高エネルギー宇宙の総合的理解@ICRR

グラビティーノ問題
不安定粒子に対する宇宙論的電磁・ハドロンシャワーからの制限

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Introduction

Supersymmetry (SUSY)

Fermion $\longleftrightarrow$ Boson

- Hierarchy Problem
  Keep electroweak scale against radiative correction
- Coupling Constant Unification in GUT

quark $\longleftrightarrow$ squarks
lepton $\longleftrightarrow$ slepton
photon $\longleftrightarrow$ photino

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

In Supersymmetric Inflationary Universe

Gravitino $\psi_{3/2}$ Production During Reheating

↓

Decay at BBN epoch

↓

Destroy Light Elements

↓ Gravitino Problem

Constraint on T_R

Plan of Talk

1. Introduction
2. Gravitino Problem
3. Radiative Decay of Gravitino
4. Hadronic Decay of Gravitino
5. Conclusion

Gravitino Problem

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)

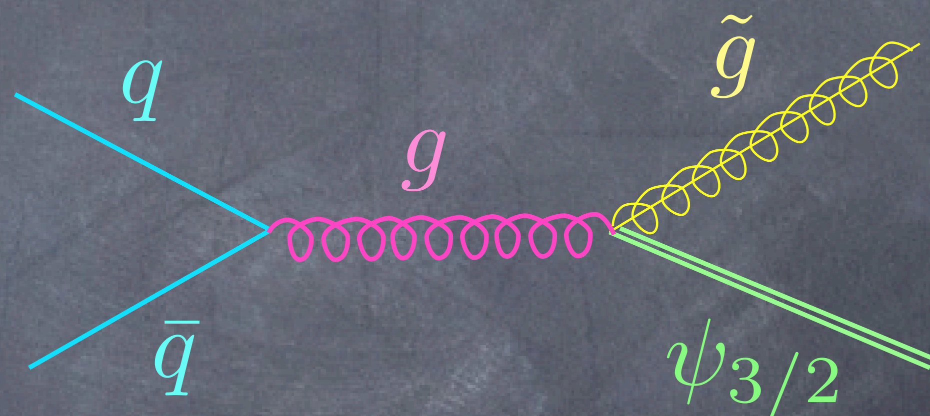
Gravitino in Inflationary Universe

Primordial gravitinos are diluted

However, gravitinos are produced during reheating

e.g.

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



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

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

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

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

~~SUSY~~ sector $M_{\rm SUSY}$ ⟷ gravity ⟷ Observable sector (s)quark,(s)lepton

- Squark, slepton masses

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

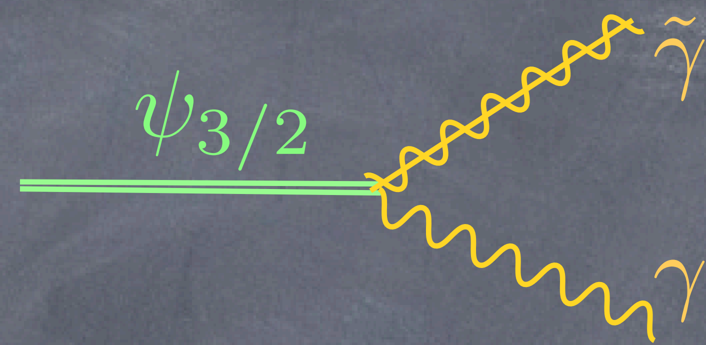
- Gravitino

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

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

Gravitino Decay and BBN

Gravitino in Gravity Med. SUSY Breaking



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

⇨ **Unstable**

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

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

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

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

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)

