Allowed parameter region in NMSSM with a long-lived slepton from a 125 GeV Higgs boson and light elements abundances

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based on Phys.Rev. D86 (2012) 095024 and an ongoing project

High Energy Physics in the LHC Era @ Valparaiso, CHILE   17th Dec. 2013

Motivation

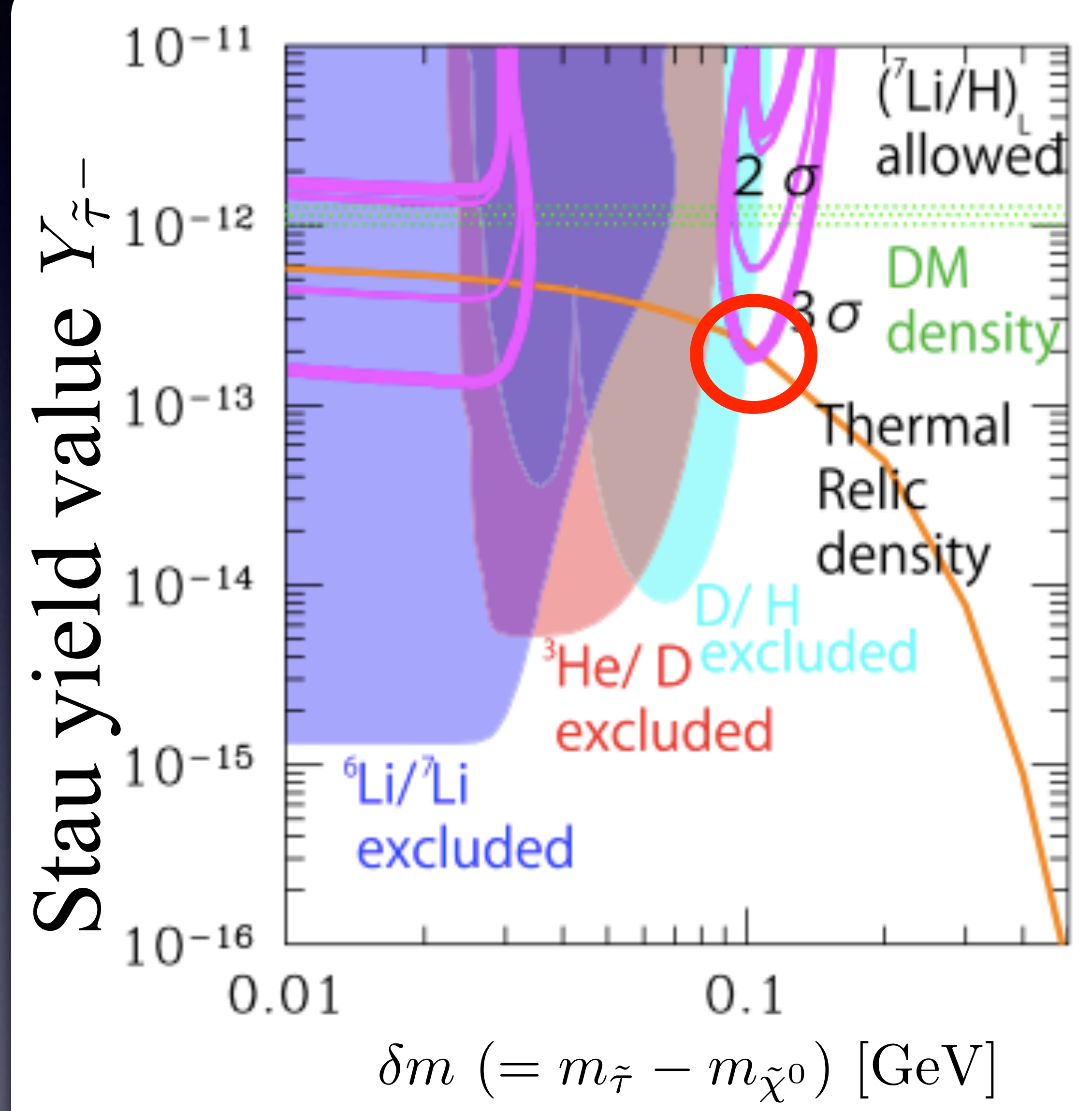
MSSM

- ✓ Light element abundances
- ✓ Dark Matter relic density

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

NMSSM

- ✓ Light element abundances
- ✓ Dark Matter relic density
- ✓ Higgs boson mass



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

Introduction -DM candidate in MSSM-

- **Stau coannihilation**

DM candidate

LSP : Bino-like neutralino $\tilde{\chi}^0 (\simeq \tilde{B}^0)$
(Lightest SUSY Particle)

NLSP : Stau $\tilde{\tau}$
(Next-to-Lightest one)

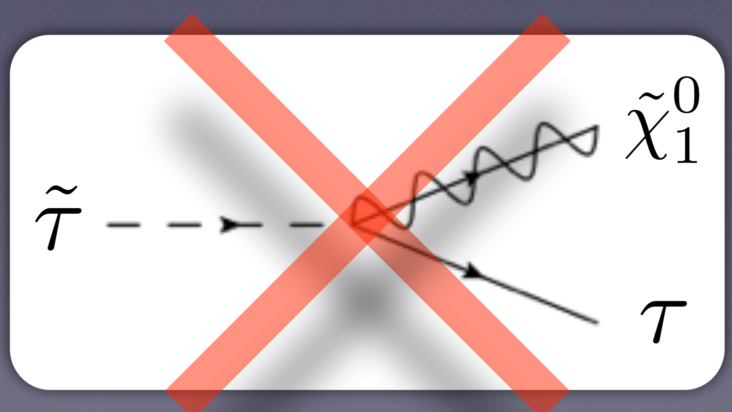
... degenerated in mass

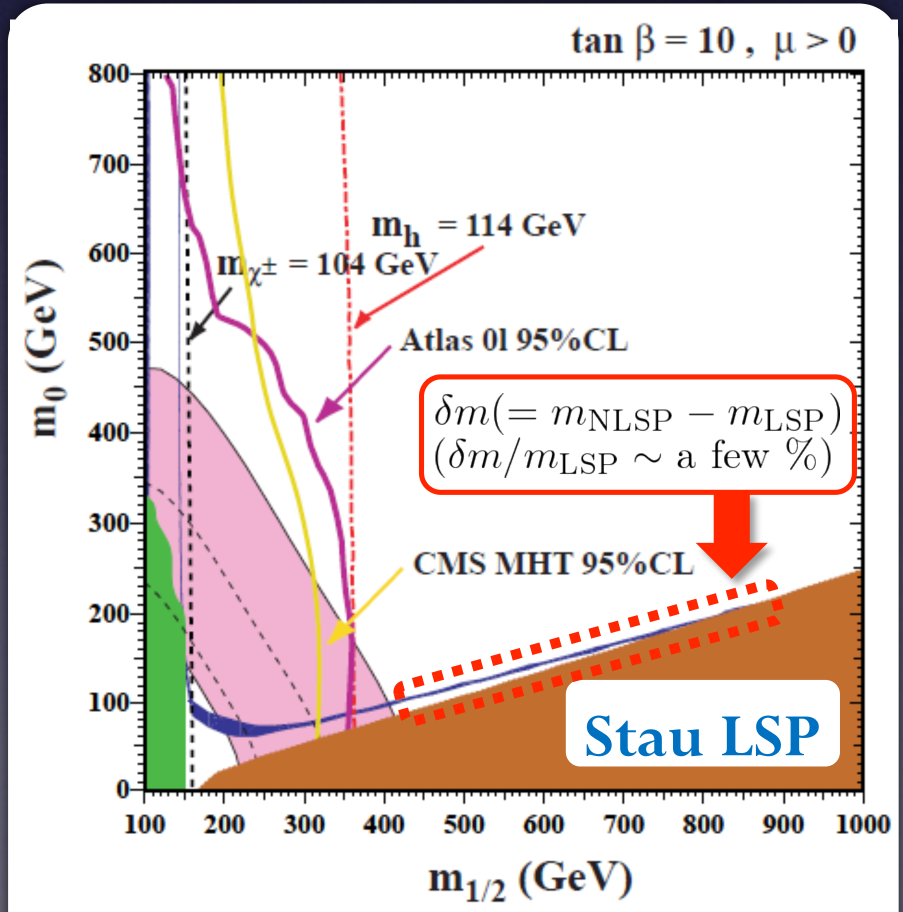
→ NLSP annihilations are also contribute to LSP DM annihilation.

→ Suitable relic density can be obtained.

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

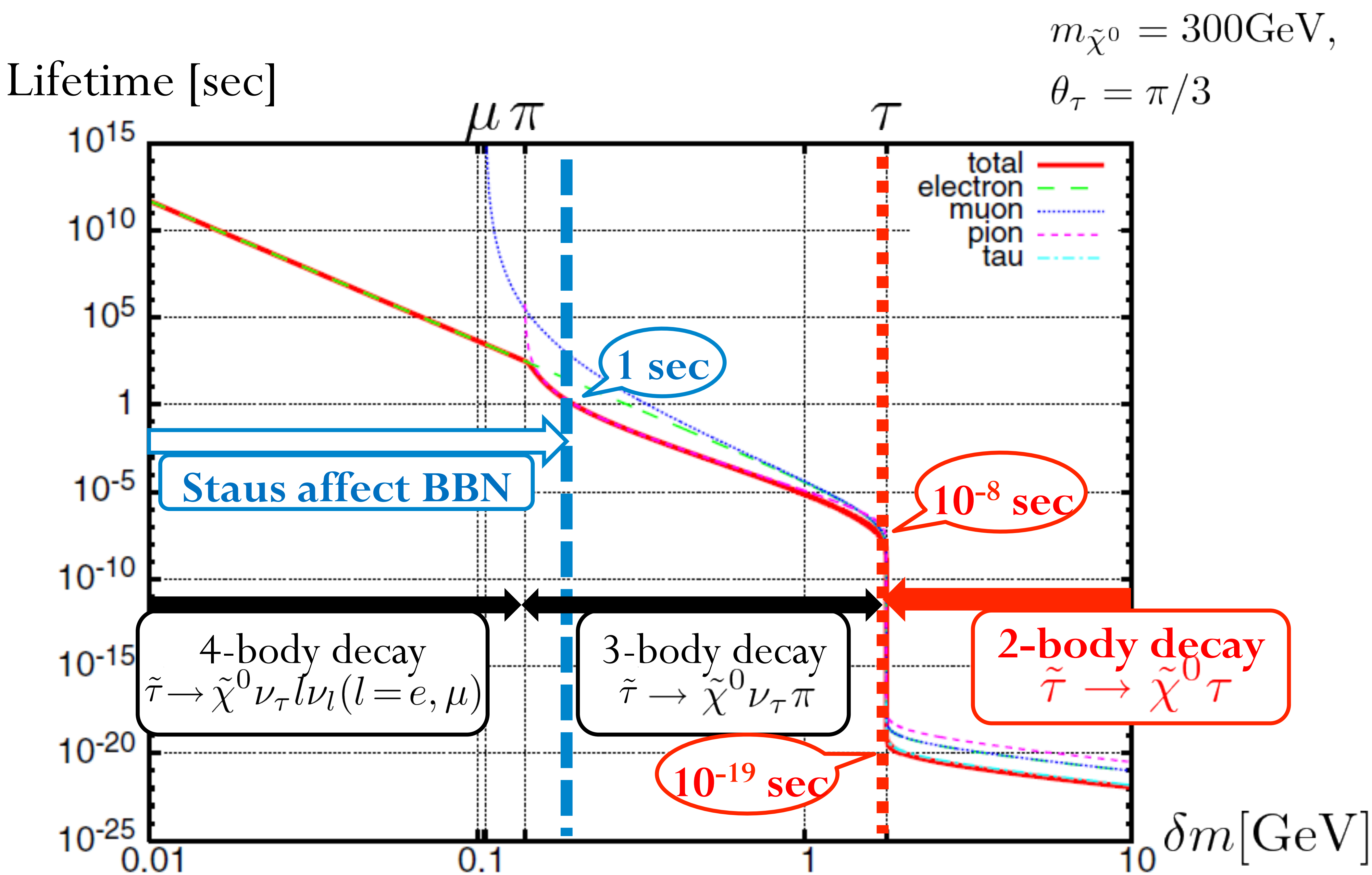
✓ **If $\delta m < m_\tau$**
stau becomes *long-lived*.





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

Introduction - long-lived stau -



T. Jittoh *et al.*, PRD **73** (2006) 055009

Introduction - flavor mixing of the stau -

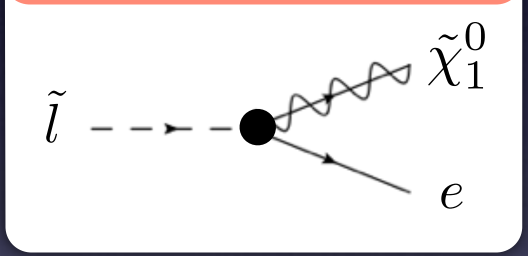
> Generalize the stau to be mixed state, '**slepton**'

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

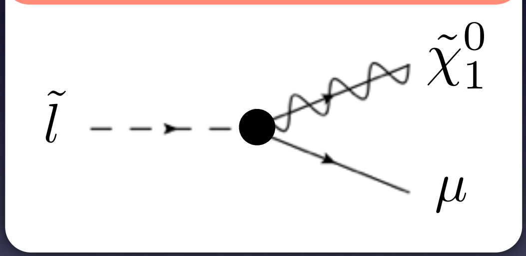
$$\tilde{f} = \cos\theta_f \tilde{f}_L + \sin\theta_f e^{i\gamma_f} \tilde{f}_R, \quad c_e^2 + c_\mu^2 + c_\tau^2 = 1$$

→ flavor violating 2-body decays are allowed!

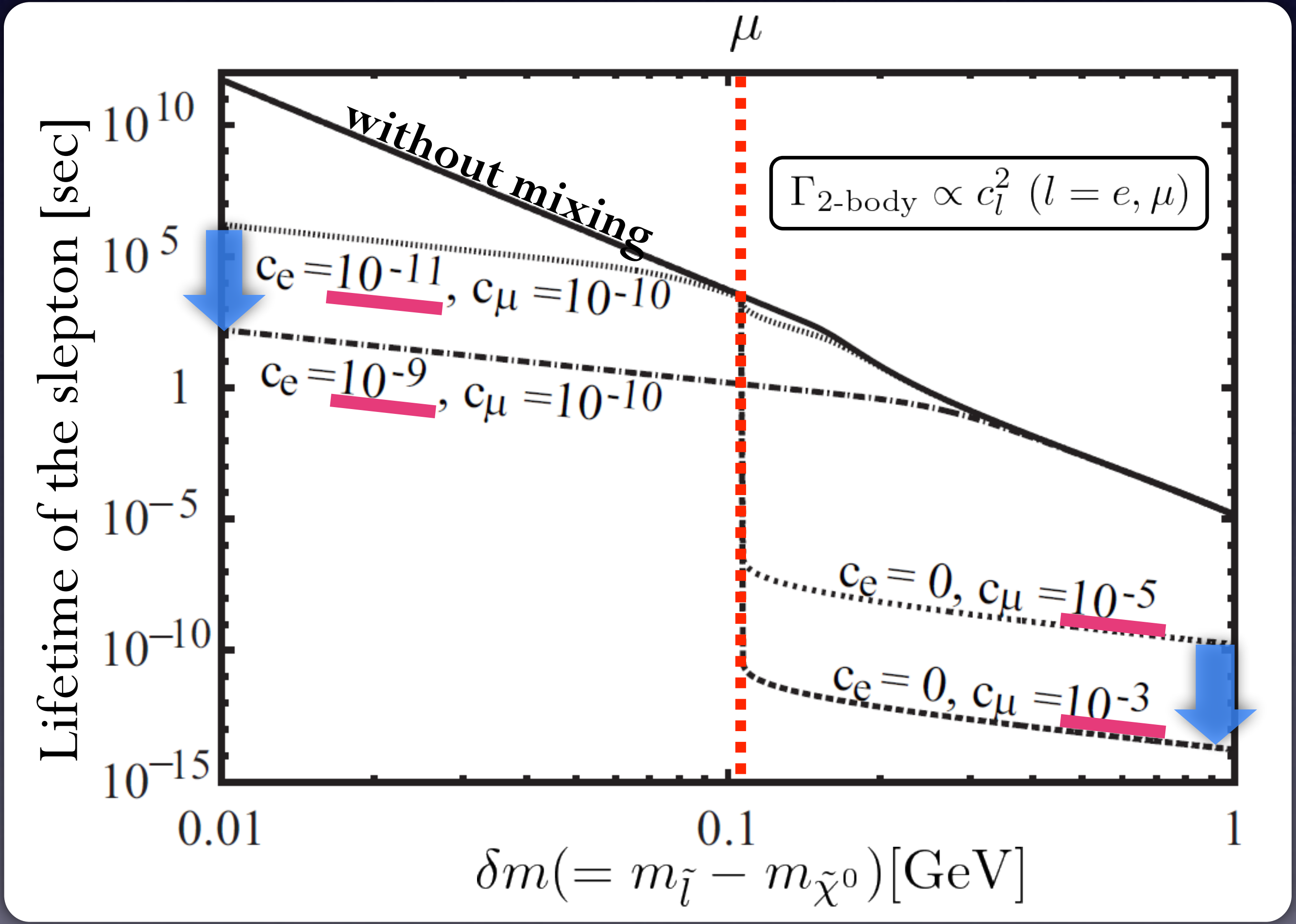
$c_e \neq 0, \ \delta m > m_e$



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



shorten the slepton lifetime



larger c_μ and/or c_e → shorter $\tau_{\tilde{l}}$

Introduciton - ^{7}Li problem and a solution -

> ^{7}Li problem

... **theor.** > **obs.** for ^{7}Li abundance in the standard BBN

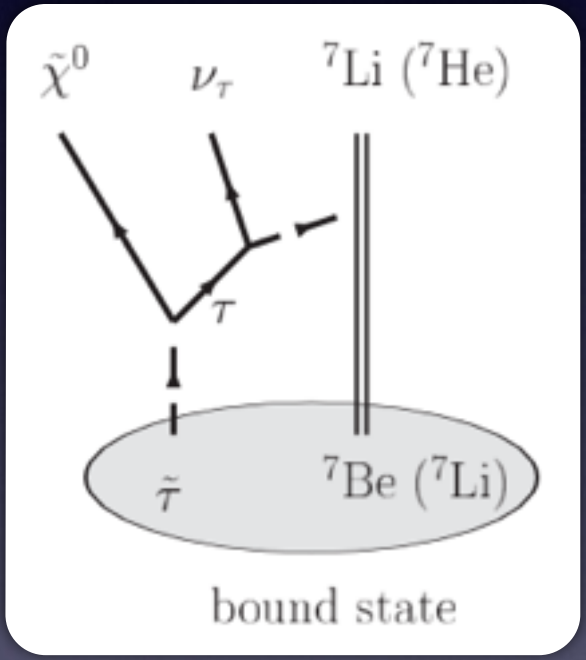
↓ A solution by exotic BBN reaction with long-lived slepton

