Long-lived charged massive particle and the effect on cosmology

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Kawasaki, Kohri, Moroi, PRD71 (2005) 083502

Kohri, Takayama, PRD (2007) in press, hep-ph/0605243

Kawasaki, Kohri, Moroi, PLB 649 (2007) 436

Jittoh, Kohri, Sato etal, arXiv:0704.2914 [hep-ph]

Cumberbatch etal, arXiv:0708.0095 [astro-ph]

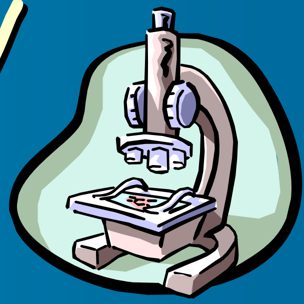
Chun, Kim, Kohri and Lyth, in preparation

Abstract

- The Standard Big Bang Nnucleosynthesis (SBBN) approximately agrees with observations.
- We can use BBN as a probe to study the early universe
- In SUSY/SUGRA cosmology, reheating temperature after Inflation should be less than 10^6GeV, in order to solve the "gravitino problem."
- We may solve the Lithium problems in SUSY/SUGRA cosmology models
- Dark matter (LSP) may be neutralinos, gravitinos, or axinos which are nonthermally produced by decays of long-lived NLSP (gravitino, sneutrino or stau)

Gravitino Problem

Introduction of SUSY



Supersymmetry (SUSY)

- Solving "Hierarchy Problem"
- Realizing "Coupling constant unification in GUT"

Fermion	⟷	Boson
quark	⟷	squark
lepton	⟷	slepton
photino	⟷	photon
gravitino	⟷	graviton

Gravitino ψ_μ is the superpartner of graviton

Spin 3/2

SUSY Breaking

- Gravity mediated SUSY breaking model

Observable sector

quark, squark, …

Only through gravity

Hidden sector

~~SUSY~~

M_{SUSY}

- Masses of squarks and sleptons

$$m_{\tilde{q}}, m_{\tilde{\ell}} = M_{SUSY}^2 / M_{pl} = 10^2 - 10^3 \ GeV$$

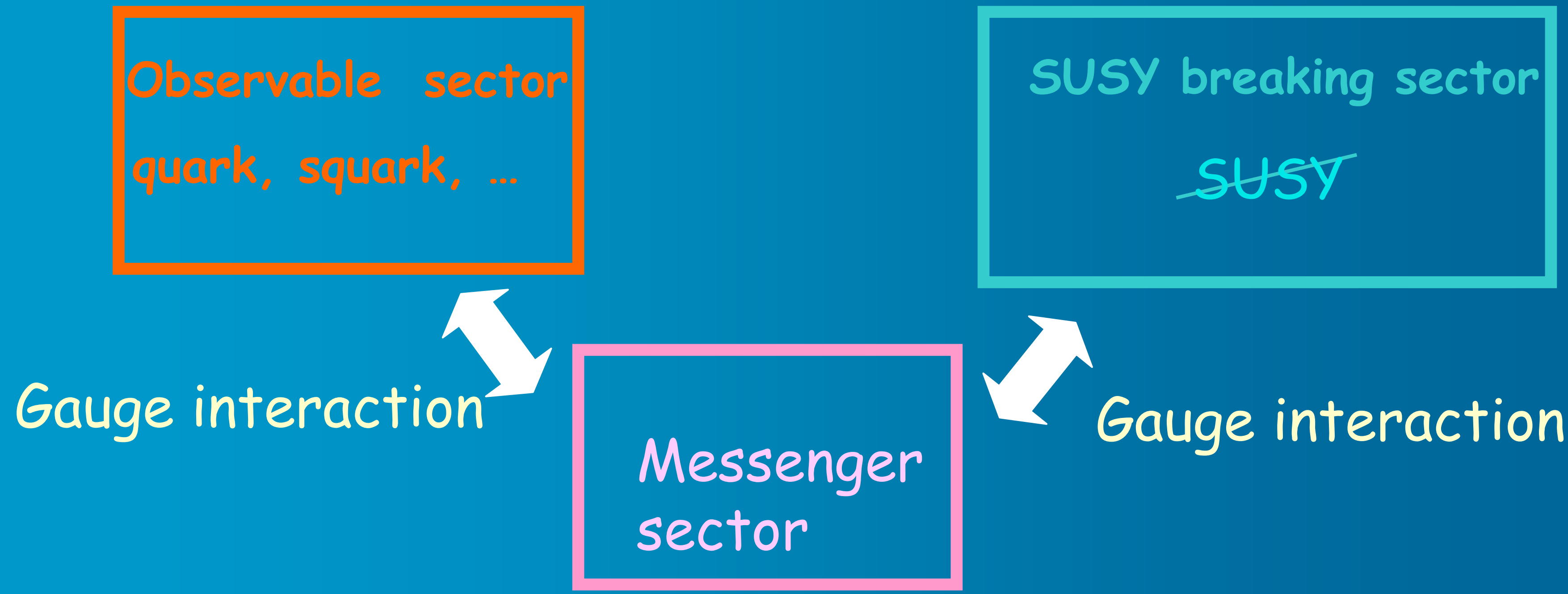
$$(M_{SUSY} = 10^{10} - 10^{11} \ GeV)$$

- Gravitino mass

$$m_{3/2} = M_{SUSY}^2 / M_{pl} = 10^2 - 10^3 \ GeV$$

SUSY Breaking II

- Gauge-mediated SUSY breaking model (Dynamical SUSY brasking)



