Effect of exotic interacting massive particles including long-lived colored particles on big bang nucleosynthesis

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Kawasaki[1], MK, PRD83, 055011, arXiv:1012.0435

MK, Kajino[2], Yoshida[1], Mathews[3], PRD80, 103501, arXiv:0906.3516

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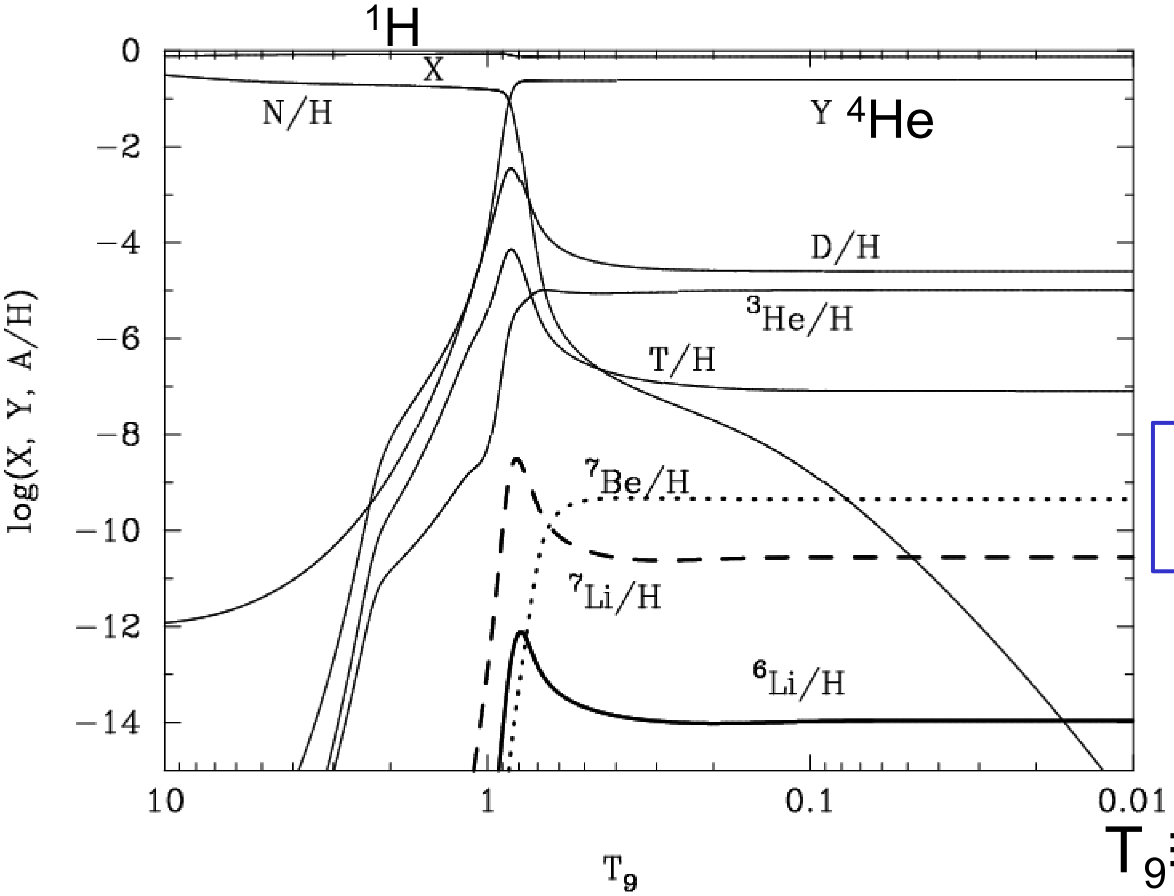
Introduction

Standard Big Bang Nucleosynthesis (BBN)



Recombination→e$^-$ capture →(^{7}Be→^{7}Li)

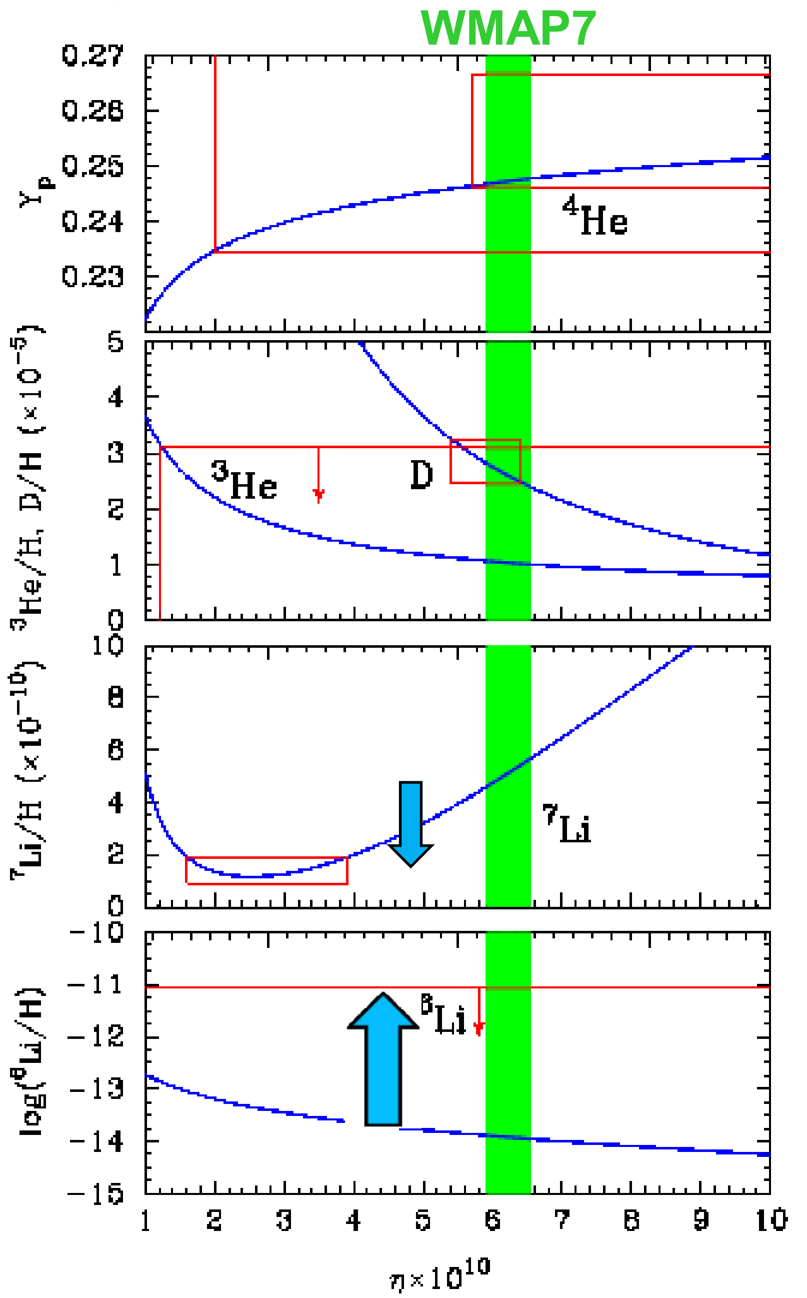
$T_9 \equiv T/(10^9 K)$

Observed abundances of light elements

- SBBN: one parameter
  baryon-to-photon ratio η

←$\eta=(6.225^{+0.157}_{-0.154})\times10^{-10}$

(WMAP: Larson et al. 2010)



Li problems

Observed abundances of light elements

- ^{7}Li in metal-poor stars are ~ 1/3 times (CMB+standard BBN prediction)

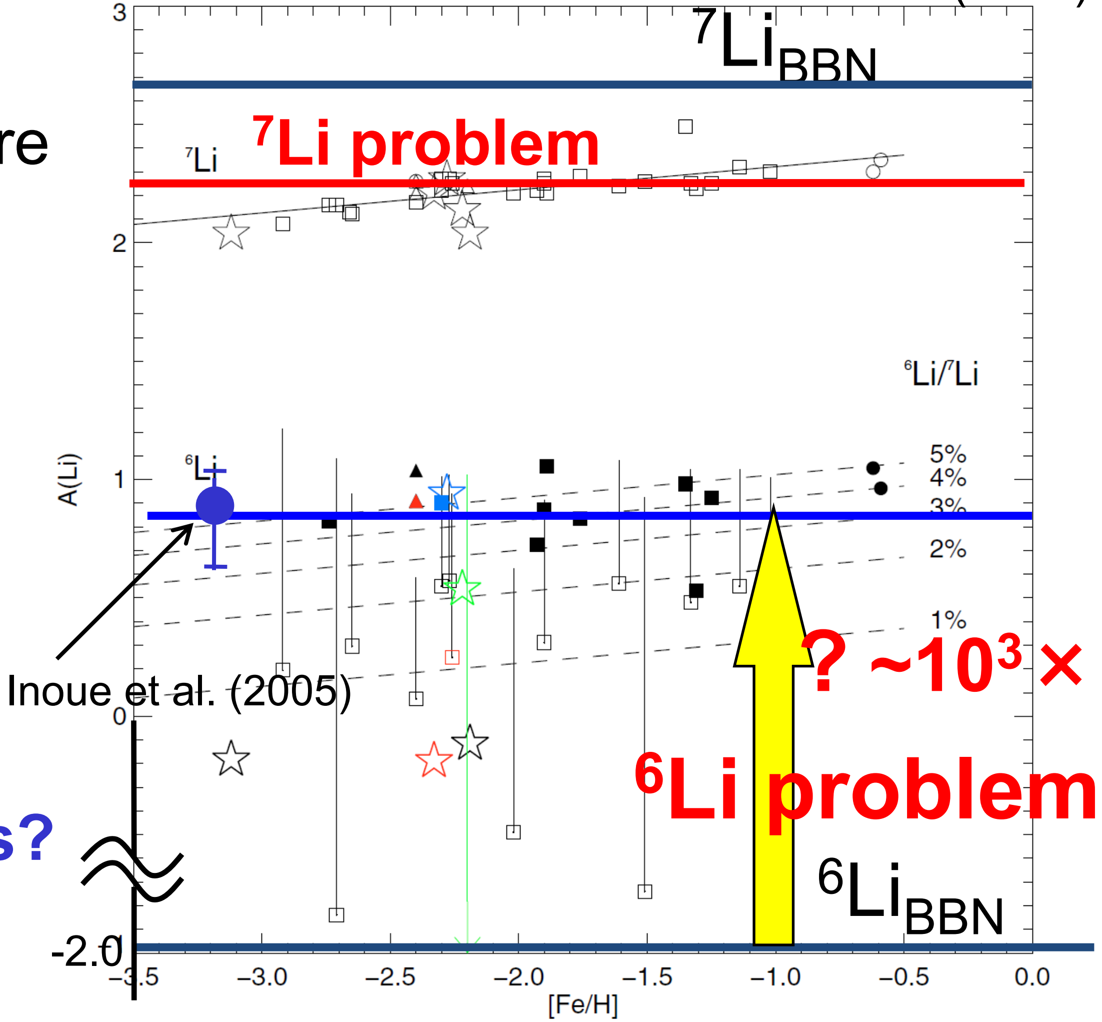
- ^{6}Li is abundant in some of the stars

Signature of new physics?

