

Title: Dynamical Calculation of the Catalyzed BBN with Precise Reaction Rates

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Abstract:

Dynamical Calculation of the Catalyzed BBN with Precise Reaction Rates

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MK et al. PRD, 76, 121302, 2007

Pirsa: 08050054

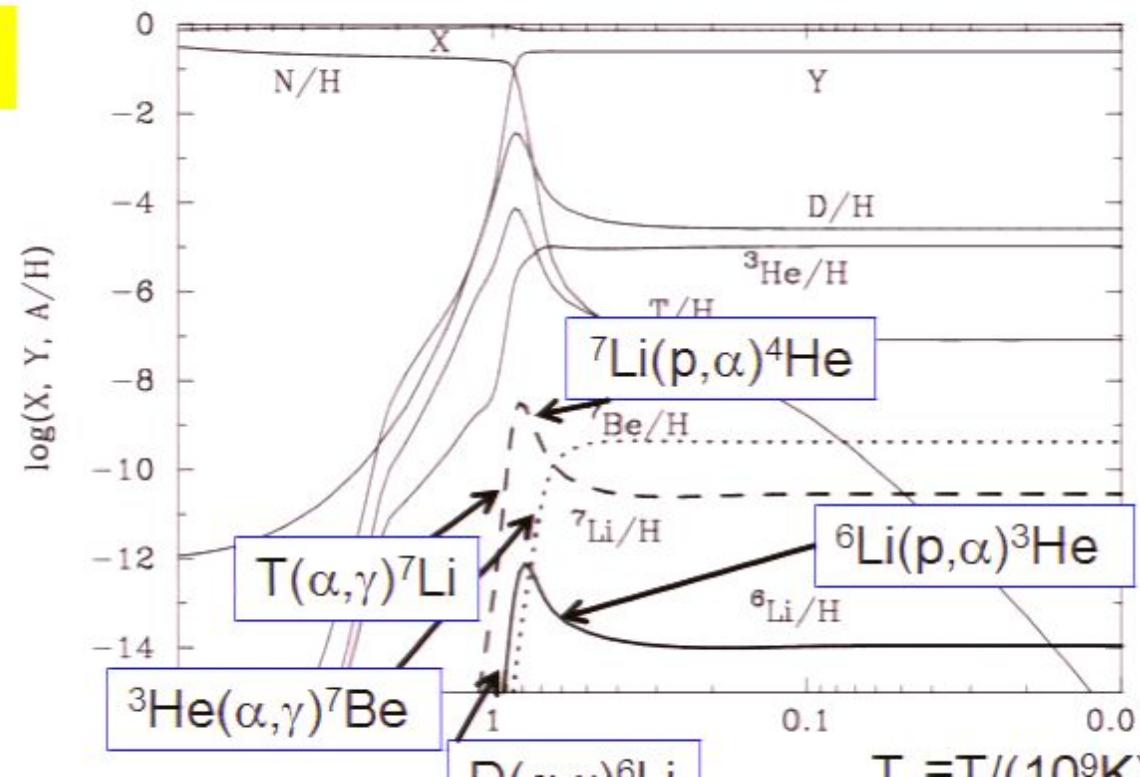
MK et al. arXiv:0711.3858 [astro-ph] (ApJ, in press, 680, 846, 2008)

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Standard big bang nucleosynthesis (SBBN)

- ① $n \leftrightarrow p$ equilibrium $(n/p)_{EQ} = \exp(-Q/T)$ $Q \equiv m_n - m_p = 1.293 \text{ MeV}$
- ② $t \sim 1 \text{ sec}, T = T_F \sim 1 \text{ MeV}$ (weak interaction freeze-out) ($1 \text{ MeV} = 1.16 \times 10^{-9} \text{ K}$)
 - ✓ Neutrinos decouple from photons $(\nu\nu^- \leftrightarrow e^+e^- \leftrightarrow \gamma\gamma)$
 - ✓ $n \leftrightarrow p$ reactions freeze-out
 - ✓ e^\pm annihilate ($T \sim m_e/3$)
 $(n/p)_{\text{freeze-out}} = \exp(-Q/T_F) \sim 1/6$
- ③ Nuclear reactions freeze-out \rightarrow final abundances

Nuclear Flow



$\tau_n = 881.9 \text{ s}$
(Mathews et al. 2005)
 $n = 6.1 \times 10^{-10}$
(Spergel et al. 2007)

SBBN prediction and observation

- Standard BBN: only parameter : baryon-to-photon ratio η

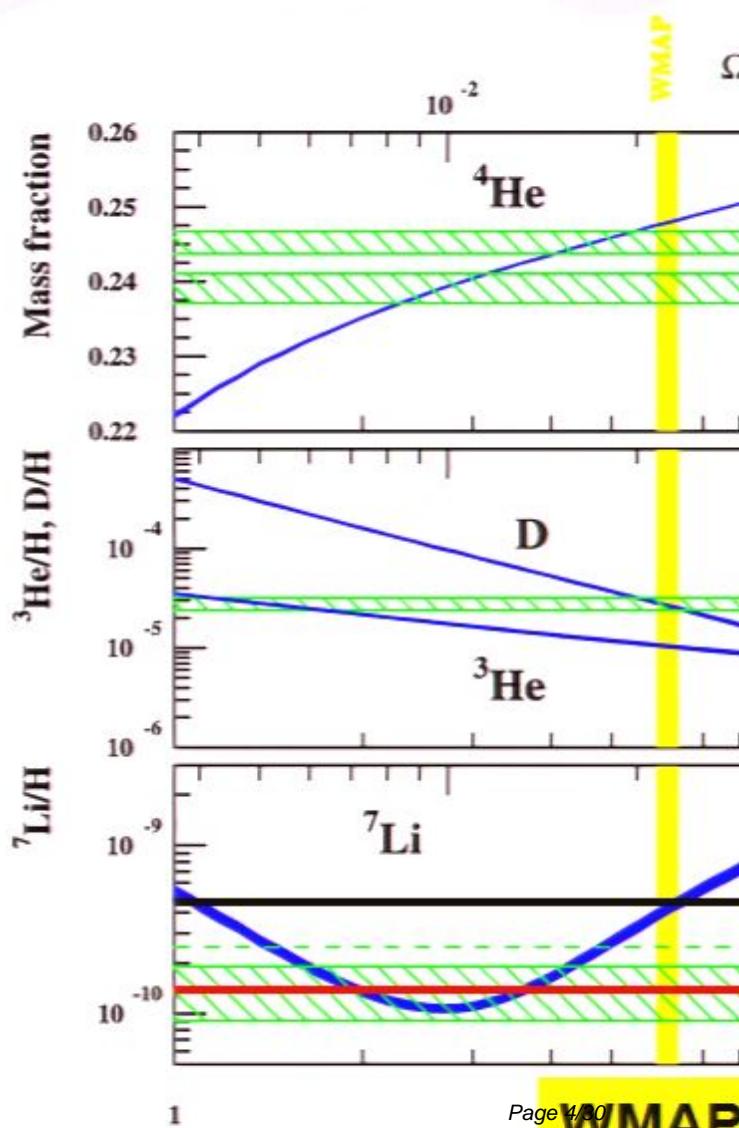
3 min. after the Big Bang

constraint on η by WMAP

$$\eta = (6.14 \pm 0.25) \times 10^{-10}$$

(Spergel et al. 2003)

Li problem! ←



^6Li & ^7Li problems

- ^7Li observed abundance of Metal-Poor Halo Star is a factor of ~ 3 smaller than CMB+BBN prediction.
- Possible high plateau abundance (+upper limits) of ^6Li has been detected.

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

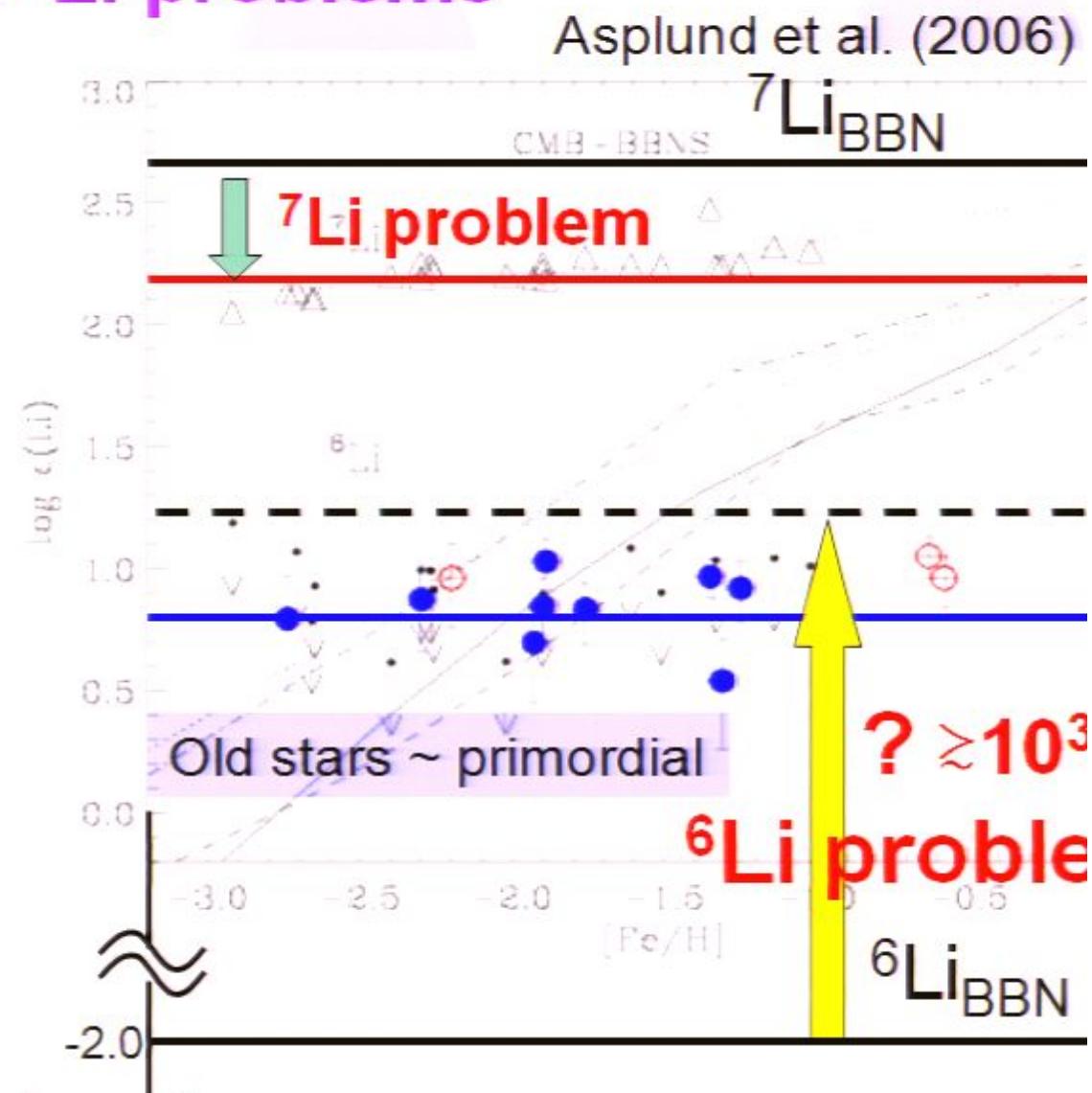
$$^6\text{Li}/\text{H} \approx 6 \times 10^{-12}$$

Candidates of differences

[^7Li] depletion in stellar atmosphere ?

