Recent Evaluation of Cosmological Parameters

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CMB spectrum

- T=2.726±0.010 K

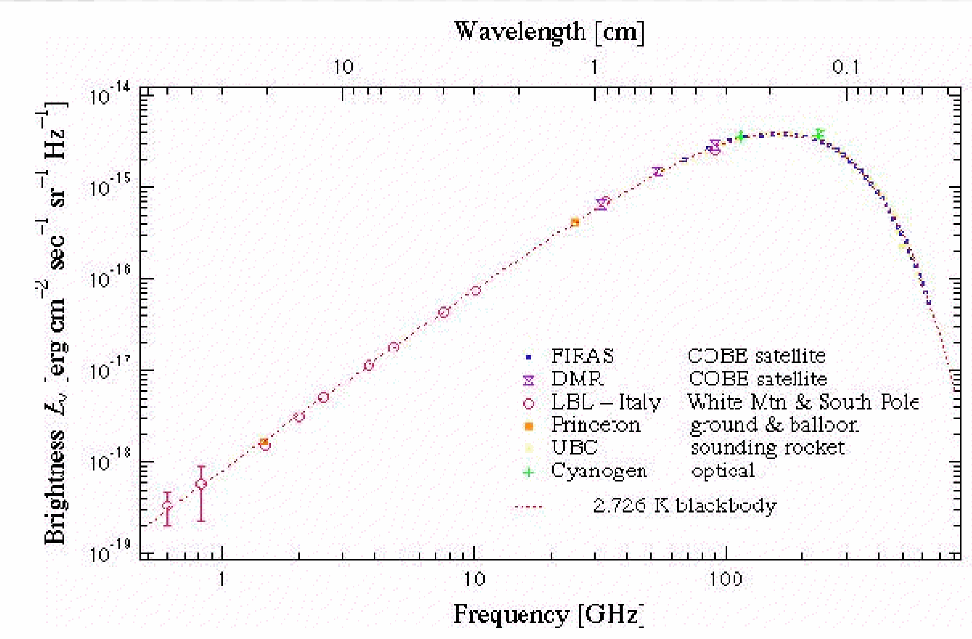

Fig. 1. Measurements of the CMB spectrum.

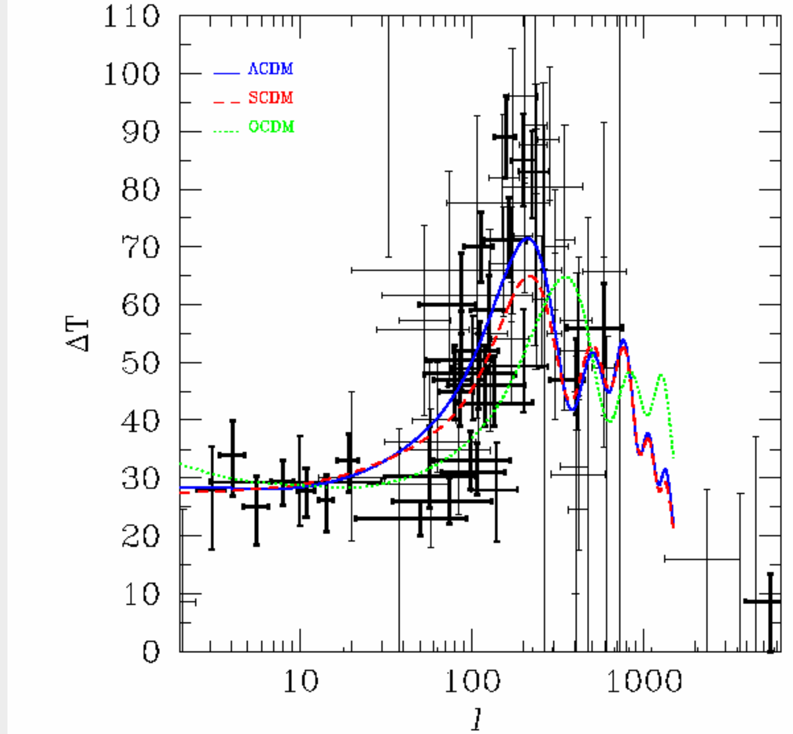

Fig. 4. Compilation of CMB Anisotropy observations. Vertical error bars represent 1σ uncertainties and horizontal error bars show the range from ℓ_{min} to ℓ_{max} of Table 1. The line thickness is inversely proportional to the variance of each measurement, emphasizing the tighter constraints. All three models are consistent with the upper limits at the far right, but the Open CDM model (dotted) is a poor fit to the data, which prefer models with an acoustic peak near $\ell = 200$ with an amplitude close to that of ΛCDM (solid).

