SPACE
TIME
&
MATTER

Cosmological Parameters 2000

LMK 2001
[redacted]

(i) HST - KEY PROJECT:

⇒ Use Cepheid DISTANCES to 25 Galaxies within 25 Mpc to calibrate secondary distance indicators: (1) Tully Fisher relation (spirals) (2) FUNDAMENTAL PLANE (Ellipticals), (3) SBFluctuations (4) SN Ia

⇒ each of these then used to measure H_0:

$H_0^{TF} = 71 \pm 4 \pm 7$

$H_0^{FP} = 78 \pm 8 \pm 10$ (82)

$H_0^{SBF} = 69 \pm 4 \pm 6$ (70)

$H_0^{SNIa} = 68 \pm 2 \pm 5$ (71)

⇒ $H_0 = \boxed{71 \pm 6}$ (±8) $km\,s^{-1}\,Mpc^{-1}$ (1σ) (9% - 1σ)

↳ LMC - DISTANCE (see fig)

(if Cepheid metallicity - 4% ⇒ $\boxed{68 \pm 6}$)

OTHER MEASURES:

(ii) S-Z Effect:

σ_e ⇒ CMB photon scattering on Cluster matter (electrons)

⇒ shift to higher energy.

$SZE \rightarrow \int \sigma_T n_e \, dl$

Compare to X Ray Intensity $\sim \int n_e^2 \, dl$

⇒ ∴ Use models ⇒ $n_e, n_e^2 \rightarrow dl \rightarrow$ physical scale ⟺ angular size!

⇒ distance measure!

(assume $dl_\perp \Rightarrow dl_\parallel$) ∴ statistical.

① SPACE

⇒ EXPANSION RATE

⇒ GEOMETRY

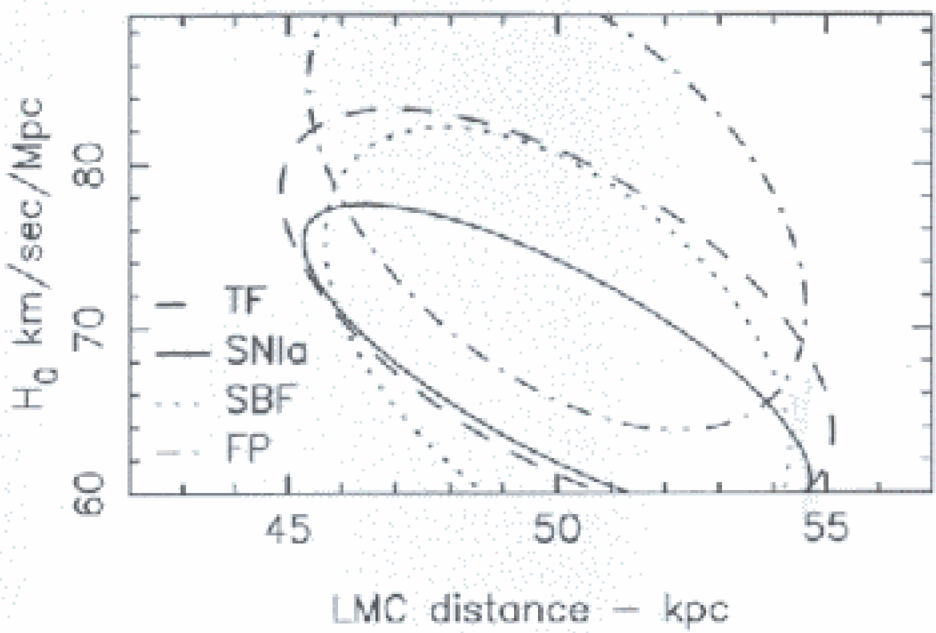
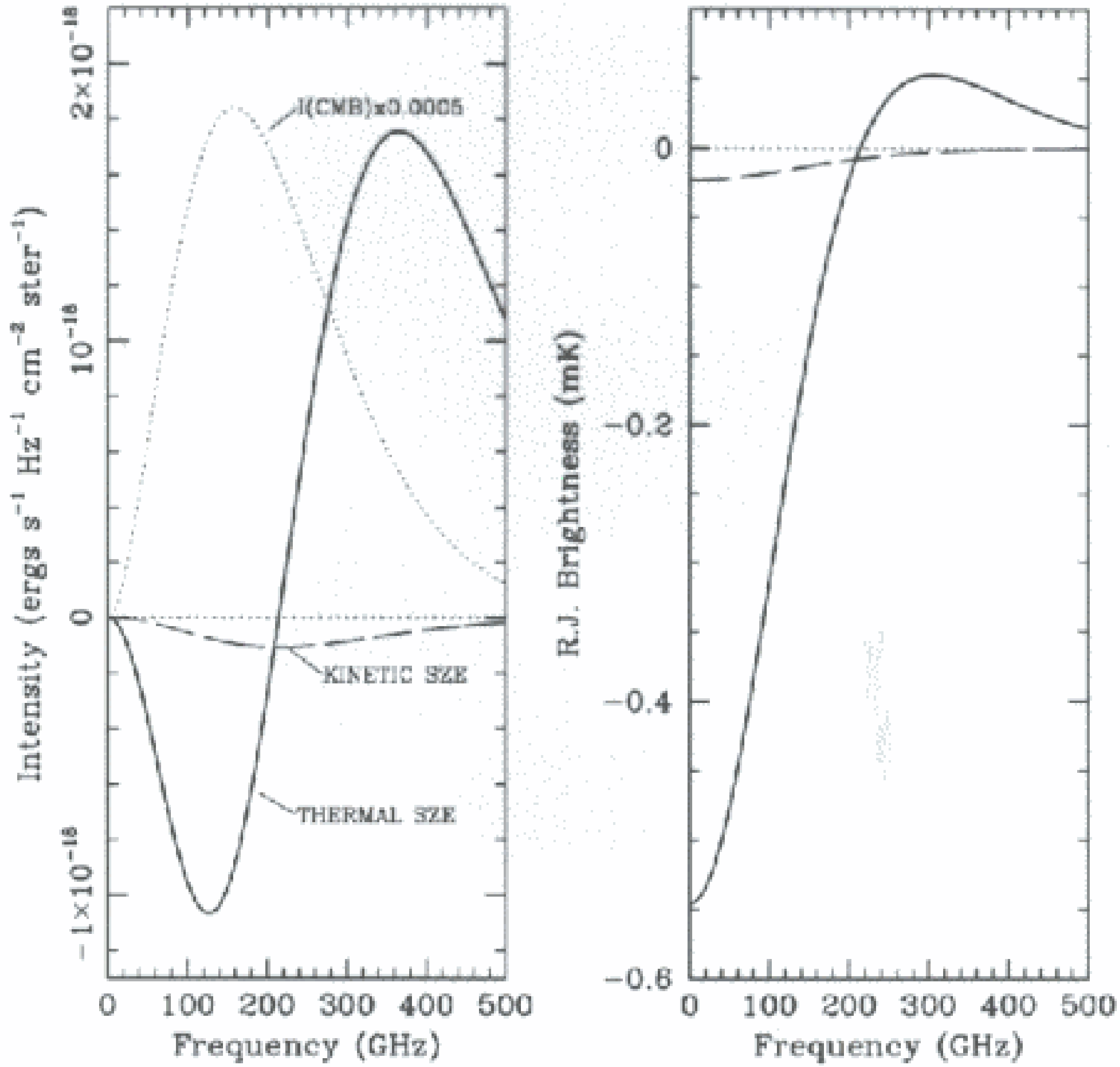
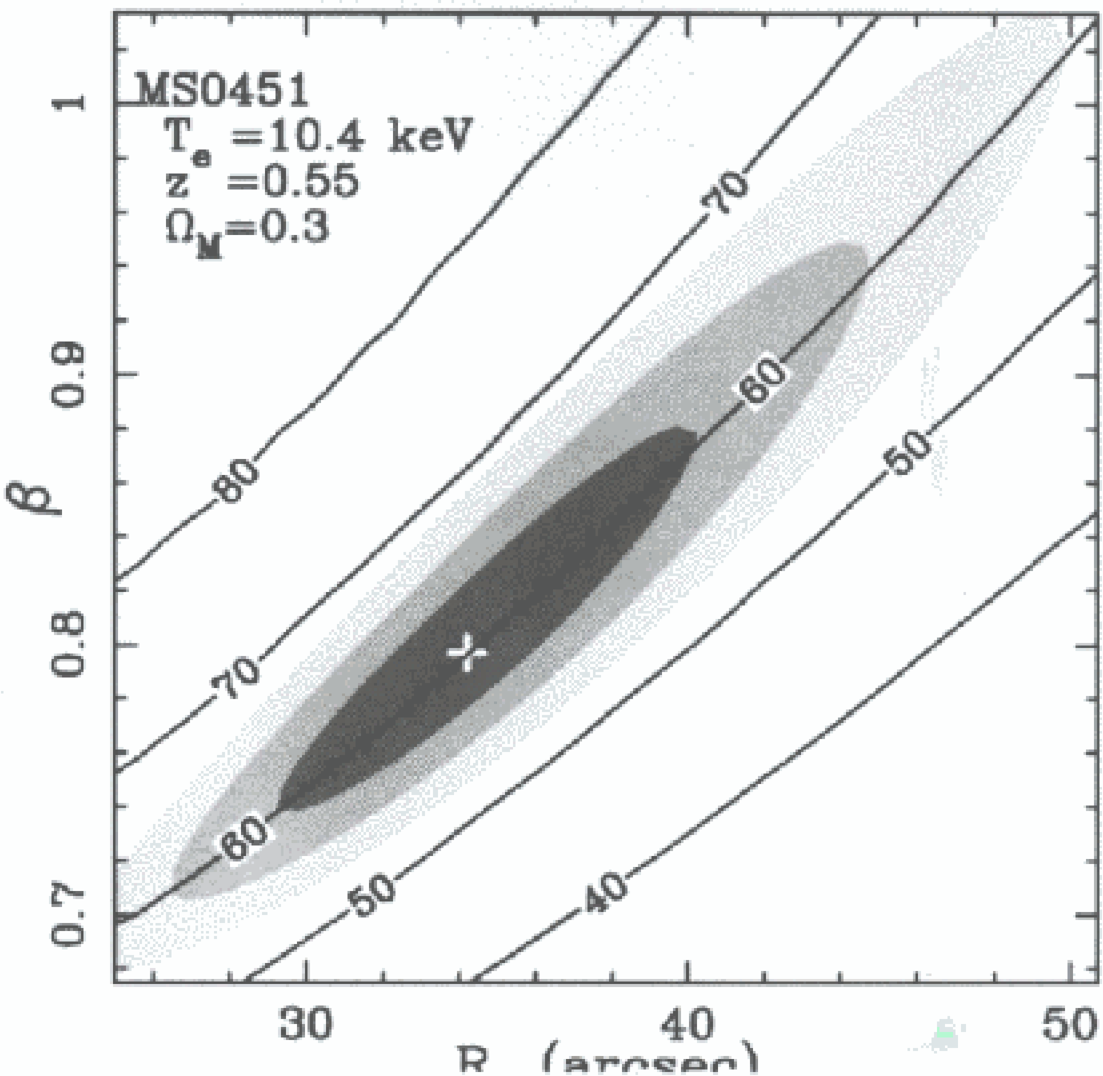
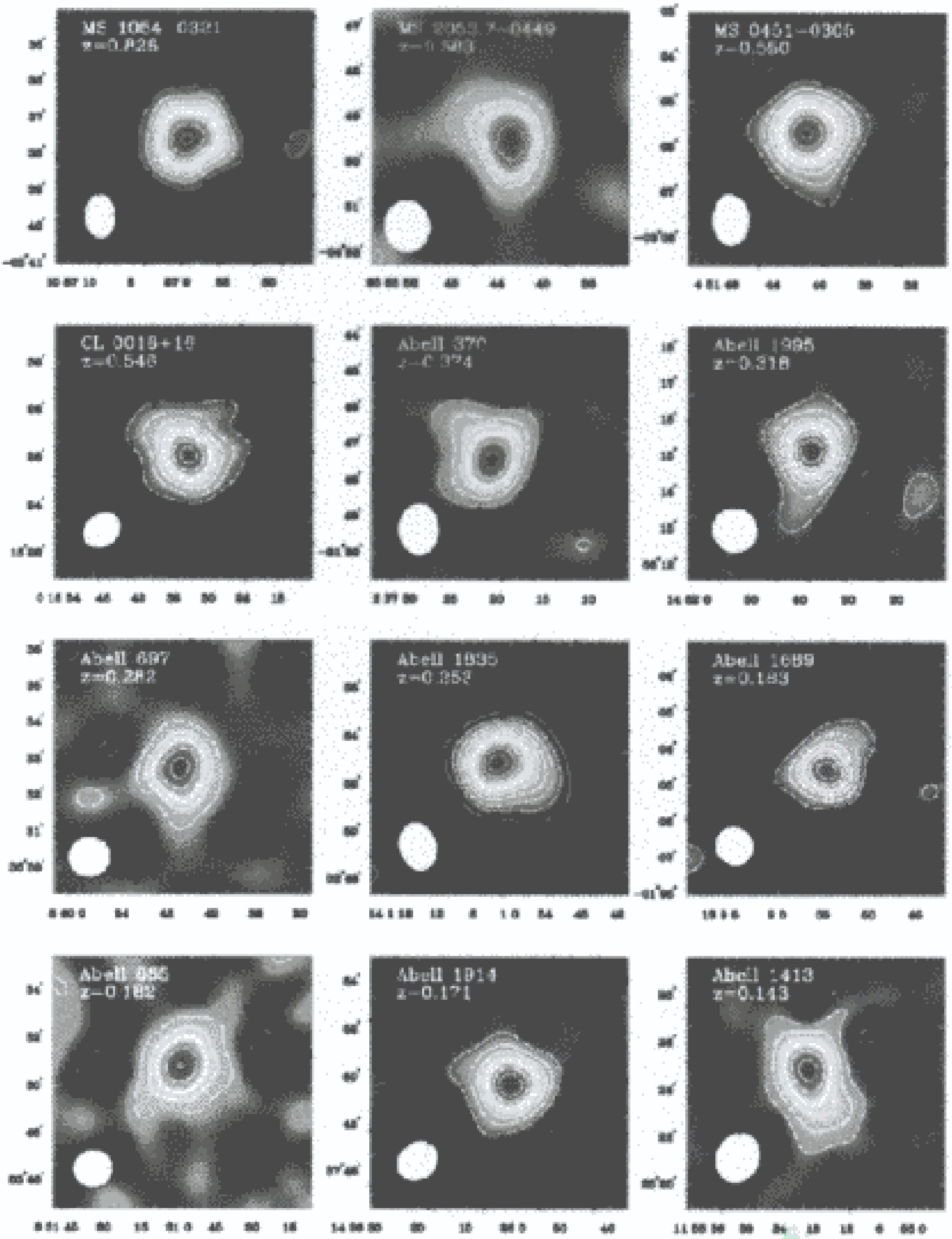


