Dark Matter Search by Big-bang Nucleosynthesis

Kazunori Kohri （郡　和範）

Physics Department, Tohoku University

(moved from Lancaster in July)

Abstract

- Small amounts of DM can annihilate even after the freezeout. Then this residual annihilation may affect BBN
- When we consider velocity-dependent cross section to fit PAMELA and Fermi data with satisfying the DM density, BBN gives us severe constraints on the cross section.

Thermal freezeout

Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle[(n_\chi)^2 - (n_\chi^{eq})^2]$$

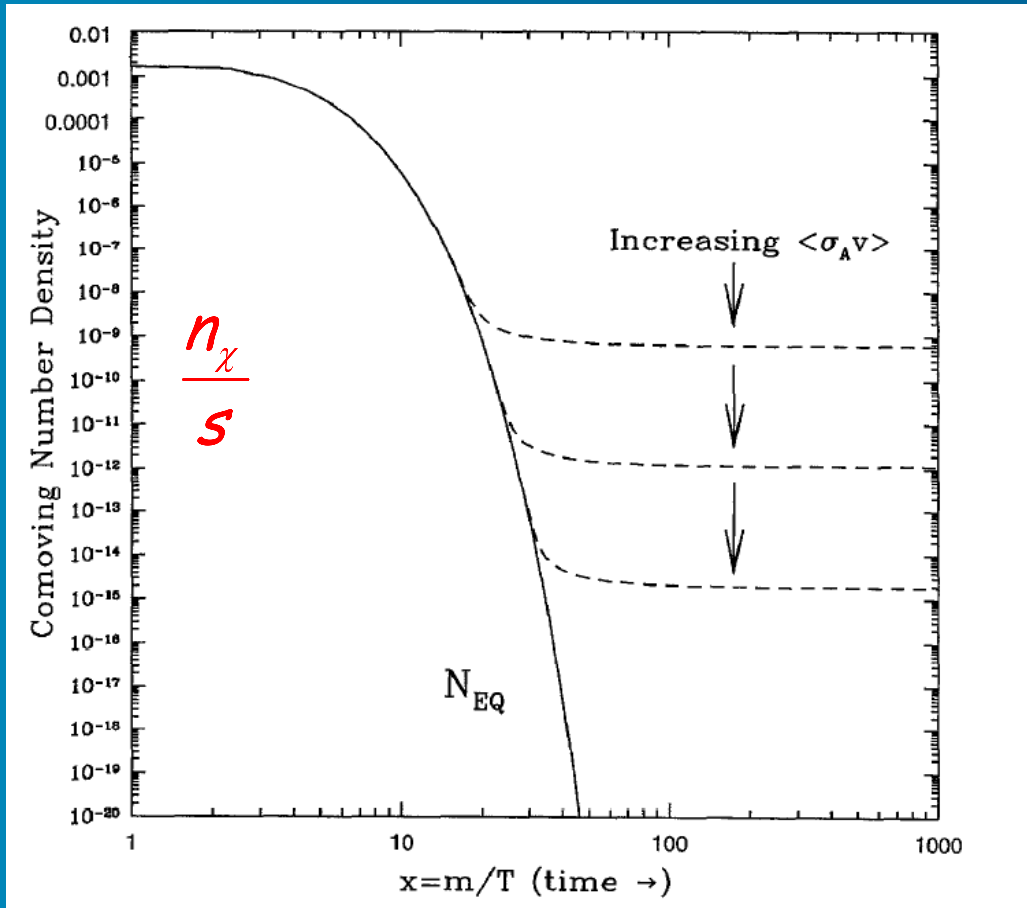
$$n_\chi \sim \left.\frac{3H}{\langle\sigma v\rangle}\right|_{\text{frezeout}}$$

$$T_{\text{Freezeout}} \sim m_\chi / 20$$

$$\Omega_\chi h^2 \sim 0.1\left(\frac{\langle\sigma v\rangle}{\left(0.1/\text{TeV}\right)^2}\right)$$

Ω_χ does not depend on m_χ

Predicting Weak-scale Physics!!!



