ニュートリノ と 宇宙論

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PLAN OF THIS TALK

1. INTRODUCTION
2. BBN AND NEUTRINO
3. LARGE SCALE STRUCTURE AND ν
4. RECENT CMB DATA AND ν
5. MeV REHEATING AND ν
6. SUMMARY

INTRODUCTION

ニュートリノ

- ニュートリノの種類の数
- 質量
- フレーバー MIXING
- レプトン数の破れ

⋮

⇓

宇宙論に大きな影響を与える

- 宇宙初期の元素合成
- ダークマター
- 宇宙の構造形成
- 宇宙背景輻射

⋮

→ ニュートリノ宇宙にとって重要な構成要素

2. BIG BANG NUCLEOSYNTHESIS AND ν (BBN)

BBN : ONE OF MAIN BASES TO SUPPORT STANDARD MODEL

$$2n + 2p \longrightarrow {}^4He$$

$T \sim 1\,MeV - 10\,keV$

$(+\ D,\ {}^3He,\ {}^7Li)$

SUCCESSFULLY PREDICTS ABUNDANCES OF LIGHT ELEMENTS

STANDARD BBN

ONLY ONE FREE PARAMETER

$$\boxed{\eta \equiv \frac{n_b}{n_\gamma}}$$ BARYON-PHOTON RATIO

THEORY + OBSERVATION

$$\longrightarrow \eta \sim 10^{-10}$$

OBSERVATION

^4He RECOMBINATION LINES FROM METAL-POOR EXTRA GALACTIC HII RESION

OLIVE, STEIGMAN, WALKER (2000)

$$Y \equiv \frac{\rho_{^4He}}{\rho_{tot}} = 0.238 \pm 0.05$$

D QUASAR ABSORPTION LINES

Burles, Tytler (1997)

$$D/H = (3.4 \pm 0.3) \times 10^{-5}$$

LOW D

Webb et al (1997)

$$D/H = (2.0 \pm 0.5) \times 10^{-4}$$

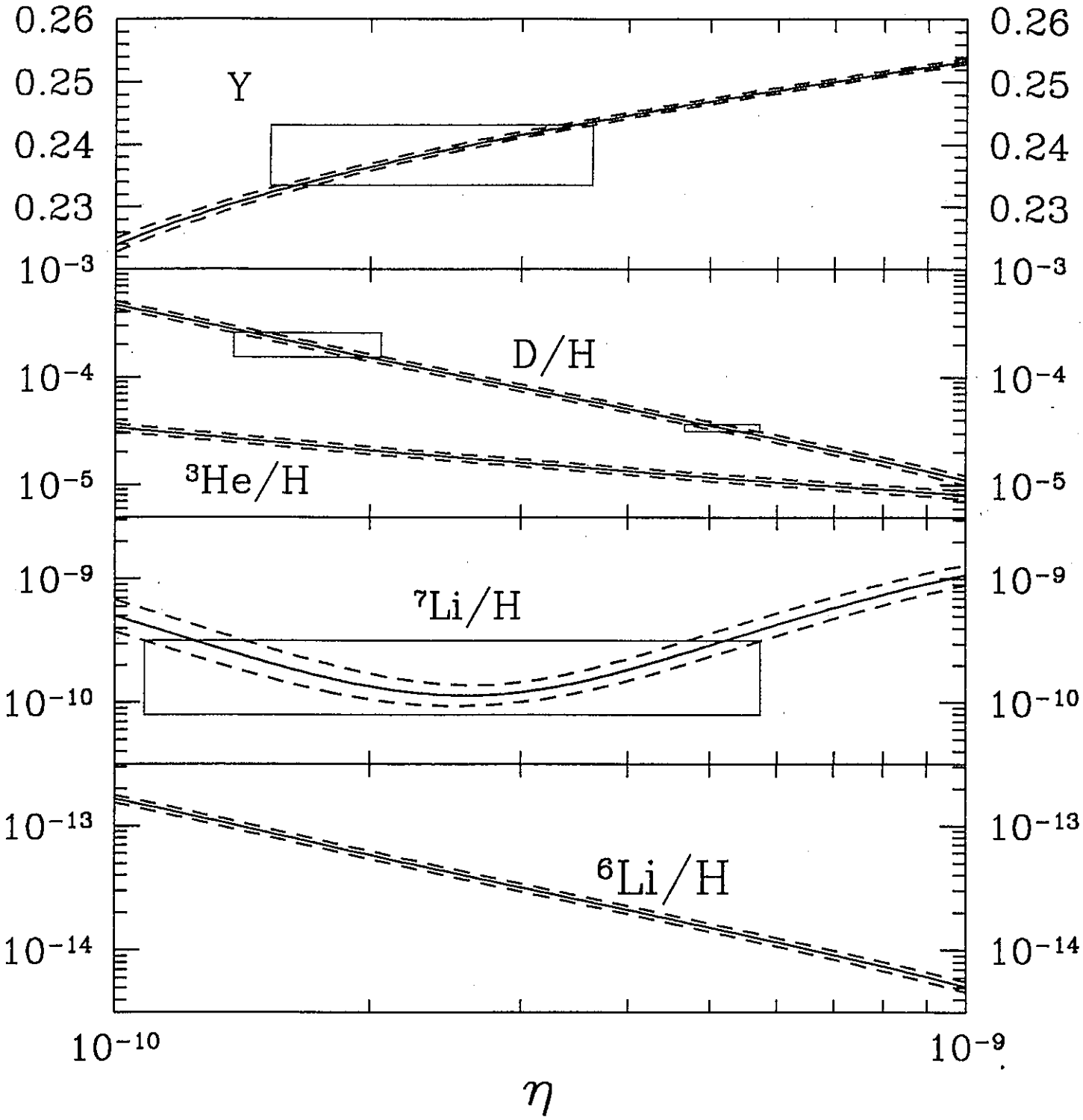
HIGH D

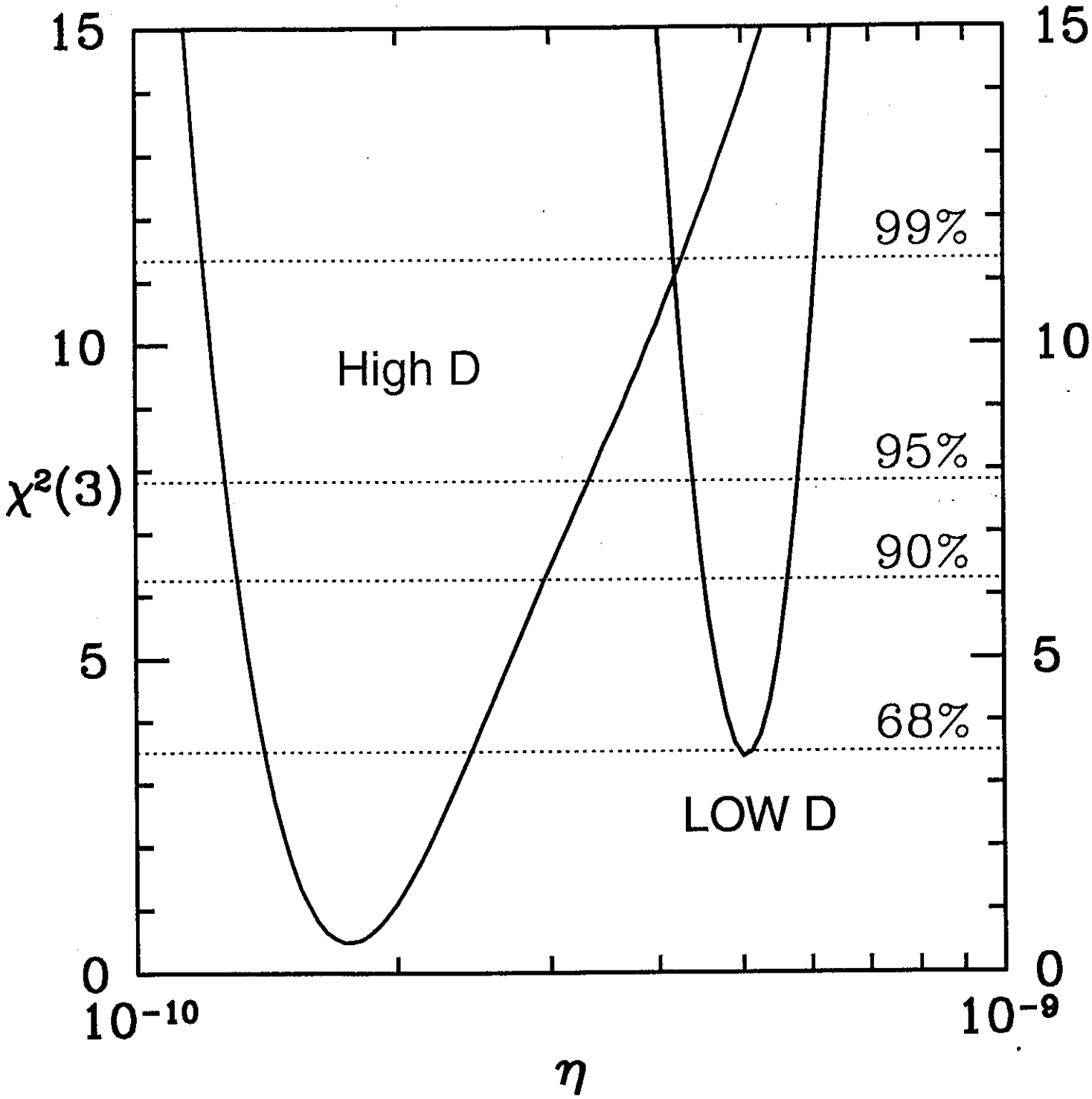
BIG DIFFERENCE

^7Li METAL POOR POP II STARS

Malaro, Primas, Bonifacio (1995)

$$^7Li/H = (1.6 \pm 0.1) \times 10^{-10}$$


0.26
0.25
0.24
0.23
Y
10^{-3}
10^{-4}
10^{-5}
D/H
^{3}He/H
10^{-9}
10^{-10}
^{7}Li/H
10^{-13}
10^{-14}
^{6}Li/H
10^{-10}
10^{-9}
η


15
10
5
0
15
10
5
0
$\chi^2(3)$
99%
95%
90%
68%
High D
LOW D
10^{-10}
10^{-9}
η

STANDARD BBN $(N_\nu = 3)$

↑ # OF NEUTRINO SPECIES

BEST FIT

$$\eta = 5.0 \times 10^{-10} \quad \text{(LOW D)}$$

$$= 1.7 \times 10^{-10} \quad \text{(HIGH D)}$$

95% CL

$$\eta = (4.4 - 5.8) \times 10^{-10} \quad \text{(LOW D)}$$

$$= (1.3 - 3.3) \times 10^{-10} \quad \text{(HIGH D)}$$

$$\Rightarrow \Omega_b h^2 = 3.7 \times 10^7 \eta \leq 0.022$$

$$\Omega_b \equiv \frac{\rho_b}{\rho_{cr}} \quad (\rho_{cr} : \text{CRITICAL DENSITY})$$

$$h \equiv H / (100\,\text{km/s/Mpc})$$

↑ HUBBLE

BBN AND NEUTRINO

BBN $\longrightarrow$ N_ν (# OF NEUTRINO SPECIES)

^{4}He ABUNDANCE $\longleftarrow$ $\frac{n}{p} \left(\equiv \frac{n_n}{n_p} \right)$

WEAK INTERACTION

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

$$e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

$T > 1$ MeV CHEMICAL EQ. ($\mu_n \simeq \mu_p$)

$\mu_\nu \simeq 0$ ASSUMED!

$$\longrightarrow \boxed{\frac{n}{p} \simeq \exp\left(-\frac{\Delta m}{T}\right)}$$

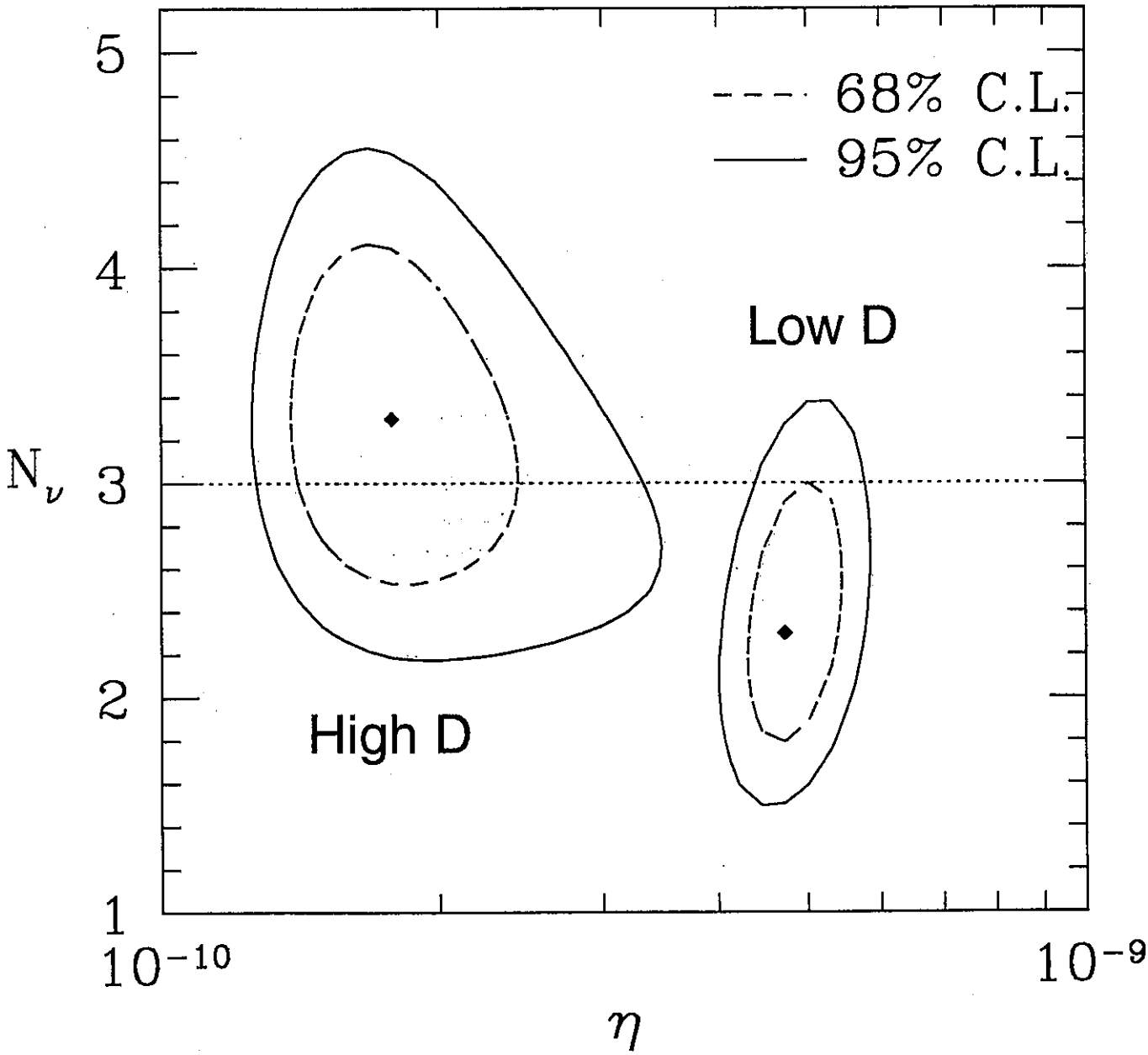
$$\Delta m = m_n - m_p = 1.293 \text{ MeV}$$

$T \sim 1$ MeV

(WEAK INT. RATE) $\sim$ (COSMIC EXPANTION RATE) $= H$

$\longrightarrow$ FREEZE-OUT OF WEAK INT. $\longrightarrow$ $\frac{n}{p}$ FIXED

$$= \exp\left(-\frac{\Delta m}{T_f}\right)$$


68% C.L.
95% C.L.
Low D
High D
5
4
3
2
1
N_ν
10^{-10}
10^{-9}
η

$$N_\nu \nearrow \longrightarrow \rho \nearrow \longrightarrow H \nearrow \longrightarrow T_f \nearrow$$

$$\longrightarrow \frac{n}{p} \nearrow \longrightarrow {}^4He \nearrow$$

CONSTRAINT ON N_ν

$\Rightarrow$

$1.4 \leq N_\nu \leq 3.4$ (LOW D)

$2.2 \leq N_\nu \leq 4.6$ (HIGH D)

(95% CL)

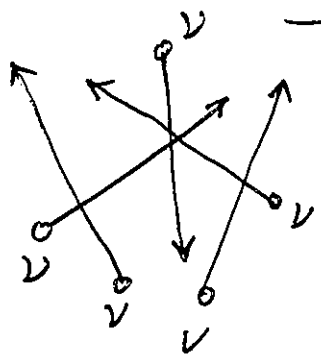
3. LARGE SCALE STRUCTURE AND ν

MASSIVE NEUTRINO $m_\nu \sim O(10)$ eV

$\longrightarrow$ HOT DARK MATTER (HDM)

"HOT" $\longrightarrow$ LARGE VELOCITY

$\longrightarrow$ FREE STREAMING MOTION



$\Big\}\ \lambda_{FS} \sim vt$

DENSITY FLUCTUATIONS OF ν WITH $\lambda \lesssim \lambda_{FS}$ ARE WASHED OUT BY ν FREE STREAMING MOTION

$$\lambda_{FS} \simeq 100\,\mathrm{Mpc} \left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^{-1}$$

$\longrightarrow$ DIFFICULT TO FORM GALAXIES $\lesssim$ 100 kpc.

