BBN and Leptogenesis in the CMSSM

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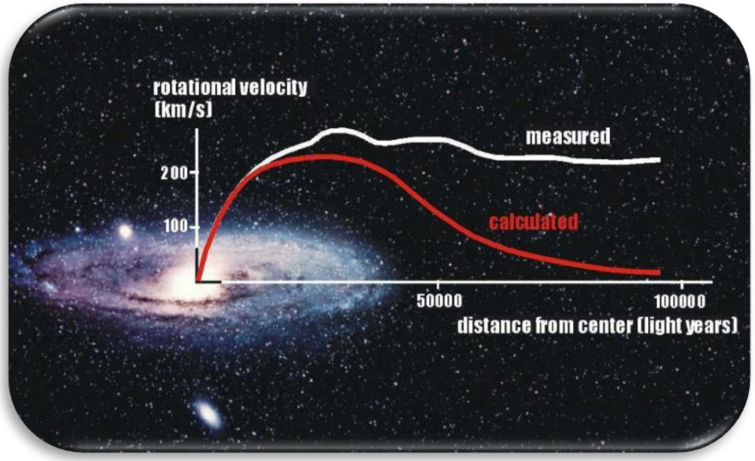
PRD97, 115013 (arXiv:1803.07686)

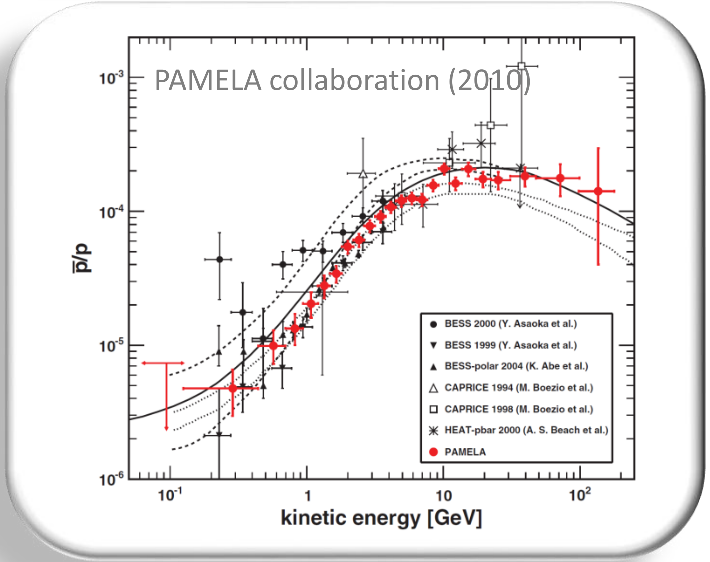
M. Kubo, J. Sato, T. Shimomura, Y. Takanishi, and MY

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

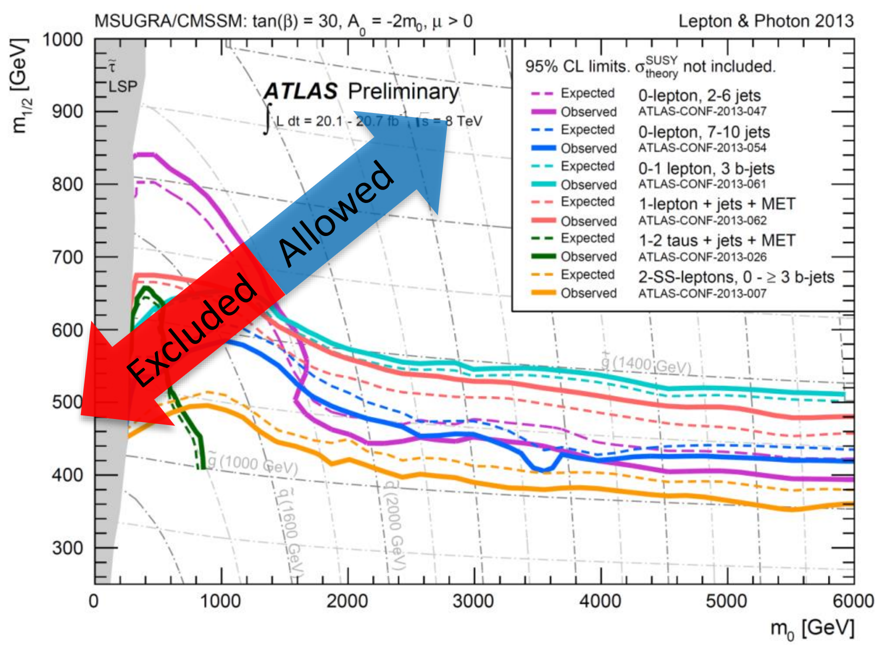
Spectrum in CMSSM with RH neutrinos

Lightest SUSY particle (LSP): Bino-like neutralino $\tilde{\chi}$ (DM)

Nest LSP (NLSP): stau-like lightest slepton $\tilde{\ell}$

Large allowed space?

