Gravitino Problem

Introduction

Supersymmetry (SUSY)

Fermion ⟷ Boson

- Hierarchy Problem
  Keep electroweak scale against radiative correction

- Coupling Constant Unification in GUT

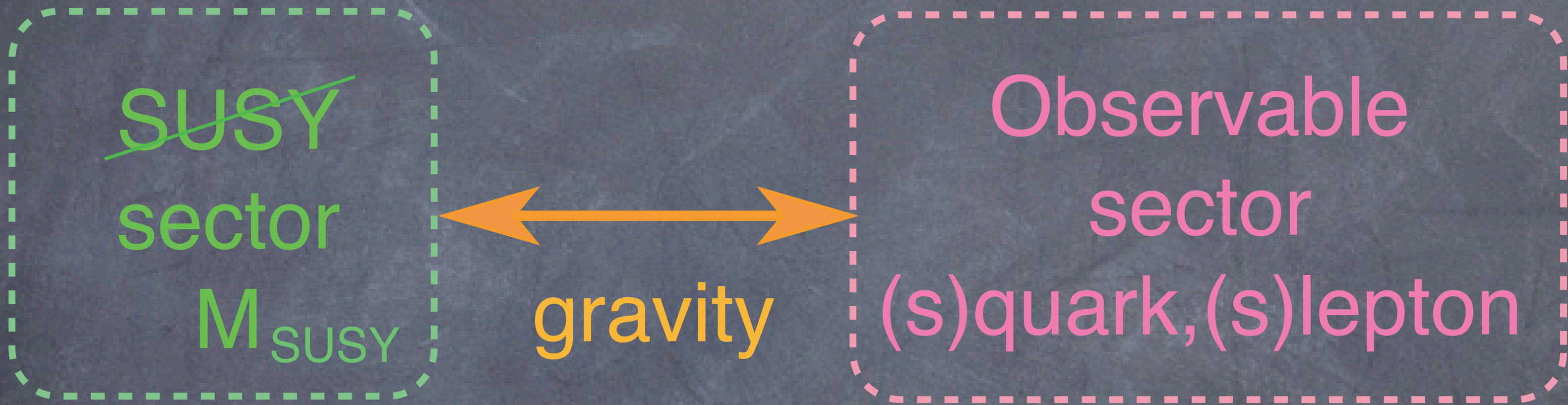
quark ⟷ squarks
lepton ⟷ slepton
photon ⟷ photino

Gravitino $\psi_{3/2}$ Superpartner of graviton

SUSY Breaking Scheme

Low Energy ~~SUSY~~ $(m_{\tilde{q}}, m_{\tilde{\ell}} \sim 1\mathrm{TeV} \gg m_q, m_\ell)$

(A) Gravity Mediated SUSY Breaking



- Squark, slepton masses

$$m_{\tilde{q}}, m_{\tilde{\ell}} \sim \frac{M_{\mathrm{SUSY}}^2}{M_p} \sim 10^{2-3}\ \mathrm{GeV}$$

- Gravitino

$$M_{\mathrm{SUSY}} \sim 10^{11-13}\ \mathrm{GeV}$$

$$\boxed{m_{3/2} \sim 10^{2-3}\ \mathrm{GeV}}$$

Gravitino Problem

Gravitino ⇨ only gravitationally suppressed int.

⇨ long lifetime

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

Standard Big Bang Cosmology $n_{3/2} \sim n_\gamma$

if gravitino decays after BBN $(m_{3/2} < 100\mathrm{TeV})$

⇨ Too Large Entropy Production

Gravitino Problem (Weinberg 1982)

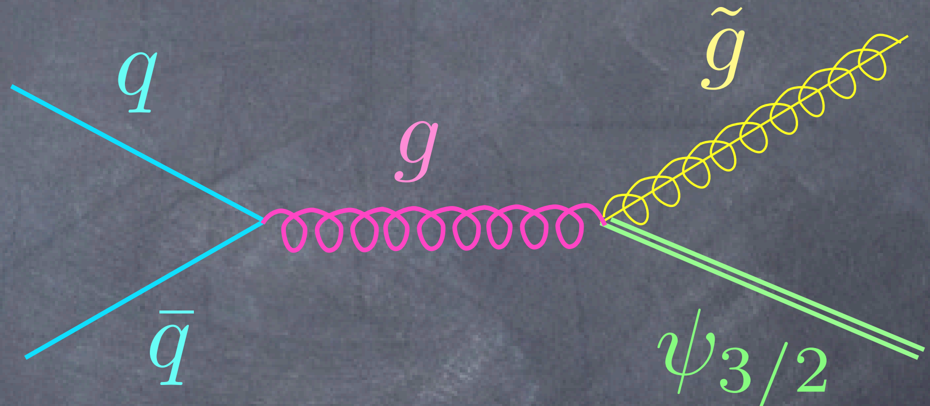
Gravitino in Inflationary Universe

Primordial gravitinos are diluted

However, gravitinos are produced during reheating

e.g.

$$q + \bar{q} \rightarrow \psi_{3/2} + \tilde{g}$$



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

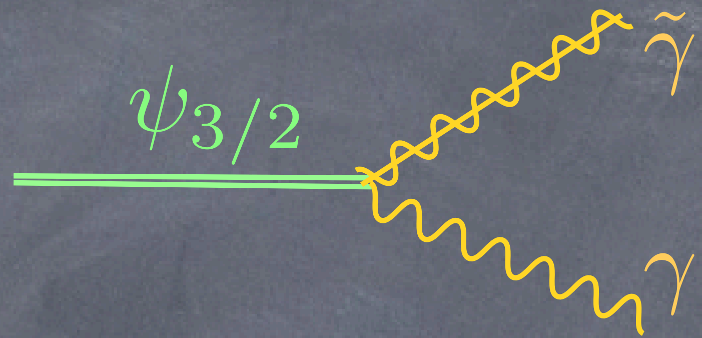
Bolz, Brandenburg, Buchmüller (2001); MK, Moroi (1995)

$$n_{3/2}/n_\gamma \sim \sigma n_q t \sim (1/M_p^2) T_R^3 (M_p/T_R^2)$$

Gravitino Decay and BBN

Gravitino in Gravity Med.
SUSY Breaking

$$m_{3/2} \sim 10^{2-3}\ \mathrm{GeV}$$



⇨ Unstable

- Radiative Decay $\psi_{3/2} \rightarrow \tilde{\gamma} + \gamma$

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

- Hadronic Decay $\psi_{3/2} \rightarrow \tilde{g} + g$

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

Decay Products
(photons, hadrons)

↓

Disastrous Effect on
Big Bang Nucleosynthesis

↓

Stringent
Constraint on T_R

Ellis, Nanopoulos,Sarkar (1985)
Reno, Seckel (1988)
Dimopoulos et al (1989)
MK, Moroi (1995)
. . . . .

Big Bang Nucleosynthesis

In the early universe (T=1 - 0.01MeV)

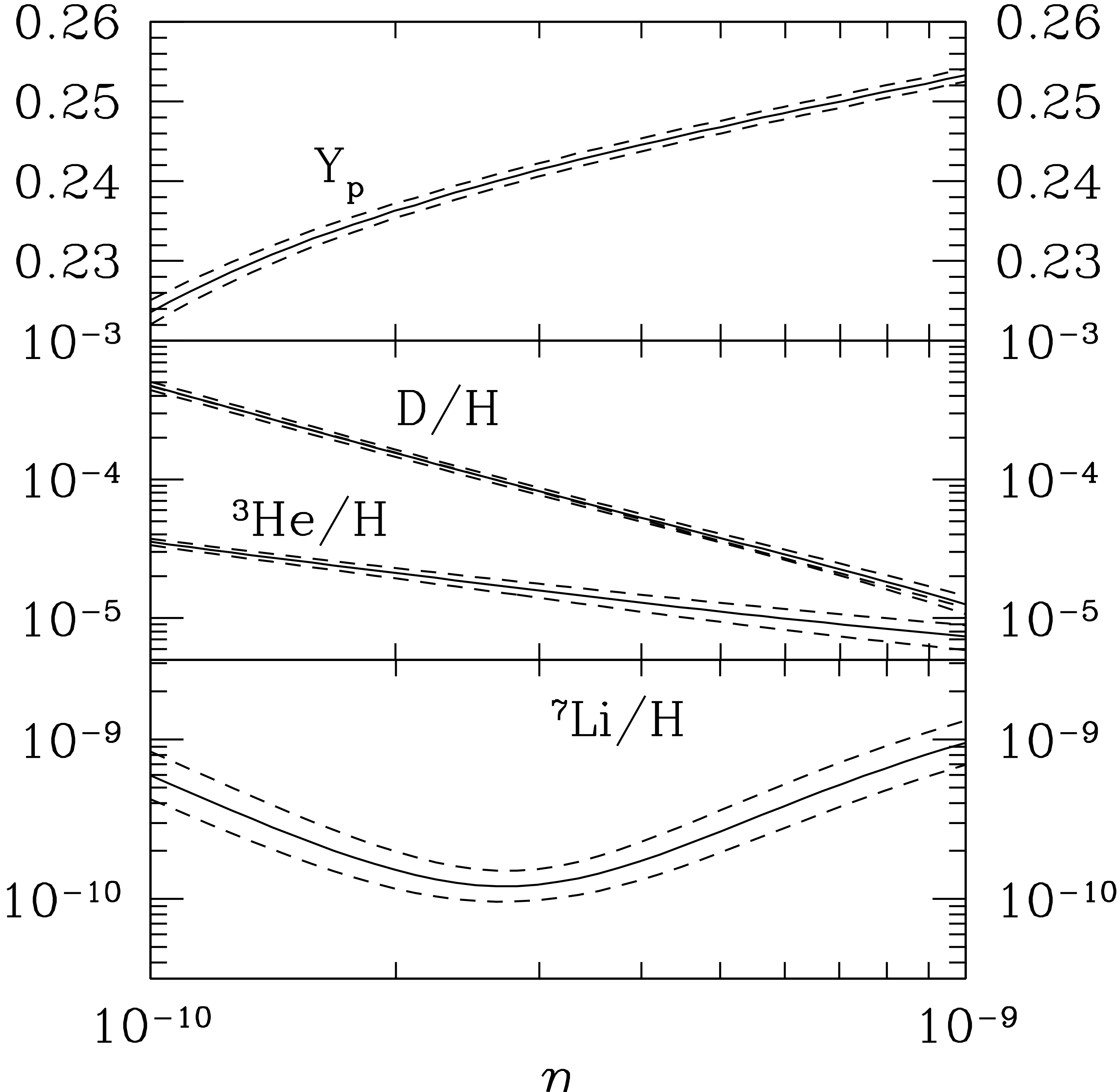
$$2p + 2n \rightarrow {}^4\mathrm{He}$$

+ small D $\quad {}^3\mathrm{He}$ $\quad {}^7\mathrm{Li}$

Abundances of Light Elements

⇧

Baryon-Photon ratio $\eta = \dfrac{n_B}{n_\gamma}$



0.26
0.25
0.24
0.23
Y_p
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
η

Observational Abundances of Light Elements

- He4

$$Y_p = 0.238 \pm 0.002 \pm 0.005$$

Fields,Olive (1998)

$$Y_p = 0.242 \pm 0.002(\pm 0.005)$$

Izotov et al. (2003)

- D/H

$$D/H = (2.8 \pm 0.4) \times 10^{-5}$$

Kirkman et al. (2003)

- Li7/H

$$\log_{10}(^7Li/H) = -9.66 \pm 0.056 \ (\pm 0.3)$$

Bonifacio et al. (2002)