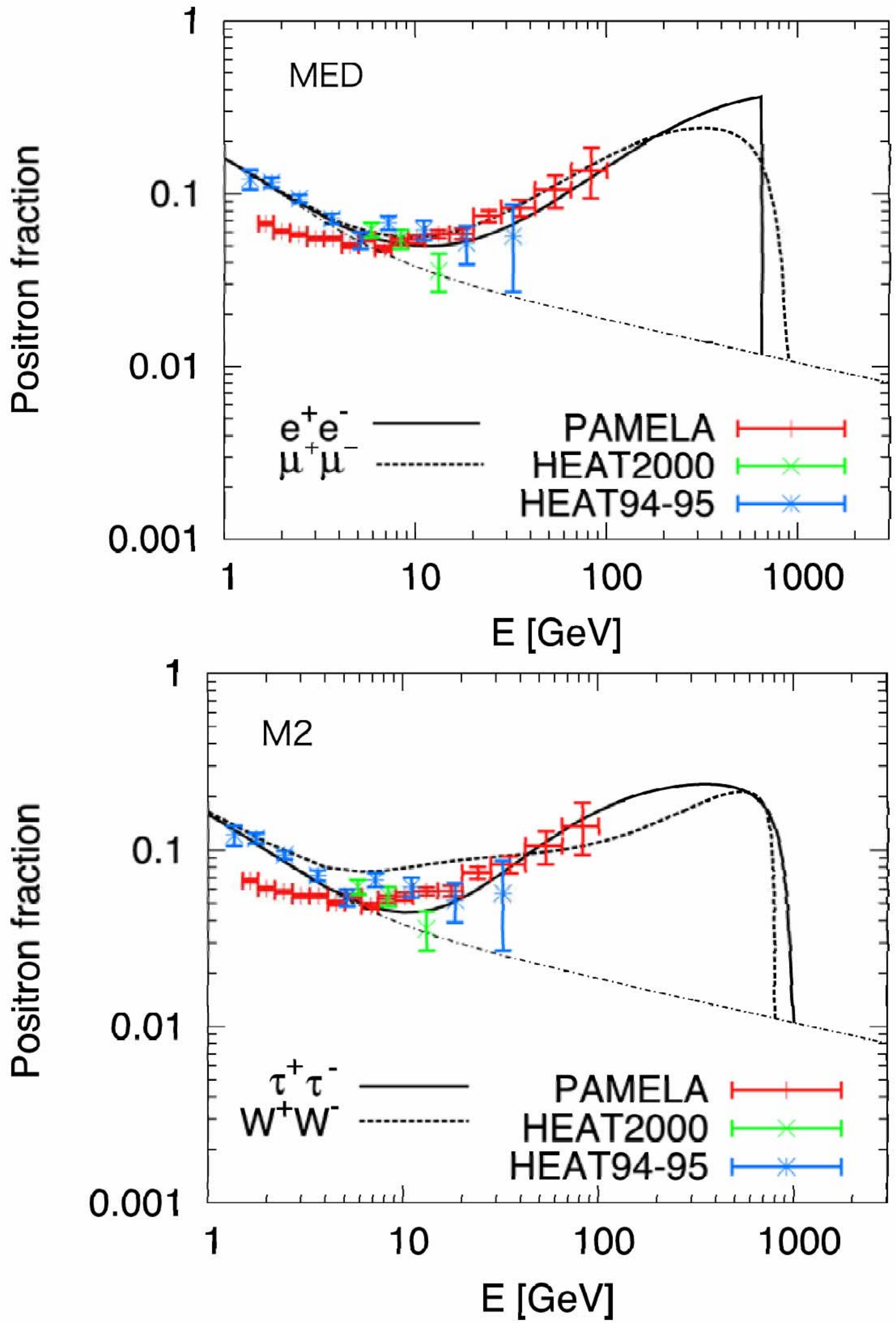
Kolb & Turner

$$\langle\sigma v\rangle = 3\times10^{-26}\,cm^3/sec$$

Positron excess in DM annihilation

Hisano, Kawasaki, Kohri, Moroi, Nakayama (09)

$$\langle \sigma v \rangle \sim 10^{-23} cm^3 / s$$

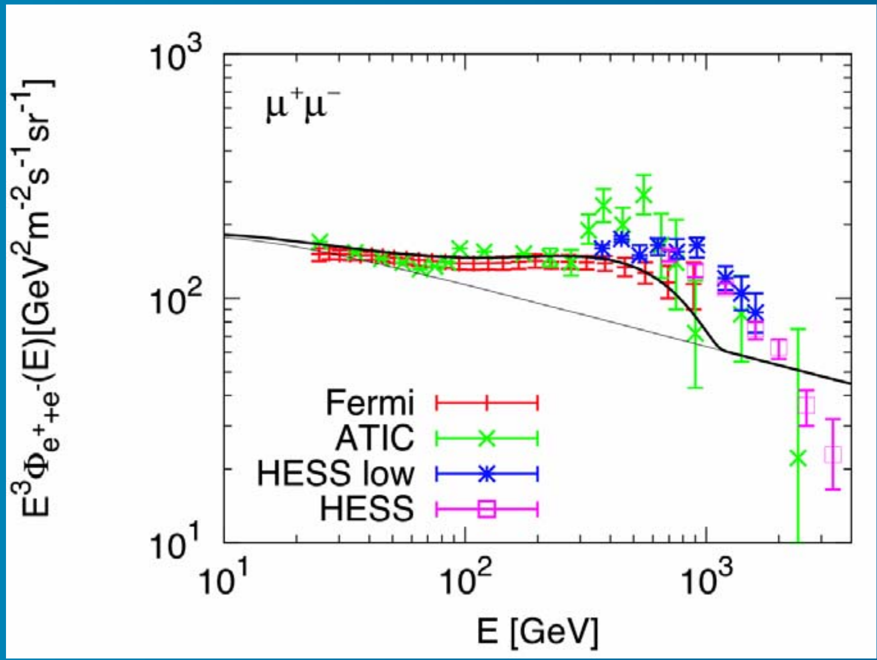


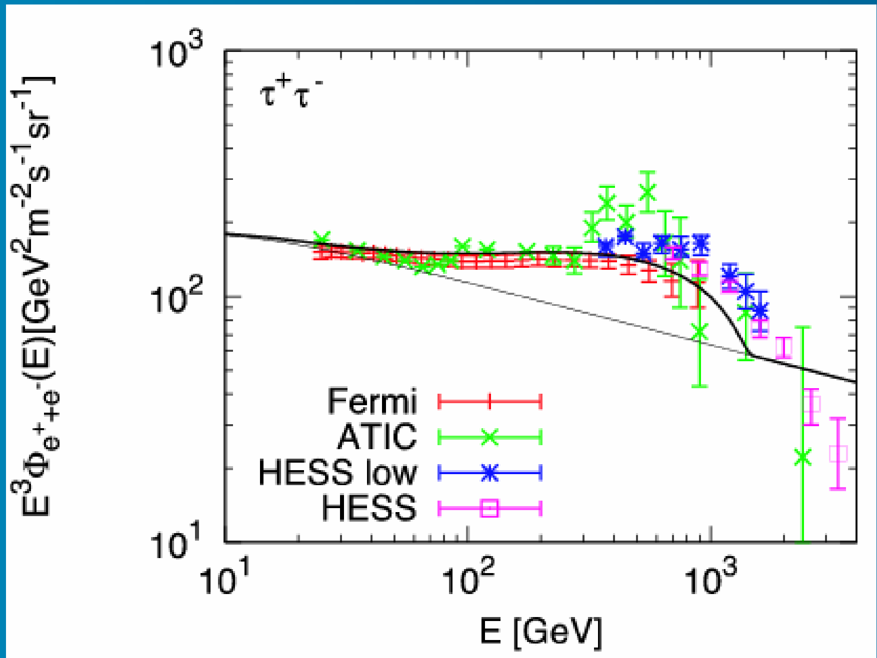
Electron/positron cutoff in DM annihilation

Hisano, Kawasaki,

Kohri, Moroi, Nakayama (09)

$$\langle \sigma v \rangle \sim 10^{-23} cm^3/s$$





Residual annihilation of DM at BBN

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} \sim -\langle \sigma v \rangle_{ann} n_{DM}^2$$

$$\Delta\left(\frac{n_{DM}}{s}\right) \sim \frac{\langle \sigma v \rangle_{ann} n_{DM}}{H} \frac{n_{DM}}{s}$$

$\ll 1$ but non-zero!