[^6Li] cosmic ray nuclear fusion $\alpha + \alpha$?

cosmological origin ?



BBN with Negatively-Charged Massive Particles

- ✓ Charged particle X^- binds to a nucleus A to form A_X (Cahn & Glashow 1981)
- ✓ Constraints on such particles (Rujula et al. 1990, Dimopoulos et al. 1993)
- ✓ Enhancement of the ^6Li abundance by $^4\text{He}_X(\text{d},X^-)^6\text{Li}$ (Pospelov 2003)
- ✓ Calculation with a quantum three-body model (Hamaguchi et al. 2003)
- ✓ Details on related physics e.g. recombination (Kohri & Takayama 2003)
- ✓ Enhancements for $^4\text{He}_X(\text{t},X^-)$, $^4\text{He}_X(^3\text{He},X^-)$, $^6\text{Li}_X(\text{p},X^-)$ (Cyburt et al. 2003)
- ✓ ^7Be destruction by $^7\text{Be}_X + \text{p} \rightarrow ^8\text{B}_X^{*\alpha}(n=2,l=1) \rightarrow ^8\text{Be}_X + \gamma$ (Bird et al. hep-ph/0703091)
- ✓ Late time CBBN (Jedamzik 2008a, 2008b)
- ✓ ^9Be production by $^8\text{Be}_X + \text{n} \rightarrow ^9\text{Be}^{*n}(1/2+) \rightarrow ^9\text{Be} + X^-$ (Pospelov arXiv:0712.064)

Goal of study

- Check if the ^6Li and ^7Li problems are resolved in dynamical BBN calculation taking account of recombination of X^- by nuclei as well as many possible nuclear reactions of X -bound nuclei.

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Model

1. Binding energy of nuclides with X-

[Assumptions]

- X⁻ has spin 0, charge -e, mass $m_X \gg 1$ GeV
- Nuclides have Gaussian charge distributions.

$$\rho(r) = Ze(\pi r_0^2)^{-3/2} \exp(-r^2 / r_0^2)$$

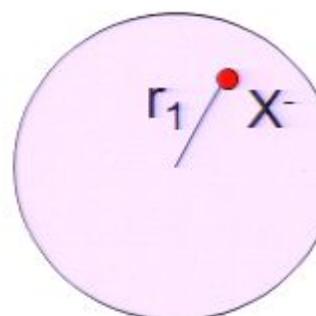
$$r_0^2 = \frac{2}{3} \langle r_c^2 \rangle$$

Two-body Schrödinger equation

$$\left[-\frac{\hbar^2}{2\mu} \nabla^2 + V(r) - E \right] \psi_{lm}(\mathbf{r}) = 0$$

$$V(r_1) = \int_0^{r_1} \rho(r) \frac{e}{r_1} d^3r = \frac{Ze}{r_1} \operatorname{erf}(r_1 / r_0)$$

mean square charge radius



We obtained binding energies by variational calculation
(Gaussian expansion method, e.Hiyama et al. 2003)

nuclide A

$$E_{\text{bind}} \approx O(0.1 - 1 \text{ MeV})$$

→ recombination occurs early in the universe

Binding energy

nuclide	r_c^{RMS} (fm)	Reference	E_{Bind} (MeV)
${}^1\text{H}$	0.875 ± 0.007	Yao et al. (2006)	0.025
${}^2\text{H}$	2.116 ± 0.006	Simon et al. (1981)	0.049
${}^3\text{H}$	1.755 ± 0.086	TUNL Nuclear Data Evaluation	0.072
${}^3\text{He}$	1.959 ± 0.030	TUNL	0.268
${}^4\text{He}$	1.80 ± 0.04	Tanihata et al. (1988)	0.343
${}^6\text{Li}$	2.48 ± 0.03	Tanihata	0.806
${}^7\text{Li}$	2.43 ± 0.02	Tanihata	0.882
${}^8\text{Li}$	2.42 ± 0.02	Tanihata	0.945
${}^6\text{Be}$	2.52 ± 0.02	We took ${}^7\text{Be}$ radius	1.234
${}^7\text{Be}$	2.52 ± 0.02	Tanihata	1.324
${}^8\text{Be}$	2.52 ± 0.02	We took ${}^7\text{Be}$ radius	1.401
${}^9\text{Be}$	2.50 ± 0.01	Tanihata	1.477
${}^7\text{B}$	2.68 ± 0.12	We took ${}^8\text{B}$ radius	1.752
${}^8\text{B}$	2.68 ± 0.12	Fukuda et al. (1999)	1.840
${}^9\text{B}$	2.68 ± 0.12	We took ${}^8\text{B}$ radius	1.917

2. Nuclear reactions of nuclei bound to X- (only non-resonant reactions)

➤ Neutron capture: (n,γ) reaction

$$\sigma_n v \sim \text{const.} \sim \langle \sigma_n v \rangle$$

■ $A(n,\gamma)B$ reaction rate is used for $A_X(n,\gamma)B_X$ rate.

➤ Reaction of charged particles:

Rate

$$\langle \sigma v \rangle = \frac{7.2 \times 10^{-19}}{AZ_1Z_2} \tau^2 e^{-\tau} S(E_0') \text{cm}^3 \text{s}^{-1}$$

$$E_0 = 0.12(Z_1^2 Z_2^2 A)^{1/3} T_9^{2/3} \text{ MeV}$$
$$E_0' = E_0 + 5T/6$$
$$\tau = 3E_0/T$$

■ We correct nuclear charges (Z_1, Z_2), reduced mass number ($A \equiv A_1 A_2 / [A_1 + A_2]$), and used S-factor: $S(E) = \sigma(E) E \exp(2\pi Z_1 Z_2 \alpha/v)$ of the corresponding reaction.

■ We changed reaction Q-value taking account of binding energy.

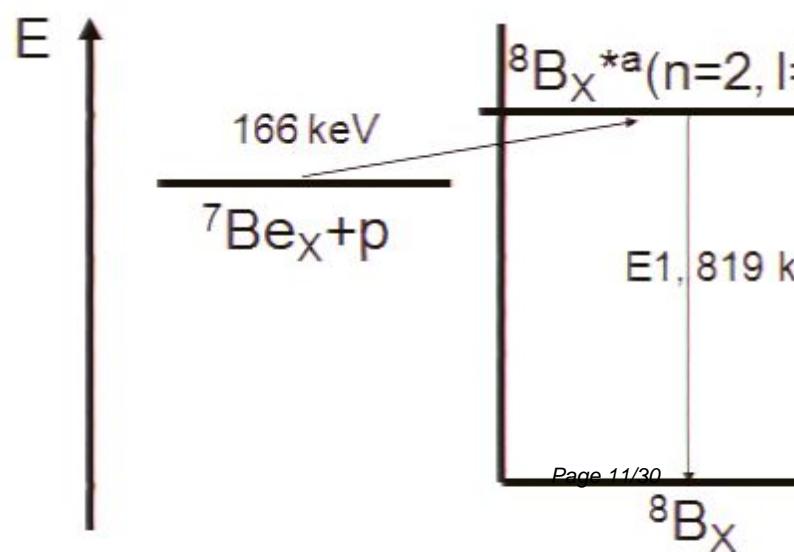
3. X⁻ transfer reaction ${}^4\text{He}_X(\text{d},\text{X}^-){}^6\text{Li}$

- Pospelov (2007) suggested that the rate of X⁻ transfer reaction ${}^4\text{He}_X(\text{d},\text{X}^-){}^6\text{Li}$ is enhanced by 7 orders of magnitude more than that of ${}^4\text{He}(\text{d},\gamma){}^6\text{Li}$
- We adopted the precise cross section for ${}^4\text{He}_X(\text{d},\text{X}^-){}^6\text{Li}$ calculated in a quantum three-body (${}^4\text{He}$, d ,X⁻) model by Hamaguchi et al. (2007).
- In ${}^4\text{He}_X(\text{d},\text{X}^-){}^6\text{Li}$ reaction, the component of the transition from the s-wave of ${}^4\text{He}_X$ -d to the s-wave of ${}^6\text{Li}$ -X⁻ dominates

4. ${}^7\text{Be}_X(\text{p},\gamma){}^8\text{B}_X$ through atomic excited state of ${}^8\text{B}_X$