- Li6/H

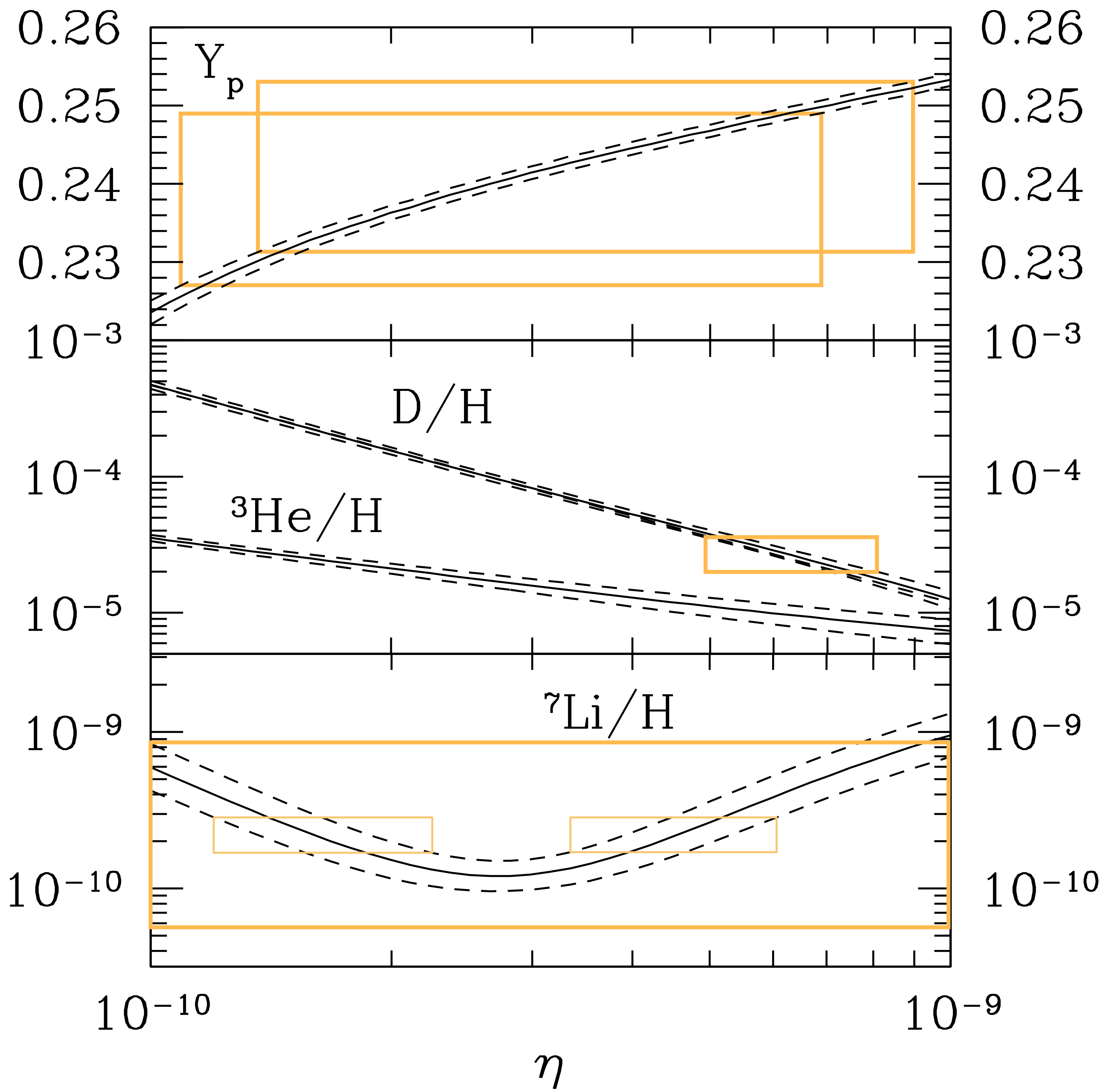
$$^6Li/H < 6 \times 10^{-11} \quad (2\sigma)$$

Smith et al. (1993)

- He3/D

$$^3He/D < 1.13 \quad (2\sigma)$$

Geiss (1993)



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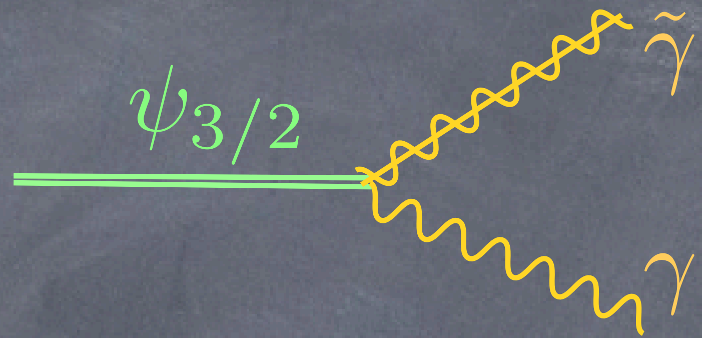
Gravitino Decay and BBN

Gravitino in Gravity Med.
SUSY Breaking



$$m_{3/2} \sim 10^{2-3}\ \mathrm{GeV}$$

⇨ Unstable

- Radiative Decay $\psi_{3/2} \rightarrow \tilde{\gamma} + \gamma$

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

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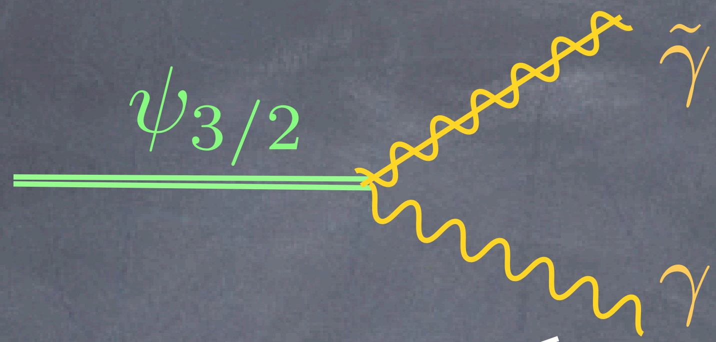
Radiative Decay

Radiative Decay



High Energy Photons

→ **Electromagnetic Cascade**

1) Photon-photon pair creation

$$\gamma + \gamma_{\mathrm{BG}} \rightarrow e^+ + e^-$$

$\epsilon_\gamma > m_e^2/22T$

2) Inverse Compton

$$e + \gamma_{\mathrm{BG}} \rightarrow e + \gamma$$

3) Photon-photon scattering

$$\gamma + \gamma_{\mathrm{BG}} \rightarrow \gamma + \gamma$$

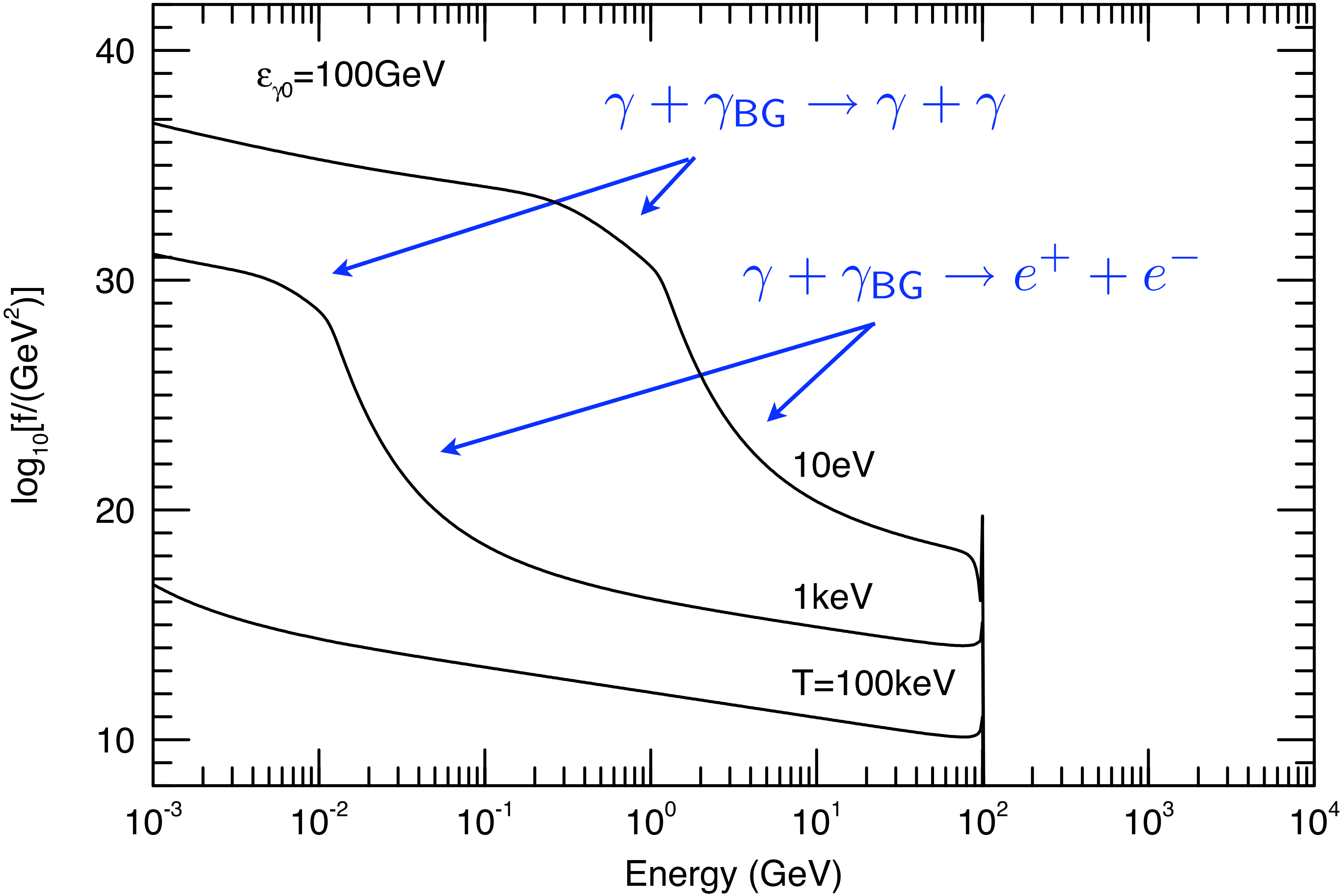
$\epsilon_\gamma > m_e^2/80T$

4) Thomson scattering

$$\gamma + e_{\mathrm{BG}} \rightarrow \gamma + e$$

Photon Spectrum

MK, Moroi (1995)



⇨ Many Soft Photons

$$\epsilon_\gamma > 2.2\text{MeV} \quad (T < 10\text{keV})$$

$$\epsilon_\gamma > 20\text{MeV} \quad (T < 1\text{keV})$$

⇨ Destroy Light Elements

$$\text{D} + \gamma \to n + p \quad [2.22 \text{ MeV}]$$

$$\text{T} + \gamma \to \text{D} + n \quad [6.2 \text{ MeV}]$$

$$^3\text{He} + \gamma \to \text{D} + p \quad [5.5 \text{ MeV}]$$

$$^4\text{He} + \gamma \to \text{T} + n \quad [19.8 \text{ MeV}]$$

$$^4\text{He} + \gamma \to {}^3\text{He} + n \quad [20.5 \text{ MeV}]$$

$$^4\text{He} + \gamma \to \text{D} + n + p \quad [26.1 \text{ MeV}]$$

etc

Non-thermal Production of D and He3

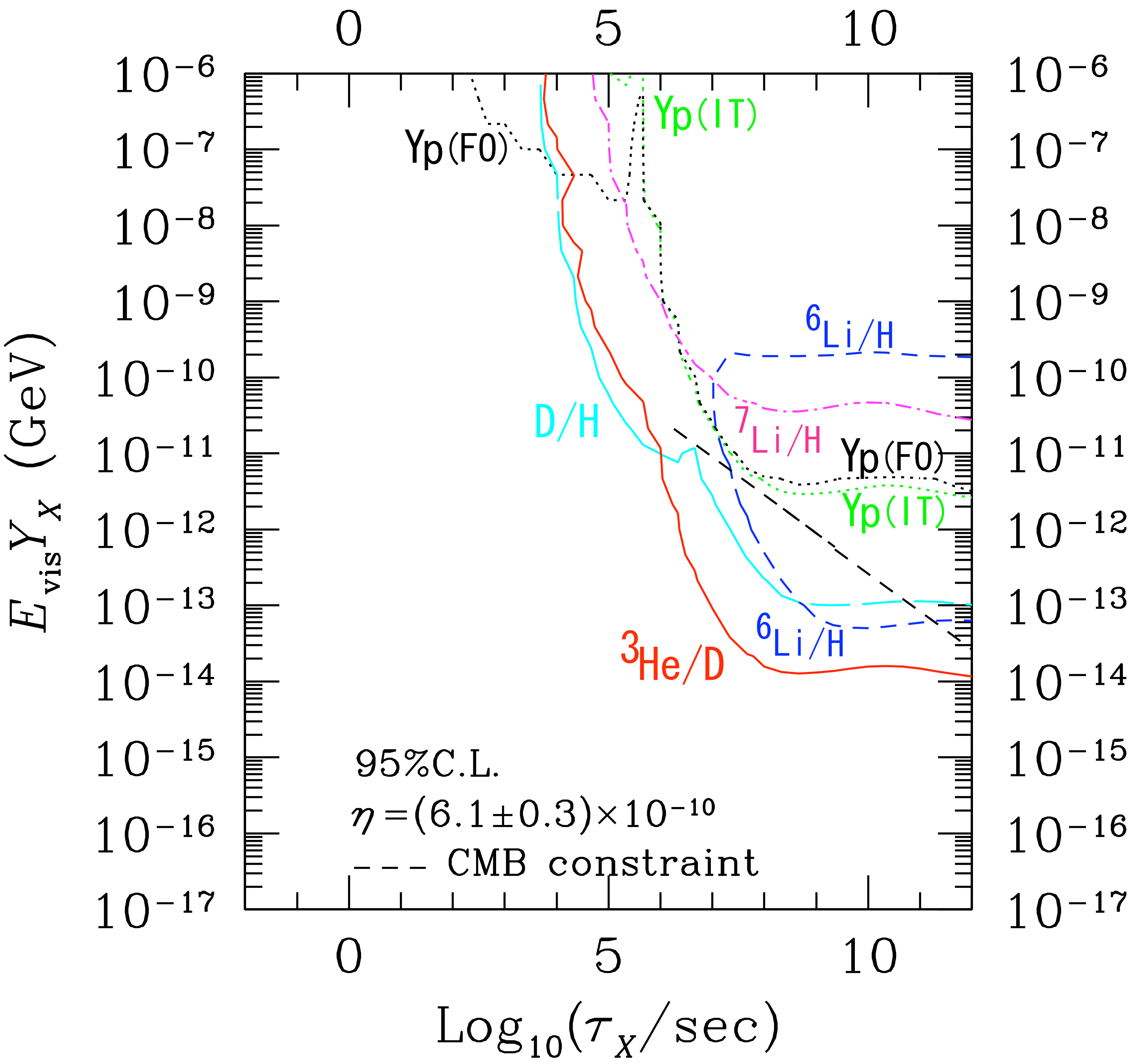
Non-thermal Production of Li6

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

$$\mathrm{T} +^4\mathrm{He} \;\rightarrow\; ^6\mathrm{Li} + n \quad [4.03\mathrm{MeV}]$$

$$^3\mathrm{He} +^4\mathrm{He} \;\rightarrow\; ^6\mathrm{Li} + p \quad [4.8\mathrm{MeV}]$$