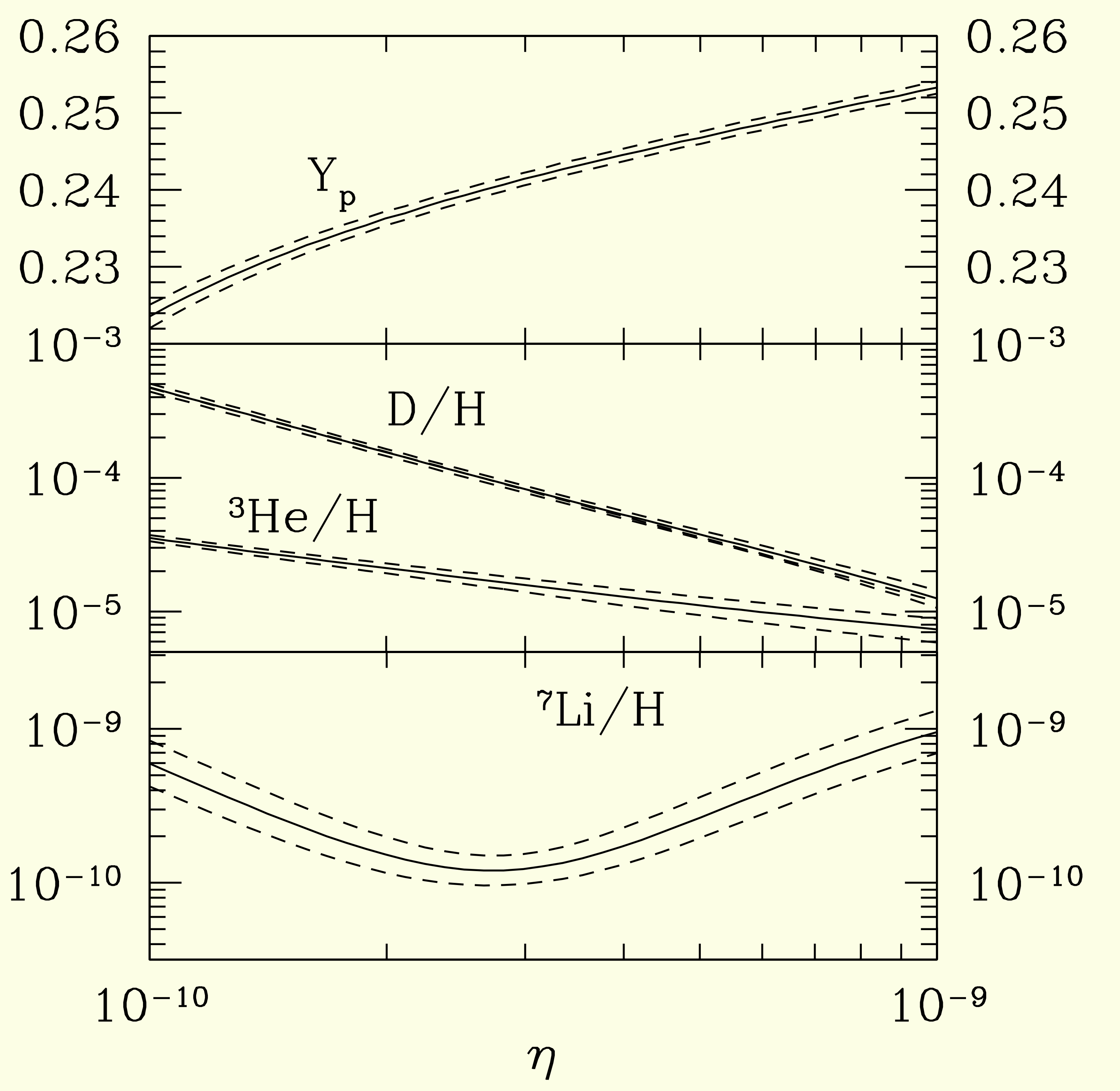
$$2p + 2n \rightarrow {}^4\mathrm{He}$$

+ 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

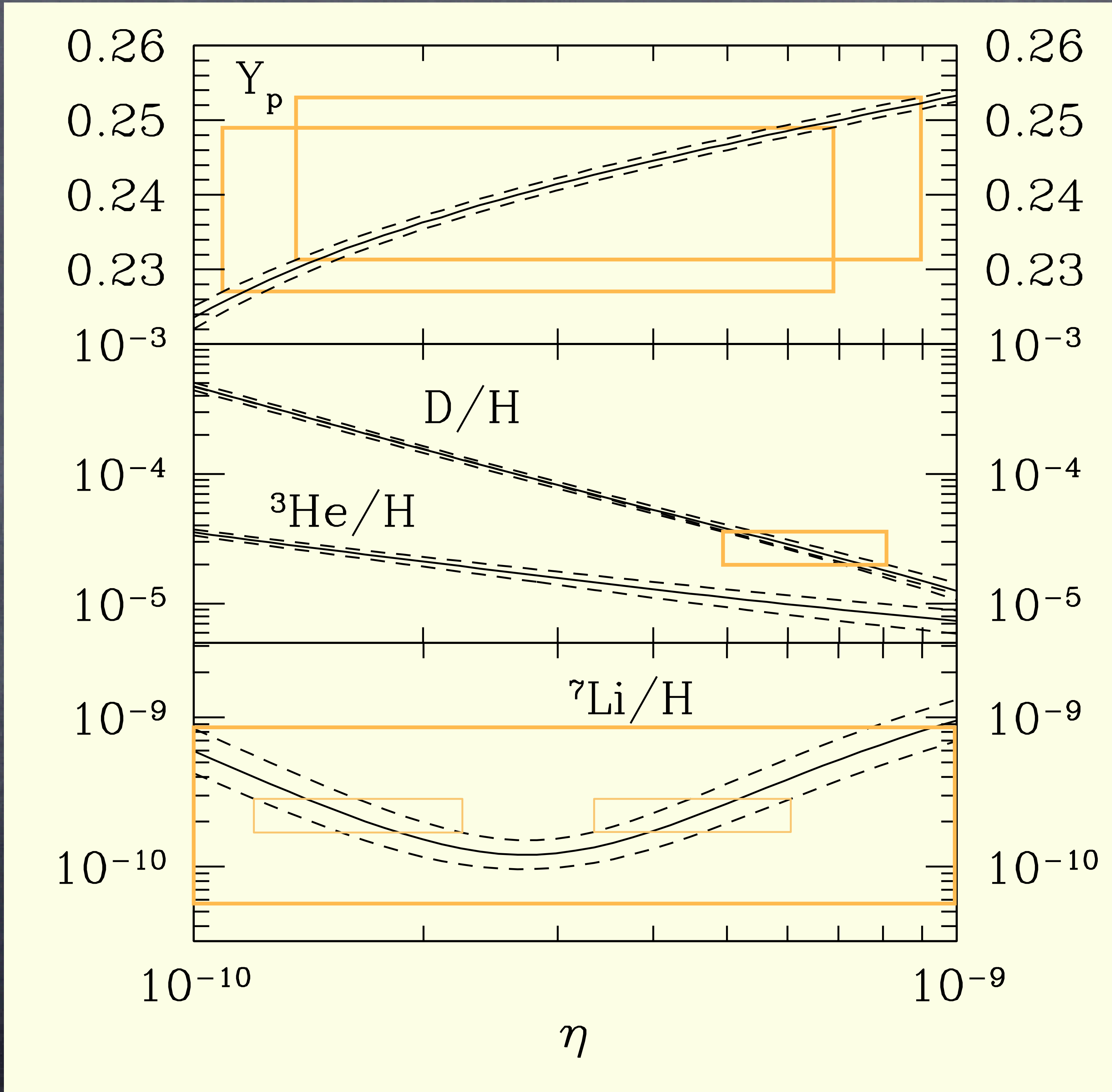
$$^6Li/H < 6 \times 10^{-11} \quad (2\sigma)$$

Smith et al. (1993)

- He3/D

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

Geiss (1993)



0.26
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D/H
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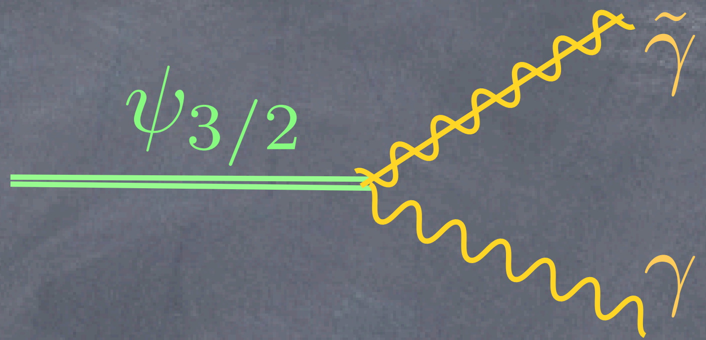
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
η

Gravitino Decay and BBN

Gravitino in Gravity Med.

SUSY Breaking



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

⇒ Unstable

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

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

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

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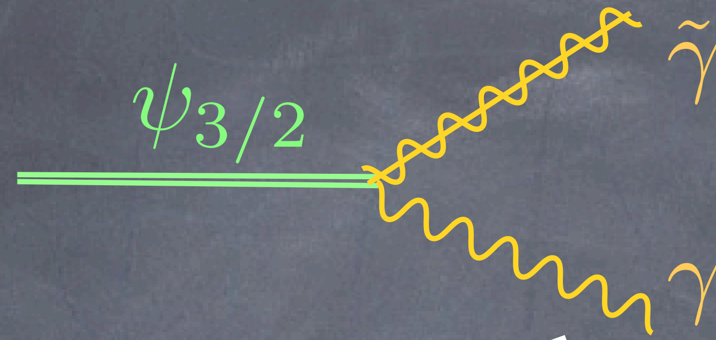
Radiative Decay

