Solving the Li problem by long lived stau in a stau-neutralino coannihilation scenario

Masato Yamanaka
(Tokyo university, ICRR)

Collaborators
Toshifumi Jittoh, Kazunori Kohri,
Masafumi Koike, Joe Sato, Takashi Shimomura

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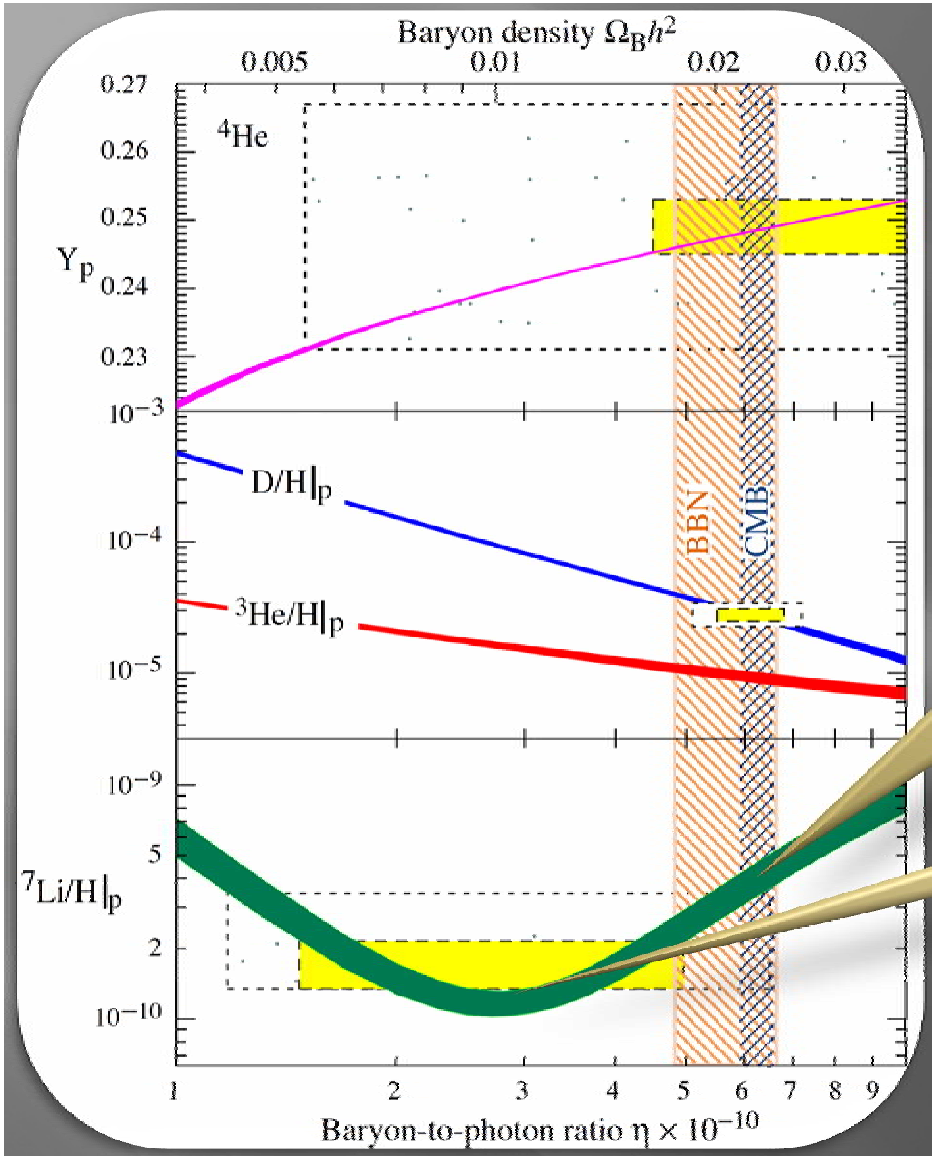


^{7}Li problem

Theoretical prediction

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

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

Observation

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

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

Predicted ^{7}Li abundance
$\neq$ observed ^{7}Li abundance

→ ^{7}Li problem

Purpose

Soving the ^{7}Li problem in a framework of Minimal Supersymmeteric Standard Model (MSSM)

Neutralino dark matter and Coannihilation scenario

Setup

Lightest Supersymmetric Particle (LSP)

→ Neutralino $\tilde{\chi}$ Dark matter ∵ R-parity conservation

Next Lightest Supersymmetric Particle (NLSP)

→ Stau $\tilde{\tau}$

DM abundance and Connihilation

Coannihilation mechanism predicts observed DM abundance

$$\tilde{\chi}\ \tilde{\chi} \to SM\ SM \quad + \quad \begin{array}{l} \tilde{\chi}\ \tilde{\tau} \to SM\ SM \\ \tilde{\tau}\ \tilde{\tau} \to SM\ SM \end{array}$$

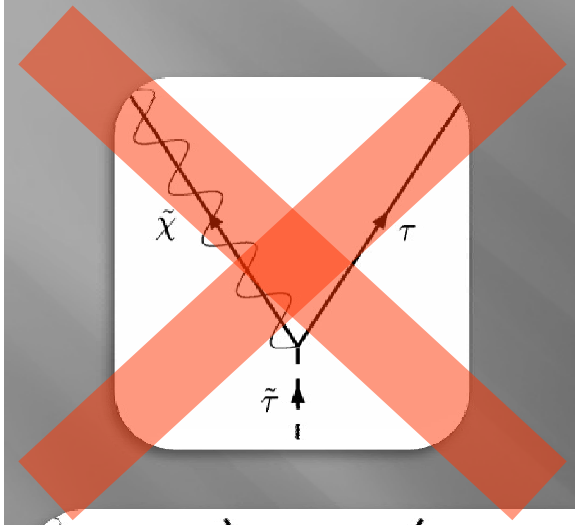
Requirement for
the coannihilation to work

