

# Big-bang nucleosynthesis with a long-lived slepton and a 125 GeV Higgs boson in the NMSSM

**Shingo Ohta (Saitama U.)**

## ● Collaborators ●

Kazunori Kohri (KEK), Masafumi Koike (Utsunomiya U.),  
Yasufumi Konishi (Saitama U.), Joe Sato (Saitama U.),  
Takashi Shimomura (Niigata U.), Kenichi Sugai (Saitama U.),  
Masato Yamanaka (Nagoya U.)

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# Introduction - DM candidate in the MSSM -

- \* A natural DM candidate in the MSSM

LSP : Bino-like neutralino  $\tilde{\chi}^0$

NLSP : Stau  $\tilde{\tau}$

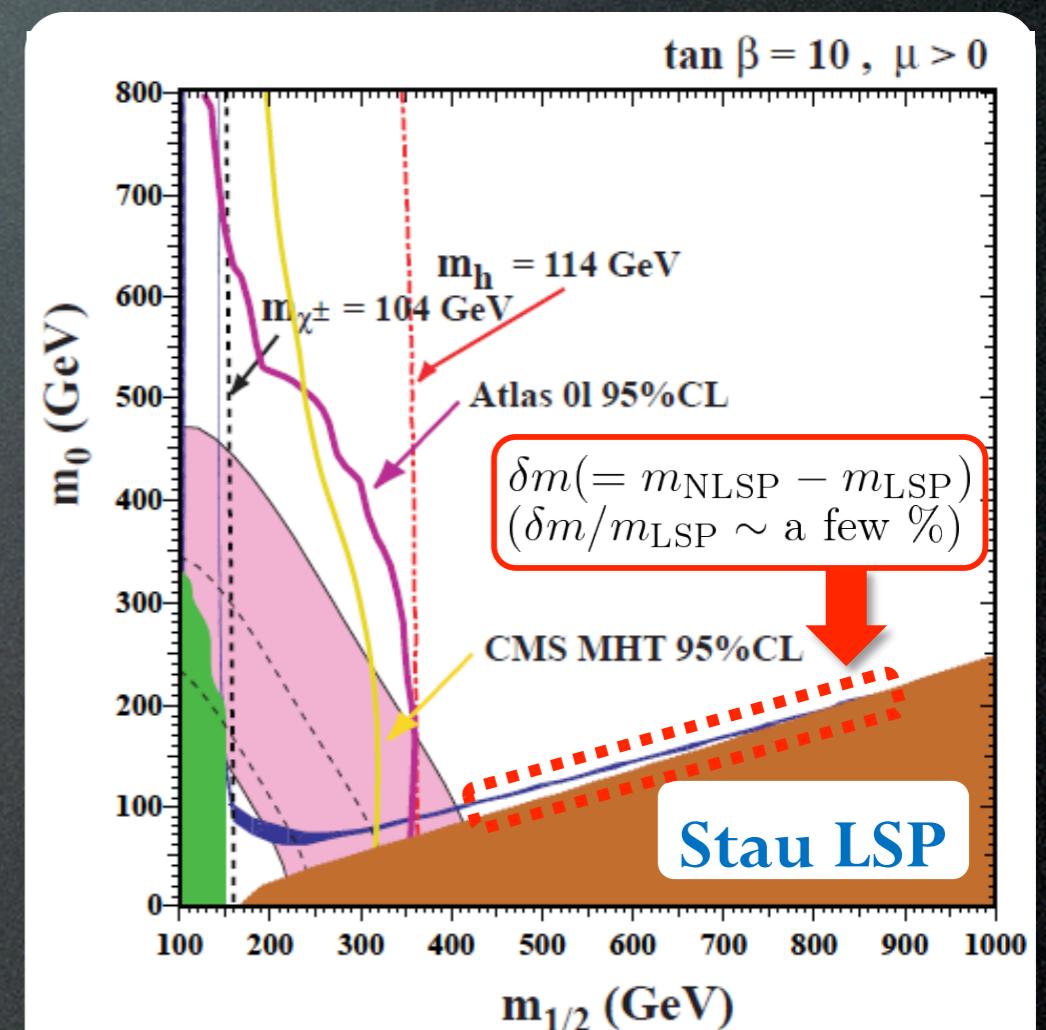
... must be degenerated in mass  
to obtain correct relic density.

## > Coannihilation

- ✓  $\delta m$  must satisfy  $\delta m/m_{\tilde{\chi}^0} < 1\%$  .
- ✓ When  $\delta m < m_\tau$

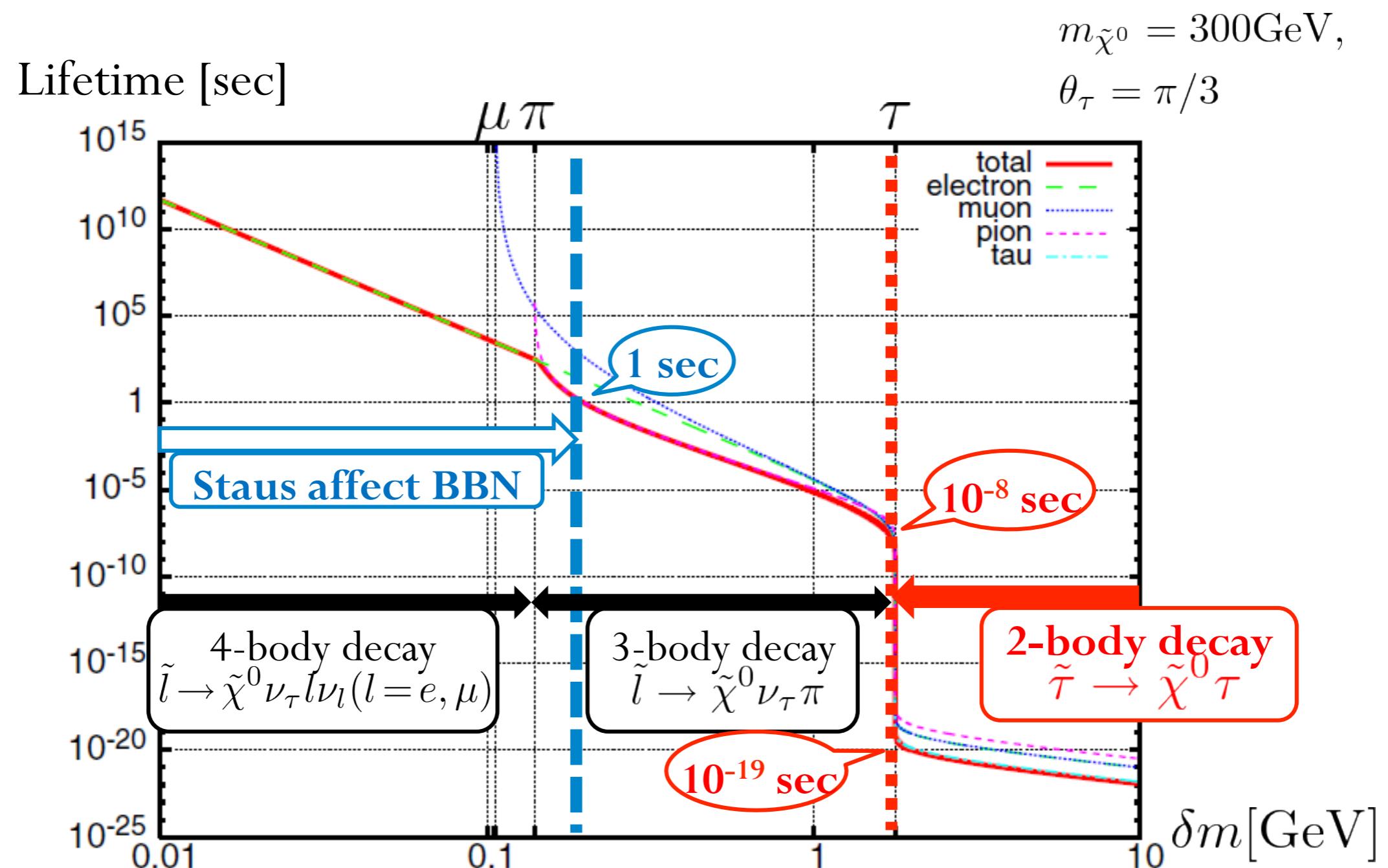
stau becomes *long-lived*.

