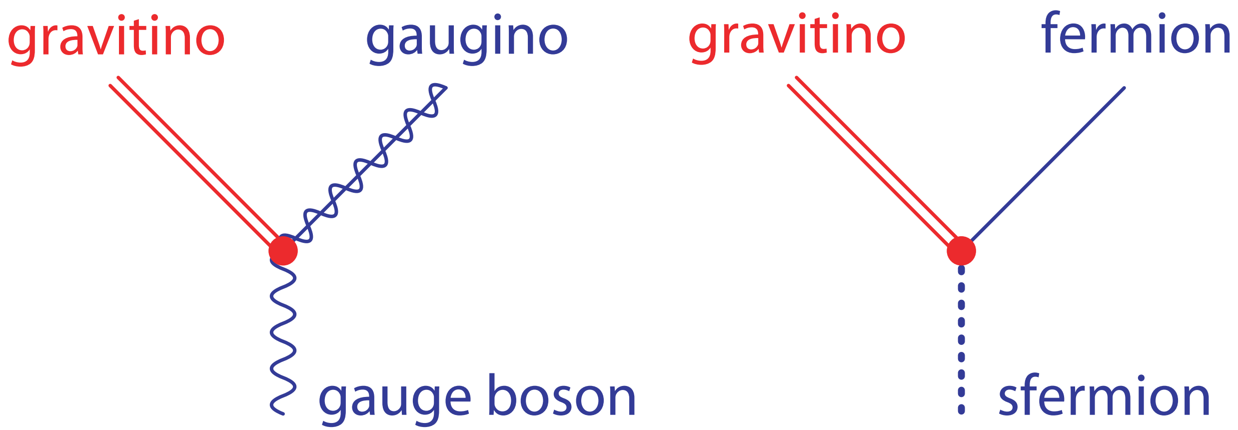
Gravitino ψ_μ: Superpartner of graviton (with spin 3/2)

[TM, Murayama & Yamaguchi; Feng, Su & Takayama]

$$\mathcal{L}_{\psi J} = -\frac{i}{2M_{\rm Pl}}\psi_\mu^\alpha J_\alpha^\mu + \text{h.c.} \simeq \frac{m_{\tilde g}}{4\sqrt{6}m_{3/2}M_{\rm Pl}}\bar\psi\sigma_{\mu\nu}\tilde g^a G^{a\mu\nu} + \cdots$$

J_μ: Supercurrent

$M_{\rm Pl} \simeq 2.4 \times 10^{18}$ GeV: Reduced Planck scale



Axino $\tilde{a}$: Superpartner of axion

[Goto & Yamaguchi; Bonometto, Gabbiani & Masiero; Chun & Kim; Covi, Kim & Roszkowski]

$$\mathcal{L}_{\text{int}} \simeq \frac{g_3^2}{32\pi^2 f_{\text{PQ}}} \int d^2\theta \mathcal{A} \mathcal{W}^\alpha \mathcal{W}_\alpha + \text{h.c.} + \cdots$$

$$\simeq \frac{g_3^2}{32\pi^2 f_{\text{PQ}}} \left[a G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + 2\bar{\tilde{a}} \sigma_{\mu\nu} \tilde{g}^a G^{a\mu\nu} \right] + \cdots$$

$\mathcal{A}$: Axion multiplet

f_{PQ}: Peccei-Quin scale

Axino mass depends on how the PQ symmetry is broken

$m_{\tilde{a}} \sim O(m_{3/2})$ or $m_{\tilde{a}} \ll O(m_{3/2})$

Right-handed sneutrino

[Asaka, Ishiwata, TM]

- ν_R is necessary to generate neutrino masses
- Neutrino masses may be Dirac type

  $\Rightarrow m_{\tilde{\nu}_R} \sim O(100\ \text{GeV})$ (in gravity mediation)
- $\tilde{\nu}_R$ can be dark matter if it is the LSP

Superpotential (assuming 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 constants are very small

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

3. Production Mechanisms

SuperWIMP can never be thermalized

⇒ How can it be produced in the early universe?