- ^{9}Be, B, C: plateau not seen

log(^{6,7}Li/H)+12

Garcia Perez et al. (2009)

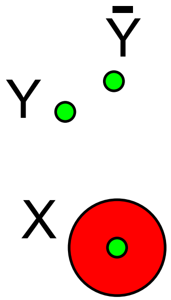


[Fe/H]=log[(Fe/H)/(Fe/H)$_\odot$]

Long-lived Heavy Colored Particles

➢long-lived heavy (m>>GeV) colored particles appear in particle models beyond the standard model
e.g., Split SUSY (Arkani-Hamed & Dimopoulos 2005), …

➢History in the early universe (J. Kang et al. 2008)



✓Long-lived exotic colored particles (Y)

✓$T<T_c \sim 180\mathrm{MeV}$
→**Y particles get confined in hadrons X**
[strongly interacting massive particle (SIMP)]
(Walfran 1979; Dover et al. 1979)

✓final abundance

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

Studies on long-lived SIMP (X) in BBN

- ➢NX force is the same as NΛ force

(Dicus & Teplitz 1980, Plaga 1995, Mohapatra & Teplitz 1998)

✓Mass of X is implicitly assumed to be $m_X \sim m_\Lambda = 1$ GeV

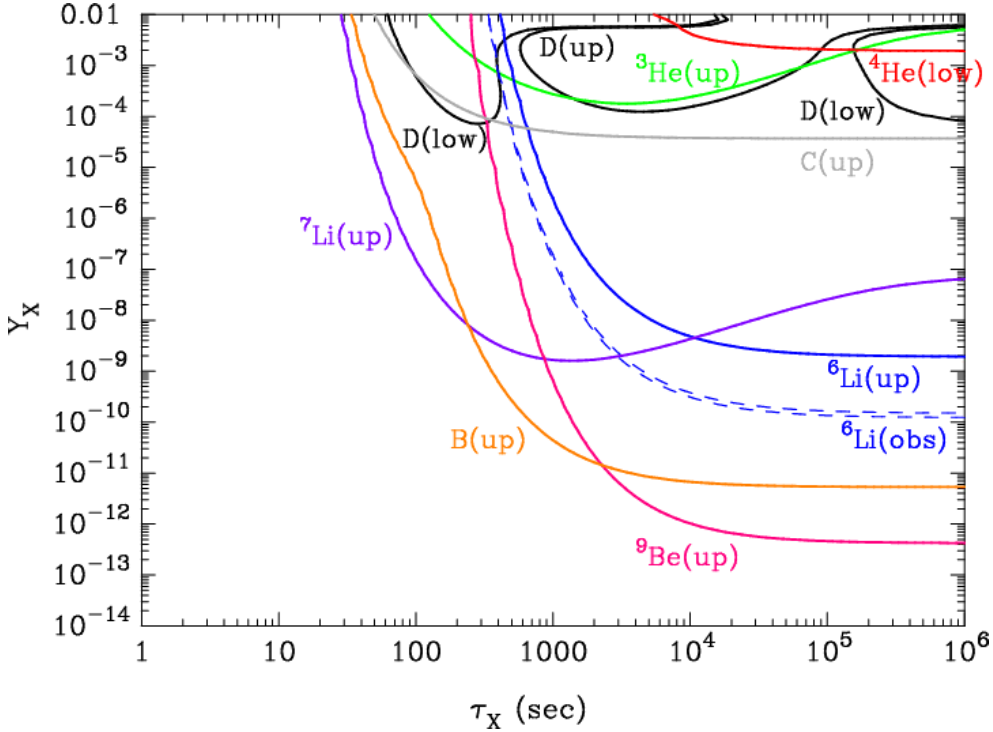
- ➢NX force is same as the NN force, and $m_X >> 1$GeV

(MK et al. 2009)

✓Estimation of binding energies between A and X, and reaction rates

✓Nonequilibrium calculation of abundances

Abundance n_X/n_b



lifetime τ_X

✓^{9}Be and B can be produced more than in SBBN

✓^{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)

Goal

- To investigate signatures of X particles on elemental abundances

- Interaction between X and N is unknown
  →studying multiple cases of interaction strength (δ)

- process of ^{7}Be destruction was found
  →solution to the ^{7}Li problem

Model

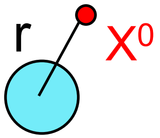
1. Binding energies of nuclides to an X

[Assumption]

parameter 1

- X (spin 0, **charge 0**, mass $\boxed{m_X}$)
- XN potential is Gaussian

Yahiro et al. (1986)



nucleon N

parameter 2

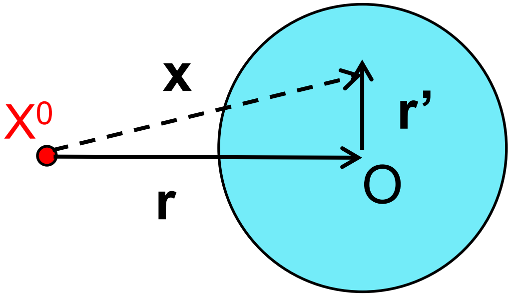
$$v(r) = v_0 \delta \exp\left[-(r/r_0)^2\right]$$

$$v_0 = -72.15\ \mathrm{MeV}\ \text{and}\ r_0 = 1.484\ \mathrm{fm}$$

δ=1 reproduces the binding energy of n+p

- XA potential: integration of (XN potential multiplied by nucleon densities)