Constraint



Yp(FO)
Yp(IT)
^{6}Li/H
^{7}Li/H
D/H
^{3}He/D
95%C.L.
η=(6.1±0.3)×10^{-10}
CMB constraint
$E_{vis}Y_X$ (GeV)
$Log_{10}(\tau_X/sec)$

He3/D Constraint

Chemical Evolution of He3 and D

Whenever He3 is destroyed, D is also destroyed

→ $\frac{^3\mathrm{He}}{\mathrm{D}}$ Increasing Function of time

Observation Gives Upper Limit

$$^3\mathrm{He}/\mathrm{D} < 1.13\ (2\sigma)$$

Geiss (1993)

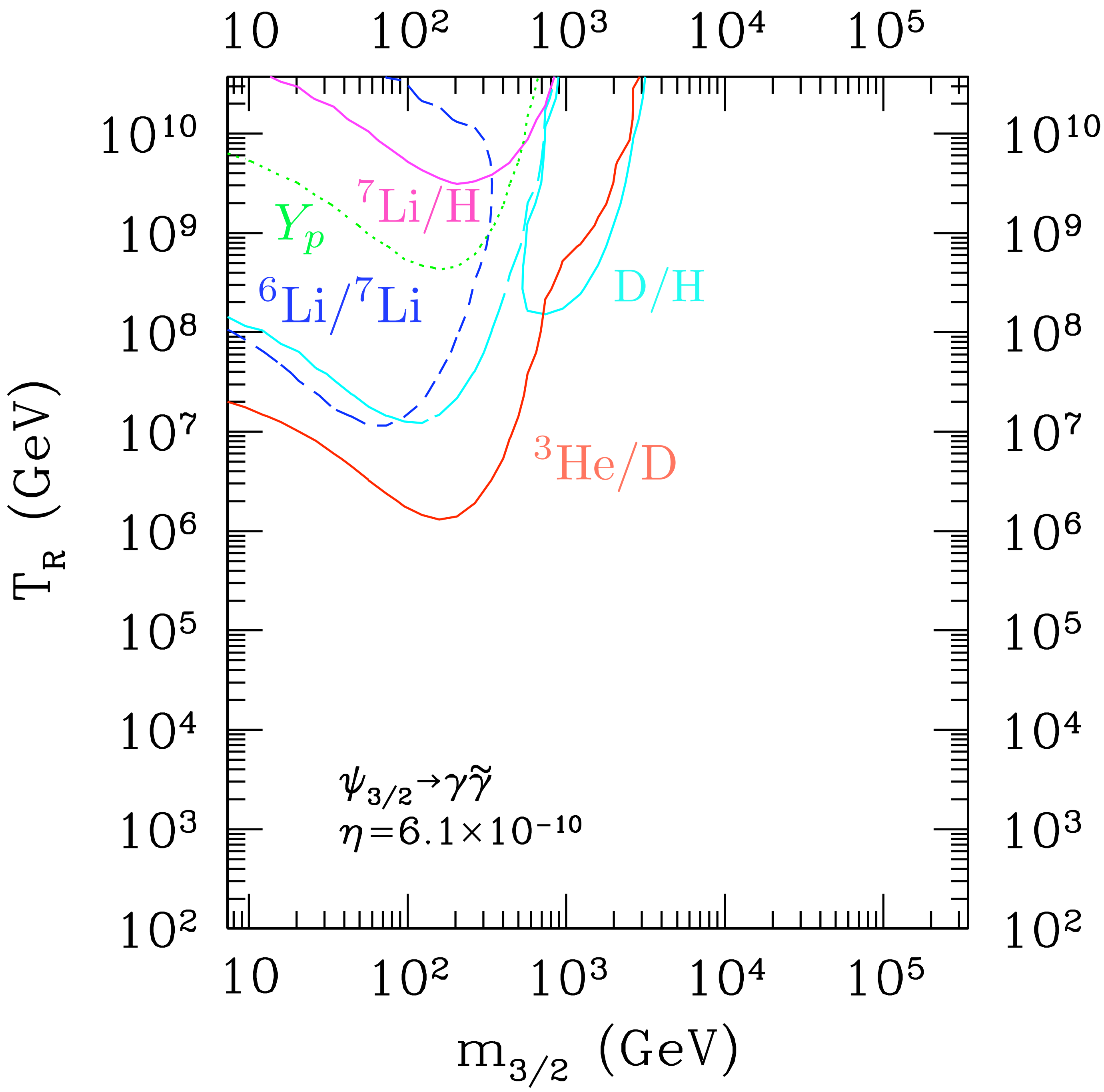
$t \lesssim 10^6\,\mathrm{sec}$ Destruction of D

$t \gtrsim 10^6\,\mathrm{sec}$ Overproduction of He3

Application to Gravitino Problem

$$Y_{3/2} = 1.9 \times 10^{-12} \left[1 + \left(\frac{m_{\tilde{g}}^2}{3m_{3/2}^2} \right) \right] \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right)$$
$$\times \left[1 + 0.045 \ln \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right) \right] \left[1 - 0.028 \ln \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right) \right]$$

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

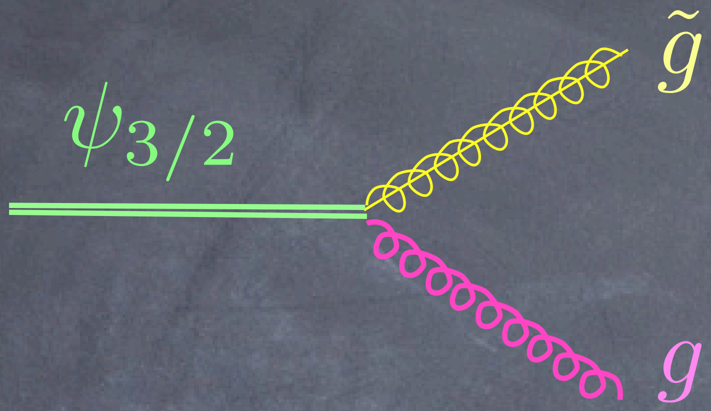


10
10^2
10^3
10^4
10^5
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
^{7}Li/H
Y_p
^{6}Li/^{7}Li
D/H
^{3}He/D
$\psi_{3/2} \to \gamma\tilde{\gamma}$
$\eta = 6.1 \times 10^{-10}$
T_R (GeV)
$m_{3/2}$ (GeV)

Hadronic Decay

Hadronic Decay

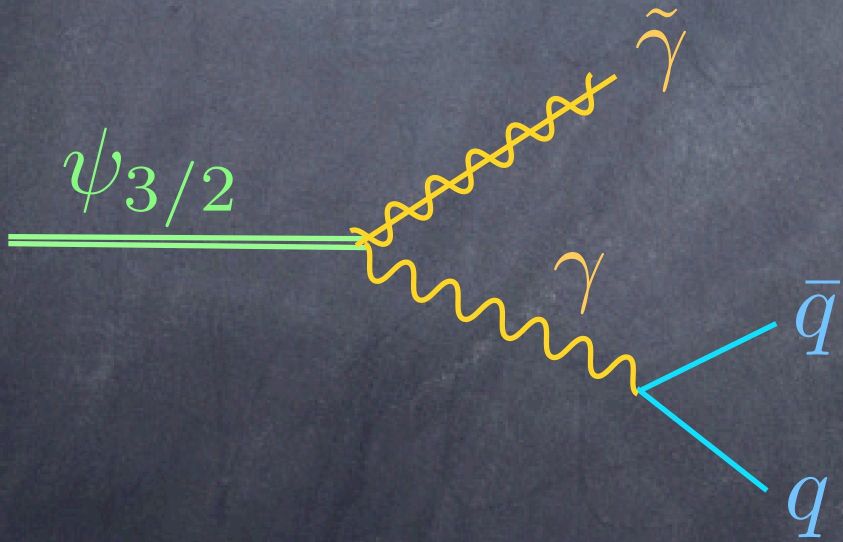
Reno, Seckel (1988)
Dimopoulos et al (1989)



$B_h \sim 1$

Two hadron jets
with E = m/2

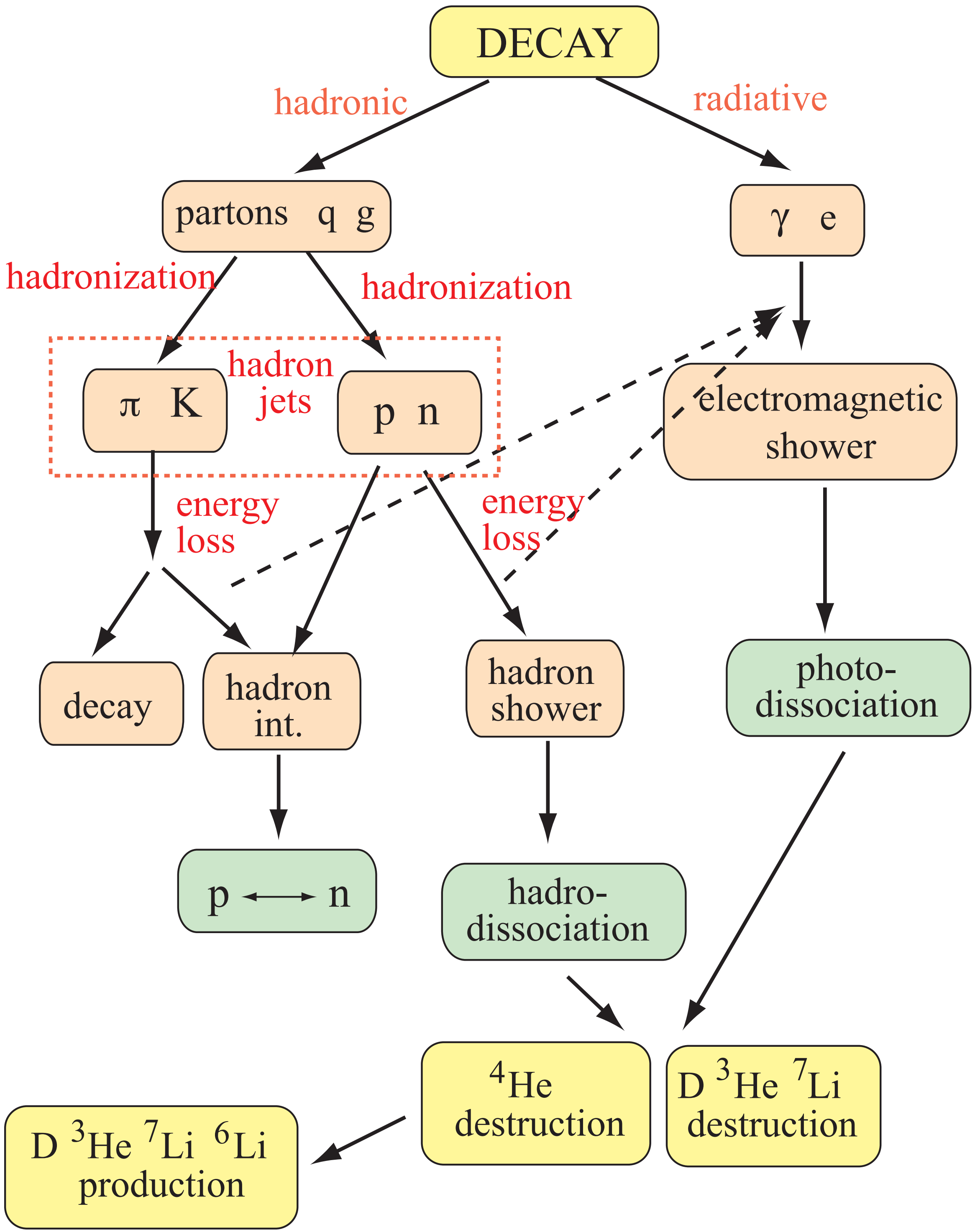
Even if gravitino only decay into photino



