Big-bang nucleosynthesis and Leptogenesis in CMSSM

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- PRD 73 (2006) 055009, 76 (2007) 125023, 78 (2008) 055007, 82 (2010) 115030, 84 (2011) 035008, D 86 (2012) 095024, D89 (2014) 7, 075006,
- PRD97(2018)11,115013

1.Introduction

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At this moment

- ☑ Higgs Doublet was found
- ☑ No New Physics @ LHC
- ☑ No New (Quark) Flavor Violation

SM works quite well

Go beyond SM

- ☑ Dark Matter candidate
- ☑ Baryon Asymmetry
- ☑ Lepton Flavor Violation among Neutrino
- ☑ Lithium Problem(s) in Big-Bang Nucleosynthesis

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☑ Baryon Asymmetry

☑ Lepton Flavor Violation among Neutrino

☑ Lithium Problem(s) in Big-Bang Nucleosynthesis

Go beyond SM

Constrained minimal SUSY standard model (CMSSM) with RH- neutrinos can solve them!? Keeping the good feature of SM

2.Clues for BSM

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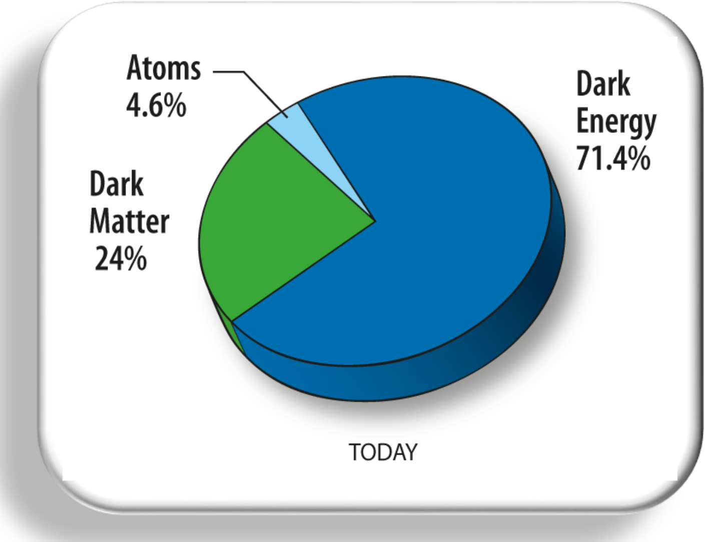
2.1 DM Abundance



Neutral Stable Particle(s) required:

$$0.1126 \leq \frac{m_{\tilde{\chi}_1^0}\, nh^2}{\rho_c} \leq 0.1246 \quad (3\sigma \text{ C.L.})$$

[PDG2016]

2.2 Baryon Asymmetry in the universe

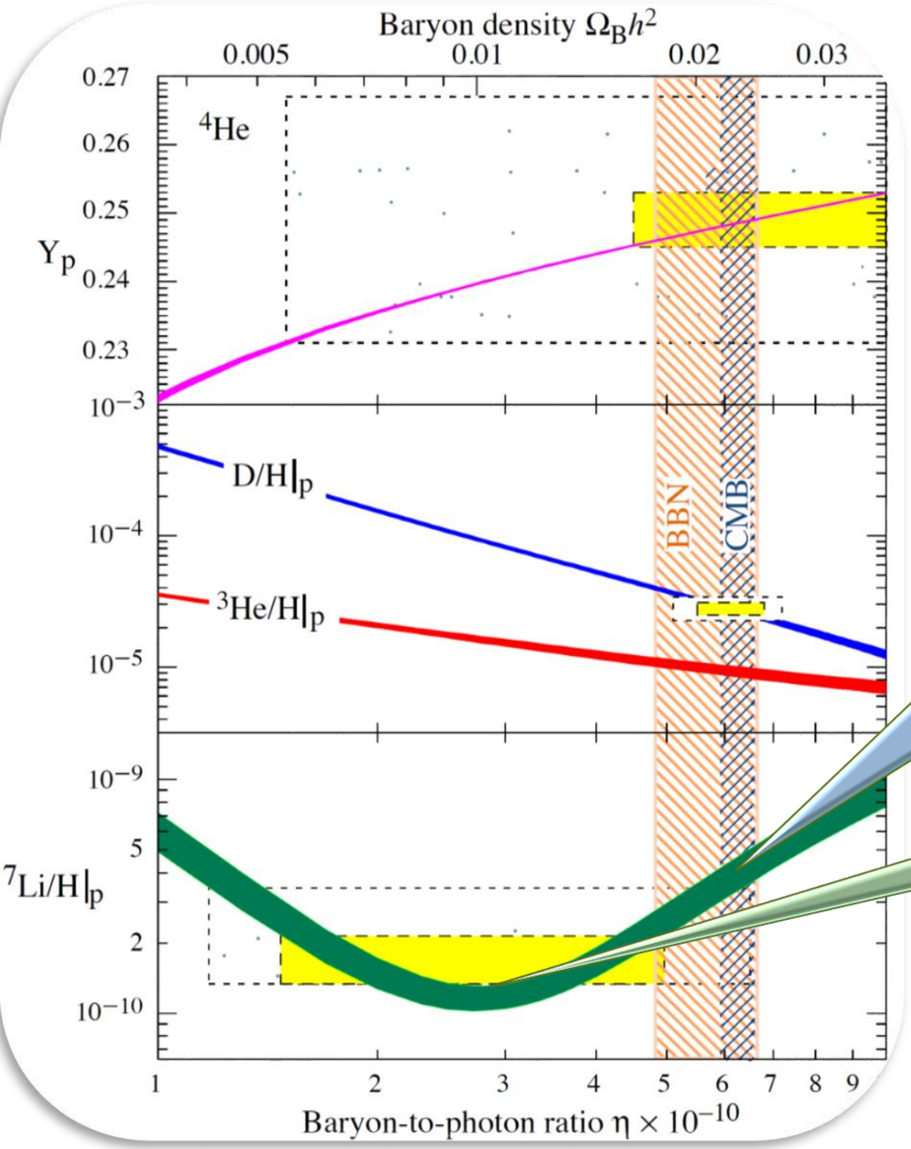
Our universe is made from only matter.

$$\Omega_b h^2 = 0.0223 \pm 0.0002 \ (1\sigma)$$

[PDG2016]

Origin(s) of asymmetry is required

2.3 Li problem(s)



Theoretical prediction

$$\left(4.15\,^{+0.49}_{-0.45}\right)\times 10^{-10}$$

A. Coc, et al., astrophys. J. 600, 544(2004)

Observation

$$\left(1.26\,^{+0.29}_{-0.24}\right)\times 10^{-10}$$

P. Bonifacio, et al., astro-ph/0610245

Predicted ^{7}Li abundance

$\neq$ observed ^{7}Li abundance

⇒ ^{7}Li problem

$$^{6}\mathrm{Li/H} \sim 6 \times 10^{-12}$$

1000 times higher than SBBN ?
Steffen et al 2012

Lithium 6 Problem

Or

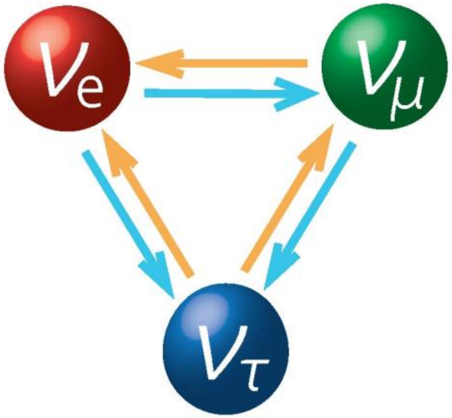
$$^{6}\mathrm{Li/H} = (0.85 \pm 4.33) \times 10^{-12}$$

Upper bound ?
Lind et al 2013

2.4 Neutrino Oscillation : Lepton Flavor Violation

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of **neutrino oscillations**, which shows that **neutrinos have mass**".

http://www.nobelprize.org/



Lepton mixing and Mass differene

$$U_{\mathrm{MNS}} = \widehat{U}\ \mathrm{diag}\left(1, e^{i\alpha}, e^{i\beta}\right) \quad ,$$

$$\widehat{U} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\Delta m^2_{12} = (6.93 - 7.96) \times 10^{-5}\ (\mathrm{eV}^2)\,, \quad \Delta m^2_{23} = (2.42 - 2.66) \times 10^{-3}\ (\mathrm{eV}^2)\,,$$

$$\sin^2\theta_{12} = (0.250 - 0.354), \quad \sin^2\theta_{23} = (0.381 - 0.615), \quad \sin^2\theta_{13} = (0.0190 - 0.0240)$$

$$s_{23} = \sqrt{0.441}\,,\ s_{13} = \sqrt{0.02166}\,,\ s_{12} = \sqrt{0.306}\,,$$
$$\alpha = 0\,,\ \beta = 0\,,\ \delta = 261^\circ \quad .$$

3.Solution by CMSSM with RH ν

3.1 DM abundance and LHC result

Neutralino ~ Bino-like DM

☑ Coannihilation region Griest,Seckel

DM and Stau : degenerate in mass

DM and Stau pair-annihilate at decoupling from thermal history to give appropriate abundance

$$m_\chi \sim 400\text{GeV}$$

☑ Imposing 125GeV Higgs, muon g-2 etc, tight degenerasy,

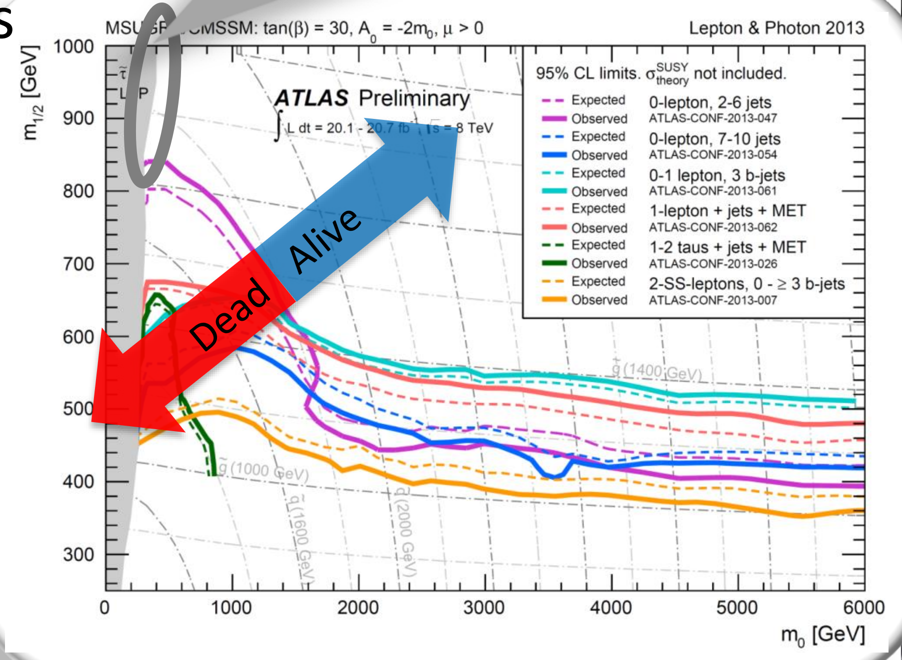
$$\delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}} < m_\tau$$

[L. Aparicio, D. Cerdeno, L. Ibanez, JHEP(2012)]

[M. Citron,J. Ellis, F.Luo ,et al, PRD87(2013)]

