Low reheating temperature and thermalization of neutrino background in the early universe

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Introduction

◇ Standard cosmology

Hot big-bang universe

- BBN ($T \lesssim \mathcal{O}(1)$ MeV, $t \gtrsim 1$ sec) in RD
- CMB ($T \sim \mathcal{O}(1)$ 0.1 eV) in MD
- LSS ($T \lesssim \mathcal{O}(1)$ 0.1 eV) in MD

◇ Modern cosmology

Inflation scenario in supergravity

i) Entropy production after inflation (reheating)

Decay of inflaton field MD $\longrightarrow$ RD

inflaton → photon

ii) Late-time Entropy production

Decay of long-lived massive particle

$*$ gravitino $\psi_{3/2}$

$*$ moduli (dilaton) ϕ

$$\tau_\phi \simeq \mathcal{O}(1)\,\mathrm{sec}\left(m_\phi/100\mathrm{TeV}\right)^{-3}$$

$$\Downarrow$$

BBN is spoiled for $m_\phi \sim 1$ TeV? (Moduli problem)

$\boxed{\text{MD} \longrightarrow \text{RD (Hot big bang universe)?}}$

Neutrino thermalization is subtle for $T_R \simeq \mathcal{O}(1)$ MeV

Reheating temperature T_R and BBN

$$\Gamma \equiv 3H(T_R) = 1/\tau$$

$$T_R = 0.6\sqrt{\Gamma M_G} \qquad (1/\tau \leftrightarrow T_R)$$

$$\left(\because \quad H^2 = \frac{g_* \pi^2}{90}\frac{T^4}{M_G^2} \quad (\mathrm{RD}) \right)$$

i) Upper bound of T_R

To avoid gravitino over production

$$T_R \lesssim 10^7 - 10^9 \ \mathrm{GeV}$$

for $m_{3/2} = 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$

J. Ellis et al. (1992)
Holtmann, Kawasaki, Kohri, Moroi (1999)
Bolz, Brandenburg, Buchmuller (2001)

ii) Lower limit of T_R

① Background neutrinos are thermalized?

e^+e^-, γ are thermalized rapidly

($\because$ ν decoupling is at $T \simeq 2-3$ MeV)

Kawasaki, Kohri, Sugiyama (1999)

② Produced hadrons raise n/p

Kawasaki, Kohri, Sugiyama (2000)

cf)

more precise computation of ν thermalization,

Giudice, Kolb, Riotto, Semikoz, Tkachev (2001)

§ Neutrino thermalization & BBN

If Neutrino background is not sufficiently thermalized,

i) Weak Interaction Rate is modified

$$n + \nu_e \longleftrightarrow p + e^-$$
$$n + e^+ \longleftrightarrow p + \overline{\nu_e}$$
$$n \longleftrightarrow p + e^- + \overline{\nu_e}$$

$$\Gamma_{n\nu\to pe} \sim \int_0^\infty dp_\nu \sqrt{(Q+p_\nu)^2 - m_e^2}\,(p_\nu+Q)\,p_\nu^2\,(1-g_e(p_\nu))\,f_{\nu_e}(p_\nu)$$

$f_{\nu_e}(p_\nu) \downarrow \;\Rightarrow\; \Gamma_{n\leftrightarrow p} \downarrow \;\Rightarrow\;$ freezeout earlier

$\Rightarrow (n/p)_f \uparrow \;\Rightarrow\; Y \uparrow$

$$\boxed{\Delta Y \simeq +0.19 \left(-\frac{\Delta\Gamma_{n\leftrightarrow p}}{\Gamma_{n\leftrightarrow p}}\right)}$$

ii) Neutrino Energy density

$$N_\nu^{eff} \equiv \frac{\rho_{\nu_e}+\rho_{\nu_\mu}+\rho_{\nu_\tau}}{\rho_\nu^{STD}} \le 3 \;?$$

$\rho_\nu \downarrow \;\Rightarrow\; H(T_\gamma) \downarrow \;\Rightarrow\;$ freeze out later

$\Rightarrow (n/p)_f \downarrow \;\Rightarrow\; Y \downarrow$

$$\Delta Y \simeq -0.1 \left(-\frac{\Delta\rho}{\rho}\right)$$

Boltzmann Equation

$$\frac{\partial f_{\nu_i}(p,T)}{\partial t} - H(t)\, p_1 \frac{\partial f_{\nu_i}(p,T)}{\partial p_1} = I_{coll}$$

$$I_{coll} = \frac{1}{2E_1} \iiint d^3\hat{p}_2\, d^3\hat{p}_3\, d^4\tilde{p}_4\, (2\pi)^4 \delta^{(4)}(p_1+p_2-p_3-p_4)\, S\, |M|^2_{12\to 34}\, F(f_1,f_2,f_3,f_4)$$

$$d^3\hat{p}_i \equiv \frac{d^3 p_i}{2E_i (2\pi)^3}$$

$$F(f_1, f_2, f_3, f_4) = f_3 f_4 (1-f_1)(1-f_2) - f_1 f_2 (1-f_3)(1-f_4)$$

S: symmetrization factor

$|M|$: Scattering amplitude

① annihilation ($e^+e^- \leftrightarrow \nu\bar{\nu}$)

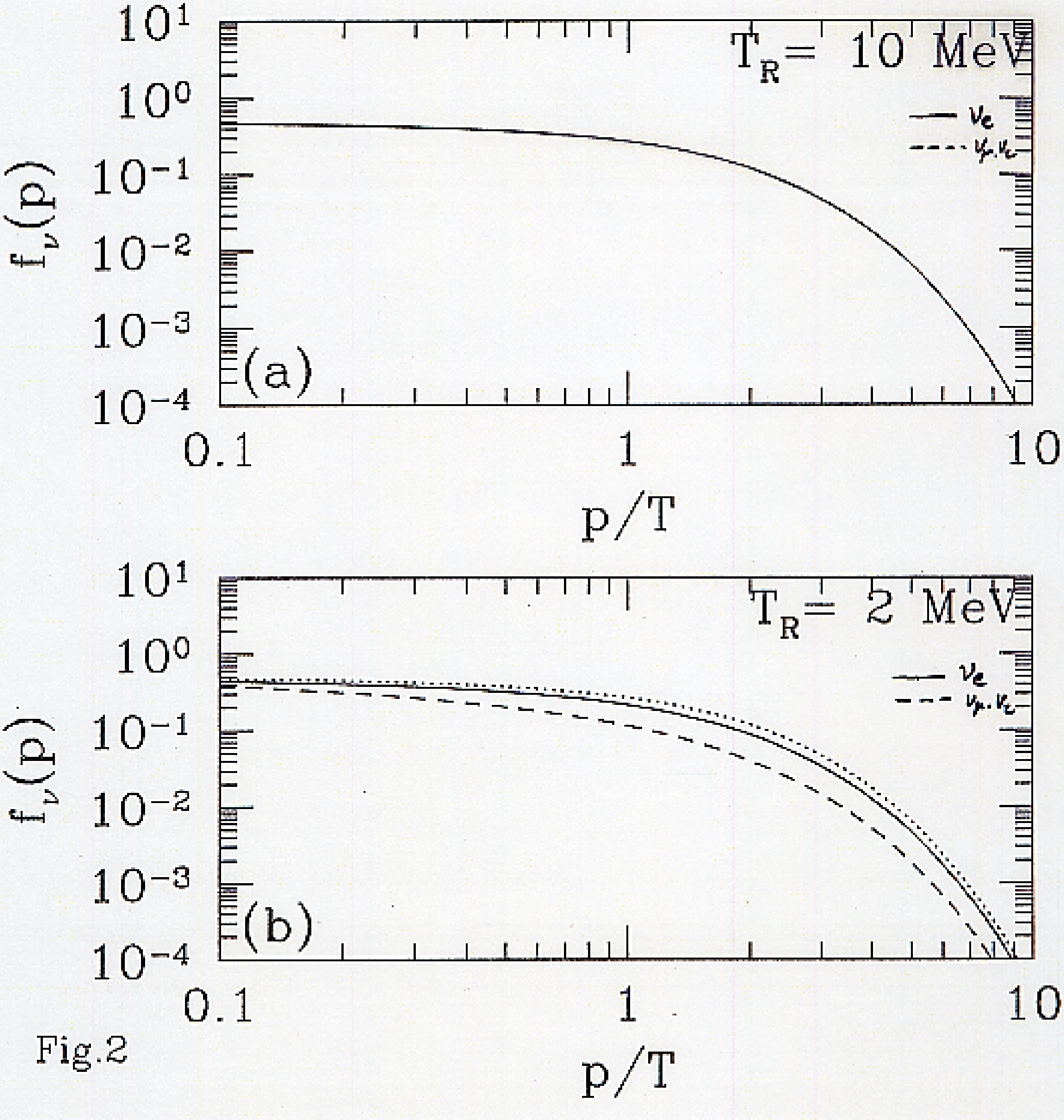
$$S|M|^2 = 32 G_F^2 \left[(C_V+C_A)^2 (p_1\cdot p_4)^2 + (C_V-C_A)^2 (p_1\cdot p_3)^2 \right]$$