$B_h \sim \alpha/4\pi \sim 0.001$

Two hadron jets
with E = m/3

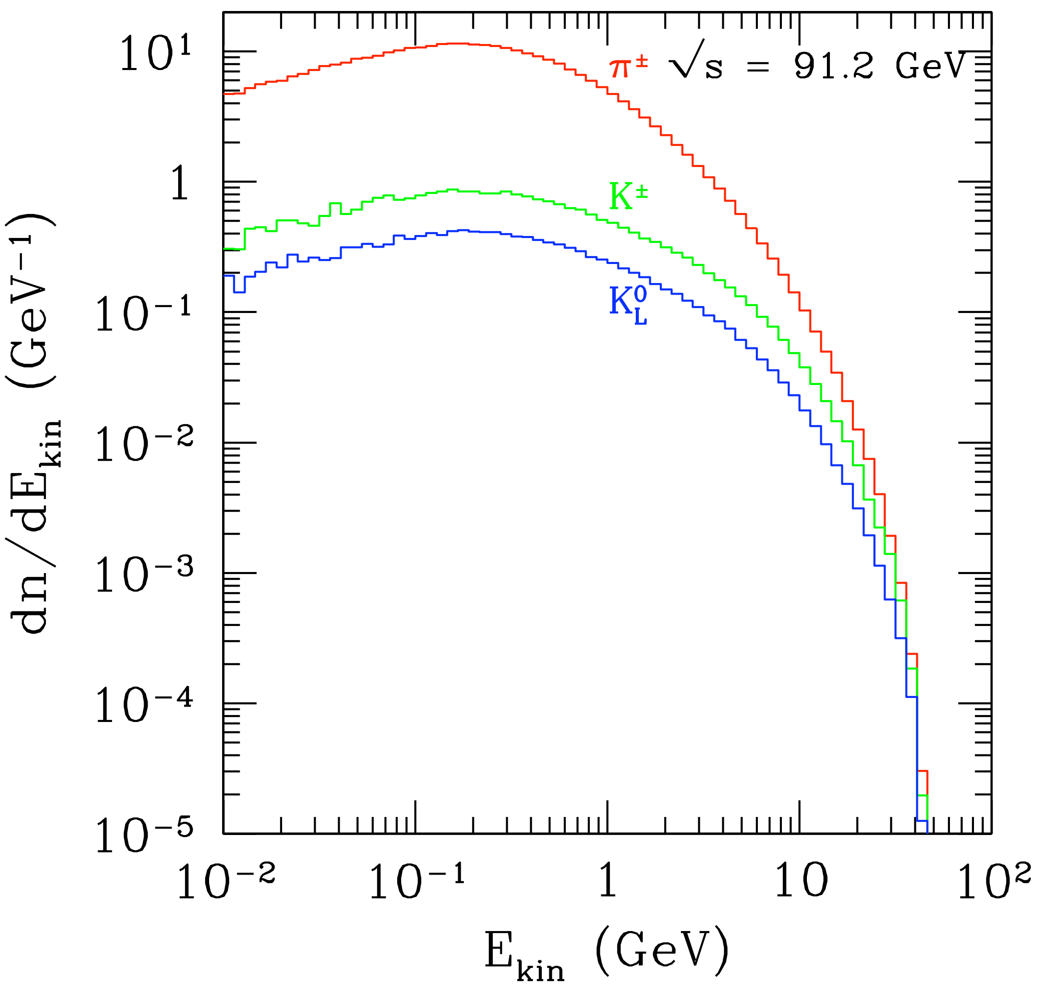
Overview

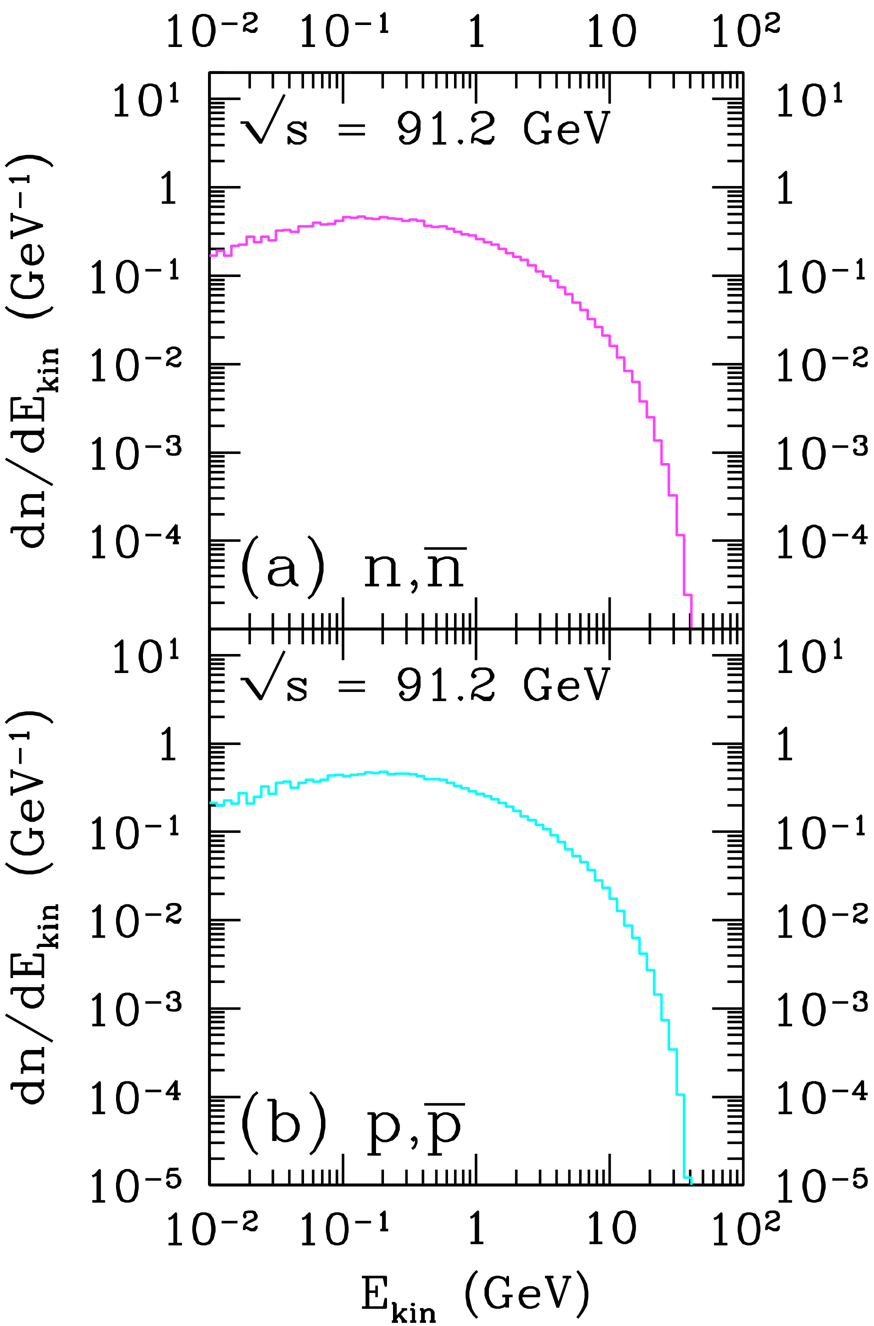


DECAY
hadronic
radiative
partons q g
γ e
hadronization
hadronization
π K
hadron jets
p n
electromagnetic shower
energy loss
energy loss
decay
hadron int.
hadron shower
photo-dissociation
p ⟷ n
hadro-dissociation
⁴He destruction
D ³He ⁷Li destruction
D ³He ⁷Li ⁶Li production

Spectrum of hadron jets

JETSET 7.4





Kohri 2001

Effect of hadron injection on BBN

(I) Early stage of BBN

Reno, Seckel (1988)
Kohri (2001)

Pion

$$\pi^+ + n \to \begin{cases} p + \pi^0 \\ p + \gamma \end{cases}$$

$$\tau_{\pi^\pm} = 2.6 \times 10^{-8}\,\mathrm{sec}$$

$$\pi^- + p \to \begin{cases} n + \pi^0 \\ n + \gamma \end{cases}$$

Kaon

$$K^- + p \to \Sigma^- + \pi^0, \cdots$$

$$\tau_{K^\pm} = 1.2 \times 10^{-8}\,\mathrm{sec}$$

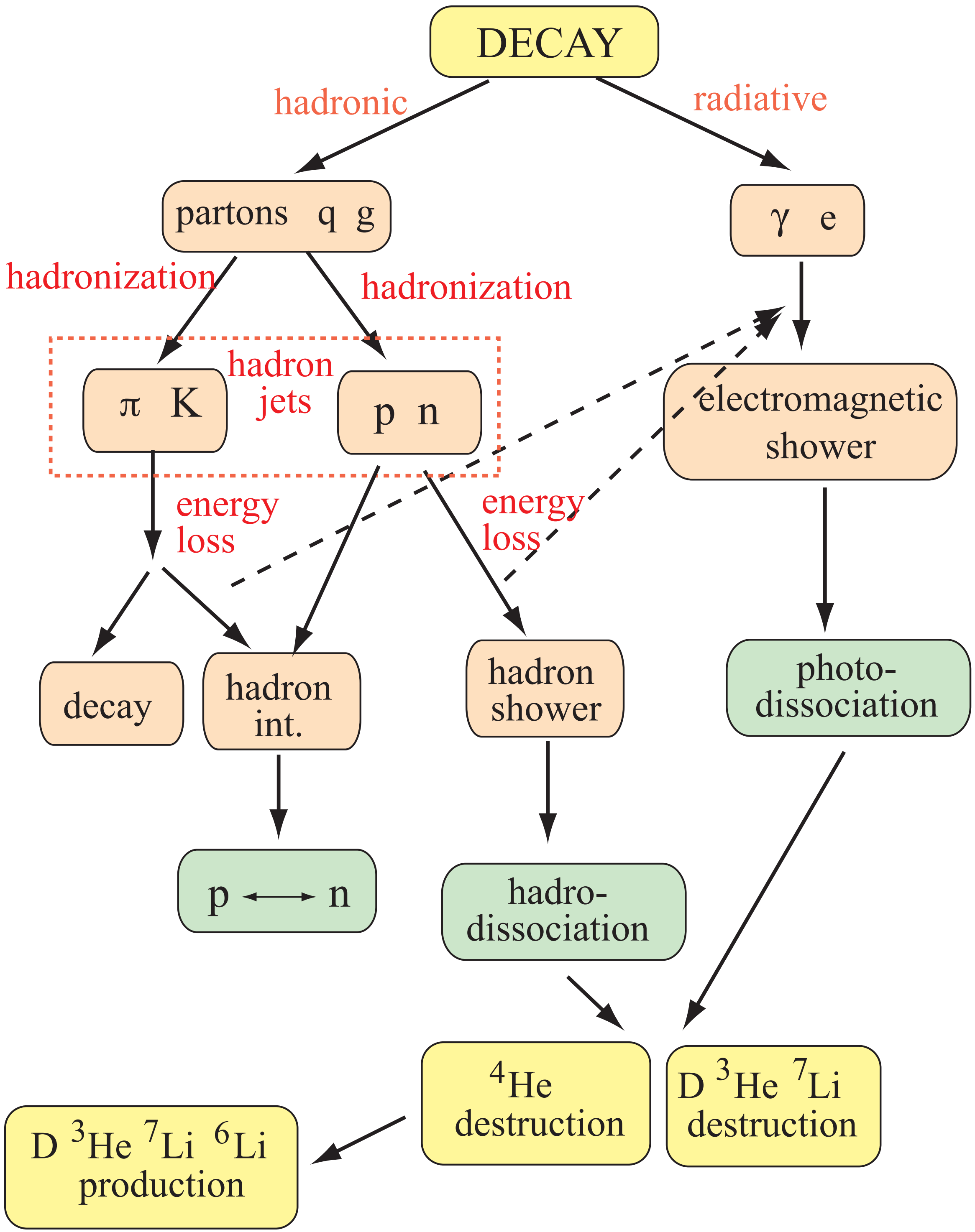
$$K_L + N \to N' + \ldots \qquad N, N' = p, n$$

$$\tau_{K_L} = 5.2 \times 10^{-8}\,\mathrm{sec}$$

Hadron-Nucleon interaction rate

$$\Gamma_{N\to N'} \sim 10^8\,\mathrm{sec}^{-1}(\sigma v/10\mathrm{mb})(T/2\mathrm{MeV})^3$$