Radiative Decay



High Energy Photons

Electromagnetic Cascade

1) Photon-photon pair creation

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

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

2) Inverse Compton

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

3) Photon-photon scattering

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

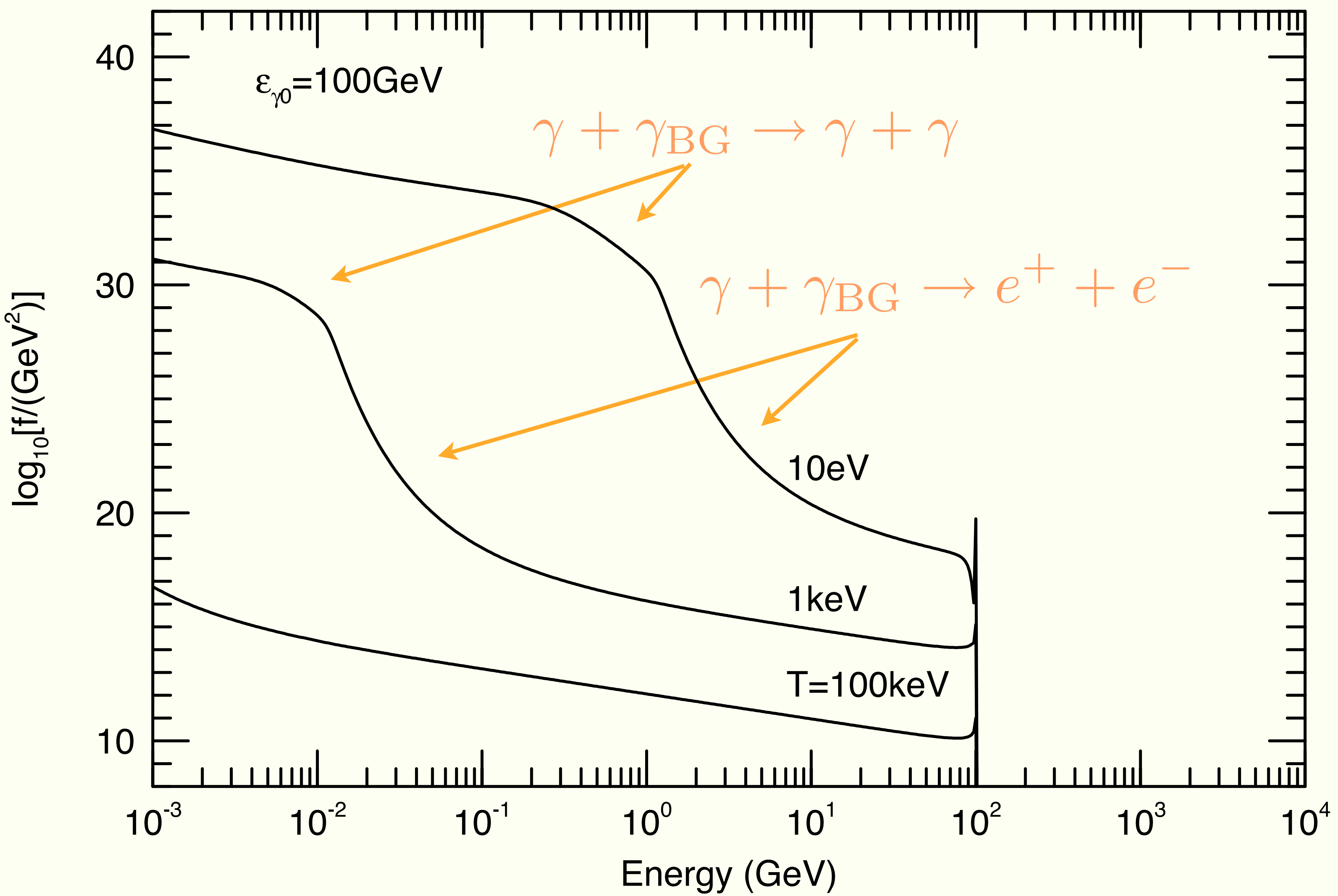
$$\epsilon_\gamma > m_e^2/80T$$

4) Thomson scattering

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

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

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

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

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

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

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

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

etc

	Photodissociation Reactions	1-σ Uncertainty	Threshold Energy
1.	$\mathrm{D} + \gamma \rightarrow p + n$	6%	2.2 MeV
2.	$\mathrm{T} + \gamma \rightarrow n + \mathrm{D}$	14%	6.3 MeV
3.	$\mathrm{T} + \gamma \rightarrow p + 2n$	7%	8.5 MeV
4.	${}^3\mathrm{He} + \gamma \rightarrow p + \mathrm{D}$	10%	5.5 MeV
5.	${}^3\mathrm{He} + \gamma \rightarrow n + 2p$	15%	7.7 MeV
6.	${}^4\mathrm{He} + \gamma \rightarrow p + \mathrm{T}$	4%	19.8 MeV
7.	${}^4\mathrm{He} + \gamma \rightarrow n + {}^3\mathrm{He}$	5%	20.6 MeV
8.	${}^4\mathrm{He} + \gamma \rightarrow p + n + \mathrm{D}$	14%	26.1 MeV
9.	${}^6\mathrm{Li} + \gamma \rightarrow$ anything	4%	5.7 MeV
10.	${}^7\mathrm{Li} + \gamma \rightarrow 2n +$ anything	9%	10.9 MeV
11.	${}^7\mathrm{Li} + \gamma \rightarrow n + {}^6\mathrm{Li}$	4%	7.2 MeV
12.	${}^7\mathrm{Li} + \gamma \rightarrow {}^4\mathrm{He} +$ anything	9%	2.5 MeV
13.	${}^7\mathrm{Be} + \gamma \rightarrow p + {}^6\mathrm{Li}$	4%	
14.	${}^7\mathrm{Be} + \gamma \rightarrow$ anything except ${}^6\mathrm{Li}$	9%	

Non-thermal Production of Li6

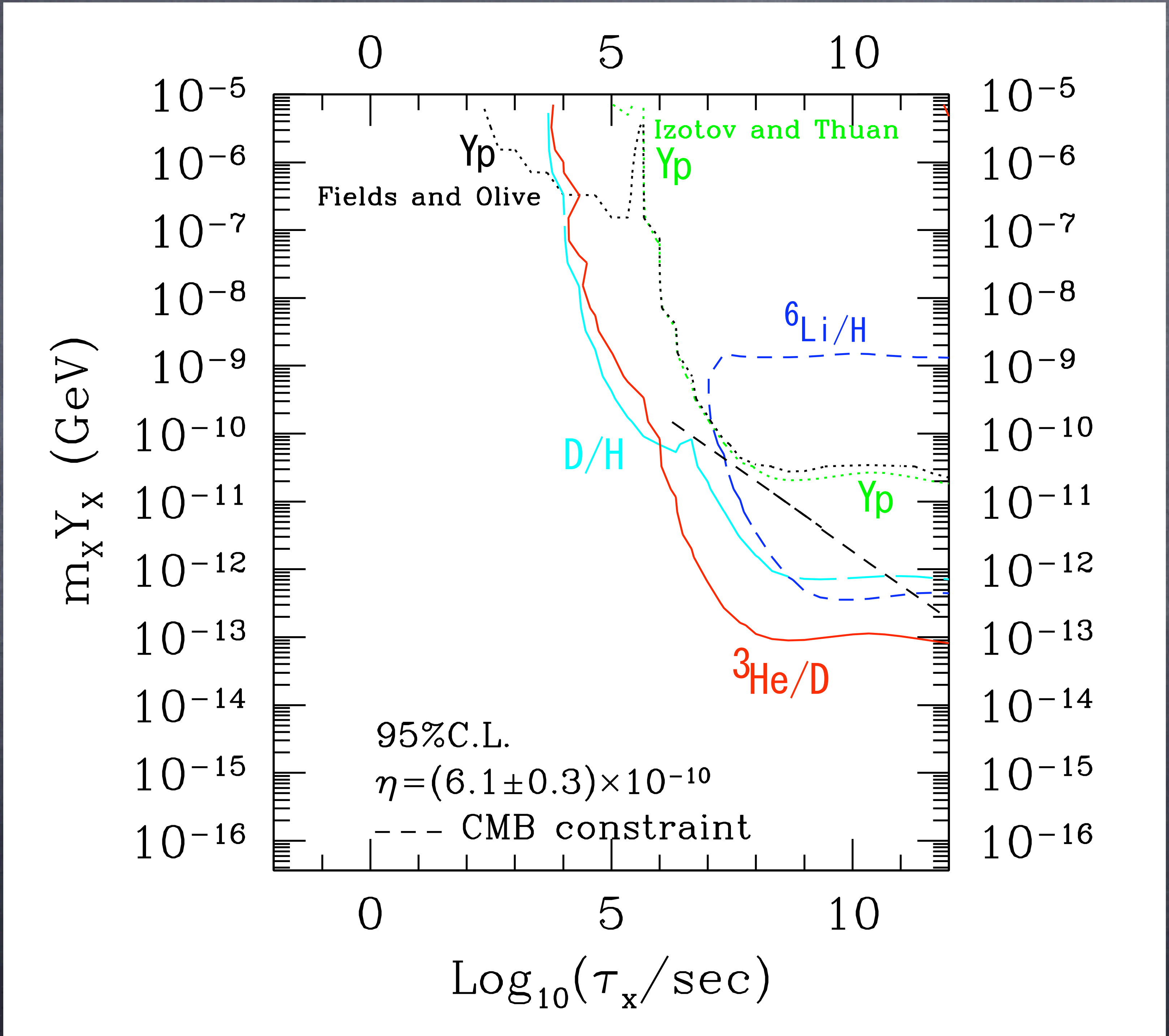
Dimopoulos et al (1989)
Jedamzik (2000)

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

$$\begin{aligned} \mathrm{T} +^4\mathrm{He} \ &\to \ ^6\mathrm{Li} + n \quad [4.03\mathrm{MeV}] \\ ^3\mathrm{He} +^4\mathrm{He} \ &\to \ ^6\mathrm{Li} + p \quad [4.8\mathrm{MeV}] \end{aligned}$$

$$\frac{dE}{dx} = \frac{Z^2\alpha}{v^2}\omega_p^2 \ln\left(\frac{\Lambda m_e v^2}{\omega_p}\right) \qquad \omega_p^2 = 4\pi n_e \alpha / m_e$$