Internal Conversion

BBN era
$T \sim (1 - 0.01)$MeV
$\Leftrightarrow t \sim (1 - 10^3)$sec

$$(^7\mathrm{Be}\ \tilde{l}^-) \to\ ^7\mathrm{Li} + \tilde{\chi}_1^0 + \nu_l$$
$$(^7\mathrm{Li}\ \tilde{l}^-) \to\ ^7\mathrm{He} + \tilde{\chi}_1^0 + \nu_l$$

$\sim \mathcal{O}(10^3)$ sec to form bound states



... reduce resultant abundance of ^{7}Li

T. Jittoh et al., PRD76, 125023 (2007)

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

Allowed region in MSSM

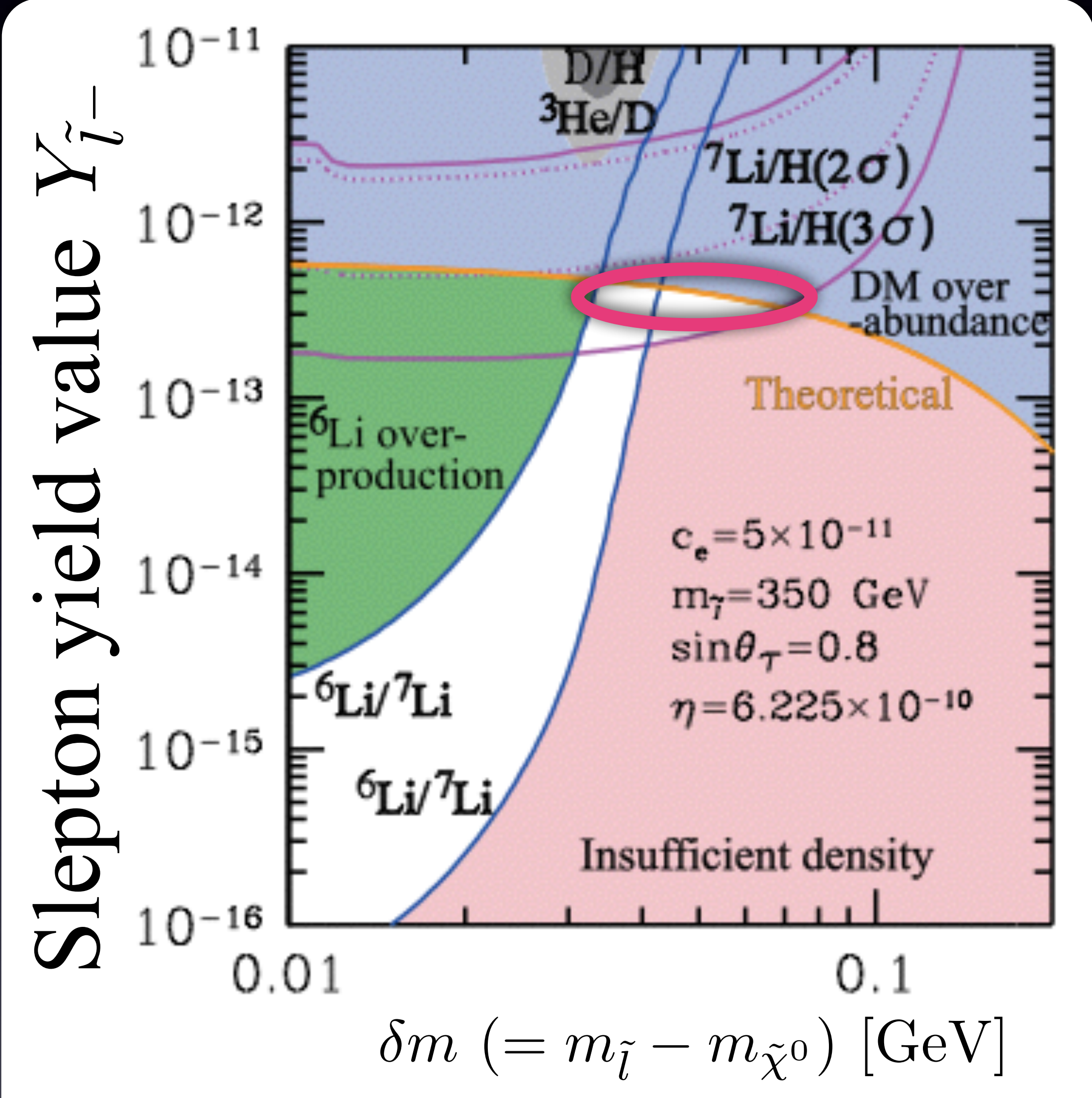
MSSM

- ✓ Light element abundances
- ✓ Dark Matter relic density

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

NMSSM

- ✓ Light element abundances
- ✓ Dark Matter relic density
- ✓ Higgs boson mass



K. Kohri et al., PRD86, 095024 (2012)

With flavor mixing

NMSSM (Z_3-invariant)

- Superpotential and soft SUSY breaking terms

$$W = W_{\rm MSSM} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3$$

$$-\mathcal{L}_{\rm soft} = -\mathcal{L}_{\rm soft}^{\rm MSSM} + m_S^2 |S|^2 + \lambda A_\lambda H_u \cdot H_d S + \frac{1}{3}\kappa A_\kappa S^3 + h.c.$$

★ Higgs boson mass

$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin 2\beta - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2$$

$$+ \frac{3m_t^4}{16\pi^2 v^2}\left\{\log\frac{m_s^2}{m_t^2} + \frac{X_t^2}{m_s^2}\left(1 - \frac{X_t^2}{12 m_s^2}\right)\right\} + \cdots$$

$$\left(X_t \equiv A_t - \mu \cot\beta,\ m_s \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \right)$$

✓ Parameters in the Higgs sector

$$\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle,\ \mu_{\rm eff} \equiv \lambda s\ (s = \langle S \rangle)$$

Neutralinos in 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

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

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

✓ We consider two cases;

- **Singlino-like neutralino LSP** … not exist in MSSM
- **Bino-like neutralino LSP** … almost same as one in MSSM

Singlino-like neutralino LSP

> **Interaction relevant to the slepton decay**

$$-\mathcal{L}_{\tilde{\chi}^0_1\text{-}l\text{-}\tilde{l}} = \tilde{l}^* \overline{\tilde{\chi}^0_1}(G_{L1}P_L + G_{R1}P_R)l + \text{h.c.}$$

$$G_{L1} = \frac{m_l g_2}{\sqrt{2}m_W \cos\beta} \sin\theta_l e^{i\gamma_l} N_{1\tilde{H}^0_d},$$

$$G_{R1} = \frac{m_l g_2}{\sqrt{2}m_W \cos\beta} \cos\theta_l N_{1\tilde{H}^0_d},$$

- G_{L1} and G_{R1} are typically small comparing to those in the case of bino-like neutralino LSP.

→
- **Longer lifetime of the slepton ($\tau_{\tilde{l}}$)**
- **Longer timescale of Internal Conversion (τ_{IC})**

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

Bino-like neutralino LSP

> **Interaction relevant to the slepton decay**

include NMSSM parameters (do not depend on κ)

$$-\mathcal{L}_{\tilde{\chi}_1^0\text{-}l\text{-}\tilde{l}} = \tilde{l}^* \overline{\tilde{\chi}_1^0}(G_{L1}P_L + G_{R1}P_R)l + \text{h.c.}$$

$$G_{L1} = \frac{g_2}{\sqrt{2}} \tan\theta_W \cos\theta_l - \frac{m_l g_2}{\sqrt{2} m_W \cos\beta} \sin\theta_l e^{i\gamma_l} N_{1\tilde{H}_d^0},$$

$$G_{R1} = \sqrt{2} g_2 \tan\theta_W \sin\theta_l e^{i\gamma_l} + \frac{m_l g_2}{\sqrt{2} m_W \cos\beta} \cos\theta_l N_{1\tilde{H}_d^0}$$

- The second terms are typically small comparing to the first terms in G_{L1} and G_{R1}.

($N_{1\tilde{H}_d^0} \to 0$ ⇒ same as in bino neutralino in MSSM)

✓ Parameters : λ, $\tan\beta$, s

Strategy

NMSSM
- ✓ Light element abundances
- ✓ Dark Matter relic density
- ✓ Higgs boson mass

1. Search for allowed region on λ-κ plane

✓ **Theoretical constraints :**
- *lifetime of the slepton* $\tau_{\tilde{l}}$
- *timescale of the internal conversion processes* τ_{IC}

2. Select several points allowed from phenomenology

✓ **Phenomenological constraints :**
- *the Higgs boson mass* m_h
- *DM relic density* $\Omega_{\mathrm{DM}} h^2$
- *etc.*

→ NMSSMTools

U. Ellwanger, C.Hugonie

3. Confirm the points to give suitable light element abundances

✓ Nuclear network calculation (show the results on δm-$Y_{\tilde{l}^-}$ plane)

Theoretical constraints

- **Lifetime of the slepton**

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

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

$({}^4\text{He}\ \tilde{l}^-) + \text{D} \to {}^6\text{Li} + \tilde{l}^-$

... to avoid over-production of ^{6}Li.

... to form bound state with nuclei for IC.

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

- **Timescale of the Internal Conversion**

$\tau_{IC} < 0.1\tau_{\tilde{l}}$ ... to reduce enough amount of ^{7}Li.

- **Rate of dominant component in the LSP neutralino**

$N^2_{1\tilde{S}} > 0.9$ … for singlino-like LSP

$N^2_{1\tilde{B}} > 0.9$ … for bino-like LSP

Phenomenological constraints

- **Dark matter relic density**

$$0.1118 \leq \Omega_{\rm DM} h^2 \leq 0.1280 \ (3\sigma)$$

by Planck Collaboration

- **Higgs boson mass**

$$m_h = 125.0 \pm 3 \ \text{GeV}$$

… uncertainty among calculation codes

(NMSSMTools, SPheno, etc..)

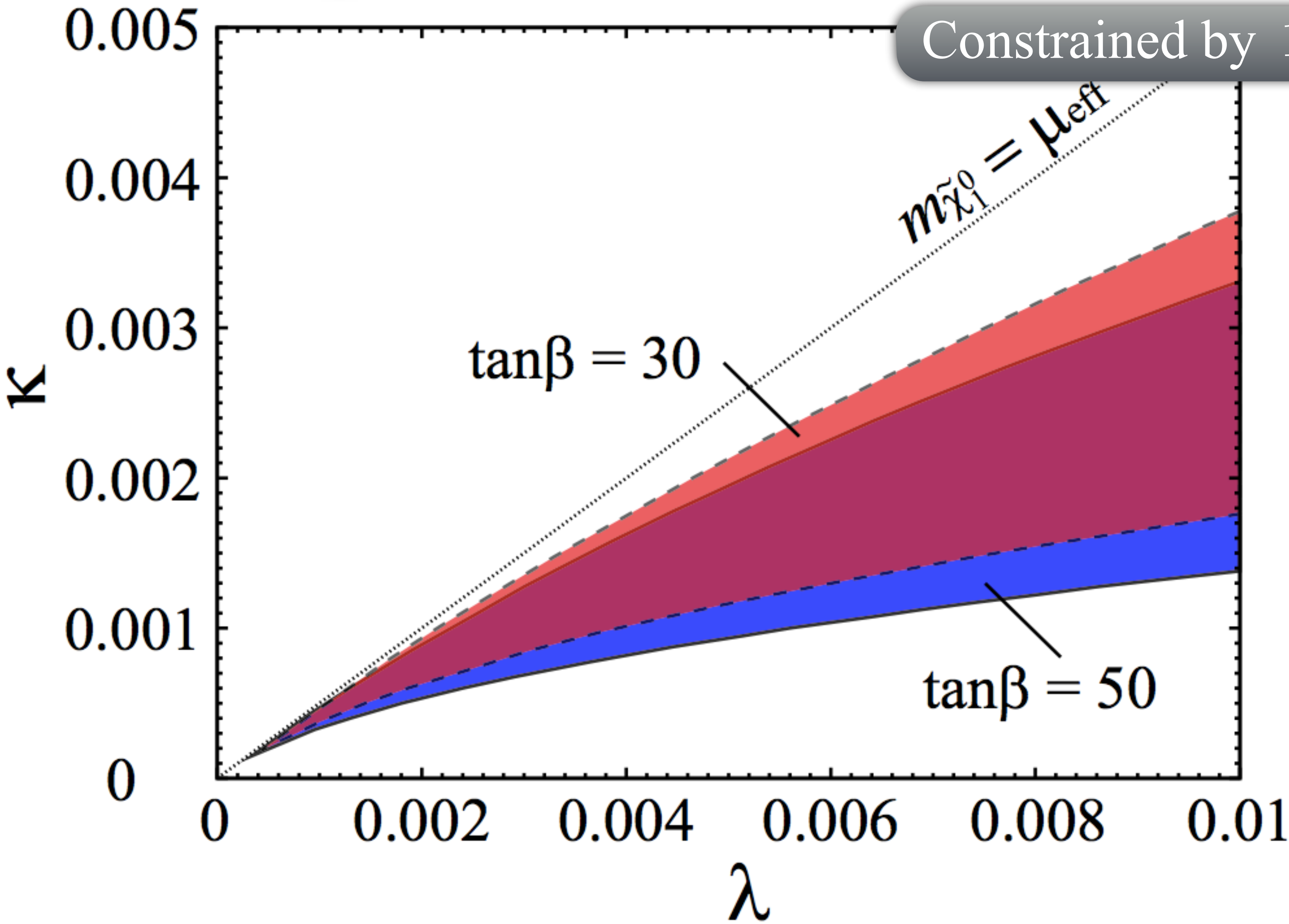
We also check $(g-2)_\mu$, and branching ratios of rare decays $B_s \to \mu^+\mu^-$ and $b \to s\gamma$ calculated by NMSSMTools.