$$\frac{m_{NLSP} - m_{LSP}}{m_{LSP}} < 10\%$$

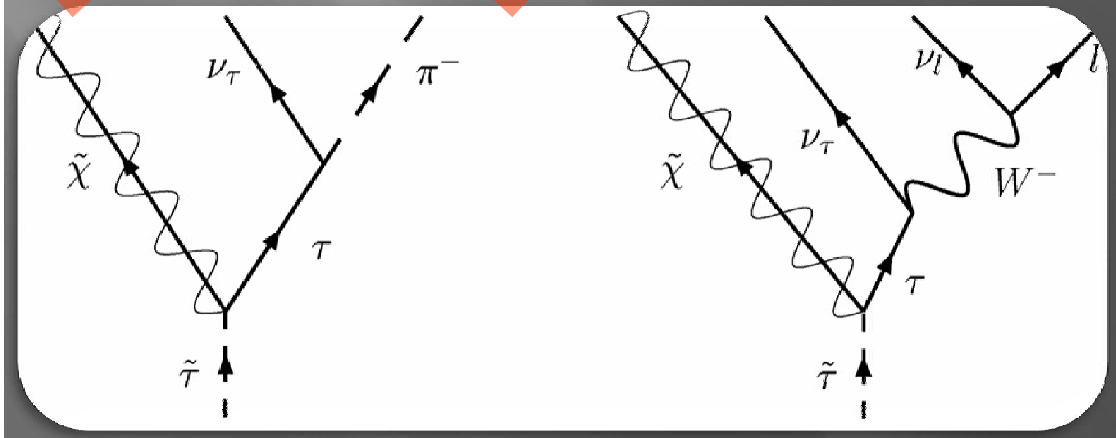
Long lived stau

Attractive parameter region in coannihilation scenario

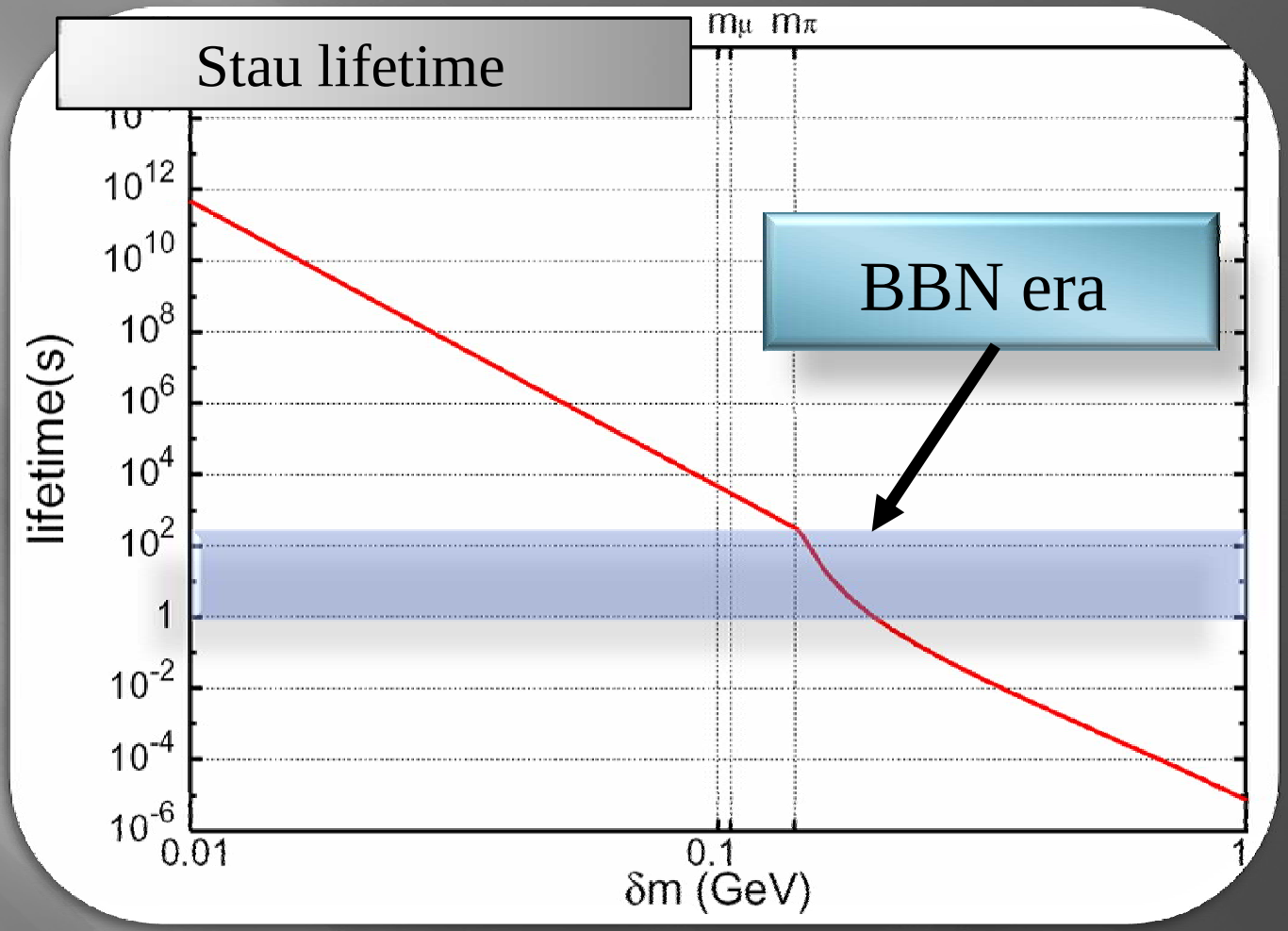
$\delta m \equiv$ NLSP mass $-$ LSP mass $<$ tau mass (1.77GeV)



NLSP stau can not two body decay



Stau has a long lifetime due to phase space suppression !!