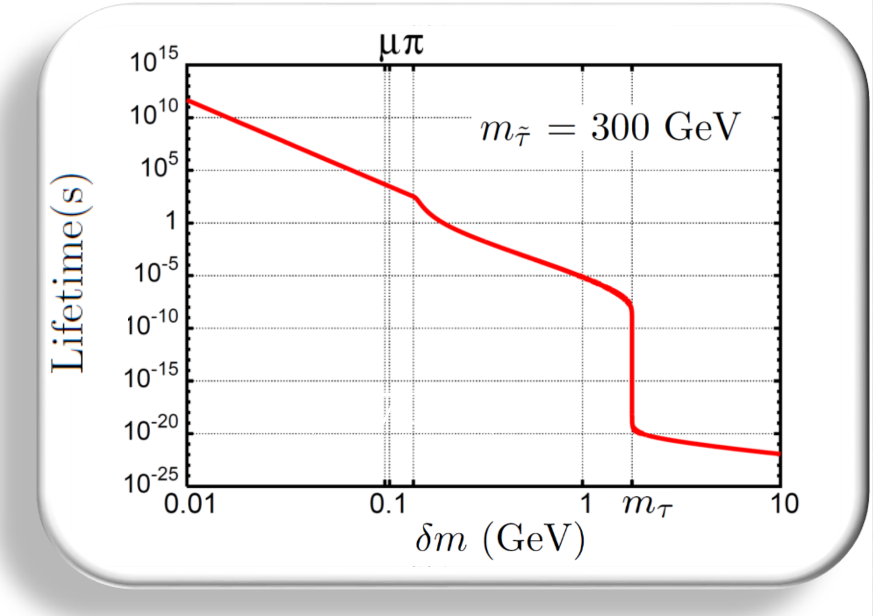
DM abundance can be explained

Coannihilation region

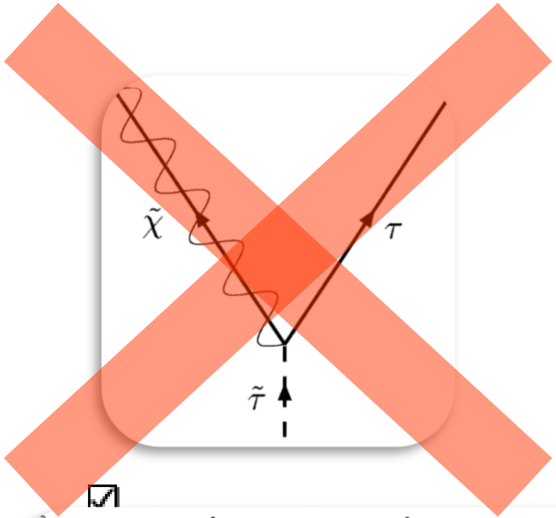


Very fortunately

Stau is long-lived at $\delta m < m_\tau$ since 2-body decay is kinematically prohibited

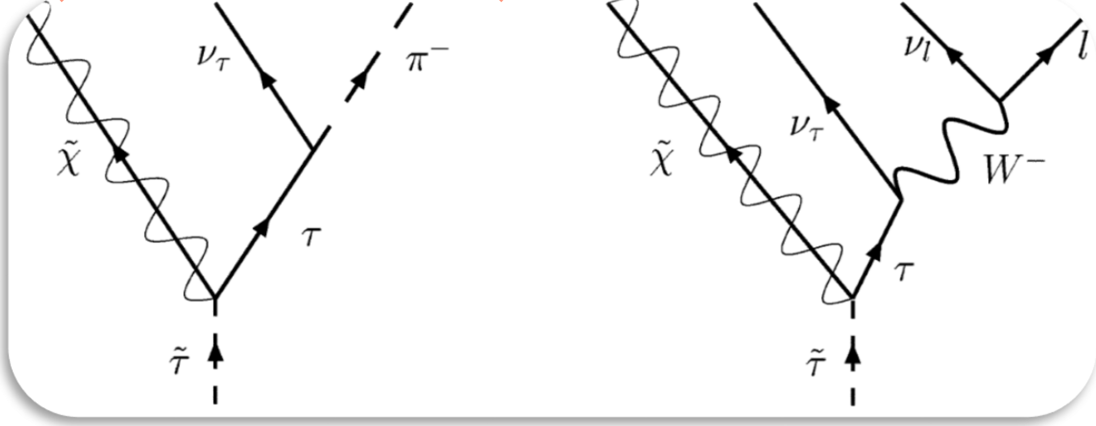


[T. Jittoh, J. S T. Shimomura, M.Yamanaka, PRD73 (2006)]



Can not decay into two body

with lepton flavor conservation



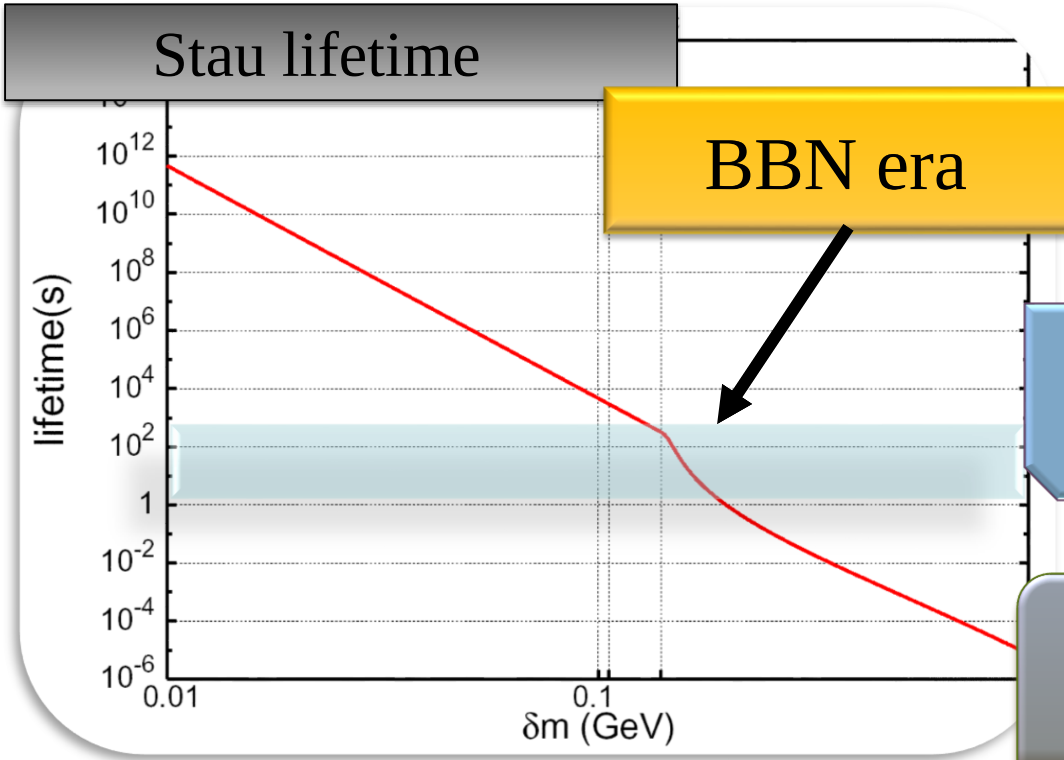
Phase space suppression

→ Long-lived particle

Solution to Li Problem

Coming back later

long-lived stau in the coannihilation scenario



Stau lifetime

BBN era

Surviving until the BBN era !!

Stau can affect
Big-Bang Nuclepsynthesis !

Lithium Problem can be solved

3.2 Lepton Mixing

Seesaw mechanism

$$\mathscr{W}_l = \widehat{E}^c_\alpha \left(Y_\mathrm{E}\right)_{\alpha\beta} \widehat{L}_\beta \cdot \widehat{H}_d + \lambda_{\beta i} \widehat{L}_\beta \cdot \widehat{H}_u \widehat{N}^c_i - \frac{1}{2} \left(M_\mathrm{N}\right)_{ij} \widehat{N}^c_i \widehat{N}^c_j$$

$\widehat{L}_\alpha$ and $\widehat{E}^c_\alpha$ $(\alpha = e, \mu, \tau)$ $(Y_E)_{\alpha\beta} = y_\alpha \delta_{\alpha\beta}$ is assumed

SU(2) doublet and singlet leptons

$\widehat{N}^c_i$ $(i = 1, 2, 3)$ Right-handed neutrinos

Below RH neutrino scale

$$\mathscr{L}^\nu_m = -\frac{1}{2} \nu_{L\alpha} \left(m_\nu\right)_{\alpha\beta} \nu_{L\beta} + h.c. \ ,$$

$$\left(m_\nu\right)_{\alpha\beta} = v_u^2 \ \left(\lambda_\nu\right)_{\alpha i} M_i^{-1} \left(\lambda_\nu\right)_{i\beta} \ ,$$

$$\left(m_\nu\right) = U^*_\mathrm{MNS} \, \mathrm{D}_{m_\nu} \, U^\dagger{}_\mathrm{MNS} \qquad \mathrm{D}_{m_\nu} = \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

Tiny masses and lepton mixing

Lepton mixing and Mass differene

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In this talk we will fix the parameters

$$s_{23} = \sqrt{0.441}\,, \ s_{13} = \sqrt{0.02166}\,, \ s_{12} = \sqrt{0.306}\,,$$
$$\alpha = 0\,, \ \beta = 0\,, \delta = 261^\circ \ .$$

$$m_{\nu_1} = 0.001\ ({\rm eV})$$

There remains degrees of freedom in the parameters

$$\lambda_\nu = \frac{1}{v_u} U^*_{\mathrm{MNS}} \sqrt{\mathrm{D}_{m_\nu}}\, R \sqrt{M} \ ,$$

Casas & Ibarra

$$R = \begin{pmatrix} \widetilde{c}_{13}\widetilde{c}_{12} & \widetilde{c}_{13}\widetilde{s}_{12} & \widetilde{s}_{13} \\ -\widetilde{c}_{23}\widetilde{s}_{12} & \widetilde{c}_{23}\widetilde{c}_{12} - \widetilde{s}_{23}\widetilde{s}_{13}\widetilde{s}_{12} & \widetilde{s}_{23}\widetilde{c}_{13} \\ \widetilde{s}_{23}\widetilde{s}_{12} - \widetilde{c}_{23}\widetilde{s}_{13}\widetilde{c}_{12} & -\widetilde{s}_{23}\widetilde{c}_{12} - \widetilde{c}_{23}\widetilde{s}_{13}\widetilde{s}_{12} & \widetilde{c}_{23}\widetilde{c}_{13} \end{pmatrix}$$

$$\widetilde{c}_{ij} = \cos z_{ij}$$

$$z_{ij} = x_{ij} + \sqrt{-1}\, y_{ij}$$

6 parameters+

R is a complex orthogonal matrix, $R^{\mathrm{T}} R = 1$

3.3 Baryon asymmetry

Leptogenesis

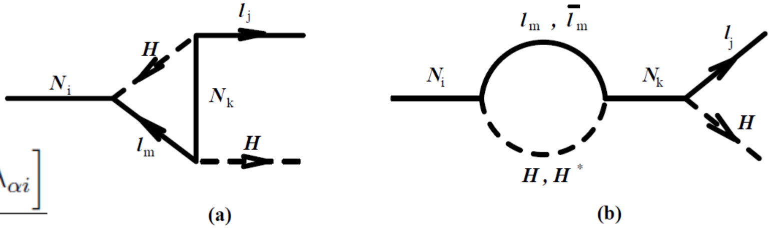
Fukugita&Yanagida

Generate Lepton asymmetry and Convert to Baryon number

$$\varepsilon^i_\alpha \equiv \frac{\Gamma(N_i \to \ell_\alpha \phi) - \Gamma(N_i \to \bar{\ell}_\alpha \phi^\dagger)}{\Gamma(N_i \to \ell_\alpha \phi) + \Gamma(N_i \to \bar{\ell}_\alpha \phi^\dagger)}$$

(a) $$\varepsilon^i_\alpha(\mathrm{vertex}) = -\frac{1}{8\pi}\sum_j \frac{M_j}{M_i}\log\left[1+\frac{M_i^2}{M_j^2}\right]\frac{\Im\left[\left(\lambda^\dagger\lambda\right)_{ji}\lambda^*_{\beta i}\lambda_{\alpha i}\right]}{\left(\lambda^\dagger\lambda\right)_{ii}}$$

(b) $$\varepsilon^i_\alpha(\mathrm{wave}) = -\frac{2}{8\pi}\sum_j \frac{M_i}{M_j^2 - M_i^2}\frac{\Im\left\{\left[M_j\left(\lambda^\dagger\lambda\right)_{ji} + M_i\left(\lambda^\dagger\lambda\right)_{ij}\right]\lambda^*_{\beta i}\lambda_{\alpha i}\right\}}{\left(\lambda^\dagger\lambda\right)_{ii}}$$



Covi&Roulet&Vissani

$$Y_B = (8/23)Y_{B-L} \quad ⇒ \quad 2.414\times10^{-10} \lesssim |Y_{B-L}| \lesssim 2.561\times10^{-10}$$