$$V(r) = \int v(\boldsymbol{x})\rho(\boldsymbol{r}')\, d\boldsymbol{r}',$$



- $A \geq 2$ nuclei have Gaussian nucleon densities

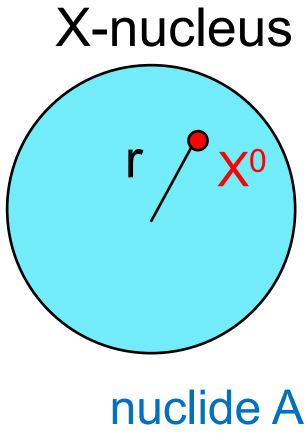
nucleus A

Model

1. Binding energies of nuclides to an X

Schrödinger equation→binding energies and wave functions

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



2. Reaction rates

- Calculated binding energies→reaction Q-values

[notation] (1) 1+2→3+4 reaction: 1(2,3)4

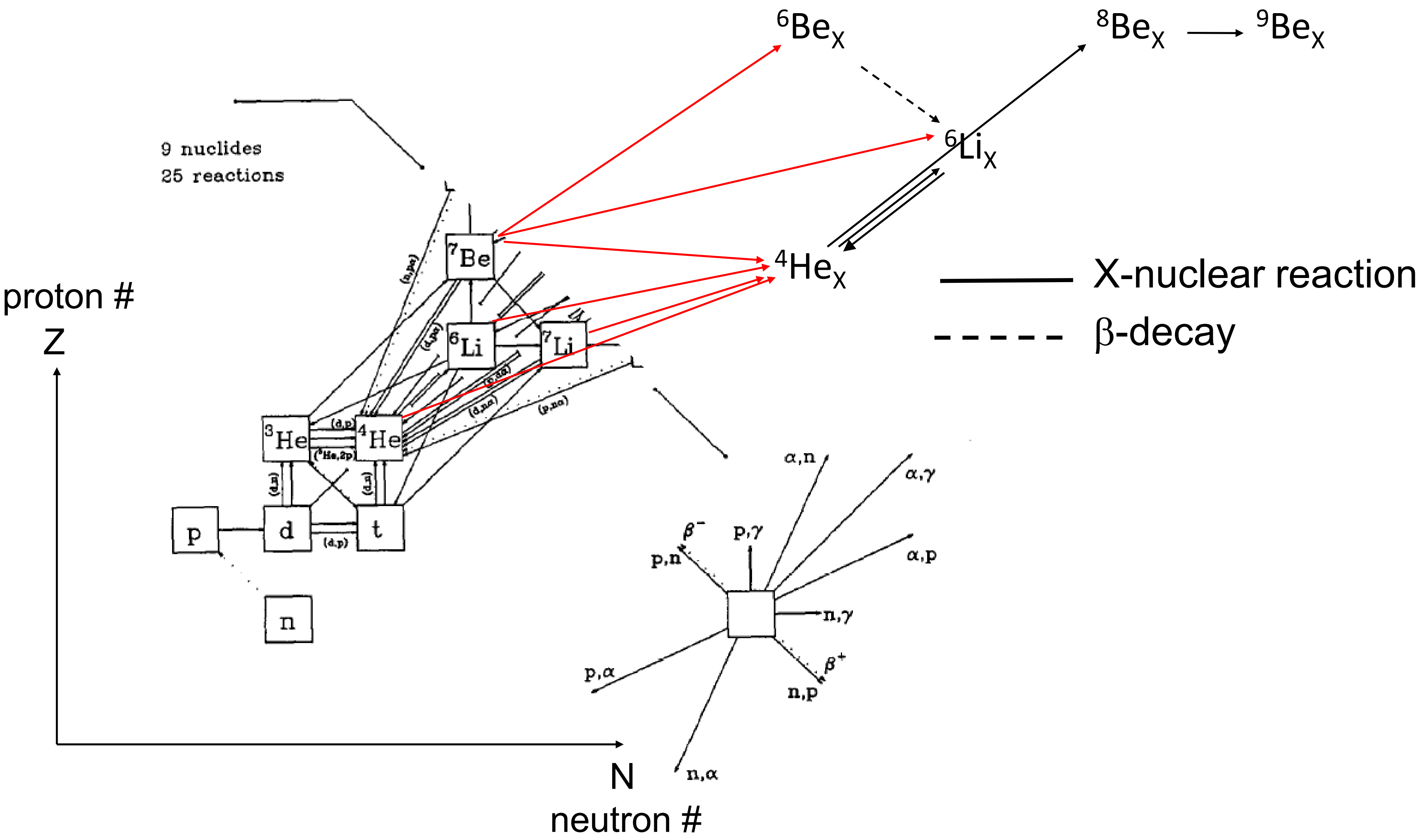
(2) bound state of A and X: A_X

See Kawasaki & MK (2011) for details

✓**Uncertainties** in estimated binding energies and reaction rates

3. Reaction network

- Up to $^{9}Be_X$

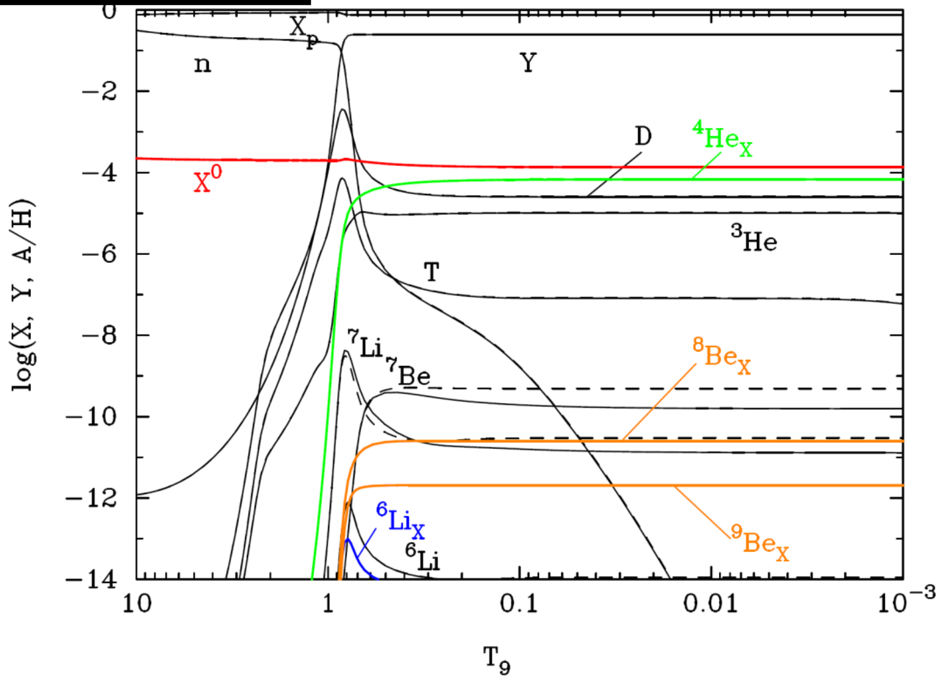


Result 1: Nuclear flow

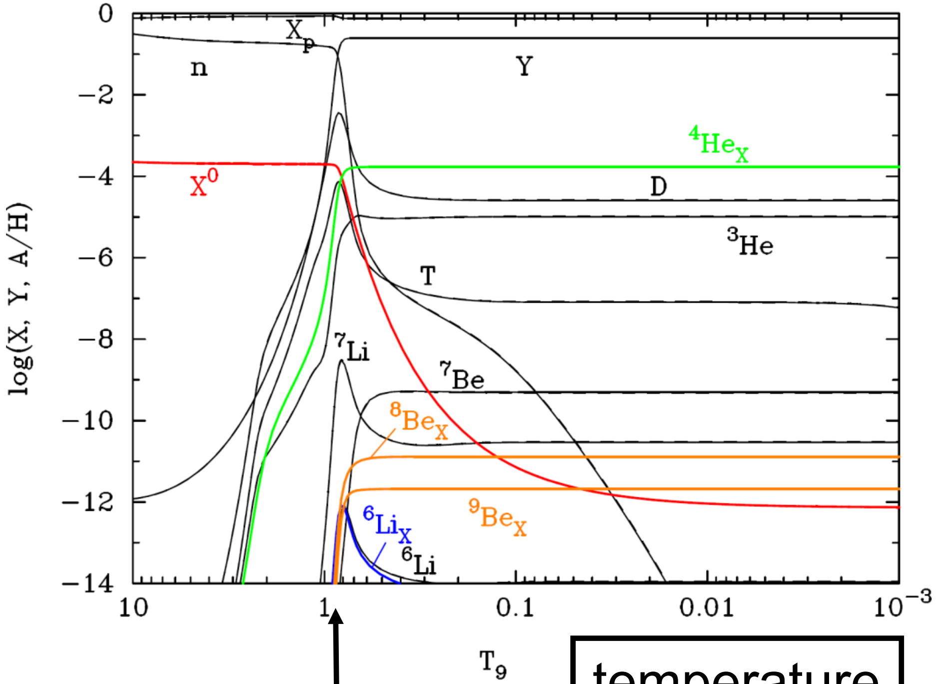
◆$n_X = 1.7 \times 10^{-4} n_b$, $m_X = 100\,\mathrm{GeV}$, $\tau_X \gg 200\,\mathrm{s}$

Abundance

Case 1 (δ=0.1)



Case 2 (δ=0.2)



X-capture

temperature

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

✓$T_9 \gtrsim 1$: Xs are in the free state.

✓$T_9 \sim 1$: ^{4}He is produced
→X is captured by ^{4}He [1/3 (Case1), ~1 (Case2)]

✓^{7}Be & ^{7}Li react with free X→destroyed

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

Result 2: reduction of Li abundance

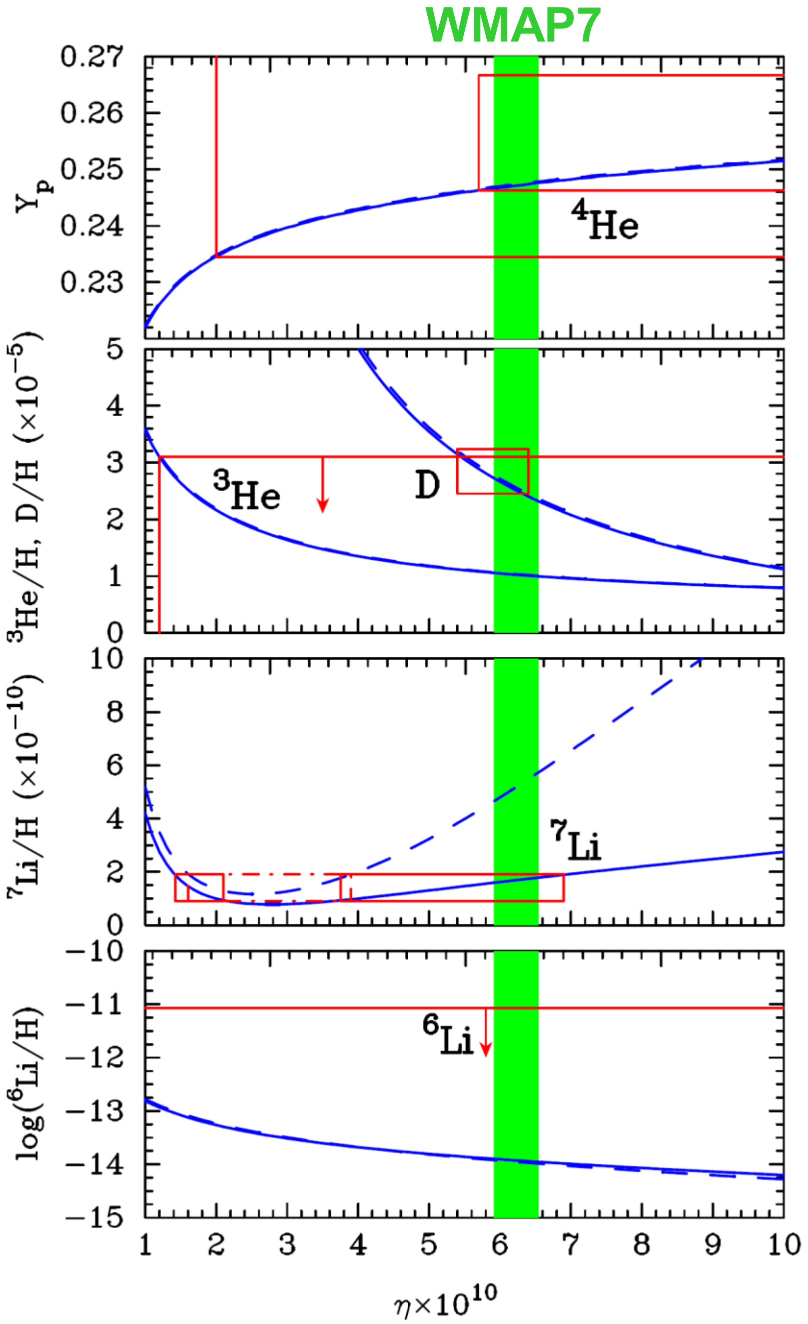
Solid line ：BBN including X

- ◆m_x=100GeV, $n_x=1.7\times10^{-4}n_b$,
- ◆τ_x>>200s
- ◆Case 1 (δ=0.1)

