Big bang nucleosynthesis and dark matter

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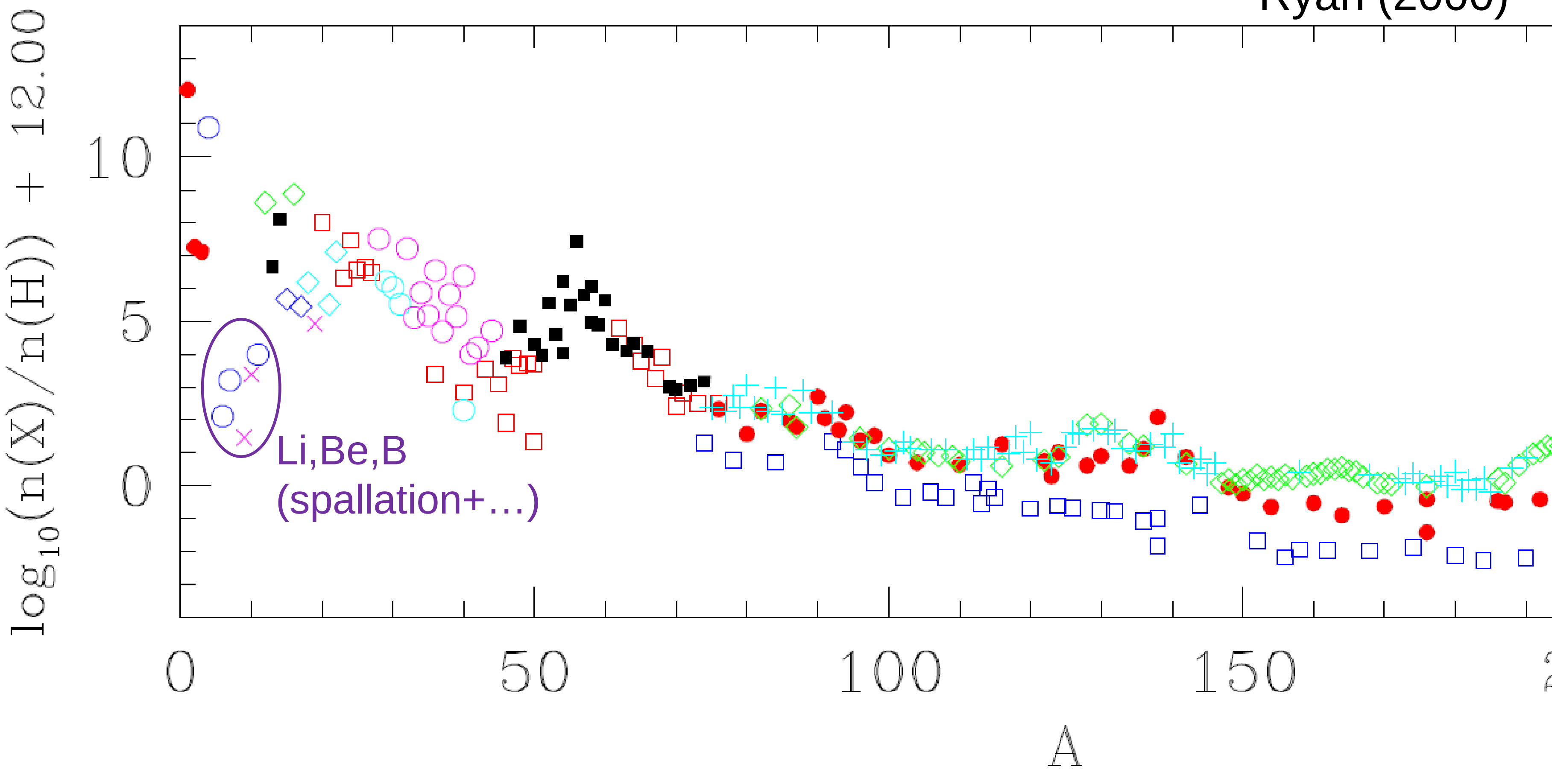
Solar abundance