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



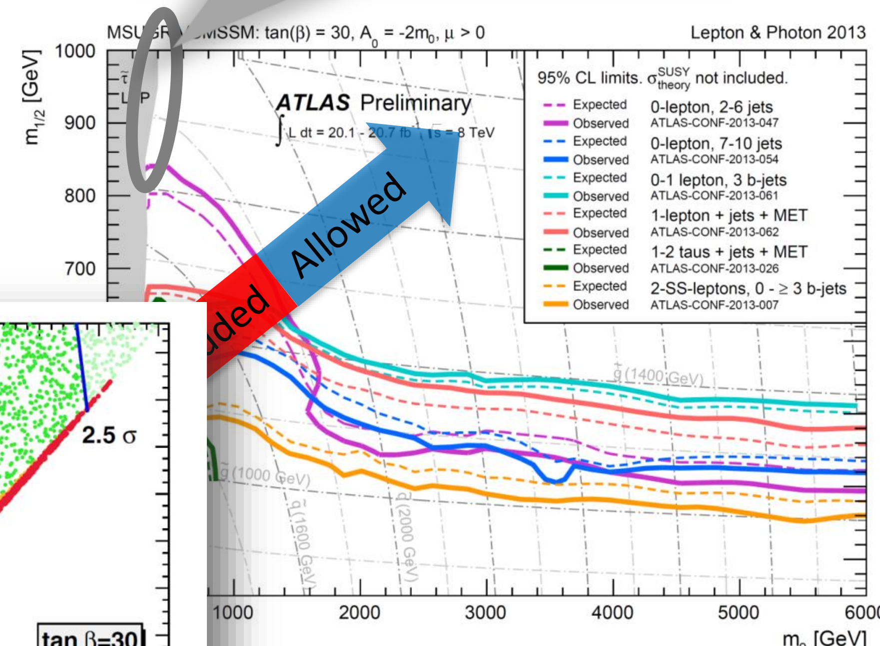
DM and BBN

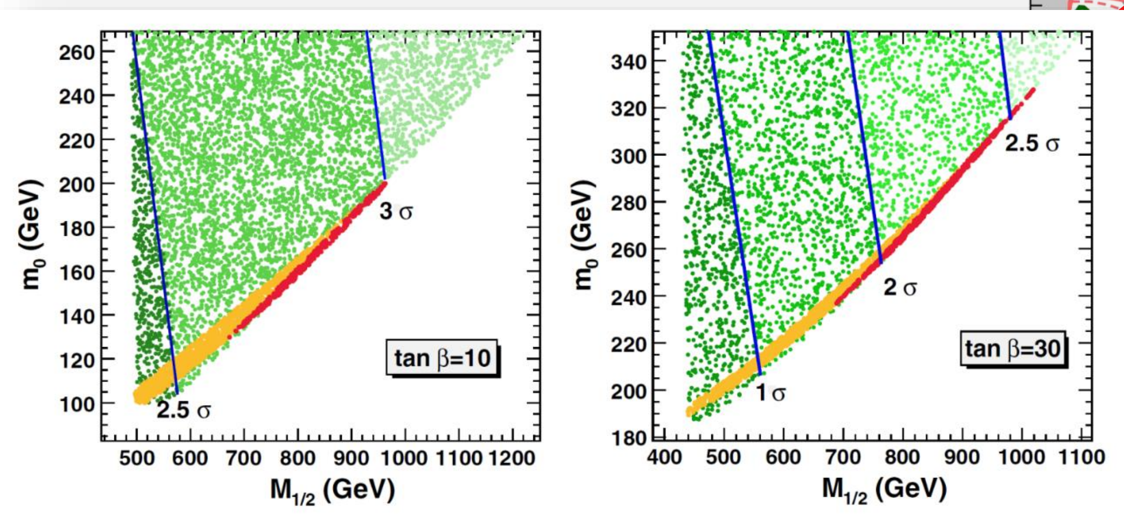
Realistic region in light of Higgs mass, muon g-2, and so on

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

L. Aparicio, D. Cerdeno, L. Ibanez, JHEP (2012)
M. Citron, J. Ellis, F. Luo, et al, PRD (2013)

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

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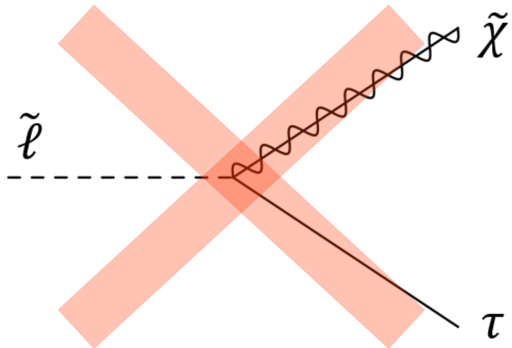
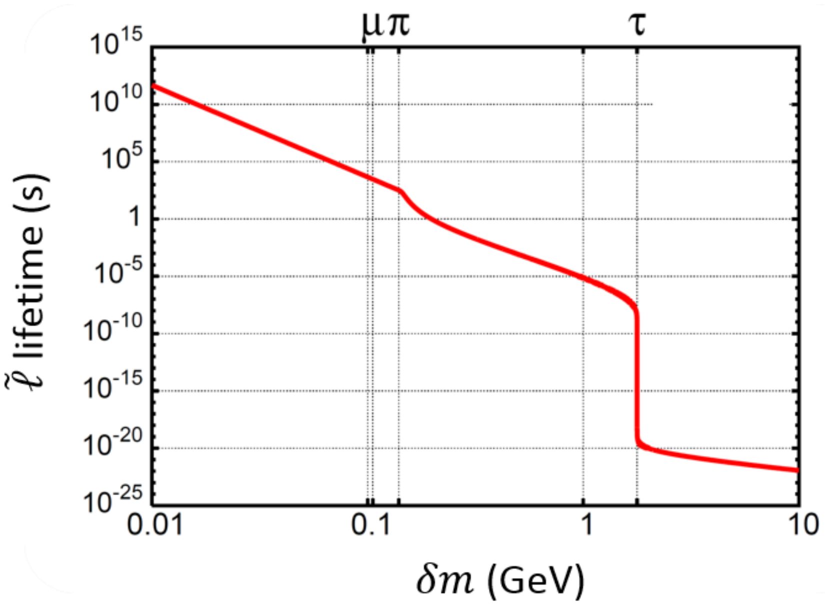