$\Rightarrow$ PURE HDM ✗

(COLD + HOT) DARK MATTER MODEL
(CHDM)

BEST MODEL FOR LSS ($\Omega_\nu = 0.2$, $\Omega_c = 0.8$?, $\Omega_B = 0.1$)

$\downarrow$

$m_\nu \simeq 5\,eV$

Gawiser, Silk (1988)

HOWEVER

HIGH REDSHIFT SN DATA

Riess et al AJ. 116 (1998) 1009
Perlmutter et al ApJ. 517 (1999) 565

STRONGLY SUGGEST COSMOLOGICAL CONSTANT

$\Omega_\Lambda \gtrsim 0.5$ ← COSMOLOGICAL CONST.

$\Omega_m \lesssim 0.5$ ← MATTER (DM + BARYON)

⇒ CHDM DOES NOT GIVE A GOOD FIT

FURTHERMORE

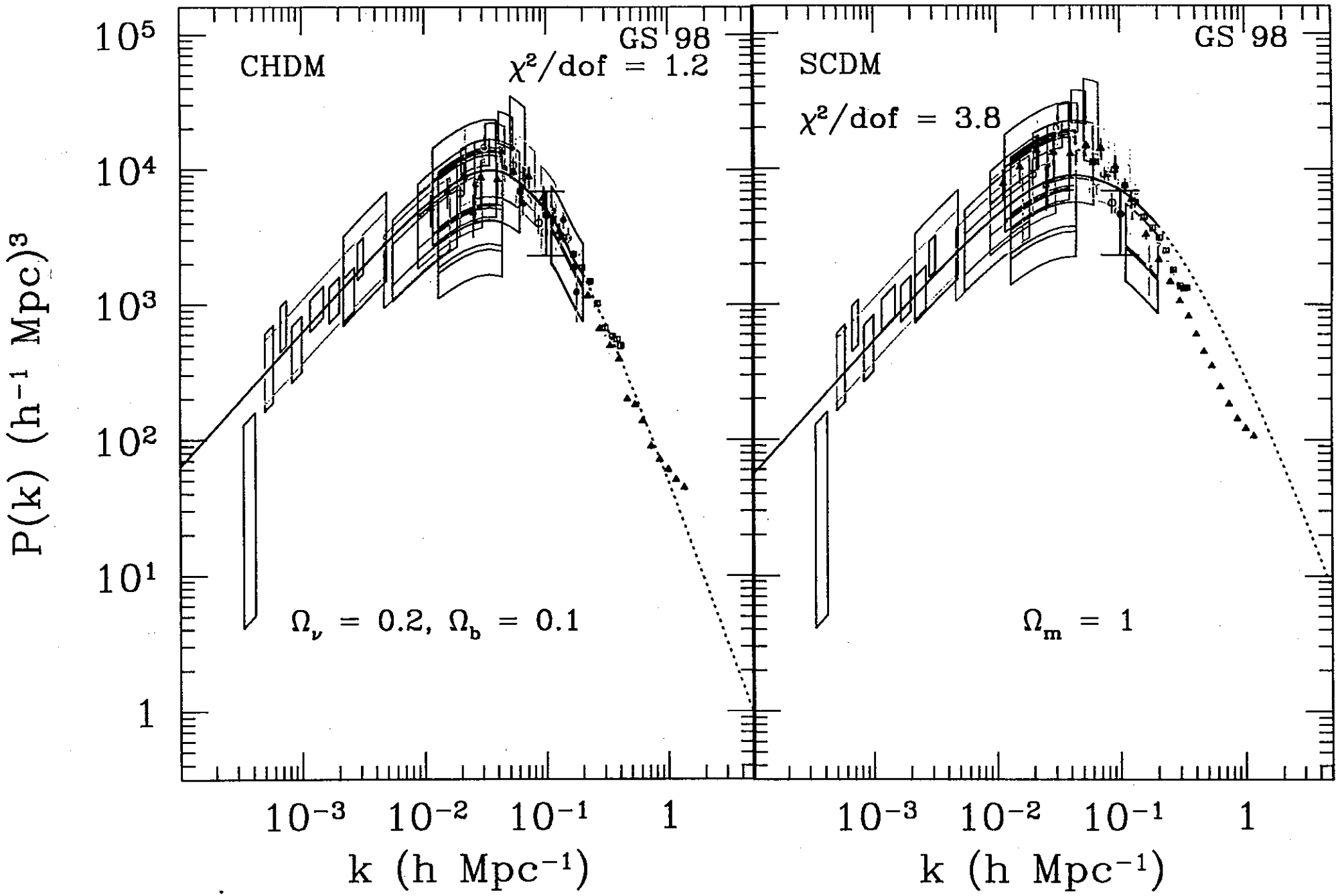
$\Omega_\nu \nearrow$ ⇒ DENSITY FLUCTUATIONS ↘

⇒ CLUSTER ABUNDANCE ↘

→ CONSTRAINT ON m_ν

Fukugita, Liu, Sugiyama (2000)

$h < 0.8$ $\Omega_m = 0.4$ → $m_\nu < 1.8\,eV$



E. Gawiser, J.Silk Science 280 (1998)1405

Table 1: Cosmological parameters of our models. Parameters marked with a * were optimized (*59*).

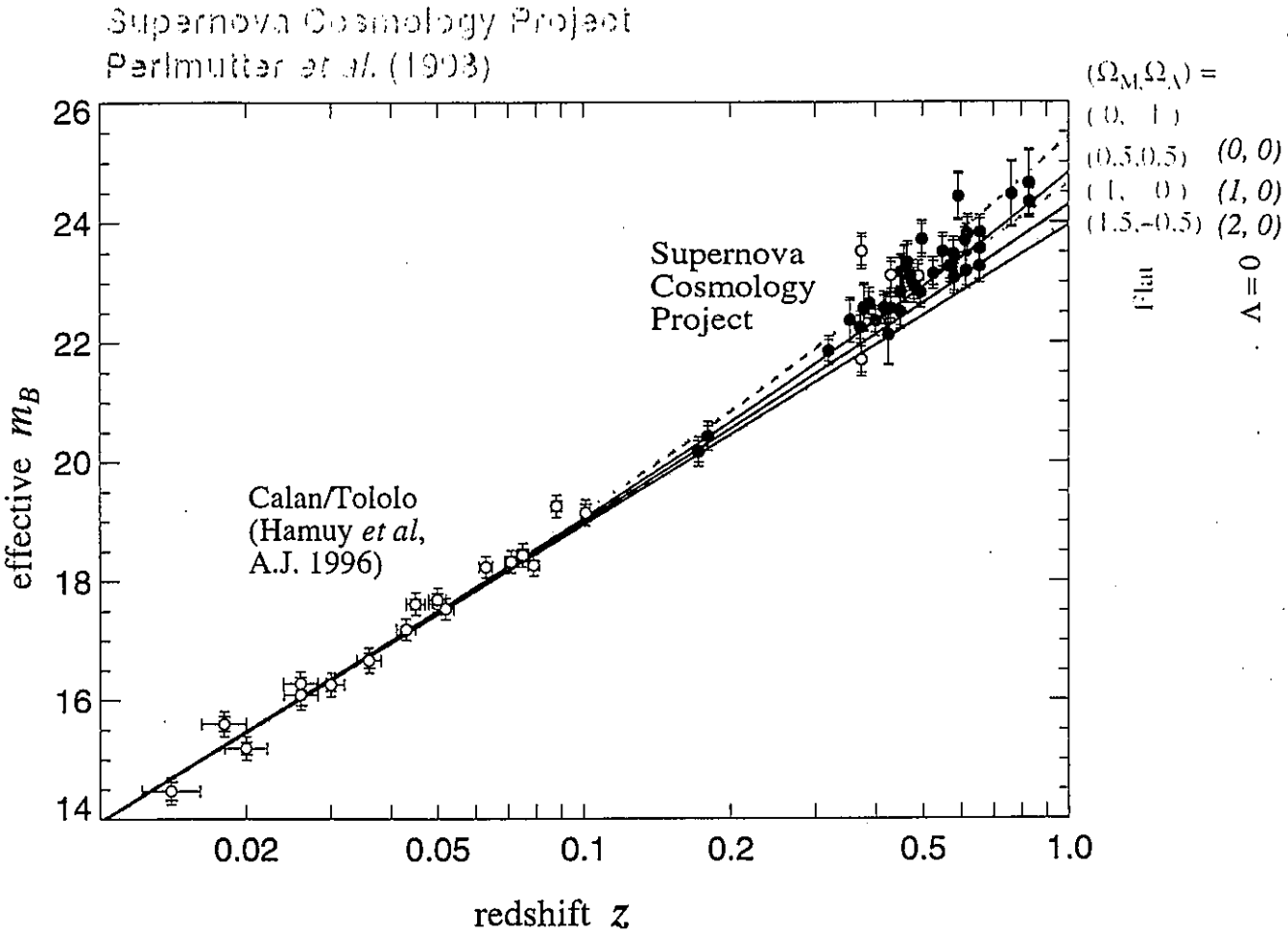
Model	Ω	Ω_Λ	Ω_m	Ω_c	Ω_ν	Ω_b	h	n	Age (Gyr)
SCDM	1.0	0	1.0	0.95	0	0.05	0.5	1.0	13
TCDM	1.0	0	1.0	0.90	0	0.10*	0.5	0.8*	13
CHDM	1.0	0	1.0	0.70	0.2*	0.10*	0.5	1.0*	13
OCDM	0.5	0	0.5*	0.45	0	0.05*	0.6*	1.0*	12
ΛCDM	1.0	0.5	0.5*	0.45	0	0.05*	0.6*	1.0*	14
ϕCDM	1.0	0	0.92	0.87	0	0.05	0.5	1.0	13
BCDM	1.0	0.88	0.12	0.08	0	0.04	0.8	1.6	15
ICDM	1.0	0.8	0.2	0.17	0	0.03	0.7	-1.8	15
PBH BDM	1.0	0.6	0.4	0	0	0.10	0.7	-2.0	13
Strings+Λ	1.0	0.7	0.3	0.25	0	0.05	0.5	~ 1	19

Table 2: Best-fit normalizations and biases. The normalization of each model is given by σ_8 or the value of dT at $\ell = 10$, which can be compared to the COBE normalization of $dT = 27.9\mu$K.

Model	dT_{10} (μK)	σ_8	b_{clus}	b_{cfa}	b_{lcrs}	b_{apm}	b_{iras}
SCDM	25.4	1.08	2.12	0.83	0.72	0.89	0.57
TCDM	31.2	0.79	2.73	1.13	1.01	1.18	0.83
CHDM	27.1	0.75	2.52	1.11	1.01	1.13	0.78
OCDM	29.0	0.77	2.67	1.25	1.11	1.10	0.93
ΛCDM	26.8	1.00	2.14	0.91	0.82	0.87	0.68
ϕCDM	27.6	0.74	3.12	1.35	1.20	1.31	0.98
BCDM	24.8	1.76	1.30	0.48	0.40	0.41	0.37
ICDM	28.2	0.83	2.95	1.25	1.12	1.02	0.97
PBH BDM	29.9	0.78	2.74	1.21	1.09	1.10	0.92
Strings+Λ	21.2	0.32	6.95	3.10	2.86	2.62	2.48

Table 3: Chi-squared values for our models, computed from data at $k \leq 0.2h\mathrm{Mpc}^{-1}$ (*60*). P is the probability of getting χ^2 greater than or equal to the observed value if a model is correct.

Model d.o.f.	χ^2_{CMB} 34	$\chi^2_{\sigma_8}$ 3	χ^2_{clus} 8	χ^2_{cfa} 2	χ^2_{lcrs} 5	χ^2_{apm} 9	χ^2_{iras} 9	χ^2_{total} 70	χ^2/d.o.f.	P
SCDM	46	36	37	0.2	8	121	18	266	3.8	$< 10^{-7}$
TCDM	51	5	27	0.4	6	49	11	148	2.1	1.8×10^{-7}
CHDM	30	4	20	3	9	10	11	86	1.2	0.09
OCDM	36	2	24	2	11	42	12	128	1.8	2.9×10^{-5}
ΛCDM	30	3	26	2	12	46	13	132	1.9	1.1×10^{-5}
ϕCDM	32	4	30	0.1	5	71	12	155	2.2	$< 10^{-7}$
BCDM	32	38	33	1	125	225	56	511	7.3	$< 10^{-7}$
ICDM	61	3	17	2	21	50	16	170	2.5	$< 10^{-7}$
PBH BDM	65	4	22	2	9	30	11	142	2.0	8.3×10^{-7}
Strings+Λ	64	37	20	0.3	8	43	10	182	2.6	$< 10^{-7}$

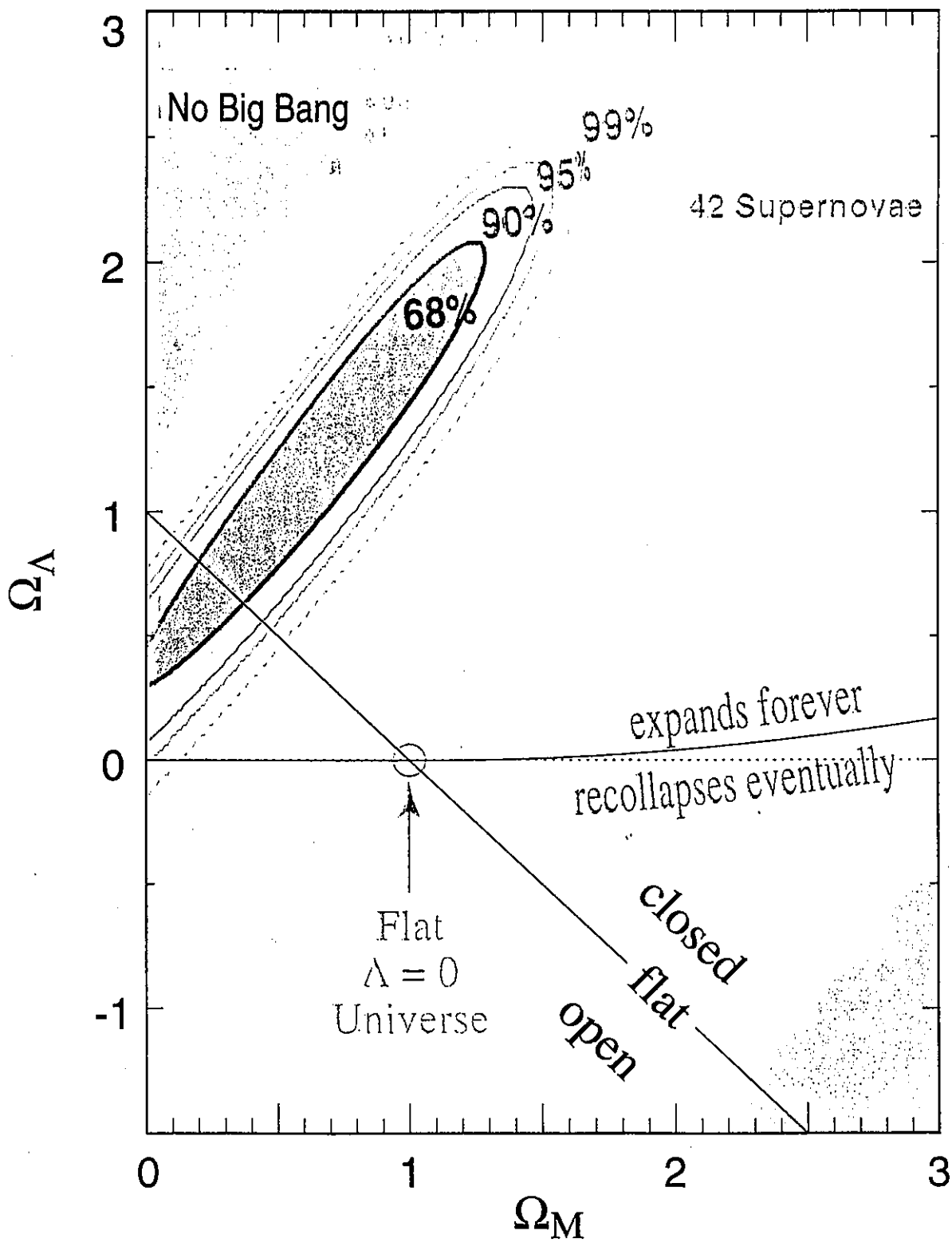


In flat universe: $\Omega_M = 0.28$ [$\pm$ 0.085 statistical] [$\pm$ 0.05 systematic]