Density fluctuations in CMB

- $P(k) \propto k^n$, $n \sim 1$
- $P(k,z) = D(z) k^n T(k)$
- Fluctuation $\Rightarrow$ CMB at $z \sim 1000$
- CMB multipoles $\Delta T/T = \sum_{lm} a_{lm} Y_{lm}$ or if symmetric $\langle (\Delta T/T)^2 \rangle = \sum_l C_l (2l+1)/4\pi$

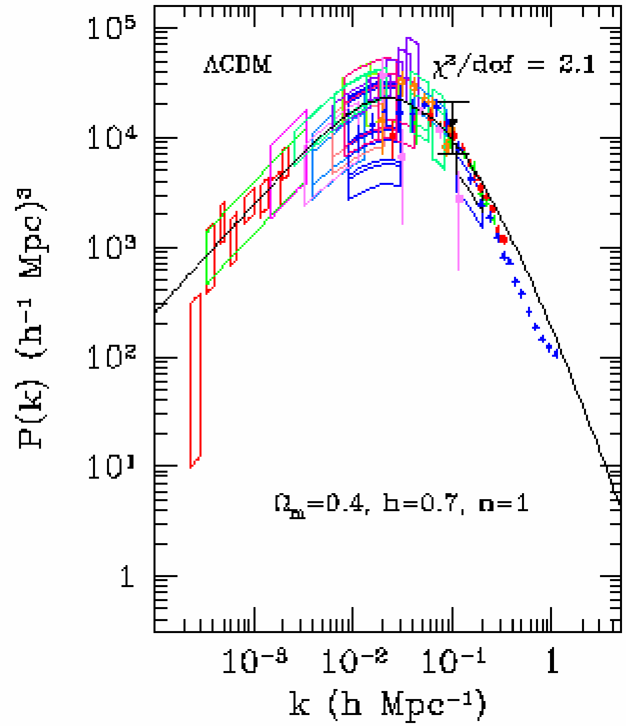

Figure 1. Power spectrum derived from large scale clustering of galaxies (shown with data points) and CMB temperature fluctuations (shown with boxes). The curve is the model power spectrum of a flat CDM universe with a cosmological constant. The figure is taken from Gawiser and Silk [9].

Paradigms in cosmology

1. Hot Big Bang and subsequent Friedman expansion
2. Cold dark matter dominates the universe today
3. Inflation in some early period

1 has many evidences.
2,3 are rather hypothetical.

Hubble constant

- HST Key Project (Cepheids < 20Mpc)
  $H_0 = (70\text{-}75) \pm 10$ km/s/Mpc
- Max. brightness of SNe Ia is not standard
  $H_0 = 64 \pm 3$ km/s/Mpc
- Surface brightness fluctuation
  $H_0 = 77 \pm 7,\ 74 \pm 4,\ 71 \pm 7,\ 74 \pm 7$ km/s/Mpc
- M.F.'s summary:
  $H_0 = (71 \pm 7) \times (1.15\text{-}0.95)$ km/s/Mpc

Cosmic age

- Turn off point in the HR diagram of globular clusters
- Uncertainty comes from LMC distance
  (longer LMC distance $\Rightarrow$ shorter age)
- Min. 12$\pm$1 Gyr – Max. 18$\pm$2 Gyr