② Scattering ($\nu e^\pm \leftrightarrow \nu e^\pm$)

$$S|M|^2 = 64 G_F^2 (C_V^2 + C_A^2)\left[(p_1\cdot p_2)^2 + (p_1\cdot p_4)^2 \right]$$

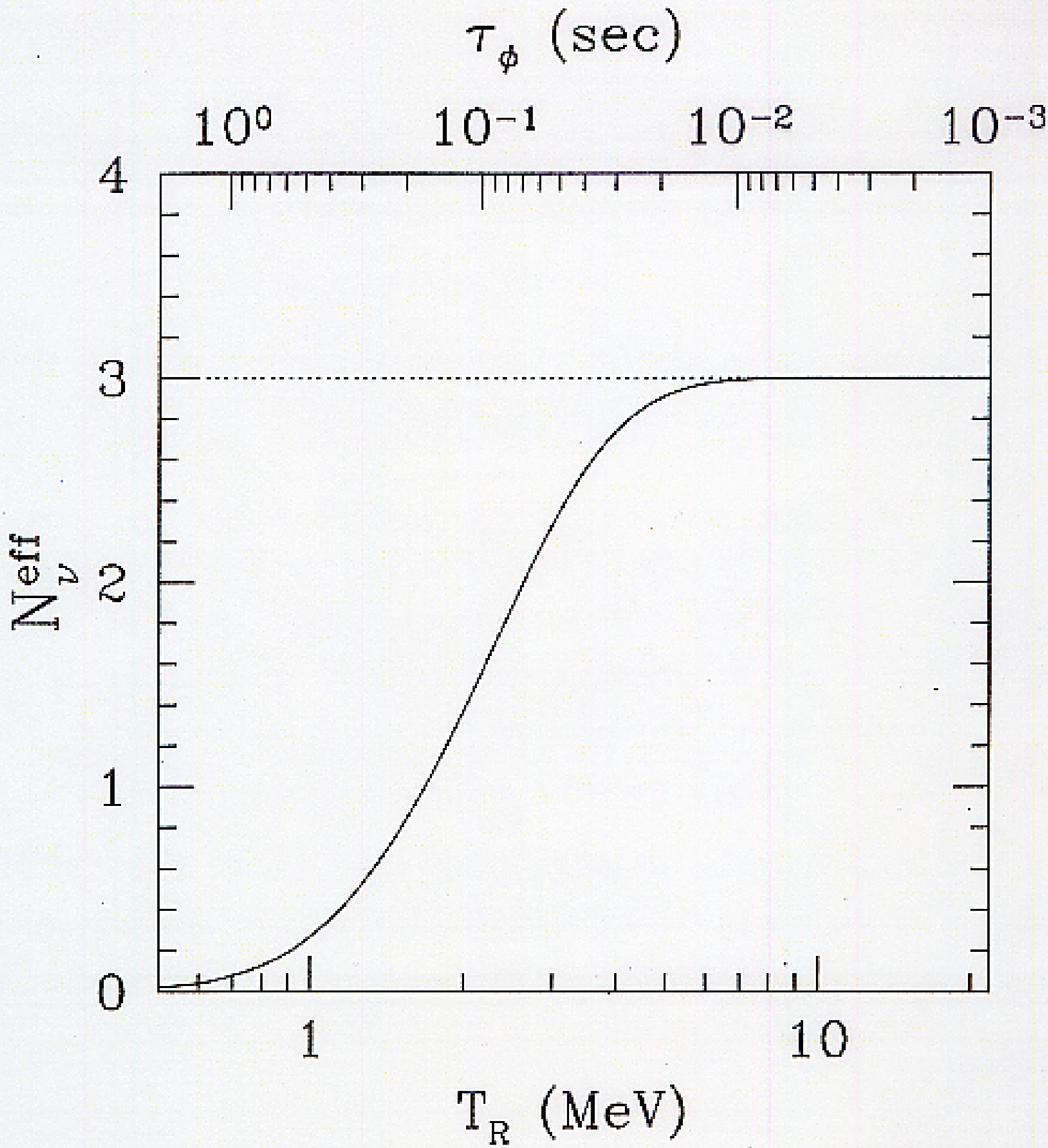
$$\begin{cases} C_V = \frac{1}{2} + 2\sin^2\theta_W \\ C_A = 1/2 \end{cases} \quad \text{for } \nu_e$$

$$\begin{cases} C_V = -\frac{1}{2} + 2\sin^2\theta_W \\ C_A = -\frac{1}{2} \end{cases} \quad \text{for } \nu_\mu, \nu_\tau \qquad (\sin^2\theta_W \simeq 0.231)$$