Lain&Shaposhnikov

↕

$$\Omega_b h^2 = 0.0223 \pm 0.0002 \ (1\sigma)$$

Flavored Leptogenesis

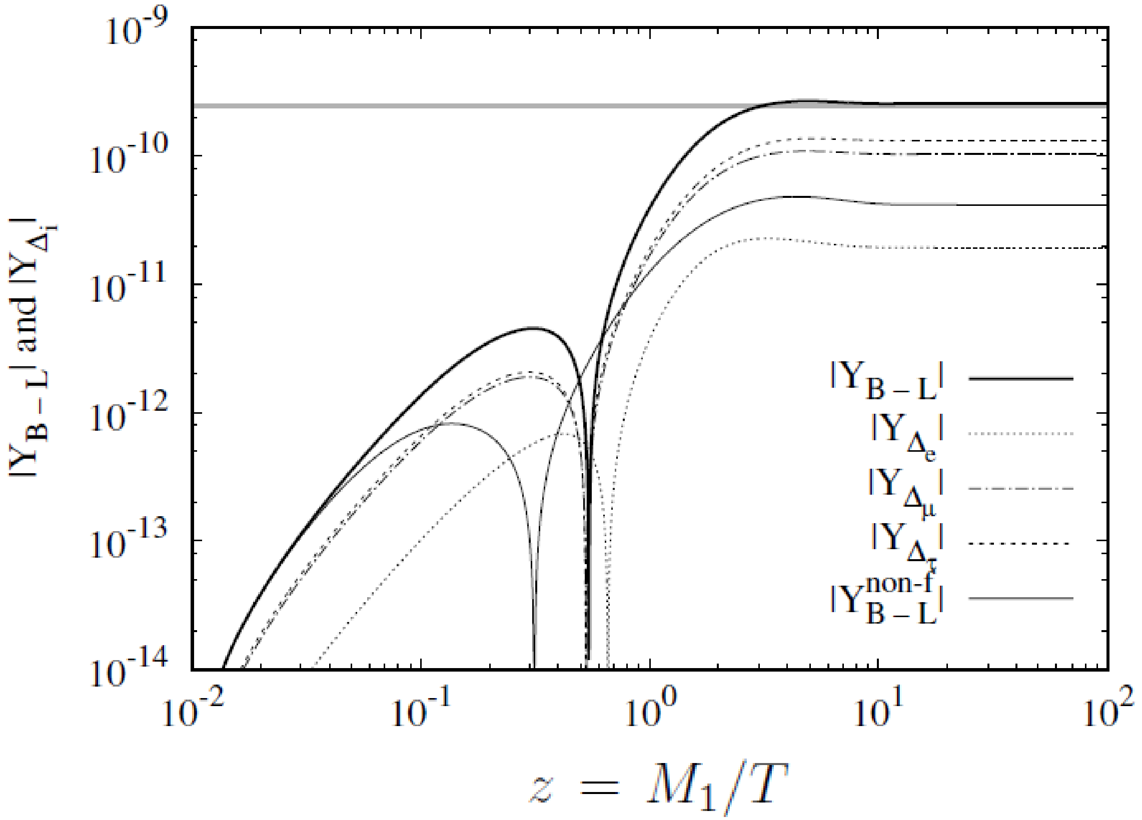
3.3 Baryon asymmetry

Leptogenesis

Fukugita&Yanagida

Generate Lepton asymmetry and Convert to Baryon number

Flavored Leptogenesis



3.4 Li problem(s) and a solution by long-lived stau

A. Coc, et al., astrophys. J. 600, 544(2004)

Predicted ^{7}Li abundance $(4.15^{+0.49}_{-0.45})\times 10^{-10}$

$\neq$ observed ^{7}Li abundance $(1.26^{+0.29}_{-0.24})\times 10^{-10}$

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→ ^{7}Li problem

$^6\mathrm{Li/H}\sim\ 6\times 10^{-12}$

1000 times higher than SBBN ?

Steffen et al 2012

Or

$^6\mathrm{Li/H}=(0.85\pm 4.33)\times 10^{-12}$

Upper bound ?

Lind et al 2013

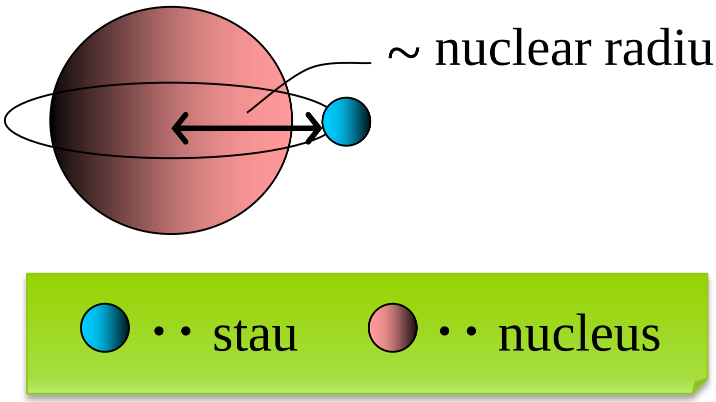
Lithium 6 Problem (?)

Solving the Li problem with “stau”

$$\tilde{\ell}_1 = \sum_{f=e,\mu,\tau} C_f \tilde{f} \qquad C_\tau \sim 1 \gg C_e, C_\mu \qquad \tilde{f} = \cos\theta_f \tilde{f}_L + \sin\theta_f \tilde{f}_R$$

Key ingredient for solving the ^{7}Li problem

Negative-charged stau can form a bound state with nuclei



Formation rate

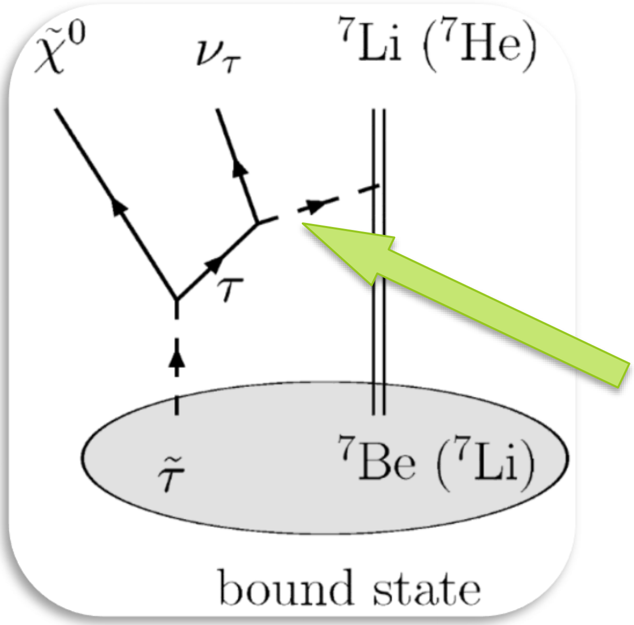
→ Solving the Boltzmann Eq.

New processes

- Internal conversion in the bound state
- Stau catalyzed fusion
- Spallation process of nucleus in the bound state

Internal conversion

PRD76,78



Hadronic current

- Closeness between stau and nucleus

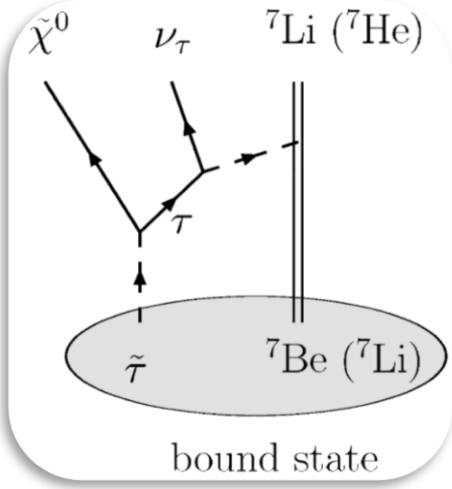
→ Overlap of the wave function : **UP**

Interaction rate of hadronic current : **UP**

- $\tilde{\tau}^+$ does not form a bound state

→ No cancellation processes

Internal conversion rate



The lifetime of the stau-nucleus bound state

$$\tau_{\mathrm{IC}} = \frac{1}{|\psi|^2 \cdot (\sigma v)}$$

- Wave function of the bound state

$$|\psi|^2 = \frac{1}{\pi a_{\mathrm{nucl}}^3}$$

(nuclear radius

$$a_{\mathrm{nucl}} = (1.2 \times A^{1/3})$$
)

- (σ v) is evaluated by using *ft*-value

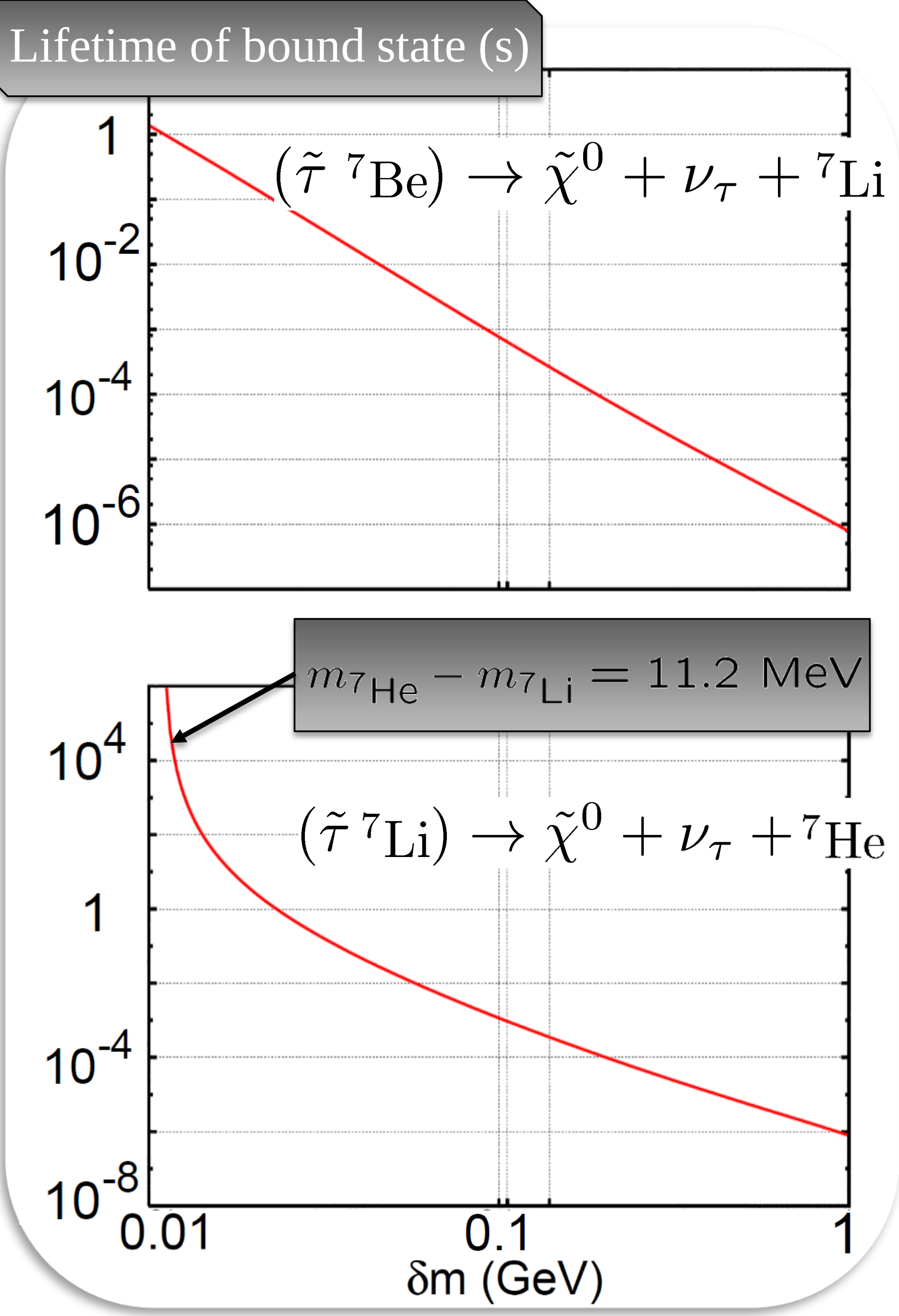
$$(\sigma v) \propto (ft\text{-}value)^{-1}$$

