BBN constraint on long-lived strongly interacting relic particles

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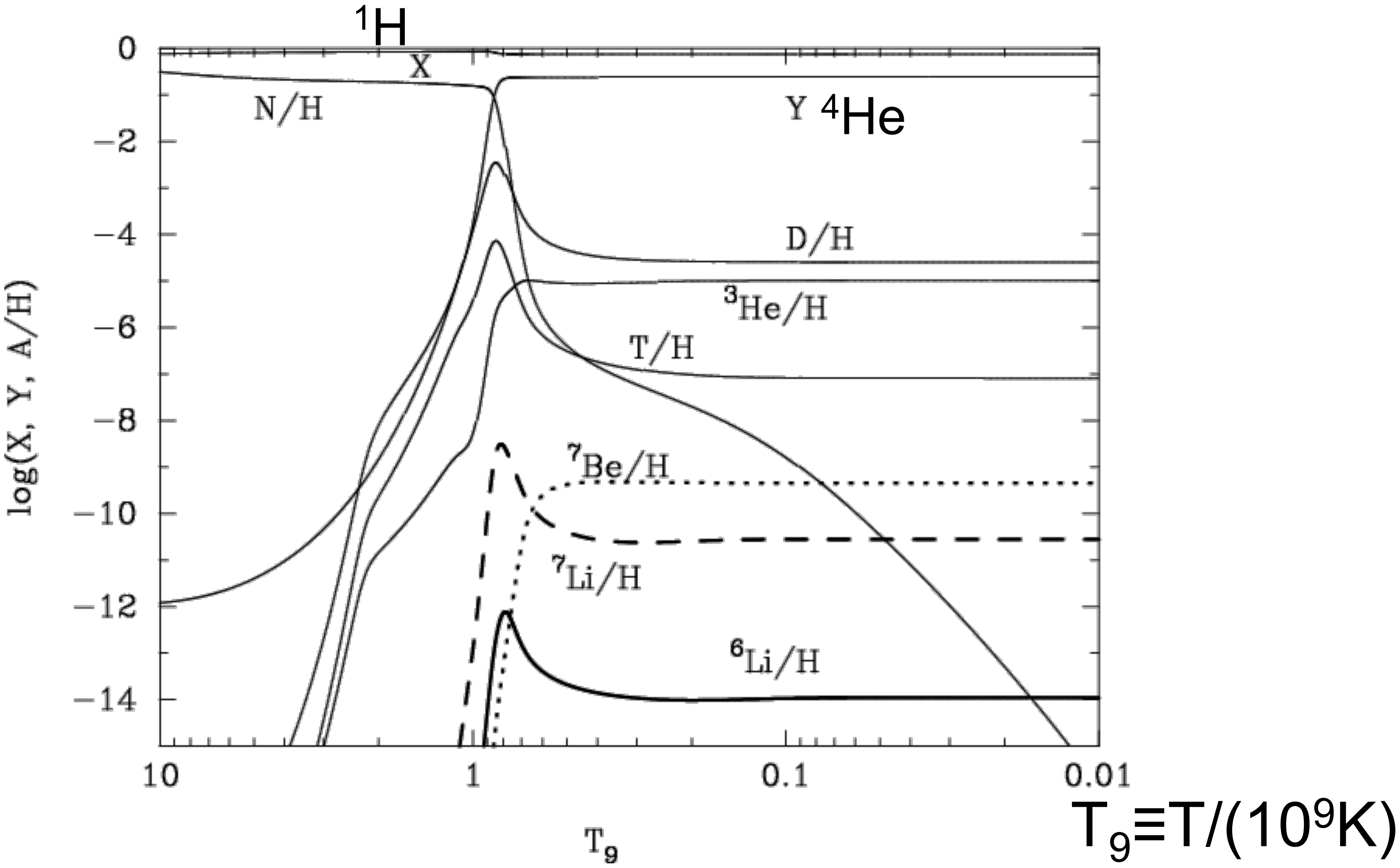
Introduction

Standard Big Bang Nucleosynthesis (SBBN)



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

Observations of light element abundances

- D, ^{3}He, ^{4}He : consistent with SBBN

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

  possible primordial abundances

  (Talk by Prof. Jedamzik)

