Basics of Theoretical Astronomy and Astrophysics - 6
December 19, 2016

Particle and Nuclear Processes in the Early Universe

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OUTLINE

Universe is likely to be flat and accelerating!

$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$

- **What is the CDM, $\Omega_{CDM} = 0.23$?**
  Relic SUSY particles?
- **What is DARK ENERGY, $\Omega_\Lambda = 0.73$?**
  Mass-Energy Flow in Extra-Dimensional Cosmology !

LECTURE

- **CMB Anisotropies (t ~ $3.8\text{x}10^5$ y) constrain cosmic evolution from RD – Last Photon Scatt. – MD – Λ-dominated Universe.**
- **Redshift-magnitude relation of the Type Ia SNe (t ~ 1-10 Gy) constrains turn over from Cosmic Deceleration – Acceleration.**
- **Big-Bang Nucleosynthesis (t ~ 3 min) constrains as a CANDLE of dark side of the Universe.**

Big-Bang Nucleosynthesis

Why is it important ? What is the impact ?

- ＊ Unique OBSREVABLE in the Early Universe at $t < 3\text{min}$!
- ＊ Constrains Particle Physics & Dark Matter !
- ＊ Constrains Cosmic Evolution !

How to determine the cosmological parameters ($\Omega_i = \rho_i / \rho_C$) ?

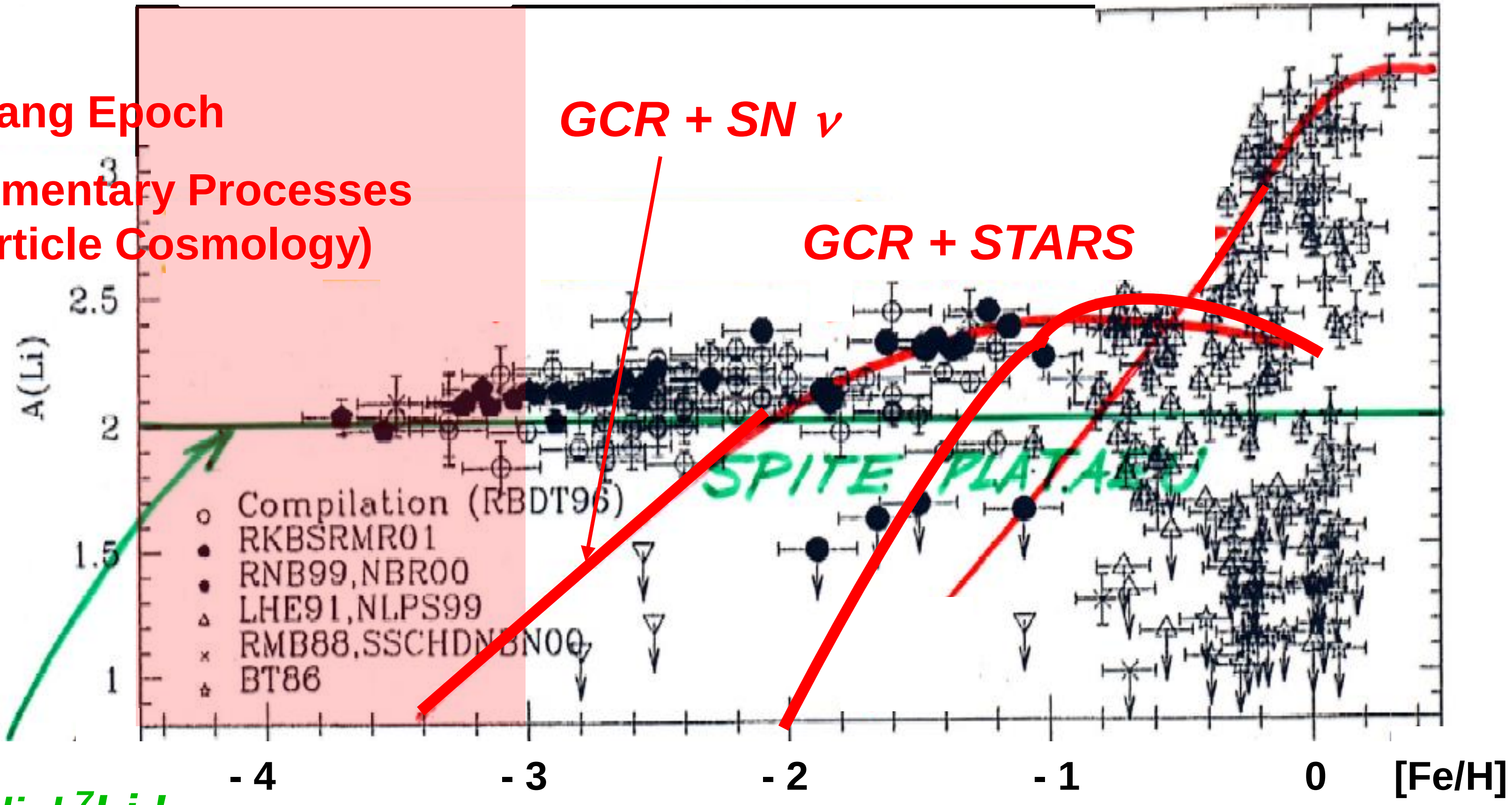
- $\Omega_{\gamma\nu} < 0.01\%$ $\Omega_\gamma \rightarrow$ Temperature of CBR (Cosmic Background Radiation)
  $\Omega_\nu \rightarrow$ Upper limit from neutrino oscillation
- $\Omega_\Lambda = 68\%$ Ia Supernovae CMB (Cosmic Background Anisotropies)
- $\Omega_{CDM} = 27\%$ Ia Supernovae CMB (Cosmic Background Anisotropies)
  Gravitaional Lensing
- $\Omega_B = 5\%$ Big-Bang Nucleosynthesis (BBN)
  CMB (Cosmic Background Anisotropies)

＊ $\Omega_{\gamma\nu} + \Omega_{CDM} + \Omega_B + \Omega_\Lambda = 1$ From all above combination

＊ Cosmic Age All above combination → 13.8 Gy

Big-Bang → Galaxy Forms → Star Forms

Ryan, Kajino, Beers, Suzuki, Romano, Matteucci & Rosolankova 2001, ApJ 549, 55.



Big-Bang Epoch

→ Elementary Processes
(Particle Cosmology)

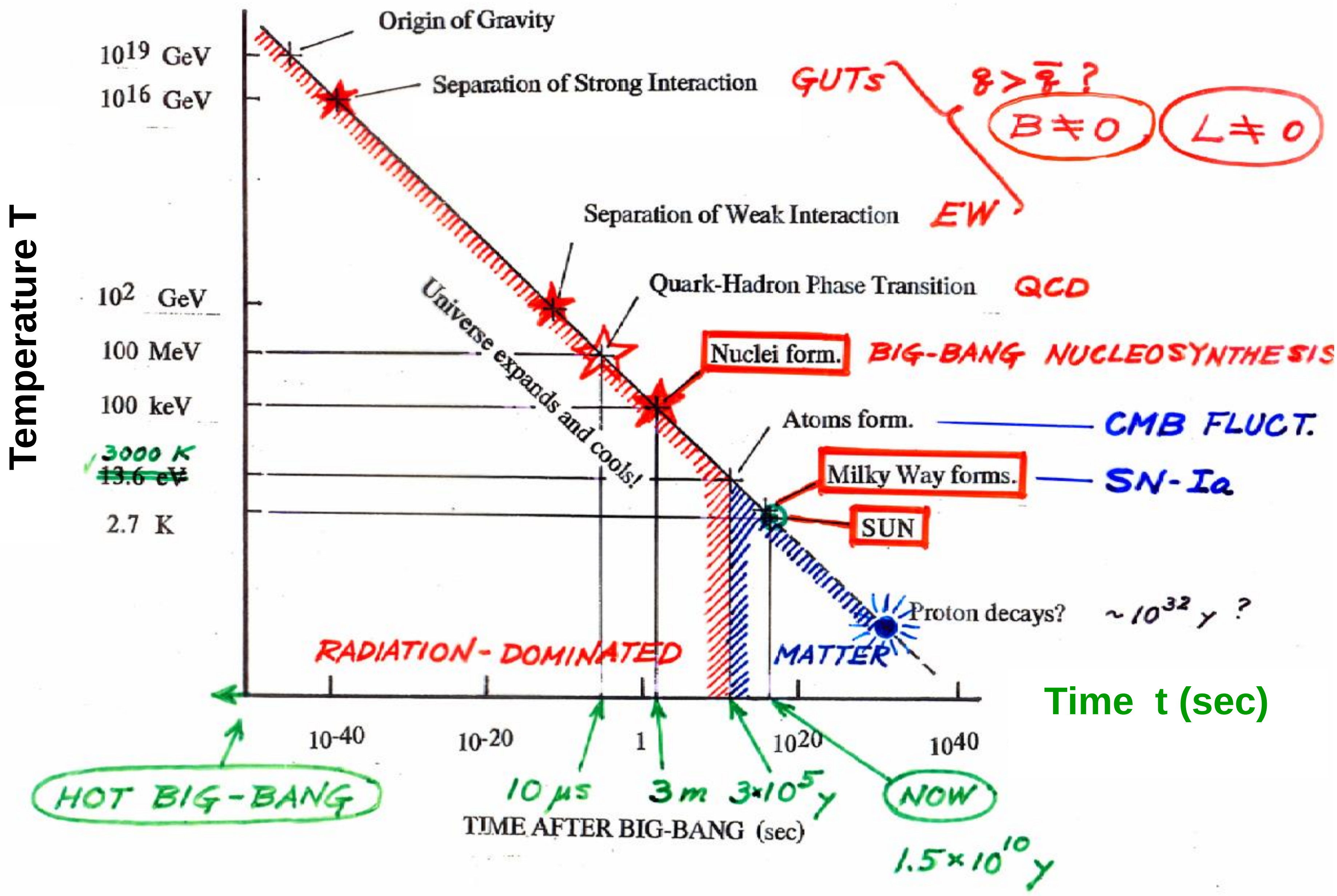
GCR + SN ν

GCR + STARS

Primordial ^{7}Li !

Early Universe **10My** **100My** **1Gy** **10Gy** ***TIME***

Thermal History of the Early Big-Bang Universe



First Three Minutes of the Universe

COMPLETE SYMMETRY!

(1) $t=0$: Universe began from ~~NOTHING~~ !

$$N_B = N_q = N_e = N_Q = \cdots = 0$$

(2) $t \sim 10^{-39}$ sec : GUTs PHASE TRANSITION

$\wr$

$t \sim 10^{-10}$ sec : EW (Weinberg-Salam) PHASE TRANSITION

$T \sim 100$ GeV

- Particles pair created. $\gamma+\gamma \rightleftarrows \nu+\bar{\nu} \rightleftarrows e^+ + e^- \rightleftarrows q+\bar{q} \cdots$
- CP-VIOLATION & BARYOGENESIS $\longrightarrow$ $B \neq 0$

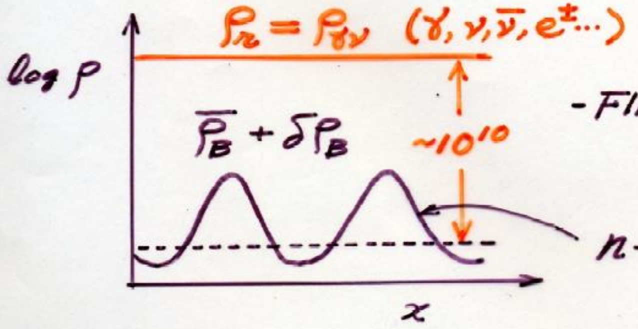
$$\frac{N_B - N_{\bar{B}}}{N_B} \simeq \left(\frac{n_B}{n_\gamma}\right)_0 \equiv \eta \sim 10^{-10} - 10^{-8}$$

? $\upharpoonleft\downharpoonright$

$L \neq 0$!

(3) $t \sim 10^{-4}$ sec : QCD PHASE TRANSITION

$T \sim 100$ MeV



- FIRST ORDER PH. TR.

$\longrightarrow$ $\delta\rho_B \neq 0$!

(4) $t \sim 1$ sec : WEAK INTERACTIONS DECOUPLE.

$T \sim 1$ MeV

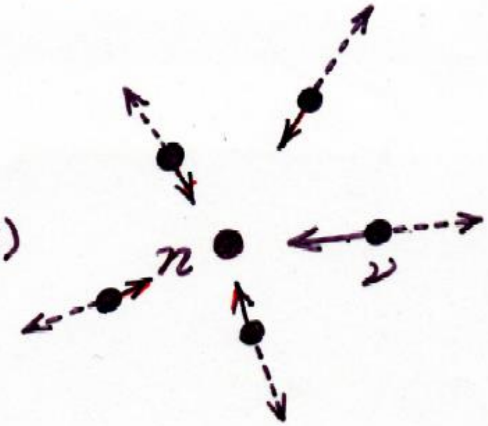
- $n + \nu_e \not\rightleftarrows p + e^-$, $n/p \simeq \exp(\underbrace{\Delta m}_{1.29\text{ MeV}}/T)\exp(-t/\tau_n) < 1$

EXPANSION vs. INTERACTION

Expansion Time

$$t_H = H^{-1} = \left(\frac{\dot{R}}{R}\right)^{-1} = 2t$$

$$= \frac{0.73\ \text{sec}}{(T/\text{MeV})^2} \quad \text{——} \ (*)$$



Collision Time

$$t_c = \frac{1}{n_\nu \sigma_W v_c}$$

$$n + \nu_e \rightleftarrows p + e^-$$

$$\sigma_W \approx G_F E_\nu^2 \sim G_F T^2 \sim 4\times 10^{-44}\ \text{cm}^2\ (T/\text{MeV})^2$$

F.-D. $$n_\nu = \frac{g_\nu}{h^3}\iiint \frac{d^3p}{\exp(\epsilon-\mu)/T+1} \underset{\mu \ll T}{\approx} \frac{3}{4}\left(\frac{g_\nu}{g_\gamma}\right) n_\gamma = 2.3\times 10^{31} \times (T/\text{MeV})^3\ \text{cm}^{-3}$$

B.-E. $$n_\gamma = \frac{g_\gamma}{h^3}\iiint \frac{d^3p}{\exp \epsilon/T - 1} = \frac{\zeta(3)}{\pi^2} g_\gamma T^3$$

$$\zeta(3) = 1.20206$$

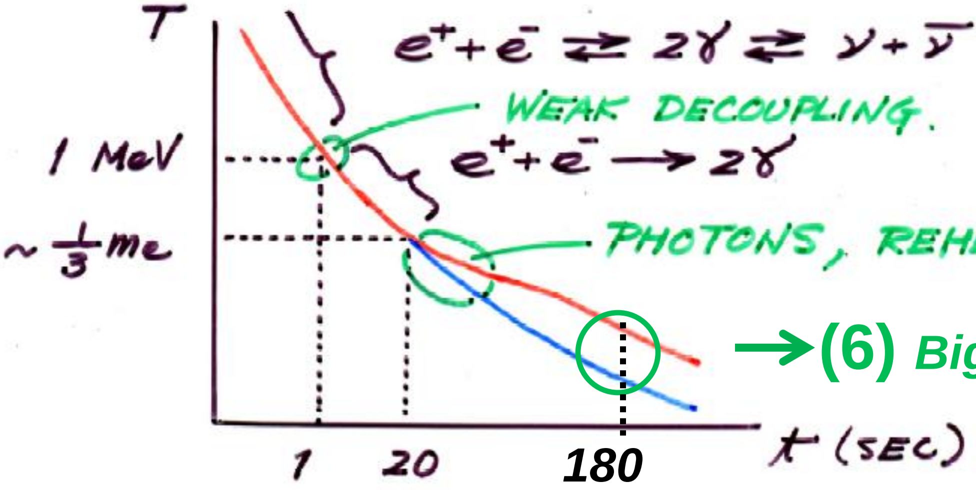
$$t_c \approx 35 \times (T/\text{MeV})^{-5}\ \text{sec} \quad \text{——} \ (**)$$

$\therefore\ t_H = t_c \longrightarrow$ $T \approx 1.3$ MeV

$t_H < t_c$ WEAK INTERACTIONS DECOUPLE !

(5) $t \sim 20$ sec
$T \sim \frac{1}{3} m_e \sim 3\times10^9$ K

$e^+ + e^- \rightleftarrows 2\gamma$ EQUILIBRIUM DECOUPLES.



→**(6)** ***Big-Bang Nucleosynthesis***
~ 3 min

ENTROPY, conserved :

BEFORE $e^\pm$-ANNIHILATION ; $S \sim \overset{\overset{\gamma \quad e^\pm}{2\times(1+2\times\frac{7}{8})}}{g} T^3 = \frac{11}{4}\times 2T^3$.

AFTER " ; $S' \sim \underset{\underset{\gamma}{2\times 1}}{g'} T'^3 = 2T'^3$

$$S = S' \longrightarrow T = \left(\frac{11}{4}\right)^{1/3} T'$$

$$\therefore T_\gamma = \left(\frac{11}{4}\right)^{1/3} T_\nu$$

George Gamow’s predictions in 1948

If the Universe began from the Fire Ball of hot Big-Bang and then expanded, then:

1. We can detect today the Cosmic Background Radiation of T = 5 K !

   → 2.7K CBR was discovered by Penzias & Wilson (1965)

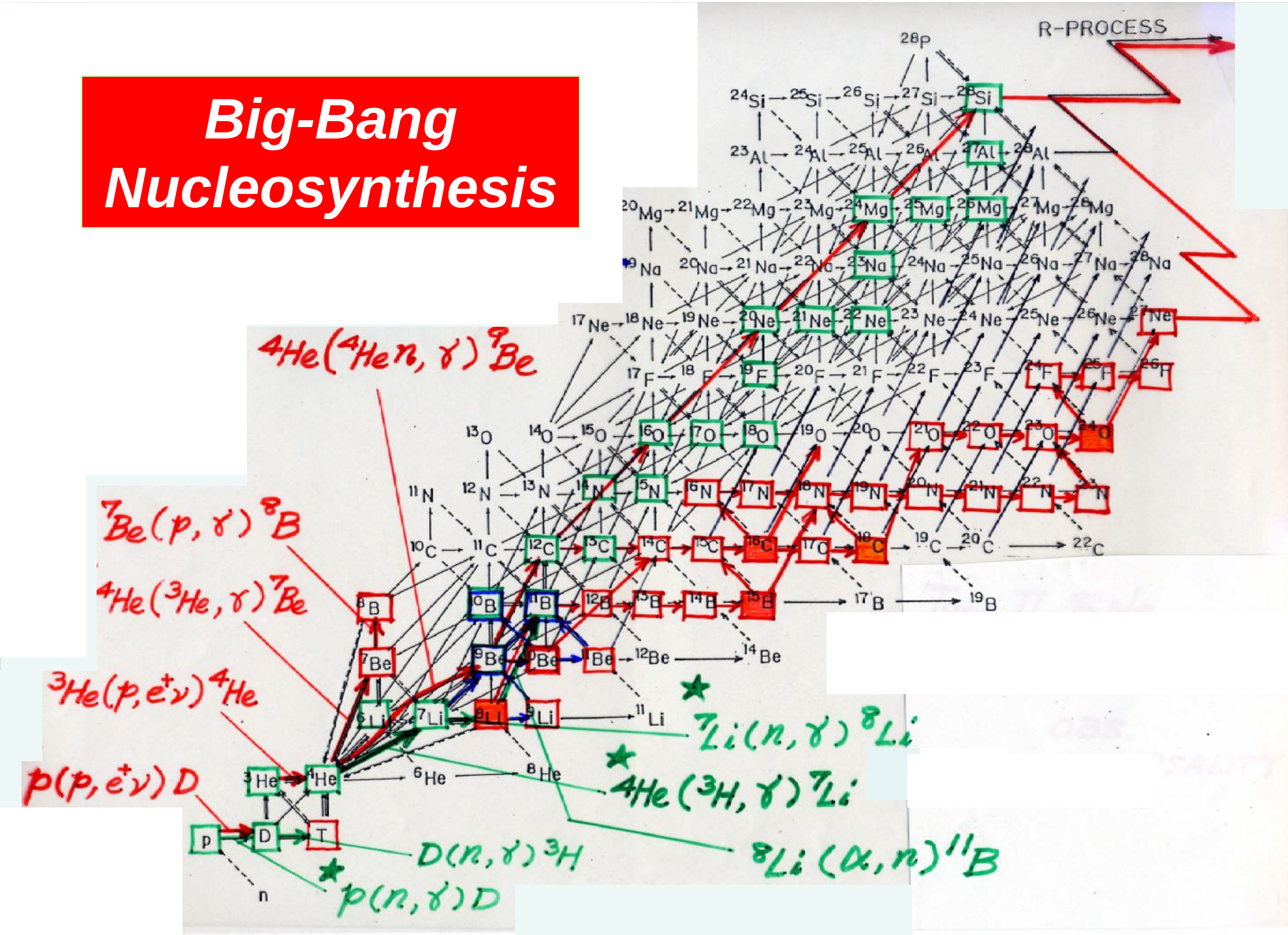
   → CMB anisotropies by Smoot & Mathar (1992)

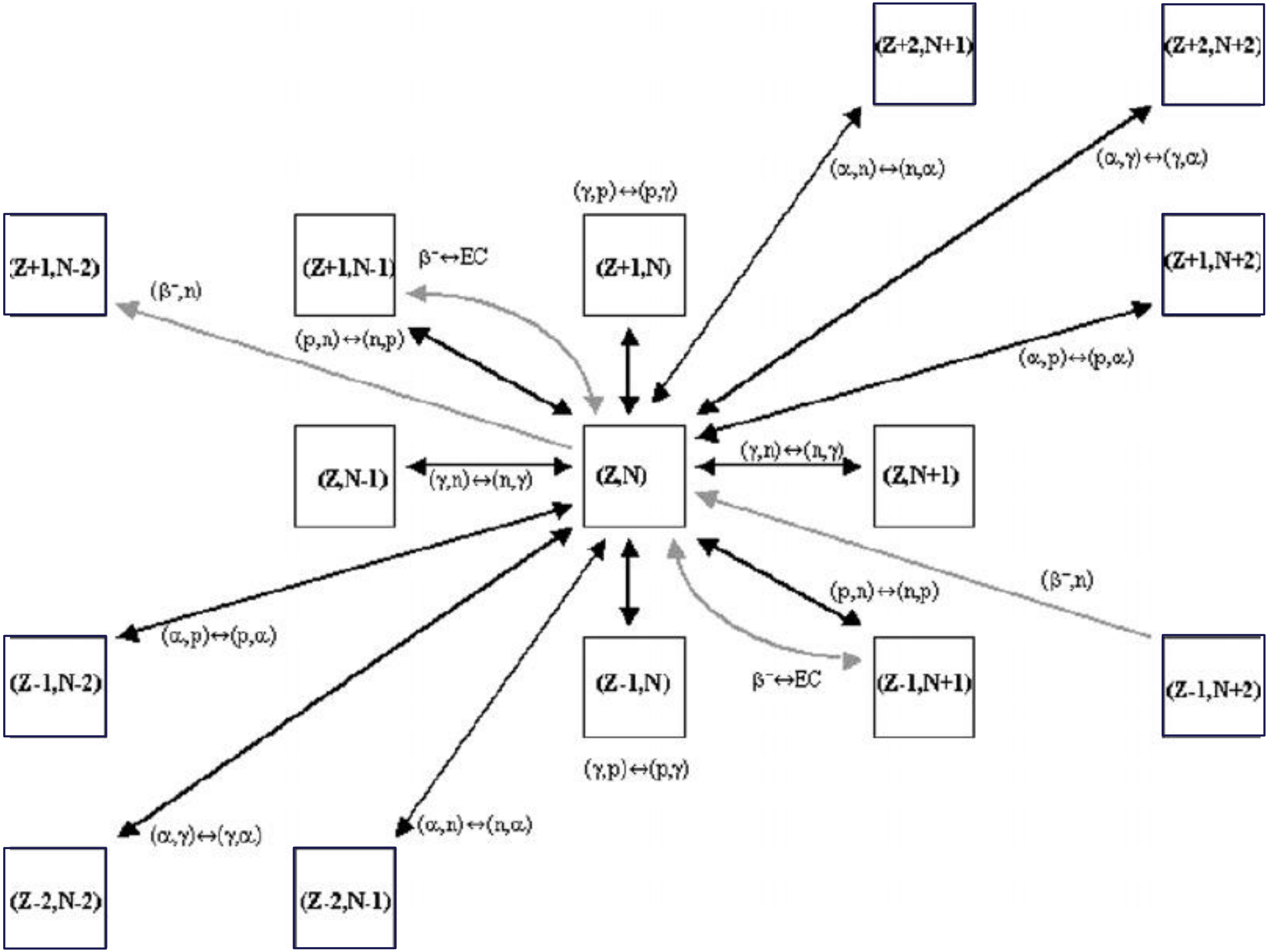
2. In the hot Big-Bang Universe were created almost all atomic nuclides !