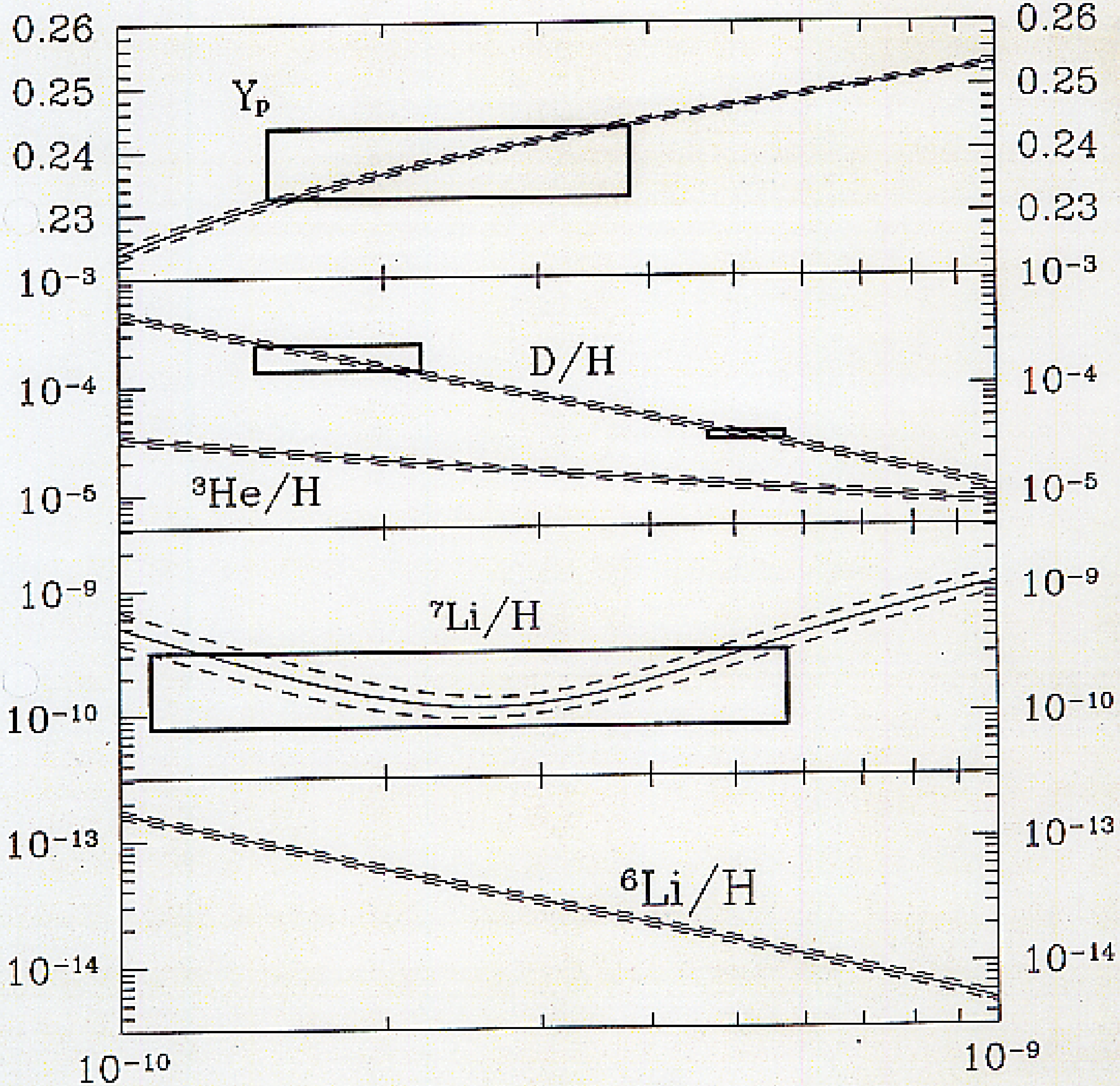
$T_R = 10$ MeV
ν_e
ν_μ, ν_τ
(a)
$f_\nu(p)$
p/T
$T_R = 2$ MeV
ν_e
ν_μ, ν_τ
(b)
$f_\nu(p)$
p/T

Fig.2



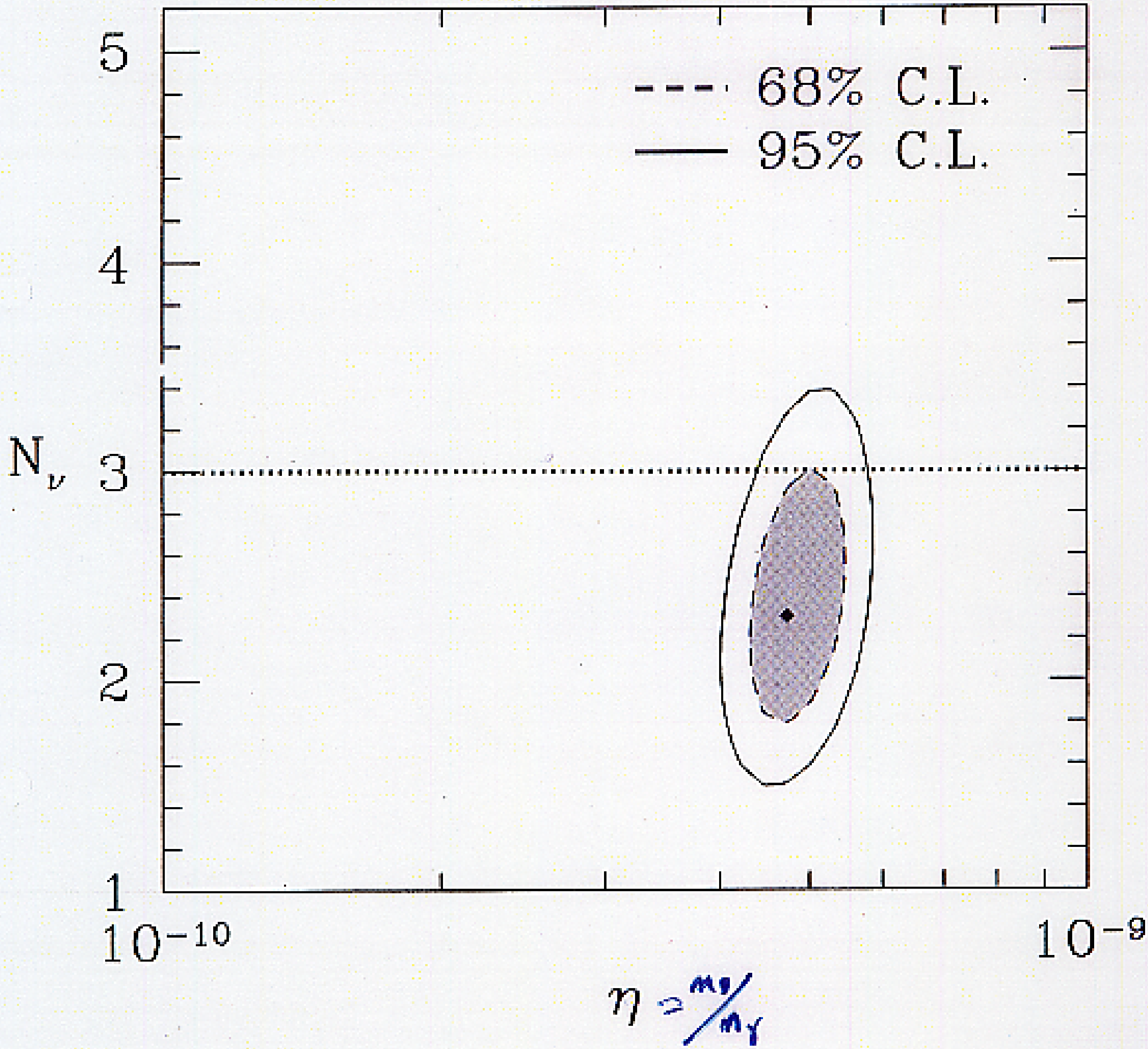
τ_ϕ (sec)
10^0
10^{-1}
10^{-2}
10^{-3}
4
3
2
1
0
N_ν^{eff}
1
10
T_R (MeV)

