Language: 英語/English

KEK 物理セミナー Physics Seminar

10月10日 (金) October 10 (Fri)
16:00 ~ 17:00

4号館 345号室 Room 345 in the 4th Building

Cosmological implications for the neutrino mass

Matts Roos
(Univ. of Helsinki)

- Abstract:
  The neutrino mass recently determined from cosmological data is smaller than any terrestrial laboratory value. This review talk intends to give the astrophysical and cosmological background to particle physicists with little or no such knowledge.

Past presentations are archived at our home page, http://seminar.kek.jp/physics/ .

Organizers: T. Komatsubara and I. Adachi

2003.9.16

NEUTRINO COSMOLOGY

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RELIC NEUTRINO PROPERTIES

GALAXY FORMATION

OBSERVATIONS

CONCLUSIONS

RELIC NEUTRINO PROPERTIES

THE UNIVERSE IS EXPANDING

AT A RATE

$H = h \cdot 100 \frac{km}{s \cdot Mpc}$ THE HUBBLE PARAMETER (H_0 TODAY)

$h = 0.71$

$1\ Mpc = 3.085 \cdot 10^{19}\ km$ MEGAPARSEC

PARTICLES COLLIDE

AT A RATE $\Gamma = \langle N v \sigma(E) \rangle$

PARTICLES REMAIN IN THERMAL EQUILIBRIUM AS LONG AS

$$\Gamma \geq H. \qquad (1)$$

WHEN THE UNIVERSE EXPANDS, THE NUMBER DENSITIES N_i OF PARTICLES i PER m^3 DECREASE.

UNTIL THE CONDITION (1) IS NO LONGER FULFILLED:

THE PARTICLES DECOUPLE.