   → ^{4}He & ^{7}Li, discovered by astronomer (1980’)

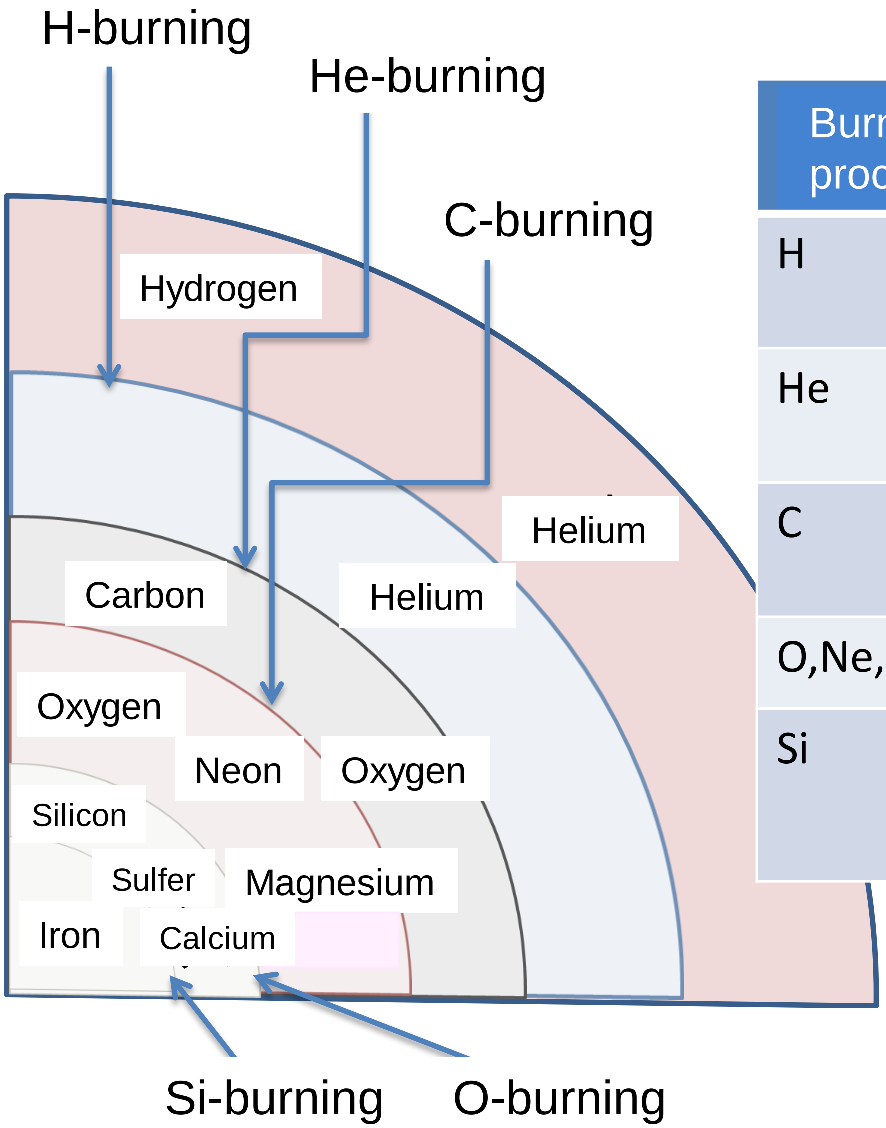
Big-Bang Nucleosynthesis !

Big-Bang Nucleosynthesis




(Z+2,N+1)
(Z+2,N+2)
(α,n)↔(n,α)
(α,γ)↔(γ,α)
(γ,p)↔(p,γ)
(Z+1,N-2)
(Z+1,N-1)
β^-↔EC
(Z+1,N)
(Z+1,N+2)
(β^-,n)
(p,n)↔(n,p)
(α,p)↔(p,α)
(Z,N-1)
(γ,n)↔(n,γ)
(Z,N)
(γ,n)↔(n,γ)
(Z,N+1)
(β^-,n)
(p,n)↔(n,p)
(α,p)↔(p,α)
(Z-1,N-2)
(Z-1,N)
β^-↔EC
(Z-1,N+1)
(Z-1,N+2)
(γ,p)↔(p,γ)
(α,γ)↔(γ,α)
(α,n)↔(n,α)
(Z-2,N-2)
(Z-2,N-1)

Stellar Evolution of Massive Stars → Supernova Explosion



Burning process	Main reaction processes	Final product	T $(10^{8}\mathrm{K})$
H	pp chain CNO cycle	$^{4}\mathrm{He}$	0.15 0.2
He	$3\alpha \rightarrow {}^{12}\mathrm{C}$ ${}^{12}\mathrm{C}+\alpha \rightarrow {}^{16}\mathrm{O}$	$^{12}\mathrm{C}$ $^{16}\mathrm{O}$	1.5
C	${}^{12}\mathrm{C}+{}^{12}\mathrm{C} \rightarrow {}^{20}\mathrm{Ne}+\alpha$ $\rightarrow {}^{24}\mathrm{Mg}$	$^{20}\mathrm{Ne}$ $^{24}\mathrm{Mg}$	7
O,Ne,Mg	${}^{16}\mathrm{O}+{}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si}+\alpha$	$^{28}\mathrm{Si}$	>15
Si	${}^{28}\mathrm{Si}+\alpha \rightarrow {}^{32}\mathrm{S}$ ···· ····	$^{56}\mathrm{Fe}$	40

Nuclear Statistical Equilibrium (NSE)

$$Z\,p + N\,n \longleftrightarrow A(Z,N) + \gamma$$

Gibbs free energy:

$$Z\,\mu_p + N\,\mu_n \;=\; \mu_A \;+\; \mu_\gamma, \qquad \mu_\gamma = 0$$

Mass difference:

$$Q_A = Z\,m_p + N\,m_n - m_A$$

Binding Energy of Nucleus A

Saha Equation

$$Y_{A(Z,N)} \approx \boxed{\left[S^{1-A}\right]} G\pi^{\frac{1}{2}(A-1)} 2^{\frac{1}{2}(A-3)} A^{3/2} \left(\frac{T}{m_b}\right)^{\frac{3}{2}(A-1)} Y_p^Z Y_n^N \boxed{e^{Q_A/T}}$$

Entropy/Baryon: S = 10^{+10} (in Big-Bang), 10^{+2} (in Supernovae)

H, D, ^{3,4}He, ^{6,7}Li Fe-Co-Ni

Baryon-to-Photon Ratio, $\eta = n_B/n_\gamma$, vs. Entropy per Baryon, S/k

Entropy density = s

$$s = 2\pi^2/45 \cdot g^* \cdot T^3 + s(NR)$$

$$g^* = \sum_{\text{Bosons}} g_B (T_B/T)^4 + 7/8 \sum_{\text{Fermions}} g_F (T_F/T)^4$$

Photon number density = n_γ

$$n_\gamma = \zeta(3)/\pi^2 \cdot g_\gamma \cdot T^3$$

Entropy per Baryon = S/k

$$S/k = s_\gamma/n_B \doteqdot 3.6\, n_\gamma/n_B = 3.6\, \eta^{-1}$$

Early Universe 10^9 $\eta = n_B/n_\gamma = 10^{-9}$ $\Omega_B h^2 = 3.73\text{x}10^7 \eta$

Decoupling from Nuclear Statistical Equilibrium, diving into Dynamical Primordial (Big-Bang) Nucleosynthesis

$T \sim 1\,\mathrm{MeV}$

$X_p \sim X_n \sim 1$

- $D + \gamma \rightleftarrows p + n \;;\; Q_D = 2.2\ \mathrm{MeV}$

$$X_D = 3 \times 1.2 \times \pi^{-1/2} \times 2^{1/2} \times 2^{5/2} \times \left(\frac{T\ \mathrm{MeV}}{1000\ \mathrm{MeV}}\right)^{3/2} \times \eta \times X_p X_n \exp(Q_D/T)$$

$$\sim \quad \mathcal{O}(1) \quad \times 10^{-9/2} \times 10^{-8} \times 1 \times 1 \times 10$$

$$\sim 10^{-11.5}$$

Very Small !

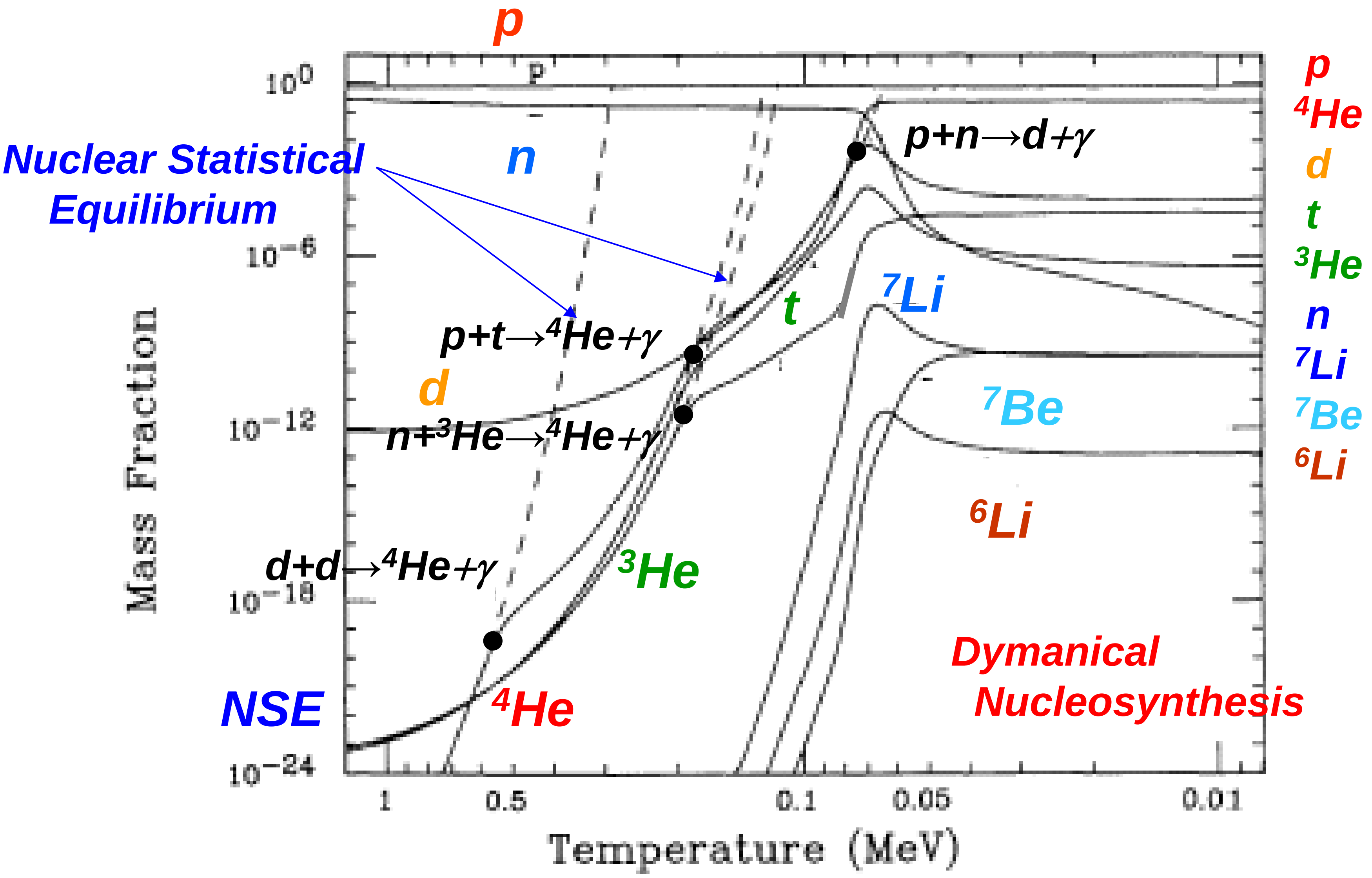
- $^4He + \gamma \rightleftarrows 2p + 2n \;;\; Q_\alpha = 28.3\ \mathrm{MeV}$

$$X_{^4He} \sim \quad \mathcal{O}(1) \quad \times 10^{-27/2} \times (10^{-8})^3 \times 1 \times 1 \times 10^{13}$$

$$\sim 10^{-25}$$

Too small !

Evolution of Abundances



Big-Bang Nucleosynthesis (BBN) Theory stands on precise particle and nuclear physics!

Relevant nuclear reaction rates are known within the accuracy of 5－15% !

→ Nuclear physics is not responsible for the Li problems of factor of ~ 3 for ^{7}Li, 3 order of magnitude for ^{6}Li !

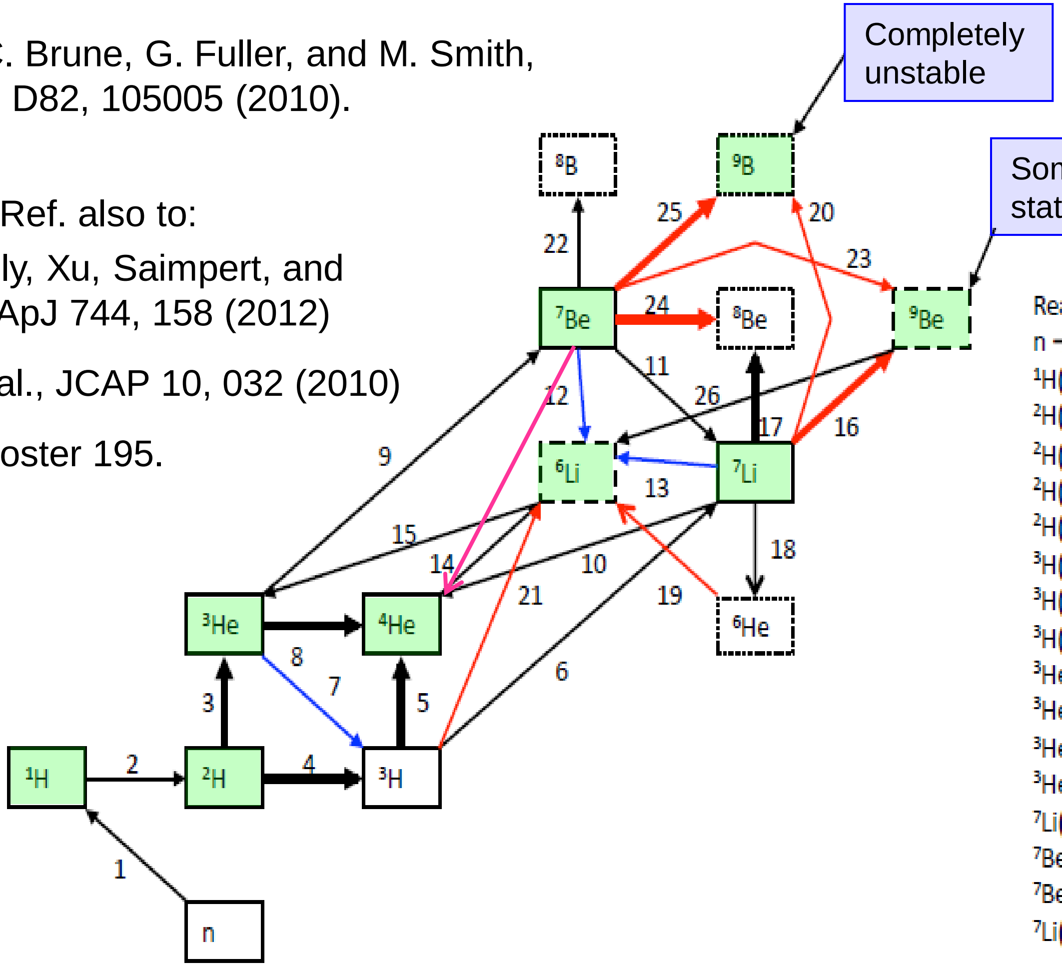
R. Boyd, C. Brune, G. Fuller, and M. Smith, Phys. Rev. D82, 105005 (2010).

Ref. also to:

Coc, Goriely, Xu, Saimpert, and Vangioni, ApJ 744, 158 (2012)

Cyburt, et al., JCAP 10, 032 (2010)

Li, et al., Poster 195.



Reaction Key	
n → ^{1}H	1
$^{1}H(n,g)^{2}H$	2
$^{2}H(^{2}H,n)^{3}He$	3
$^{2}H(^{1}H,g)^{3}He$	
$^{2}H(^{2}H,^{1}H)^{3}H$	4
$^{2}H(n,g)^{3}H$	
$^{3}H(^{2}H,n)^{4}He$	5
$^{3}H(^{1}H,g)^{4}He$	
$^{3}H(^{4}He,g)^{7}Li$	6
$^{3}He(n,^{1}H)^{3}H$	7
$^{3}He(^{2}H,^{1}H)^{4}He$	8
$^{3}He(n,g)^{4}He$	
$^{3}He(^{4}He,g)^{7}Be$	9
$^{7}Li(^{1}H,^{3}He)^{4}He$	10
$^{7}Be(n,^{1}H)^{7}Li$	11
$^{7}Be(n,^{2}H)^{6}Li$	12
$^{7}Li(n,2n)^{6}Li$	13

Reaction Key	
$^{4}He(^{2}H,g)^{6}Li$	14
$^{6}Li(^{1}H,^{4}He)^{3}He$	15
$^{7}Li(^{3}H,n)^{9}Be$	16
$^{7}Li(^{3}He,^{1}H)^{9}Be$	
$^{7}Li(^{2}H,n)^{8}Be$	17
$^{7}Li(^{1}H,g)^{8}Be$	
$^{7}Li(^{3}He,^{2}H)^{8}Be$	
$^{8}Be \rightarrow {}^{4}He+{}^{4}He$	
$^{7}Li(^{3}H,^{4}He)^{6}He$	18
$^{6}He \rightarrow {}^{6}Li$ or $^{4}He+{}^{2}H$	19
$^{7}Li(^{3}He,n)^{9}B$	20
$^{3}He(^{3}H,g)^{6}Li$	21
$^{7}Be(^{1}H,g)^{8}B$	22
$^{7}Be(^{3}H,^{1}H)^{9}Be$	23
$^{7}Be(^{2}H,^{1}H)^{8}Be$	24
$^{7}Be(^{3}H,^{2}H)^{8}Be$	
$^{7}Be(^{3}He,^{1}H)^{9}B$	25
$^{7}Be(^{3}H,n)^{9}B$	
$^{9}Be(^{1}H,^{4}He)^{6}Li$	26

The Power of BBN is that the Physics is Accessible

Thermodynamic Equilibrium of Particles and Nuclei

$$n_i(p)dp = \frac{1}{2\pi^2} g_i\, p^2 \left[\exp\left(\frac{E_i(p)-\mu_i}{kT}\right) \pm 1\right]^{-1} dp$$

$$\rho_i = \int p\,[n_i(p) + n_{\bar{i}}(p)]\,dp$$

$$\rho_\gamma = \frac{\pi^2}{15}(kT_\gamma)^4 \quad , \quad \rho_{\nu_i} = \frac{7}{8}\frac{\pi^2}{15}(kT_\nu)^4$$

$$\rho = \rho_\gamma + \rho_{\nu_i} + \rho_i = \frac{\pi^2}{30} g_{eff}(kT)^4$$

$$g_{\mathrm{eff}}(T) = \sum_{\mathrm{bose}} g_{\mathrm{bose}} + \frac{7}{8}\sum_{\mathrm{fermi}} g_{\mathrm{fermi}}$$

Cosmic Expansion

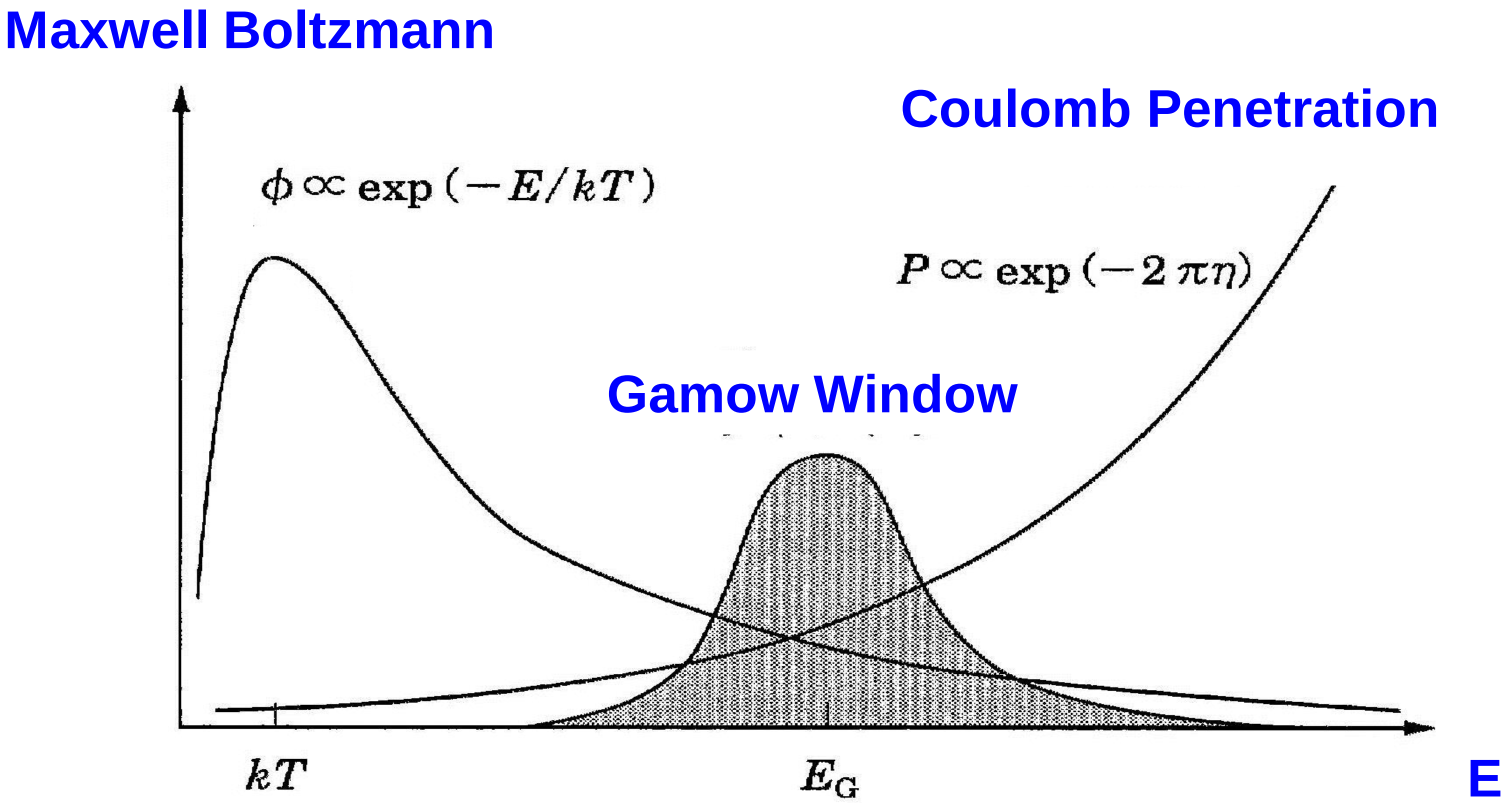
$$H^2(t) = \left(\frac{1}{R}\frac{dR}{dt}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2}$$

