Non-WIMP DM Candidates in SUSY Models

Takeo Moroi (Tokyo)

Cosmic Frontier Meeting, '13.03.07 @ SLAC

1. Introduction

The lightest superparticle (LSP): candidate of dark matter

The most "popular" one: Lightest neutralino

Other candidates with extremely weak interactions

- Gravitino
- Axino
- Right-handed sneutrino (with Dirac-type neutrino masses)
- $\cdots$

Here, I review:

- How they are produced (to be DM)
- Possible signals and constraints

2. Production

Candidates of non-WIMP DM

- Gravitino (superpartner of graviton)

$$\mathcal{L} \; = \; \frac{i}{2M_{\mathsf{Pl}}}\bar{\psi}_\mu \sigma_{\nu\rho}\gamma_\mu \tilde{g}^a G^a_{\mu\nu} + \cdots$$

- Axino (if Peccei-Quinn symmetry exists)

$$\mathcal{L}_{\mathsf{int}} = \frac{g_3^2}{32\pi^2 f_a}\left[a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + 2\bar{\tilde{a}}\gamma_5 \sigma_{\mu\nu}\tilde{g}^a G^{a\mu\nu}\right] + \cdots$$

- Right-handed sneutrino (with Dirac-type neutrino masses)

$$\mathcal{L} = y_\nu \tilde{H}_u l \tilde{\nu}_R + \mathsf{h.c.}$$

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

All the above candidates interact extremely weakly

Production mechanism 1: Scattering in thermal bath

$$\frac{dn_{\mathsf{LSP}}}{dt} + 3Hn_{\mathsf{LSP}} = [\dot{n}_{\mathsf{LSP}}]_{\mathsf{scatt}} \equiv \langle \sigma v \rangle n_{\mathsf{rad}}^2$$

n_{rad}: number density of radiation

Change of N_{LSP} in a comoving frame in one Hubble time

$$\Delta \left(\frac{n_{\mathsf{LSP}}}{n_{\mathsf{rad}}} \right) \sim \frac{[\dot{n}_{\mathsf{LSP}}]_{\mathsf{scatt}}}{Hn_{\mathsf{rad}}} \sim \langle \sigma v \rangle M_{\mathsf{Pl}} T$$

Ω_{LSP} is sensitive to what the LSP is

- Gravitino and axino: $D = 5$ interaction $\Rightarrow \langle \sigma v \rangle \sim (\mathsf{const})$

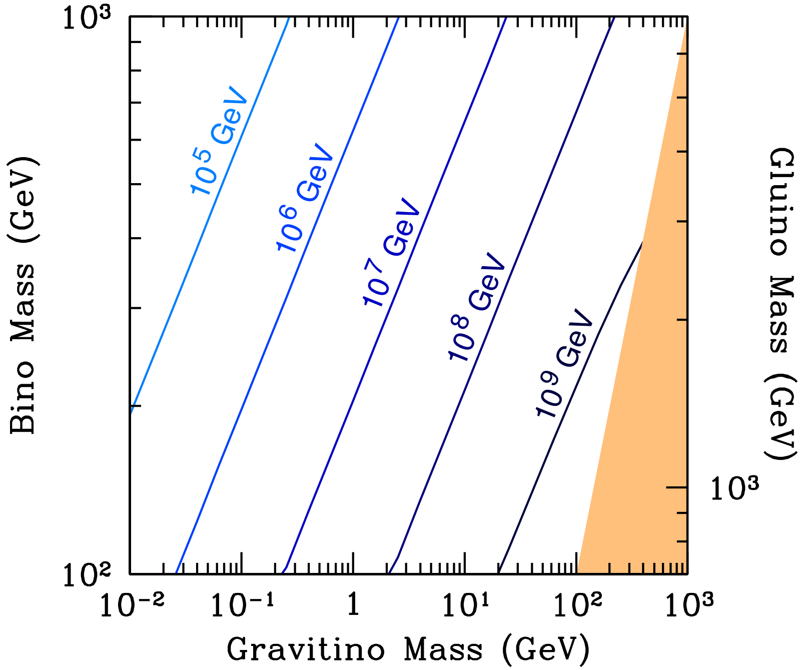
  $\Rightarrow \Omega_{\mathsf{LSP}}$ is proportional to T_{R}

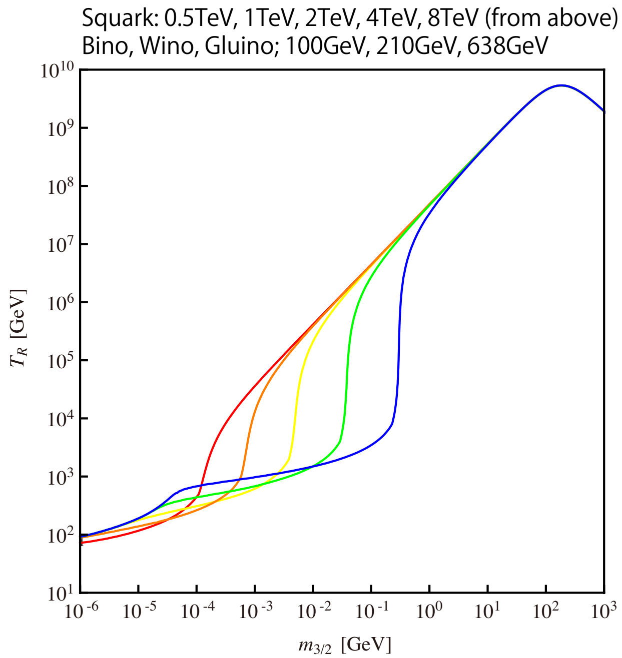
- $\tilde{\nu_R}$: $D = 4$ interaction $\Rightarrow \langle \sigma v \rangle \sim E^{-2}$