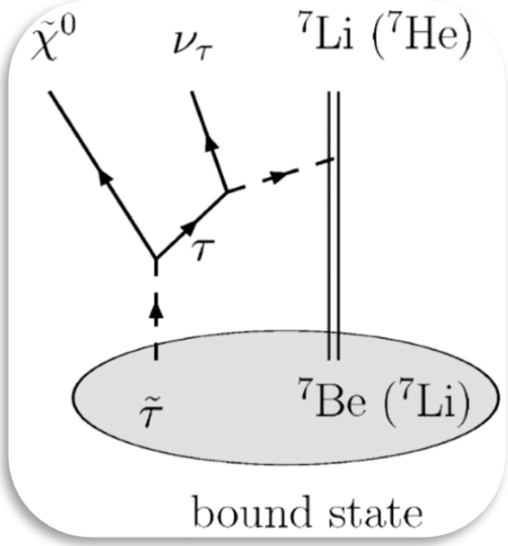
ft-value of each processes

^{7}Be → ^{7}Li • • • $ft = 10^{3.3}$ sec (experimental value)

^{7}Li → ^{7}He • • • similar to ^{7}Be → ^{7}Li (no experimental value)

Interaction rate of internal conversion



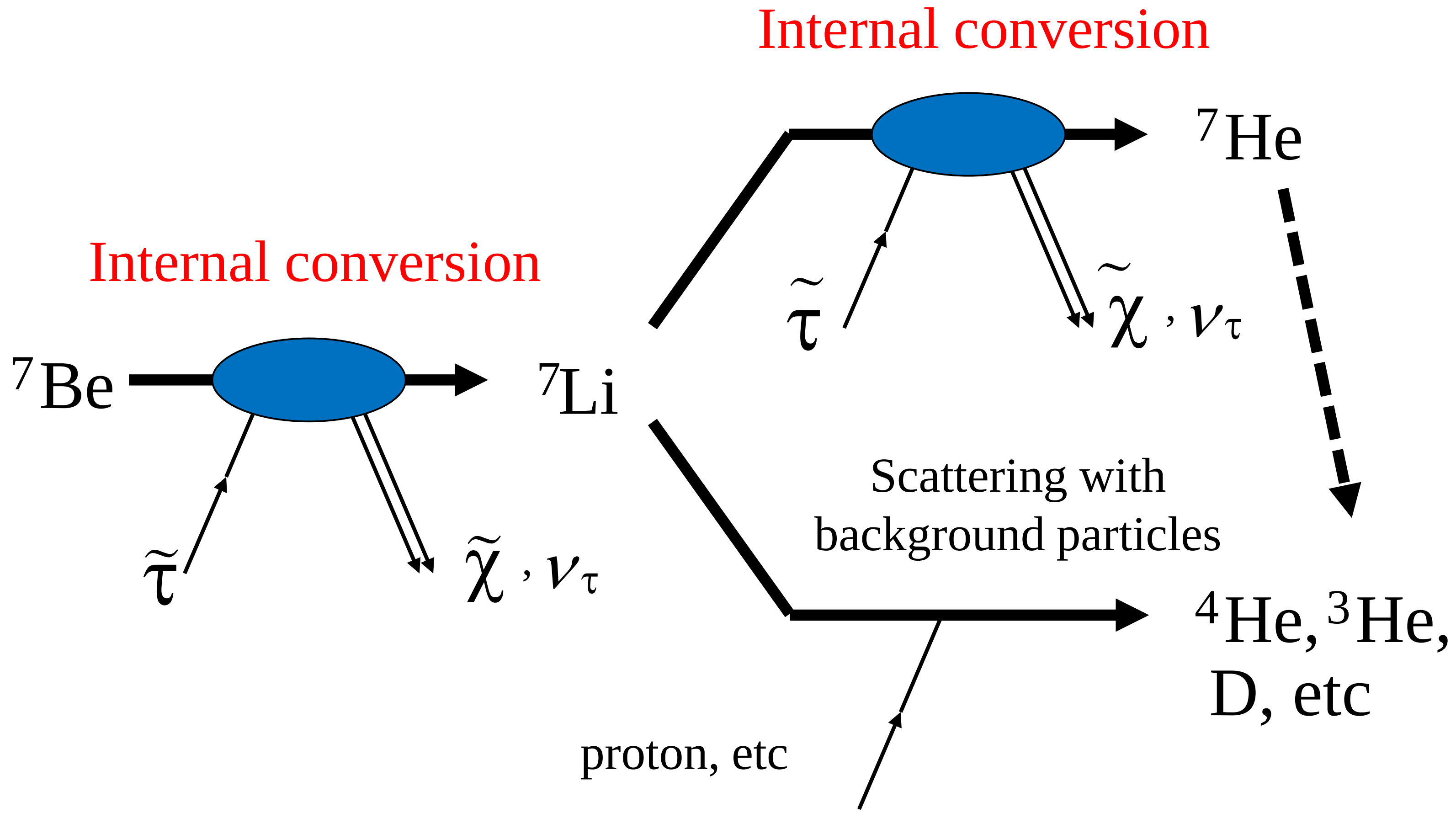


Very short lifetime

↓

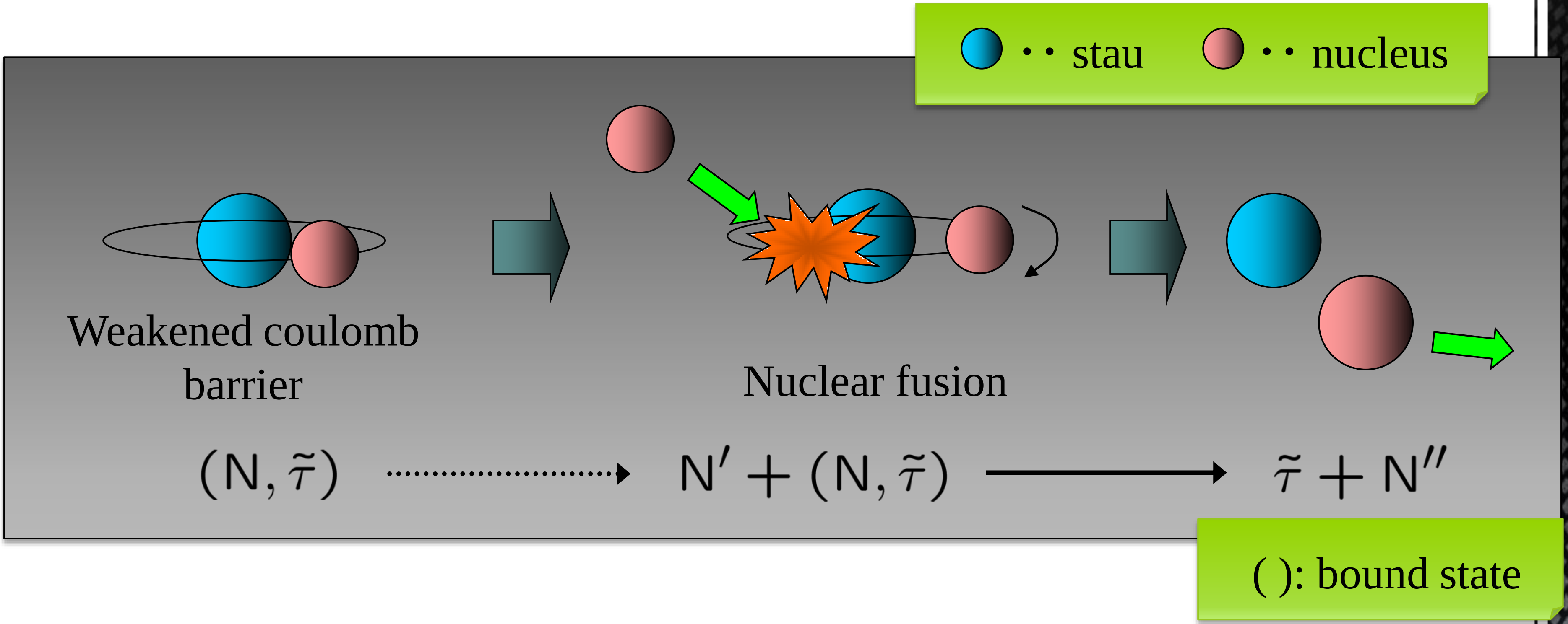
Signifficant process
for reducing ^{7}Li abundance

Li destruction chain with internal conversion



Stau catalyzed fusion

[M. Pospelov, PRL. 98 (2007)]



● ·· stau ● ·· nucleus

Weakened coulomb barrier

Nuclear fusion

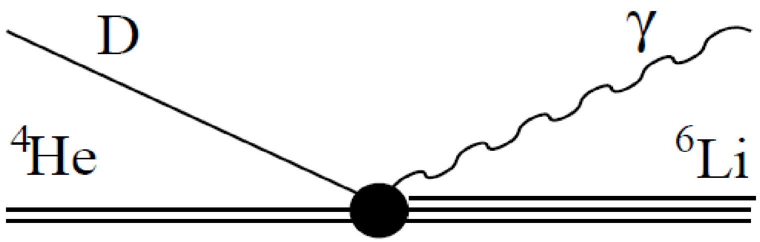
$$(N,\tilde{\tau}) \dashrightarrow N' + (N,\tilde{\tau}) \longrightarrow \tilde{\tau} + N''$$

( ): bound state

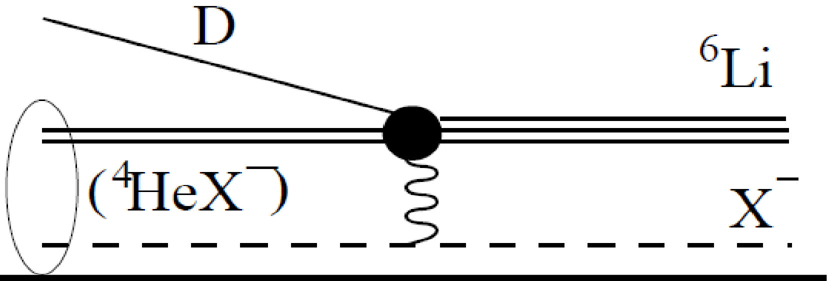
Ineffective for reducing ^{7}Li and ^{7}Be