Results

Case 1. Singlino-like LSP, small λ-κ region

1. The region allowed from theoretical constraints

Constrained by $10^3\text{sec} < \tau_{\tilde{l}} < 10^5\text{sec}$



$m_{\tilde{\chi}_1^0} = 350$ GeV

$\delta m = 0.1$ GeV

$\sin\theta_l = 0.8$

$\gamma_l = 0$

$c_e = 10^{-4.5}$

✓ Larger κ, and/or $\tan\beta$, smaller λ

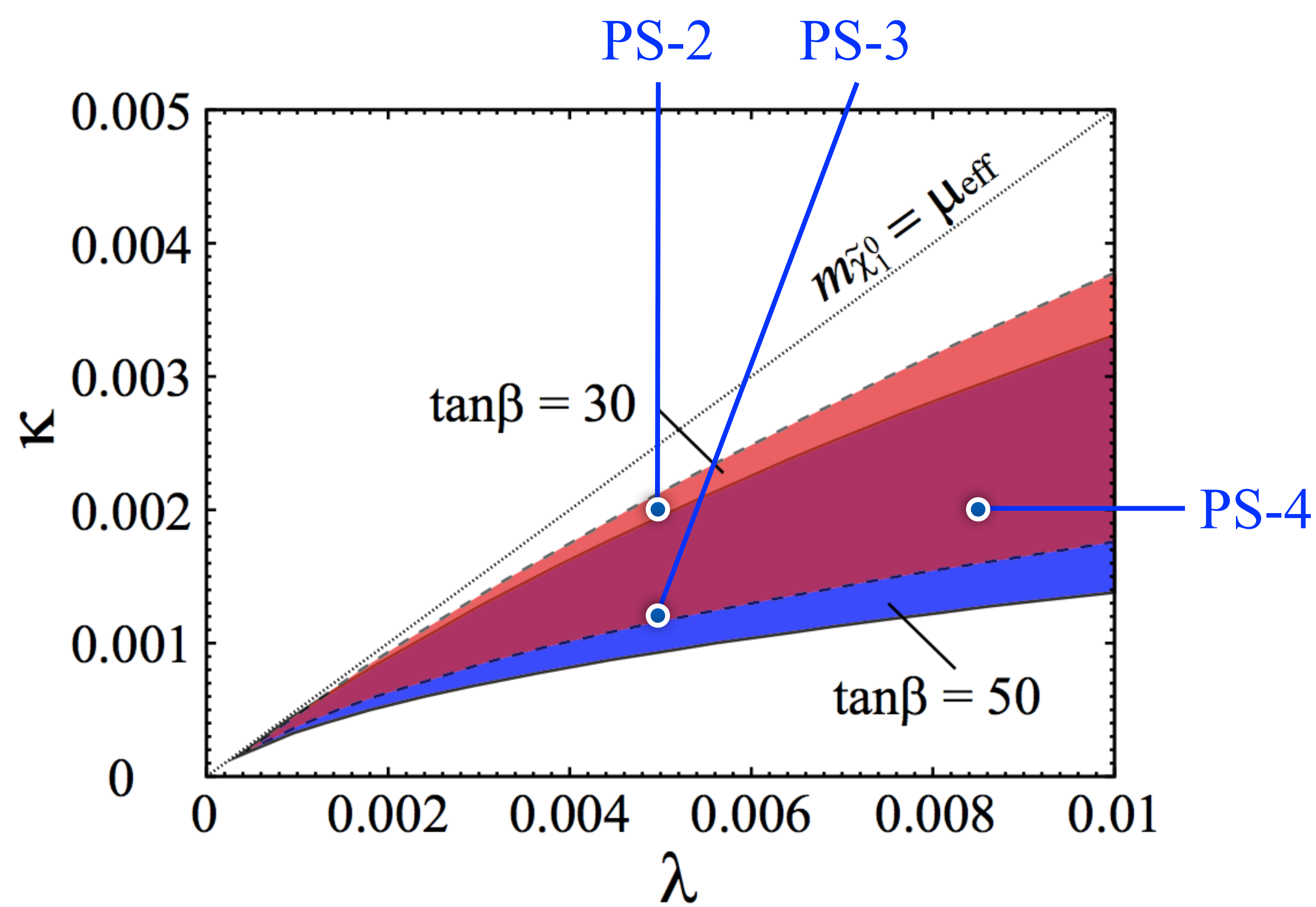
→ larger G_{L1} → shorter $\tau_{\tilde{l}}$ and $\tau_{\rm IC}$

2. The points which satisfy phenomenological constraints

Input	PS-1, PS-2	PS-3	PS-4
M_2	1000.0	1000.0	1000.0
A_t	-7200.0	-7200.0	-7200.0
A_τ	-7200.0	-1000.0	-400.00
$m_{\tilde{L}_3}$	409.72	416.69	416.16
$m_{\tilde{E}_3}$	383.90	388.08	387.75
λ	0.0050	0.0050	0.0085
κ	0.0020	0.0 012	0.0020
A_λ	800.00	800.00	800.00
A_κ	-100.00	-100.00	-100.00
$\mu_{\rm eff}$	426.39	714.61	728.81
$\tan\beta$	30.000	30.000	30.000
Output			
h_1^0	125.30	124.82	124.55
h_2^0	315.13	317.05	317.06
h_3^0	3512.5	4512.6	5424.1
a_1^0	226.20	226.83	226.81
a_2^0	3512.6	4512.6	5424.1
$H^\pm$	3511.2	4501.2	5411.7
$\tilde{b}_1$	3093.1	3089.9	3089.8
$\tilde{b}_2$	3108.0	3111.2	3111.3
$\tilde{t}_1$	2932.3	2932.1	2932.1
$\tilde{t}_2$	3265.3	3265.5	3265.5
$\tilde{\tau}_1$	350.10	350.10	350.10
$\tilde{\tau}_2$	443.35	453.37	452.59
$\tilde{g}$	3193.7	3193.7	3193.7
$\tilde{\chi}_1^0$	350.00	350.00	350.00
$\tilde{\chi}_2^0$	418.18	485.45	485.76
$\tilde{\chi}_3^0$	-440.50	722.15	735.99
$\tilde{\chi}_4^0$	502.72	-731.60	-746.16
$\tilde{\chi}_5^0$	1035.9	1040.8	1041.8
$\tilde{\chi}_1^\pm$	433.78	719.76	733.82
$\tilde{\chi}_2^\pm$	1035.9	1040.8	1041.8
$\Omega_{\tilde{\chi}_1^0}h^2$	0.12306	0.11354	0.11509
$\sigma_{\rm SI}[\rm cm^2]$	4.3172×10^{-51}	8.6107×10^{-52}	6.0035×10^{-51}
δa_μ	$1.1604\times10^{-9}(2\sigma)$	$9.0488\times10^{-10}(3\sigma)$	$8.9167\times10^{-10}(3\sigma)$
$\mathrm{Br}(B_s^0\to\mu^+\mu^-)$	$3.4352\times10^{-9}(1\sigma)$	$3.4450\times10^{-9}(1\sigma)$	$3.4727\times10^{-9}(1\sigma)$
$\mathrm{Br}(b\to s\gamma)$	$3.0310\times10^{-4}(2\sigma)$	$3.0086\times10^{-4}(3\sigma)$	$3.0029\times10^{-4}(3\sigma)$

Assumption:

$$m_{Q_{1,2}} = m_{Q_3},\ m_{U_{1,2}} = m_{U_3},\ m_{D_{1,2}} = m_{D_3},$$
$$m_{L_{1,2}} = m_{L_3},\ m_{E_{1,2}} = m_{E_3},$$
$$M_1 = M_2/2,\ M_3 = 3M_2,\ A_{e,\mu} = A_\tau$$



… suitable m_h and $\Omega_{\rm DM}h^2$ are obtained.

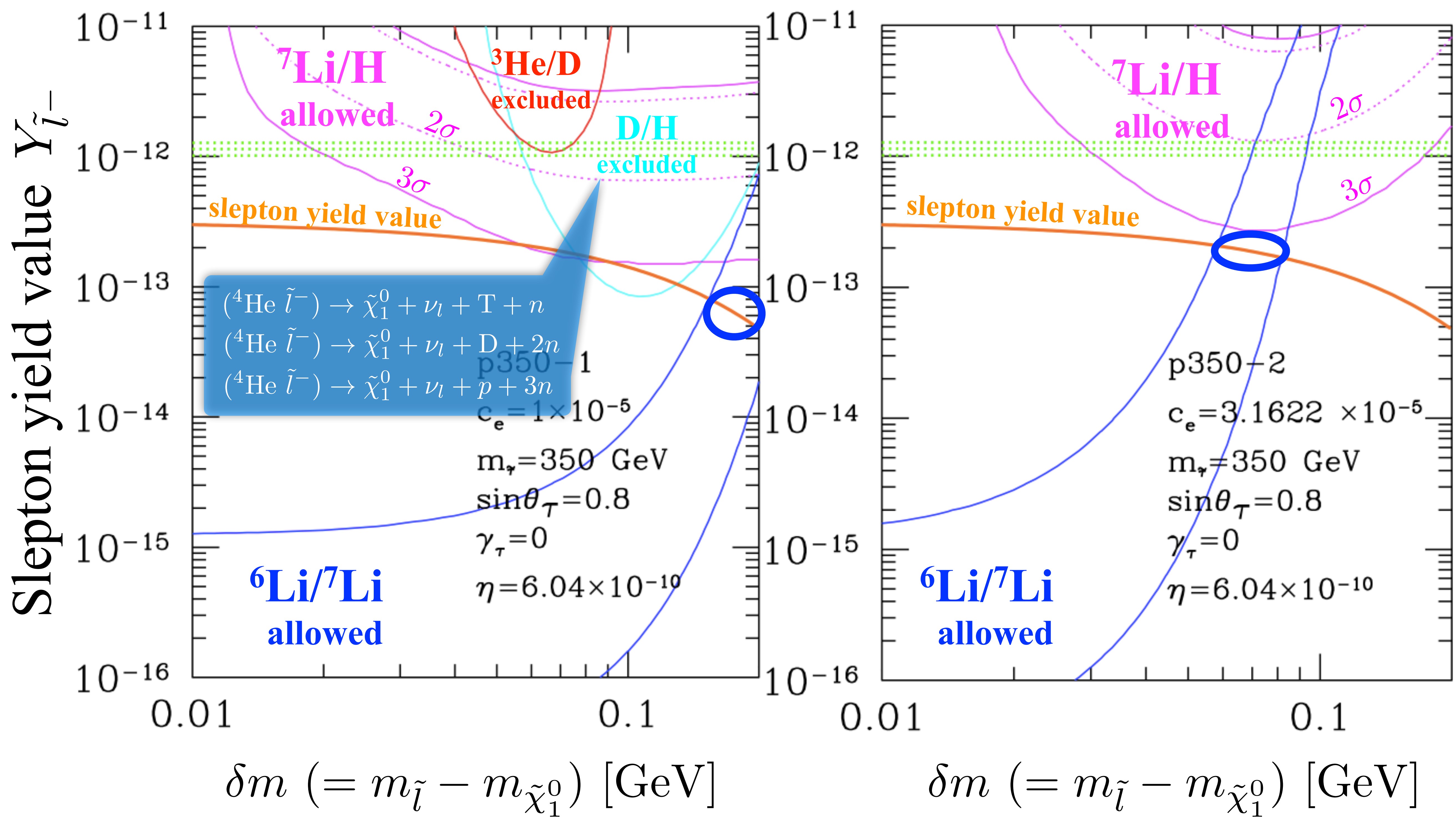
realized by large 1-loop contribution (same as MSSM)

