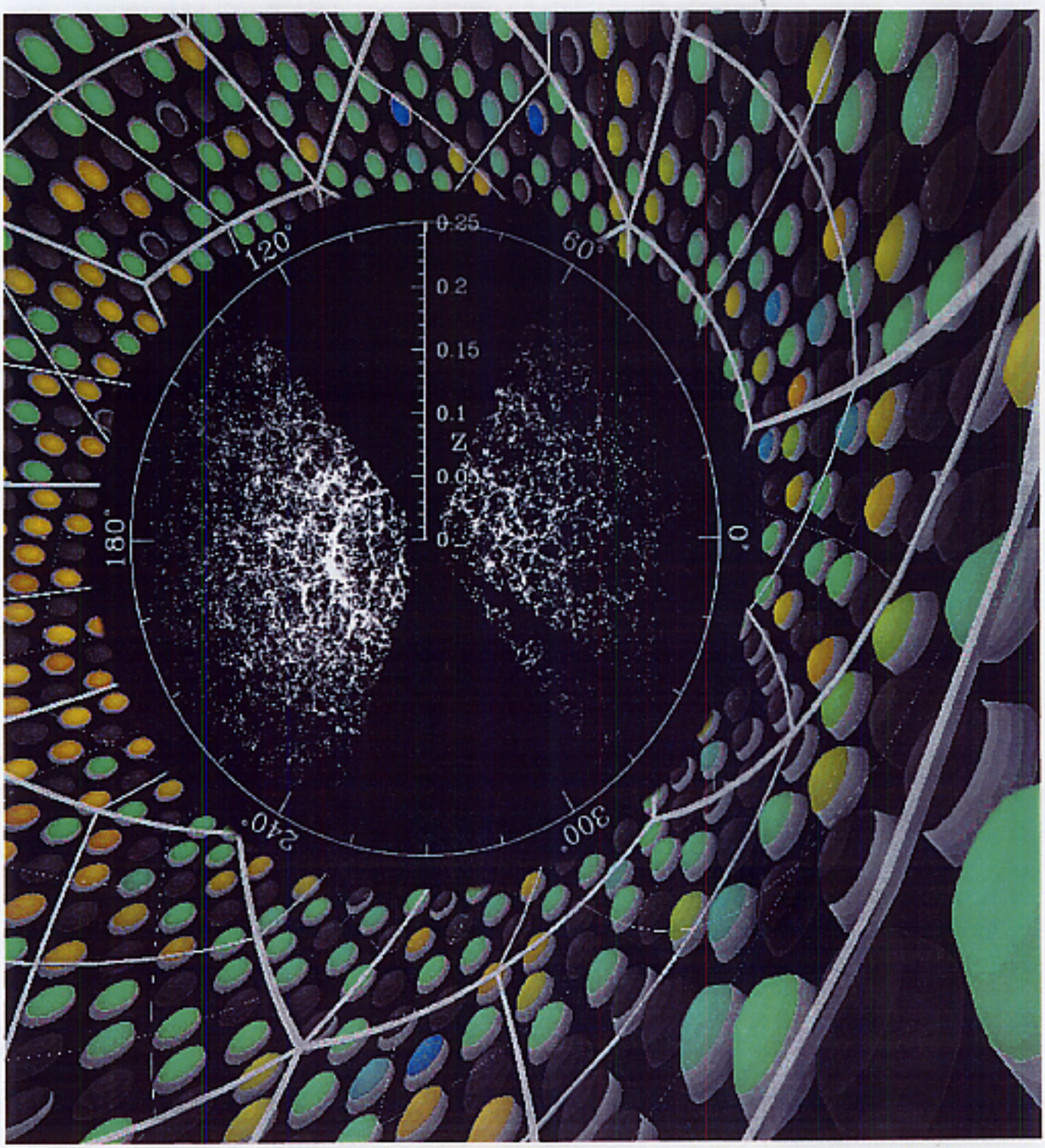
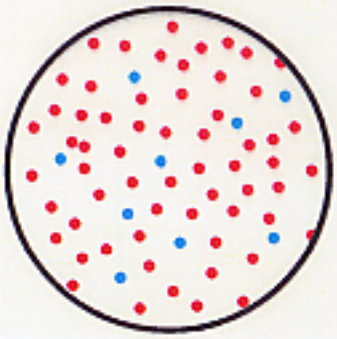
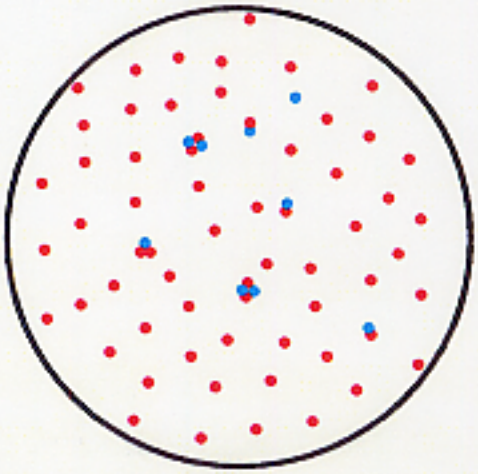
Neutrinos & BBN