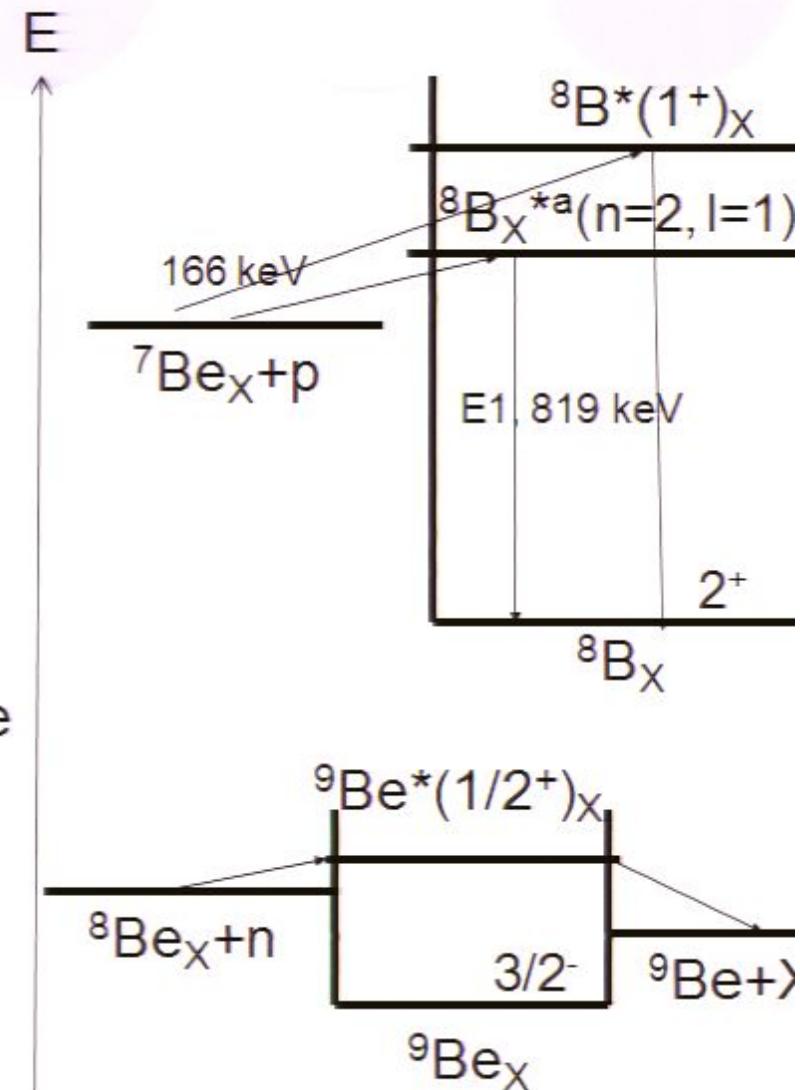
- Bird et al. (2007) suggested that the resonant reaction ${}^7\text{Be}_X + \text{p} \rightarrow {}^8\text{B}_X^{*\text{a}}(n=2, l=1) \rightarrow {}^8\text{B}_X + \gamma$ contribute to destruction of ${}^7\text{Be}$.

- We adopted this process, and added the ${}^8\text{Be}_X(\text{p},\gamma){}^9\text{B}_X$ reaction through atomic excited state of ${}^9\text{B}_X$.



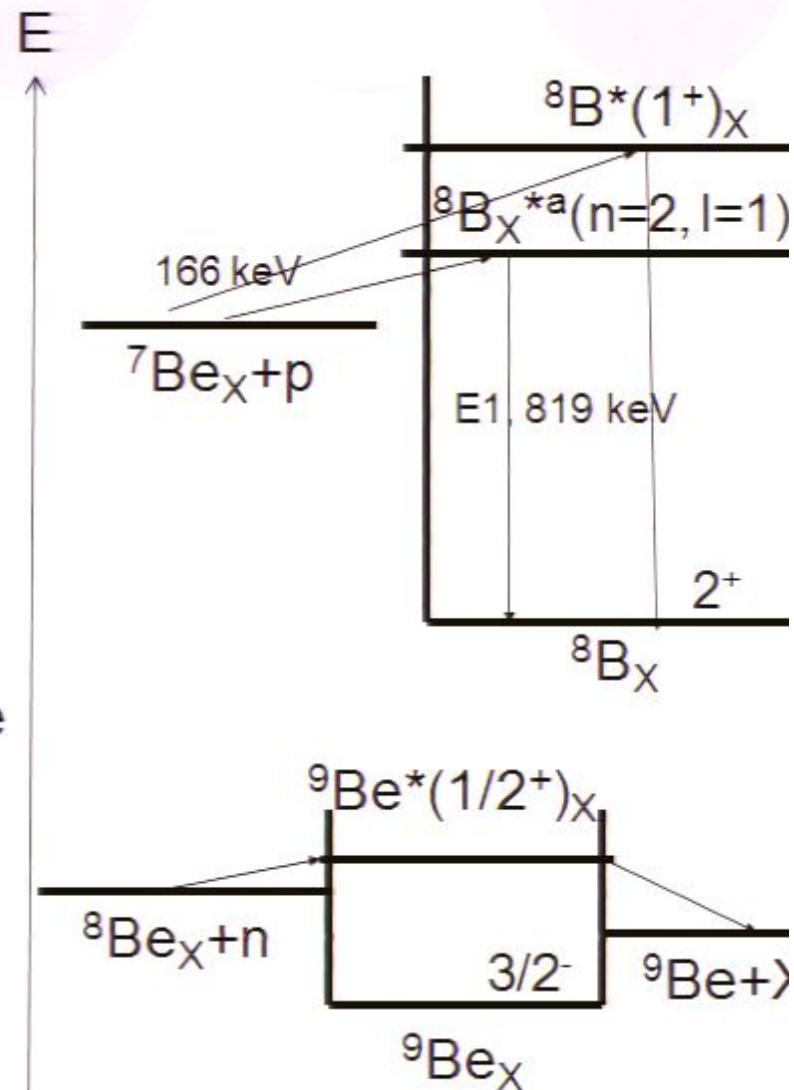
Possible reactions

- Atomic excited state of a nucleus and X⁻
(e.g., ${}^7\text{Be}_X + p \rightarrow {}^8\text{B}_X^{*\alpha}(n=2) \rightarrow {}^8\text{B}_X + \gamma$
; Bird et al. 2007)
- Atomic state between a nuclear excited state and X⁻
(e.g., ${}^7\text{Be}_X + p \rightarrow {}^8\text{B}^*(1^+)_X \rightarrow {}^8\text{B}_X + \gamma$
; MK et al. 2007)
- X⁻ transfer reaction through an atomic state to a separate state
(e.g., ${}^8\text{Be}_X + n \rightarrow {}^9\text{Be}^*(1/2^+)_X \rightarrow {}^9\text{Be} + X$
; Pospelov 2007 arXiv0712.0647)



Possible reactions

- Atomic excited state of a nucleus and X^-
(e.g., ${}^7\text{Be}_X + p \rightarrow {}^8\text{B}_X^{*\alpha}(n=2) \rightarrow {}^8\text{B}_X + \gamma$
; Bird et al. 2007)
- Atomic state between a nuclear excited state and X^-
(e.g., ${}^7\text{Be}_X + p \rightarrow {}^8\text{B}^*(1+)_X \rightarrow {}^8\text{B}_X + \gamma$
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- X^- transfer reaction through an atomic state to a separate state
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${}^7\text{Be}_X(p,\gamma){}^8\text{B}_X$ through ${}^8\text{B}^*(1^+)_X$

➤ Resonant reaction rate:

$$\langle \sigma v \rangle_R = \hbar^2 \left(\frac{2\pi}{\mu k_B T} \right)^{3/2} \omega_\gamma \exp\left(-\frac{E}{k_B T}\right)$$

$$\omega_\gamma = \frac{2I+1}{(2I_1+1)(2I_2+1)} \frac{\Gamma_l \Gamma_\gamma}{\Gamma_{\text{tot}}}$$

Γ_γ γ -decay width

Γ_l decay width into 2 charged particles of relative angular momentum

$$\Gamma_l \approx \frac{3\hbar}{R} \left(\frac{2}{AM_u} \right)^{1/2} \theta_l^2 E_c^{1/2} \exp \left[bE^{-1/2} + 1.05(ARz_1 z_2)^{1/2} - 7.62(l + \frac{1}{2})^2 (ARz_1 z_2)^{-1/2} \right]$$

$R = 1.4(A_1^{1/3} + A_2^{1/3}) \times 10^{-13}$ cm interaction radius

M_u

atomic mass unit

θ_l^2

dimensionless reduced width

$E_c = 1.44$ MeV fm $z_1 z_2 / R$

height of Coulomb barrier

$b = 31.28 z_1 z_2 A^{1/2}$ (keV $^{1/2}$)

Sommerfeld parameter

• We deduce the spin parity for ${}^8\text{B}(0.770 \text{ MeV})$ to be $I^\pi = 1^+$ from the conjugate analog state of ${}^8\text{Li}(1^+, 0.9809 \text{ MeV})$ and ${}^7\text{Be}_X + p \rightarrow {}^8\text{B}^*(1^+)_X \rightarrow {}^8\text{B}_X + \gamma$ reaction proceeds through a p-wave ($l=1$).

- $\theta_1^2 = 0.82$ from a standard resonant rate for ${}^7\text{Be} + \text{p} \rightarrow {}^8\text{B}^*(1^+) \rightarrow {}^8\text{B} + \gamma$
- $\Gamma_\gamma = 25 \pm 4 \text{ meV}$ (Ajzenberg-Selove 1988)
- Correcting the charge, reduced mass, and energy, we obtain

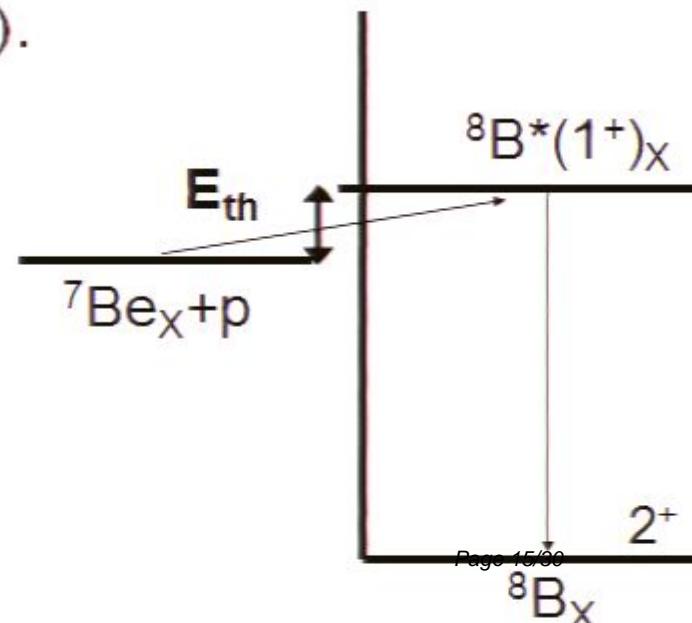
$$\Gamma_{1,X} \approx 1.7 \times 10^6 \text{ eV} \exp \left[-\frac{93.9}{(E_{\text{th}} / \text{keV})^{1/2}} \right]$$

- We assumed (MK et al. 2007) uniform charge distribution of radius $r_0 = 1.2A^{1/3} \text{ fm}$
(Cahn & Glashow 1981).

