Long-lived charged massive particle and its effect on cosmology

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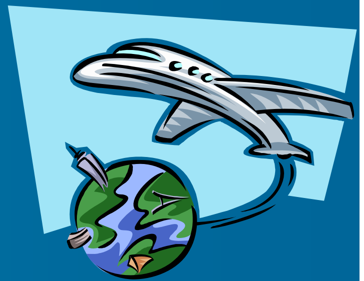


Kawasaki, Kohri, Moroi, PLB625 (2005) 7

Kawasaki, Kohri, Moroi, PRD71 (2005) 083502

Kohri, Moroi, Yotsuyanagi, PRD73 (2006) 123511

Kohri, Takayama, hep-ph/0605243

Kanzaki et al, hep-ph/0609246

Kawasaki, Kohri, Moroi, hep-ph/0703122

Abstract

- The Standard BBN (SBBN) approximately agrees with observations.
- In SUSY/SUGRA cosmology, reheating temperature after Inflation should be low, in order to solve the "gravitino problem."
- We may solve the Lithium problems in SUSY cosmology scenarios
- Dark matter may be neutralinos or gravitinos which are nonthermally produced by decaying particles.

Big-Bang Nucleosynthesis (BBN)

- In the early universe at T > 0.1 MeV

  Neutron to proton ratio was fixed

  $$n \leftrightarrow p + e^- + \bar{\nu}_e \Rightarrow (n/p)_{\text{freezeout}} \sim 1/7$$

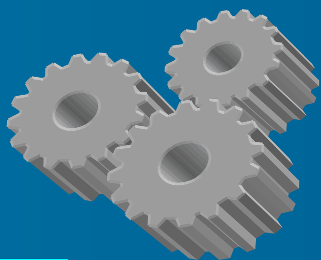
  Only through weak interaction

- Then, T < 0.1 MeV

  $2n + 2p \rightarrow {}^4\text{He}$ + little D, T, ^{3}He, ^{7}Li (^{7}Be), and ^{6}Li

Light element abundances

Baryon to photon ratio $\eta = n_B / n_\gamma$



Time evolution of light elements

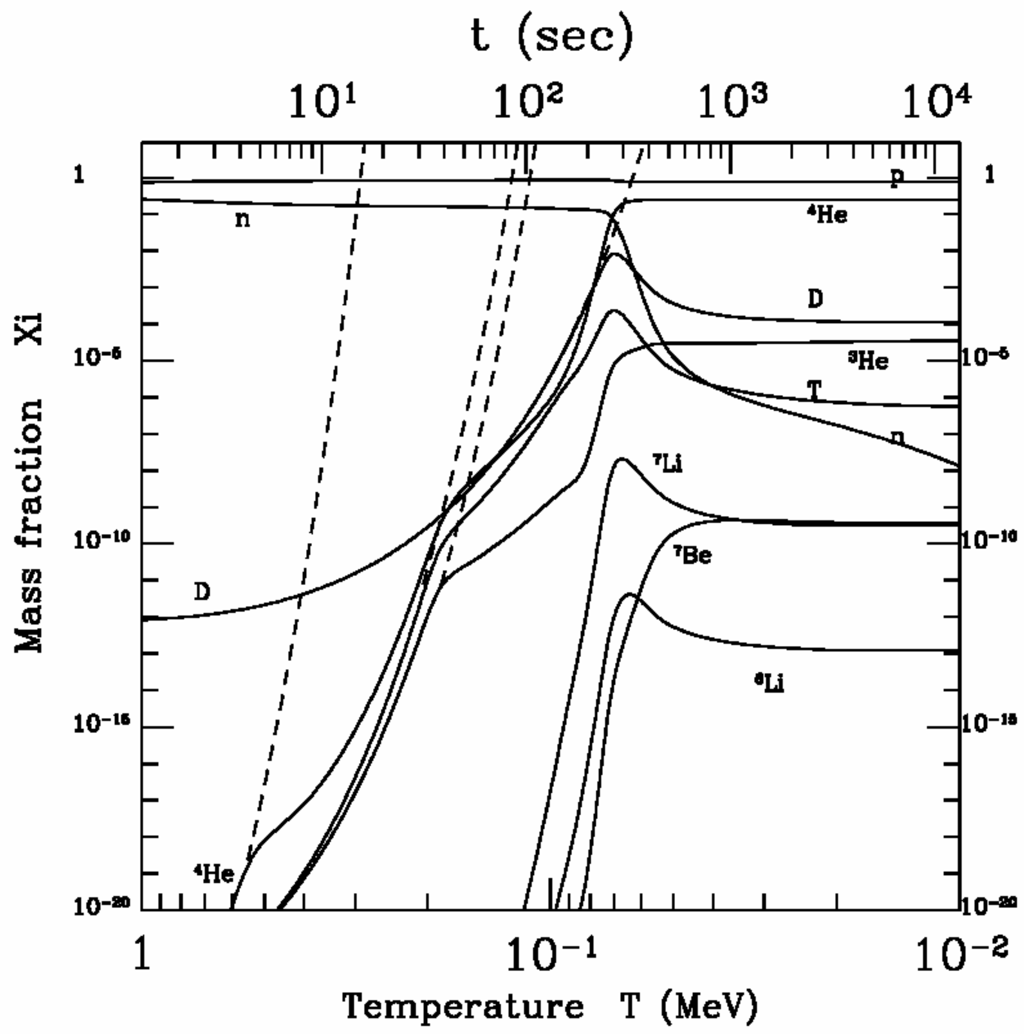


FIG. 2. Time evolution of the light element abundances at $\eta = 3.162 \times 10^{-10}$ The dashed line denotes the nuclear statistical equilibrium value of each light element.

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)

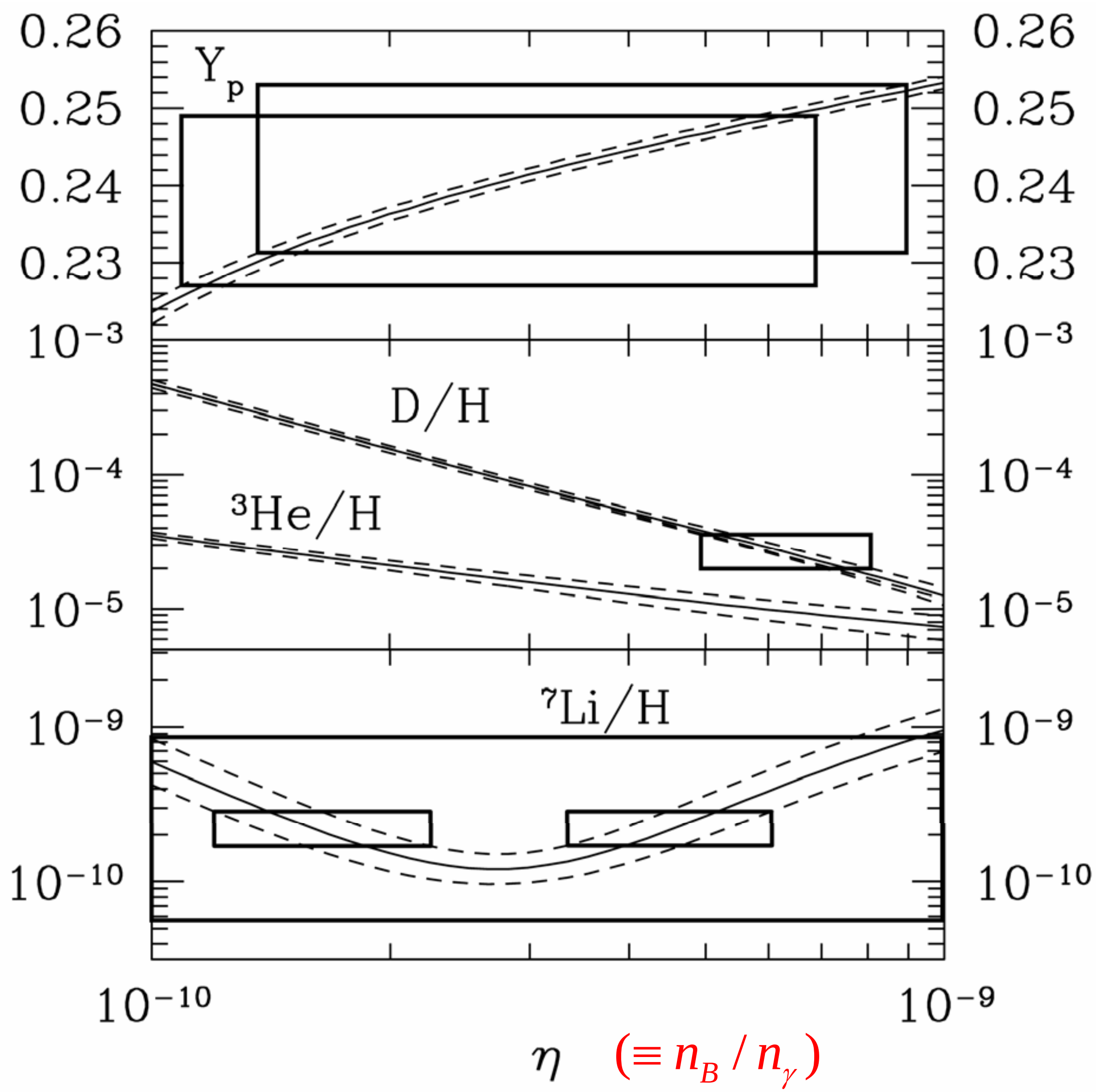
- Li6/H $^{6}Li/{}^{7}Li < 0.046 \pm 0.022 \pm 0.084$