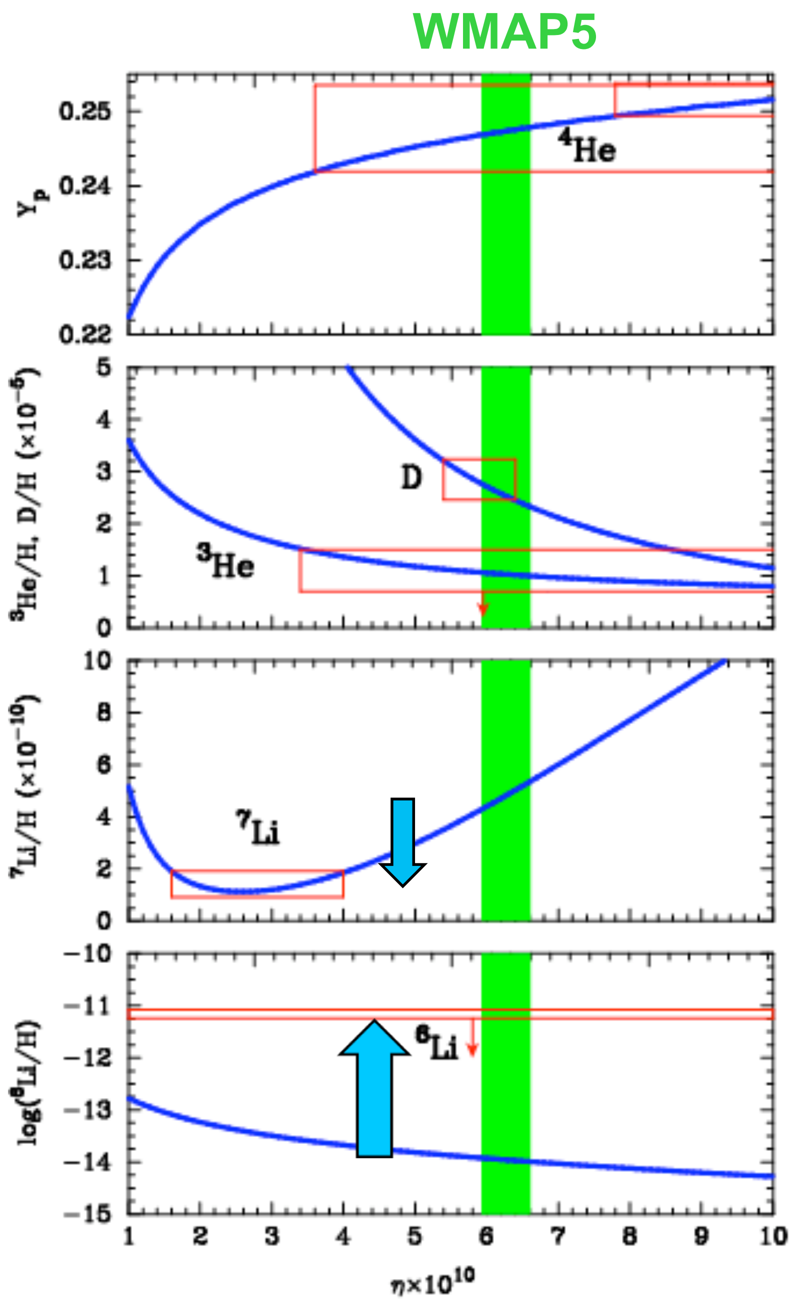
  Li problems

  (e.g. Asplund et al., Astrophys. J. 644, 229 2006)

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

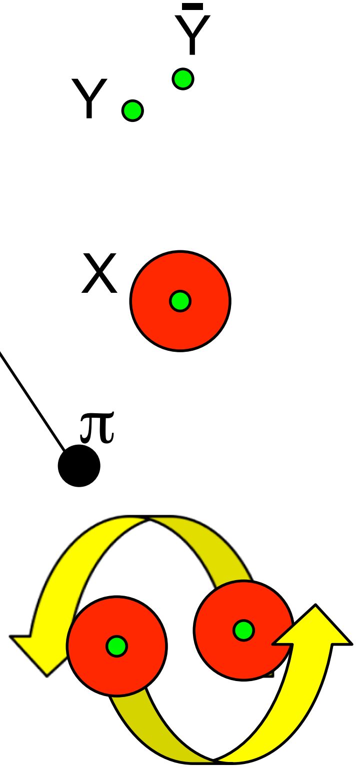
  primordial abundances

  not determined



Long-lived Heavy Colored Particles

Kang et al. JHEP 9, 86 (2008)



✓In the early universe, hypothetical colored particles (Y) annihilate→ relic abundance $n_Y/s \sim 10^{-14}$ ($n_Y/n_b \sim 10^{-4}$)