Nuclear Reactions

$$\frac{dY_i}{dt} = \sum_{ijk} N_i \left(\frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!} \langle n_k \sigma_{lk} v \rangle - \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_k!} \langle n_j \sigma_{ij} v \rangle \right)$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int S(E) \exp(-2\pi\eta) \exp(-E/kT) dE$$

$$\sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta)$$



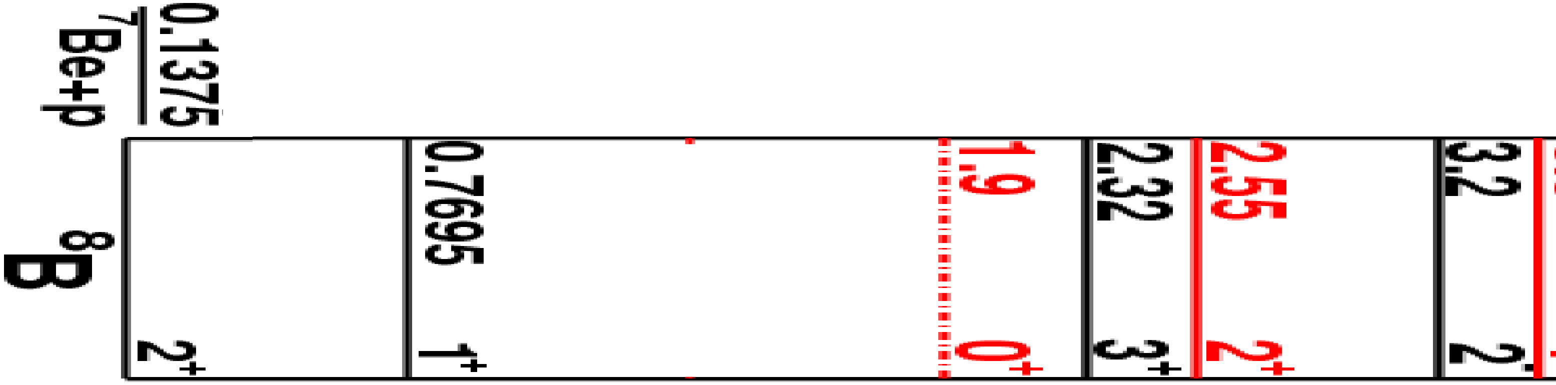
Maxwell Boltzmann

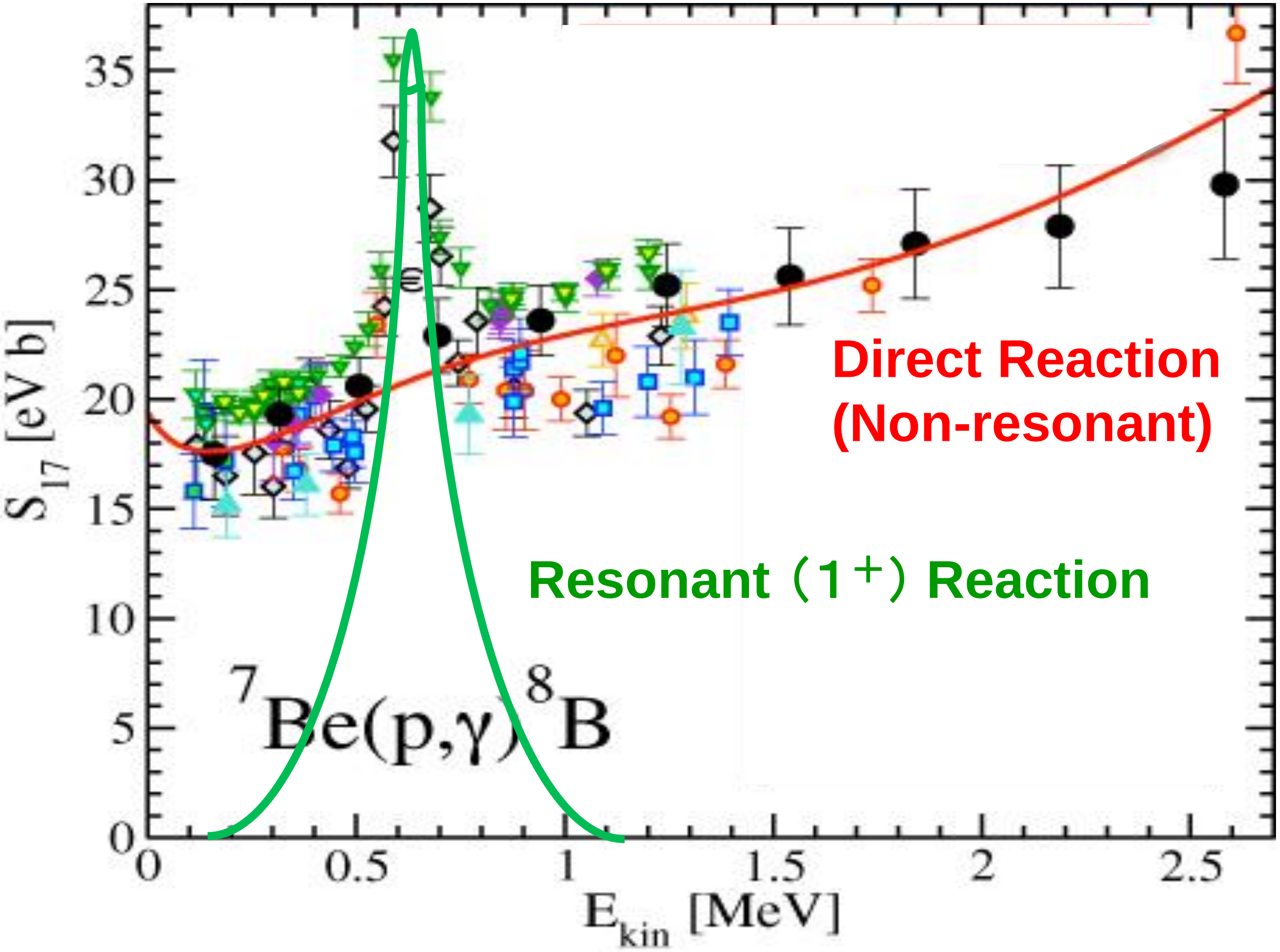
Coulomb Penetration

Gamow Window

E

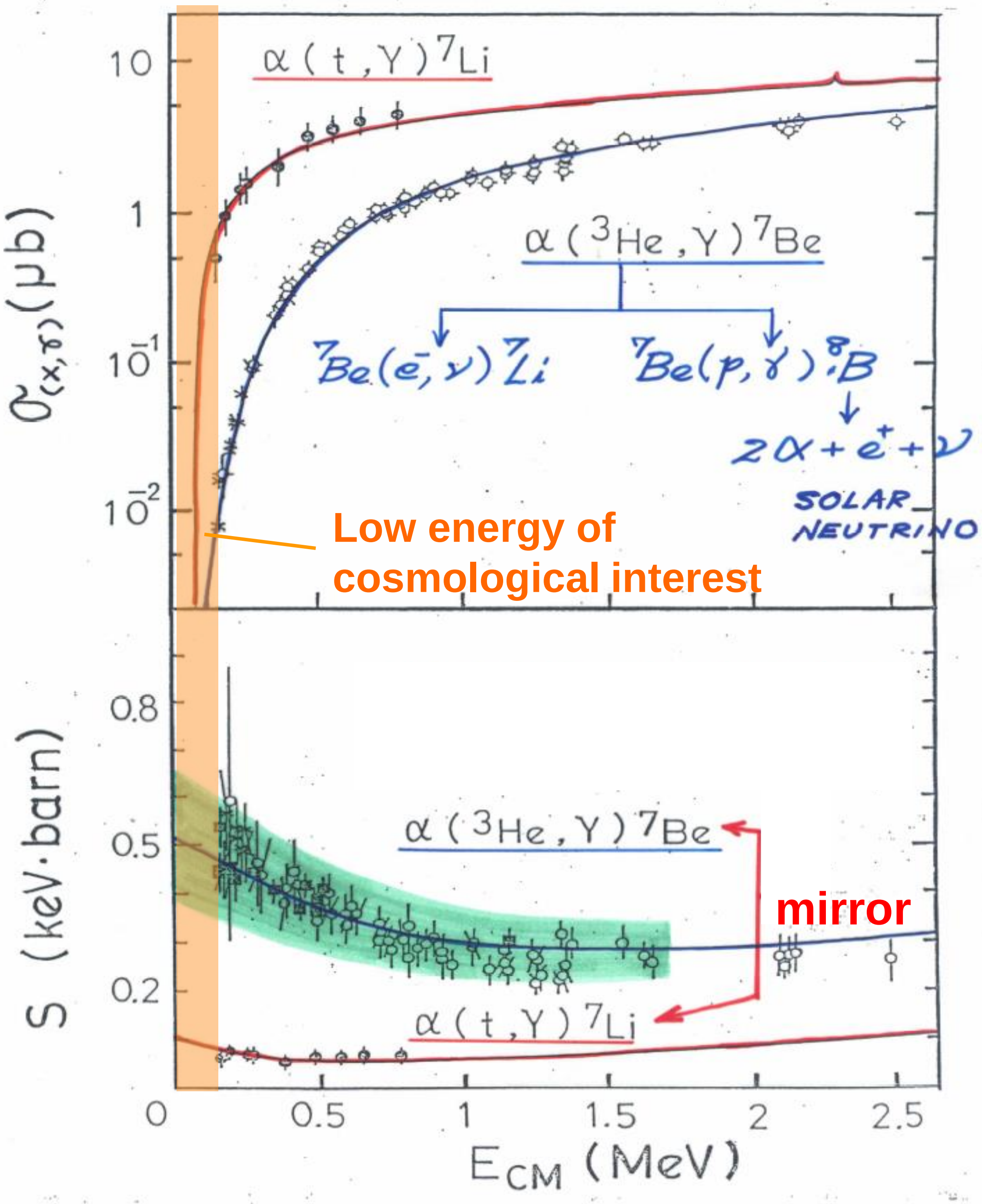
$$E_G = \left(\frac{\mu}{2}\right)^{1/3} \left(\frac{\pi Z_A Z_a e^2 kT}{\hbar}\right)^{2/3}$$





Direct Reaction (Non-resonant)

Resonant（1$^+$）Reaction



Cross section

decreases exponentially due to the Coulomb barrier, which makes laboratory experiment extremely difficult at astrophysical low energies!

Astrophysical S-factor

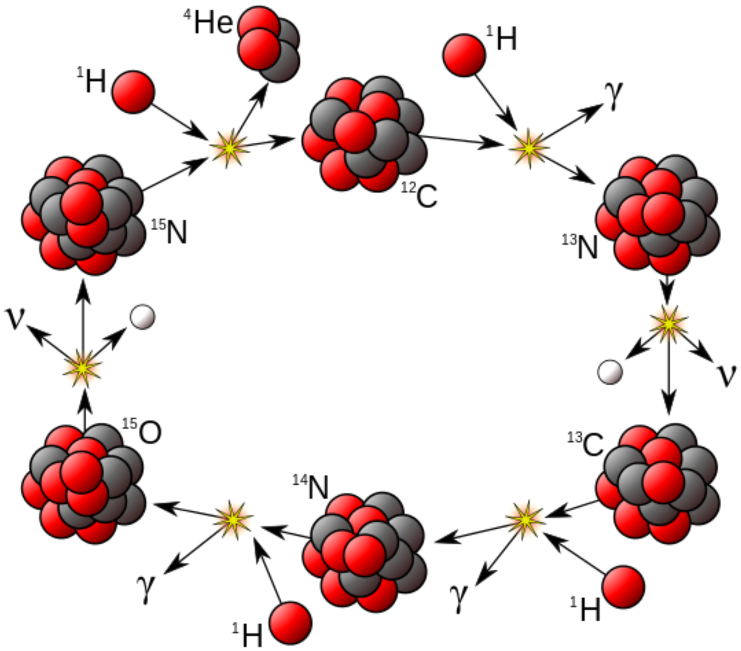
$$S(E) = E\,\sigma(E)\exp(2\pi\eta)$$

Hans A. Bethe（1906－2005）

原子核・素粒子物理学者。「原子核反応理論への貢献、特に星の内部におけるエネルギー生成（CNOサイクル反応）の発見」に対して1967年ノーベル物理学賞受賞。

- 荷電粒子のエネルギー損失ベーテ公式
- ベーテ・ワイツゼッカーの原子核質量公式

CNOサイクル



・ラムシフトの正確な量子論計算

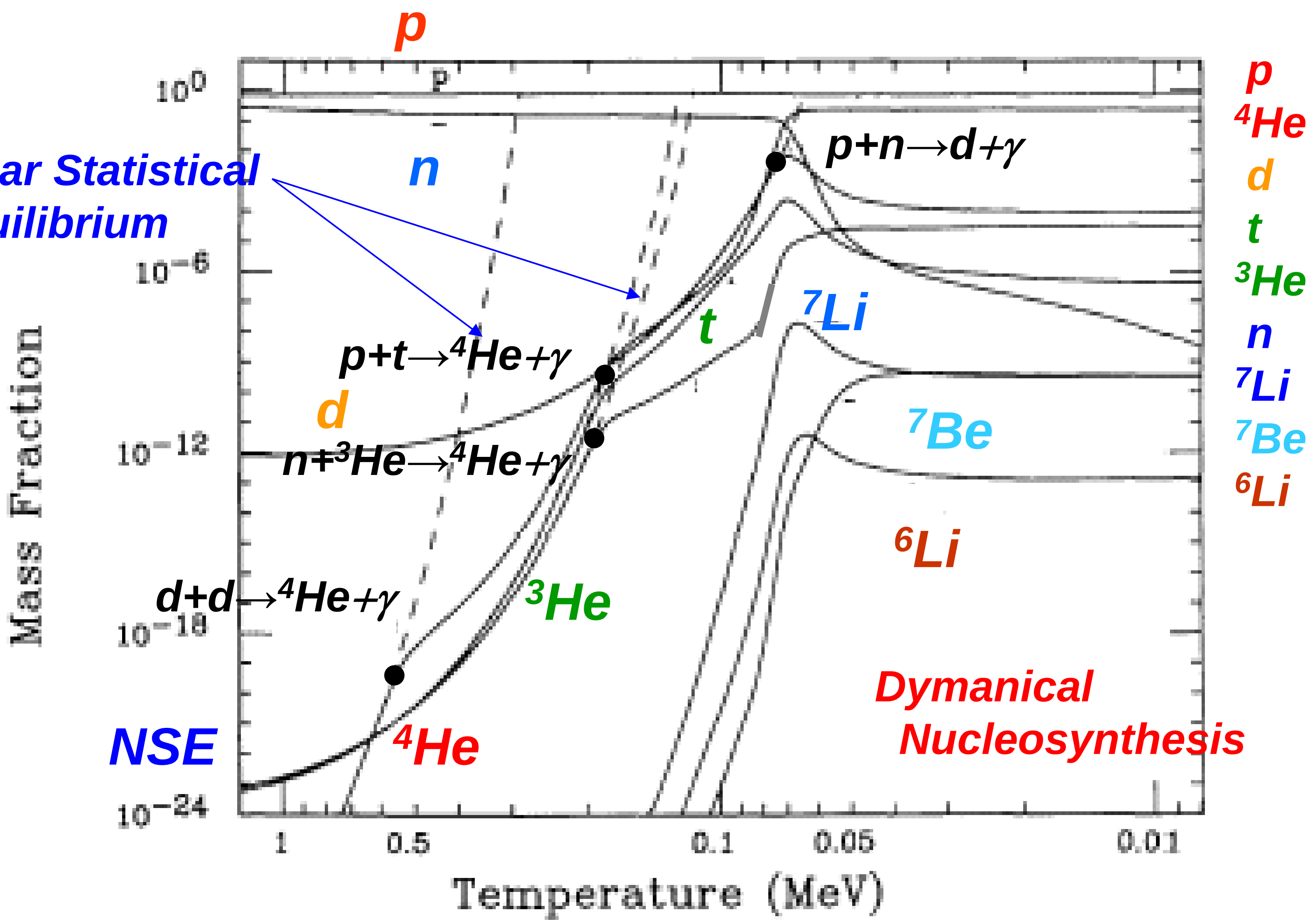
→　量子電磁力学の完成に決定的な影響！
（リチャード・ファインマン、フリーマン・ダイソン）

・ベーテ仮説（Bethe anstaz）：量子多体系の厳密解を求める方法 の提唱

→　ベーテ仮説（Bethe anstaz）：量子多体系の厳密解を求める方法 の提唱
→　超弦理論
→　超伝導理論
→　**超新星ニュートリノ振動理論**

物理学のあらゆる分野の研究に用いられている。

Evolution of Abundances



Nuclear Statistical Equilibrium

NSE

Dymanical Nucleosynthesis

$p+n \rightarrow d+\gamma$

$p+t \rightarrow {}^4He+\gamma$

$n+{}^3He \rightarrow {}^4He+\gamma$

$d+d \rightarrow {}^4He+\gamma$

p

n

d

t

^{3}He

^{4}He

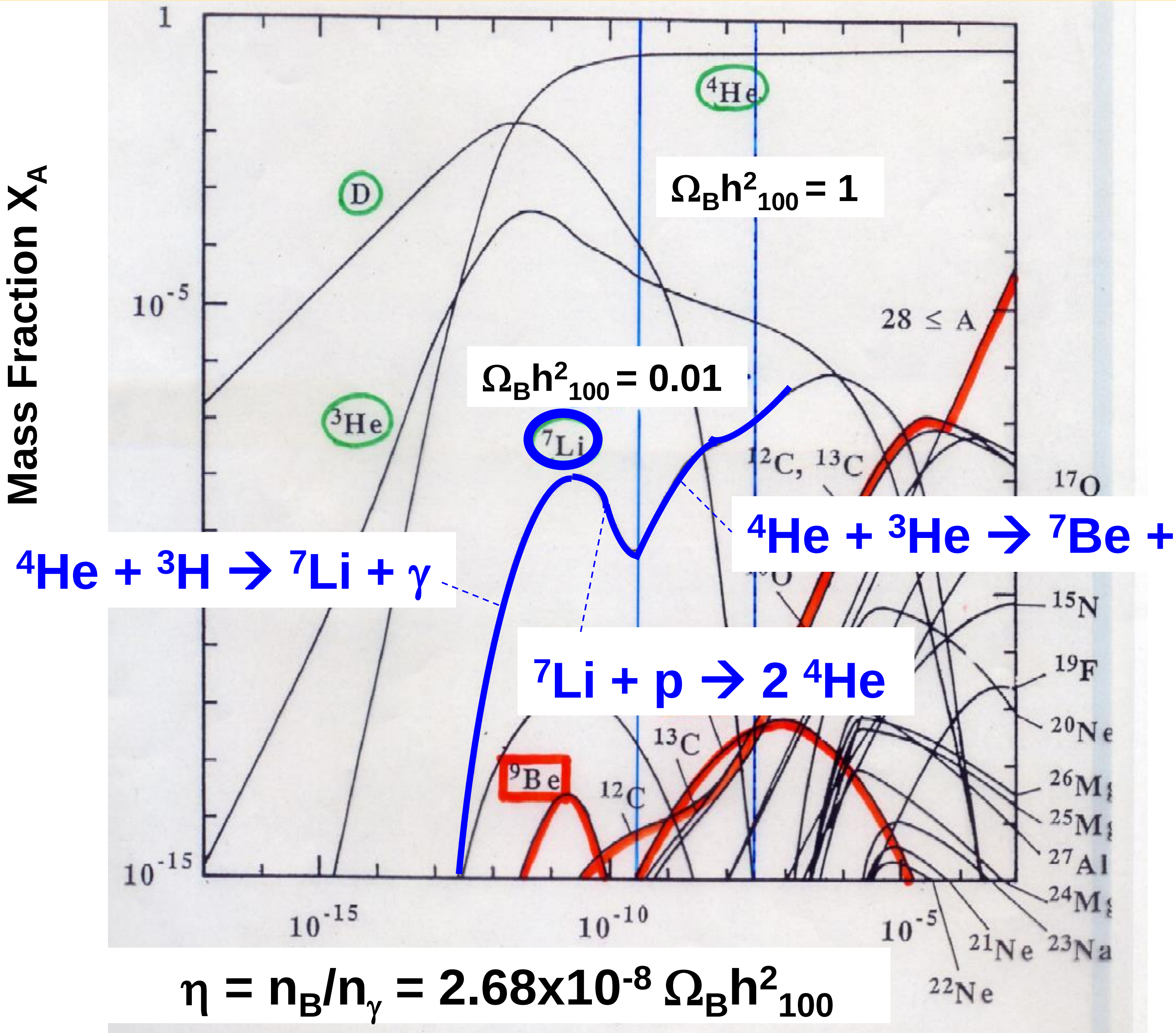
^{7}Li

^{7}Be

^{6}Li

p
^{4}He
d
t
^{3}He
n
^{7}Li
^{7}Be
^{6}Li

Big-Bang (Primordial) Nucleosynthesis



$\Omega_B h^2_{100} = 1$

$\Omega_B h^2_{100} = 0.01$

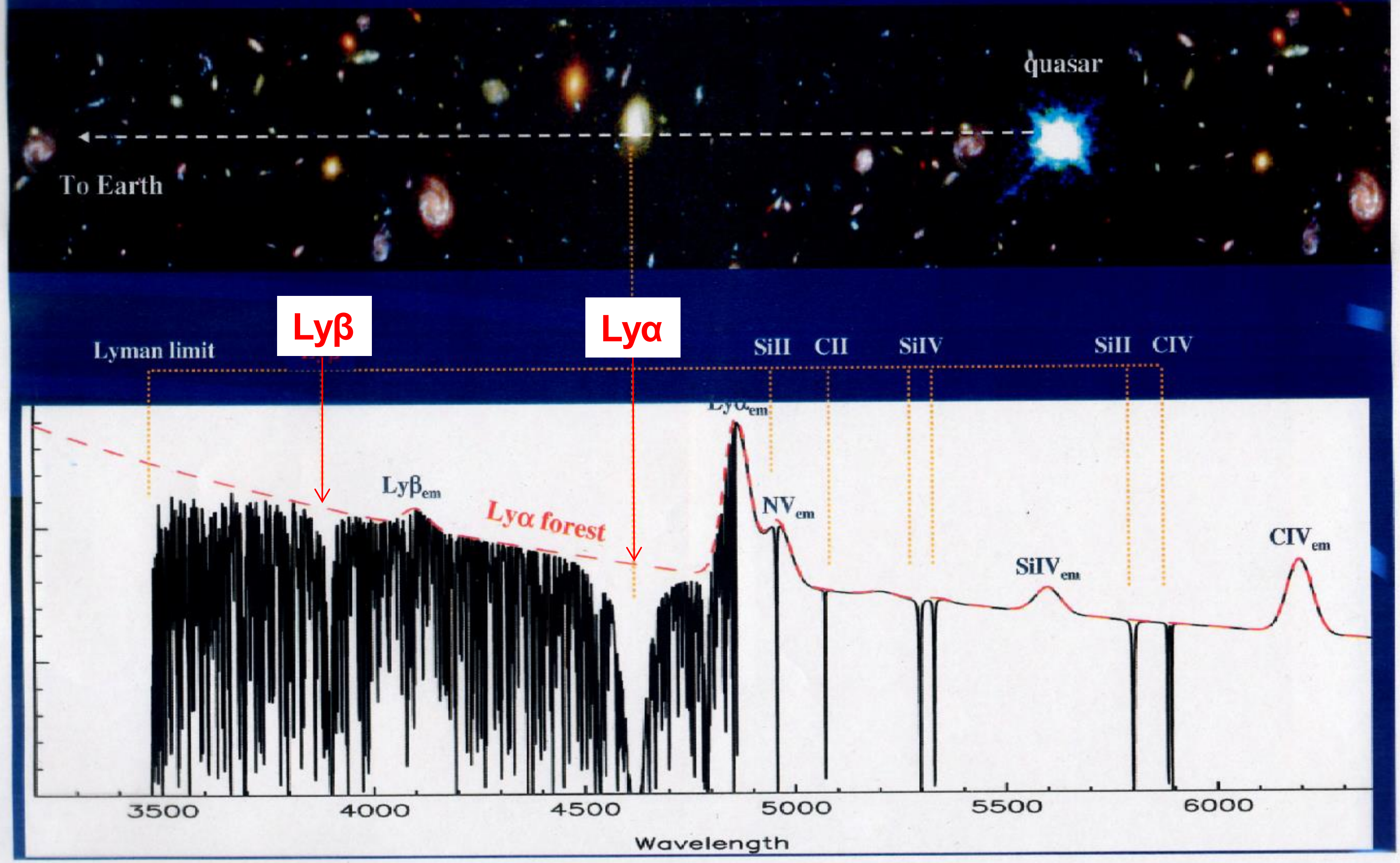
$^4\text{He} + {}^3\text{He} \rightarrow {}^7\text{Be} + \gamma$

$^4\text{He} + {}^3\text{H} \rightarrow {}^7\text{Li} + \gamma$

$^7\text{Li} + p \rightarrow 2\ {}^4\text{He}$

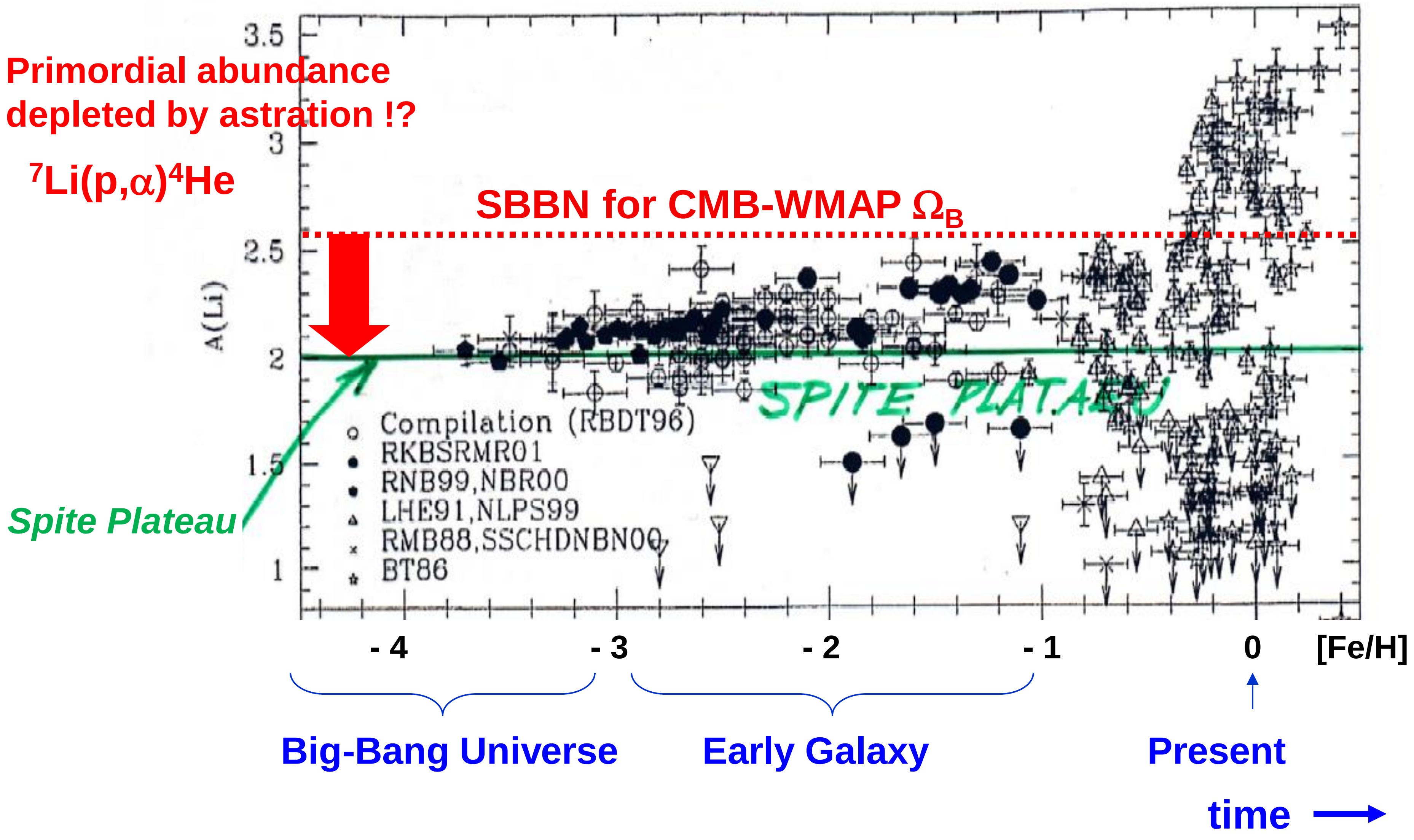
$\eta = n_B/n_\gamma = 2.68\text{x}10^{-8}\ \Omega_B h^2_{100}$

Quasar absorption in DLA systems



^{7}Li Abundance vs. Neutrino Process

Ryan, Kajino, Beers, Suzuki, Romano,
Matteucci & Rosolankova 2001, ApJ 549, 55.