  $\Rightarrow \Omega_{\mathsf{LSP}}$ is insensitive to T_{R}

Reheating temperature to realize $\Omega_{\text{Gravitino}} = \Omega_c$

- $\Omega_{\text{Gravitino}} \propto T_{\text{R}}, m_{3/2}$
- Decay contribution dominates when $m_{3/2}$ is small

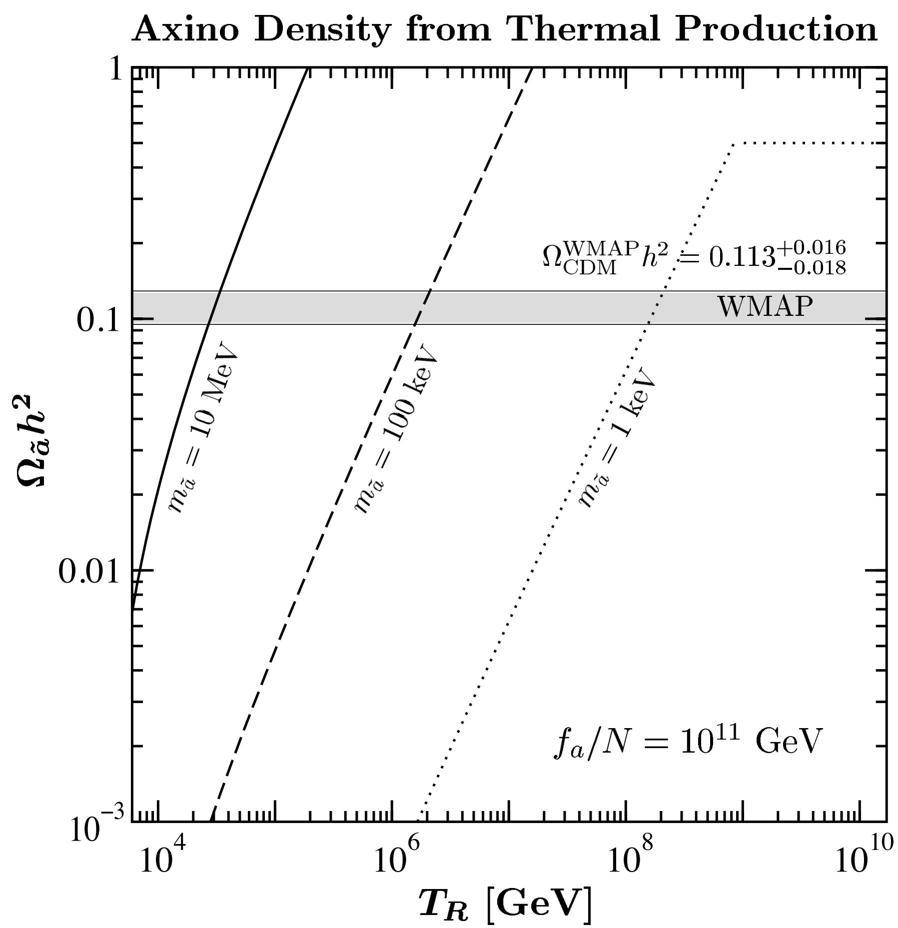




[Left: Kawasaki, Kohri, TM & Yotsuyanagi; Right: Cheung, Elor & Hall]

$\Rightarrow$ Upper bound on the reheating temperature is obtained

Density parameter of axino (for $f_a = 10^{11}$ GeV)