Overview



DECAY
hadronic
radiative
partons q g
γ e
hadronization
hadronization
π K
hadron
jets
p n
electromagnetic
shower
energy
loss
energy
loss
decay
hadron
int.
hadron
shower
photo-
dissociation
p n
hadro-
dissociation
4He
destruction
D 3He 7Li
destruction
D 3He 7Li 6Li
production

p-n interchange interaction rate

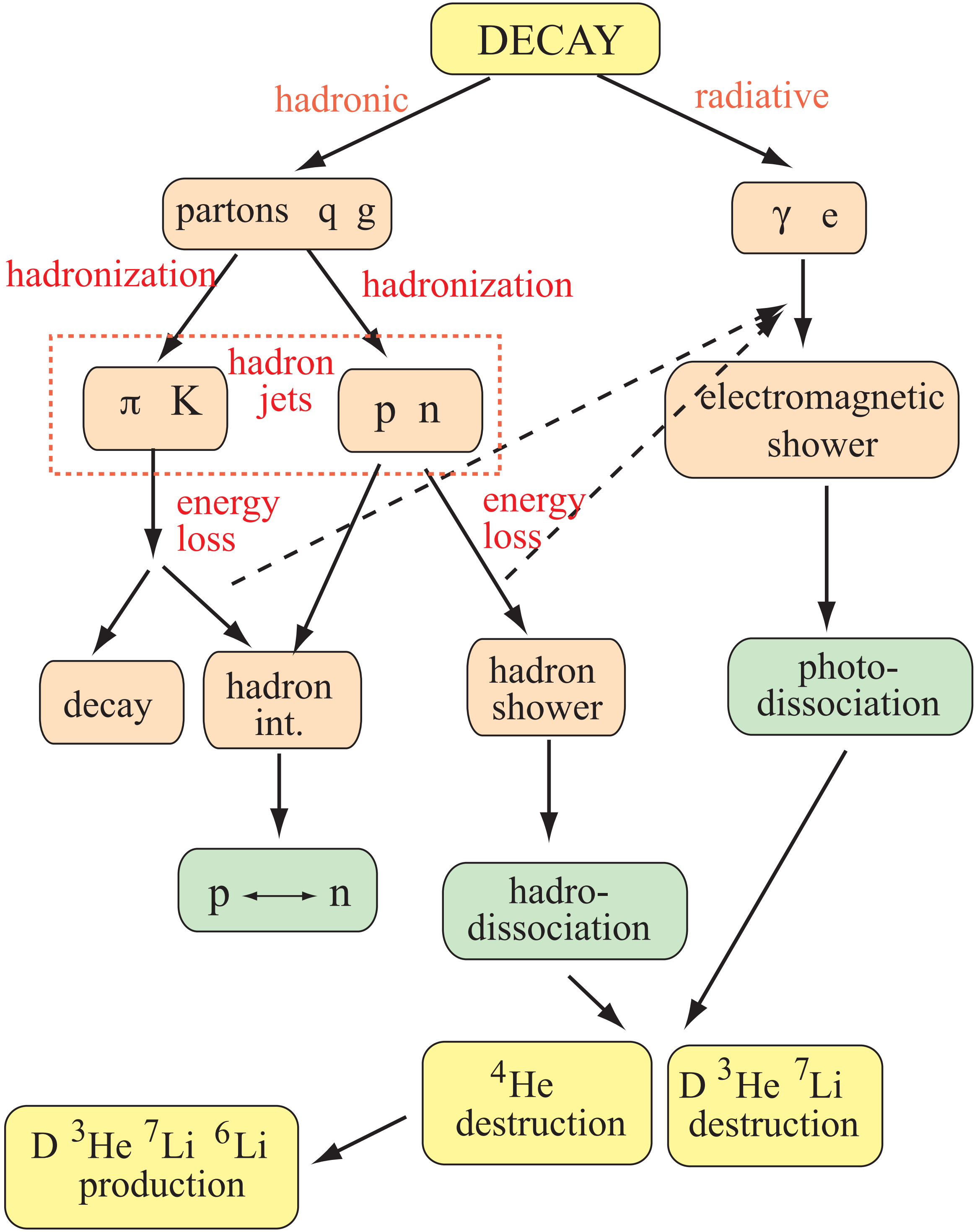
$$\Gamma_{N\to N'} = \Gamma^{\rm std}_{N\to N'} + \Gamma^{\pi,{\rm K}}_{N\to N'}$$

➡ n-p ratio increases
(std: n/p ~ 1/7)

$$n + \nu_e \leftrightarrow p + e^-$$

➡ More He4

Overview


DECAY
hadronic
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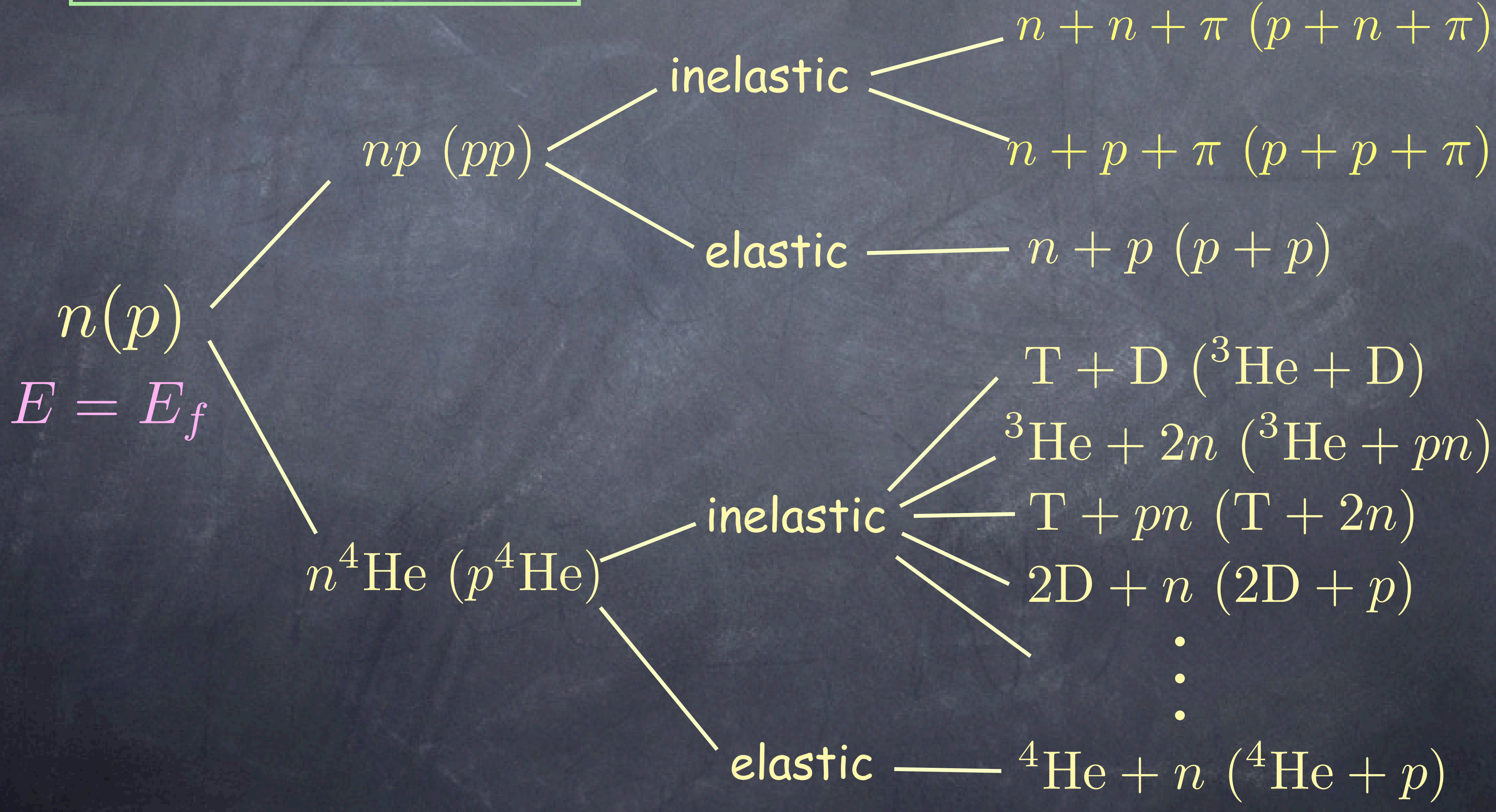
4He destruction
D 3He 7Li destruction
D 3He 7Li 6Li production

Effect of hadron injection on BBN

(II) Late stage of BBN

Dimopoulos et al (1989)

Hadron Shower



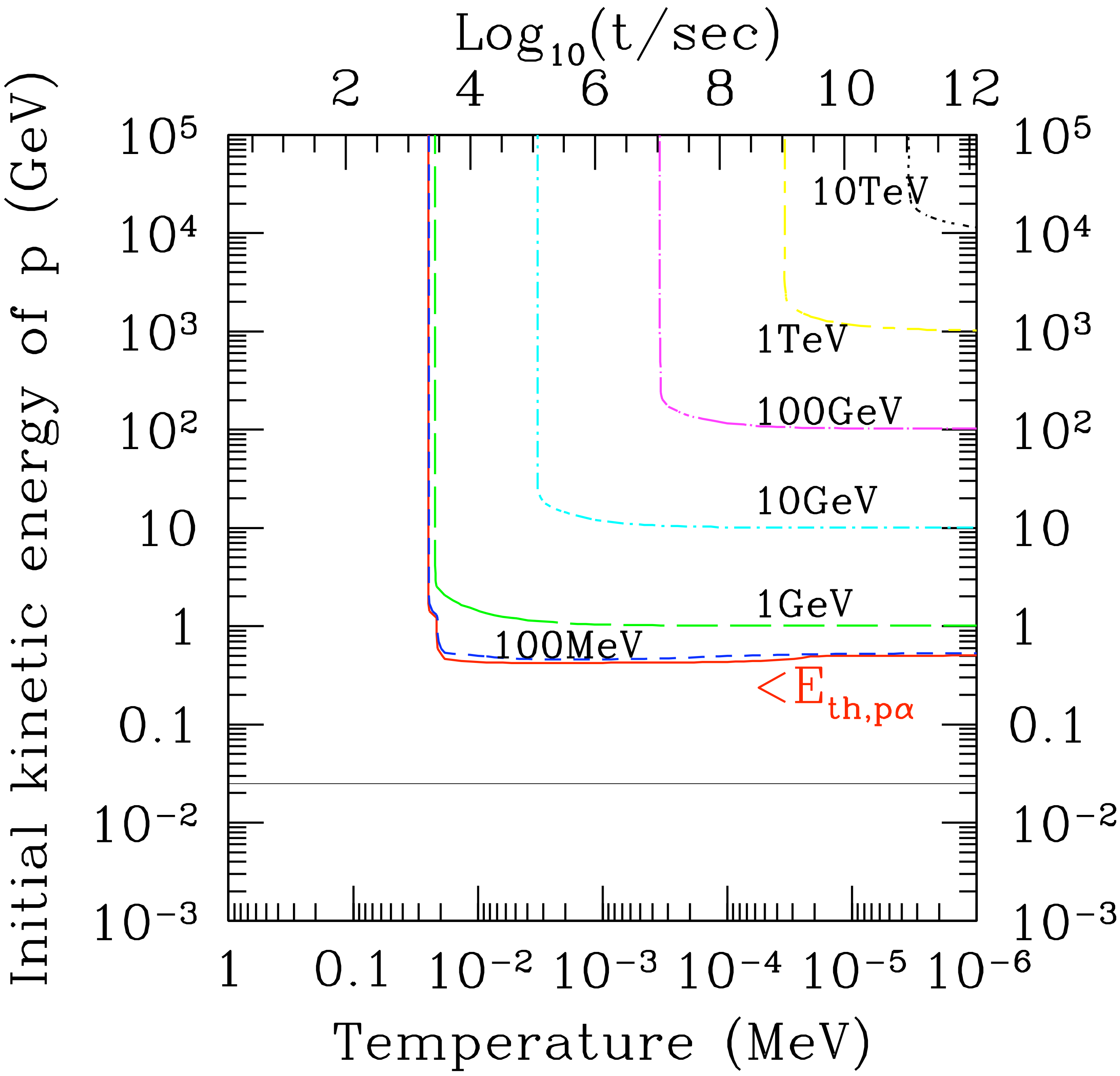
Energy Loss

High energy hadrons lose their energy by Coulomb and Compton scatterings off background photons and electrons before they interacts with nuclei

