Charged SUSY particles and their effects on cosmology

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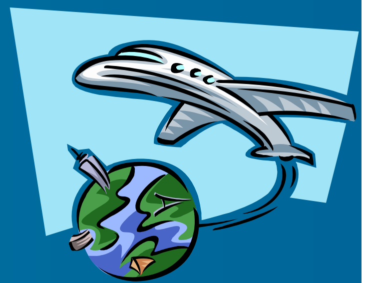


Kawasaki, Kohri, Moroi, PLB625 (2005) 7

Kawasaki, Kohri, Moroi, PRD71 (2005) 083502

Kohri, Moroi, Yotsuyanagi, PRD73 (2006) 123511

Kohri and Takayama, hep-ph/0605243

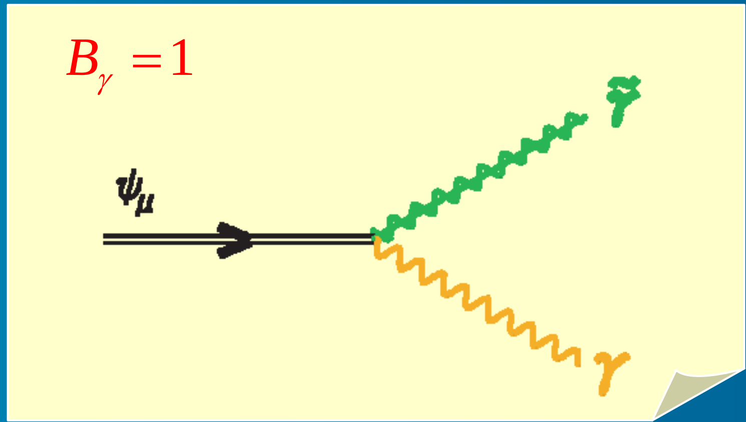
Kanzaki et al, hep-ph/0609246

Gravitino Decay and BBN

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

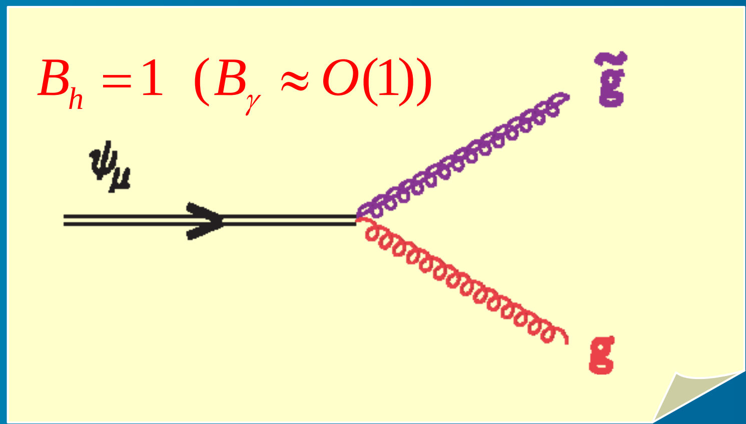
- Radiative decay

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

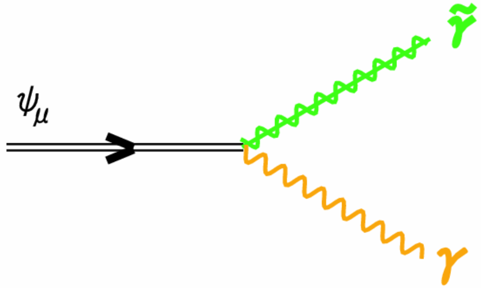


- Hadronic decay

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



Radiative decay of gravitino



1) Electro-magnetic cascade

$$\gamma + \gamma_{\rm BG} \to e^+ + e^-$$
$$\gamma + e^-_{\rm BG} \to \gamma + e^-, \quad e^- + \gamma_{\rm BG} \to e^- + \gamma$$
$$\gamma + \gamma_{\rm BG} \to \gamma + \gamma$$

2) many soft photons are produced

3) Photo-dissociation of light elements

$$\mathrm{D} + \gamma \to p + n,$$
$${}^4\mathrm{He} + \gamma \to {}^3\mathrm{He} + n, \quad \mathrm{T} + p,$$
$${}^3\mathrm{He} + \gamma \to \mathrm{D} + p + n, \quad \mathrm{etc.}$$

Non-thermal Li6 Production

Dimopoulos et al (1989)
Jedamzik (2000)
Kawasaki,Kohri,Moroi (2001)