∵ stau can not weaken the barrieres of Li^{3+} and Be^{4+} sufficiently

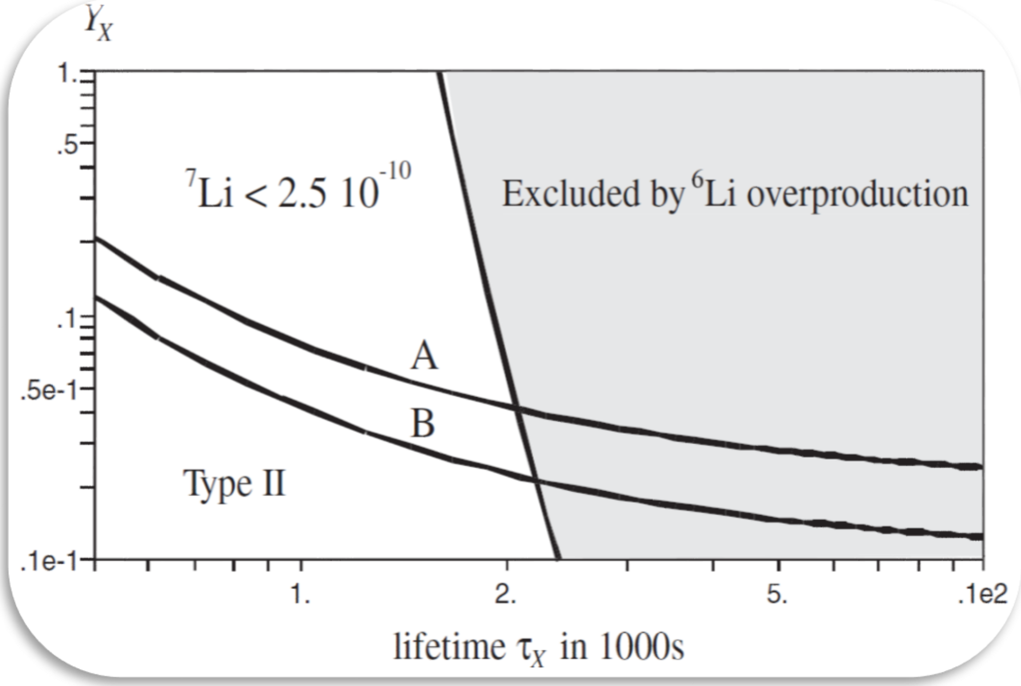
Stau catalyzed fusion



Standard BBN process



Catalyzed BBN process



Catalyzed BBN cause over production of ^{6}Li

↓

Constraint on stau life time

Or solution to Li6

^{4} He spallation process

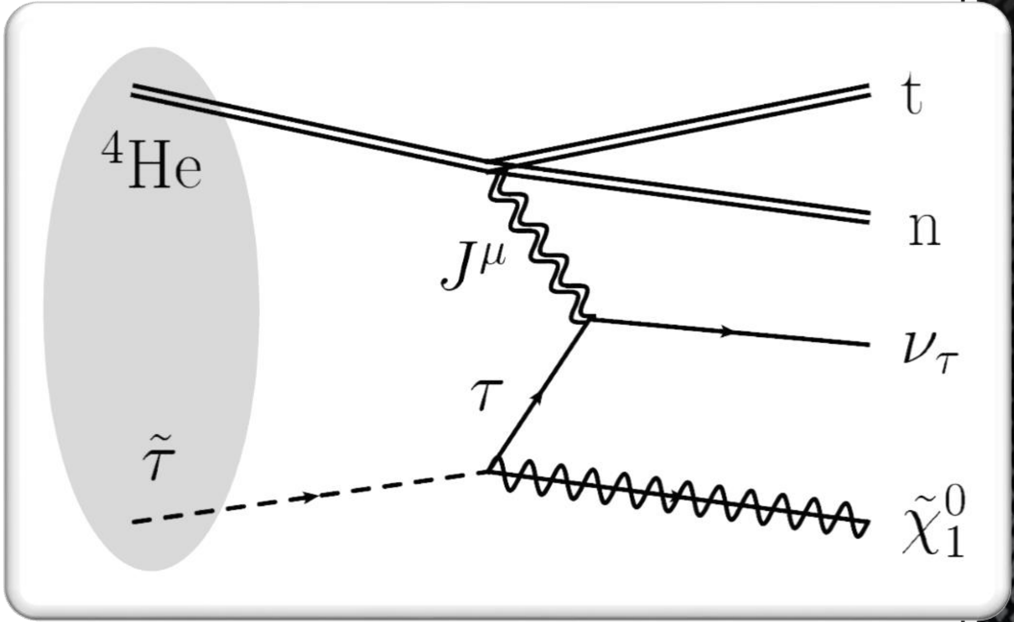
PRD 84

Bound state formation via EM int.

$$\tilde{\tau} + {}^4\mathrm{He} \to (\tilde{\tau}\,{}^4\mathrm{He})$$

Spallation process

$$\begin{aligned} (\tilde{\tau}^4\mathrm{He}) &\to \tilde{\chi}^0 + \nu_\tau + t + n \\ (\tilde{\tau}^4\mathrm{He}) &\to \tilde{\chi}^0 + \nu_\tau + d + n + n \\ (\tilde{\tau}^4\mathrm{He}) &\to \tilde{\chi}^0 + \nu_\tau + p + n + n + n \end{aligned}$$



Reaction rate $$\Gamma\big((\tilde{\tau}\,{}^4\mathrm{He}) \to \tilde{\chi}_1^0 \nu_\tau \mathrm{tn}\big) = |\psi|^2 \cdot \sigma \mathrm{v}_{\mathrm{tn}}$$

Upper bound for lifetime from not to produce much t/d

Favored parameter space in MSSM

Mass differencee $\delta m < m_\mu$

Lifetime

$$\tau_{\tilde{l}}(\tilde{l}_1 \rightarrow \tilde{\chi}_1^0 + e) \simeq \frac{8\pi}{g^2 \tan^2\theta_W} \frac{m_{\tilde{l}}}{(\delta m)^2} \frac{1}{\cos^2\theta_e + 4\sin^2\theta_e} \frac{1}{C_e^2}$$

$1700 \text{ s} \le \tau_{\tilde{\ell}} \le 5000 \text{ s} \Leftrightarrow 2.0 \times 10^{-10} \le C_e \le 3.5 \times 10^{-10}$ **Li7 Problem**

$3500 \text{ s} \le \tau_{\tilde{\ell}} \le 5000 \text{ s} \Leftrightarrow 2.0 \times 10^{-10} \le C_e \le 2.5 \times 10^{-10}$ **Li6&7 Problem**

$\delta m = 10 \text{ MeV and } \sin\theta_e = 0.6$

In addition, to have enough slepton $C_\mu < \mathcal{O}(10^{-5})$

Number density of long-lived slepton

$$\widetilde{\ell}_1^{\pm}\gamma \leftrightarrow \widetilde{\chi}_1^0\tau^{\pm}, \quad \widetilde{\ell}_1^{\pm}\gamma \leftrightarrow \widetilde{\chi}_1^0\mu^{\pm},$$
$$\widetilde{\ell}_1^{\pm}\tau^{\mp} \leftrightarrow \widetilde{\chi}_1^0\gamma, \quad \widetilde{\ell}_1^{\pm}\mu^{\mp} \leftrightarrow \widetilde{\chi}_1^0\gamma, \quad \widetilde{\ell}_1^{\pm}e^{\mp} \leftrightarrow \widetilde{\chi}_1^0\gamma$$

Should be suppressed

4.Parameter Search

4.Parameter Search

Free parameters

From CMSSM

$$m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)$$

Almost fixed by DM and lifetime of the lightest slepton
In addition to Higgs mass ∼ 125 GeV
Here we assume for simplicity

$$m_\chi = 380\mathrm{GeV},\ \delta m = 10\mathrm{MeV}$$

➡ $$m_{1/2} = 887.0\,(\mathrm{GeV})\ ,\quad A_0 = -3090\,(\mathrm{GeV})$$

$$m_0 \approx [707.3, 707.4]\,(\mathrm{GeV})$$

With the assumption

$$\tan\beta = 25$$

From neutrino physics

Free parameters

From RH neutrino

$$\mathscr{W}_l = \widehat{E}^c_\alpha \left(Y_{\mathrm{E}}\right)_{\alpha\beta} \widehat{L}_\beta \cdot \widehat{H}_d + \lambda_{\beta i} \widehat{L}_\beta \cdot \widehat{H}_u \widehat{N}^c_i - \frac{1}{2} \left(M_{\mathrm{N}}\right)_{ij} \widehat{N}^c_i \widehat{N}^c_j$$

With Casas Ibarra parametrization $\lambda_\nu = \frac{1}{v_u} U^*_{\mathrm{MNS}} \sqrt{\mathrm{D}_{m_\nu}}\ R \sqrt{M}$

$$R = \begin{pmatrix} \widetilde{c}_{13}\widetilde{c}_{12} & \widetilde{c}_{13}\widetilde{s}_{12} & \widetilde{s}_{13} \\ -\widetilde{c}_{23}\widetilde{s}_{12} & \widetilde{c}_{23}\widetilde{c}_{12} - \widetilde{s}_{23}\widetilde{s}_{13}\widetilde{s}_{12} & \widetilde{s}_{23}\widetilde{c}_{13} \\ \widetilde{s}_{23}\widetilde{s}_{12} - \widetilde{c}_{23}\widetilde{s}_{13}\widetilde{c}_{12} & -\widetilde{s}_{23}\widetilde{c}_{12} - \widetilde{c}_{23}\widetilde{s}_{13}\widetilde{s}_{12} & \widetilde{c}_{23}\widetilde{c}_{13} \end{pmatrix}$$

→ **6+3+1 parameters**

$$z_{ij} = x_{ij} + \sqrt{-1}\ y_{ij}$$

3 complex angles = 6 parameters to be searched

$M_i \ (i = 1, 2, 3) \ (\mathrm{RH}\ \nu\ \mathrm{masses})$ 3 mass parameters

M_1 is free parameter

1. $M_2 = 2 \times M_1, \ M_3 = 40 \times M_1$
2. $M_2 = 4 \times M_1, \ M_3 = 40 \times M_1$
3. $M_2 = 10 \times M_1, \ M_3 = 40 \times M_1$

$m_{\nu_1} = 0.001 \ (\mathrm{eV})$

Normal Hierarchy assumed

For Numerical Analysis

RGE : SPheno
DM : micrOMEGAs
Leptogenesis : Original Code by Yamanaka

5.Result

5. Result

☑ Dark Matter & related

Kind of Input

$$\Omega h^2 = 0.115 \Longleftrightarrow m_\chi = 380\mathrm{GeV},\ \delta m = 10\mathrm{MeV}$$

