Big Bang Nucleosynthesis with long-lived strongly interacting relic particles

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MK et al. Phys. Rev. D 80, 103501 (2009) [arXiv:0906.3516]

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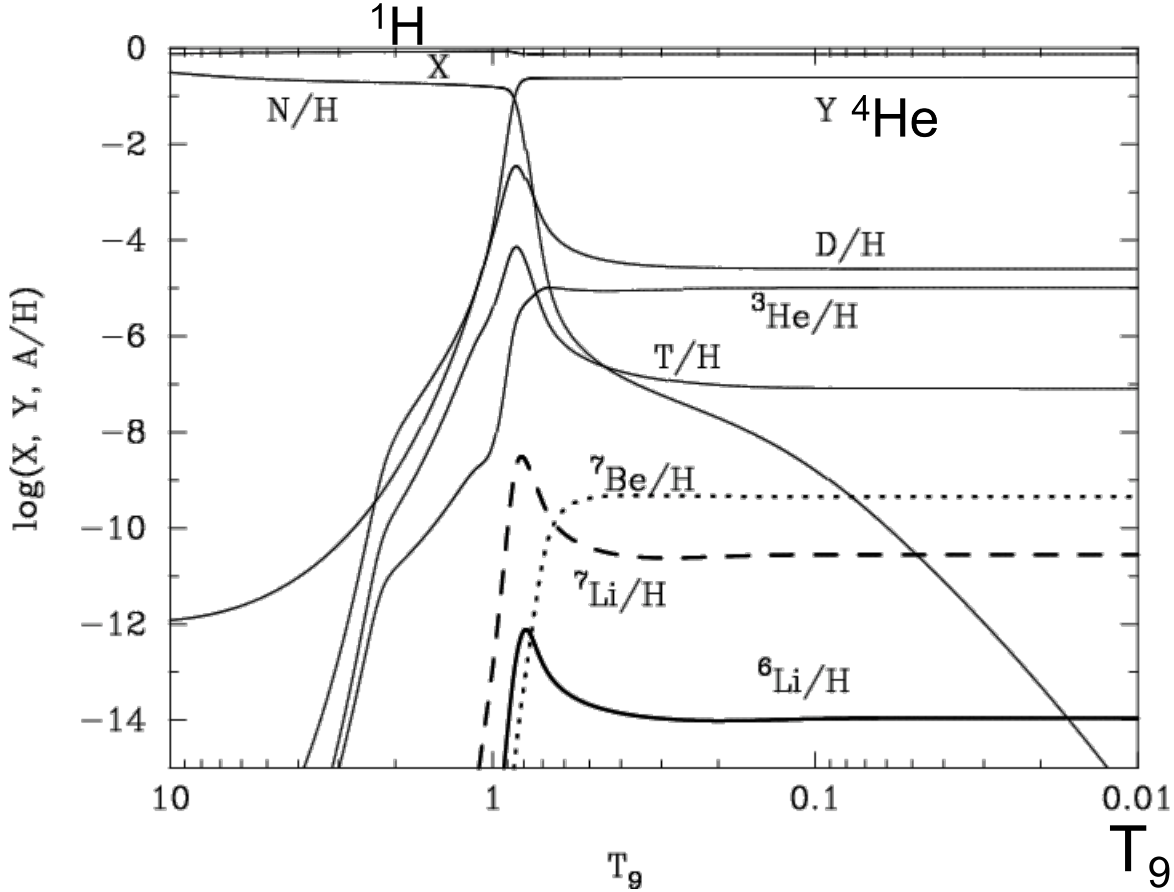
Introduction

Standard Big Bang Nucleosynthesis (SBBN)



$T_9 \equiv T/(10^9 K)$

- Mass # A=5(^{5}He, ^{5}Li): unstable to particle decay
  →A≥6 not produced much
- A=8(^{8}Be): unstable to α-decay
  →A≥9 not produced much