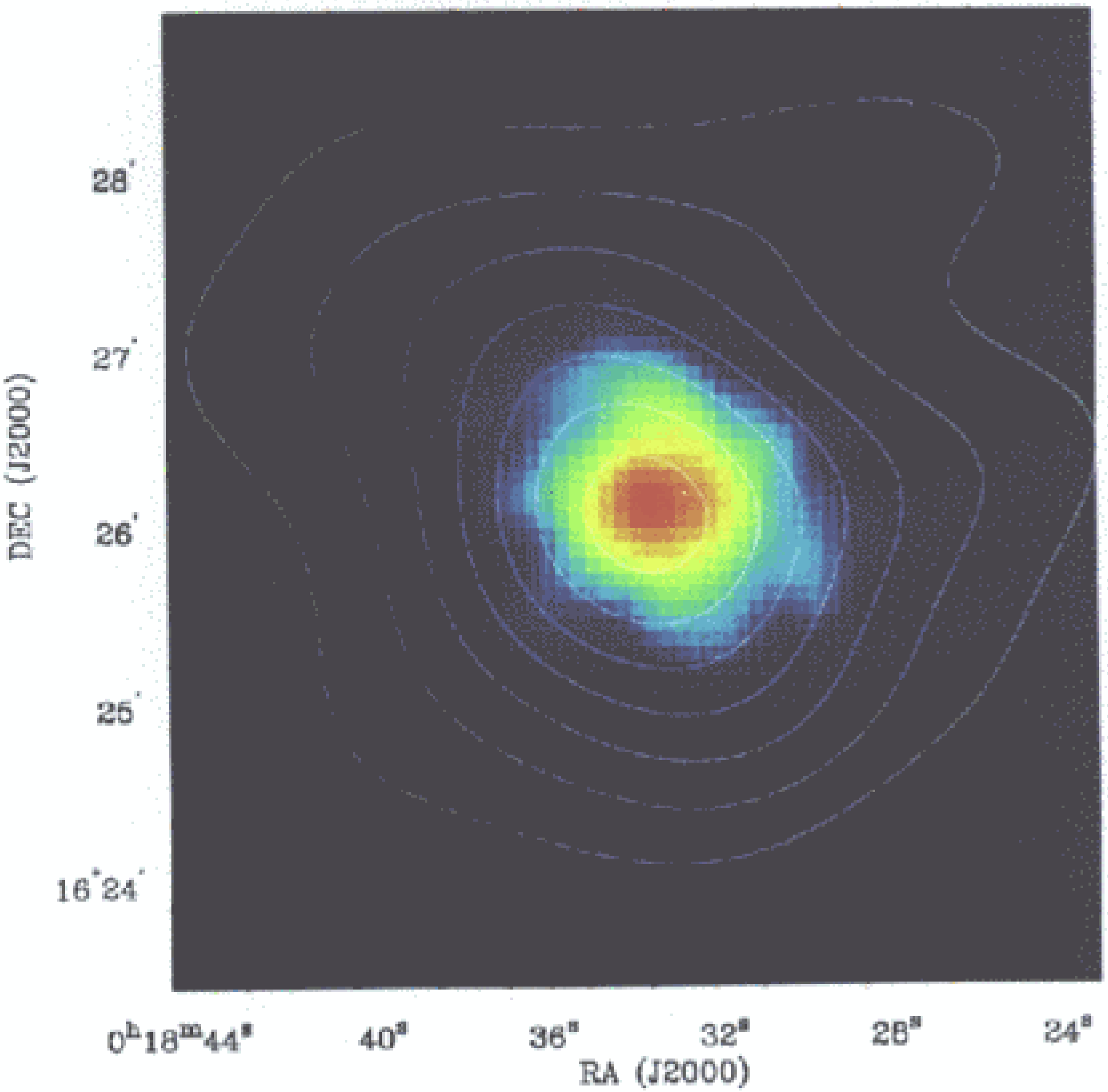
Fig. 5.— *The Key Project calibration constrains H_0 in four ways, but these are each, in turn, dependent on the assumed distance of the Large Magellanic Cloud which provides the reference Cepheid PL relation for the project.*



I(CMB)x0.0005
KINETIC SZE
THERMAL SZE
Intensity (ergs s^{-1} Hz^{-1} cm^{-2} ster^{-1})
2×10^{-18}
10^{-18}
0
-1×10^{-18}
Frequency (GHz)
0
100
200
300
400
500
R.J. Brightness (mK)
0
−0.2
−0.4
−0.6
Frequency (GHz)
0
100
200
300
400
500


MS0451
T_e =10.4 keV
z =0.55
Ω_M=0.3
β
R (arcsec)
80
70
60
50
40
0.7
0.8
0.9
1
30
40
50


MS 1054-0321
z=0.826
MS 2053.7-0449
z=0.583
MS 0451-0305
z=0.550
CL 0016+16
z=0.546
Abell 370
z=0.374
Abell 1995
z=0.318
Abell 697
z=0.282
Abell 1835
z=0.252
Abell 1689
z=0.183
Abell 665
z=0.182
Abell 1914
z=0.171
Abell 1413
z=0.143


28'
27'
DEC (J2000)
26'
25'
16°24'
0h18m44s
40s
36s
32s
28s
24s
RA (J2000)

(ii) $H_0 = 60 \pm 10 \; km\,s^{-1}\,Mpc^{-1}$ SZE

(iii) Type Ia SN ⇒ (other group)

$H_0 = 64^{+8}_{-6} \; km\,s^{-1}\,Mpc$

(iv) SBF - Galaxy Density Field

$H_0 = 74 \pm 4 \; km\,s^{-1}\,Mpc^{-1}$

(v) TIME-DELAY: GRAV. LENSING Q 0957+561 ($T_d = 417 \pm 3d$)

$H_0 = 69^{+18}_{-12}(1-\kappa)$ or $74^{+18}_{-17}(1-\kappa)$

(κ-cluster properties)

AVERAGE = $69.7 \pm 2.5 \; km\,s^{-1}\,Mpc^{-1}$

⇒ $H_0 \in \{63 - 77\}$ 99% CL

(B) GEOMETRY

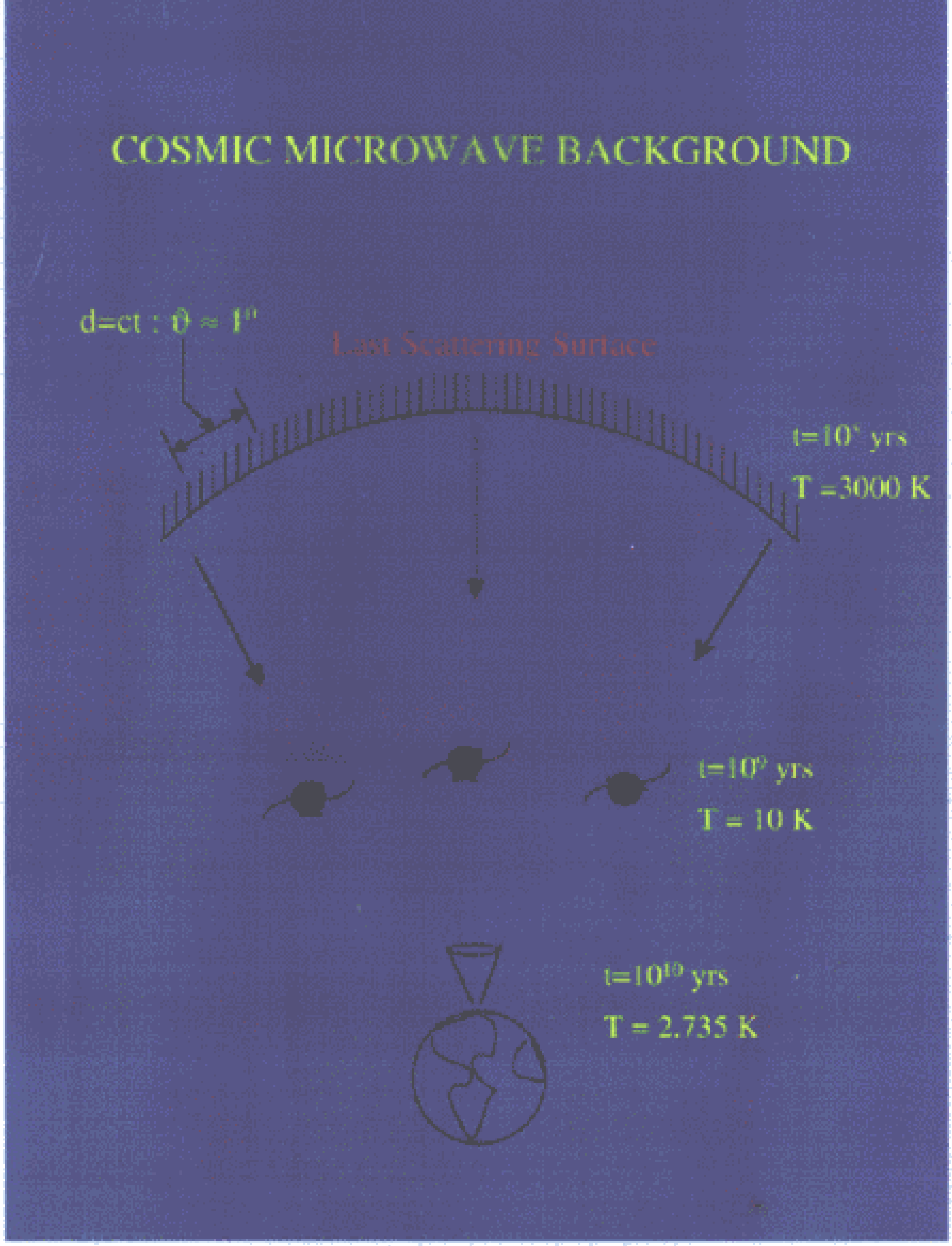
⇒ CMB: A FIDUCIAL LENGTH!