$m_{3/2} < 10\text{GeV}$

Reviews of Long-Lived Massive particle (NLSP) in SUSY/SUGRA Cosmology

The interaction related with gravitions is highly suppressed

$$g \sim m_{3/2} / m_{pl}$$

$$\Gamma_{NLSP \to LSP} \sim g^2 m_{3/2}$$

$$\sim m_{3/2}^3 / m_{pl}^2$$

$$\sim (1 - 10^6 \, sec)^{-1}$$

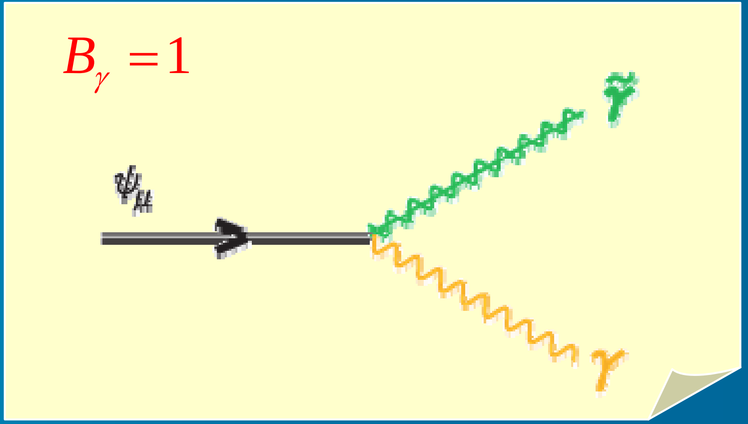
For $m_{3/2} \sim$ 100GeV - 10TeV

Gravitino Decay and BBN

1. Gravitinos are unstable in Gravity Mediation ~~SUSY~~

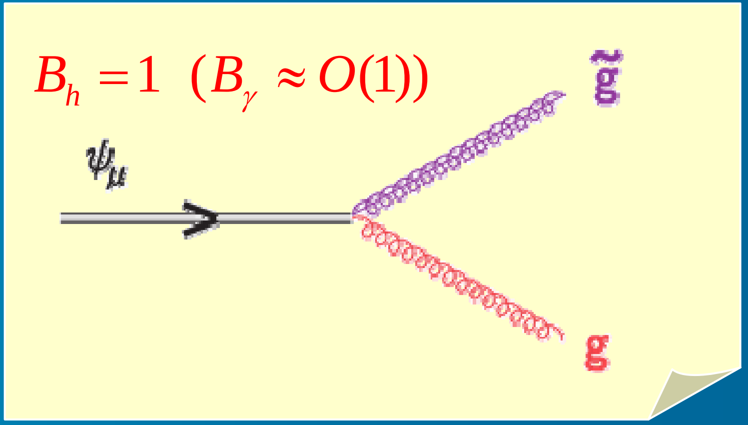
- Radiative decay

$$\tau(\psi_{3/2} \to \gamma + \tilde{\gamma}) = 4 \times 10^8 \sec \left(\frac{m_{3/2}}{100\ \mathrm{GeV}} \right)^{-3}$$



- Hadronic decay

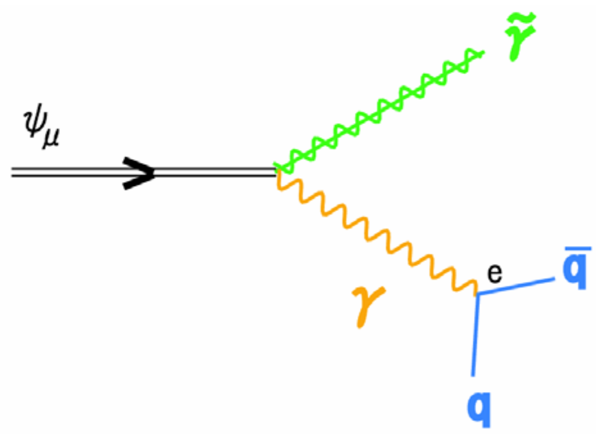
$$\tau(\psi_{3/2} \to g + \tilde{g}) = 6 \times 10^7 \sec \left(\frac{m_{3/2}}{100\ \mathrm{GeV}} \right)^{-3}$$



Hadronic decay

Reno, Seckel (1988)

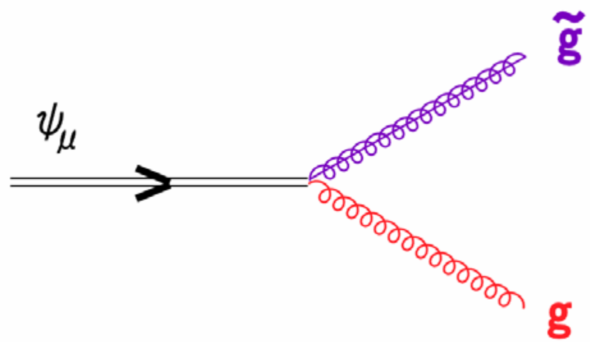
S. Dimopoulos et al.(1989)



$$B_h \approx \alpha / 4\pi \approx 10^{-3}$$

Two hadron jets with

$E_{jet} = m_X / 3$



$$B_h = 1$$

One hadron jet with

$E_{jet} = m_X / 2$

NLSP decays during/after BBN epoch producing high energy photons and hadrons

↓

Destruction/Production of light elements

↓

Severer constraints on the reheating temperature T_R

Lindley (1984,1985), Khlopov and Linde (1984)

Ellis, Kim, Nanopoulos, (1984); Ellis, Nanopoulos, Sarkar (1985)

Kawasaki and Sato (1987)

Reno and Seckel (1988), Dimopoulos,Esmailzadeh, Hall, Starkman (1988)

Kawasaki, Moroi (1994), Kawasaki, Kohri, Moroi (2001), Kohri(2001)

Jedamzik (2000), Cyburt, Ellis, Fields, Olive (2003)

Kawasaki, Kohri, Moroi (2004)

Observational Light Element Abundances

- He4 $Y_p = 0.2516 \pm 0.004$

Fukugita, Kawasaki (2006)

Peimbert,Lridiana, Peimbert(2007)

Izotov,Thuan, Stasinska (2007)

- D/H $D/H = (2.82 \pm 0.26) \times 10^{-5}$

O'Meara et al. (2006)

- Li7/H $\log_{10}\left({}^{7}Li/H\right) = -9.63 \pm 0.06\ (\pm 0.3)_{syst.}$

Melendez,Ramirez(2004)