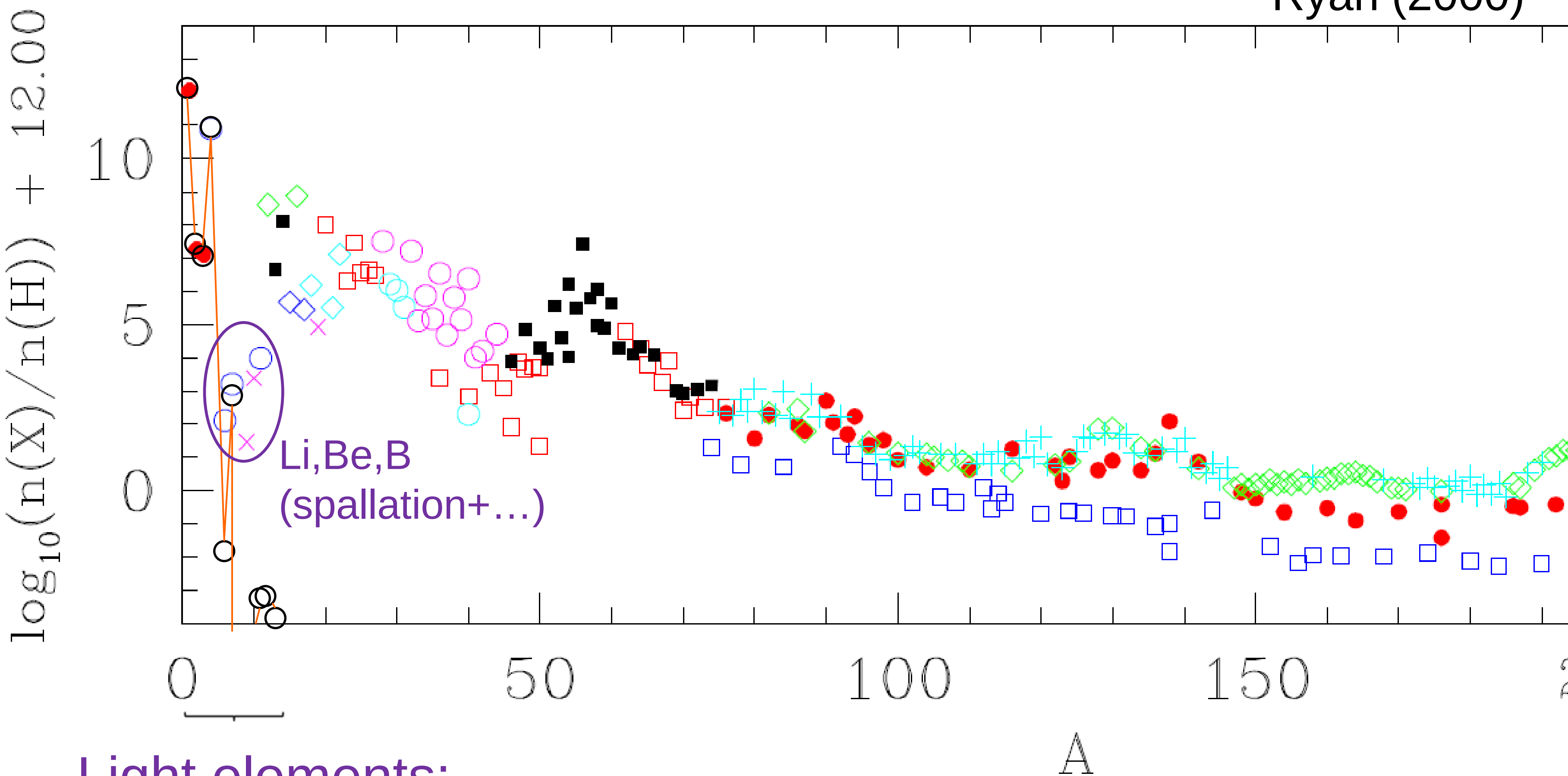
Ryan (2000)



Solar abundance

- Standard big bang nucleosynthesis (BBN) model

Ryan (2000)



Light elements:
Probe of nucleosynthesis in the early universe

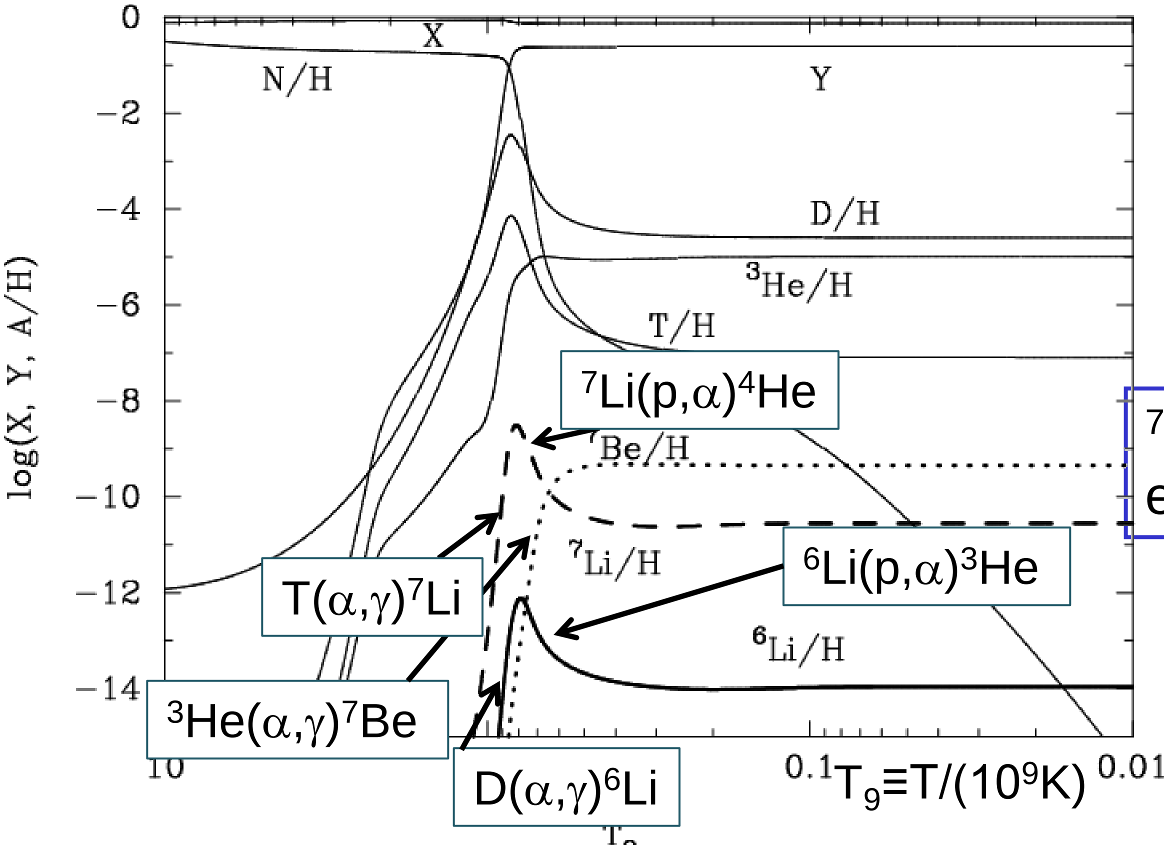
Standard Big Bang nucleosynthesis (SBBN)

- n↔p equilibrium $(n/p)_{EQ}=\exp(-Q/T)$ $Q\equiv m_n-m_p=1.293\,\mathrm{MeV}$
- t~1sec, $T=T_F\sim 1\,\mathrm{MeV}$(week interaction freeze-out) ($1\,\mathrm{MeV}=1.16\times 10^{10}\,\mathrm{K}$)
  - ✓ $\nu\bar{\nu} \cancel{\leftrightarrow} e^+e^- \longleftrightarrow \gamma\gamma$
  - ✓ $n \cancel{\leftrightarrow} p$
  - ✓ $e^\pm \longrightarrow \gamma\gamma$ ($T\sim m_e/3$)

  $(n/p)_{\text{freeze-out}}=\exp(-Q/T_F)\sim 1/6$

Kawano code (1992)

$\eta=n_b/n_\gamma=6.\times 10^{-10}$



^{7}Be→^{7}Li

e^--capture after recombination

Effect of cold dark matter (DM) on BBN

➢Weakly interacting DMs affect BBN through cosmic expansion rate.