- To fit the PAMELA and ATIC2/Fermi positron and electron signals,

$$\langle \sigma v \rangle \sim 10^{-23} cm^3 / s$$

$O(10^3)$ times larger than canonical value,

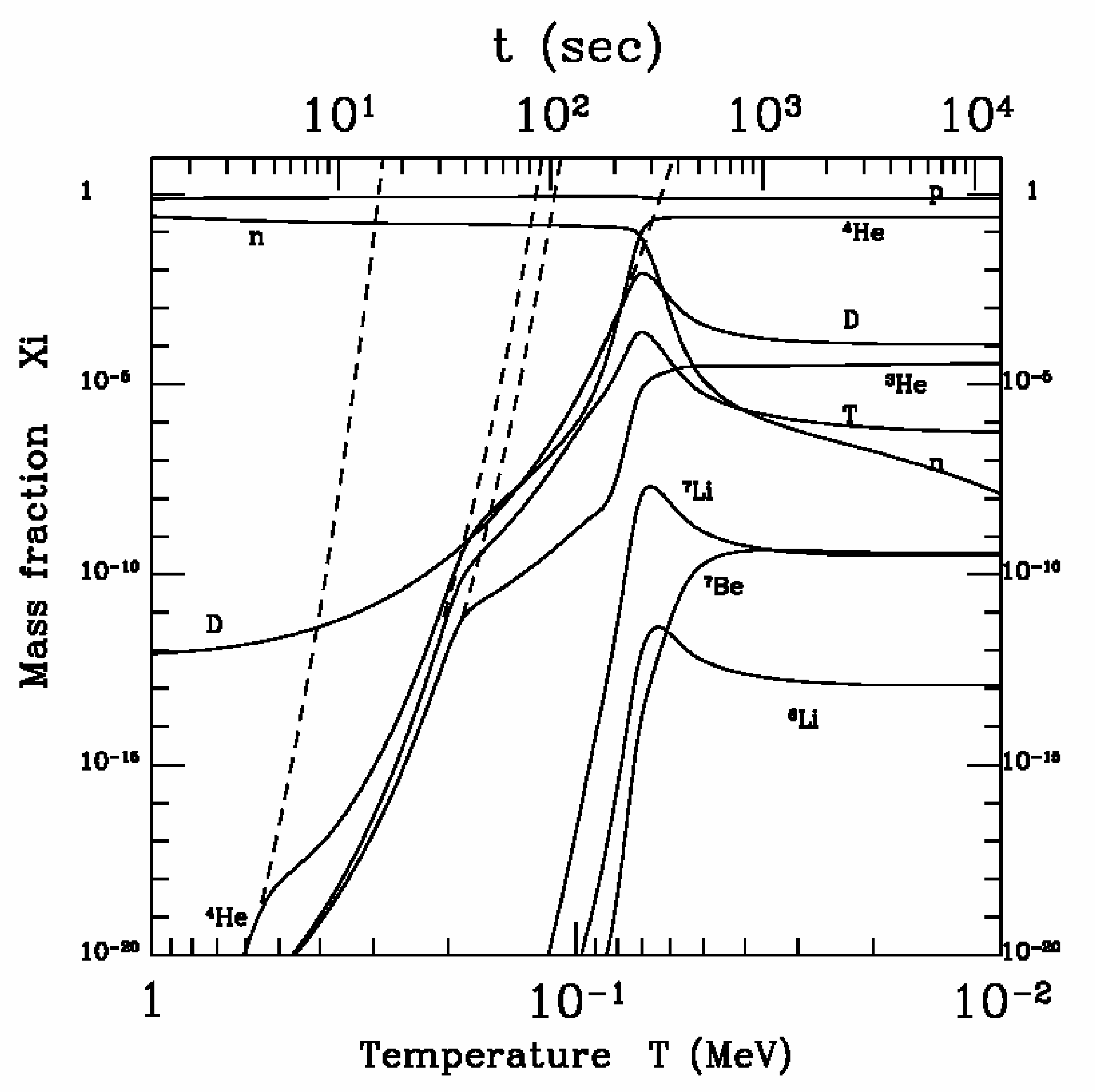
$$\langle \sigma v \rangle_{canonical} \sim 3 \times 10^{-26} cm^3 / s$$

Big-Bang Nucleosynthesis (BBN)

Very strong cosmological tools to study long-lived particles with lifetime longer than 10^{-2} sec

Theoretical predictions are constrained by observational D, 3He, ^{4}He, ^{6}Li and ^{7}Li abundances with their conservative errors.