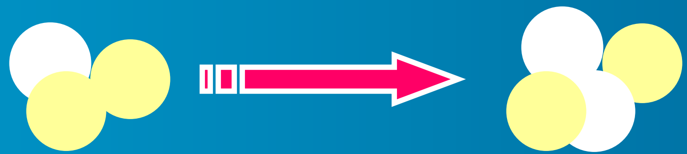
i. He3 (T) production

$$^4\mathrm{He} + \gamma \rightarrow \begin{cases} n + {}^3\mathrm{He} \\ p + T \end{cases}$$

ii. Li6 production

$$T + {}^4\mathrm{He} \rightarrow {}^6\mathrm{Li} + n \; [8.4\ \mathrm{MeV}]$$

$$^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^6\mathrm{Li} + p \; [7.0\ \mathrm{MeV}]$$

T, ^{3}He  ^{4}He

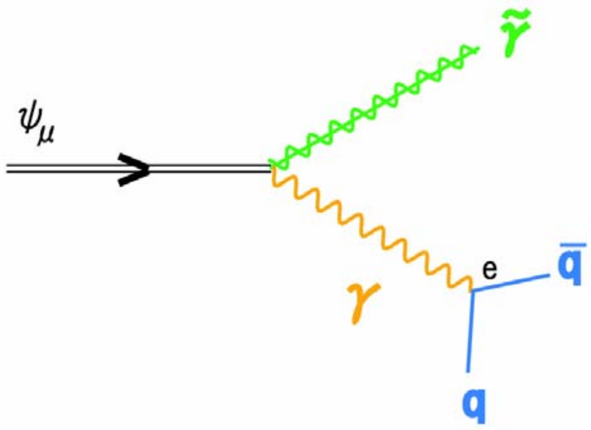
Coulomb energy loss by background electrons

$$\frac{dE}{dx} = \frac{4\pi\alpha^2 Z^2 \Lambda n_e}{m_e \beta}, \qquad \Lambda \sim O(1)$$

Hadronic decay

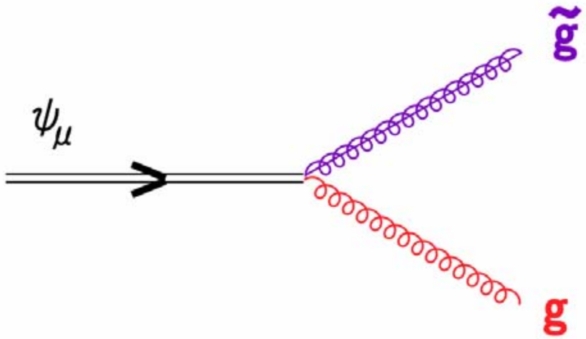
Reno, Seckel (1988)

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 $E_{jet} = m_X / 2$

(I) Early stage of BBN (before/during BBN)

Reno and Seckel (1988) Kohri (2001)

Extraordinary inter-conversion reactions between n and p

cf) $n + \pi^{+} \rightarrow p + \pi^{0}$ $p + \pi^{-} \rightarrow n + \pi^{0}$

$$\Gamma_{n \leftrightarrow p} = \Gamma^{weak}_{n \leftrightarrow p} + \Gamma^{strong}_{n \leftrightarrow p}$$