Long-lived slepton due to phase space suppression

Will be “a good medicine” for BBN



T. Jittoh, J. Sato, T. Shimomura, MY, PRD (2006)

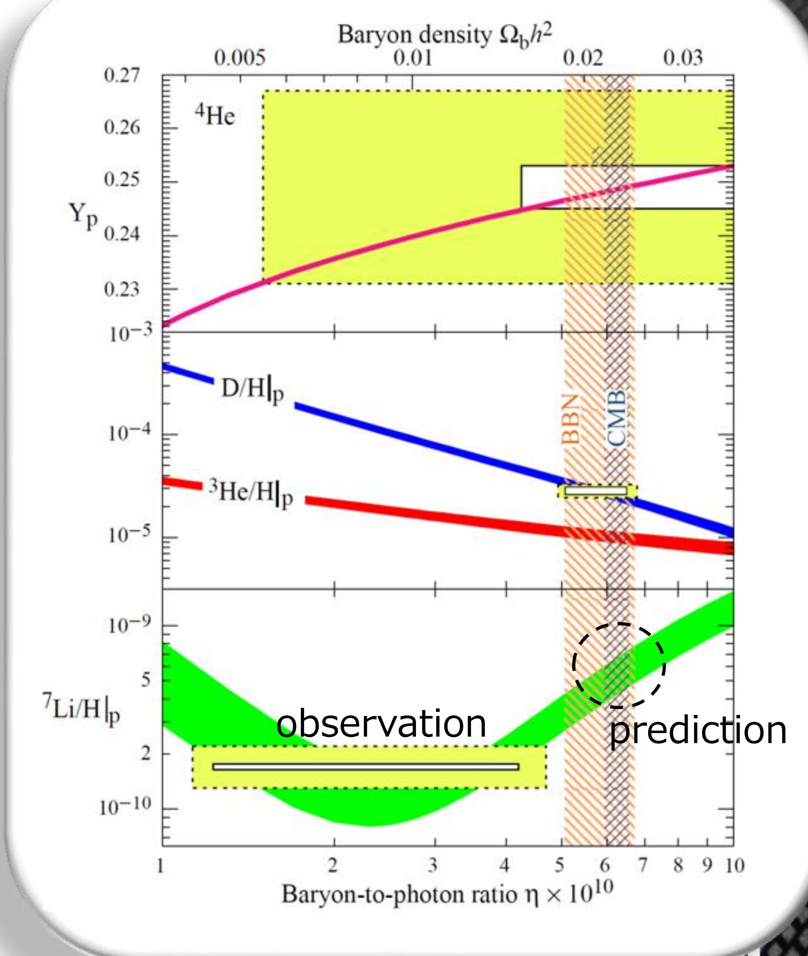
DM and BBN

BBN successfully predicts light element abundances, **except for Li7**

Li7 problem

Discrepancy between observed and predicted Li abundance

F. Spite and M. Spite, Astron. Astrophys. (1982)



Idea-1 We are in a special galaxy

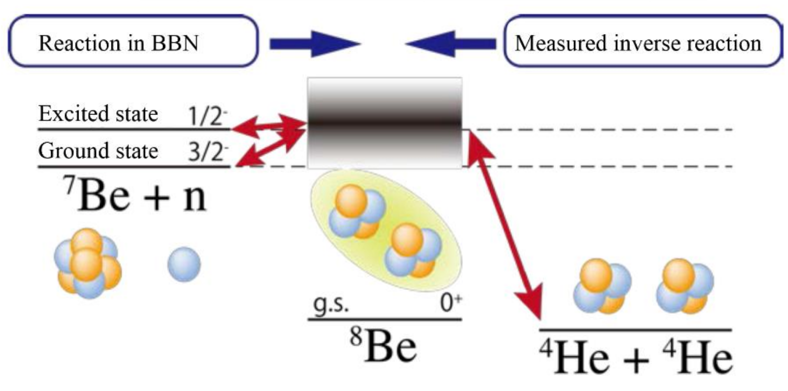
No! Lack of Li7 out of galaxy

A. Mucciarelli, et al. (2014)

Idea-2 A nuclear reaction solves Li7 prob.

No! Confirmed to be tiny contribution

T. Kawabata, et al. PRL (2017)



The Li7 problem becomes more serious

DM and BBN

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

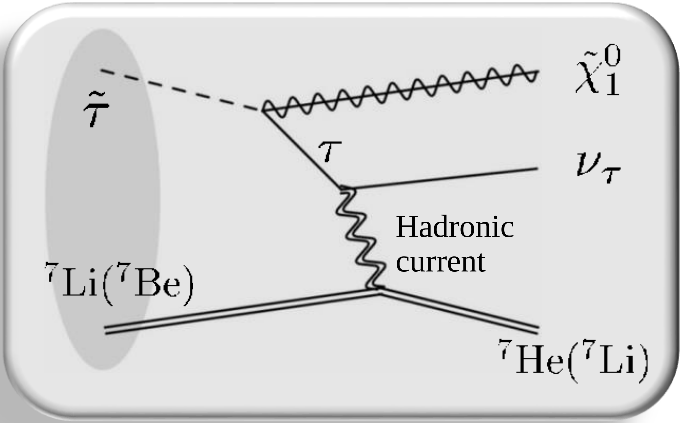
Forming exotic atoms $(\tilde{\tau}\,^7\text{Be}), (\tilde{\tau}\,^7\text{Li})$

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

Nuclear conversion in the exotic atoms

$$\left(\tilde{\ell}\,^7\text{Be}\right) \to {}^7\text{Li} + \nu_\tau + \tilde{\chi}$$

$$\left(\tilde{\ell}\,^7\text{Li}\right) \to {}^7\text{He} + \nu_\tau + \tilde{\chi}$$



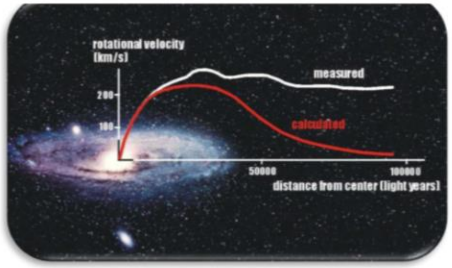
Li7 is sufficiently reduced, and the Li7 problem is solved

T. Jittoh, K. Kohri, M. Koike, J. Sato, T. Shimomura, M.Y., PRD76
C. Bird, K. Koopmans, M. Pospelov, PRD78

Aim

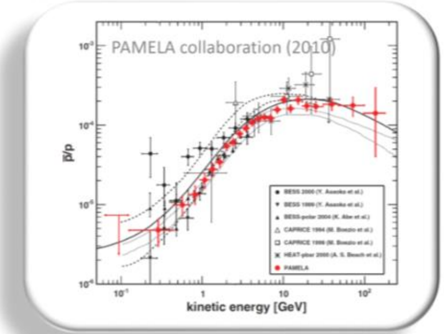
If this scenario describes our universe, the baryon asymmetry must be generated

Current status



Evidence of new physics

- Dark matter ☑
- Big-bang nucleosynthesis ☑
- Neutrino mass ☐
- Baryon asymmetry ☐
- etc.