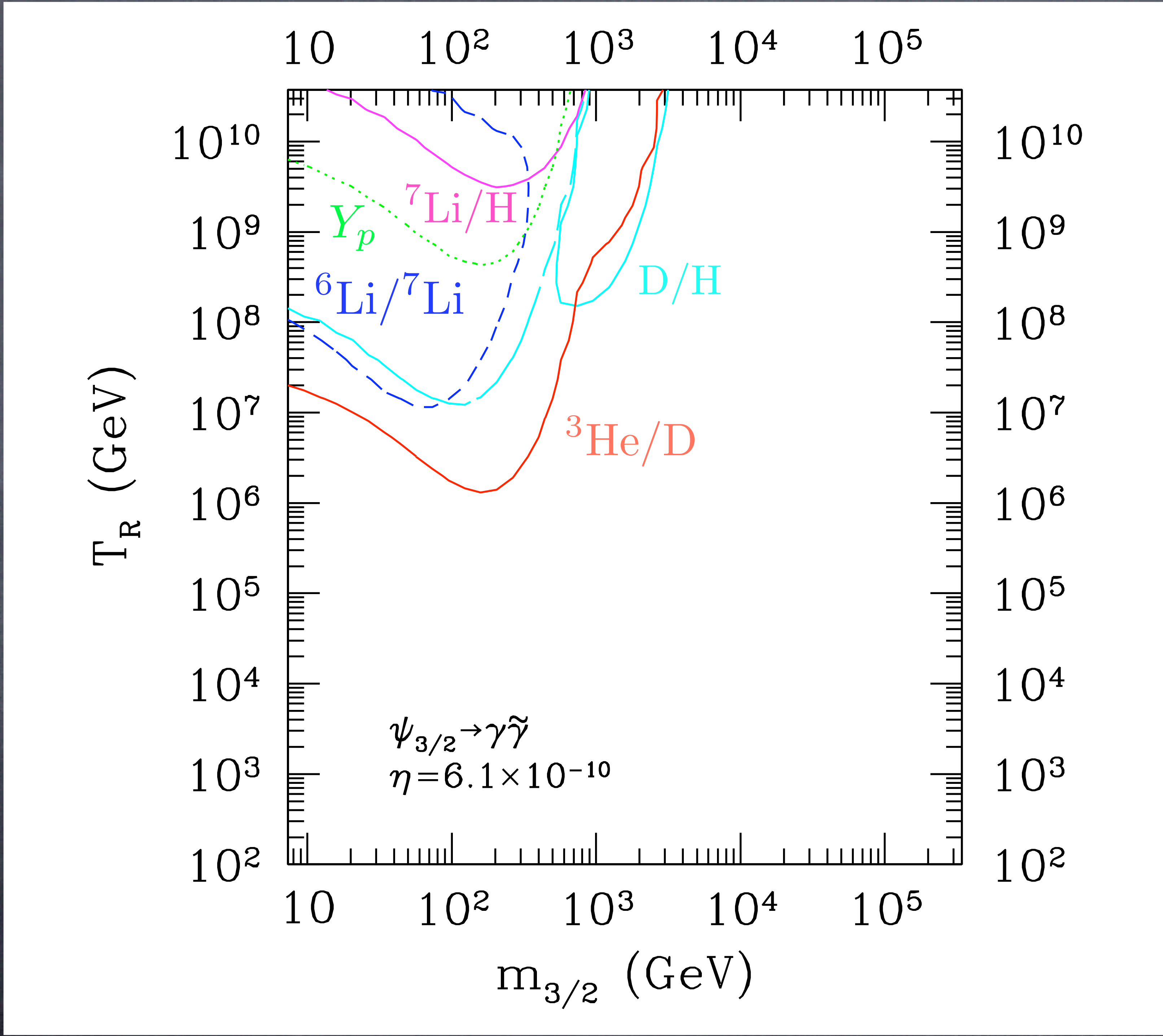
Constraint



Izotov and Thuan
Yp
Yp
Fields and Olive
6Li/H
D/H
Yp
3He/D
95%C.L.
η=(6.1±0.3)×10−10
- - - CMB constraint
m_X Y_X (GeV)
Log10(τ_X/sec)

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

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

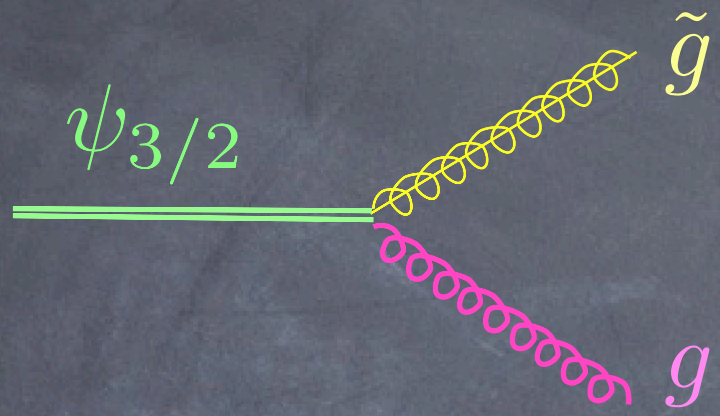


10
10^2
10^3
10^4
10^5
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
^{7}Li/H
Y_p
^{6}Li/^{7}Li
D/H
^{3}He/D
$\psi_{3/2} \to \gamma\tilde{\gamma}$
$\eta = 6.1 \times 10^{-10}$
T_R (GeV)
$m_{3/2}$ (GeV)

Hadronic Decay

Hadronic Decay

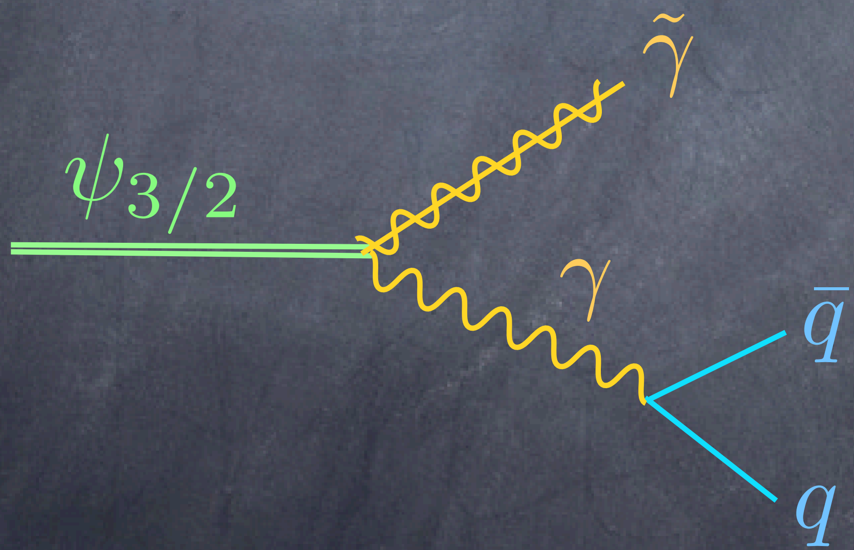
Reno, Seckel (1988)
Dimopoulos et al (1989)



$B_h \sim 1$

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

However, a reliable constrain was not obtained for hadronic decay

- Process is very complicated

- Hadron spectrum in hadron jets
- hadonic cascade processes
- Energy loss processes by background plasma
- . . . .