Primordial abundance depleted by astration !?

^{7}Li(p,α)^{4}He

SBBN for CMB-WMAP Ω_B

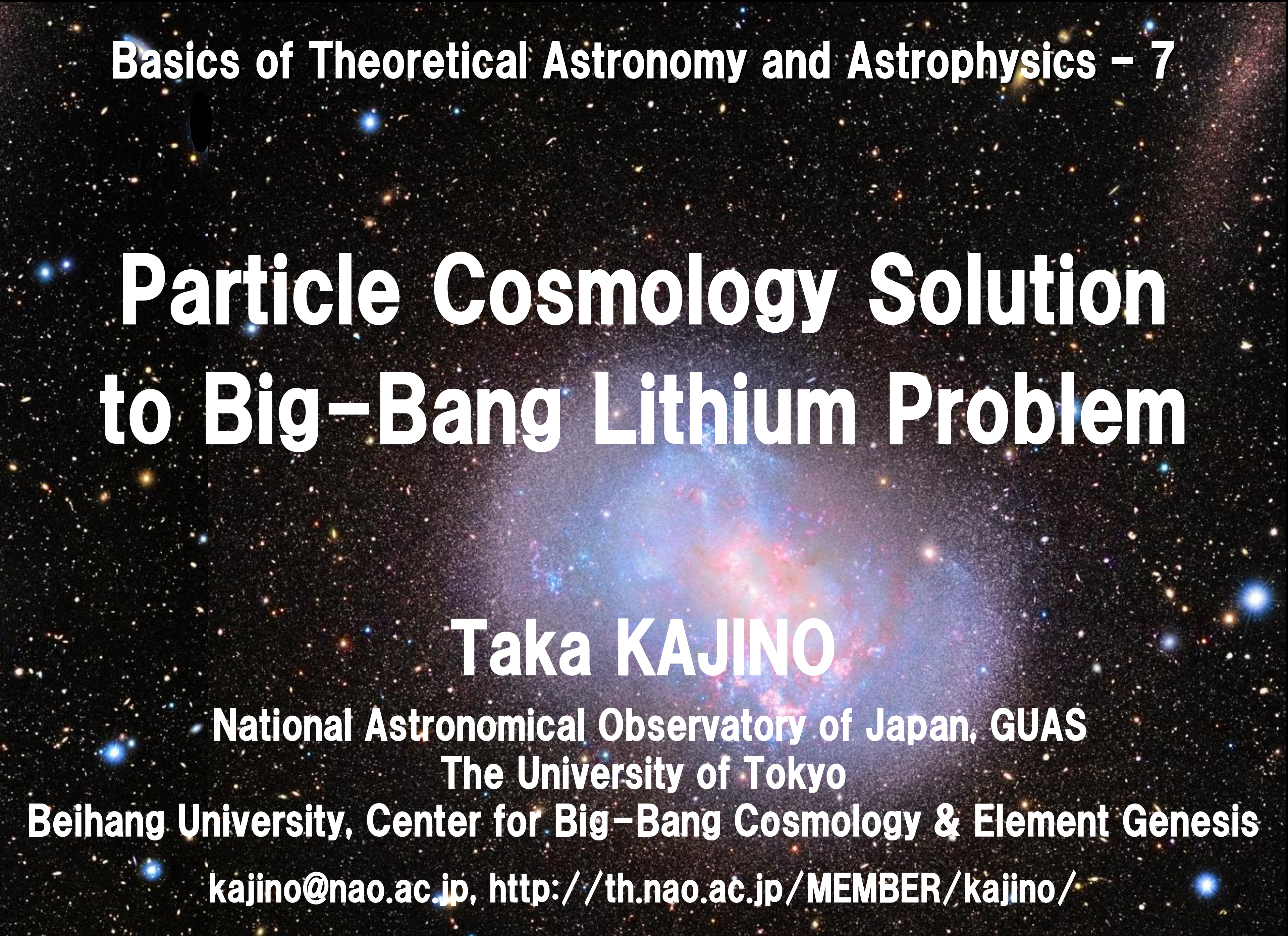
Spite Plateau

Big-Bang Universe

Early Galaxy

Present

time →



Basics of Theoretical Astronomy and Astrophysics - 7

Particle Cosmology Solution to Big-Bang Lithium Problem

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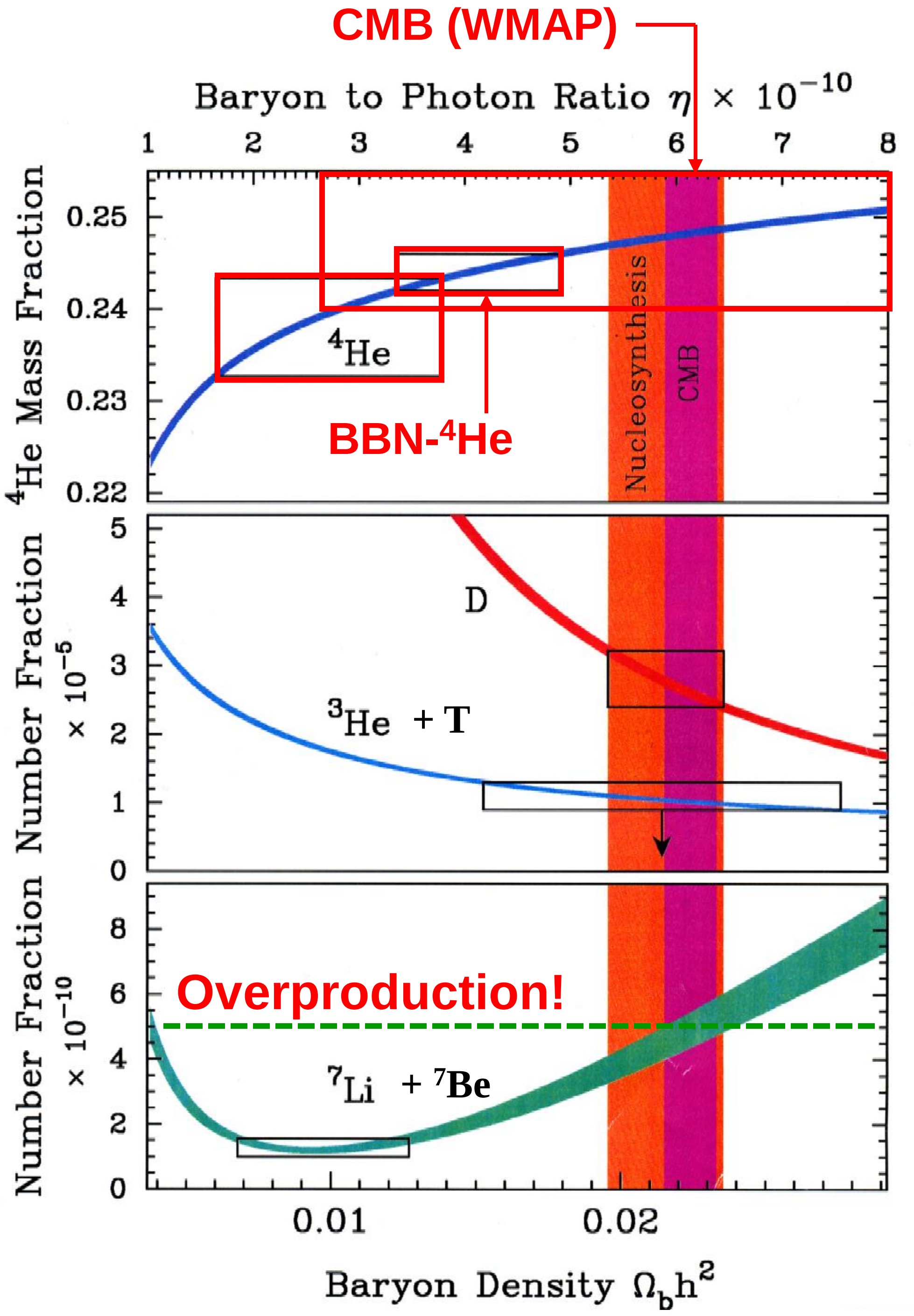
kajino@nao.ac.jp, http://th.nao.ac.jp/MEMBER/kajino/

Big-Bang Nucleosynthesis D, ^{3}He, ^{4}He and ^{7}Li



Y_p - Extragalactic HII Regions

$0.240 \leq Y_p \leq 0.244$

Izotov & Thuan (2003)

$0.240 \leq Y_p \leq 0.258$

Olive & Skillman (2004)

D - QSO absorption systems

$2.4\text{x}10^{-5} \leq D/H \leq 3.2\text{x}10^{-5}$

Kirkman et al. (2003)

WMAP

^{7}Li – Halo Stars

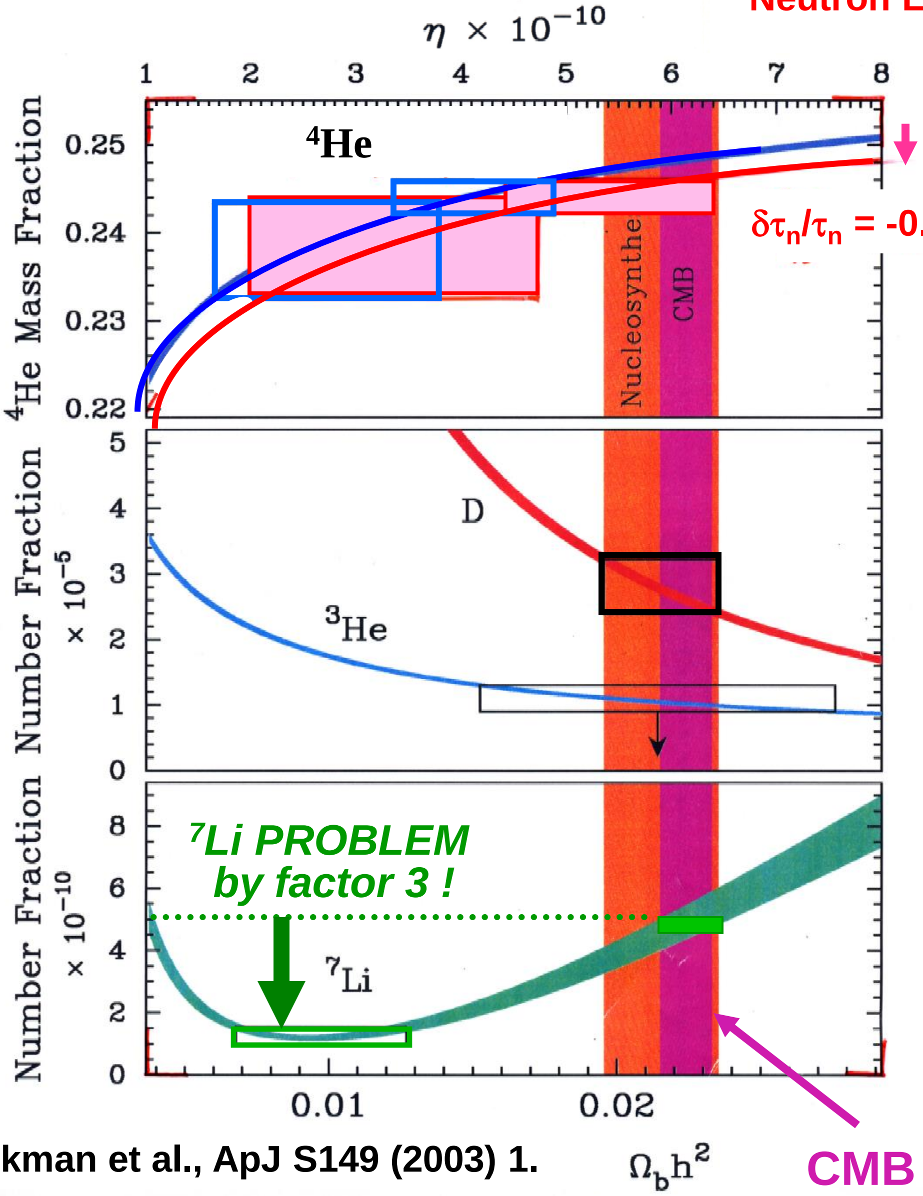
$0.9\text{x}10^{-10} \leq {}^7Li/H \leq 1.91\ \text{x}10^{-10}$

Ryan et al. (2000 –)

Big-Bang Nucleosynthesis is now a Precise Science ~1%

Smith, Kawano & Malaney, ApJ S85(2003) 219; Mathews, Kajino & Shima, PRD71 (2005) 21302 (R).

Neutron Life

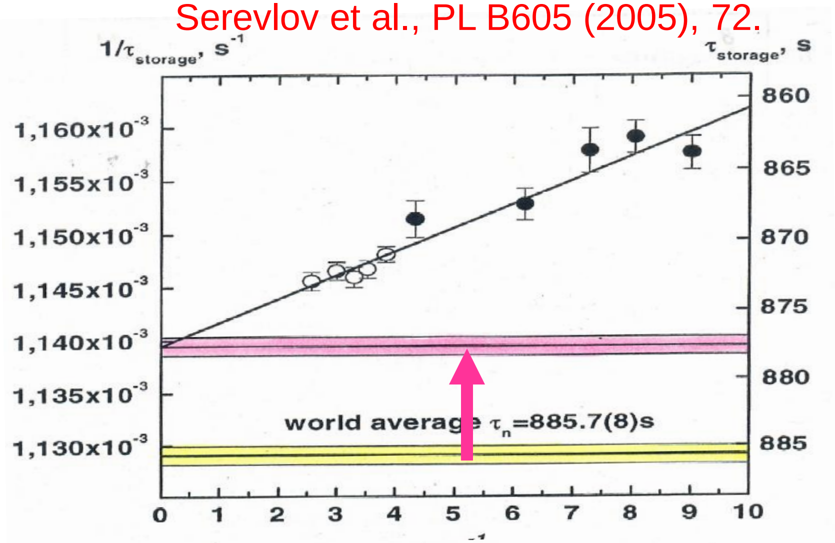


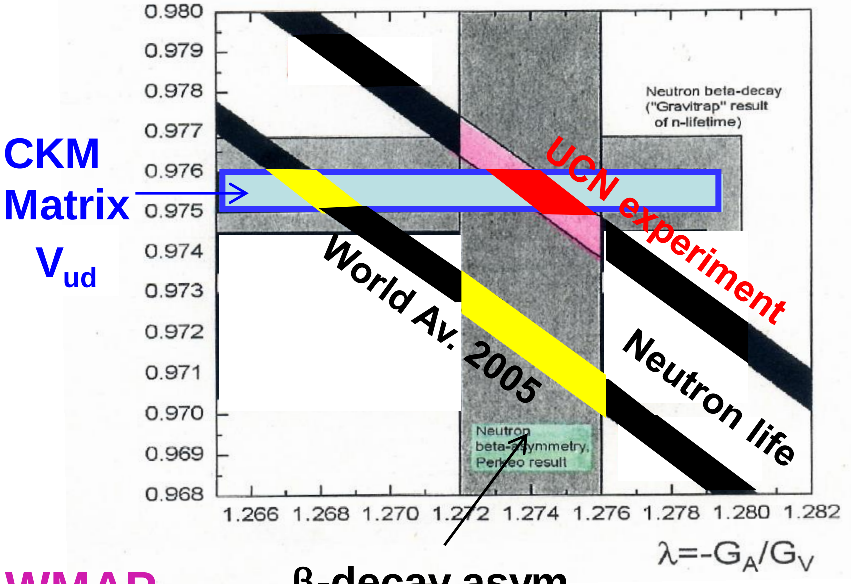
Kirkman et al., ApJ S149 (2003) 1.

CMB - WMAP

New UCN Experiment

Serevlov et al., PL B605 (2005), 72.



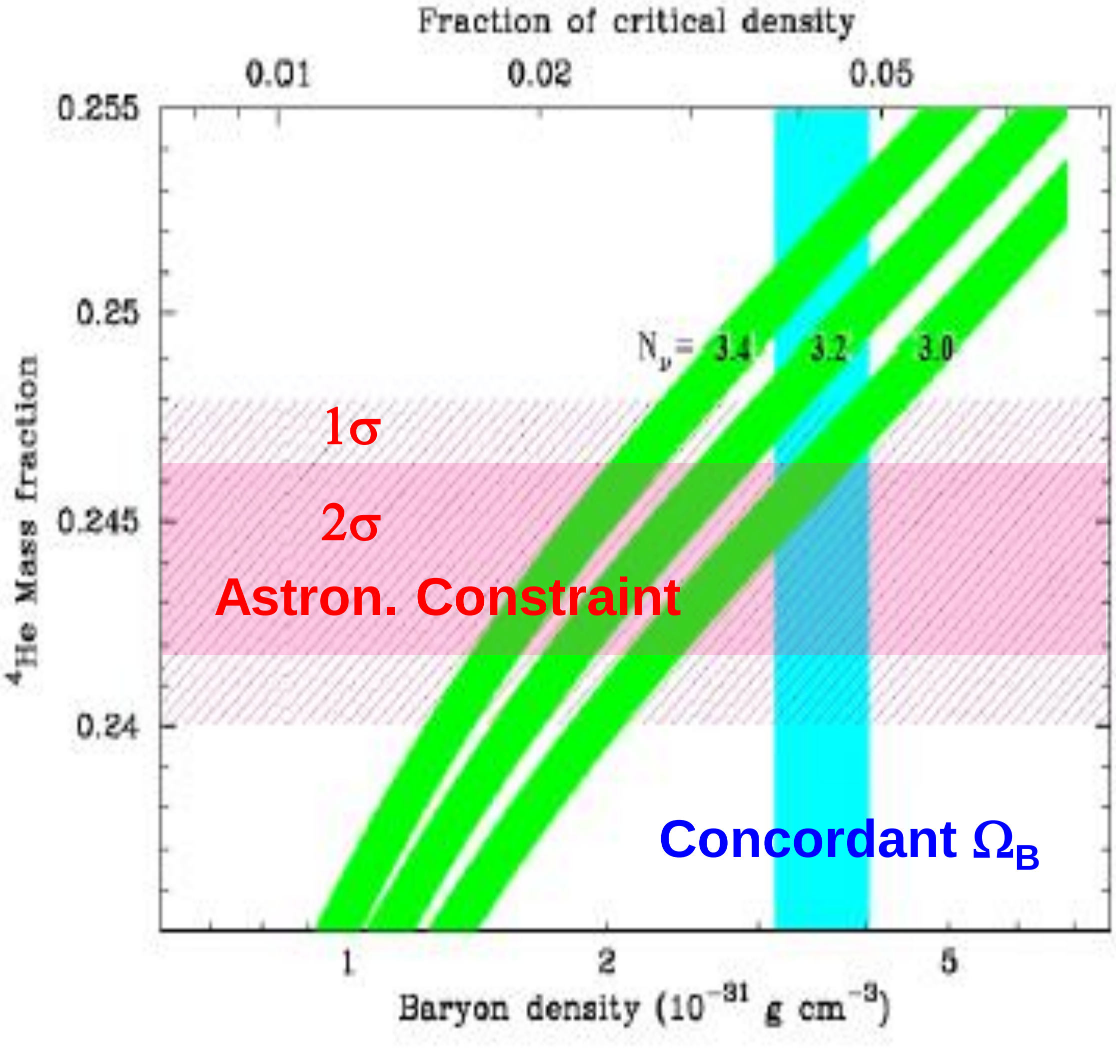


β-decay asym.

Constraining ν-Family from Big-Bang Helium

David N. Schramm

David Schramm pushed to use the observed limit of primordial abundance of ^{4}He in order to determine the number of flavors of active ν's.



$N_\nu \approx 3$

$(\nu_e, \nu_\mu, \nu_\tau)$

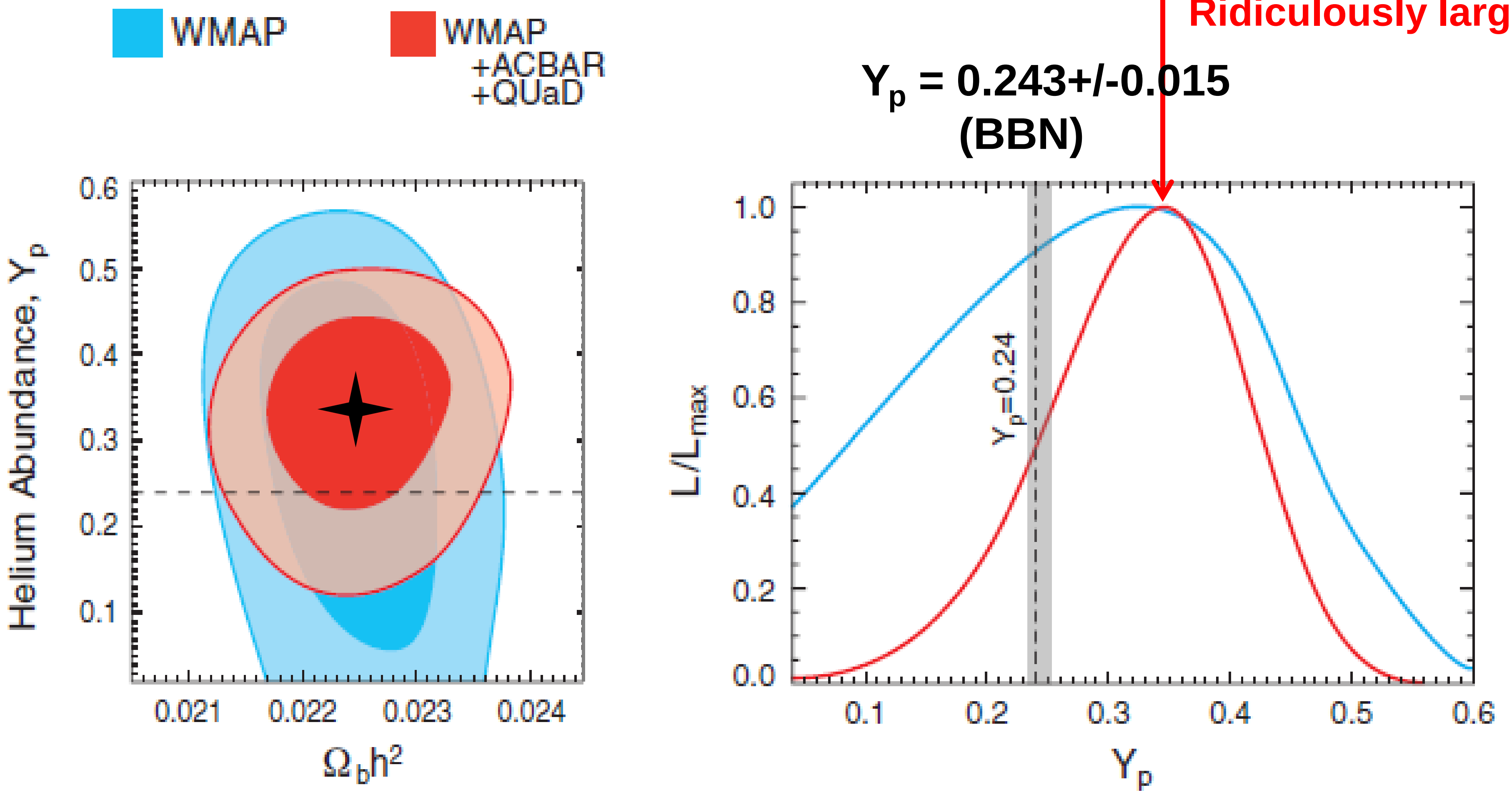
WMAP 7yr data: E. Komatsu et al.,

The Astrophysical Journal Supplement Series, 192:18 (47pp), 2011 February

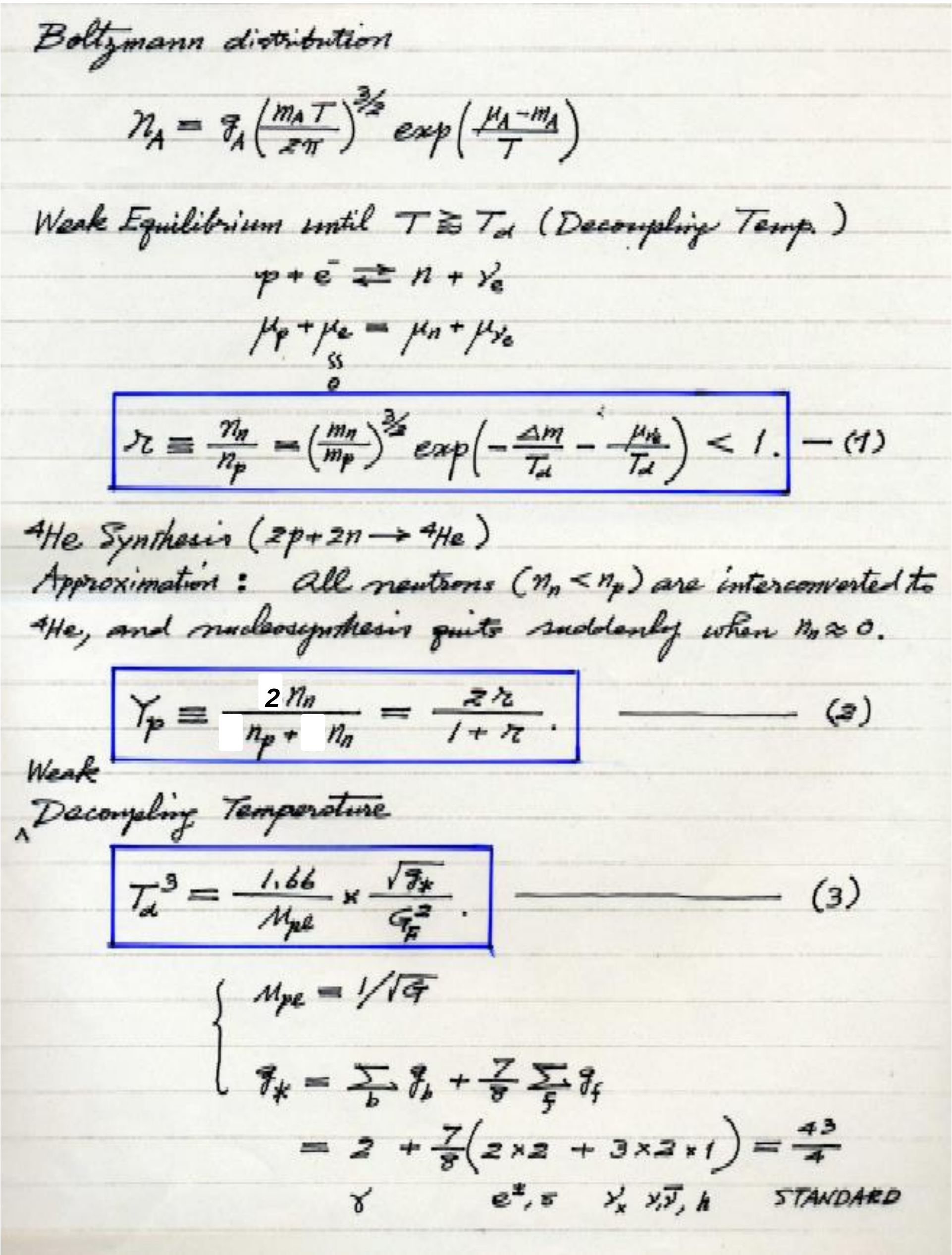
Combined data —— $Y_p = 0.345$

Ridiculously large!