05

EXPANSION / CONTRACTION

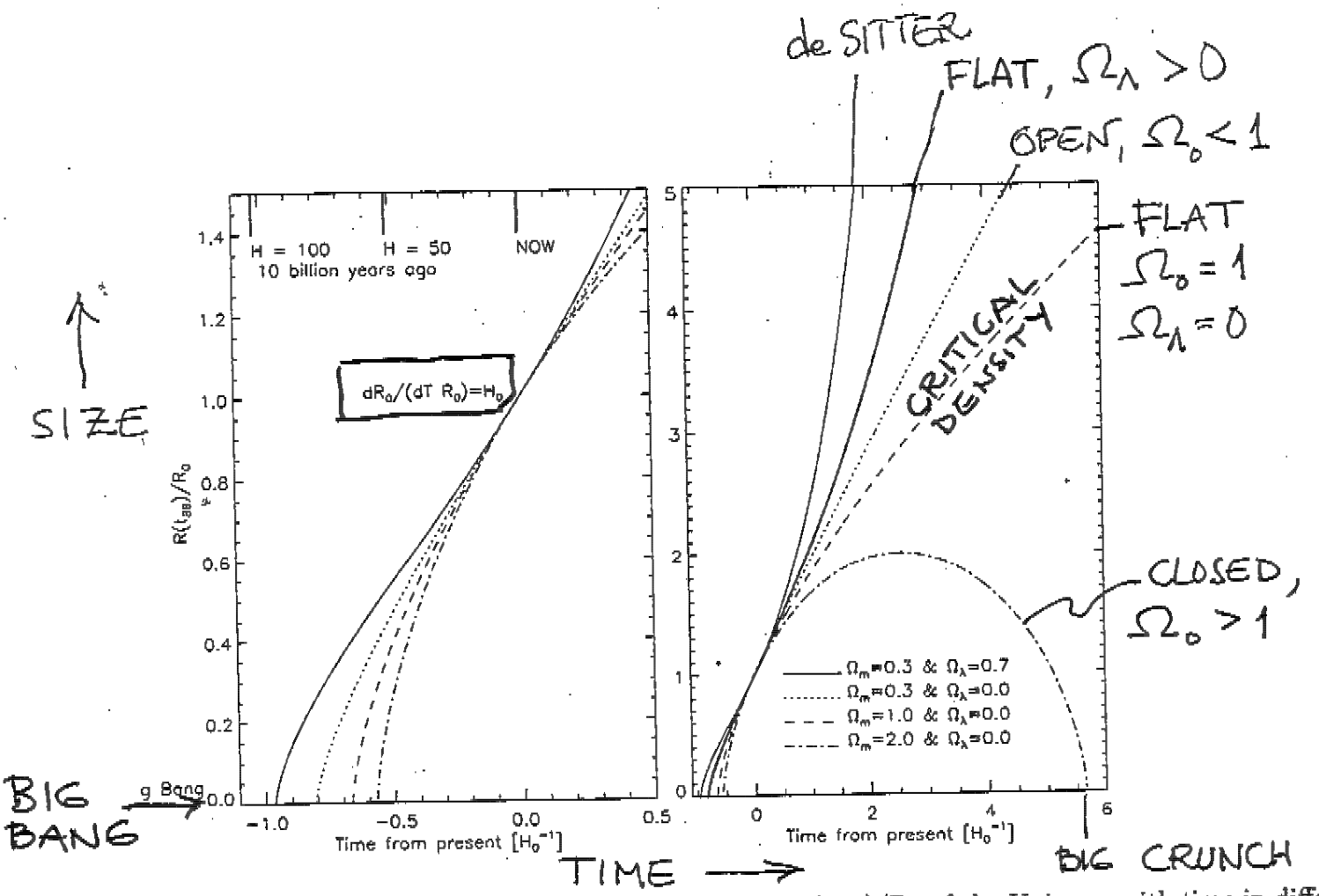


Figure 4.1: The behaviour of the scale factor $R(t_{BB})/R_0$ of the Universe with time in diffe cosmologies (left panel: past, right panel: future). The scale factor describes the size of Universe $R(t_{BB})$ scaled to the current one R_0. t_{BB} measures the time elapsed from the Bang in different models. Scale factor = 0 corresponds to the Big Bang. The cosmic expar in models with higher Ω_m decelerates faster in the future (dot, dash, dash-dot). If Ω_m exc unity, the expansion will change to contraction in the future (dash-dot). The higher the the more recent the Big Bang. In the models with non-zero cosmological constant (solid the expansion will accelerate in the future, and the Big Bang is in more distant past, allo greater age for the Universe. In upper left corner is illustrated the point that higher H_0 smaller age for the given model Universe, because the expansion is faster with high H_0: less time is needed for the Universe to reach the current size.

FROM J. Nevalainen thesis.

THE UNIVERSE AT

$t = 0.1$ s AFTER BIG BANG
WAS AT TEMPERATURE $T_\gamma = 10^{11}$ °K
AND ENERGY $E = 10$ MeV

CONTAINED
γ . e^-, e^+, ν_τ , ν_μ , ν_e

IN THERMAL EQUILIBRIUM.
ALL THE FERMIONS HAD THE SAME FERMI DISTRIBUTION WITH TEMPERATURES

$$T_{e^-} = T_{\nu_e} = \dots = T_\gamma$$

ν_τ , ν_μ DECOUPLED AT 3.7 MeV
ν_e DECOUPLED AT 2.3 MeV ;
THEY WERE RELATIVISTIC ,
THEY CONTINUED TO HAVE
THE SAME FERMI DISTRIBUTION

AT $E \lesssim 0.2$ MeV MOST OF THE $e^{\pm}$ DISAPPEAR BY ANNIHILATION

THE ENTROPY OF THE $e^{\pm}$ IS TAKEN OVER BY THE γ

TOTAL ENTROPY IS CONSERVED.

THIS REHEATS THE PHOTONS BUT NOT THE NEUTRINOS.

FROM NOW ON

$$T_\nu = \left(\frac{11}{4}\right)^{-\frac{1}{3}} T_\gamma = \frac{T_\gamma}{1.40} . \qquad (2)$$

NUMBER DENSITIES.

INTEGRATE THE BLACKBODY SPECTRUM TO FIND $N_\gamma(T_\gamma)$.

INTEGRATE THE FERMI DISTRIBUTION TO FIND $N_\nu(T)$.

$\therefore$ WHEN $T_\nu = T_\gamma$,

$$N_\nu = \frac{3}{4} N_\gamma .$$

WHEN $T_\nu = T_\gamma / 1.40$,

$$N_\nu = \frac{3}{11} N_\gamma \qquad (3)$$

V.4

DENSITY PARAMETERS Ω

ARE DEFINED AS DENSITIES NORMALIZED TO

ρ_c, THE CRITICAL DENSITY.

EXAMPLES $\rho_c = \frac{3H_0^2}{8\pi G}$

Ω_r RADIATION DENSITY PARAMETER

Ω_b BARYON —"— —"—

Ω_m MATTER —"— —"—

Ω_ν NEUTRINO —"— —"—

$$\Omega_\nu = \frac{3}{11}\frac{N_\gamma}{\rho_c h^2}\sum_i m_{\nu_i} = \frac{3\langle m_\nu\rangle}{94.0\ h^2\ eV} \qquad (4)$$

ASSUMING 3 NEUTRINO FAMILIES.

TODAY THE γ TEMPERATURE IS VERY WELL KNOWN

$T_\gamma = 2.725 \pm 0.001\ ^\circ K$

$\therefore\ T_\nu = 1.949 \pm 0.001\ ^\circ K \simeq 1.68 \cdot 10^{-4}\ eV$

If $m_\nu \simeq \mathcal{O}(1\ eV)$

THE NEUTRINOS ARE NON-RELATIVISTIC AND ACT AS DARK MATTER,

THEN $\Omega_\nu = \mathcal{O}(6\%)$.

GALAXY FORMATION

THE FORCE OF GRAVITY MAKES A HOMOGENEOUS MATTER DISTRIBUTION UNSTABLE

→ IT EXPANDS OR CONTRACTS.

TRUE ON ALL SCALES: THE WHOLE UNIVERSE OR TINY LOCAL SCALES.