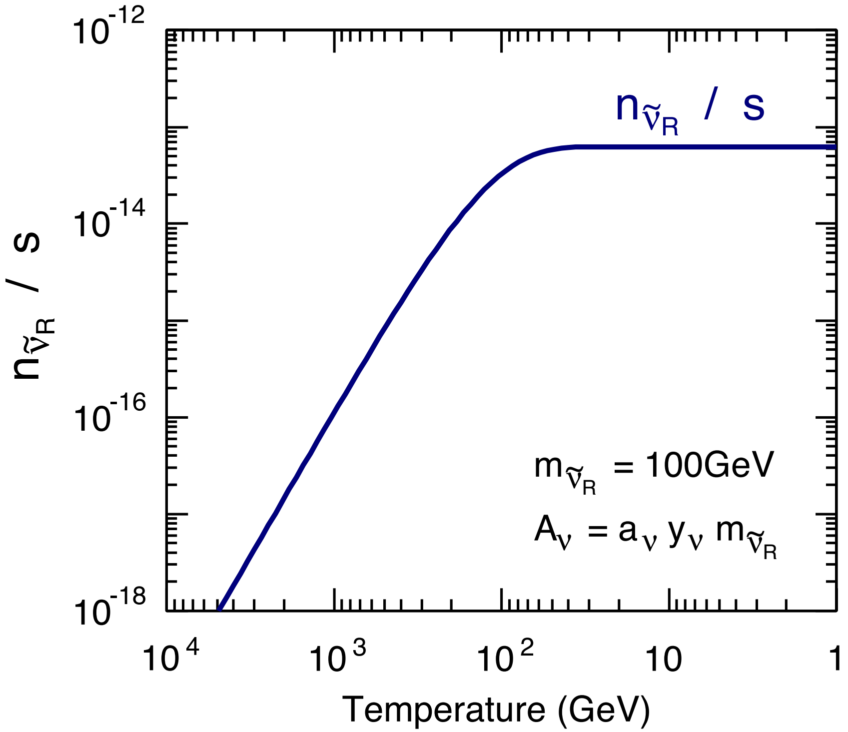


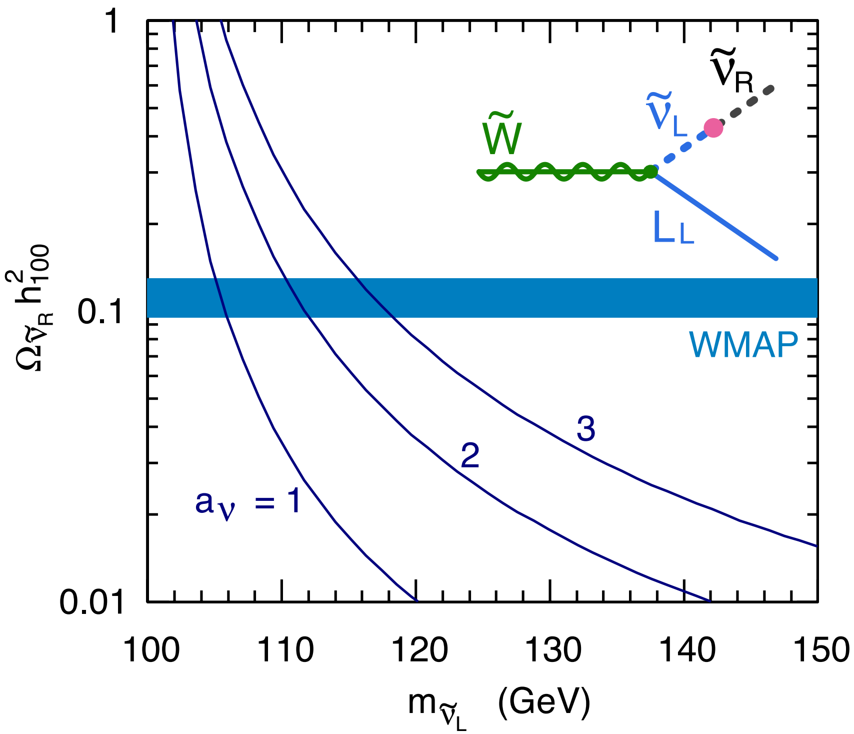
[Brandenburg & Steffen]

$\Rightarrow$ Relatively low reheating temperature is needed

$\tilde{\nu}$ production is dominated at $T \sim m_{\tilde{\nu}_R}$ (freeze-in)

[Asaka, Ishiwata & TM ('06); Hall, Jedamzik, March-Russell & West ('09)]





- $\Omega_{\tilde{\nu}_R}$ is insensitive to the thermal history at $T \gg T_{\rm F}$
- $\Omega_{\tilde{\nu}_R} \ll \Omega_c$, if the A-parameter is small

Production mechanism 2: Decay of the MSSM particles

- If $X \to \text{DM} + \cdots$ happens after the freeze-out of X:

$$\Omega_{\text{LSP}}^{(\text{decay})} = \frac{m_{\text{LSP}}}{m_X} \Omega_X^{(\text{would-be})}$$

- The MSSM-LSP often decays after its freeze-out
  - $\tilde{\nu}_L \to \text{gravitino} + \nu_L$
  - $\tilde{B} \to \tilde{\nu}_R + \nu_L$ (via left-right mixing)
  - $\cdots$

Late-time decay of the MSSM-LSP may also affect:

- Big-bang nucleosynthesis (BBN)
- Free-streaming length of DM (DM may become “warm”)

3. Signals (BBN, Cosmic Ray, Free-Streaming)

If $\tau_{\text{MSSM-LSP}} \gtrsim 1$ sec, BBN is affected

- In particular, hadro-dissociation of light elements are important, if hadrons are emitted by the decay

However, it may help improving the ^{7}Li problem:

[Feng, Rajaraman & Takayama ('03); Jedamzik ('04)]

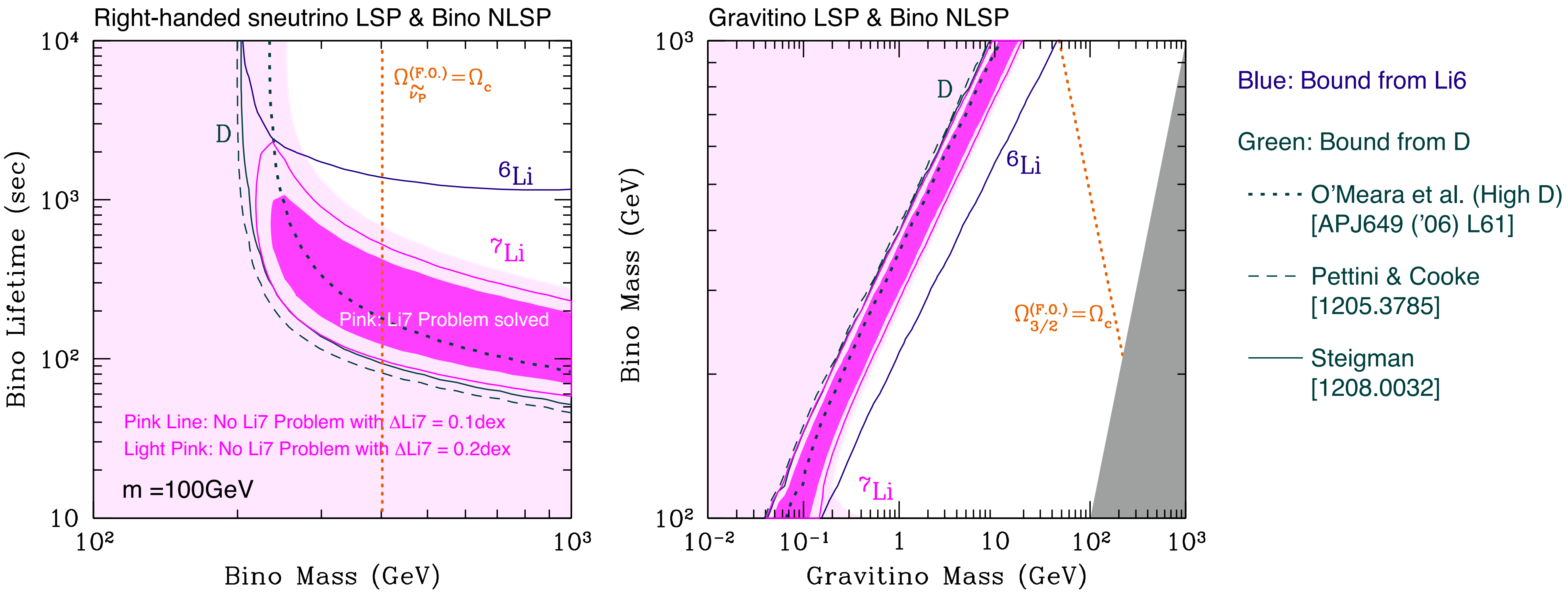
- $[^7\text{Li/H}]^{(\text{th})}_{\text{BBN}} = (5.24^{+0.71}_{-0.62}) \times 10^{-10}$ (standard BBN prediction)
- $[^7\text{Li/H}]^{(\text{obs})}_{\text{stars}} = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$ (from metal-poor halo stars)