→

$$H \equiv \frac{\dot{a}}{a} = \left(\frac{8\pi G}{3}\rho\right)^{1/2}$$

a scale factor of universe
G Newton's constant
ρ Total energy density

$$\rho = \rho_{\mathrm{R}} + \rho_{\mathrm{M}}$$

$$\rho_{\mathrm{R}} = \frac{\pi^2}{30} g_* T^4 = 7.1\times10^{-13}\,\mathrm{GeV}^4 \left(\frac{g_*}{3.36}\right)\left(\frac{T}{10^9 K}\right)^4$$

g_* Statistical dof of relativistic species
T Photon temperature

$$\rho_{\mathrm{M}} = (\Omega_{\mathrm{b}} + \Omega_{\mathrm{DM}})\rho_{\mathrm{C}} \left(\frac{T}{T_0}\right)^3 = 5.3\times10^{-22}\,\mathrm{GeV}^4 \left(\frac{\Omega_{\mathrm{b}} h^2 + \Omega_{\mathrm{DM}} h^2}{0.133}\right)\left(\frac{T}{10^9 K}\right)^3$$

WMAP 7 (ΛCDM+SZ+lens)

$$\rho_{\mathrm{C}} = \frac{3H_0^2}{8\pi G}$$ Critical density

$$\Omega_{\mathrm{i}} = \frac{\rho_{\mathrm{i}}}{\rho_{\mathrm{C}}}$$ Density parameter

H_0 Present Hubble parameter $h = H_0 /(100\mathrm{kms}^{-1}\mathrm{Mpc}^{-1})$

$T_0 = 2.725K$ (Mather et al. 1999) Present photon temperature

→Effect of CDM is negligible

Measured abundances of light elements (H, He, Li)

- D : Absorption systems in the foreground of QSO

  (Pettini et al. Mon. Not. R. Astron. Soc. 2008)

  $\log D/H = -4.55 \pm 0.03$

- ^{3}He : HII regions in our Galaxy (Bania, Rood, Balser, Nature, 2002)

  $^{3}He/H = (1.9 \pm 0.6) \times 10^{-5}$

- ^{4}He : HII regions in metal-poor outer galaxies

  $Y(=4n_{He}/n_{B}) = 0.2565 \pm 0.0051$ (Izotov, Thuan, Astrophys. J. 2010)

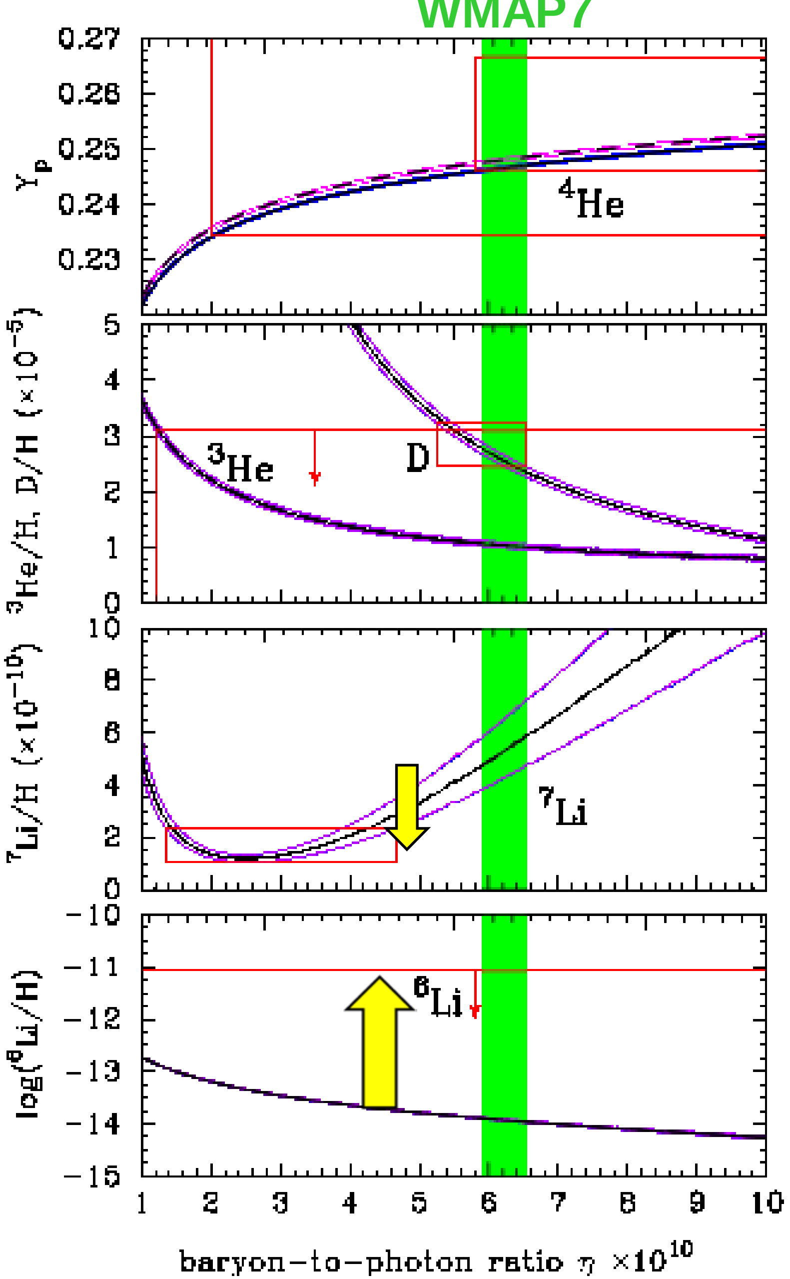
  0.2561 ± 0.0108 (Aver, Olive, Skillman, JCAP, 2010)

- ^{7}Li : Metal-Poor Halo Stars (Sbordone et al. Astron. Astrophys. 2010)

  $\log {}^{7}Li/H = -12 + (2.199 \pm 0.086)$ [95% C.L.]