✓$T<T_c \sim 180$MeV→heavy partons get confined in hadrons (X)

✓X+X form the bound state→decay into lower energy states →annihilate →final abundance

$$\frac{n_X}{n_b} \approx 10^{-8} \left(\frac{R}{\mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{T_B}{180\mathrm{MeV}}\right)^{-3/2} \left(\frac{m}{\mathrm{TeV}}\right)^{1/2}$$

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

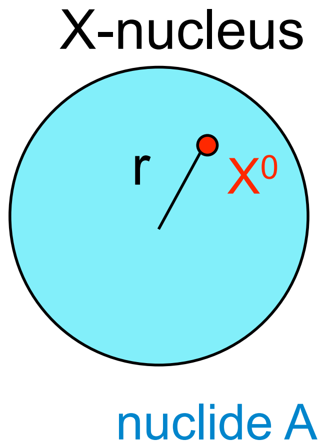
  1)nucleon+X: well reproducing the binding energy of n+p system

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

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

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

→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~$\mathcal{O}$(10MeV) → Xs capture nuclei early in BBN epoch!

2. Nuclear reaction rates for X-nuclei

- Only non-resonant reactions are considered
- Binding energies of X-nuclei → Q-values

i) Radiative X-capture: $A(X,\gamma)A_X$

✓ $A(n,\gamma)B$ rate

ii) Radiative n-capture: $A_X(n,\gamma)B_X$ → E1 hindered

✓ $A(n,\gamma)B$ rate $\times 10^{-3}$

iii) Reactions of charged particles:

✓ Correction for reduced mass in the thermonuclear reaction rates

✓ Reactions which become of negative Q-value when X is attached:

→ correction for the Coulomb penetration factor for entrance and exit channels in the cross section expression

