BBN and Leptogenesis in the CMSSM

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Realistic CMSSM from the view points of Higgs, DM, BBN, and baryon asymmetry
Evidence of new physics

- Dark matter
- Big-bang nucleosynthesis (BBN)
- Neutrino mass
- Baryon asymmetry
- etc.

Candidate of new physics: **CMSSM with seesaw mechanism**

Let’s see DM and BBN in this scenario
DM and BBN

Spectrum in CMSSM with RH neutrinos

Lightest SUSY particle (LSP): Bino-like neutralino $\tilde{\chi}^{0}$ (DM)
Nest LSP (NLSP): stau-like lightest slepton $\tilde{\ell}$

Large allowed space?

No!
Over abundance of DM in most of space!!
DM and BBN

Realistic region in light of Higgs mass, muon $g-2$, and so on

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


Consistent with observed DM
Coannihilation region

Red: DM relic OK, $\delta m < m_{\tau}$
Orange: DM relic OK, $\delta m > m_{\tau}$
DM and BBN

Realistic region in light of Higgs mass, muon g-2, and so on

\[ \delta m \equiv m_{\tilde{\ell}} - m_{\tilde{\chi}} < m_{\tau} \]


Long-lived slepton due to phase space suppression

Will be “a good medicine” for BBN

DM and BBN

BBN successfully predicts light element abundances, except for Li7

Li7 problem

Discrepancy between observed and predicted Li abundance


Idea-1 We are in a special galaxy
No! Lack of Li7 out of galaxy
A. Mucciarelli, et al. (2014)

Idea-2 A nuclear reaction solves Li7 prob.
No! Confirmed to be tiny contribution

The Li7 problem becomes more serious
DM and BBN

In the BBN era \((t_U \sim 1\text{min})\), positive charged \(^7\text{Be}, ^7\text{Li}\) are synthesized

Forming exotic atoms \((\tilde{\ell}^7\text{Be}), (\tilde{\ell}^7\text{Li})\)

Negative charged \(\tilde{\ell}^-\) is produced at \(t_U \sim 10^{-10}\text{sec}\) and survives until BBN

Nuclear conversion in the exotic atoms

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

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

**Li7 is sufficiently reduced, and the Li7 problem is solved**

C. Bird, K. Koopmans, M. Pospelov, PRD78
Aim

If this scenario describes our universe, the baryon asymmetry must be generated

Candidate of new physics: CMSSM with seesaw mechanism

Let’s see DM and BBN in this scenario

Aim

- Accounting for baryon asymmetry in the scenario
- Find a unique signal/relation to confirm the scenario
CMSSM with RH neutrinos

CMSSM parameter: \( M_{1/2}, m_0, A_0, \tan \beta, \text{sign}(\mu) \)

RH neutrino: \( \mathcal{W} = (\hat{y}_l)_{\alpha L} L_\alpha H_d E^c_\alpha + (y_{\nu})_{\alpha i} L_\alpha H_u N^c_i + (\hat{M}_R)_{i N^c_i N^c_i} \)

LSP: Bino-like neutralino \( \tilde{\chi} \)

NLSP: stau-like slepton \( \tilde{\ell} = \sum_{f=e,\mu,\tau} C_f \tilde{f} \quad \tilde{f} = \cos \theta_f \tilde{f}_L + \sin \theta_f \tilde{f}_R \)
CMSSM with RH neutrinos

**Constraint**
- DM relic density $\theta_f$
- light element abundances $C_f$
- baryon asymmetry $(\nu_\nu)_{\alpha i}$ and $M_R$

RH neutrino: $\mathcal{W} = (\hat{y}_\ell)_\alpha L_\alpha H_d E^c_\alpha + (y_\nu)_{\alpha i} L_\alpha H_u N^c_i + (\hat{M}_R)_i N^c_i N^c_i$

slepton mixing $C_f$ and LR mixing $\theta_f$ are generated through RG equations

NLSP: stau-like slepton $\tilde{\ell} = \sum_{f=e,\mu,\tau} C_f \tilde{f}$

$\tilde{f} = \cos \theta_f \tilde{f}_L + \sin \theta_f \tilde{f}_R$

$\nu$ structure is constrained by cosmology, and leads to distinctive signatures
Neutrino Yukawa

Neutrino Yukawa in terms of “observables” (Casas-Ibarra parametrization)

\[ \lambda_{\alpha j} = v^{-1} \left[ \sqrt{M} R \sqrt{m U^+} \right]_{\alpha j} \]

Complex Orthogonal matrix

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

9 complex angles!

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

No constraint from \( \nu \) oscillation exp.