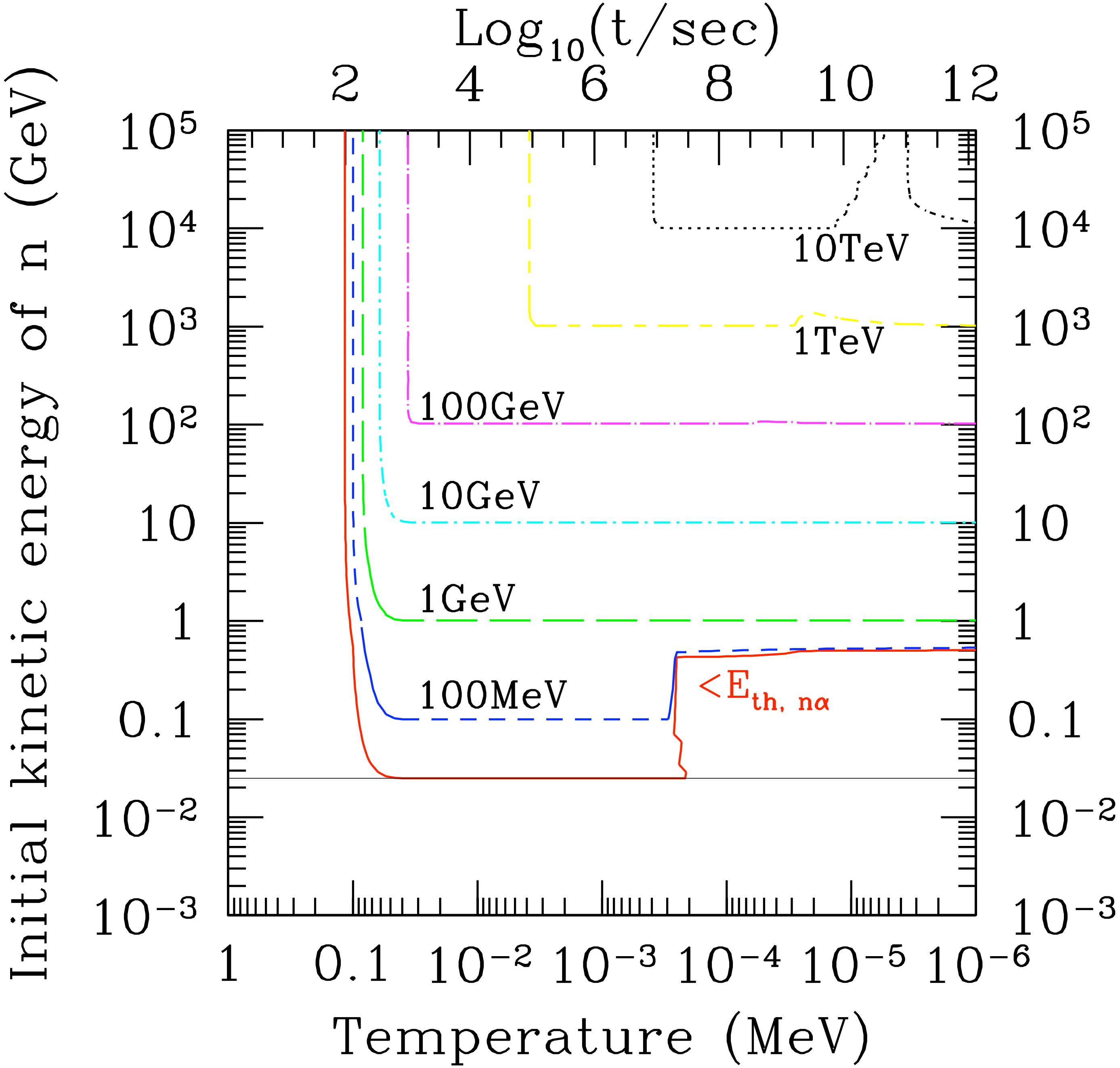
- Non-relativistic Nucleus $v_N > v_e$

$$\frac{dE}{dt} = -\frac{4\pi\alpha^2\Lambda Z^2 n_e}{m_e v_N} \qquad \Lambda \sim O(1)$$