One possibility:

Scattering and decay of MSSM particles in thermal bath

Boltzmann equation (for SuperWIMP X)

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma_{\text{prod}} v_{\text{rel}} \rangle n_{\text{MSSM}}^2 + \langle \Gamma_{\text{prod}} \rangle n_{\text{MSSM}}$$

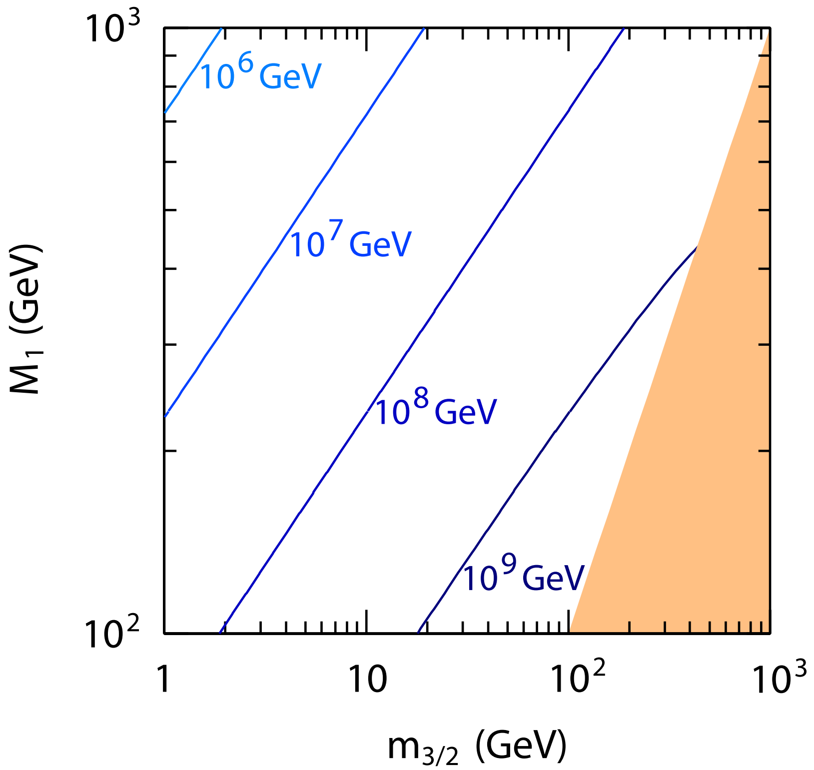
$\langle \sigma_{\text{prod}} v_{\text{rel}} \rangle$ and $\langle \Gamma_{\text{prod}} \rangle$ depend on what the SuperWIMP is

If the dominant interaction is dipole-moment type (dim. $= 5$):

$\Rightarrow$ Production rate is enhanced at higher temperature

$\Rightarrow$ SuperWIMP production occurs mostly at the reheating

Reheating temperature to realize gravitino CDM



$$T_{\mathsf{R}} \equiv \left(\frac{10}{g_* \pi^2} M_{\mathsf{Pl}}^2 \Gamma_{\mathsf{inf}}^2 \right)^{1/4}$$