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

Let's see DM and BBN in this scenario

<u>Aim</u>

- ☑ Accounting for baryon asymmetry in the scenario
- ☑ Find a unique signal/relation to confirm the scenario

CMSSM with RH neutrinos

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

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

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

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

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

CMSSM with RH neutrinos

y_ν structure is constrained by cosmology, and leads to distinctive signatures

<u>constraint</u>

- DM relic density ⟶ θ_f
- light element abundances ⟶ C_f
- baryon asymmetry ⟶ $(y_\nu)_{\alpha i}$ 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 θ_f
are generated through RG equations

NLSP : stau-like slepton $\tilde{\ell} = \sum_{f=e,\mu,\tau} C_f \tilde{f}$ $\quad \tilde{f} = \cos\theta_f \tilde{f}_L + \sin\theta_f \tilde{f}_R$

Neutrino Yukawa

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

J. A. Casas and A. Ibarra, NPB (2001)

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

Complex Orthogonal matrix

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

9 complex angles! $z_{ij} = x_{ij} + \sqrt{-1}\, y_{ij}$

No constraint from ν oscillation exp.

Cosmology can set constraints on the complex angles!

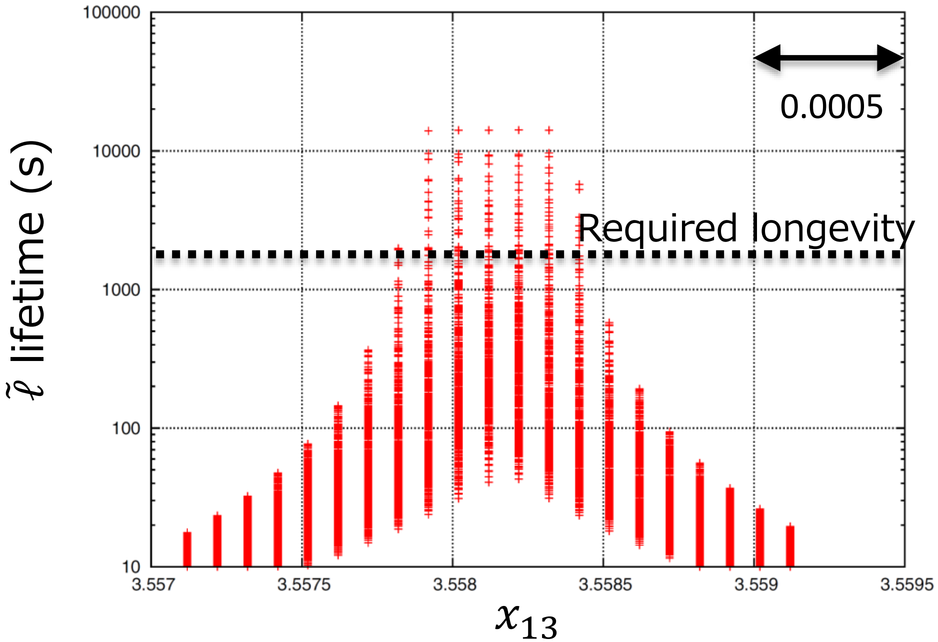
Neutrino Yukawa

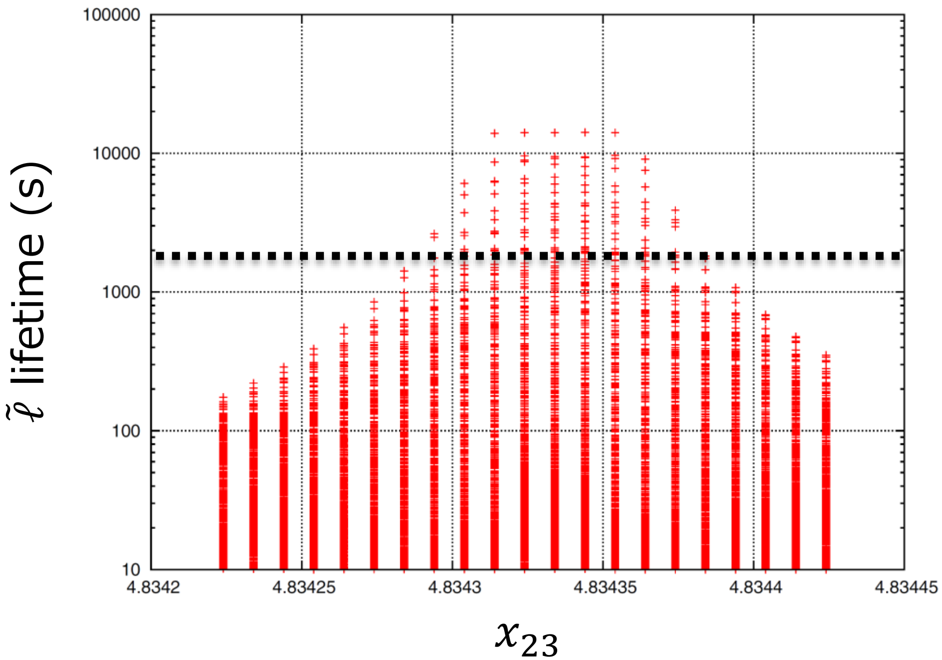
<u>Requirement to solve Li7 prob.</u>
Sufficient longevity of $\tilde{\ell}$

$\tilde{\ell}$ lifetime is sensitive to $\tilde{\ell}$ mixing, and indirectly to y_ν