→ $E_{\text{th}} = 0 \text{ MeV}$

- If $E_{\text{th}} \sim 30 \text{ keV}$, this reaction channel contributes to destroying ${}^7\text{Be}_X$.

- But this resonance is found to be too high to operate effectively.
(MK et al. 2008)



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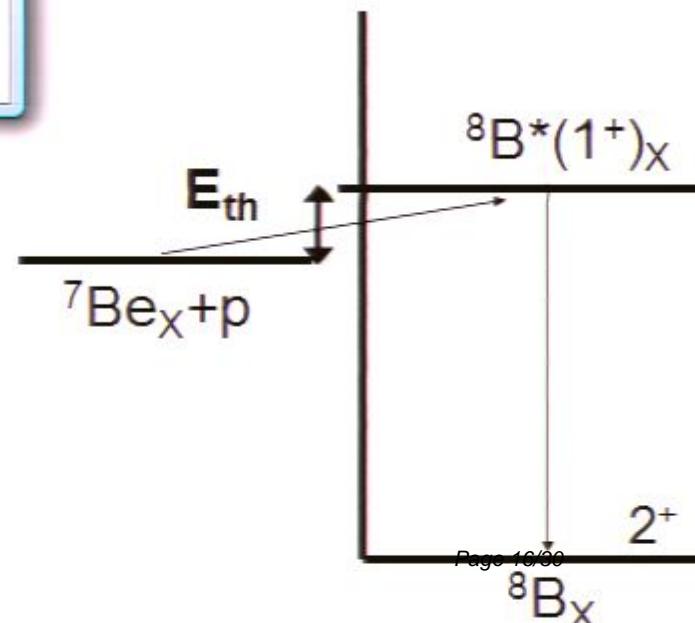
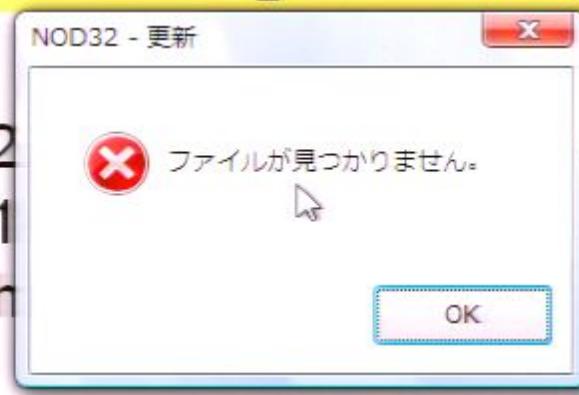
- We assumed (MK et al. 2008) distribution of radius $r_0 = 1.5 \text{ fm}$ (Cahalan et al. 2008)

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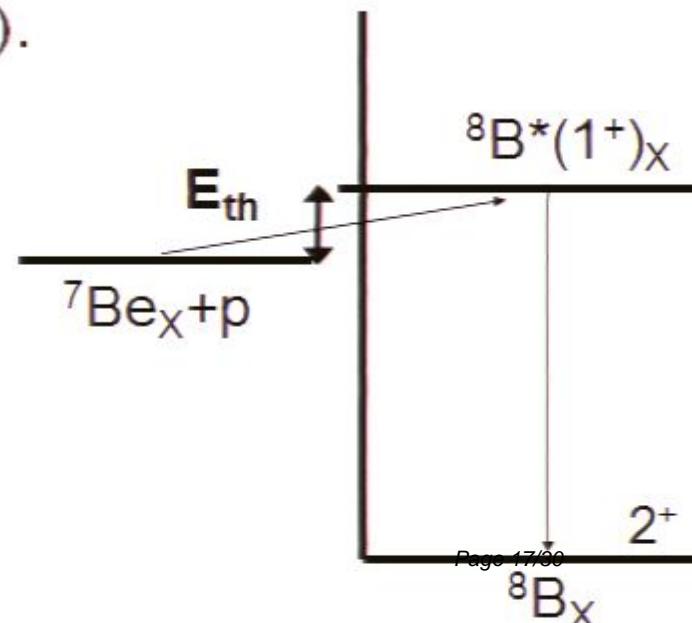
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Calculation

SBBN

t : time

↓ radiation dominant

$$T(t) \rightarrow \rho, p, \frac{d\rho}{dT}, \frac{dp}{dT} (\gamma, e^\pm, \nu, \text{baryon})$$



- Hubble expansion rate
- reaction rate •



$\frac{dY_i}{dt}$: abundance change rate



$$\frac{dT}{dt}, \frac{d\eta}{dt}, \frac{d\phi_e}{dt}$$



$T(t), \eta(t), \phi_e(t), Y_i(t)$

time integration

(2nd order Runge-Kutta)

new processes

- **recombination** process of X-

E

r

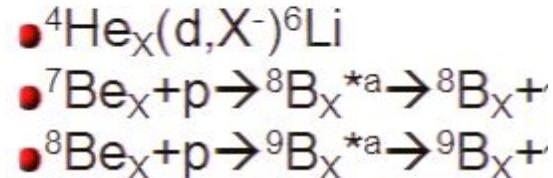
V_{coul}

ionization

recombination

- **new BBN** reactions of X-bound nuclides

Including



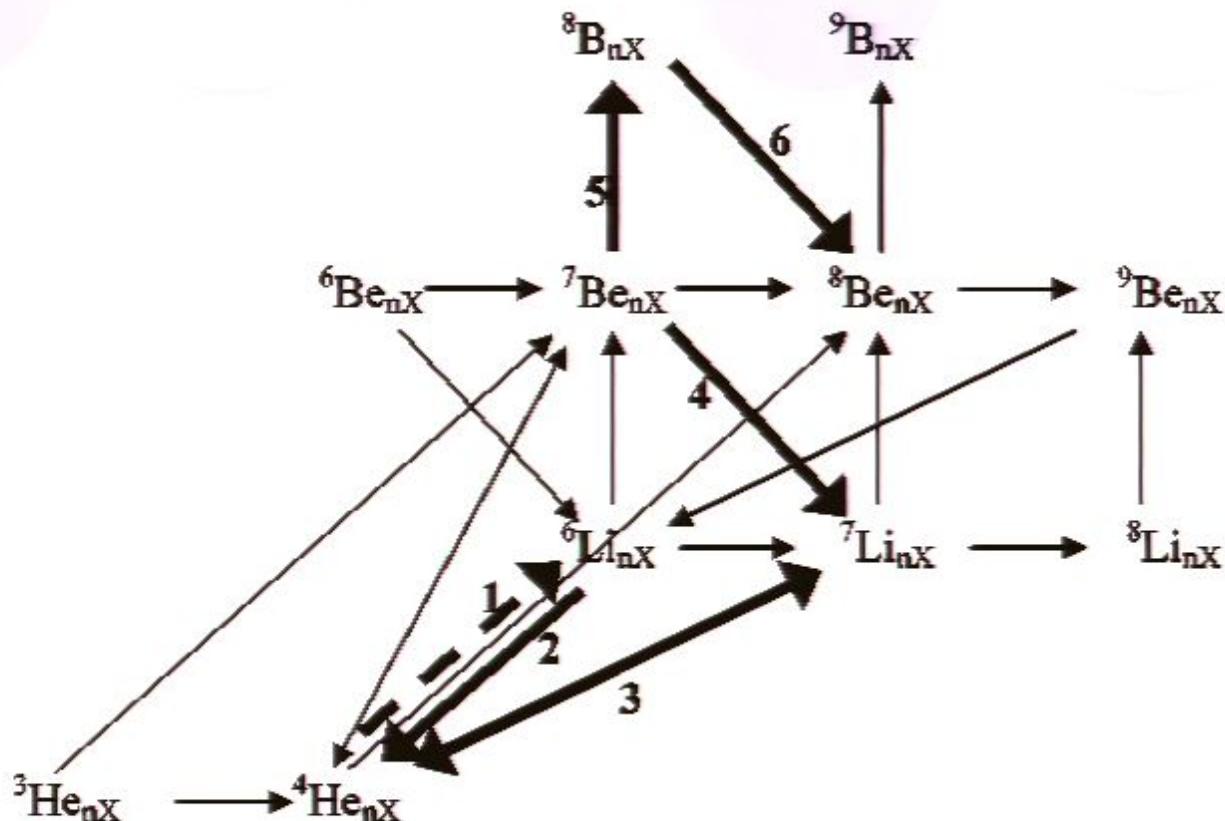
$$\frac{dY_A}{dt} = \left(\frac{dY_A}{dt} \right)_{SBBN} + \left(\frac{dY_A}{dt} \right)_{recon ioniz}$$

$$\frac{dY_{AX}}{dt} = \left(\frac{dY_{AX}}{dt} \right)_{newBBN} - \left(\frac{dY_A}{dt} \right)_{re ioniz}$$

Solve fully dynamically!

Nuclear reaction network

➤ Up to C isotopes included



Effective reactions

1. $^4\text{He}_X(d, X^-)^6\text{Li}$
2. $^6\text{Li}_X(p, ^3\text{He}X^-)^4\text{He}$
3. $^4\text{He}_X(t, \gamma)^7\text{Li}_X$ & $^7\text{Li}_X(p, \alpha X^-)^4\text{He}$
4. $^7\text{Be}_X(X^0)^7\text{Li}$
5. $^7\text{Be}_X(p, \gamma)^8\text{B}_X$
6. $^8\text{B}_X(e^+ \nu_e)^8\text{Be}_X$

Precise reaction rates by Prof. Kamimura et al.