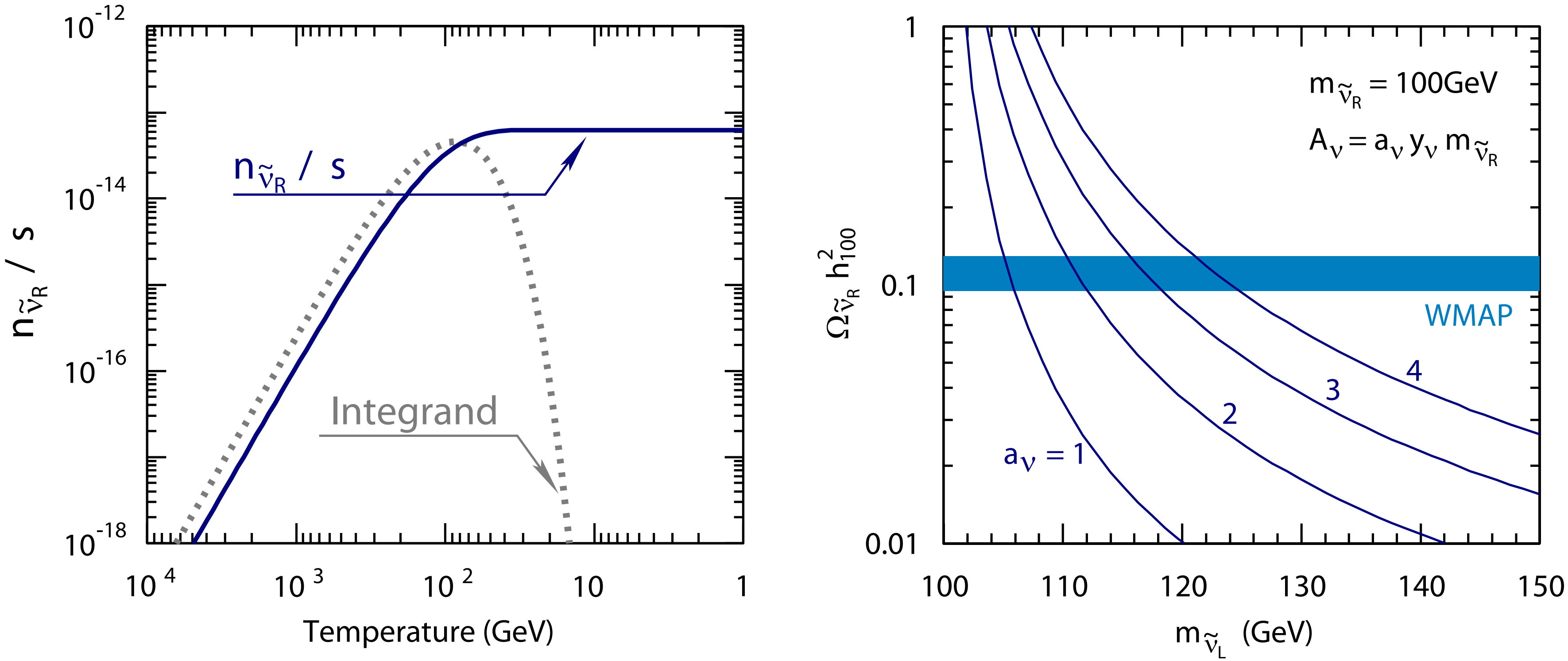
$$\Rightarrow \Omega_{3/2} \propto T_{\mathsf{R}},\ m_{3/2}^{-1}$$

[Kanzaki, Kawasaki, Kohri & Moroi]

The case of $\tilde{\nu}_R$-LSP: renormalizable interaction (dim. ≤ 4)

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

$\Rightarrow$ Enhanced L-R mixing when A_ν is large



$\tilde{\nu}_R$ production is dominated when $T \sim m_{\tilde{\nu}_R}$

$\Rightarrow$ $\Omega_{\tilde{\nu}_R}$ is insensitive to the thermal history at $T \gg m_{\tilde{\nu}_R}$

Thermal relic MSSM-LSP decays into SuperWIMP

MSSM-LSP: Lightest superparticle in the MSSM sector

- MSSM-LSP decays after its freeze-out

$$\Omega^{(\text{decay})}_{\text{SuperWIMP}} = \frac{m_{\text{SuperWIMP}}}{m_{\text{MSSM-LSP}}} \Omega^{(\text{would-be})}_{\text{MSSM-LSP}}$$

- $\Omega^{(\text{decay})}_{\text{SuperWIMP}}$ depends on MSSM parameters

Another possibility: Decay of inflaton (or moduli)

- $\Omega^{(\text{inflaton})}_{\text{SuperWIMP}}$ strongly depends on the model of inflation

$\Omega_{\text{SuperWIMP}}$ is model-dependent

$\Rightarrow \Omega_{\text{SuperWIMP}} = \Omega_{\text{CDM}}$ is realized in wide parameter space