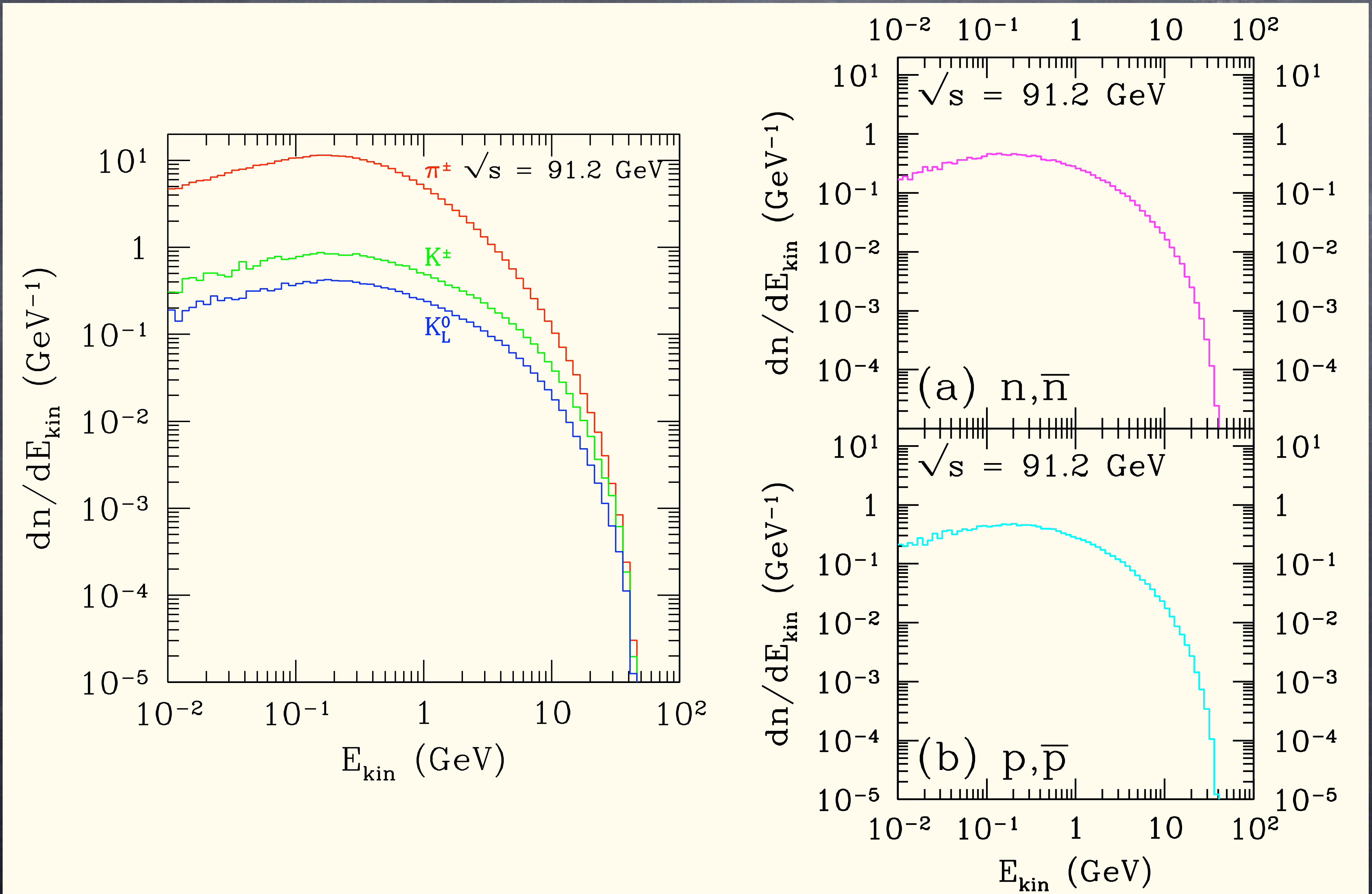
New Calculation

MK. Kohri, Moroi astro-ph/0402490

- Take into account energy loss processes for high enrgy neuclei
- Take into account energy distribution of nucleons in elastic processes
- Take a reasonable value for energy of nucleus after inelastic processes with use of many experimental data
- JETSET is used for obtaining initial hadron spectrum
- Take account of neutron decay
- Evaluate uncertainties in reaction rates and so on