Note:

Traditionally:

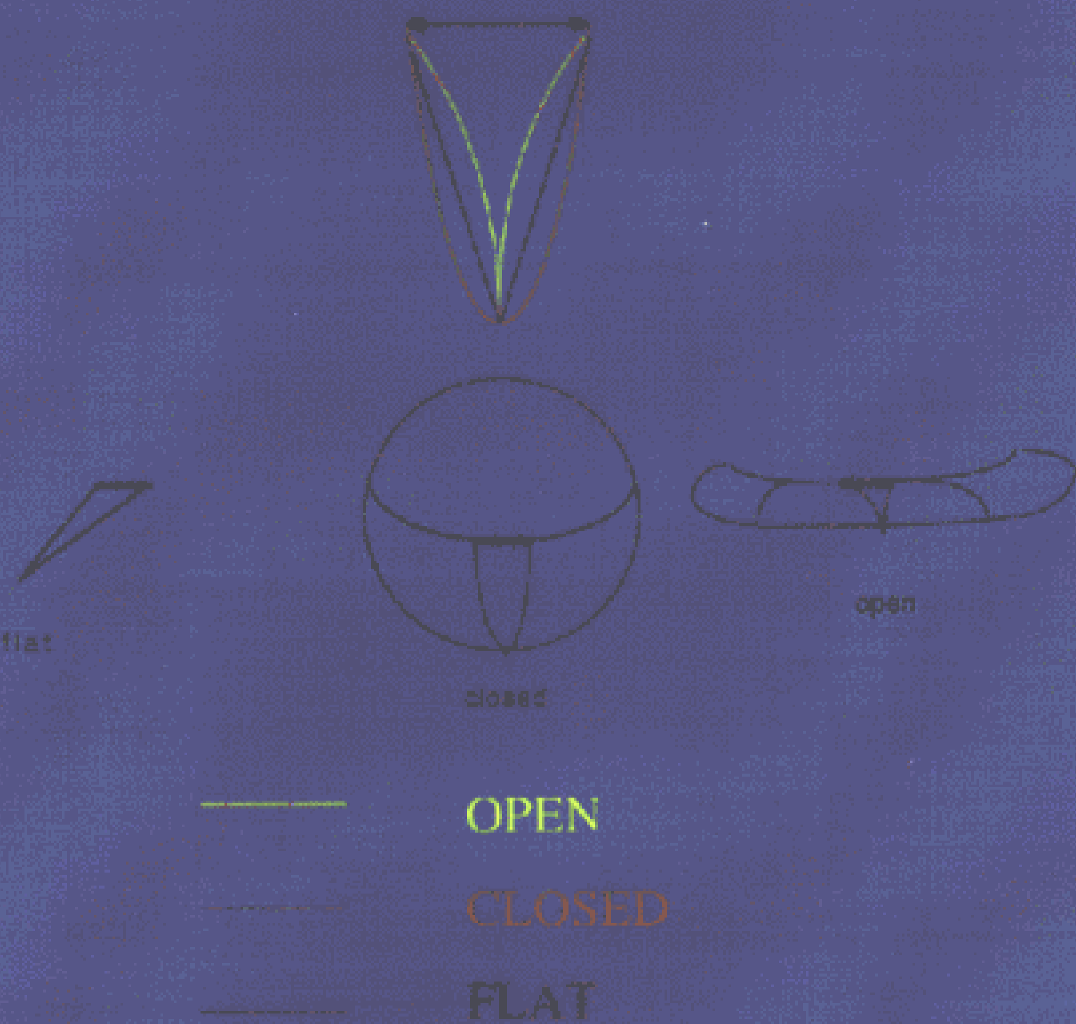
$$H^2 = \frac{8\pi G}{3}\rho + \frac{k}{R^2}$$

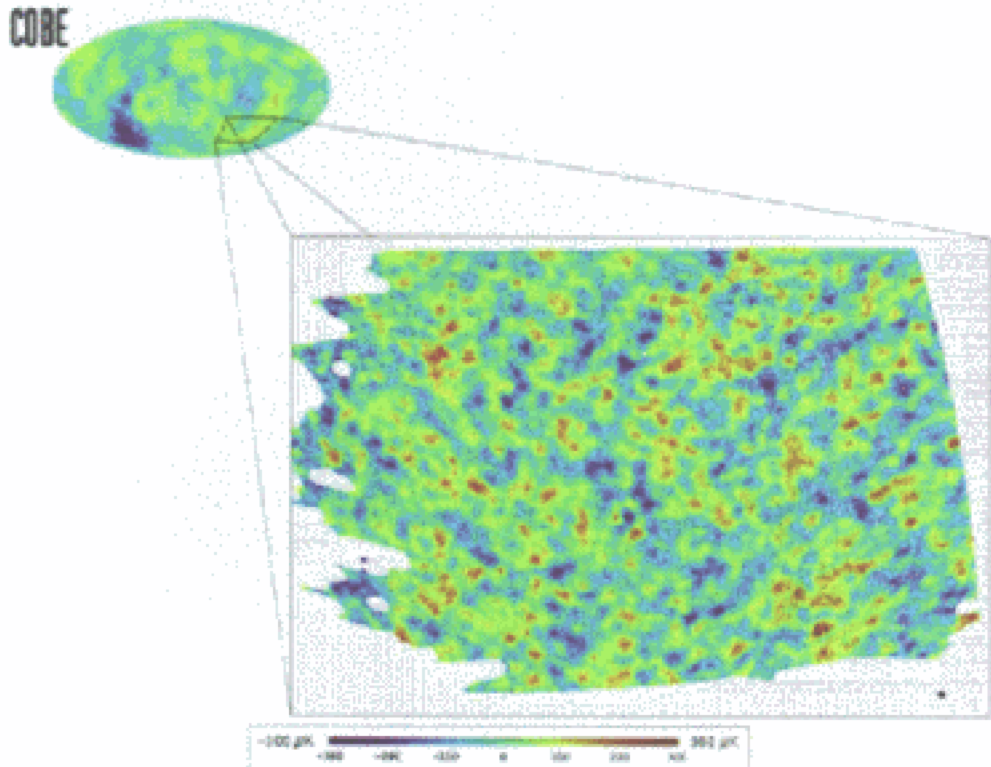
curvature

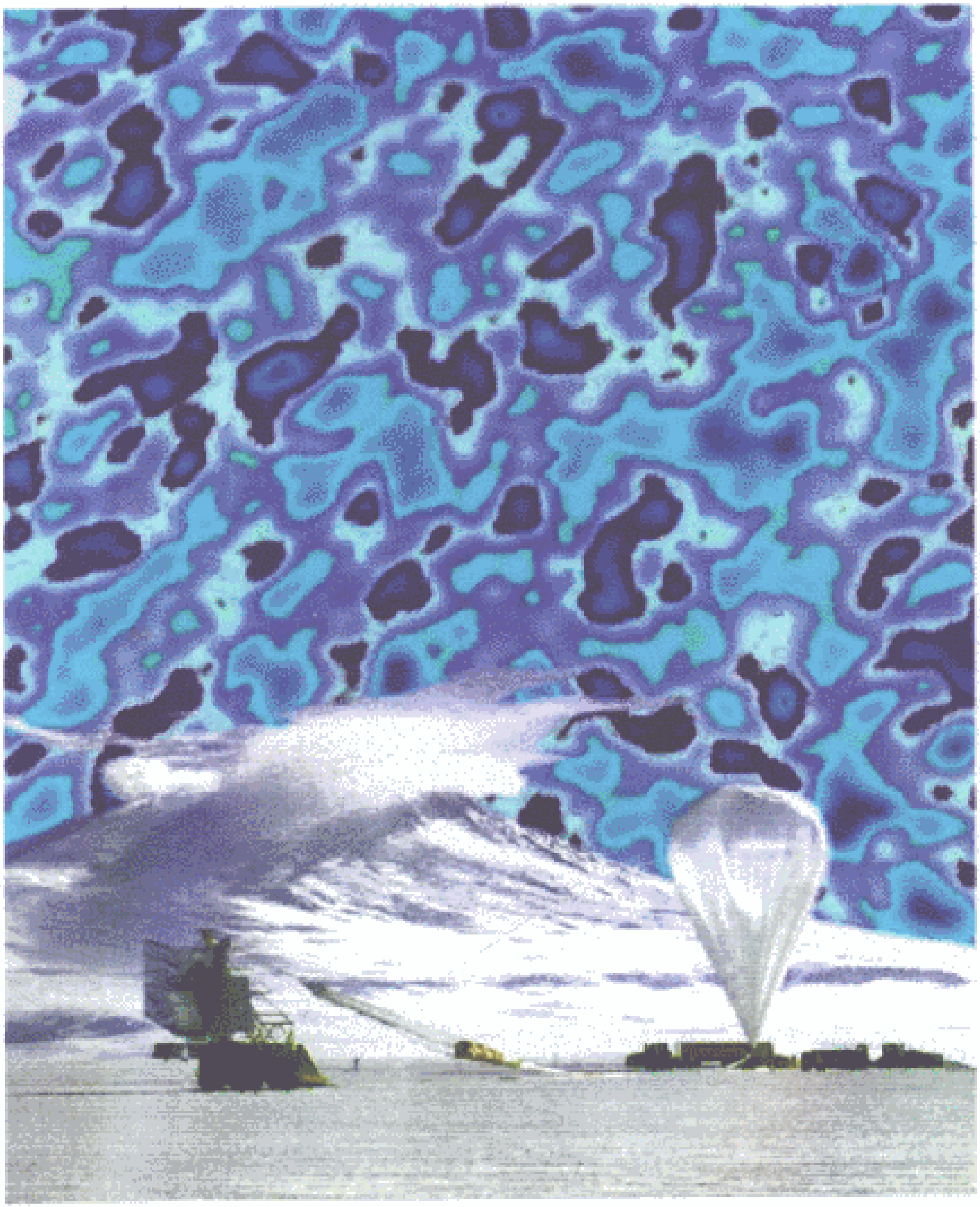

COSMIC MICROWAVE BACKGROUND
$d=ct : \vartheta \approx 1^{0}$
Last Scattering Surface
$t=10^{5}$ yrs
T =3000 K
$t=10^{9}$ yrs
T = 10 K
$t=10^{10}$ yrs
T = 2.735 K

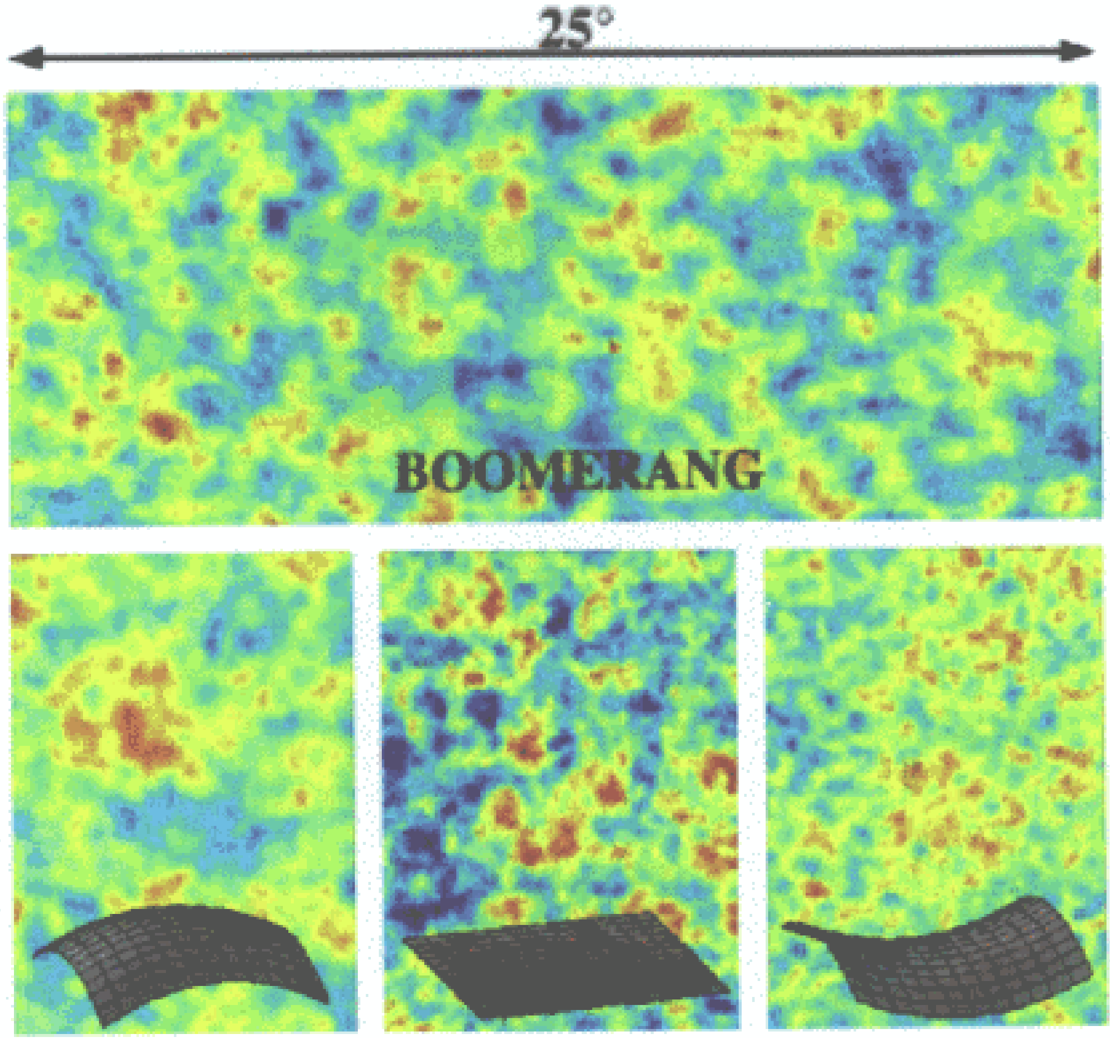
Angular Size of a Fixed Scale in Open, Closed, and Flat Universes:

First Scale to Collapse after Recombination (≈distance spanned by light ray =horizon size)




COBE




25°
BOOMERANG

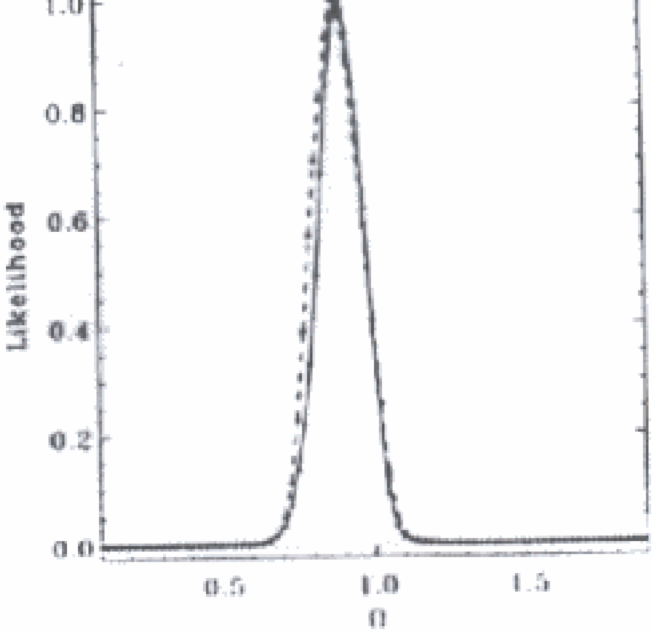
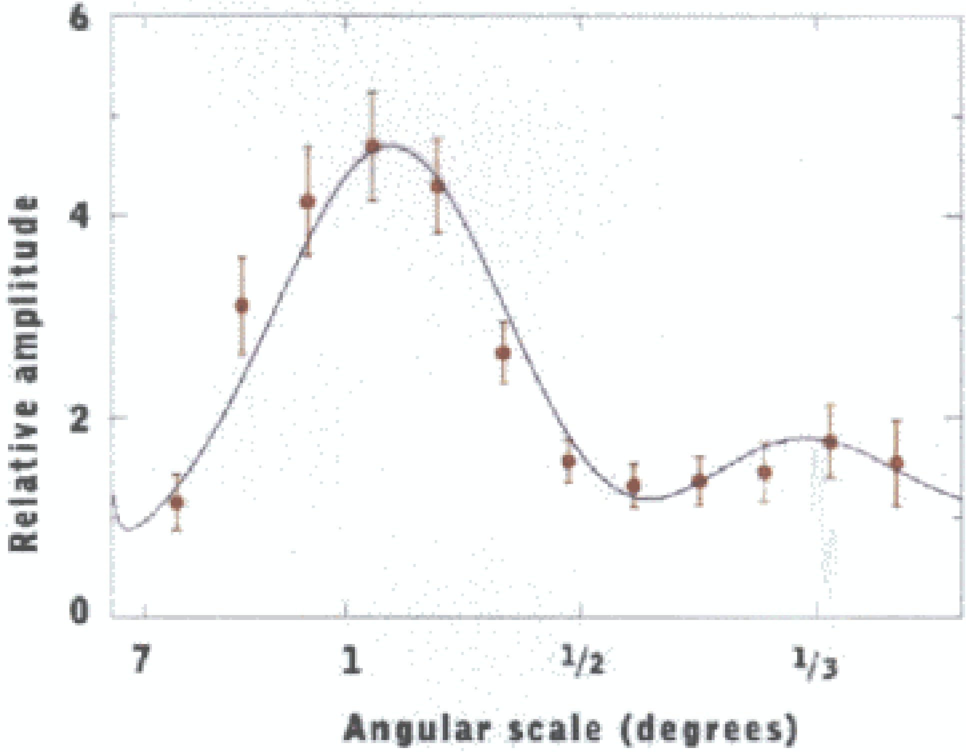


FIG. 1.—Likelihood function of the total energy density of the universe Ω. The solid line was obtained by maximizing over all other parameters over the ranges described in the text, while the dashed line was obtained by constraining $\Omega_b h^2 = 0.0190 \pm 0.0024$ and $H_0 = 65 \pm 7$ km s^{-1} Mpc^{-1}. The intersections with the horizontal line give the bounds for 95% confidence.

Figure 1 shows the likelihood of the total energy density of the universe, Ω. We obtain the solid line if we maximize over all the remaining parameters; we get the dashed line if we impose the big bang nucleosynthesis (BBN) constraint $\Omega_b h^2 = 0.0190 \pm 0.0024$ (Tytler et al. 2000), and restrict $H_0 = 65 \pm 7$ km s^{-1} Mpc^{-1} (Freedman 1999). The two likelihoods differ very little. From the solid line we see that $0.75 < \Omega < 1.05$ at the 95% confidence level.

We identified the other tightly constrained parameters from a principal component analysis of the likelihood function (Efstathiou & Bond 1999). In Figure 2 we plot the likelihoods for three well-constrained parameters, the physical baryon density, $\Omega_b h^2$, the physical cold dark matter density, $\Omega_{cdm} h^2$, and the spectral index of primordial scalar fluctuations, n_s. The likelihood for each parameter was obtained by maximizing over all the remaining parameters.



Relative amplitude
6
4
2
0
7
1
1/2
1/3
Angular scale (degrees)

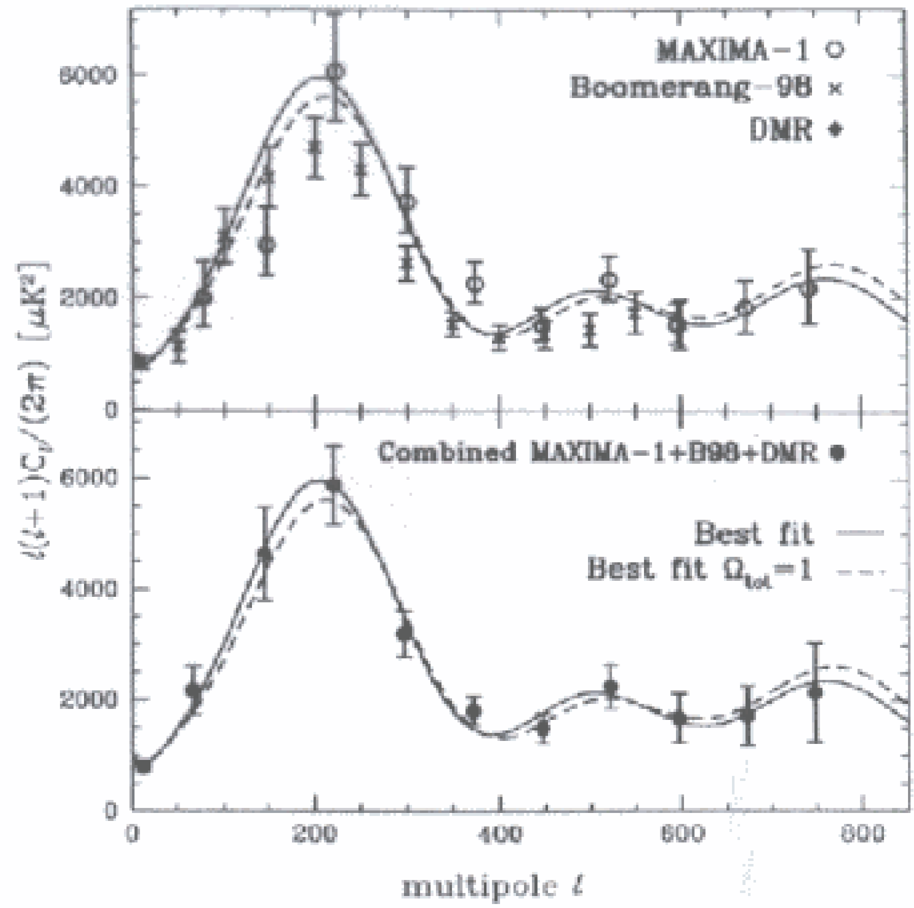


FIG. 1: CMB power spectra, $\mathcal{C}_\ell = \ell(\ell+1)C_\ell/2\pi$. Top: MAXIMA-1, B98 and COBE-DMR. Bottom: maximum-likelihood fit to the power in bands for the three spectra, marginalized over beam and calibration uncertainty. In both panels the curves show the best fit model in the joint parameter estimation with weak priors and the best fit with $\Omega_{tot} = 1$. These models have $\{\Omega_{tot}, \Omega_\Lambda, \Omega_b h^2, \Omega_c h^2, n_s, \tau_C\}$={1.2, 0.5, 0.03, 0.12, 0.95, 0}, {1, 0.7, 0.03, 0.17, 0.975, 0}. They remain the best fits when the large scale structure prior [22] is added, and when the SN prior [20] is added the $\Omega_{tot} = 1$ model becomes the best fit in both cases.