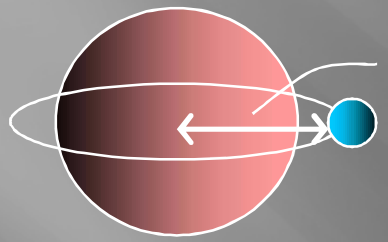
$\tilde{\tau}$ survive until BBN era

Stau provides additional processes
to reduce the primordial ^{7}Li abundance !!

Stau-nucleus bound state

Key ingredient for solving the ^{7}Li problem

Negative-charged stau can form a bound state with nuclei



stau nucleus

Formation rate

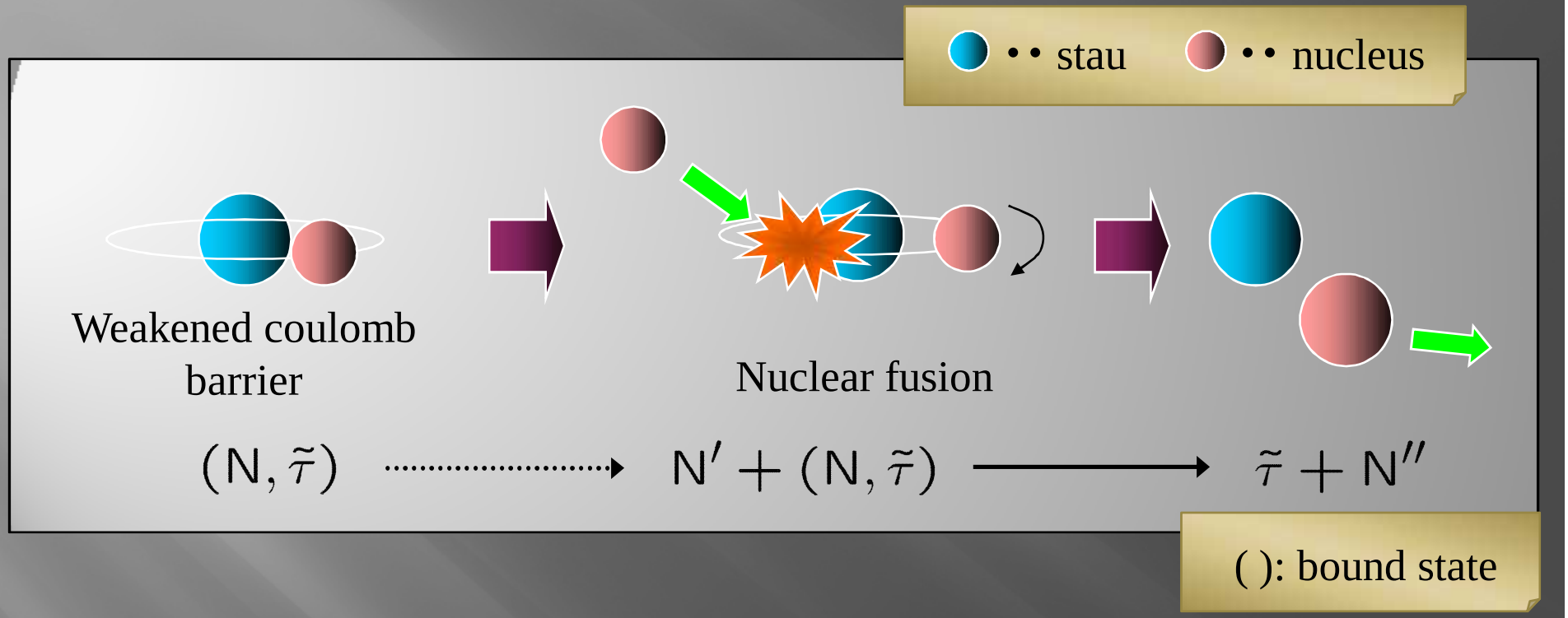
⟶ Solving the Boltzmann Eq.