Hadron induced exchange

$$\Gamma_{n \leftrightarrow p} \uparrow \quad \Rightarrow \quad n/p \uparrow$$

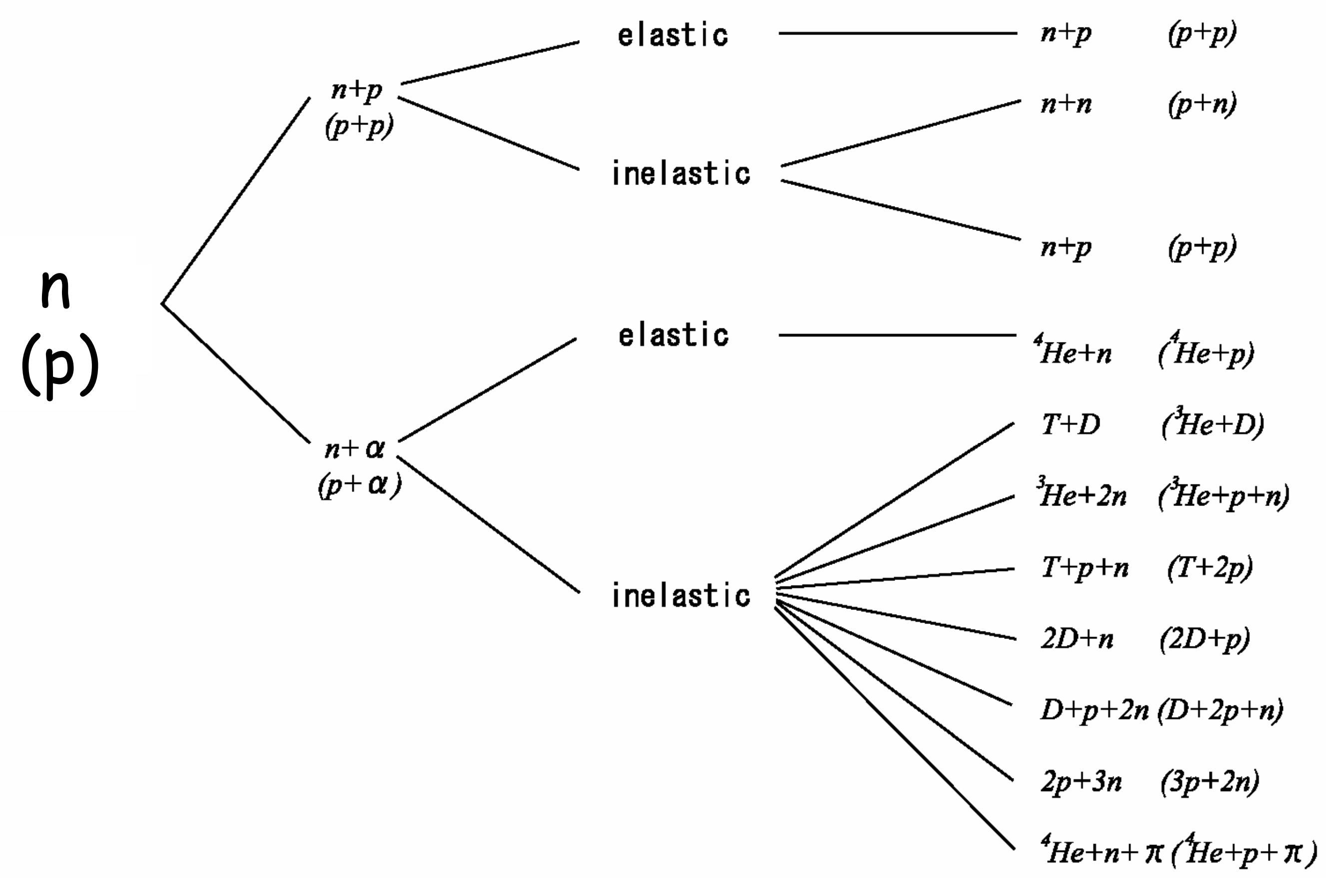
Even after freeze-out of n/p in SBBN

More He4, D, Li7 ...

(II) Late stage of BBN

S. Dimopoulos et al. (1988)
Kawasaki, Kohri, Moroi (2004)
Jedamzik (2006)

Hadronic showers and "Hadro-dissociation"

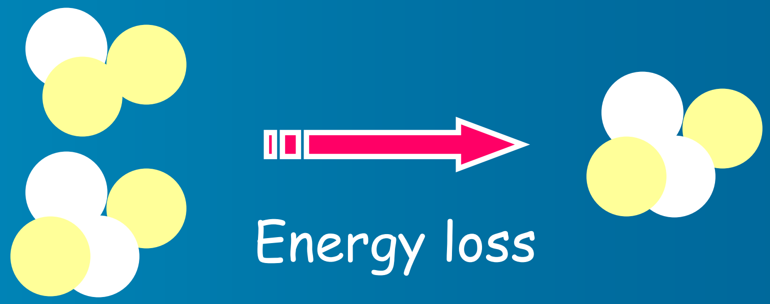


Non-thermal Li, Be Production by energetic hadrons

Dimopoulos et al (1989)