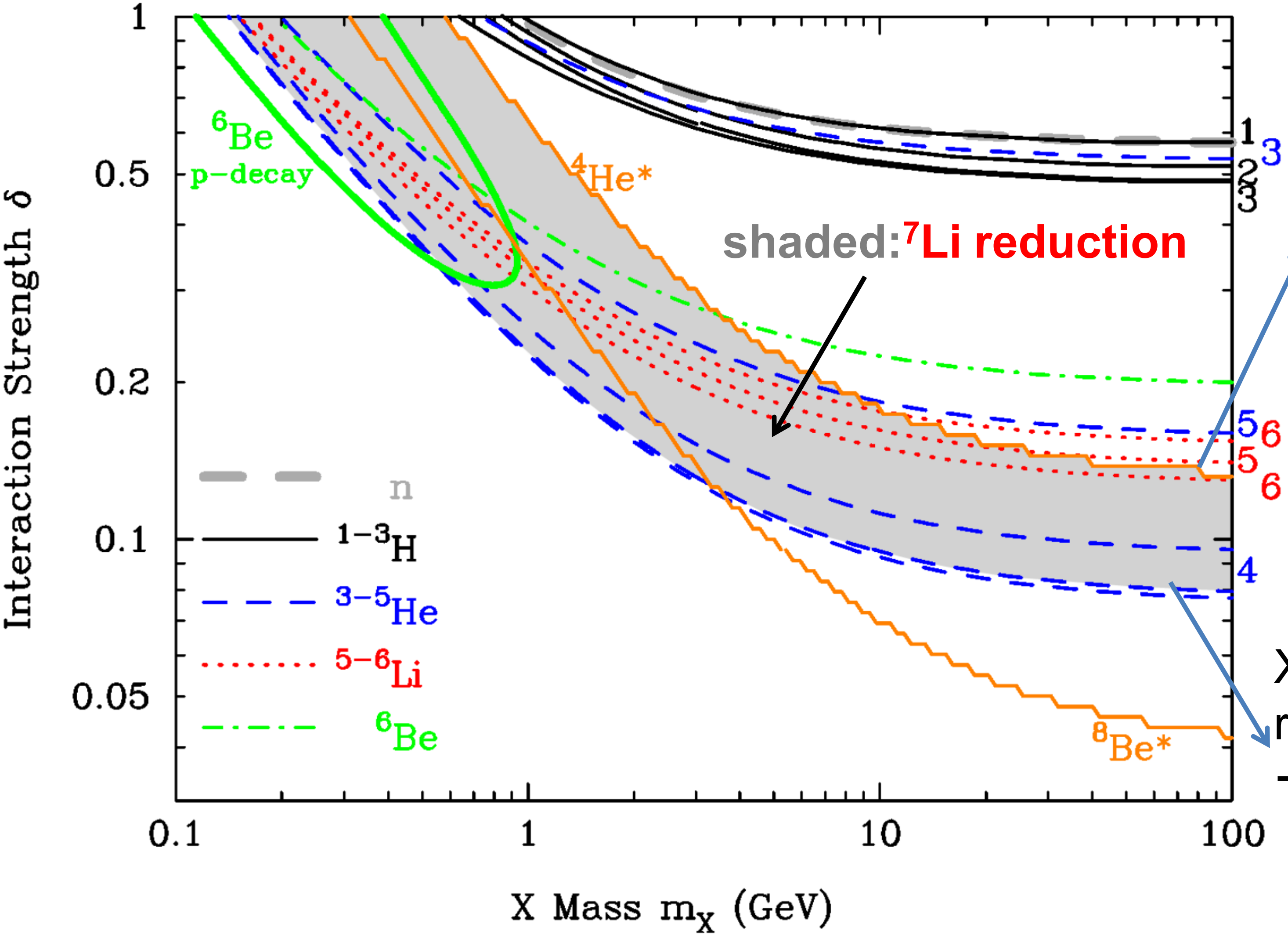
Dashed line：standard BBN

➢^{7}Li reduces

→new solution to the ^{7}Li problem



Result 3: Parameter region for Li reduction



shaded:^{7}**Li reduction**

$^4\mathrm{He}_X^*$(L=1) exists

→^{7}Be destruction is **hindered**

X(^{7}Be,^{3}He) $^4\mathrm{He}_X$ reaction Q<0

→^{7}Be destruction does **not occur**

Summary

- We study **effects of long-lived strongly interacting massive particle X^0 on BBN**

- Evolutions of elemental abundances are calculated in cases of **XN force weaker than the NN force [δ~0.1]**

  → **sub-SIMP**

  - ✓ **^{7}Be and ^{7}Li are destroyed via X^0 capture**

    $X(^7Be,^3He)^4He_X$, $X(^7Li,t)^4He_X$

  - ✓ If there is no excited state of ^4He_X (L=1)

    → significant fraction of the X^0s escape capture by ^{4}He

  - ✓ We show a possibility of **resolving the ^{7}Li problem**

    → Constraint on parameter region is derived

Processes affecting elemental abundances

	Model	^{6}Li problem solved ?	^{7}Li problem solved ?	Signatures on other nuclides ?
Density fluctuation [$z\sim10^9$]	Inhomogeneous BBN	no	no	**^{9}Be**[1]
Existence of particle [$z\sim10^9$]	**sub-SIMP X^0 [2]**	**?**	**✓**	**^{9}Be ?**
	SIMP X^0 [3]	no	no	**^{9}Be and/or ^{10}B**
	CHAMP X^- *	✓[4]	✓[5,6]	no *
Decay of particle [$z\lesssim10^9$]	Hadronic decay	✓[7]	✓[7]	**^{9}Be?** [8]
	Radiative decay	✓[9]	no	no
Early stars [$z\sim O(10)$]	Early cosmic ray	✓[10]	no	**^{9}Be and ^{10,11}B** [11]

* Latest calculation: MK el al. PRD 81, 083521 (2010)

[1] Boyd, Kajino (1989)
[2] Kawasaki, MK (2011)
[3] MK, Kajino, Yoshida, Mathews (2009)
[4] Pospelov (2007)
[5] Bird, Koopmans, Pospelov (2008) [stronger]
[6] MK, Kajino, Boyd, Yoshida, Mathews (2007) [weaker]
[7] Dimopoulos, Esmailzadeh, Hall, Starkman (1988)
[8] Pospelov, Pradler (2010)
[9] Jedamzik (2000); Kawasaki, Kohri, Moroi (2001)
[10] Rollinde, Vangioni, Olive (2006)
[11] Rollinde, Maurin, Vangioni, Olive, Inoue (2008); MK (2008)

Model

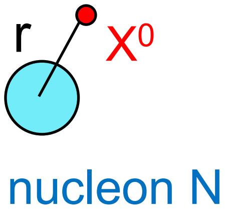
1. Binding energies of nuclides to an X

[Assumption]

parameter 1

- X (spin 0, **charge 0**, mass m_X)
- XN potential is Gaussian
  reproducing the binding energy and
  scattering phase shift of n+p system

Yahiro et al. (1986)



parameter 2

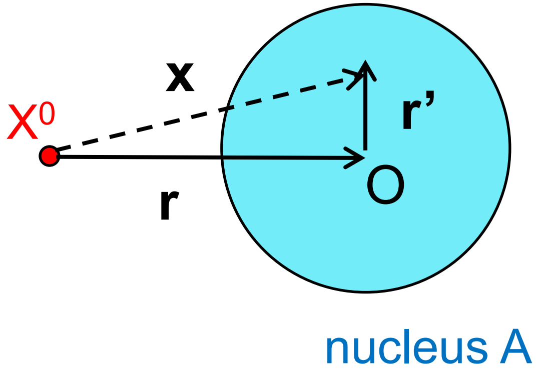
$$v(r) = v_0 \delta \exp\left[-(r/r_0)^2\right]$$

$$v_0 = -72.15 \text{ MeV and } r_0 = 1.484 \text{ fm}$$

- XA potential: integration of XN potential multiplied by nucleon densities

$$V(r) = \int v(\boldsymbol{x}) \rho(\boldsymbol{r}') \, d\boldsymbol{r}',$$

→**<u>nuclear deformation</u> by interaction of X is not considered**



- $A \geq 2$ nuclei have Gaussian nucleon densities

2. Reaction rates

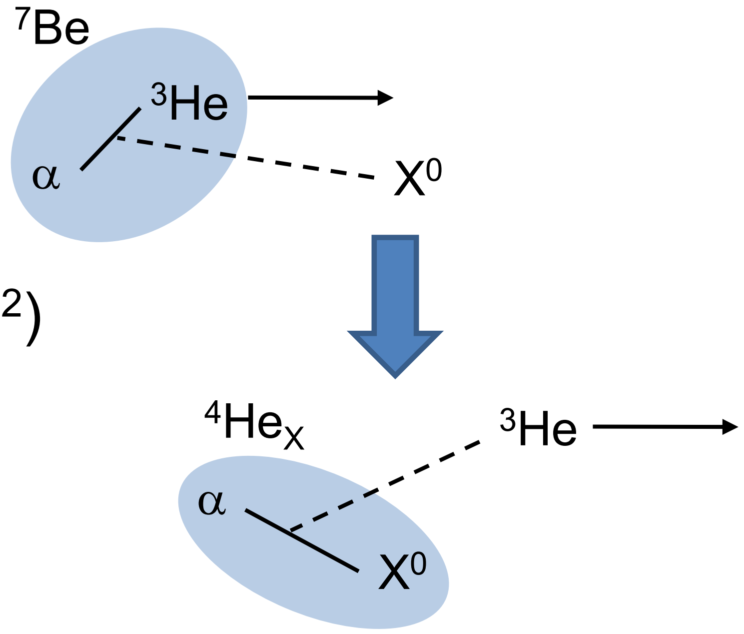
- Nonresonant components only
- m_X=100GeV
- Calculated binding energies → reaction Q-values