Observed abundances of light elements

- Standard BBN (SBBN):
  one parameter
  baryon-to-photon ratio η
  $\leftarrow \eta=(6.225^{+0.157}_{-0.154}) \times 10^{-10}$
  (WMAP: Larson et al. 2010)



Li problems

[Rates]
The recommendation of
JINA REACLIB V1.0 (Cyburt et al. 2010)

Observed Li abundances

- ^{7}Li in metal-poor stars

  (Spite & Spite 1982)

  ~ 1/3 times

  (CMB+standard BBN

  prediction)

- ^{6}Li is abundant in

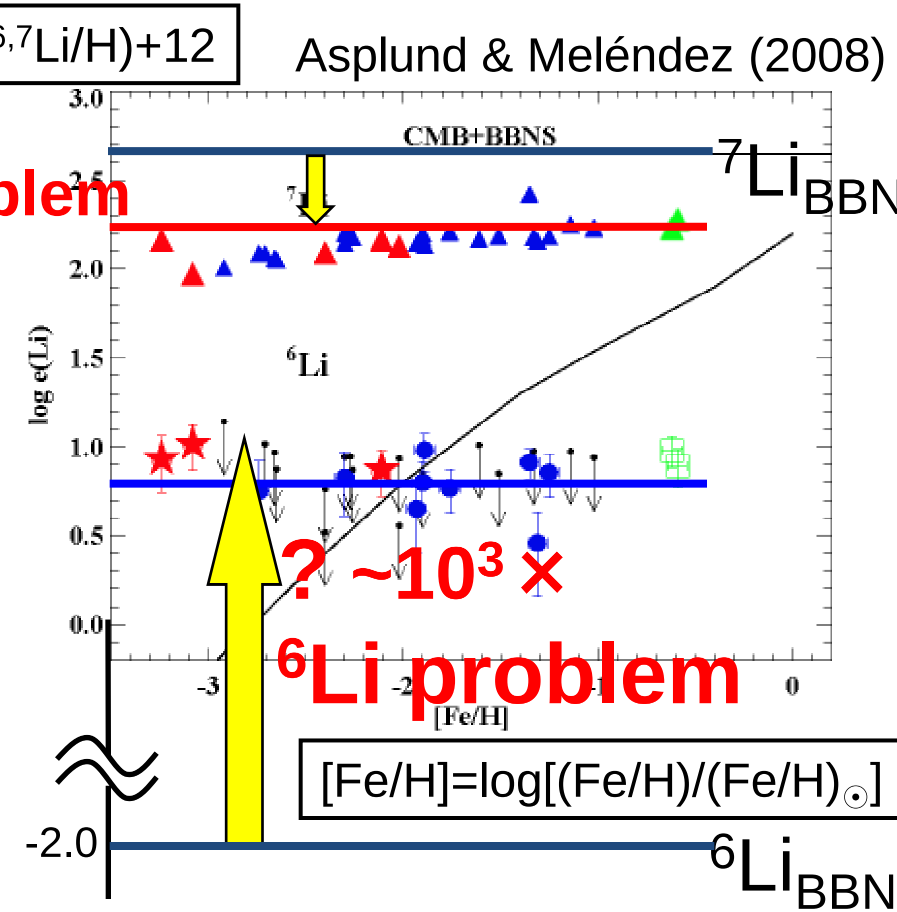
  some of the stars

  (Asplund et al. 2006)

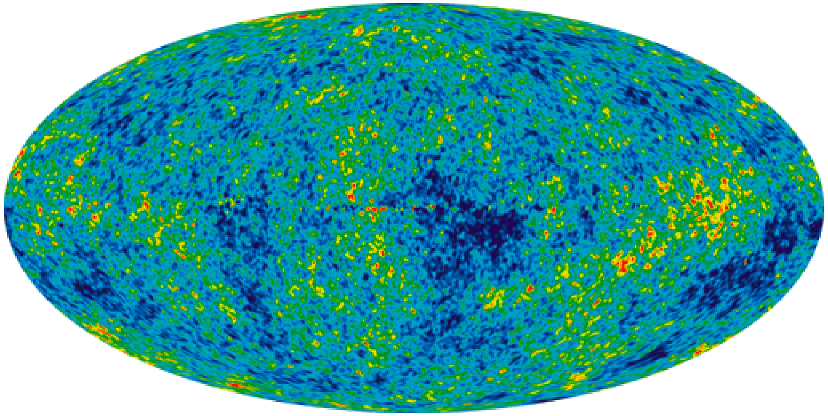
Signature of new physics?