3. BBN Constraints

Lifetime of the MSSM-LSP is usually long

$\Rightarrow$ It may decay after BBN

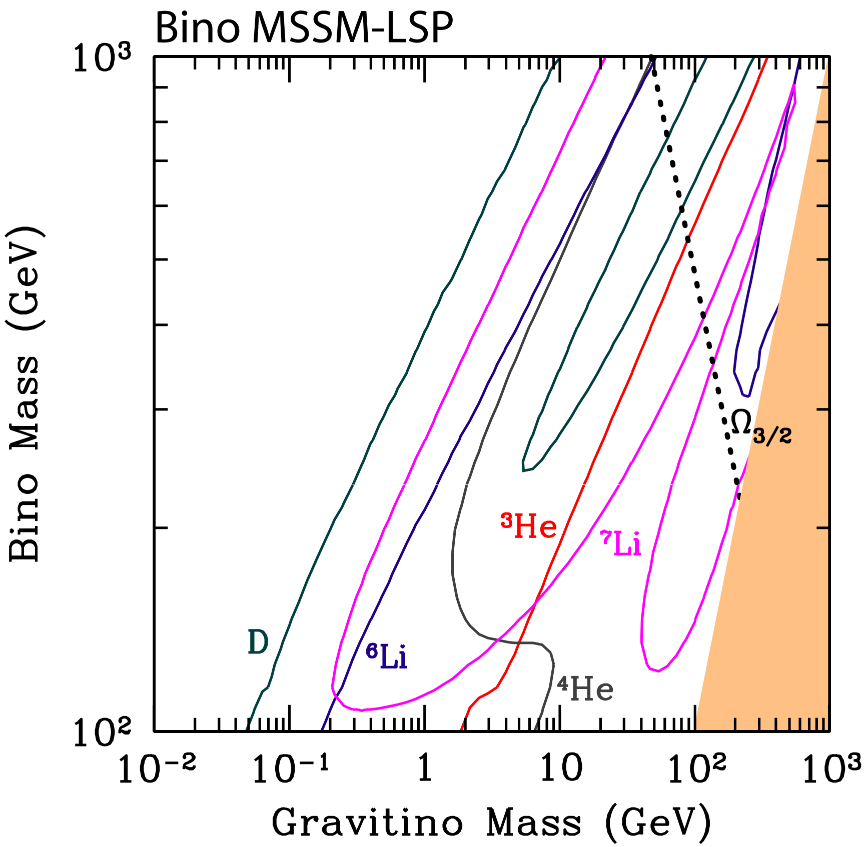
$\Rightarrow$ Abundances of light elements may be affected

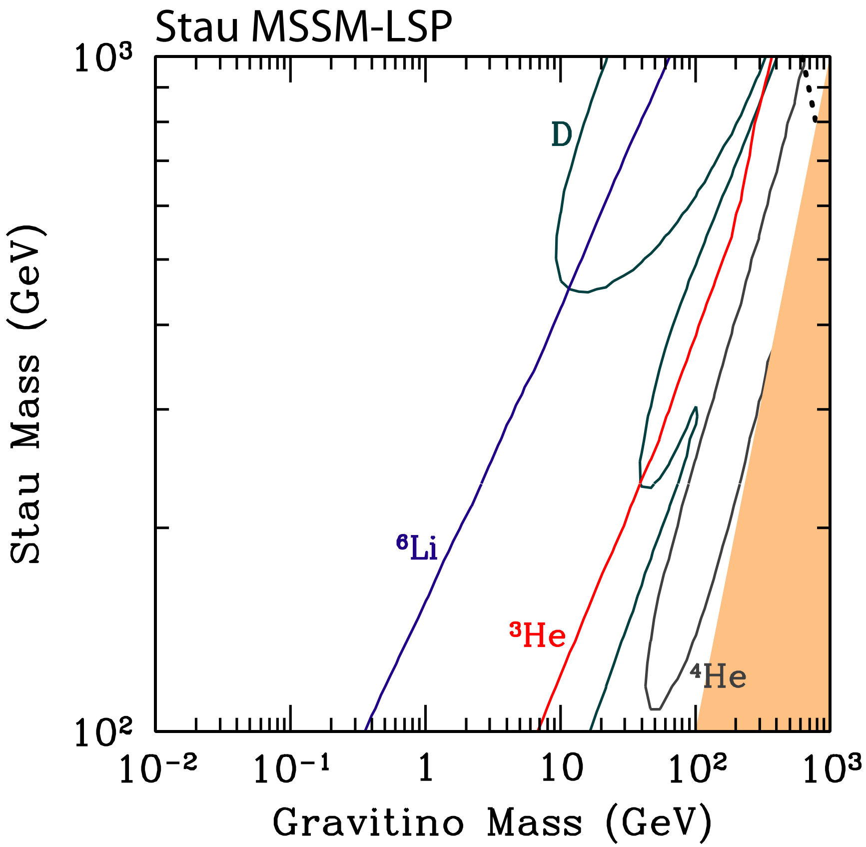
BBN constraints depend on

- Mass (parent & daughter)
- Primordial abundance
- Lifetime
- Hadronic and electromagnetic branching ratios