New processes

- Stau catalyzed fusion
- Internal conversion in the bound state

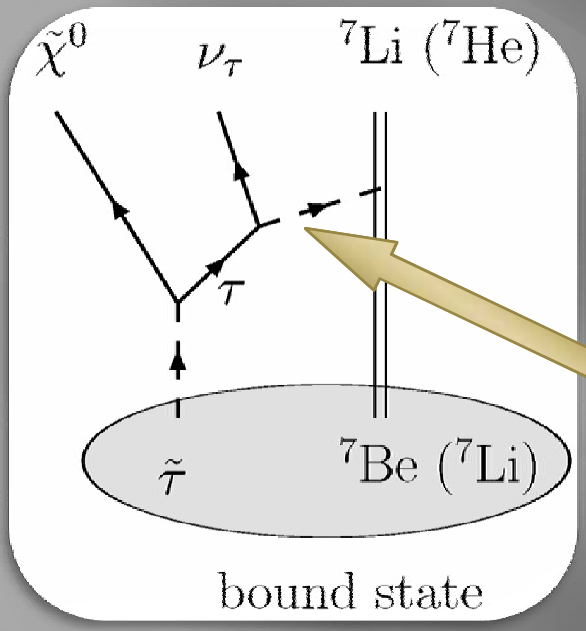
Stau catalyzed fusion

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



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

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



Internal conversion

Hadronic current

- Closeness between stau and nucleus

  Overlap of the wave function : UP

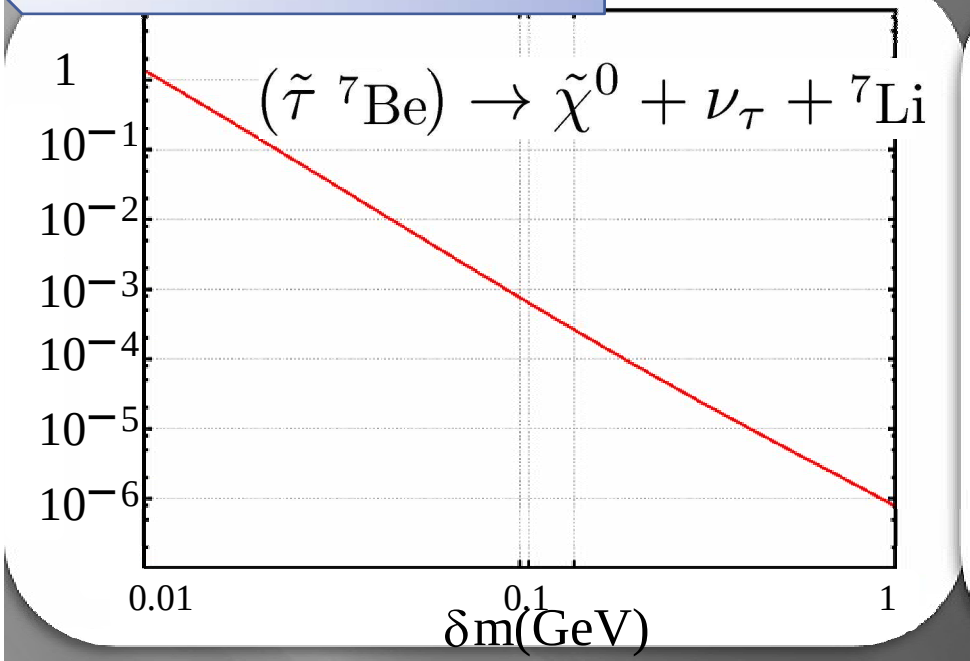
  Interaction rate of hadronic current : UP

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

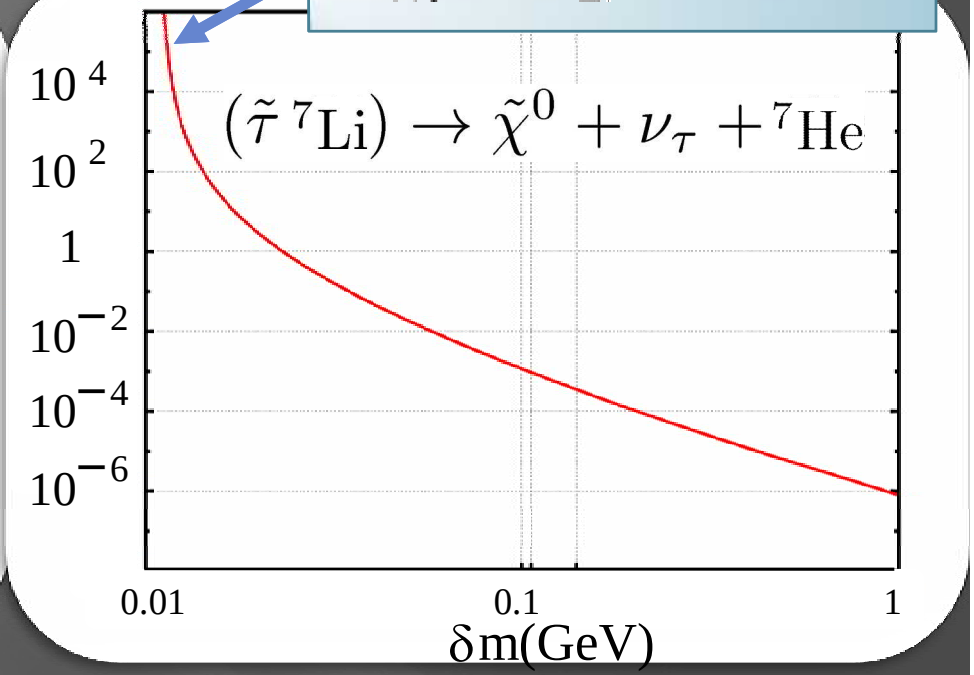
  No cancellation processes

Interaction rate of Internal conversion

Lifetime of bound state (s)