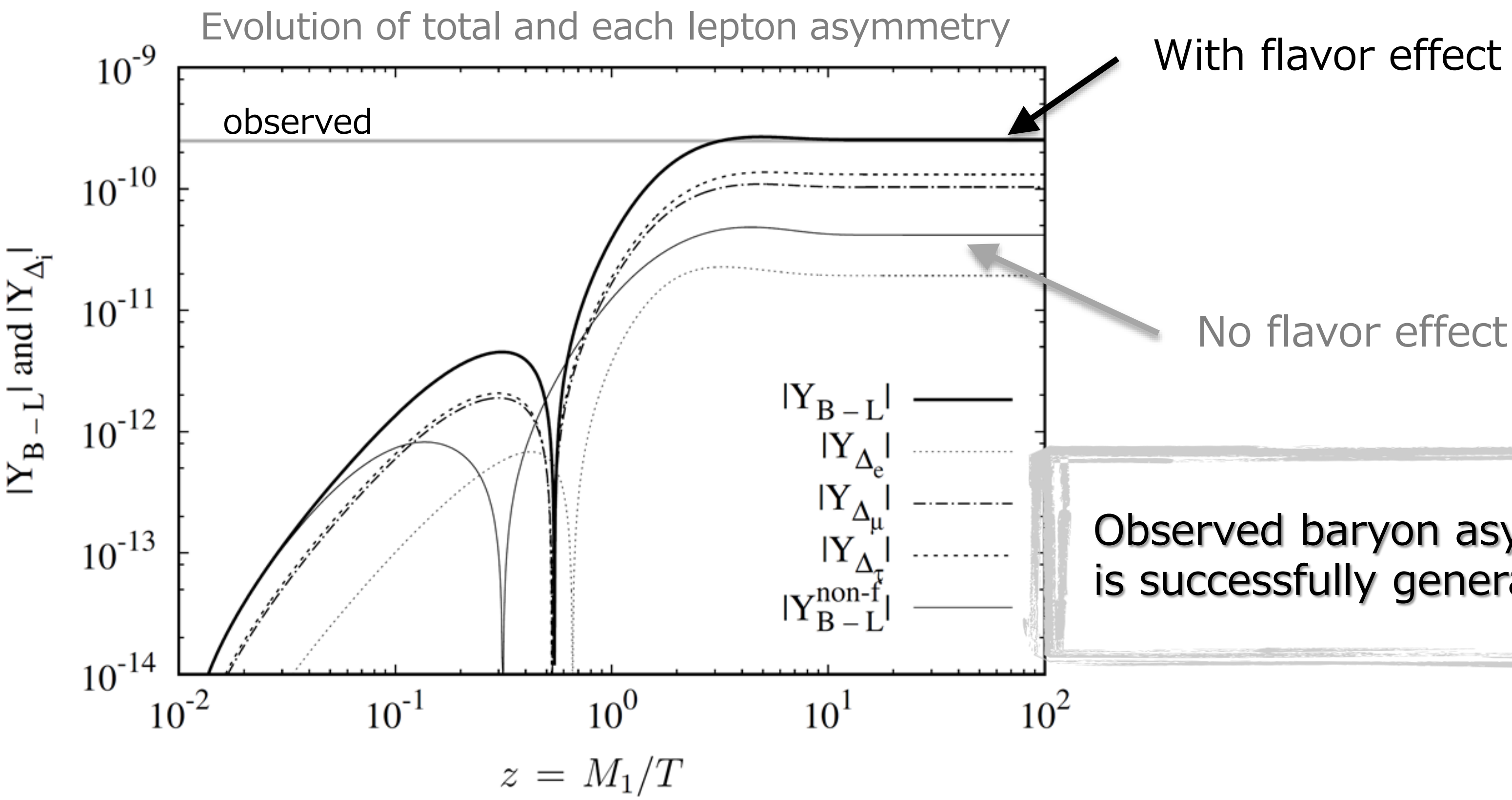
Larger M_1 corresponds to larger y_ν, and leads to large $\tilde{\ell}$ mixing which reduces $\tilde{\ell}$

BBN puts bounds on M_1 and y_ν structure via $\tilde{\ell}$ lifetime





Baryon asymmetry



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 μ LFV in near future

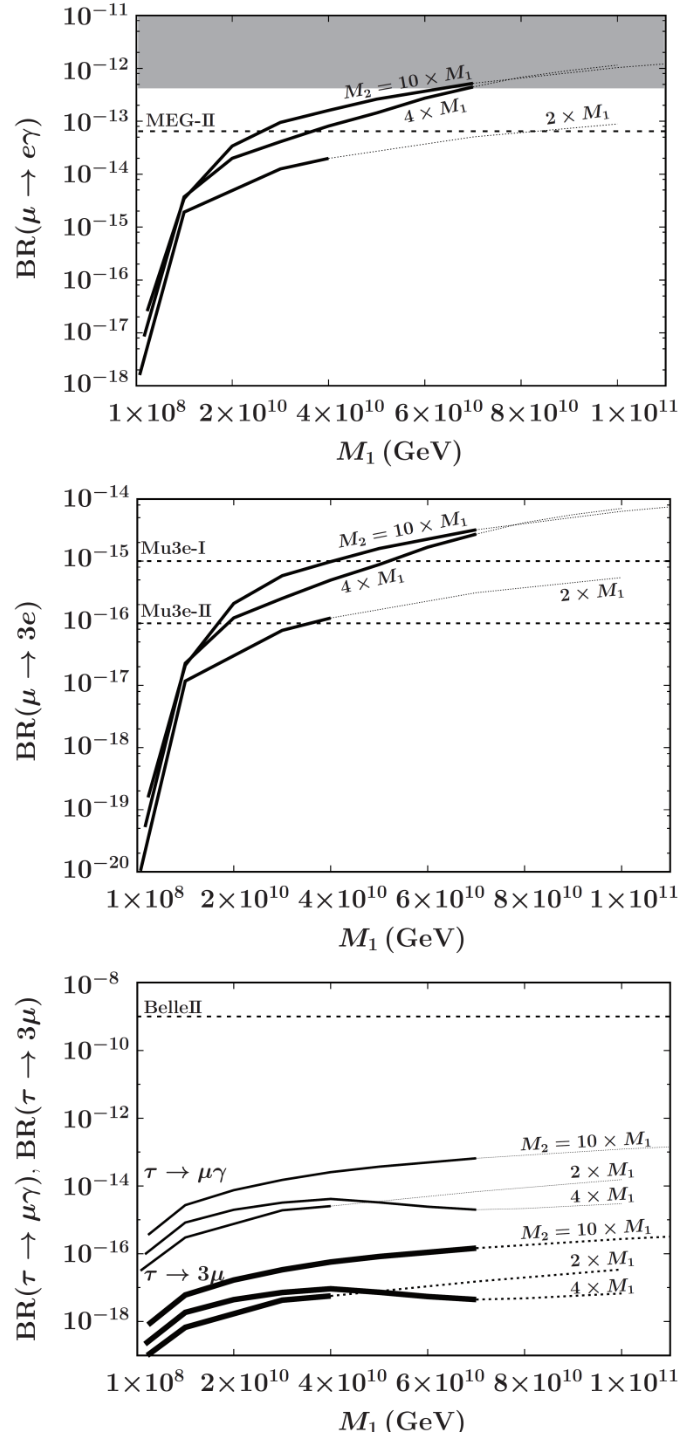
Waiting for MEG-II, Mu3e, COMET, Mu2e, DeeMe