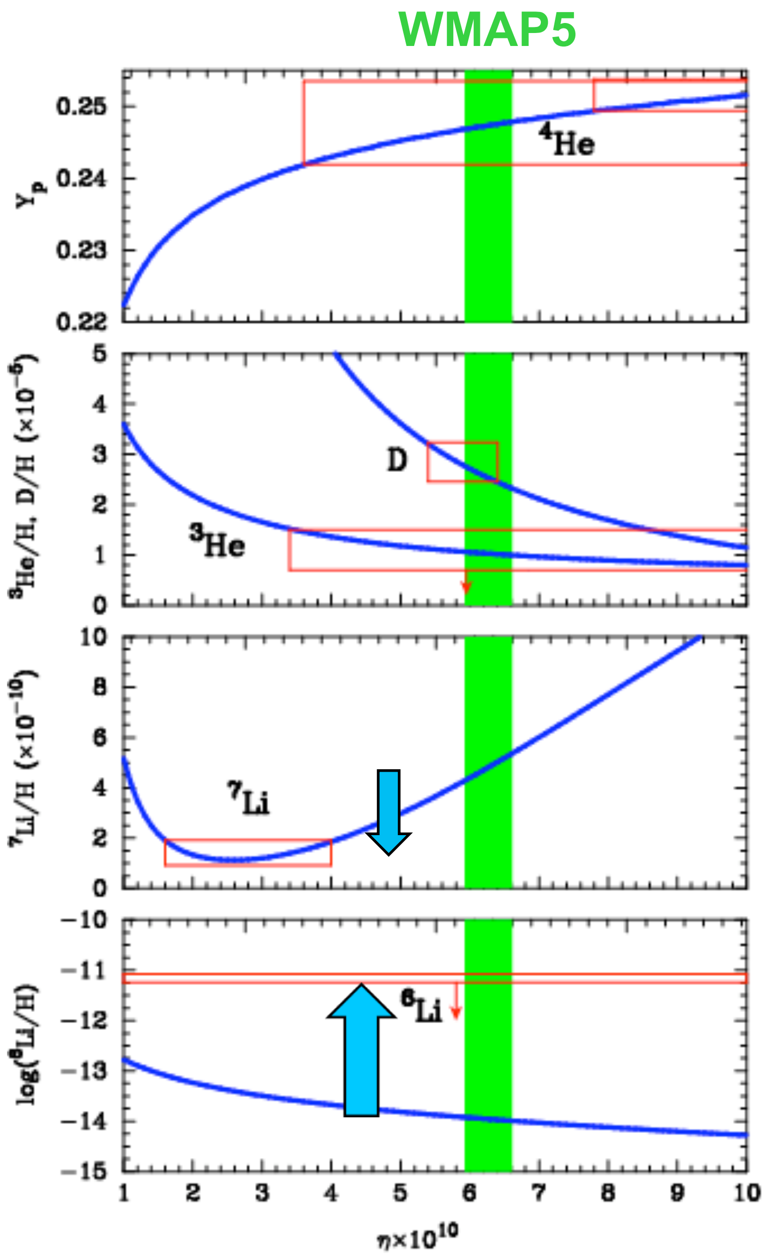
Observations of light element abundances

- ^{6}Li ,^{7}Li : Metal-poor stars

  possible primordial abundances

Li problems

Talk by Jedamzik



- ^{9}Be, B C : Metal-poor stars

  primordial abundances

  not determined

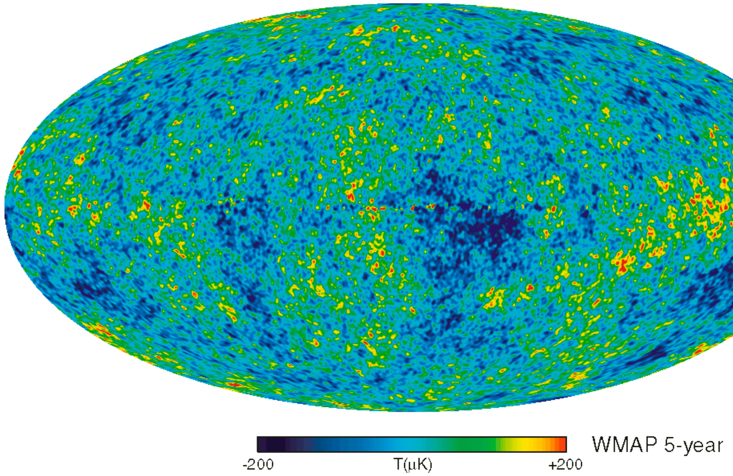
Cosmological processes

➢**Nonthermal processes triggered by decay of exotic particles**

(Ellis et al. 1985-, Reno & Seckel 1988, Dimopoulos et al. 1988-, Kawasaki et al. 1988-, Jedamzik 2000-)

➢**Exotic nuclear reactions by bound states between negatively charged exotic particles and nuclides**

(Pospelov 2007, Kohri & Takayama 2007, Kawasaki et al. 2007-, Hamaguchi et al. 2007, Jedamzik 2008-)



The WMAP Science Team

➢Standard cosmological model includes
- ✓**Dark matter**
- ✓Dark energy (accelerated expansion)

→Need for beyond the standard model including dark matter
(e.g. SUSY, extra-dimensions)