$\tilde{\tau} \cancel{\rightarrow} \tilde{\chi}^0 \tau$



J. Ellis *et al.*, JCAP 1110 (2011) 024

# Introduction - Long-lived stau -



# Introduction - Intergenerational mixing -

$$\tilde{\tau} \rightarrow \tilde{l} = \sum_{f=e,\mu,\tau} c_f \tilde{f}$$

$$\begin{aligned}\tilde{f} &= \cos \theta_f \tilde{f}_L + \sin \theta_f \tilde{f}_R \\ c_e^2 + c_\mu^2 + c_\tau^2 &= 1\end{aligned}$$

$$\tilde{l} \rightarrow \tilde{\chi}^0 \mu$$

$(c_\mu \neq 0, \delta m > m_\mu)$

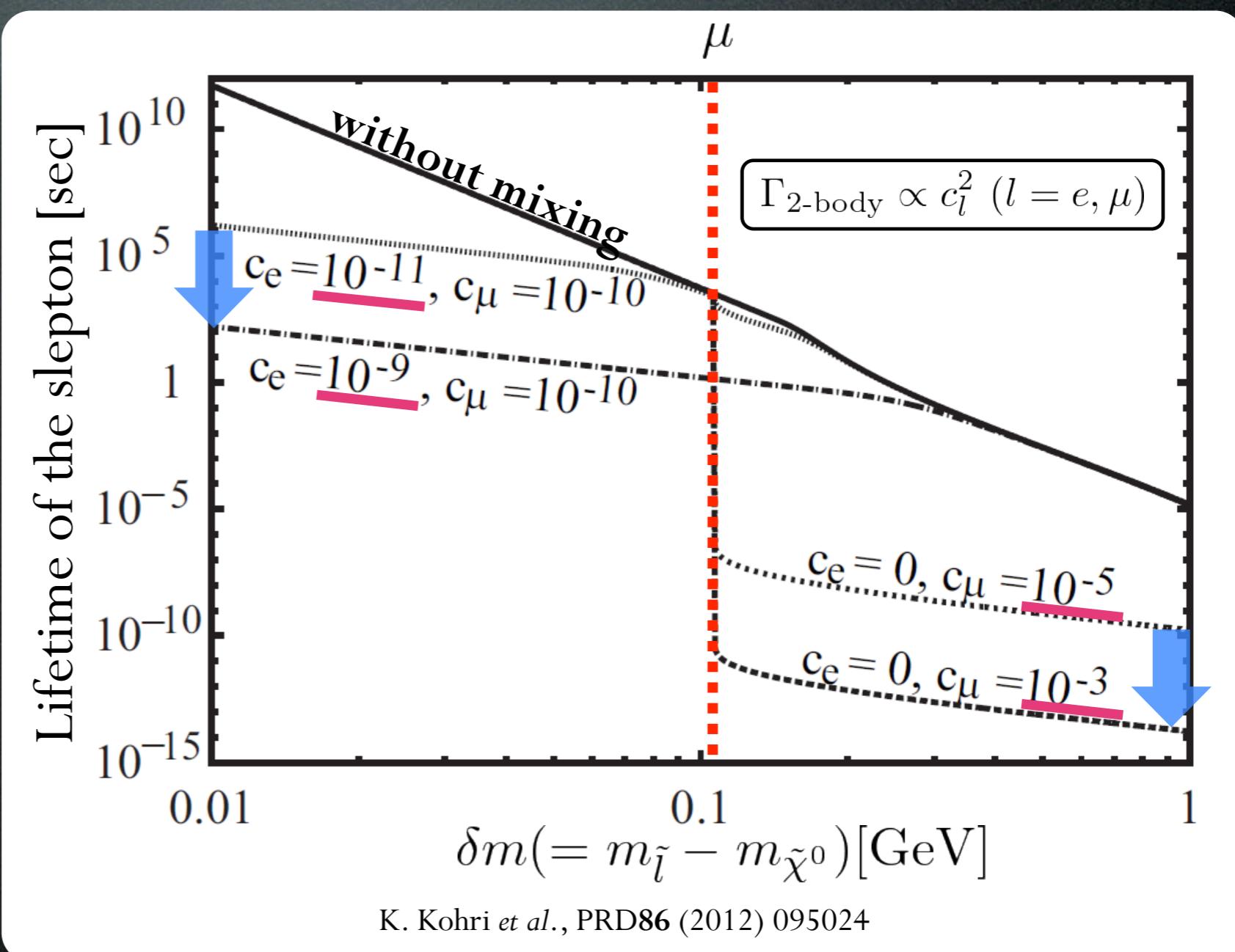
$$\tilde{l} \rightarrow \tilde{\chi}^0 e$$

$(c_e \neq 0, \delta m > m_e)$

larger  $c_\mu$  and/or  $c_e$



shorter  $\tau_{\tilde{l}}$



# Introduction - ${}^7\text{Li}$ problem and a solution -

\*  ${}^7\text{Li}$  abundance

**${}^7\text{Li}$  problem**

R. H. Cyburt *et al.*, JCAP **0811** (2008) 012

**theoretical > observed ... 3-4 times larger**

$$\log_{10}({}^7\text{Li}/\text{H}) = -9.35 \pm 0.06, \quad -9.63 \pm 0.06$$

T. Jittoh *et al.*, PRD **84**, 035008 (2011) J. Melendez and I. Ramirez, Astrophys. J. **615** (2004) L33

✓ Internal Conversion  $\tau_{\text{IC}} \sim \mathcal{O}(10^3)\text{sec}$

T. Jittoh et al., PRD **76**, 125023 (2007)

$$({}^7\text{Be} \tilde{\tau}^-) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7\text{Li},$$

$$({}^7\text{Li} \tilde{\tau}^-) \rightarrow \tilde{\chi}^0 + \nu_\tau + {}^7\text{He}$$

... reduce resultant abundance.