**Cosmology can set constraints on the complex angles!**
Neutrino Yukawa

**Requirement to solve Li7 prob.**

**Sufficient longevity of \( \tilde{\ell} \)**

\( \tilde{\ell} \) lifetime is sensitive to \( \tilde{\ell} \) mixing, and indirectly to \( y_\nu \)

Larger \( M_1 \) corresponds to larger \( y_\nu \), and leads to large \( \tilde{\ell} \) mixing which reduces \( \tilde{\ell} \)

**BBN puts bounds on \( M_1 \) and \( y_\nu \) structure via \( \tilde{\ell} \) lifetime**
Baryon asymmetry

Evolution of total and each lepton asymmetry

With flavor effect

No flavor effect

Observed baryon asymmetry is successfully generated

Necessary to take into account the flavor effect for precise understanding

Flavor effect for leptogenesis

Off-diagonal element of Neutrino Yukawa

\( \tilde{\ell} \) flavor mixing and \( \tilde{\ell} \) lifetime
BR(LFV decay) vs $M_1$

Prediction in light of Higgs, DM, BBN, baryon asymmetry in the CMSSM with RH neutrino

- Should be confirmed by $\mu$ LFV in near future
  Waiting for MEG-II, Mu3e, COMET, Mu2e, DeeMe

- Tiny BR for tau LFV decay
  Tiny flavor mixing of stau is required for the slepton lifetime to be long enough

- $M_1$ lower bound from baryon asymmetry
  $M_1 \propto$ (neutrino Yukawa), and small Yukawa cannot generate sufficient lepton number
Distinctive signatures at collider

- Clear linear relation of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ to $m_{\tilde{\chi}_1^0}$ (from $\delta m < m_{\tau}$)
  
  Accurate prediction of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ by measuring $m_{\tilde{\nu}} (= m_{\tilde{\chi}_1^0})$

- (Number of track of long-lived slepton) $\approx$ (Number of missing $E_T$)

- Light stop $m_{\tilde{t}} \sim 1$ TeV due to large $A_0$ to achieve $m_H = 125$ GeV
Summary

New physics candidate: CMSSM
  - Gauge unification
  - Hierarchy problem
  - etc.

$\tilde{\ell} - \tilde{\chi}$ coannihilation
  - DM abundance

$\delta m < m_\tau$
  - Li7 problem
  - Higgs mass
  - muon g-2
Summary

New physics candidate: CMSSM
- Gauge unification
- Hierarchy problem
- etc.

Seesaw mechanism
- Baryon asymmetry
- Neutrino mass

Flavored SUSY leptogenesis sets lower bound on $M_1$, and BBN sets the upper one.
A unique prediction for CLFV

$\tilde{\ell}$-$\tilde{\chi}$ coannihilation
- DM abundance

$\delta m < m_\tau$
- Li7 problem
- Higgs mass
- Muon $g-2$

CMSSM coannihilation scenario with seesaw mechanism can describe our universe!
Backup slides
Coannihilation mechanism

**Mass degeneracy of LSP and NLSP reduces the relic density of LSP**

\[ m_{\tilde{\chi}} \approx m_{\tilde{\ell}} \]

- Large rate of \( \tilde{\chi} + \text{SM} \rightarrow \tilde{\ell} + \text{SM} \)
- Large rate of \( \tilde{\ell} + \tilde{\ell} \leftrightarrow \text{SM} + \text{SM} \)
- Long chemical equilibrium of SUSY and SM particles

![Graph showing the comoving number density](image)
DM relic abundance

DM relic abundance  \( \text{PLANCK 2015 results} \)

\[ 0.1126 \leq \Omega_{\text{DM}} h^2 \leq 0.1246 \]

Freeze out of total SUSY density \( @T \approx m_{\tilde{\chi}}/25 \)

\[ n \equiv n_{\tilde{\chi}} + n_{\tilde{\ell}^-} + n_{\tilde{\ell}^+} \]

CMSSM parameters \( (M_{1/2}, m_0, A_0, \tan\beta, \text{etc.}) \) are constrained by this condition

Note: Slepton density is not frozen yet!
Slepton density continues to decrease as long as being in kinetic equilibrium with SM sector through SUSY-SM scattering:

\[ \tilde{\ell} \gamma \leftrightarrow \tilde{\chi}_1 \gamma, \quad \tilde{\ell} \gamma \leftrightarrow \tilde{\chi}_1 \mu, \quad \tilde{\ell}_\tau \leftrightarrow \tilde{\chi}_1 \gamma, \quad \tilde{\ell}_\mu \leftrightarrow \tilde{\chi}_1 \gamma, \quad \tilde{\ell}_e \leftrightarrow \tilde{\chi}_1 \gamma \]