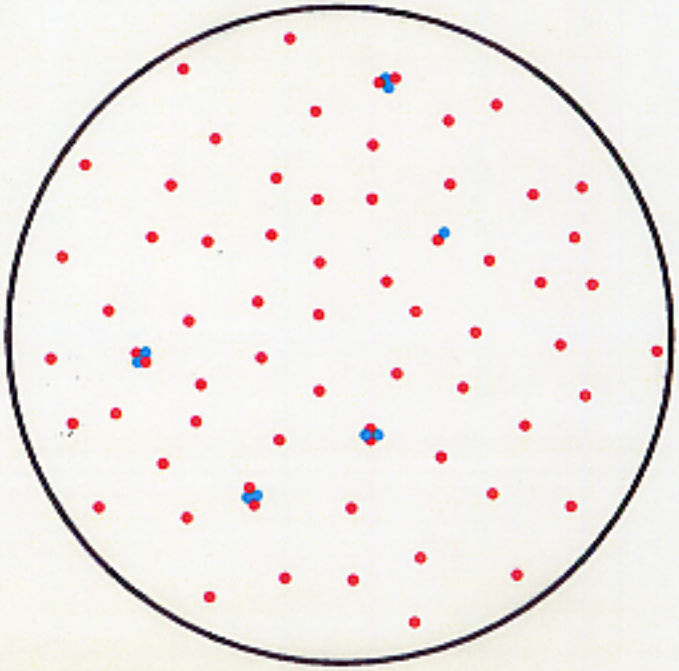


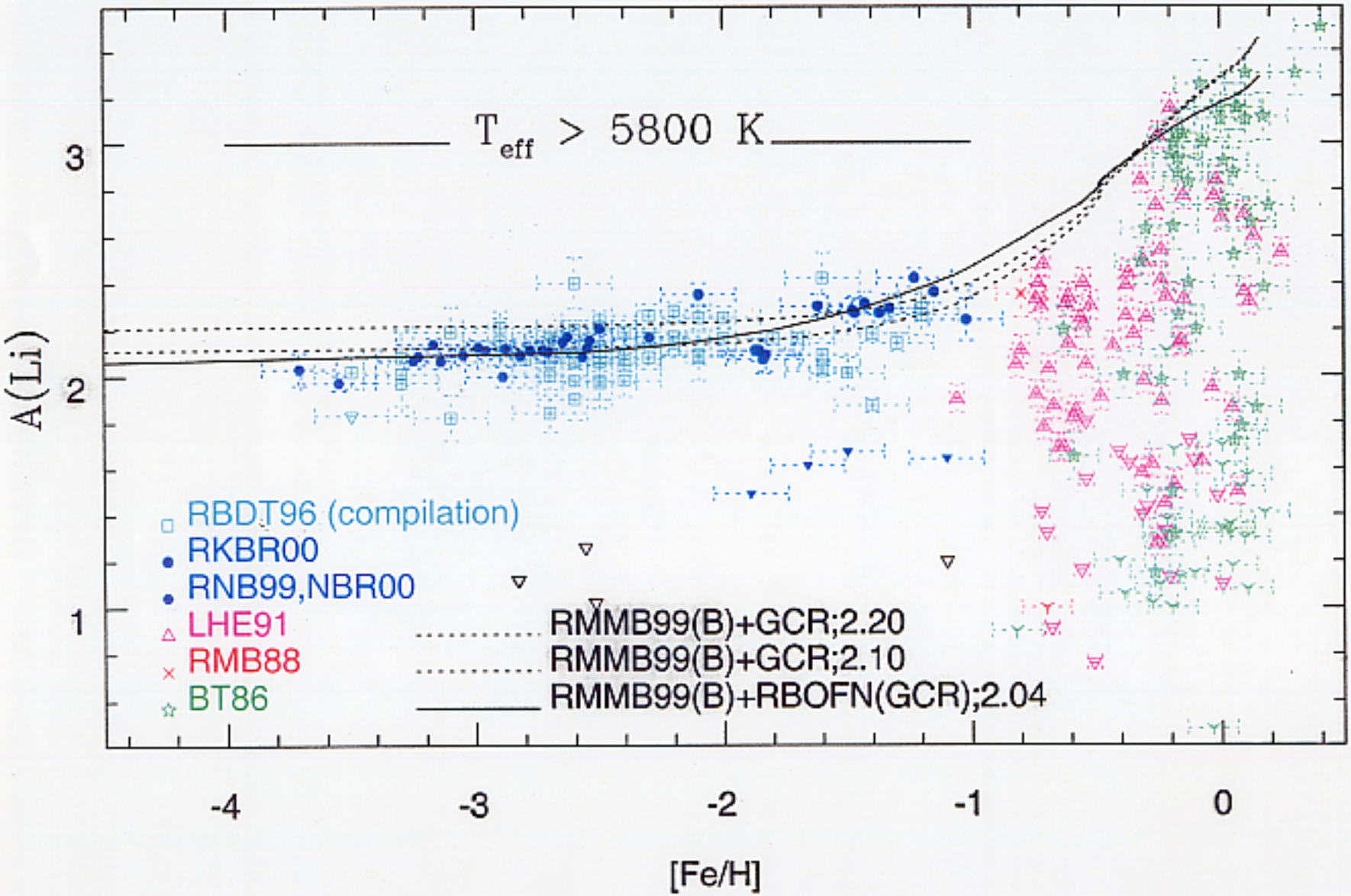
$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho_{\text{relativistic}}$$

t(s)	T(keV)	
1	1000	Weak Freezeout $\frac{n}{p} \cong \frac{1}{7}$
100	100	First Bound Nuclei $^2H, ^3H, ^3He, ^4He$
10^4	10	Nuclear Freezeout
		End of BBN








T_eff > 5800 K
A(Li)
3
2
1
-4
-3
-2
-1
0
[Fe/H]
RBDT96 (compilation)
RKBR00
RNB99,NBR00
LHE91
RMB88
BT86
RMMB99(B)+GCR;2.20
RMMB99(B)+GCR;2.10
RMMB99(B)+RBOFN(GCR);2.04

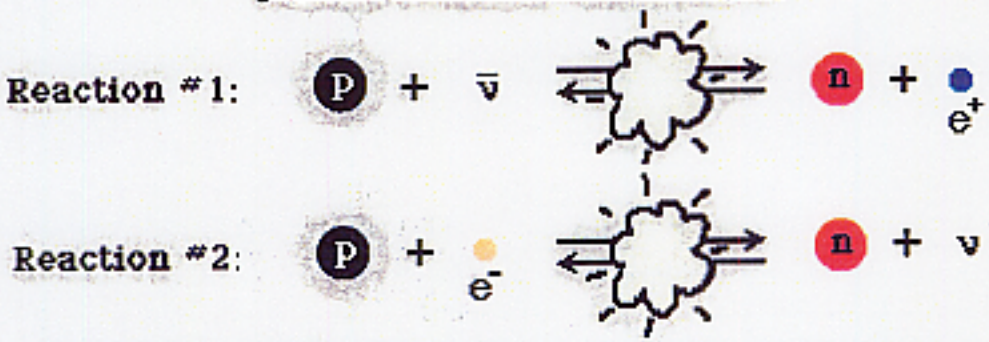
Standard Big Bang Nucleosynthesis

Simple Model: one free parameter: entropy/baryon

Universe is homogeneous and isotropic

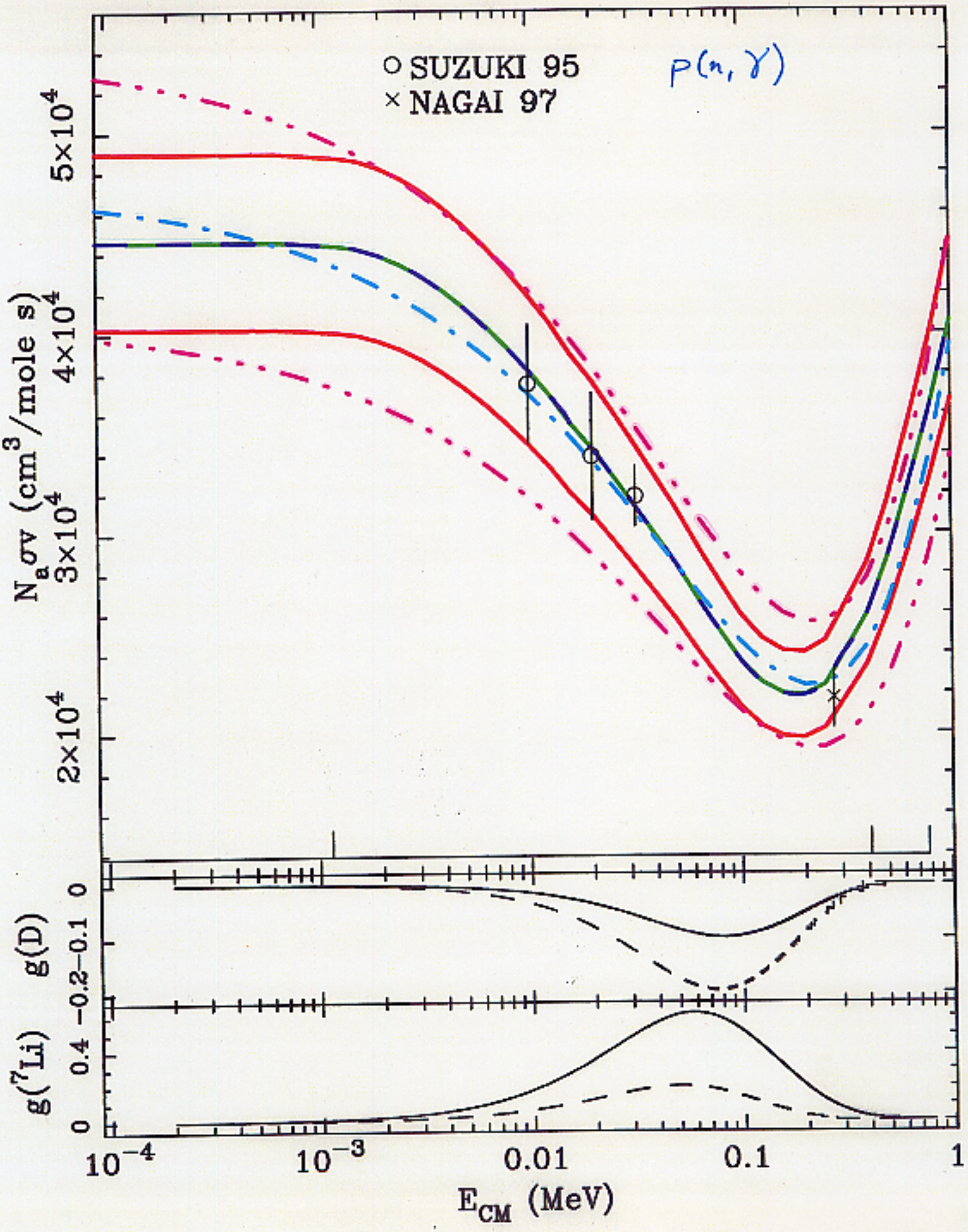
Competition between nuclear reaction rates and expansion rate of the universe