Asplund et al(2006)

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

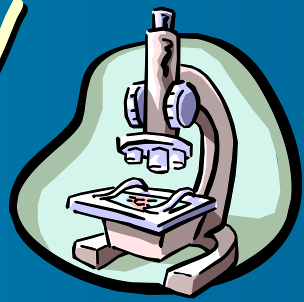
Geiss and Gloeckler (2003)

SBBN



0.26
0.25
0.24
0.23
Y_p
10^{-3}
10^{-4}
10^{-5}
D/H
^{3}He/H
10^{-9}
10^{-10}
^{7}Li/H
10^{-10}
10^{-9}
$\eta \quad (\equiv n_B / n_\gamma)$

Introduction of SUSY



- Supersymmetry (SUSY)
  - Solving "Hierarchy Problem"
  - Realizing "Coupling constant unification in GUT"

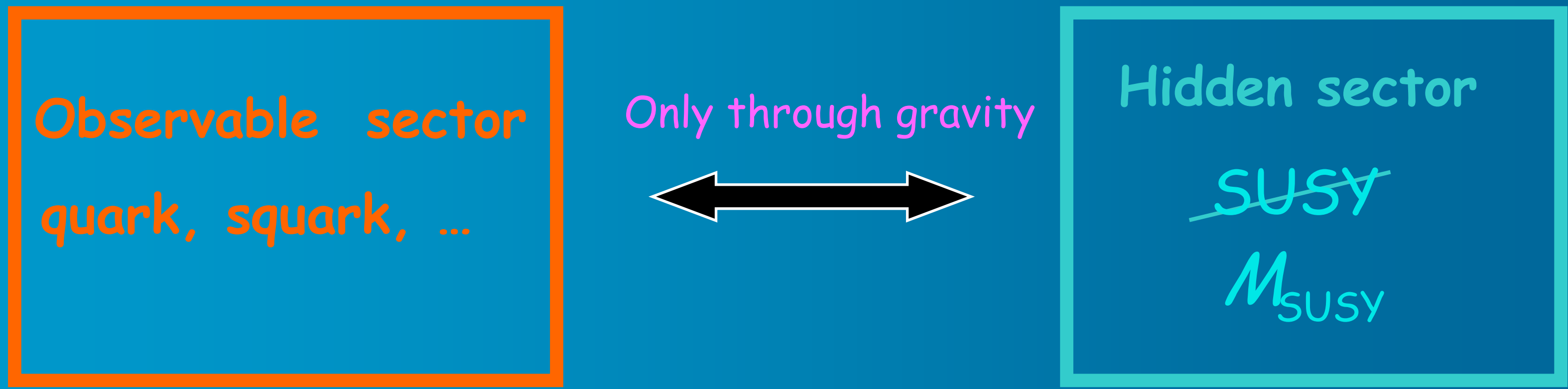
Fermion		Boson
quark	⟷	squark
lepton	⟷	slepton
photino	⟷	photon
gravitino	⟷	graviton

Gravitino ψ_μ is the superpartner of graviton

Spin 3/2

SUSY Breaking

- **Gravity mediated SUSY breaking model**



- Masses of squarks and sleptons

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

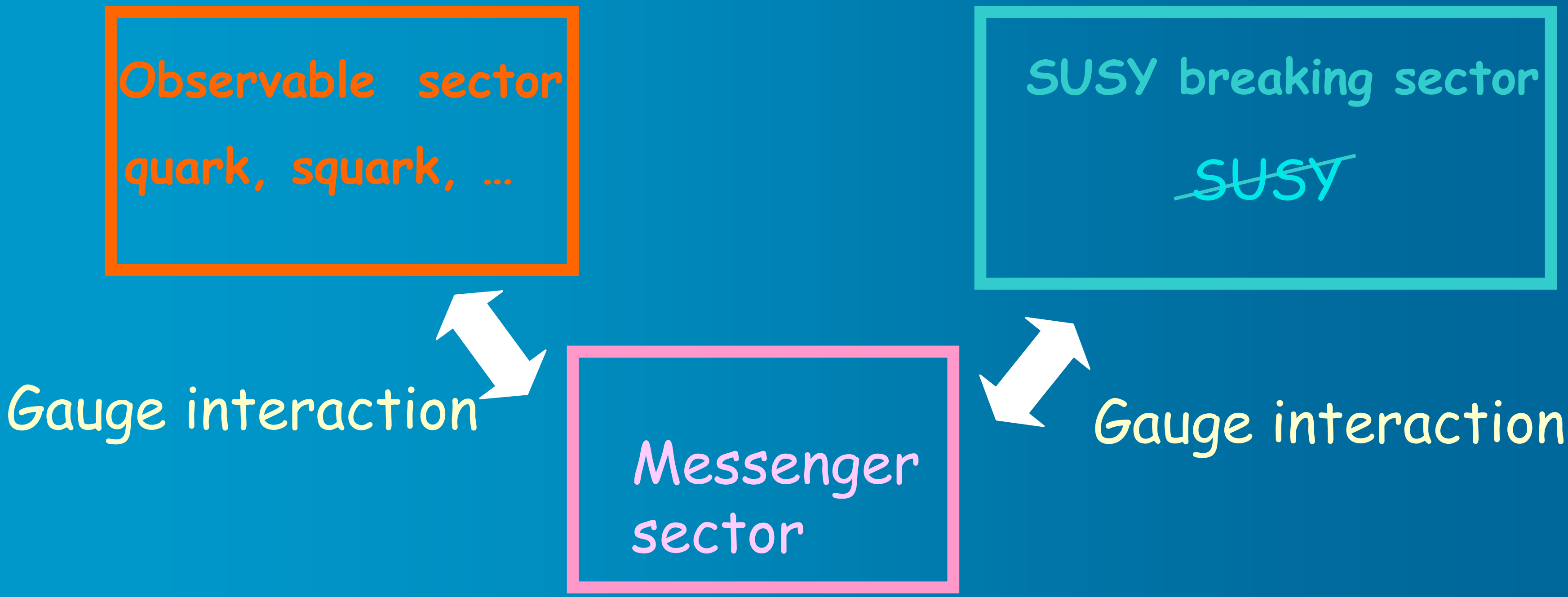
$$(M_{SUSY} = 10^{10} - 10^{11} \ GeV)$$

- 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)



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

Gravitino problem (old version -1)

Cosmological gravitino problem

If gravitinos were abundant as photons,

$$\frac{n_{3/2}}{n_\gamma} \sim \mathcal{O}(1)$$

1) When gravitino decays after BBN epoch $(\psi_\mu \to \gamma + \tilde{\gamma})$

$$\tau_{3/2} \simeq 4 \times 10^8 \,\mathrm{sec} \left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)^{-3}$$

Long lifetime only through gravity

Then, $$\frac{n_B}{n_\gamma} \ll 10^{-10}$$

⇓ to avoid the problem

$$m_{3/2} \gtrsim 100\mathrm{TeV}$$

(Weinberg 82)

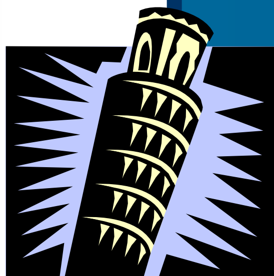
Gravitino problem (old version -2)

2) If gravitino is stable, $\Omega_{3/2} \lesssim 1$

$\Downarrow$

$$m_{3/2} \lesssim 1\text{keV}$$

(Pagel, Primack 82)



Gravitino with $m_{3/2} \sim 100\text{GeV}$ is exclude ?

No. Inflation dilutes gravitinos!