iv) $A_X(n,p)B_X$

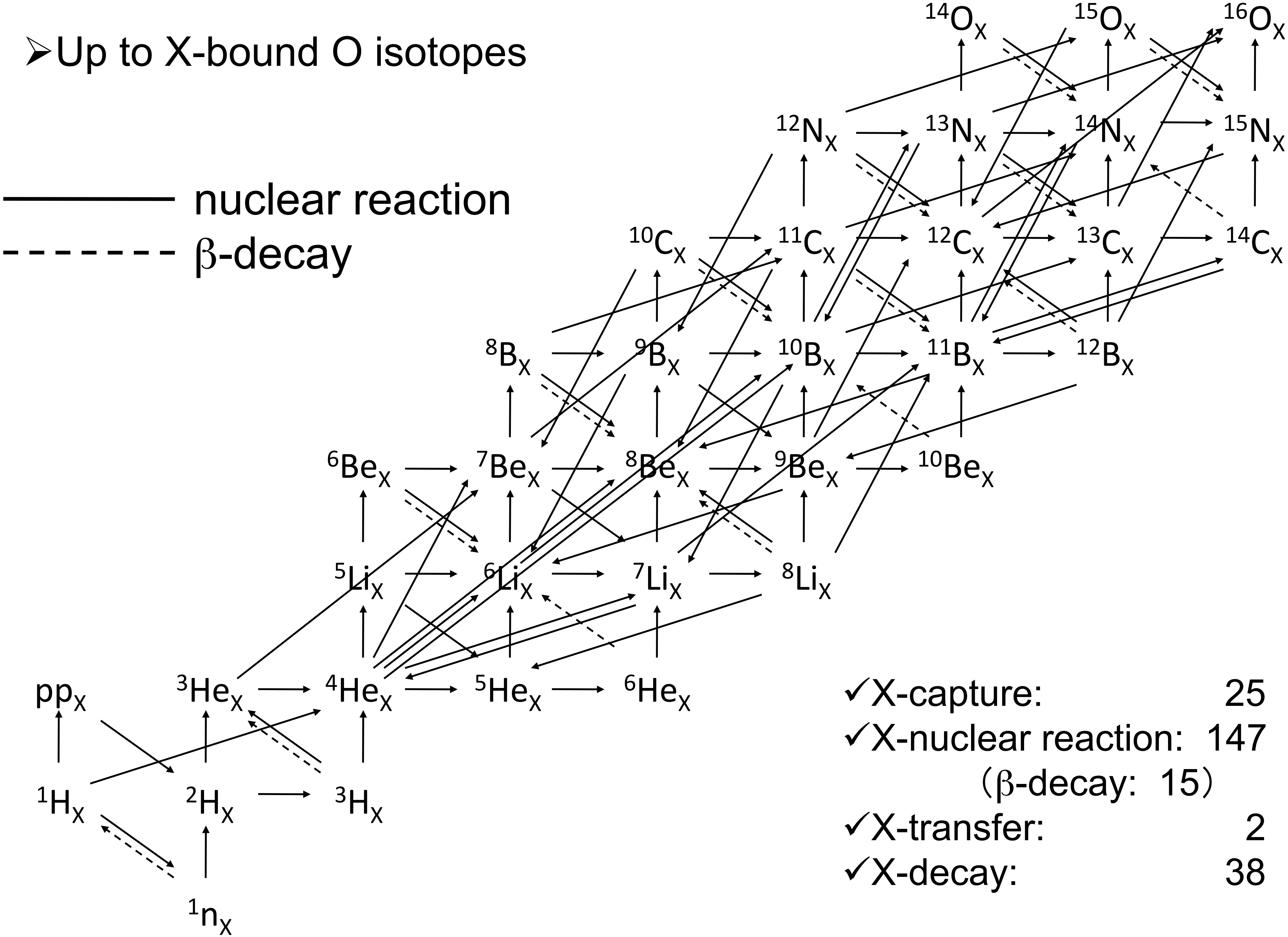
✓ $A(n,p)B$ rate

v) β-decay of A_X:

✓ Standard β−decay rate corrected for Q-value

3. Nuclear reaction network

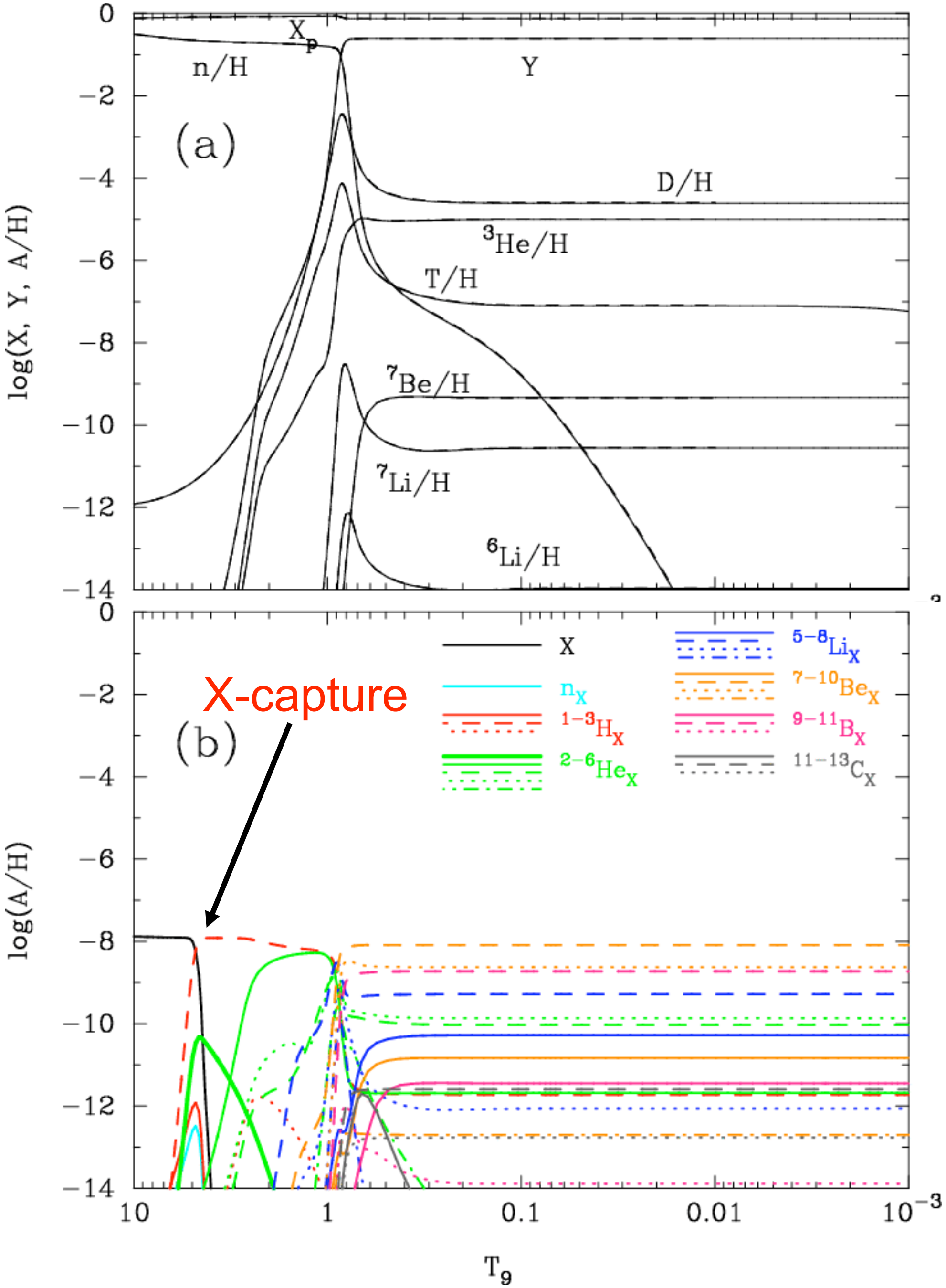
- Up to X-bound O isotopes



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

Abundance

Result



Nuclear flow

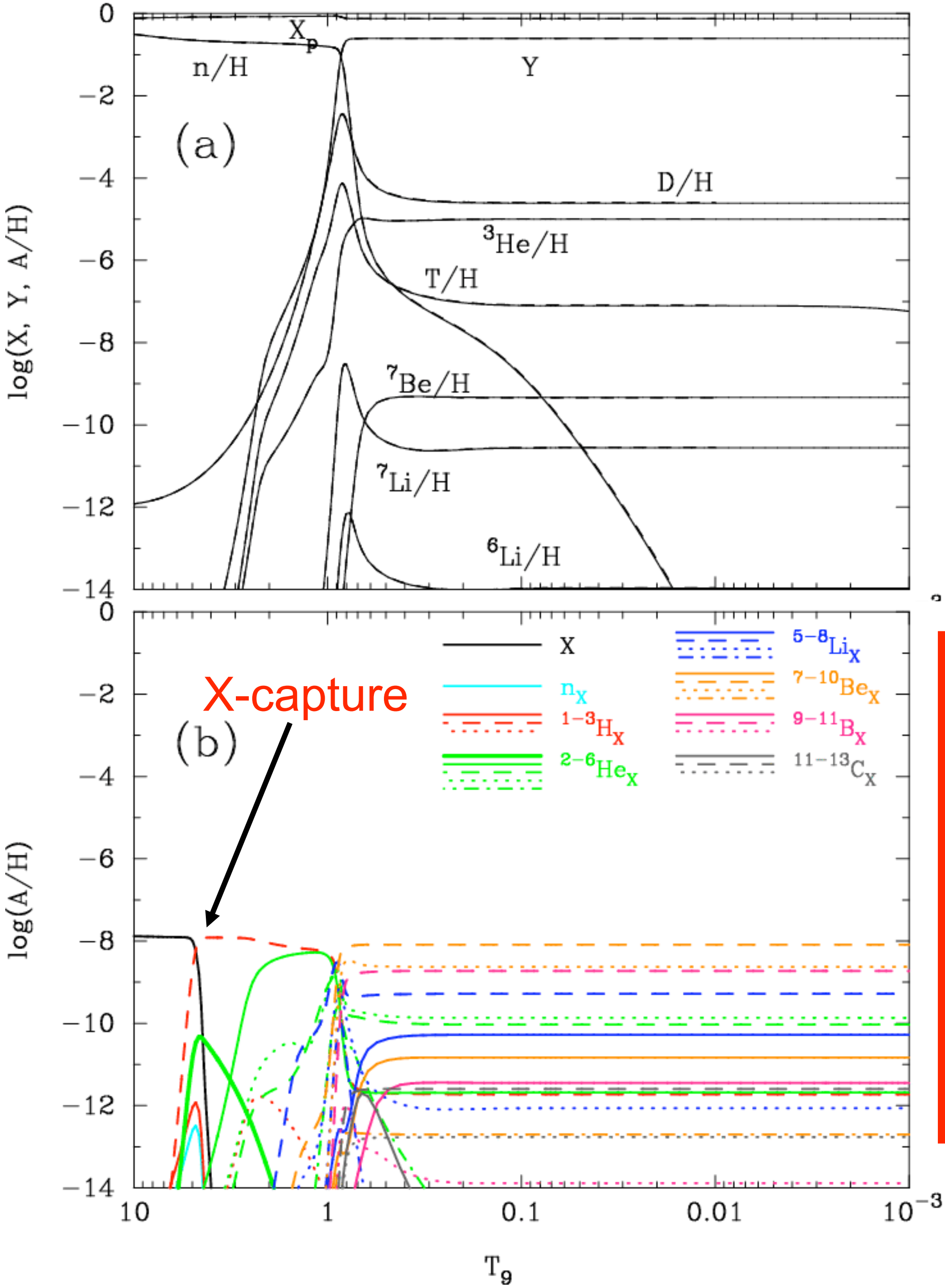
◆m_X>>1GeV, $n_X=10^{-8}n_b$, $\tau_X=\infty$