*NMSSMTools ver.4.1.1, *GeV

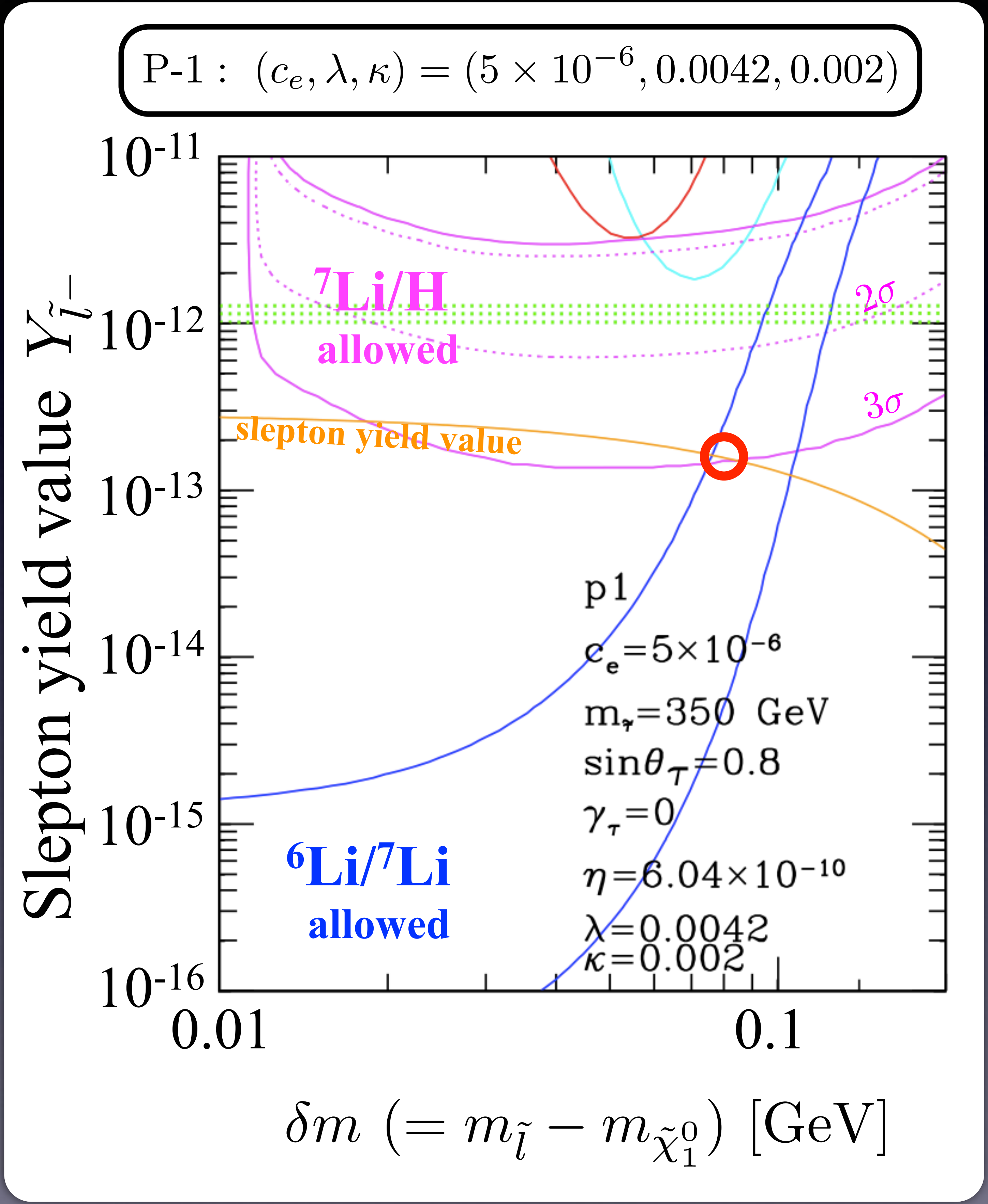
3. Results of BBN calculation

PS-1 : $(c_e, \lambda, \kappa) = (10^{-5}, 0.005, 0.002)$

PS-2 : $(c_e, \lambda, \kappa) = (10^{-4.5}, 0.005, 0.002)$



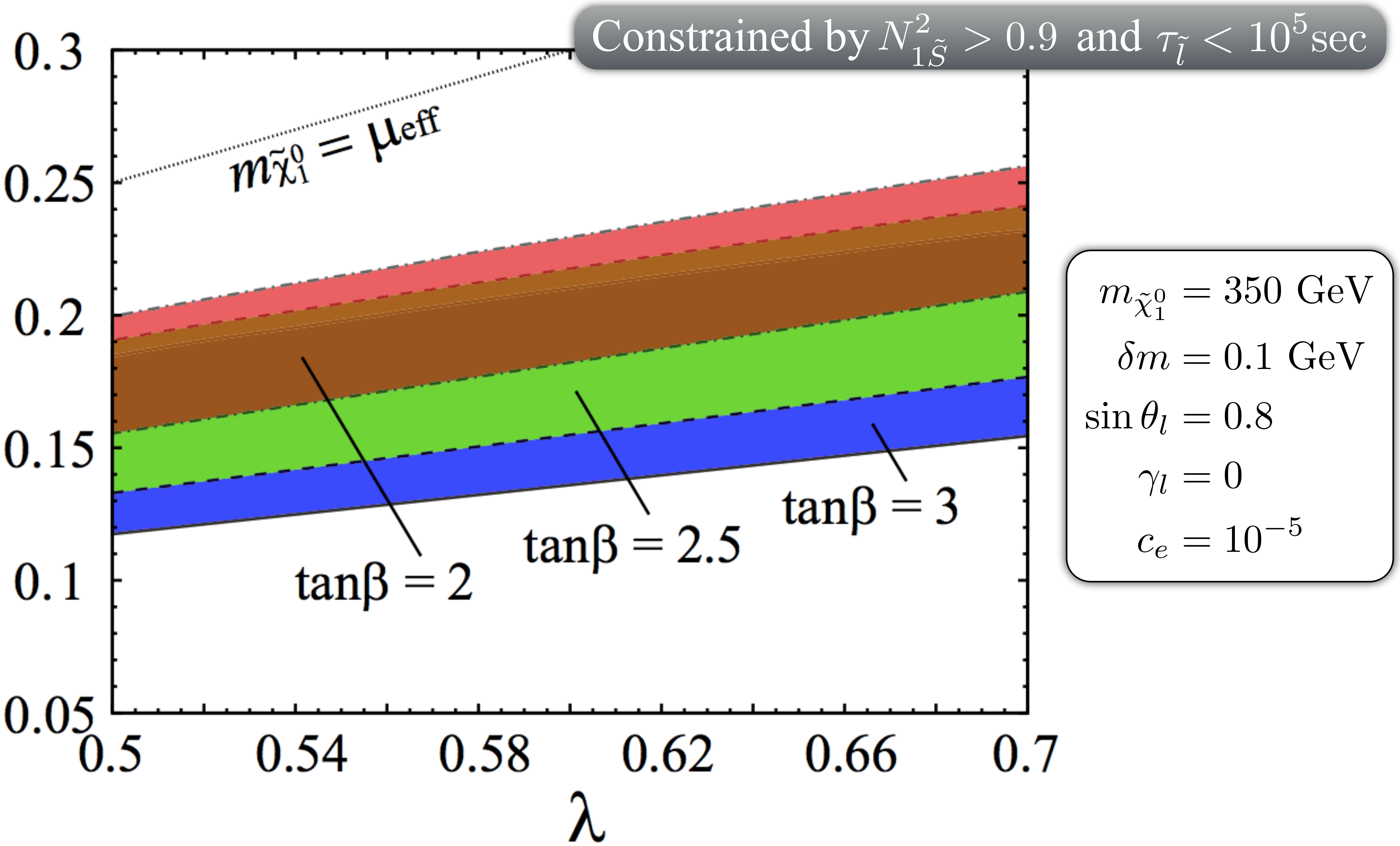
3. Results of BBN calculation



Results

Case 2. Singlino-like LSP, large λ-κ region

1. The region allowed from theoretical constraints

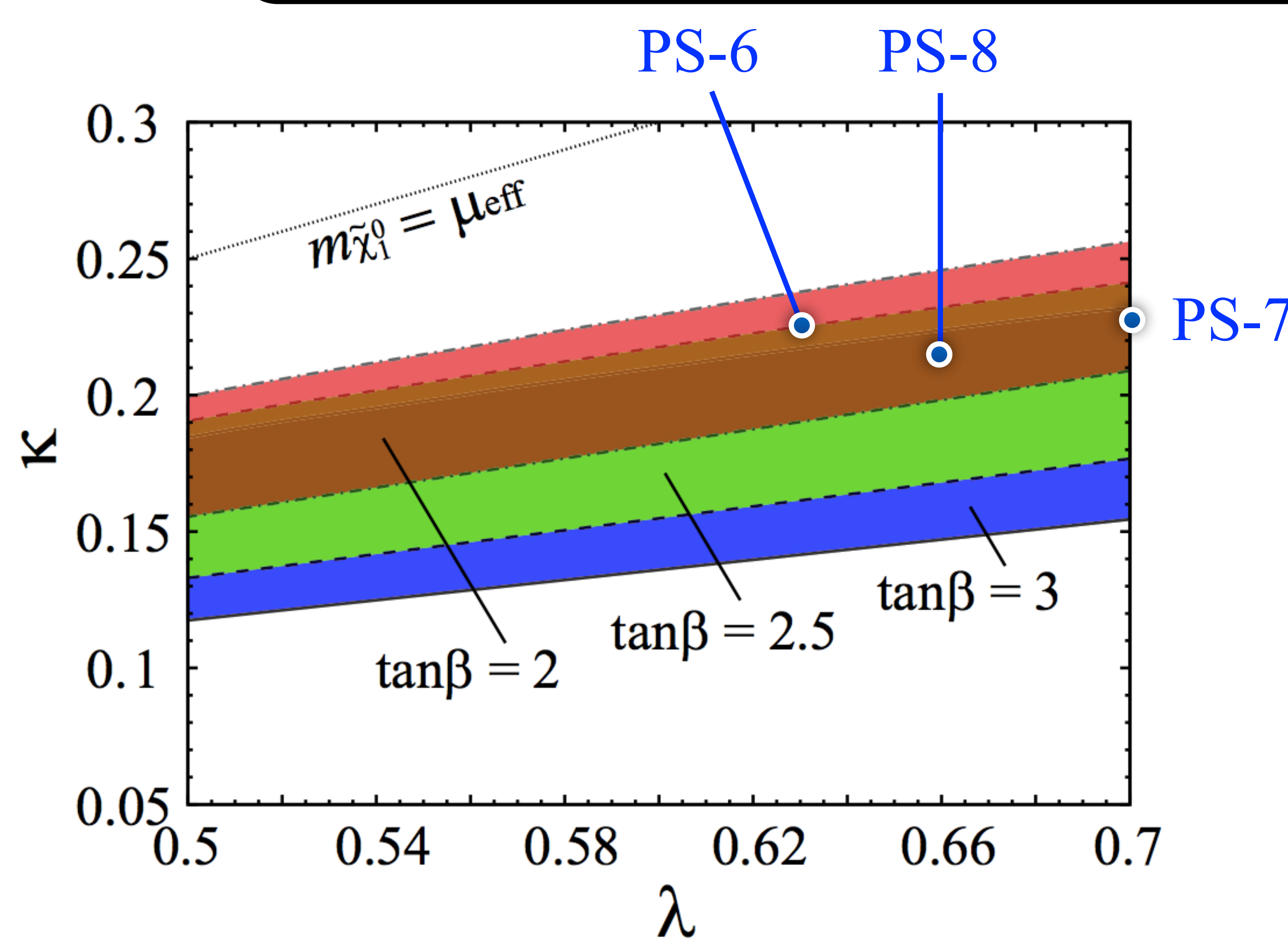


2. The points which satisfy phenomenological constraints

Input	PS-5, PS-6	PS-7	PS-8
M_2	1000.0	1000.0	1000.0
A_t	−1500.0	−1500.0	−1500.0
A_τ	−1500.0	−1500.0	−1500.0
$m_{\tilde{L}_3}$	356.97	357.38	357.40
$m_{\tilde{E}_3}$	353.31	353.53	353.55
$m_{\tilde{Q}_3}$	1000.0	1000.0	1000.0
$m_{\tilde{U}_3}$	1000.0	1000.0	1000.0
$m_{\tilde{D}_3}$	1000.0	1000.0	1000.0
λ	0.6300	0.7000	0.6600
κ	0.2300	0.2300	0.2150
A_λ	1050.0	1080.0	1150.0
A_κ	−10.000	−50.000	−100.00
$\mu_{\rm eff}$	479.78	527.45	531.54
$\tan\beta$	2.5000	2.5000	2.5000
Output			
h_1^0	124.33	126.41	125.95
h_2^0	365.73	361.55	347.64
h_3^0	1306.0	1384.4	1428.4
a_1^0	142.35	204.78	256.15
a_2^0	1304.6	1383.5	1427.5
$H^\pm$	1299.0	1375.8	1420.7
$\tilde{b}_1$	822.97	822.79	822.77
$\tilde{b}_2$	830.40	830.58	830.60
$\tilde{t}_1$	703.40	701.86	701.68
$\tilde{t}_2$	953.20	954.76	954.89
$\tilde{\tau}_1$	350.10	350.10	350.10
$\tilde{\tau}_2$	364.09	364.70	364.75
$\tilde{g}$	2881.7	2881.7	2881.7
$\tilde{\chi}_1^0$	350.00	350.00	350.00
$\tilde{\chi}_2^0$	456.22	472.39	472.62
$\tilde{\chi}_3^0$	−498.62	−548.29	−550.81
$\tilde{\chi}_4^0$	528.51	556.97	558.88
$\tilde{\chi}_5^0$	1011.7	1013.2	1013.4
$\tilde{\chi}_1^\pm$	476.01	522.67	526.66
$\tilde{\chi}_2^\pm$	1011.7	1013.1	1013.3
$\Omega_{\tilde{\chi}_1^0} h^2$	0.11220	0.11939	0.12643
$\sigma_{\rm SI}[{\rm cm}^2]$	3.3230×10^{-45}	1.9286×10^{-45}	6.6097×10^{-46}
δa_μ	$1.2586\times10^{-10}(>3\sigma)$	$1.2364\times10^{-10}(>3\sigma)$	$1.2299\times10^{-10}(>3\sigma)$
${\rm Br}(B_s^0\to\mu^+\mu^-)$	$3.5365\times10^{-9}(1\sigma)$	$3.5368\times10^{-9}(1\sigma)$	$3.5370\times10^{-9}(1\sigma)$
${\rm Br}(b\to s\gamma)$	$3.1812\times10^{-4}(2\sigma)$	$3.1743\times10^{-4}(2\sigma)$	$3.1677\times10^{-4}(2\sigma)$

Assumption:

$$m_{Q_{1,2}} = m_{Q_3},\ m_{U_{1,2}} = m_{U_3},\ m_{D_{1,2}} = m_{D_3},$$
$$m_{L_{1,2}} = m_{L_3},\ m_{E_{1,2}} = m_{E_3},$$
$$M_1 = M_2/2,\ M_3 = 3M_2,\ A_{e,\mu} = A_\tau$$



… suitable m_h and $\Omega_{\rm DM} h^2$ are obtained.

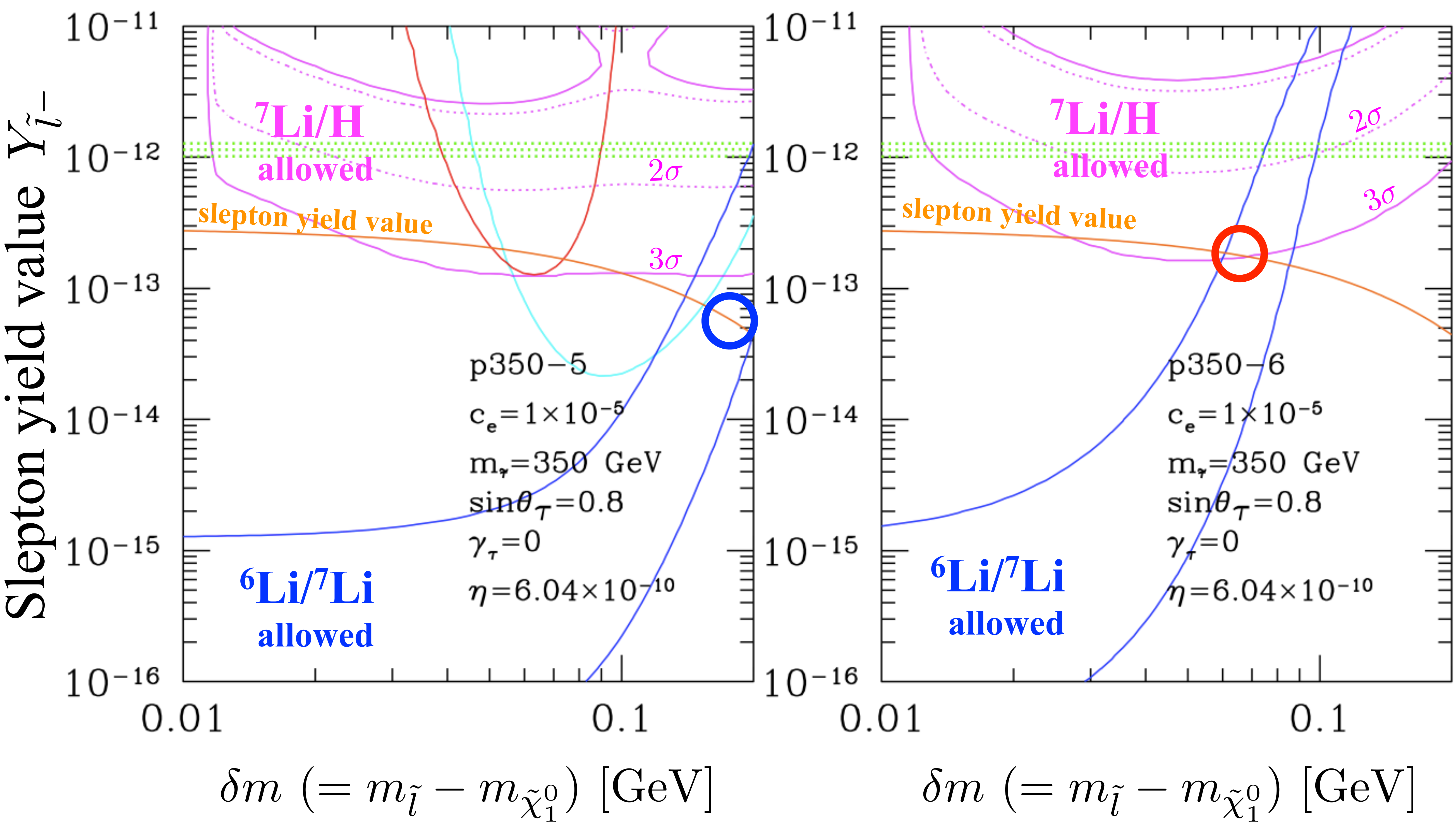
realized by large tree contribution
(different from MSSM)

*NMSSMTools ver.4.1.1, *GeV

3. Results of BBN calculation

$\mathrm{PS\text{-}5}: \; (c_e, \lambda, \kappa) = (10^{-5.5}, 0.63, 0.23)$

$\mathrm{PS\text{-}6}: \; (c_e, \lambda, \kappa) = (10^{-5}, 0.63, 0.23)$



Results

Case 3. Bino-like LSP, large λ-κ region

Results

Case 3. Bino-like LSP, large λ-κ region

✓ G_{L1} and G_{R1} are almost independent from λ, κ, and $\tan\beta$.

✓ We choose points at which suitable DM relic density and the Higgs boson mass without taking the theoretical conditions into account.

2. The points which satisfy phenomenological constraints

Input	PB-1	PB-2	PB-3	PB-4
M_2	713.14	713.25	713.36	712.97
A_t	−1500.0	−1500.0	−1500.0	−1500.0
A_τ	−1500.0	−1500.0	−1500.0	−1500.0
$m_{\tilde{L}_3}$	359.32	359.32	359.32	359.32
$m_{\tilde{E}_3}$	354.76	354.76	354.76	354.76
$m_{\tilde{Q}_3}$	1000.0	1000.0	1000.0	1000.0
$m_{\tilde{U}_3}$	1000.0	1000.0	1000.0	1000.0
$m_{\tilde{D}_3}$	1000.0	1000.0	1000.0	1000.0
λ	0.6000	0.6800	0.6800	0.6000
κ	0.2000	0.2000	0.3200	0.3200
A_λ	1500.0	1480.0	1000.0	1500.0
A_κ	−100.00	−100.00	−100.00	−100.00
$\mu_{\rm eff}$	900.00	900.00	900.00	900.00
$\tan\beta$	2.0000	2.0000	2.0000	2.0000
Output				
h_1^0	124.19	126.51	125.23	124.35
h_2^0	609.68	552.89	844.57	960.06
h_3^0	2014.2	1983.6	1793.5	2115.8
a_1^0	304.76	289.22	372.60	379.68
a_2^0	2014.3	1983.7	1792.3	2114.5
$H^\pm$	2007.0	1974.3	1783.8	2108.5
$\tilde{b}_1$	988.74	988.71	988.67	988.80
$\tilde{b}_2$	996.89	996.85	996.82	996.95
$\tilde{t}_1$	853.45	853.41	853.37	853.51
$\tilde{t}_2$	1132.2	1132.1	1132.1	1132.2
$\tilde{\tau}_1$	350.10	350.10	350.10	350.10
$\tilde{\tau}_2$	367.13	367.13	367.13	367.13
$\tilde{g}$	2068.2	2068.5	2068.8	2067.7
$\tilde{\chi}_1^0$	350.00	350.00	350.00	350.00
$\tilde{\chi}_2^0$	602.38	534.28	696.36	697.51
$\tilde{\chi}_3^0$	699.76	699.36	842.69	−906.34
$\tilde{\chi}_4^0$	−907.56	−909.78	−908.00	914.24
$\tilde{\chi}_5^0$	934.51	934.66	944.68	984.08
$\tilde{\chi}_1^\pm$	697.54	697.56	697.21	697.60
$\tilde{\chi}_2^\pm$	929.52	929.50	929.28	929.61
$\Omega_{\tilde{\chi}_1^0}h^2$	0.11964	0.11964	0.11956	0.11968
$\sigma_{\rm SI}[{\rm cm}^2]$	7.7946×10^{-46}	7.5748×10^{-46}	7.3740×10^{-46}	7.4233×10^{-46}
δa_μ	$1.3321\times10^{-10}(>3\sigma)$	$1.3370\times10^{-10}(>3\sigma)$	$1.3398\times10^{-10}(>3\sigma)$	$1.3296\times10^{-10}(>3\sigma)$
${\rm Br}(B_s^0\to\mu^+\mu^-)$	$3.5382\times10^{-9}(1\sigma)$	$3.5382\times10^{-9}(1\sigma)$	$3.5381\times10^{-9}(1\sigma)$	$3.5383\times10^{-9}(1\sigma)$
${\rm Br}(b\to s\gamma)$	$3.1732\times10^{-4}(2\sigma)$	$3.1754\times10^{-4}(2\sigma)$	$3.1907\times10^{-4}(2\sigma)$	$3.1668\times10^{-4}(2\sigma)$

Assumption:

$m_{Q_{1,2}} = m_{Q_3},\ m_{U_{1,2}} = m_{U_3},\ m_{D_{1,2}} = m_{D_3},$

$m_{L_{1,2}} = m_{L_3},\ m_{E_{1,2}} = m_{E_3},$

$M_1 = M_2/2,\ M_3 = 3M_2,\ A_{e,\mu} = A_\tau$

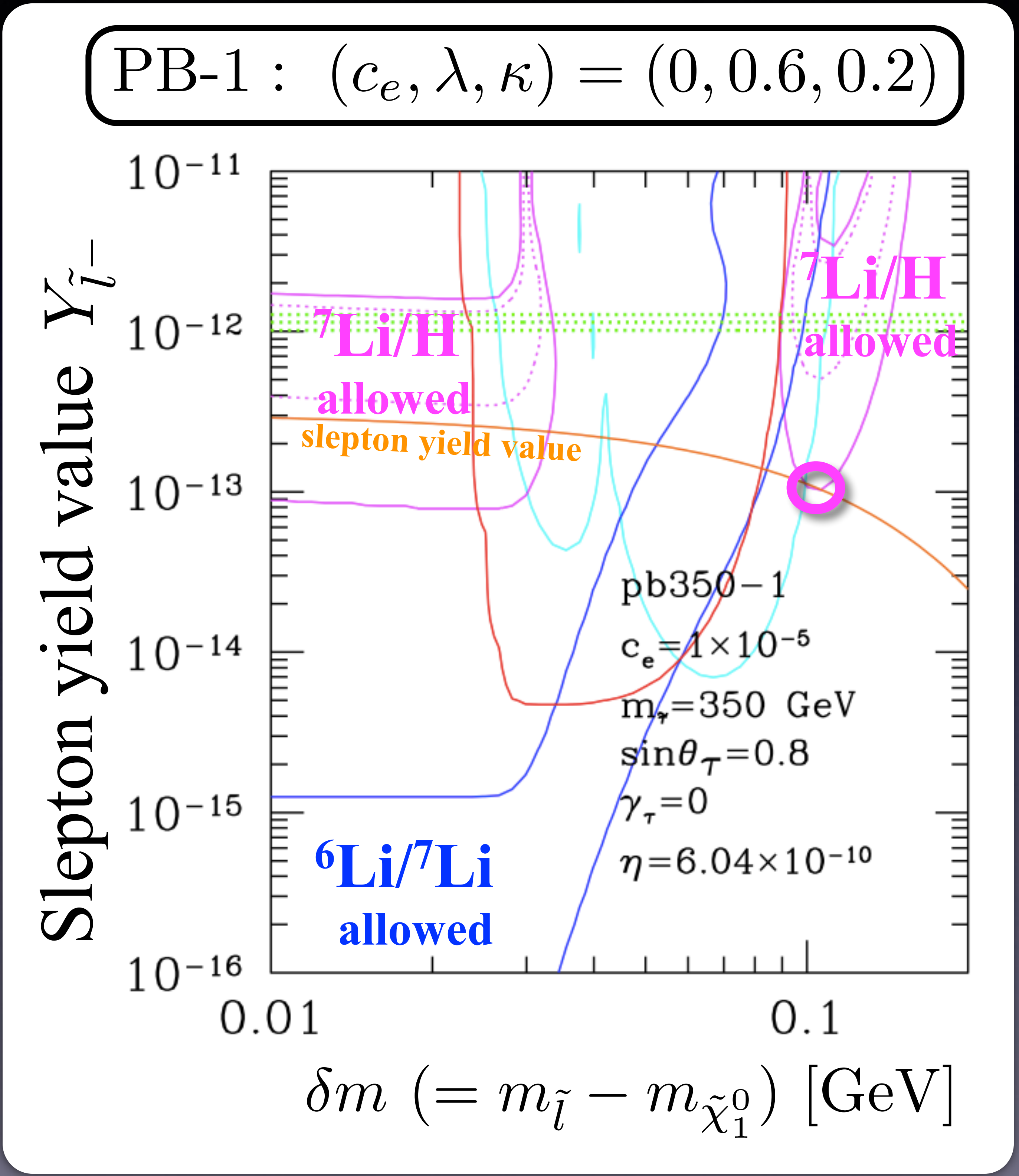
Parameters	PB-1	PB-2	PB-3	PB-4
c_e	0	0	0	0
λ	0.6	0.68	0.68	0.6
κ	0.2	0.2	0.32	0.32

… suitable m_h and $\Omega_{\rm DM}h^2$ are obtained.

realized by large tree contribution (different from MSSM)

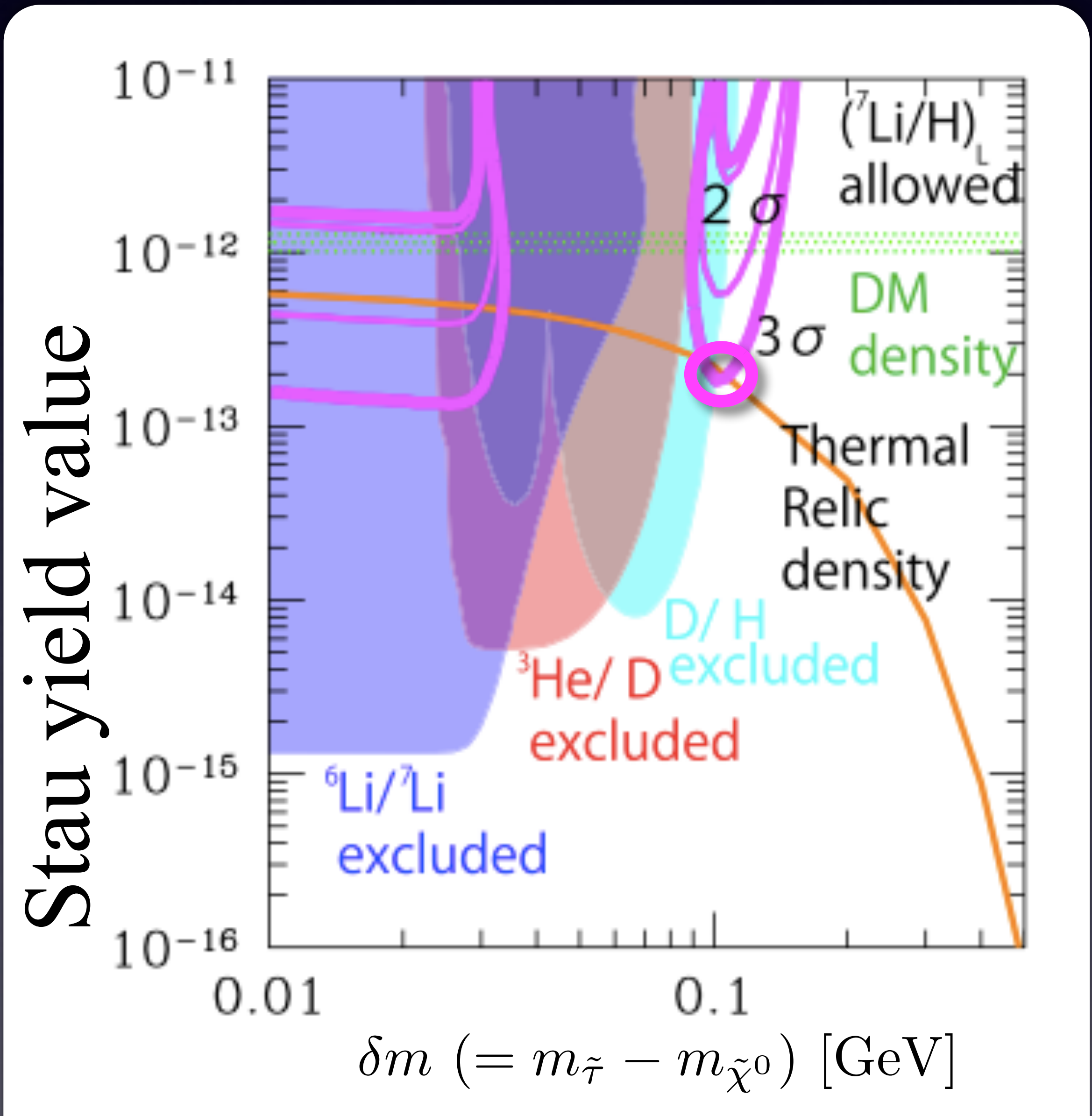
*NMSSMTools ver.4.1.1, *GeV

3. Results of BBN calculation



NMSSM

MSSM



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

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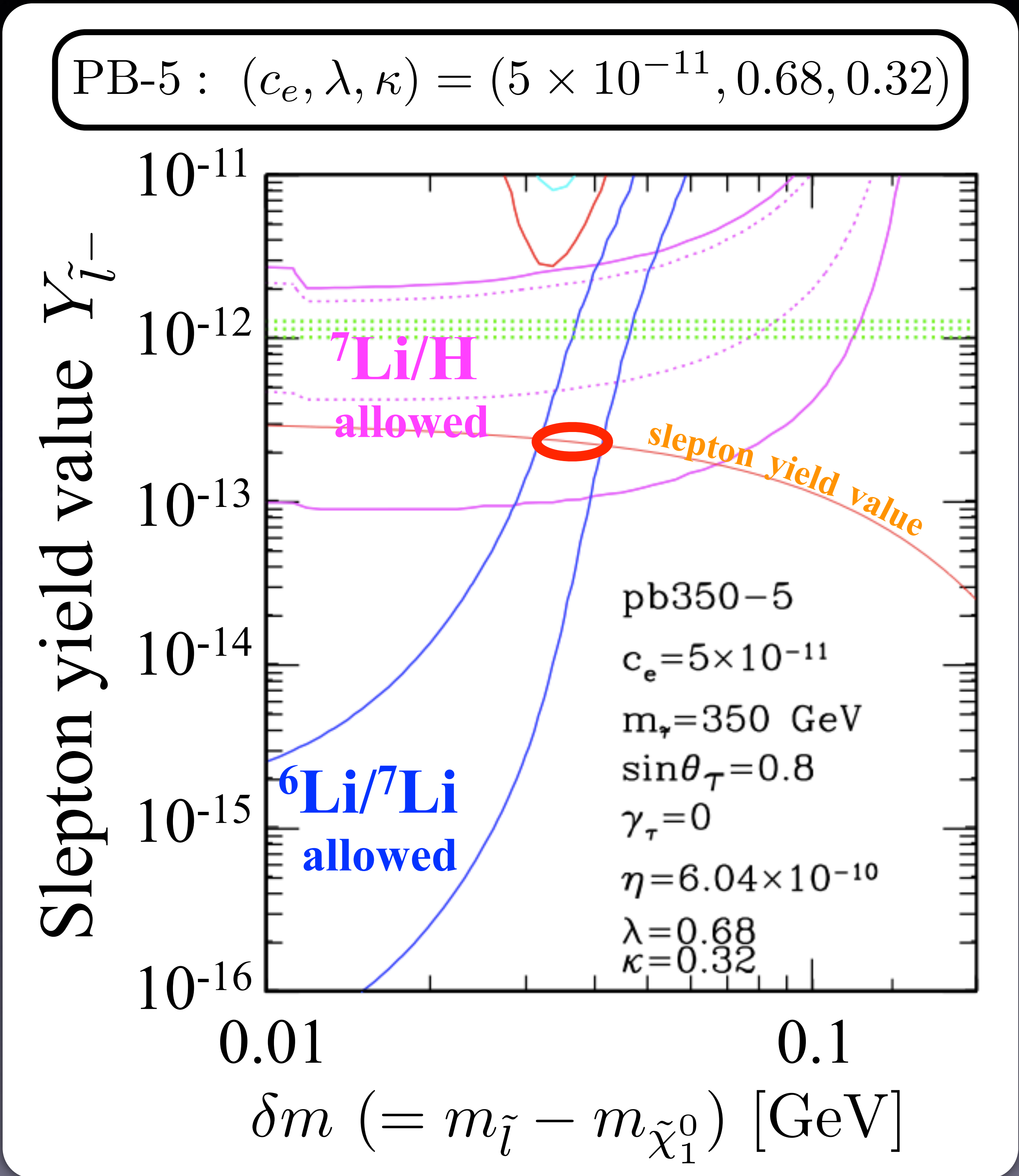
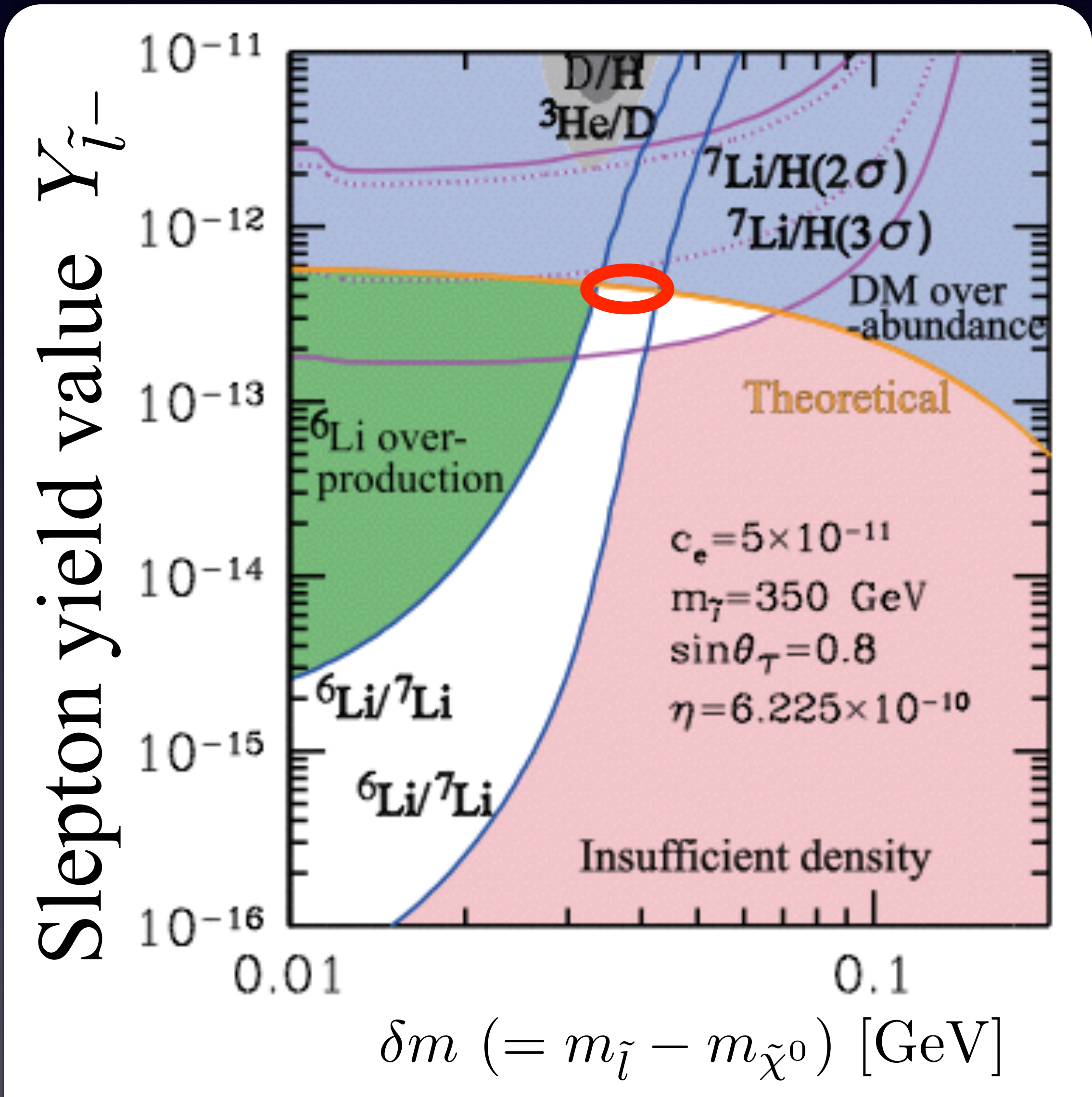


← NMSSM

↓ MSSM



K. Kohri et al., PRD86, 095024 (2012)

Summary

Motivation

MSSM
- ✓ Light element abundances
- ✓ Dark Matter relic density

→

NMSSM
- ✓ Light element abundances
- ✓ Dark Matter relic density
- ✓ Higgs boson mass

Strategy

✓ Search for allowed region on λ-κ plane
(theoretical constraints; $\tau_{\tilde{l}}$, $\tau_{\rm IC}$, and $N^2_{1\tilde{S}}(N^2_{1\tilde{B}})$)

✓ Select several points allowed from phenomenology ($\Omega_{\tilde{\chi}^0_1}h^2$ and m_h)

✓ Confirm the points to give suitable light element abundances

Results

We have found several points where suitable light element abundances (including ^{7}Li and ^{6}Li), DM relic density, and Higgs boson mass are obtained;

(1) Singlino-like neutralino LSP, small λ-κ , (2) Singlino-like neutralino LSP, large λ-κ ,

(3) Bino-like neutralino LSP, large λ-κ .

Backup

Bing-Bang Nucleosynthesis (BBN)

... primordial synthesis of light elements nuclei.