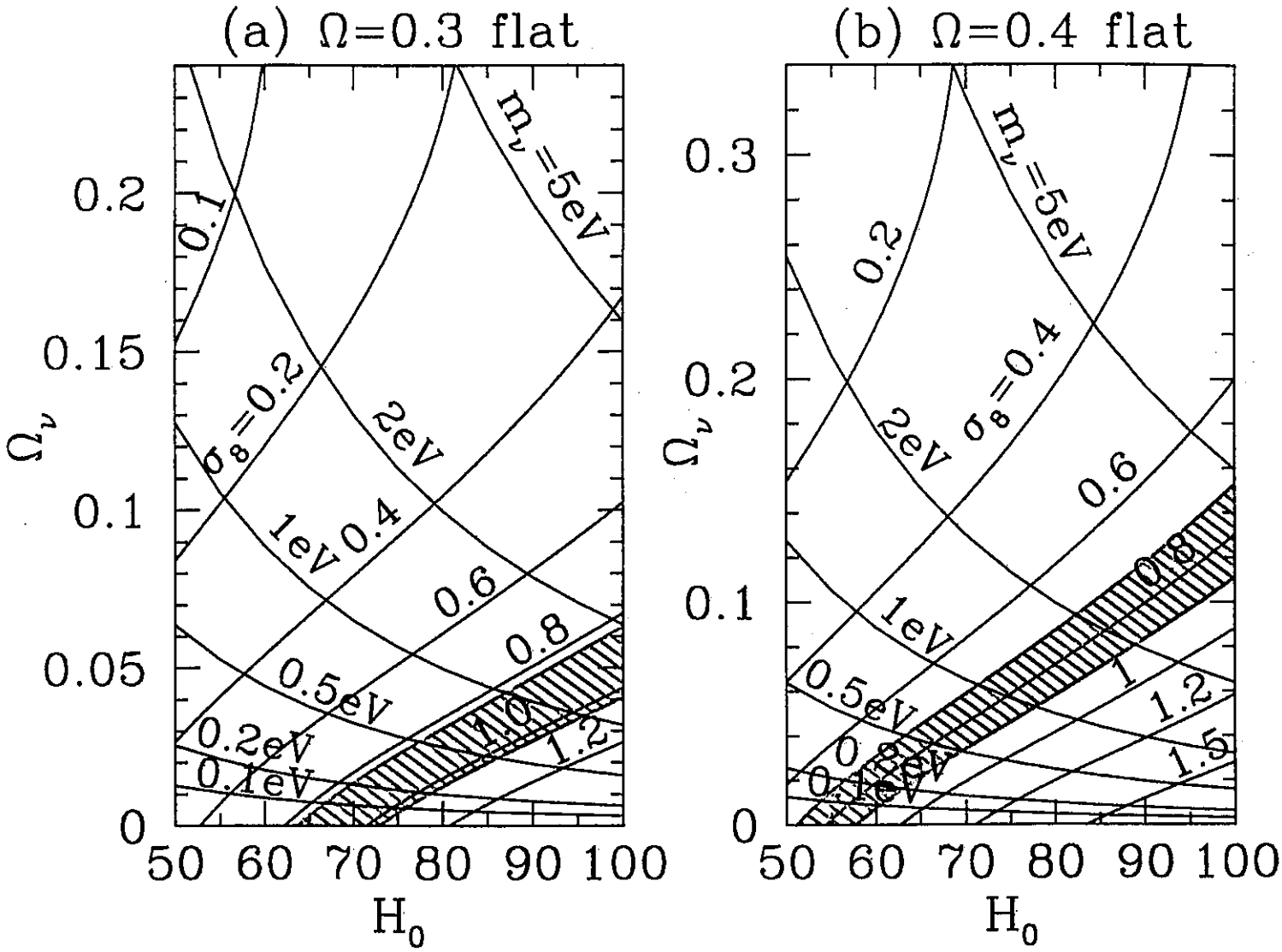
Prob. of fit to $\Lambda = 0$ universe: 1%

astro-ph/9812133

Supernova Cosmology Project
Perlmutter *et al.* (1998)



Ap.J.
astro-ph/9812133


(a) Ω=0.3 flat
(b) Ω=0.4 flat
Ω_ν
H_0
m_ν=5eV
2eV
1eV
0.5eV
0.2eV
0.1eV
σ_8=0.2
σ_8=0.4
0.1
0.2
0.4
0.6
0.8
1.0
1.2
1
1.5
0
0.05
0.1
0.15
0.2
0.3
50 60 70 80 90 100

4. RECENT CMB DATA AND NEUTRINO

CMB ANISOTROPIES

$$\frac{\delta T(\hat{k})}{T} = \sum_{l,m} a_{lm} Y_{l,m}(\hat{k})$$

SPHERICAL HARMONICS

ANGULAR POWER SPECTRUM

$$C_l \equiv \langle |a_{lm}|^2 \rangle$$

NEW DATA

BOOMERANG (2000) de Bernardis et al Nature 404 (2000) 9

MAXIMA (2000) Hanany et al Ap. J Lett. (2000)