$Y_p = 0.238 \pm 0.002 \pm 0.005$

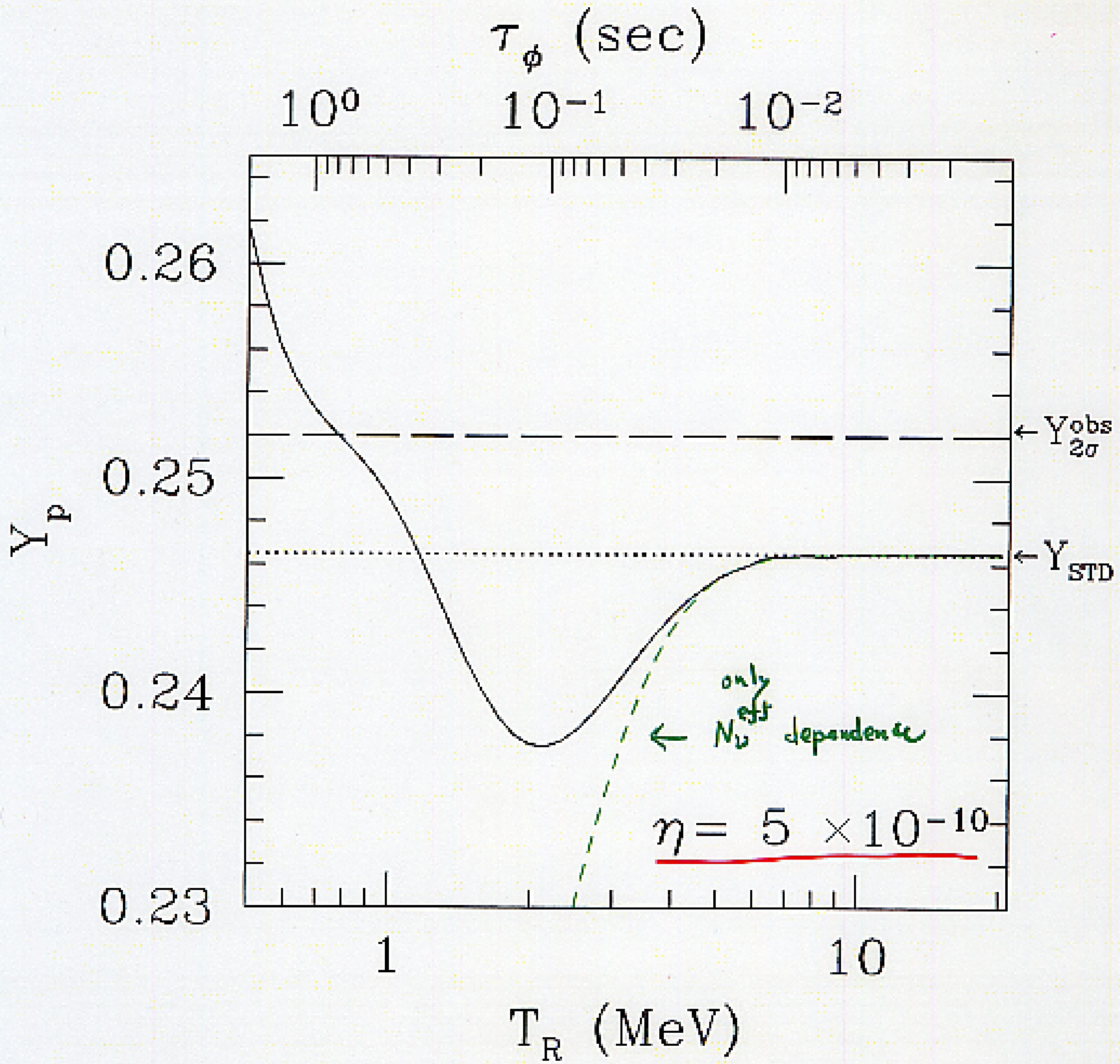


$\eta = \frac{n_B}{n_\gamma}$

$\Omega_B h^2 = 0.02 \left(\frac{\eta}{5\times10^{-10}}\right)$

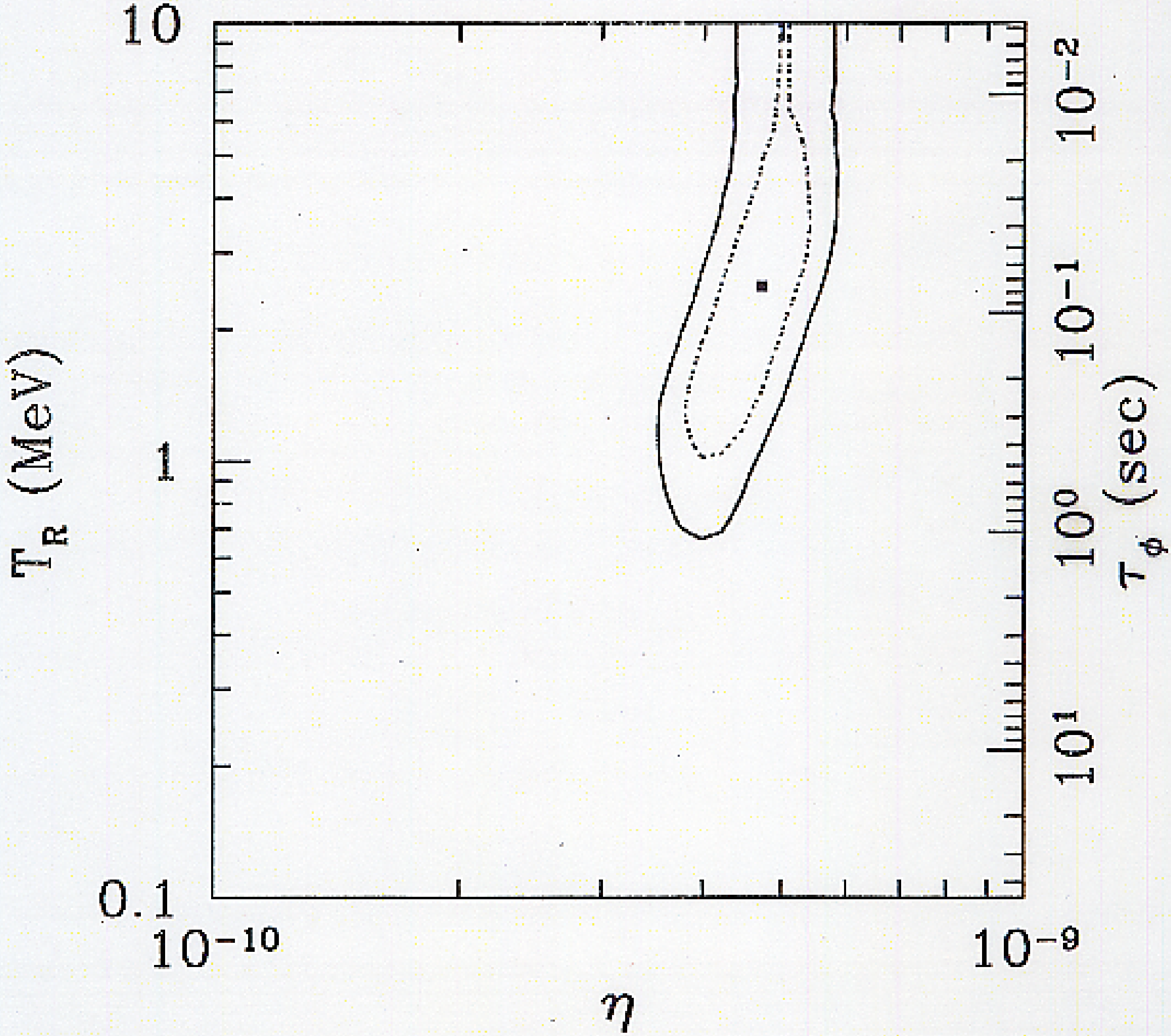


68% C.L.
95% C.L.
N_ν
5
4
3
2
1
10^{-10}
10^{-9}
$\eta = m_B / m_\gamma$

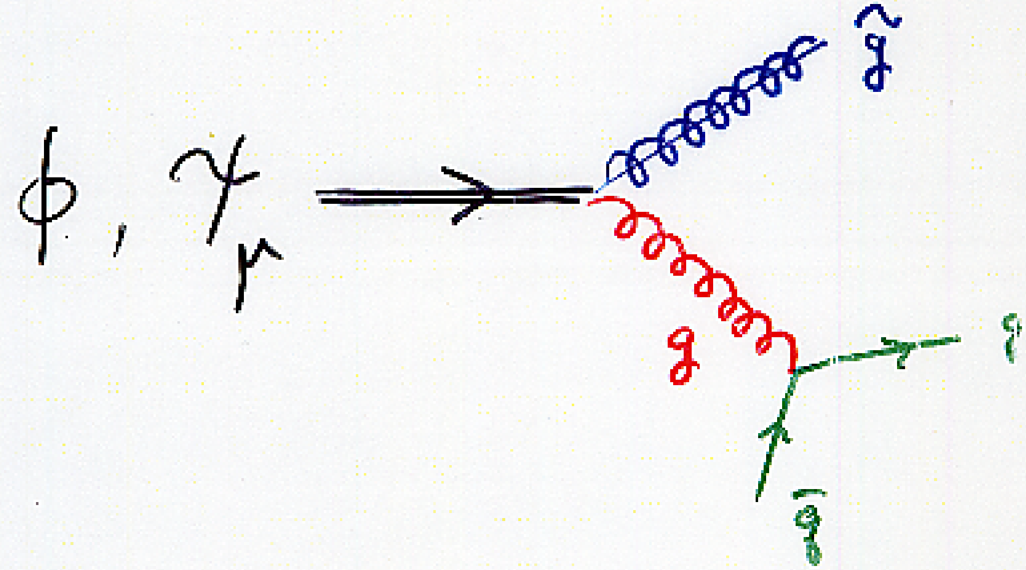