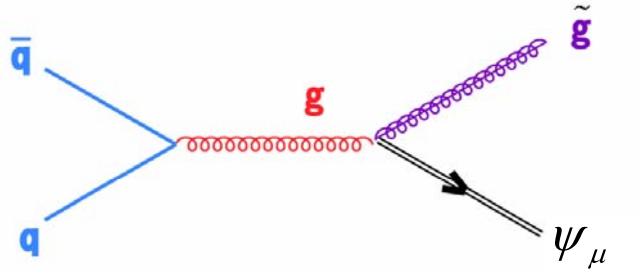
Gravitino production after inflation

I) Inflation dilutes primordial gravitinos

$$n_{3/2}/s \to 0$$

II) Reheating process produces gravitinos again

e. g. , $$q + \overline{q} \to \psi_{3/2} + \tilde{g}$$



$$Y_{3/2} \equiv \frac{n_{3/2}}{n_\gamma} \simeq 10^{-11} \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right)^1$$

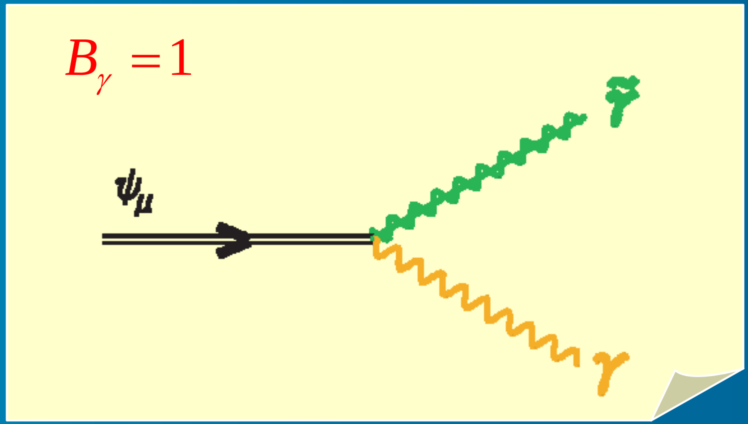
Because,
$$\frac{\Delta n_{3/2}}{n_\gamma} \sim \Gamma \Delta t \sim \frac{1}{M_G^2} T_R^3 \times \frac{M_G}{T_R^2} \propto T_R$$

Gravitino Decay and BBN

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

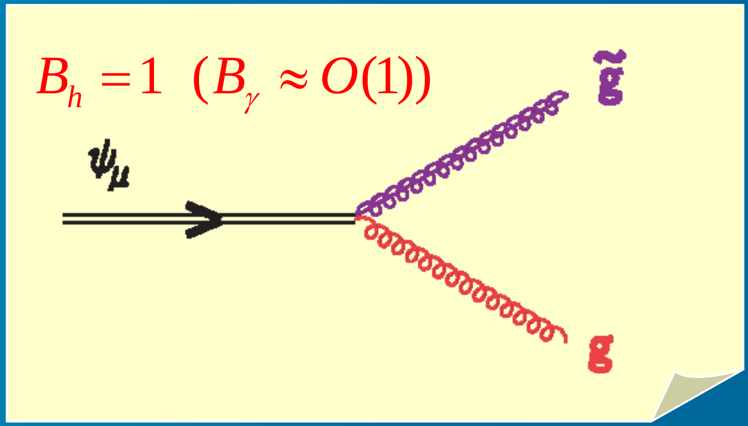
- Radiative decay

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



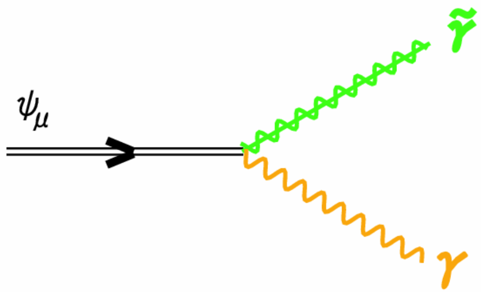
- Hadronic decay

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



Radiative Decay

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

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

Non-thermal Li6 Production

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

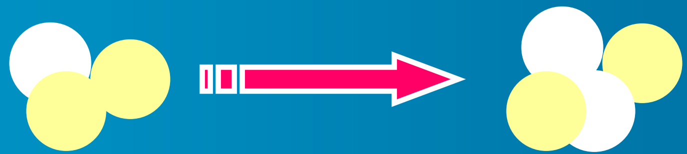
i. He3 (T) production

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

ii. Li6 production

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

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

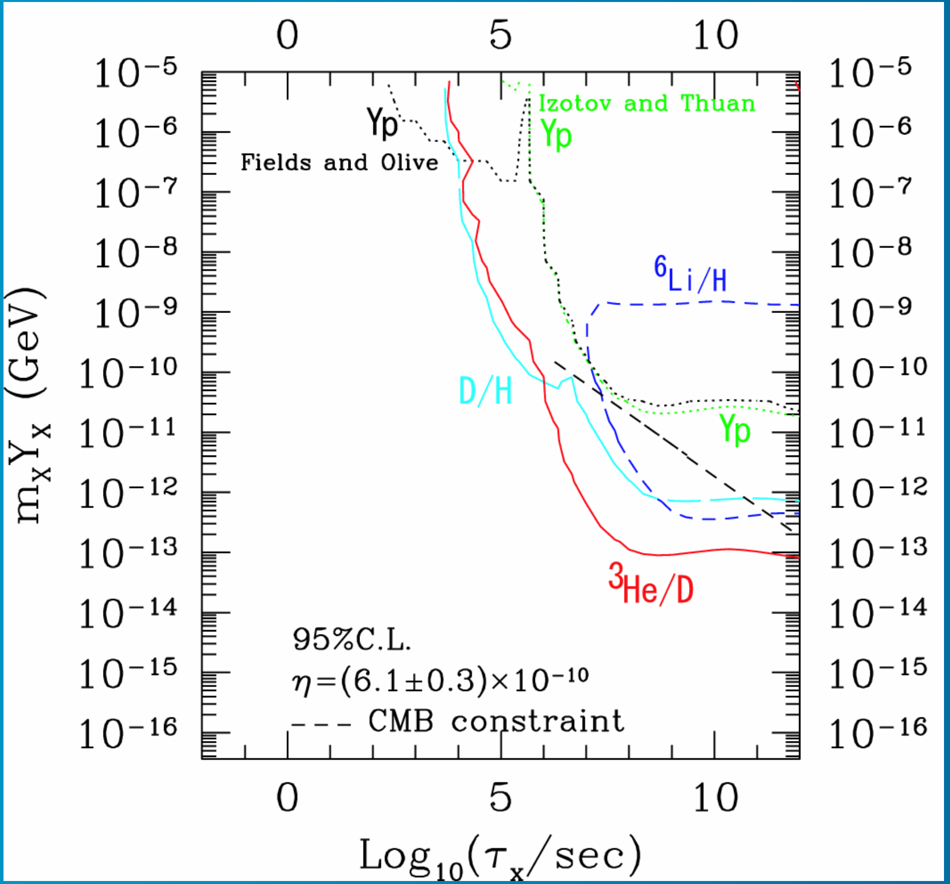
T, ^{3}He  ^{4}He

Coulomb energy loss by background electrons

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

Photodissociation

$$Y_{3/2} \equiv \frac{n_{3/2}}{n_\gamma}$$



Kawasaki, Kohri, Moroi (2001)

Relation among variables

- Yield variable and reheating temperature

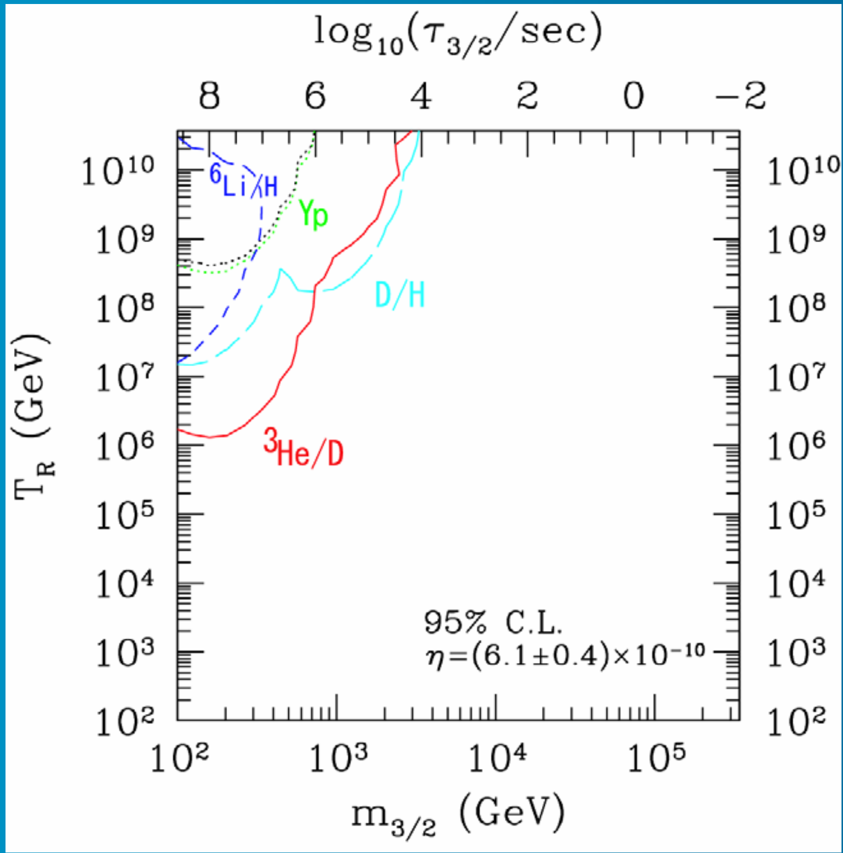
$$Y_{3/2} \equiv \frac{n_{3/2}}{n_\gamma} = 1.1 \times 10^{-11} \left(\frac{T_R}{10^{10}\, GeV} \right)$$