RESULT

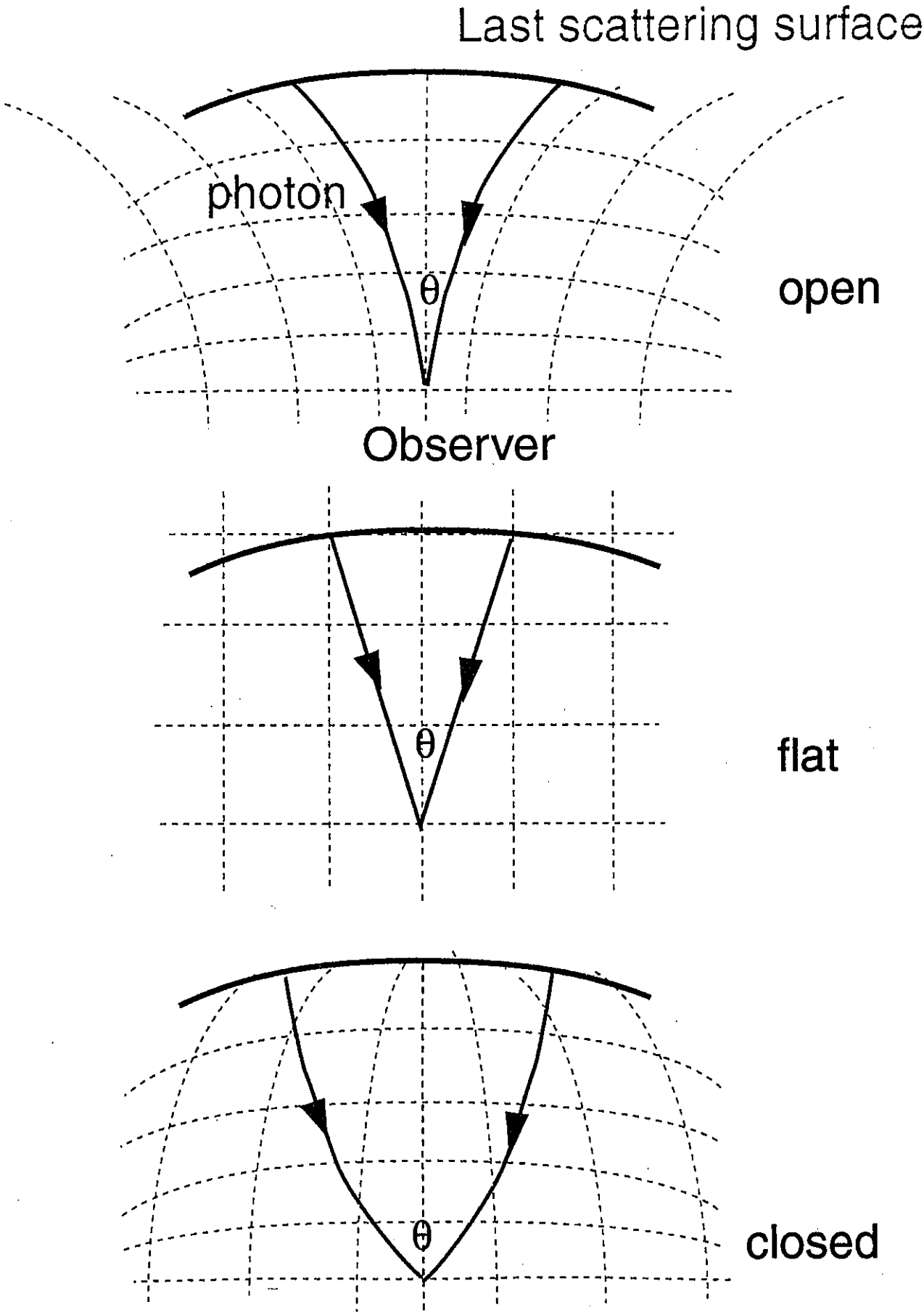
① FIRST PEAK AT $l \sim 200$

→ FLAT UNIVERSE

→ INFLATION

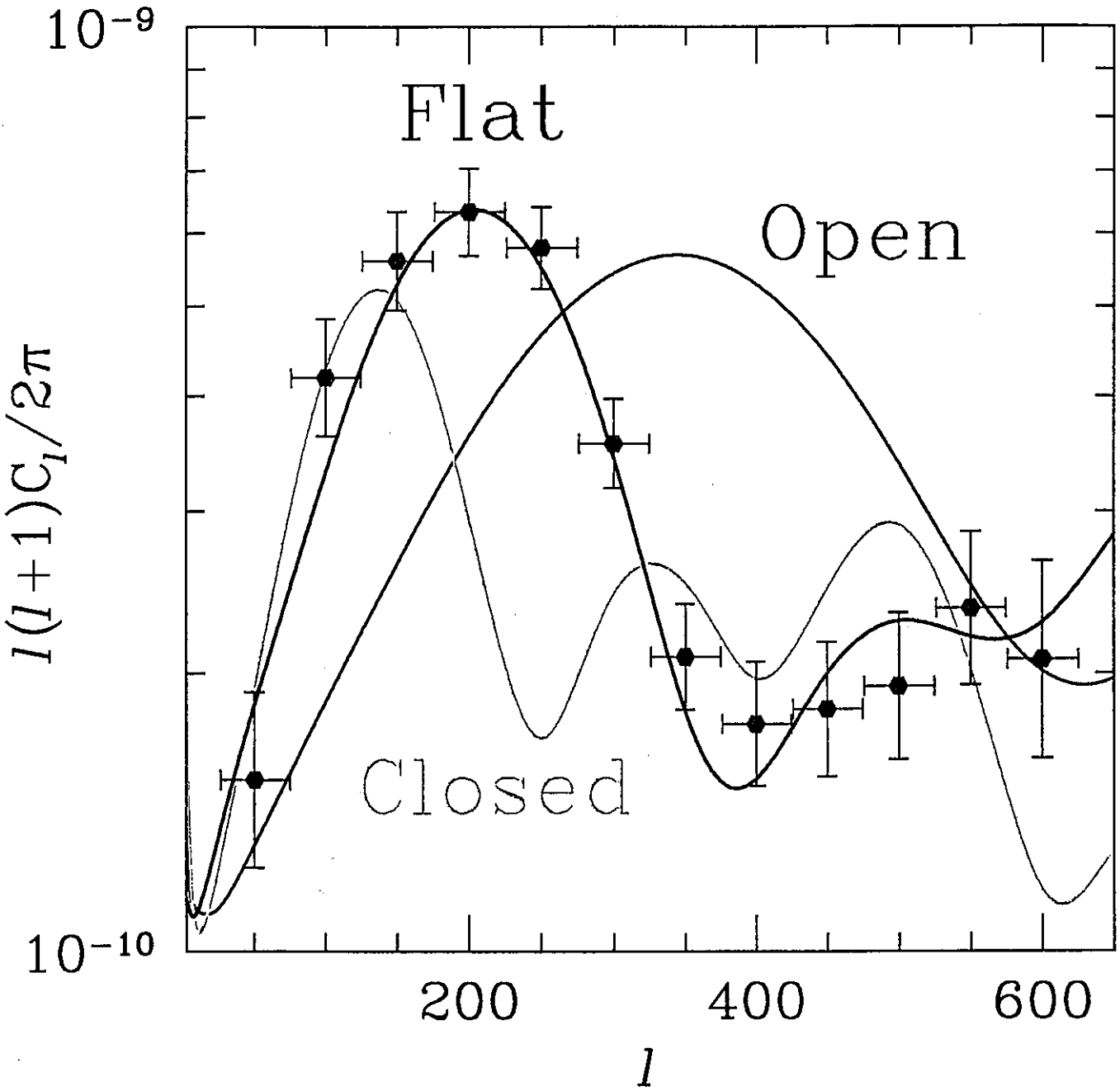
② TOO LOW SECOND PEAK

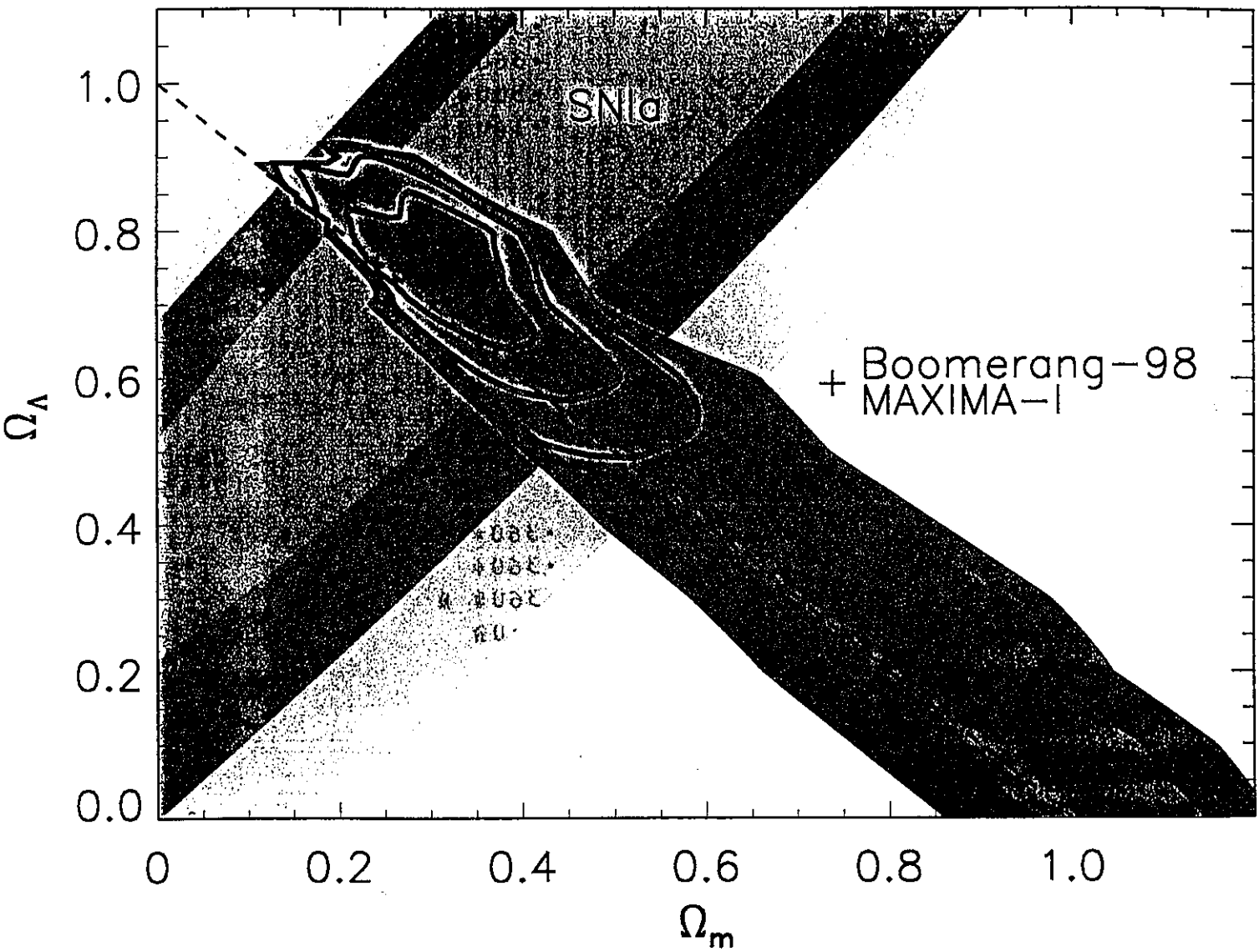
→ HIGH BARYON DENSITY


Last scattering surface
photon
θ
open
Observer
θ
flat
θ
closed

$h = 0.87,\ \Omega_b h^2 = 0.03,\ \Omega_c = 0.36$

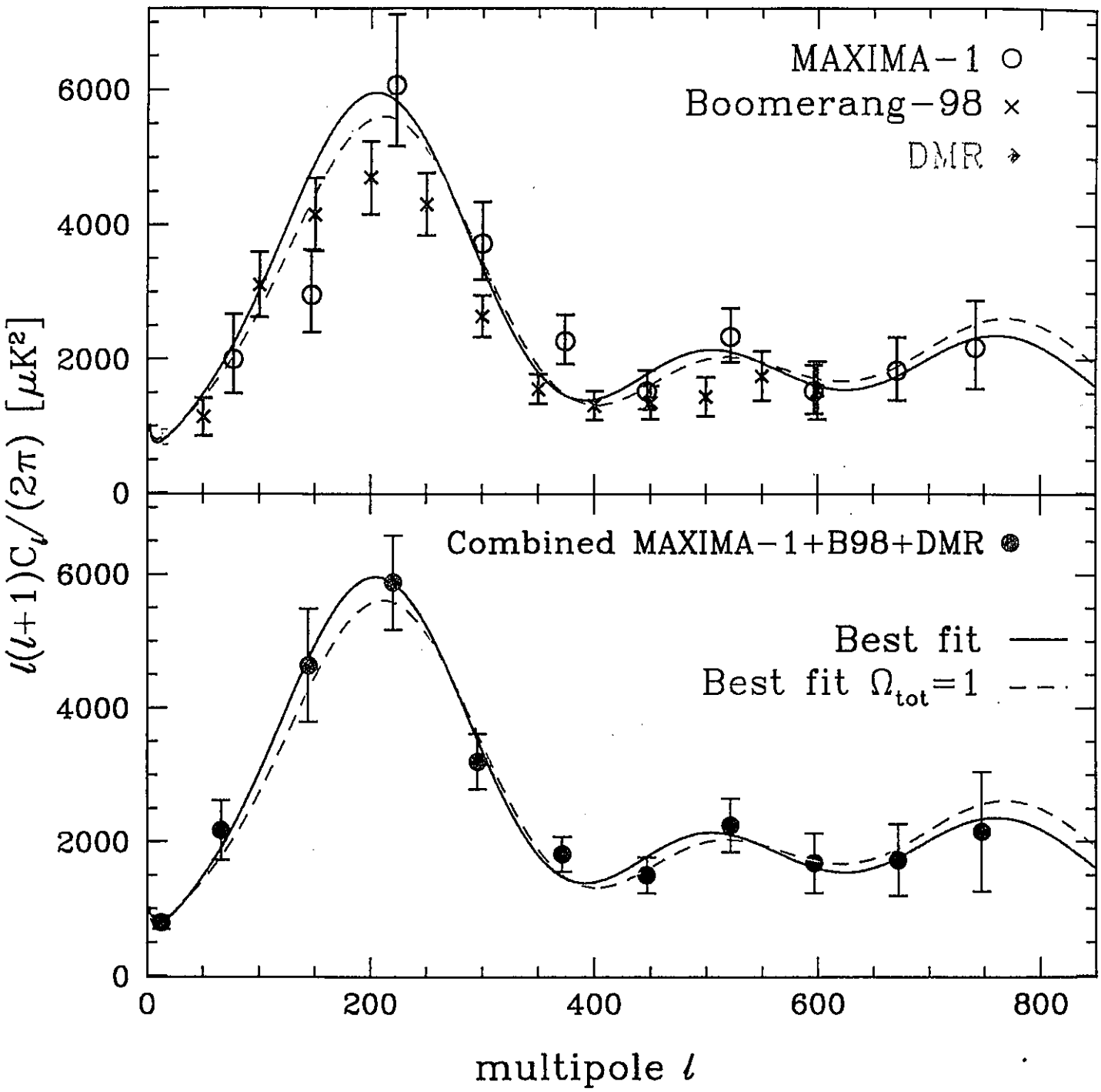
$\Omega_\Lambda = 0$ (open) **0.6(flat)** 0.9(closed)





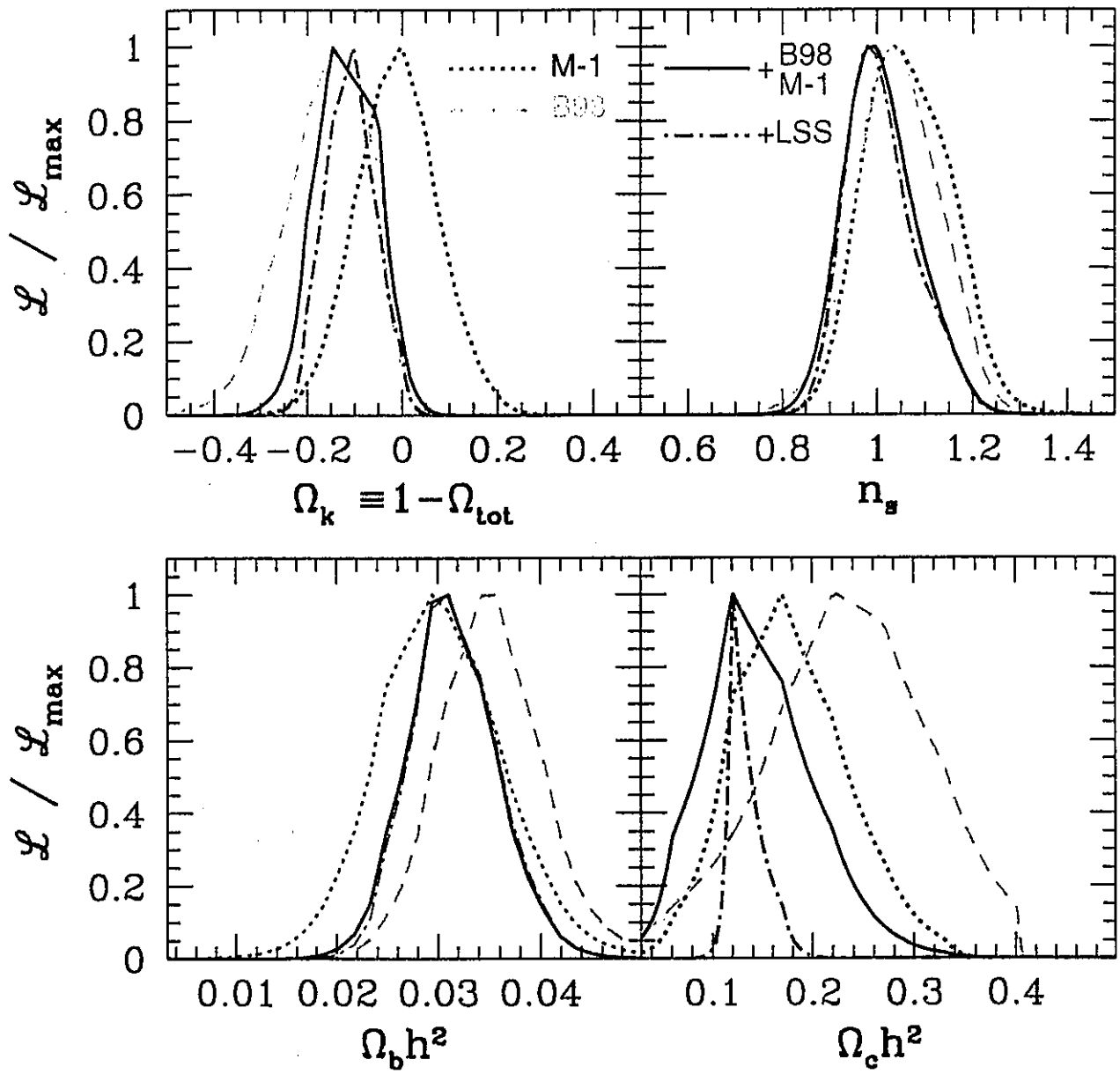
$\Omega_{tot} = 1.09 \pm 0.06$
$\Omega_b h^2 = 0.032 \pm 0.005$
$\Omega_c h^2 = 0.10 \pm 0.04$

A.H.Jaffe et al. astro-ph/0007333



best fit: $\Omega_b h^2 = 0.03$

A.H.Jaffe et al. astro-ph/0007333



A.H.Jaffe et al. astro-ph/0007333

CMB (COMBINED WITH SN DATA)

$\rightarrow \quad \Omega_b h^2 = 0.032 \pm 0.005$

$\Updownarrow \quad \leftarrow$ INCONSISTENT

BBN: $\Omega_b h^2 < 0.022$

ONE SOLUTION

DEGENERATE $\nu_e \leftarrow$ LARG CHEMICAL POTENTIAL μ_{ν_e}

$$\xi_{\nu_e} \equiv \frac{\mu_{\nu_e}}{T} > 0 \qquad \left(f = \frac{1}{e^{\frac{E-\mu}{T}}+1} \right)$$