② TIME

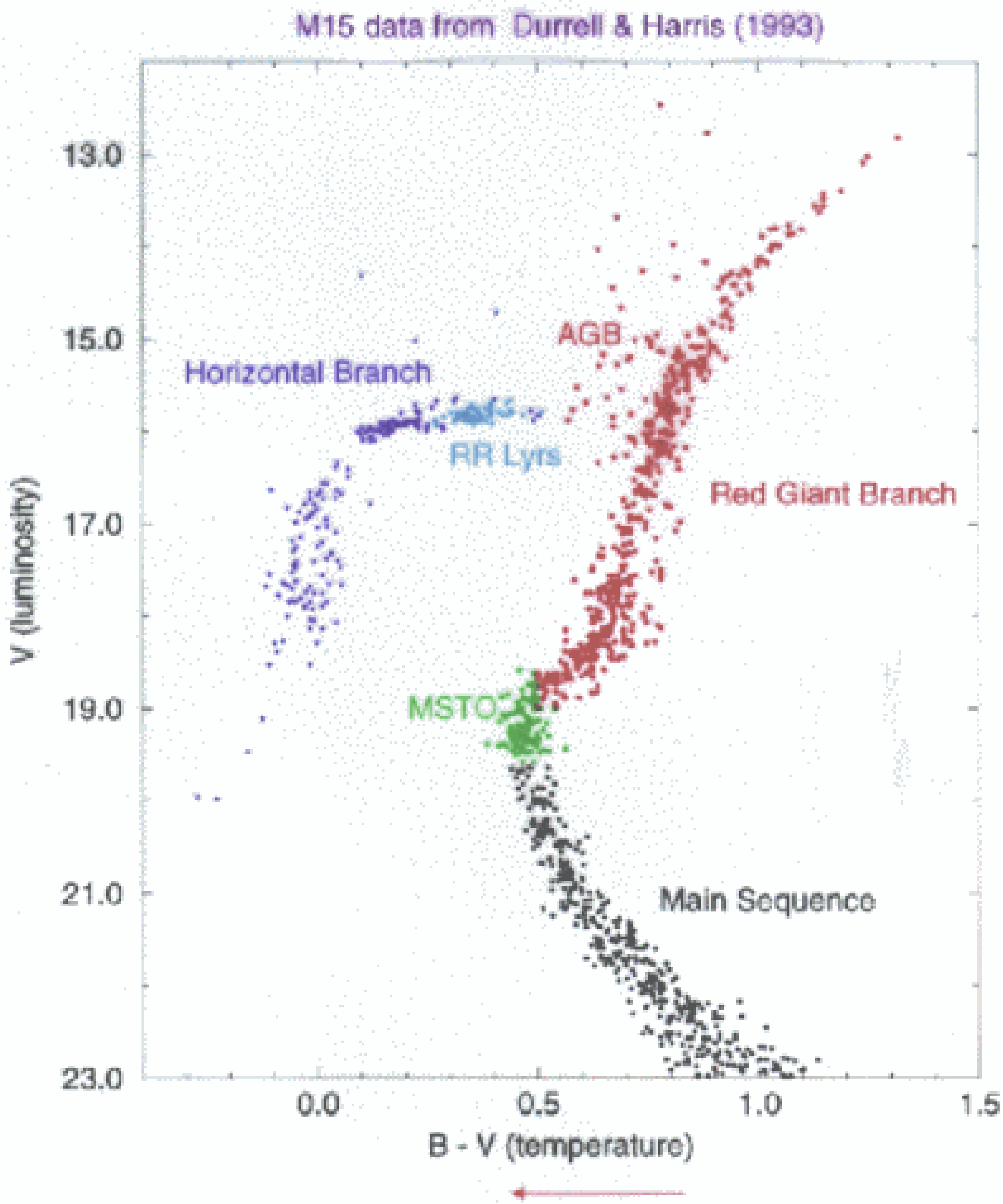
⇒ STELLAR AGES

⇒ HUBBLE AGE

⇒ CONSISTENT EQ OF STATE

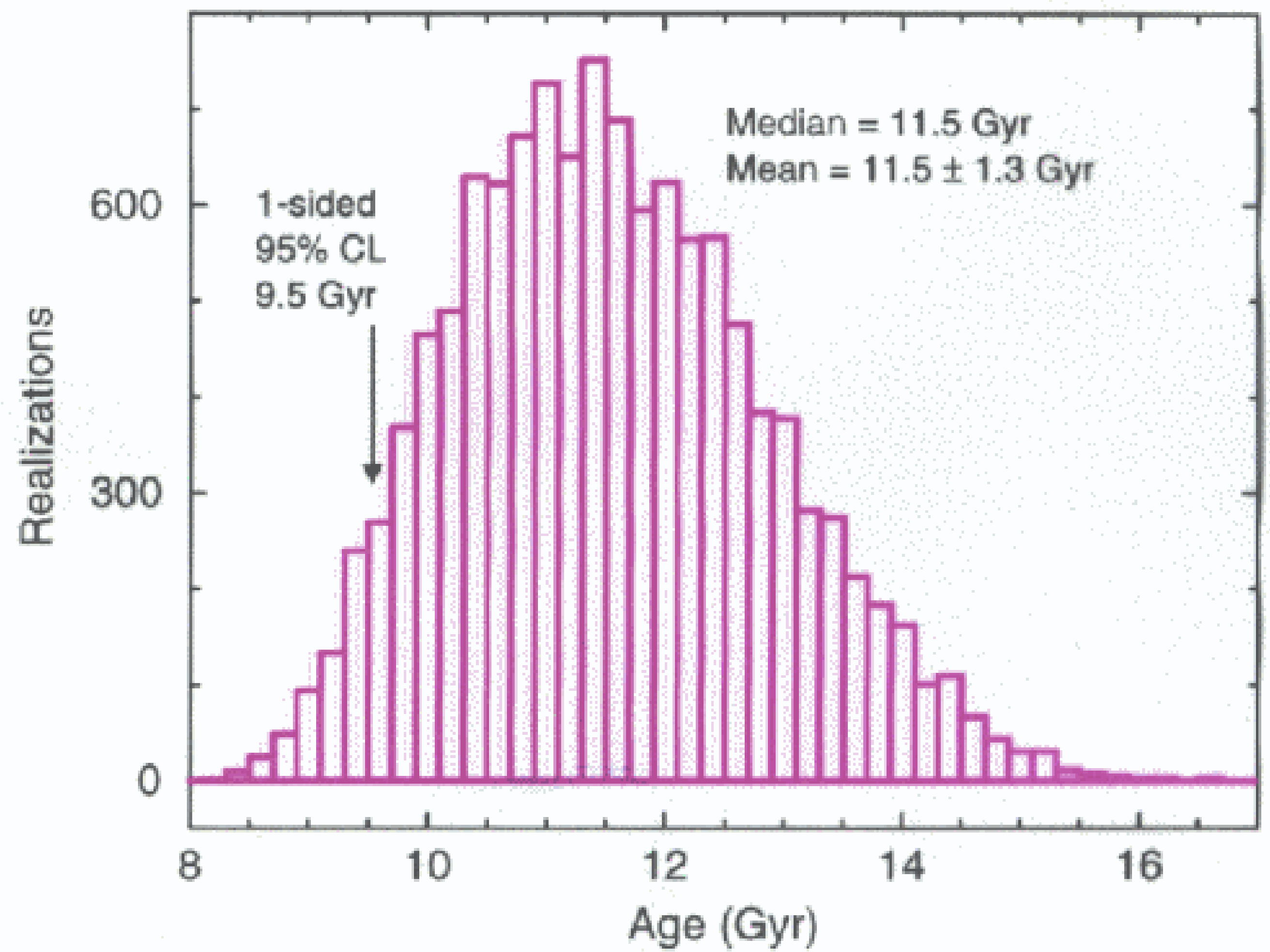
$$\Omega_{TOT} \simeq 1.1 \pm .12 \quad 95\% \text{ CL}$$

$\Rightarrow$ AN $\approx$ FLAT UNIVERSE



M15 data from Durrell & Harris (1993)
13.0
15.0
17.0
19.0
21.0
23.0
V (luminosity)
Horizontal Branch
RR Lyrs
AGB
Red Giant Branch
MSTO
Main Sequence
0.0
0.5
1.0
1.5
B - V (temperature)

BC, PD, PK, LK Ap.J. Eb 98



(c) STELLAR AGES

⇒ POSITION OF MSTO ⇒ AGE

⇒ KEY UNCERTAINTY ⇒ $M_V(RR)$

⇒ RR-Lyrae Luminosity

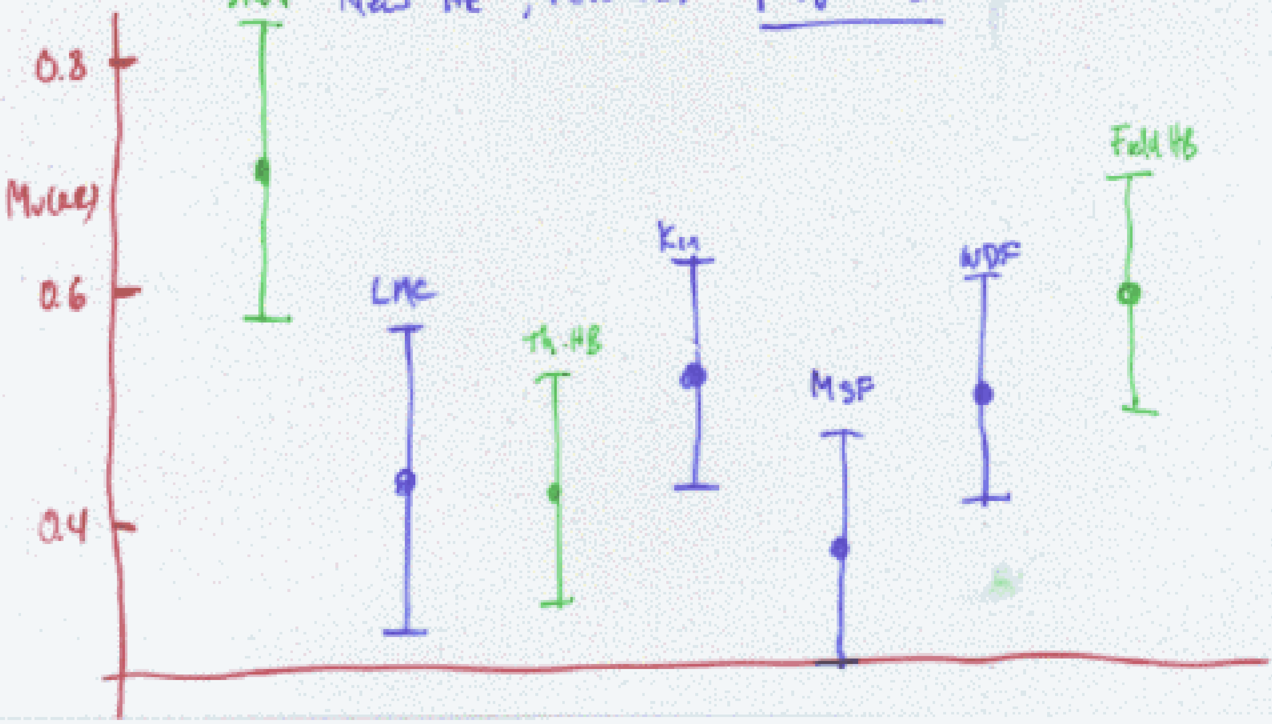
⇒ RR-Lyrae Distance Modulus

B.C., P.D., P.K., L.K '98 :

AGE = 11.5 ± 1.3 Gyr ($\approx 2\sigma$)

Change : B.C. + LMK '00 :

Since New He^Y, reactions. $M_V(RR)$



⇒ New Age

$\approx$ $12.7 \left\{ {}^{+3}_{-2} \right\}$ (2σ)

∴ New <u>Lower</u> limit ~ 11 Gyr !

Hubble Age:

$H_0 \sim 70 \pm 7$ + $\Omega_{TOT} = 1$

⇒

Ω_m	Ω_x	t_0
1	0	9 ± 1
0.2	0.8	15 ± 1.5
0.3	0.7	13.5 ± 1.5 ← ≈ BF
0.35	0.65	12.7 ± 1.4

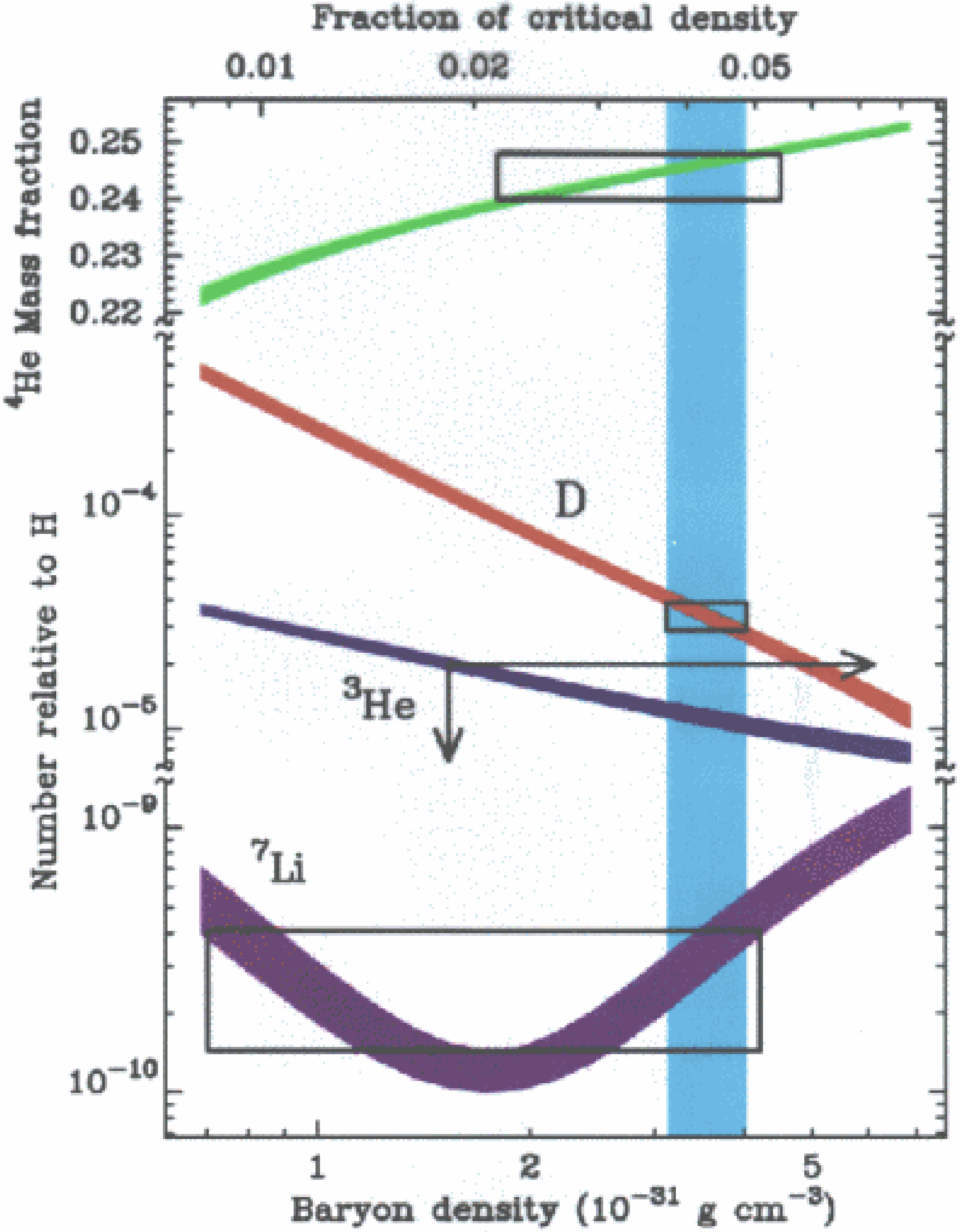
→ definitively requires Ω_x $(w = P/\rho < 0)$