✓T_9~5: Xs capture nucleons
✓$T_9 \gtrsim 1$: ^2H_X & ^3He_X form abundantly
✓T_9~1: Deuterons increase
→(d,p), (d,n) reactions operate
→heavy X-nuclei are produced
(up to $^{13}C_X$)

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

Abundance

Result



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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 earlier

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

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

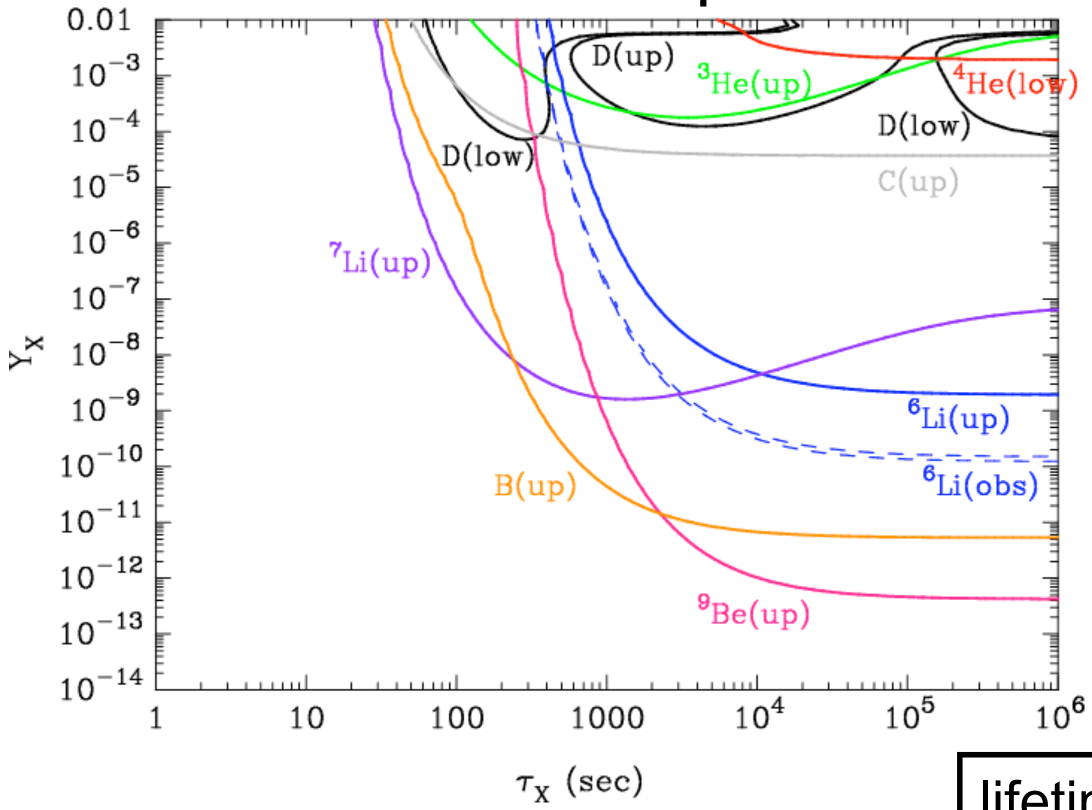
Parameter search

✓Calculation including the decay of X^0
✓Decay-triggered nucleosynthesis NOT considered

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

✓$^{10}B/^{11}B\sim10^5$ **high ratio**
c.f. Galactic CR ($^{10}B/^{11}B\sim0.4$)
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 Q-values and reaction rates for X^0 capture of nuclides and nuclear reaction on X-nuclei
  - ✓ We perform a dynamical BBN calculation including such reactions

[Result]

- BBN in existence of X^0
  - ✓ $T_9 \sim 5$ X^0 captures a nucleon
  - ✓ $T_9 \sim 1$ 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
- Solution for ^6Li or ^7Li problems? No
- Constraints on the lifetime and abundance of X^0 are derived
  → relic abundance $n_X/n_b \sim 10^{-8}$ → $\tau_X \lesssim 200s$