Ω and λ

- H_0-t_0 matching: $t_0=f(\Omega,\lambda)/H_0 \Rightarrow \Omega<0.8$-$0.9$
- M/L ration of galaxies $\Rightarrow \Omega=0.2$-0.5
- Peculiar velocity – overdensity relation $\Rightarrow \Omega=0.2$-0.5
- SN Ia Hubble diagram$\Rightarrow \Omega=0.8\ \lambda\ -0.4\pm0.4$
- Gravitational lensing frequency$\Rightarrow \lambda<0.8$
- Shape parameter of the transfer function $\Rightarrow \Omega\sim0.35$
- Matching of the cluster abandance $\Rightarrow \Omega<0.5$
- Multipoles of CMB temperature $\Rightarrow \Omega+\lambda\sim1$
- Evolution of cluster abandance $\Rightarrow \Omega=0.2$-0.45 and ~1
- <u>M.F.'s conclusion</u>: $\Omega=0.2$-0.5 and finite λ

New CMB experiments -1

- Beam size 10’ (smaller than COBE)
- BOOMERanG (Antarctia)
- MAXIMA (northern sky)

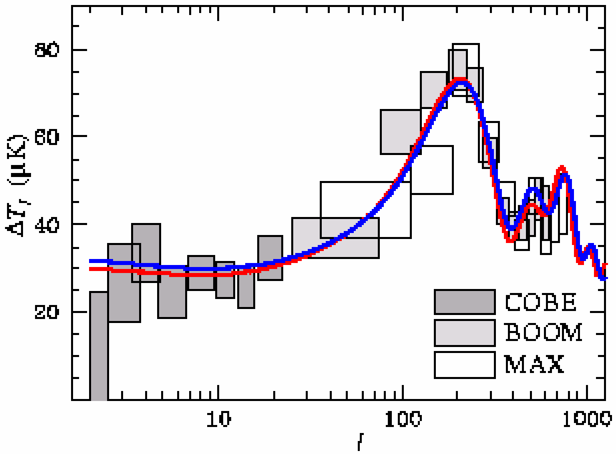

Figure 3. CMB multipoles $\Delta T_\ell = \sqrt{\ell(\ell+1)C_\ell/2\pi}$ from BOOMERanG and MAXIMA experiments (the normalisations are shifted within one sigma calibration error), together with the COBE 4 year data. The curves show the prediction of the CDM structure formation model. The thick solid curve represents the model that satisfies the joint constraint: $\Omega = 0.35$, $\lambda = 0.65$, $h = 0.75$, $\Omega_b h^2 = 0.023$ and $n = 0.95$. The grey curve is the model that is a good fit to CMB alone: $\Omega = 0.3$, $\lambda = 0.7$, $h = 0.9$, $\Omega_b h^2 = 0.03$ and $n = 1$. Note a high baryon abundance for the latter. Figure is taken from Hu et al.[53].

New CMB experiments -2

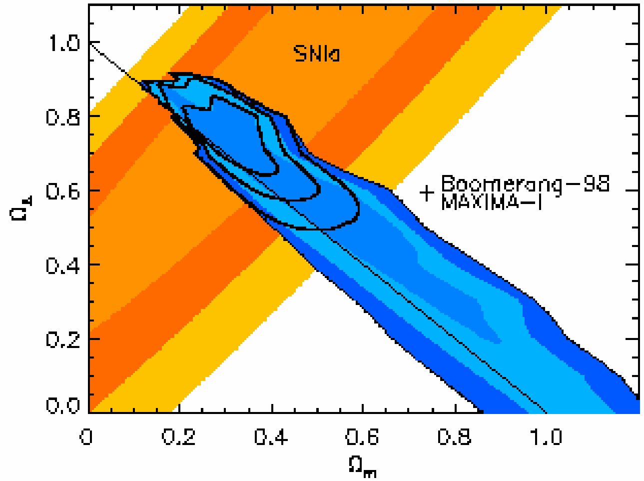

Figure 4. Constraints on the $\Omega - \lambda$ plane derived from CMB multipoles and a type Ia supernova Hubble diagram, taken from Jaffe et al.[54].The labels are: $\Omega_m \equiv \Omega$ and $\Omega_\Lambda \equiv \lambda$. The three levels of shading mean 1, 2 and 3 sigma. The contours show the joint constraint. The straight line indicates flat universes.