Spectrum of hadron jets

JETSET 7.4



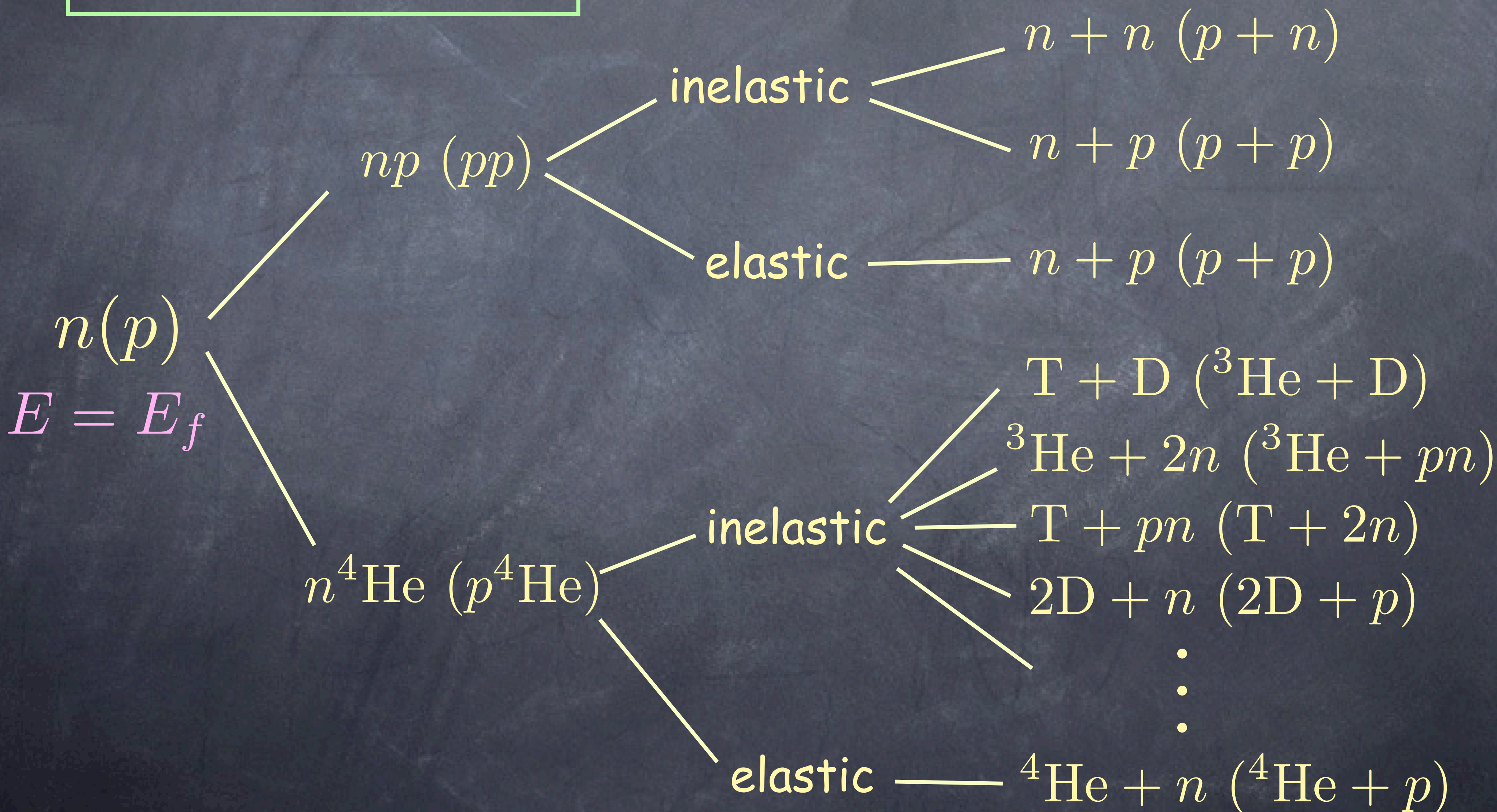
Kohri 2001

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

$$v_N > \langle v_e \rangle$$

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

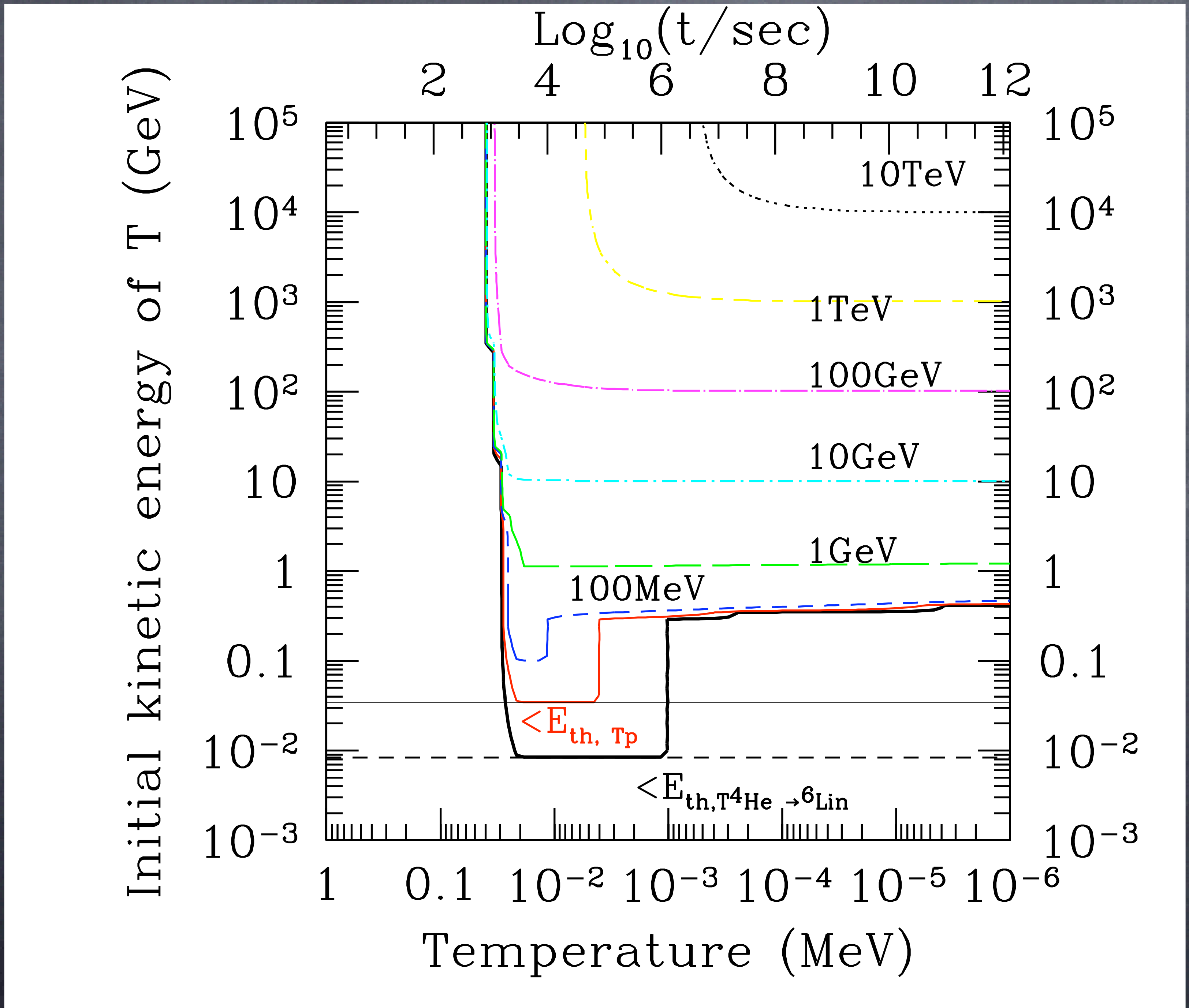
- Non-relativistic Nucleus

$$v_N < \langle v_e \rangle$$

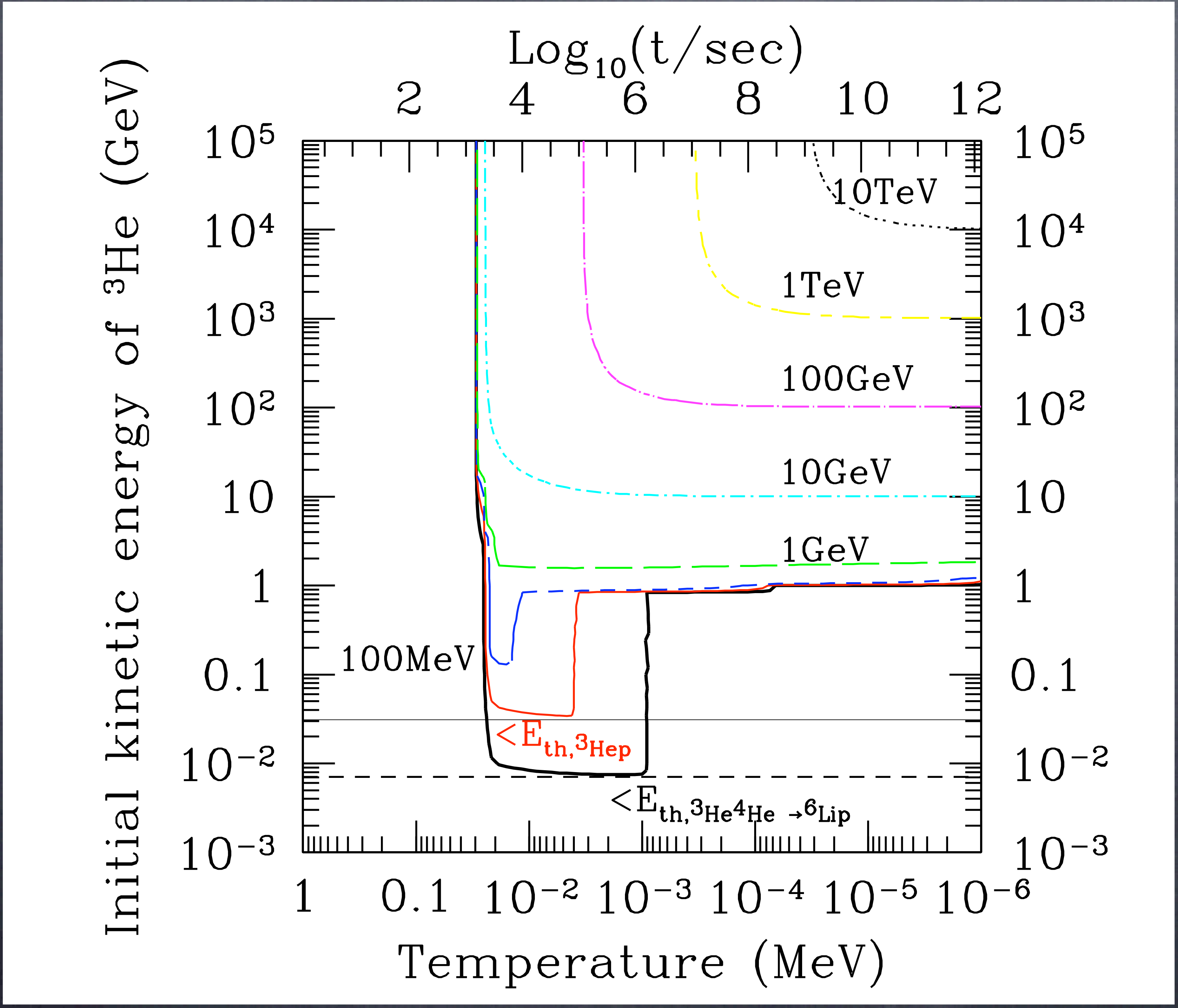
$$\frac{dE}{dt} = \frac{4\pi\alpha^2 v_N^2 \Lambda n_e}{3 m_e \langle v_e \rangle} \qquad \Lambda \sim O(1)$$

Inefficient Energy Loss !