③ MATTER

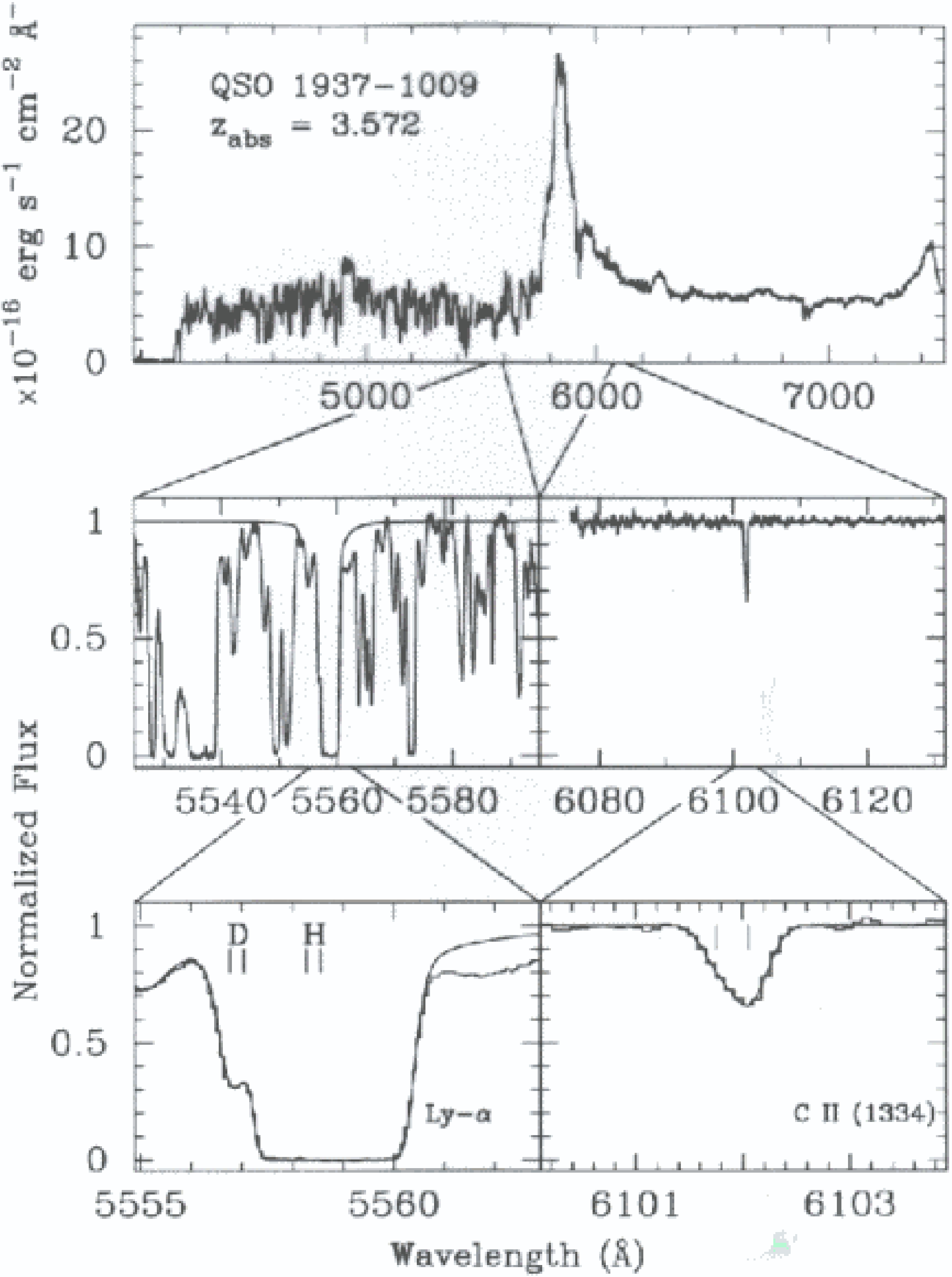
⇒ $\Omega_B h^2$ ⇒ consistency or crisis?

⇒ Ω_M : {LSS, X-Ray, SZE, GL, SNIa} ⇐ N.B.D.M!

⇒ eq. of state.



Fraction of critical density
0.01
0.02
0.05
⁴He Mass fraction
0.25
0.24
0.23
0.22
Number relative to H
10⁻⁴
10⁻⁵
10⁻⁹
10⁻¹⁰
D
³He
⁷Li
1
2
5
Baryon density (10⁻³¹ g cm⁻³)


QSO 1937−1009
z_{abs} = 3.572
$\times 10^{-16}$ erg s^{-1} cm^{-2} Å^{-1}
Normalized Flux
D
H
Ly−α
C II (1334)
Wavelength (Å)

(c) $\Omega_B h^2$:

BBN : Deuterium $(D/H) = (3.3 \pm 0.5) \times 10^{-5}$ (2σ)

$$\Omega_B h^2 = .0190 \pm .0018 \quad (2\sigma)$$

⇑ (D/H, nucl. reactions)

⇒ ALL L.E. $(\Omega_B h^2 : .016 - .025)$ worst case

CMB : 2nd peak :

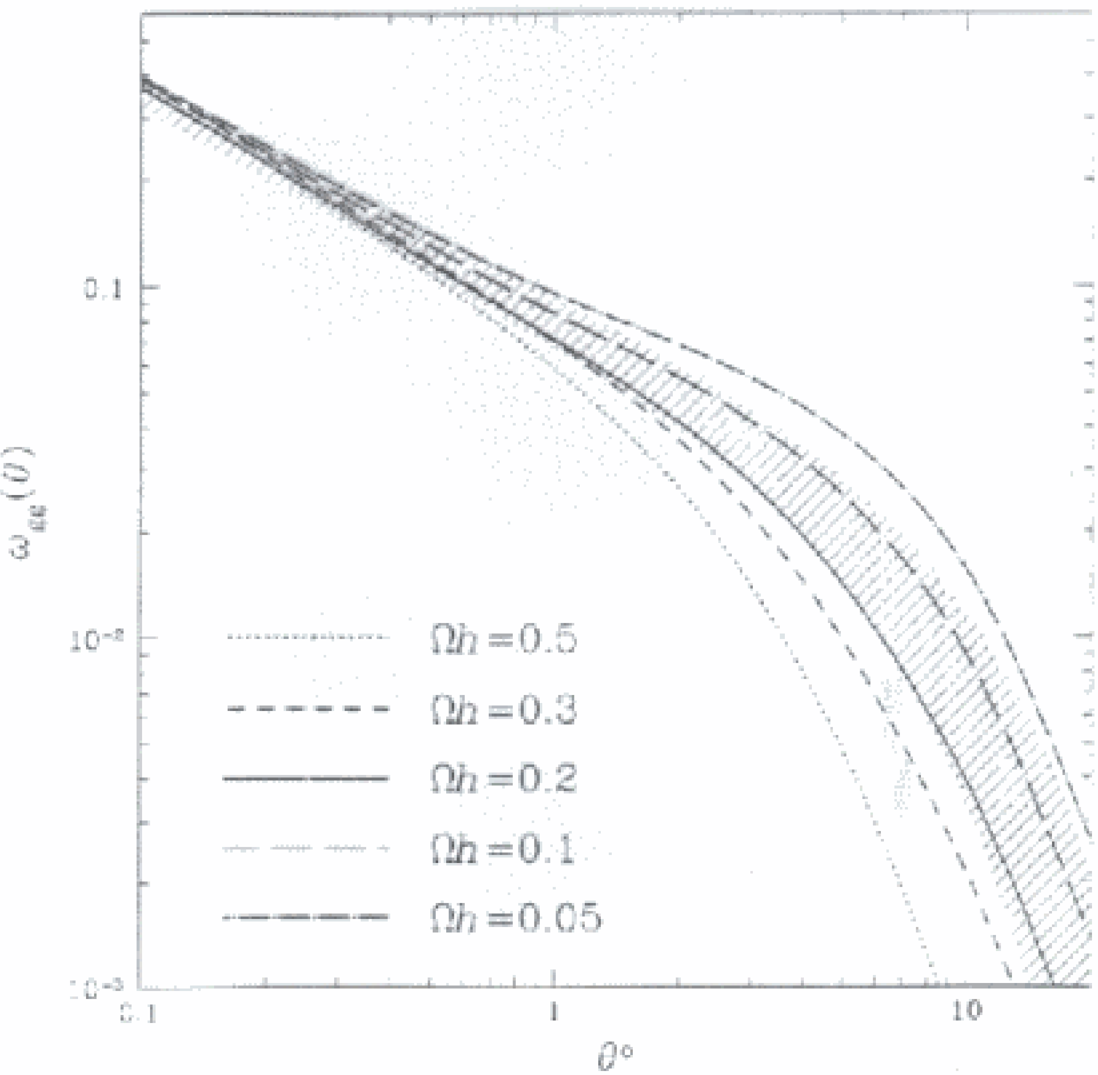
$$\Omega_B h^2 = .032 \pm .009 \quad (2\sigma)$$

Consistency, or Crisis ? :

⇒ too early : CMB ... depends on other params, early .... ..

$$\therefore \quad \Omega_B = .03 - .06 = .045 \pm .015$$

Figure 3



0.1
10^{-2}
10^{-3}
$\omega_{gg}(\theta)$
$\Omega h = 0.5$
$\Omega h = 0.3$
$\Omega h = 0.2$
$\Omega h = 0.1$
$\Omega h = 0.05$
0.1
1
10
θ°

Ω_M.

(a) LSS: $.25 \lesssim \Omega_M h \lesssim .35$

(b) Cluster Evolution: $\Omega_M < 0.5$

* (c) X-RAY CLUSTERS:

(i) X-RAYS: HOT GAS $T \sim 10^7$ K

Hydrostatic Eq: $\langle T, R \rangle \rightarrow (M_{gas}, M_{TOT})$

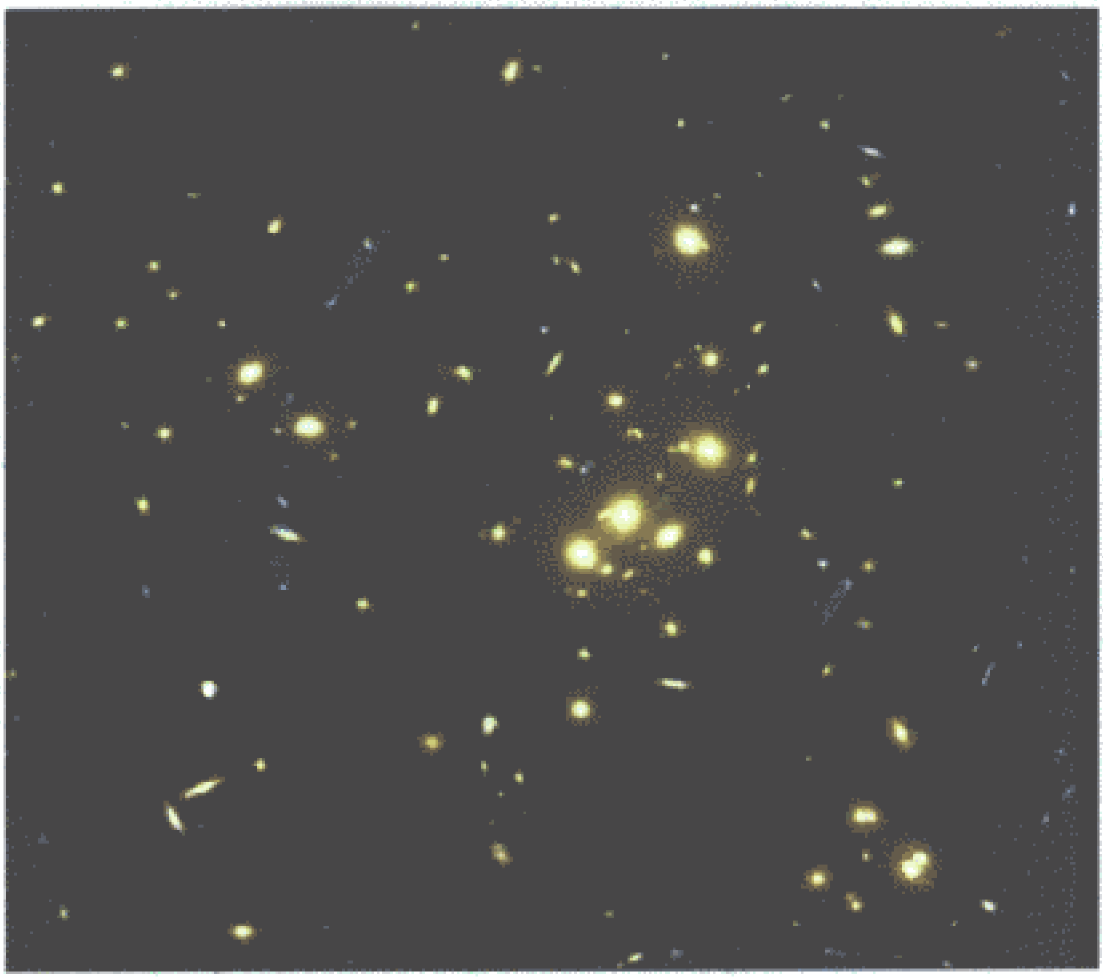
$$f_B = \frac{M_{gas}}{M_{TOT}} \lesssim \frac{\Omega_B}{\Omega_M} \simeq (.212 \pm .006)\, h_{50}^{-3/2}$$