BBN constraints on gravitino LSP case

Thermal relic density of the MSSM-LSP is assumed





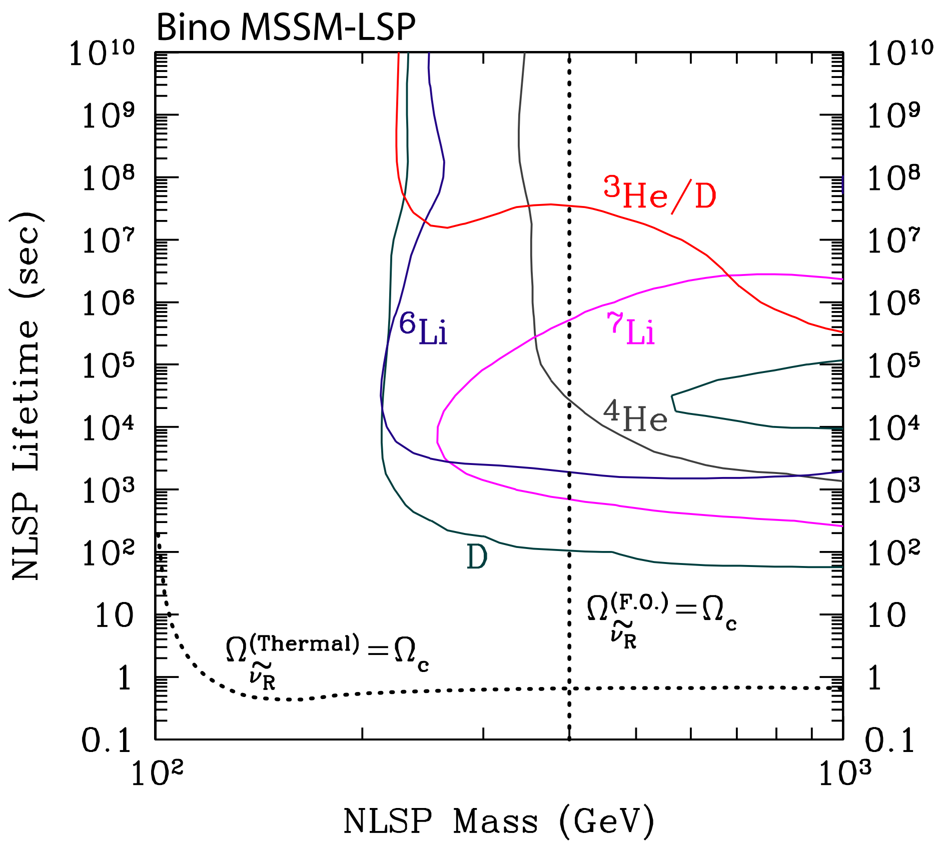
⇒ Gravitino should be lighter than $\sim 0.1 - 10$ GeV

⇒ Simple leptogenesis scenario does not work

BBN constraints on $\tilde{\nu}_R$-LSP case (MSSM-LSP = Bino)

$\Omega^{(\text{thermal})}$ and $\Gamma_{\tilde{\nu}_R}$ are both determined by the A-parameter

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



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

$m_{\tilde{\nu}_L} = 1.2 m_{\tilde{B}}$

$\tilde{B} \to \nu_L \tilde{\nu}_R (+Z)$

[Ishiwata, Kawasaki, Kohri & TM]

4. High Energy Cosmic Ray

"PAMELA anomaly" may be due to the decay of CDM

$\Leftrightarrow$ Of course, other explanations may be possible, though

Relevant lifetime for the PAMELA anomaly: $\sim 10^{26}$ sec

$\Rightarrow$ Such a long lifetime can be realized with very small RPV

Examples: SuperWIMP decay via R-parity violation (RPV)

- Gravitino $\rightarrow W^{\pm}l^{\mp}, Z\nu, \cdots$ (with $\mathcal{L}_{\rm RPV} = B_{\rm RPV}\tilde{L}H_u$)