  [Cyburt, Fields, Olive ('08)]

  $\Rightarrow 4.3 - 5.3\sigma$ discrepancy

  $\Rightarrow$ The ^{7}Li problem may not exist if a significant depletion occurs in stars

Case with Bino NLSP (decaying into $\tilde{\nu}_R$ / gravitino)



- The "primordial" abundances should be understood better using observed values
- No ^{7}Li problem, if ~ 40 % of ^{7}Li was depleted in stars

High energy cosmic ray

⇒ If R-parity is very weakly broken, the LSP decays with very long lifetime

⇒ High energy cosmic rays (e^+, $\bar{p}$, etc.) are produced

My personal interest: The "PAMELA excess" of e^+ flux

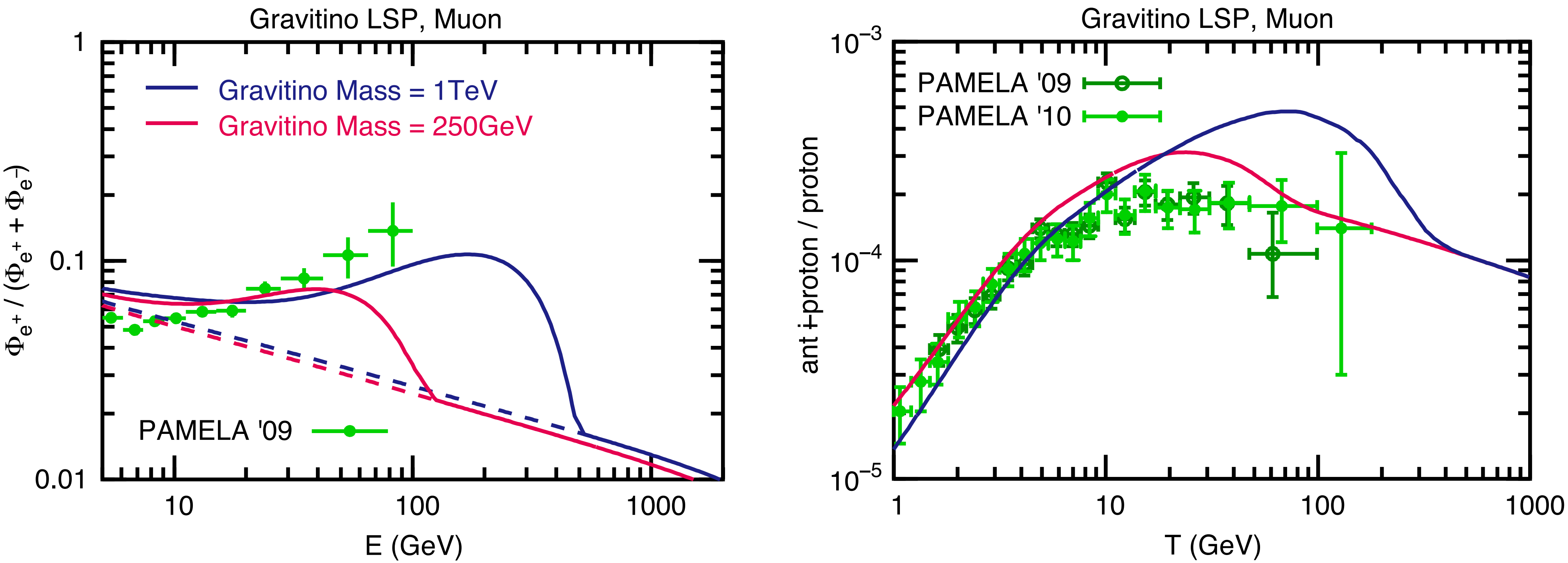
⇒ The "PAMELA excess" may be explained if $\tau_{\rm DM} \sim 10^{26-27}$ sec (although pulsars may be the reason)

⇒ Check point 1: $\bar{p}$ flux

⇒ Check point 2: $e^+ + e^-$ total flux

Gravitino DM with $\mathcal{L}_{\text{RPV}} = B_{\text{RPV}} \tilde{L}_2 H_d + \text{h.c.}$