- In this scenario, **^{7}Be is destroyed via a reaction with X**
  - → Destruction efficiency depends on **escape fraction of X from capture by ^{4}He**
  - → Two cases for different fractions are considered (interaction strength: δ=0.1 & 0.2)

[notation] (1) 1+2 → 3+4 reaction: 1(2,3)4

(2) bound state of A and X: A_X

2-1. Non-radiative reactions



i) X(^{7}Be,^{3}He)^{4}He$_X$

- **✓^{6}Li(n,α)^{3}H rate is adopted (nonresonant component)**
- **✓Reduced mass dependence of cross section is corrected** ($\sigma \propto \mu^{-2}$)

ii) Other X capture reactions ← Similar to i)

$$X(^6\mathrm{Li}, d)^4\mathrm{He}_X, \quad X(^7\mathrm{Li}, t)^4\mathrm{He}_X$$

$$X(^7\mathrm{Be}, p)^6\mathrm{Li}_X \quad X(^7\mathrm{Be}, n)^6\mathrm{Be}_X$$

iii) ^{6}Li$_X$(p,^{3}He)^{4}He$_X$ [Case 2]

^{6}Li$_X$(p,^{3}HeX)^{4}He [Case 1]

✓^{6}Li(p,^{3}He)^{4}He rate is adopted

iv) ^{8}Be$_X$(d,p)^{9}Be$_X$

✓^{7}Be(d,pα)^{4}He$_X$ rate is adopted

v) ^{8}Be$_X$(d,n)^{9}B$_X$

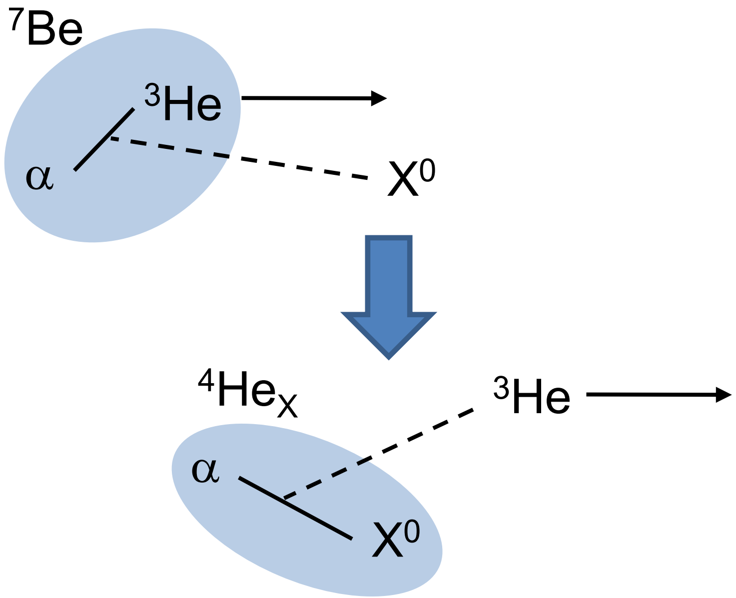
✓Q<0 → neglected

2. Reaction rates

➢Calculated binding energies→reaction Q-values

[notation] (1) 1+2→3+4 reaction: 1(2,3)4
(2) bound state of A and X: A_X

2-1. Non-radiative reactions



i) $X(^7Be,{}^3He)^4He_X$

✓**$^6Li(n,\alpha)^3H$ rate is adopted**

✓**Reduced mass factor
is corrected** ($\sigma \propto \mu^{-2}$)

…

See Kawasaki & MK (2011) for details

✓**Uncertainties** in estimated binding energies and reaction rates

2-2. Radiative reactions

$X(\alpha,\gamma)^{4}He_X$ $^{4}He_X(d,\gamma)^{6}Li_X$ $^{4}He_X(\alpha,\gamma)^{8}Be_X$

- ➢Wave functions of bound & scattering states are calculated with the code RADCAP(Bertulani 2003)
  - →cross sections
  - →reaction rates are fitted as a function of temperature

2-3. β-decay ($^{6}\mathrm{Be}_X(,\beta^+\nu_e)^{6}\mathrm{Li}_X$)

✓ $^{6}\mathrm{He}(,\beta^-\bar{\nu}_e)^{6}\mathrm{Li}$ rate is used after correction for the Q-value

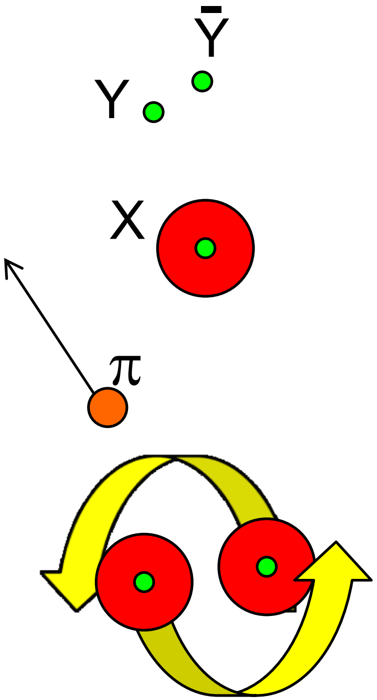
✓Large uncertainties in estimation of binding energies and reaction rates

→realistic calculation with a quantum many-body models are needed

Long-lived Heavy Colored Particles

- ➢Existence of long-lived heavy (m>>GeV) colored particles are suggested in particle models beyond the standard model e.g., Split SUSY (Arkani-Hamed & Dimopoulos 2005), …

- ➢History in the early universe : (J. Kang et al. JHEP 9, 86, 2008)



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

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

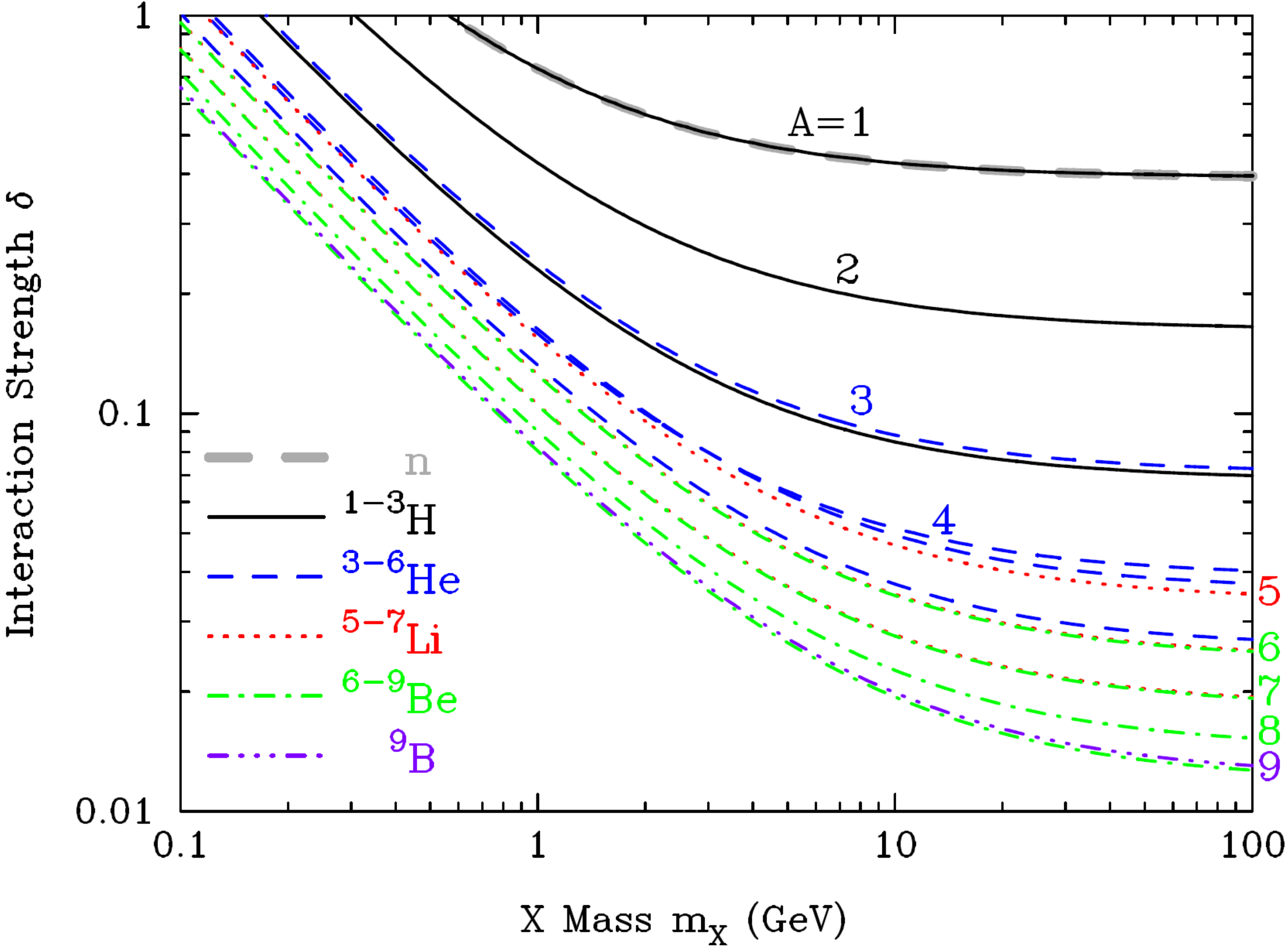
✓X+X form the bound state→decay into lower energy states →annihilate →final abundance