IN THE PRIMORDIAL PLASMA THERE ARE LOCAL DENSITY FLUCTUATIONS

(BARYONIC DENSITY, DARK MATTER, ν,)
ORIGINALLY QUANTUM FLUCTUATIONS

THEY EXPAND LINEARLY AT A RATE SLOWER THAN H, EVENTUALLY REACHING A MAXIMUM SIZE, AND THEN COLLAPSE NONLINEARLY.

THERE ARE TWO OPPOSING FORCES: ATTRACTIVE GRAVITATION, AND REPULSIVE RADIATION PRESSURE.

IF THE NEUTRINOS ARE EXACTLY MASSLESS, THEY DON'T FEEL EITHER FORCE.

IN OVERDENSE REGIONS
GRAVITY > RADIATION PRESSURE
MATTER CONTRACTS LOCALLY,
ATTRACTS SURROUNDING MATTER,
INFLOW.

IN UNDERDENSE REGIONS
GRAVITY < RADIATION PRESSURE
THE FLUCTUATIONS MOVE AS SOUND WAVES (SPEED C_s) IN THE FLUID TRANSPORTING ENERGY AWAY.

$$t_s = \lambda / C_s \qquad (5)$$

THE LIMITING CASE IS THE

JEANS WAVELENGTH

$$\lambda_J = \sqrt{\frac{\pi}{G\bar{\rho}}}\, C_s \qquad (6)$$

LIGHT, MASSIVE NEUTRINOS

MOVE UNHINDERED OUT OF REGIONS WITH $\lambda < \lambda_J$, WHERE

λ_J = JEANS LENGTH WHEN THE NEUTRINOS BECOME NONRELATIVISTIC.

$\therefore$ THE NEUTRINOS WILL DAMP THE FLUCTUATIONS AT A RATE WHICH DEPENDS ON THEIR rms VELOCITY.

$\therefore$ CONSEQUENCES

(i) NEUTRINOS AFFECT THE CLUSTERING TIME SCALE

(ii) FREE STREAMING OF RELATIVISTIC NEUTRINOS ERASES SMALL SCALE STRUCTURES.
HOWEVER, THIS IS PARTIALLY MASKED BY OTHER EFFECTS.