→existences of exotic particles

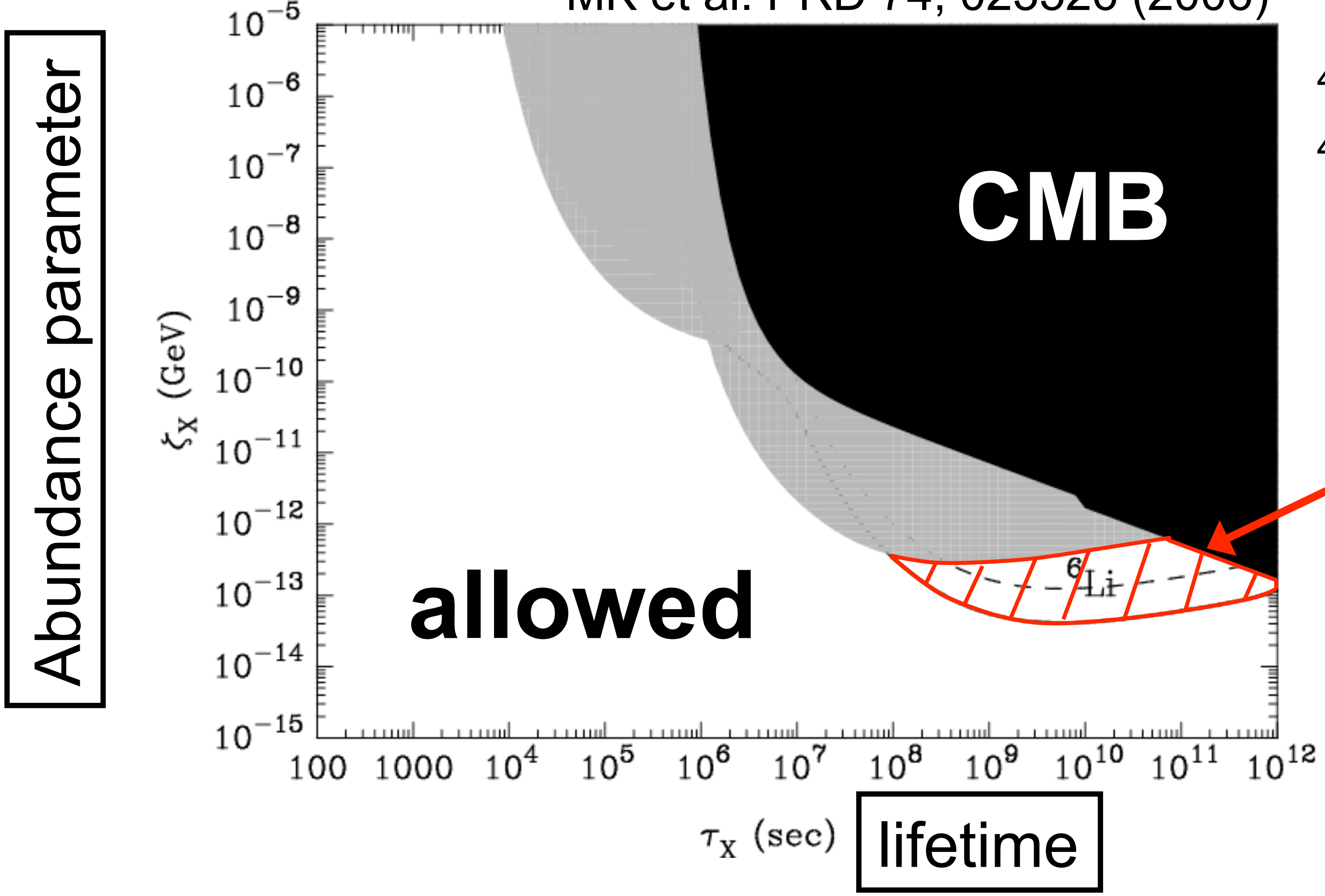
ex)
✓slepton(NLSP)
(Feng et al. 2003)
✓gluino(split SUSY)
(Arkani-Hamed et al. 2005)

➢Particles other than SM particles
①production in high energy colliders
②effect in the early universe
long-lived→light element

^{6,7}Li problems

^{6}Li production by the radiative particle decay

MK et al. PRD 74, 023526 (2006)



$^4He(\gamma,n)^3He(\alpha,p)^6Li$

$^4He(\gamma,p)^3H(\alpha,n)^6Li$

$\lesssim$10×MPHSs ^{6}Li

^{6}Li production!

$\tau_X = 10^8\text{-}10^{12}$sec

$\zeta_X \sim 10^{-12.5}$GeV

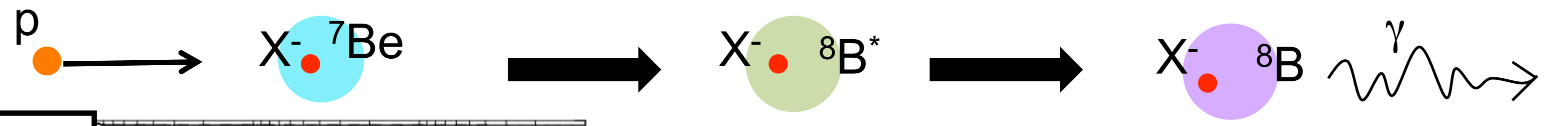
- Constraint from new ^{4}He photodisintegration data

  → factor of up to 3 uncertainty in ^{6}Li production

MK et al. PRD 79, 123513 (2009)