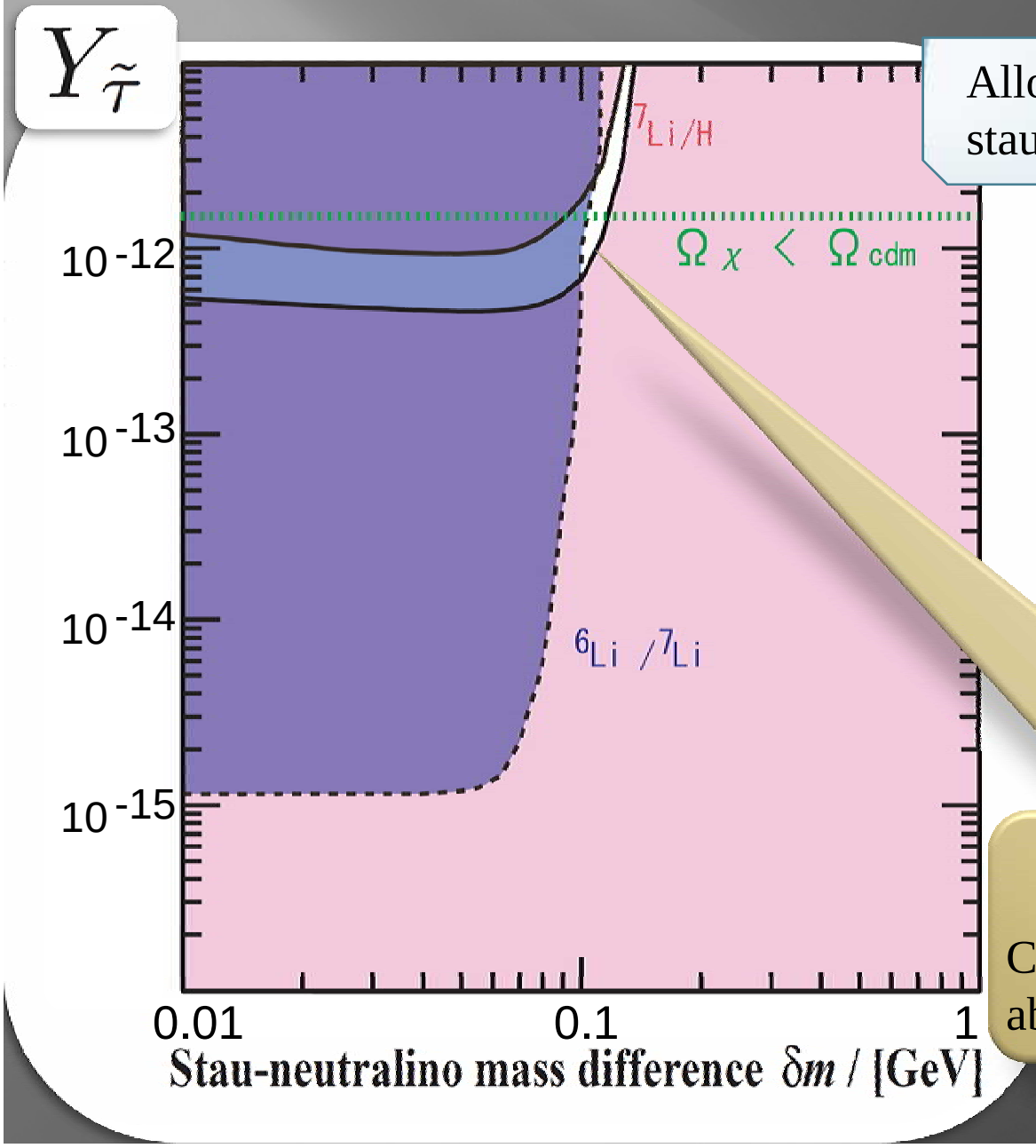
$m_{^7\mathrm{He}} - m_{^7\mathrm{Li}} = 11.2$ MeV



Rapid interaction

significant process for reducing ^{7}Li abundance !