- Li6/H

$^{6}Li/{}^{7}Li < 0.046 \pm 0.022 \pm 0.084$

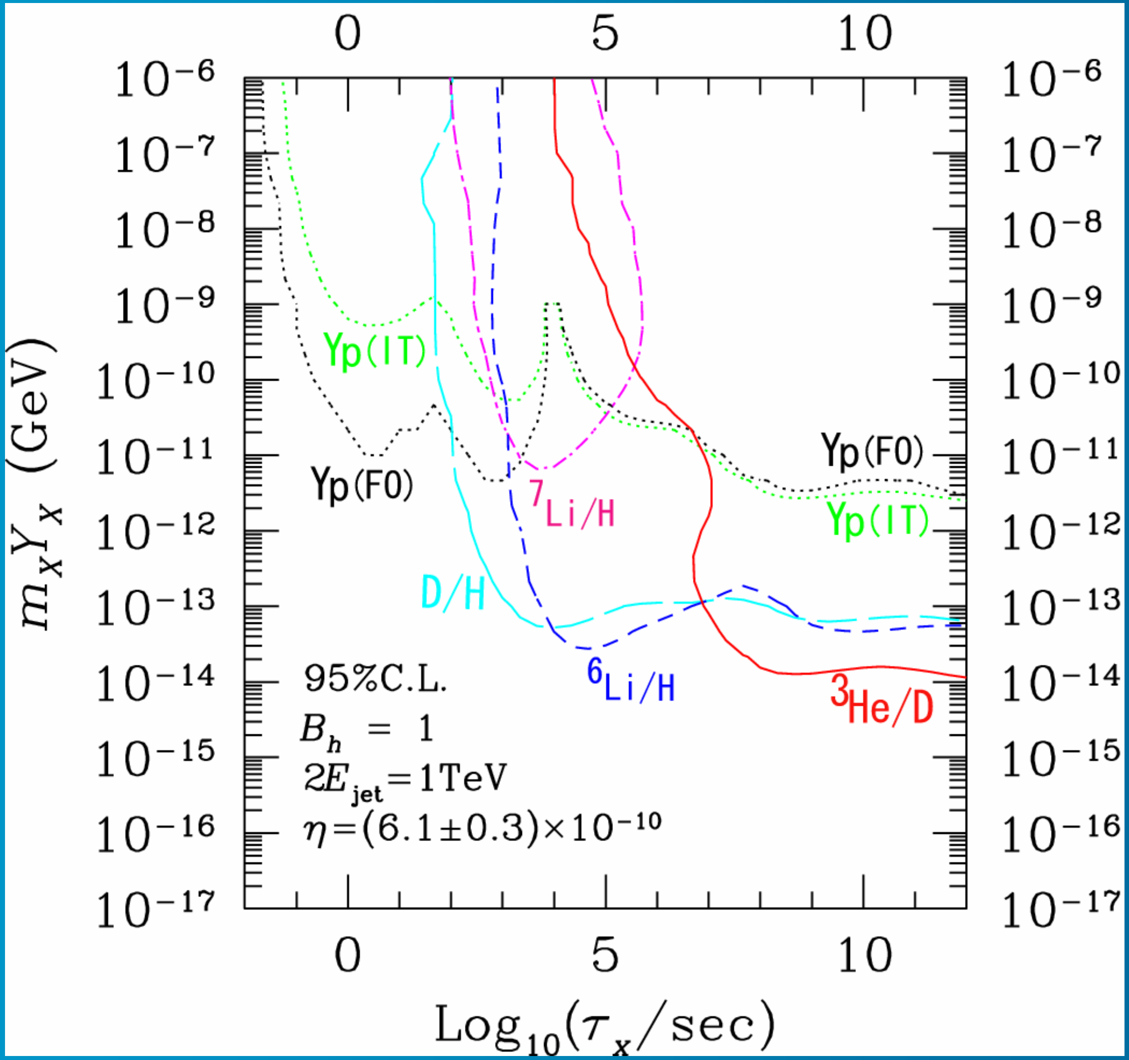
Asplund et al(2006)

- He3/D $^{3}He/D < 0.83 + 0.27$

Geiss and Gloeckler (2003)

Constraints on massive particle X

$$Y_X \equiv \frac{n_X}{s}$$



Contours of light elements in ($m_x Y_x$, τ_x) plane in "hadrodissociation" scenario

Relation among variables

- Yield variable and reheating temperature

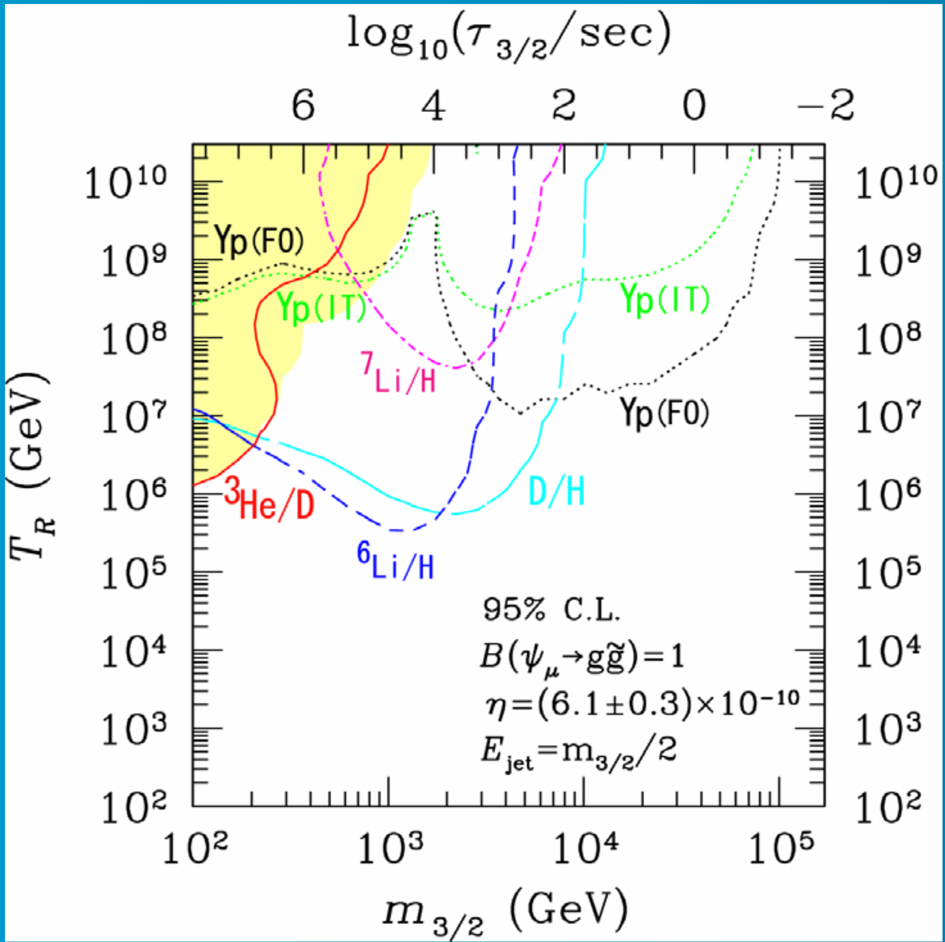
$$Y_{3/2} \equiv \frac{n_{3/2}}{n_\gamma} = 1.1 \times 10^{-11} \left(\frac{T_R}{10^{10}\, GeV} \right)$$