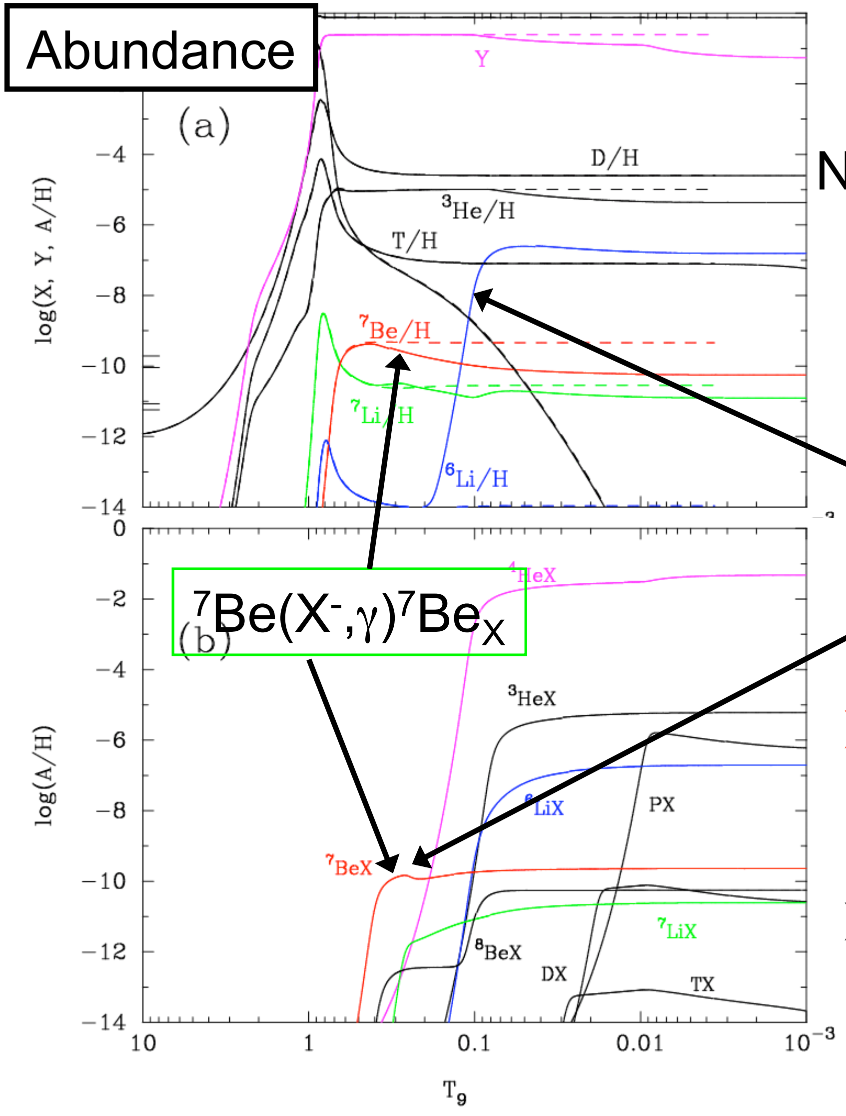
BBN in existence of negatively charged particle X^-

- Resonant reaction through X-nucleus for nuclear excited state



MK et al. PRD 76, 121302 (2007)

Abundance



$^7Be(X^-,\gamma)^7Be_X$

Network calculation (MK el al. ApJ 680, 846 2008)
with realistic cross sections by
Kamimura et al. PThPh 121, 1059 (2009)

(m_X>>1GeV, $n_X=0.05n_b$, $\tau_X=\infty$)

$^4He_X(d,X^-)^6Li$ (Pospelov 2007)

$^7Be_X+p \rightarrow {}^8B_X^{*a} \rightarrow {}^8B_X+\gamma$ (Bird et al. 2008)

- **^7Li reduction and/or ^6Li production**
  but for very high abundance of $n_X/n_b>0.04$
- Nuclides of A≥9 are not produced much

Temperature $T_9=T/(10^9\ K)$

Conclusion of our study

^{6,7}Li problems in Big Bang Nucleosynthesis

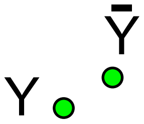
Model	^{6}Li problem solved?	^{7}Li problem solved?	Other nuclides with possible signatures
Radiative decay	**YES**	NO	NO
Leptonic X^{-}	**YES**	**YES**	**NO**
Strong int. X^{0}	**NO**	**NO**	**^{9}Be and/or ^{10}B**
Early cosmic ray	**YES**	NO	**^{9}Be and ^{10,11}B**

MK, ApJ 681, 18 (2008)

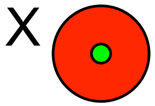
- Exotic particles could have affected the light element synthesis.
- Early cosmic ray nucleosynthesis also could have affected.
- Future observation of Be, B abundance is important to figure out the solutions to the Li problems.