  $\Rightarrow$ Important check point: anti-proton flux

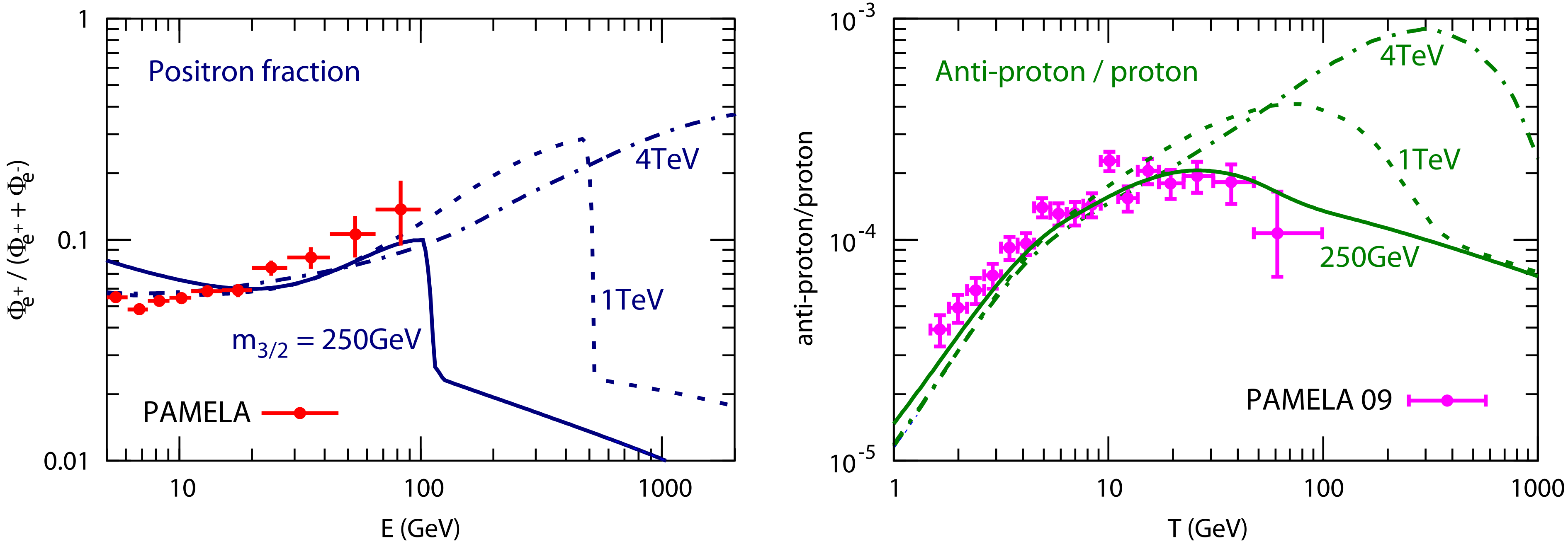
- $\tilde{\nu}_R \rightarrow l^{\pm}l^{\mp}$ (with $W_{\rm RPV} = \lambda LLE$)

- $\cdots$

Gravitino dark matter with bi-linear RPV: $\mathcal{L}_{\rm RPV} = B_{\rm RPV} \tilde{L} H_u$

$\Rightarrow$ Gravitino decays as $\psi_\mu \to W^\pm l^\mp, Z\nu, \cdots$

GALPROP results (with best-fit model parameters)



[Ishiwata, Matsumoto & TM]

$\Rightarrow$ $m_{3/2} \lesssim 200 - 300$ GeV for the gravitino-LSP case

$\Rightarrow$ No anti-proton constraint for the case with $\tilde{\nu}_R \to l^\pm l^\mp$

5. Summary

There are well-motivated candidates of SuperWIMPs

- $\Rightarrow$ They can be the LSP
- $\Rightarrow$ SuperWIMPs are viable candidates of dark matter
- $\Rightarrow$ Rich phenomenology is expected with SuperWIMP dark matter

SuperWIMP dark matter is an interesting possibility

- $\Rightarrow$ You may come up with your own model
- $\Rightarrow$ It is dangerous to impose too stringent constraints on properties of the MSSM-LSP