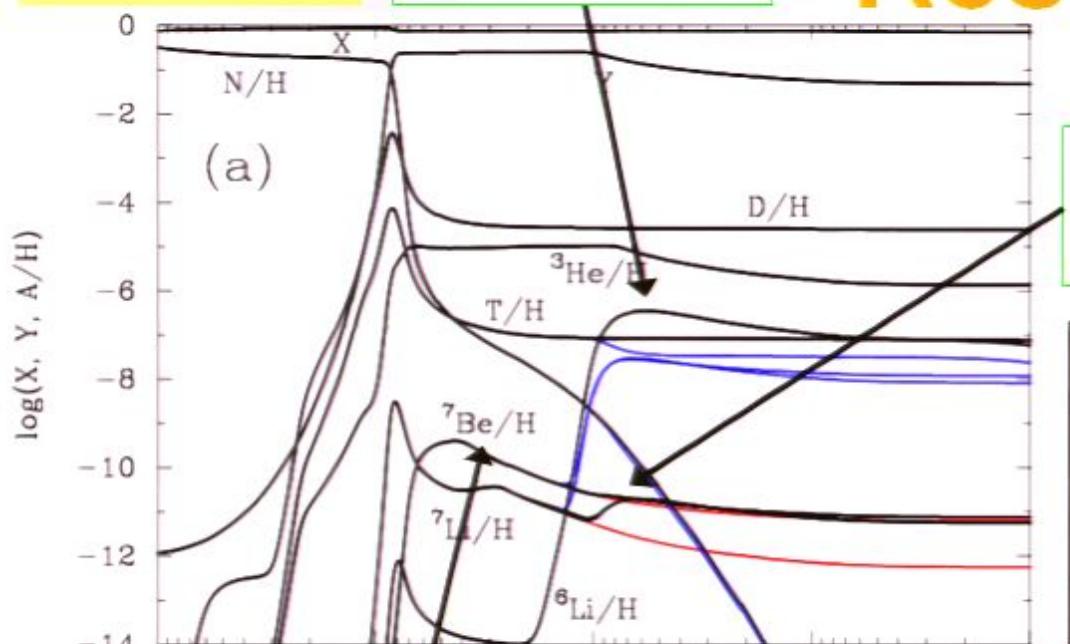
	MK et al. (2008)	Kamimura et al.
$\rightarrow {}^4\text{He}_X(\text{d},\text{X}^-){}^6\text{Li}$	Hamaguchi et al. (2006)	(smaller than rates in Cyburt (2006))
$\rightarrow {}^4\text{He}_X(\text{t},\text{X}^-){}^7\text{Li}$	0	similar
$\rightarrow {}^4\text{He}_X({}^3\text{He},\text{X}^-){}^7\text{Be}$	Deduced from SBBN	$\sim 1/3$
$\rightarrow {}^6\text{Li}_X(\text{p},\alpha\text{X}^-){}^3\text{He}$	Deduced from SBBN	mass dependence
$\rightarrow {}^7\text{Li}_X(\text{p},\alpha\text{X}^-){}^4\text{He}$	Bird et al. (2007)	
$\rightarrow {}^7\text{Be}_X(\text{p},\gamma){}^8\text{B}_X$		

Abundance

 ${}^4\text{He}_X(\text{d}, X^-){}^6\text{Li}$

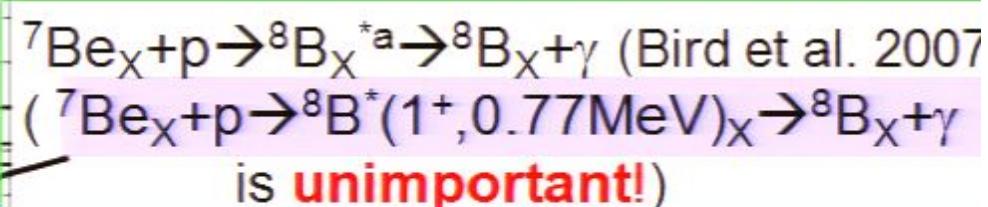
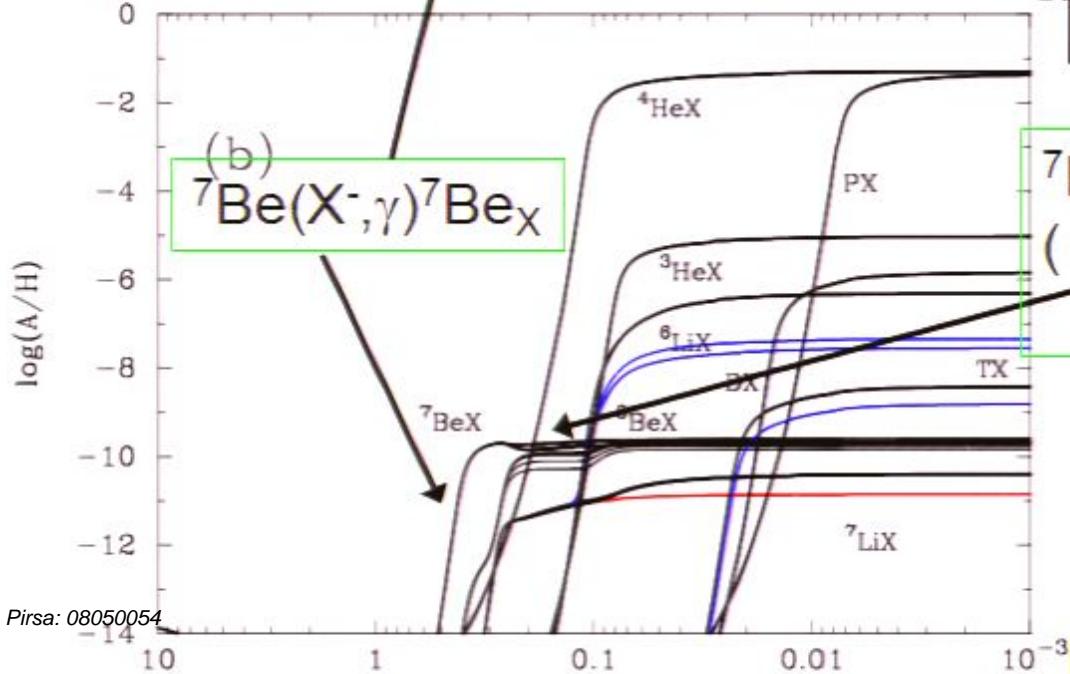
Result

Nuclear flow

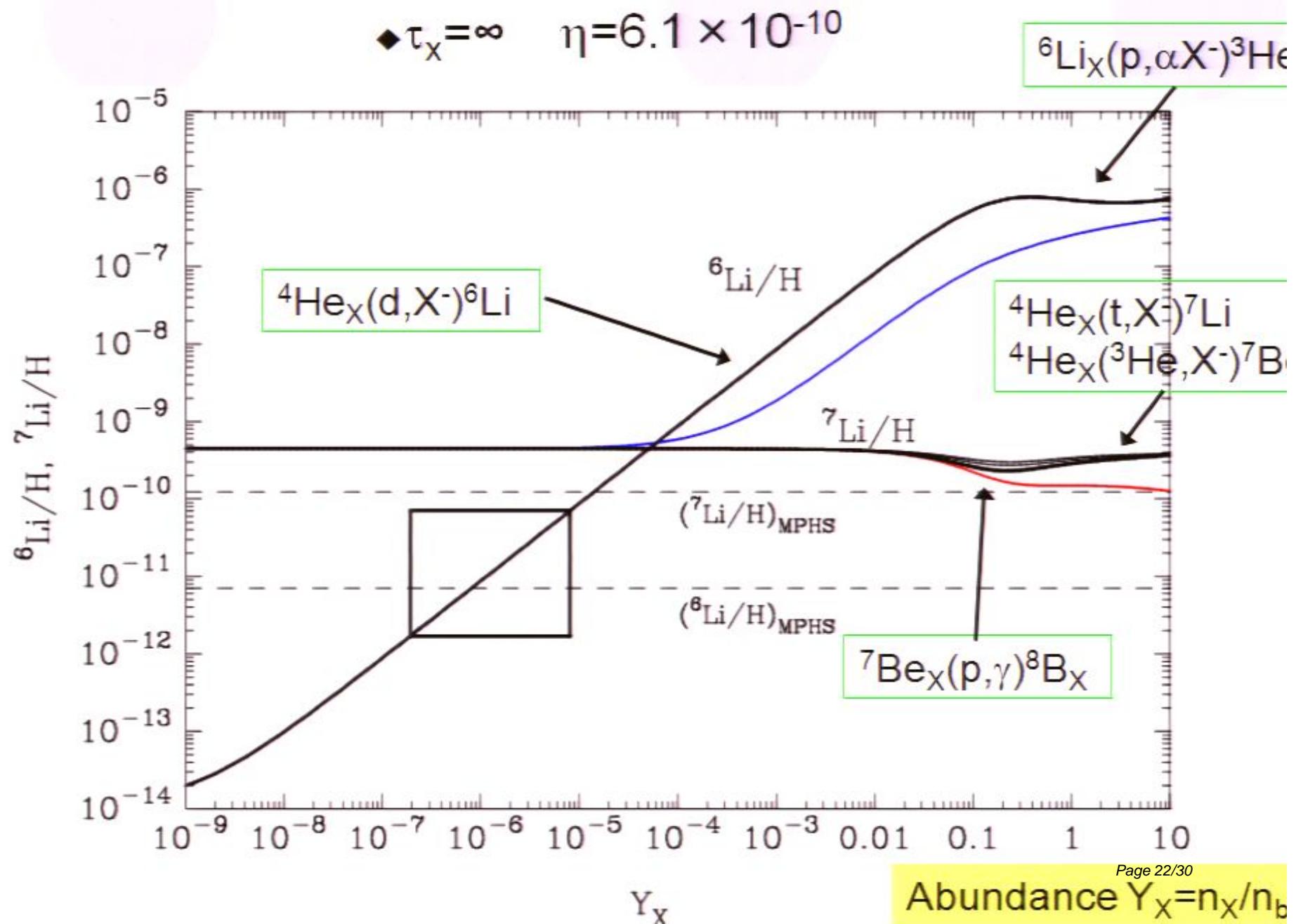
 $\blacklozenge n_x = 0.1 n_b, \tau_x = \infty$ 

${}^4\text{He}_X(t, X^-){}^7\text{Li}$
 ${}^4\text{He}_X({}^3\text{He}, X^-){}^7\text{Be}$

- Kamimura ($m_x = 50, 100, 500 \text{ GeV}$)
- Kamimura ($m_x = \infty$)
- ${}^4\text{He}_X(t, X^-), {}^4\text{He}_X({}^3\text{He}, X^-)$ rates = 0 (MK et al. 2008)
- ${}^4\text{He}_X(t, X^-), {}^4\text{He}_X({}^3\text{He}, X^-)$ rates by Cyburt et al. (2006)