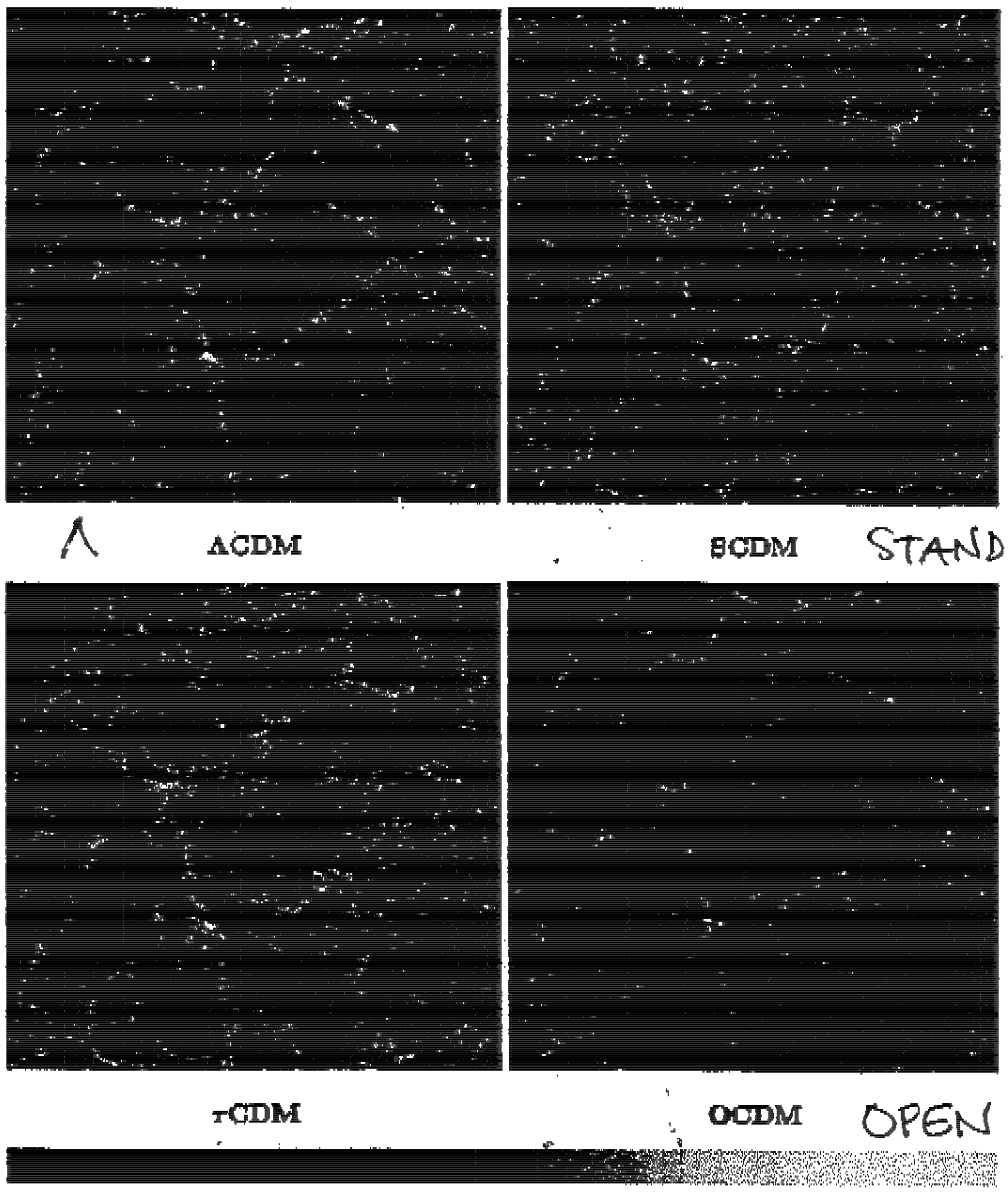
C13

LARGE-SCALE STRUCTURES

SIMULAATIO

NEUTRINOS NEEDED ONLY TO FREE STREAM AND SMEAR OUT TOO SMALL-SCALE CDM FLUCTUATIONS.

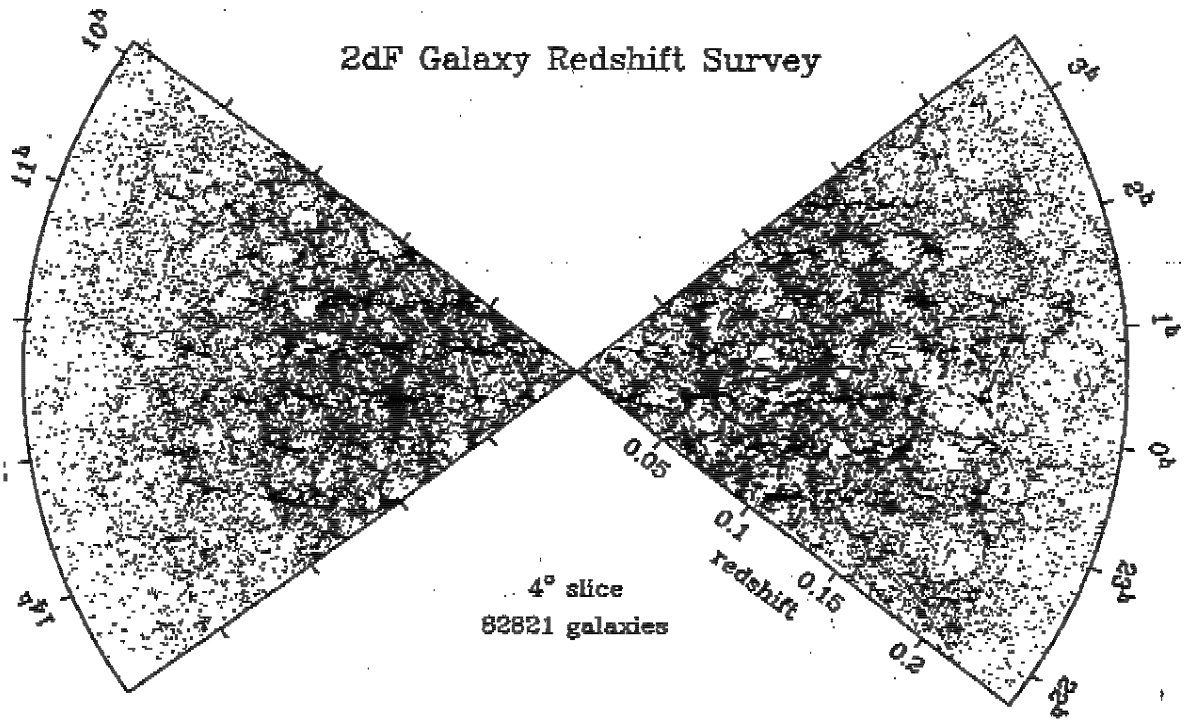
$z=0$



The VIRGO Collaboration 1996

Click here to get this mosaic in full resolution (and beauty...).
Use one of the following links to get detailled views of the models:

- **CMD with cosmological constant**
- **Standard CDM**
- **A CDM variant**


2dF Galaxy Redshift Survey
10h
11h
14h
3h
2h
1h
0h
23h
22h
0.05
0.1
0.15
0.2
redshift
4° slice
82821 galaxies