- Lifetime and mass

$$\tau(\psi_{3/2} \to \gamma + \tilde{\gamma}) = 4 \times 10^{8}\, sec \left(\frac{m_{3/2}}{100\ GeV} \right)^{-3}$$

Upper bound on reheating temperature

Kawasaki, Kohri, Moroi (2004)



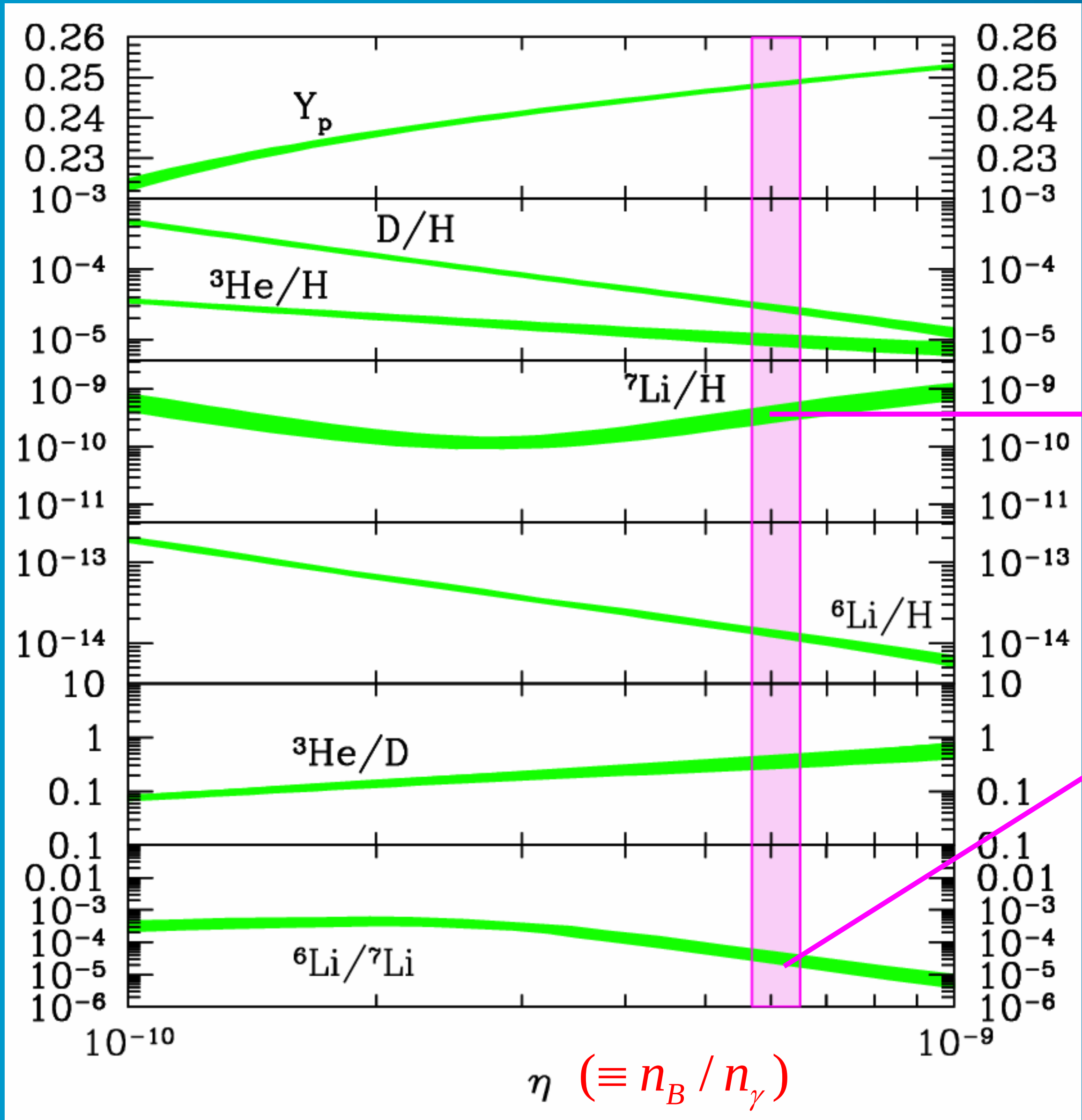
$$B_h(\psi_\mu \to g + \tilde{g}) = 1$$

$$T_R = 10^9 \mathrm{GeV}\left(Y_{3/2}/10^{-12}\right)$$

$$m_{3/2} = 500\mathrm{GeV}\ (\tau_{3/2}/4\times10^5 \mathrm{sec})^{-1/3}$$

Lithium Problems

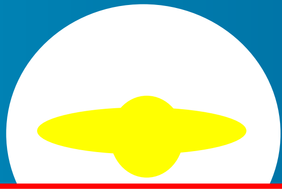
SBBN



$(^7Li/H)_{SBBN}=(4\text{-}5)\times10^{-10}$

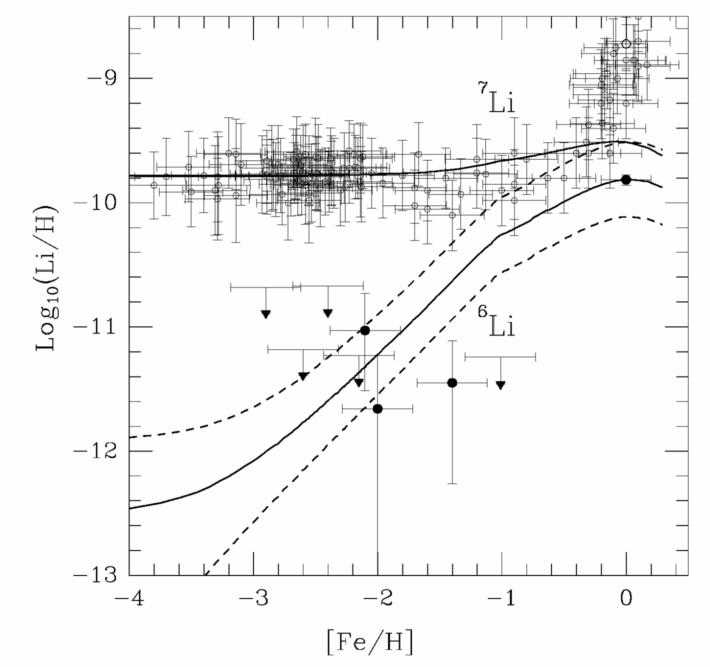
$Li6/Li7 \sim 3.3 \times 10^{-5}$

Lithium 7



a factor of two or three smaller !!!

● Expected that there is little depletion in stars.



Lemoine et al., 1997

$$^7\mathrm{Li}/\mathrm{H} = 1.23^{+0.68}_{-0.32} \times 10^{-10}$$

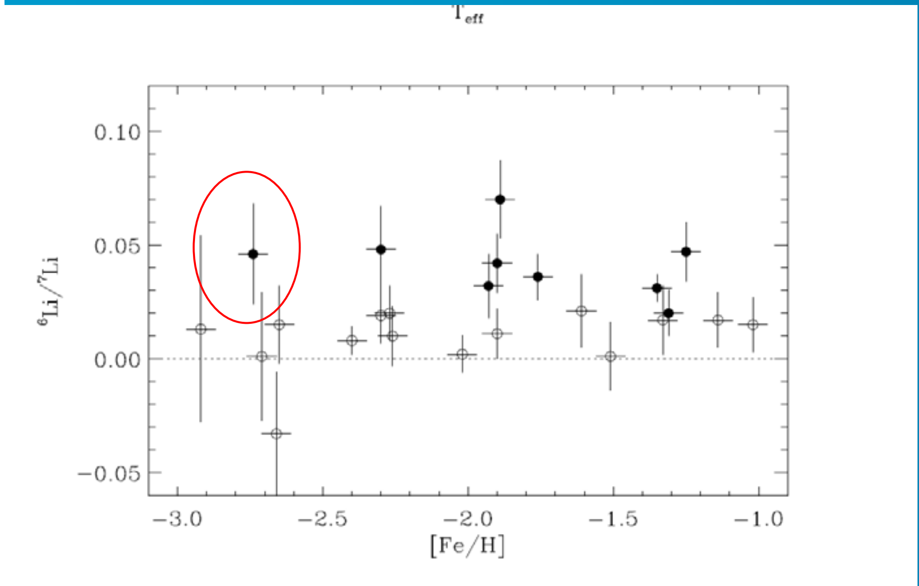
Ryan et al.(2000)

Bonifacio et al.(2006)

Lithium 6

Asplund et al.(2006)

- Observed in metal poor halo stars in Pop II