- ^{9}Be, B:

  plateau not seen yet



Cosmological processes



The WMAP Science Team

- Standard cosmological model includes **Dark Matter**

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

$$\Omega h^2 \simeq 0.1 \times \left(\frac{\langle \sigma v \rangle_{\mathrm{freeze}}}{3 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}} \right)^{-1}$$

relic abundance of weak-scale thermal particle is consistent

→Existences of exotic particles

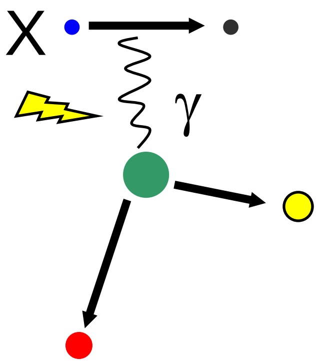
- **<u>Long-lived exotic particles</u> might have affected light element abundances**

ex)
✓slepton (NLSP)
(Feng et al. 2003)

Effects of exotic particles on BBN

- 1. Nuclear reactions triggered by exotic decay

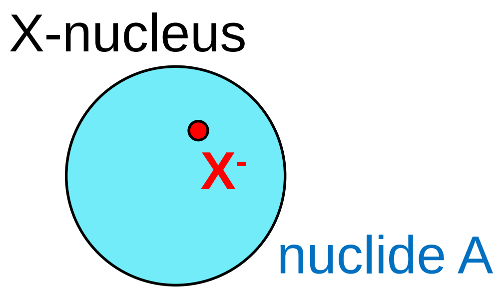
  (Lindlely 1979, Ellis et al. 1985-, Reno & Seckel 1988,
  Dimopoulos et al. 1988-, Kawasaki et al. 1988-, Jedamzik 2000-)



- 2. Nuclear reactions of <u>exotic atoms</u>

  (Cahn & Glashow 1981)

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



Cooling of backgruond photon by axion

- Erken, Sikivie, Tam, Yang, PRL (2012), PRD (2012)
  suggested a possibility that axion Bose Einstein condensates, and
  interact with background photon via gravitational interaction
  in an epoch between BBN and cosmological recombination.
  → In this model, the baryon to photon ratio is lower in the BBN epoch.

- BBN+axion BBN model: consistent ^{7}Li & inconsistent D
- Erken, Sikivie, Tam, Yang suggested
  Uncertainties in measured D abundance &
  possibility that D is burnt by nonstandard stellar process

- D: only destroyed in star.
- ^{3}He: can be produced, and also destroyed in stars.
  → Galactic chemical evolution models usually predict that
  (D+^{3}He)/H abundance ratio slightly increases in interstellar medium
  (Chiappini, Renda, Matteucci, Astron. Astrophys. 2002).

1. BBN + radiatively decaying long-lived particle

- Assume : exotic particle (X) decays
  $\rightarrow \gamma$ emerges with energy $\mathbf{E_{\gamma 0}}$

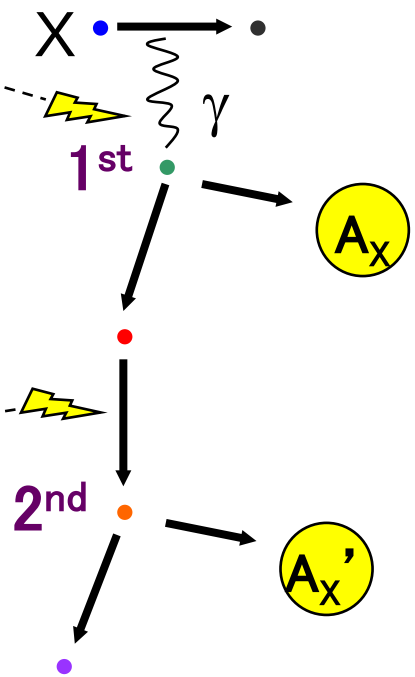
life time

$\boxed{\tau_X}$

abundance parameter

$$\boxed{\zeta_X = \frac{n_X^0}{n_\gamma^0} E_{\gamma 0}}$$

Interactions with background γ and $e^{\pm}$
(Kawasaki & Moroi 1995)



1. **Primary process**

- Nonthermal γ reacts with background nuclei

(Cyburt et al. 2003)

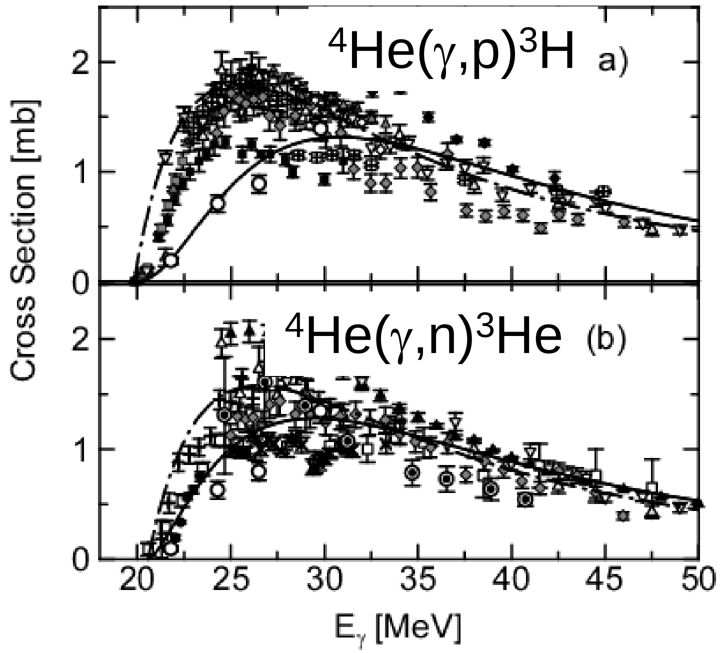
Interactions with background γ and $e^{\pm}$
(Kawasaki et al. 2005)

2. **Secondary process** (Cyburt et al. 2003)

- Reactions between primary product with background nuclei

✓**Destruction processes of d,t,^{3}He,^{6}Li produced in 1st processes**

◆^{2}H(p,pn)p ◆^{3}H(p,dp)n ◆^{3}He(p,dp)p
◆^{3}H(p,2np)p ◆^{3}He(p,2pn)p
◆^{6}Li(p,^{3}He)^{4}He



Smaller cross sections

○: data of Laser Compton experiment

(Shima et al. Phys. Rev. C, 2005)

(Kii, Shima, Nagai, Baba, Nucl. Instrum. Meth. A

——— functions fitted

(only ○data in $E_\gamma \leq 30$MeV)