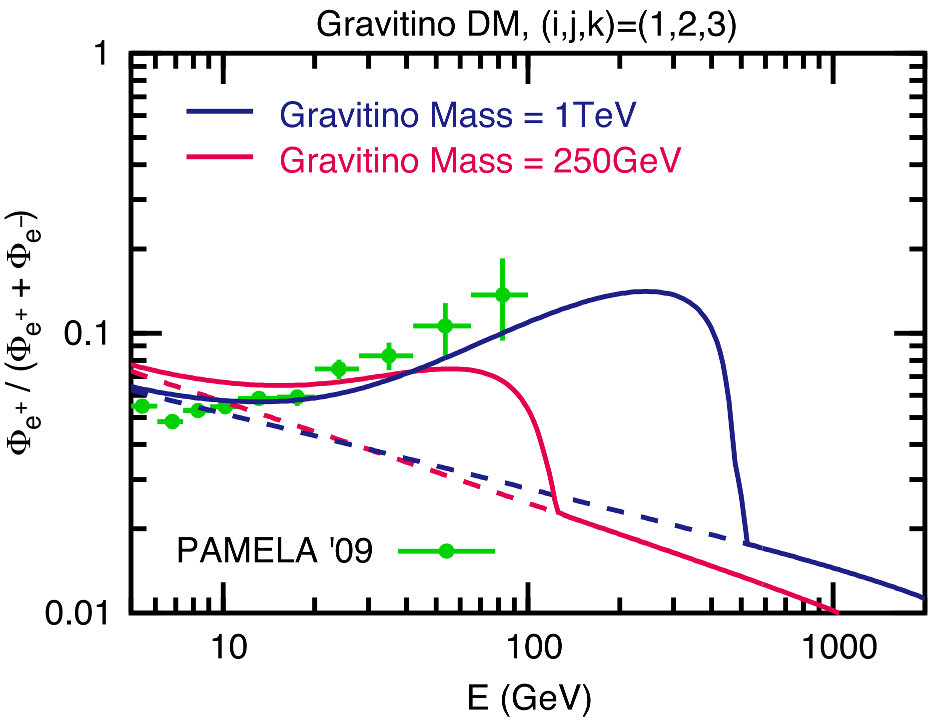
- $\psi_\mu \to \gamma\nu_\mu$, $Z\nu_\mu$, $W\mu$, and $h\nu_\mu$
- $\bar{p}$ production occurs

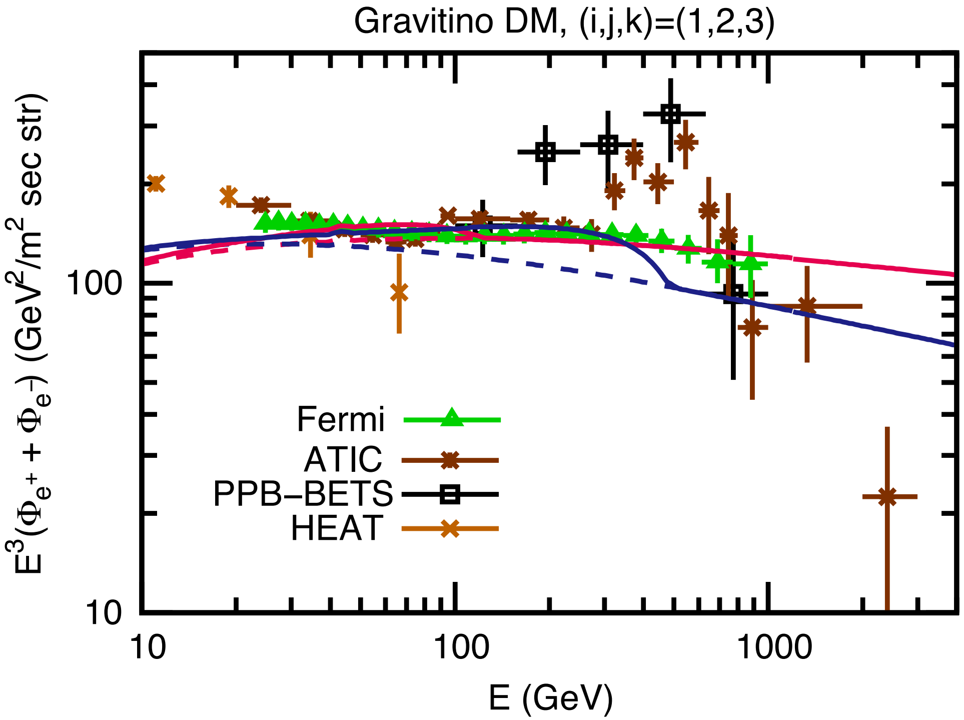


[Ishiwata, Matsumoto & TM ('10)]