- ^{6}Li plateau?



$$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 0.002 - 0.090$$

$$^{7}\mathrm{Li}/\mathrm{H} \approx (1.1 - 1.5)\times 10^{-10}$$

still disagrees with SBBN

Astrophysically, factor-of-two depletion of Li7 needs a factor of O(10) Li6 depletion (Pinsonneault et al '02)

We need more primordial Li6?

Solving Li7 problem in Hadronic decay of neutral particles

Jedamzik (04); Jedamzik etal (05)

Kohri, Moroi, Yotsuyanagi (2005)

Cumberbatch etal (2007)

Severer observations

Ryan etal ('00), Asplund etal ('05)

$$(n_{^7\mathrm{Li}}/n_{\mathrm{H}})^{\mathrm{obs}} = 1.23^{+0.68}_{-0.32} \times 10^{-10}$$

$\eta = (2-4)\times 10^{-10}$ at 2σ

?

~~$(^7\mathrm{Li/H})_{\mathrm{SBBN}} = (4\text{-}5)\times 10^{-10}$~~

~~$(\eta = \eta_{\mathrm{WMAP}} = (6.1\pm 0.6)\times 10^{-10})$~~

Neuron emission from hadronic shower

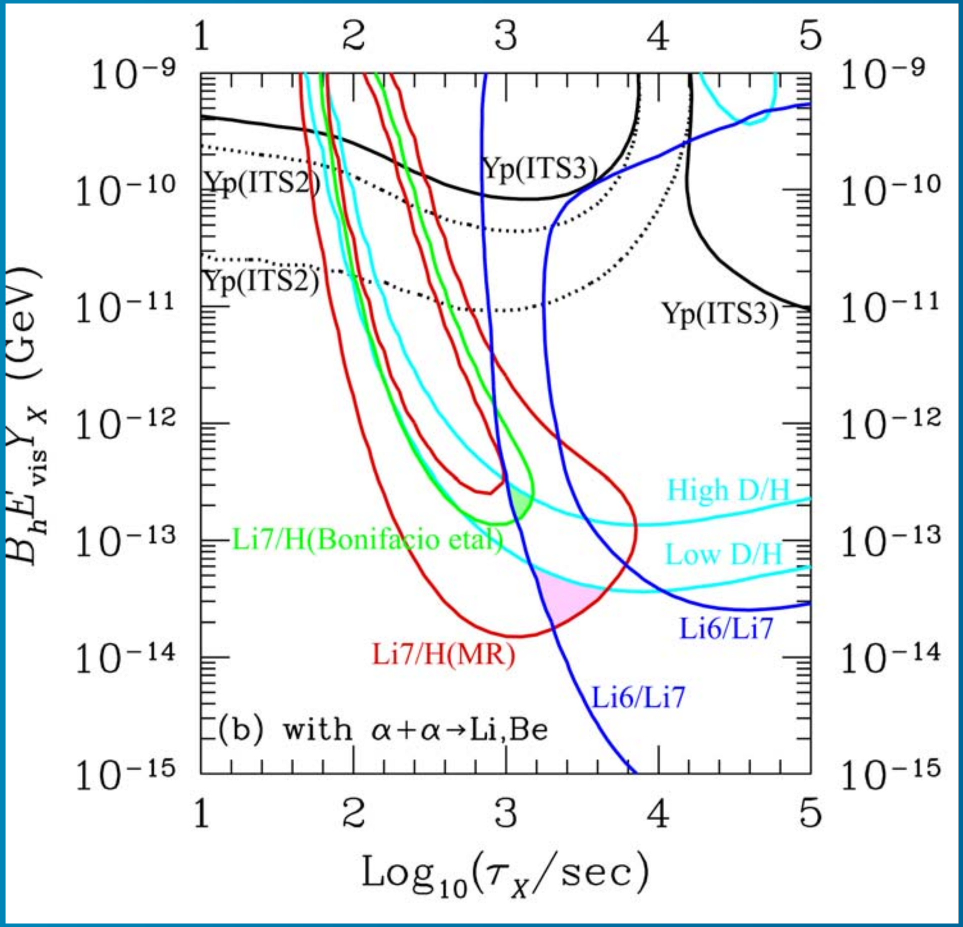
$$^7\mathrm{Be} + n \to \ldots \to 2\ ^4\mathrm{He}$$