- 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 (2001)



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

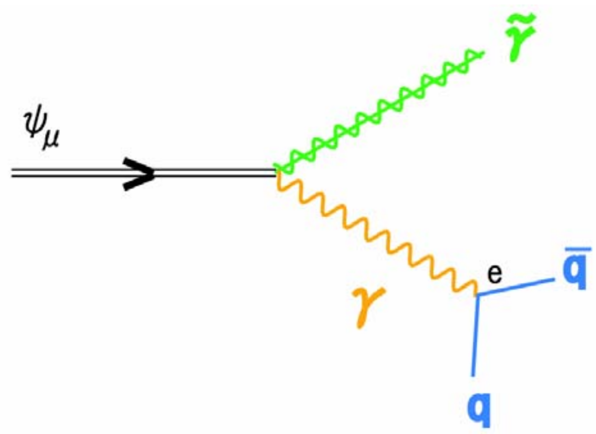
$$m_{3/2} = 10^3\,\mathrm{GeV}\ (\tau_{3/2}/4\times10^5\,\mathrm{sec})^{-1/3}$$

Hadronic Decay

Hadronic decay

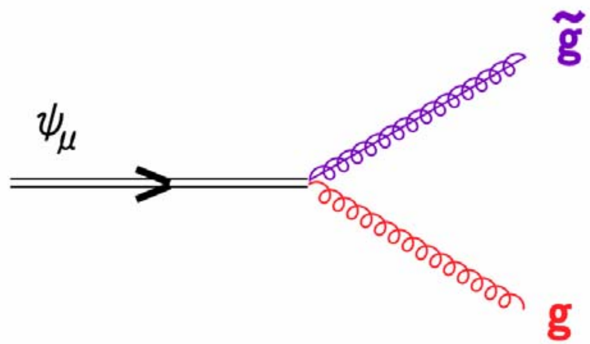
Reno, Seckel (1988)

S. Dimopoulos et al.(1989)



Two hadron jets with $E_{jet} = m_X / 3$

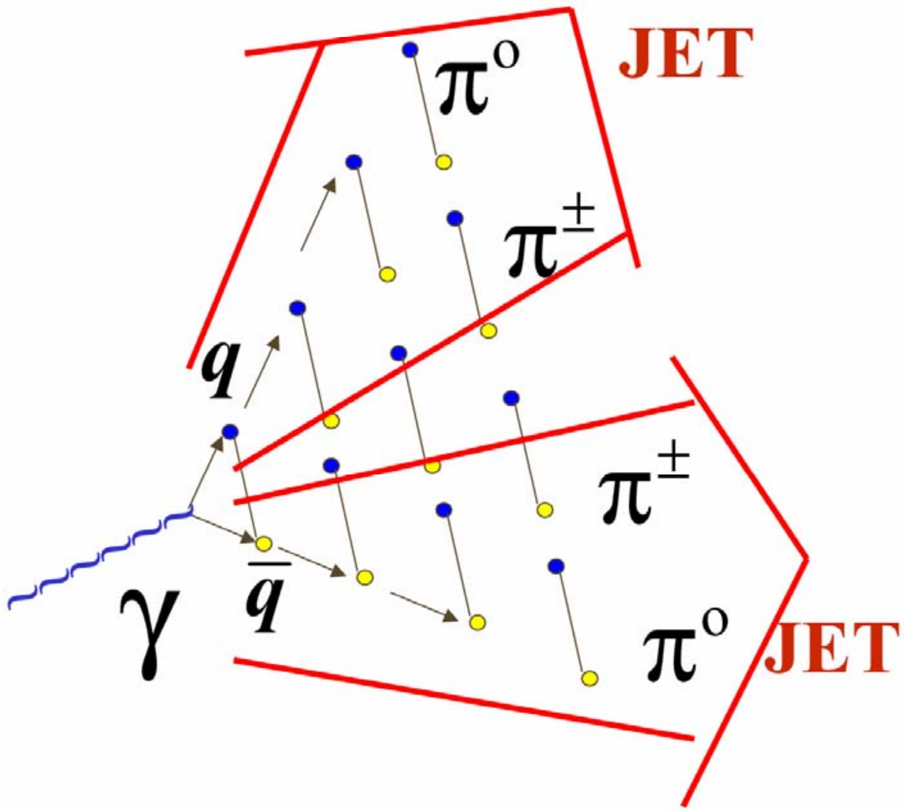
$$B_h \approx \alpha / 4\pi \approx 10^{-3}$$



One hadron jet with $E_{jet} = m_X / 2$

$$B_h = 1$$

Quark Emission and Hadron Jets



$q = u, d, s, ...$

Hadron-fragmentation Monte Carlo event generator,
JETSET 7.4 (PYTHIA 5.7)

Sjostrand (1994)

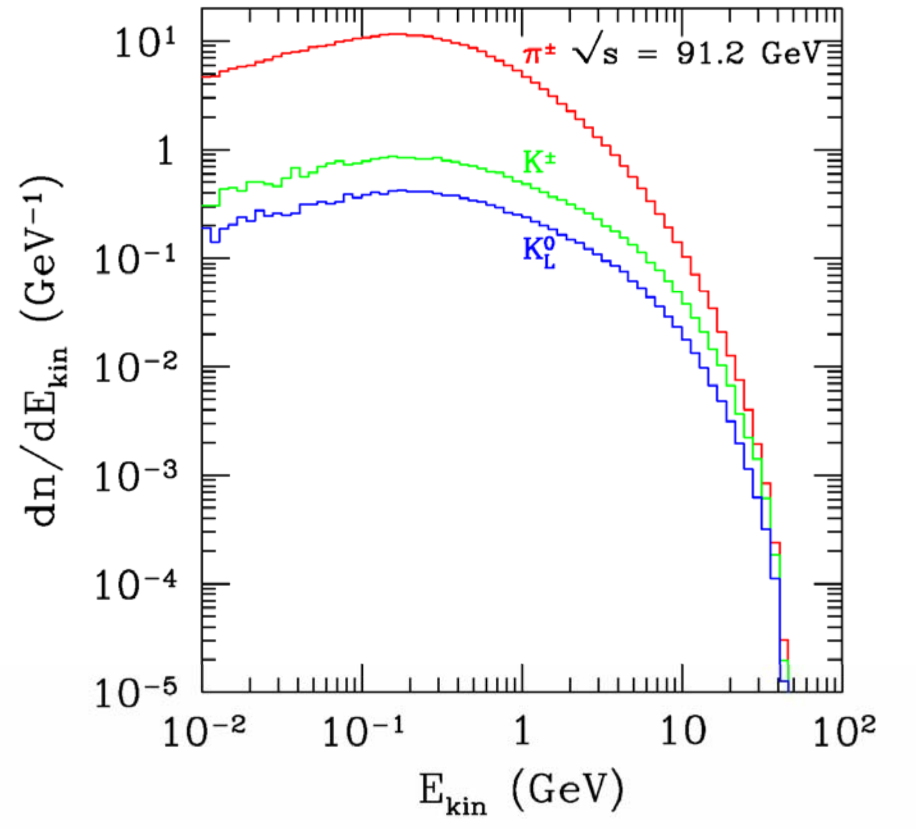
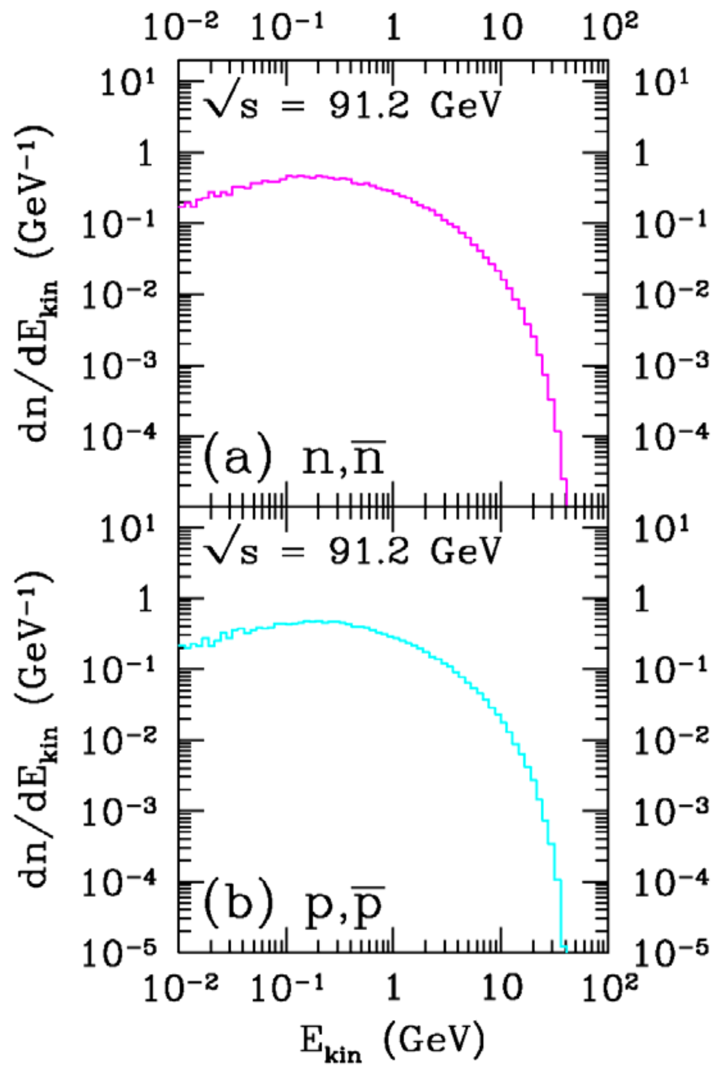