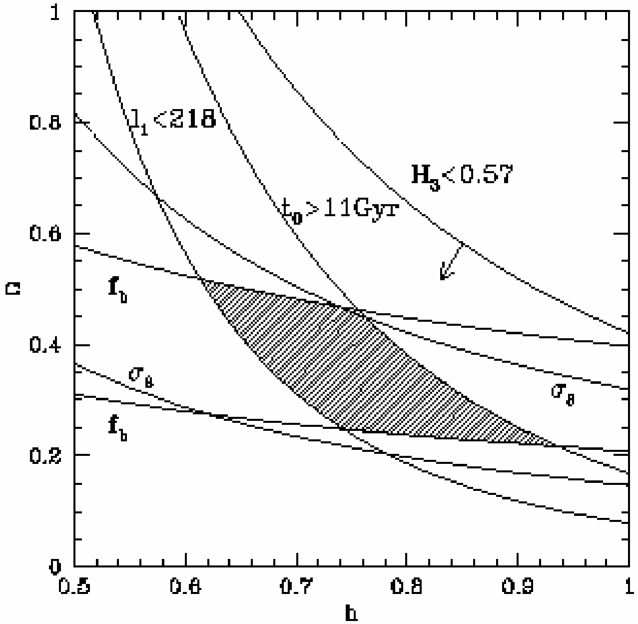

Figure 5. Constraints on the $h - \Omega$ plane derived from the new CMB experiments. ℓ_1 stands for the position of the first peak, H_3 is the ratio of the heights of the third peak to the second, the curves labelled by 'σ_8' are obtained by the match of CMB data with the cluster abundance, and those with 'f_b' are the constraint from the CMB and the cluster baryon fraction. Cosmic age $t_0 > 11\,Gyr$ is also plotted. The curves are taken from [53].

New CMB experiments -3

- CMB data + Large scale structure
  $\Omega=0.4\pm0.2$
  $H_0=75\pm15$
  $\lambda=1-\Omega+(+0.2,-0.1)$
- On-going experiments
  DASI, CBI, MAP...

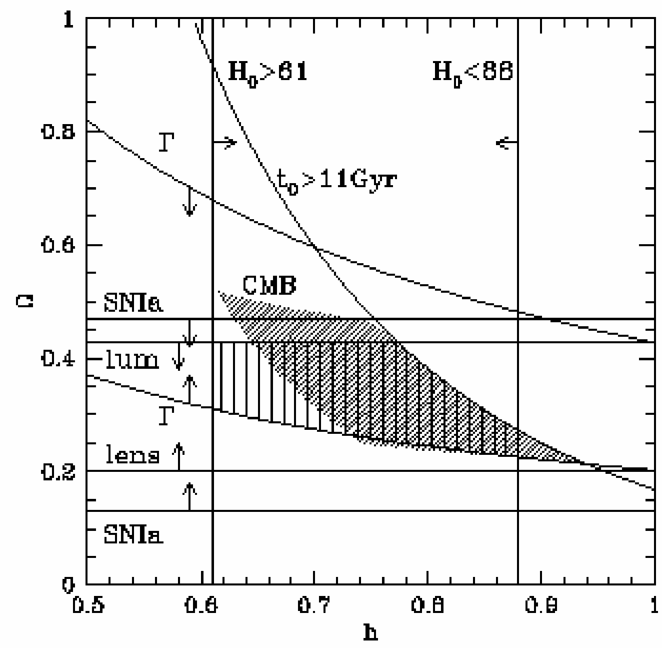

Figure 6. Summary of constraints shown in the $h-\Omega$ plane. Constraints shown by lines correspond to (1), (2), (5)-(7) of §3 and the range of the Hubble constant in §2. The allowed region derived from CMB (corresponding to (3), (8) and (9) of §3 and cosmic age) is shown by thick shading, while those derived independent of CMB are indicated by light shading.

Matter content: baryons

- Nucleosynthesis (D, ^{4}He, ^{7}Li)
  $\Rightarrow \Omega_b h^2 = 0.00367((n_b/n_\gamma)/10^{-10})$
  Olive et al.: 0.04-0.010 and 0.015-0.023
  Tytler: 0.019-0.021
- Relative height of even and odd peaks in CMB multipole
  $\Rightarrow \Omega_b h^2 > 0.019$
- Stars
  $\Rightarrow \Omega_{star} = 0.004 \pm 0.002$
  at h=0.7