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

- Standard BBN theory
  ... based on the SM

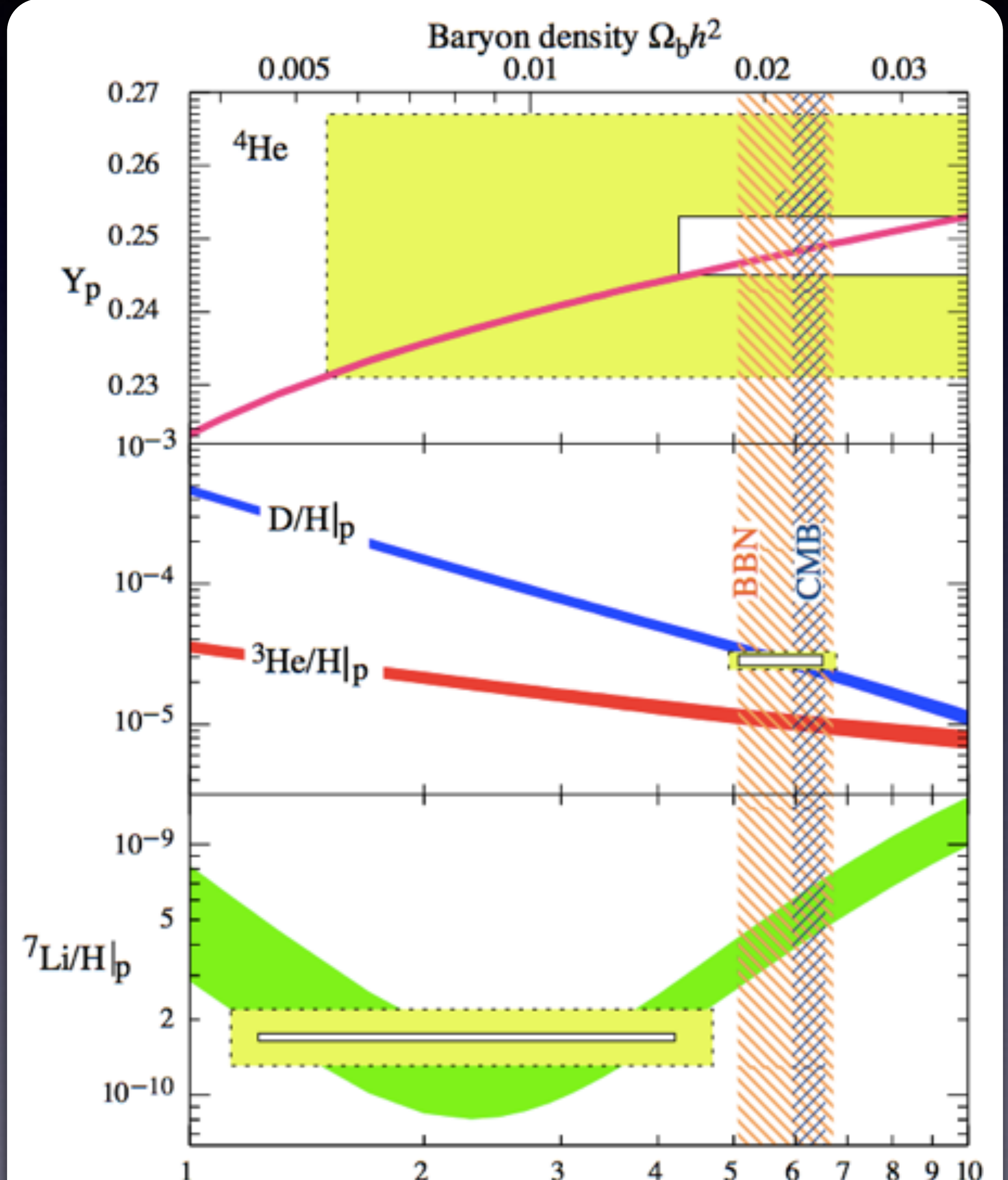
  ✓ Predicts light element abundances from only one parameter, η .

$$\eta \equiv \frac{n_{\rm baryon}}{n_{\rm photon}} = (6.225 \pm 0.170) \times 10^{-10}$$

WMAP9 result

✓ Consistent predictions with obs. in most species of light elements.

D, ^{4}He → OK!



by PDG 2012

Bing-Bang Nucleosynthesis (BBN)

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

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Lithium problems

✓ **Lithium-7 (^{7}Li) problem**

theory > observation

$\log_{10}(^7\text{Li/H}):\ -9.35 \pm 0.006 \quad -9.63 \pm 0.06$

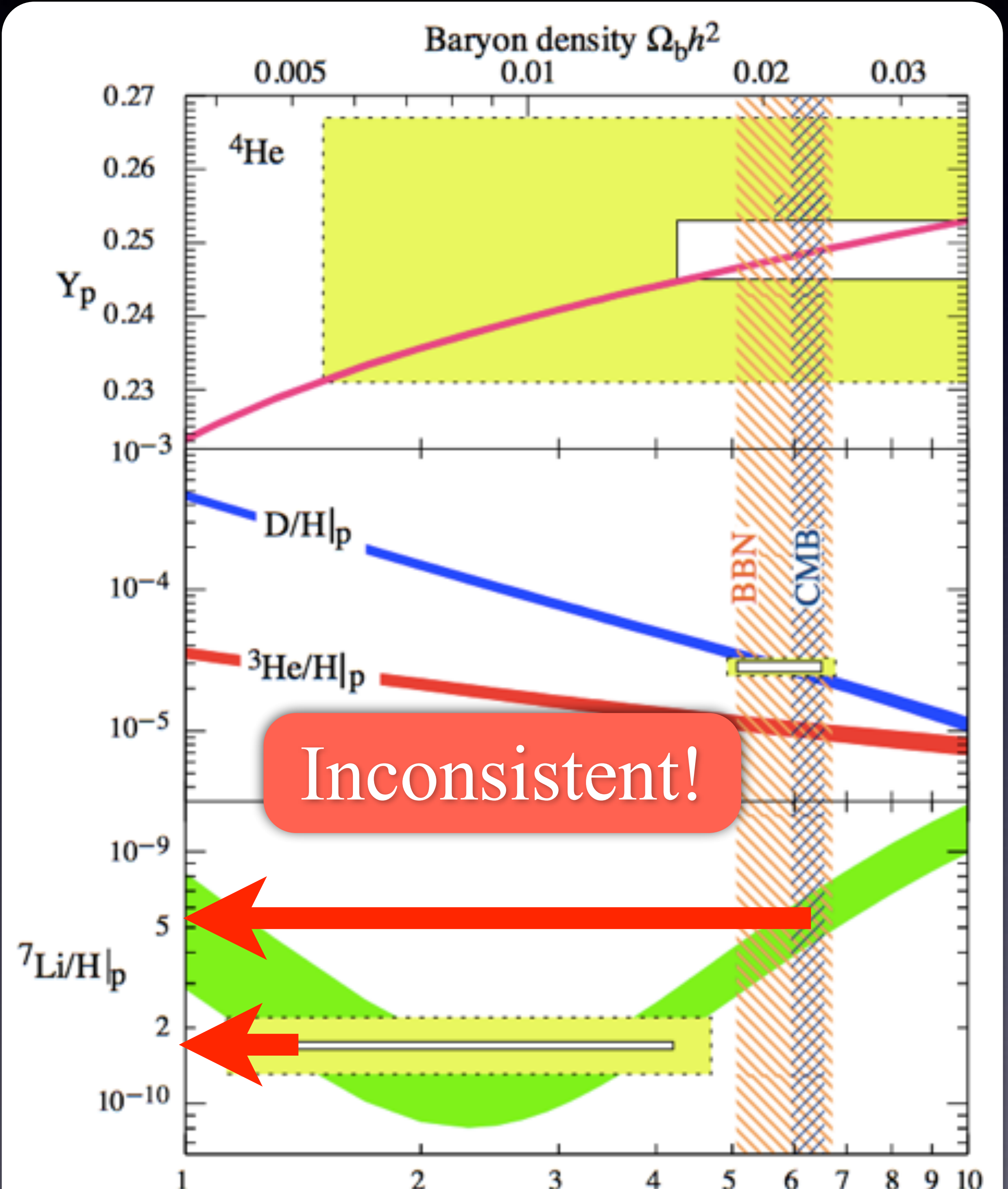
T. Jittoh et al., PRD 84, 035008 (2011),
J. Melendez and I. Ramirez, Astrophys. J. 615, L33 (2004)

✓ **Lithium-6 (^{6}Li) problem**

theory < observation

$^6\text{Li}/^7\text{Li}:\ \lesssim 10^{-4} \quad 0.046 \pm 0.022$

Vangioni-Flam E et al., New Astron 4:245(1999)
M. Asplund et al., Astrophys. J. 644, 229 (2006)



by PDG 2012

Bing-Bang Nucleosynthesis (BBN)

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

- Standard BBN theory
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Lithium problems

can be solved by exotic BBN reactions

✓ **Lithium-7 (^{7}Li) problem**

theory > observat

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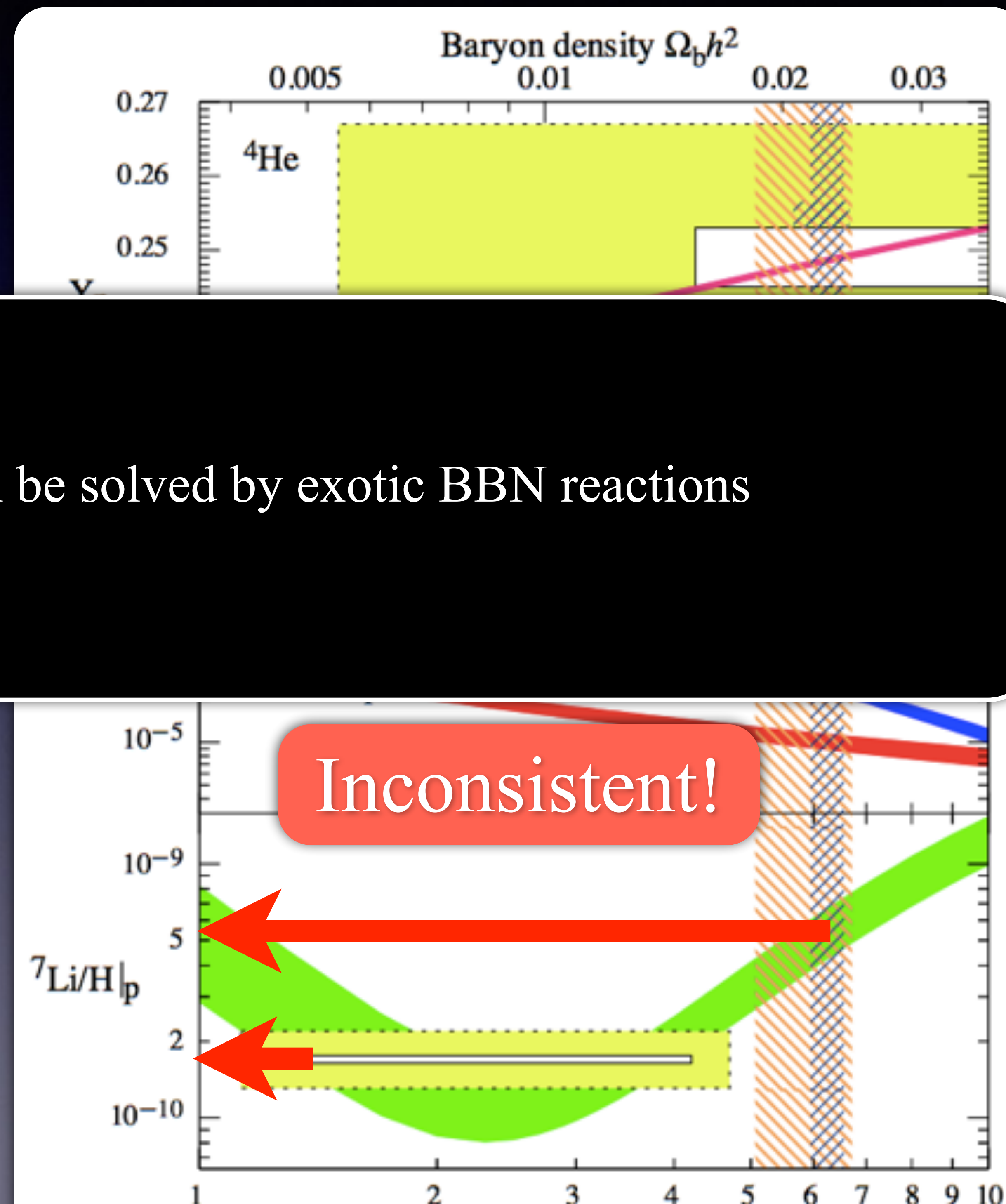


by PDG 2012

Relic stau density at the BBN

- Total number density of the SUSY particles

  ... annihilation and creation processes of SUSY particles, $\tilde{\chi}^0$ and $\tilde{\tau}$, are frozen out at T_f $(m_{\tilde{\chi}^0}/T_f \simeq 25)$

  → $n_{\tilde{\chi}^0} + n_{\tilde{\tau}^\pm}$ is fixed

  ... this sum is the relic number density of the Dark Matter, n_{DM}.

  *all SUSY particles eventually decay into the LSP

- Stau relic density

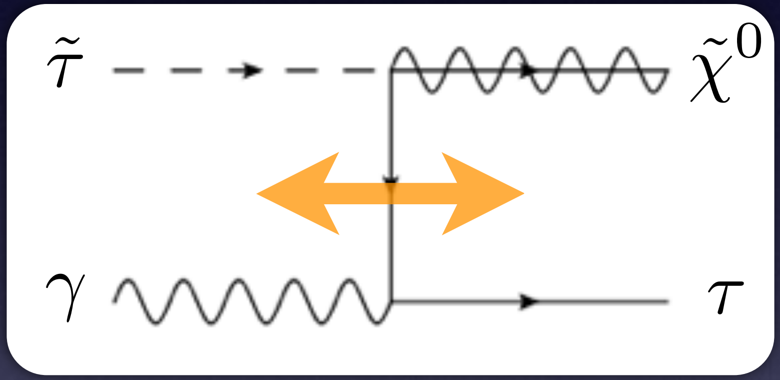
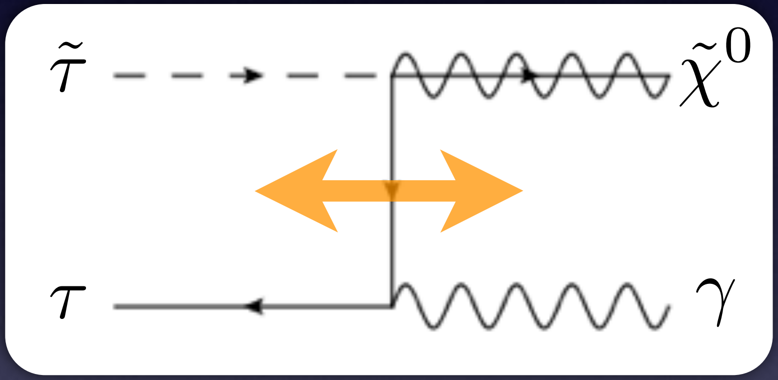
  ✓ **Even after the freeze out, stau number density is not yet fixed!**

  $n_{\tilde{\chi}^0}$, $n_{\tilde{\tau}^-}$ and $n_{\tilde{\tau}^+}$ are still evolving (with fixed n_{DM}) as the termperature of the Universe drops.