$$N + {}^4He \rightarrow \begin{cases} {}^3He + X \\ T + X \end{cases}$$

$$N + {}^4He \rightarrow {}^4He^* + X$$



① T(He3) – He4 collision

$$T + {}^4He \rightarrow {}^6Li + n \quad [8.4\ \mathrm{MeV}]$$

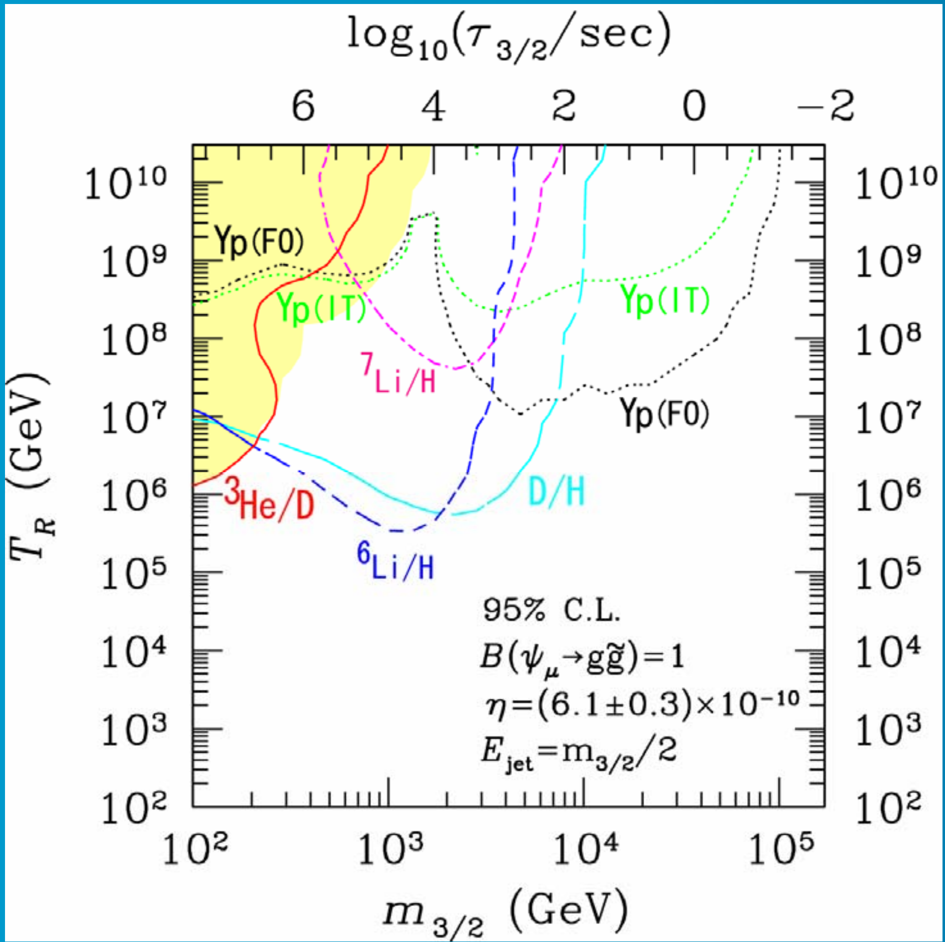
$${}^3He + {}^4He \rightarrow {}^6Li + p \quad [7.0\ \mathrm{MeV}]$$

② He4 – He4 collision

$${}^4He + {}^4He \rightarrow {}^6Li, {}^7Li, {}^7Be + \ldots$$

Upper bound on reheating temperature

Kawasaki, Kohri, Moroi (2004)



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

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

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

Sneutrino NLSP, Gravitino LSP and inplication for Thermal Leptogenesis

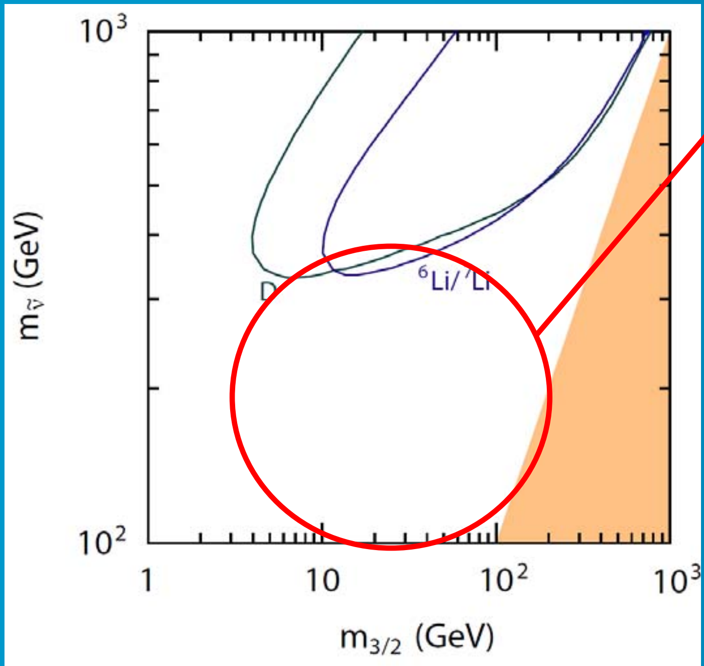
Kanzaki, Kawasaki, Kohri, Moroi (2006)