Numerical result for solving the ^{7}Li problem



Allowed region as a function of stau relic density and mass difference

$$Y_{\tilde{\tau}} \equiv n_{\tilde{\tau}}/s$$

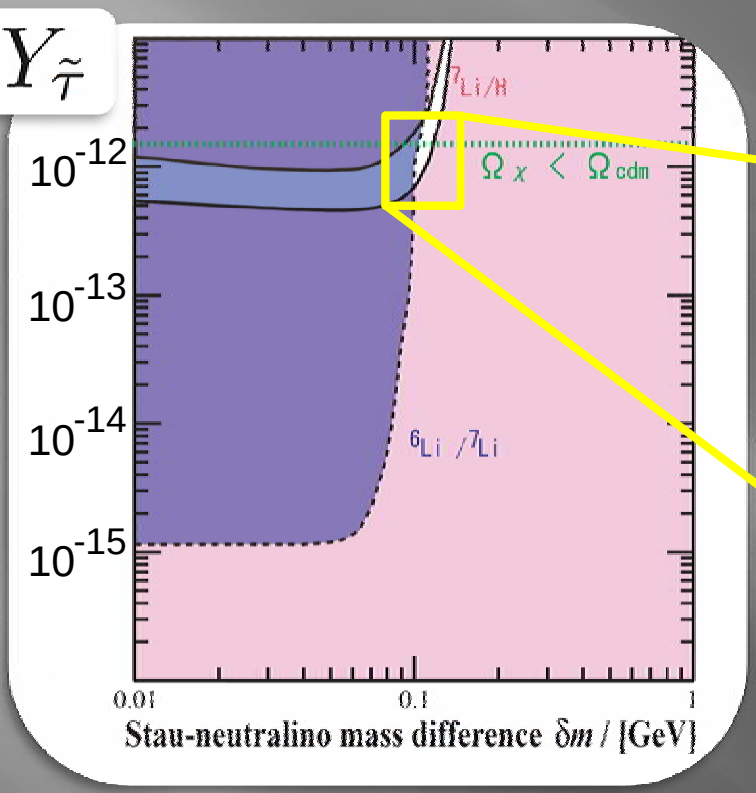
$n_{\tilde{\tau}}$: stau number density

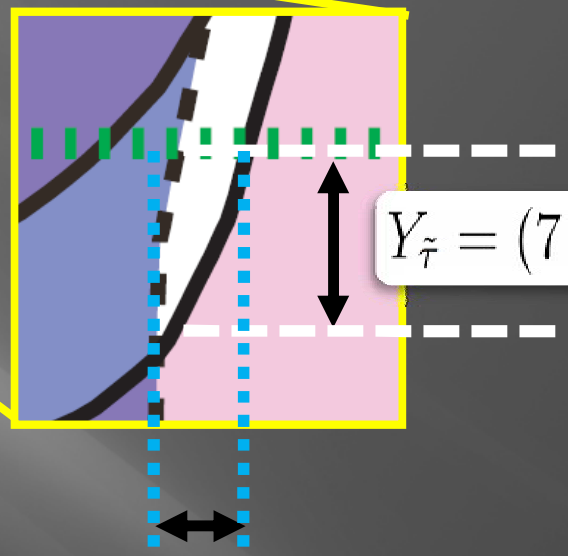
s : entropy density

Allowed region

Consistent with all the observational abundance of light-elements

Allowed region and prediction





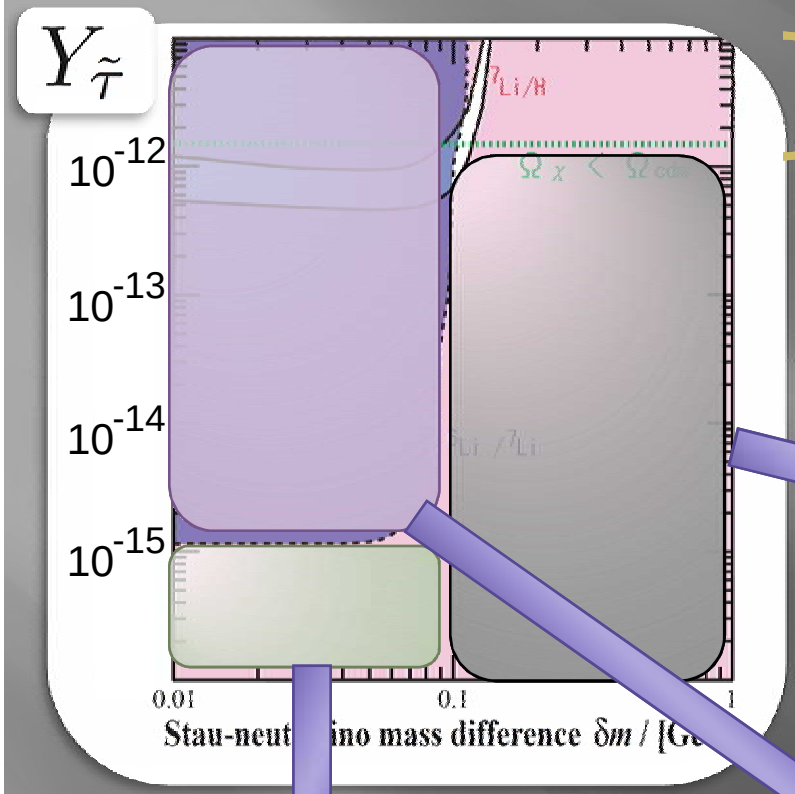
$Y_{\tilde{\tau}} = (7 - 10) \times 10^{-13}$

$\delta \mathrm{m} = (100 - 120)$ MeV

Strict constraint on δm and $Y_{\tilde{\tau}}$

$\delta \mathrm{m} = (100 - 120)$ MeV $\qquad Y_{\tilde{\tau}} = (7 - 10) \times 10^{-13}$

Forbidden region



Overclosure of the universe

Stau decays before forming a bound state

- Lifetime of stau $\lesssim \mathcal{O}(10^2)$ sec
- Formation time $(^7\mathrm{Be}\ \tilde{\tau}) \sim \mathcal{O}(10^2)$ sec
  $(^7\mathrm{Li}\ \tilde{\tau}) \sim \mathcal{O}(10^3)$ sec

Bound states are not formed sufficiently

Insufficient reduction

Over production of ^{6}Li due to stau catalyzed fusion

Summary

- We investigated solution of the Li problem in the MSSM,
  in which the LSP is lightest neutralino and the NLSP is lighter stau

- Long lived stau can form a bound state with nucleus and provides
  new processes for reducing Li abundance

  → Stau-catalyzed fusion

  → Internal conversion process

- We obtained strict constraint on the mass difference between stau
  and neutralino, and the yield value of stau

$\delta \mathrm{m} = (100 \text{ - } 120)\ \mathrm{MeV} \qquad Y_{\tilde{\tau}} = (7 - 10) \times 10^{-13}$

Appendix

Convention and Lagrangian

$$\mathcal{L}_{int} = \tilde{\tau}^* \bar{\tilde{\chi}}^0 (g_L P_L + g_R P_R)\tau + \frac{G_F}{\sqrt{2}} \nu_\tau \gamma_\mu P_L \tau J^\mu$$

$$+ \frac{4G_F}{\sqrt{2}} (\bar{l}\gamma^\mu P_L \nu_l)(\bar{\nu}_\tau \gamma_\mu P_L \tau) + h.c.$$

$$\tilde{\tau} = \cos\theta_\tau \tilde{\tau}_L + \sin\theta_\tau e^{-i\gamma_\tau} \tilde{\tau}_R,$$

$$g_L = \frac{g}{\sqrt{2}\cos\theta_W} \sin\theta_W \cos\theta_\tau,$$

$$g_R = \frac{\sqrt{2}g}{\cos\theta_W} \sin\theta_W \sin\theta_\tau e^{i\gamma_\tau}$$

θ_τ : mixing angle between $\tilde{\tau}_R$ and $\tilde{\tau}_L$

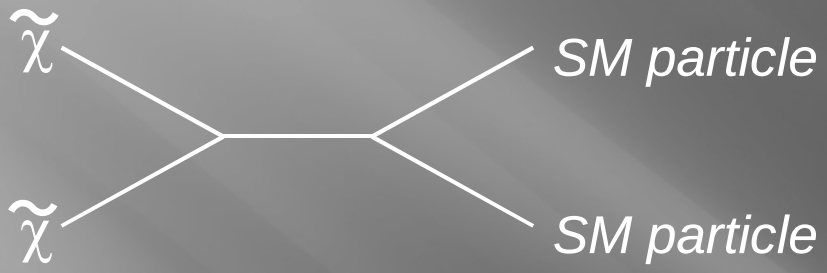
γ_τ : CP violating phase

g : Weak coupling

θ_W : Weinberg angle

Naïve calculation of neutralino DM abundance

DM reduction process without coannihilation processes



Neutralino pair annihilation

Cross section is too weak to reduce the number density of neutralino DM

Observed DM abundance

$$\Omega_{DM} h^2 = 0.11$$

$$\propto m_{DM} \times n_{DM}$$

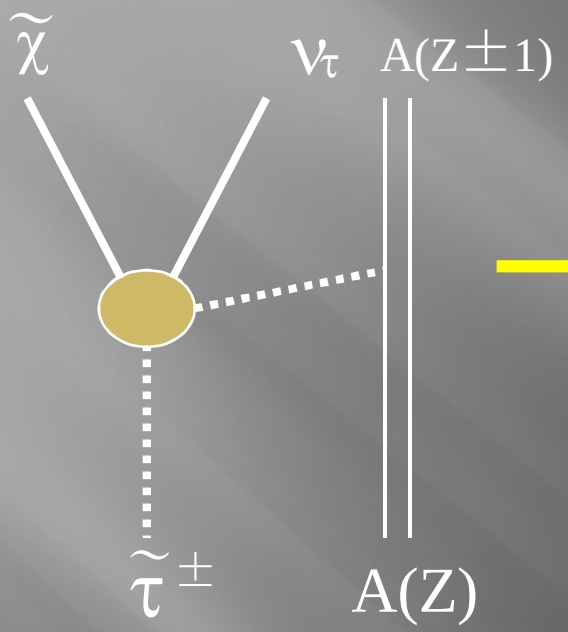
$$m_{DM} = (\text{constant}) \frac{1}{n_{DM}}$$

Not consistent !