Long-lived Heavy Colored Particles Y

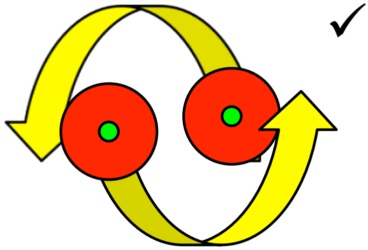
Kang et al. JHEP 9, 86 (2008)



✓In the early universe, hypothetical colored particles Y are produced and annihilate



✓$T<T_c\sim180\text{MeV}$→Y particles get confined in hadrons (X)



✓X+X form the bound state→annihilate →final abundance

$$n_X \approx 10^{-8} n_b$$

Goal

- ➢Calculate the BBN in existence of heavy exotic strongly interacting particles
- ➢Derive a constraint on their abundance and lifetime
- ➢Check signatures on light element abundances

Model

1. Binding energies of nuclides and X systems

[Assumption]

- X (spin 0, **charge 0**, mass m_X>>1 GeV)
- X interacts as strongly as nucleons

→Nuclear potential

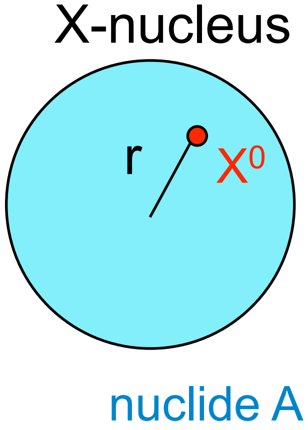
1)nucleon+X: well reproducing the binding energy of n+p system

$$V_N(r) = \begin{cases} -25.5\,\mathrm{MeV} & (\mathrm{for}\ r \le 2.5\,\mathrm{fm}) \\ 0 & (\mathrm{for}\ 2.5\,\mathrm{fm} < r) \end{cases}$$

2)other nuclides: Woods-Saxon (V_0=50MeV, a=0.6fm, R=$\langle r_m^2\rangle^{1/2}$)

$$V_N(r) = -\frac{V_0}{1+\exp[(r-R)/a]}$$

→Schrödinger equation→binding energies and wave functions



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

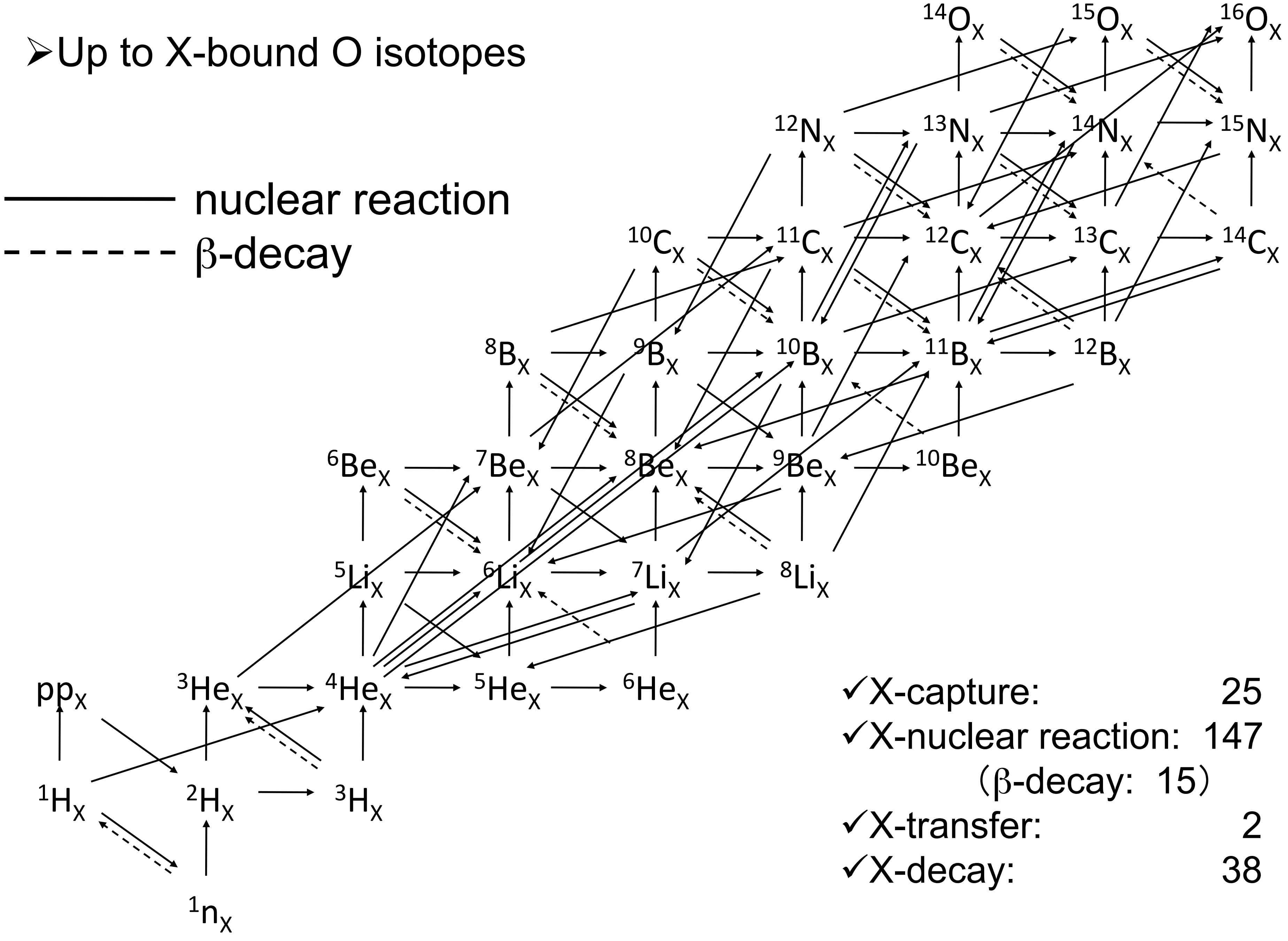
Binding energies~O(10MeV) → Xs capture nuclei early in BBN epoch!