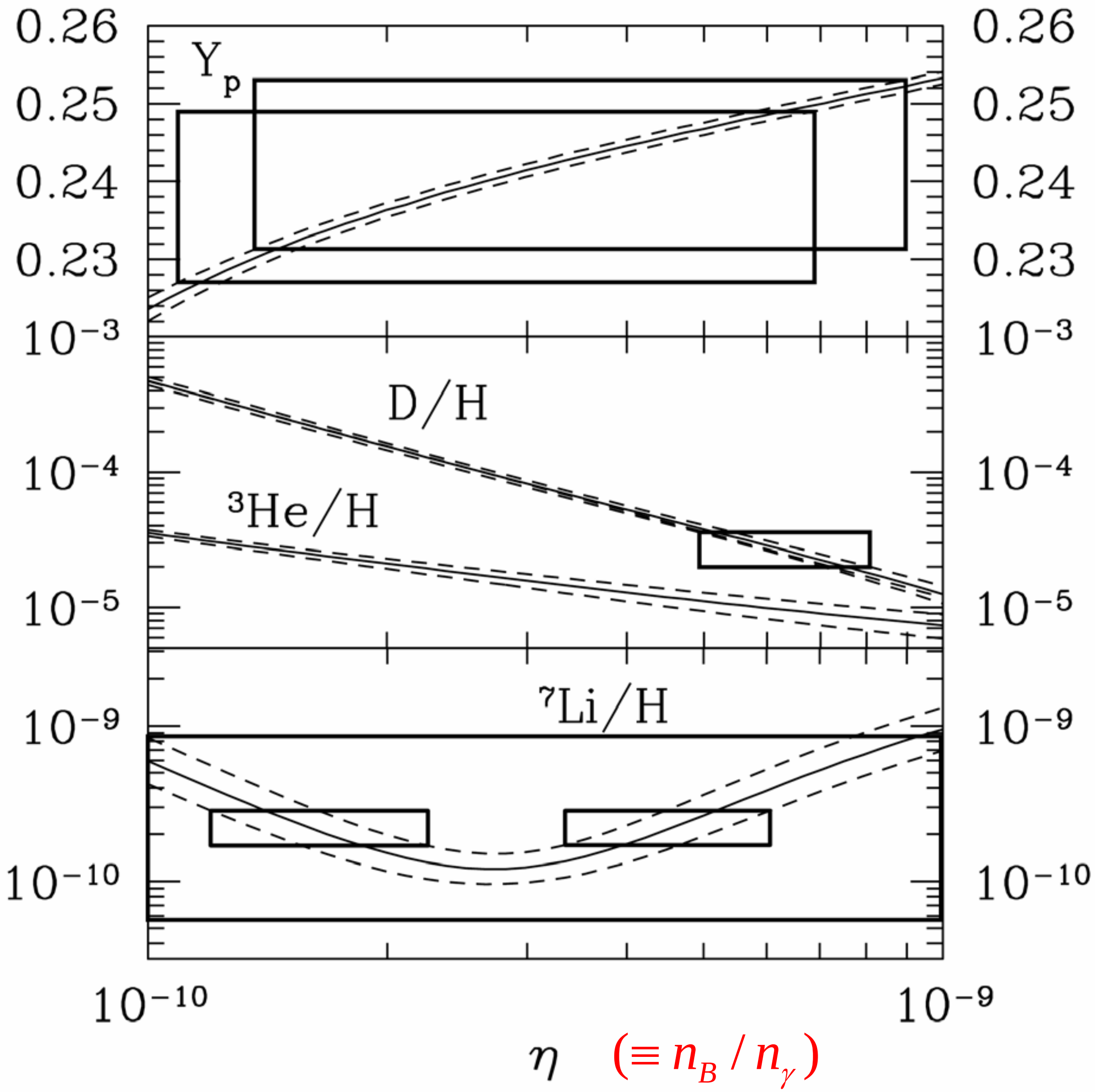
Time evolution of light elements



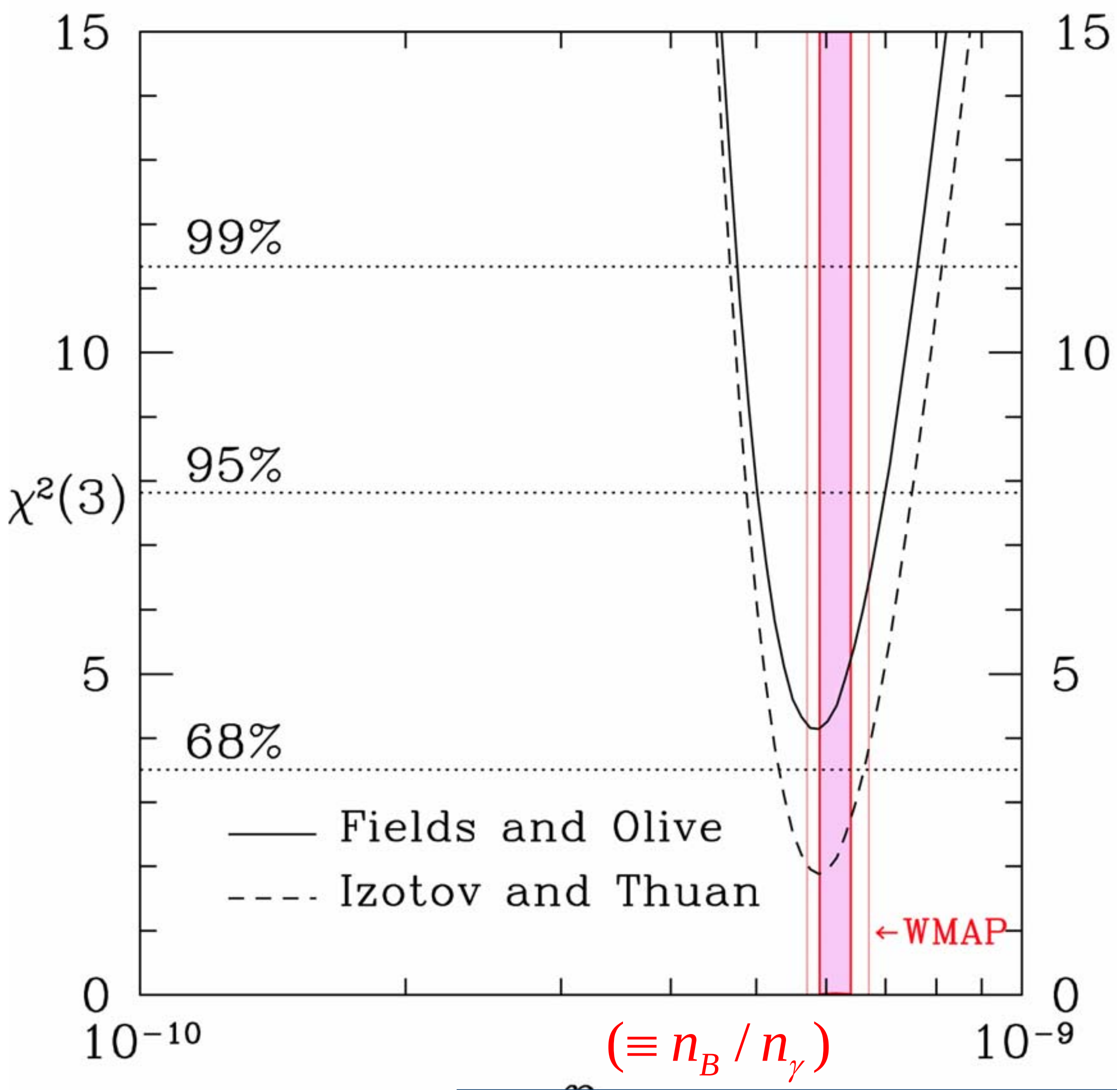
Observational Light Element Abundances

- He4 $Y_p = 0.2516 \pm 0.004$ — Fukugita, Kawasaki (2006); Peimbert,Lridiana, Peimbert(2007); Izotov,Thuan, Stasinska (2007)
- D $D/H = (2.82 \pm 0.26) \times 10^{-5}$ — O'Meara et al. (2006)
- Li7 $\log_{10}\left({}^7Li/H\right) = -9.90 \pm 0.09\ (+0.35)_{syst.}$ — Melendez,Ramirez(2004)
- Li6 ${}^6Li/{}^7Li < 0.046 \pm 0.022\ (+0.106)_{sys}$ — Asplund et al(2006)
- He3 ${}^3He/D < 0.83 + 0.27$ — Geiss and Gloeckler (2003)

SBBN



Yp
D/H
3He/H
7Li/H
0.26
0.25
0.24
0.23
10−3
10−4
10−5
10−9
10−10
10−10
10−9
η (≡ nB / nγ)