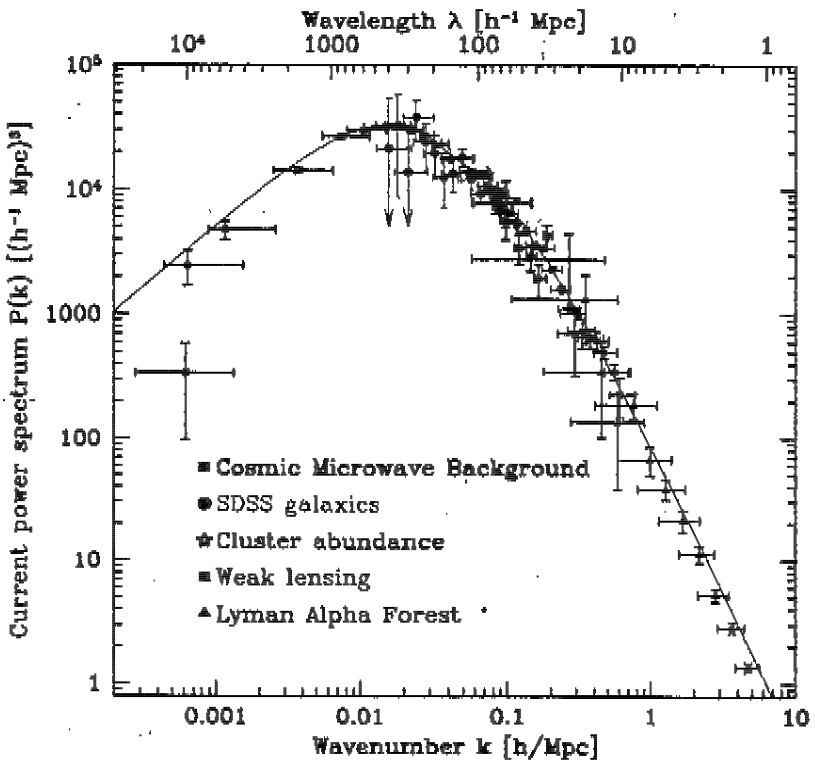


FIG. 11 Power spectrum of density inhomogeneity today obtained from a variety of measurements including large-scale structure, CMB, weak lensing, rich clusters and the Lyman-alpha forest. The curve is the theoretical prediction for the consensus cosmology model (from Tegmark *et al.*, 2002).

OBSERVATIONS

I. LARGE SCALE STRUCTURES

SEEN IN 2dFGRS (2 degree Field Galaxy Redshift Survey)

ARE FOURIER-ANALYZED,

MOCK UNIVERSES ARE MONTE-CARLO-GENERATED.

PARAMETERS:

$\Omega_\nu h \Rightarrow \Omega_\nu$ AND h ANTICORRELATED

$\Omega_m h$, $\Omega_b h \Rightarrow$ INTERFERE WITH THE NEUTRINO SIGNAL.

n_s = SCALAR SPECTRAL INDEX: THE MATTER FLUCTUATIONS CAN BE FITTED WITH A POWER

$$P(k) = k^{n_s}$$

Ω_ν AND n_s ARE ANTICORRELATED.

b = BIAS BETWEEN GALAXIES AND MASS

σ_8 = NORMALIZATION OF AVERAGE FLUCTUATION AMPLITUDE WITHIN 8 Mpc.

II. COSMIC MICROWAVE BACKGROUND.

THIS DOES NOT FEEL ANY EFFECT OF NEUTRINOS,

BUT IS NEEDED TO REMOVE DEGENERACIES IN THE LSS PARAMETERS.

PARAMETERS

$\Omega_m h^2$, $\Omega_b h^2$, n_s

AND 5 OTHER PARAMETERS.

III. HUBBLE SPACE TELESCOPE

USING 5 DIFFERENT METHODS, HAS DETERMINED INDEPENDENTLY

$$h = 0.71 \pm \begin{matrix} 0.04 \\ 0.03 \end{matrix}$$

IV. X-RAY-LUMINOUS GALAXY CLUSTERS

f_{GAS} = BARYONIC MASS FRACTION, X-RAYS

$f_{GAS} \neq$ THE UNIVERSAL VALUE Ω_b / Ω_m,
THERE IS A KNOWN CORRECTION ($\sim 16\%$).

$\Rightarrow$ A WEAK, LINEAR DEPENDENCE OF σ_8 ON Ω_m.

THIS HELPS TO DETERMINE Ω_ν.

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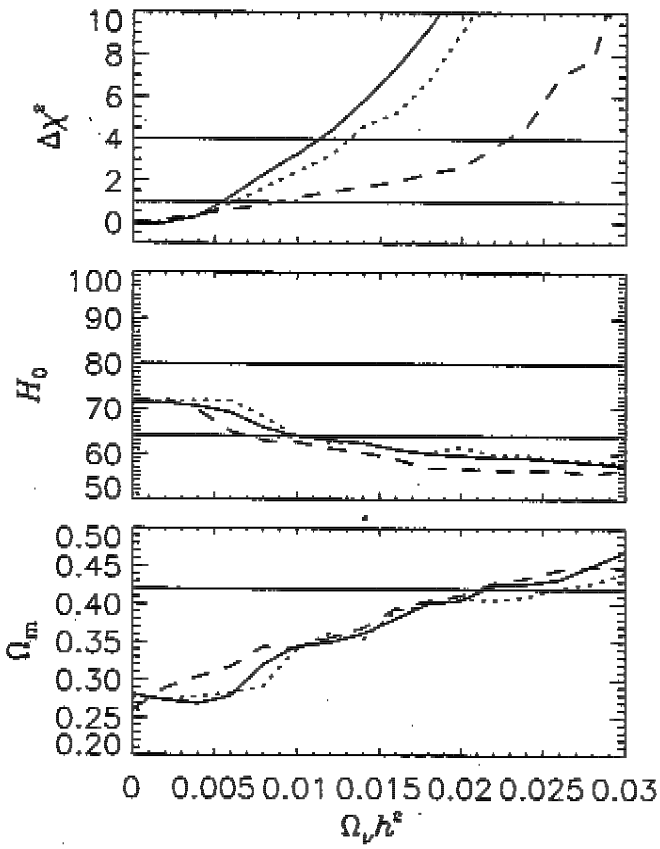