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

Model

1. Binding energies of nuclides to an X

Contours corresponding to binding energies=0.1MeV

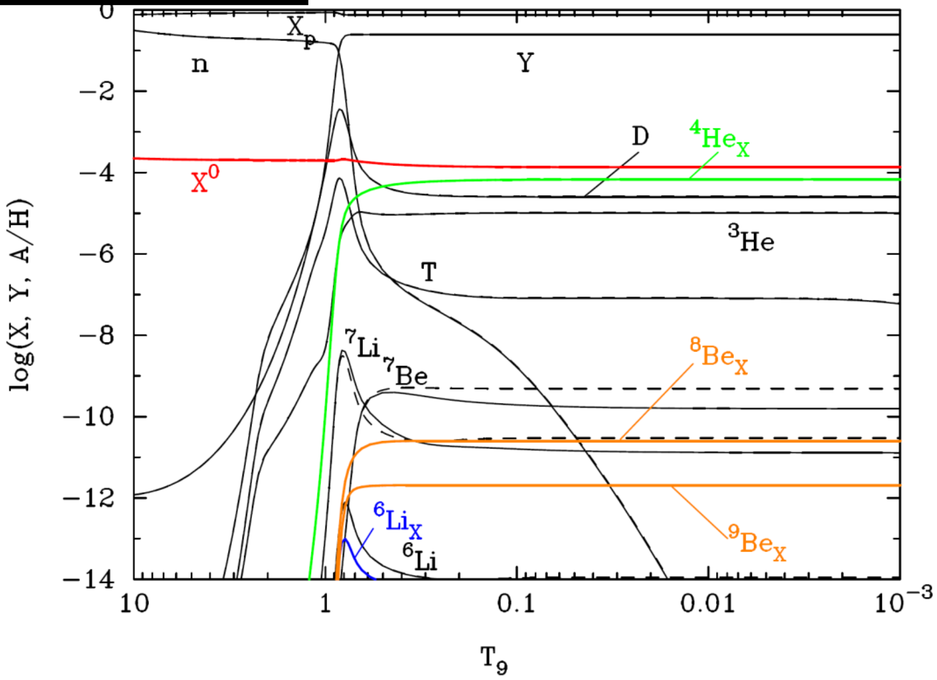


Result 1: Nuclear flow

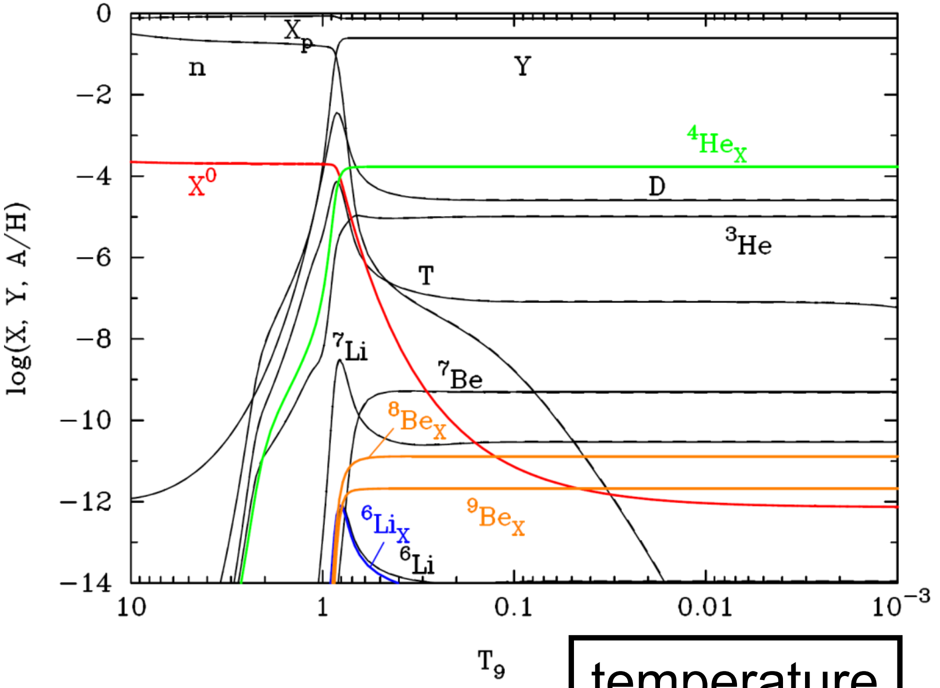
◆$n_X = 1.7 \times 10^{-4} n_b$, $m_X = 100\text{GeV}$, $\tau_X >> 200\text{s}$

Abundance

Case 1 ($\delta=0.1$)



Case 2 ($\delta=0.2$)



temperature

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

✓no excited $^4He_X(L=1)^*$

→E1 transition
(^4He+X) p-wave → ^4He_X ground state is dominant

→**X-capture by ^4He is weak**

✓Excited $^4He_X(L=1)^*$

→E1 transition
(^4He+X) s-wave → ^4He_X excited state is dominant

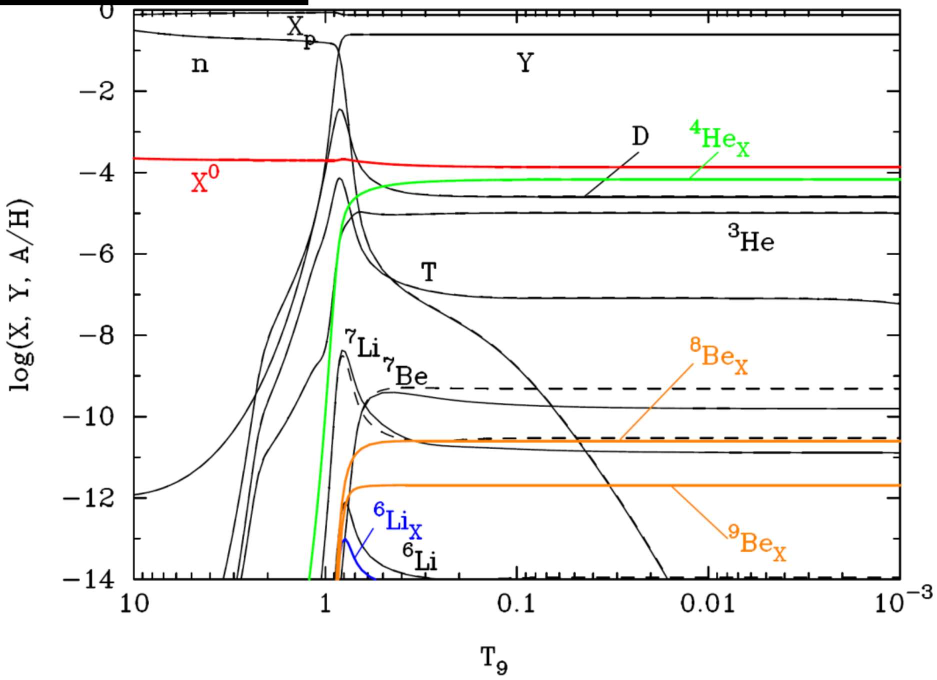
→**X capture by ^4He is strong**

Result 1: Nuclear flow-1

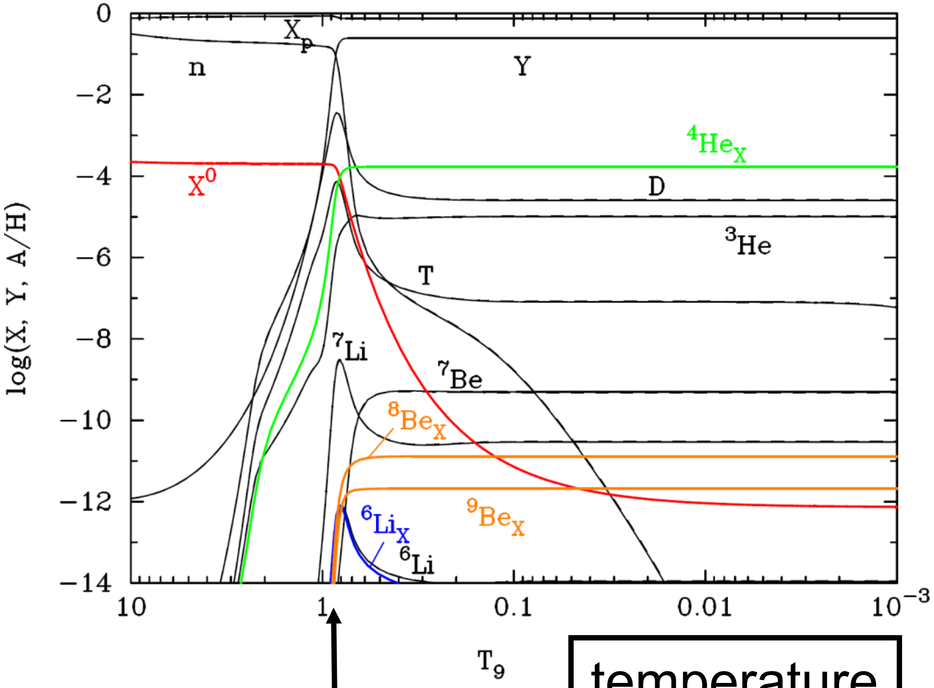
◆$n_X = 1.7 \times 10^{-4} n_b$, $\tau_X >> 200$s

Abundance

Case 1 (δ=0.1)



Case 2 (δ=0.2)



temperature

X-capture

✓$T_9 \gtrsim 1$: Xs are in the free state.