☑ Tiny BR for tau LFV decay

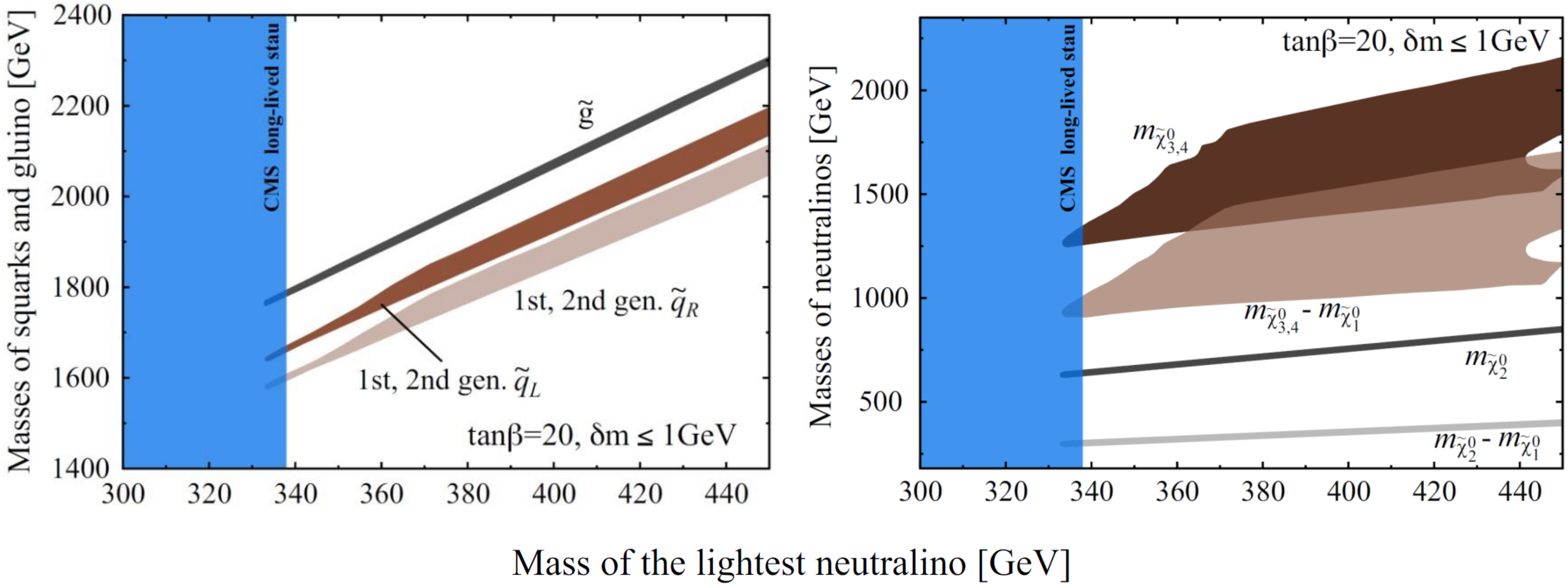
Tiny flavor mixing of stau is required for the slepton lifetime to be long enough

☑ 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 $m_{\tilde{\chi}^0_1}$ (from $\delta m < m_\tau$)

  Accurate prediction of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ by measuring $m_{\tilde{\ell}}$ ($= m_{\tilde{\chi}^0_1}$)

- ☑ (# of track of long-lived slepton) $\simeq$ (# of missing E_T)

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

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.

Flavored SUSY leptogenesis sets lower bound on M_1, and BBN sets the upper one

→ a unique prediction for CLFV

Seesaw mechanism

- baryon asymmetry
- neutrino mass

$\tilde{\ell}$-$\tilde{\chi}$ 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

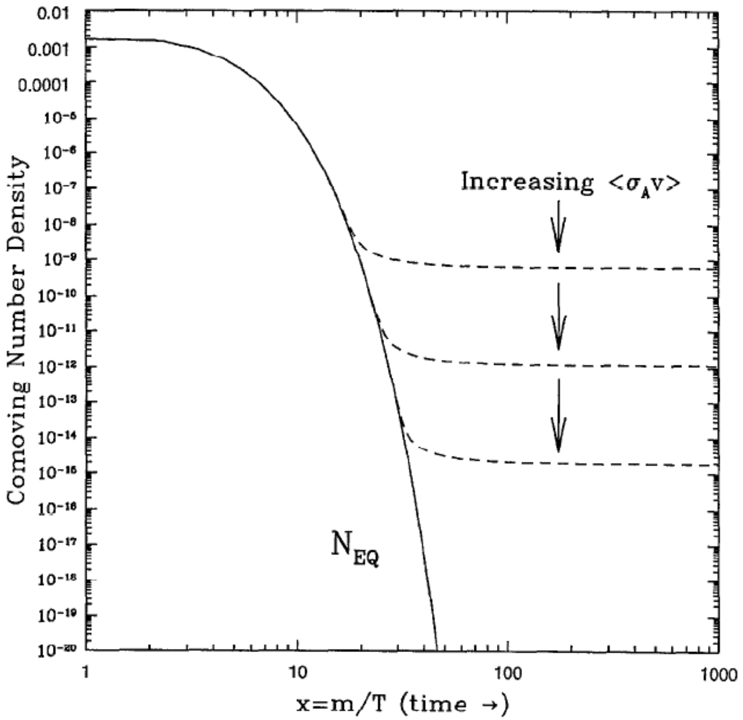
Mass degeneracy of LSP and NLSP reduces the relic density of LSP