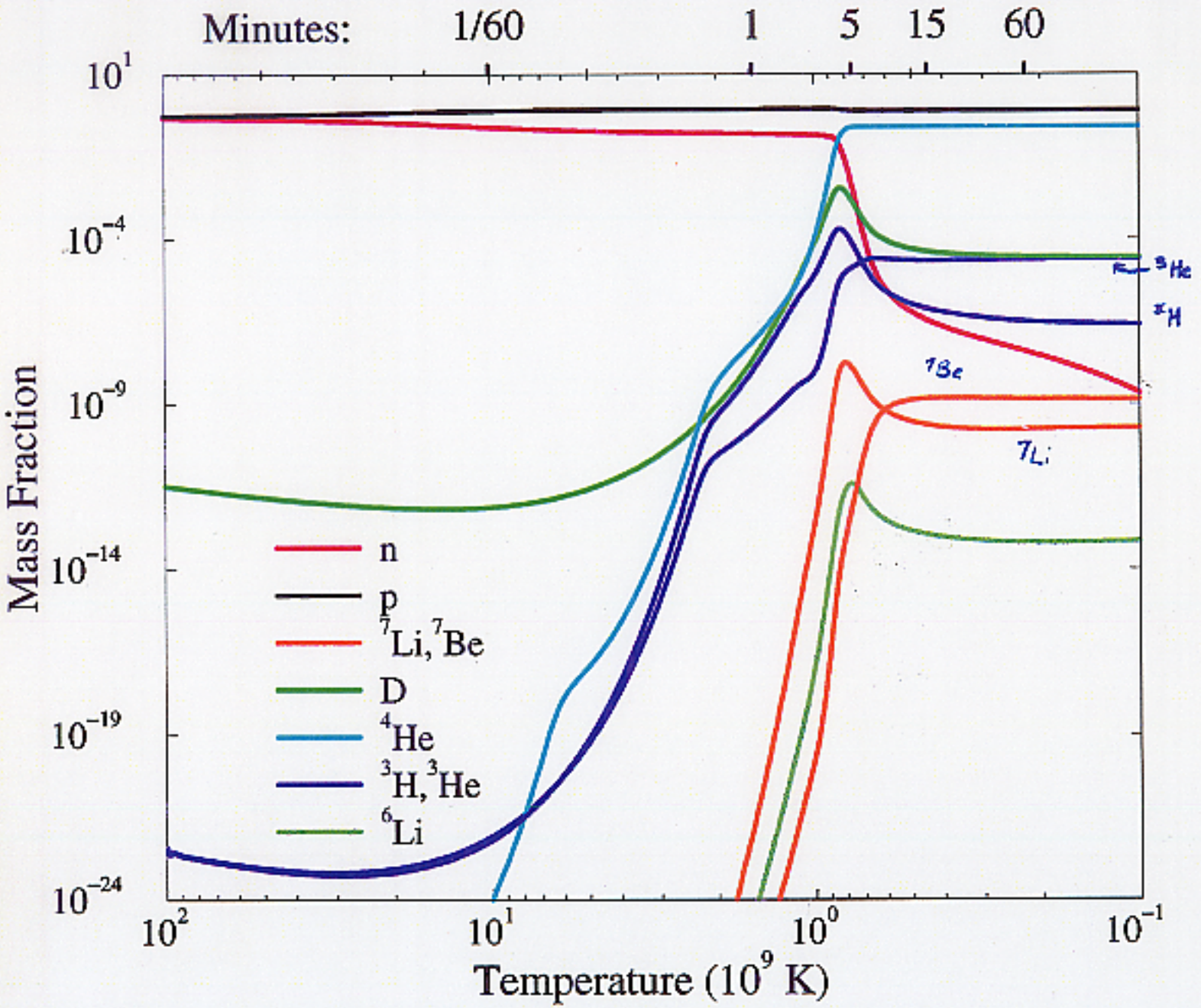
<u>proton/neutron conversions</u>

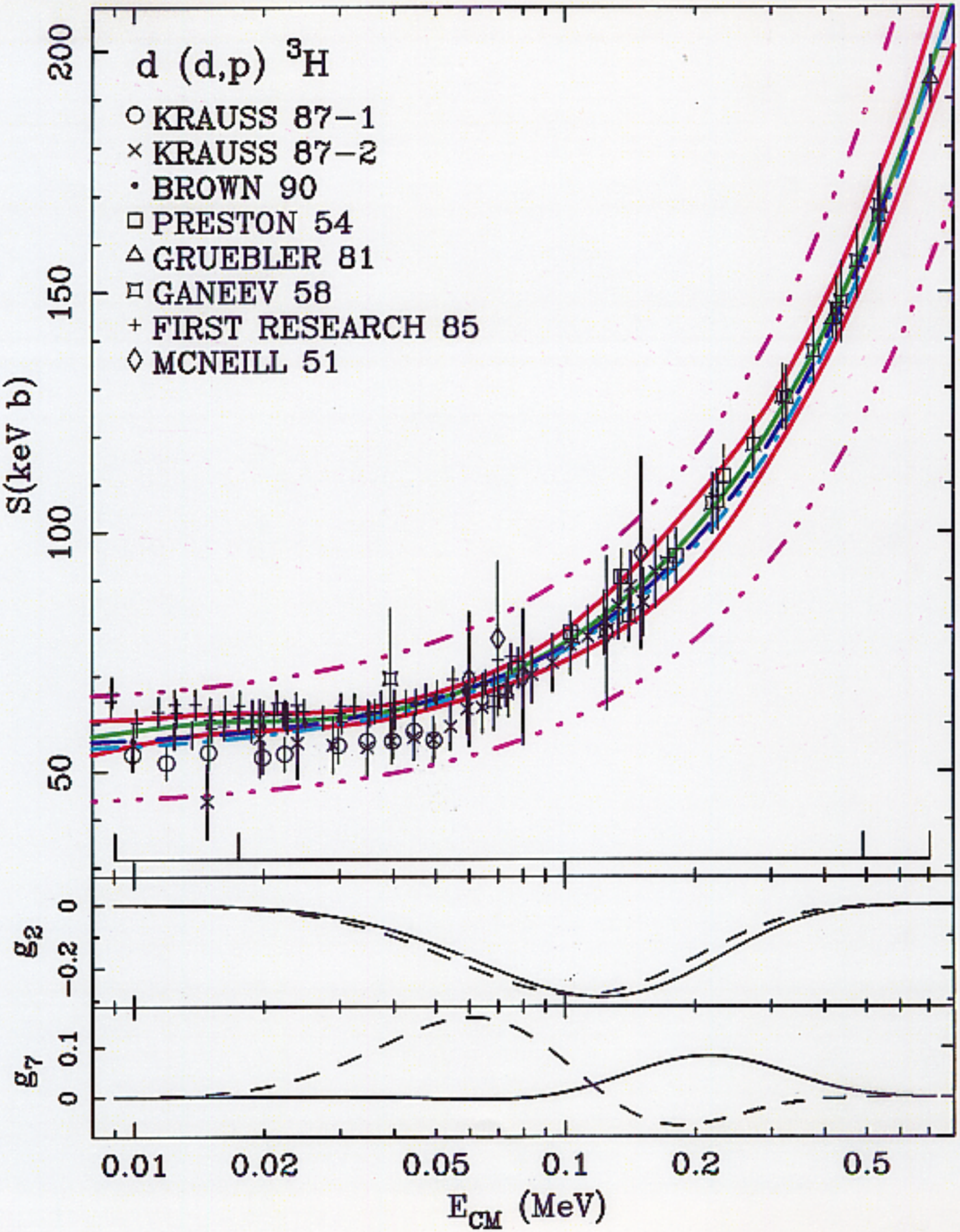


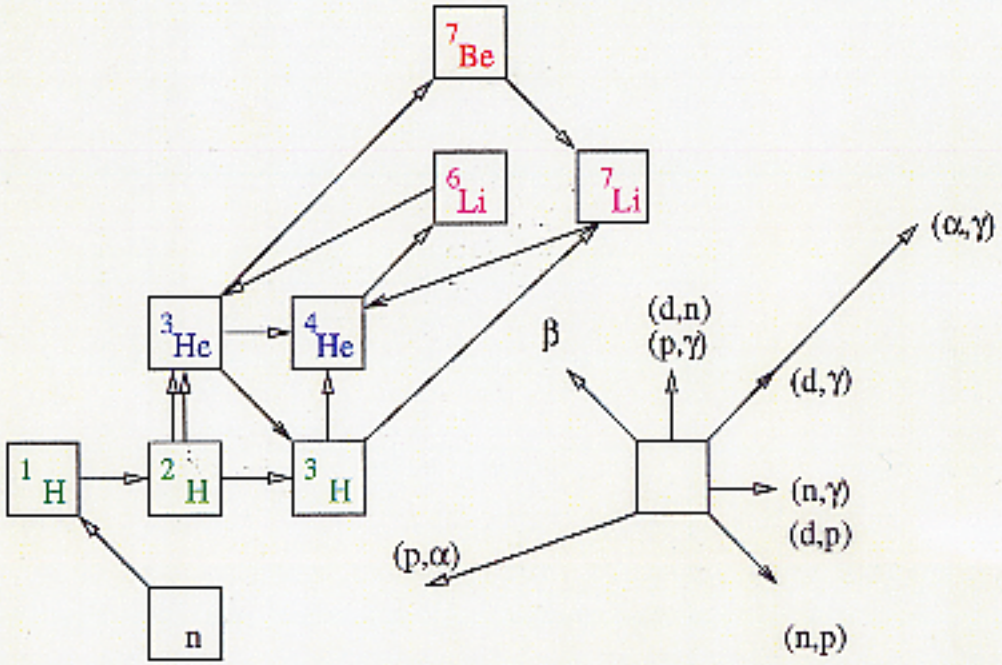
(The double arrows indicate these reactions go both ways.)