$$\eta_{WMAP} = (6.225 \pm 0.160) \times 10^{-10}$$

Annihilation during/after BBN epoch

Electromagnetic mode

$DM + DM \to \gamma$ and / or $e^{\pm}$ emission

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

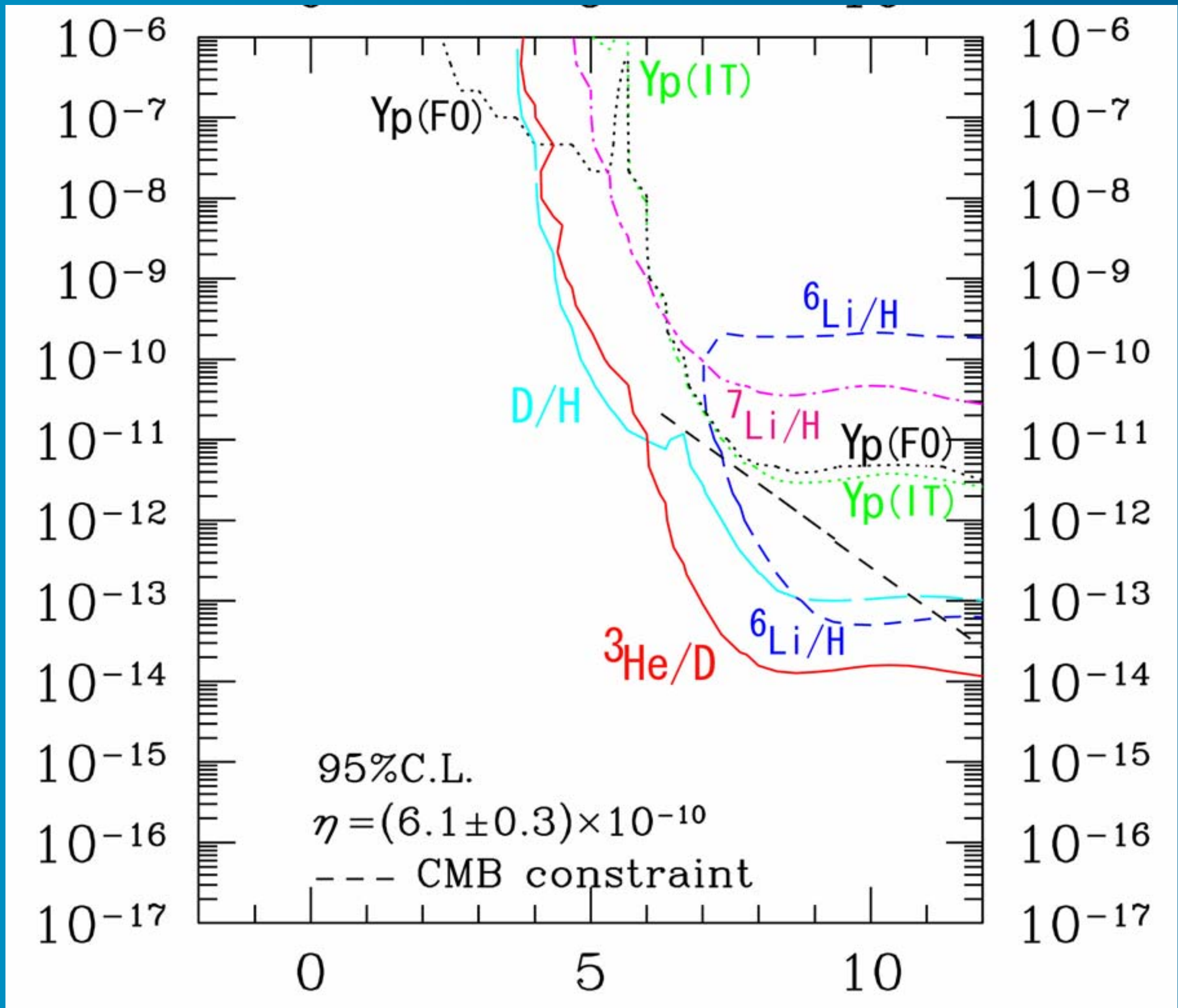
$$\mathrm{D} + \gamma \to p + n,$$
$$^{4}\mathrm{He} + \gamma \to {}^{3}\mathrm{He} + n, \quad \mathrm{T} + p, \quad D + p + n$$
$$^{3}\mathrm{He} + \gamma \to \mathrm{D} + p + n, \quad \text{etc.}$$

He3/D ~ O(1)

Constraints on electromagnetic modes

Kawasaki, Kohri, Moroi (04)

$\log_{10}\left(\frac{\Delta\rho/s}{\mathrm{GeV}}\right)$



$\log_{10}(t/\mathrm{sec})$

Hadronic mode

$$DM + DM \rightarrow \begin{pmatrix} q + \bar{q} \\ W^{\pm} \\ Z \end{pmatrix} \rightarrow \begin{pmatrix} p, \bar{p} \\ n, \bar{n} \\ \pi^0 \rightarrow 2\gamma \\ \pi^{\pm} \end{pmatrix}$$

(I) Early stage of BBN (T > 0.1MeV)

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

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

Even after freeze-out of n/p in SBBN

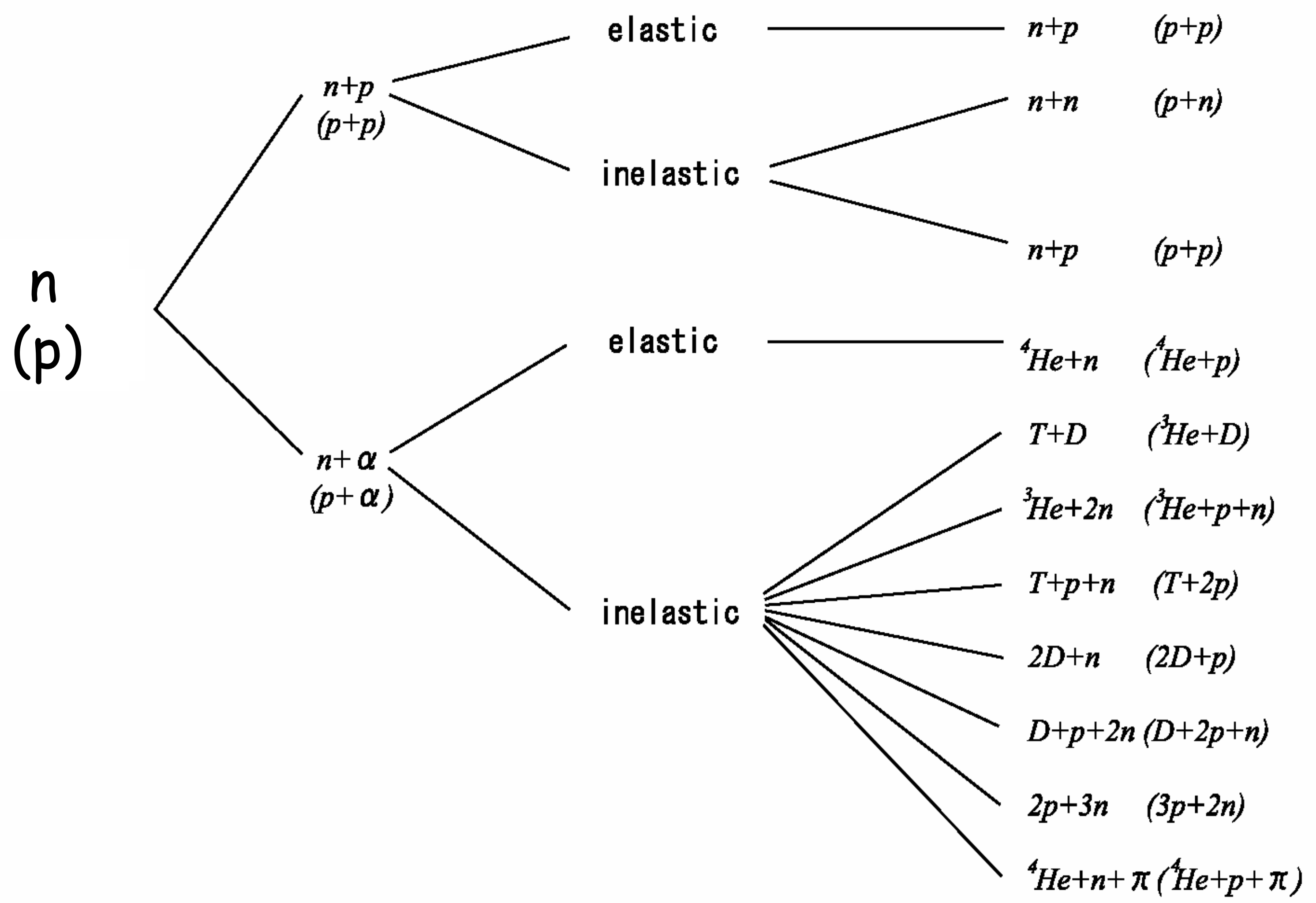
More He4, D, Li7 ...