$Y_p = 0.243 +/- 0.015$
(BBN)



Effect of Neutro-Life on BBN-^{4}He : $2p + 2n \longrightarrow {}^4He$



Boltzmann distribution

$$n_A = g_A\left(\frac{m_A T}{2\pi}\right)^{3/2} \exp\left(\frac{\mu_A - m_A}{T}\right)$$

Weak Equilibrium until $T \gtrsim T_d$ (Decoupling Temp.)

$$p + e^- \rightleftarrows n + \nu_e$$

$$\mu_p + \underset{0}{\underset{\wr\wr}{\mu_e}} = \mu_n + \mu_{\nu_e}$$

$$\boxed{r \equiv \frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{\Delta m}{T_d} - \frac{\mu_{\nu_e}}{T_d}\right) < 1.} \text{ — (1)}$$

^{4}He Synthesis ($2p + 2n \rightarrow {}^4He$)

Approximation : All neutrons ($n_n < n_p$) are interconverted to ^{4}He, and nucleosynthesis quits suddenly when $n_n \approx 0$.

$$\boxed{Y_p \equiv \frac{2n_n}{n_p + n_n} = \frac{2r}{1 + r}.} \text{ ———— (2)}$$

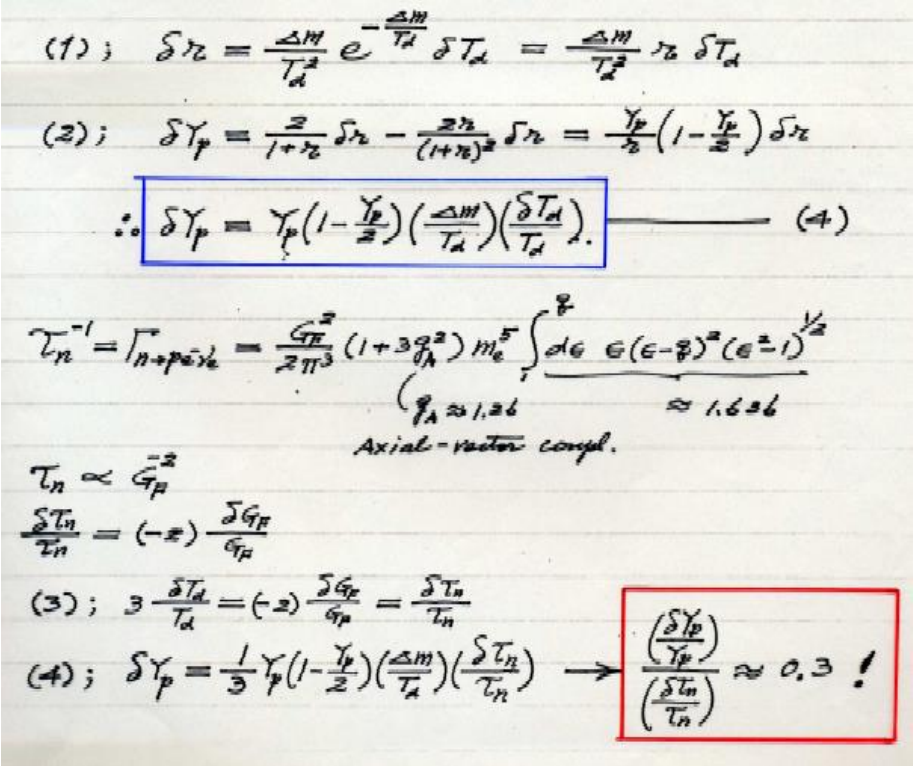
Weak Decoupling Temperature

$$\boxed{T_d^3 = \frac{1.66}{M_{pl}} \times \frac{\sqrt{g_*}}{G_F^2}.} \text{ ———— (3)}$$

$$\begin{cases} M_{pl} = 1/\sqrt{G} \\ g_* = \sum_b g_b + \frac{7}{8}\sum_f g_f \end{cases}$$

$$= \underset{\gamma}{2} + \frac{7}{8}\left(\underset{e^\pm,\ \mp}{2 \times 2} + \underset{\nu_x\ \nu,\bar{\nu},\ h}{3 \times 2 \times 1}\right) = \frac{43}{4} \quad \text{STANDARD}$$

1st effect: $\delta\tau_n \rightarrow \delta T_d \rightarrow \delta(n/p) \longrightarrow \delta({}^4He)$



$$(1);\quad \delta r = \frac{\Delta m}{T_d^2} e^{-\frac{\Delta m}{T_d}} \delta T_d = \frac{\Delta m}{T_d^2} r\, \delta T_d$$

$$(2);\quad \delta Y_p = \frac{2}{1+r}\delta r - \frac{2r}{(1+r)^2}\delta r = \frac{Y_p}{r}\left(1 - \frac{Y_p}{2}\right)\delta r$$

$$\therefore \boxed{\delta Y_p = Y_p\left(1 - \frac{Y_p}{2}\right)\left(\frac{\Delta m}{T_d}\right)\left(\frac{\delta T_d}{T_d}\right).} \text{ ———— (4)}$$

$$\tau_n^{-1} = \Gamma_{n \to p e \bar{\nu}_e} = \frac{G_F^2}{2\pi^3}\underset{\substack{(g_A \approx 1.26 \\ \text{Axial-vector coupl.}}}{(1 + 3g_A^2)} m_e^5 \underbrace{\int_1^q d\epsilon\, \epsilon(\epsilon - q)^2(\epsilon^2 - 1)^{1/2}}_{\approx 1.636}$$

$$\tau_n \propto G_F^{-2}$$

$$\frac{\delta\tau_n}{\tau_n} = (-2)\frac{\delta G_F}{G_F}$$

$$(3);\quad 3\frac{\delta T_d}{T_d} = (-2)\frac{\delta G_F}{G_F} = \frac{\delta\tau_n}{\tau_n}$$

$$(4);\quad \delta Y_p = \frac{1}{3}Y_p\left(1 - \frac{Y_p}{2}\right)\left(\frac{\Delta m}{T_d}\right)\left(\frac{\delta\tau_n}{\tau_n}\right) \rightarrow \boxed{\frac{\left(\frac{\delta Y_p}{Y_p}\right)}{\left(\frac{\delta\tau_n}{\tau_n}\right)} \approx 0.3\ !}$$

2nd effect: $\delta\tau_n \rightarrow \delta n \longrightarrow \delta({}^4He)$

Freezeout time of $p + n \rightleftarrows D + \gamma$ changes.

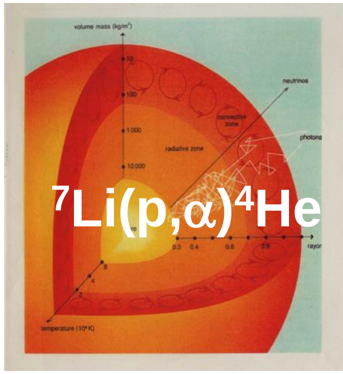
NET EFFECT:

$$\boxed{\delta\tau_n < 0 \longrightarrow \delta({}^4He) < 0}$$

Plateau like HIGH ^{6,7}Li ABUNDANCE --- primordial ?

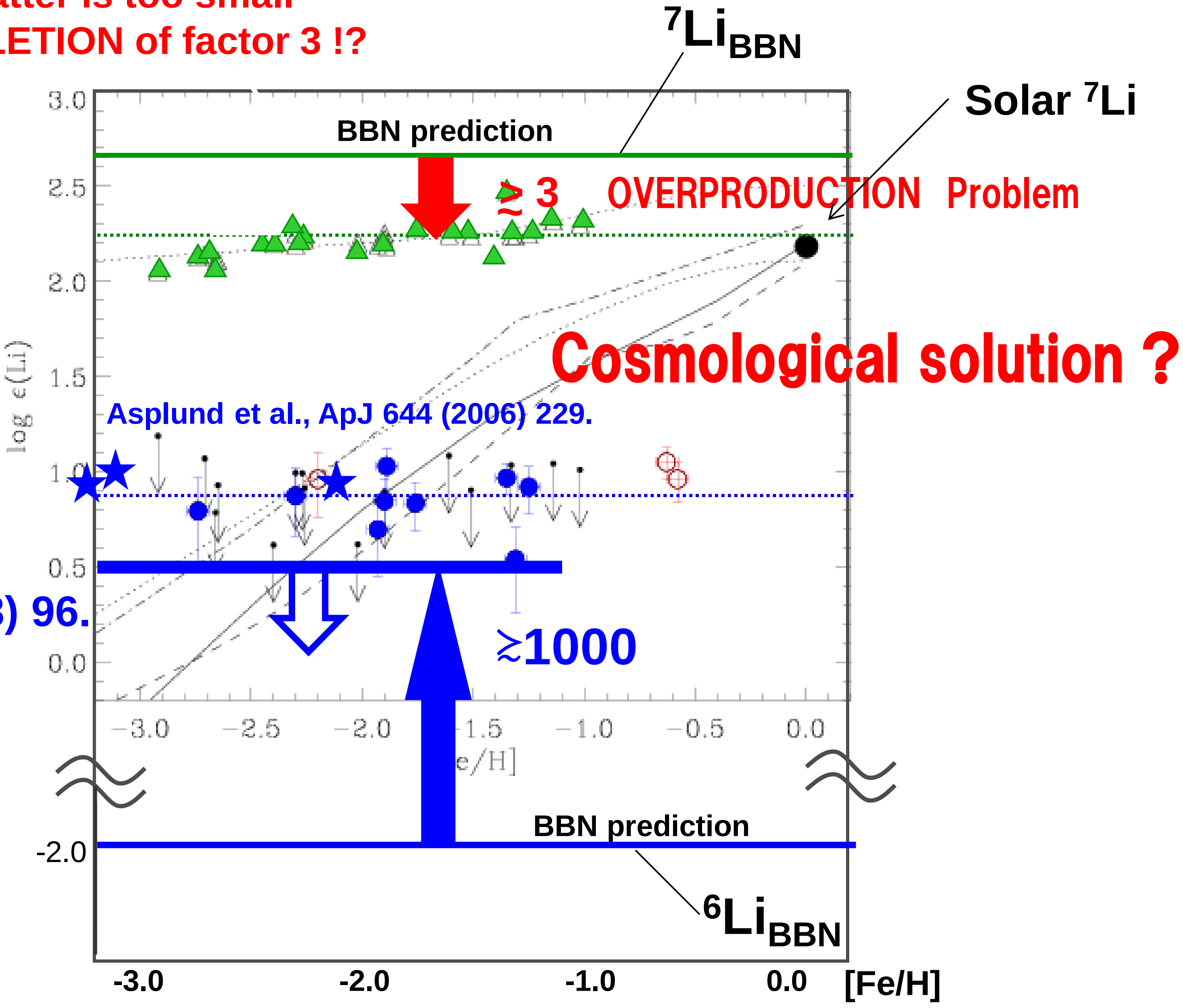
Abundance scatter is too small
to accept DEPLETION of factor 3 !?

T = 1~3x10^6 K



Lind et al.,
A&A 554 (2013) 96.

Upper limit !



A&A 554, A96 (2013)
DOI: 10.1051/0004-6361/201321406
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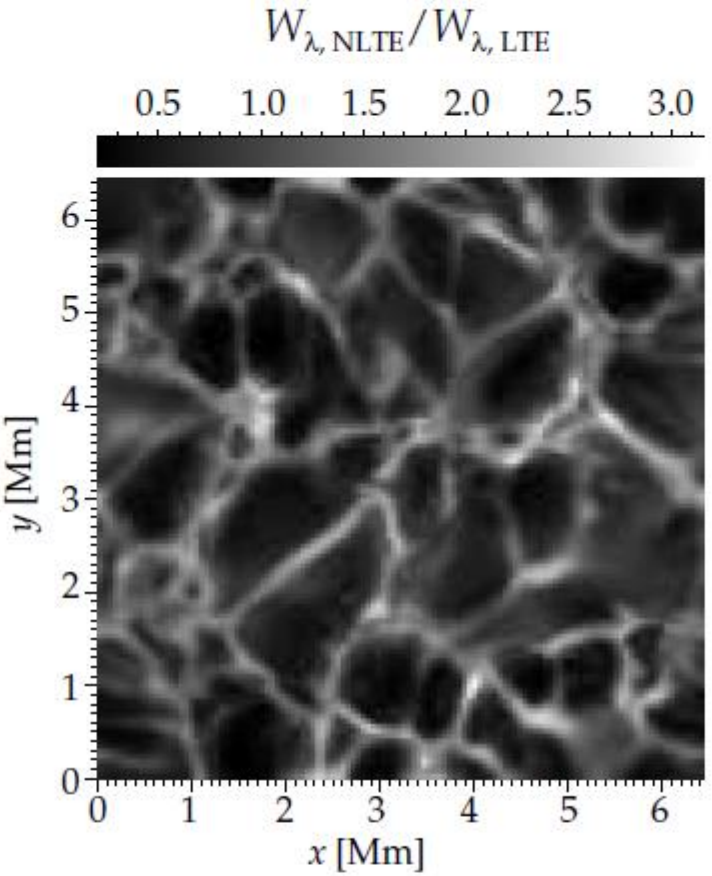
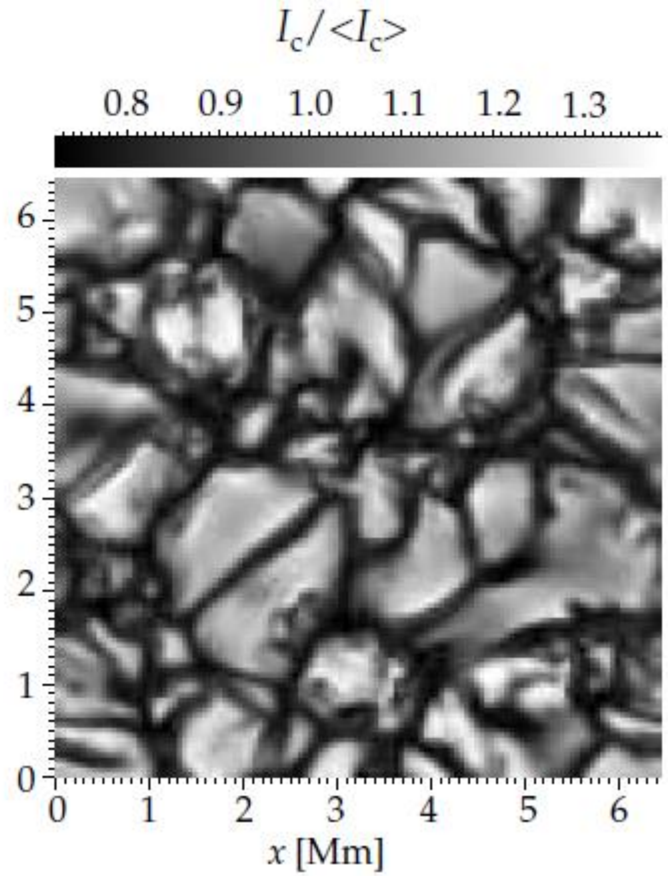
Astronomy & Astrophysics

The lithium isotopic ratio in very metal-poor stars★,★★

K. Lind[1,2], J. Melendez[3], M. Asplund[4], R. Collet[4], and Z. Magic[1]



Ratio between NLTE and LTE equivalent widths.



Simulated relative continuum intensity.

Center for Theoretical Underground Physics and Related Areas (CETUP*) on NEUTRINO PHYSICS & ASTROPHYSICS
July 15 - 26 2013, Lead, SD

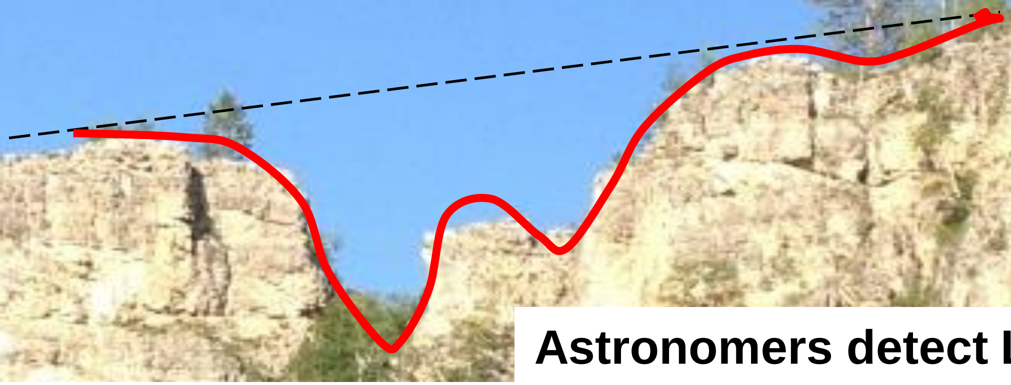

Raymond Davis, Jr.

Homestake Mine, SD

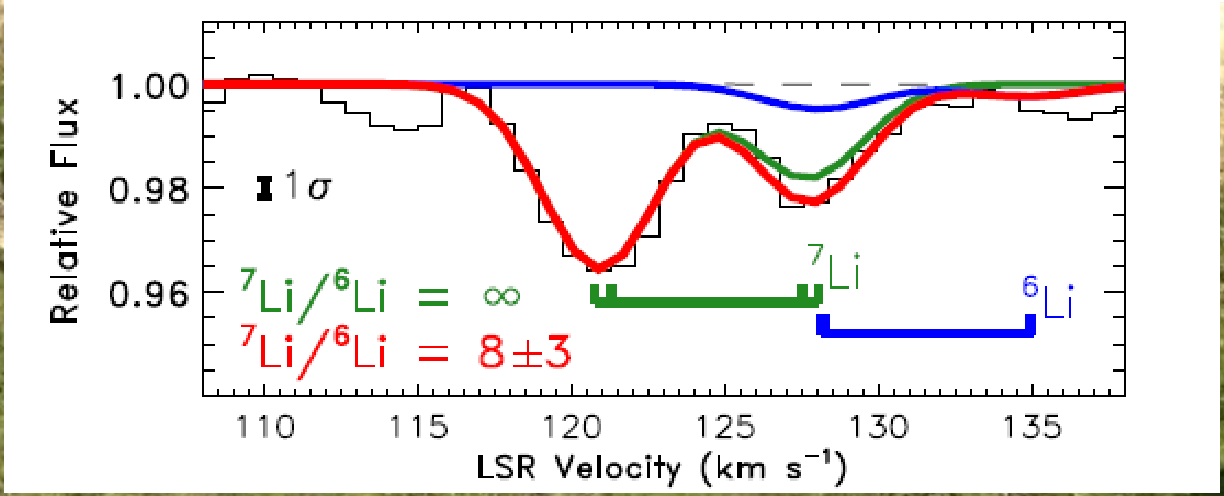
Nuclear Fusion Reactions in the Sun:

$^4He + ^3He \rightarrow ^7Be + \gamma$

$^7Be + p \rightarrow ^8B^* \rightarrow 2\,^4He + \nu$ $^7Be + e \rightarrow ^7Li + \nu$



Astronomers detect Li-doublets



1. Massive Charged DM Particle Model (e.g. SUSY stau)

Ellis et al. (1986); Moroi and Kawasaki (1994); Jedamzik PRL 84 (2000) 3248; Cyburt et al., PRD 67 (2003) 103521; Ellis et al. PLB619 (2005) 30; Pospelov, PRL 98 (2007) 231301; Hamaguchi et al. PL B650 (2007) 208; Bird et al. PRD78 (2008), 083010; Kusakabe, Kajino & Mathews, D74 (2006), 023526 — till 2014

^{6}Li abundance is found to be enhanced by ∼10^3 through the exotic nuclear reaction $^4\mathrm{He}_X(d, X^-)^6\mathrm{Li}$.

^{7}Li problem (factor ∼3 overproduction) still REMAINS !

Our Model

Kusakabe, Kim, Cheoun, Kajino, Kino & Mathews, ApJS 214（2014）5.