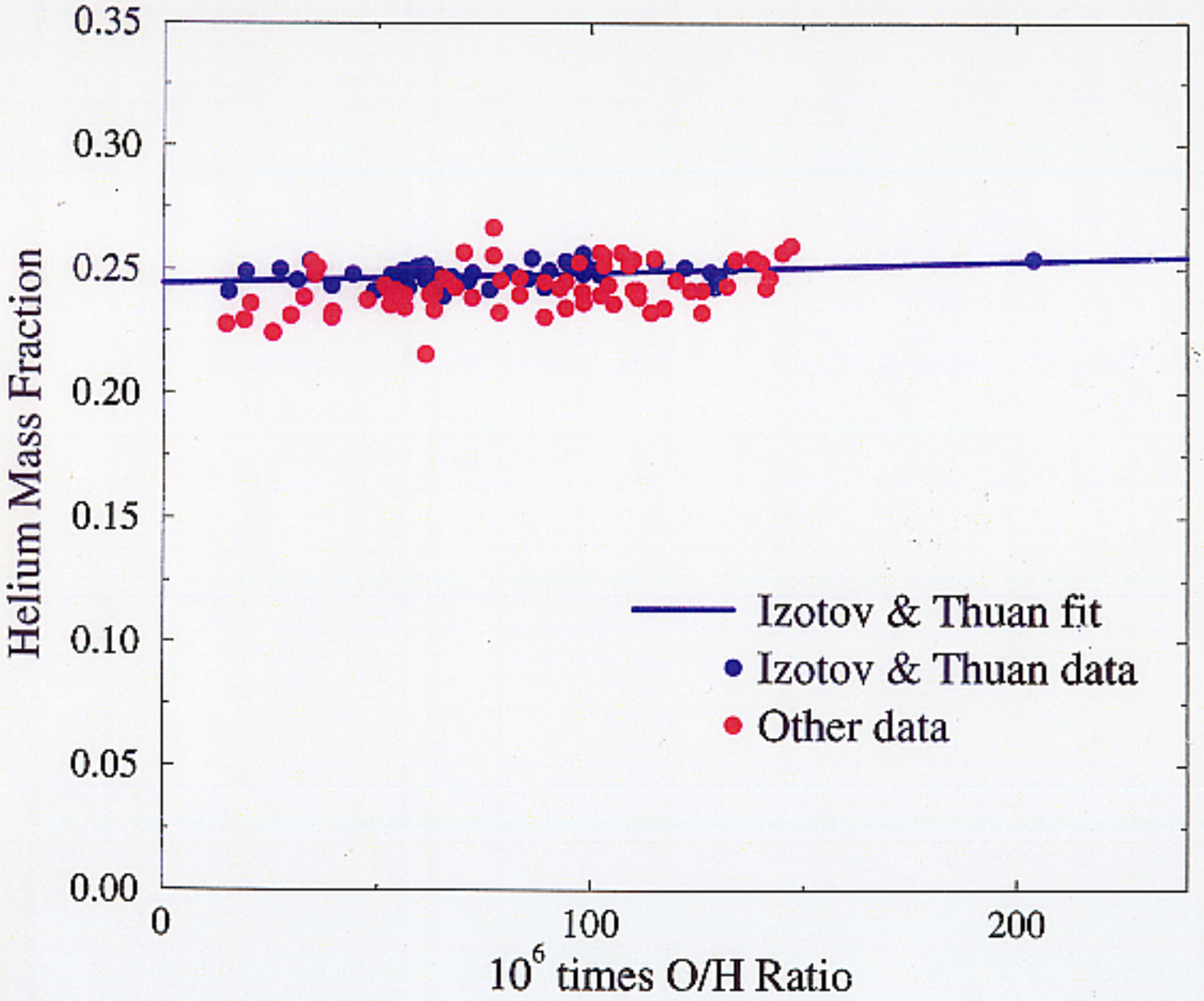
No stable nuclei at A=5 and A=8

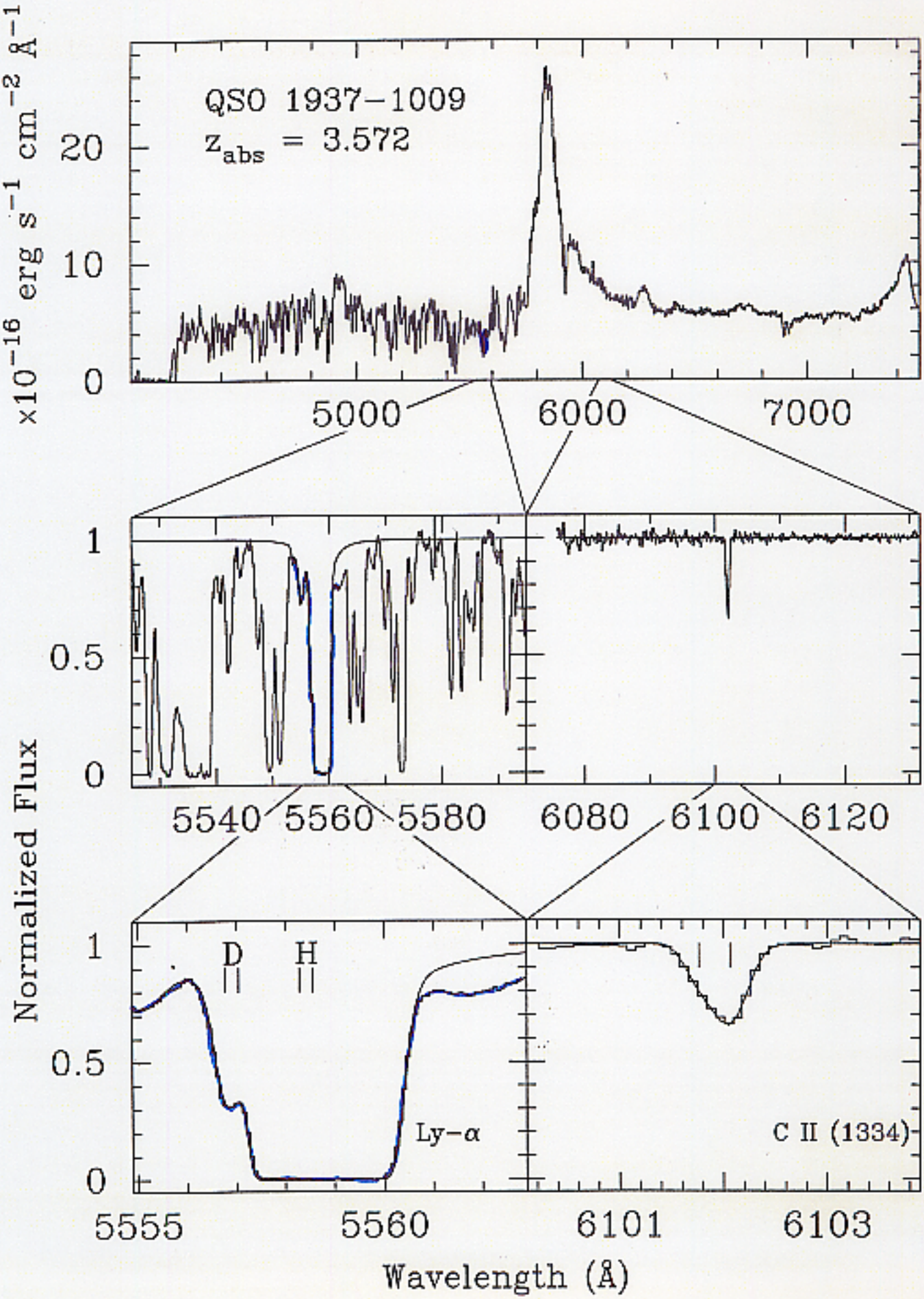

SUZUKI 95
NAGAI 97
p(n, γ)
$N_a\sigma v$ (cm^3/mole s)
5×10^4
4×10^4
3×10^4
2×10^4
g(D)
0
−0.1
−0.2
g(^{7}Li)
0.4
0
10^{-4}
10^{-3}
0.01
0.1
1
E_{CM} (MeV)


Minutes:
1/60
1
5
15
60
10^{1}
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
Mass Fraction
n
p
^{7}Li, ^{7}Be
D
^{4}He
^{3}H, ^{3}He
^{6}Li
^{3}He
^{3}H
^{7}Be
^{7}Li
10^{2}
10^{1}
10^{0}
10^{-1}
Temperature (10^{9} K)


d (d,p) ^{3}H
KRAUSS 87−1
KRAUSS 87−2
BROWN 90
PRESTON 54
GRUEBLER 81
GANEEV 58
FIRST RESEARCH 85
MCNEILL 51
S(keV b)
200
150
100
50
g_2
0
−0.2
g_7
0.1
0
0.01
0.02
0.05
0.1
0.2
0.5
E_{CM} (MeV)


^{7}Be
^{6}Li
^{7}Li
^{3}He
^{4}He
^{1}H
^{2}H
^{3}H
n
β
(d,n)
(p,γ)
(α,γ)
(d,γ)
(n,γ)
(d,p)
(p,α)
(n,p)


0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Helium Mass Fraction
0
100
200
10^6 times O/H Ratio
Izotov & Thuan fit
Izotov & Thuan data
Other data


QSO 1937−1009
z_{abs} = 3.572
$\times 10^{-16}$ erg s^{-1} cm^{-2} Å^{-1}
20
10
0
5000
6000
7000
1
0.5
0
5540
5560
5580
6080
6100
6120