Fig. 1. The top panel shows χ^2 as a function of $\sum m_\nu$ for different choices of priors. The dotted line is for WMAP + 2dFGRS data alone, the dashed line is with the additional Wang *et al.* data. The full line is for additional HST and SNI-a priors as discussed in the text. The horizontal lines show $\Delta\chi^2 = 1$ and 4 respectively. The middle panel shows the best fit values of H_0 for a given $\sum m_\nu$. The horizontal lines show the HST key project 1σ limit of $H_0 = 72 \pm 8$ km s Mpc^{-1}. Finally, the lower panel shows best fit values of Ω_m. In this case the horizontal line corresponds to the SNI-a 1σ upper limit of $\Omega_m < 0.42$.

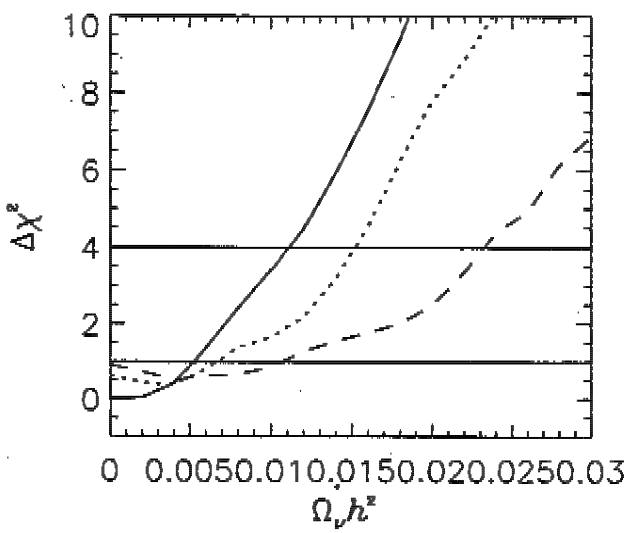

Fig. 5. $\Delta\chi^2$ as a function of $\sum m_\nu$ for various different values of N_ν. The full line is for $N_\nu = 3$, the dotted for $N_\nu = 4$, and the dashed for $N_\nu = 5$. $\Delta\chi^2$ is calculated relative to the best fit $N_\nu = 3$ model.