- · - · - fitted to old data

Calculation

Spectrum of nonthermal photons

- Primary γ interacts with CBRs to realize an equilibrium spectrum $p_\gamma(E_\gamma)$
  - pair creation ($\gamma\gamma_{bg} \to e^+e^-$)
  - inverse Compton ($e^\pm + \gamma_{bg} \to e^\pm + \gamma$)
- Then it degrades its energy by
  - Compton scattering ($\gamma + e^\pm_{bg} \to \gamma + e^\pm$)
  - Bethe–Heitler process ($\gamma + \text{nuclus}_{bg} \to e^+ + e^- + \text{nucleus}$)
  - photon–photon scattering ($\gamma\gamma_{bg} \to \gamma\gamma$)
- Reaction rates are high and quasi static equilibrium spectrum is obtained

$$N_\gamma^{QSE}(E_\gamma) = \frac{n_X p_\gamma(E_\gamma)}{\Gamma_\gamma(E_\gamma)\tau_X}$$

Primary process

Rate equation

Particle # related

Mole fraction $Y_j = \frac{X_j}{A_j} = \frac{N_j}{\rho N_A}$

$$\frac{dY_A}{dt} = \sum_P N_A(P)\left(-\frac{Y_A}{N_A(P)!}[A\gamma]_P + \frac{Y_P}{N_P(P)!}[P\gamma]_A\right)$$

Present photon # density

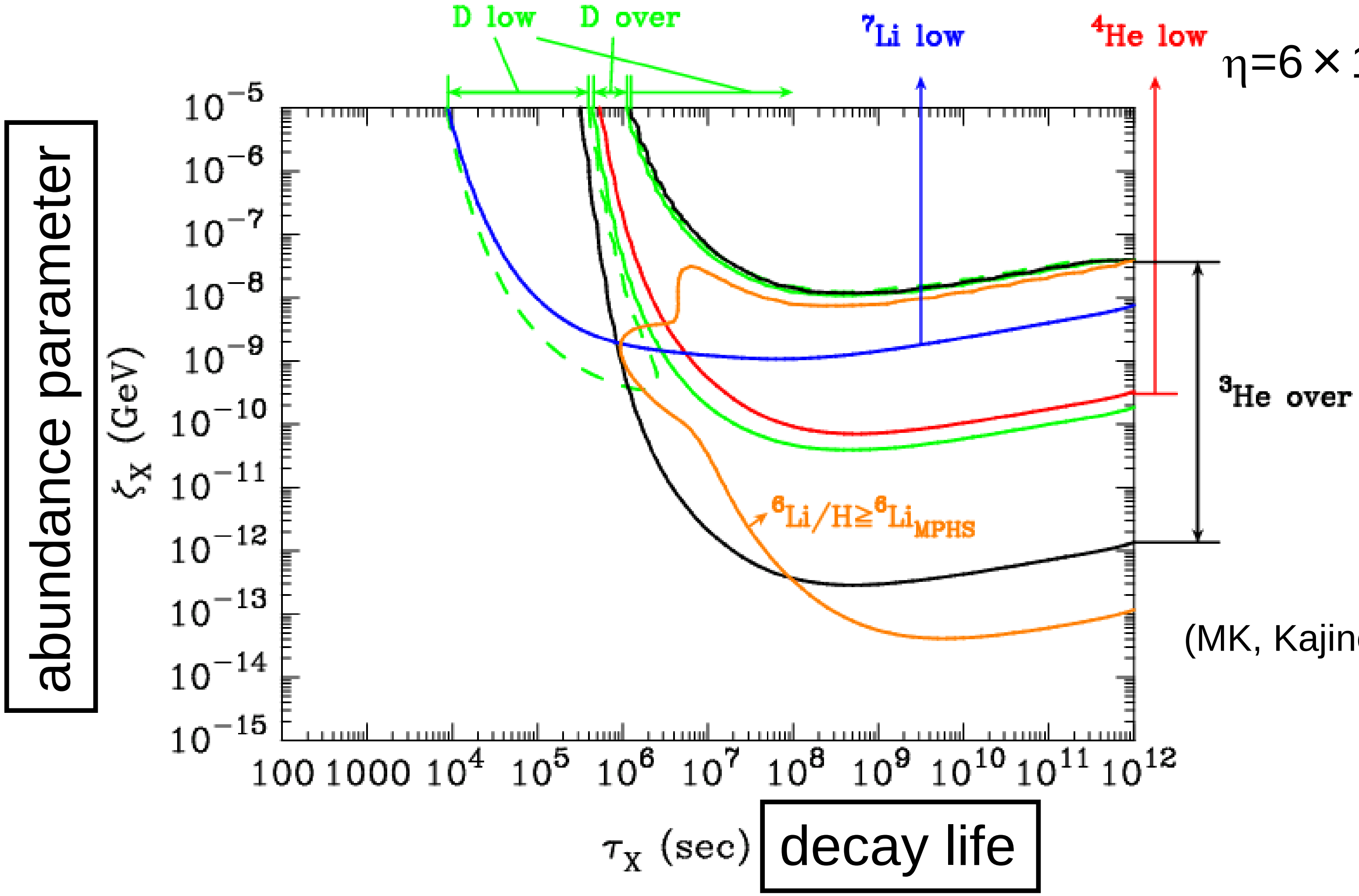
$$\zeta_X = \frac{n_X^0}{n_\gamma^0} E_{\gamma 0}$$

$$H_r = \sqrt{\frac{8\pi G\rho_{rad}^0}{3}}$$

$$[A\gamma]_P \equiv \frac{n_\gamma^0 \zeta_X}{\tau_X}\left(\frac{1}{2H_r t}\right)^{3/2} \exp(-t/\tau_X)\int_0^\infty \left(\frac{\tau_X}{E_{\gamma 0} n_X} N_\gamma^{QSE}(E_\gamma)\right)\sigma_{\gamma + A \to P}(E_\gamma)$$

Parameter search (SBBN+decaying particle)