Li7 can be reduced! (Jedamzik)

$(^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \gamma)$

More Li6 can be also produced!

$$^3\mathrm{He} + {}^4\mathrm{He} \to {}^6\mathrm{Li} + p$$



NLSP might be Slepton? (stau or sneutrino)

✓LSP would be gravitino, or neuralino with small mass-difference

✓Neutralino NLSP would be excluded by BBN because of high hadronic branching ratio

Feng, Su, and Takayama (2003)

Steffen (2006)

Kanzaki, Kawasaki, Kohri, Moroi (2006)

CHArged Massive Particle (CHAMP)

Kohri and Takayama, hep-ph/0605243
See also literature, Cahn-Glashow ('81)

Many candidates of long-lived CHAMP

stau, ...

More massive elements capture CHAMP earlier

$T_c \sim E_{bin}/40 \sim 10\text{keV}$
$(E_{bin} \sim \alpha^2 m_i \sim 100\text{keV})$

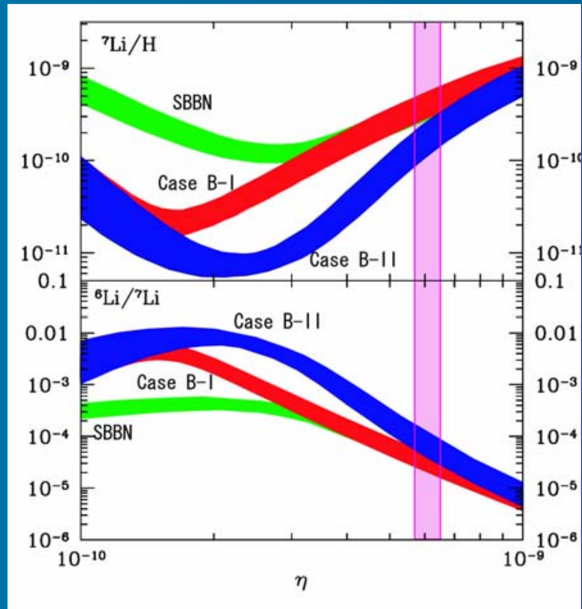
CHAMP captured-nuclei change the nuclear reaction rates

CHAMP BBN (CBBN) may solve Lithium problem?

Kohri and Takayama, hep-ph/0605243

Short lifetime (< 10^3 sec)

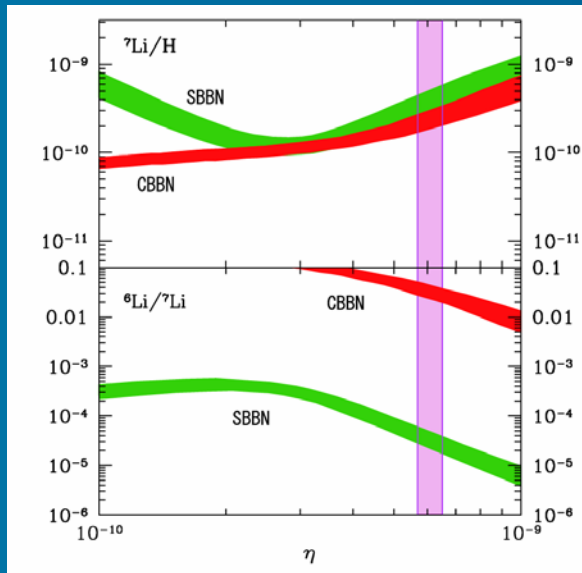
- Only Be7 and Li7 captures CHAMP
- Be7 (n,a)He4 and Li7(p,a)He4 are enhanced



Long lifetime (> 10^6 sec)

- Z=1 elements, proton, D, and T are captured
- He4(d, g)Li6 and Be7(d, p a)He4 are enhanced

(See also, recent work by Jedamzik, arXiv:0707.2070)



However, the Bohr radius might be too large to completely suppress the coulomb field? (Kohri and Takayama, hep-ph/0605243)