2. Nuclear reaction rates for X-nuclei

- ➢Binding energies of X-nuclei→Q-values
- ➢Estimation of nuclear reaction and β-decay rates for X-nuclei
  - ✓adopting measured cross section
  - ✓correcting for Q-value and mass numbers of reactant particles

3. Nuclear reaction network

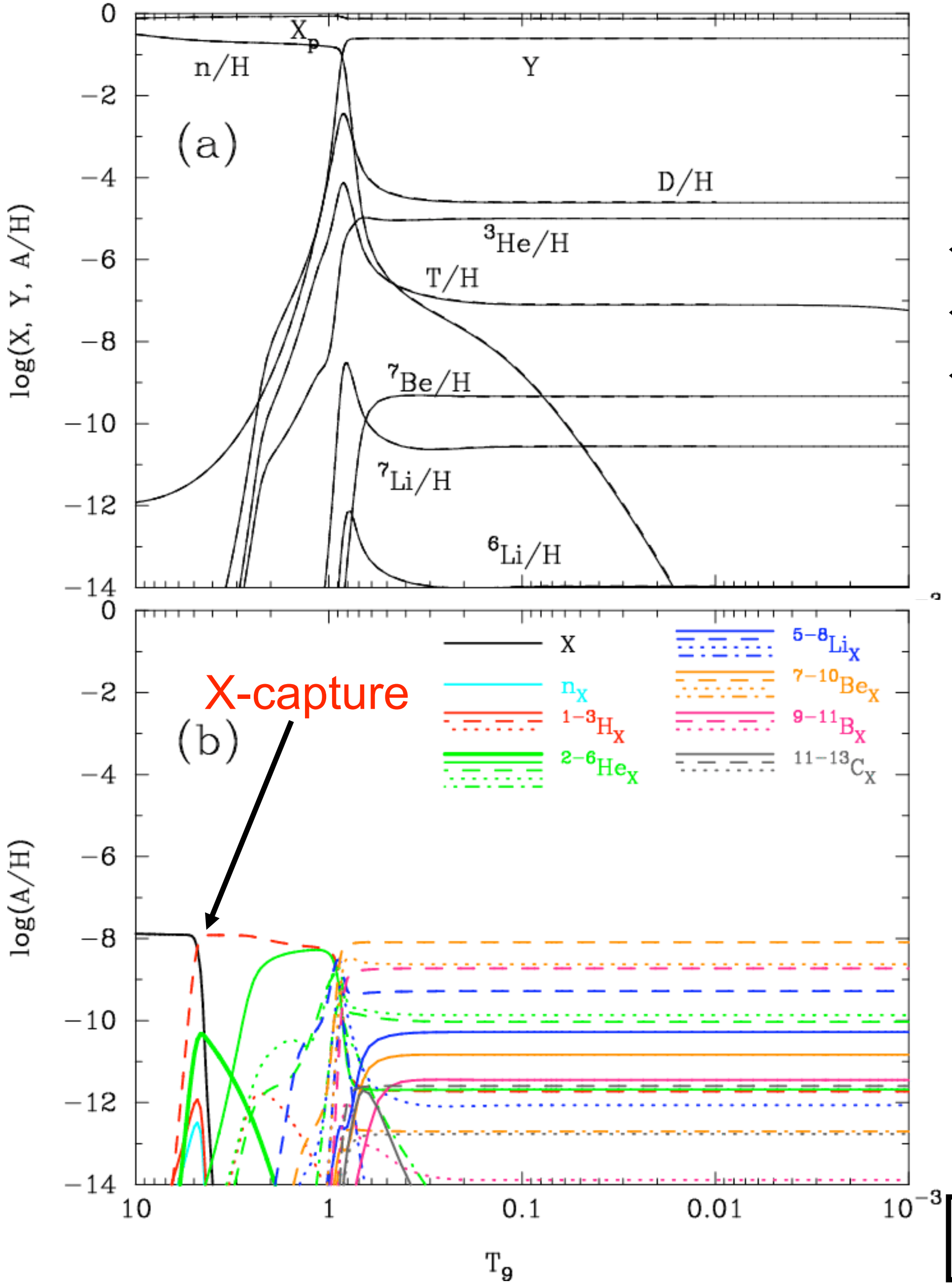
- ➢Up to X-bound O isotopes



✓X-capture:	25
✓X-nuclear reaction:	147
（β-decay: 15）	
✓X-transfer:	2
✓X-decay:	38