Relic stau density at the BBN

- Evolution of the stau number density until the BBN era
  ... described by Boltzmann equations for the stau

  > Exchange processes of $\tilde{\tau}$ and $\tilde{\chi}^0$

  ✓ In thermal equilibrium, $Y_{\tilde{\tau}}/Y_{\tilde{\chi}^0} \sim e^{-\delta m/T} \quad (Y_i = n_i/s)$

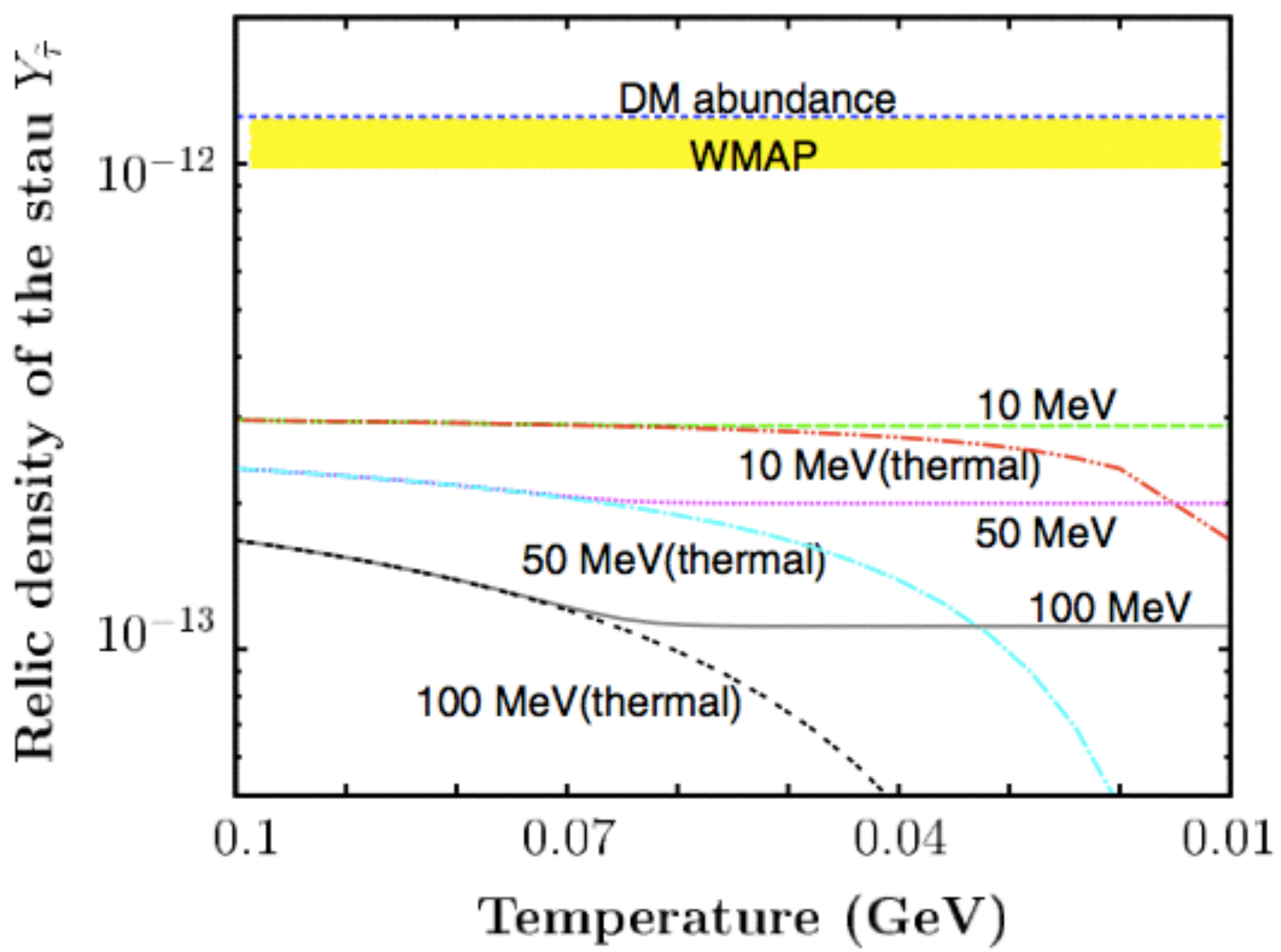
  ✓ The exchange processes are frozen out at $T_{f(\mathrm{ratio})}$

  ... compete between the reaction rates and the Hubble expansion rate.

Relic stau density at the BBN

- Evolution of the stau number density until the BBN era
  ... described by Boltzmann equations for the stau

  > Exchange



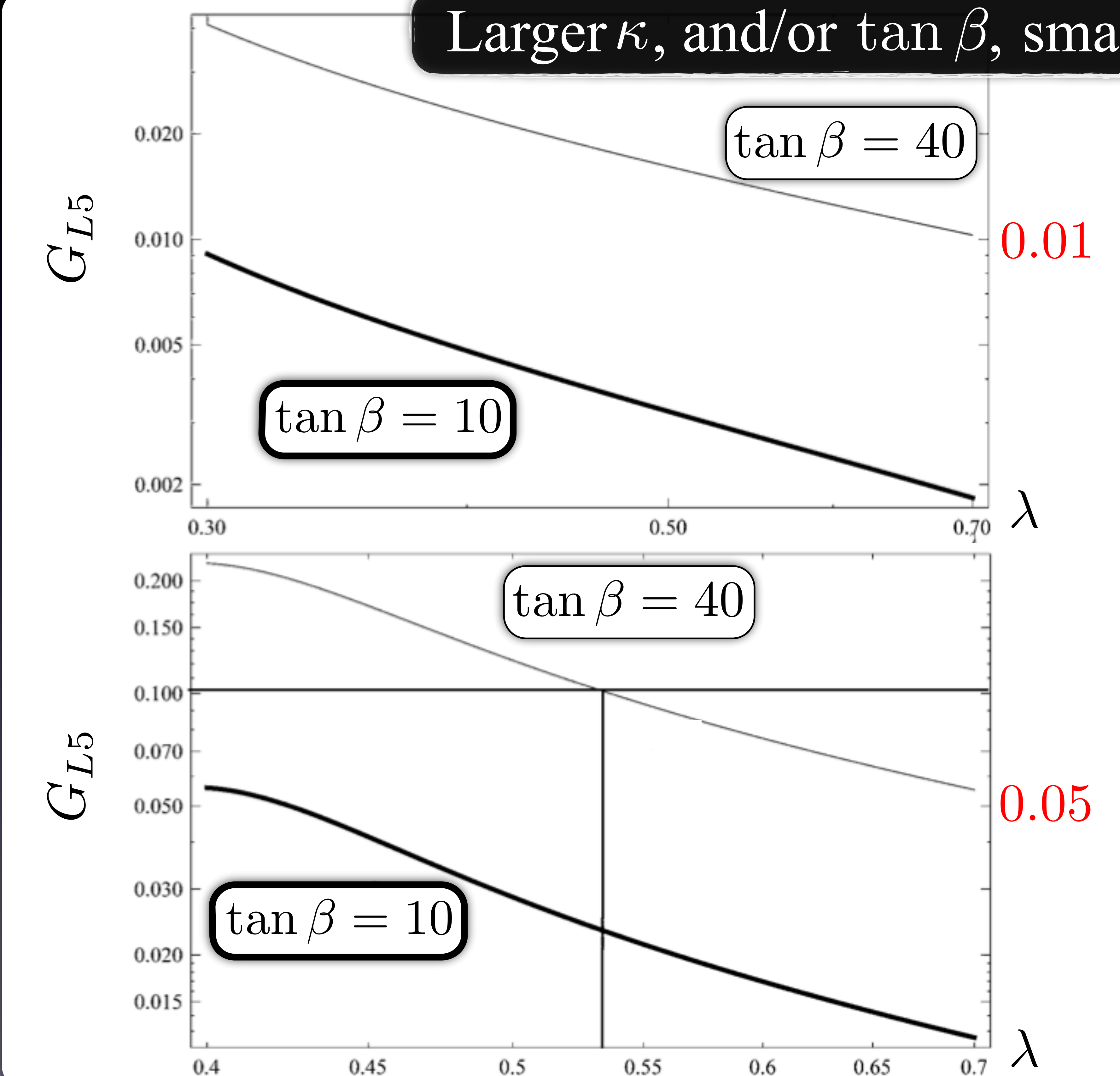
T. Jittoh et al., PRD 82, 115030 (2010)

✓ In therm ... n_i/s)

✓ The exch

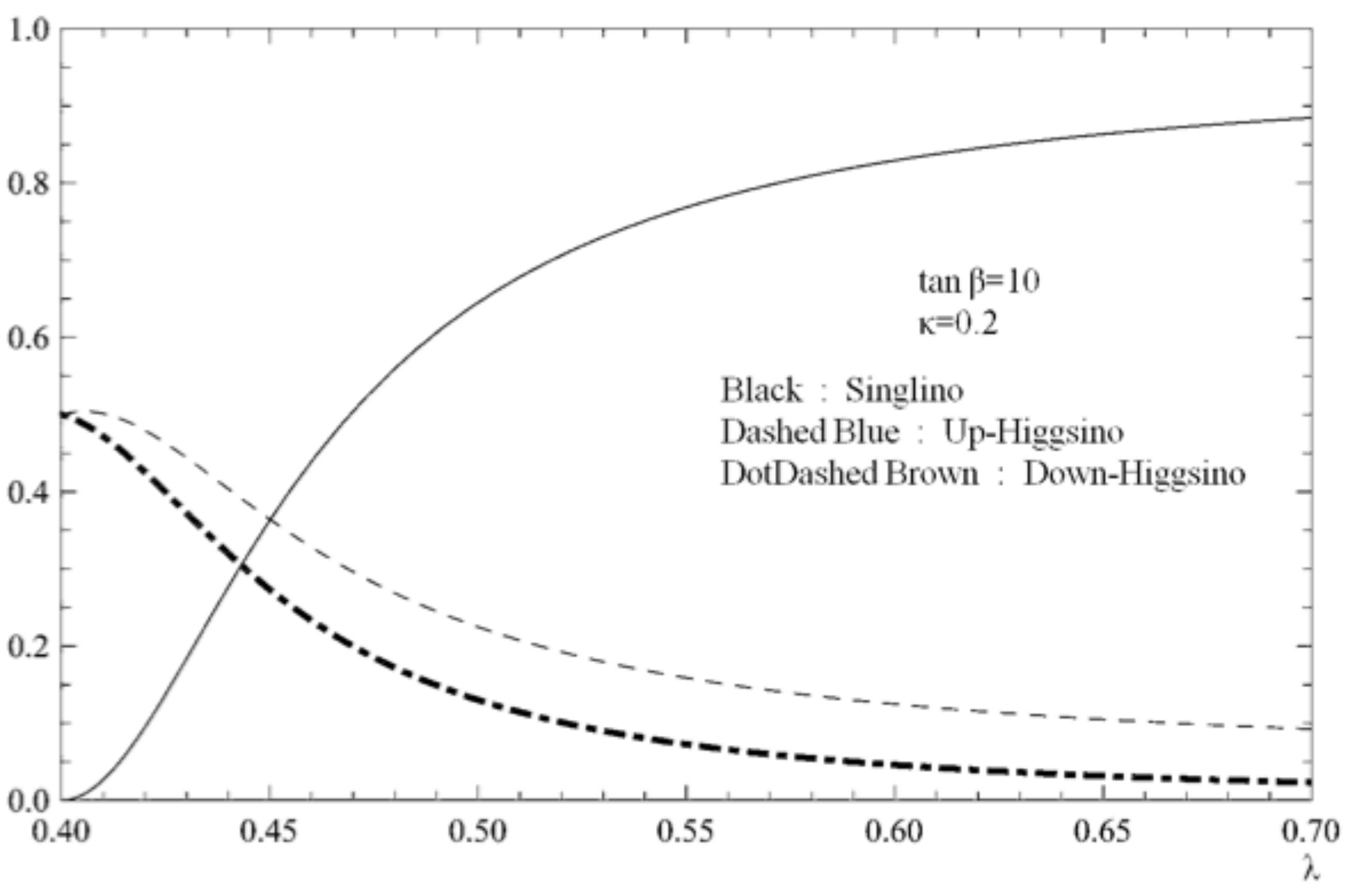
... compe ... e expansion rate.

Larger κ, and/or $\tan\beta$, smaller λ ⟹ larger G_{L5}

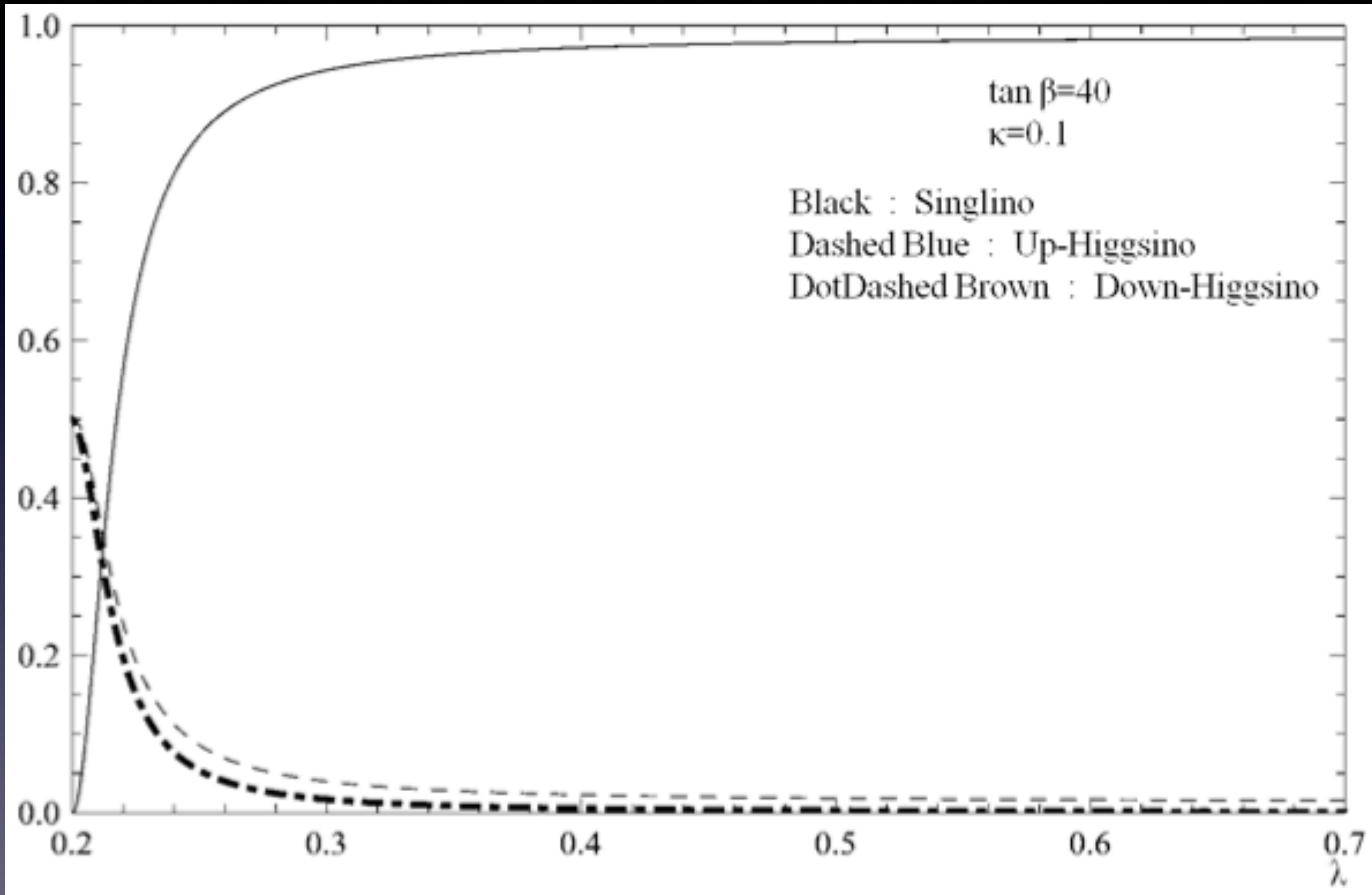


$\kappa = 0.1$

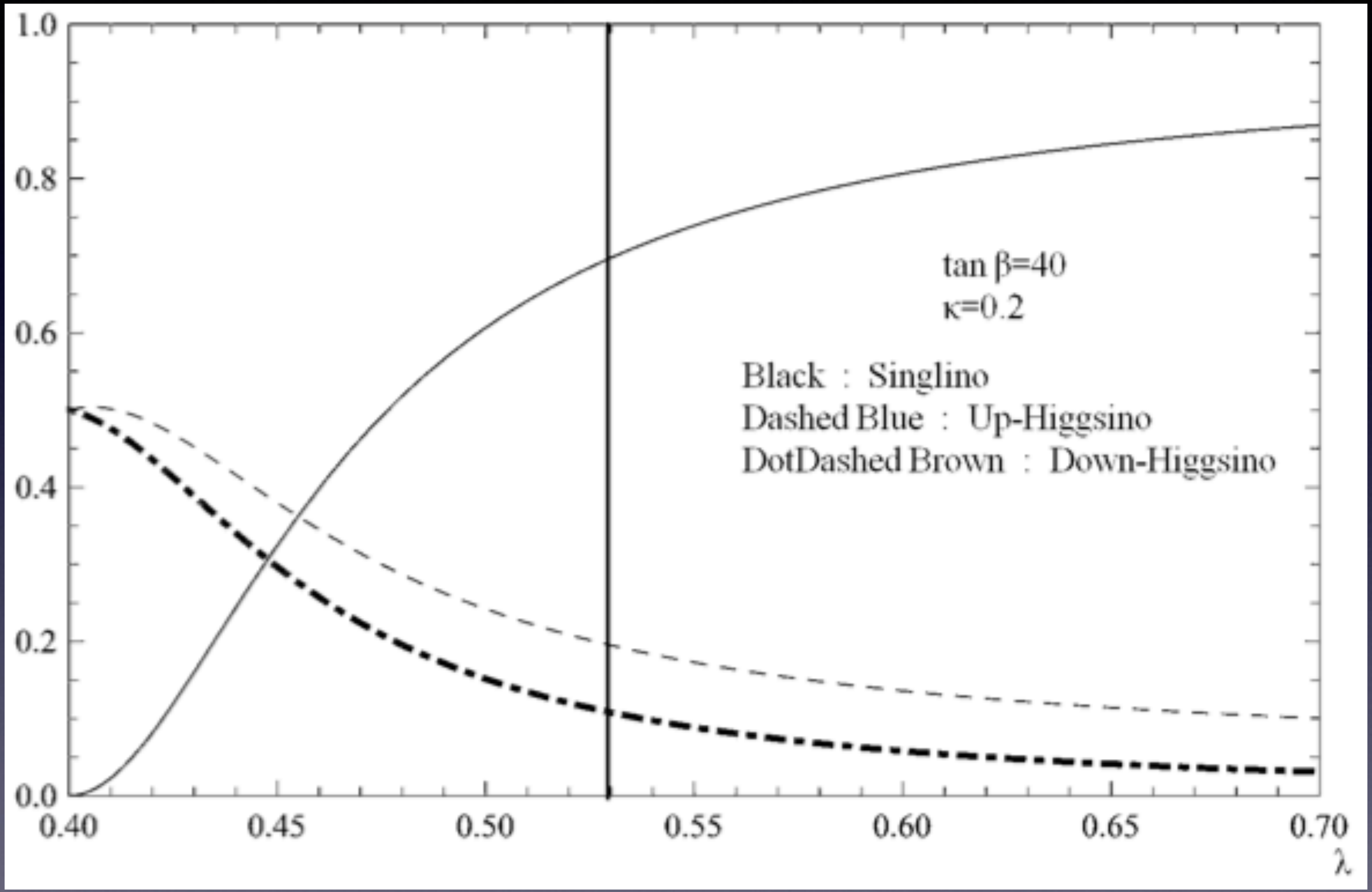
$\kappa = 0.2$



1.0
0.8
0.6
0.4
0.2
0.0
0.40
0.45
0.50
0.55
0.60
0.65
0.70
λ
tan β=10
κ=0.2
Black : Singlino
Dashed Blue : Up-Higgsino
DotDashed Brown : Down-Higgsino



tan β=40
κ=0.1
Black : Singlino
Dashed Blue : Up-Higgsino
DotDashed Brown : Down-Higgsino
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.3
0.4
0.5
0.6
0.7
λ