✓$T_9 \sim 1$: ^{4}He is produced

→X is captured by ^{4}He [1/3 (Case1), large portion (Case2)]

✓nuclear reaction of ^4He_X

→heavy X-nuclei are produced

$$^4\mathrm{He}_X(t, {}^7\mathrm{Li})X \quad {}^4\mathrm{He}_X(d,\gamma){}^6\mathrm{Li}_X$$

$$^4\mathrm{He}_X(\alpha,\gamma){}^8\mathrm{Be}_X \, {}^8\mathrm{Be}_X(d,p){}^9\mathrm{Be}_X$$

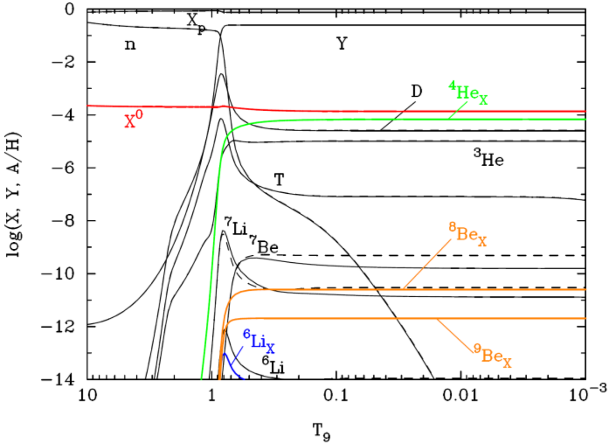
✓^{7}Be & ^{7}Li react with free X→destroyed

$$\boxed{X({}^7\mathrm{Be}, {}^3\mathrm{He}){}^4\mathrm{He}_X \quad X({}^7\mathrm{Li}, t){}^4\mathrm{He}_X}$$

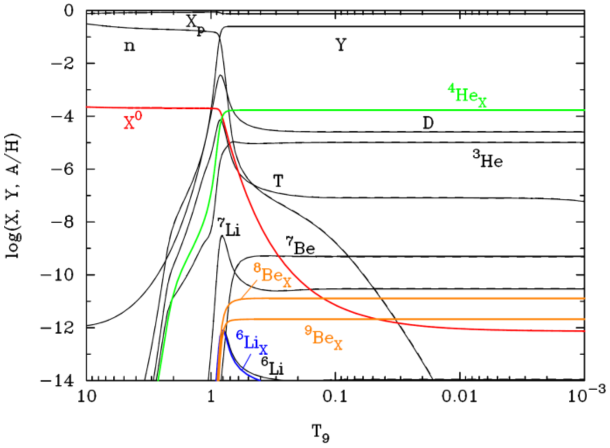
Result 1: Nuclear flow-2

Abundance

Case 1 (δ=0.1)



Case 2 (δ=0.2)



T_9=T/(10^9 K) temperature

✓no excited ^4He_X(L=1)*

→E1 transition from (^{4}He+X) p-wave to ^4He_X ground state is dominant

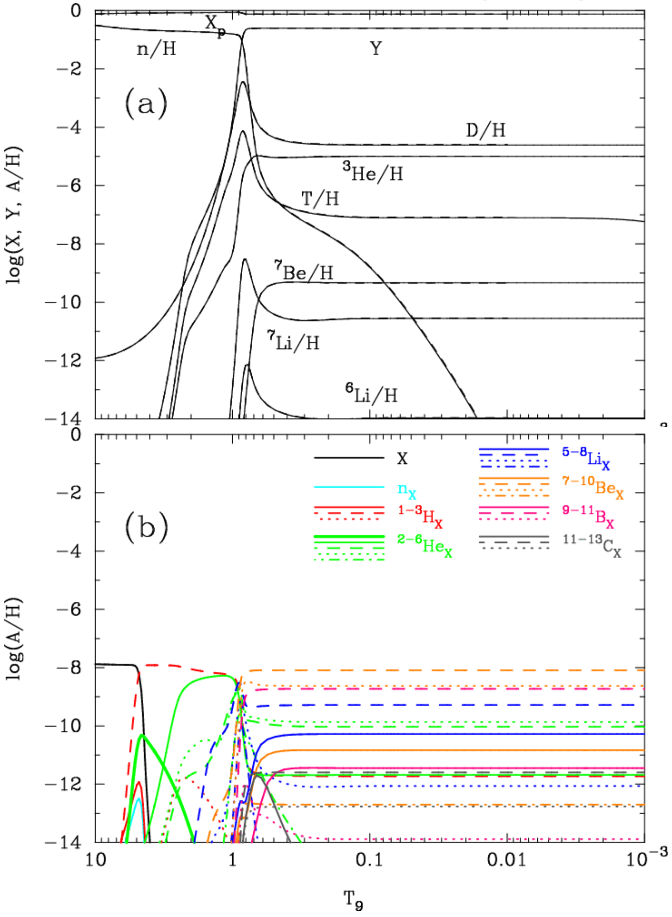
→X-capture by ^{4}He is weak

✓Excited ^4He_X(L=1)*

→E1 transition from (^{4}He+X) s-wave to ^4He_X excited state is dominant

→X capture by ^{4}He is strong

MK et al. 2009 (δ~1)



Bound states of X & ^{5}A exist

→heavy X-nuclei efficiently form

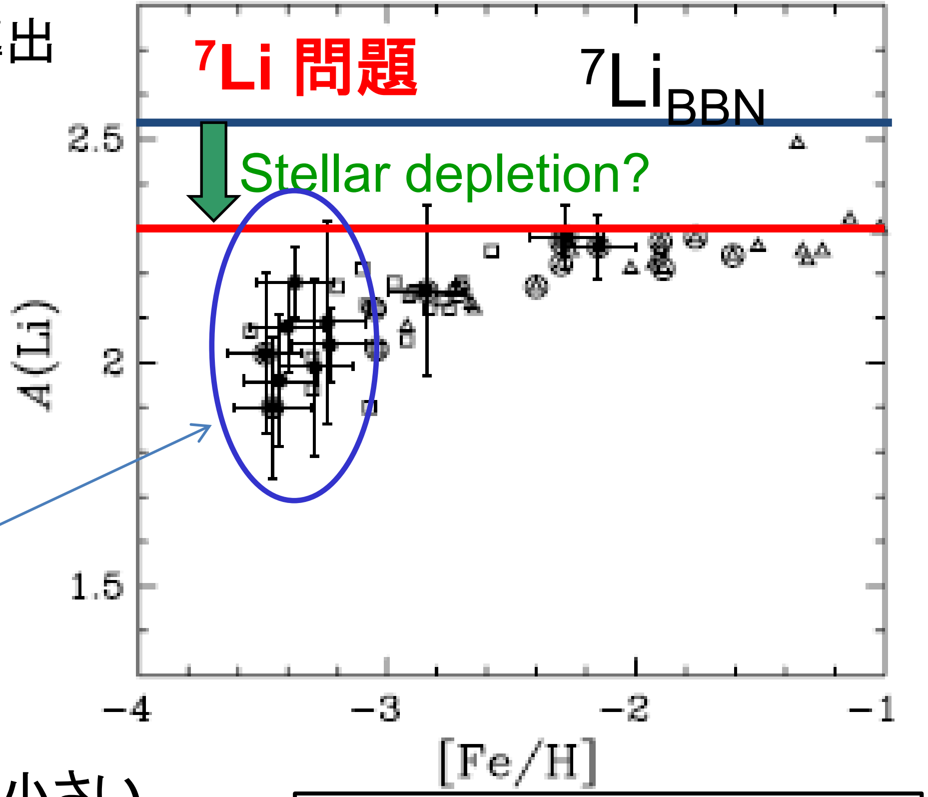
^{7}Li問題

[Li組成分析]

- ➢LiI 6708 A lineのスペクトルfitでLi組成導出
- ➢ドップラー補正はFeI線の位置から決定
- ➢^{6}Liの寄与は無視
- ➢fitパラメターはLi組成（と波長シフト）

log(^{7}Li/H)+12

Aoki et al. (2009)



[Fe/H]=log{(Fe/H)/(Fe/H)$_{\odot}$}

[Fe/H]<-3で平均的にLi組成が低い

A(Li)=2.03±0.09

- ➢標準偏差が測定誤差(0.07-0.23 dex)より小さい
  →Li組成の分散を未検出
- ➢high metallicity star A(Li)=2.27より0.24dex 小さい
  （Asplund et al. (2006)の[Fe/H]=-2.5-- -2.0の星
  A(Li)=2.23より0.27dex 小さい）

→この差は大きい

^{6}Li問題

Inoue et al. (2005)

[Li組成分析]

- LiI 6708 A lineのスペクトルfitで Li同位体比導出

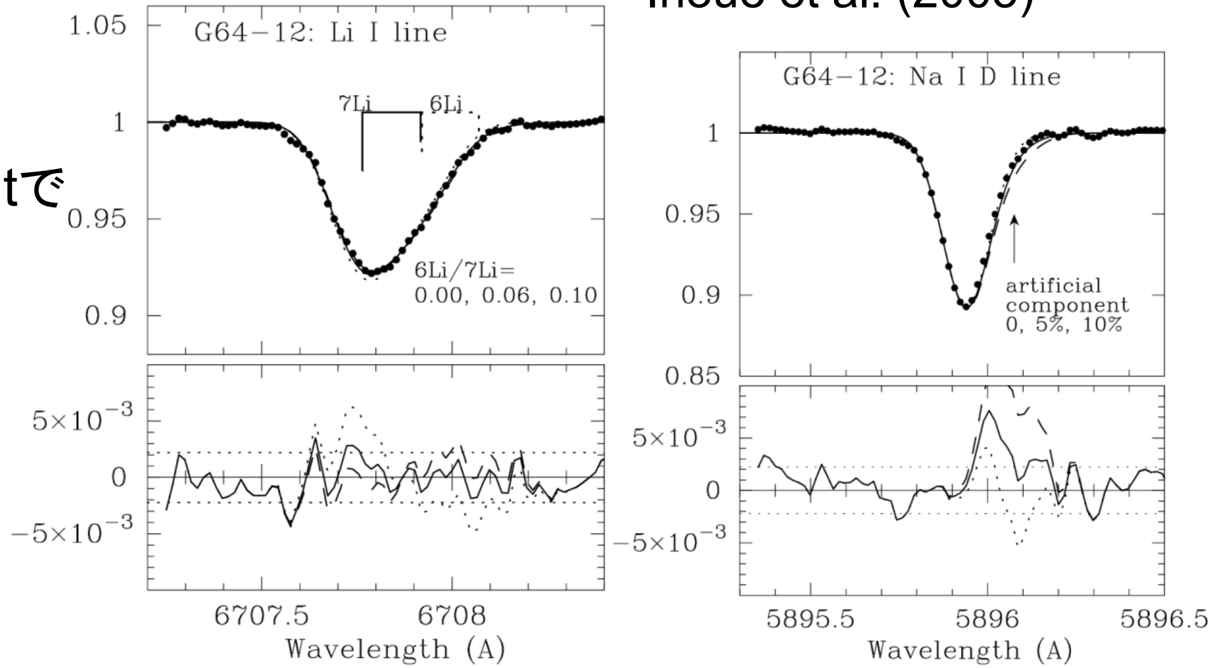


Figure 1. Left: Observed spectra (filled circles) of the Li I line in G 64-12 compared with synthetic spectra (curves) assuming ^{6}Li/^{7}Li=0 (dotted), 0.06 (solid) and 0.1 (dashed). The bottom panel shows the difference between synthetic and observed spectra, with the horizontal dotted lines marking $\pm 1\sigma$ in the observed flux. Right: Same as left, except for the Na I D line. The synthetic spectra include artificial line asymmetries that mimic ^{6}Li in the Li I line at levels of 0 (dotted), 5 (solid) and 10 (dashed) %.