Final Energy of T



Final Energy of He3



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

↓

Run BBN code

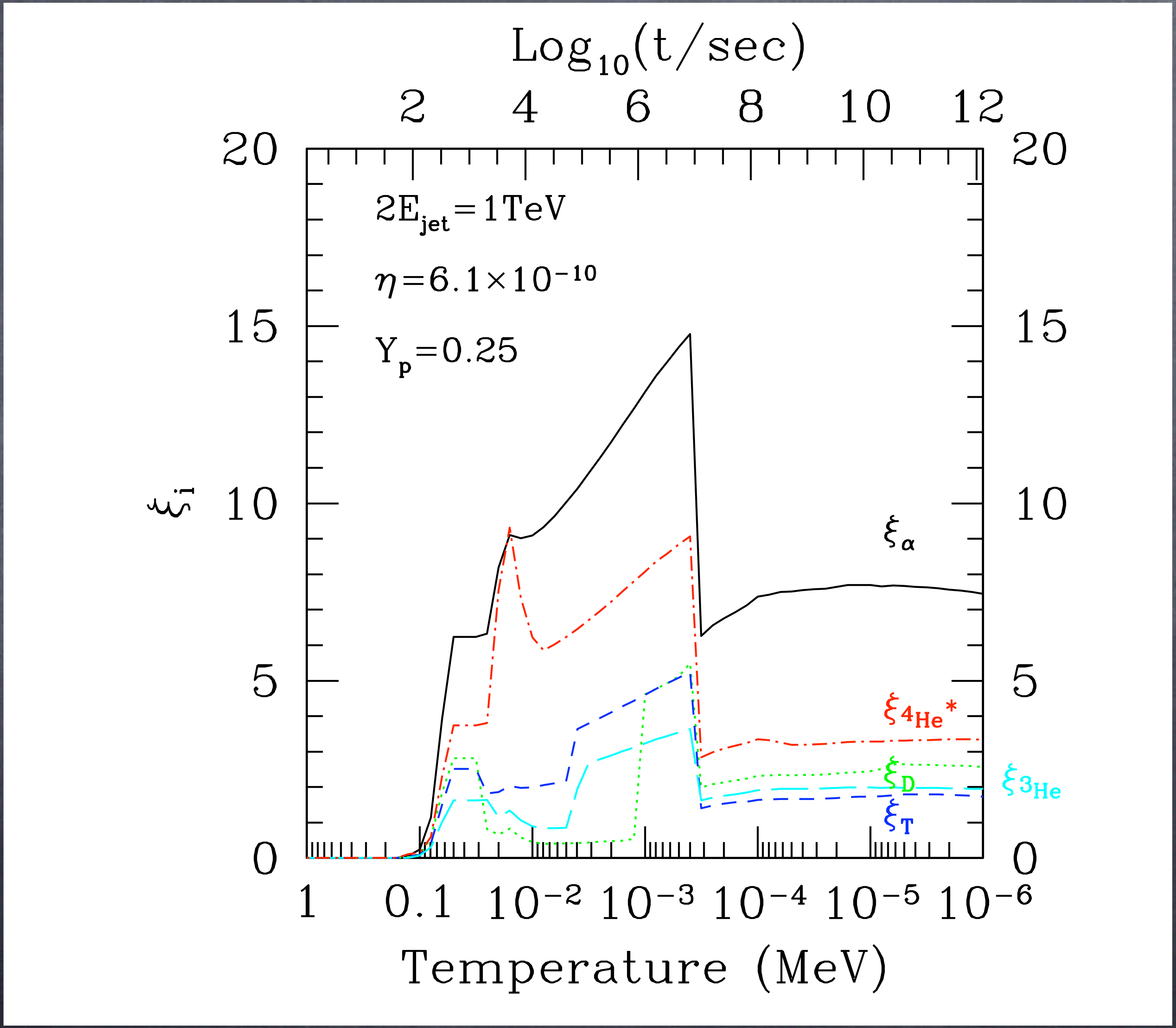
↓

Compare theoretical and observational abundances of light elements

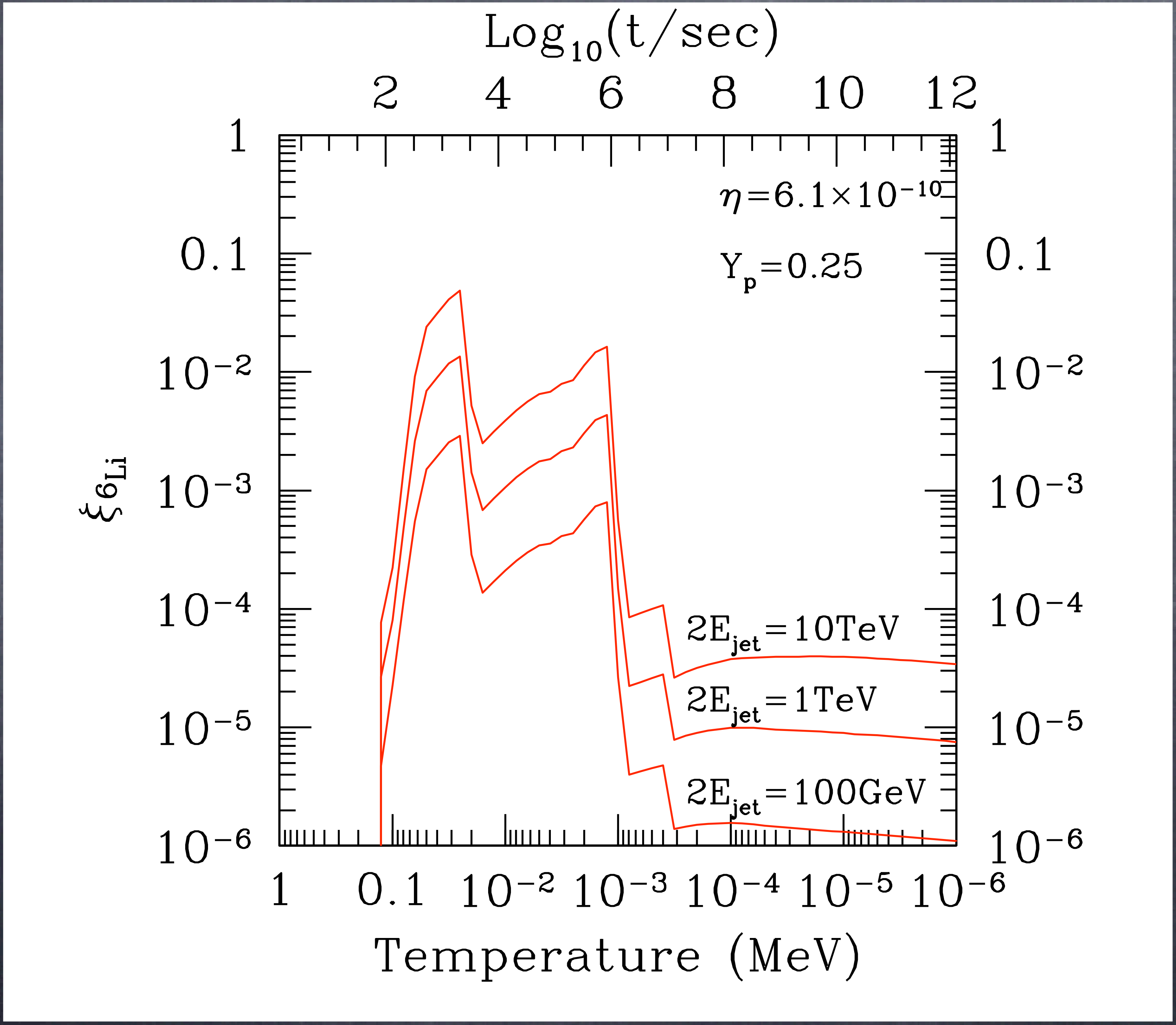
↓

Constraint on abundance and lifetime of gravitino

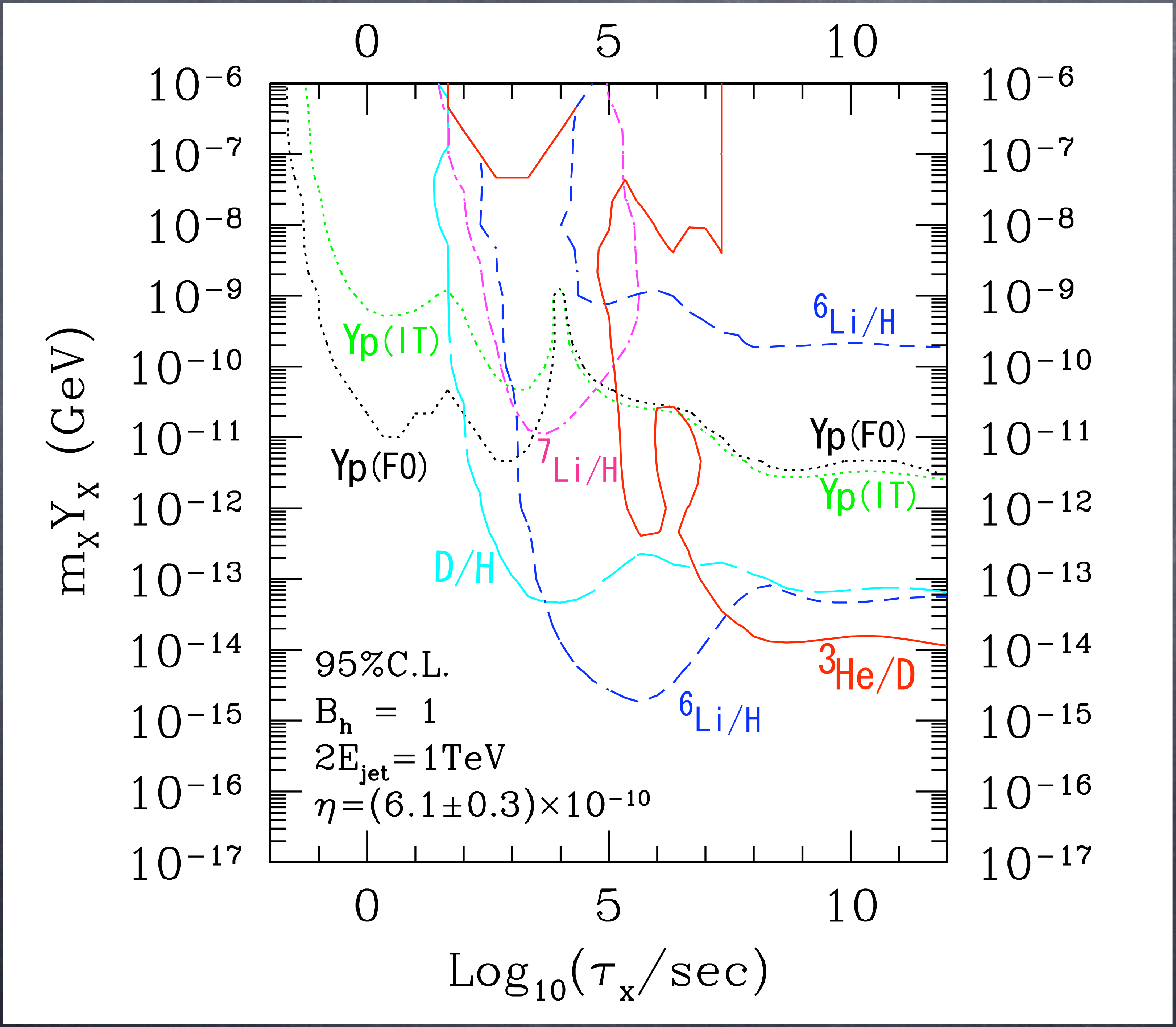
ξ_i : number of nuclei "i" produced per one massive particle decay



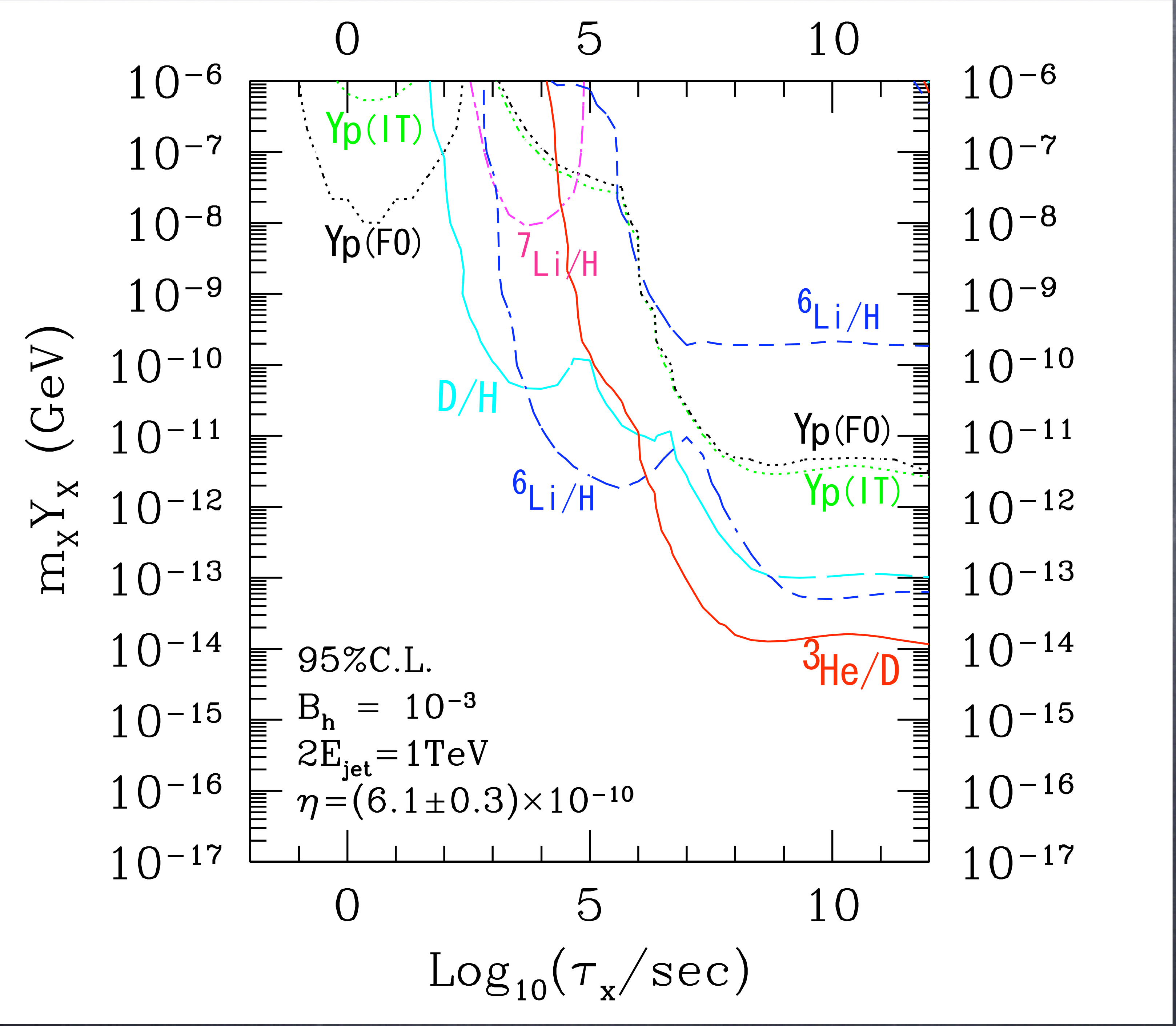
ξ_i : number of nuclei "i" produced per one massive particle decay



Constraint on Abundance and Lifetime



Constraint on Abundance and Lifetime (2)



Non-thermal Production of Li6

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

$$\begin{array}{lcll} \mathrm{T} + {}^{4}\mathrm{He} & \rightarrow & {}^{6}\mathrm{Li} + n & [4.03\mathrm{MeV}] \\ {}^{3}\mathrm{He} + {}^{4}\mathrm{He} & \rightarrow & {}^{6}\mathrm{Li} + p & [4.8\mathrm{MeV}] \end{array}$$

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

$$T_R \lesssim 10^4 - 10^7 \text{ GeV}$$

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