**BBN era**

$$T \sim (1 - 0.01)\text{MeV} \\ \Leftrightarrow t \sim (1 - 10^3)\text{sec}$$

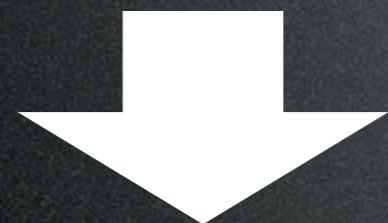
$\tilde{\tau}$  must have enough long lifetime and sufficient relic density.  
... at least,  $\tau_{\tilde{\tau}} \sim 10^3\text{sec}$  and  $Y_{\tilde{\tau}} = n_{\tilde{\tau}}/s \sim 10^{-13}$  for  $\delta m \sim 100\text{MeV}$

# Motivation

## MSSM

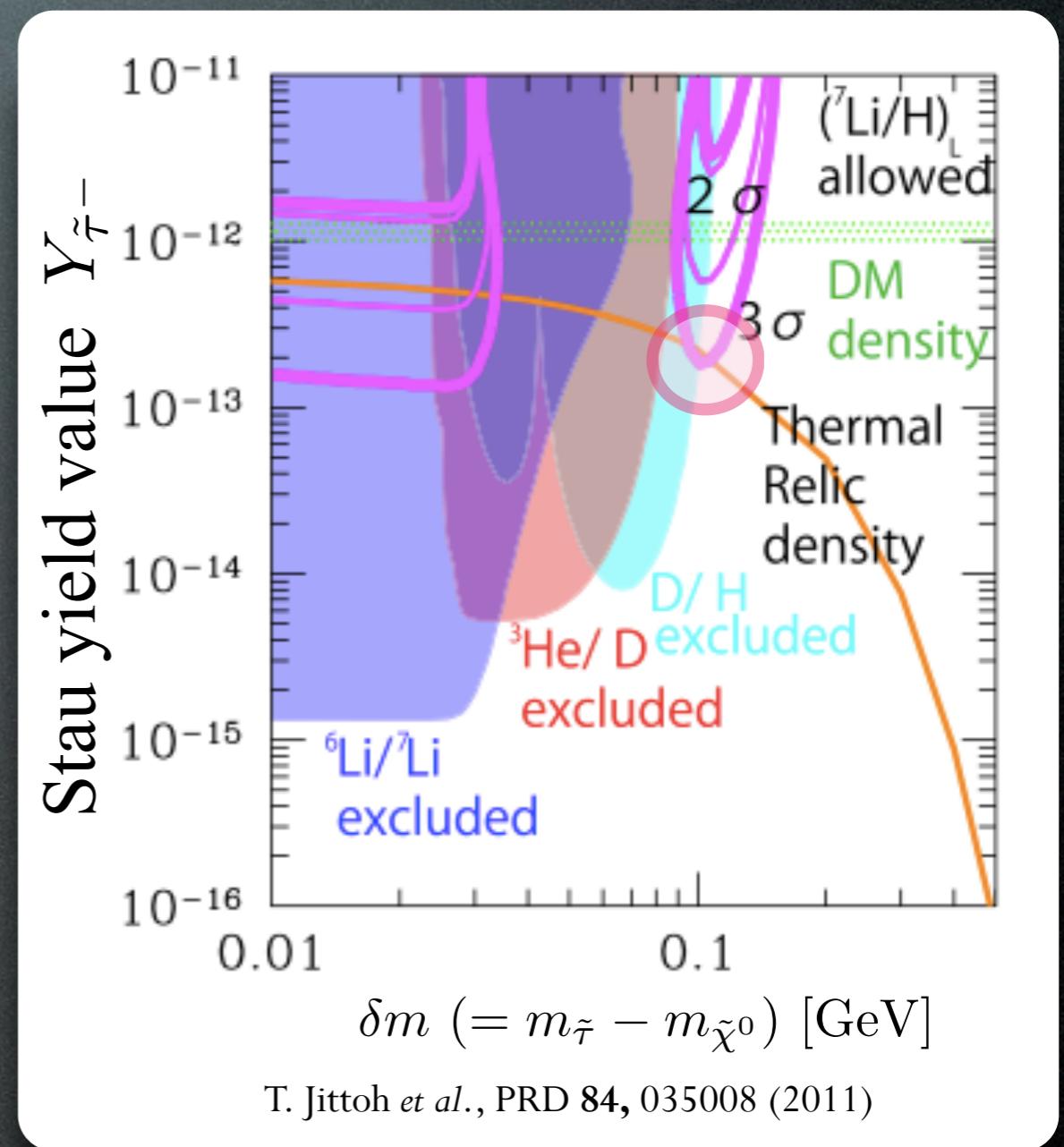
- ✓ Dark Matter relic density
- ✓ Light elements abundance

T. Jittoh *et al.*(2010, 2011), K. Kohri *et al.*(2012)



## NMSSM

- ✓ Dark Matter relic density
- ✓ Light elements abundance
- ✓ Higgs boson mass



T. Jittoh *et al.*, PRD 84, 035008 (2011)

# NMSSM ( $Z_3$ -invariant)

$$W = W_{\text{MSSM}} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$
$$-\mathcal{L}_{\text{soft}} = -\mathcal{L}_{\text{soft}}^{\text{MSSM}} + m_S^2 |S|^2 + \lambda A_\lambda H_u \cdot H_d S + \frac{1}{3} \kappa A_\kappa S^3 + h.c.$$

★ Higgs boson mass

$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$
$$+ \frac{3m_t^4}{16\pi^2 v^2} \left\{ \log \frac{m_s^2}{m_t^2} + \frac{X_t^2}{m_s^2} \left( 1 - \frac{X_t^2}{12m_s^2} \right) \right\} + \dots$$
$$( X_t \equiv A_t - \mu \cot \beta, \ m_s \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} )$$

✓ Parameters in the Higgs sector

$$\lambda, \ \kappa, \ A_\lambda, \ A_\kappa, \ \tan \beta, \ \mu_{\text{eff}} = \lambda s \quad (s = \langle S \rangle)$$