- 9つのMPHSsで^{6}Liの検出 (Asplund et al. 2006)

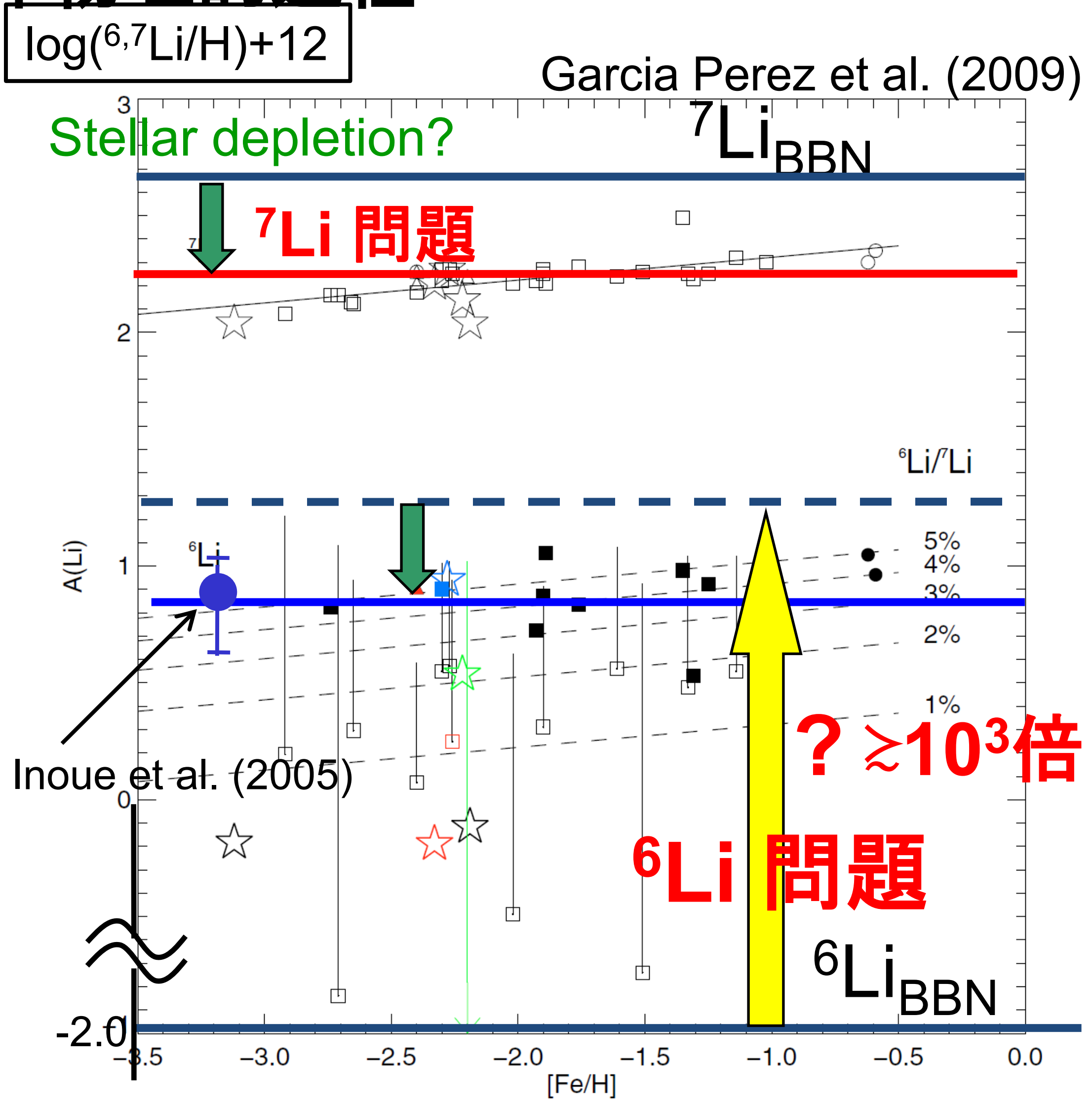
- しかし、大気の3D効果を取り入れる必要がある (Cayrel et al. 2007)

- 3D効果を考慮すると、検出とされた星の数が9→4に減る
- しかし、確かに^{6}Liがある星も存在 (Garcia Perez et al. 2009)

天体物理的過程

[^{6}Li合成]

- ➢初期の宇宙線αと背景αのα+α (Montmerle 1977)
  - ✓銀河形成前の超新星宇宙線 (Rollinde et al. 2005)
  - ✓銀河形成中の構造形成ショック宇宙線 (Suzuki & Inoue 2002)
- ➢超新星ejectaα+星周αのα+α (Nakamura et al. 2006)
- ➢MPHSフレア^{3}Heの^{4}He(^{3}He,p) (Tatischeff &Thibaud 2007)



$[Fe/H]=\log[(Fe/H)/(Fe/H)_\odot]$

[^{6,7}Li減少]

- ➢銀河初期の超高効率化学進化(星内燃焼→ejection)(Piau et al. 2006)
- ➢MPHS表面での原子拡散･乱流混合 (Richard et al. 2005)

始原組成の観測的制限1

- D : QSOの方向にある吸収系 (Pettini et al. 2008)

  log D/H=-4.55±0.03 (2σ)

- ^{3}He :銀河系のHII region (Bania et al. 2002)

  ^{3}He/H=(1.9±0.6)×10^{-5} (2σ, 上限)

- ^{4}He : metal-poor outer galaxiesのHII region

  (Izotov & Thuan, 2010) Y=0.2565±0.0051 (2σ)

  (Aver et al. 2010) Y=0.2561±0.0108 (2σ)

- ^{6}Li : Metal-Poor Halo Star (Asplund et al. 2006)
  [隕石の^{6}Li組成(Lodders 2003)を超えない]

  ^{6}Li/H =(7.1±0.7)×10^{-12} (2σ, 上限)

- ^{7}Li : Metal-Poor Halo Star (Ryan et al. 2000)

  ^{7}Li/H=$(1.23^{+0.68}_{-0.32})\times 10^{-10}$ (95% CL)

始原組成の観測的制限2

- ^{9}Be : Metal-Poor Halo Star (Ito et al. 2009)

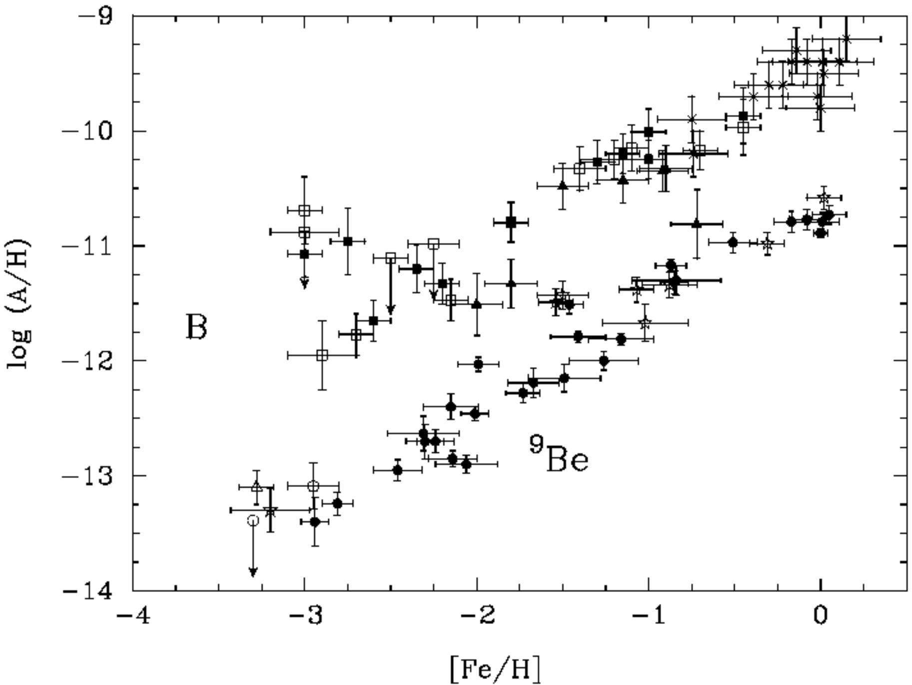
^{9}Be/H<10^{-14}

- B : Metal-Poor Halo Star (Duncan et al. 1997, Garcia Lopez et al. 1998)

B/H<10^{-12}

- C : Metal-Poor Halo Star (Suda et al. compilation arXiv:0806.3697)

C/H<10^{-8}



Suda et al. (2008)