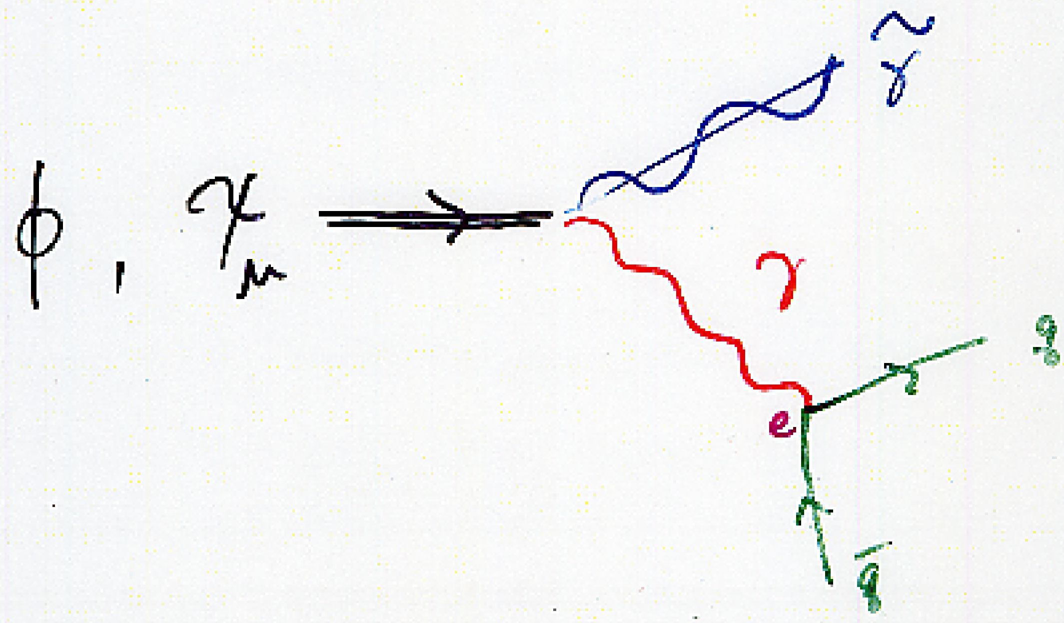
τ_ϕ (sec)
10^0
10^{-1}
10^{-2}
0.26
0.25
0.24
0.23
Y_p
$\leftarrow Y_{2\sigma}^{obs}$
$\leftarrow Y_{STD}$
only
$\leftarrow N_\nu^{eff}$ dependence
$\eta = 5 \times 10^{-10}$
1
10
T_R (MeV)

Kawasaki, Kohri, Sugiyama (1999)
PRL 82, 4168
PRD 62, 023506, (2000)