FIG. 3. Plot of the spectrum of the produced mesons ($\pi^+ + \pi^-$, $K^+ + K^-$, and K^0_L) as a function of the kinetic energy $E_{\rm kin}$. This is the case that the center of mass energy is $\sqrt{s} = 91.2$ GeV which corresponds to the Z^0 resonance. They are computed by using the JETSET 7.4 Monte Carlo event generator.



Kohri (2001)

Electromagnetic stopping of emitted hadrons?

There is a question if high energy hadrons are stopped,
until they scatter off the ambient nuclei in the electromagnetic plasma of $e^{\pm}$ and γ.

$$R_{\rm stop}(E_i, T, Yp) \equiv n_N \int_{E_i}^{E_{\rm th}} \langle \sigma\beta \rangle \left(\frac{dE}{dt} \right)^{-1} dE$$

where,

$$\left(\frac{dE}{dt}\right) = \left(\frac{dE}{dt}\right)_{\rm Coulomb} + \left(\frac{dE}{dt}\right)_{\rm Compton} + \ldots$$

(I) If $R_{\rm stop}(E_i, T, Yp) << 1,$

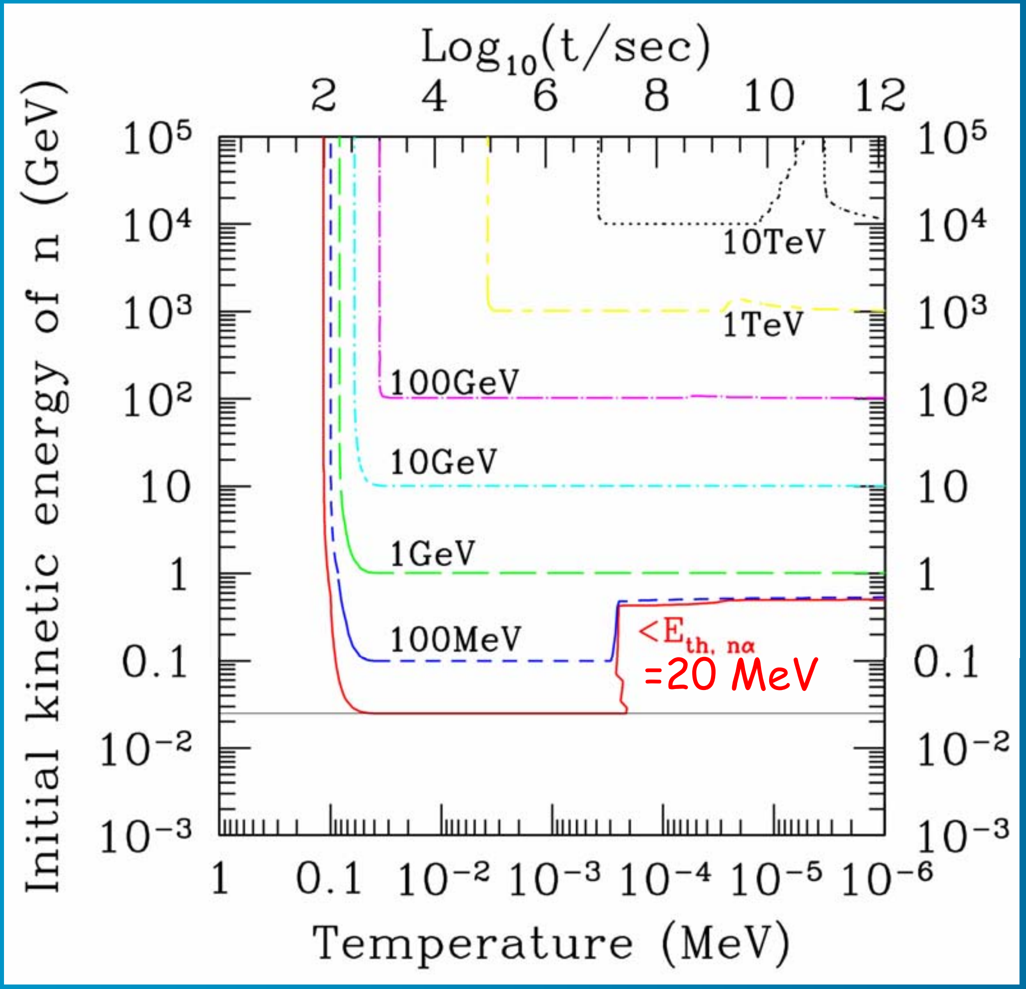
Hadrons are stopped electromagnetically

(II) If $R_{\rm stop}(E_i, T, Yp) >> 1,$

Hadrons scatter off the background nuclei with the energy E_f which is obtained by

$$n_N \int_{E_i}^{E_f} \langle \sigma\beta \rangle \left(\frac{dE}{dt} \right)^{-1} dE = 1$$

Contours of final energy of energetic neutron just before its collision



(I) If $R_{stop}(E_i, T, Yp) \ll 1$,

Inter-conversion occurs between n and p by stopped hadrons

Effective at early stage of BBN

Reno and Seckel (1988)

Kohri (2001)

(II) If $R_{stop}(E_i, T, Yp) \gg 1$,

Destruction of Helium4 occurs by energetic hadrons

S. Dimopoulos et al(1989)

Effective at late stage of BBN

Kawasaki, Kohri, Moroi(2004)

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

Reno and Seckel (1988) Kohri (2001)

