Big-bang nucleosynthesis and Leptogenesis in CMSSM

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- 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

Lithium Problem(s) in Big-Bang Nucleosynthesis

- Dark Matter candidate
- Baryon Asymmetry
- Lepton Flavor Violation among Neutrino

Go beyond SM

SM works quite well
1. Introduction

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- Dark Matter candidate
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- Lithium Problem(s) in Big-Bang Nucleosynthesis

Constrained minimal SUSY standard model (CMSSM) with RH- neutrinos can solve them!?

Keeping the good feature of SM
2. Clues for BSM
2. Clues for BSM

2.1 DM Abundance

Neutral Stable Particle(s) required:

\[ 0.1126 \leq \frac{m_{\chi_1^0} n h^2}{\rho_c} \leq 0.1246 \quad (3\sigma \text{ C.L.}) \]

2.2 Baryon Asymmetry in the universe

Our universe is made from only matter.

\[ \Omega_b h^2 = 0.0223 \pm 0.0002 \quad (1\sigma) \]

Origin(s) of asymmetry is required
2.3 Li problem(s)

Theoretical prediction
\[(4.15 \pm 0.49) \times 10^{-10}\]

Observation
\[(1.26 \pm 0.24) \times 10^{-10}\]

Predicted $^7$Li abundance ≠ observed $^7$Li abundance

$^7$Li problem
$^6\text{Li}/\text{H} \sim 6 \times 10^{-12}$

1000 times higher than SBBN?
Steffen et al. 2012

Lithium 6 Problem

Or

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

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 difference

\[ U_{\text{MNS}} = \hat{U} \ \text{diag} \ (1, e^{i\alpha}, e^{i\beta}) \]

\[
\hat{U} = \begin{pmatrix}
  c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\
  -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\
  s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]

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

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

\[ s_{23} = \sqrt{0.441} , \quad s_{13} = \sqrt{0.02166} , \quad s_{12} = \sqrt{0.306} , \]

\[ \alpha = 0 , \ \beta = 0 , \ \delta = 261^\circ . \]
3. Solution by CMSSM with RH v
3.1 DM abundance and LHC result

Neutralino $\sim$ Bino-like DM

- Coannihilation region

$\text{DM and Stau} : \text{degenerate in mass}$

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,

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

[Chen, Seckel, asian, JHEP(2012)]

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

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 Nucleosynthesis !

Lithium Problem can be solved
3.2 Lepton Mixing

Seesaw mechanism

\[ \mathcal{L}_l = \hat{E}_\alpha^c (Y_E)_{\alpha\beta} \hat{L}_\beta \cdot \hat{H}_d + \lambda_{\beta i} \hat{L}_\beta \cdot \hat{H}_u \hat{N}_i^c - \frac{1}{2} (M_N)_{ij} \hat{N}_i^c \hat{N}_j^c \]

\[ \hat{L}_\alpha \text{ and } \hat{E}_\alpha^c \ (\alpha = e, \mu, \tau) \ (Y_E)_{\alpha\beta} = y_\alpha \delta_{\alpha\beta} \text{ is assumed} \]

Right-handed neutrinos

\[ \hat{N}_i^c \ (i = 1, 2, 3) \]

Below RH neutrino scale

\[ \mathcal{L}^\nu = -\frac{1}{2} \nu_L \ (m_\nu)_{\alpha\beta} \nu_L + h.c. , \]

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

\[ (m_\nu) = U^*_{\text{MNS}} D_{m_\nu} U^\dagger_{\text{MNS}} \]

Tiny masses and lepton mixing
Lepton mixing and Mass difference

\[ U_{\text{MNS}} = \hat{U} \text{ diag } (1, e^{i\alpha}, e^{i\beta}) \]

\[ \hat{U} = \begin{pmatrix} c_{13} c_{12} & c_{13} s_{12} & s_{13} e^{-i\delta} \\ -c_{23} s_{12} - s_{23} s_{13} c_{12} e^{i\delta} & c_{23} c_{12} - s_{23} s_{13} s_{12} e^{i\delta} & s_{23} c_{13} \\ s_{23} s_{12} - c_{23} s_{13} c_{12} e^{i\delta} & -s_{23} c_{12} - c_{23} s_{13} s_{12} e^{i\delta} & c_{23} c_{13} \end{pmatrix} \]