Normalized Flux
D
H
Ly−α
C II (1334)
5555
5560
6101
6103
Wavelength (Å)

QSO D/H Abundances

at 95% cl*

QSO	z_{abs}	$\log_{10}$ D/H	χ^2	w/o 2206
New! Q1243+3047	2.525	-4.54 $\pm$0.06	0.00	0.11
Q1937-1009	3.572	-4.48 $\pm$0.08	2.45	1.56
Q0105+1619	2.536	-4.60 $\pm$0.09	1.62	2.42
Q1009+2956	2.504	-4.40 $^{+0.12}_{-0.16}$	3.18	2.64
Q2206-199	2.076	-4.78 $\pm$0.18	6.95	...
Q0347-383	3.025	-4.65 $\pm$0.25	0.74	0.92
Q0130-103	2.799	$<$-4.17	...	
W. Mean	2.5	-4.54 $\pm$0.04	3.0	1.9

$$
\begin{aligned}
& & \text{(stat)} & \quad \text{(sys)} \\
\mathrm{D/H_{QSO}} &= (2.9 \pm 0.3 & \pm 0.1) \times 10^{-5} \\
\eta &= (5.8 \pm 0.5 & \pm 0.2) \times 10^{-10} \\
\Omega_b h^2 &= 0.021 \pm 0.002 & \pm 0.001
\end{aligned}
$$

The $\geq$ Neutrino Effects

(Wagoner, Fowler & Hoyle 1967)

1) Expansion Rate

$$H^2 = \frac{8\pi G}{3}\rho$$

$$= \frac{8\pi G}{3}\left(\rho_\gamma + \rho_{e^-e^+} + \rho_{\nu_e\bar{\nu}_e} + \rho_{\nu_\mu\bar{\nu}_\mu} + \rho_{\nu_\tau\bar{\nu}_\tau} + \rho_?\right)$$

$$= \frac{8\pi G}{3}\left(\rho_\gamma + \rho_{e^-e^+} + \sum \rho_{\nu\bar{\nu}}\left(3 + \Delta N_\nu\right)\right)$$