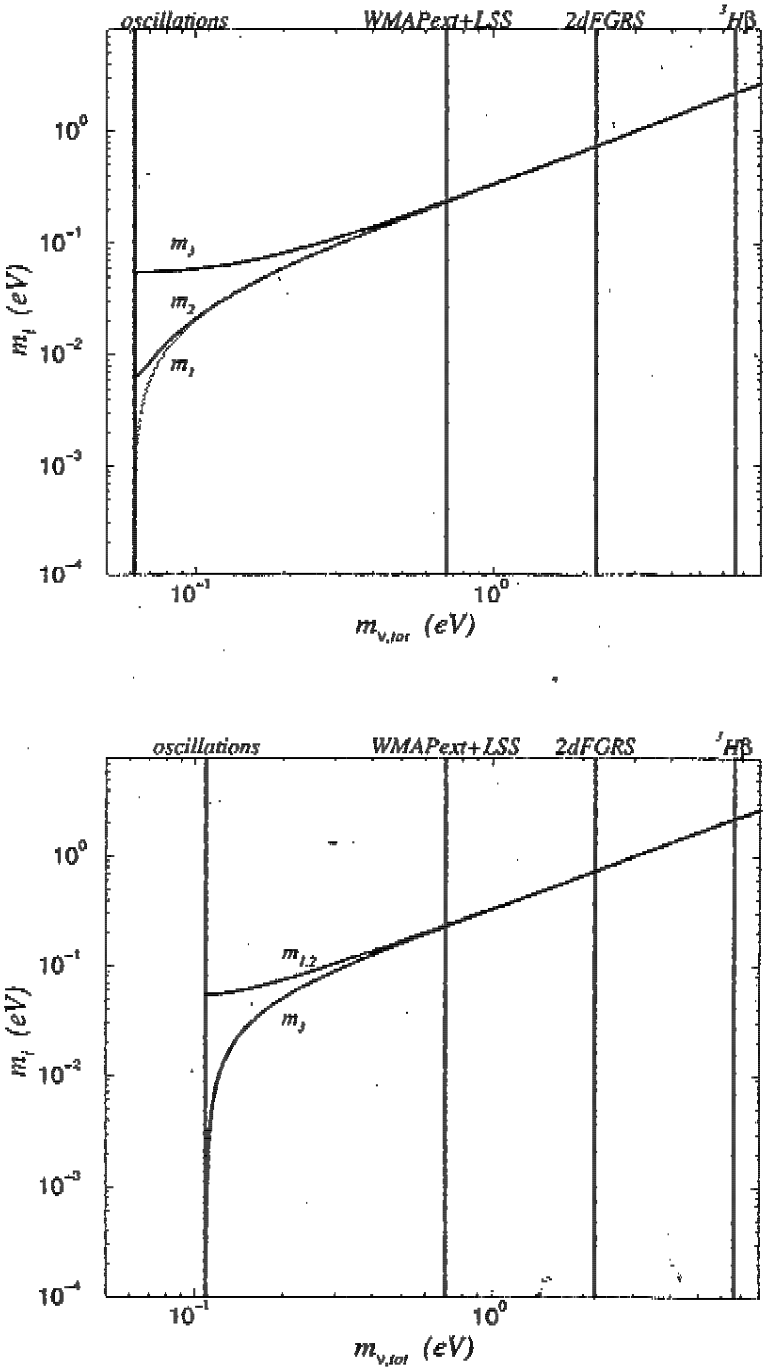

Figure 1. Neutrino mass eigenvalues as functions of their total for the cases of normal (top panel) and inverted (bottom panel) hierarchies. The vertical line marked 'oscillations' is the lower limit derived from the measured mass-squared differences for the two hierarchies. The other vertical lines are upper limits from WMAP+CBI+ACBAR+2dFGRS+Ly α, 2dFGRS, and ^{3}H β decay.

ourselves to adiabatic, linear perturbations. The basic physics is then fairly

Ω_m	$0.28^{+0.06}_{-0.05}$	$0.308^{+0.020}_{-0.024}$	0.27
σ_8	$0.78^{+0.10}_{-0.11}$	$0.74^{+0.12}_{-0.07}$	0.72
$\Omega_\nu h^2$	$0.0040^{+0.0035}_{-0.0035}$	$0.0045^{+0.0036}_{-0.0031}$	0.0055
τ	$0.13^{+0.09}_{-0.08}$	$0.13^{+0.06}_{-0.07}$	0.09