# Neutralinos in the NMSSM

\* Mass eigenstates

$$\tilde{\chi}_i^0 = N_{i\tilde{B}^0}\tilde{B}^0 + N_{i\tilde{W}^0}\tilde{W}^0 + N_{i\tilde{H}_d^0}\tilde{H}_d^0 + N_{i\tilde{H}_u^0}\tilde{H}_u^0 + N_{i\tilde{S}^0}\tilde{S}^0$$

\* Mass matrix

$$\begin{pmatrix} M_1 & 0 & -\cos \beta \sin \theta_W m_Z & \sin \beta \sin \theta_W m_Z & 0 \\ M_2 & \cos \beta \cos \theta_W m_Z & -\sin \beta \cos \theta_W m_Z & 0 & 0 \\ & & 0 & -\mu_{\text{eff}} & -\mu_\lambda \sin \beta \\ & & & 0 & -\mu_\lambda \cos \beta \\ & & & & \mu_\kappa \end{pmatrix}$$

$$\mu_{\text{eff}} = \lambda s, \quad \mu_\lambda = \lambda v, \quad \mu_\kappa = 2\kappa s$$

✓ We assume that the LSP neutralino is **Singlino-like** ( $\tilde{\chi}_5^0$ ) .

→  $M_1, M_2, \mu_{\text{eff}} \gg \mu_\kappa \quad (\lambda \gg 2\kappa)$

$m_{\tilde{\chi}_5^0} \simeq \mu_\kappa$

# Stau-tau-neutralino coupling

$$-\mathcal{L}_{\tilde{\chi}_5^0-\tau-\tilde{\tau}} = \tilde{\tau}^* \overline{\tilde{\chi}_5^0} (G_{L5} P_L + G_{R5} P_R) \tau + h.c.$$

$$G_{L5} = \frac{m_\tau g_2}{\sqrt{2} m_W \cos \beta} \sin \theta_\tau e^{i\gamma_\tau} N_{5\tilde{H}_d^0}, \quad G_{R5} = \frac{m_\tau g_2}{\sqrt{2} m_W \cos \beta} \cos \theta_\tau N_{5\tilde{H}_d^0}$$

● This coupling is typically *smaller* than that in bino-LSP case.



- **Longer** lifetime of the stau ( $\tau_{\tilde{\tau}}$ )
- **Longer** timescale of Internal Conversion ( $\tau_{IC}$ )

- ✓ Parameters :  $\lambda, \kappa, \tan \beta$
- ✓ First, we calculate  $\tau_{\tilde{\tau}}$  and  $\tau_{IC}$ , and require the values to be sufficient to solve the lithium problems.



the region where the lithium problems are solved on  $\lambda$ - $\kappa$  plane

# Requirements

- ✓ Lifetime of the stau

$$10^3 \text{ sec} < \tau_{\tilde{\tau}} < 10^5 \text{ sec}$$

... to avoid over-production of  ${}^6\text{Li}$ .  
... to form bound state with nuclei for IC.

\* Catalyzed Fusion  $\tau_{\text{CF}} \sim \mathcal{O}(10^4) \text{ sec}$



A solution of  
**the  ${}^6\text{Li}$  problem**  
( theor. < obs. )

- ✓ Timescale of the Internal Conversion

$$\tau_{\text{IC}} < 0.1 \tau_{\tilde{\tau}}$$

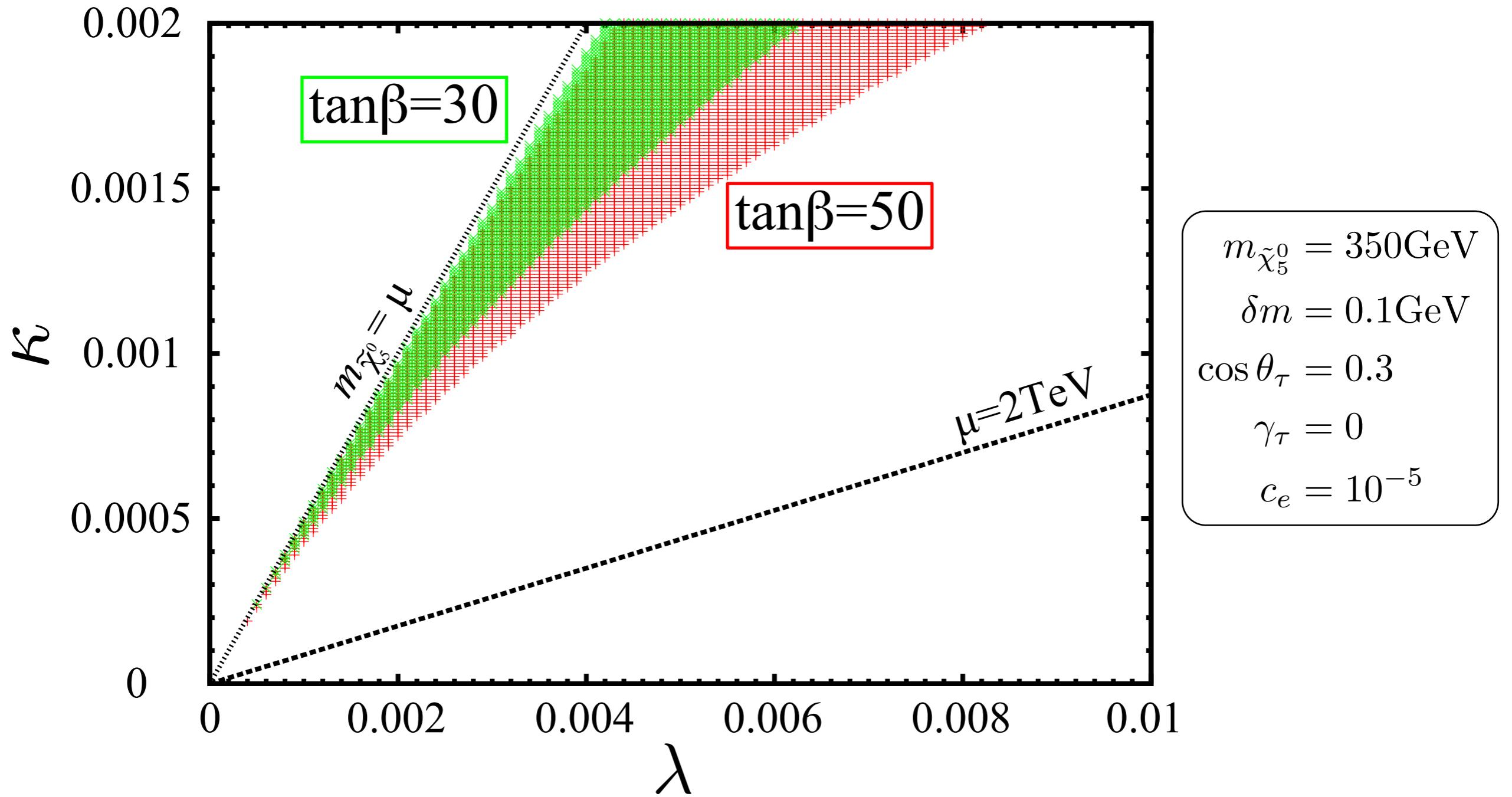
... to reduce enough amount of  ${}^7\text{Li}$ .