Gravitino DM with $W_{\text{RPV}} \propto L_1 L_2 E_3^c$

- $\psi_\mu \to \nu\mu\bar{\tau},\ \cdots$
- $\bar{p}$ production is irrelevant

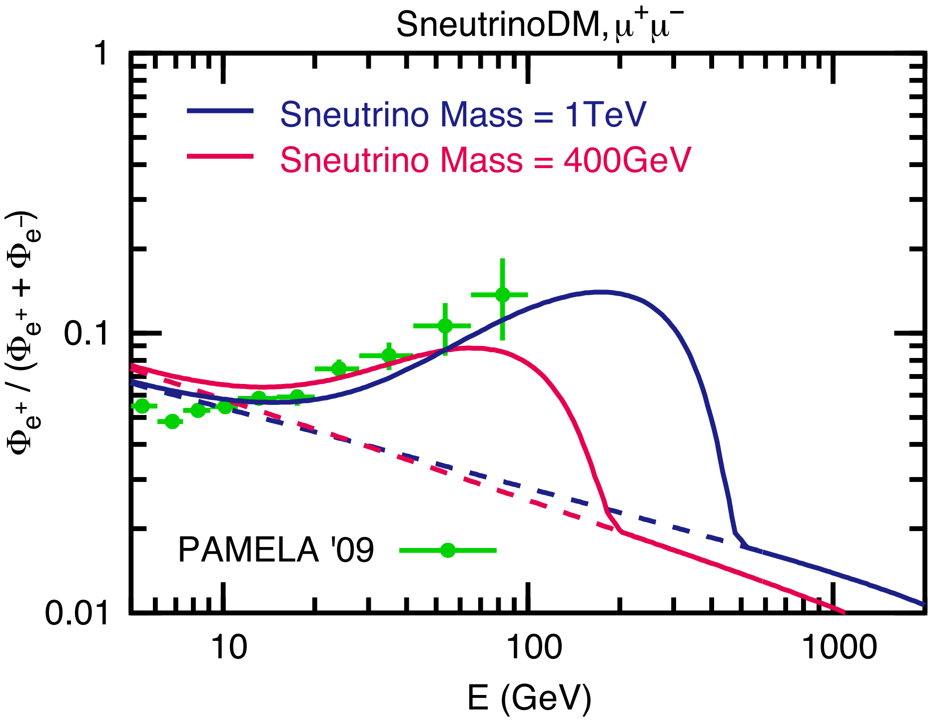


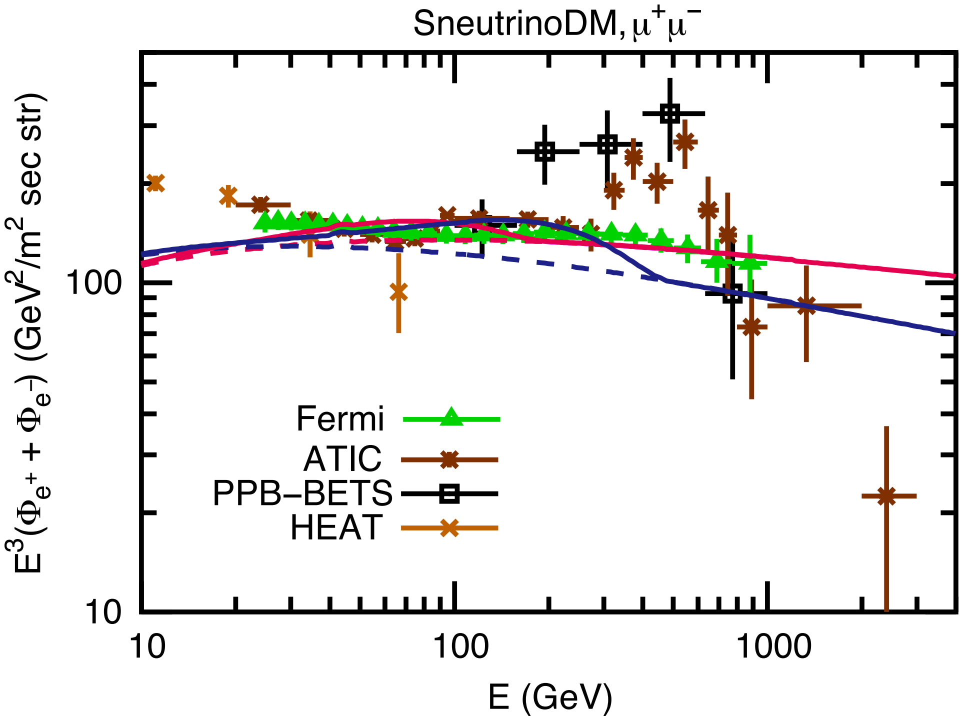


[Ishiwata, Matsumoto & TM ('10)]

$\tilde{\nu}_R$ DM with $W_{\rm RPV} \propto L_1 L_2 E_2^c$

- $\tilde{\nu}_R \to \mu\bar{\mu}$ (if $\tilde{\nu}_R \sim \tilde{\nu}_{R,1}$)
- $\bar{p}$ production is irrelevant

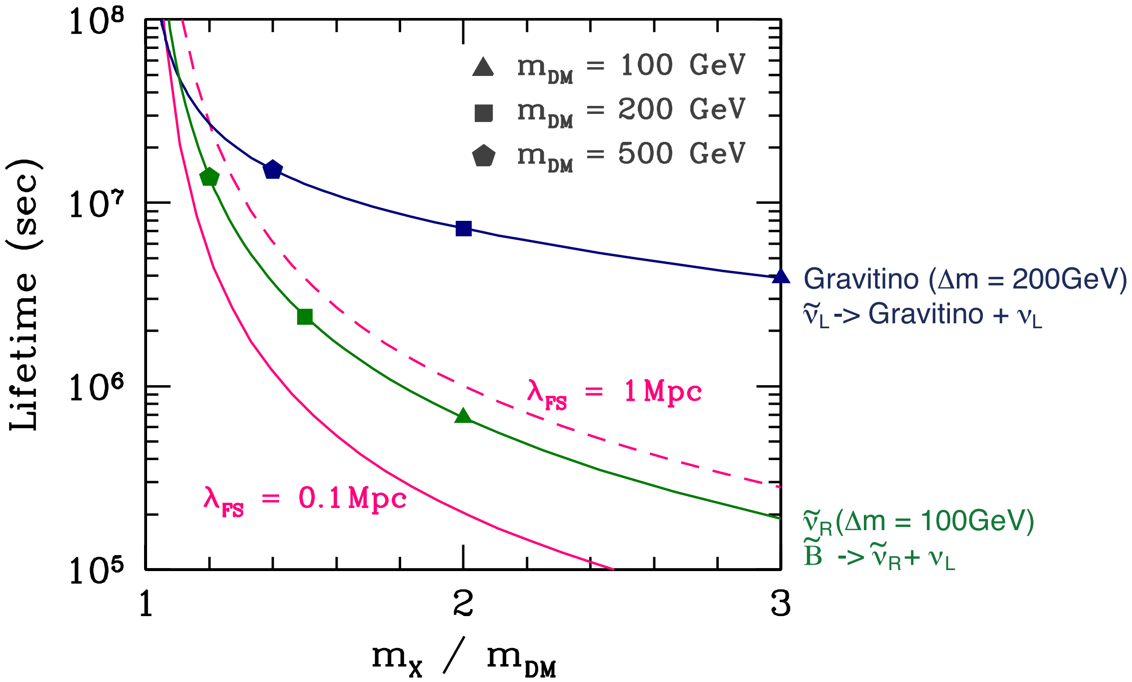




[Ishiwata, Matsumoto & TM ('10)]

Free-streaming length λ_{FS}

- λ_{FS} may be sizable, if DM originate to the NLSP decay [Cembranos, Feng, Rajaraman & Takayama ('05)]
- $\lambda_{FS} \lesssim O(0.1\ \mathrm{Mpc})$ not to smooth-out small-scale structure
- Mixed case?