(II) Late stage of BBN (T < 0.1MeV)

Hadronic showers and "Hadro-dissociation" occur

S. Dimopoulos et al. (1988)

Kawasaki, Kohri, Moroi (2004)

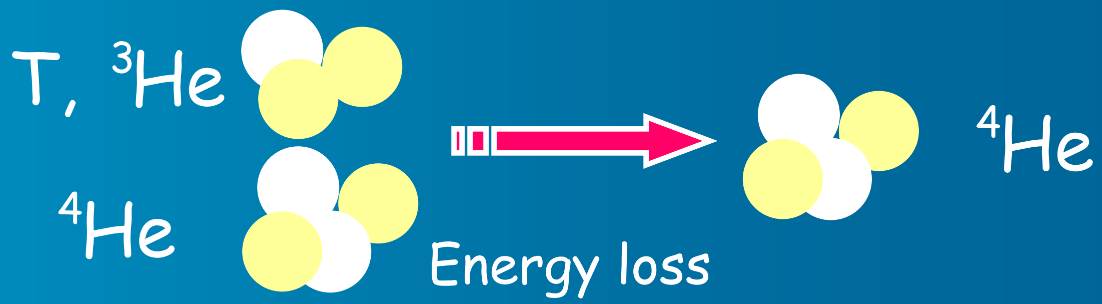


Non-thermal Li, Be Production by energetic nucleons or photons

Dimopoulos et al (1989)
Jedamzik (2000)

$$N\ (\text{or}\ \gamma) + {}^4He \rightarrow \begin{cases} {}^3He + X \\ T + X \end{cases}$$

$$N\ (\text{or}\ \gamma) + {}^4He \rightarrow {}^4He^* + X$$



① T(He3) – He4 collision

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

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

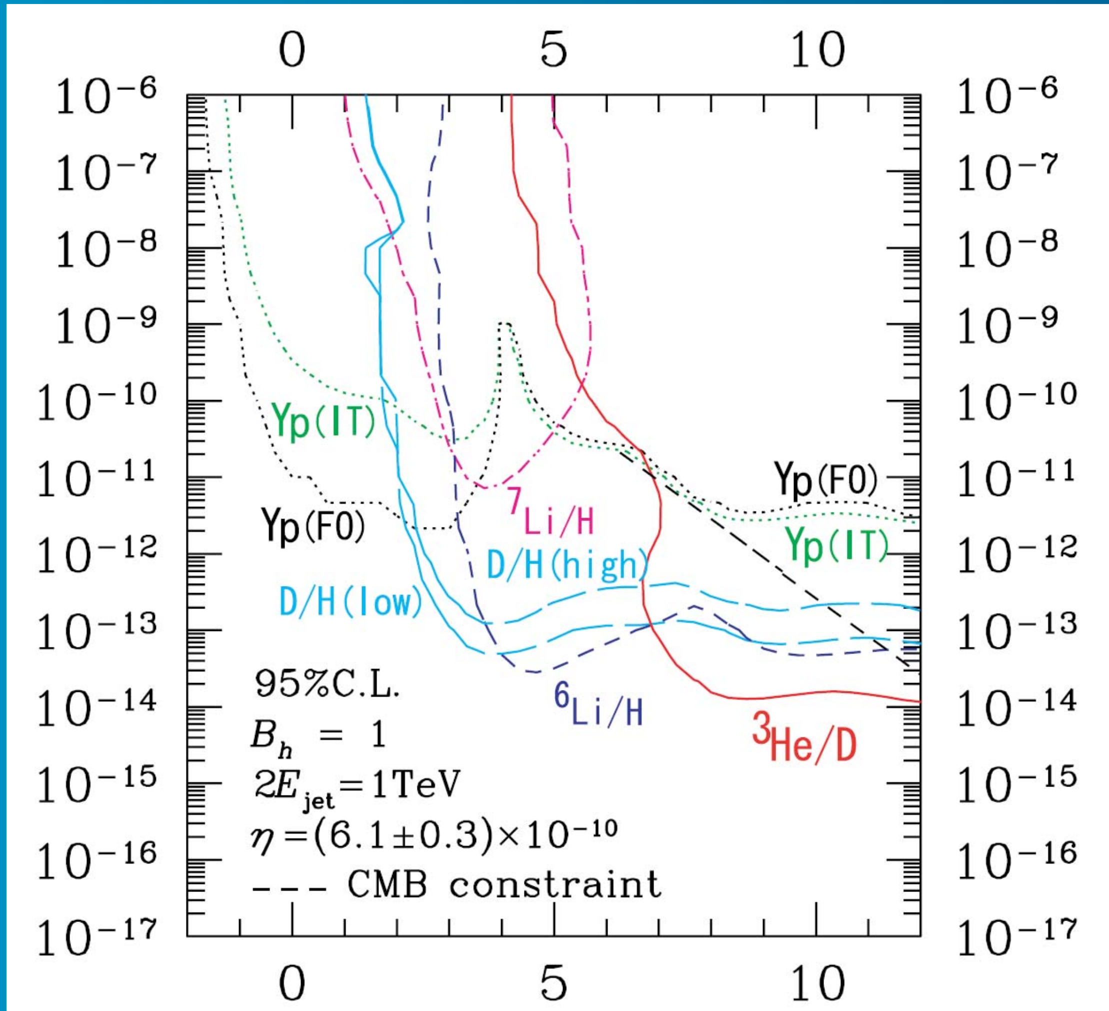
② He4 – He4 collision

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

Constraints on hadronic modes

Kawasaki, Kohri, Moroi (04)