- ✓ Singlino-component in the LSP neutralino

$$N_{5\tilde{S}}^2 > 0.9$$

... to be NMSSM specific.

# The region where the Li problems can be solved



✓ Larger  $\kappa$ , and/or  $\tan\beta$ , smaller  $\lambda$

→ larger  $G_{L5}$  → shorter  $\tau_{\tilde{\tau}}$  and  $\tau_{\text{IC}}$

# Dark matter relic density and Higgs boson mass

	BP30-350.50	BP30-400.50	BP40-350.50	BP40-400.50	BP50-350.50	BP50-400.50
$M_2$	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
$A_t$	-7200.0	-7200.0	-7200.0	-7200.0	-7200.0	-7200.0
$A_\tau$	-10000	-16000	-3600.0	-11700	-1800.0	-3600.0
$m_{\tilde{L}_3}$	480.62	547.33	485.08	584.75	479.54	556.47
$m_{\tilde{E}_3}$	368.21	423.29	368.00	420.00	369.00	423.00
$m_{\tilde{Q}_3}$	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0
$m_{\tilde{U}_3}$	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0
$m_{\tilde{D}_3}$	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0
$\lambda$	0.0040	0.0040	0.0040	0.0040	0.0020	0.0040
$\kappa$	0.0016	0.0 016	0.0014	0.0015	0.0008	0.0014
$A_\lambda$	800.00	800.00	800.00	800.00	800.00	800.00
$A_\kappa$	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00
$\mu_{\text{eff}}$	426.39	487.95	488.11	520.99	426.74	558.93
$\tan \beta$	30.000	30.000	40.000	40.000	50.000	50.000
$h_1^0$	125.34	125.24	125.20	125.17	125.29	125.08
$h_2^0$	315.13	364.51	315.70	364.89	315.40	365.40
$h_3^0$	3523.4	3839.9	4330.2	4597.7	4514.2	5258.3
$a_1^0$	226.20	241.98	226.39	242.10	226.29	242.26
$a_2^0$	3523.6	3840.3	4330.2	4598.0	4514.2	5258.3
$H^\pm$	3530.0	3872.7	4319.8	4620.5	4490.6	5241.3
$\tilde{b}_1$	3093.1	3093.8	3091.9	3091.5	3091.3	3088.8
$\tilde{b}_2$	3108.0	3107.4	3109.2	3109.6	3109.8	3112.2
$\tilde{t}_1$	2932.3	2932.2	2932.4	2932.3	2932.4	2932.4
$\tilde{t}_2$	3265.3	3265.3	3265.2	3265.2	3265.1	3265.2
$\tilde{\tau}_1$	350.10	400.10	350.10	400.10	350.10	400.10
$\tilde{\tau}_2$	497.88	567.93	502.03	601.78	497.43	576.53
$\tilde{g}$	3193.7	3193.7	3193.7	3193.7	3193.7	3193.7
$\tilde{\chi}_1^0$	350.00	400.00	350.00	400.00	350.00	400.00
$\tilde{\chi}_2^0$	418.29	461.21	461.03	473.49	418.70	480.04
$\tilde{\chi}_3^0$	-440.50	-502.85	-502.90	-536.16	-440.58	-574.21
$\tilde{\chi}_4^0$	503.28	523.29	522.69	544.41	503.08	575.33
$\tilde{\chi}_5^0$	1035.9	1036.6	1036.7	1037.2	1036.4	1037.9
$\tilde{\chi}_1^\pm$	433.78	495.52	495.66	528.53	433.98	566.13
$\tilde{\chi}_2^\pm$	1035.9	1036.6	1036.7	1037.2	1036.4	1037.9
$\Omega h^2$	0.12168	0.12198	0.12337	0.12501	0.12135	0.12466
$N_{5\tilde{S}^0}$	0.99998	0.99998	0.99999	0.99999	0.99999	0.99999
$\sin \theta_\tau$	0.93890	0.93336	0.94155	0.95400	0.93617	0.93805

Common inputs:

$$M_1 = M_2/2, \quad M_3 = 3M_2,$$

$$A_{\tilde{f}} = -3600 \text{GeV} (\text{except for } A_{t,\tau}),$$

$$m_{\tilde{L}_{1,2}}, \quad m_{\tilde{E}_{1,2}}, \quad m_{\tilde{Q}_{1,2}}, \quad m_{\tilde{U}_{1,2}}, \quad m_{\tilde{D}_{1,2}} = 3 \text{TeV}$$

$m_h \sim 125 \text{GeV}$

$\delta m = 0.1 \text{GeV}$

PLANCK Collaboration

$$0.112 \leq \Omega_{\tilde{\chi}} h^2 \leq 0.128 \quad (3\sigma)$$

the lightest neutralino is almost singlino

\*GeV

\*used NMSSMTools ver.4.0.0

# Summary

- ✓ We have investigated allowed parameter region where the lithium problems are solved with long-lived slepton on  $\lambda$ - $\kappa$  plane in the NMSSM.
- ✓ We have shown that such allowed parameter region exist.
- ✓ We found some points in the region where DM relic density and Higgs boson mass are obtained correctly.

.....  
↓ this talk

- ✓ We will calculate stau relic density and reaction rates for exotic BBN processes in order to confirm whether the sample points give correct light elements abundance.
- ✓ We also consider the case with bino-like neutralino LSP.

Backup

# Stau-tau-neutralino coupling

$$-\mathcal{L}_{\tilde{\chi}_5^0 - \tau - \tilde{\tau}} = \tilde{\tau}^* \overline{\tilde{\chi}_5^0} (G_{L5} P_L + G_{R5} P_R) \tau + h.c.$$

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$$N_{5\tilde{H}_d^0} = \frac{1}{N} \frac{\mu_{\text{eff}} (\mu_{\text{eff}} \cos \beta - \mu_\kappa \sin \beta)}{\mu_\kappa^2 - \mu_{\text{eff}}^2}$$