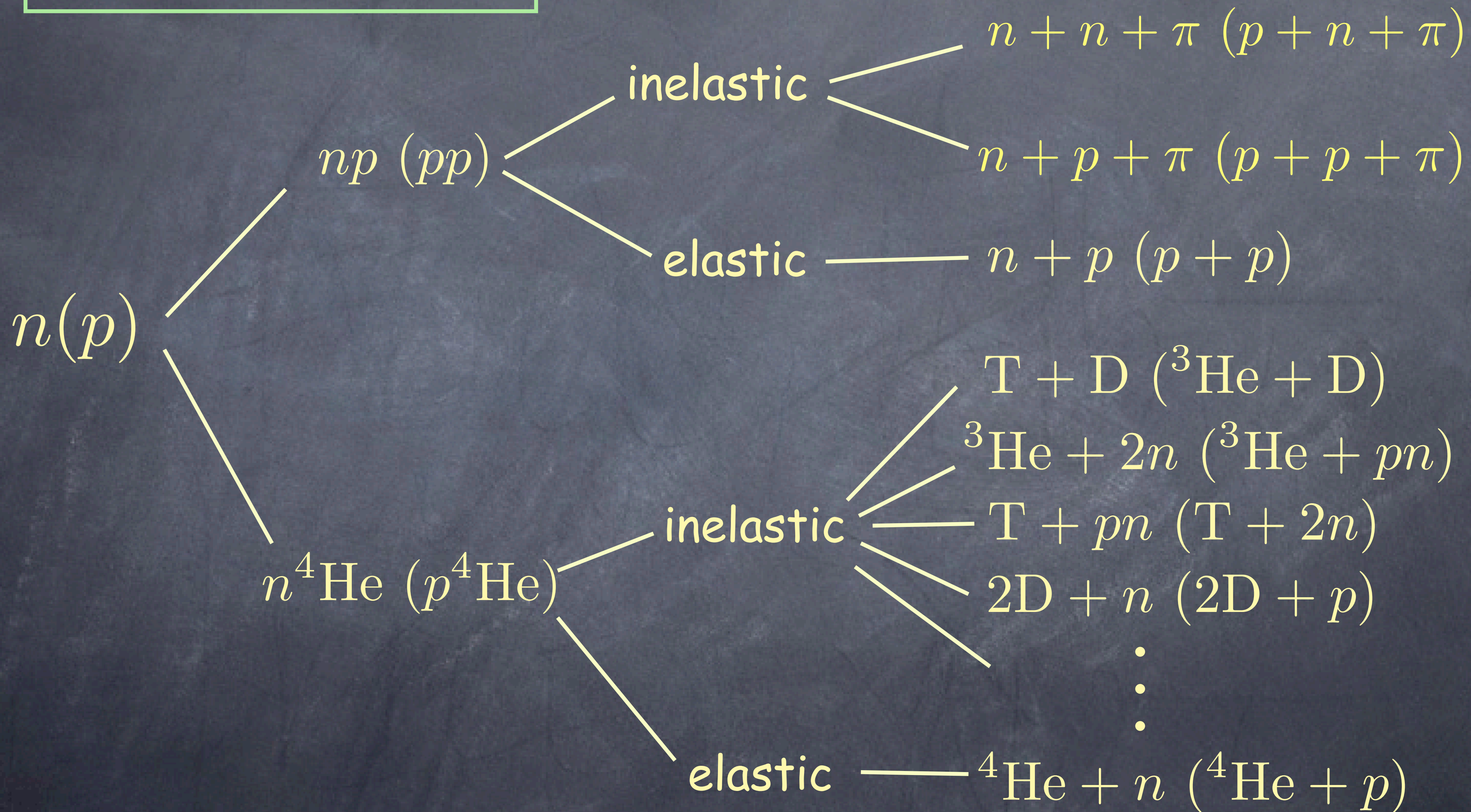
Final Energy of Proton



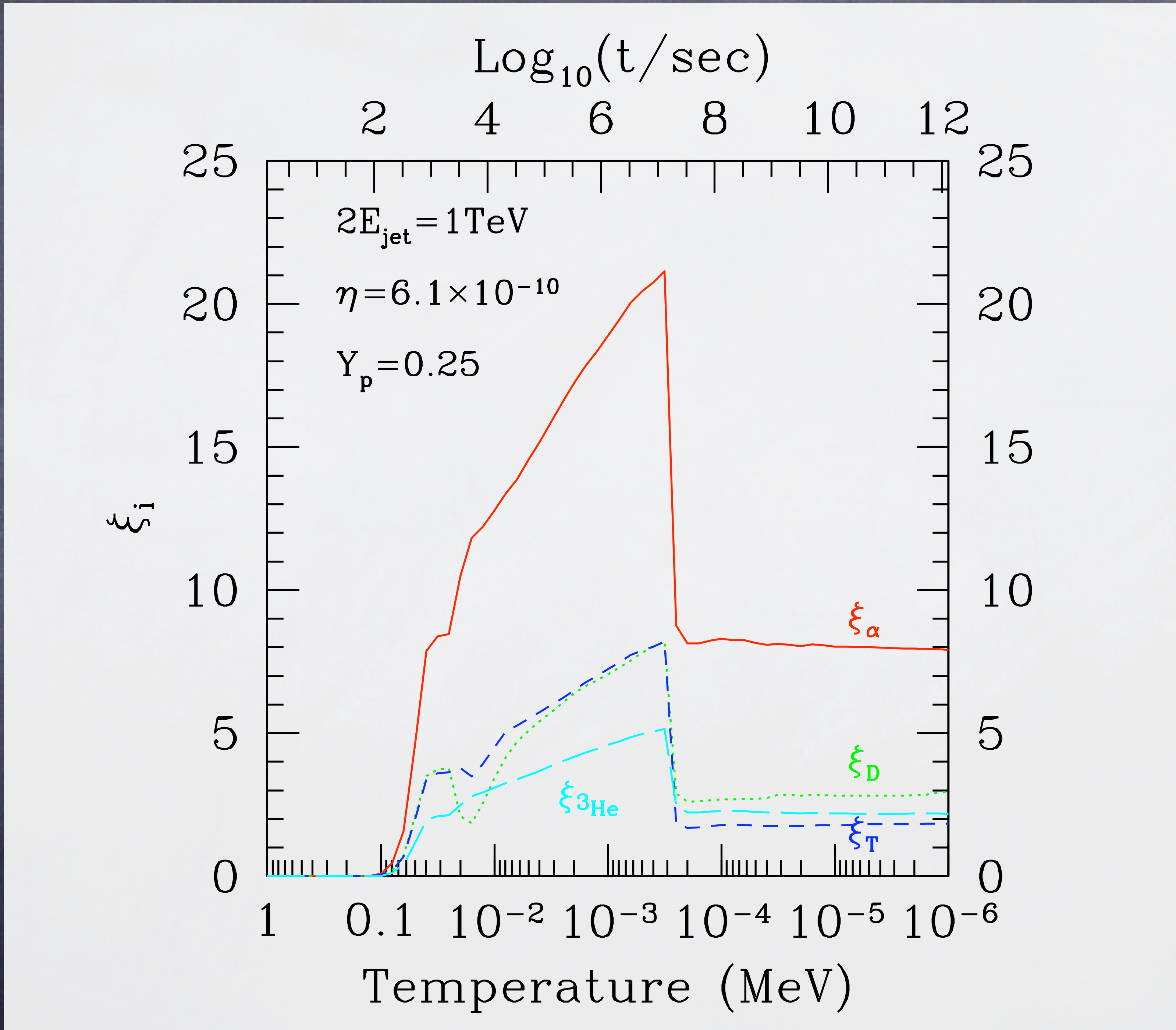
Final Energy of Neutron



Hadron Shower



ξ_i : number of nuclei "i" produced per one massive particle decay



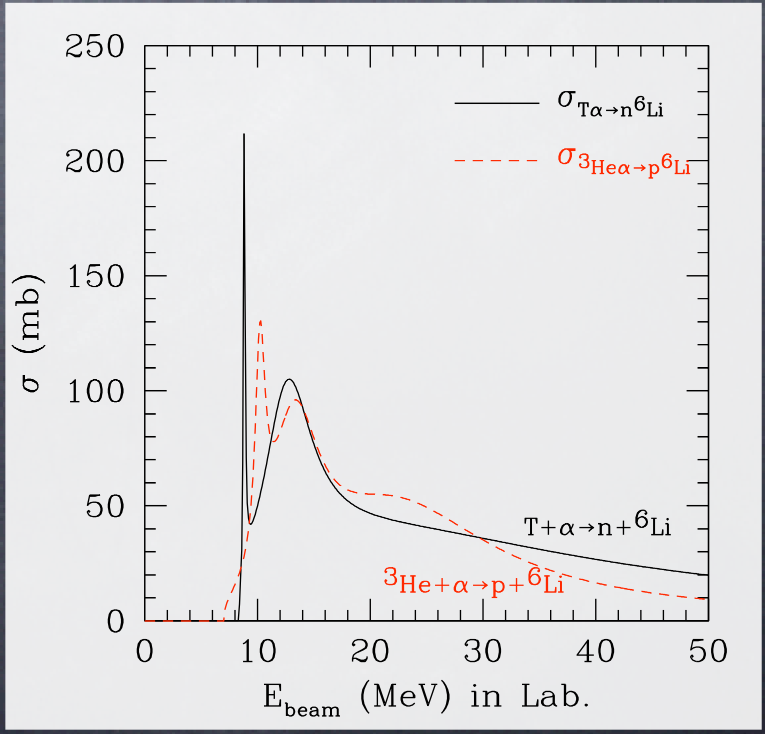
Non-thermal Production of Li6

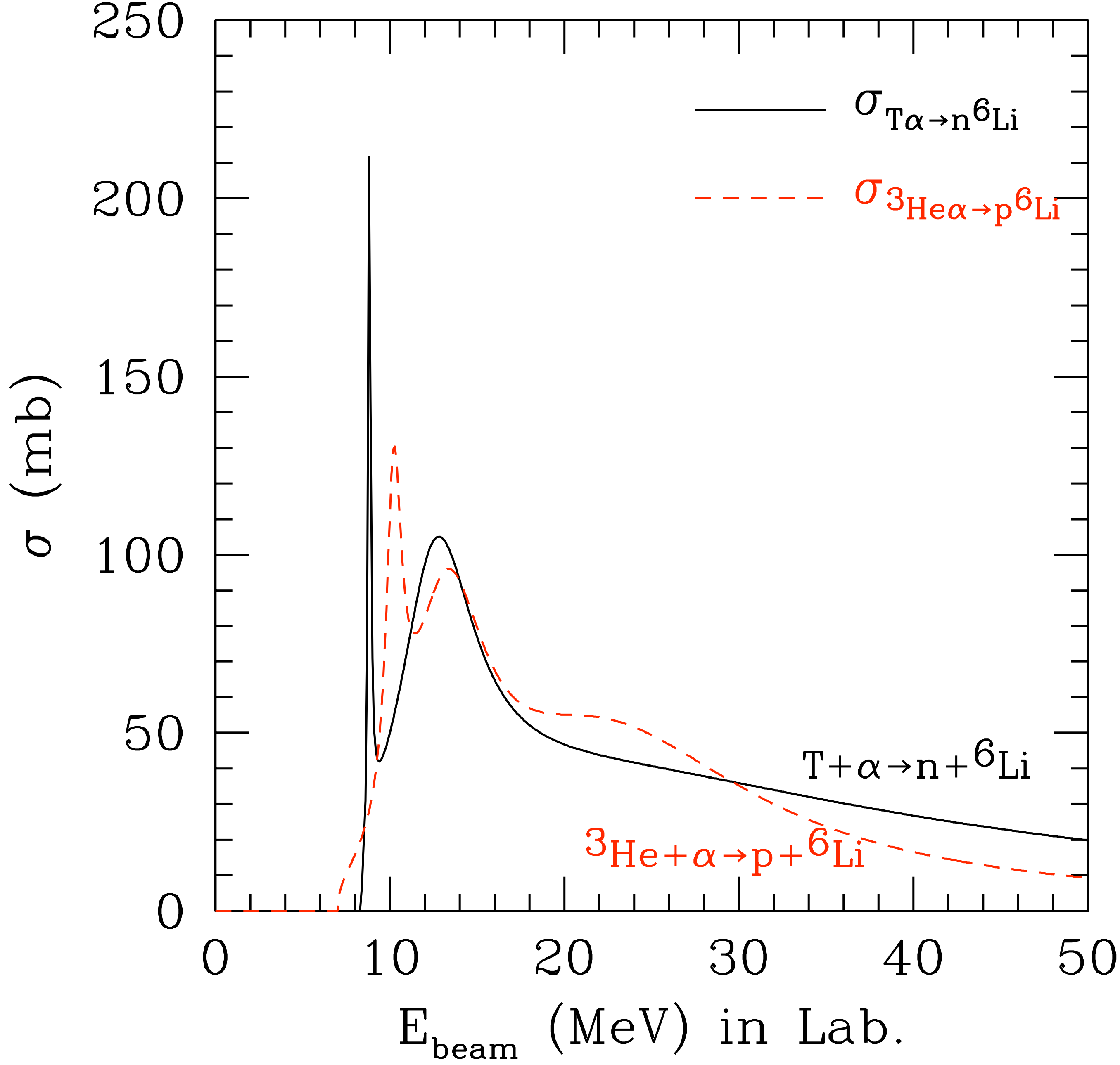
$$^{4}\mathrm{He} + N \to N' + {}^{3}\mathrm{He},\ \ N' + \mathrm{T}$$

$$\mathrm{T} + {}^{4}\mathrm{He} \ \to\ {}^{6}\mathrm{Li} + n \quad [4.03\mathrm{MeV}]$$

$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \ \to\ {}^{6}\mathrm{Li} + p \quad [4.8\mathrm{MeV}]$$

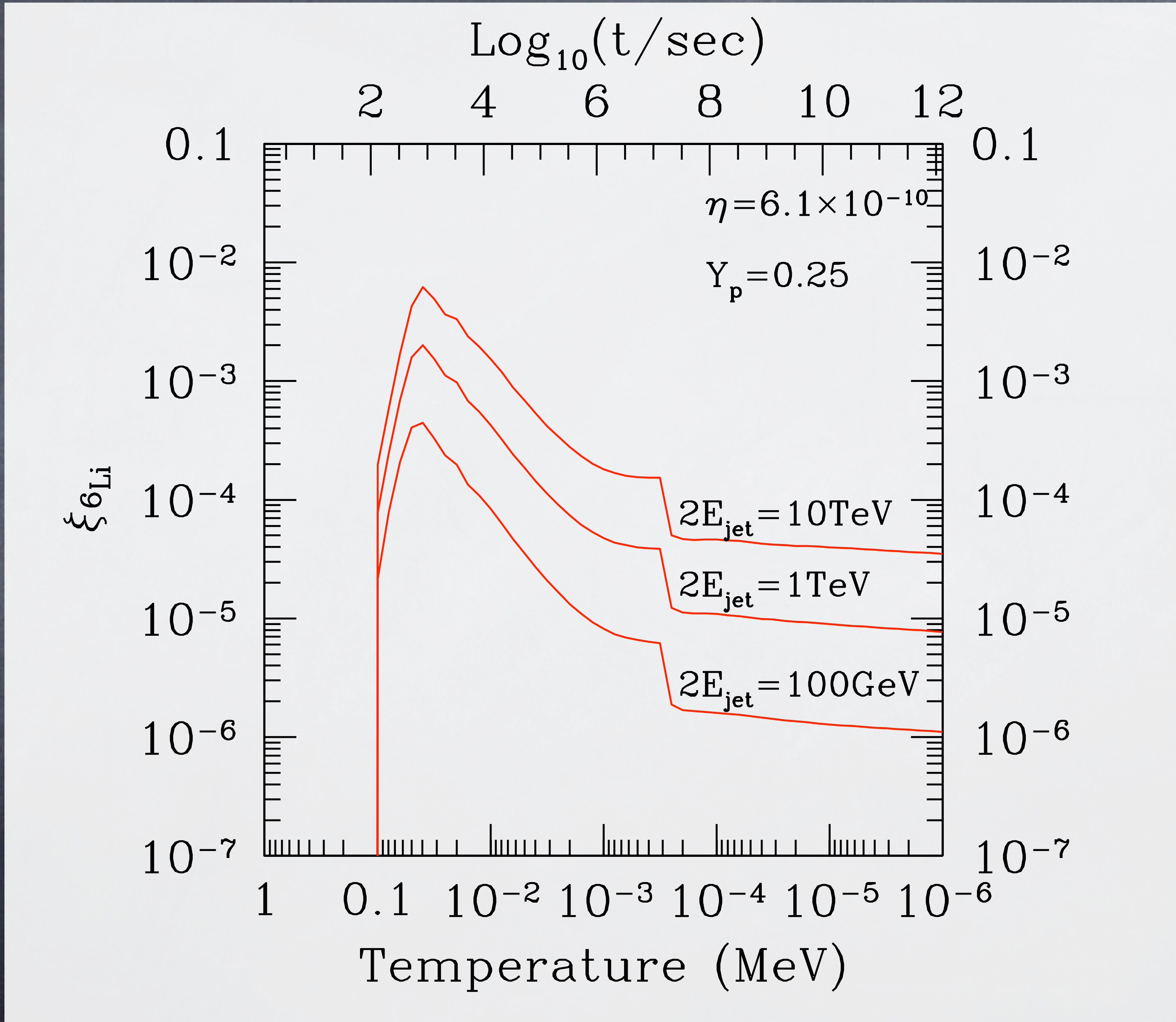
T,He3 enegy loss He4





$\sigma_{T\alpha\to n^6Li}$
$\sigma_{^3He\alpha\to p^6Li}$
$T+\alpha\to n+{}^6Li$
${}^3He+\alpha\to p+{}^6Li$
σ (mb)
0
50
100
150
200
250
0
10
20
30
40
50
E_{beam} (MeV) in Lab.

ξ_i : number of nuclei "i" produced per one massive particle decay



Estimate non-thermal production and destruction rates for D, T, He3, He4, Li6, Li7