$\log_{10}\left(\frac{\Delta\rho / s}{GeV}\right)$



$\log_{10}(t / sec)$

Residual annihilation of DM at BBN

- To fit the PAMELA and ATIC2/Fermi positron and electron signals ,

$$\langle \sigma v \rangle \sim 10^{-23} cm^3 / s$$

- At least it must emit charged leptons

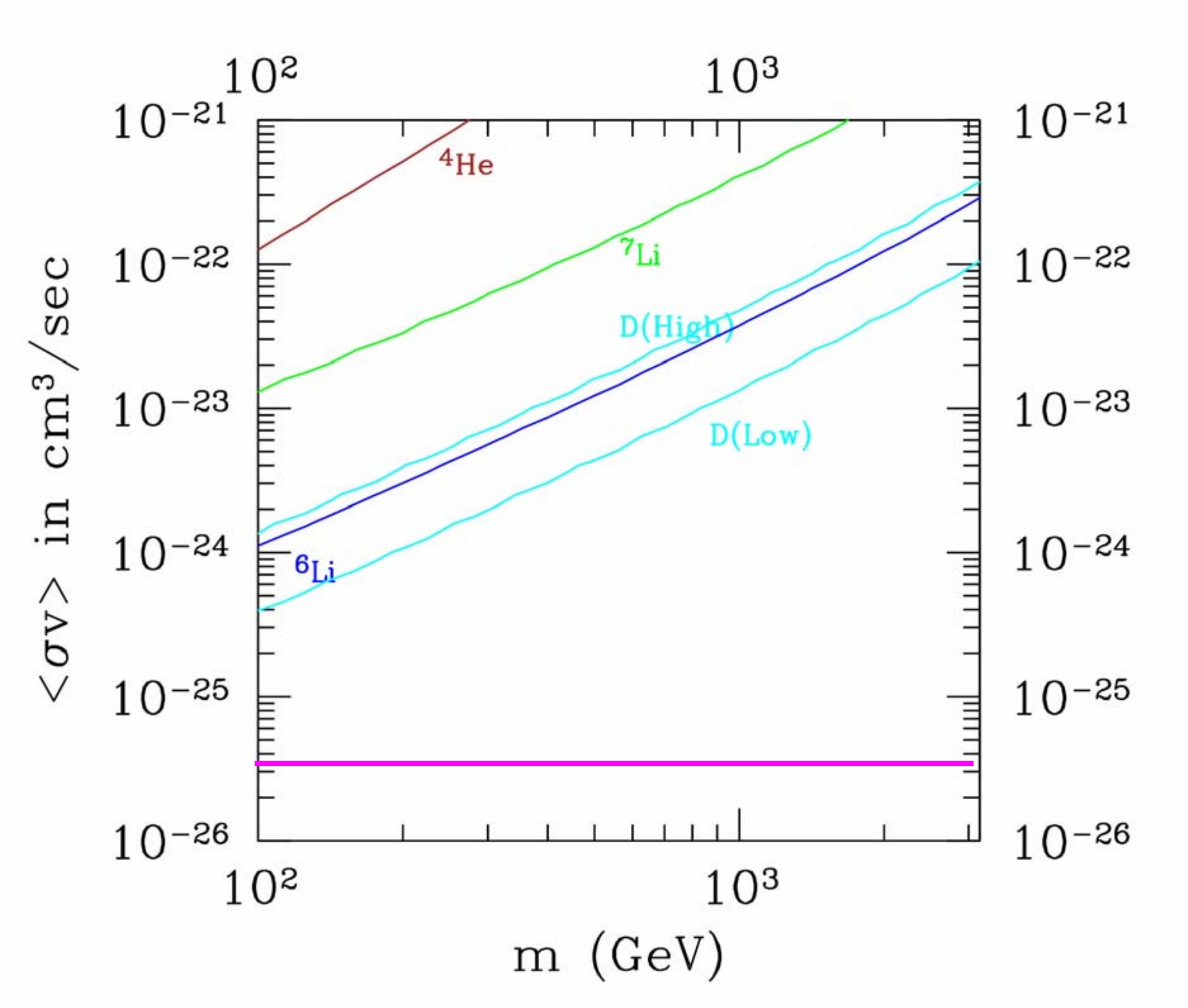
Electromagnetic cascade shower is induced