- Affects Freeze-out Temperature T_f

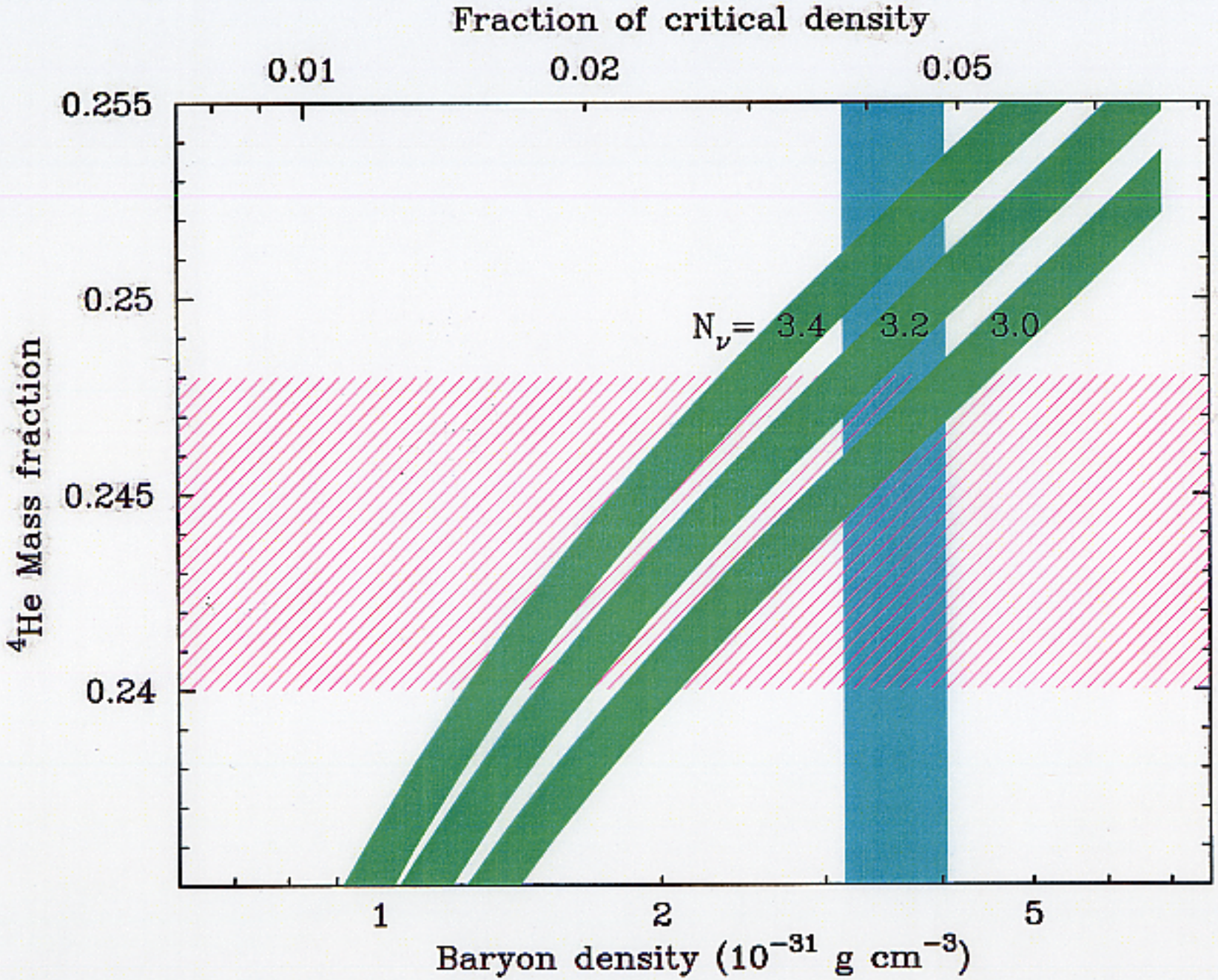
$$\Gamma(T_f) = H(T_f)$$

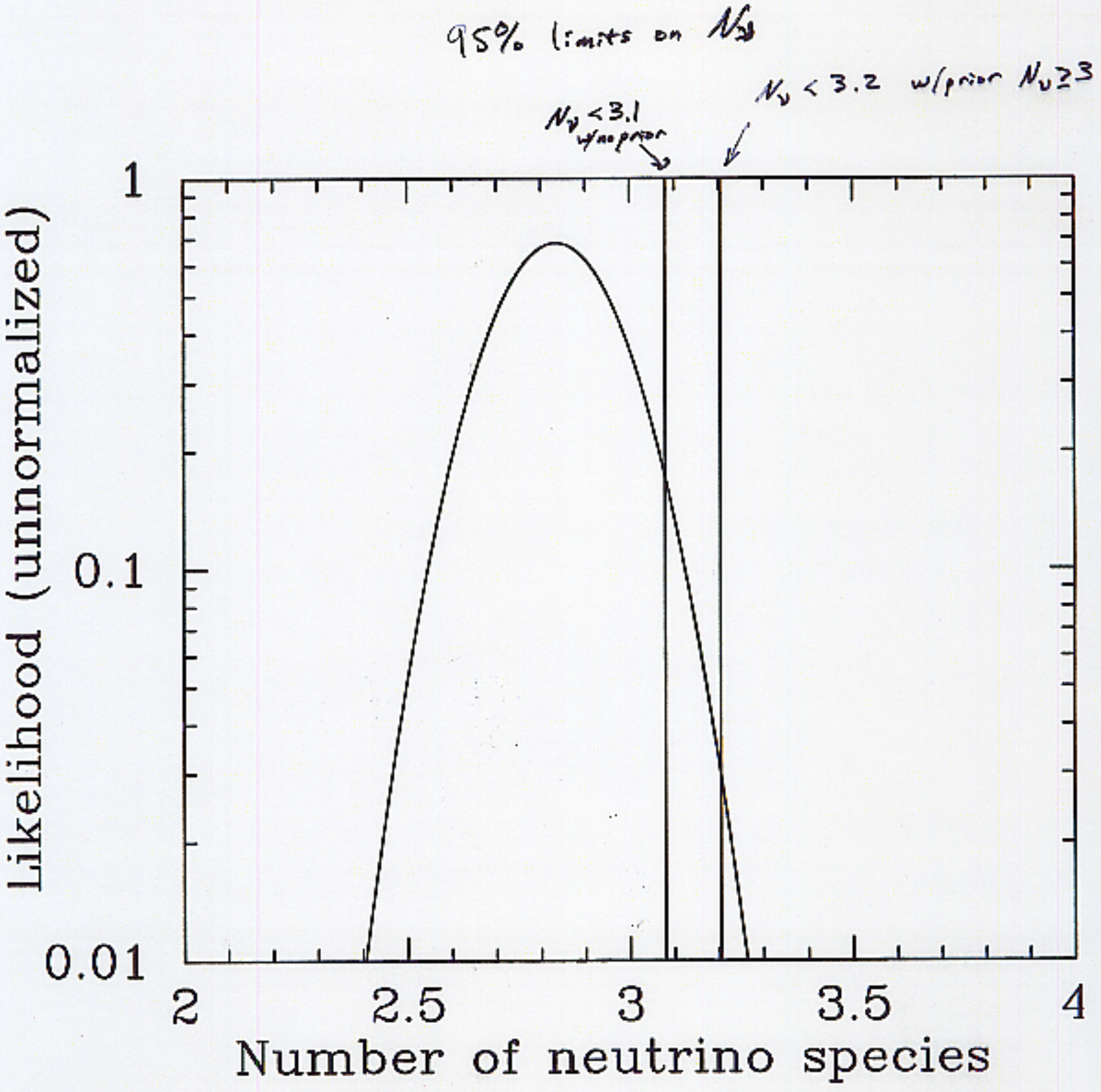
Classic Example:

$$\left(\frac{n}{p}\right)_{freezeout} = e^{-(\Delta m + \mu_e)/kT_f}$$

Net Result...