SUSY Leptonic “stau” (NLS-particle) X^- , when gravitino is DM, is bound to ^{4}He, ^{7}Li, ^{7}Be and catalyzes 2nd burst of BBN:

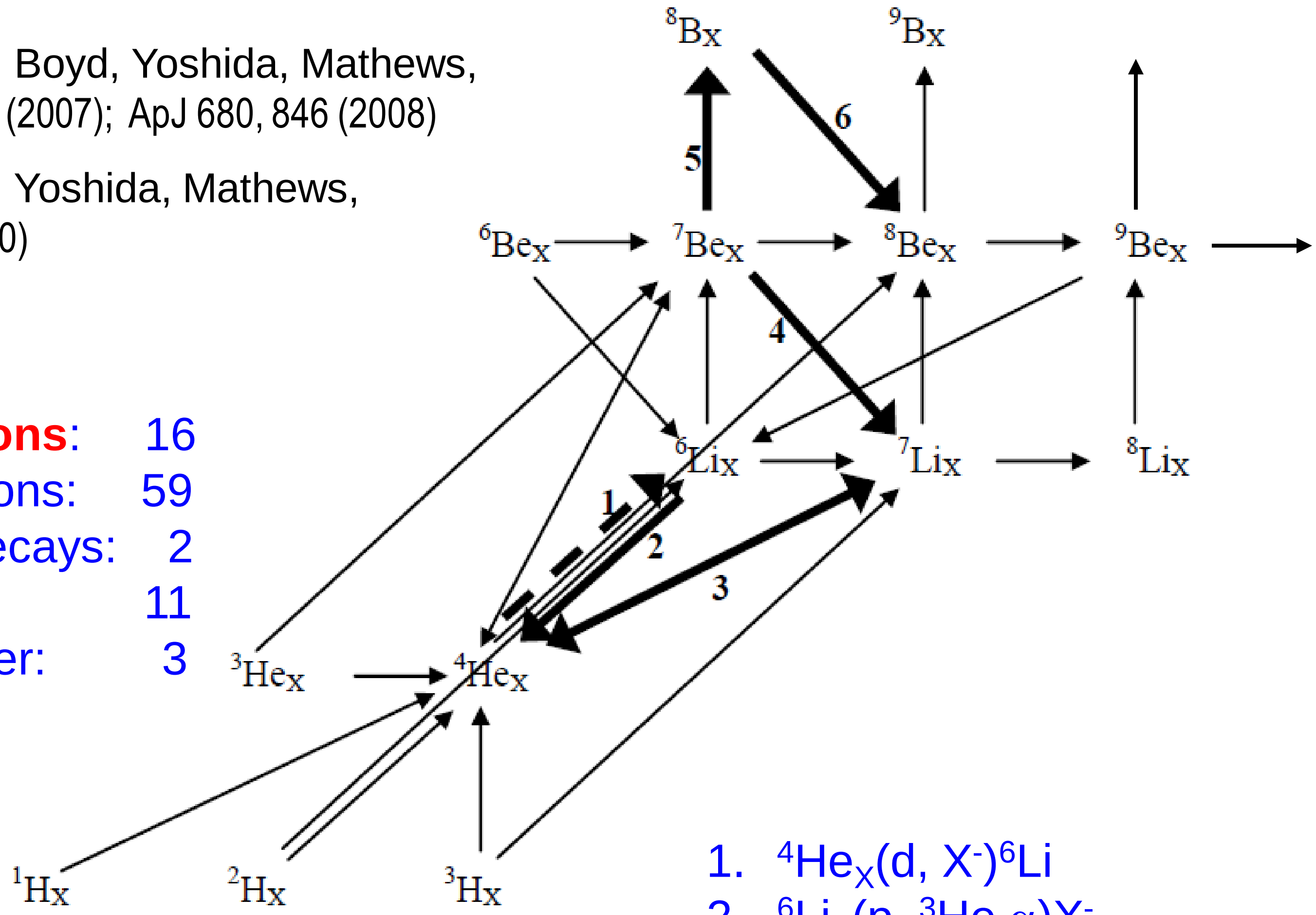
$$^7\mathrm{Be}(e^-, \gamma)^7\mathrm{Be}^{3+}(X^-, e^-)^7\mathrm{Be}_X \qquad ^7\mathrm{Be}_X(p, \gamma)^8\mathrm{B}_X{}^*$$

$$^7\mathrm{Be}(X^-, \gamma)^7\mathrm{Be}_X$$

Exotic Nuclear Reaction Network up to Carbon

Kusakabe, Kajino, Boyd, Yoshida, Mathews,
PRD 76, 76, 0121302 (2007); ApJ 680, 846 (2008)

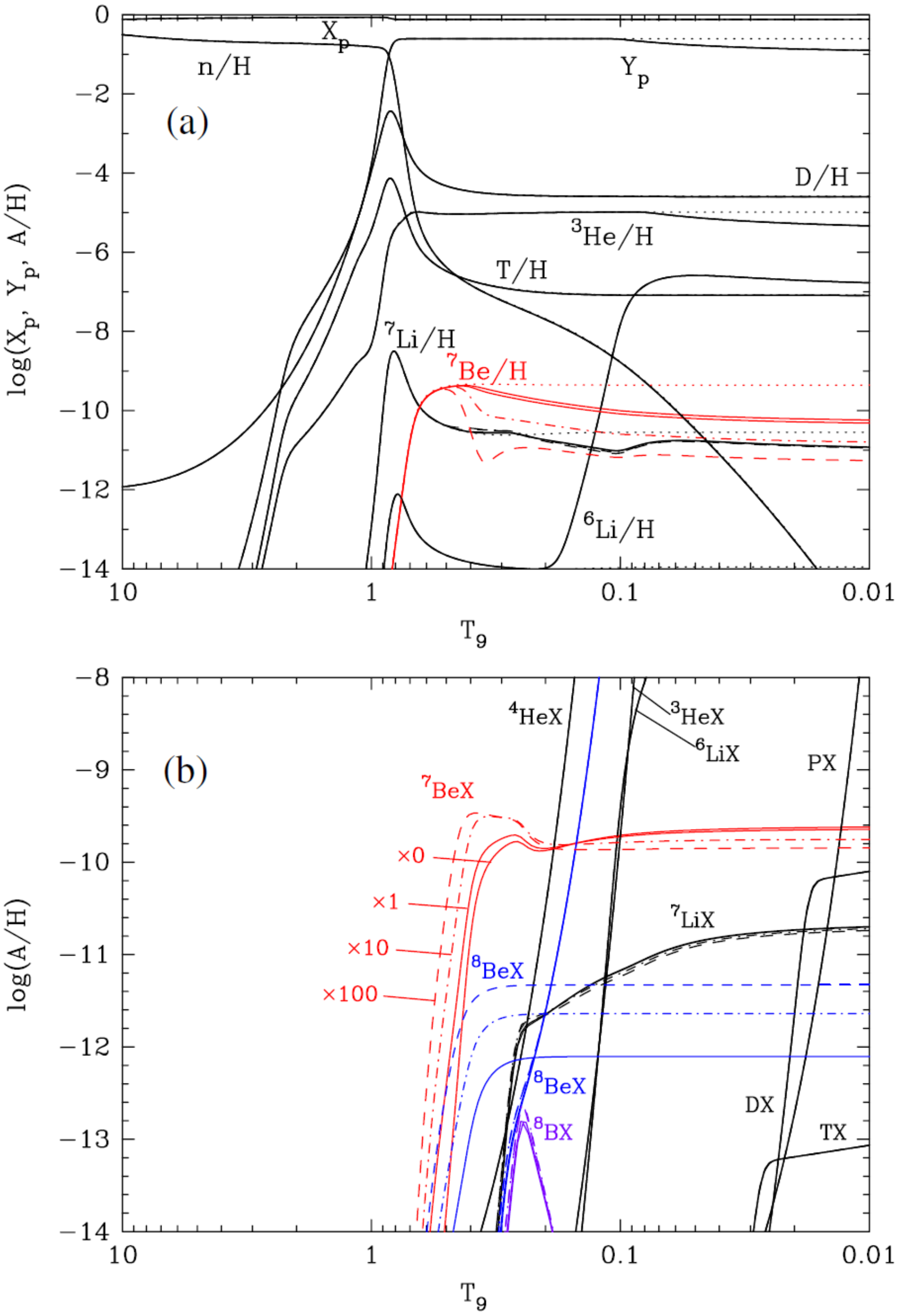
Kusakabe, Kajino, Yoshida, Mathews,
PRD 81, 083521 (2010)



X^- recombinations:	16
X nuclear reactions:	59
including β-decays:	2
X-decays:	11
X^- charge transfer:	3

1. $^4He_X(d, X^-)^6Li$
2. $^6Li_X(p, {}^3He\ \alpha)X^-$
3. $^4He_X(t, \gamma)^7Li_X$ & $^7Li_X(p, 2\alpha)X^-$
4. $^7Be_X(, X^0)^7Li$
5. **$^7Be_X(p, \gamma)^8B_X{}^*$**
6. $^8B_X(, e^+\nu_e)^8Be_X$

**Important reactions
for resolving Lithium Problem**



Calculated Result

$n_X=0.05n_b$, m_X>>1 GeV, τ_X>>200 s,
$\eta=6.19\times10^{-10}$ (WMAP 9yr)

^{7}Be recombinations

$^{7}\mathrm{Be}(X^{-},\gamma)^{7}\mathbf{Be_{X}}$

$^{7}\mathrm{Be}(e^{-},\gamma)^{7}\mathbf{Be^{3+}(X^{-},e^{-})^{7}Be_{X}}$

^{8}B resonant reactions

$\mathbf{^{7}Be_{X}}+p\rightarrow\mathbf{^{8}B_{X}^{*a}}\rightarrow{}^{8}B_{X}+\gamma$

$\rightarrow\mathbf{^{8}B_{X}^{*}}\rightarrow{}^{8}B_{X}+\gamma$

—— $\sigma=0$

━━ $\sigma_s=17.5$ Mb (standard)

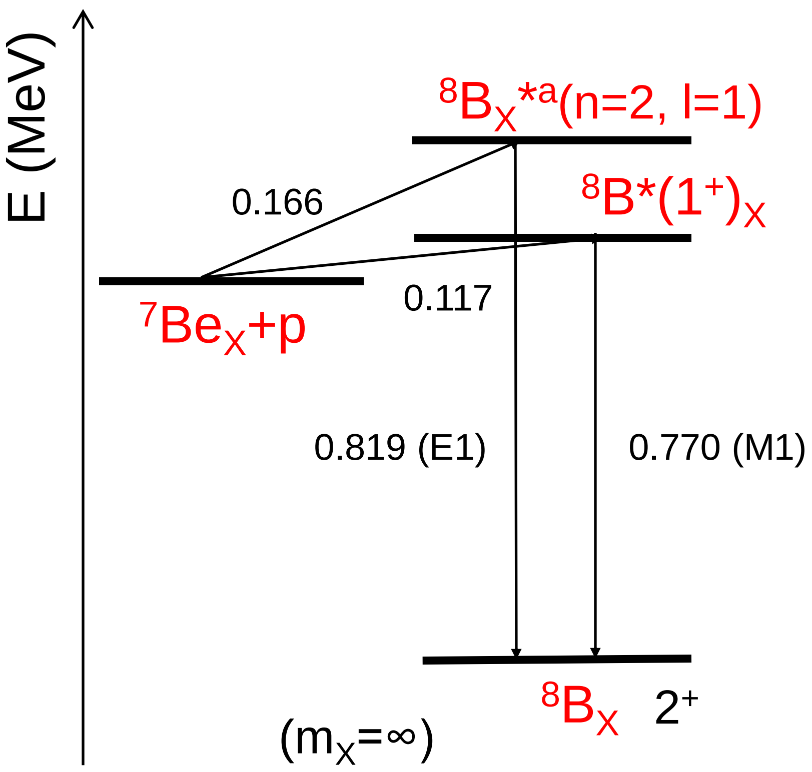
–·–·– $\sigma=10\sigma_s$

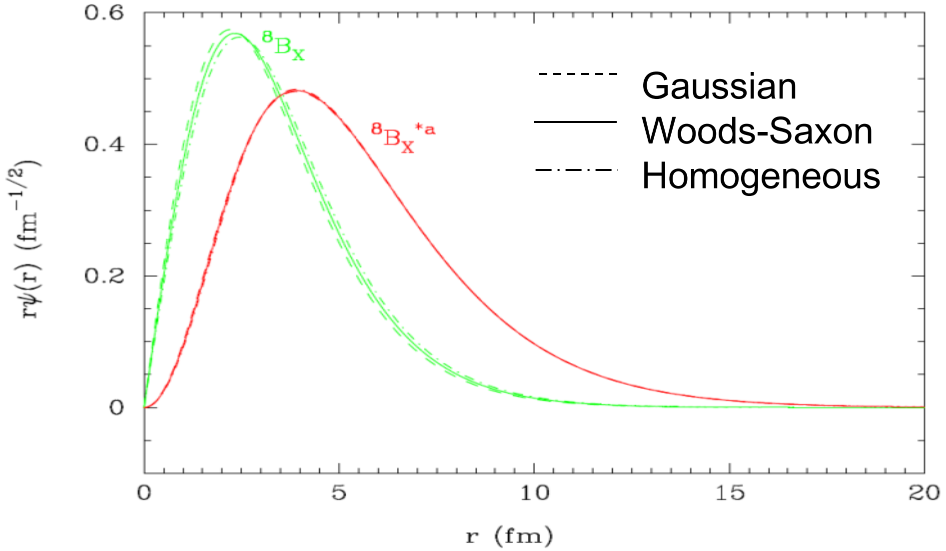
– – – $\sigma=100\sigma_s$

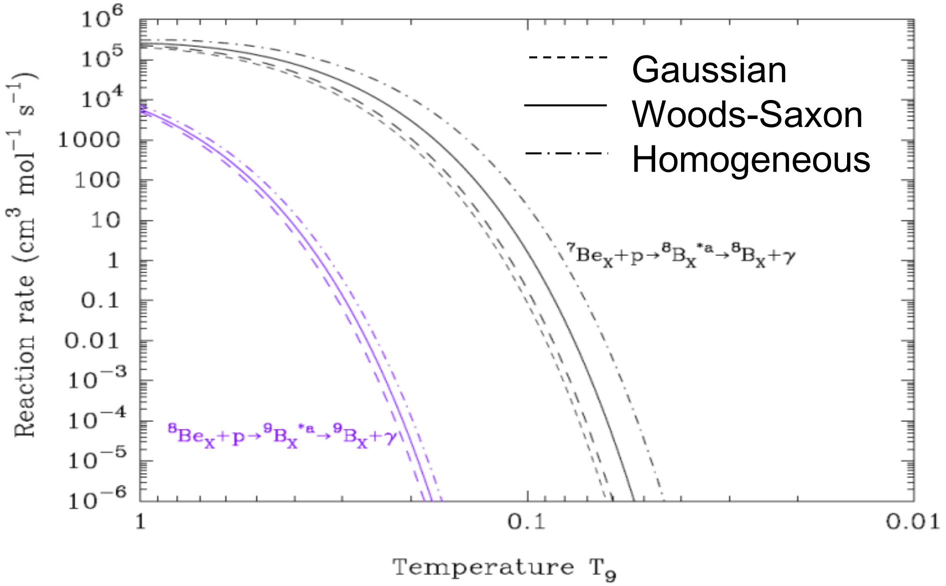
Significance of Resonant Reactions

We adopted cross section calculations in quantum three-body model.

(Kamimura et al. 2008)







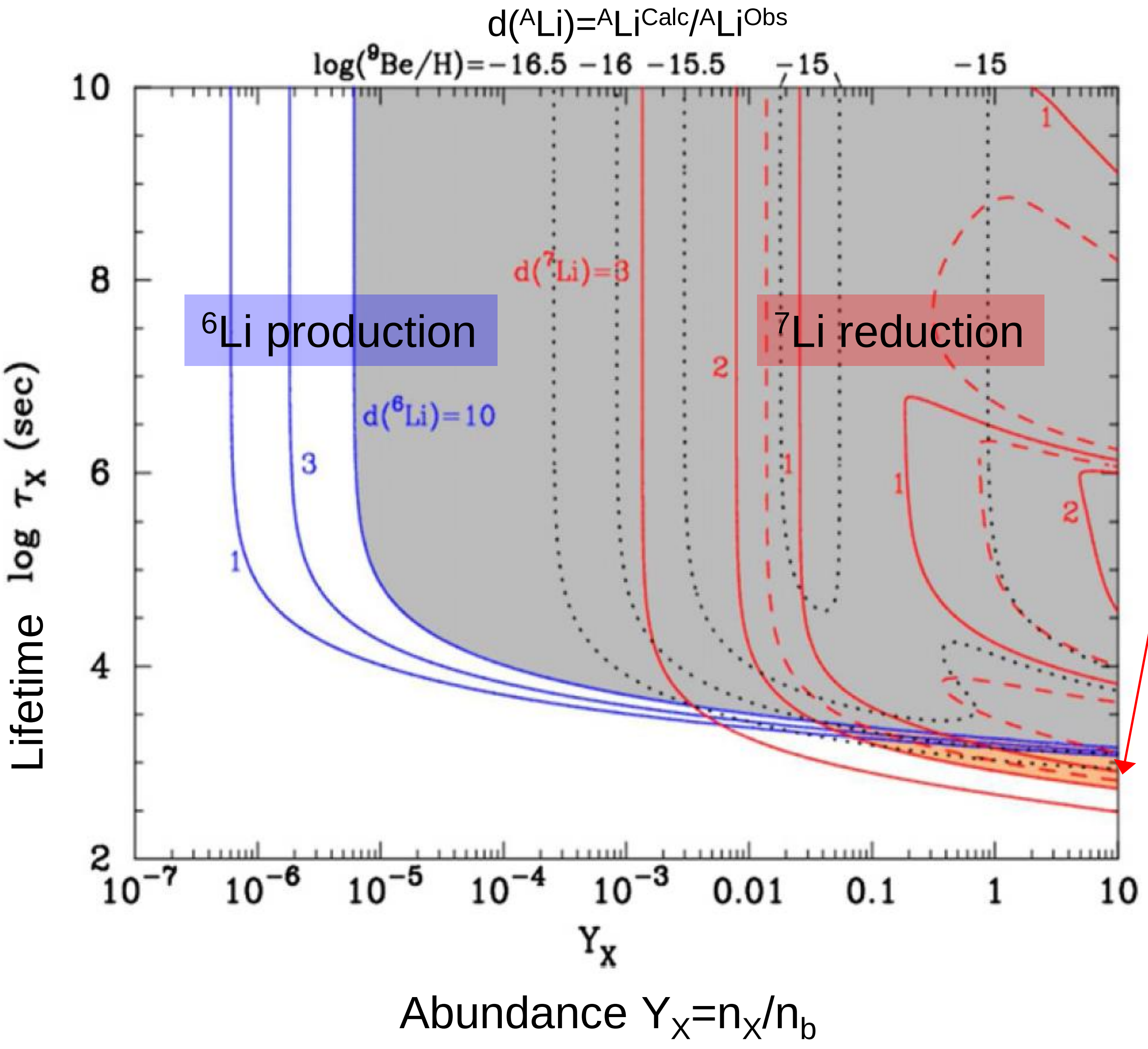
Bird et al. (2007)

$^7Be_X+p \rightarrow \mathbf{{}^8B_X{}^{*a}} \rightarrow {}^8B_X+\gamma$

Kusakabe, Kajino, et al. (2007)

$^7Be_X+p \rightarrow \mathbf{{}^8B_X{}^{*}} \rightarrow {}^8B_X+\gamma$

Particle Properties of X^- for resolving Li-Problem



$\eta = 6.19 \times 10^{-10}$
(WMAP 9yr)

Region for
^{7}Li reduction w/o
^{6}Li overproduction

Solving DM Problem
for m_X=100 GeV

$Y_X \gtrsim 0.04$

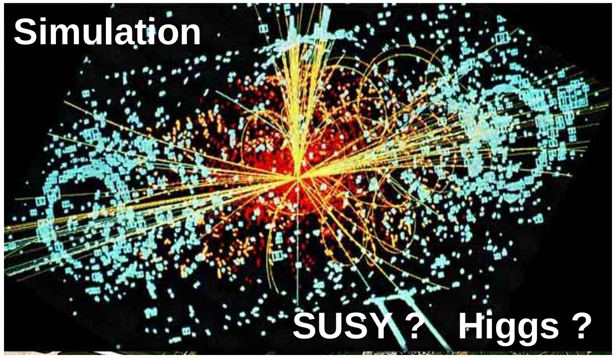
$\tau_X \approx (0.6-3) \times 10^3$ s

To test at LHC@CERN

What is Dark Matter ?
What is the Unified Theory of Elementary Forces?

LHC tests Astronomical Paradigms !

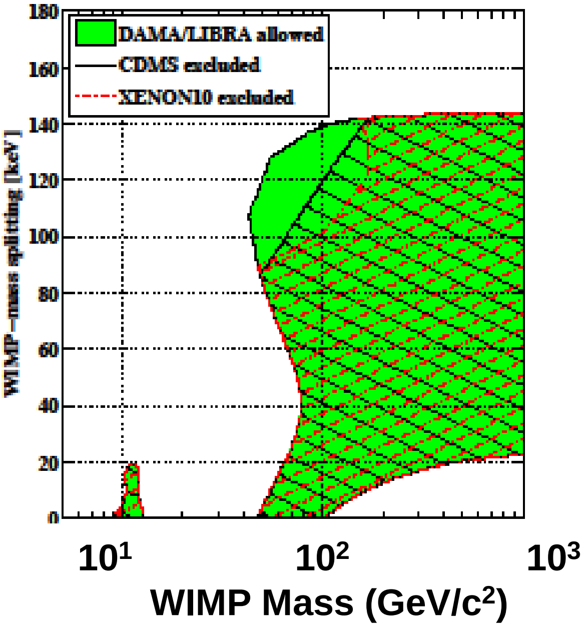
Hunting SUSY and Higgs Particles ++



CDMS II Experiment

Z. Ahmed et al. (CDMS Collaboration), Science, 327 (2010), 1619.

50GeV < m_{WIMP} < 170GeV



2. Magnetized, Massive Sterile Neutrinos

M. Kusakabe, A. B. Balantekin, T. Kajino & Y. Pehlivan, PR D87 (2013), 085045.

Cosmological: $\nu_S \longrightarrow \nu + \gamma_{NT}$

Parent ν_S could be massive!

sterile ($m_\nu \neq 0$, $\mu_\nu \neq 0$)   active/sterile

Magnetic Moment of massive neutrino X

$$|\mu_{\rm eff}|^2 = |\mu_{ij}|^2 + |\epsilon_{ij}|^2.$$

$$\boxed{\tau_X^{-1}} = \frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3$$

$$= 5.308\ {\rm s}^{-1}\left(\frac{\mu_{\rm eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{\rm eV}\right)^3$$

Decoupling Temp. is Max [1MeV, $m_X/20$]

$$\boxed{\frac{n_X}{n_\gamma}} = \frac{4}{11}\frac{n_{{\rm d}X}(m_X)}{n_\gamma(T_{\rm d})} = \frac{2\pi^2}{11\zeta(3)}\frac{n_{{\rm d}X}(m_X)}{T_{\rm d}^3}.$$

$$n_{{\rm d}X}(m_X) = \frac{g_X}{2\pi^2}\int_0^\infty dp\,\frac{p^2}{\exp\left[\sqrt{p^2 + m_X^2}/T_{\rm d}(m_X)\right] + 1}$$

γ_{NT} affects BBN by photodisintegration.

Nuclei	threshold (MeV)	Reaction
^{7}Be	1.587	^{7}Be(γ, α)^{3}He
D	2.225	^{2}H(γ, n)^{1}H
^{7}Li	2.467	^{7}Li(γ, t)^{4}He
^{3}He	5.494	^{3}He(γ, p)^{2}H
^{3}H	6.527	^{3}H(γ, n)^{2}H
^{4}He	19.814	^{4}He(γ, p)^{3}H

Calculated Result

M. Kusakabe, A. B. Balantekin,
T. Kajino & Y. Pehlivan,
Ohys. Rev. D87 (2013), 085045.

Current Constraints

Laboratory: $\mu_\nu < 2.9 \times 10^{-11} \mu_B$

Astrophysical: $\mu_\nu < 3 \times 10^{-12} \mu_B$

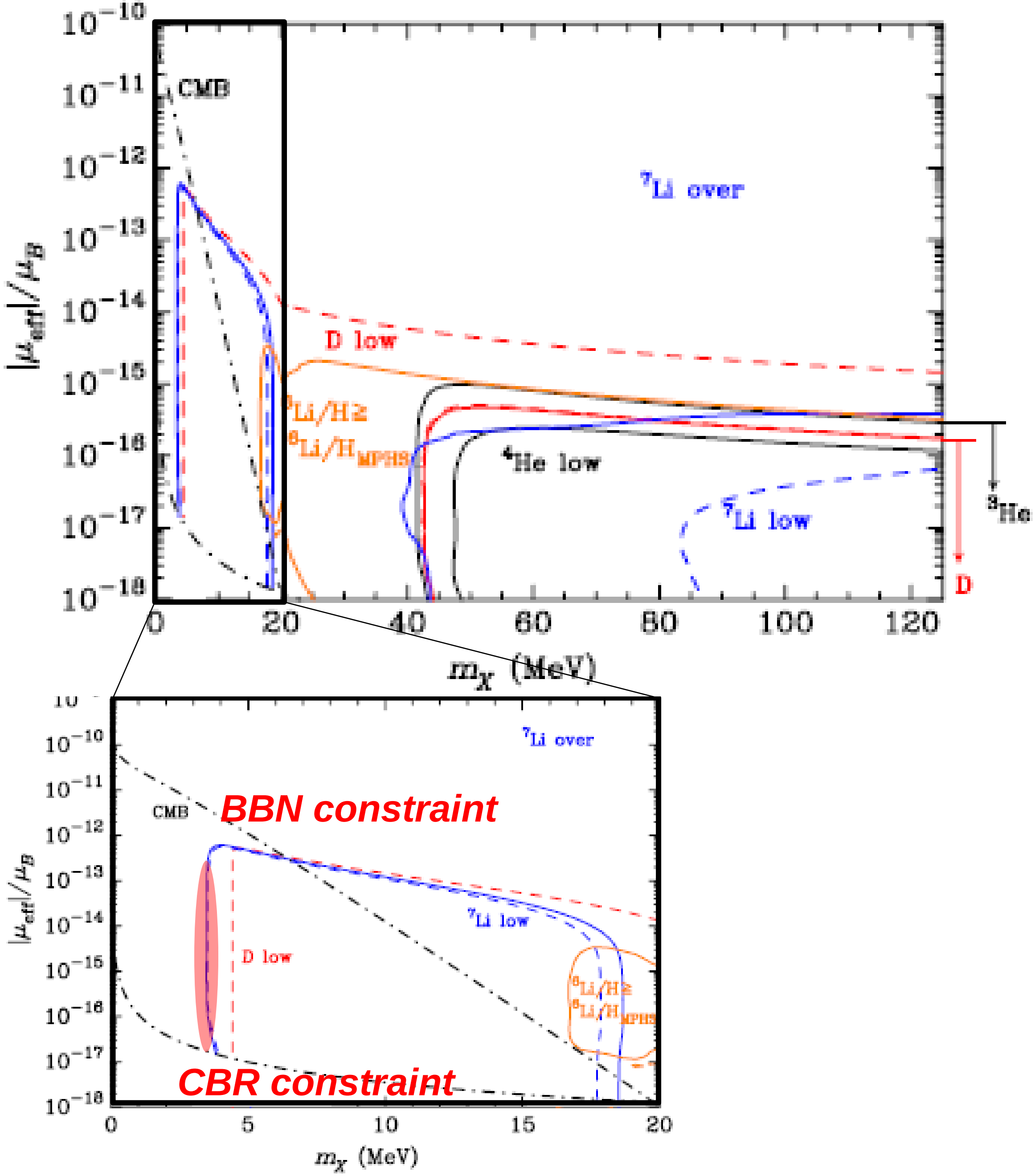
BBN Constraint

$10^{-17}\mu_B < \mu_\nu < 10^{-12}\mu_B$

Shorter τ_X

↕

longer τ_X



3. Axion, as a Dark Matter Candidate

QCD – Strong CP Problem

Although QCD Lagangian (i.e. strong interaction) breaks CP symmetry, CP symmetry is NOT strongly violated experimentally with neutron dipole moment.