$\rightarrow \quad n_{\nu_e} > n_{\bar{\nu}_e}$

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

$n_{\nu_e} > n_{\bar{\nu}_e} \quad \rightarrow$ LESS n

$\rightarrow$ LESS ^4He

$\rightarrow \quad \Omega_B \nearrow$

HOWEVER

FOR $N_\nu = 3$

$$\eta \leq 6 \times 10^{-10}$$

$$\Omega_b h^2 \leq 0.022$$

LARGE N_ν, ξ_{ν_e} $\longrightarrow$ CMB & BBN BECOME CONSISTENT

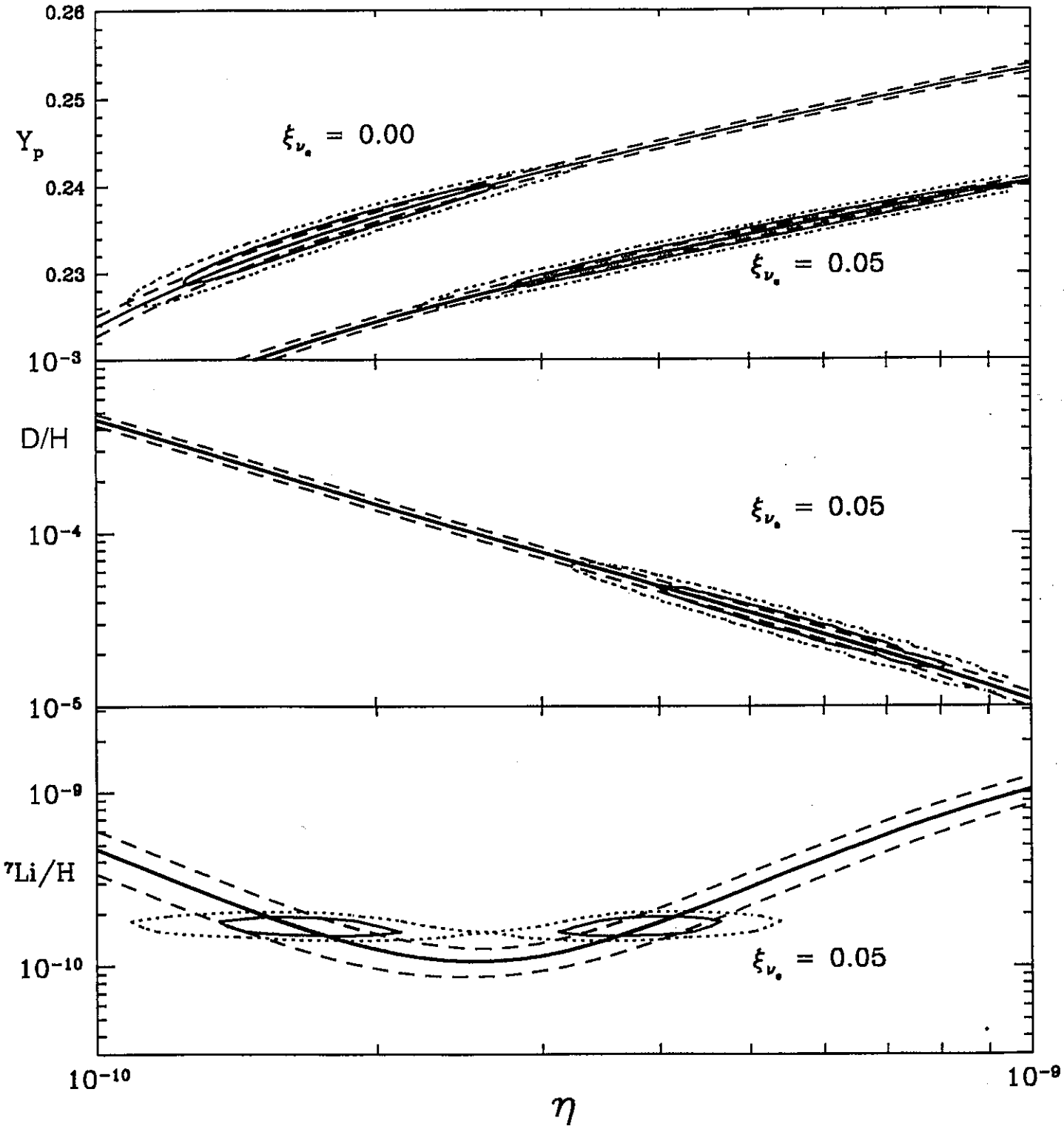
Esposito et al (2000) astro-ph/0007419

95% CL OVERLAP REGION

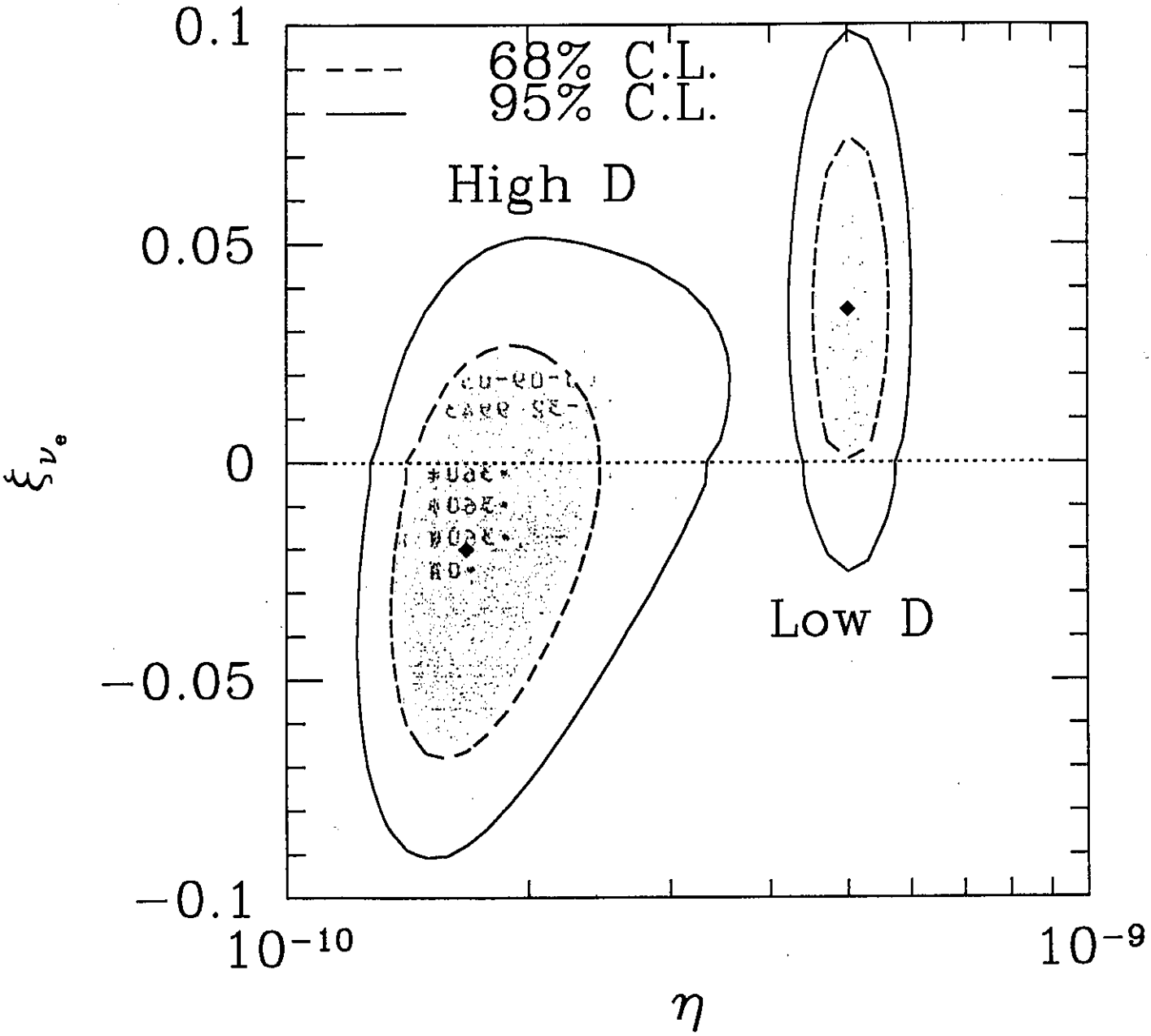
$$4 \leq N_\nu \leq 13$$

$$0.024 \leq \Omega_b h^2 \leq 0.034$$

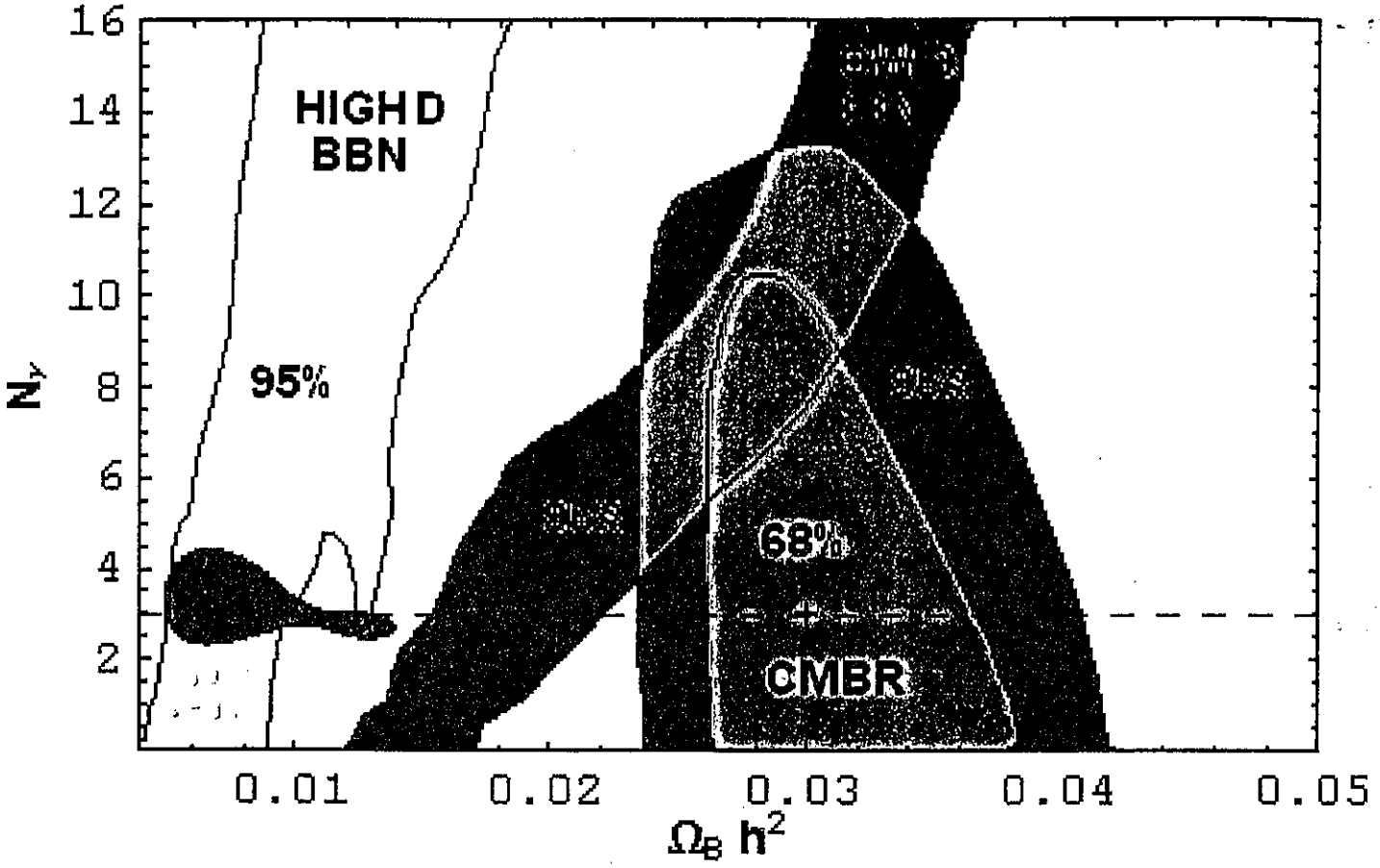
$$0.07 \leq \xi_{\nu_e} \leq 0.43$$



K.Kohri,MK,K.Sato, ApJ 490(1997) 72



K.Kohri,MK,K.Sato, ApJ 490(1997) 72



S.Esposito et al, astro-ph/0007419

CAN LARGE ξ_{ν_e} BE PRODUCED ?

LARGE ξ_{ν_e} $\Longleftrightarrow$ LARGE ASYMMETRY BETWEEN ν_e AND $\bar{\nu}_e$

$$\eta_{\nu_e} = \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \simeq \frac{\xi_{\nu_e}}{1.5}$$

STERILE - ACTIVE ν OSCILLATION

Dolgov, Hansen, Raffelt, Semikoz
Foot, Volkas ...

$$\bar{\nu}_e \longrightarrow \bar{\nu}_s$$

RESONANT CONVERSION TAKES PLACE

IF
$$\frac{\delta m^2 \cos 2\theta}{2E} = \pm C_1 \eta_{\nu_e} G_F T^3 - C_2 \frac{G_F^2 T^9 E}{\alpha}$$

NEUTRINO

ANTI-NEUTRINO

$C_1 = 0.79 \quad C_2 = 0.61$

$\delta m^2 = m_s^2 - m_{\nu_e}^2 < 0$

$\rightarrow$ INSTABILITY FOR η_{ν_e}

$\rightarrow$ η_{ν_e} RAPIDLY INCREASES

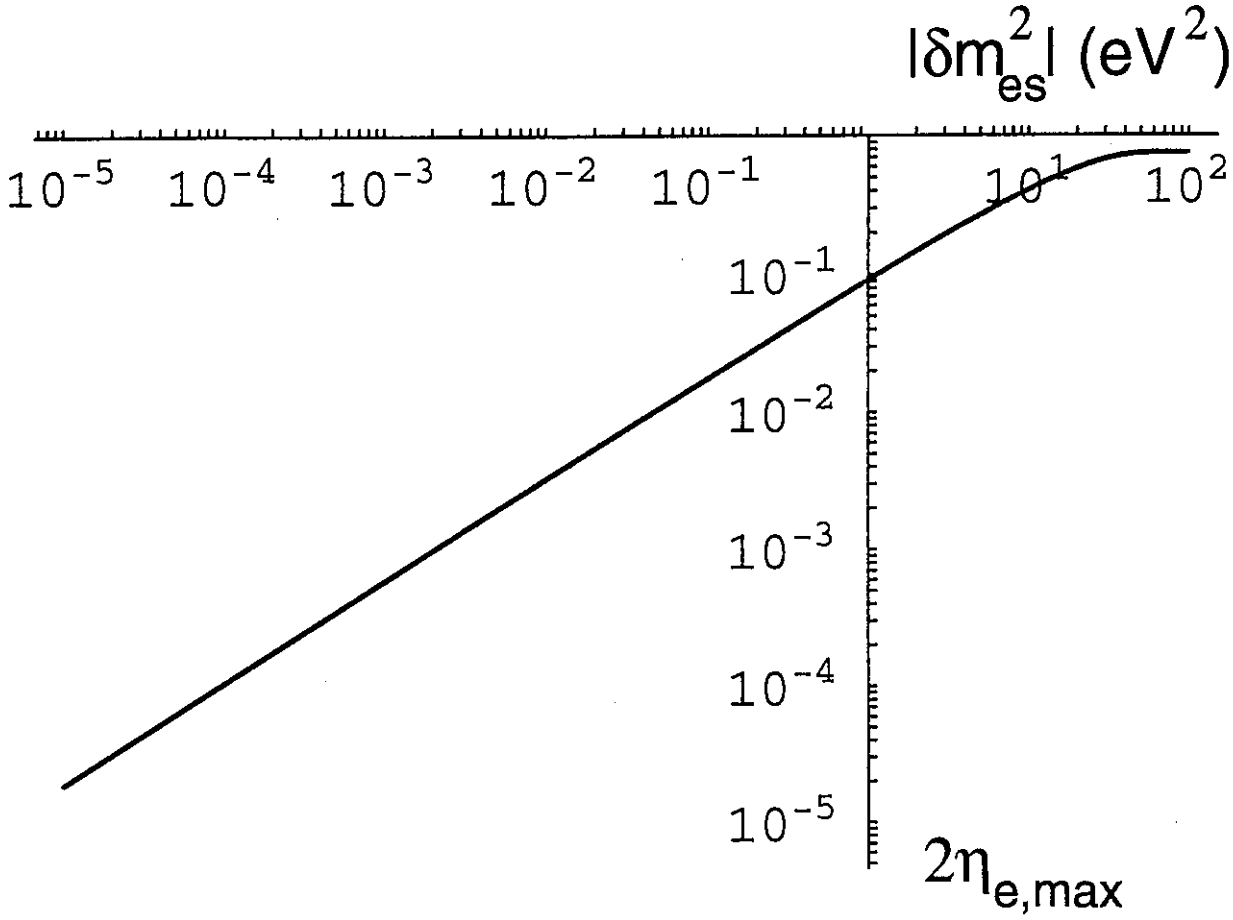
AT $T \sim 1\,\mathrm{MeV}$

$$\eta_{\nu_e} = 0.05 \left| \frac{\delta m^2}{\mathrm{eV}^2} \right|^{2/3}$$

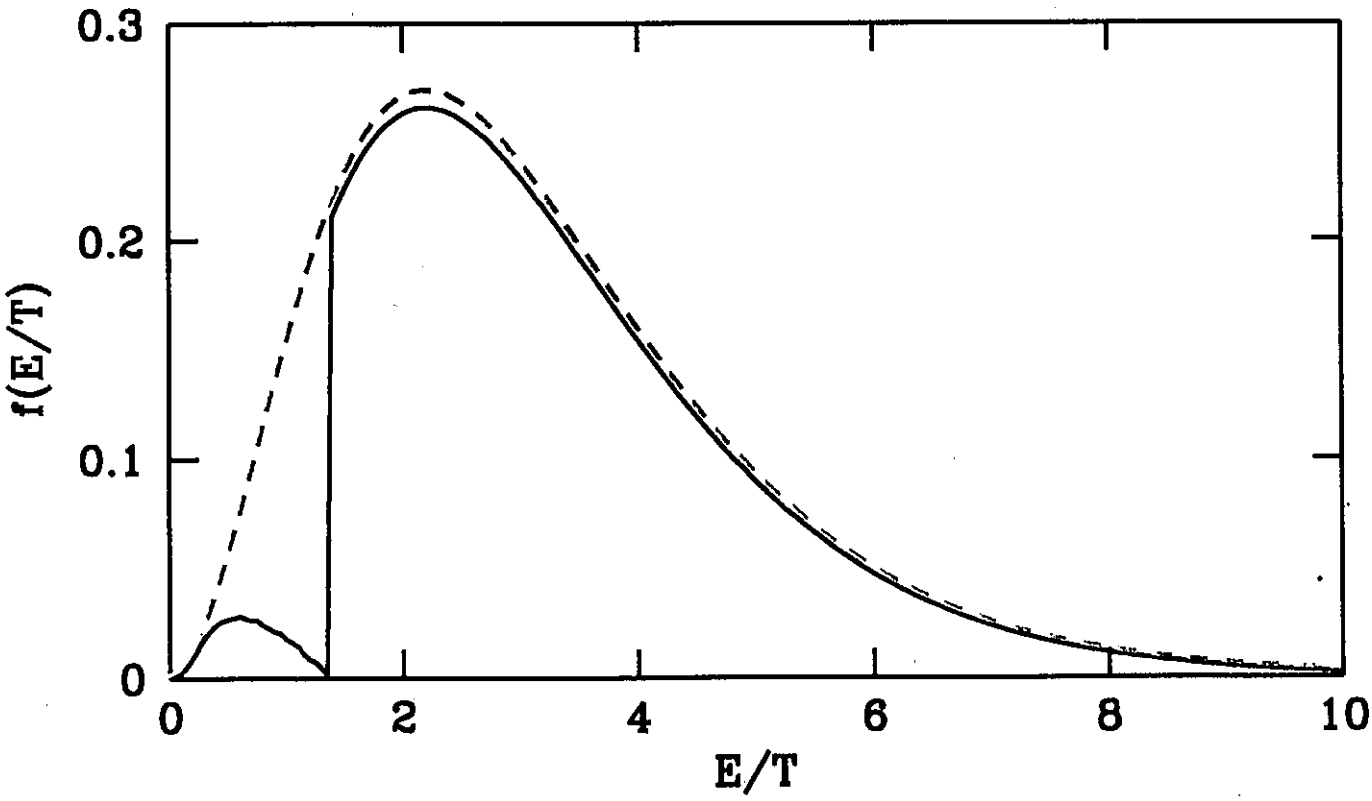
FOR $|\delta m^2| \lesssim 1\,\mathrm{eV}^2$

STERILE ν ?

LARGE m_{ν_e} ?