$\eta = 6 \times 10^{-10}$(WMAP)

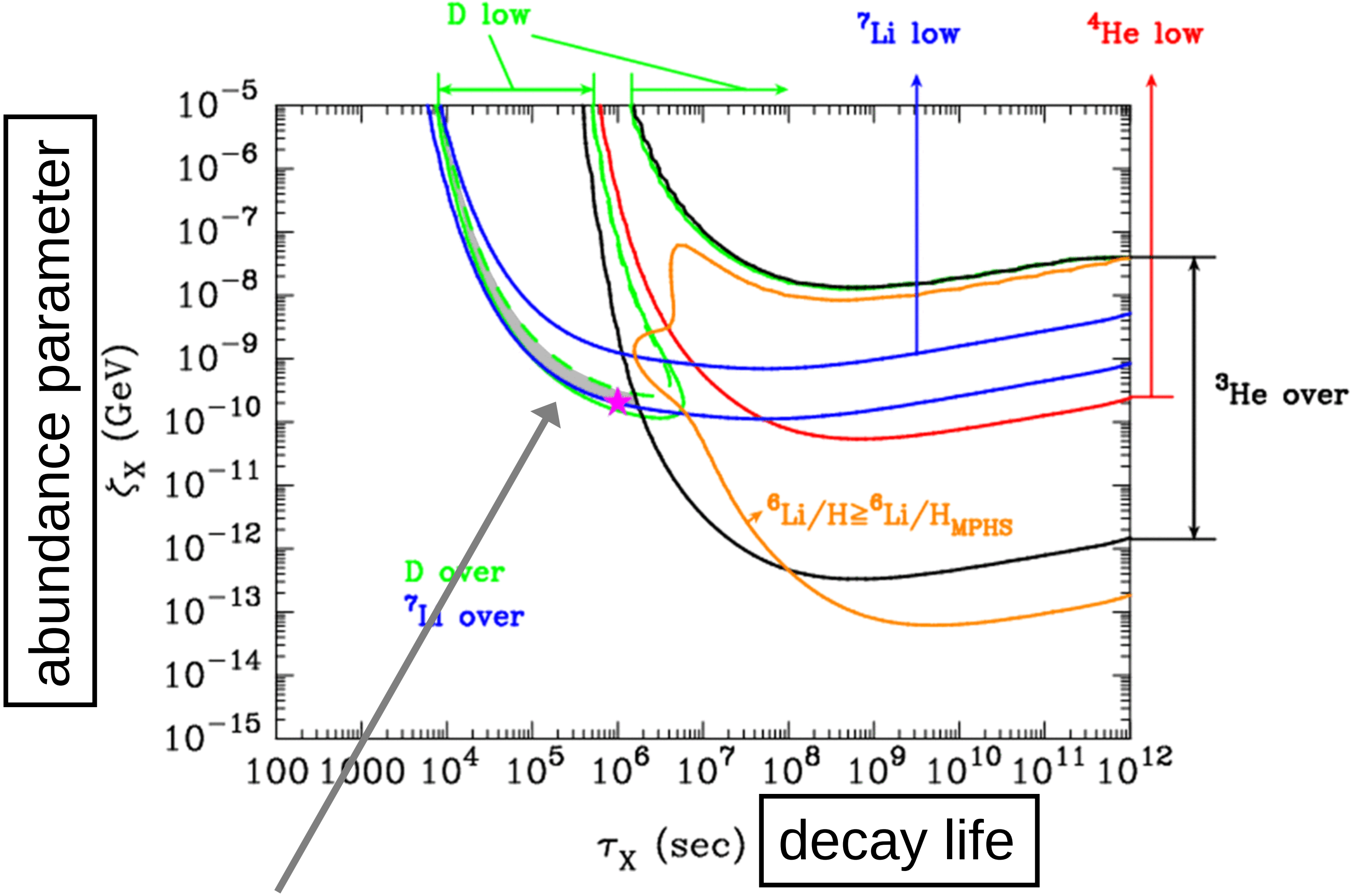


(MK, Kajino, Mathews, 2006)

Reactions of ^{7}Be destruction (^{7}Li reduction):
^{7}Be(γ,p)^{6}Li, ^{7}Be(γ,α)^{3}He, ^{7}Be(γ,2pn)^{4}He

Significant ^{7}Be destruction is accompanied with strong D destruction [^{2}H(γ,n)^{1}H]
→solution to the Li problem is not obtained.

Parameter search (BBN+axion+decaying particle)



D destruction [^{2}H(γ,n)^{1}H]