Extraordinary inter-conversion reactions between n and p

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

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

Hadron induced exchange

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

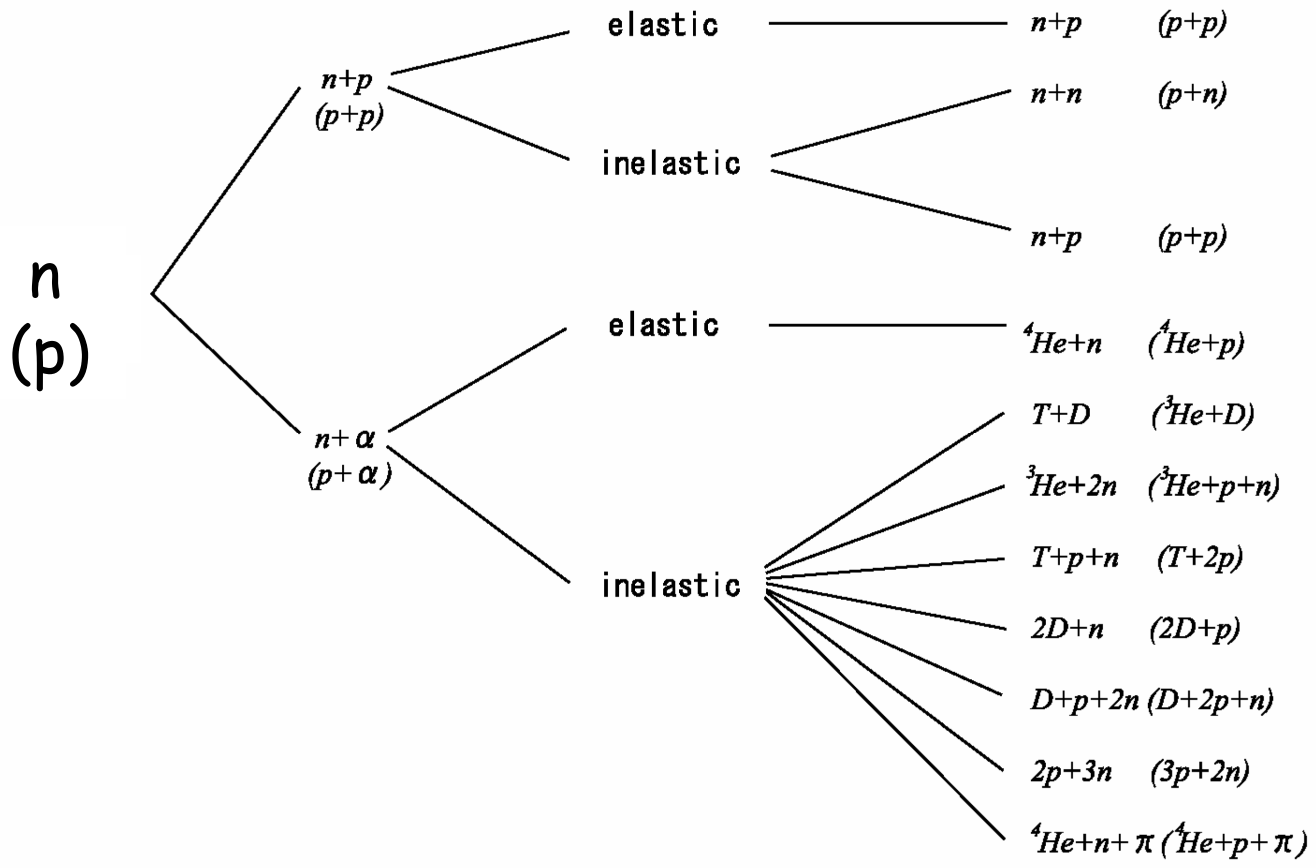
Even after freeze-out of n/p in SBBN

More He4, D, Li7 ...

(II) Late stage of BBN

Hadronic showers and "Hadro-dissociation"

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

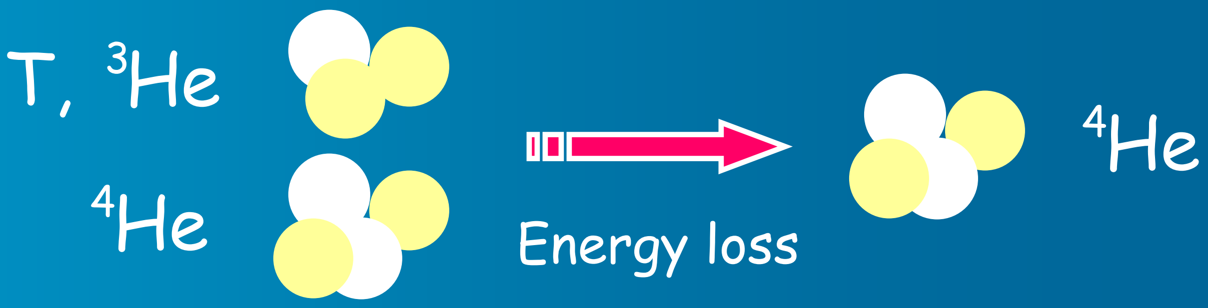


Non-thermal Li, Be Production by energetic hadrons

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

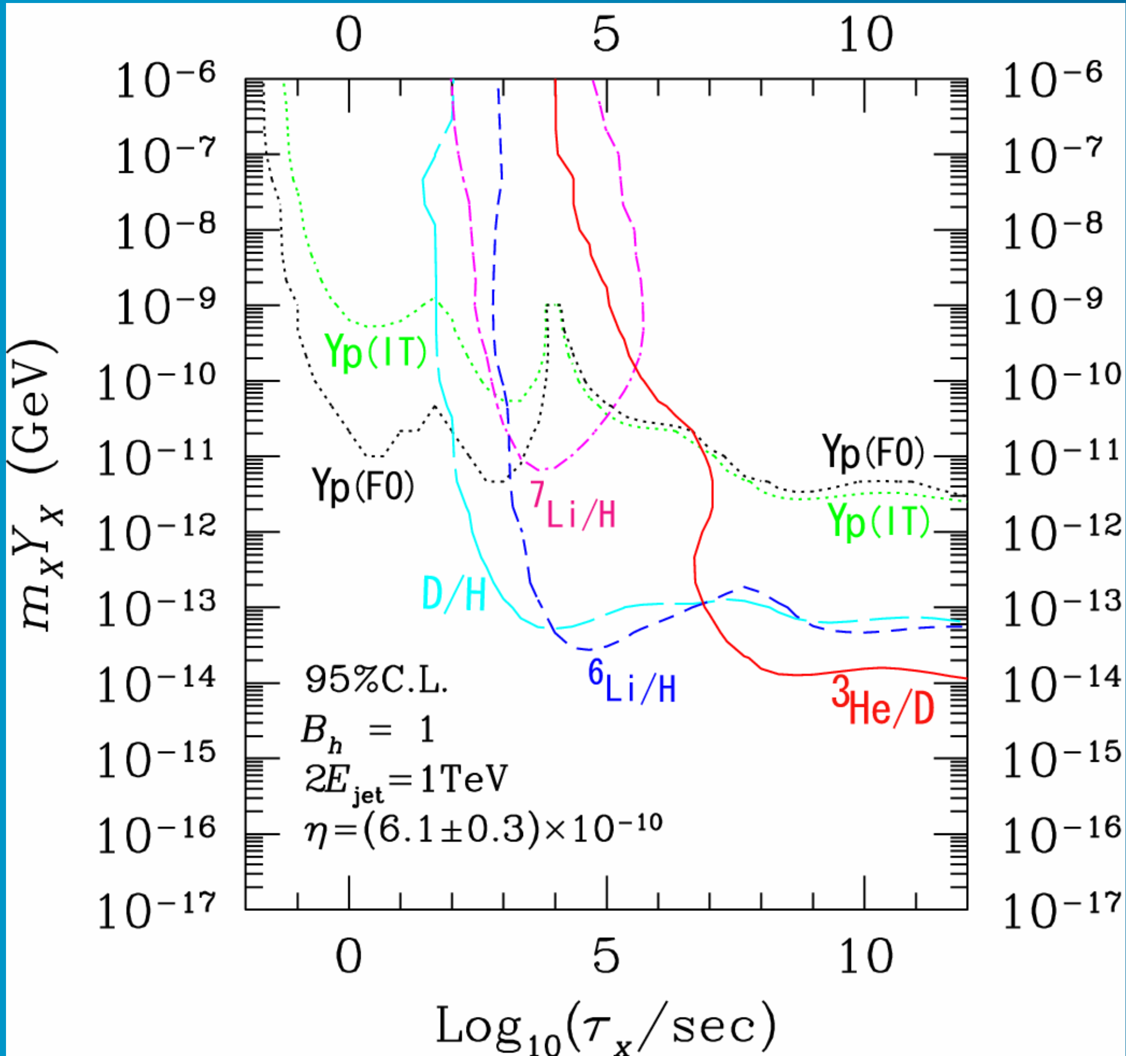
$$T + {}^4He \rightarrow {}^6Li + n \quad [8.4\ MeV]$$