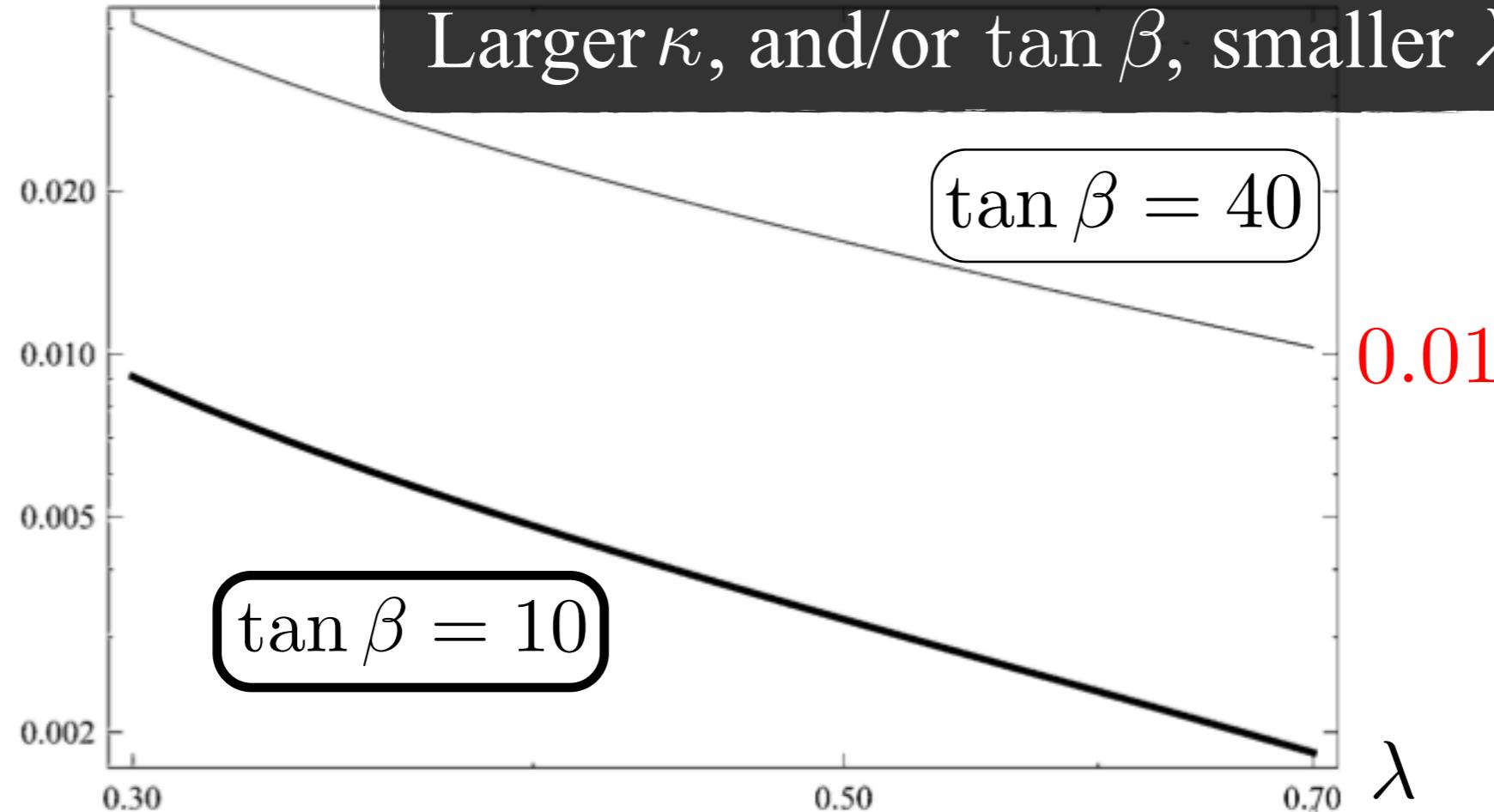
$$N \equiv \left\{ 1 + \left( \frac{\mu_{\text{eff}} (\mu_{\text{eff}} \sin \beta - \mu_\kappa \cos \beta)}{\mu_\kappa^2 - \mu_{\text{eff}}^2} \right)^2 + \left( \frac{\mu_{\text{eff}} (\mu_{\text{eff}} \cos \beta - \mu_\kappa \sin \beta)}{\mu_\kappa^2 - \mu_{\text{eff}}^2} \right)^2 \right\}^{1/2}$$

$$\mu_{\text{eff}} = \lambda s, \quad \mu_\lambda = \lambda v, \quad \mu_\kappa = 2\kappa s$$

✓ Parameters :  $\lambda, \kappa, \tan \beta$

Larger  $\kappa$ , and/or  $\tan \beta$ , smaller  $\lambda \rightarrow$  larger  $G_{L5}$