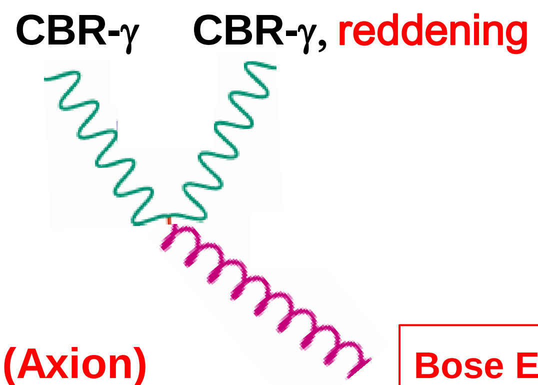
⇒ **Peccei-Quinn (1977) : U(1) is dynamically broken to restore CP symmetry.**

$$L = L_0 + \frac{\theta}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma}\boldsymbol{E}\cdot\boldsymbol{B}a$$

$$m_a = 0.62 \times 10^{-5}\,\mathrm{eV}\left(\frac{F_a}{10^{12}\,\mathrm{GeV}}\right)^{-1}$$

$$10^{9-10}\,\mathrm{GeV} \lesssim F_a \lesssim 10^{12-13}\,\mathrm{GeV}$$

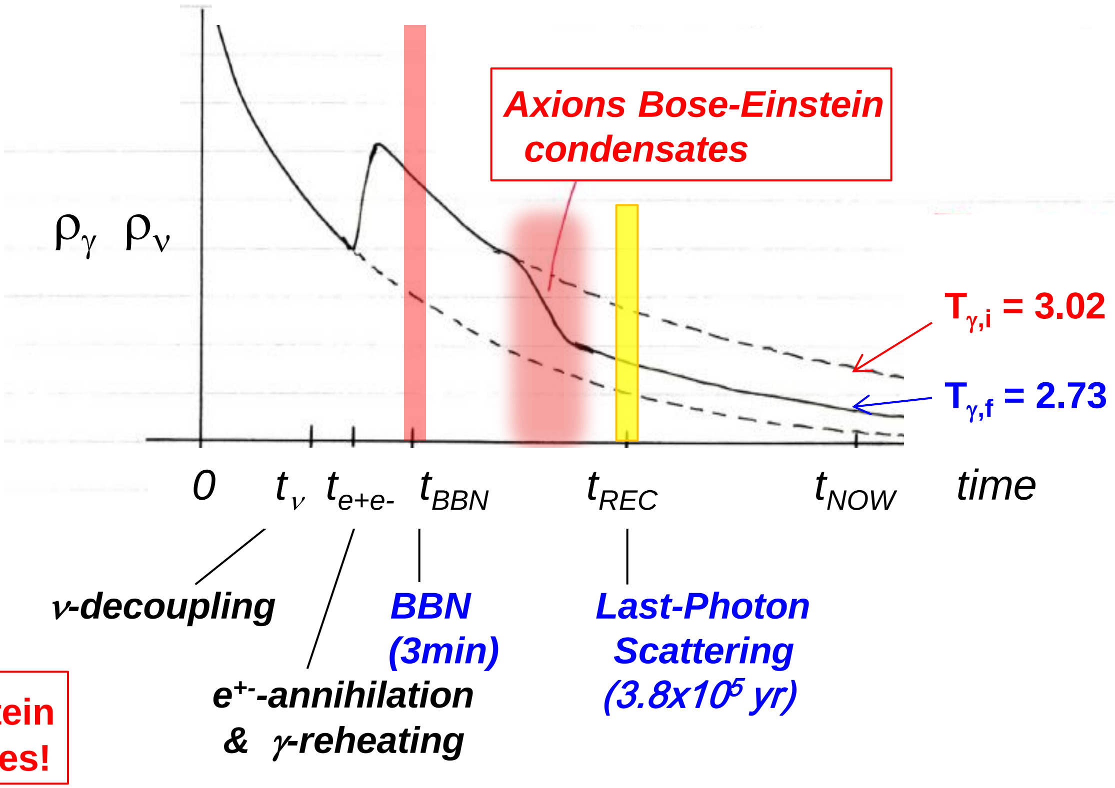


a (Axion)

Nambu-Goldstone Boson ➡ **Bose Einstein condensates!**

Cosmological Application

Erken, Sikivie, Tam & Yang, PRL 108 (2012), 061304.



Axion Dark Matter Model

**Erken, Sikivie, Tam & Yang,
PRL 108 (2012), 061304.**

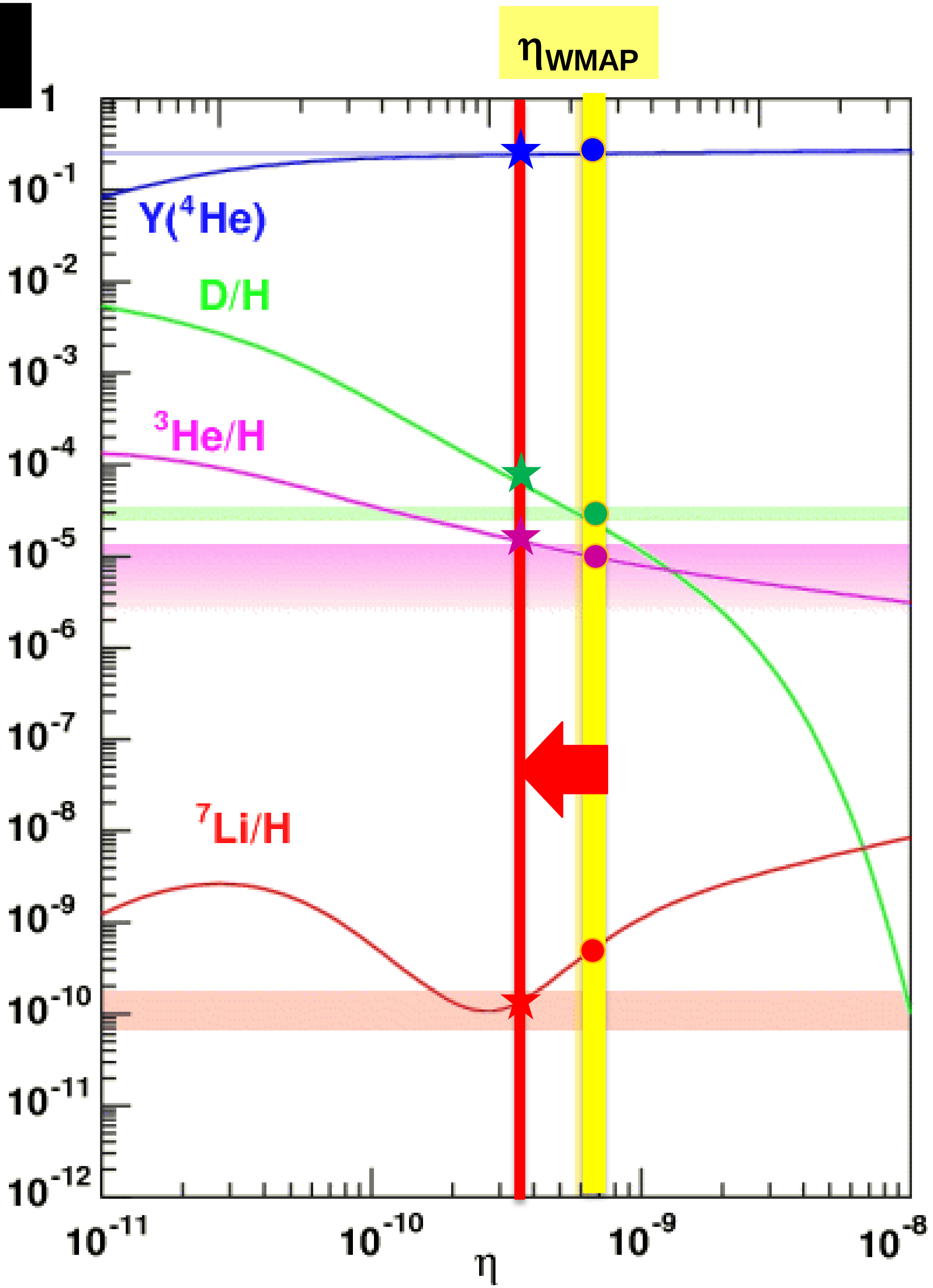
Dark matter "axions" Bose-Einstein condensate, and cool CBR-photons after the BBN epoch (3min) and before the photon last scattering epoch (3.8×10^5 yr) .

$$\eta = n_B/n_\gamma$$

$$n_\gamma \propto T_\gamma^{\ 3}$$

$$\eta_{BBN} < \eta_{WMAP}$$

D overproduction !



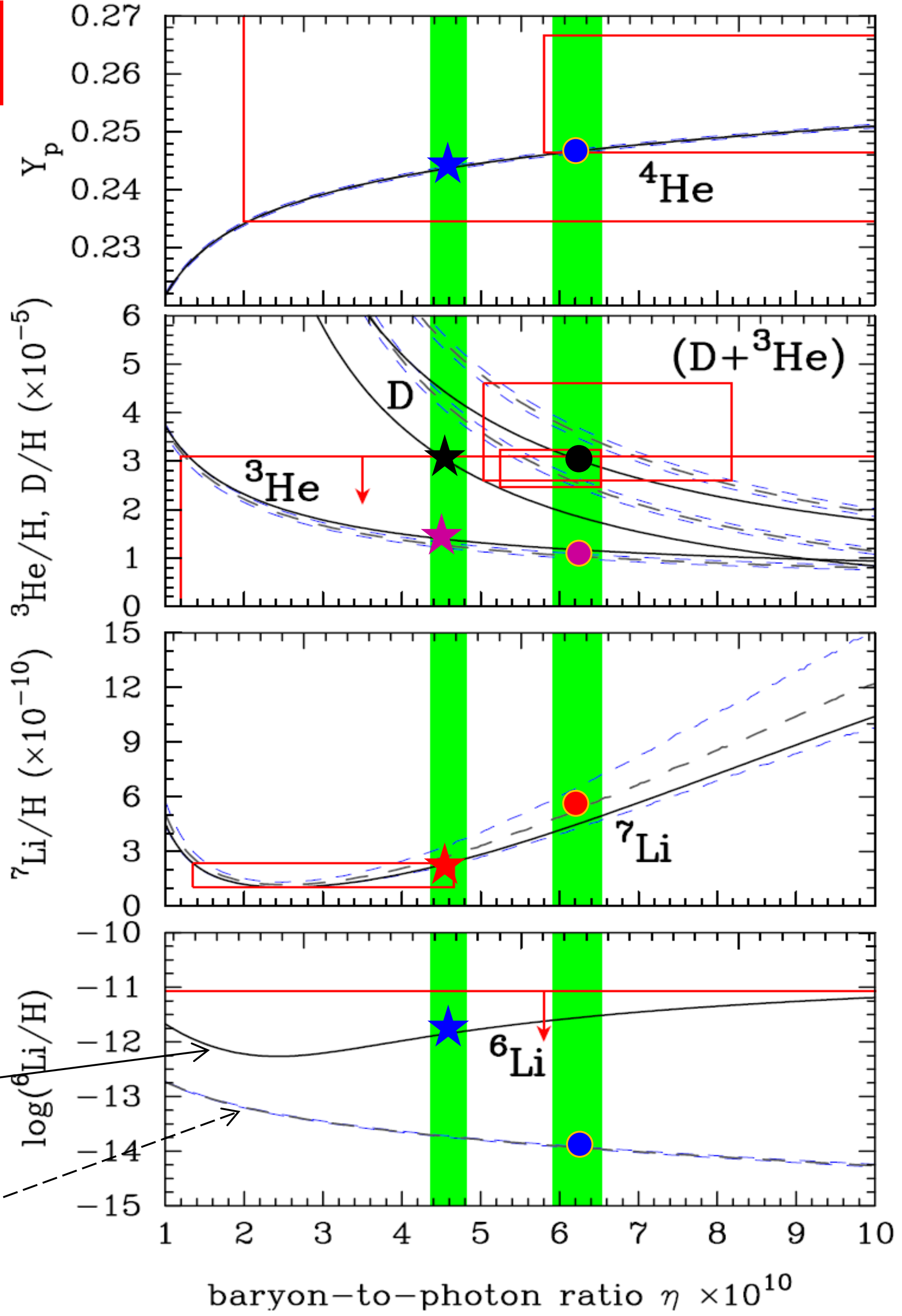
Hybrid Axion DM Model

Kusakabe, Balantekin, Kajino & Pehlivan (2013), Phys. Lett. B718, 704.

Axions + ($X^0 \rightarrow \gamma_{NT}$)

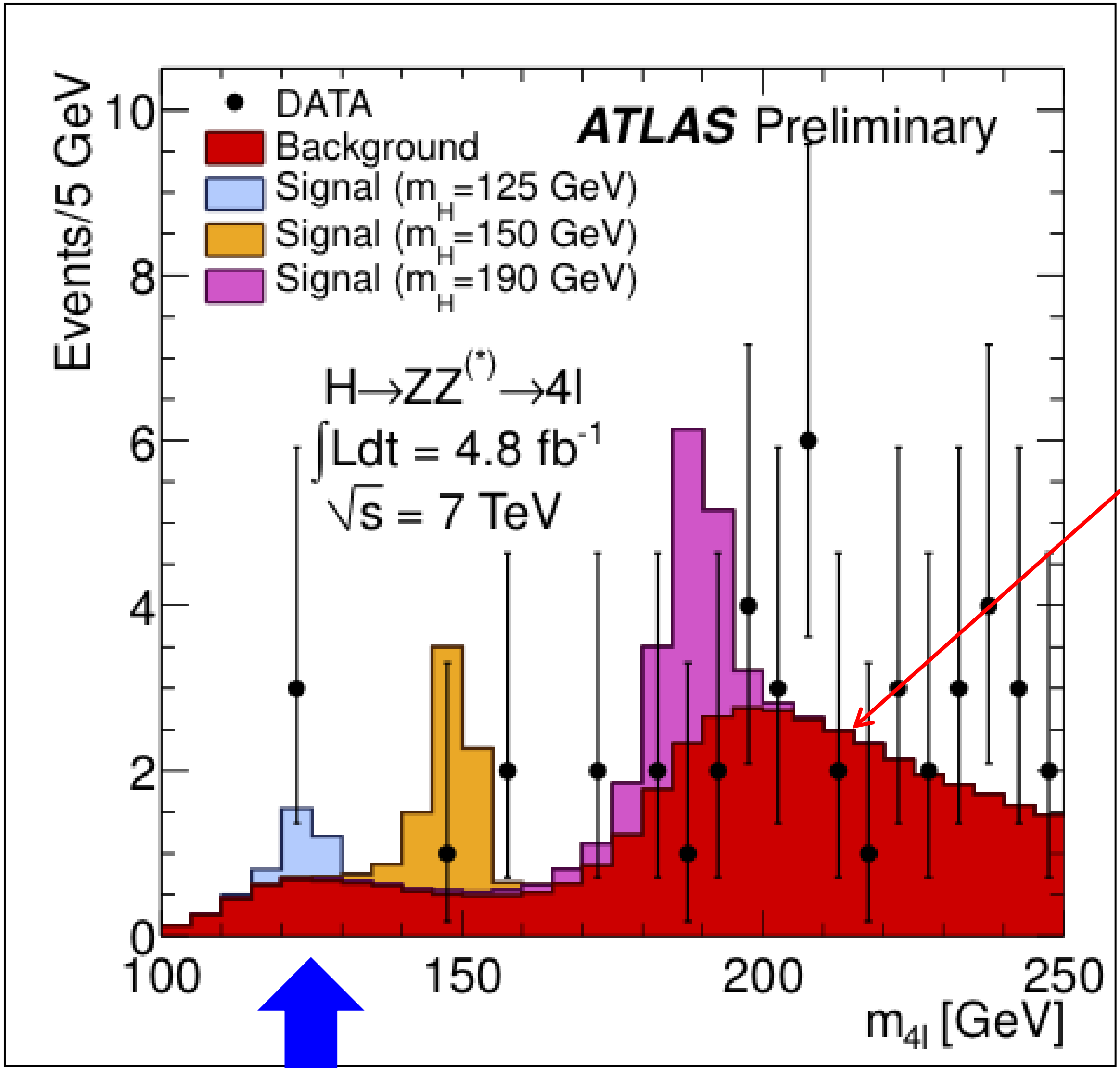
Three difficulties in BBN are resolved !

- **^{7}Li-overproduction**
- **D-overproduction**
- **^{6}Li/^{7}Li ~ 1 %**



Hybrid Axion DM BBN

Standard BBN



バックグラウンド

~125GeV

4つのレプトン(e,μ)のエネルギーや運動量から$m^2=E^2-p^2$でもとめた質量

アクシオン： アクシオンは非常に軽いが、熱的でないいわゆる傾斜 (misaligned) アクシオンは、極低温でボーズ・アインシュタイン縮退状態にあるので冷たい暗黒物質に分類される。アクシオンの存在は強い相互作用が CP を保存することの解決策として提案されたが、数々の実験や観測で存在可能範囲が非常に狭まっており、現在開いている窓は、ほぼ質量が $10^{-6} \sim 10^{-3}$eV 程度に限られる。アクシオンは 2 個のフォトンに崩壊できるので、強い電磁場に通せば、アクシオン質量に等しいエネルギーを持つフォトンが放出される。マイクロ波技術を使った実験が進行中である。

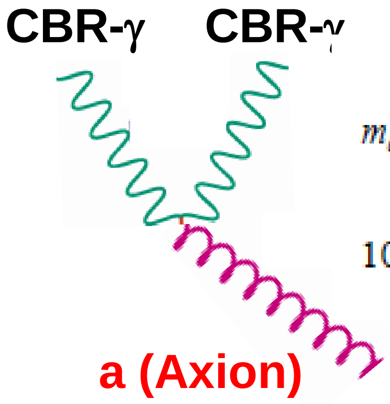
QCD – Strong CP 問題（標準モデルの範囲）

強い相互作用（QCD）はCP対称性を破るが、実験的に（中性子双極子モーメント）はCP 対称性を保存。

⇒ Peccei-Quinn (1977) : U(1) is dynamically broken to restore CP symmetry.

$$L = L_0 + \frac{\theta}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

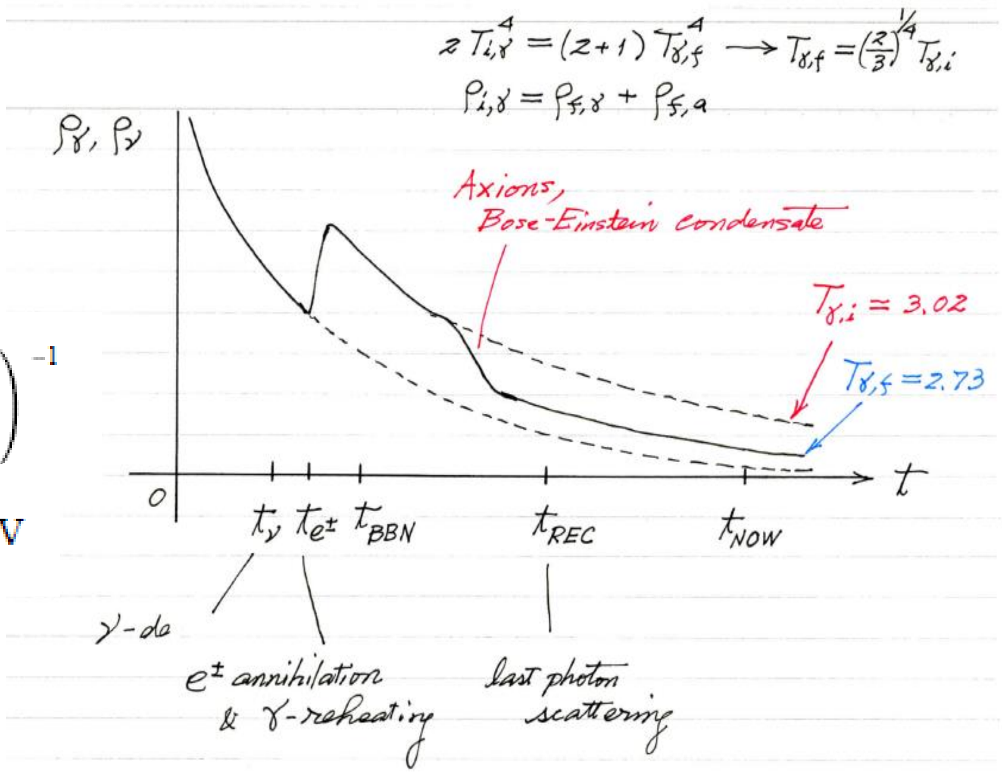
$$\mathcal{L}_{a\gamma} = -g_{a\gamma} \boldsymbol{E} \cdot \boldsymbol{B} a$$



Nambu-Goldstone Boson

$$m_a = 0.62 \times 10^{-5}\,\mathrm{eV} \left(\frac{F_a}{10^{12}\,\mathrm{GeV}} \right)^{-1}$$

$$10^{9-10}\,\mathrm{GeV} \lesssim F_a \lesssim 10^{12-13}\,\mathrm{GeV}$$

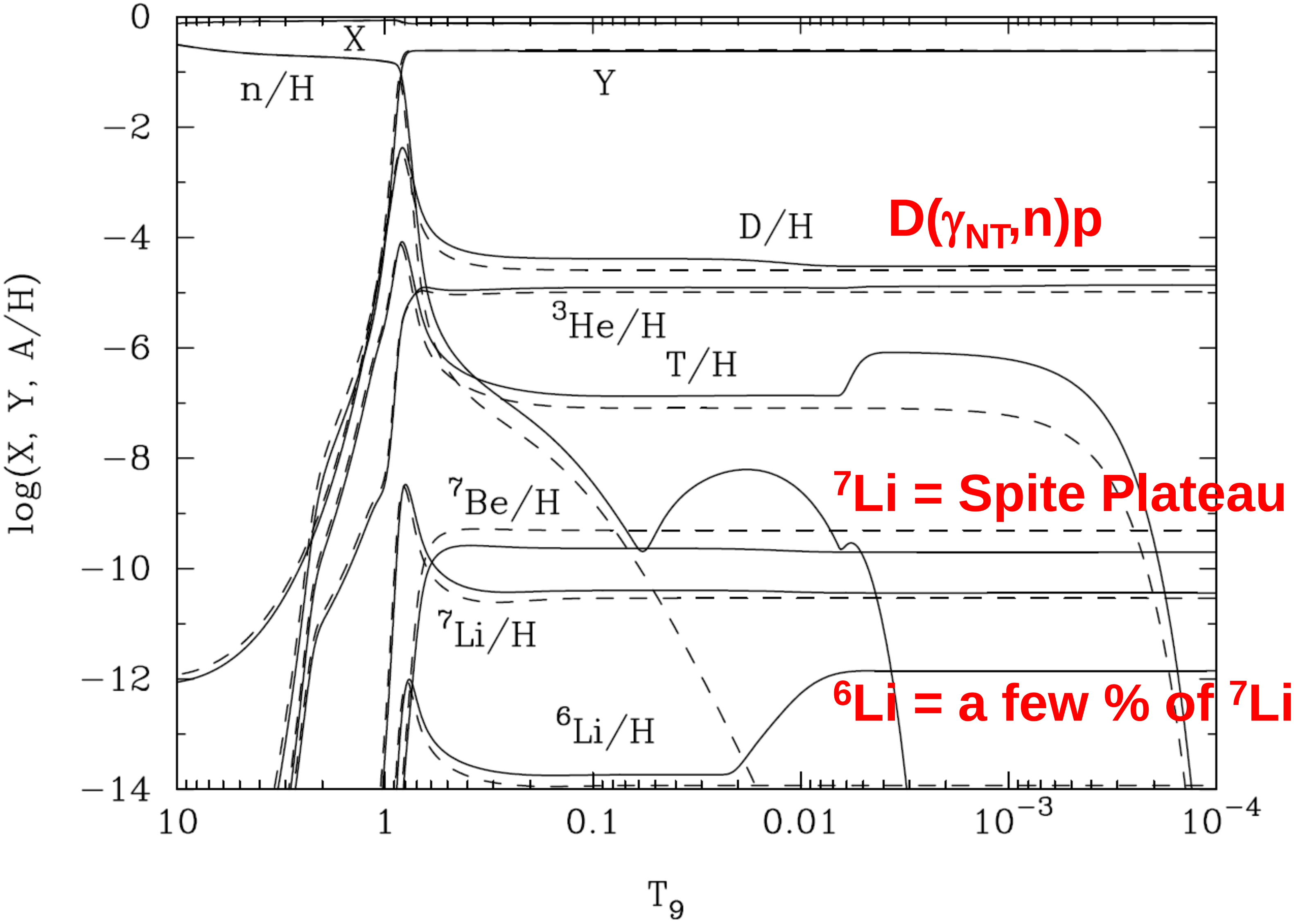


Hybrid Axion DM Model

Kusakabe, Balantekin, Kajino & Pehlivan (2012), arXiv:1202.5603.