R.Buras,D.V. Semikoz hep-ph/0009266



X. Shi,G.M. Fuller, K. Abazajian, PRD60 (1999)063002

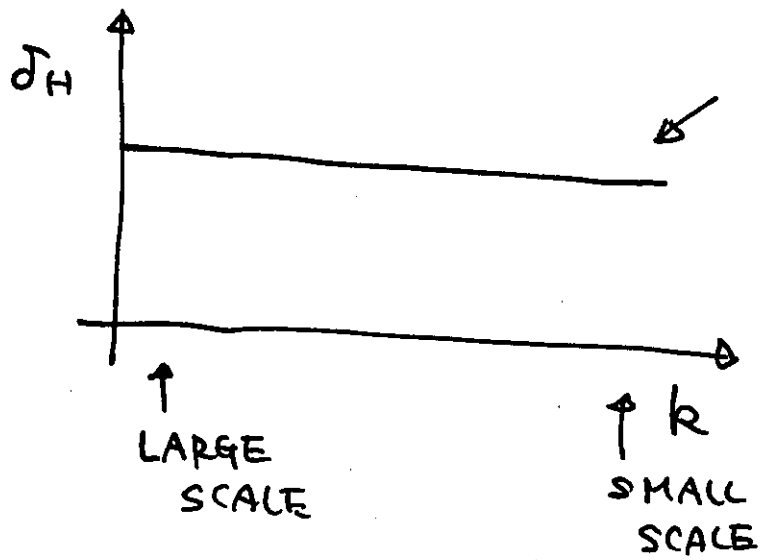
ANOTHER SOLUTION

SPECTRUM OF DENSITY FLUCTUATIONS

NOT SCALE INVARIANT

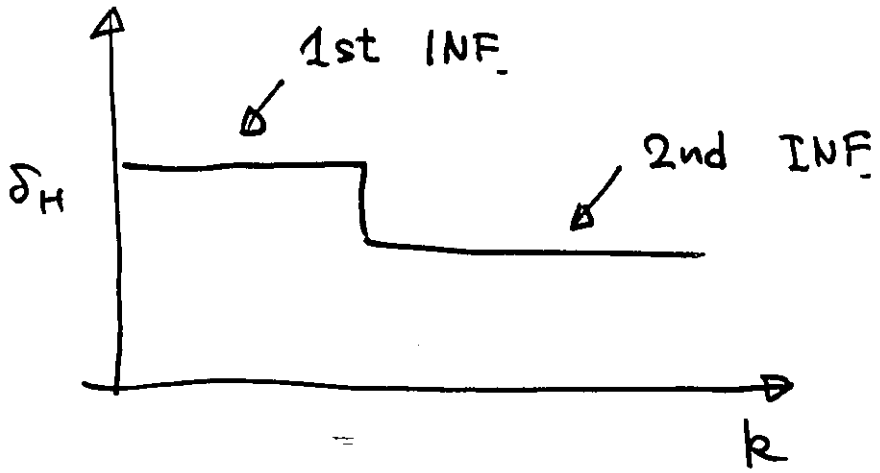
DOUBLE INFLATION

SINGLE INFLATION



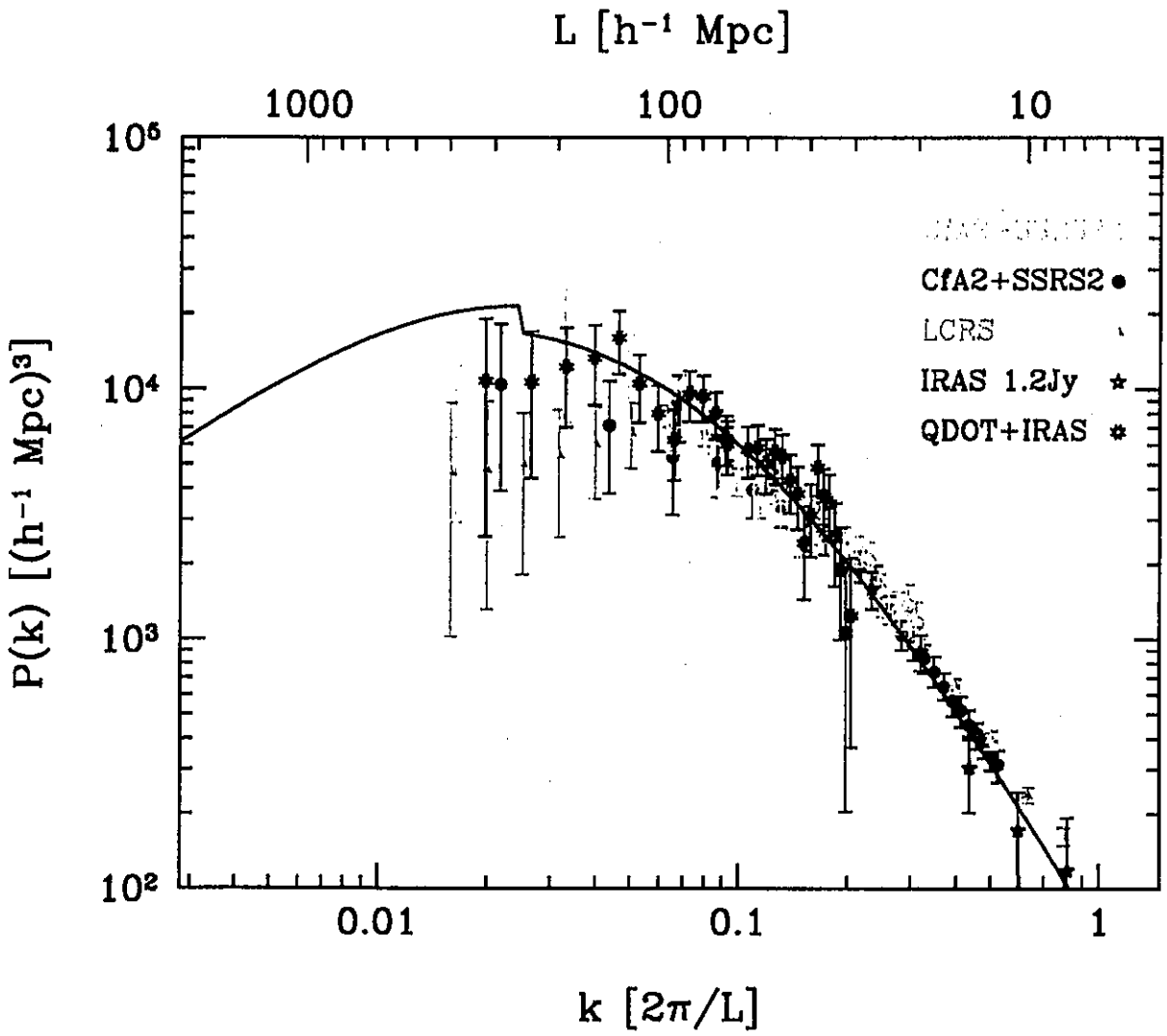
δ_H: AMPLITUDE OF DENSITY FLUCTUATIONS AT HORIZON CROSSING

DOUBLE INFLATION

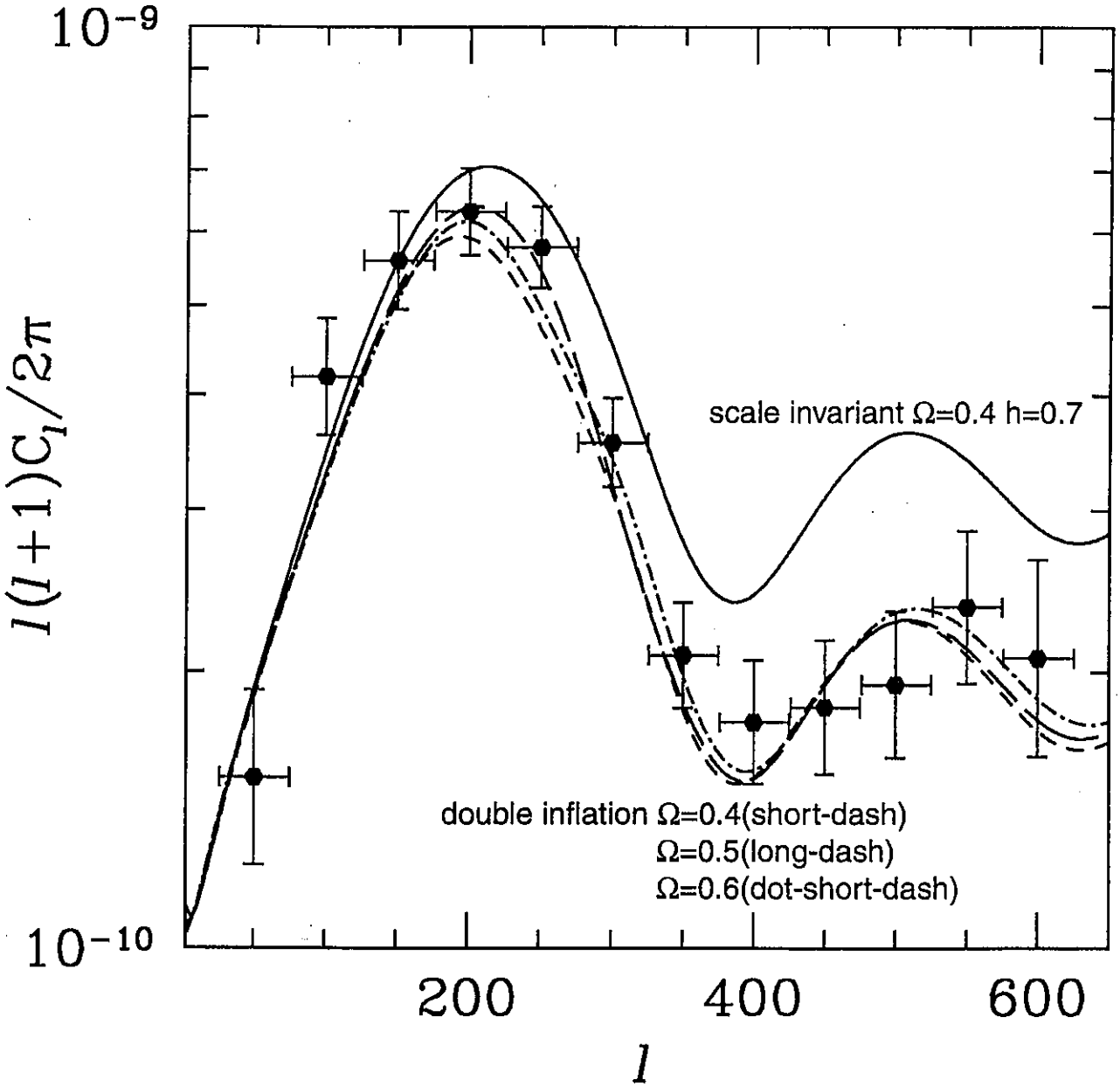


$\delta_H \downarrow$

AT SMALL SCALE!



T.Kanazawa, MK, N.Sugiyama, T.Yanagida astro-ph/00006445



T.Kanazawa, MK, N.Sugiyama, T.Yanagida astro-ph/00006445

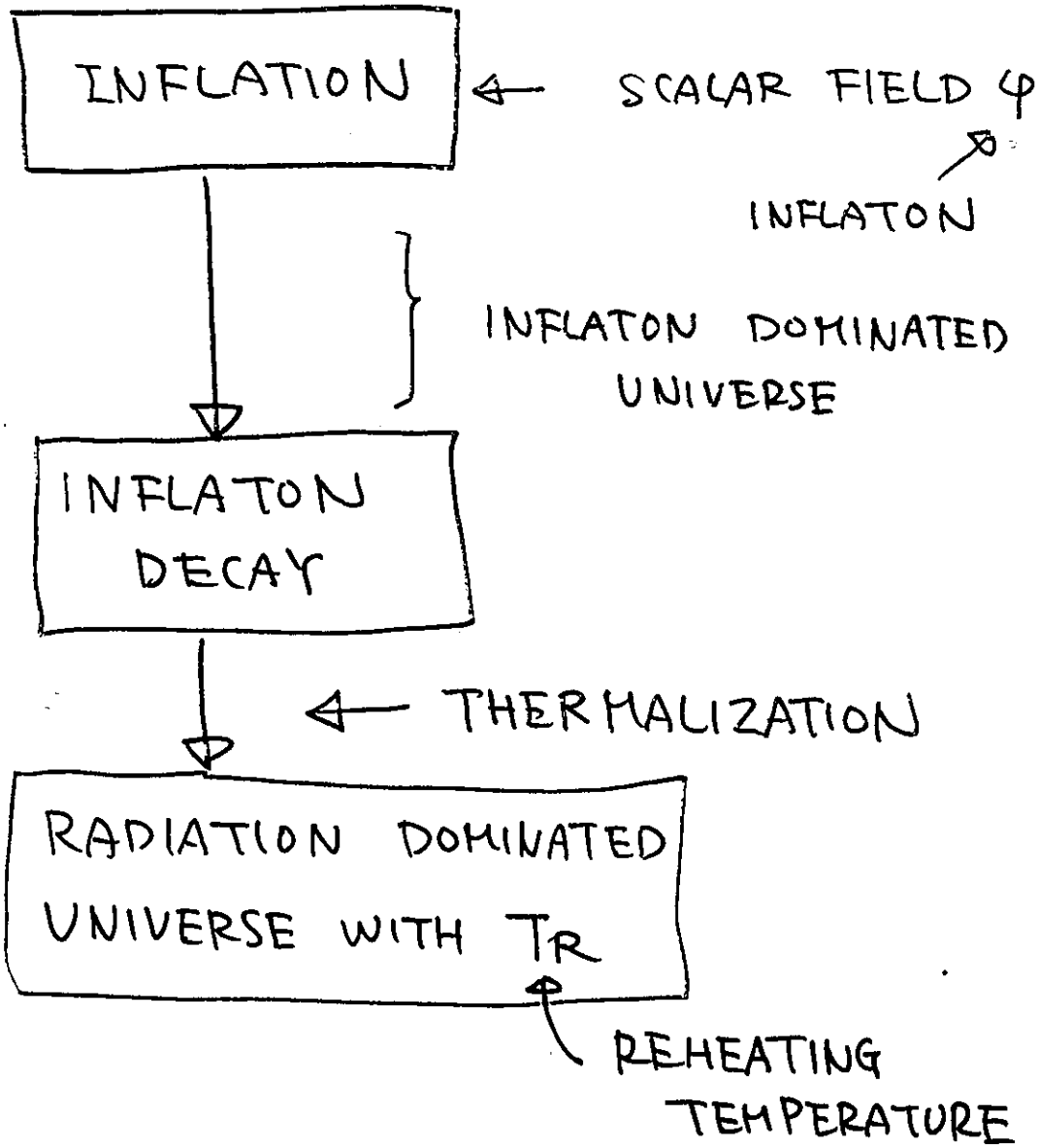
5. MeV REHEATING AND NEUTRINO

SUCCESS OF BBN

$\longrightarrow$ HOT BIG BANG

WHEN THE UNIVERSE BECOMES HOT?