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

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

In this talk we will fix the parameters

\[ s_{23} = \sqrt{0.441} , \quad s_{13} = \sqrt{0.02166} , \quad s_{12} = \sqrt{0.306} , \quad m_{\nu_1} = 0.001 \text{ (eV)} \]

\[ \alpha = 0 , \quad \beta = 0 , \quad \delta = 261^\circ \]
There remains degrees of freedom in the parameters

\[ \lambda_\nu = \frac{1}{v_u} U_{\text{MNS}}^* \sqrt{D_{m_\nu}} \ R \ \sqrt{M} , \]  

\[ R = \begin{pmatrix}
\tilde{c}_{13} \tilde{c}_{12} & \tilde{c}_{13} \tilde{s}_{12} & \tilde{s}_{13} \\
-\tilde{c}_{23} \tilde{s}_{12} & \tilde{c}_{23} \tilde{c}_{12} - \tilde{s}_{23} \tilde{s}_{13} \tilde{s}_{12} & \tilde{s}_{23} \tilde{c}_{13} \\
\tilde{s}_{23} \tilde{s}_{12} - \tilde{c}_{23} \tilde{s}_{13} \tilde{c}_{12} & -\tilde{s}_{23} \tilde{c}_{12} - \tilde{c}_{23} \tilde{s}_{13} \tilde{s}_{12} & \tilde{c}_{23} \tilde{c}_{13}
\end{pmatrix}
\]

\[ \tilde{c}_{ij} = \cos z_{ij} \]

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

6 parameters+

\[ R \text{ is a complex orthogonal matrix, } R^T R = 1 \]
3.3 Baryon asymmetry

Leptogenesis

Generate Lepton asymmetry and Convert to Baryon number

\[ \varepsilon^i_\alpha \equiv \frac{\Gamma(N_i \rightarrow \ell_\alpha \phi) - \Gamma(N_i \rightarrow \ell_\alpha \phi^\dagger)}{\Gamma(N_i \rightarrow \ell_\alpha \phi) + \Gamma(N_i \rightarrow \ell_\alpha \phi^\dagger)} \]

(a) \[ \varepsilon^i_\alpha \text{(vertex)} = -\frac{1}{8\pi} \sum \frac{M_j}{M_i} \log \left[ 1 + \frac{M_j^2}{M_i^2} \right] \mathfrak{S} \left[ (\lambda^i\lambda)_{ji} \lambda^*_j \lambda^i \right] \]

(b) \[ \varepsilon^i_\alpha \text{(wave)} = -\frac{2}{8\pi} \sum \frac{M_i}{M_j - M_i^2} \mathfrak{S} \left\{ \left[ M_j (\lambda^i\lambda)_{ji} + M_i (\lambda^i\lambda)_{ij} \right] \lambda^*_i \lambda^i \right\} \]

\[ Y_B = \left( \frac{8}{23} \right) Y_{B-L} \rightarrow 2.414 \times 10^{-10} \lesssim |Y_{B-L}| \lesssim 2.561 \times 10^{-10} \]

\[ \Omega_b h^2 = 0.0223 \pm 0.0002 \text{ (1}\sigma\text{)} \]

Flavored Leptogenesis
3.3 Baryon asymmetry

Leptogenesis

Generate Lepton asymmetry and Convert to Baryon number

Flavored Leptogenesis

Fukugita&Yanagida

\[ z = \frac{M_1}{T} \]
3.4 Li problem(s) and a solution by long-lived stau


Predicted $^7$Li abundance ≠ observed $^7$Li abundance

$^7$Li problem

$(4.15 \pm 0.49) \times 10^{-10}$


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

Steffen et al 2012

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

Lind et al 2013

1000 times higher than SBBN ?