4. Summary

The lightest neutralino is not the only candidate of DM

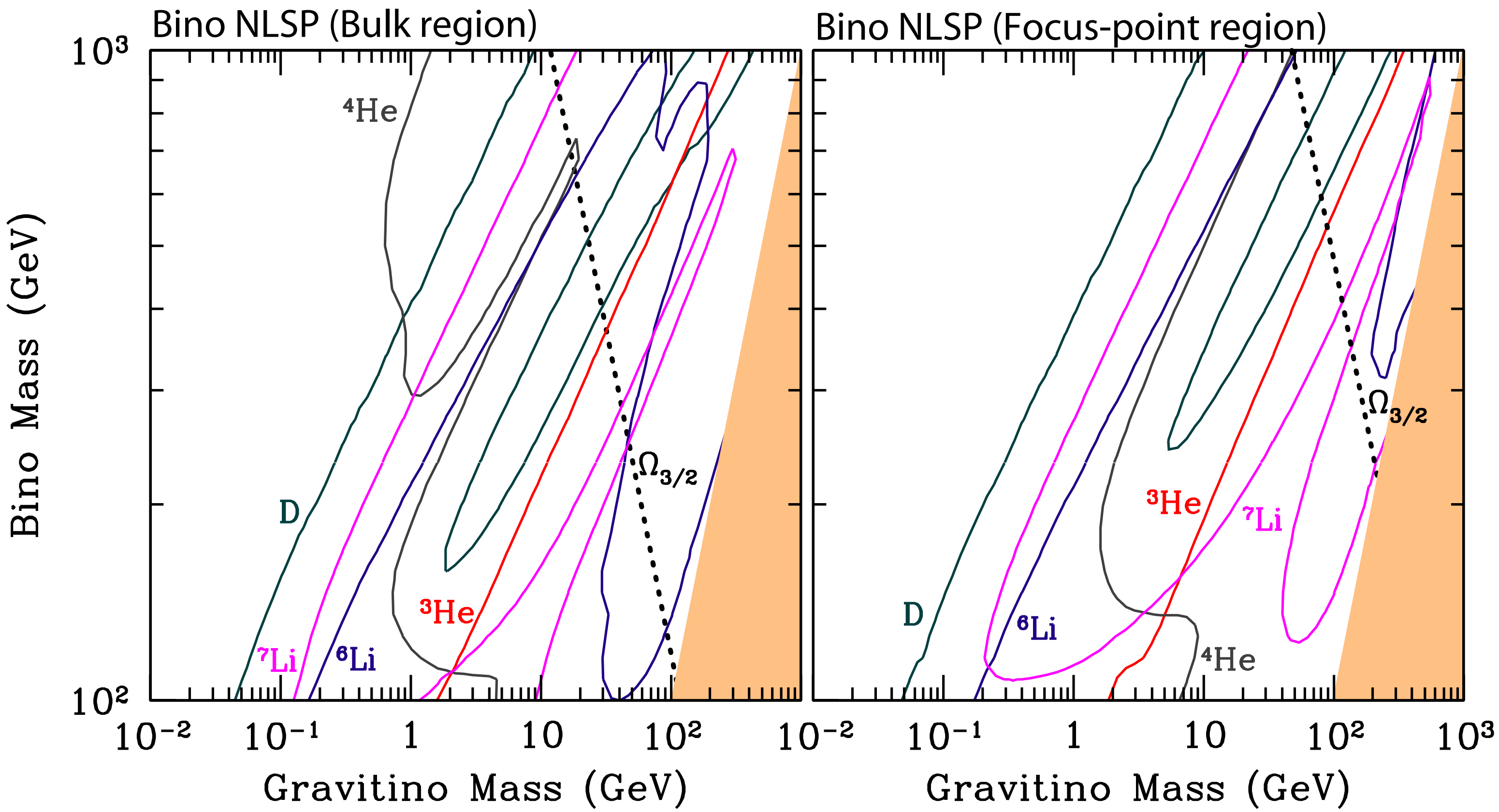
- Gravitino (& Goldstini)
- Axino
- $\tilde{\nu}_R$
- $\cdots$

Although their interaction is extremely weak, we may see

- Effects on BBN
- High energy cosmic ray
- Effects on small-scale structure
- $\cdots$