$m_{\tilde{\chi}} > 46$ GeV

[PDG 2006 (J. Phys. G 33, 1 (2006))]

Destruction of nuclei with free stau



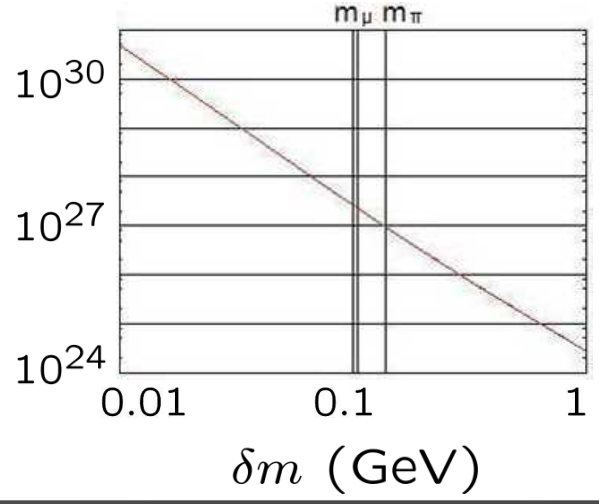
Negligible due to

- Cancellation of destruction
- Smallness of interaction rate

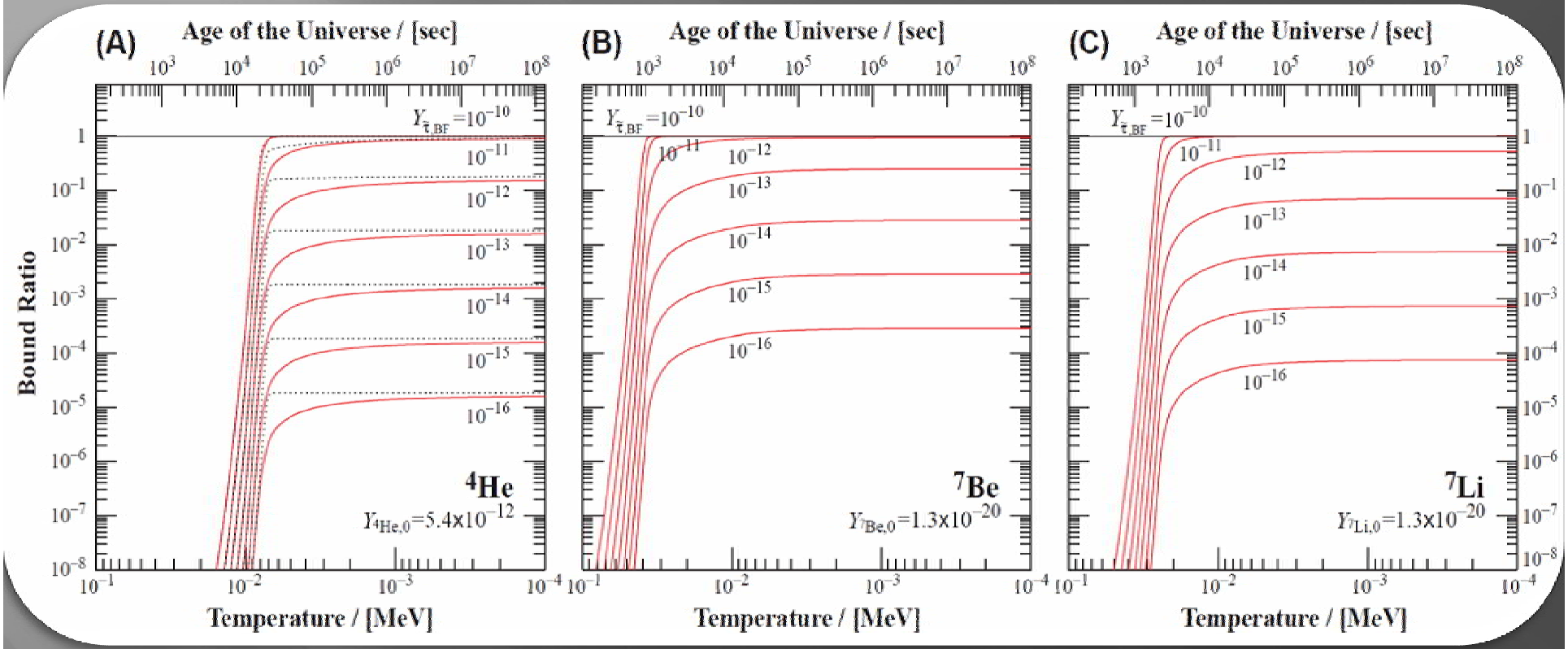
$$\tilde{\tau}^{+} + {}^{7}\mathrm{Li} \rightarrow {}^{7}\mathrm{Be} + \tilde{\chi}^{0} + \nu_{\tau}$$

$$\tilde{\tau}^{-} + {}^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li} + \tilde{\chi}^{0} + \nu_{\tau}$$