$$H \uparrow \Rightarrow T_f \uparrow \Rightarrow \left(\frac{n}{p}\right)_f \uparrow \Rightarrow {}^4He \uparrow$$


Fraction of critical density
0.01
0.02
0.05
0.255
0.25
0.245
0.24
^{4}He Mass fraction
N_ν= 3.4
3.2
3.0
1
2
5
Baryon density (10^{-31} g cm^{-3})


95% limits on N_ν
$N_\nu < 3.2$ w/prior $N_\nu \geq 3$
$N_\nu < 3.1$ w/no prior
1
0.1
0.01
Likelihood (unnormalized)
2
2.5
3
3.5
4
Number of neutrino species

2) Neutrino Degeneracy $\xi = \mu/kT$

- All active flavors:

$$\rho_{\nu\bar{\nu}} = T_0^4 \left(\frac{7\pi^2}{120}\right)\left[1 + \frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4\right]$$

$$= \rho_{\nu\bar{\nu}}(\xi = 0)\left[1 + \Delta N_\nu\right]$$

independent of sign(ξ)

And, for electron neutrino only ξ_e at weak freeze-out:

$$\left(\frac{n}{p}\right)_f = e^{-(\Delta m + \mu_e)/kT_f} = e^{-\frac{\Delta m}{kT}} e^{-\xi_e}$$

$$= \frac{n}{p}(\xi_e = 0)\, e^{-\xi_e}$$

Exponential Dependence!

Neutrino Oscillations / Mixing

Abazajian, Beacom, & Bell (2002)
Dolgov et al. (2002)
Wong (2002)

Complex evolution of ν_e, ν_μ, ν_τ ...

Large Mixing Angles yield "equilibration"

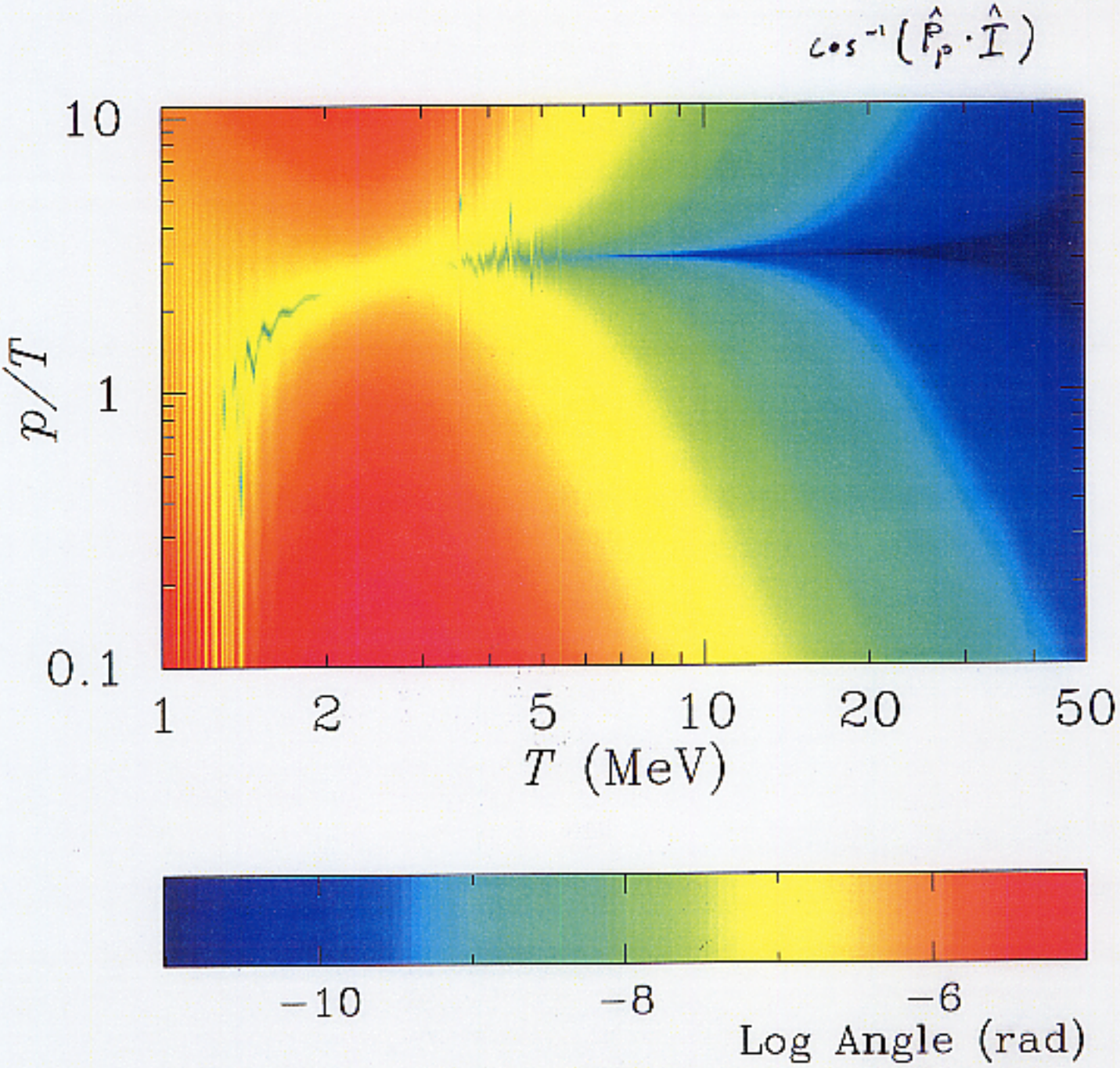
$$\xi_e \approx \xi_\mu = \xi_\tau \approx \overline{\Sigma \xi_i}$$

Oversimplified!