$$\tilde{\nu} \to \nu + \psi_\mu$$

Thermal-relic sneurinos can not produce sufficient DM $\Omega_{3/2}$

$$Y_{\tilde{\nu}} \sim 2\times10^{-14}\left(m_{\tilde{\nu}}/100\mathrm{GeV}\right)$$

Fujii, Ibe, Yanagida (04)



This region might be excluded in neutralino / stau NLSP scenarios

Feng, Su, Tankayama (04)

Steffen (06)

Only reheating process can produce sufficient Gravitino DM

$\Omega_{3/2}h^2 \sim 0.11$

Lighter gravitino mass

larger gaugino mass ($\sigma \propto M_1^2$) → Overproduction of Gravitinos for a fixed T_R

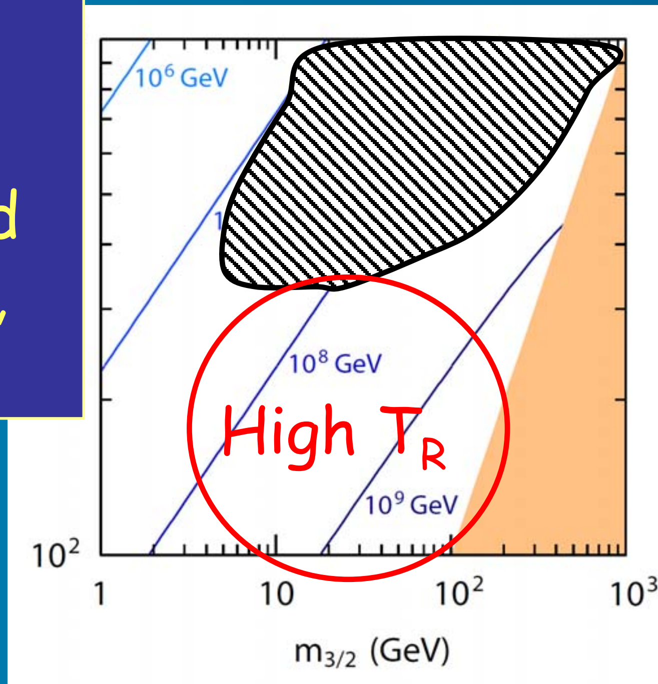
Different from neutralino / stau NLSP scenario !

Thermal Leptogensis (Fukugita and Yanagida (1986), Buchmuller, Bari, Pluacher (05)) does still work!

Higher T_R can be realized at

Larger gravitino mass

lighter gaugino mass



Solving Li7 problem in Hadronic decay

Jedamzik (04); Jedamzik etal (05)

Kohri, Moroi, Yotsuyanagi (2005)

Kohri et al (2006)