Slepton density continues to decrease as long as being in kinetic equilibrium:

\[
n_{\tilde{\ell}^-} = \frac{n_{\tilde{\ell}_1^-}}{n_{\tilde{\chi}_1^0}} \frac{n_{\tilde{\chi}_1^0}}{n} n = n \frac{e^{-\delta m/T}}{2 \left( 1 + e^{-\delta m/T} \right)}
\]
Slepton density

Kinetic equilibrium with SM sector through SUSY-SM scattering

\[ \tilde{\ell}_\gamma \leftrightarrow \tilde{\chi}_\tau, \quad \tilde{\ell}_\gamma \leftrightarrow \tilde{\chi}_\mu, \]
\[ \tilde{\ell}_\tau \leftrightarrow \tilde{\chi}_\gamma, \quad \tilde{\ell}_\mu \leftrightarrow \tilde{\chi}_\gamma, \quad \tilde{e} \leftrightarrow \tilde{\chi}_\gamma \]

Kinetic freeze-out temperature strongly depends on slepton mixing

Large density is required for solving Li7 (Li6) problem

- Upper bound on slepton mixing
- Upper bound on Majorana mass
Leptogenesis

To correctly constrain each component of $(y_\nu)_{ai}$, it’s important to take into account spectator and flavor effects

$$\frac{dY_{N_1}}{dz} = -\frac{z}{sH(z = 1)} \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \left[ \gamma_D + 2\gamma_{S_s} + 4\gamma_{S_t} \right]$$

$$\frac{dY_{\Delta_i}}{dz} = -\frac{z}{sH(z = 1)} \left\{ \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \epsilon_{1i} \gamma_D + K_i^0 \sum_j \left[ \frac{1}{2} (C_{ij}^l + C_j^H) \gamma_D \right. \right.$$  

$$\left. + \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \left( C_{ij}^l \gamma_{S_s} + \frac{C_j^H}{2} \gamma_{S_t} \right) + (2C_{ij}^l + C_j^H) \left( \gamma_{S_t} + \frac{\gamma_{S_s}}{2} \right) \right]\frac{Y_{\Delta_i}}{Y_{\nu l}^{eq}} \right\}$$

- $Y_i = n_i/s$  (s: entropy density)
- $z = M_1/T$
- $\gamma_D, (\gamma_{S_s}, \gamma_{S_t})$: reduced thermal averaged decay rate (cross section)
Leptogenesis

- Conversion rate of flavored $L$ asymmetry onto flavored $(B - L)$ asymmetry

$$Y_{Li} = -(C_{ie}^l Y_{\Delta e} + C_{i\mu}^l Y_{\Delta \mu} + C_{i\tau}^l Y_{\Delta \tau})$$

$$\frac{dY_{\Delta i}}{dz} = - \frac{z}{sH(z = 1)} \left\{ \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \epsilon_{1i} \gamma_D + K_i^0 \sum_j \left[ \frac{1}{2} (C_{ij}^l + C_{ij}^H) \right] \gamma_D \right\}$$

$$+ \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \left( C_{ij}^l \gamma_{S_s} + \frac{C_{ij}^H}{2} \gamma_{S_t} \right) + (2C_{ij}^l + C_{ij}^H) \left( \gamma_{S_t} + \frac{\gamma_{S_s}}{2} \right) \frac{Y_{\Delta i}^{eq}}{Y_l^{eq}} \right\}$$

- Conversion rate of spectator contribution onto flavored $(B - L)$ asymmetry

$$Y_H - Y_{\bar{H}} = -(C^H_e Y_{\Delta e} + C^H_\mu Y_{\Delta \mu} + C^H_\tau Y_{\Delta \tau})$$
Leptogenesis

- Flavored decay parameter determined by structure of neutrino Yukawa

- Flavored CP asymmetry

\[
\frac{dY_{\Delta_i}}{dz} = -\frac{z}{sH(z = 1)} \left\{ \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \epsilon_{1i} \gamma_D + \sqrt{\kappa_i} \sum_j \left[ \frac{1}{2} \left( C_{ij}^l + C_{ij}^H \right) \gamma_D \right. \right. \\
\left. \left. + \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \left( C_{ij}^l \gamma_{S_s} + \frac{C_{ij}^H}{2} \gamma_{S_t} \right) + (2C_{ij}^l + C_{ij}^H) \left( \gamma_{S_t} + \frac{\gamma_{S_S}}{2} \right) \right] \frac{Y_{\Delta_i}}{Y_{l}^{eq}} \right\}
\]

Each component of neutrino Yukawa strongly affects the final baryon asymmetry