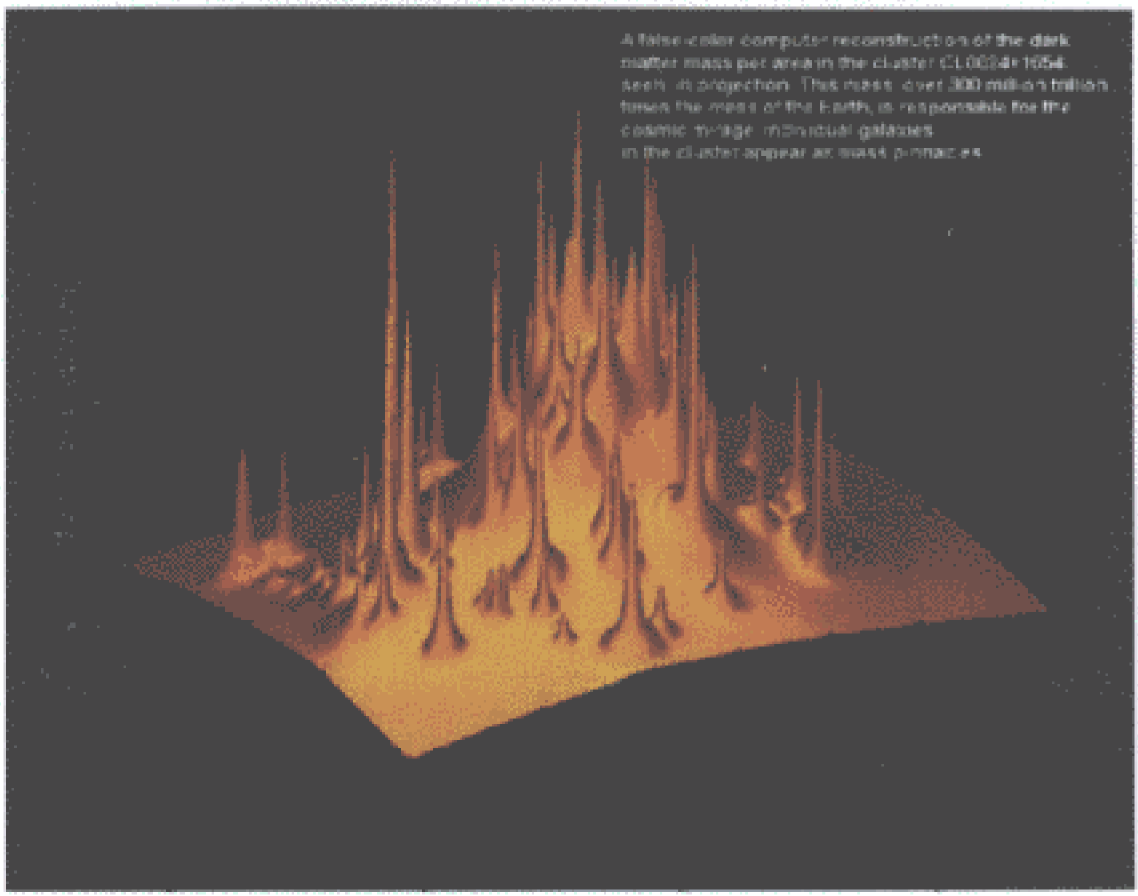
$$\Rightarrow \Omega_M \lesssim \frac{\Omega_B}{f_B} \simeq 0.45\, h_{50}^{-1/2}$$

* (ii) SZE: INDEP EST. OF M_{gas}: $\int n_e \, dl$
$\Rightarrow f_B$.

$$\Omega_M h_{50} \lesssim 0.50$$

H = 63–76 $\Rightarrow$ $\Omega_M \approx .35 \pm .1$ $\Rightarrow$ DM $\neq$ BARYONS!





A false-color computer reconstruction of the dark matter mass per area in the cluster CL0024+1654 seen in projection. This mass, over 300 million trillion times the mass of the Earth, is responsible for the cosmic mirage. Individual galaxies in the cluster appear as mass pinnacles.

N. Bahcall et al. '98

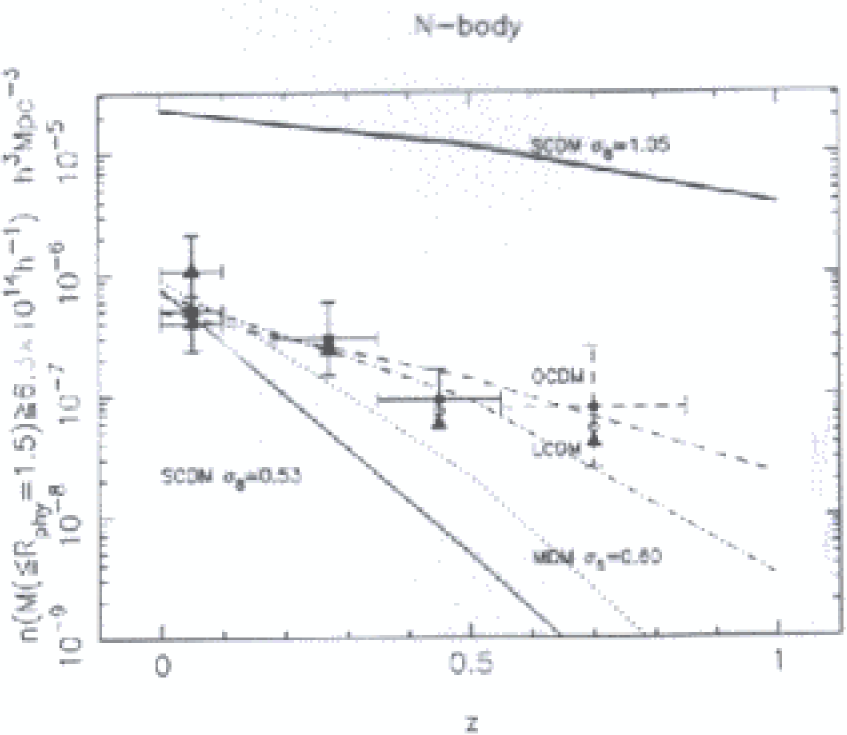
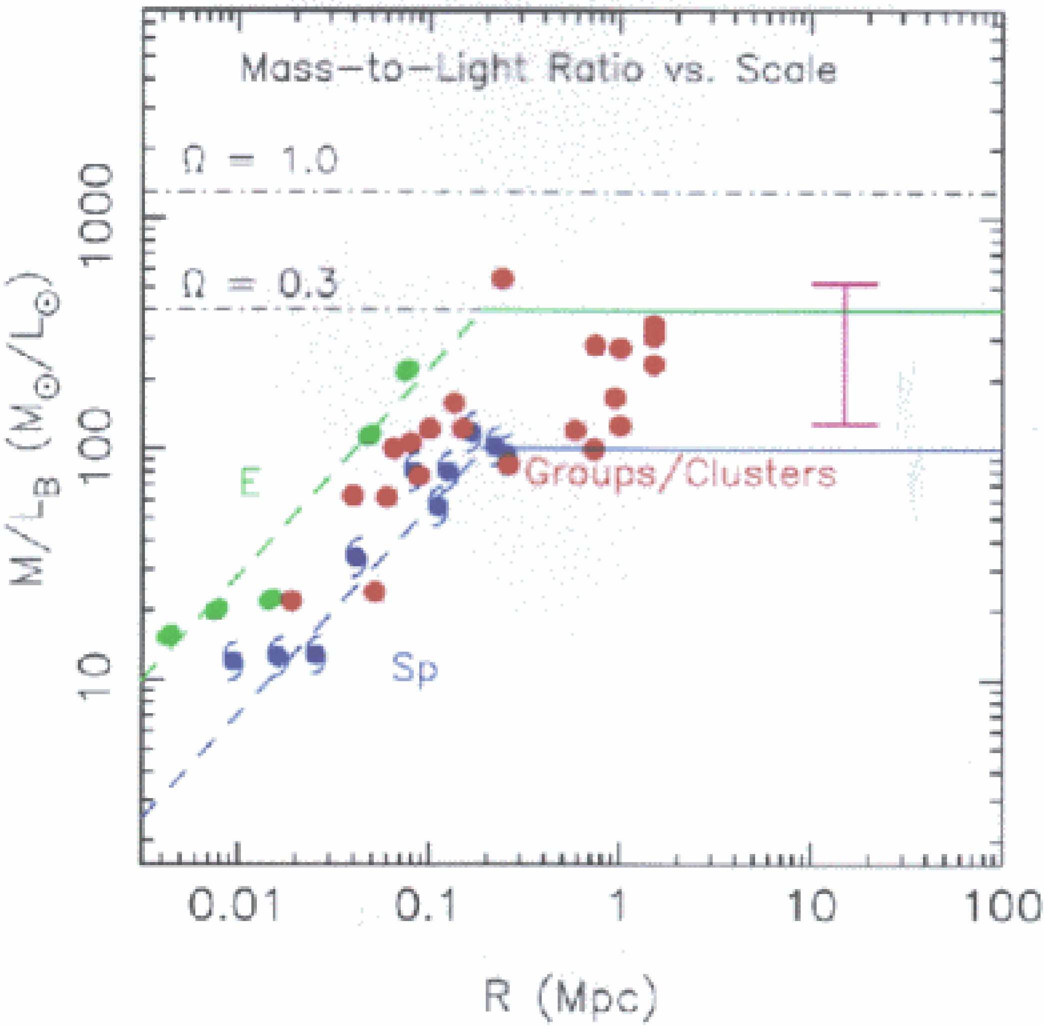
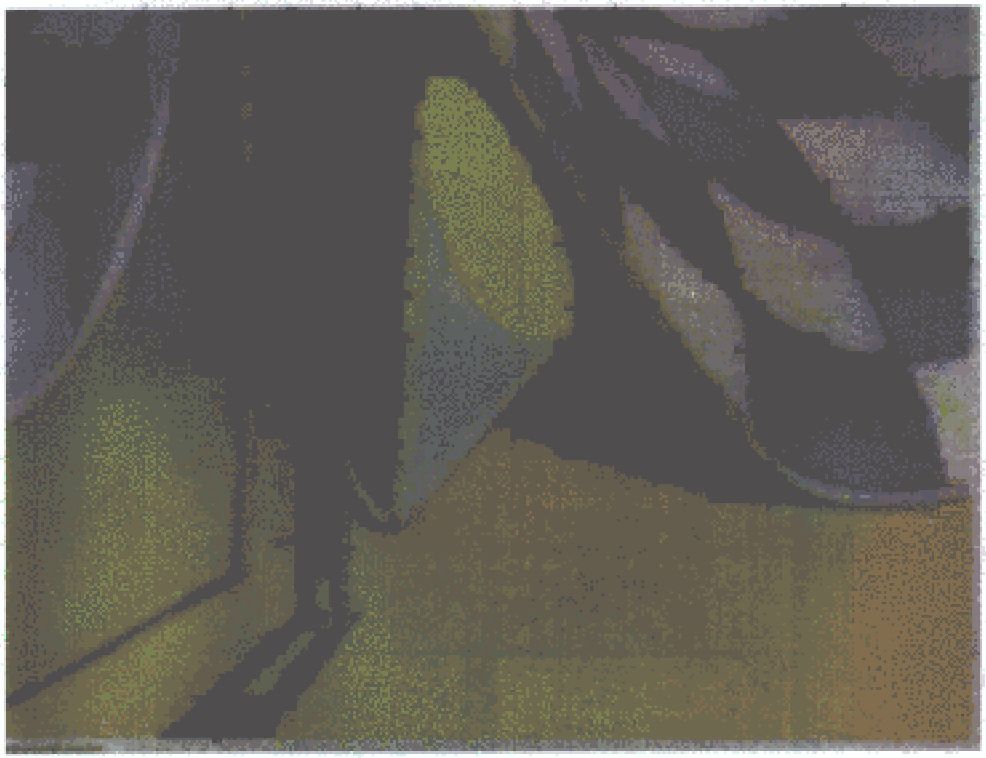
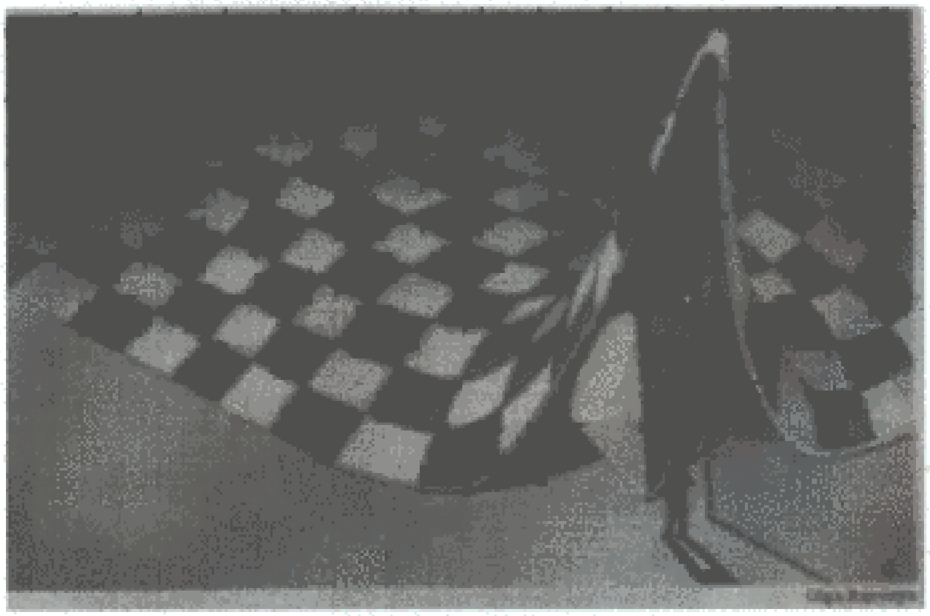