severer observations

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

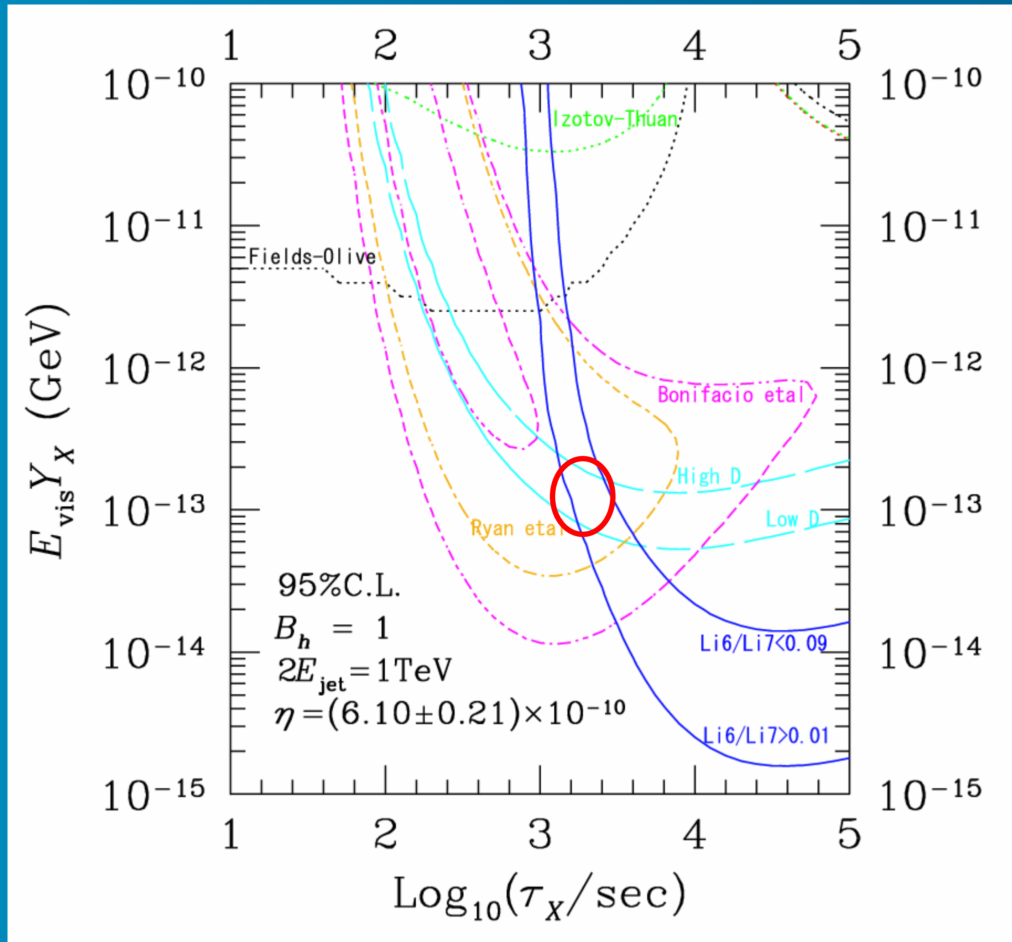
$$(n_{^7\mathrm{Li}}/n_{\mathrm{H}})^{\mathrm{obs}} = 1.23^{+0.68}_{-0.32} \times 10^{-10}$$

$\eta = (2-4) \times 10^{-10}$ 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

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

Li7 can be reduced!

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

More Li6 can be also produced!

$$\alpha + \alpha \rightarrow {}^6\mathrm{Li} + \mathrm{D}$$

CHArged Massive Particle (CHAMP) and Cosmology

Cahn and Glashow (1981)

Kohri and Takayama, hep-ph/0605243

Many candidates of long-lived CHAMP, e.g., scalar leptons (stau etc) as NLSPs, which eventually decays into DM (gravitino) and standard particles

More massive elements tend to capture CHAMP earlier because of larger binding energy of the bound states ($T_{capture} = E_{bin}/40 \sim$ 1-10 keV, $E_{bin} \sim \alpha^2 Z^2_{champ} Z^2_{nuc} m_{nuc}$)
Note that ligher nuclei have been freezeout after T= $T_{capture}$

CHAMP captured-nuclei change the nuclear reaction rates through the modifications of the Coulomb suppression factor and their kinematics.

Only Be7 and Li7 can be reduced without changing D, He3, and He4 abundances

Binding energy Ebin ~ $\alpha^2 Z^2_{champ} Z^2_{nuc} m_{nuc}$

Nucleus(X)	binding energy (MeV)	atomic number
H	0.025	Z=1
D	0.050	Z=1
T	0.075	Z=1
^{3}He	0.270	Z=2
^{4}He	0.311	Z=2
^{5}He	0.431	Z=2
^{5}Li	0.842	Z=3
^{6}Li	0.914	Z=3
^{7}Li	0.952	Z=3
^{7}Be	1.490	Z=4
^{8}Be	1.550	Z=4
^{10}B	2.210	Z=5