Pospelov's effect

Pospelov (2006),**hep-ph/0605215**

- CHAMP bound state with ^{4}He can enhance the rate

$$D + ({}^4He, C^-) \rightarrow {}^6Li + \gamma$$

- Enhancement of cross section

$$\sim (\lambda_\gamma / a_{Bohr})^5 \sim (30)^5 \sim 10^8$$

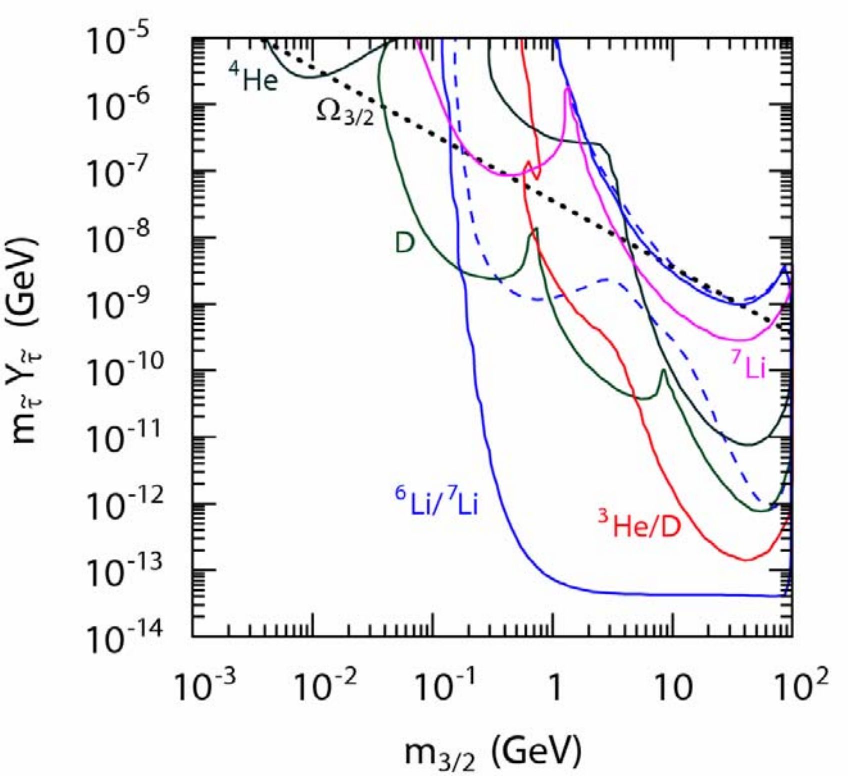
Confirmed by Hamaguchi etal (07), hep-ph/0702274

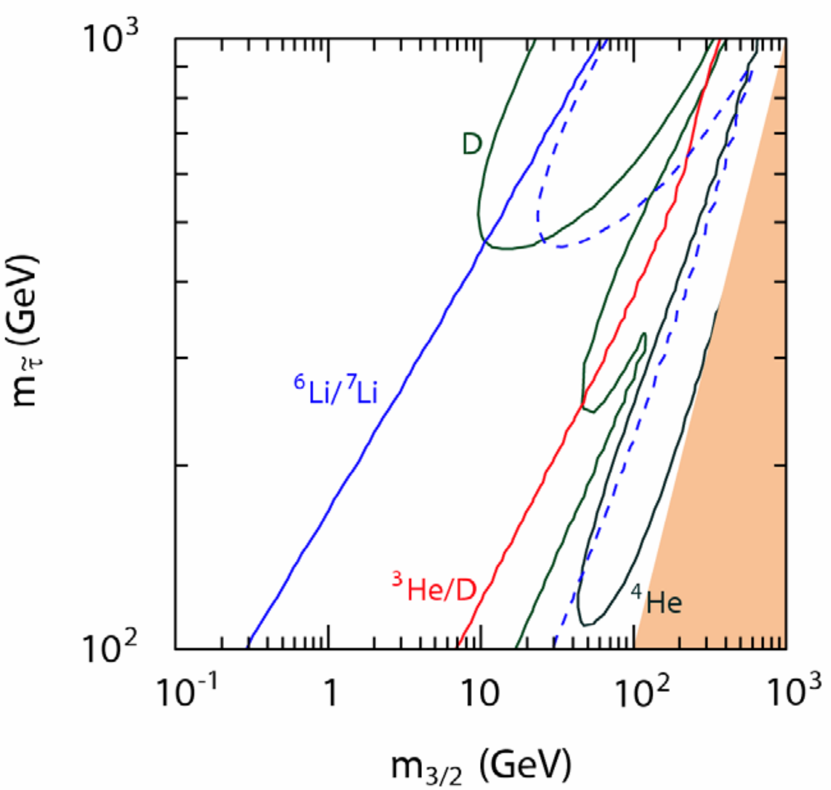
BBN Catalysis!!!

BBN in stau NLSP and gravitino LSP Scenario in gauge mediation

Kawasaki, Kohri, Moroi PLB 649 (07) 436

See also, Jedamzik, arXiv:0707.2070



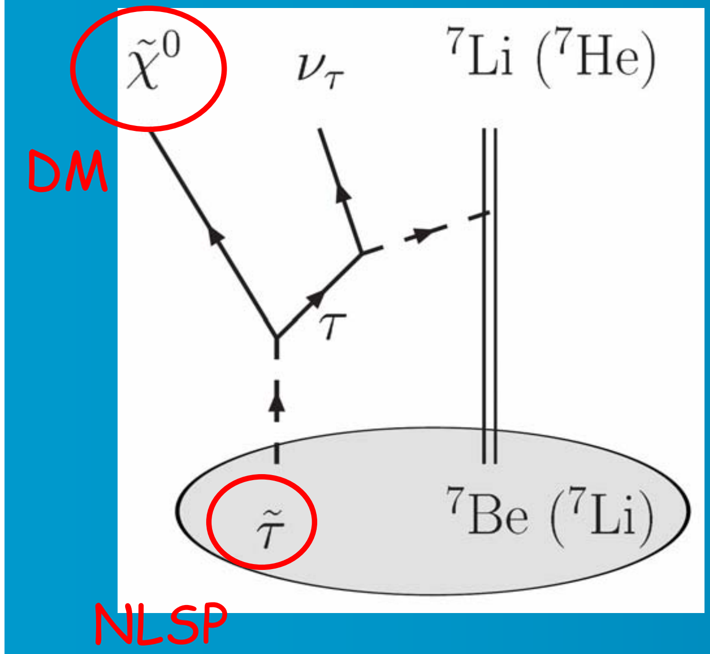


Difficulties in CBBN for long lifetime (> 1000 sec)