- It might also emit hadrons

Hadronic cascade shower is induced

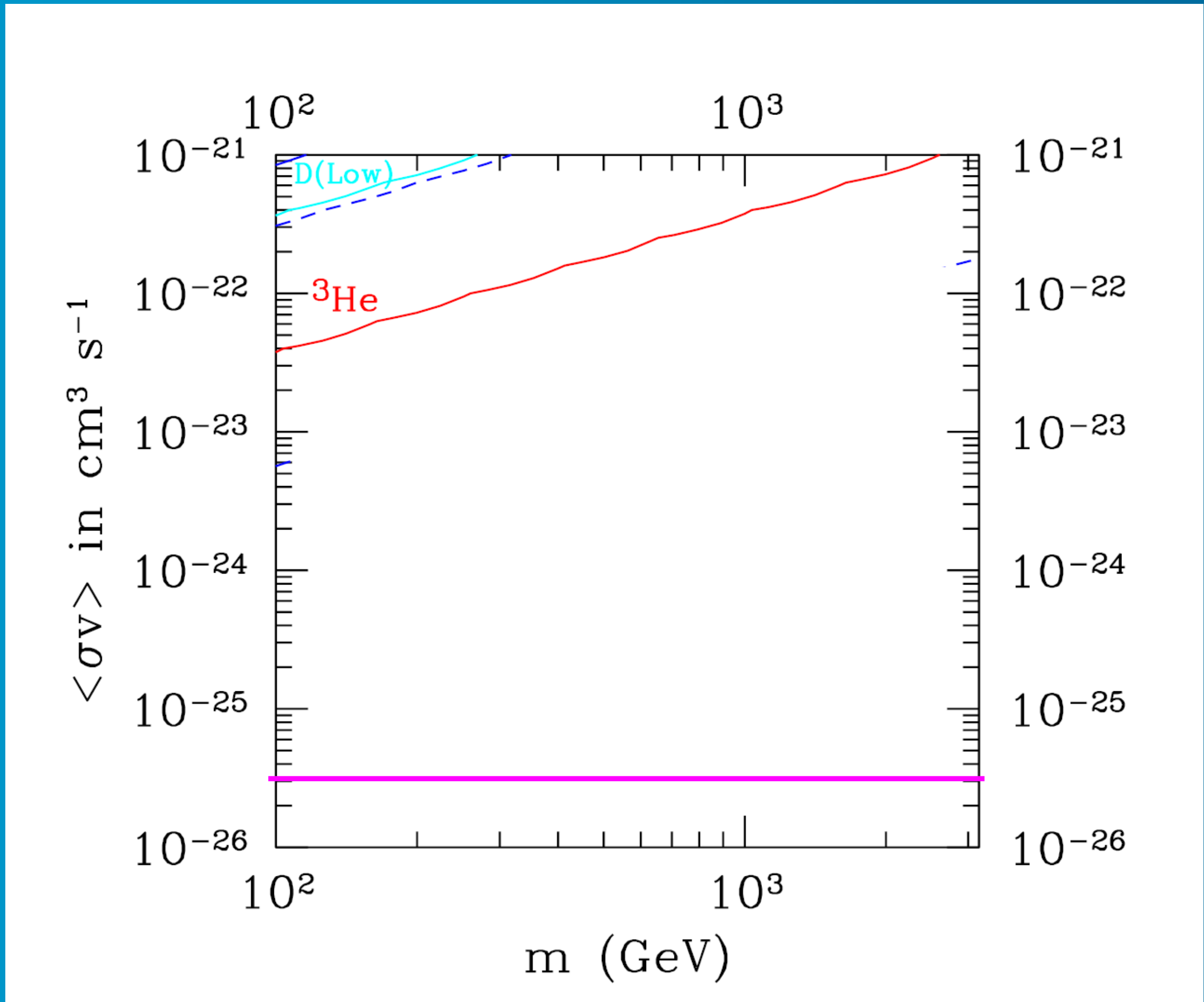
Hadron emission (W^+W^-)

Hisano, Kawasaki, Kohri, Moroi, Nakayama (09)



Charged-lepton (e^+e^-) emission

Hisano, Kawasaki, Kohri, Moroi, Nakayama (09)



What is the origin of Boost Factor?

$BF = \langle \sigma v \rangle_{obs} / \langle \sigma v \rangle_{canonical}$

- Local enhancement of DM density in astrophysics

- Sommerfeld effect   Arkani-Hamed et al (08) (see also Hisano-Matsumoto-Nojiri 03)

  - Light particle exchange ($m < \alpha m_{DM}$)
  - Non-perturbative effect
  - Enhancement to $\langle \sigma v \rangle \sim 10^{-23}$ cm^3/s without violating Unitarity and perturbation theory

Velocity-dependent annihilation cross section?

- Sommerfeld or Breit-Wigner enhancement

Arkani-Hamed et al (08)

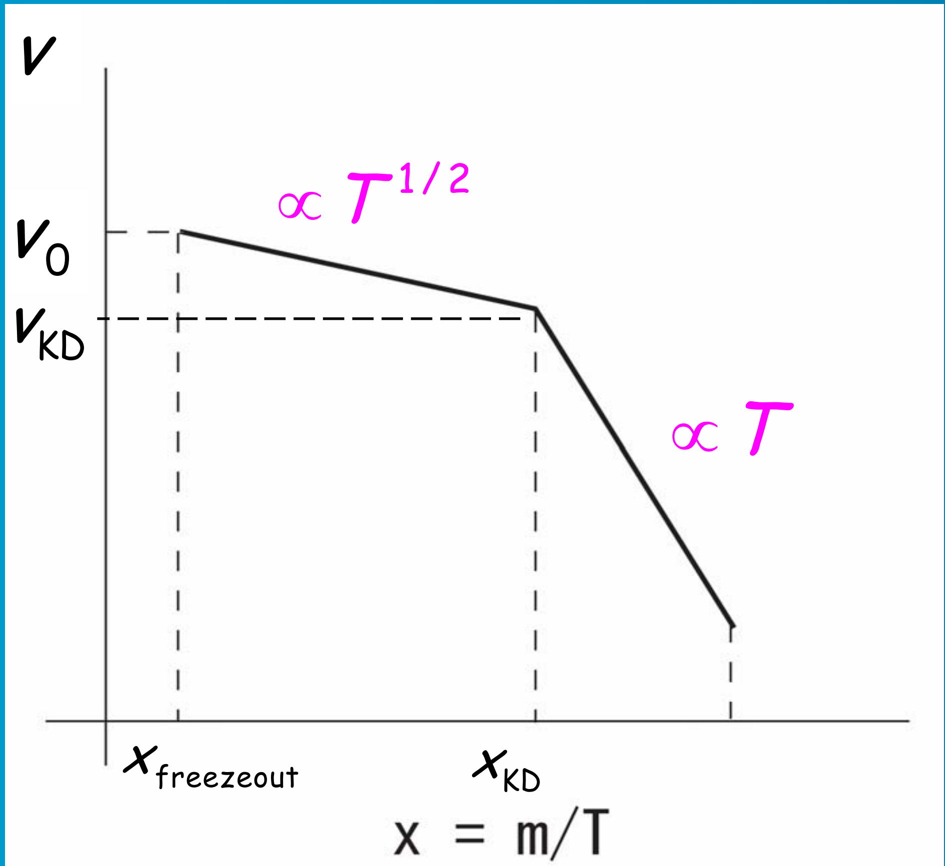
Ibe, Murayama, Yanagida (08)

$$\langle \sigma v \rangle \sim \frac{(\sigma v)_0}{\varepsilon + (v/v_0)^n} \quad \text{with n=1,2,4, ...}$$

$$v_0 = v(T = T_{\text{freezeout}}) \sim O(1)$$

$$\varepsilon \ll 1 \ (\text{e.g., } \sim 10^{-3})$$

Velocity of DM has been redshifted



$v \sim \sqrt{3T/m}$ (before kinetic decoupling)

$v \sim v_{KD}(T/T_{KD})$ (after kinetic-decoupling)

$$(v/v_0)^{-1} \sim 10^6 \left(\frac{m}{\mathrm{TeV}}\right)^{1/2} \left(\frac{T_{KD}}{\mathrm{MeV}}\right)^{1/2} \left(\frac{T}{0.1\mathrm{keV}}\right)^{-1}$$

Summary

- In annihilation scenarios, we need $O(10^3)$ boost factor to fit the positron and electron excess
- Adopting Sommerfeld or Breit-Wigner enhancement affects BBN (and CMB) significantly