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

② He4 – He4 collision

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

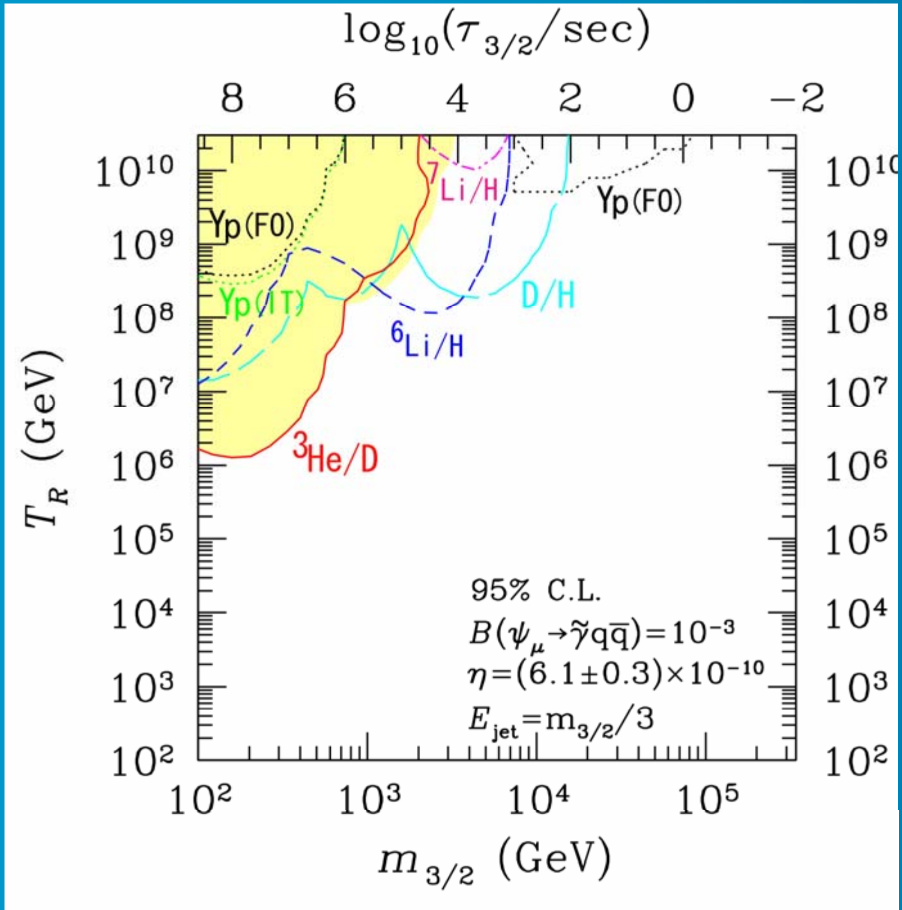
For massive particle X



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

Upper bound on reheating temperature

Kawasaki, Kohri, Moroi (2004)



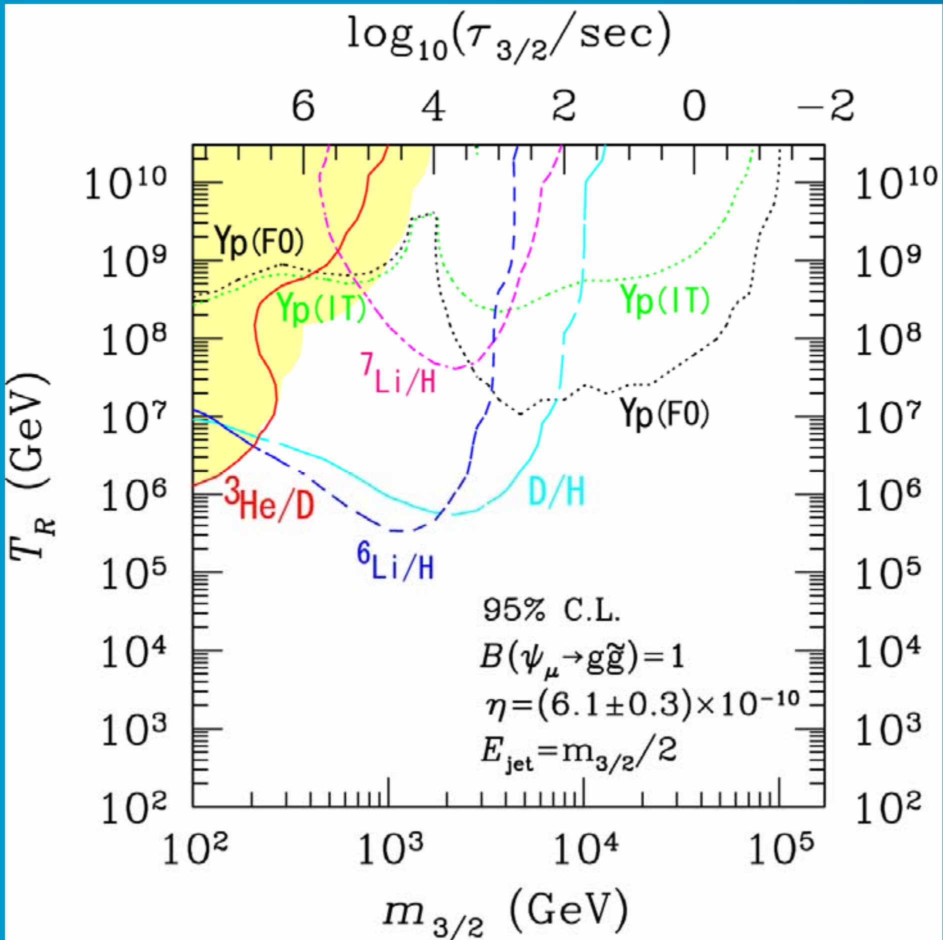
$$B_h(\psi_\mu \to \tilde{\gamma} + q + \bar{q}) = 10^{-3}$$

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

$$m_{3/2} = 10^3\,\mathrm{GeV}\,(\tau_{3/2}/4\times10^5\,\mathrm{sec})^{-1/3}$$

Upper bound on reheating temperature

Kawasaki, Kohri, Moroi (2004)

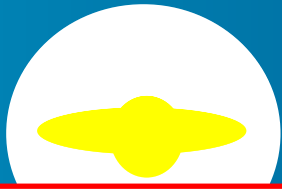


$$B_h(\psi_\mu \to g + \tilde{g}) = 1$$

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

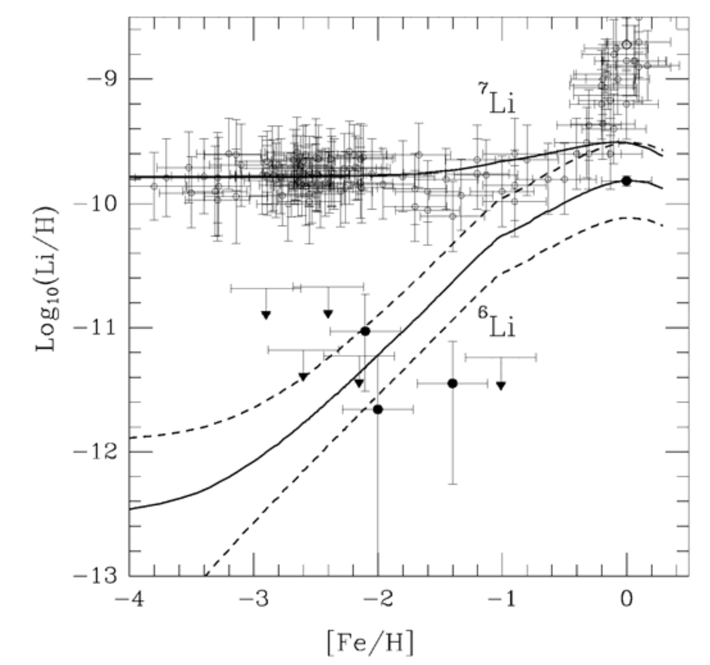
$$m_{3/2} = 500GeV\ (\tau_{3/2}/4\times 10^5 sec)^{-1/3}$$

Lithium 7



a factor of two or three smaller !!!

- Expected that there is little depletion in stars.



Lemoine et al., 1997

$$^{7}\mathrm{Li/H} = 2.19^{+2.2}_{-1.1} \times 10^{-10} \quad (1\sigma)$$

Bonifacio et al.(2002)

Melendez,Ramirez(2004)

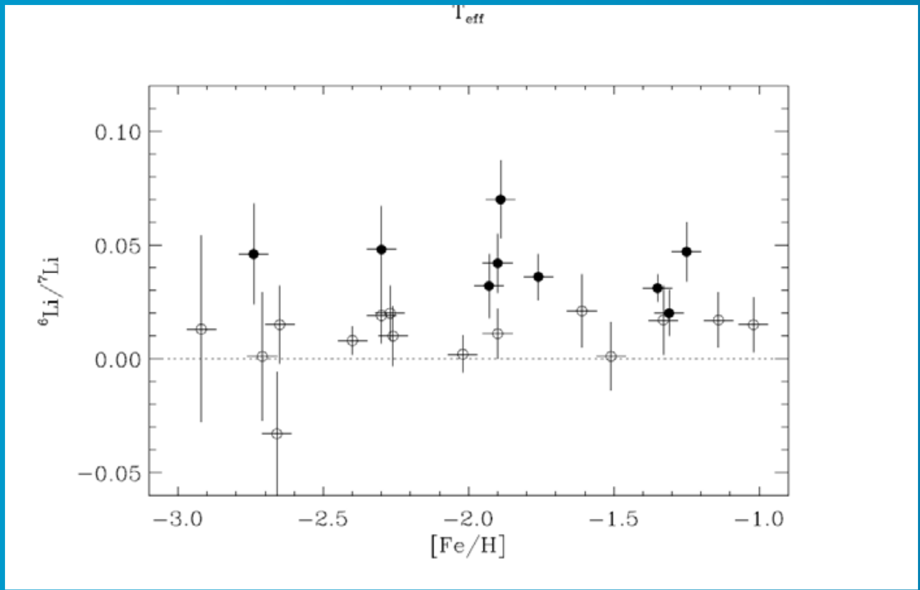
$$^{7}\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (1\sigma)$$

Ryan et al.(2000)

Lithium 6

Asplund et al.(2006)

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



$$^6\mathrm{Li}/^7\mathrm{Li} = 0.01 - 0.09$$

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

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?