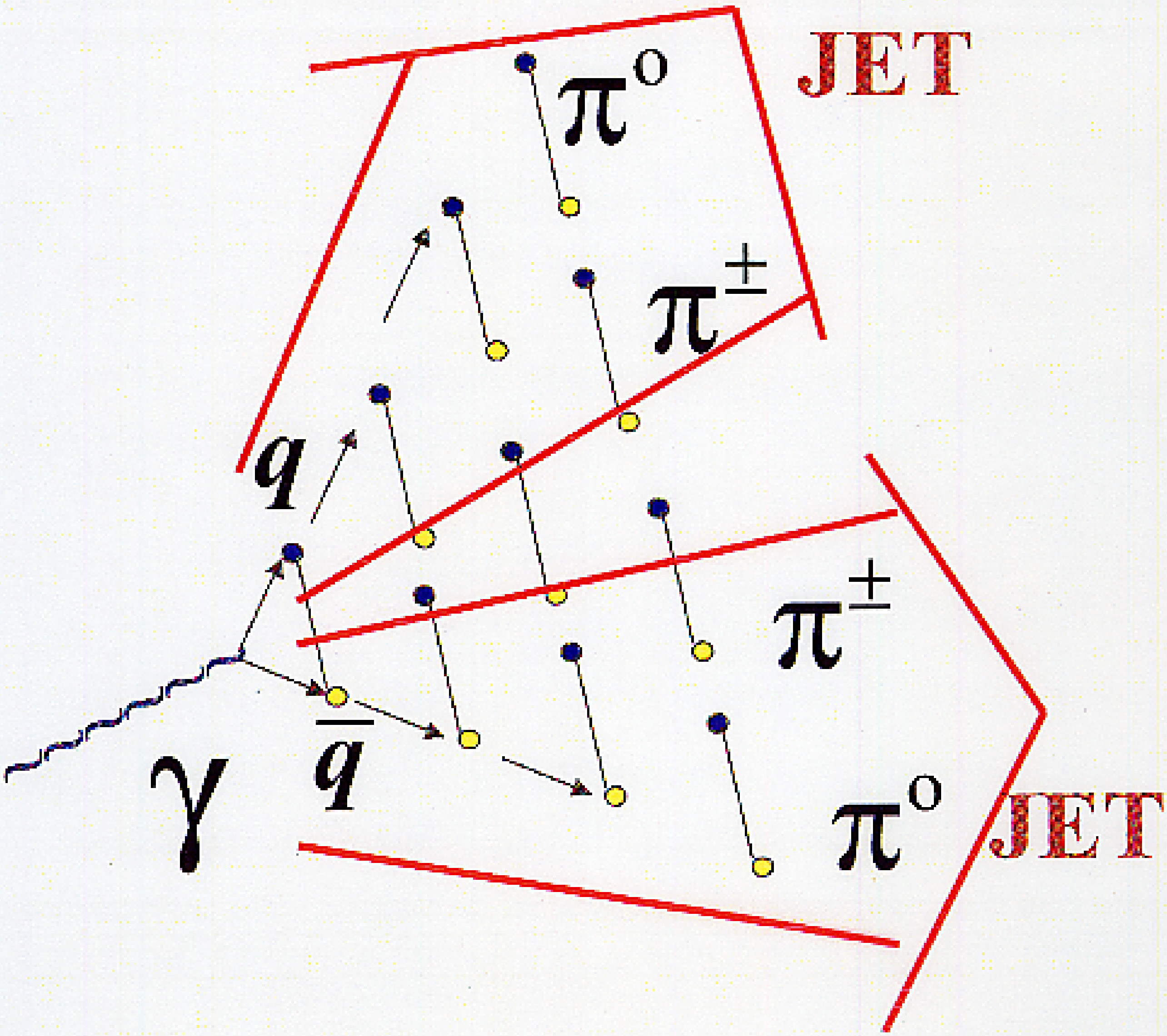
§ Hadronic decay & Reheating





$$B_h \gtrsim \frac{e^2}{4\pi} \simeq \alpha \sim 0.01$$

Quark Emission and Hadron Jets

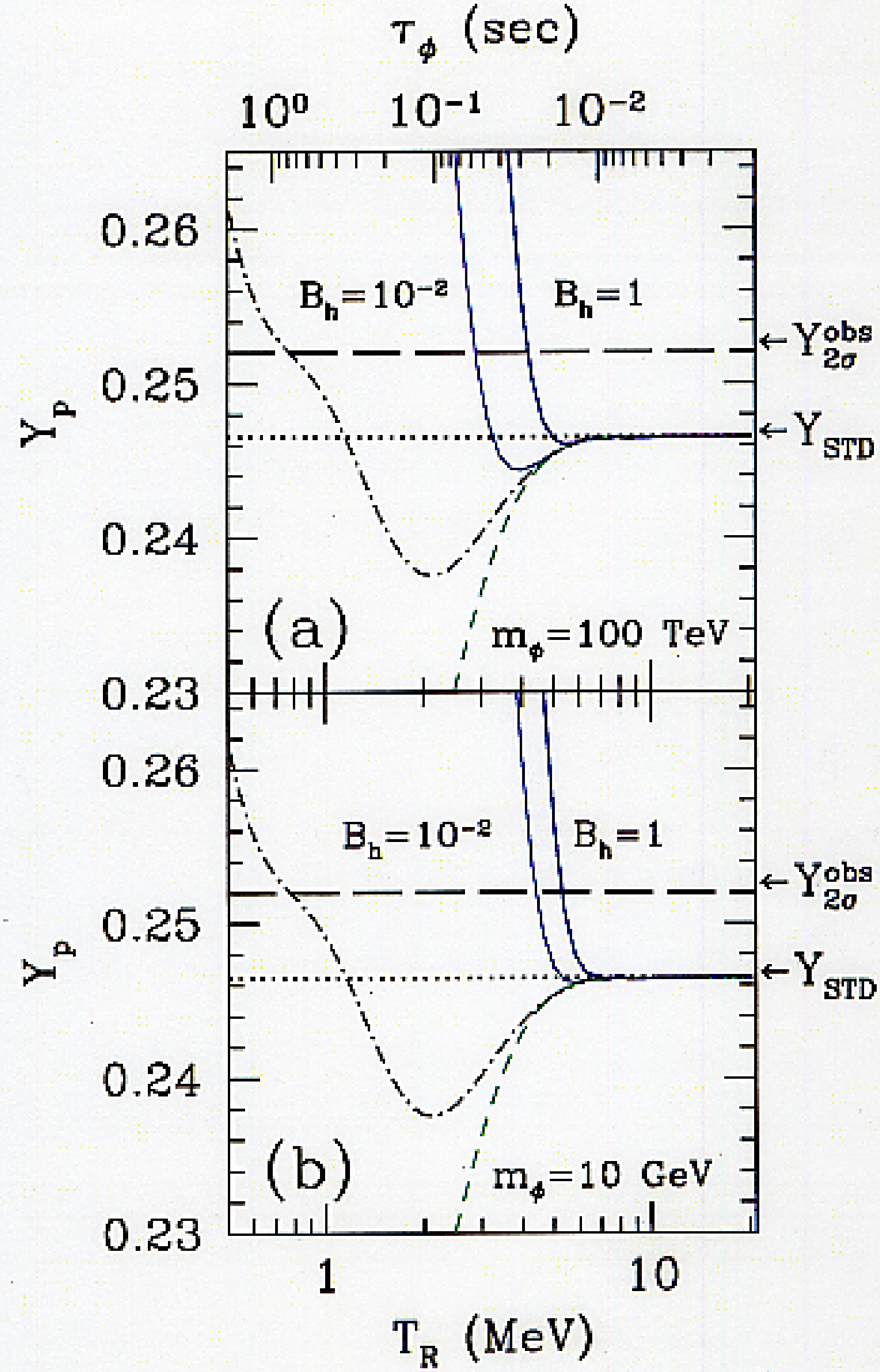


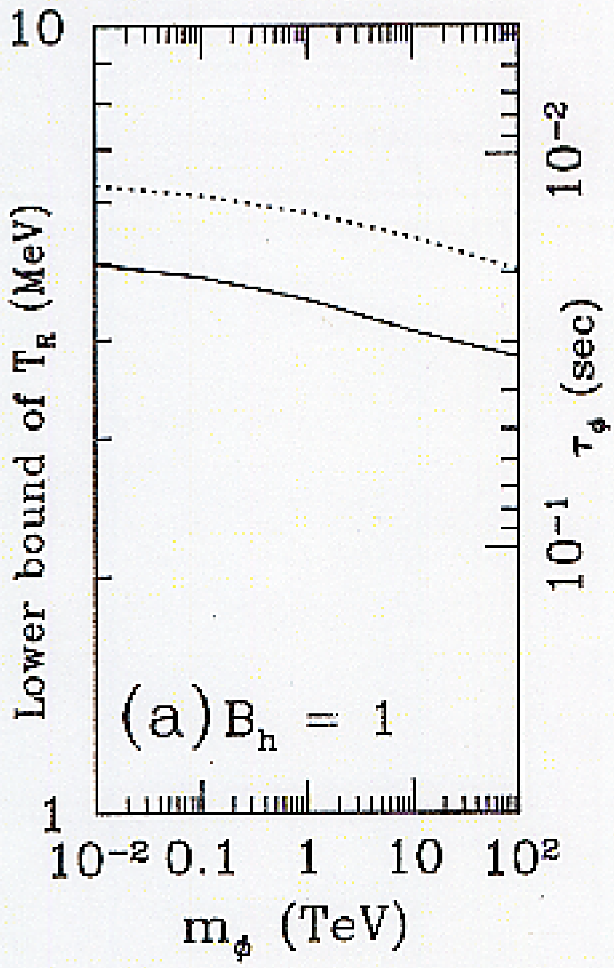
$q = \mathrm{u, d, s, \ldots}$

$\pi^+ + n \longrightarrow p + \pi^0$

$\pi^- + p \longrightarrow n + \pi^0$ 入れ換える!