Time evolution of light elements

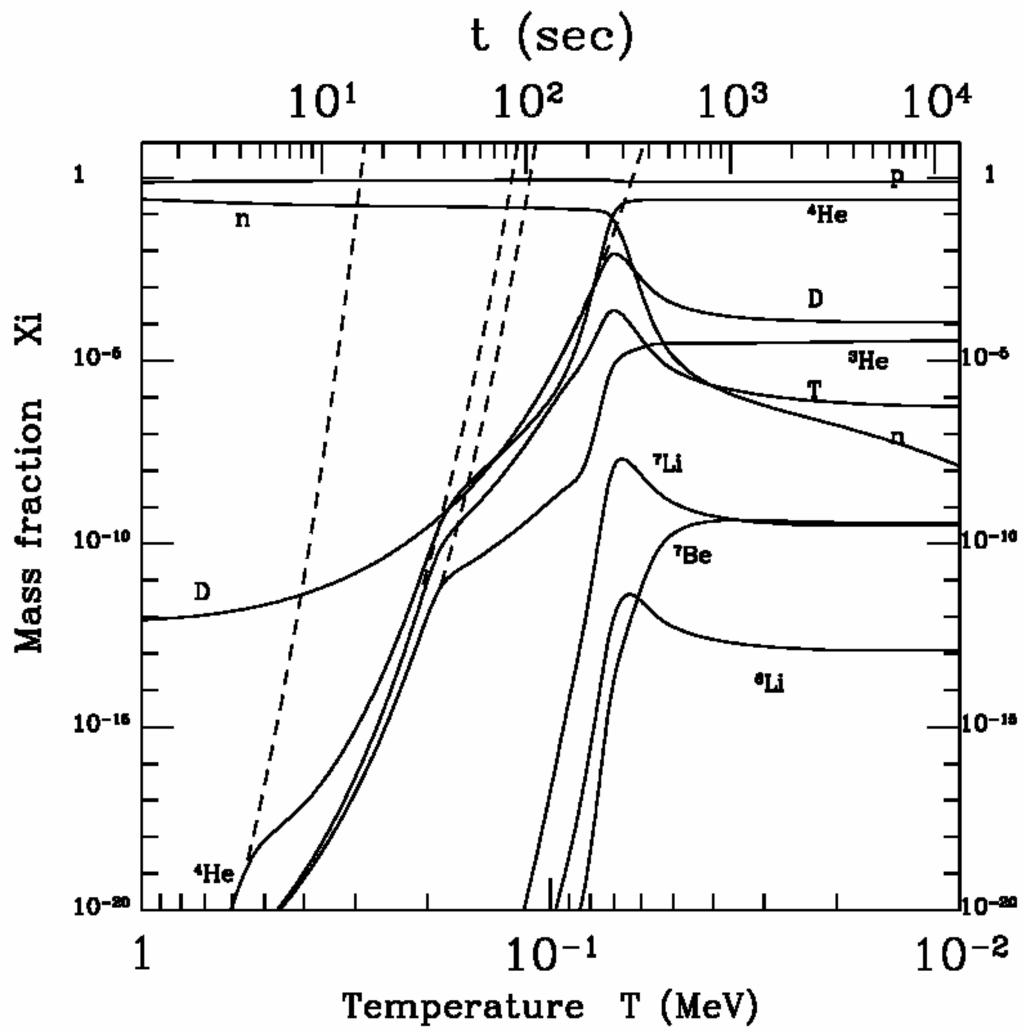


FIG. 2. Time evolution of the light element abundances at $\eta = 3.162 \times 10^{-10}$ The dashed line denotes the nuclear statistical equilibrium value of each light element.

CHAMP (ChArged Massive Particle) and BBN

Pospelov (06)

Kohri and Takayama (06)

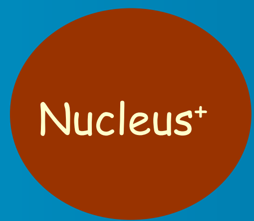
Kaplinghat and Rajaraman (06)

Cyburt, et at (06)

Charged particles may recombine with light elements to form bound states such as a hydrogen atom in the early Universe for $T < E_{bin}/40$ (~ 1-10 keV) C-

At least

- Charge suppression



- Kinetic energy modification into the order of binding energy

$E_{bin} = \alpha^2 m_{nuc} \sim O(0.1) - O(1)$ MeV (note that E~T in SBBN)

Pospelov's Effect? - possible enhancement of cross sections in quadrupole -

Interesting!, but still some unclear points
(lack of cross section data of He4(d, γ)Li6 at E < 0.1 MeV, etc…)