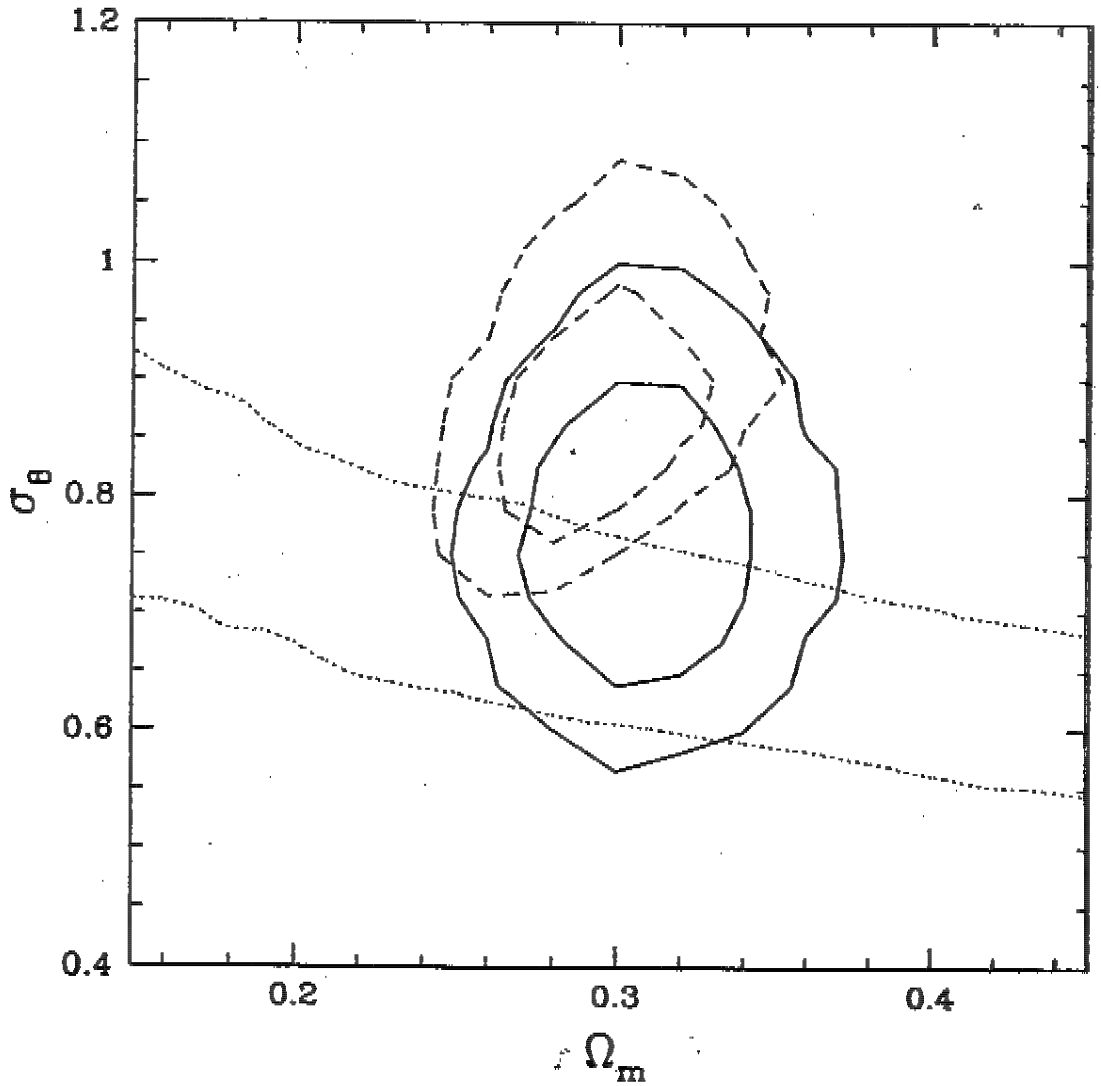

Figure 3. Joint 68.3 and 95.4 per cent confidence limits on σ_8 and Ω_m from the analysis of the CMB+2dF+f_{gas} data, allowing (solid curve) and excluding (dashed curve) a contribution to the energy density of the universe from massive neutrinos. The dotted curve shows the 95.4 per cent confidence limit from the analysis of the local cluster XLF from Allen *et al.* 2003

data of $\sigma_8 = 0.86^{+0.08}_{-0.07}$ (dashed curve in Fig. 3), which is only marginally consistent with the cluster XLF constraints. When the neutrino density is included as a free

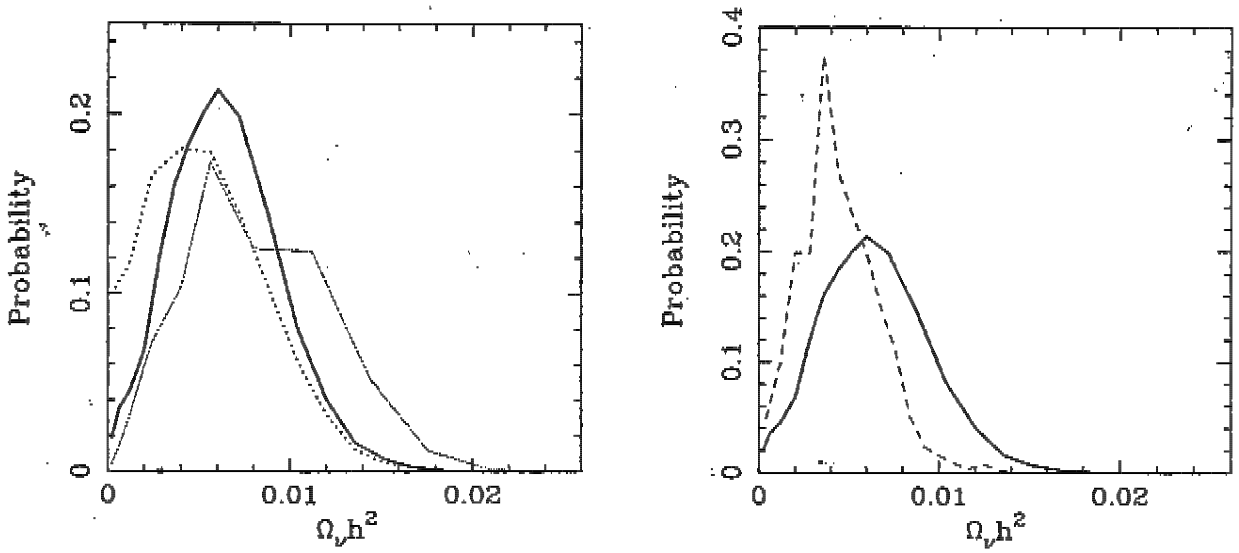

Figure 4. (a) Marginalized probability distribution for $\Omega_\nu h^2$ from the analysis of the CMB+2dF+$f_{\rm gas}$ (dotted curve), CMB+$f_{\rm gas}$+XLF data (grey curve) and CMB+2dF+$f_{\rm gas}$+XLF (dark, solid curve) data. In all cases we have allowed for the presence of tensor components (b) The dashed curve shows the results from the CMB+2dF+$f_{\rm gas}$+XLF data from the analysis without tensor components. The dark, solid curve is the same as in (a).

CONCLUSIONS

$$\Omega_\nu h^2 = 0.0059 \,{}^{+0.0033}_{-0.0027}$$

$$\therefore \sum_i m_{\nu_i} = 0.56 \,{}^{+0.30}_{-0.26}$$

FROM EQ. (4).

IF ALL ν'S HAVE $\simeq$ EQUAL MASS IT IS

$$m_\nu \approx 0.2 \pm 0.1$$