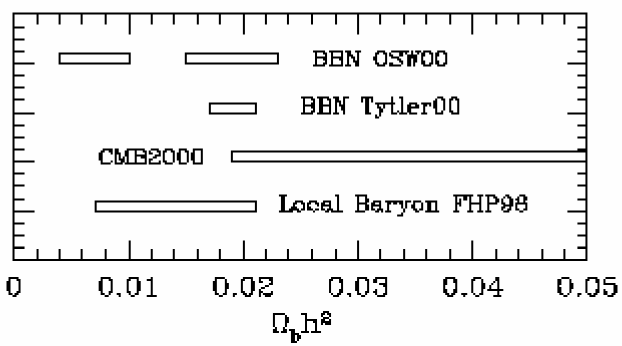

Figure 7. Baryon abundances inferred from CMB (discussed above), nucleosynthesis (BBN)[56,59],and accounting the local baryon distribution[60].

Matter content: dark matter

- WIMPs:
  Neutralino ($\tan\beta > 3$, $M_\chi > 50$GeV)
- Massive neutrino:
  CMB-cluster abandance matching $\Rightarrow \sum m_\nu < 4$eV
  (solar ν+direct meas. $0.05 < \sum m_\nu < 8.4$eV)
- SIMPs:
  N-body sim w/CDM predict singular core of halo

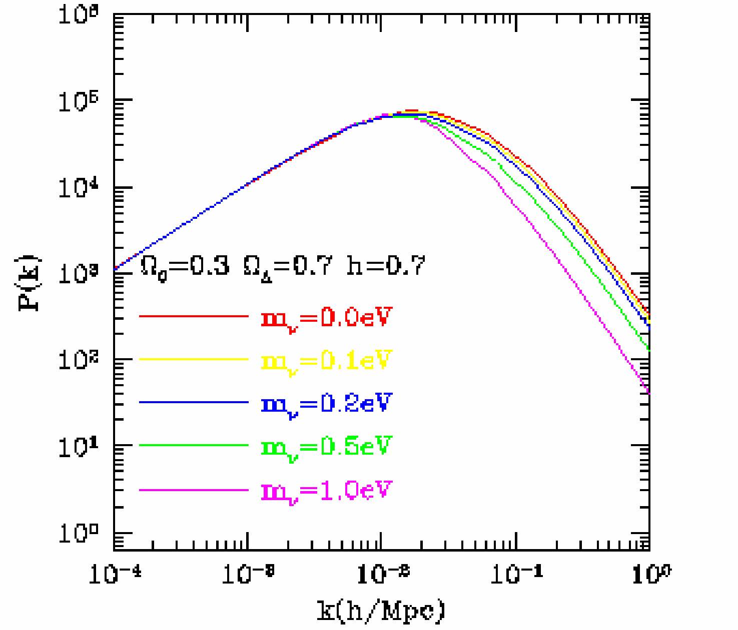

Figure 8. Effect of massive neutrinos on the power spectrum. The three species of neutrinos are assumed to have equal mass, *i.e.*, $\sum_i m_{\nu_i}$ is three times the value indicated by labels. The curve on the top is with $m_\nu = 0$.

Matter content: MACHO

- Massive Astrophysical Compact Halo Objects as CDM
- Aborted stars or stellar remnants
- Observable through magnitute amplification by gravitational lensing
- Observation by MACHO, EROS, MOA
  $\Rightarrow$ Events corresponding to 0.1-1M_{sun}
  $\Rightarrow$ 0.2 or <0.4 of halo matter

Theory of λ and inflation

- Cosmological constant
  - Time varying λ
  - Exact symmetry
  - Anthropic principle
- Inflation
  - Φ^{α} potential
  - $V_0(1-(\varphi/\mu)^p)$ type potential
  - Hybrid (two fields)

Conclusion

- H_0=62-83 km/s/Mpc
- Ω=0.25-0.48
- λ=0.75-0.52
- Poorly understood:
  - vacuum energy
  - CDM
  - scaler fields (inflation)

COSMIC ENERGY DENSITY BUDGET

entity		fraction		observation
vacuum		70%		invisible
CDM		26%		invisible
baryon		4%		
	warm gas		3%	invisible
	stars		**0.5%**	optical
	hot gas		**0.5%**	X-rays
neutrino		>0.1%		invisible

Note:–bold face means observable components