Lithium 6 Problem (?)
Solving the Li problem with “stau”

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

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: \( \uparrow \)
- Interaction rate of hadronic current: \( \uparrow \)
- \( \tilde{\tau}^+ \) does not form a bound state
- No cancellation processes
Internal conversion rate

The lifetime of the stau-nucleus bound state

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

Wave function of the bound state

\[ |\psi|^2 = \frac{1}{\pi a_{\text{nucl}}^3} \]

nuclear radius

\[ a_{\text{nucl}} = (1.2 \times A^{1/3}) \]

(\(\sigma v\)) is evaluated by using ft-value

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

ft-value of each processes

\( ^7\text{Be} \rightarrow ^7\text{Li} \quad \cdots \quad ft = 10^{3.3} \text{ sec (experimental value)} \)

\( ^7\text{Li} \rightarrow ^7\text{He} \quad \cdots \) similar to \( ^7\text{Be} \rightarrow ^7\text{Li} \) (no experimental value)
Lifetime of bound state (s)

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

\[ m_{^7\text{He}} - m_{^7\text{Li}} = 11.2 \text{ MeV} \]

\[ (\tilde{\tau} \, ^7\text{Li}) \rightarrow \tilde{\chi}^0 + \nu_\tau + ^7\text{He} \]

**Interaction rate of internal conversion**

**Very short lifetime**

Significant process for reducing $^7\text{Li}$ abundance
Li destruction chain with internal conversion

- $^7\text{Be}$ → $^7\text{Li}$
  - Internal conversion
    - $\tilde{\tau}$
    - $\tilde{\chi}$, $\nu_\tau$

- $^7\text{Li}$
  - Internal conversion
    - $\tilde{\tau}$
    - $\tilde{\chi}$, $\nu_\tau$

- Scattering with background particles
  - $^7\text{He}$
  - $^4\text{He}$, $^3\text{He}$, D, etc
  - Proton, etc
Stau catalyzed fusion

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

Ineffective for reducing $^7\text{Li}$ and $^7\text{Be}$

$\because$ stau can not weaken the barrieres of $\text{Li}^{3+}$ and $\text{Be}^{4+}$ sufficiently

(N, $\bar{\tau}$) $\rightarrow$ $N'$ + (N, $\bar{\tau}$) $\rightarrow$ $\bar{\tau}$ + N''

( ): bound state
Stau catalyzed fusion

Standard BBN process

Catalyzed BBN process

Catalyzed BBN cause over production of $^6\text{Li}$

Constraint on stau life time

Or solution to Li6
\textbf{4 He spallation process} \hspace{1cm} \textbf{PRD 84}

Bound state formation via EM int.

\[ \tilde{\tau} + ^4\text{He} \rightarrow (\tilde{\tau}^4\text{He}) \]

Spallation process

\[
\begin{align*}
(\tilde{\tau}^4\text{He}) & \rightarrow \tilde{\chi}^0 + \nu_\tau + t + n \\
(\tilde{\tau}^4\text{He}) & \rightarrow \tilde{\chi}^0 + \nu_\tau + d + n + n \\
(\tilde{\tau}^4\text{He}) & \rightarrow \tilde{\chi}^0 + \nu_\tau + p + n + n + n
\end{align*}
\]

Reaction rate

\[ \Gamma ( (\tilde{\tau}^4\text{He}) \rightarrow \tilde{\chi}_1^0 \nu_\tau \text{tn}) = |\psi|^2 \cdot \sigma v_{\text{tn}} \]

Upper bound for lifetime from not to produce much t/d
Favored parameter space in MSSM

Mass difference

\[ \delta m < m_\mu \]

Lifetime

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

\[ 1700 \, s \leq \tau_\ell \leq 5000 \, s \iff 2.0 \times 10^{-10} \leq C_e \leq 3.5 \times 10^{-10} \]

\[ 3500 \, s \leq \tau_\ell \leq 5000 \, s \iff 2.0 \times 10^{-10} \leq C_e \leq 2.5 \times 10^{-10} \]

\[ \delta m = 10 \, \text{MeV} \text{ and } \sin \theta_e = 0.6 \]

Li7 Problem

Li6&7 Problem

In addition, to have enough slepton

\[ C_\mu < \mathcal{O}(10^{-5}) \]