CHAMP BBN (CBBN) may solve Lithium problem? I

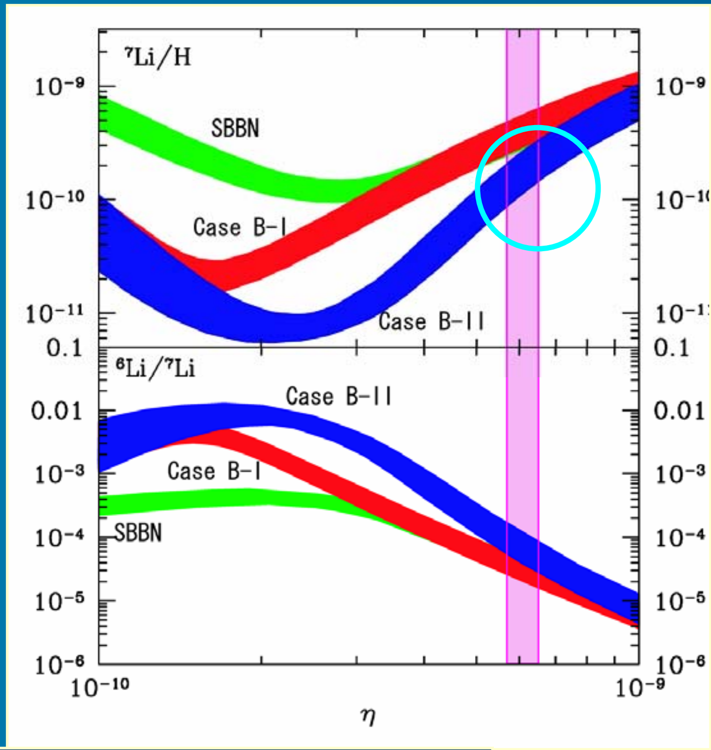
Kohri and Takayama, hep-ph/0605243

Short lifetime (< 10^6 sec)

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

However, the experimental data of the cross section for Be7 (n,a)He4 is not sufficent at E = O(E_{bin})

Here 10 times larger uncertainty in p-wave mode is assumed (see Serpico et al (04) [B-II case]



We need correct experimental data at E = E_{bin}

CHAMP BBN (CBBN) may solve Lithium problem? II

Kohri and Takayama, hep-ph/0605243

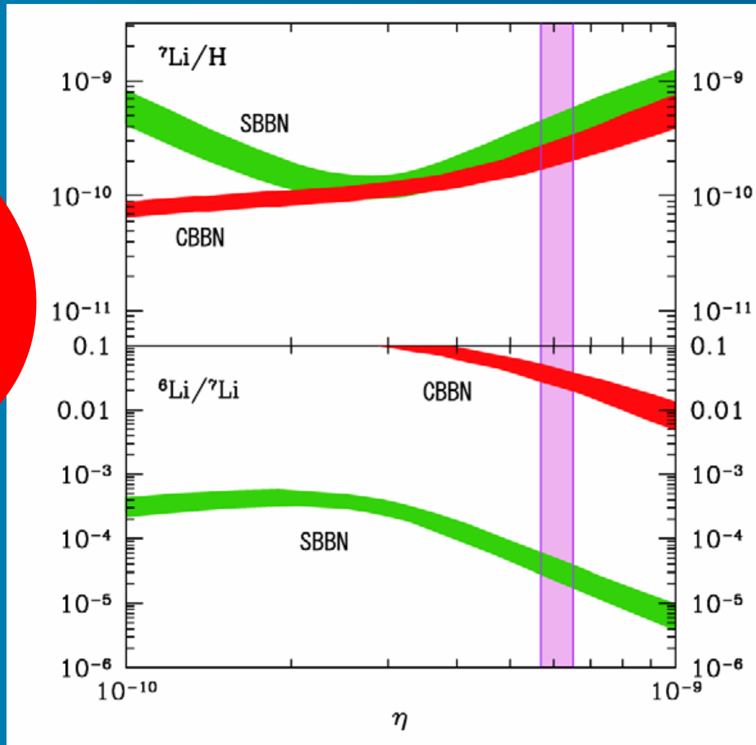
Long lifetime (> 10^6 sec)

Z_{nuc} =1 nuclei (proton, D, and T) are captured

He4(d, g)Li6 and Be7(d, p a)He4 are enhancecd

However, CHAMP may change its partner from p,D, T into more massive ones before nuclear reactions occur because

$a_{Bohr} > r_{nuc}$



Should we solve the three body problem?

Discussion and Conclusion

- The radiative and hadronic decay products destroy He4, by which D,He3, Li6 are overproduced.
- The constraint on reheating temperature after primordial inflation becomes very stringent in Hadronic decay scenario of unstable gravitino.

$$T_R \leq 3 \times 10^5 GeV - 10^7 \ GeV$$

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

- Hadronic-decay scenario may solve the Li problem
- Gravitino LSP, Sneutrino NLSP scenario agree with Thermal Leptogeneis
- CHAMP BBN is attractive (Kohri and Takayama '06, Cyburt etal '06) or might be dangerous? (Pospelov '06).