Spin independent Cross section : satisfy LUX

$$\sigma^{\mathrm{SI}} = 1.05 \times 10^{-47}\ \mathrm{cm}^2$$

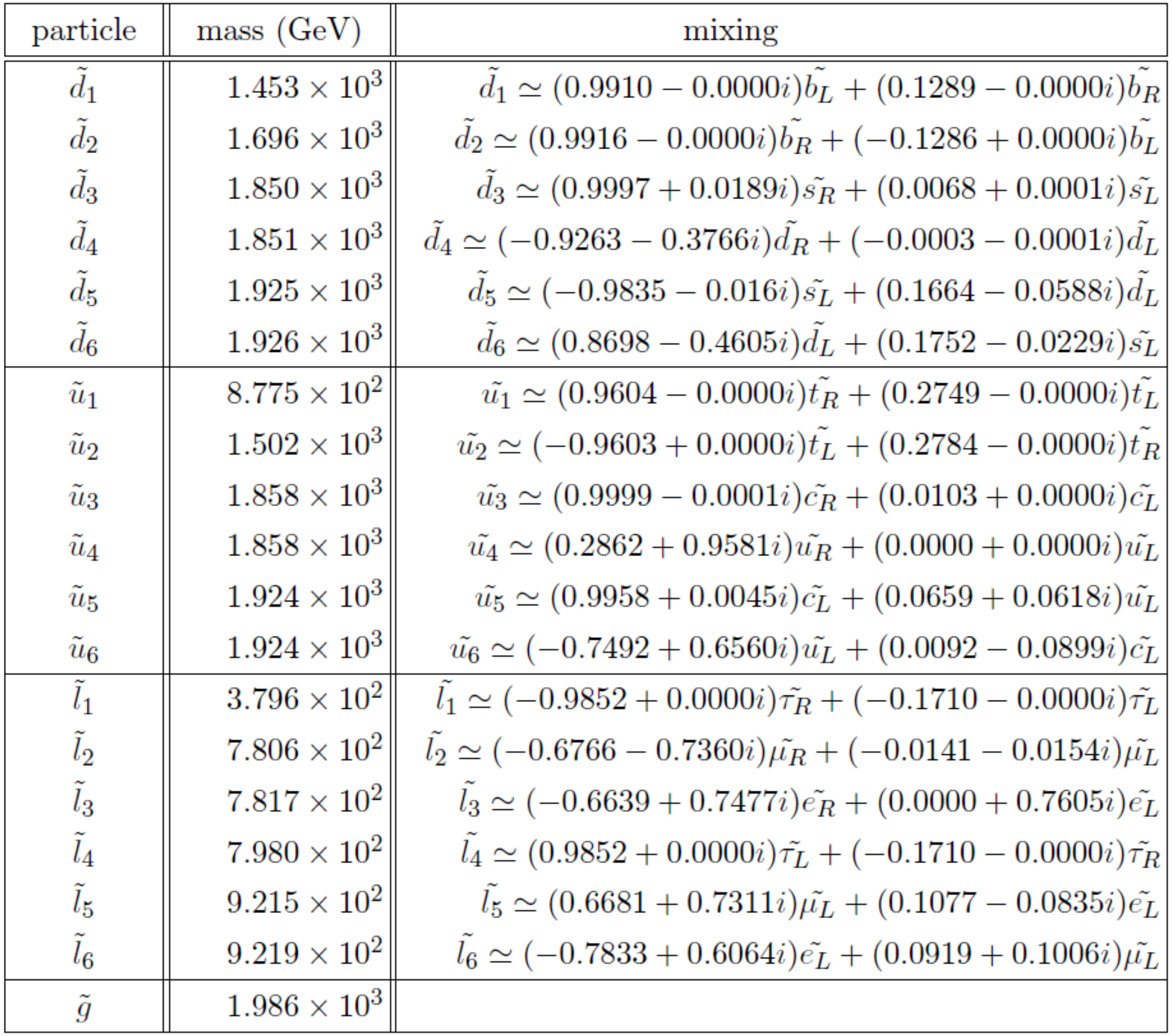
Other predictions from MSSM

$\delta a_\mu = 3.537 \times 10^{-10}$ Putting theoretical value to 3 sigma

All the other SM processes are consistent with experimental bounds too

SUSY Mass Spectrum

On the edge



particle	mass (GeV)	mixing
$\tilde{d}_1$	1.453×10^3	$\tilde{d}_1 \simeq (0.9910 - 0.0000i)\tilde{b}_L + (0.1289 - 0.0000i)\tilde{b}_R$
$\tilde{d}_2$	1.696×10^3	$\tilde{d}_2 \simeq (0.9916 - 0.0000i)\tilde{b}_R + (-0.1286 + 0.0000i)\tilde{b}_L$
$\tilde{d}_3$	1.850×10^3	$\tilde{d}_3 \simeq (0.9997 + 0.0189i)\tilde{s}_R + (0.0068 + 0.0001i)\tilde{s}_L$
$\tilde{d}_4$	1.851×10^3	$\tilde{d}_4 \simeq (-0.9263 - 0.3766i)\tilde{d}_R + (-0.0003 - 0.0001i)\tilde{d}_L$
$\tilde{d}_5$	1.925×10^3	$\tilde{d}_5 \simeq (-0.9835 - 0.016i)\tilde{s}_L + (0.1664 - 0.0588i)\tilde{d}_L$
$\tilde{d}_6$	1.926×10^3	$\tilde{d}_6 \simeq (0.8698 - 0.4605i)\tilde{d}_L + (0.1752 - 0.0229i)\tilde{s}_L$
$\tilde{u}_1$	8.775×10^2	$\tilde{u}_1 \simeq (0.9604 - 0.0000i)\tilde{t}_R + (0.2749 - 0.0000i)\tilde{t}_L$
$\tilde{u}_2$	1.502×10^3	$\tilde{u}_2 \simeq (-0.9603 + 0.0000i)\tilde{t}_L + (0.2784 - 0.0000i)\tilde{t}_R$
$\tilde{u}_3$	1.858×10^3	$\tilde{u}_3 \simeq (0.9999 - 0.0001i)\tilde{c}_R + (0.0103 + 0.0000i)\tilde{c}_L$
$\tilde{u}_4$	1.858×10^3	$\tilde{u}_4 \simeq (0.2862 + 0.9581i)\tilde{u}_R + (0.0000 + 0.0000i)\tilde{u}_L$
$\tilde{u}_5$	1.924×10^3	$\tilde{u}_5 \simeq (0.9958 + 0.0045i)\tilde{c}_L + (0.0659 + 0.0618i)\tilde{u}_L$
$\tilde{u}_6$	1.924×10^3	$\tilde{u}_6 \simeq (-0.7492 + 0.6560i)\tilde{u}_L + (0.0092 - 0.0899i)\tilde{c}_L$
$\tilde{l}_1$	3.796×10^2	$\tilde{l}_1 \simeq (-0.9852 + 0.0000i)\tilde{\tau}_R + (-0.1710 - 0.0000i)\tilde{\tau}_L$
$\tilde{l}_2$	7.806×10^2	$\tilde{l}_2 \simeq (-0.6766 - 0.7360i)\tilde{\mu}_R + (-0.0141 - 0.0154i)\tilde{\mu}_L$
$\tilde{l}_3$	7.817×10^2	$\tilde{l}_3 \simeq (-0.6639 + 0.7477i)\tilde{e}_R + (0.0000 + 0.7605i)\tilde{e}_L$
$\tilde{l}_4$	7.980×10^2	$\tilde{l}_4 \simeq (0.9852 + 0.0000i)\tilde{\tau}_L + (-0.1710 - 0.0000i)\tilde{\tau}_R$
$\tilde{l}_5$	9.215×10^2	$\tilde{l}_5 \simeq (0.6681 + 0.7311i)\tilde{\mu}_L + (0.1077 - 0.0835i)\tilde{e}_L$
$\tilde{l}_6$	9.219×10^2	$\tilde{l}_6 \simeq (-0.7833 + 0.6064i)\tilde{e}_L + (0.0919 + 0.1006i)\tilde{\mu}_L$
$\tilde{g}$	1.986×10^3	

We will observe them soon !!

☑ Neutrino parameters

Also input. We tune the parameter to fit them first.

☑ Leptgenesis & Li ploblem(s)

There is a tension between them

$$\mathscr{W}_l = \widehat{E}^c_\alpha \left(Y_{\mathrm{E}}\right)_{\alpha\beta} \widehat{L}_\beta \cdot \widehat{H}_d + \lambda_{\beta i}\widehat{L}_\beta \cdot \widehat{H}_u \widehat{N}^c_i - \frac{1}{2}\left(M_{\mathrm{N}}\right)_{ij} \widehat{N}^c_i \widehat{N}^c_j$$

$$(m_\nu)_{\alpha\beta} = v_u^2 \; (\lambda_\nu)_{\alpha i} M_i^{-1} (\lambda_\nu)_{i\beta}$$

Leptogenesis requires significant size of $\lambda_{\alpha i}$

⇕

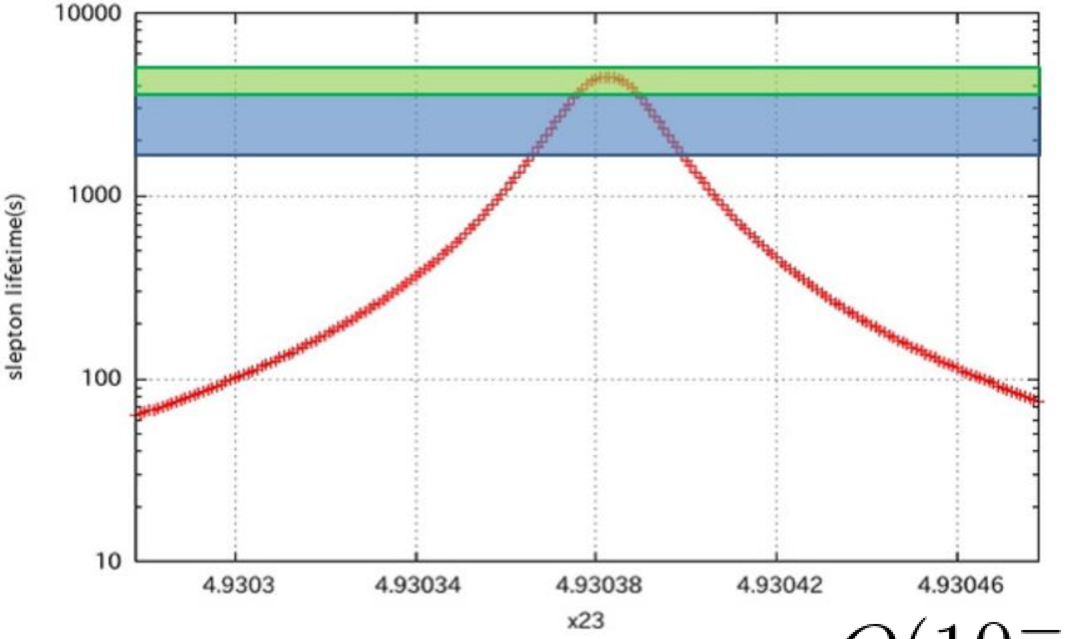
Li ploblems require quite small slepton mixings to make lifetime long enough $C_\alpha \propto \lambda^2$

Due to RGE effect

RH neutrino cannot be too massive

Very narrow parameter region

Lifetime of the lightest slepton



$\mathcal{O}(10^{-5})$ tuning

FIG. 2: The lightest slepton lifetime as a function of x_{23}. The blue and green band corresponds to the lifetime required to solve the ^{7}Li problem only and both the ^{7}Li and ^{6}Li problems, respectively.

At a large M1 solution vanished

RH nu mass range

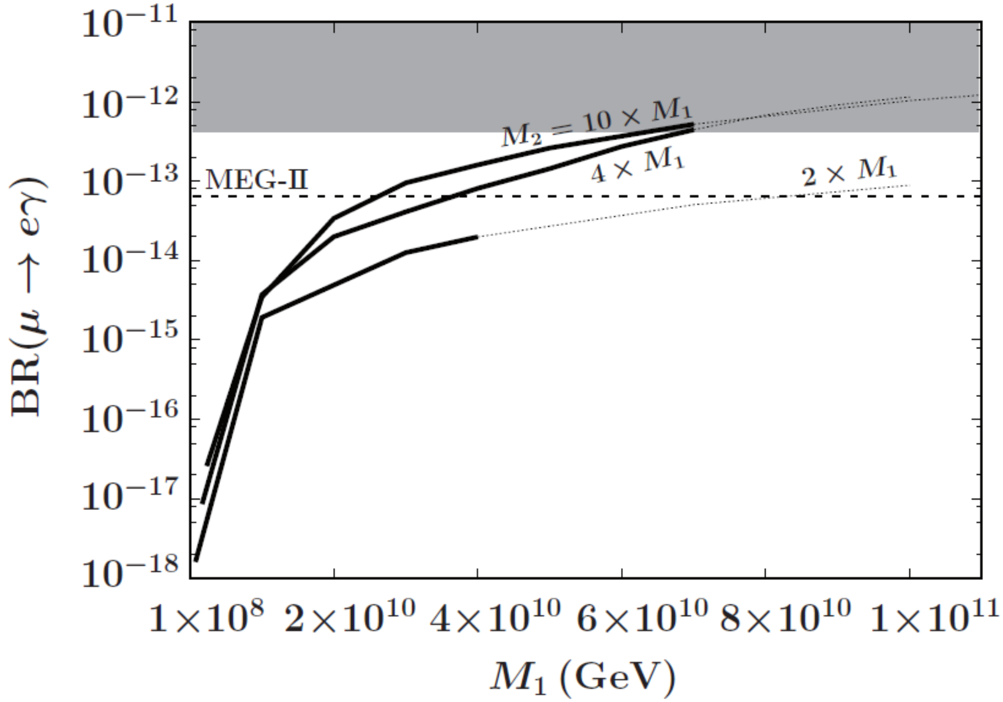
1. case of $M_2 = 2 \times M_1$, $M_3 = 40 \times M_1$

- Taking into account ^{6}Li and ^{7}Li problem

$$7.8 \times 10^8 \le M_1 \le 7.0 \times 10^{10} \ (\mathrm{GeV}) \ .$$

- Taking into account only ^{7}Li problem

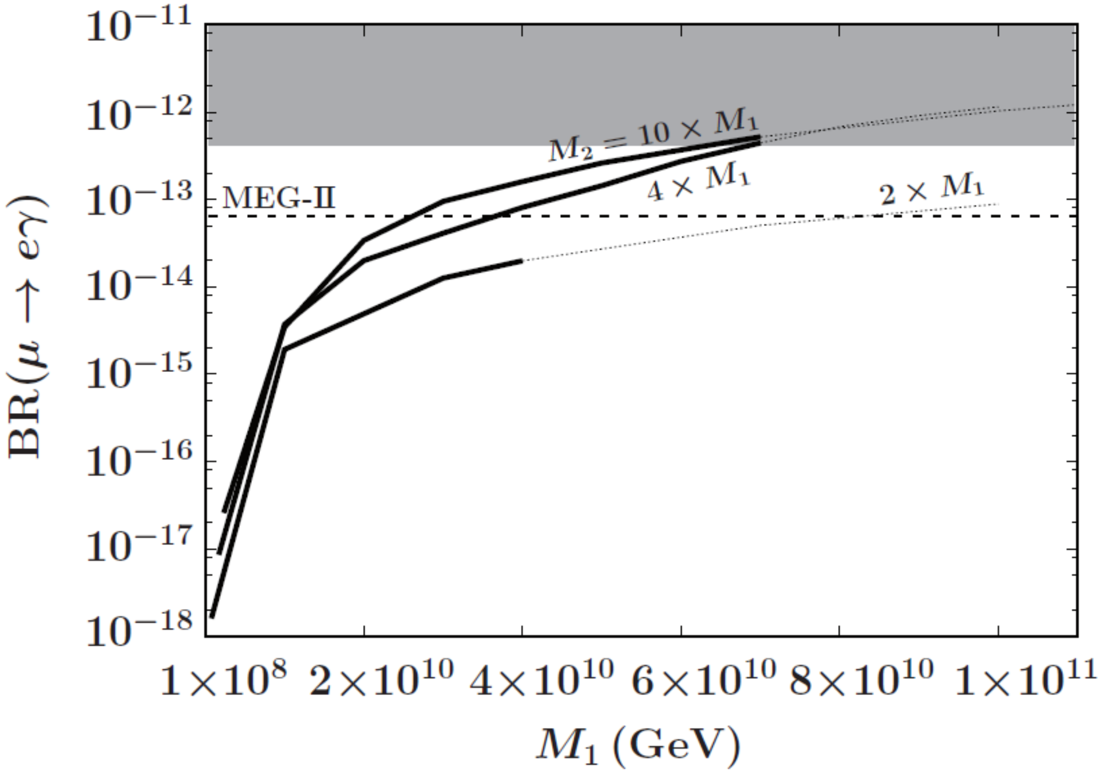
$$7.8 \times 10^8 \le M_1 \le 1.0 \times 10^{11} \ (\mathrm{GeV}) \ .$$