Number density of long-lived slepton

\[ \tilde{\ell}_1^\pm \gamma \leftrightarrow \tilde{\chi}_1^0 \tau^\pm, \quad \tilde{\ell}_1^\pm \gamma \leftrightarrow \tilde{\chi}_1^0 \mu^\pm, \]

\[ \tilde{\ell}_1^\pm \tau^\pm \leftrightarrow \tilde{\chi}_1^0 \gamma, \quad \tilde{\ell}_1^\pm \mu^\mp \leftrightarrow \tilde{\chi}_1^0 \gamma, \quad \tilde{\ell}_1^\pm e^\mp \leftrightarrow \tilde{\chi}_1^0 \gamma \]

Should be suppressed
4. Parameter Search
4. Parameter Search

Free parameters

From CMSSM

\[ m_{1/2}, \ m_0, \ A_0, \ \tan \beta, \ \text{sign}(\mu) \]

Almost fixed by DM and lifetime of the lightest slepton

In addition to Higgs mass $\sim 125$ GeV

Here we assume for simplicity

\[ m_{\chi} = 380 \text{ GeV}, \ \delta m = 10 \text{ MeV} \]

\[ m_{1/2} = 887.0 (\text{GeV}) , \ A_0 = -3090 (\text{GeV}) \]

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

With the assumption

\[ \tan \beta = 25 \]
From neutrino physics

Free parameters

From RH neutrino

\[ \mathcal{W}_l = \hat{E}_\alpha (Y_E)_{\alpha\beta} \hat{L}_\beta \cdot \hat{H}_d + \lambda_{\beta i} \hat{L}_\beta \cdot \hat{H}_u \hat{N}_i^c - \frac{1}{2} (M_N)_{ij} \hat{N}_i^c \hat{N}_j^c \]

With Casas Ibarra parametrization

\[ \lambda_\nu = \frac{1}{\nu_u} U^*_{\text{MNS}} \sqrt{D_{m_\nu}} \; R \; \sqrt{M} \]

\[ R = \begin{pmatrix} \tilde{c}_{13} \tilde{c}_{12} & \tilde{c}_{13} \tilde{s}_{12} & \tilde{s}_{13} \\ -\tilde{c}_{23} \tilde{s}_{12} & \tilde{c}_{23} \tilde{c}_{12} - \tilde{s}_{23} \tilde{s}_{13} \tilde{s}_{12} & \tilde{s}_{23} \tilde{c}_{13} \\ \tilde{s}_{23} \tilde{s}_{12} - \tilde{c}_{23} \tilde{s}_{13} \tilde{c}_{12} & -\tilde{s}_{23} \tilde{c}_{12} - \tilde{c}_{23} \tilde{s}_{13} \tilde{s}_{12} & \tilde{c}_{23} \tilde{c}_{13} \end{pmatrix} \]

6+3+1 parameters

\[ z_{ij} = x_{ij} + \sqrt{-1} \; y_{ij} \]

3 complex angles = 6 parameters to be searched
\( M_i \ (i = 1, 2, 3) \) (RH \( \nu \) masses) 3 mass parameters

\[ M_1 \text{ is free parameter} \]

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. \( M_2 = 10 \times M_1, \ M_3 = 40 \times M_1 \)

\( m_{\nu_1} = 0.001 \) (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

\[ \Omega h^2 = 0.115 \quad \leftrightarrow \quad m_\chi = 380 \text{GeV}, \quad \delta m = 10 \text{MeV} \]

Spin independent Cross section : satisfy LUX

\[ \sigma^{\text{SI}} = 1.05 \times 10^{-47} \text{ cm}^2 \]