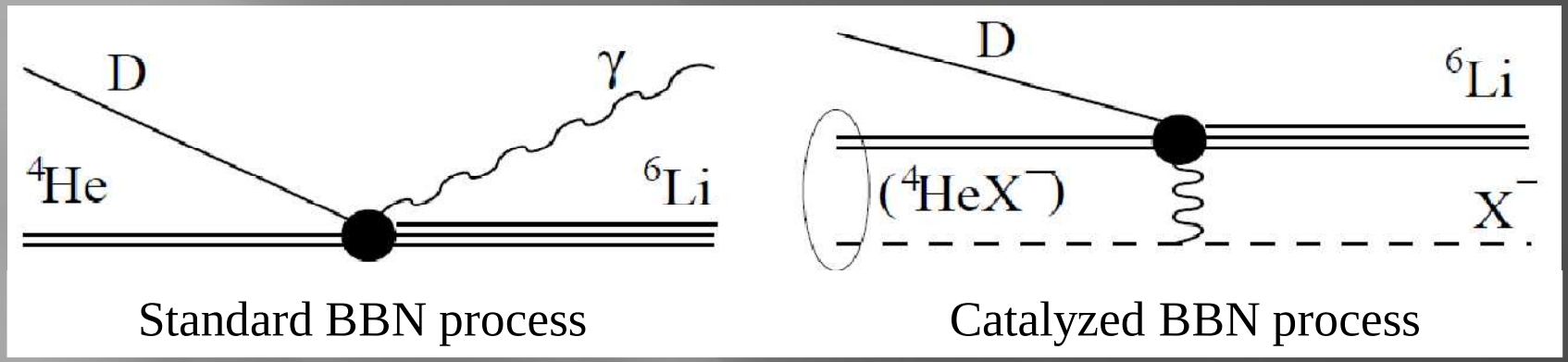
Interaction time scale (sec)



Bound ratio

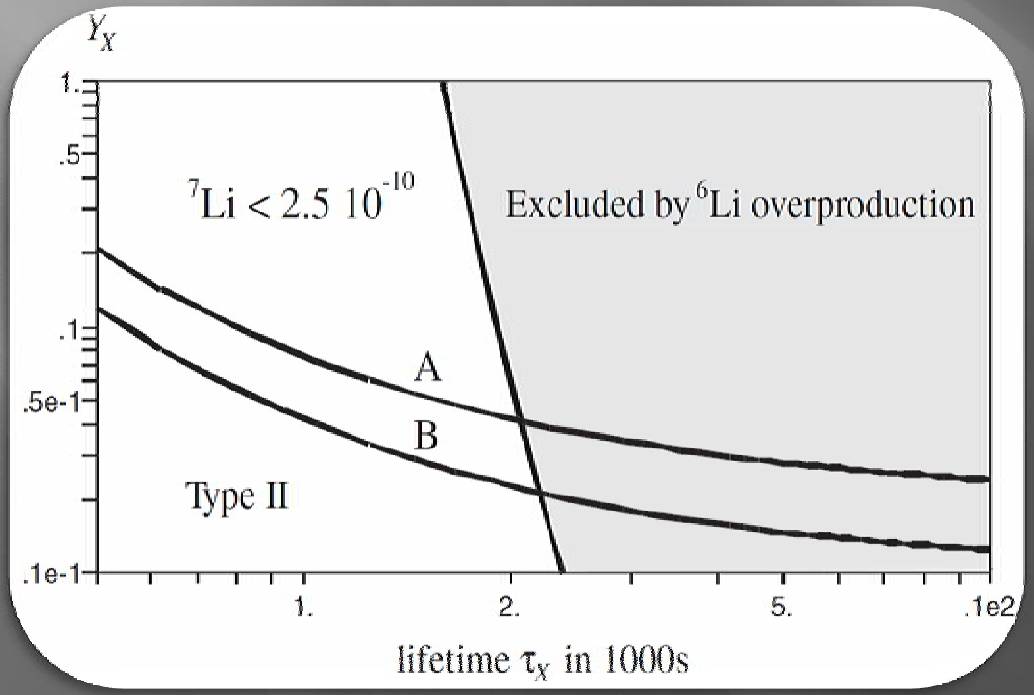

(A)
Age of the Universe / [sec]
10^3 10^4 10^5 10^6 10^7 10^8
$Y_{\tilde{\tau},BF}=10^{-10}$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Bound Ratio
1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8}
^{4}He
$Y_{^4He,0}=5.4\times10^{-12}$
10^{-1} 10^{-2} 10^{-3} 10^{-4}
Temperature / [MeV]
(B)
Age of the Universe / [sec]
10^3 10^4 10^5 10^6 10^7 10^8
$Y_{\tilde{\tau},BF}=10^{-10}$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
^{7}Be
$Y_{^7Be,0}=1.3\times10^{-20}$
10^{-1} 10^{-2} 10^{-3} 10^{-4}
Temperature / [MeV]
(C)
Age of the Universe / [sec]
10^3 10^4 10^5 10^6 10^7 10^8
$Y_{\tilde{\tau},BF}=10^{-10}$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
^{7}Li
$Y_{^7Li,0}=1.3\times10^{-20}$
10^{-1} 10^{-2} 10^{-3} 10^{-4}
Temperature / [MeV]

Constraint from stau catalyzed fusion



Standard BBN process

Catalyzed BBN process



Catalyzed BBN cause over production of Li

Constraint on stau life time

Internal conversion rate

The lifetime of the stau-nucleus bound state

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

$|\psi|^2$: wave function overlap of stau and nucleus

(σv) : cross section $\times$ relative velocity

- The bound state is in the S-state of a hydrogen-like atom

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

nuclear radius

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

- (σv) is evaluated by using *ft*-value

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

ft-value of each processes

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

^{7}Li $\rightarrow$ ^{7}He ••• similar to ^{7}Be $\rightarrow$ ^{7}Li (no experimental value)

New interaction chain reducing ^{7}Li and ^{7}Be