$m_{\tilde{\chi}} \simeq m_{\tilde{\ell}}$

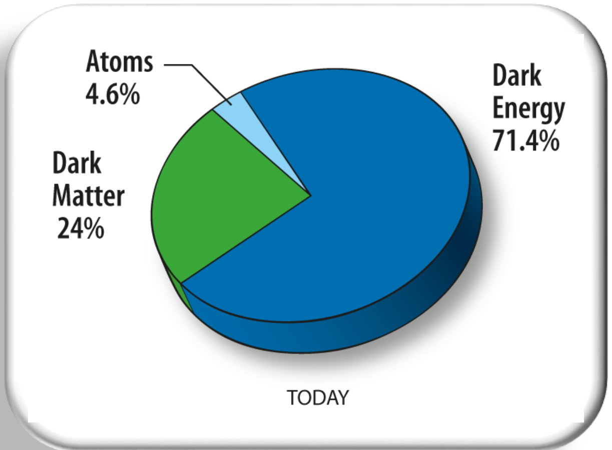
→ Large rate of $\tilde{\chi} + \mathrm{SM} \to \tilde{\ell} + \mathrm{SM}$

→ Large rate of $\tilde{\ell} + \tilde{\ell} \leftrightarrow \mathrm{SM} + \mathrm{SM}$

→ Long chemical equilibrium of SUSY and SM particles

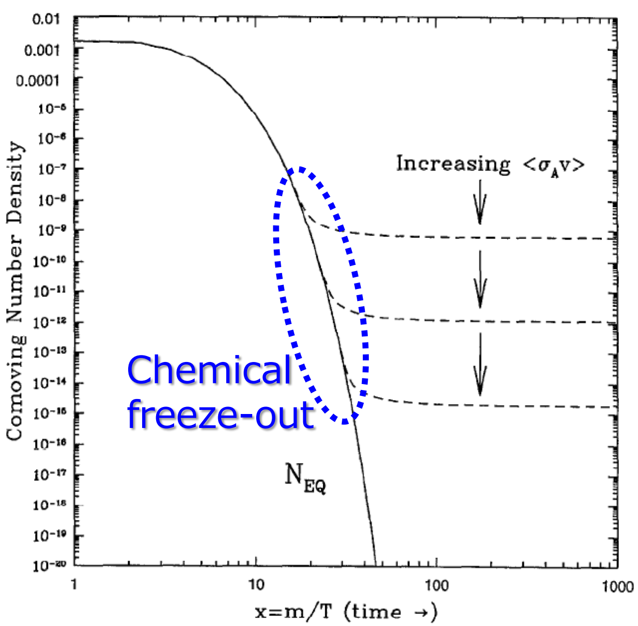


DM relic abundance



DM relic abundance PLANCK 2015 results

$$0.1126 \leq \Omega_{\rm DM} h^2 \leq 0.1246$$



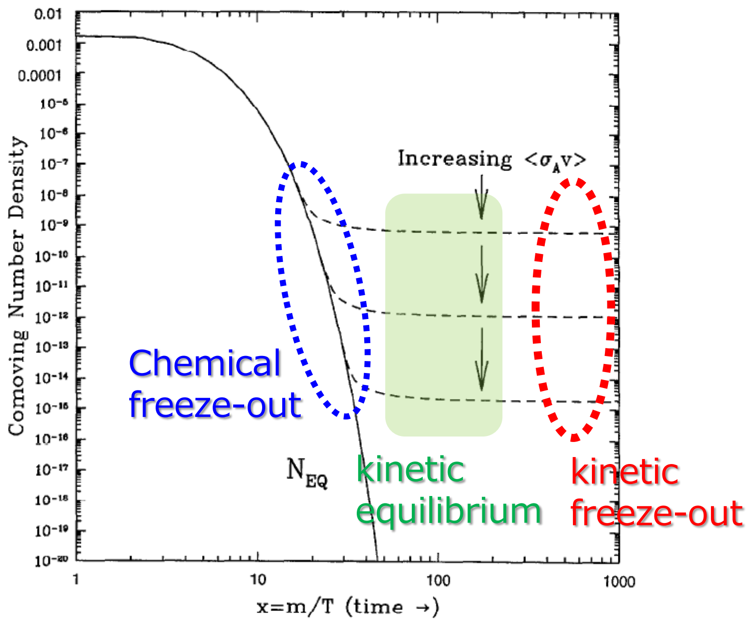
Freeze out of total SUSY density@$T \simeq m_{\tilde{\chi}}/25$

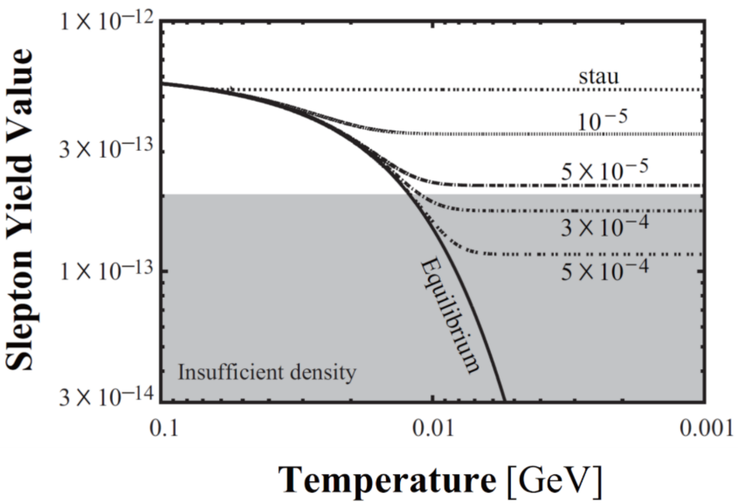
$$n \equiv n_{\tilde{\chi}} + n_{\tilde{\ell}^-} + n_{\tilde{\ell}^+}$$

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

Note: Slepton density is not frozen yet!