Parameter search 0



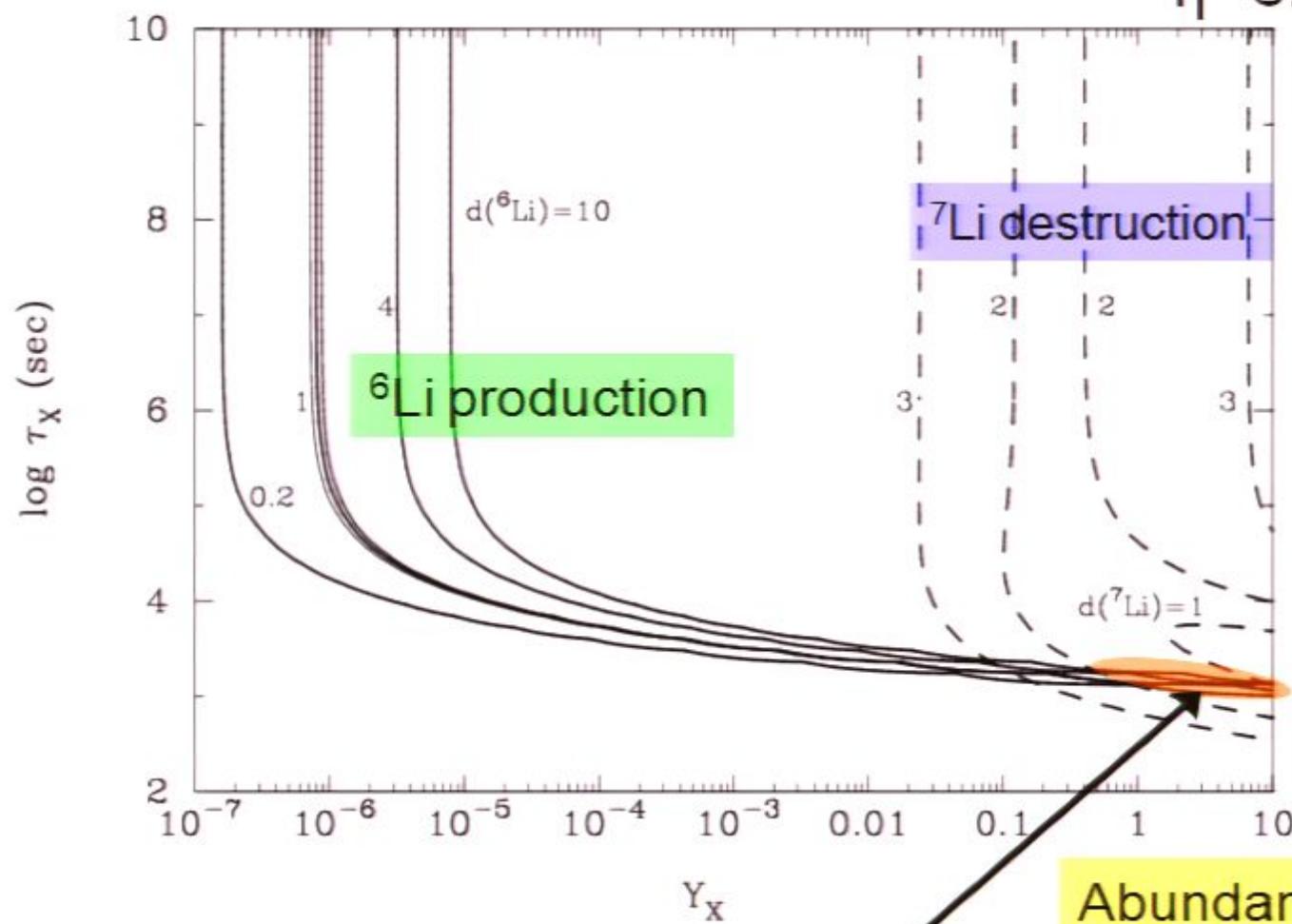
Parameter search 1

◆ $m_x > 500 \text{ GeV}$

Contours of calculated Li abundance relative to the observed value: $d(^A\text{Li}) = ^A\text{Li}^{\text{Calc}} / ^A\text{Li}^{\text{Obs}}$

$$\eta = 6.1 \times 10^{-10}$$

Lifetime τ_x



Possible parameter region leading to 7Li destruction and 6Li production !

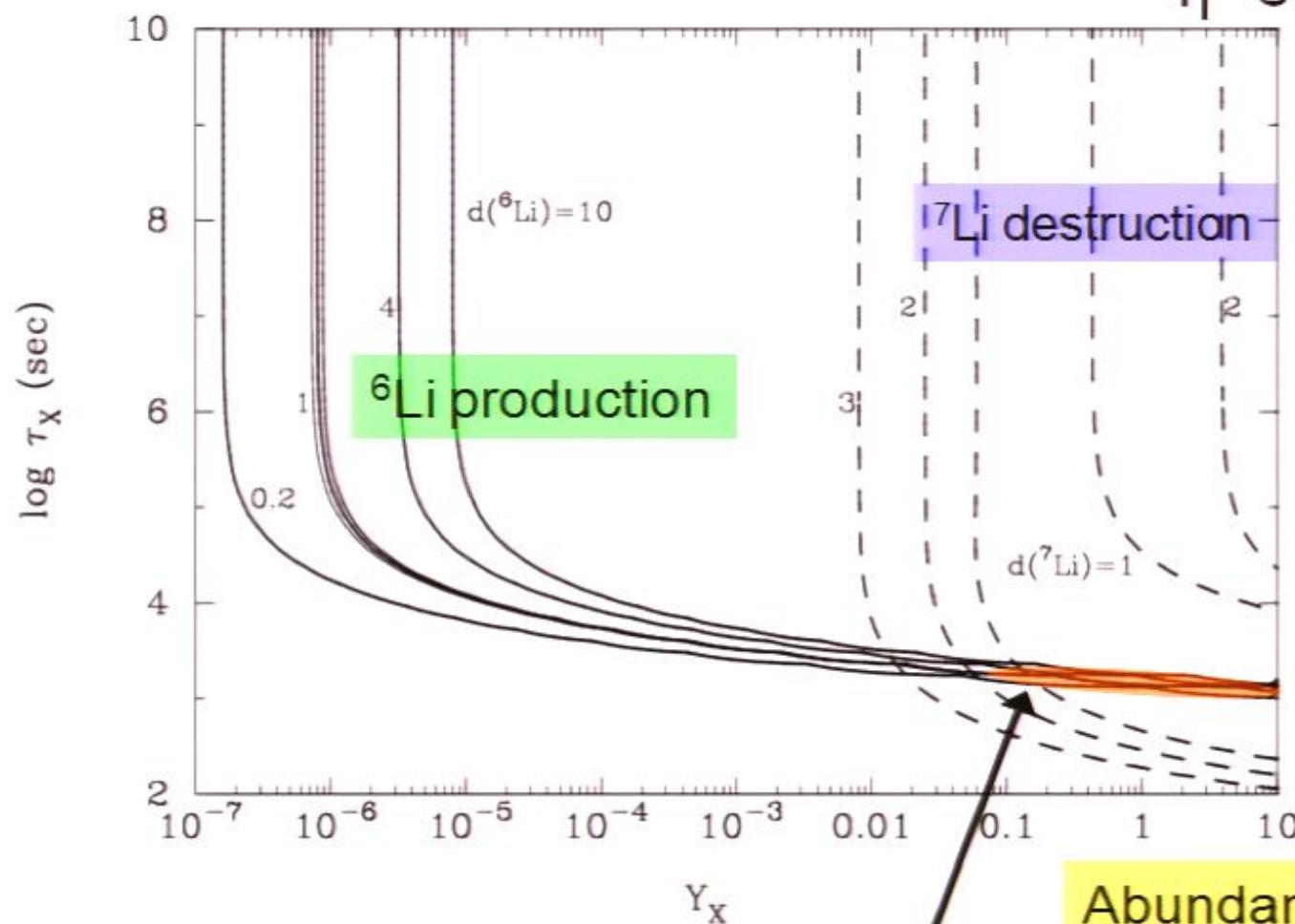
Parameter search 2

Contours of calculated Li abundance relative to the observed value: $d(^A\text{Li}) = ^A\text{Li}^{\text{Calc}} / ^A\text{Li}^{\text{Obs}}$

When weak boson exchange reaction
 $^7\text{Be}_X \rightarrow ^7\text{Li} + X^0$ (Bird et. al 2007) is included

$$[{}^7\text{Li}(p,\alpha){}^4\text{He} \\ [{}^7\text{Li}(X^-, \gamma){}^7\text{Li}_X(p,\alpha X^-){}^4\text{He}] \\ \eta = 6.1 \times 10^{-10}$$

Lifetime τ_X



Abundance $Y_X = n_X /$

Possible parameter region leading to
 ${}^7\text{Li}$ destruction and ${}^6\text{Li}$ production !

Summary

- ④ We calculated light-element nucleosynthesis during BBN with negatively-charged X^- particles dynamically with precise reaction rates derived by Professor Kamimura.
- ④ “ ^6Li problem (a factor of $\sim 10^3$) and/or ^7Li problem (a factor of ~ 3) is resolved.”
 - ▶ Related parameter region: $Y_X \gtrsim 0.04-0.6$ and $\tau_X \approx (1-3) \times 10^3 \text{ s}$
 - ▶ X^- particles enhance the production of ^6Li through $^4\text{He}(X^-, \gamma)^4\text{He}_X$ followed by the X^- transfer reaction $^4\text{He}_X(d, X^-)^6\text{Li}$ (Pospelov 2007).
 - ▶ $^7\text{Be}_X + p \xrightarrow{\text{*a}} ^8\text{B}_X \xrightarrow{\gamma} ^8\text{B}_X + \gamma$ through the atomic excited state of $^8\text{B}_X$ (Bird et al. 2007).
- ④ Quantum mechanical model calculations are necessary to estimate reaction rates of catalyzed BBN and obtain realistic results of light element abundances.
 - ▶ Transfer reactions to produce ^7Li and ^7Be are not so effective !