Gravitino Dark Matter Scenario in Gauge Mediated SUSY Breaking

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

NLSP would be Slepton (stau, sneutrino)

or Neutralino (Bino)

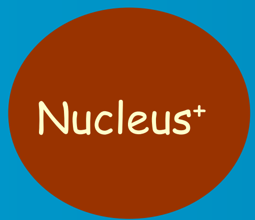
CHArged Massive Particle (CHAMP)

Kohri and Takayama, hep-ph/0605243

Many candidates of long-lived CHAMP

stau, ...

More massive elements capture CHAMP earlier



$T_c \sim E_{bin}/40 \sim 10\text{keV}$

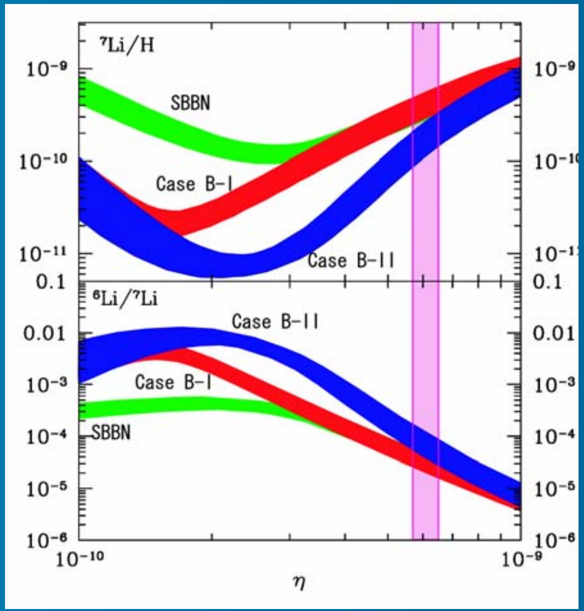
$(E_{bin} \sim \alpha^2 m_i \sim 100\text{keV})$

CHAMP captured-nuclei change the nuclear reaction rates

CHAMP BBN (CBBN) may solve Lithium problem?

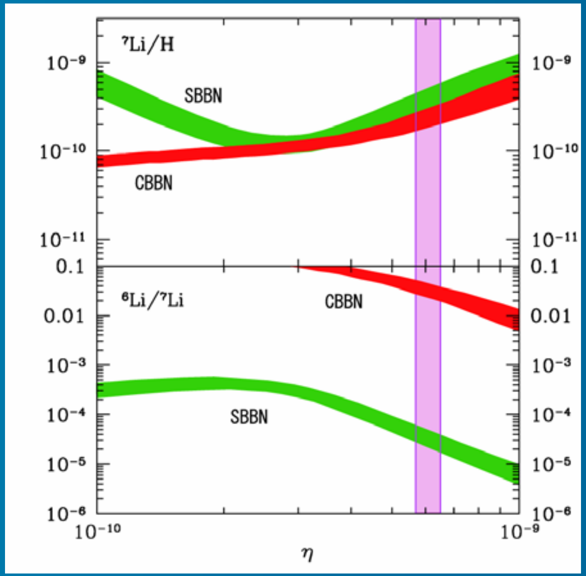
Short lifetime (< 10^6 sec)

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



Long lifetime (> 10^6 sec)

- proton, D, and T are captured
- He4(d, g)Li6 and Be7(d, p a)He4 are enhancecd



Pospelov's effect

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

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

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

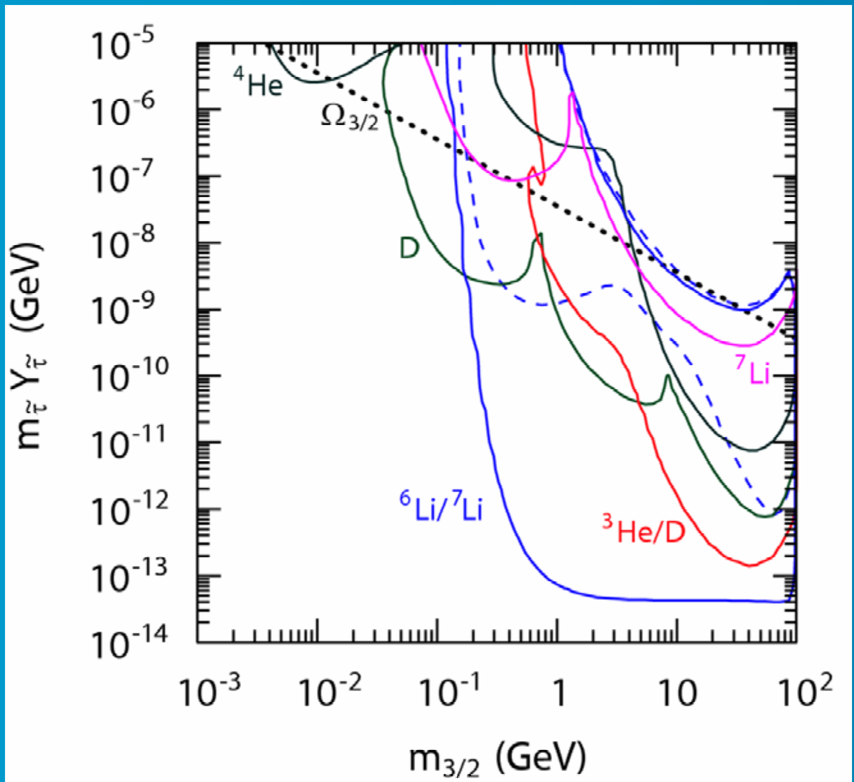
- Enhancement of cross section

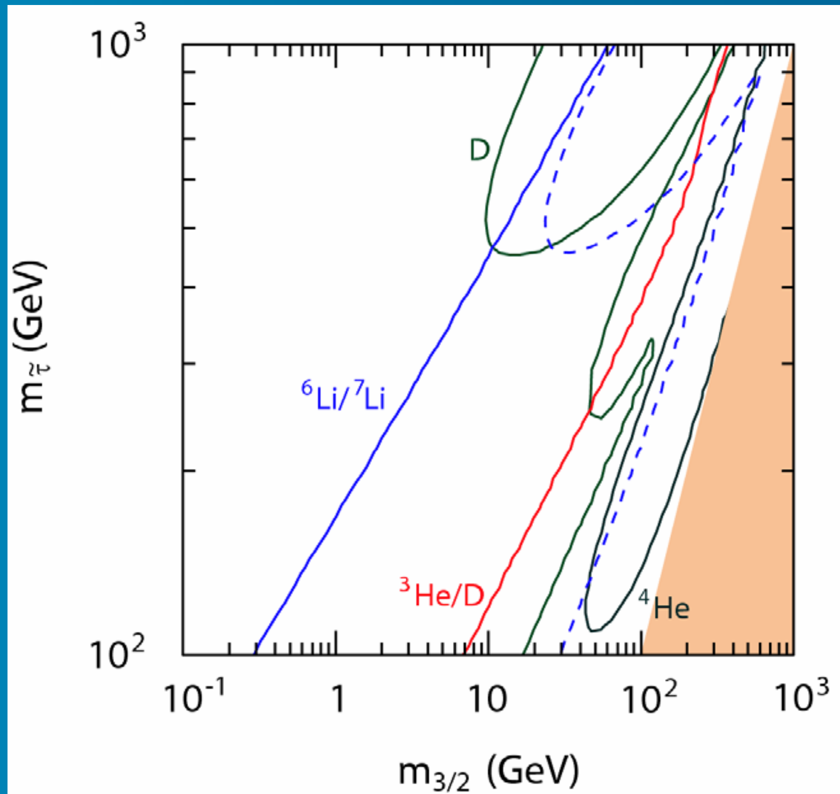
$$\sim (\lambda_\gamma / a_{Bohr})^5 \sim (30)^5 \sim 10^8$$

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

BBN in stau NLSP and gravitino LSP Scenario

Kawasaki, Kohri, Moroi (07)





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 in gravity mediated SUSY breaking scenario.

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

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

- CHAMP BBN is attractive (Kohri and Takayama '06) or might be dangerous? (Pospelov hep-ph/0605215). Then DM should be a stable gravitino in gauge-mediated SUSY breaking scenario.