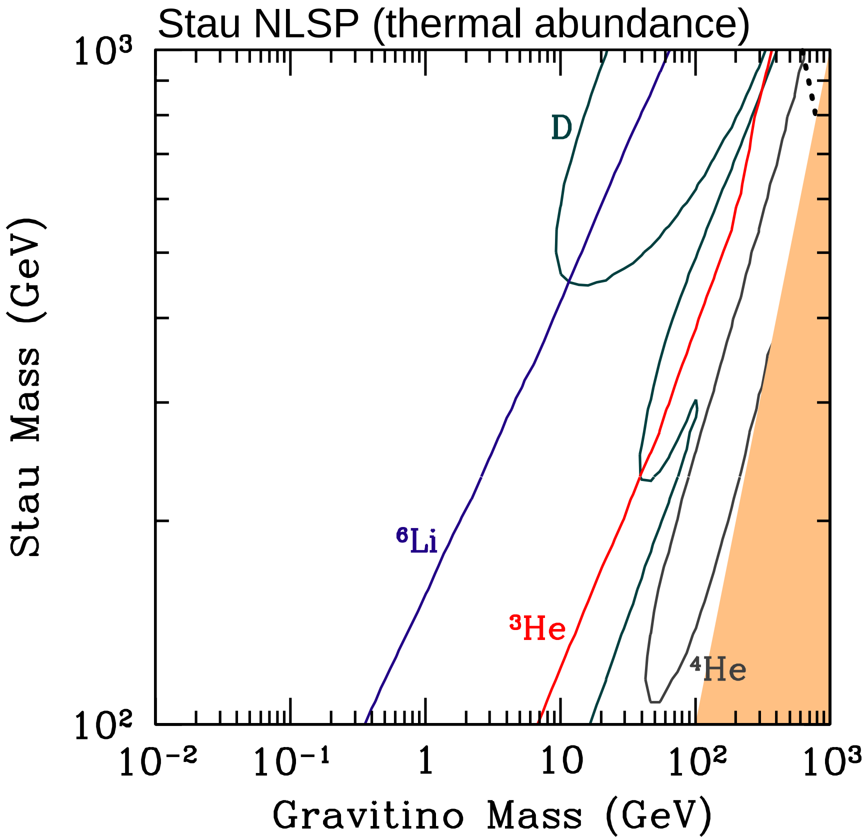
Backups

BBN constraints: Gravitino LSP + Bino NLSP



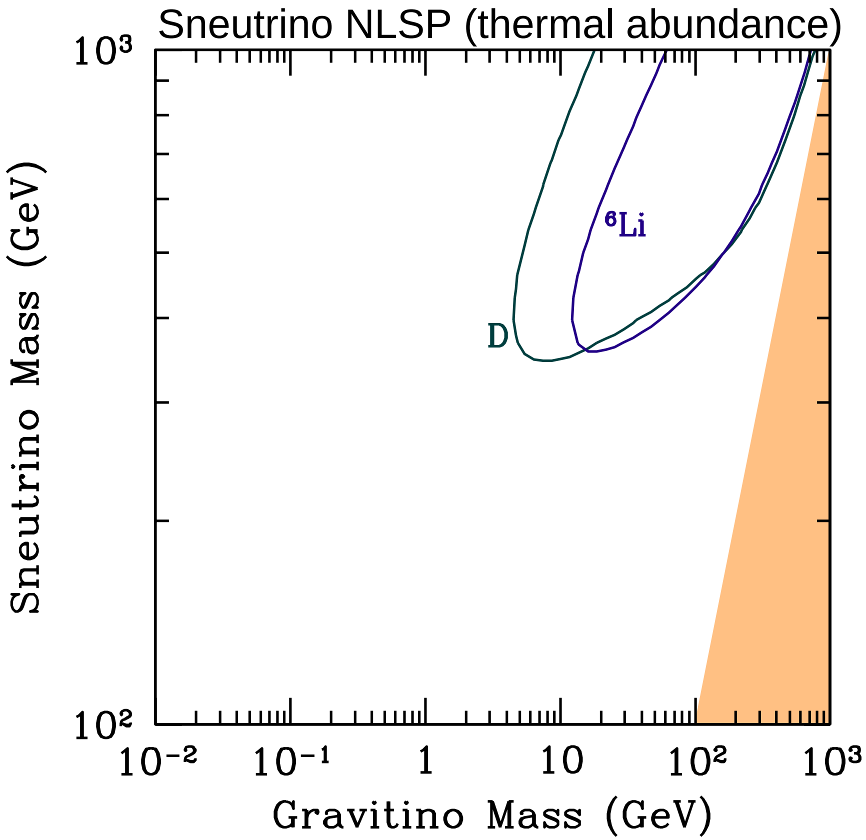
[Kawasaki, Kohri, TM & Yotsuyanagi]

BBN constraints : Gravitino LSP + Stau NLSP



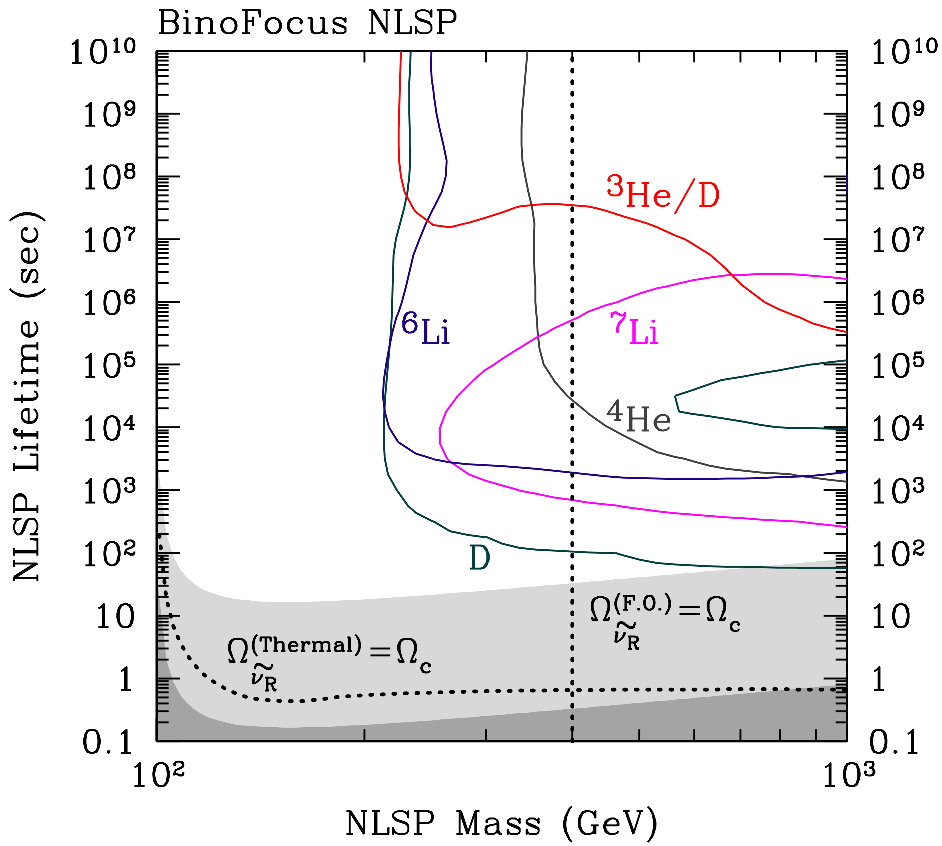
[Kawasaki, Kohri, TM & Yotsuyanagi]

BBN constraints : Gravitino LSP + Sneutrino NLSP



[Kawasaki, Kohri, TM & Yotsuyanagi]

BBN constraints: $\tilde{\nu}_R$-LSP + Bino NLSP



[Ishiwata, Kawasaki, Kohri & TM]