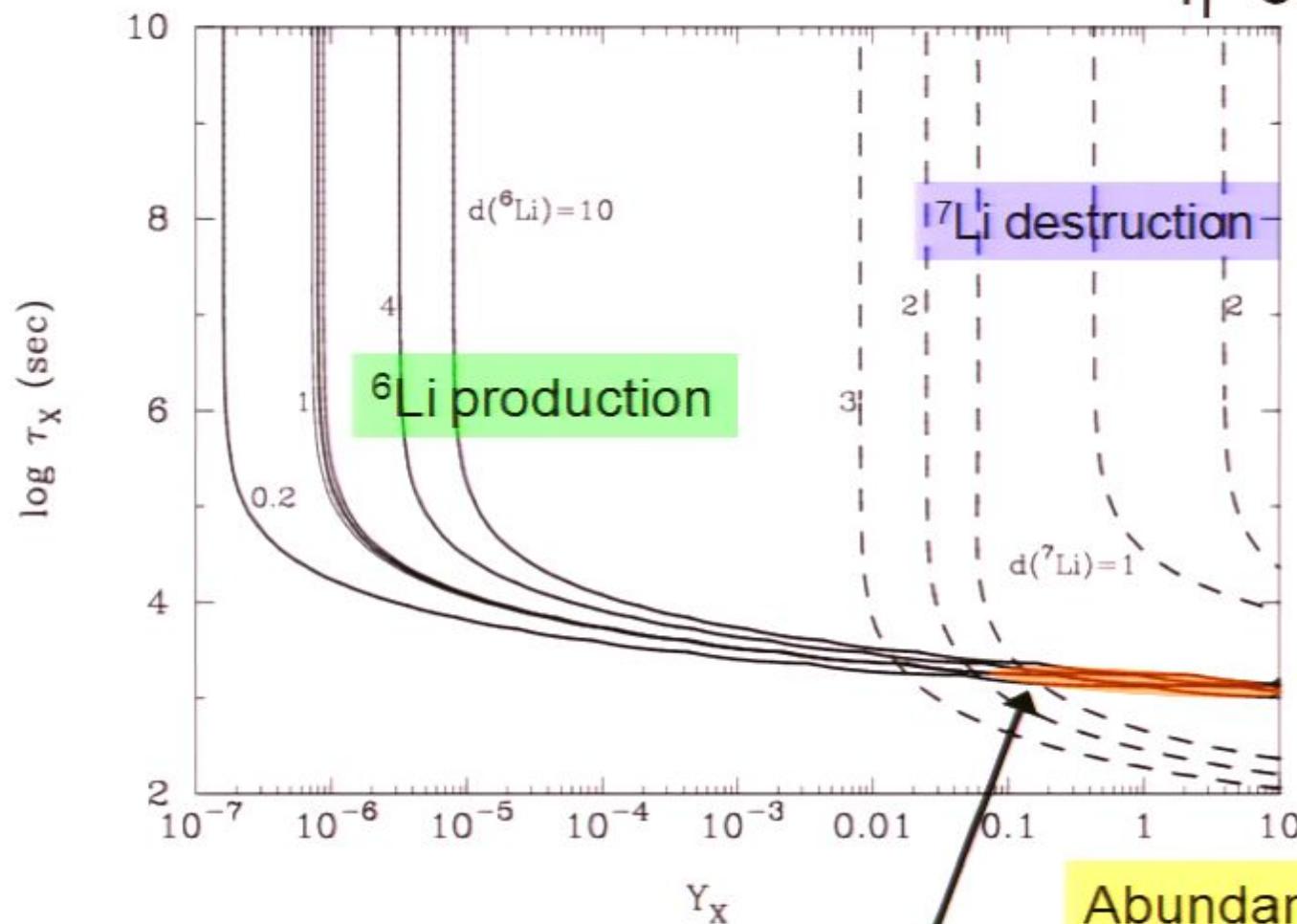
Parameter search 2

When weak boson exchange reaction
 ${}^7\text{Be}_X \rightarrow {}^7\text{Li} + X^0$ (Bird et. al 2007) is included

Contours of calculated Li abundance relative to the observed value: $d({}^A\text{Li}) = {}^A\text{Li}^{\text{Calc}} / {}^A\text{Li}^{\text{Obs}}$

$$\begin{aligned} &[{}^7\text{Li}(p,\alpha){}^4\text{He}} \\ &[{}^7\text{Li}(X^-, \gamma){}^7\text{Li}_X(p,\alpha X^-){}^4\text{He}} \\ &\eta = 6.1 \times 10^{-10} \end{aligned}$$

Lifetime τ_X



Possible parameter region leading to ${}^7\text{Li}$ destruction and ${}^6\text{Li}$ production !

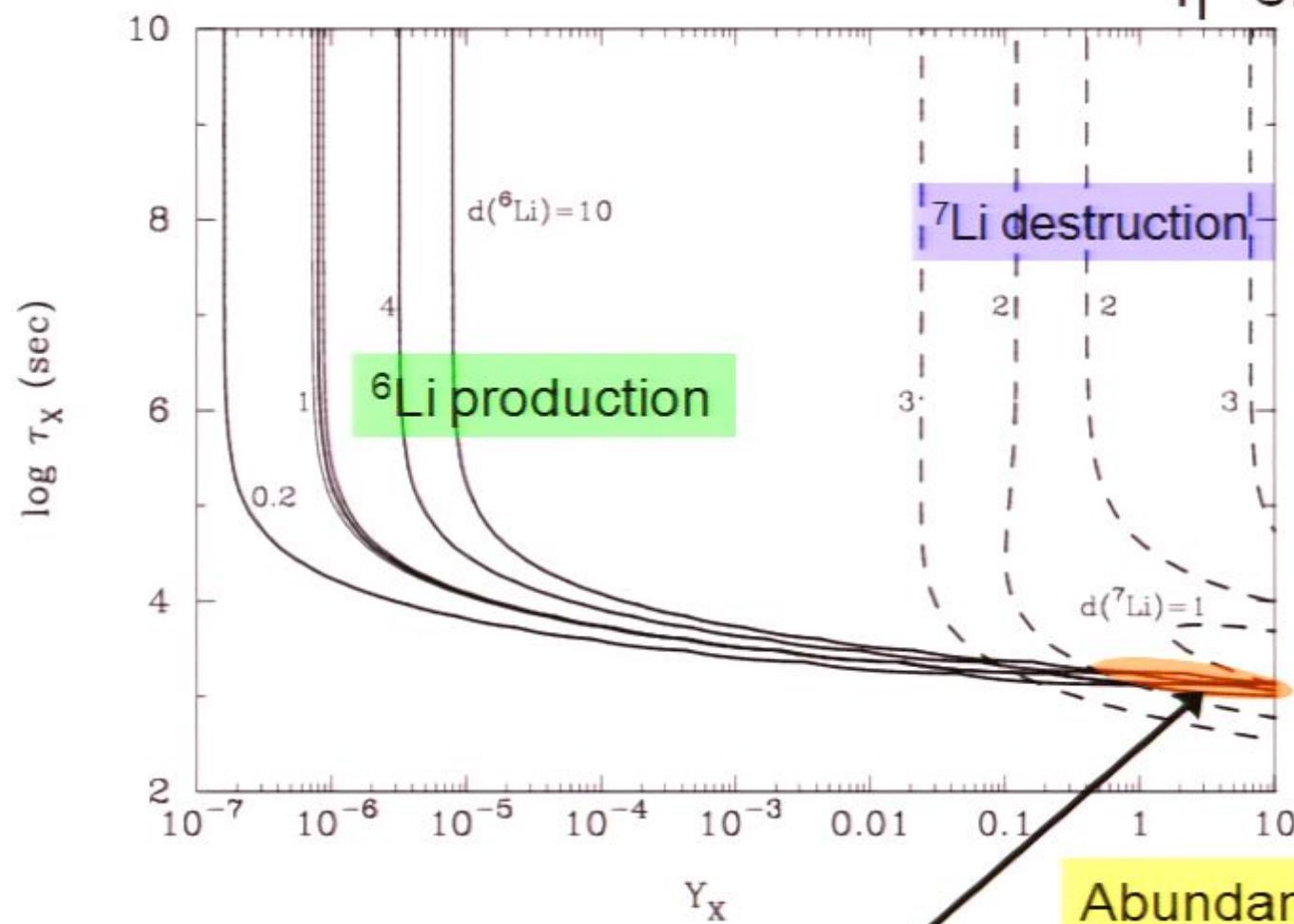
Parameter search 1

◆ $m_x > 500 \text{ GeV}$

Contours of calculated Li abundance relative to the observed value: $d(^A\text{Li}) = ^A\text{Li}^{\text{Calc}} / ^A\text{Li}^{\text{Obs}}$

$$\eta = 6.1 \times 10^{-10}$$

Lifetime τ_x



Possible parameter region leading to 7Li destruction and 6Li production !