MODERN PICTURE



BBN $\Rightarrow$ $T_R \gtrsim 1$ MeV

HOWEVER IF $T_R \sim O(1)$ MeV

NEUTRINO ARE NOT EASILY THERMALIZED

ν THERMALIZATION

$\longrightarrow$ CONSTRAINT ON T_R

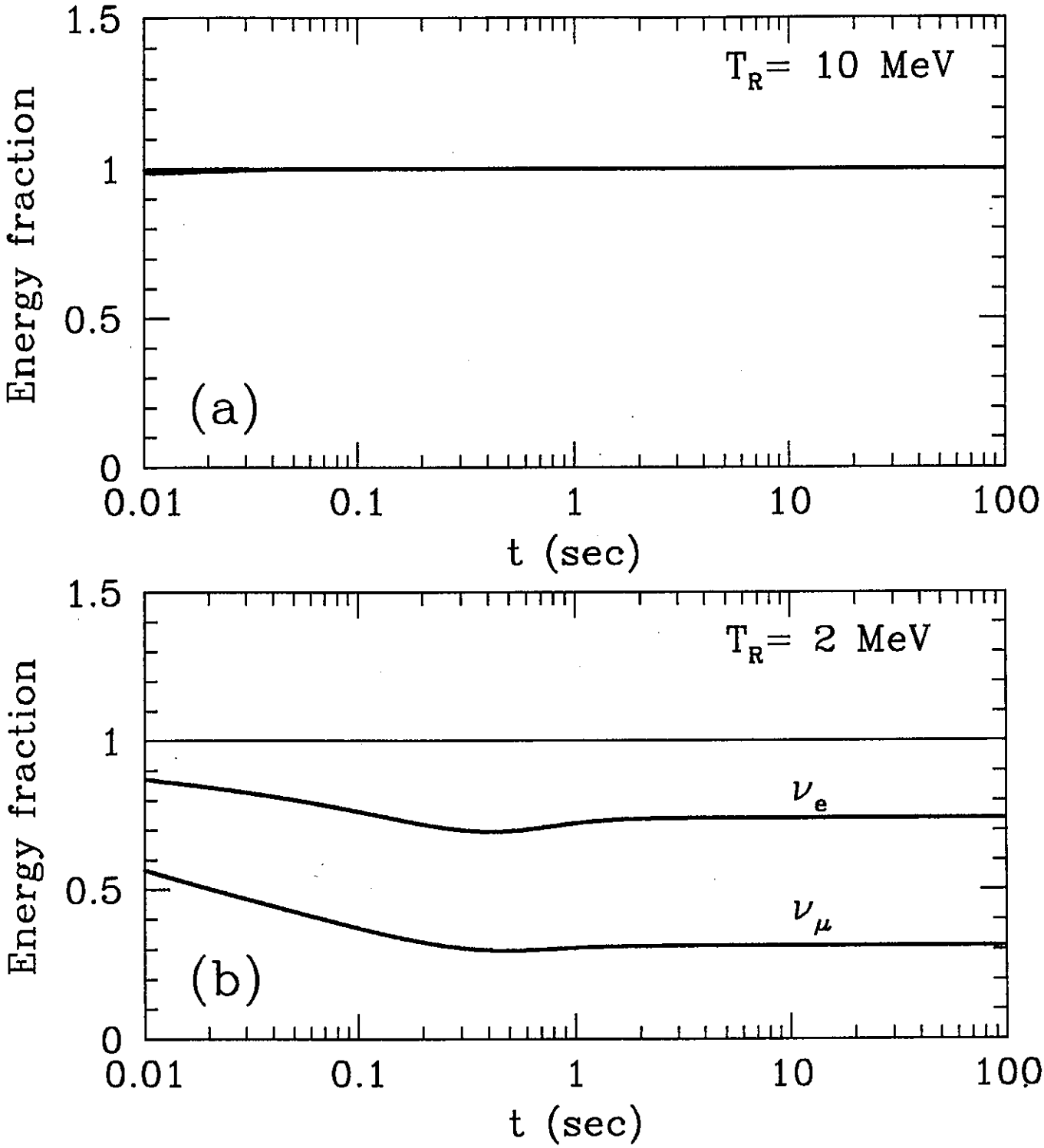
DETAILED CALCULATION BY SOLVING BOLTZMANN EQ. FOR ν NON. DISTRIBUTION

Mk. Kohri, Sugiyama (1999) (2000)

INSUFFICIENT THERMALIZATION

$$\Rightarrow \quad n_\nu < n_{\nu,\,EQ.}$$

$$\Rightarrow \begin{cases} N_\nu \searrow \longrightarrow {}^4He \searrow \\ \text{WEAK INT} \searrow \longrightarrow {}^4He \nearrow \end{cases}$$



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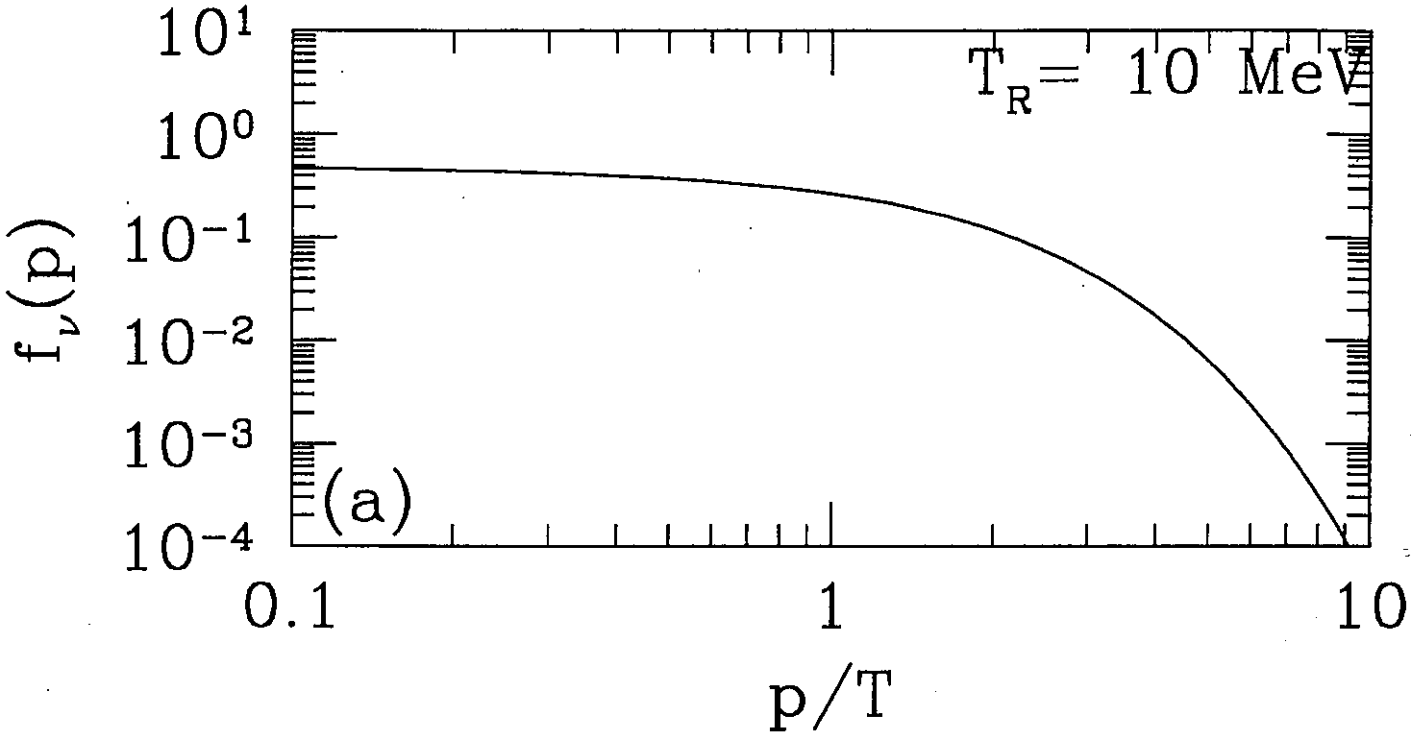

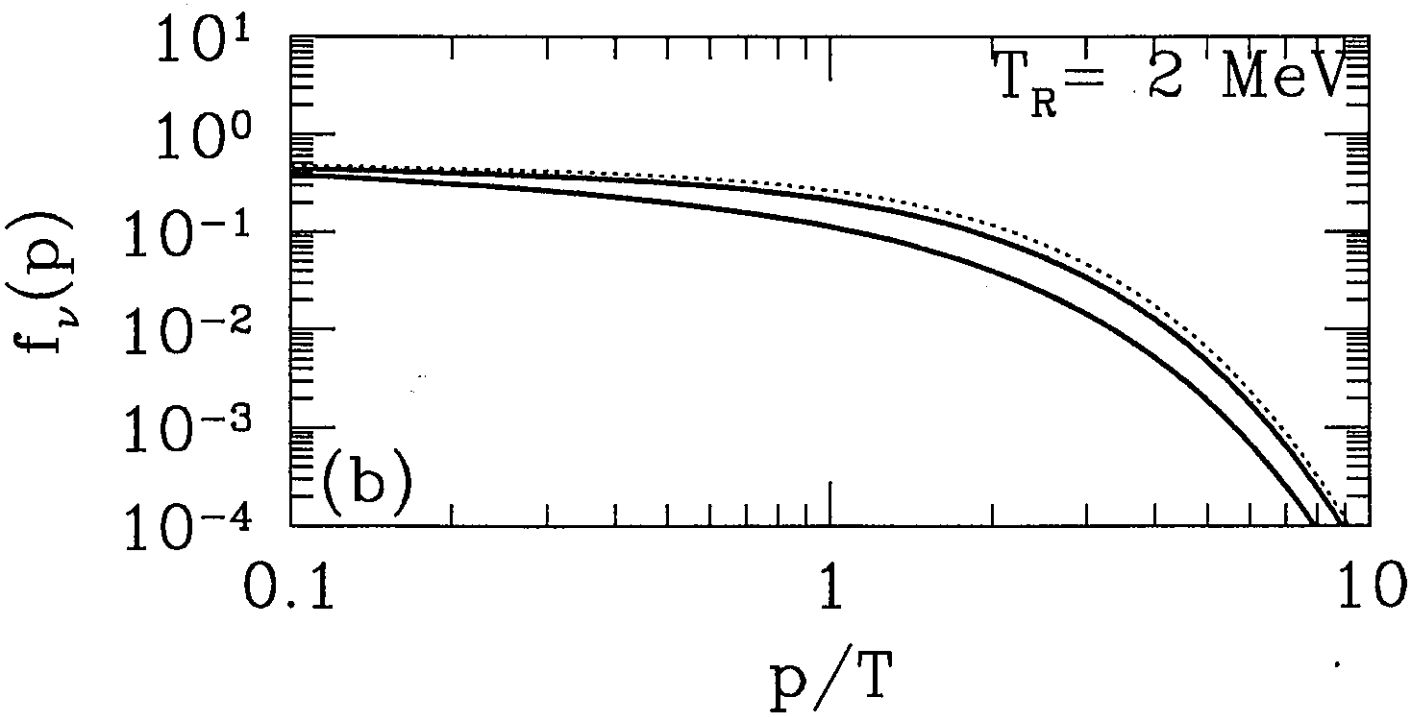

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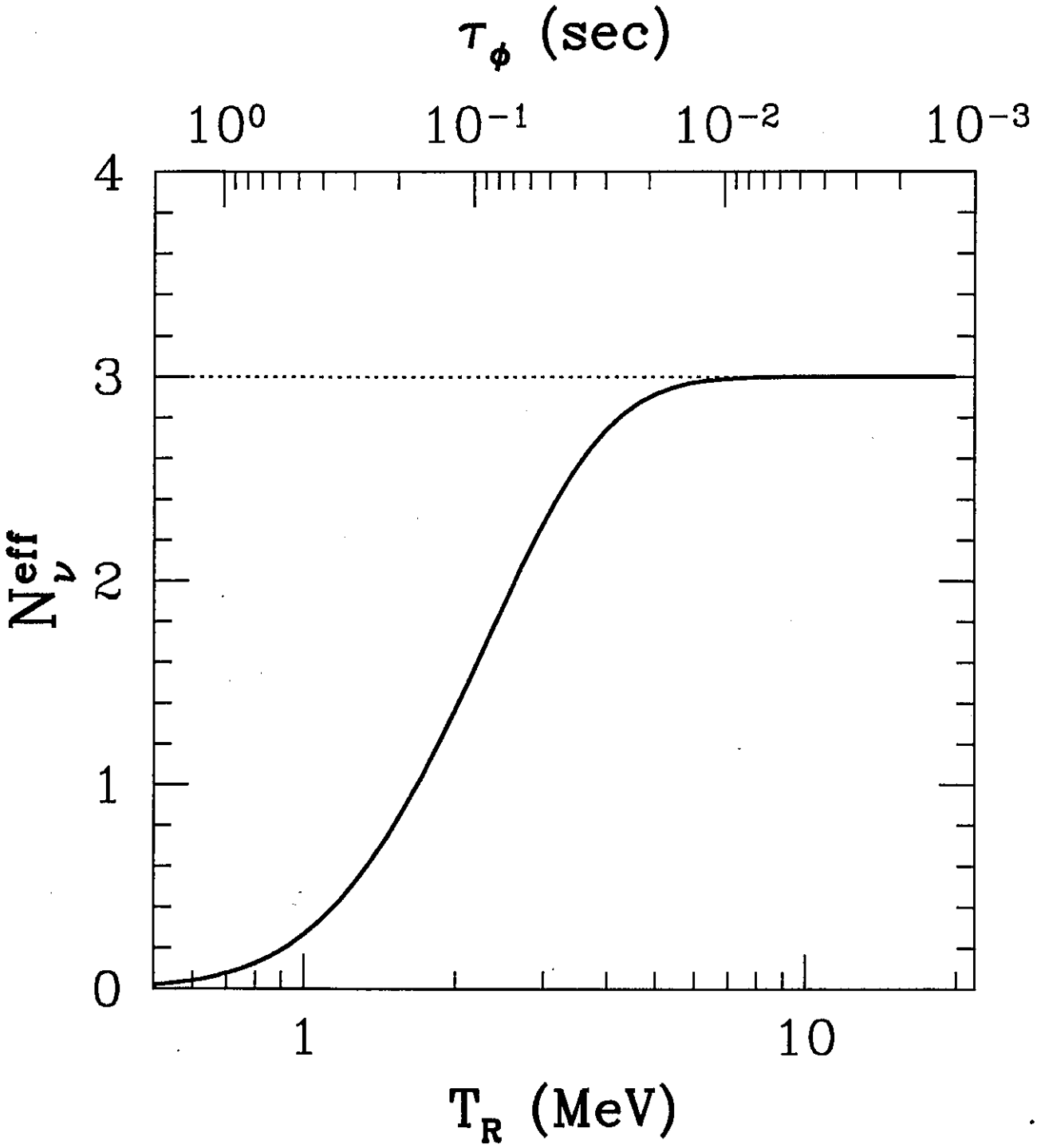

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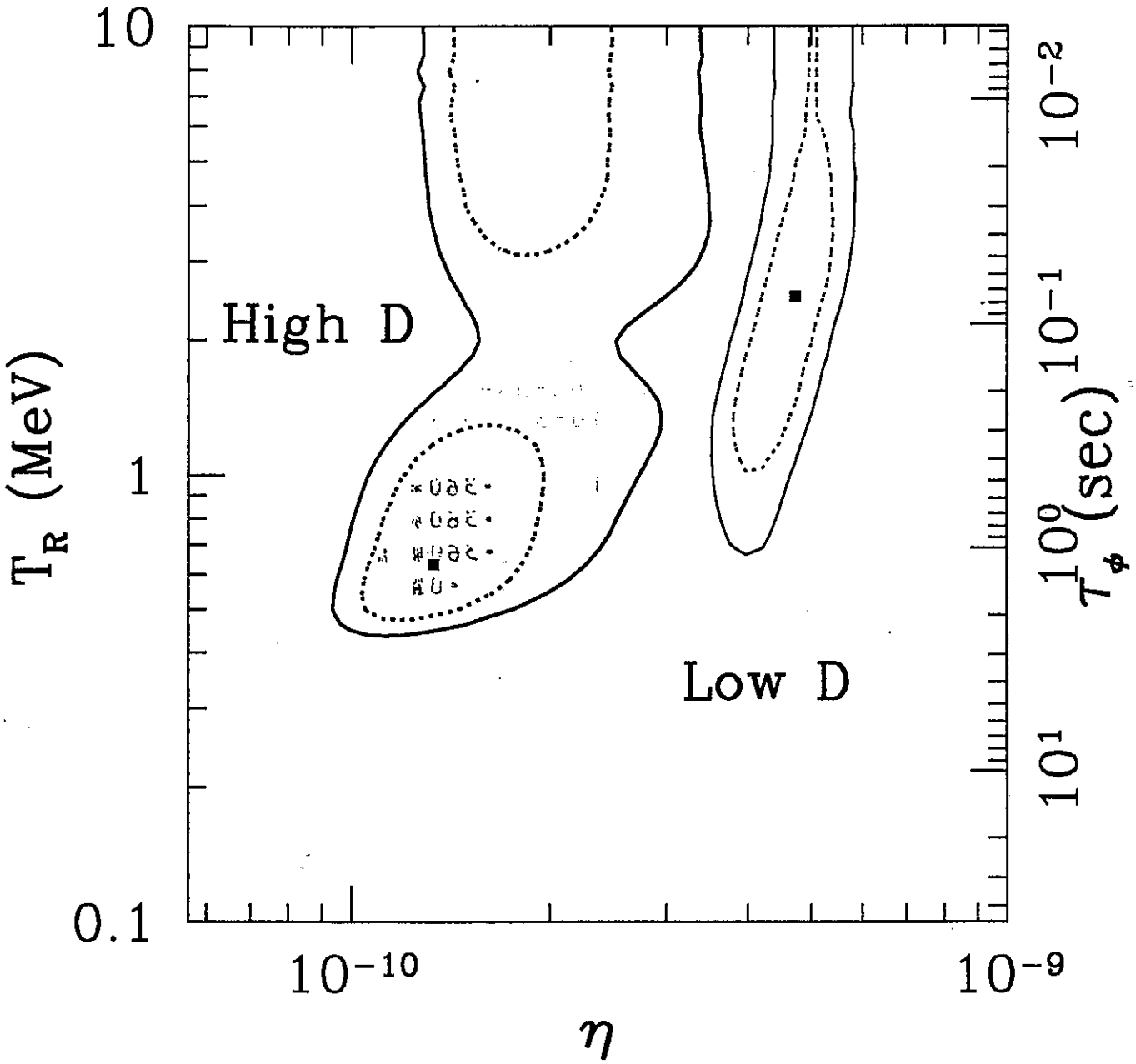