Slepton density





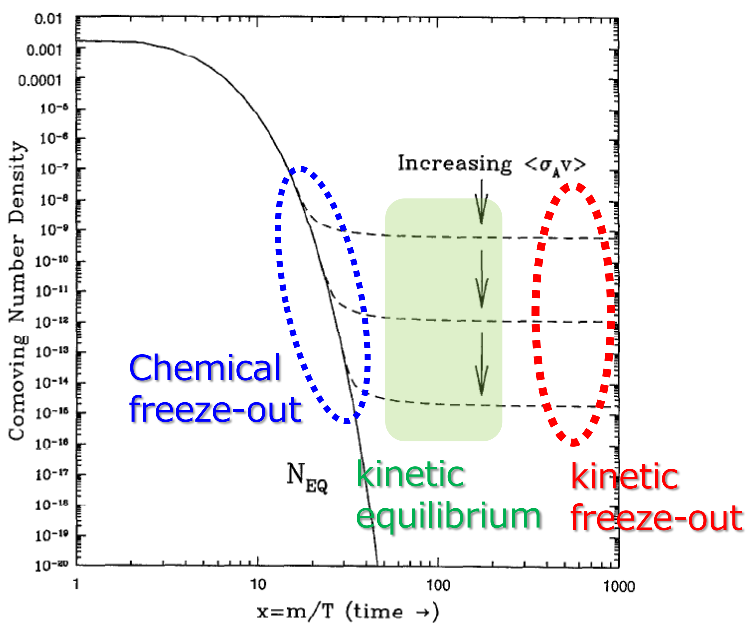
Kinetic equilibrium with SM sector through SUSY-SM scattering

$$\tilde{\ell}\gamma \leftrightarrow \tilde{\chi}\tau, \quad \tilde{\ell}\gamma \leftrightarrow \tilde{\chi}\mu,$$
$$\tilde{\ell}\tau \leftrightarrow \tilde{\chi}\gamma, \quad \tilde{\ell}\mu \leftrightarrow \tilde{\chi}\gamma, \quad \tilde{\ell}e \leftrightarrow \tilde{\chi}\gamma$$

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

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

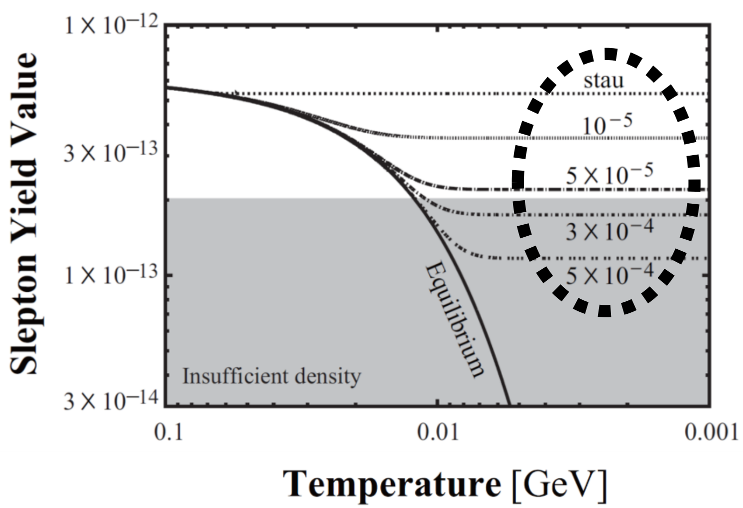
Slepton density



Kinetic equilibrium with SM sector through SUSY-SM scattering

$$\tilde{\ell}\gamma \leftrightarrow \tilde{\chi}\tau, \;\; \tilde{\ell}\gamma \leftrightarrow \tilde{\chi}\mu,$$
$$\tilde{\ell}\tau \leftrightarrow \tilde{\chi}\gamma, \;\; \tilde{\ell}\mu \leftrightarrow \tilde{\chi}\gamma, \;\; \tilde{\ell}e \leftrightarrow \tilde{\chi}\gamma$$

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 $(y_\nu)_{\alpha i}$, it's important to take into account spectator and flavor effects

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

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

- $Y_i = n_i/s$ (s: entropy density)
- $z = M_1/T$
- γ_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
- $Y_{L_i} = -(C^l_{ie} Y_{\Delta_e} + C^l_{i\mu} Y_{\Delta_\mu} + C^l_{i\tau} Y_{\Delta_\tau})$

$$\frac{dY_{\Delta_i}}{dz} = -\frac{z}{sH(z=1)} \left\{ \left(\frac{Y_{N_1}}{Y^{eq}_{N_1}} - 1 \right) \epsilon_{1i} \gamma_D + K^0_i \sum_j \left[\frac{1}{2} \left(C^l_{ij} + C^H_j \right) \gamma_D \right.\right.$$
$$\left.\left. + \left(\frac{Y_{N_1}}{Y^{eq}_{N_1}} - 1 \right) \left(C^l_{ij} \gamma_{S_s} + \frac{C^H_j}{2} \gamma_{S_t} \right) + \left(2C^l_{ij} + C^H_j \right) \left(\gamma_{S_t} + \frac{\gamma_{S_s}}{2} \right) \right] \frac{Y_{\Delta_i}}{Y^{eq}_l} \right\}$$

- Conversion rate of spectator contribution onto flavored $(B-L)$ asymmetry
- $Y_H - Y_{\overline{H}} = -(C^H_e Y_{\Delta_e} + C^H_\mu Y_{\Delta_\mu} + C^H_\tau Y_{\Delta_\tau})$

Leptogenesis

- Flavored decay parameter determined by structure of neutrino Yukawa

- Flavored CP asymmetry

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

Each component of neutrino Yukawa strongly affects the final baryon asymmetry