$G_{L5}$



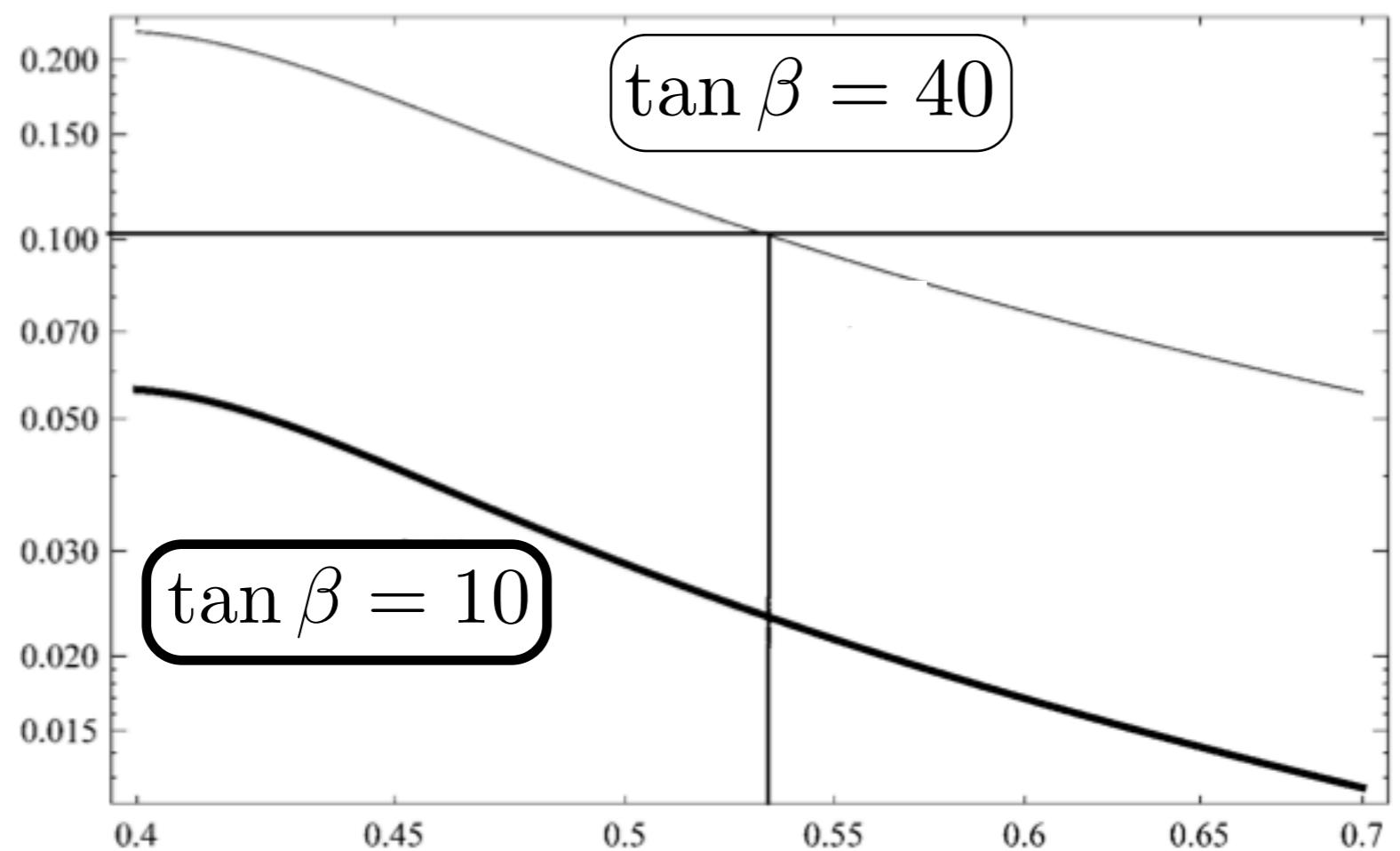
0.01

$\kappa = 0.1$

$\tan \beta = 10$

$\tan \beta = 40$

$G_{L5}$



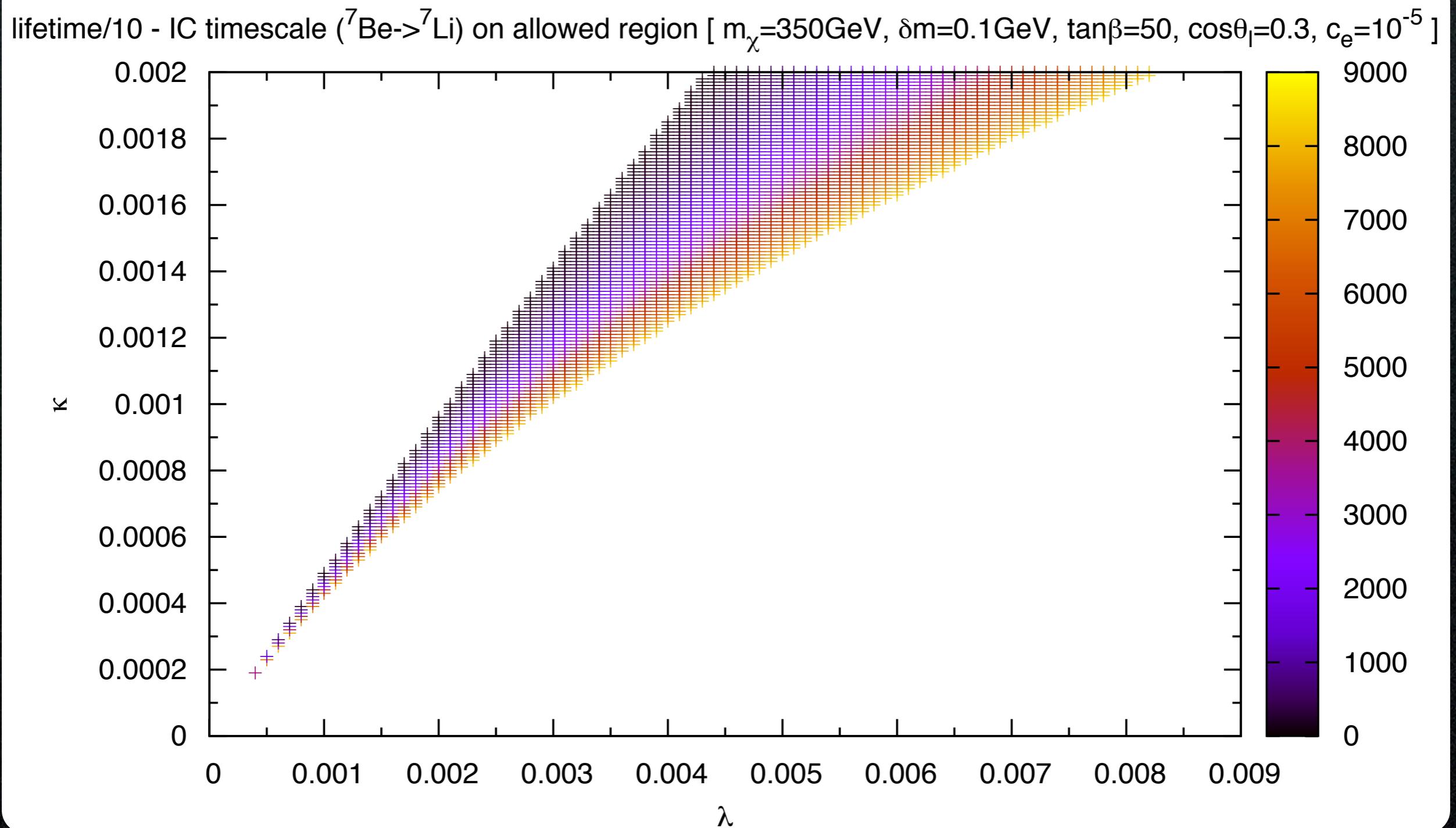
0.05

$\kappa = 0.2$

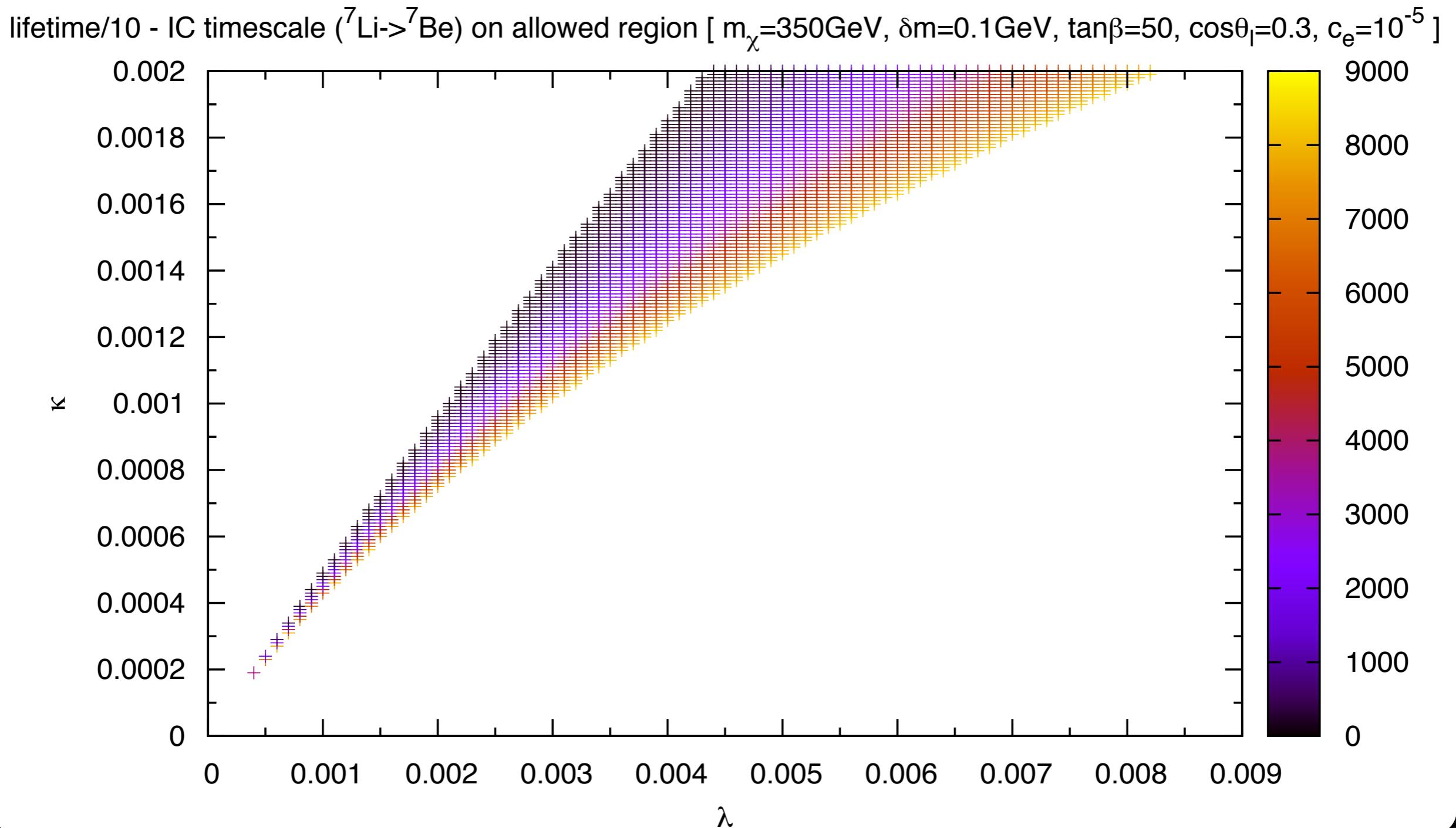
$\tan \beta = 10$

$\tan \beta = 40$

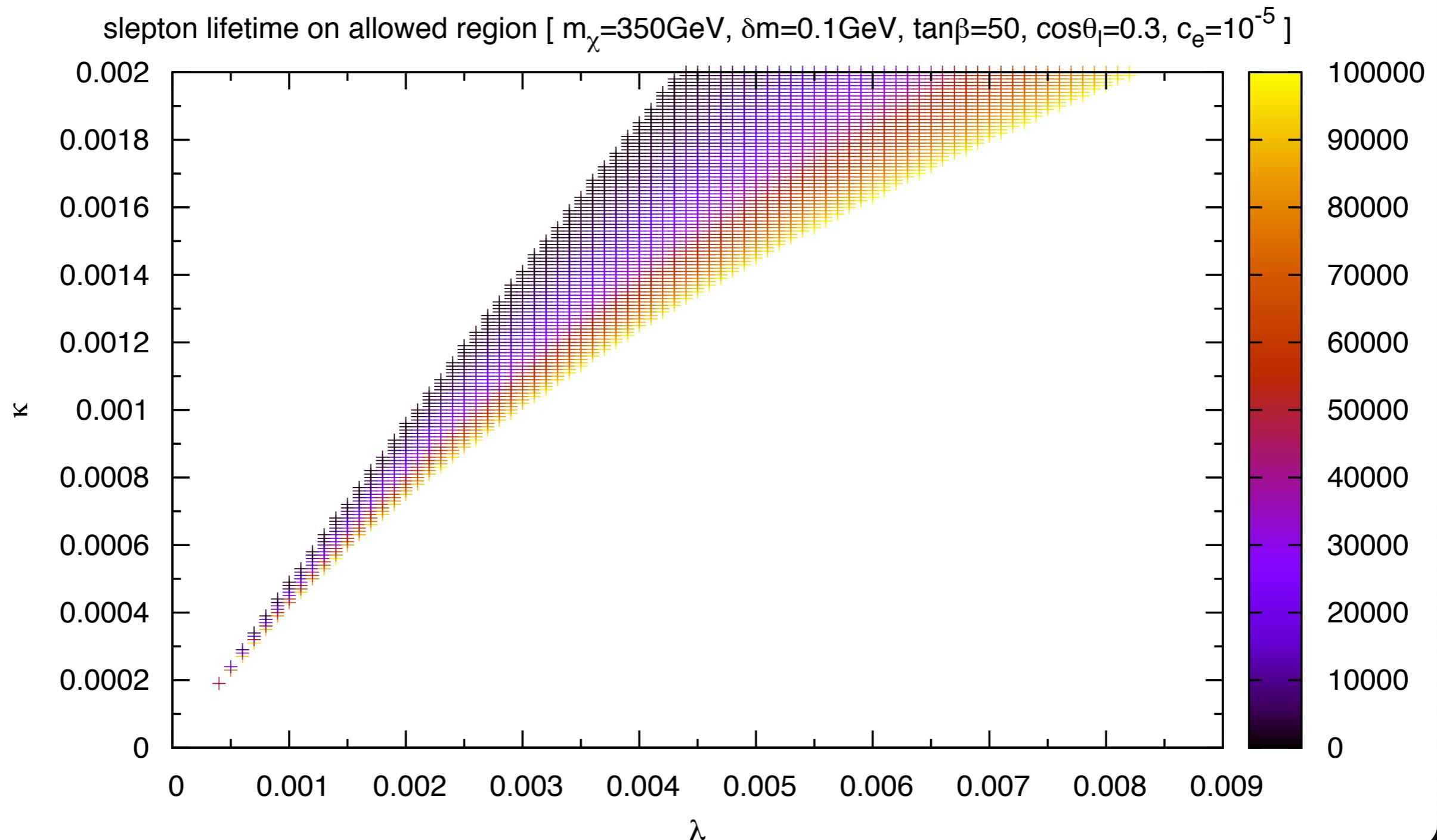
$$0.1\tau_\tau - \tau_{\text{IC}}({}^7\text{Be} \rightarrow {}^7\text{Li})$$



$$0.1\tau_\tau - \tau_{\text{IC}}({}^7\text{Li} \rightarrow {}^7\text{He})$$



# Lifetime of the slepton



$N_{5S}^2$  on allowed region [  $m_\chi=350\text{GeV}$ ,  $\delta m=0.1\text{GeV}$ ,  $\tan\beta=50$ ,  $\cos\theta_l=0.3$ ,  $c_e=10^{-5}$  ]