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

<table>
<thead>
<tr>
<th>particle</th>
<th>mass (GeV)</th>
<th>mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{d}_1$</td>
<td>$1.453 \times 10^3$</td>
<td>$\tilde{d}_1 \simeq (0.9910 - 0.0000i)\tilde{b}_L + (0.1289 - 0.0000i)\tilde{b}_R$</td>
</tr>
<tr>
<td>$\tilde{d}_2$</td>
<td>$1.696 \times 10^3$</td>
<td>$\tilde{d}_2 \simeq (0.9916 - 0.0000i)\tilde{b}_R + (-0.1286 + 0.0000i)\tilde{b}_L$</td>
</tr>
<tr>
<td>$\tilde{d}_3$</td>
<td>$1.850 \times 10^3$</td>
<td>$\tilde{d}_3 \simeq (0.9997 + 0.0189i)\tilde{s}_R + (0.0068 + 0.0001i)\tilde{s}_L$</td>
</tr>
<tr>
<td>$\tilde{d}_4$</td>
<td>$1.851 \times 10^3$</td>
<td>$\tilde{d}_4 \simeq (-0.9263 - 0.3766i)\tilde{d}_R + (-0.0003 - 0.0001i)\tilde{d}_L$</td>
</tr>
<tr>
<td>$\tilde{d}_5$</td>
<td>$1.925 \times 10^3$</td>
<td>$\tilde{d}_5 \simeq (-0.9835 - 0.016i)\tilde{s}_L + (0.1664 - 0.0588i)\tilde{d}_L$</td>
</tr>
<tr>
<td>$\tilde{d}_6$</td>
<td>$1.926 \times 10^3$</td>
<td>$\tilde{d}_6 \simeq (0.8698 - 0.4605i)\tilde{d}_L + (0.1752 - 0.0229i)\tilde{s}_L$</td>
</tr>
<tr>
<td>$\tilde{u}_1$</td>
<td>$8.775 \times 10^2$</td>
<td>$\tilde{u}_1 \simeq (0.9604 - 0.0000i)\tilde{t}_R + (0.2749 - 0.0000i)\tilde{t}_L$</td>
</tr>
<tr>
<td>$\tilde{u}_2$</td>
<td>$1.502 \times 10^3$</td>
<td>$\tilde{u}_2 \simeq (-0.9603 + 0.0000i)\tilde{t}_L + (0.2784 - 0.0000i)\tilde{t}_R$</td>
</tr>
<tr>
<td>$\tilde{u}_3$</td>
<td>$1.858 \times 10^3$</td>
<td>$\tilde{u}_3 \simeq (0.9999 - 0.0001i)\tilde{c}_R + (0.0103 + 0.0000i)\tilde{c}_L$</td>
</tr>
<tr>
<td>$\tilde{u}_4$</td>
<td>$1.858 \times 10^3$</td>
<td>$\tilde{u}_4 \simeq (0.2862 + 0.9581i)\tilde{u}_R + (0.0000 + 0.0000i)\tilde{u}_L$</td>
</tr>
<tr>
<td>$\tilde{u}_5$</td>
<td>$1.924 \times 10^3$</td>
<td>$\tilde{u}_5 \simeq (0.9958 + 0.0045i)\tilde{c}_L + (0.0659 + 0.0618i)\tilde{u}_L$</td>
</tr>
<tr>
<td>$\tilde{u}_6$</td>
<td>$1.924 \times 10^3$</td>
<td>$\tilde{u}_6 \simeq (-0.7492 + 0.6560i)\tilde{u}_L + (0.0092 - 0.0899i)\tilde{c}_L$</td>
</tr>
<tr>
<td>$\tilde{l}_1$</td>
<td>$3.796 \times 10^2$</td>
<td>$\tilde{l}_1 \simeq (-0.9852 + 0.0000i)\tilde{\tau}_R + (-0.1710 - 0.0000i)\tilde{\tau}_L$</td>
</tr>
<tr>
<td>$\tilde{l}_2$</td>
<td>$7.806 \times 10^2$</td>
<td>$\tilde{l}_2 \simeq (-0.6766 - 0.7360i)\tilde{\mu}_R + (-0.0141 - 0.1541i)\tilde{\mu}_L$</td>
</tr>
<tr>
<td>$\tilde{l}_3$</td>
<td>$7.817 \times 10^2$</td>
<td>$\tilde{l}_3 \simeq (-0.6639 + 0.7477i)\tilde{\epsilon}_R + (0.0000 + 0.7605i)\tilde{\epsilon}_L$</td>
</tr>
<tr>
<td>$\tilde{l}_4$</td>
<td>$7.980 \times 10^2$</td>
<td>$\tilde{l}_4 \simeq (0.9852 + 0.0000i)\tilde{\tau}_L + (-0.1710 - 0.0000i)\tilde{\tau}_R$</td>
</tr>
<tr>
<td>$\tilde{l}_5$</td>
<td>$9.215 \times 10^2$</td>
<td>$\tilde{l}_5 \simeq (0.6681 + 0.7311i)\tilde{\mu}_L + (0.1077 - 0.0835i)\tilde{\epsilon}_L$</td>
</tr>
<tr>
<td>$\tilde{l}_6$</td>
<td>$9.219 \times 10^2$</td>
<td>$\tilde{l}_6 \simeq (-0.7833 + 0.6064i)\tilde{\epsilon}_L + (0.0919 + 0.1006i)\tilde{\mu}_L$</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$1.986 \times 10^3$</td>
<td></td>
</tr>
</tbody>
</table>