1.0
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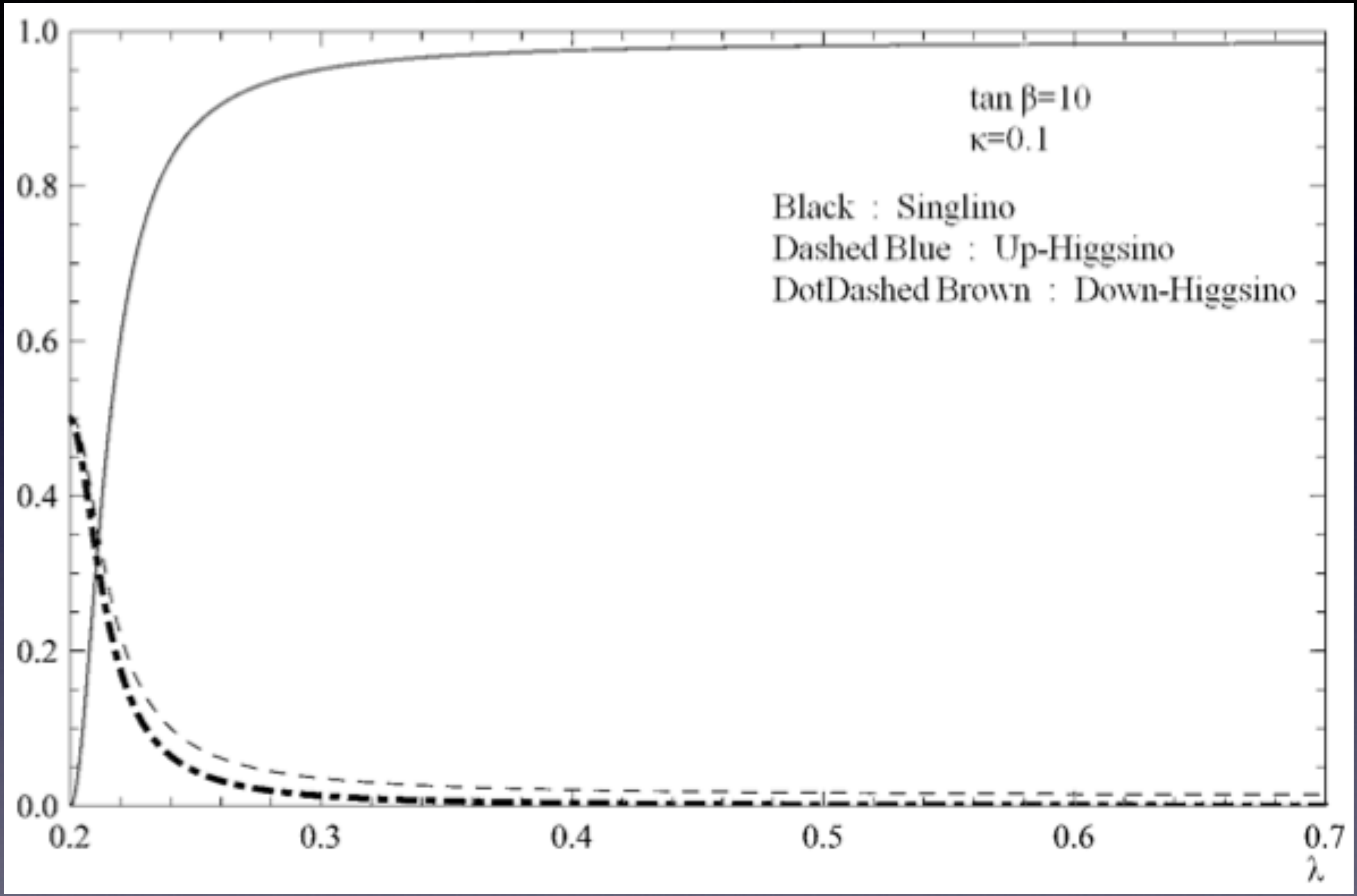

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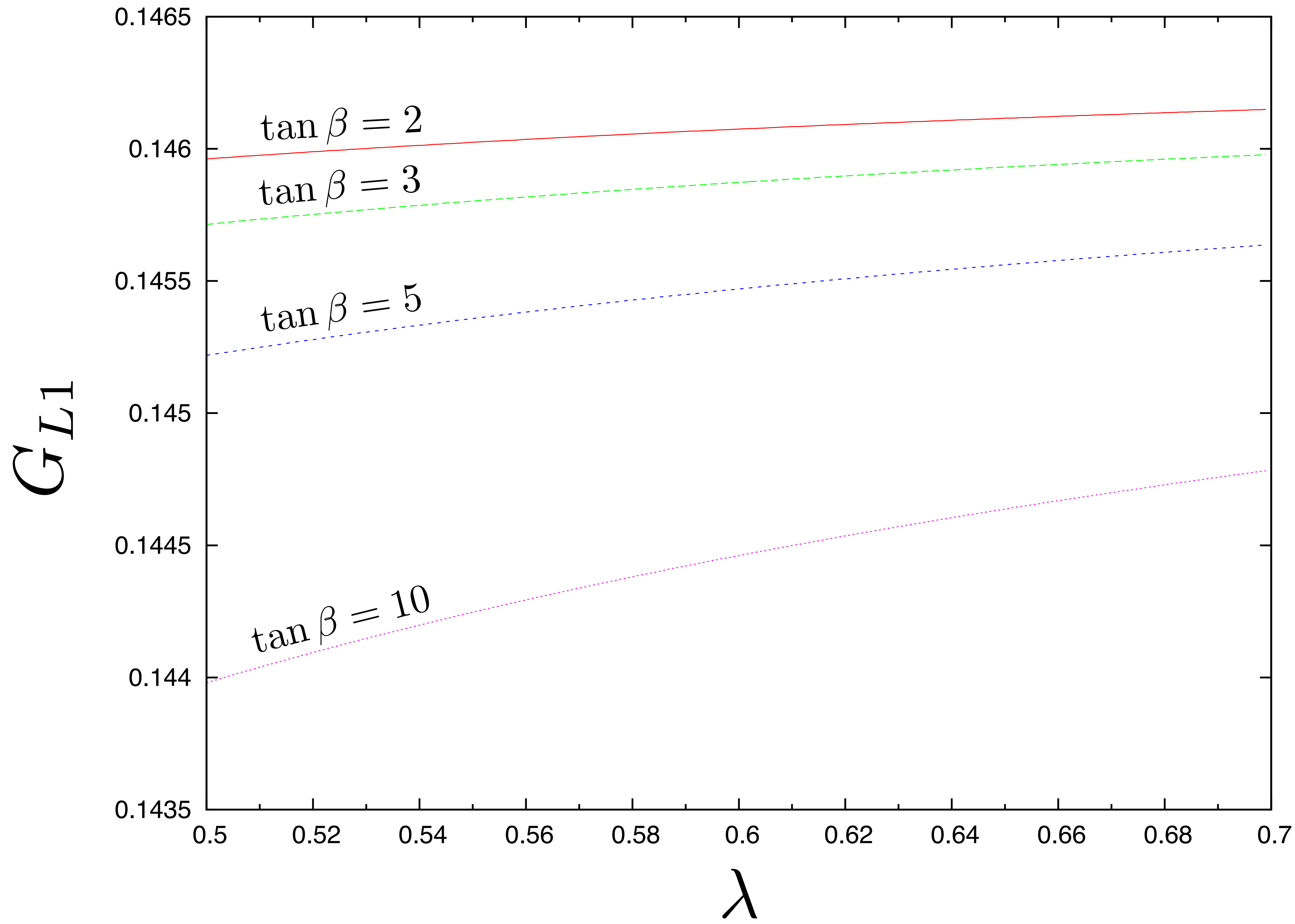
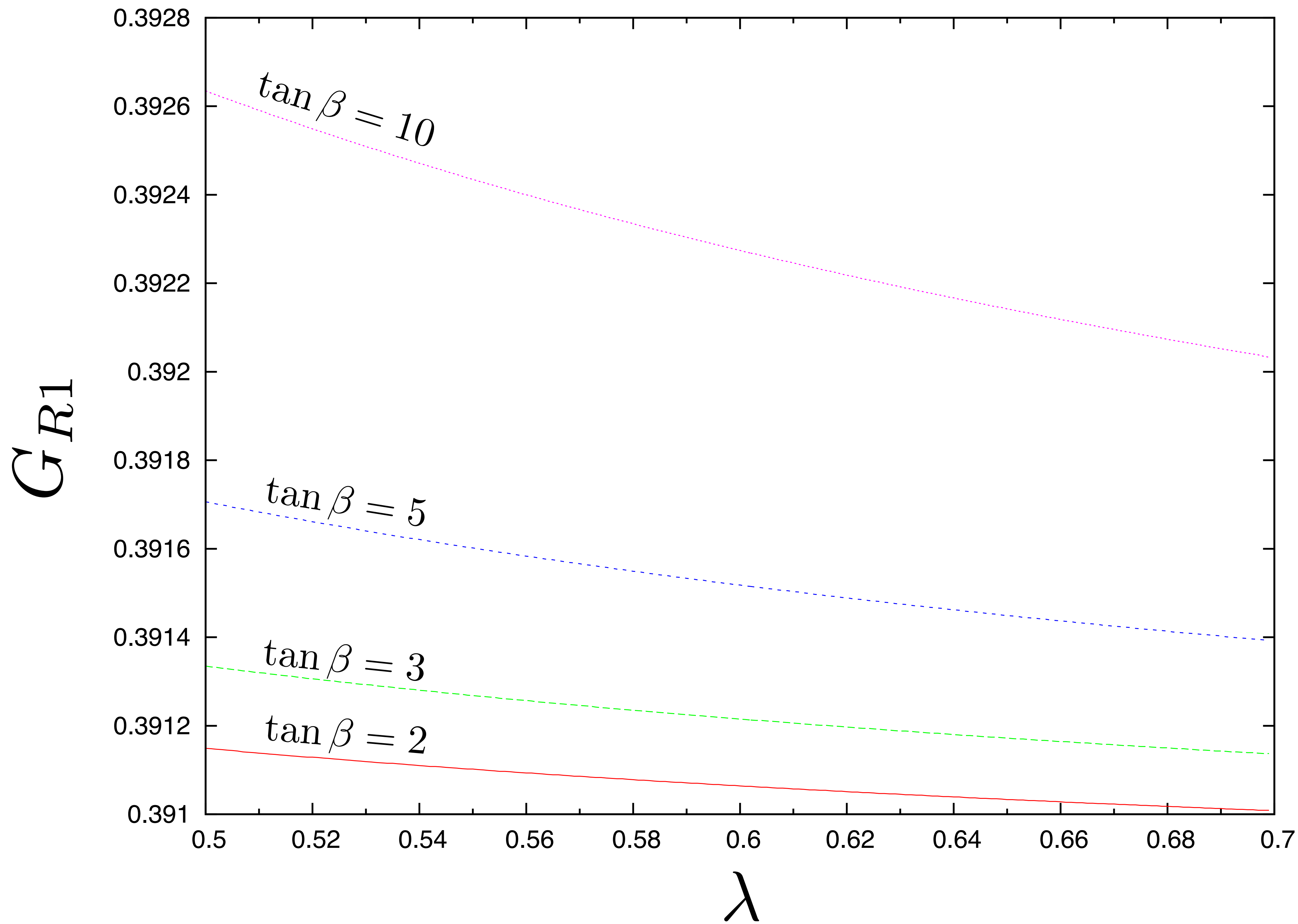
0.0
0.2
0.3
0.4
0.5
0.6
0.7
λ

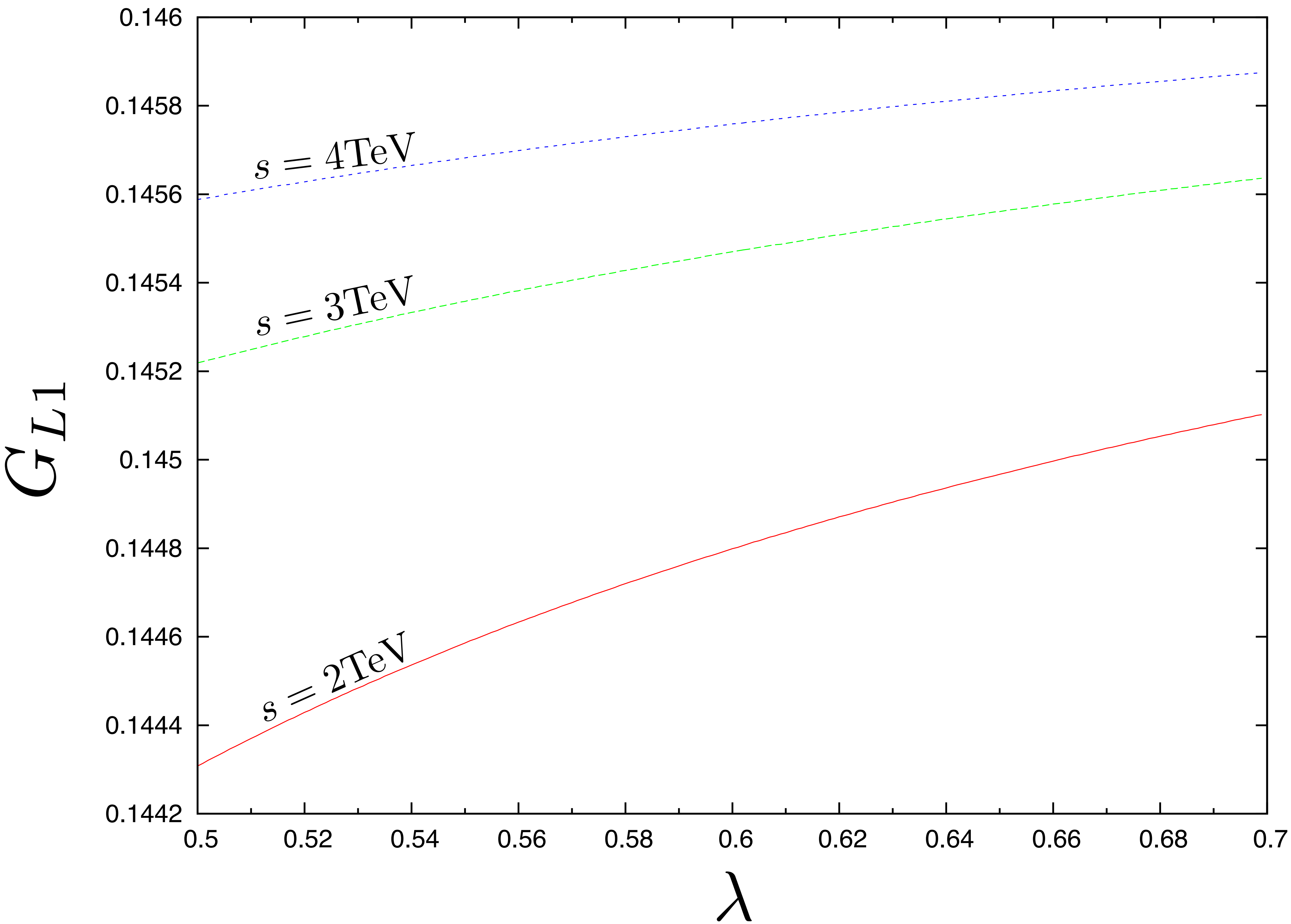
Parameter dependences of G_{L1} and G_{R1}



Parameter dependences of G_{L1} and G_{R1}



Parameter dependences of G_{L1} and G_{R1}



Parameter dependences of G_{L1} and G_{R1}