Bottom Line: Strong Constraint on ξ_e can be applied to ξ_μ and ξ_τ

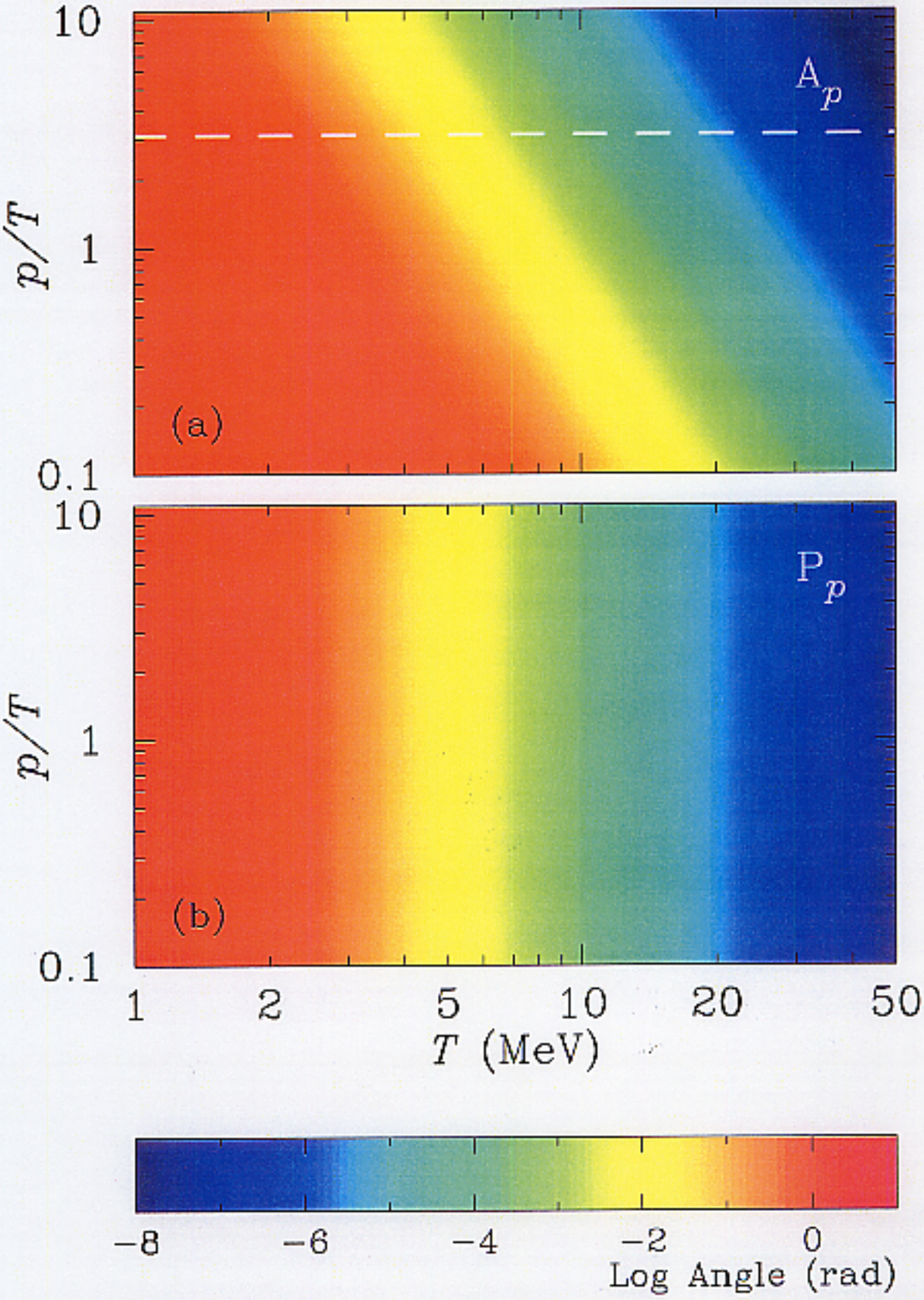
ABB find: $|\xi_e^f| \leq 0.04$

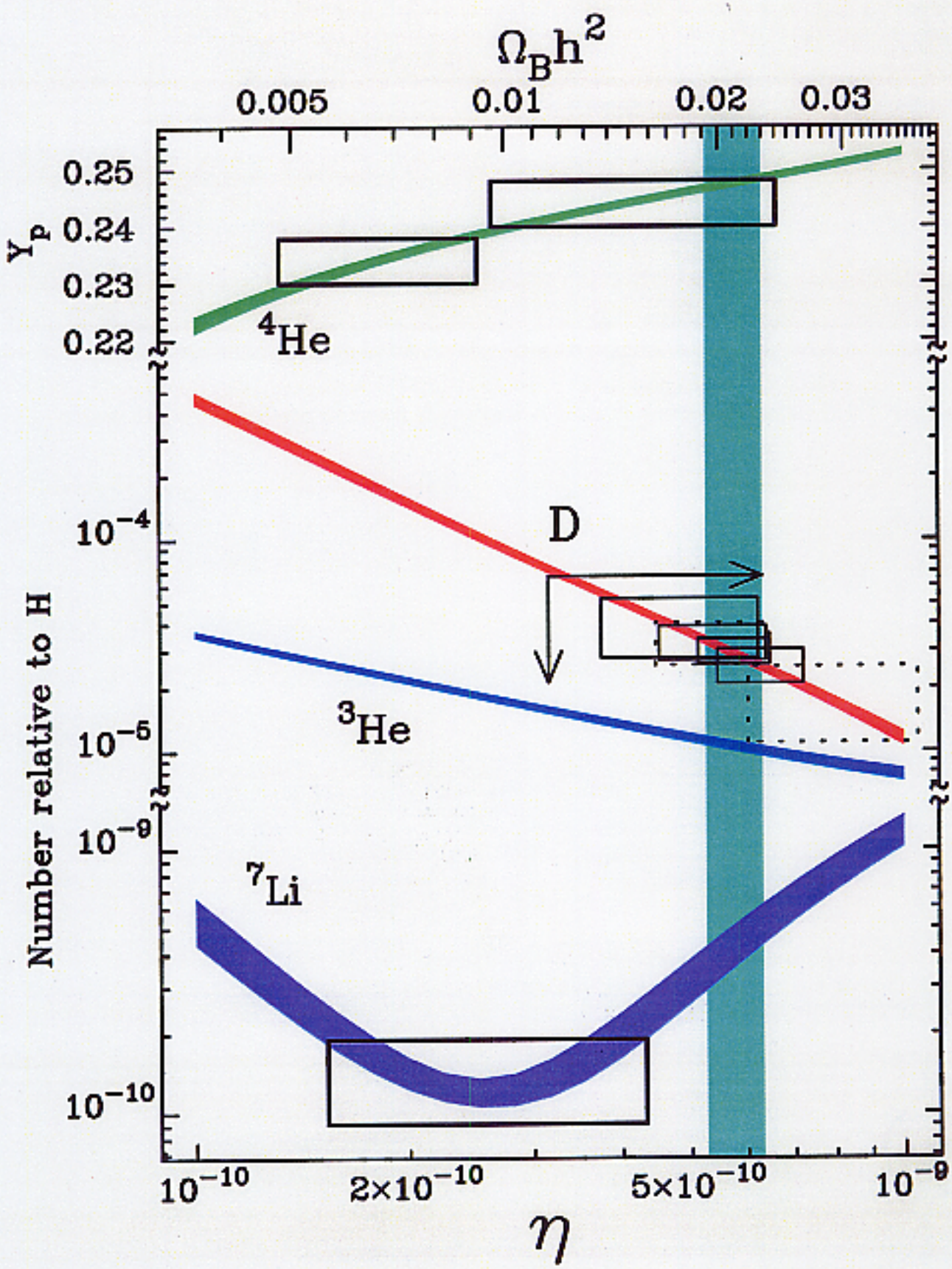
$$|\xi_\mu + \xi_\tau| \leq 0.5$$



Abazajian, Beacom & Bell (2002)

Abachjian, Beacom, Bell '02




$\Omega_B h^2$
0.005
0.01
0.02
0.03
Y_p
0.25
0.24
0.23
0.22
^{4}He
D
^{3}He
^{7}Li
Number relative to H
10^{-4}
10^{-5}
10^{-9}
10^{-10}
10^{-10}
2×10^{-10}
5×10^{-10}
10^{-9}
η

FRW BBN 2002 Scorecard

at $\eta = 5.8 \times 10^{-10}, N_\nu = 3$

	ΔN_ν	$\Delta \xi_e$	$\Delta \eta/\eta$	Observ	Nuclear
	1.0	0.1	10%	Uncertainty	
Y_p	0.014	-0.024	0.001	0.01	0.001
%^{4}He	6	-10	0.4	4	0.4
%D	13	-5	-18	15	6
%^{7}Li	-10	-7	25	$\simeq 30$	20
%^{3}He	5	-2	-6	$\simeq 50$	6