$$Y_\phi \equiv \frac{m_\phi}{s} \approx \frac{T_R^4/m_\phi}{T_R^3} \sim \frac{T_R}{m_\phi}$$





10
1
Lower bound of T_R (MeV)
10^{-2}
10^{-1}
τ_ϕ (sec)
(a) B_h = 1
10^{-2} 0.1 1 10 10^2
m_ϕ (TeV)
10
1
Lower bound of T_R (MeV)
10^{-2}
10^{-1}
τ_ϕ (sec)
(b) B_h = 0.01
10^{-2} 0.1 1 10 10^2
m_ϕ (TeV)

Constraints from LSS

fitting of galaxy power spectrum

Shape parameter

$$\Gamma_S \equiv \Omega_0 h = 0.20 \pm 0.03$$

Percival et al, 2dF collaboration (2002)

If N_ν^{eff} is changed from Late-time entropy production

$\Downarrow$

Matter radiation equality epoch is modified.

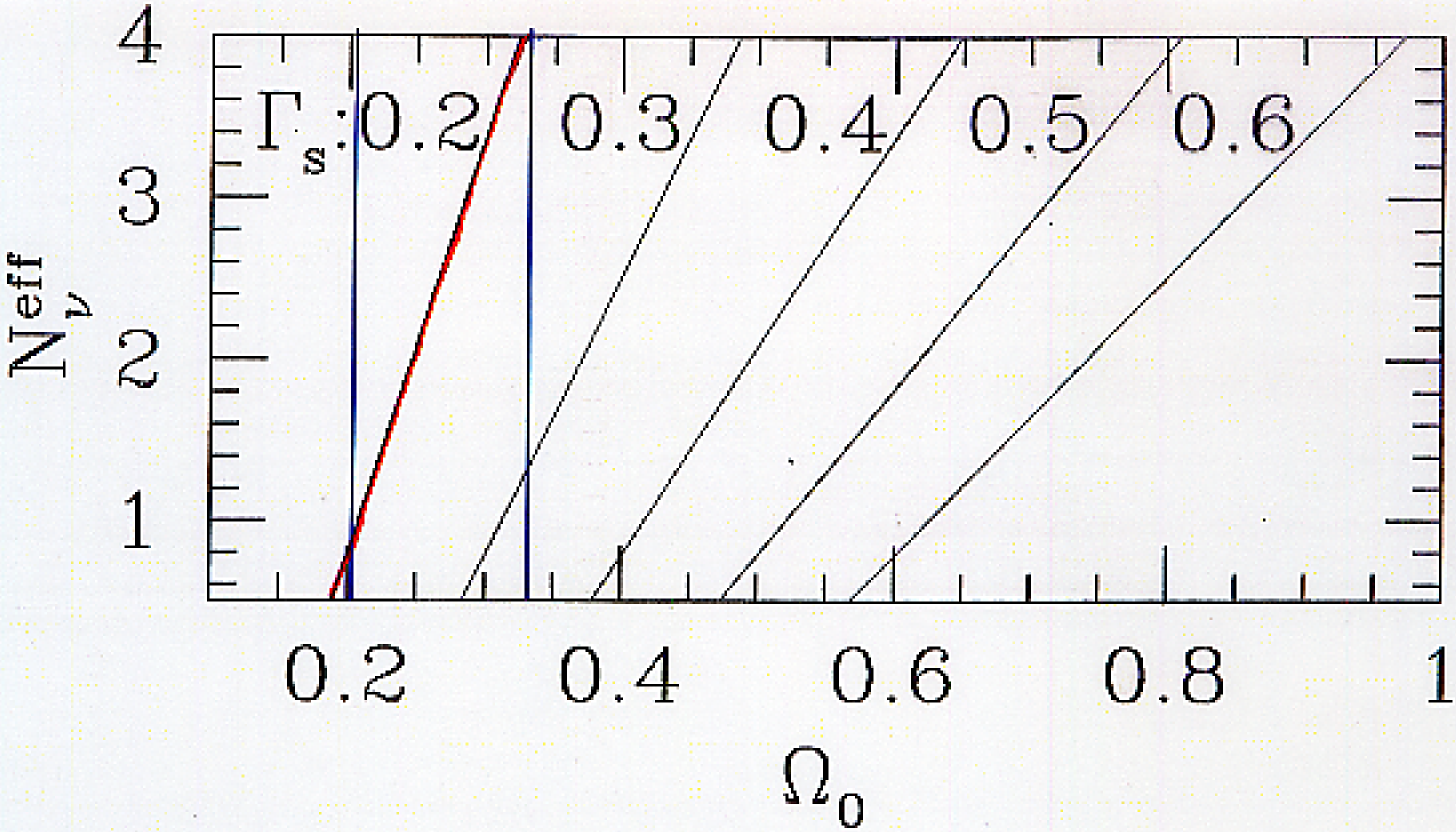
$$\Gamma_S \simeq \frac{1.68\,\Omega_0 h}{(1+0.23\,N_\nu^{eff})}$$

$$\left(\simeq \Omega_0 h \text{ for } N_\nu^{eff} = 3 \right)$$

Now,

$$\Omega_m = 0.27 \pm 0.06$$

Verde et al (2dF) (2002)



Low N_ν^{eff} favors low Ω_0 !