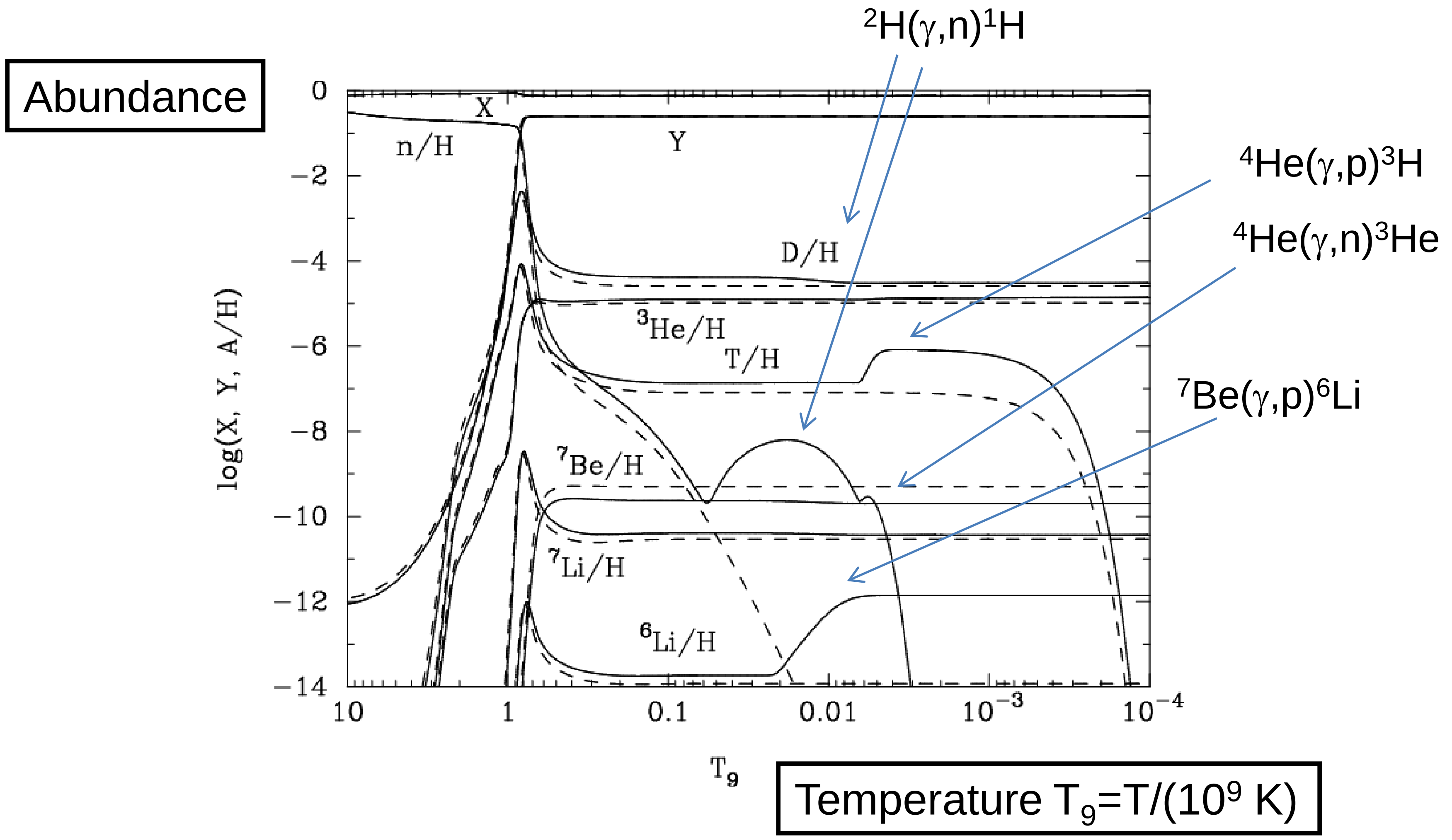
All abundances are consistent

Result

Nuclear flow

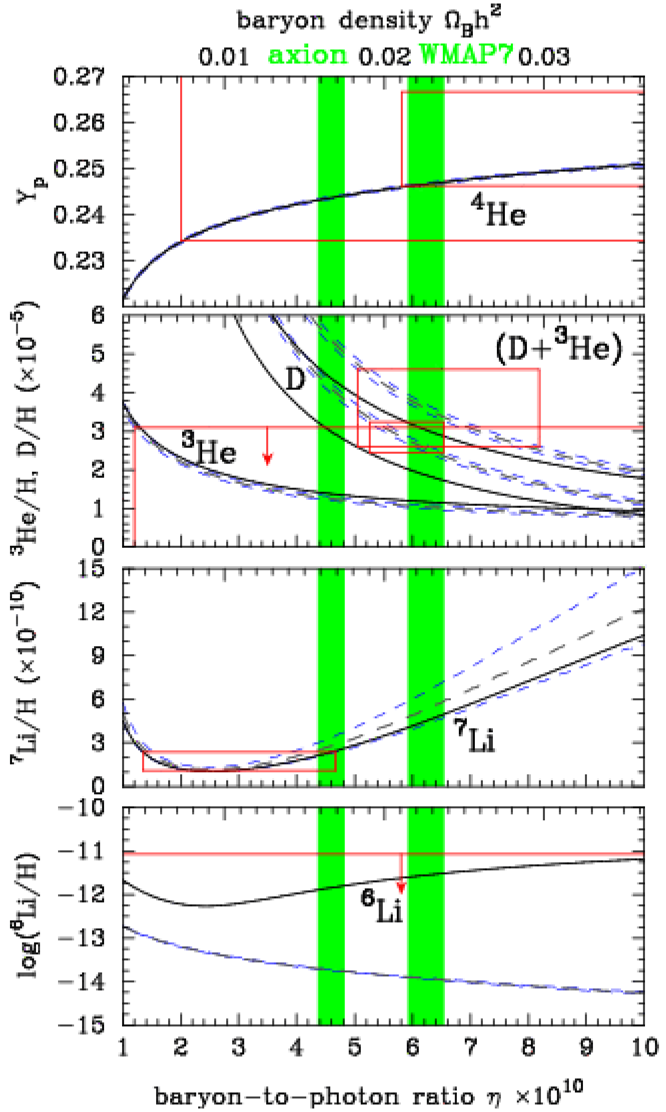
Solid line: BBN+radiatively decaying particle
($\tau_X=10^6$ s, $\zeta_X=2\text{x}10^{-10}$ s, $\eta=4.6\text{x}10^{-10}$)

Dashed line: SBBN



Result

$\Omega_B h^2 = 0.01666^{+0.00084}_{-0.00083}$ $\eta = (4.593^{+0.232}_{-0.228}) \times 10^{-10}$ $\Omega_B h^2 = 0.02258^{+0.00114}_{-0.00112}$ $\eta = (6.225^{+0.314}_{-0.309}) \times 10^{-10}$



Summary

- Primordial Li abundances may be a signature of exotic cosmological processes in the early universe

- These processes should not affect abundances of other elements significantly
  → cosmological solution to the Li problem is difficult

- If cooling of cosmic background radiation by axion is the cause of the low primordial Li abundance,
  another mechanism of D reduction is needed.

- (Axion+long-lived radiatively decaying particle) model can be a new solution.

Abundances of D and Li can be consistent with observations