Thick Line : Li 6&7

Thin line: only Li 7

Predictions for CLFV experiment

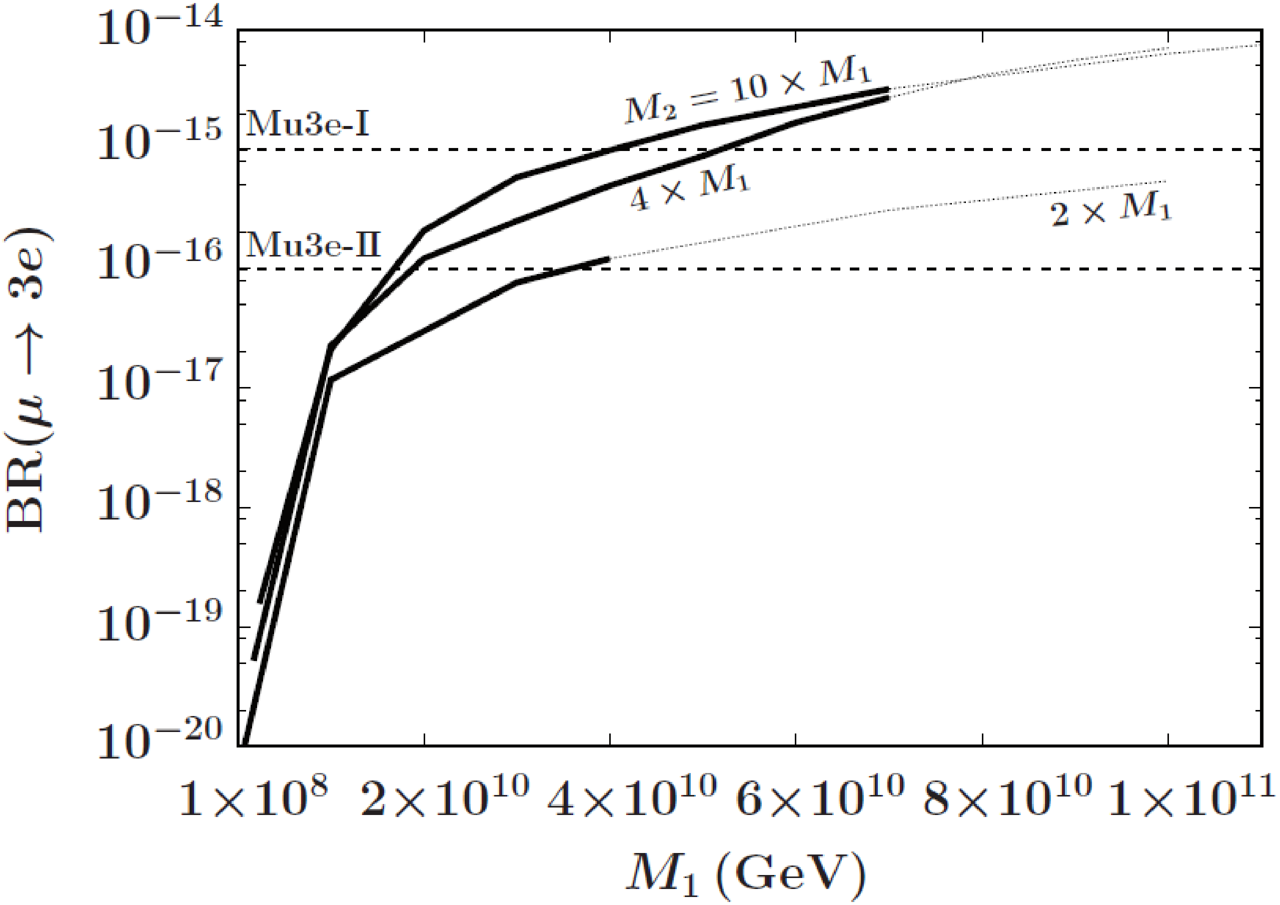


Prediction is just below the current limit with Li6+7

In our scenario, it is natural not observe any CLFV.

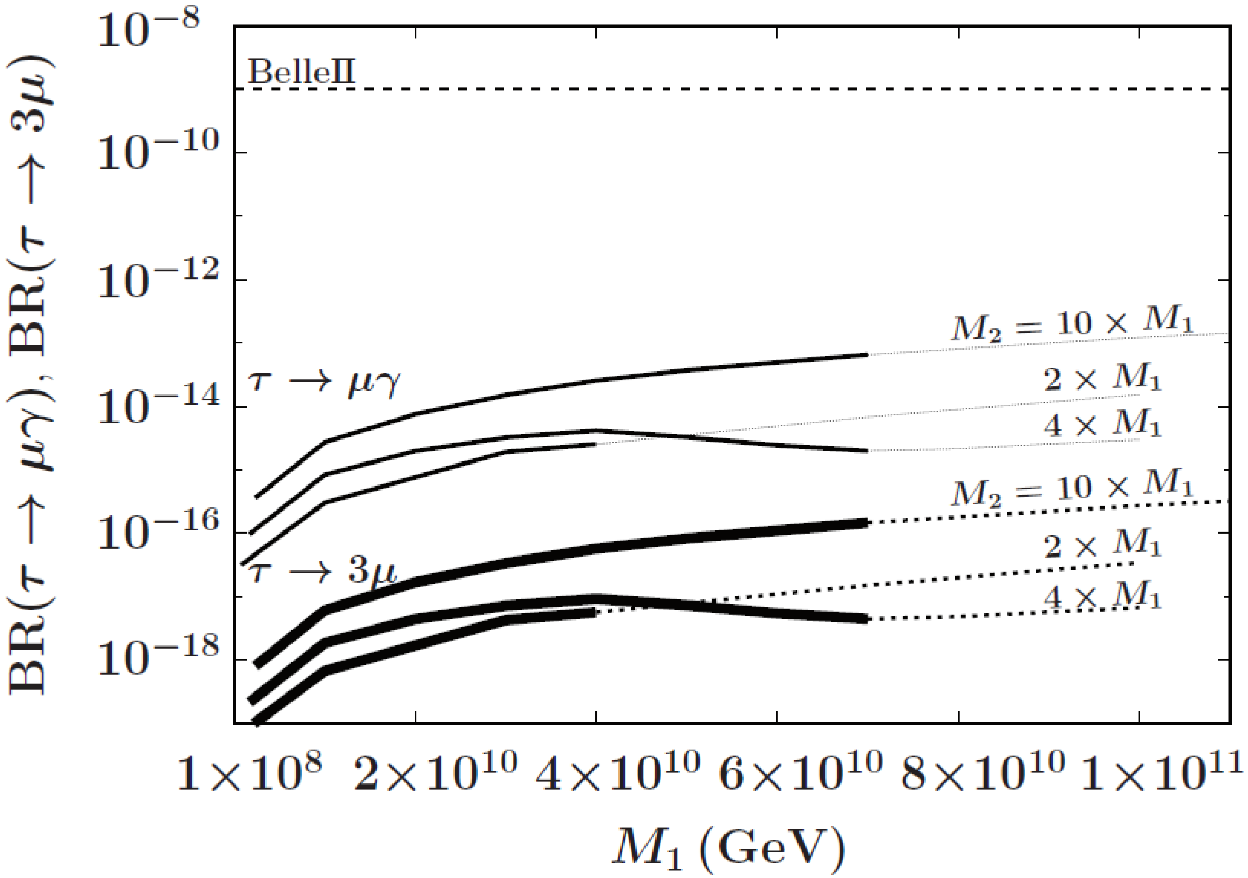
We will observe it soon

Other CLFV Process



With muon, we will observe soon

Other CLFV Process



With tau, it is impossible to observe within our lifetime

6. Summary

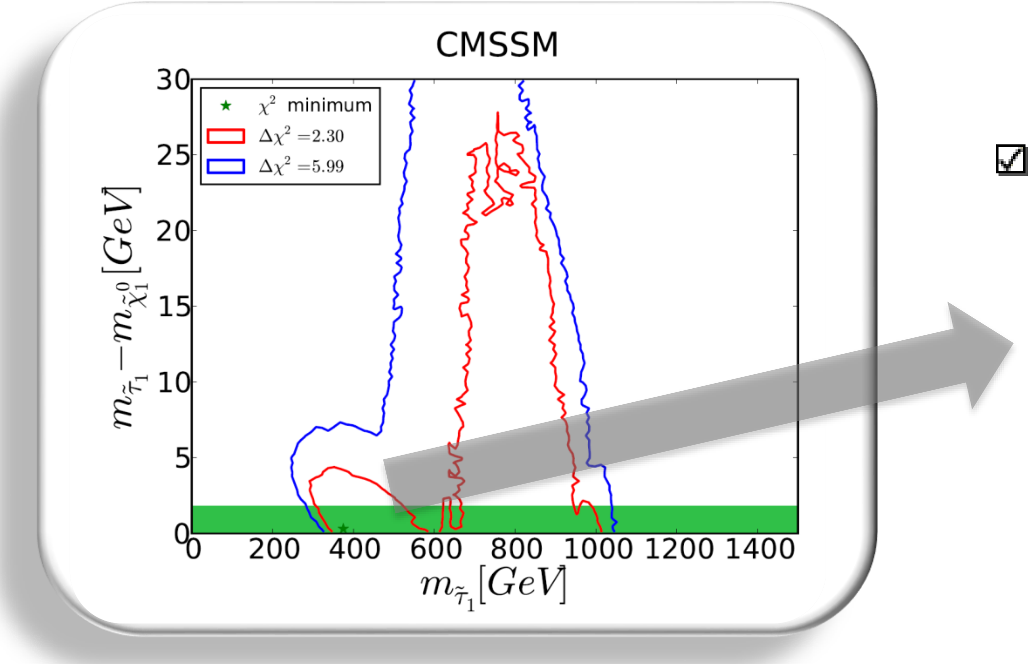
6.Summary

- ☑ Constrained minimal SUSY standard model (CMSSM) + RH nu with 4 requirement
- ☑ 4 requirement
  - Dark matter relic abundance
  - Neutrino Physics
  - **Leptogenesis**
  - **Lithium Problem(s)**

Li Problem vs Leptogenesis
Small LFV vs Large LFV

- ☑ Very stringent Predictions
  - SUSY particles will soon be observed
  - **CLFV is around current experiment bound**
  - DM direct detection in near future

どこのパラメーター領域に注目すべきか？



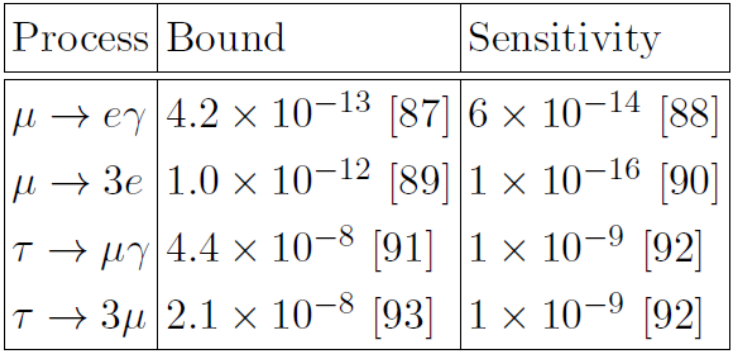
[J. Ellis, et al, PRD87 (2013)]