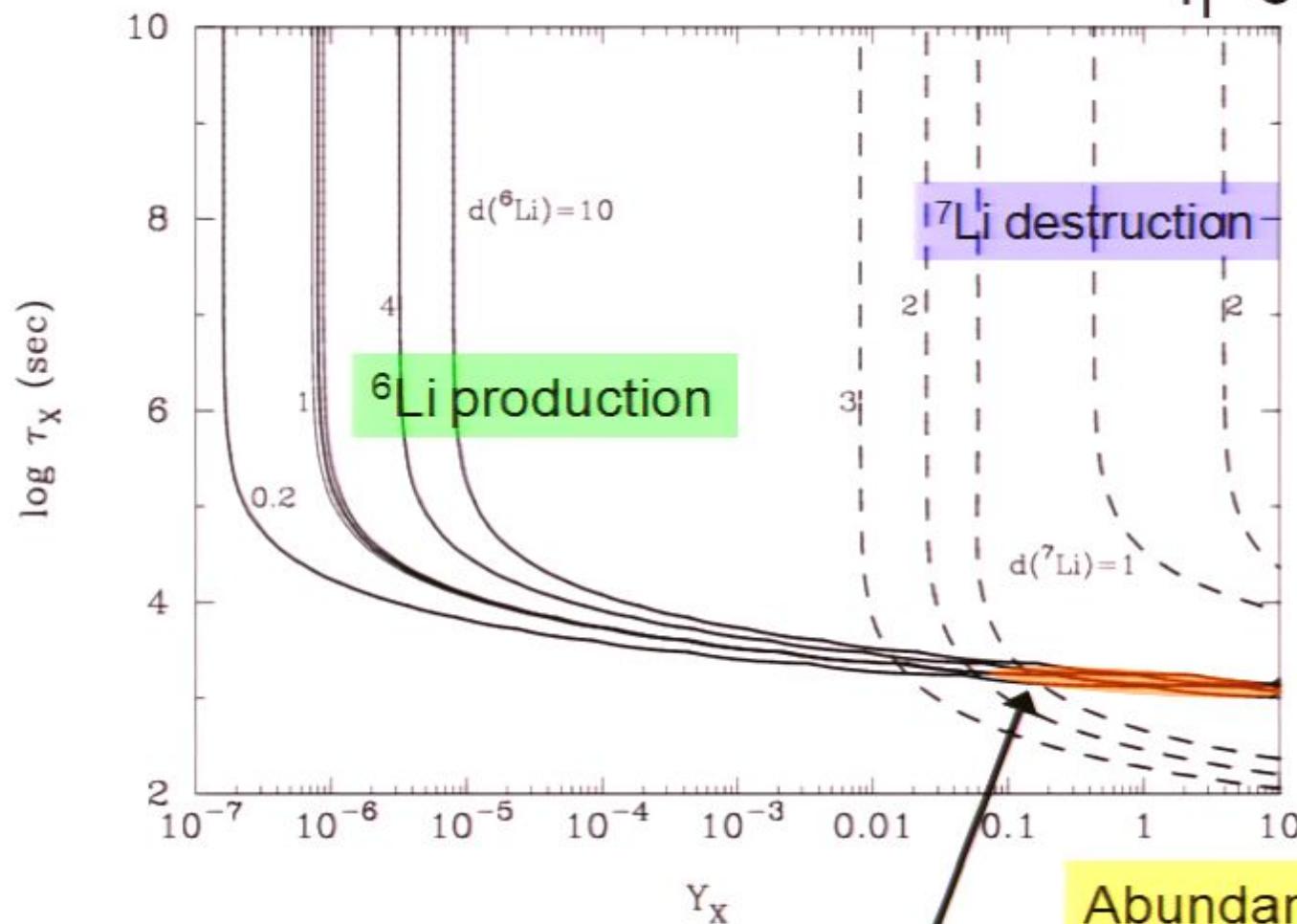
Parameter search 2

When weak boson exchange reaction
 ${}^7\text{Be}_X \rightarrow {}^7\text{Li} + X^0$ (Bird et. al 2007) is included

Contours of calculated Li abundance relative to the observed value: $d({}^A\text{Li}) = {}^A\text{Li}^{\text{Calc}} / {}^A\text{Li}^{\text{Obs}}$

$$\begin{aligned} &[{}^7\text{Li}(p,\alpha){}^4\text{He}} \\ &[{}^7\text{Li}(X^-, \gamma){}^7\text{Li}_X(p,\alpha X^-){}^4\text{He}} \\ &\eta = 6.1 \times 10^{-10} \end{aligned}$$

Lifetime τ_X

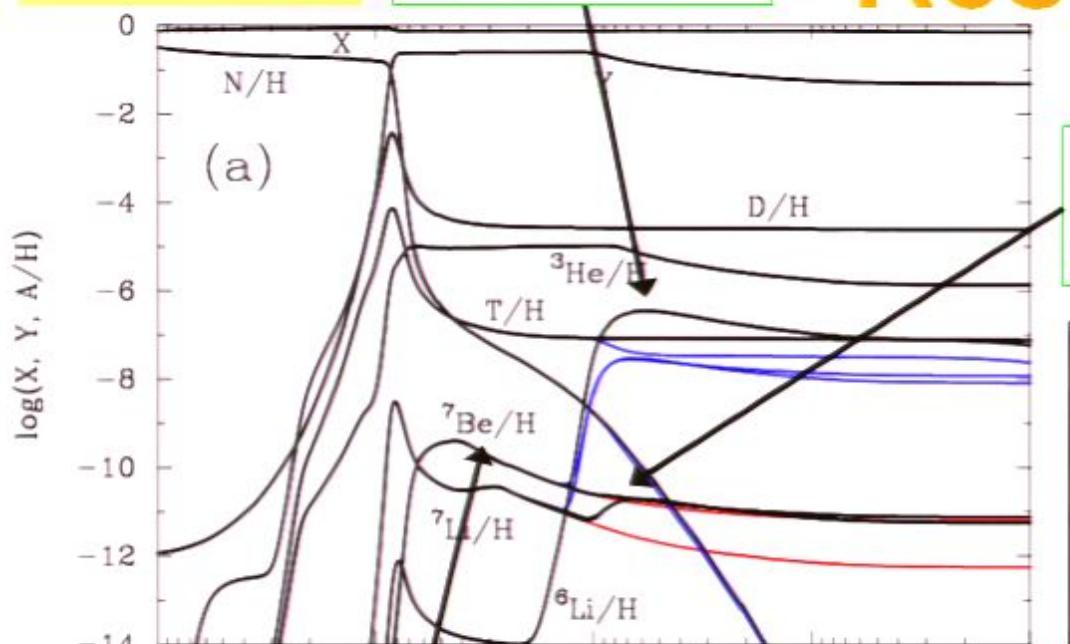


Abundance

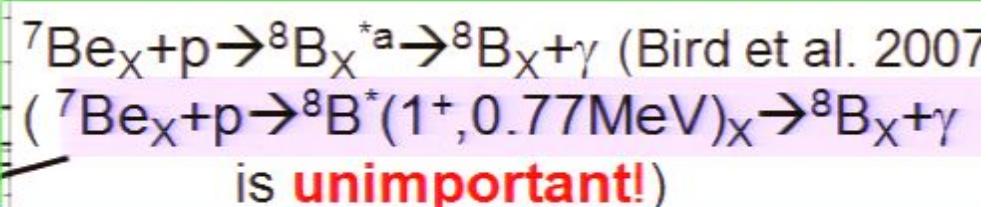
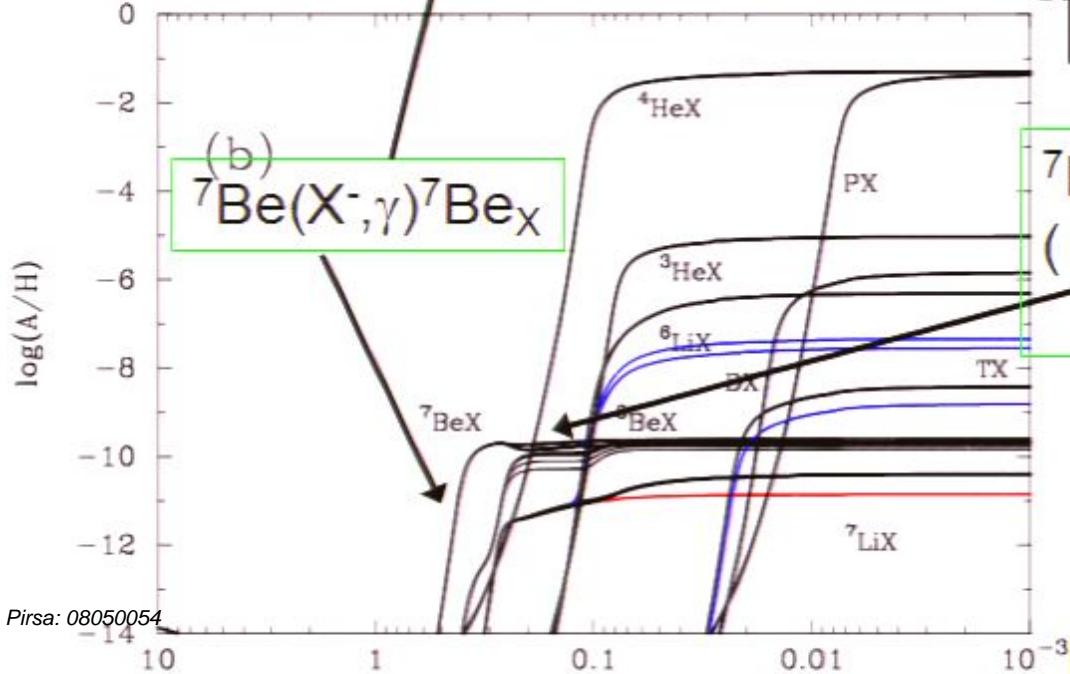
 ${}^4\text{He}_X(\text{d}, \text{X}^-){}^6\text{Li}$

Result

Nuclear flow

 $\blacklozenge n_x = 0.1 n_b, \tau_x = \infty$ 
 ${}^4\text{He}_X(\text{t}, \text{X}^-){}^7\text{Li}$
 ${}^4\text{He}_X({}^3\text{He}, \text{X}^-){}^7\text{Be}$

- Kamimura ($m_x = 50, 100, 500 \text{ GeV}$)
- Kamimura ($m_x = \infty$)
- ${}^4\text{He}_X(\text{t}, \text{X}^-), {}^4\text{He}_X({}^3\text{He}, \text{X}^-)$ rates = 0 (MK et al. 2008)
- ${}^4\text{He}_X(\text{t}, \text{X}^-), {}^4\text{He}_X({}^3\text{He}, \text{X}^-)$ rates by Cyburt et al. (2006)



Precise reaction rates by Prof. Kamimura et al.

	MK et al. (2008)	Kamimura et al.
$\rightarrow {}^4\text{He}_X(\text{d}, \text{X}^-) {}^6\text{Li}$	Hamaguchi et al. (2006)	(smaller than rates in Cyburt (2006))
$\rightarrow {}^4\text{He}_X(\text{t}, \text{X}^-) {}^7\text{Li}$	0	similar
$\rightarrow {}^4\text{He}_X({}^3\text{He}, \text{X}^-) {}^7\text{Be}$	Deduced from SBBN	$\sim 1/3$
$\rightarrow {}^6\text{Li}_X(\text{p}, \alpha \text{X}^-) {}^3\text{He}$	Deduced from SBBN	mass dependence
$\rightarrow {}^7\text{Li}_X(\text{p}, \alpha \text{X}^-) {}^4\text{He}$	Bird et al. (2007)	
$\rightarrow {}^7\text{Be}_X(\text{p}, \gamma) {}^8\text{B}_X$		