Constraints from CMB

Matter - radiation equality epoch is changed

⇓

Power spectrum of CMB anisotropy is affected

$$T(\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

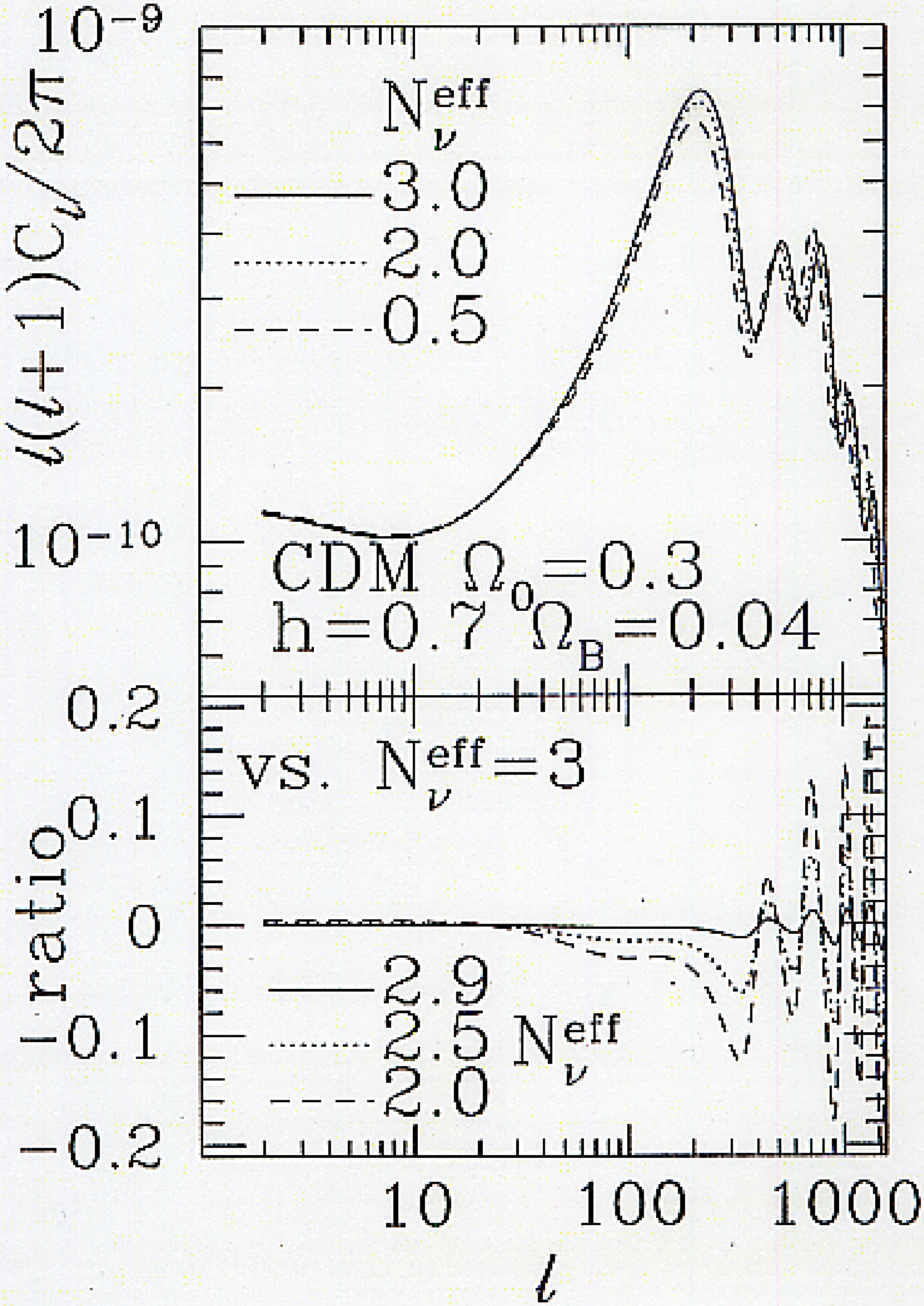
$$C_l \equiv \langle a_{lm} a_{lm}^{*} \rangle$$

Future satellite experiments have

δN_ν^{eff} sensitivities

Lopez, Dodelson, Heckler & M. Turner (1998)

δN_ν sensitivity	only C_l	including polarization
MAP ($l_{max} \simeq 1000$)	0.5	0.15
PLANCK ($l_{max} \simeq 2500$)	0.08	0.03



10^{-9}
10^{-10}
$l(l+1)C_l/2\pi$
N_ν^{eff}
3.0
2.0
0.5
CDM $\Omega_0=0.3$
$h=0.7$ $\Omega_B=0.04$
0.2
0.1
0
-0.1
-0.2
ratio
vs. $N_\nu^{eff}=3$
2.9
2.5 N_ν^{eff}
2.0
10
100
1000
l

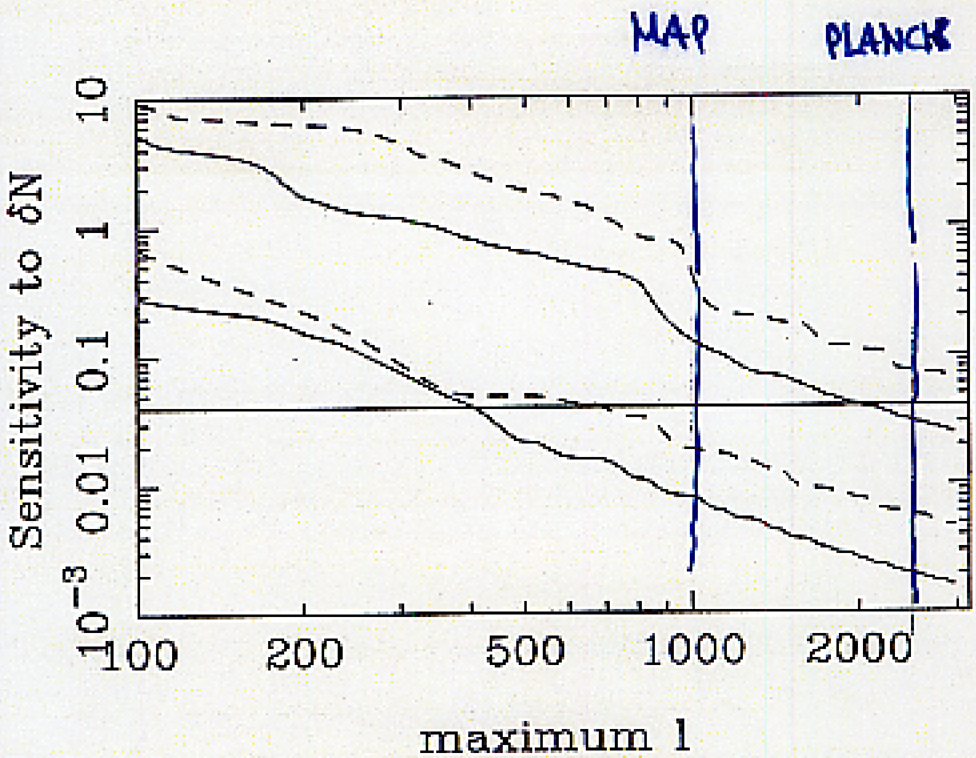


Figure 3: One-σ sensitivity to δN_ν, for an experiment cosmic-variance limited up to some maximum multipole moment. The horizontal line, $\delta N_\nu = 0.04$, is the change in effective number of neutrino families due to neutrino heating and the QED effect. The bottom two curves are for the case where all cosmological parameters except N_ν are fixed, while the top curves represent the case where all parameters are determined simultaneously. For each group, the dashed line shows the results using only temperature anisotropy data, while the solid line shows the improvement obtained by including polarization data in the analysis.

Conclusions

1) For successful BBN,

$$\begin{cases} \underline{T_R \gtrsim 0.7 \text{ MeV}} & (\text{for } B_\gamma = 1) \\ \underline{T_R \gtrsim 2.5\text{-}4 \text{ MeV}} & (\text{for } B_h = 0.01 - 1) \end{cases}$$

2) Galaxy survey gives informations for neutrino thermalization.

3) Future statellite experiments of CMB anisotropies (MAP, PLANCK) will detect the modification on N_ν^{eff}.