Stau NLSP and neutralino LSP Scenario in Gravity Mediation

Jittoh, Kohri, Sato etal, arXiv:0704.2914

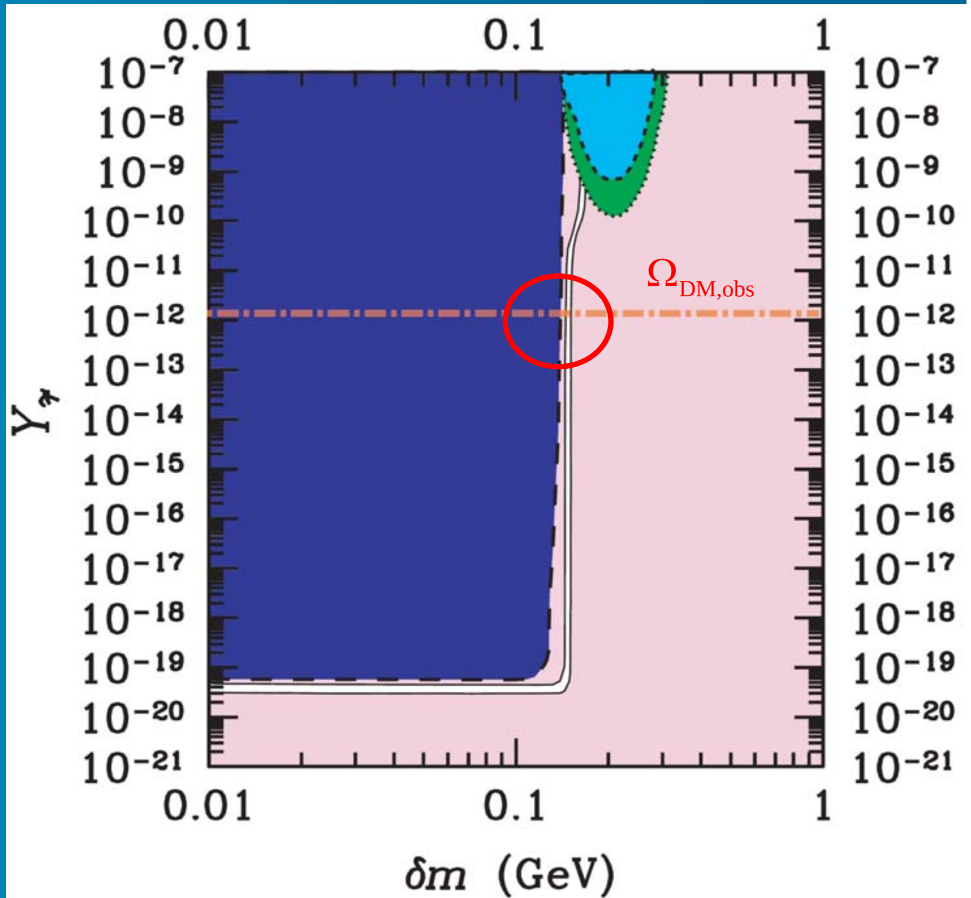
$$\delta m = m_{\tilde{\tau}} - m_{\chi_0} < 0.1\mathrm{GeV}$$



Effectively Be7, Li7 are destroyed!!!

See also Bird, Koopman and Pospelov (07)

No CBBN Catalysis



Stau NLSP and axino/flatino LSP in GUT axion models in Gravity Mediation

Chun, Kim, Kohri, and Lyth in preparation

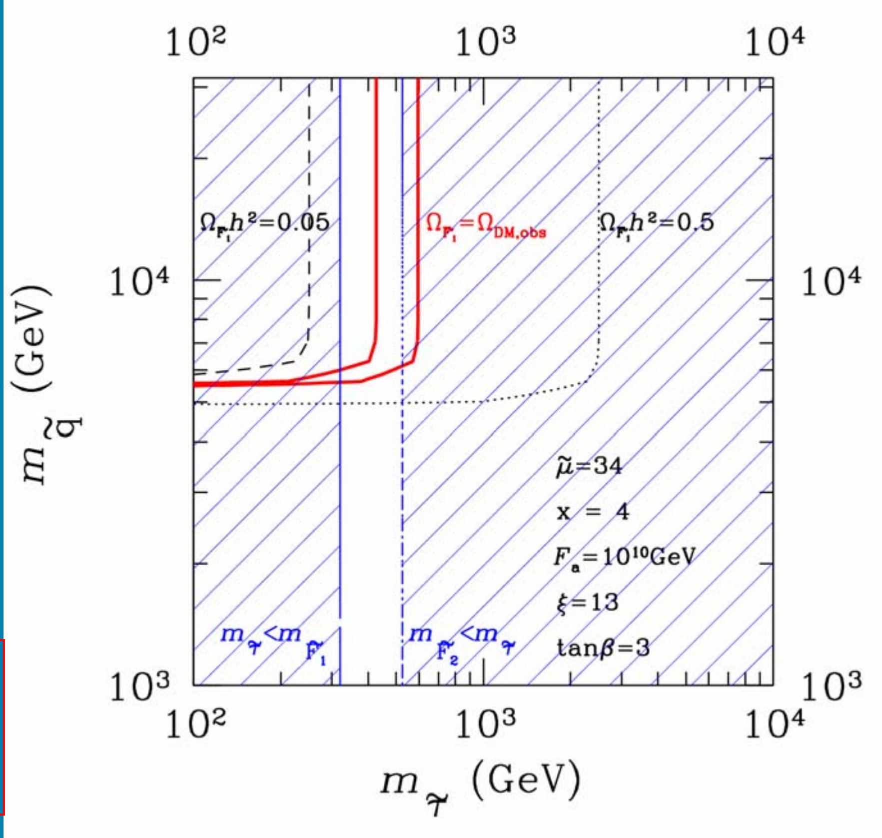
Decaying flatons reheat universe and produce staus

$T_R \sim O(10)$ GeV

Contrary to gravitino LSP models, lifetime of stau is very short

$\tau_{\tilde{\tau}} \ll 10^{-2}$ sec

No CBBN Catalysis



Or lower reheating temperatures no longer produce staus

Note also the mechanism discussed in Dr. Kasuya's today's talk

Conclusion

- The constraint on reheating temperature after primordial inflation is very stringent in Hadronic decay scenario in gravity mediated SUSY breaking models.

$$T_R \le 3 \times 10^5 \mathrm{GeV} - 10^7 \ \mathrm{GeV}$$

$$(\text{for } m_{3/2} = 100 \ \mathrm{GeV} \ - 10 \mathrm{TeV})$$

- CHAMP BBN is attractive in stau NLSP scenario. Then DM should be a stable gravitino in gauge-mediated SUSY breaking models, or neutralino with small mass difference or axinos in gravity mediated SUSY breaking models.