↓

Run BBN code

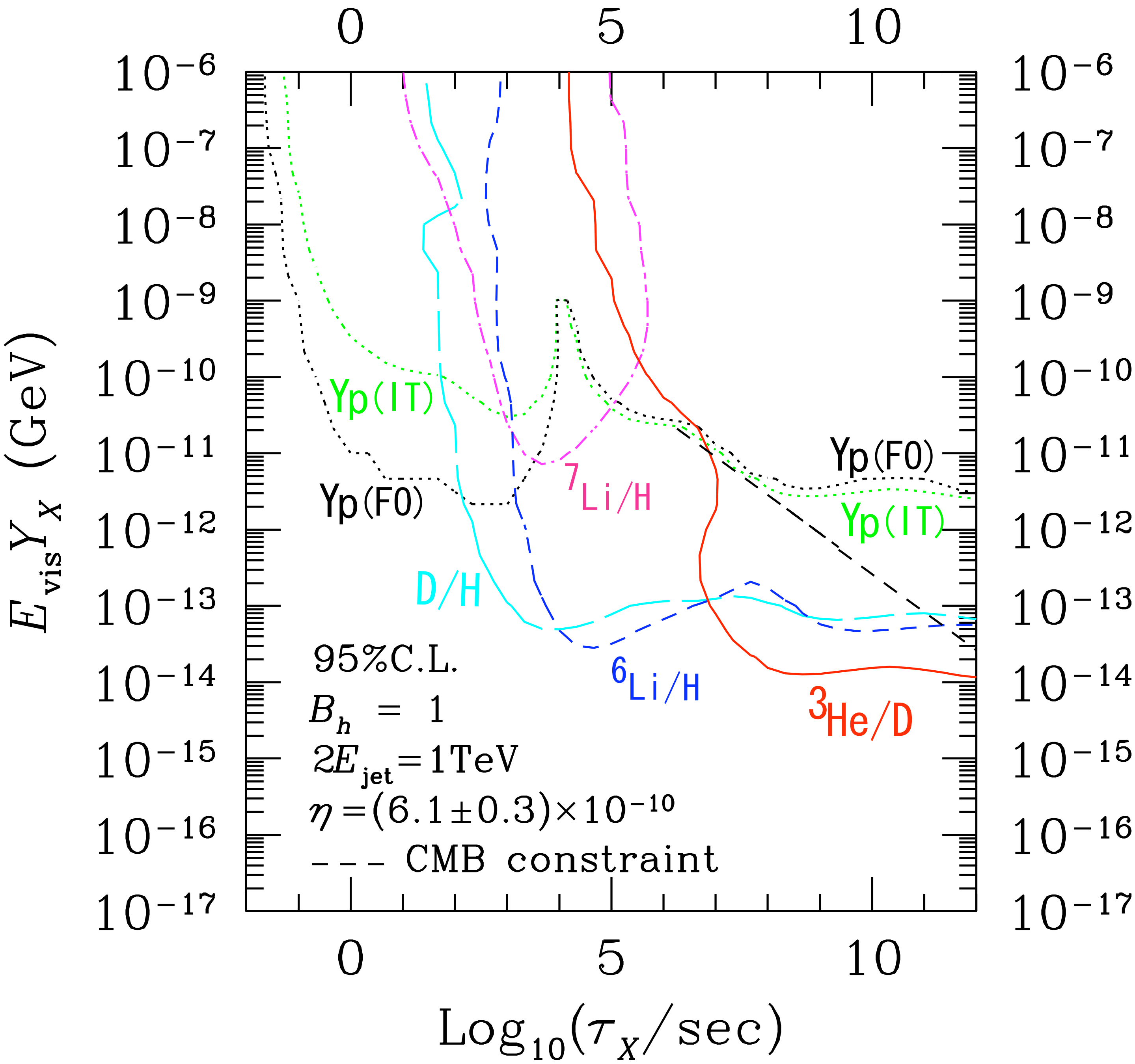
↓

Compare theoretical and observational abundances of light elements

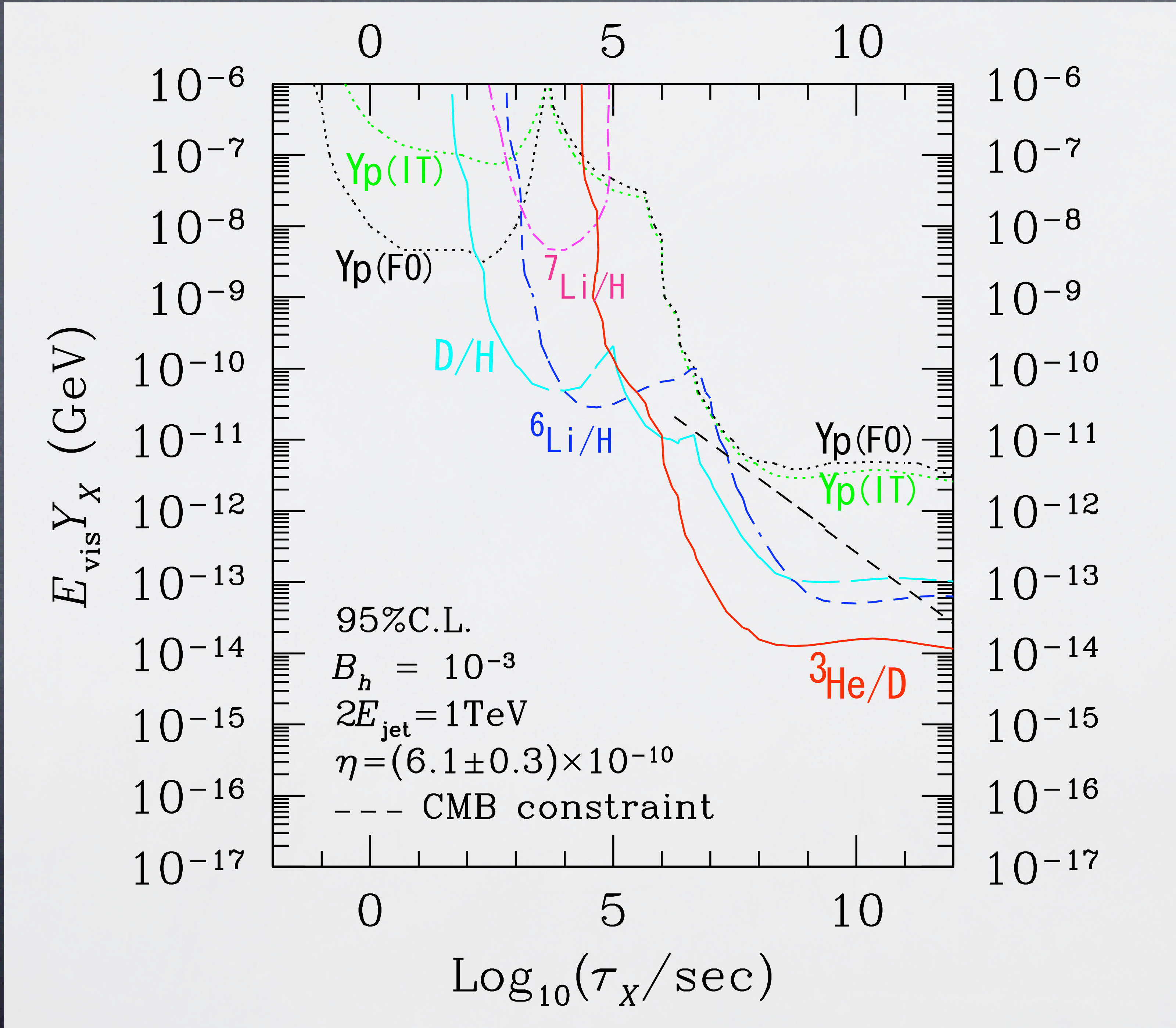
↓

Constraint on abundance and lifetime of gravitino

Constraint on Abundance and Lifetime



Constraint on Abundance and Lifetime (3)



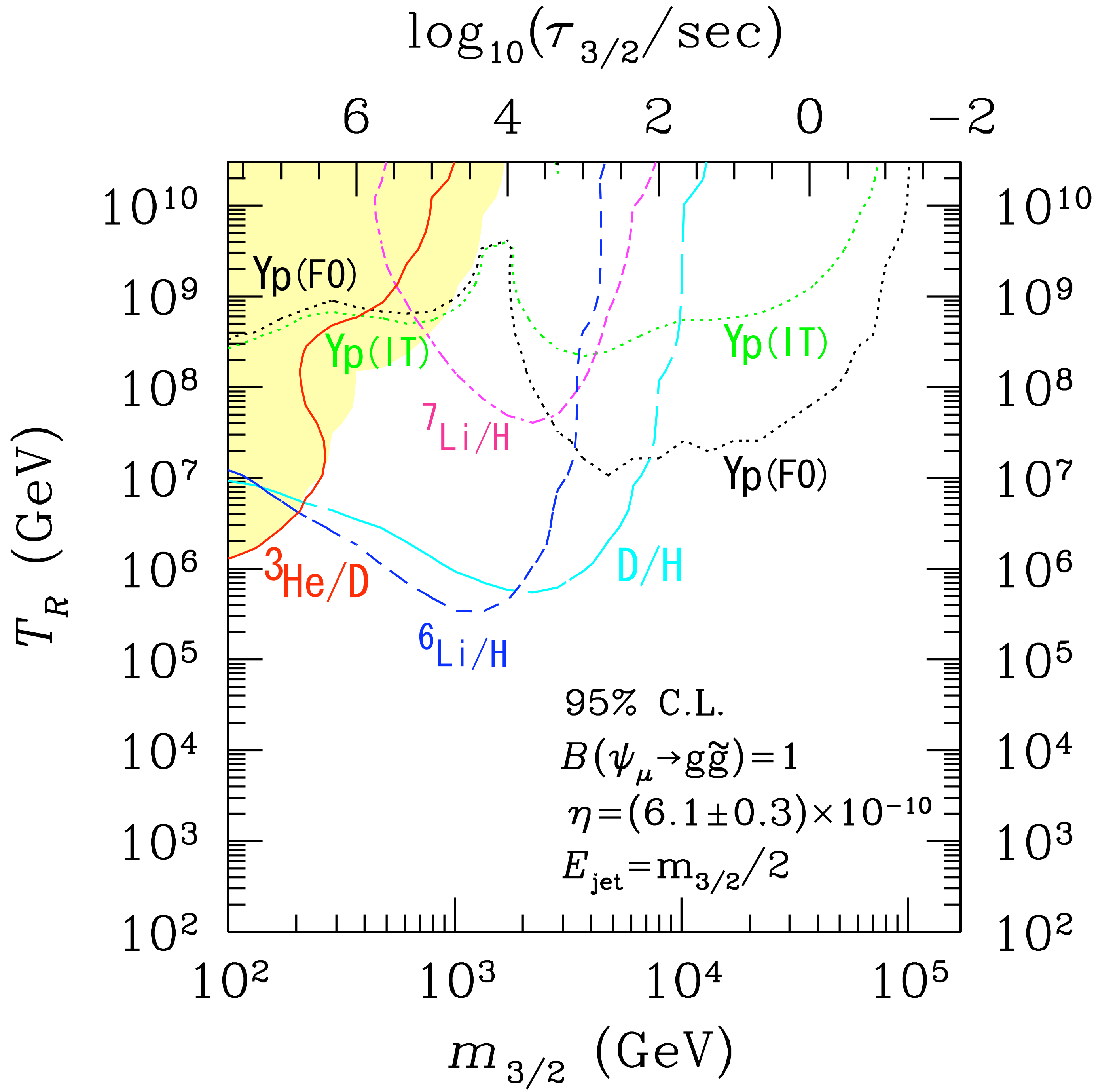
Application to Gravitino Problem

$$
\begin{aligned}
Y_{3/2} &= 1.9\times 10^{-12}\left[1+\left(\frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right)\right]\left(\frac{T_R}{10^{10}\mathrm{GeV}}\right) \\
&\times\left[1+0.045\ln\left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)\right]\left[1-0.028\ln\left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)\right]
\end{aligned}
$$

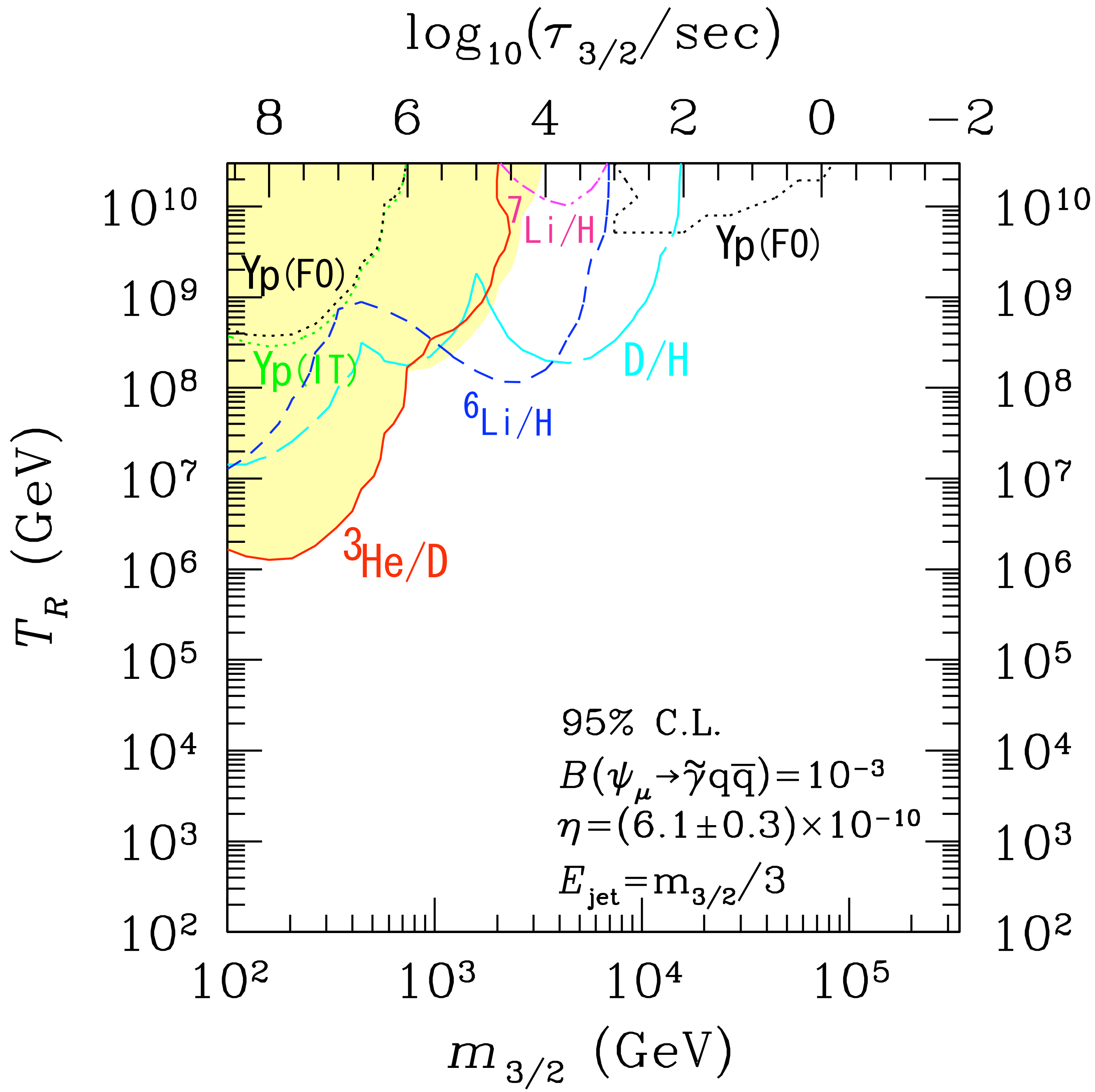
$$
\tau(\psi_{3/2}\to\tilde{g}+\gamma)\simeq 6\times 10^{7}\,\mathrm{sec}\left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)^{-3}
$$

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

Constraint on Reheating Temperature



Constraint on Reheating Temperature (2)



Conclusion

- Decay products destroy He4, which leads to overproduction of D, He3, Li6
- In particular, for hadronic decay, the constraint on reheating temperature is very stringent

$$T_R \lesssim 10^5 - 10^7 \text{ GeV}$$

$$\text{for} \quad m_{3/2} = 100 \text{ GeV} \ - 3 \text{ TeV}$$