Result

Abundance



Nuclear flow

◆$m_x >> 1\mathrm{GeV}$, $n_x = 10^{-8} n_b$, $\tau_x = \infty$

✓$T_9 \sim 5$: Xs capture nucleons

✓$T_9 \gtrsim 1$: ^2H_X & ^3He_X form abundantly

✓$T_9 \sim 1$: Deuterons increase

→(d,p), (d,n) reactions operate

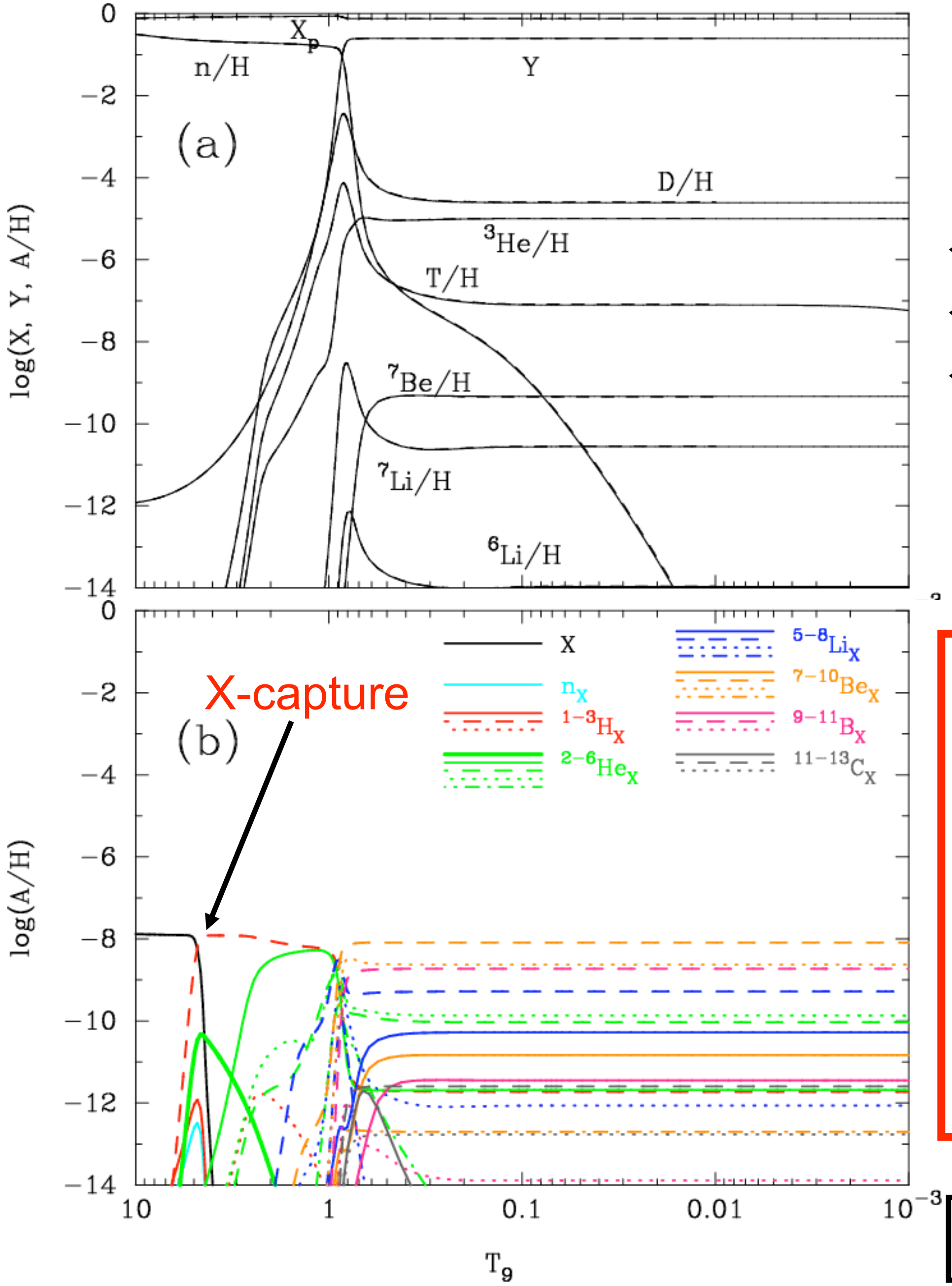
→heavy X-nuclei are produced

(up to $^{13}C_X$)

Temperature $T_9 = T/(10^9\ \mathrm{K})$

Result

Abundance



X-capture

Temperature $T_9=T/(10^9\ \mathrm{K})$

Nuclear flow

◆$m_x \gg 1\,\mathrm{GeV}$, $n_x=10^{-8}n_b$, $\tau_x=\infty$

✓$T_9\sim5$: Xs capture nucleons
✓$T_9\gtrsim1$: ^2H_X & ^3He_X form abundantly
✓$T_9\sim1$: Deuterons increase
→(d,p), (d,n) reactions operate
→heavy X-nuclei are produced
(up to $^{13}C_X$)

X^0 has a great impact on BBN!