☑ 125GeV Higgs、muon g-2 なども含めると尤もらしい領域は？

$$\delta m < m_\tau$$

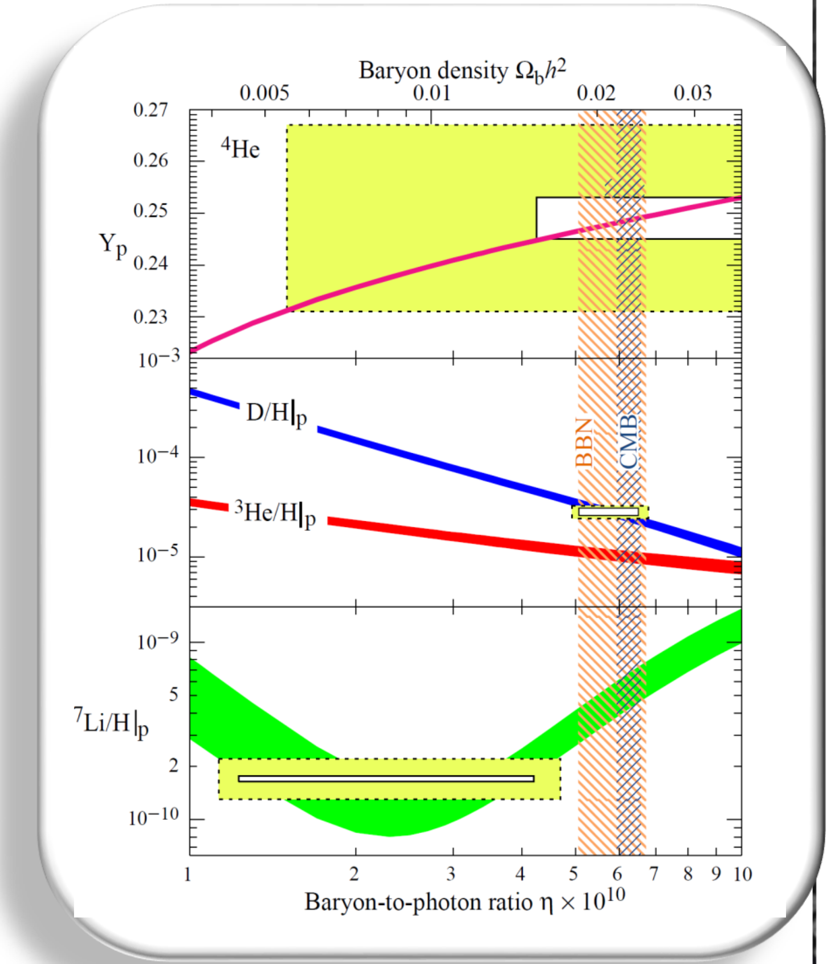
$$\delta m = m_{\tilde\tau_R} - m_{\tilde\chi}$$

暗黒物質とスタウの質量差



Process	Bound	Sensitivity
$\mu \to e\gamma$	4.2×10^{-13} [87]	6×10^{-14} [88]
$\mu \to 3e$	1.0×10^{-12} [89]	1×10^{-16} [90]
$\tau \to \mu\gamma$	4.4×10^{-8} [91]	1×10^{-9} [92]
$\tau \to 3\mu$	2.1×10^{-8} [93]	1×10^{-9} [92]

リチウム7問題



☑ Prediction

$$^7\mathrm{Li/H} = (4.15^{+0.49}_{-0.45}) \times 10^{-10}$$

☑ Observation

$$^7\mathrm{Li/H} = (1.26^{+0.29}_{-0.24}) \times 10^{-10}$$

☑ Discrepancy: ^{7}Li problem

☑ No solutions by modifying nucleus reaction rates

☑ Find mechanism to reduce both ^{7}Li and ^{7}Be at the BBN epoch

☑ req4 : Stau (and DM(Lightest Neutralino)) mass

$$339[\mathrm{GeV}] \leq m_{\tilde{\tau}} \leq 450[\mathrm{GeV}]$$

LHC bound

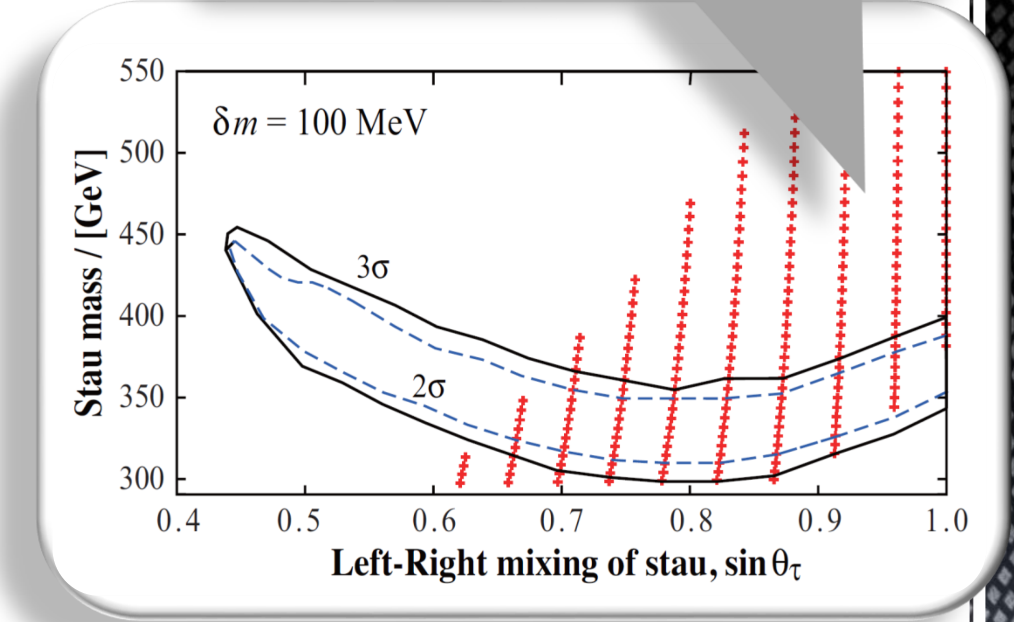
- Sufficient bound states
  = Enough Stau at BBN

Strongly correlated with
Number density of DM

DM abundance (fixed)
= number density × mass

- Direct measurement at LHC

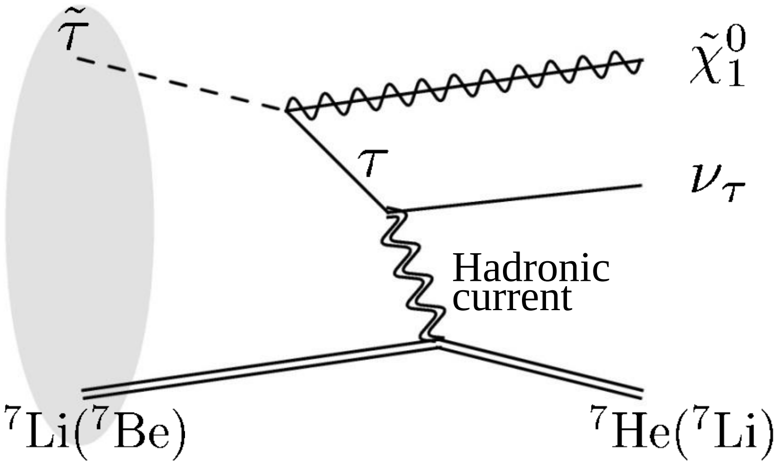
Red Point : BBN
“Islands” :DM Abundance

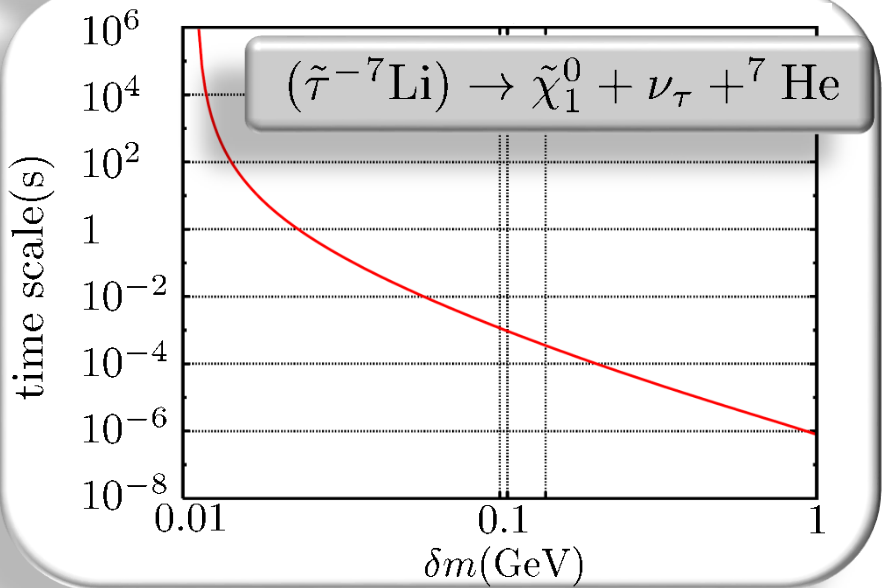


[T. Jittoh, K. Kohri, M. Koike, J. S, T. Shimomura, M.Yamanaka, PRD82(2010)]

Internal conversion for solving the lithium7 problem

[T. Jittoh, K. Kohri, M. Koike, J. Sato, T. Shimomura, MY, PRD76 (2007)]





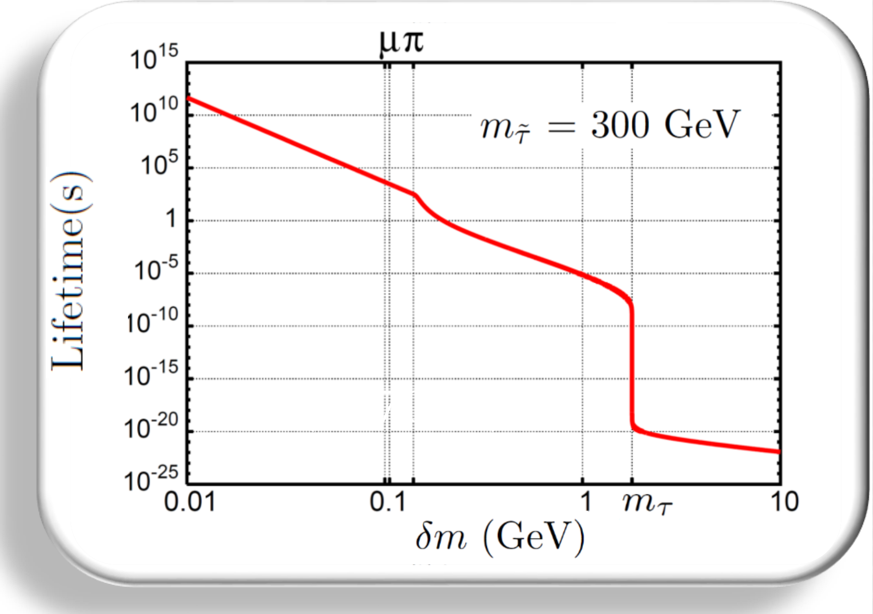
$(\tilde{\tau}^{-7}\mathrm{Li}) \to \tilde{\chi}_1^0 + \nu_\tau +{}^7\mathrm{He}$

- ☑ Mechanism to reduce both ^{7}Li and ^{7}Be
- ☑ Nuclear transformation by the bound state $(\tilde{\tau}^{-7}\mathrm{Li})$ and $(\tilde{\tau}^{-7}\mathrm{Be})$

  (cf. electron capture)
- ☑ ^{7}Li is immediately destroyed once forming the bound state

Very fortunately

☑ Stau is long-lived at $\delta m < m_\tau$ since 2-body decay is kinematically prohibited



[T. Jittoh, J. Sato, T. Shimomura, MY, PRD73 (2006)]

☑ $\delta m > m_\tau$ のCMSSMを調べるだけでは見落とす現象や制限あり

☑ CMSSMの確立に向け、実現可能性大の領域を丁寧に洗い直すべき

研究目的：新たな現象、それに伴う特典・制限を含め、
現実的CMSSMの検証可能性を真摯に解析