DM = Axions + Relic $X^0 \rightarrow \gamma_{NT}$

$\eta = 4.6 \times 10^{-10}$



$D(\gamma_{NT},n)p$

^{7}Li = Spite Plateau

^{6}Li = a few % of ^{7}Li

Variation of strong coupling const. α

Grand unification models

$$\boxed{\Delta(m/\Lambda_{QCD})/(m/\Lambda_{QCD})=35\Delta\alpha/\alpha}$$

1. Proton mass $M_p=3\Lambda_{QCD}$, measure m_e/M_p
2. Nuclear magnetic moments $\mu=g\ eh/4M_pc$

   $g=g(m_q/\Lambda_{QCD})$

3. Nuclear energy levels

→ **Big-Bang Nucleosynthesis**

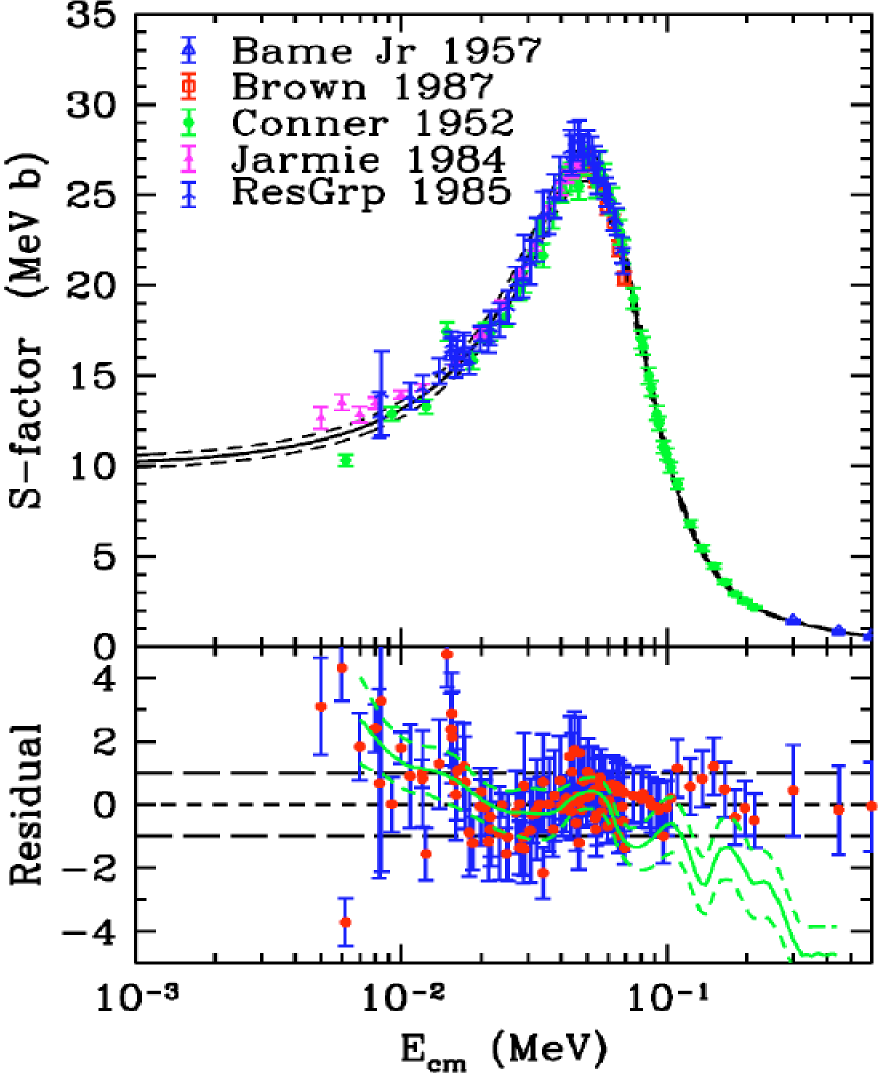
$$\boxed{\delta E(A)/E(A) = K\ \delta(m_q/\Lambda_{QCD})/(m_q/\Lambda_{QCD})}$$

K-values: V.V. Flambaum and R.B. Wiringa, PRC79, 034302 (2009)

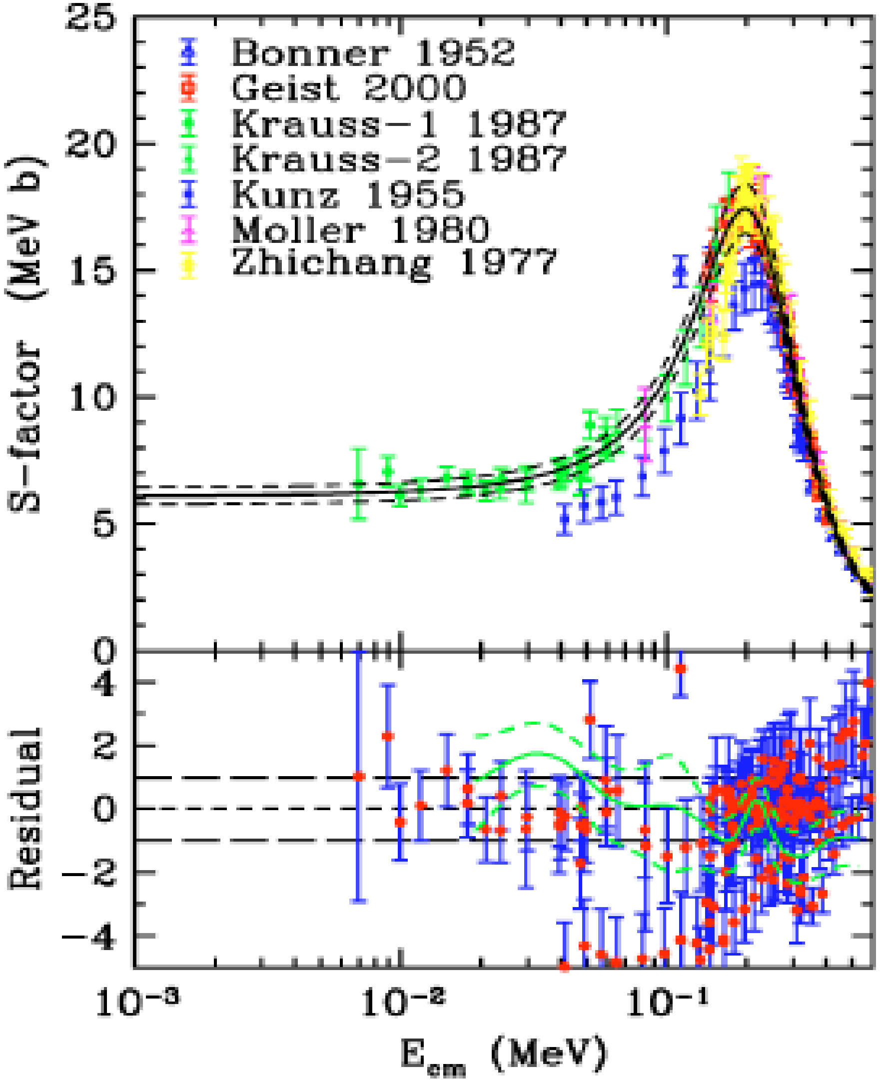
Richard H. Cyburt

PHYSICAL REVIEW D 70, 023505 (2004)

$D(t,n)^4He$



$D(^3He,p)^4He$

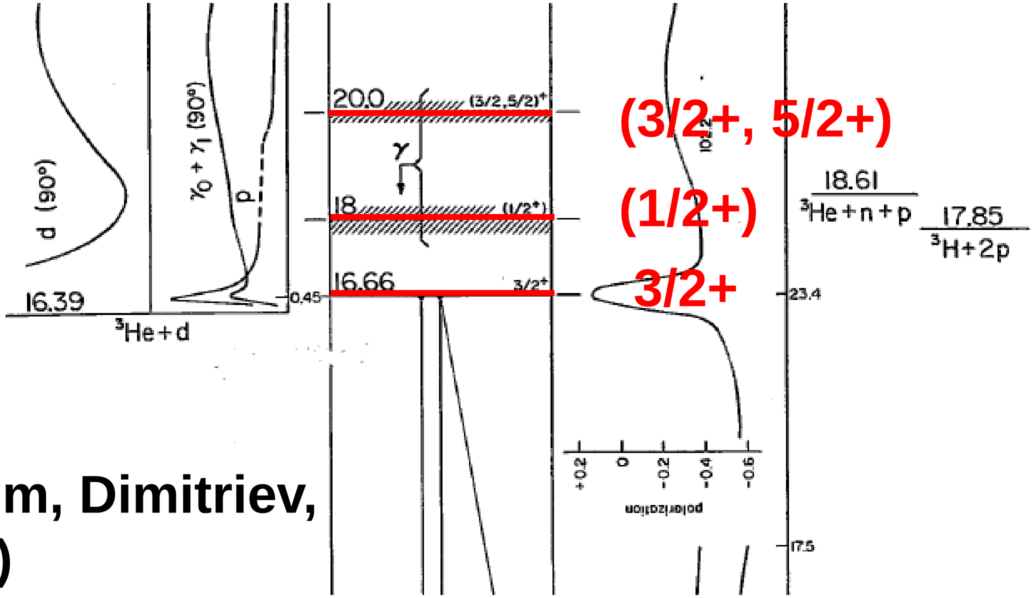


1s-wave

D + ^{3}He

1+ ½+

Berengut, Flambaum, Dimitriev, PL B683, 114 (2101)



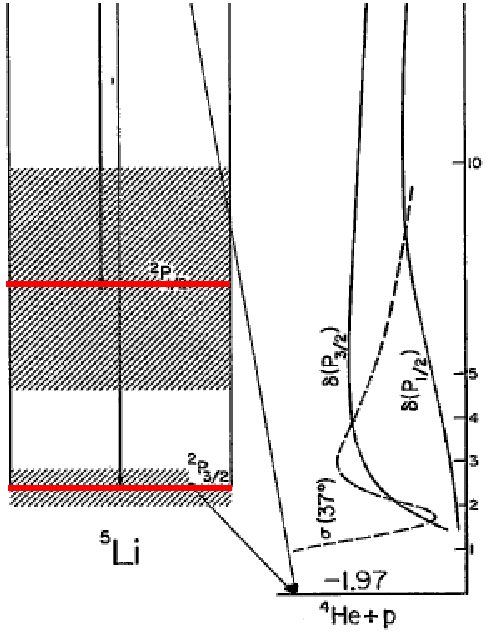
(3/2+, 5/2+)

(1/2+)

3/2+

0d-wave

D(^{3}He,p)^{4}He



P 1/2-

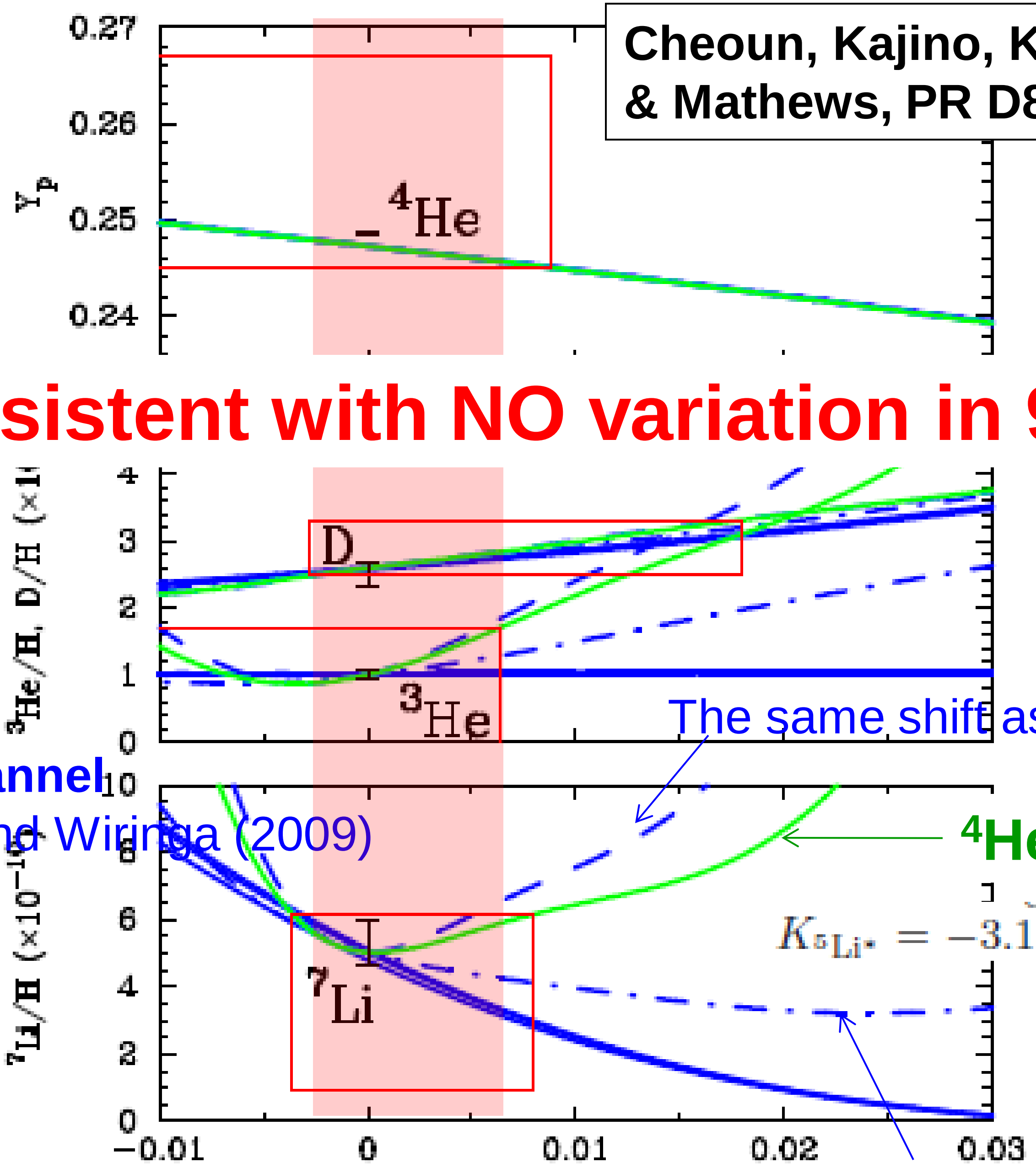
P 3/2-

0p-wave

0+ ½+

^{4}He + p

Cheoun, Kajino, Kusakabe & Mathews, PR D84 (2011), 43001.



Consistent with NO variation in 95% C.L. !

^{3}He(t)+D channel

Flambaum and Wiringa (2009)

The same shift as g.s.

^{4}He+p/n channel

$K_{^5\mathrm{Li}^*} = -3.131,\ K_{^5\mathrm{He}^*} = -2.867$

The same average shift.

$\delta(m_q/\Lambda_{QCD}) / (m_q/\Lambda_{QCD})$

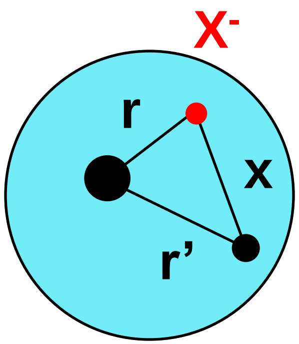
Binding Energies of Exotic X-Nuclides

Assumption
X^- is a spinless (S=0), charged, massive (m_X) SUSY particle.

(e.g. stau)

Nuclear Charge Density Distribution

X-nucleus: A_X



Nucleus: A

(1) Woods-Saxon $\rho(r') = \dfrac{ZeC}{1+\exp[(r'-R)/a]}$

(2) Gaussian $\rho(r') = Ze(\pi b)^{-3/2}\exp\left(-r'^2/b^2\right)$ $b = \sqrt{2/3}\langle r_c{}^2\rangle^{1/2}$

(3) Homogeneous $\rho(r') = \dfrac{3Ze}{4\pi r_0{}^3}H(r_0 - r')$ $r_0 = \sqrt{5/3}\langle r_c{}^2\rangle^{1/2}$

Schrödinger Equation

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(r) - E\right]\psi(\mathbf{r}) = 0 \qquad V(r) = \int_0^\infty \frac{-e\rho(r')}{x}\,d^3r'$$

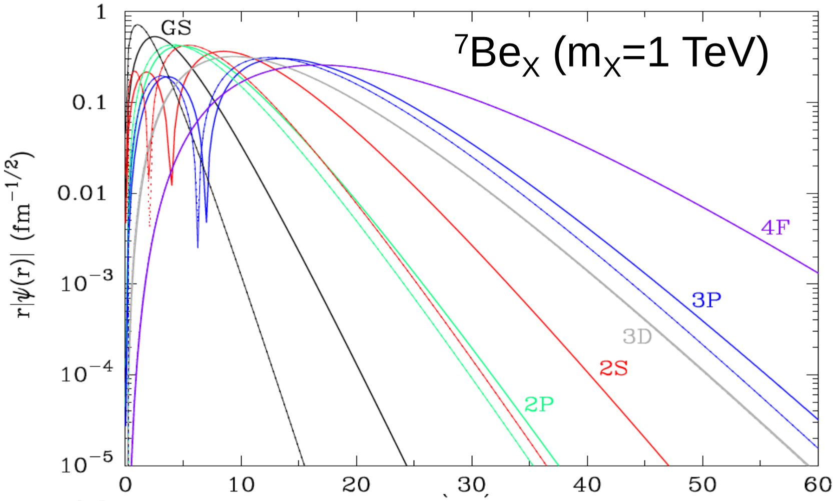
Binding energies and wave functions are solved in

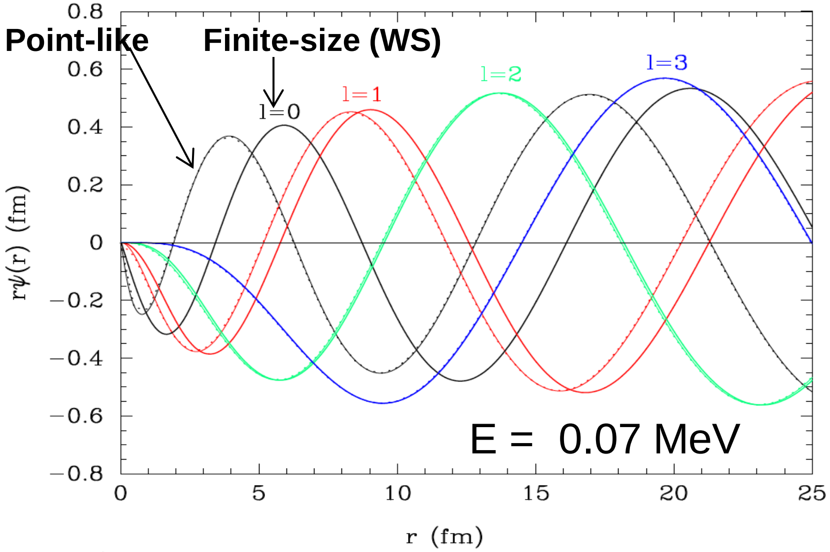
- variational method (Gaussian expansion method, c.f. Hiyama et al. 2003)
- numerical integration (RADCAP code, by Bertulani 2003)

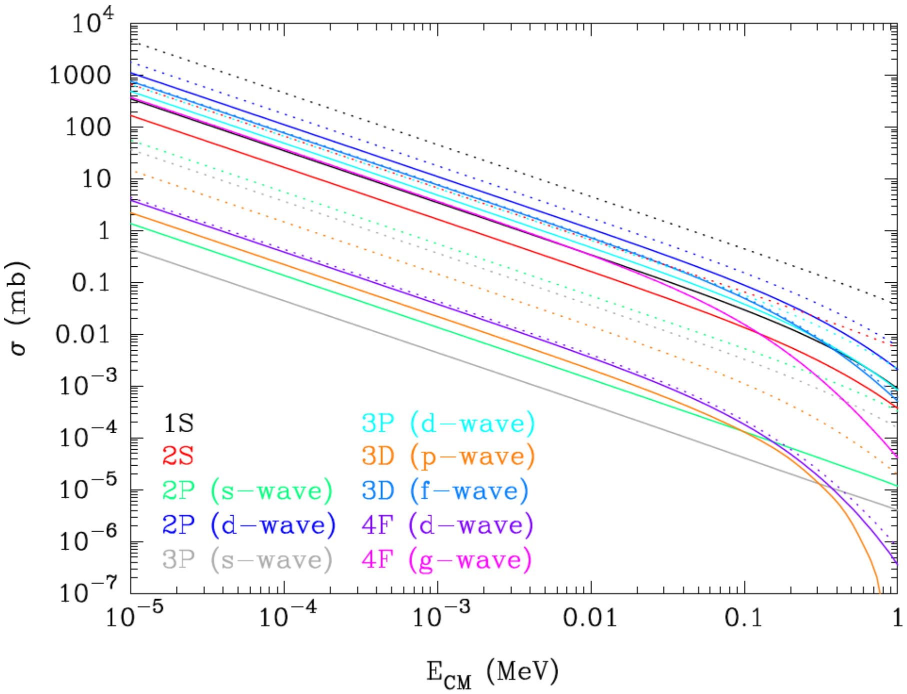
Possible Range of Recombination Cross Section of X⁻

Sensitive to <u>Finite-Size Effect</u> of Nuclear Charge Density Distribution.

→ Very different binding energies & wave functions

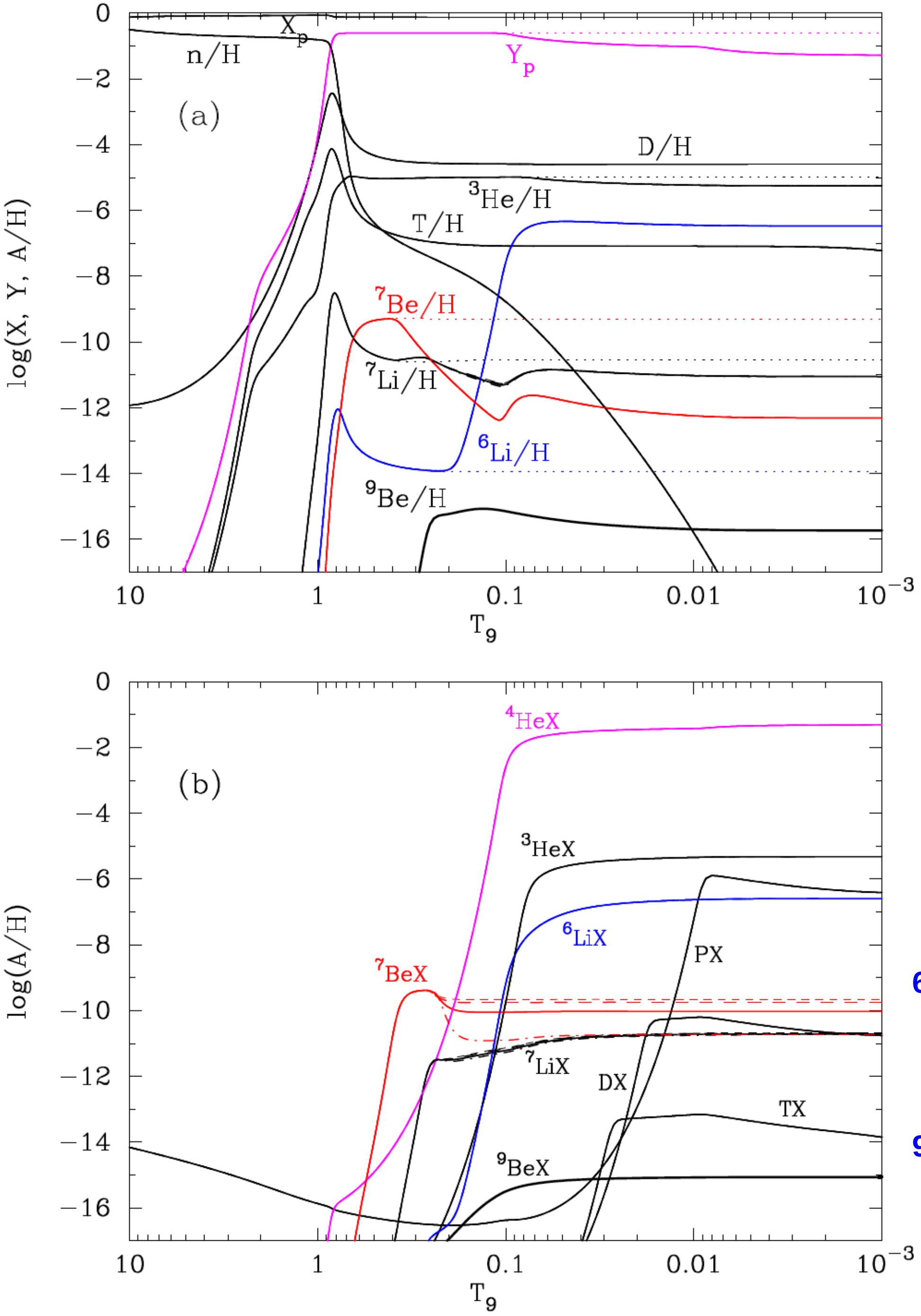






→ We included many possible transitions.

Calculated Result



$n_X=0.05n_b$, $\tau_X>>200$ s, $\eta=6.19\times10^{-10}$
$m_X=1$ TeV (WMAP 9yr)

The resonance height of $^8B_X{}^*$ is sensitive to the nuclear charge distribution.

Amount of ^{7}Be destruction significantly depends on the charge distribution.

– – – – – – Gaussian
——— Woods-Saxon
–·–·–·– homogeneous

^{6}Li could be at the level of ^{6}Li/^{7}Li～0.01.

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

^{9}Be could be produced abundantly.

$^7Li_X(d, X^-)^9Be$