We will observe them soon !!
Neutrino parameters

Also input. We tune the parameter to fit them first.
Leptogenesis & Li ploblem(s)

There is a tension between them

\[ \mathcal{L}_i = \hat{E}_\alpha^c (Y_E)_{\alpha\beta} \hat{L}_\beta \cdot \hat{H}_d + \lambda_{3i} \hat{L}_\beta \cdot \hat{H}_u \hat{N}_i^c - \frac{1}{2} (M_N)_{ij} \hat{N}_i^c \hat{N}_j^c \]

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

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

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 $^6\text{Li}$ and $^7\text{Li}$ problem

$$7.8 \times 10^8 \leq M_1 \leq 7.0 \times 10^{10} \text{ (GeV)}.$$ 

- Taking into account only $^7\text{Li}$ problem

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

**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 to observe any CLFV.

We will observe it soon
Other CLFV Process

With muon, we will observe soon
With tau, it is impossible to observe within our lifetime.
6. Summary
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- Constrained minimal SUSY standard model (CMSSM) + RH nu with 4 requirement
- 4 requirement
  - Dark matter relic abundance
  - Neutrino Physics
  - **Leptogenesis** Li Problem vs Leptogenesis
  - **Lithium Problem(s)** 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
どのパラメーター領域に注目すべきか？

☑ 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
<table>
<thead>
<tr>
<th>Process</th>
<th>Bound</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$4.2 \times 10^{-13}$ [87]</td>
<td>$6 \times 10^{-14}$ [88]</td>
</tr>
<tr>
<td>$\mu \to 3e$</td>
<td>$1.0 \times 10^{-12}$ [89]</td>
<td>$1 \times 10^{-16}$ [90]</td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
<td>$4.4 \times 10^{-8}$ [91]</td>
<td>$1 \times 10^{-9}$ [92]</td>
</tr>
<tr>
<td>$\tau \to 3\mu$</td>
<td>$2.1 \times 10^{-8}$ [93]</td>
<td>$1 \times 10^{-9}$ [92]</td>
</tr>
</tbody>
</table>
Prediction

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

Observation

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

Discrepancy: $^7\text{Li}$ problem

No solutions by modifying nucleus reaction rates

Find mechanism to reduce both $^7\text{Li}$ and $^7\text{Be}$ at the BBN epoch
req4: Stau (and DM(Lightest Neutralino)) mass

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

- Sufficient bound states = Enough Stau at BBN
- Strongly correlated with Number density of DM
- DM abundance (fixed) = number density \( \times \) mass
- Direct measurement at LHC

Red Point: BBN “Islands”: DM Abundance

Internal conversion for solving the lithium7 problem


- Mechanism to reduce both $^7$Li and $^7$Be

- Nuclear transformation by the bound state ($\tilde{\tau}^{-7}$Li) and ($\tilde{\tau}^{-7}$Be)
  
  \[ (\tilde{\tau}^{-7}\text{Li}) \rightarrow \tilde{\chi}_1^0 + \nu_\tau + ^7\text{He} \]

- $^7$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

- $\delta m > m_\tau$ 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