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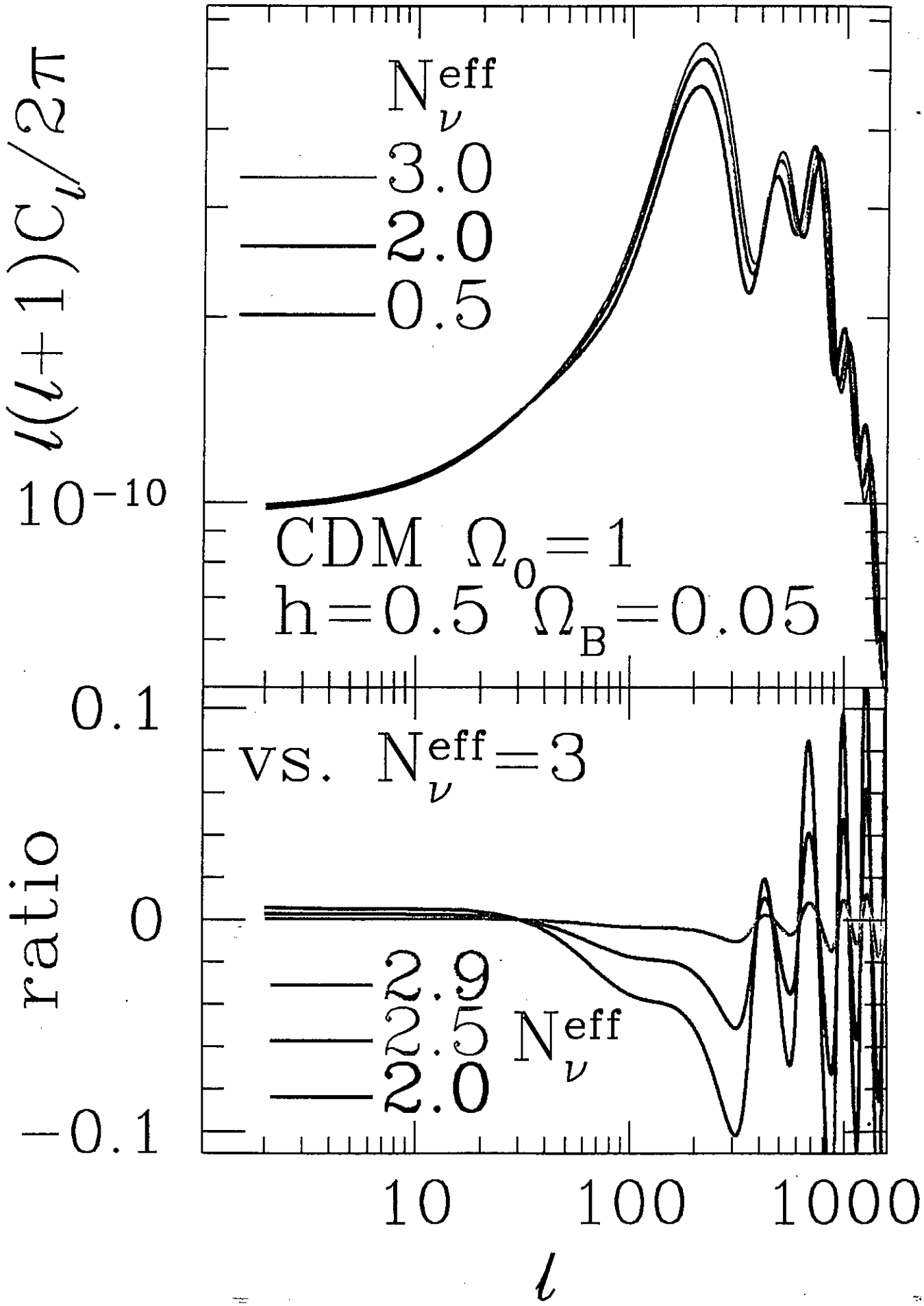
RESULT

$T_R \gtrsim 0.4$ MeV (HIGH D)

$\gtrsim 1$ MeV (LOW D)

N_ν BECOMES AS LOW AS 0.2



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NEUTRINO AND COSMOLOGY

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1 INTRODUCTION

NEUTRINO HAS BEEN PLAYING IMPORTANT ROLES IN COSMOLOGY

NEUTRINO AND COSMOLOGY

- BIG BANG NUCLEOSYNTESIS (BBN)

  WEAK INTERACTION BETWEEN ν AND NUCLEON DETERMINES ^{4}He ABUNDANCE

- MASSIVE ν IS A CANDIDATE FOR DARK MATTER

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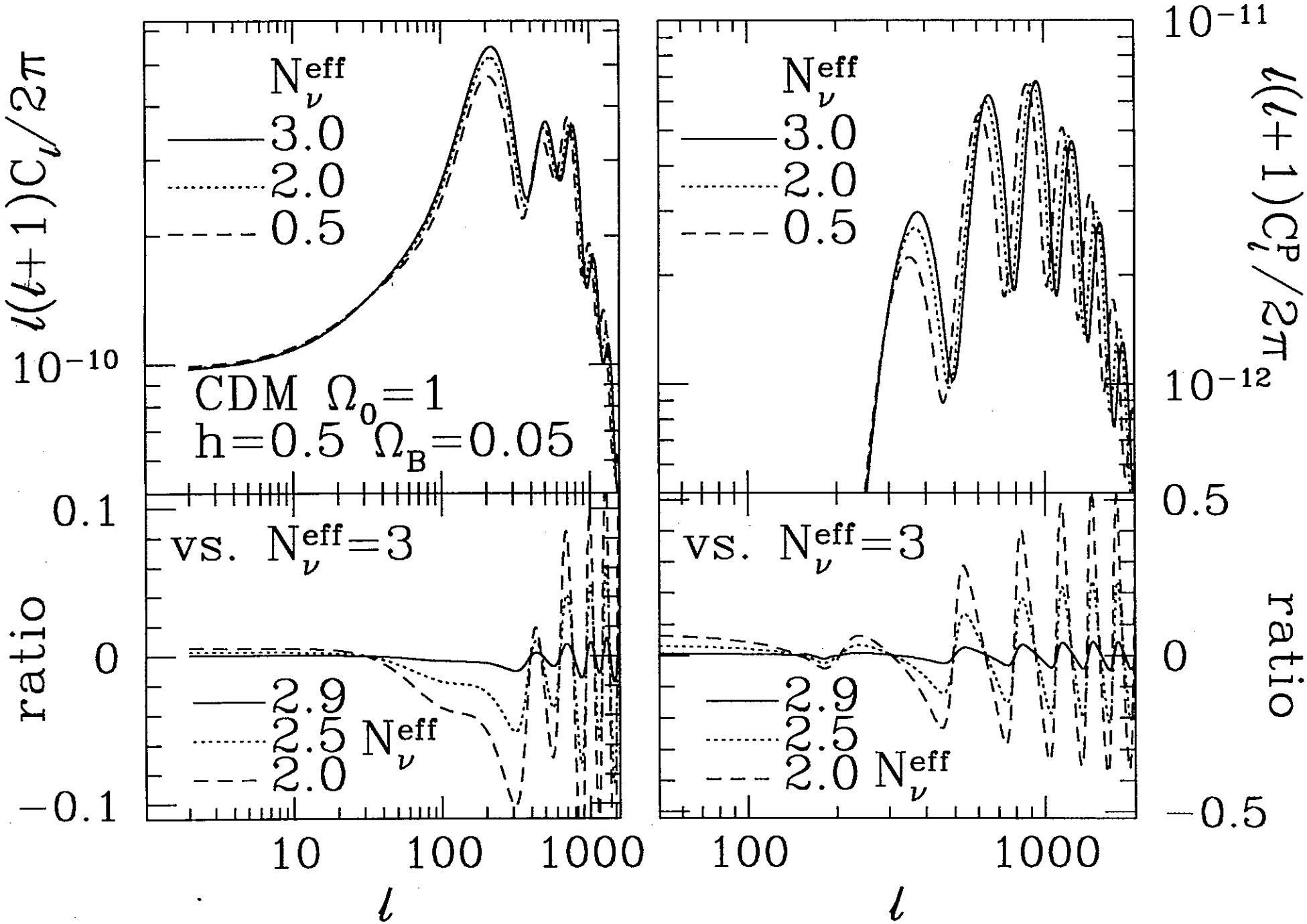
- RECENT MEASUREMENT OF COSMIC MICROWAVE BACKGROUND (CMB)

  $\rightarrow$ DEGENERATE ν ?

ν COSMOLOGY IS STILL INTERESTING SUBJECT !



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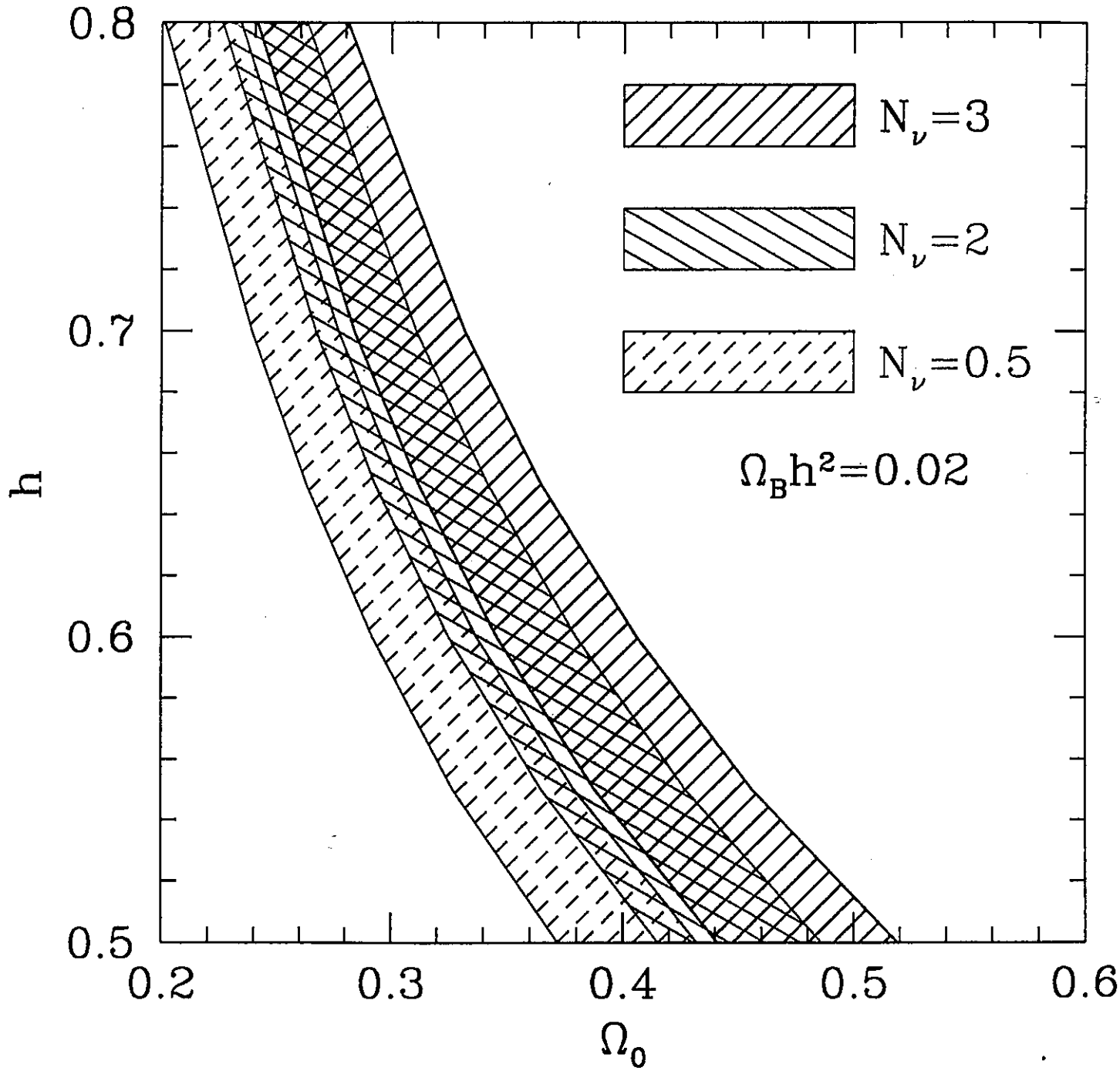

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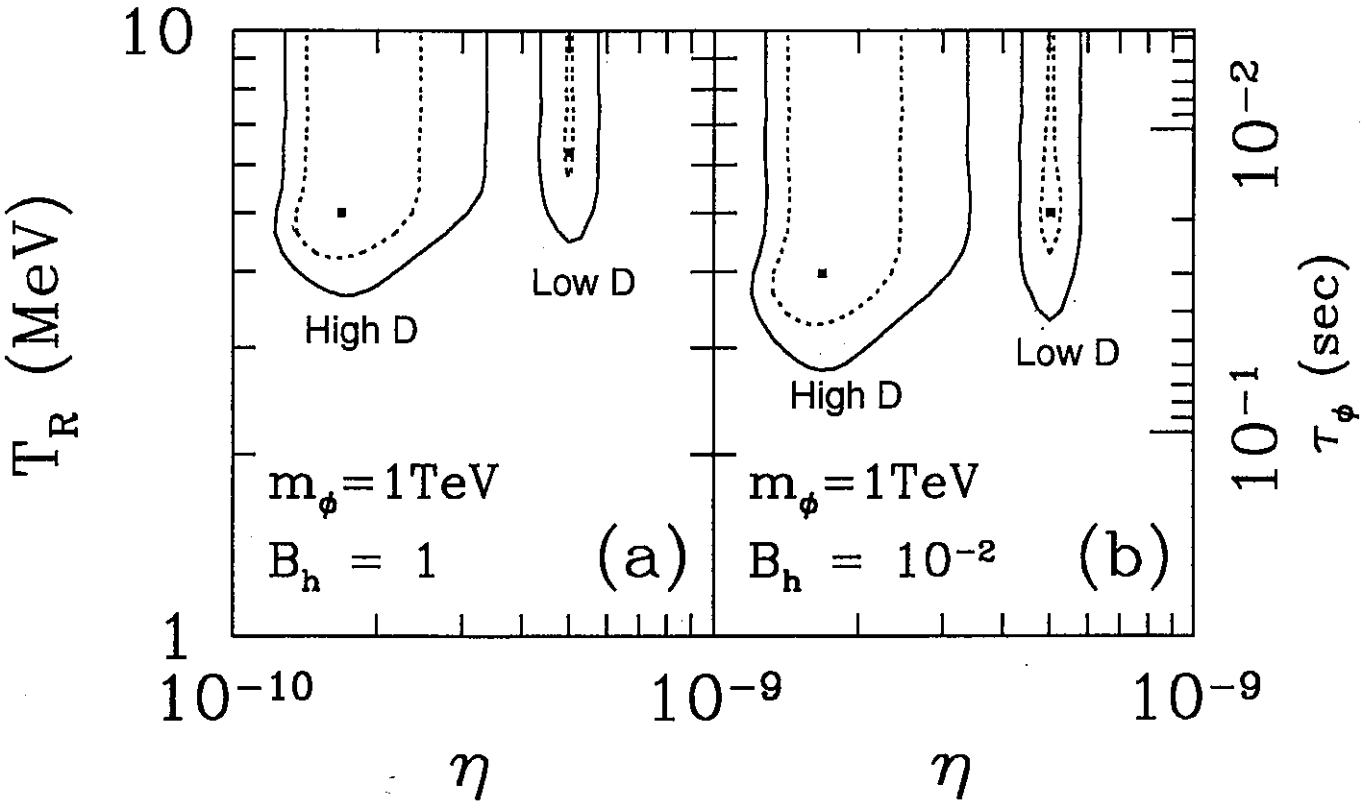
6. SUMMARY

NEUTRINO COSMOLOGY IS

STILL INTERESTING SUBJECT!



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