➢Strongly interacting X^0s have large binding energy to nuclides and large cross sections for capture of nuclides
→Bound states form early

➢^5Li_X , ^5He_X , ^8Be_X are stabilized against particle decay→heavy X-nuclei can form

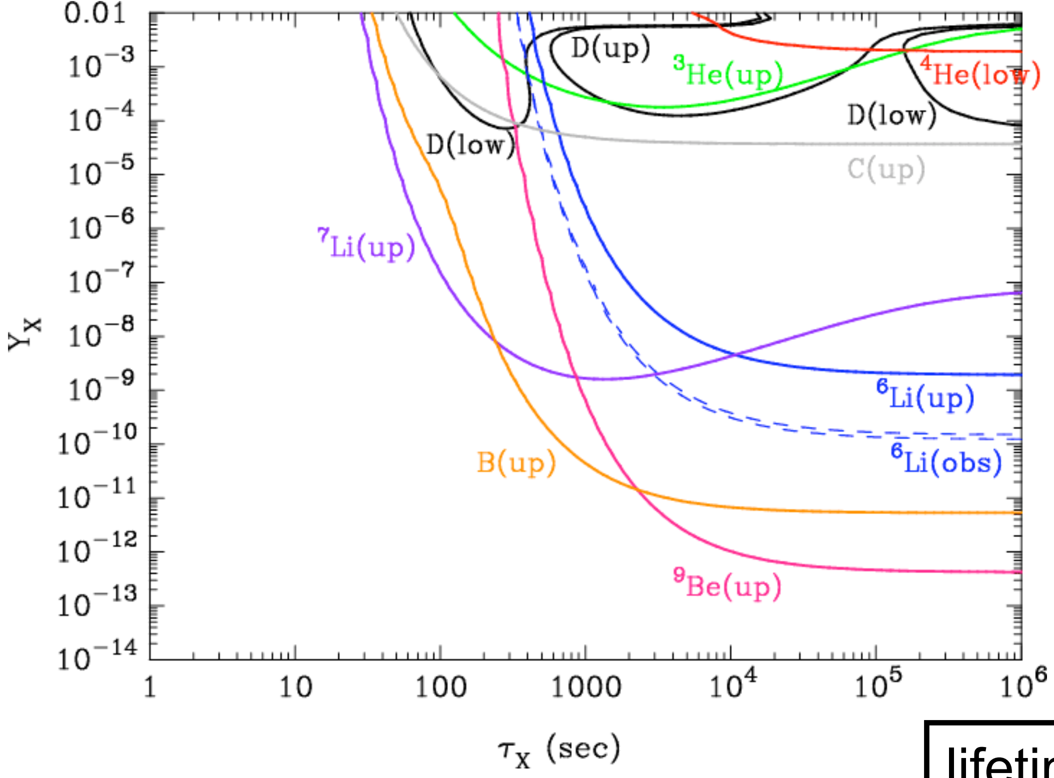
Parameter search

✓Calculation including the decay of X^0

Contours for observational constraints on primordial abundances

Abundance $Y_X=n_X/n_b$

$\eta=6.3\times10^{-10}$



lifetime τ_X

✓^{9}Be and B could be produced more than SBBN predictions

✓^{10}B/^{11}B~10^5 **high ratio**
c.f. Galactic CR (^{10}B/^{11}B~0.4)
SN ν-process (^{10}B/^{11}B<<1)

✓relic abundance $Y_X\approx10^{-8}$
→$\tau_X \lesssim 200$s

- ➢A solution for ^{6}Li or ^{7}Li problems are not found
- ➢X^0 abundance is constrained from observation of ^{7}Li, B, ^{9}Be

Summary

➢We study the effect of long-lived strongly interacting particles (X^0) on BBN

- ✓X^0 is assumed to interact as strongly as a nucleon
- ✓We calculate BBN including such particle dynamically

[Result]

➢BBN in existence of X^0

- ✓T_9~5 X^0 captures a nucleon
- ✓T_9~1 D forms → heavy X-nuclei are produced through D-capture

✓X-nuclei are produced at relatively high temperature →Nuclear reactions operate efficiently→ heavy X-nuclei

➢Constraints on the lifetime and abundance of X^0 are derived →$\tau_X \lesssim 200$s