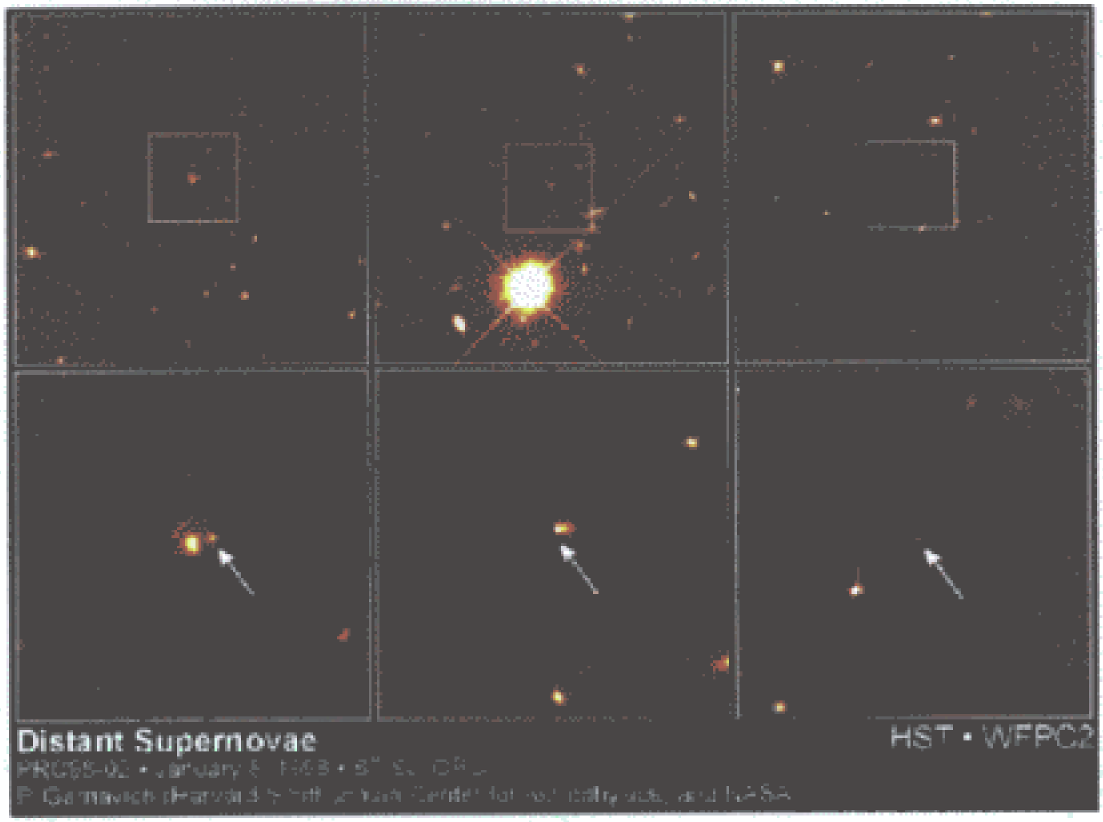
Fig. 2 The evolution of cluster abundance with redshift for massive, coma-like clusters ($M_{1.5} \geq 6.3 \times 10^{14} h^{-1} M_{\odot}$). The lines represent model predictions; the data points are from the CNOC survey. From Bahcall, Fan and Cen (1997) (updated fig.).

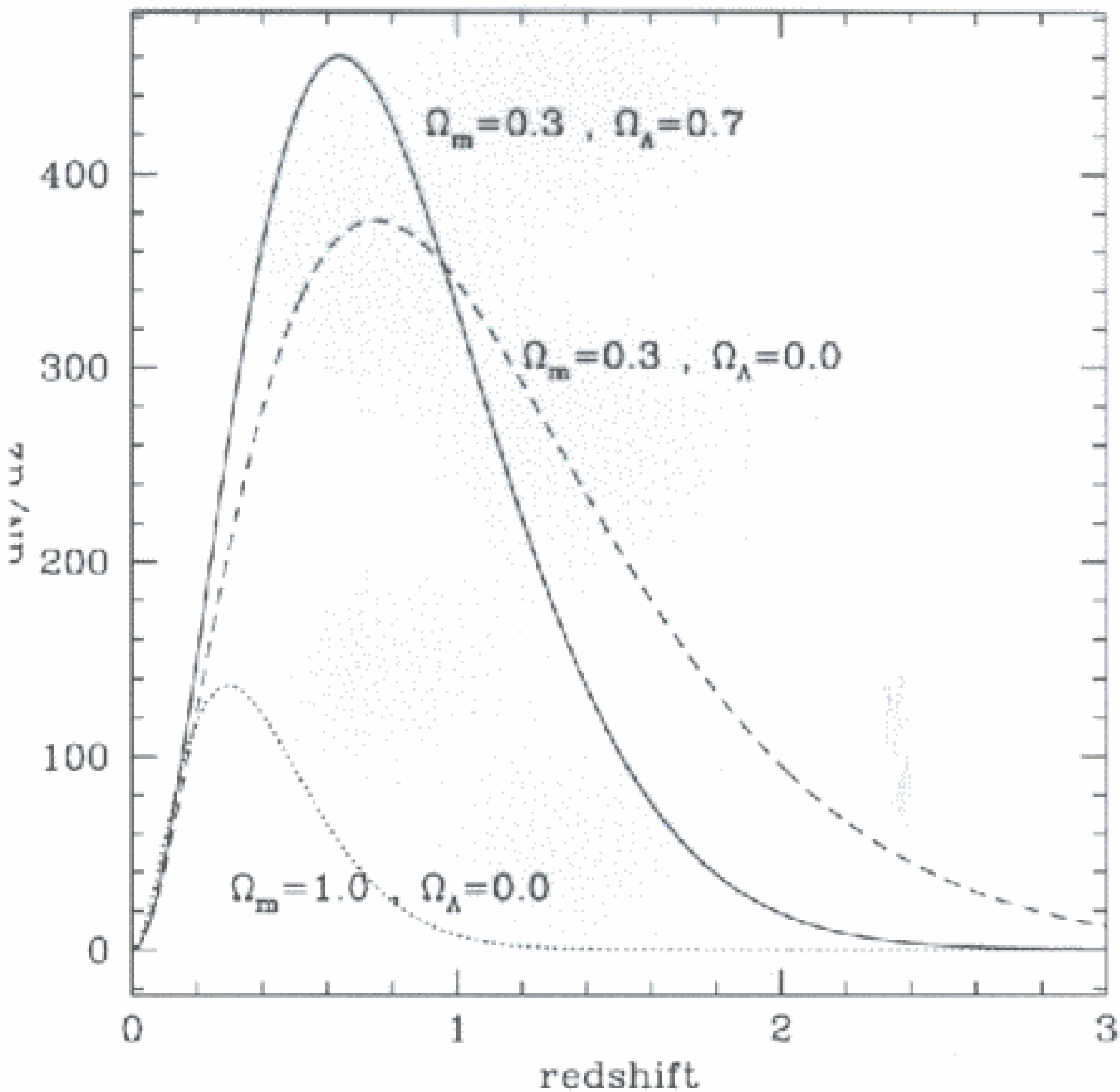


Mass-to-Light Ratio vs. Scale
Ω = 1.0
Ω = 0.3
E
Sp
Groups/Clusters
M/L_B (M_⊙/L_⊙)
1000
100
10
0.01
0.1
1
10
100
R (Mpc)

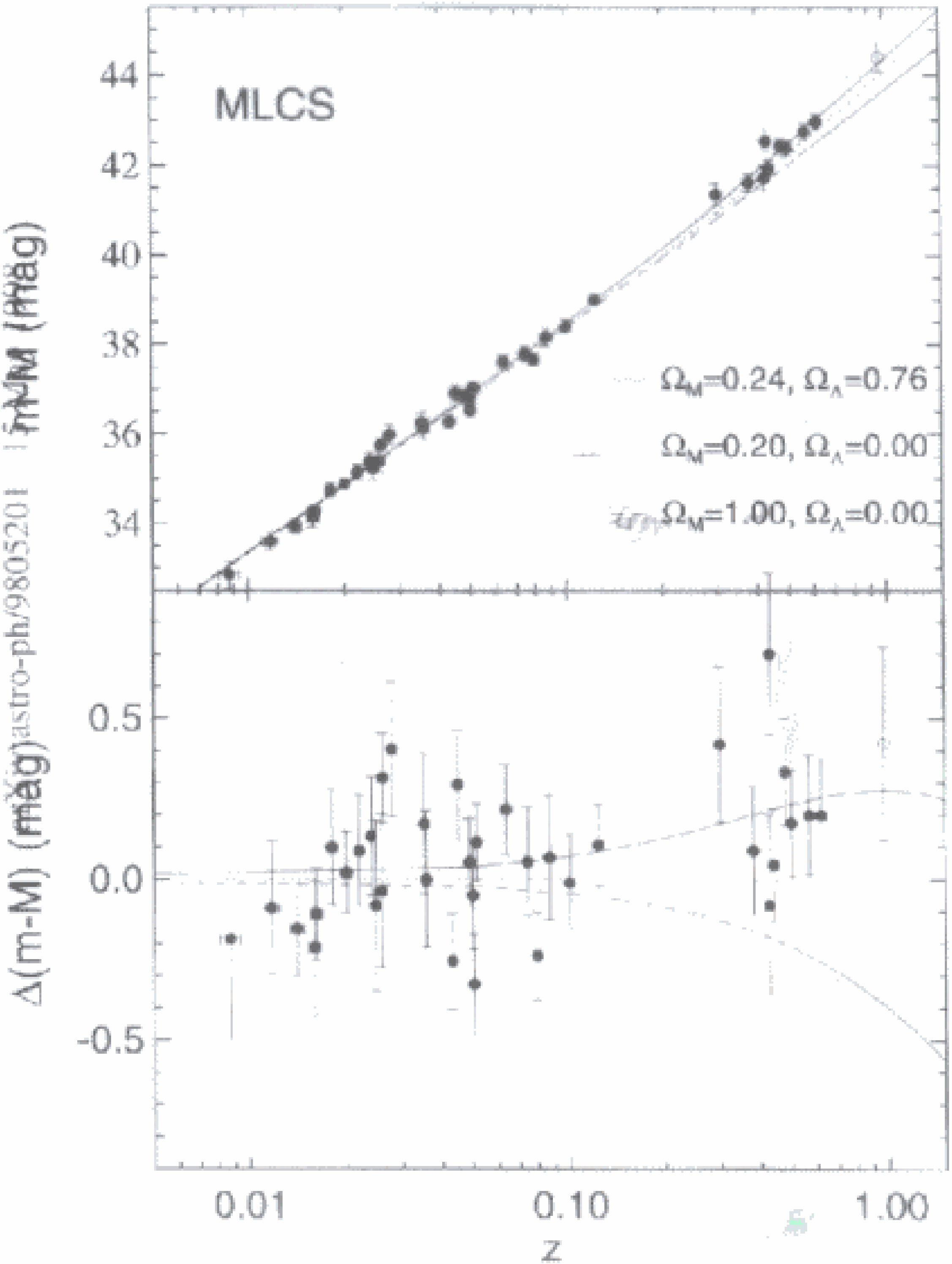





Distant Supernovae
HST • WFPC2



The Future: Clusters : SZE,


MLCS
m-M (mag)
Ω_M=0.24, Ω_Λ=0.76
Ω_M=0.20, Ω_Λ=0.00
Ω_M=1.00, Ω_Λ=0.00
Δ(m-M) (mag)
z
0.01
0.10
1.00

($/\rho$)

{ 0 | ... }
{ 1/3 | rad }
{ -1 – 0 | X }

DARK ENERGY $\{-1 \le w \le 0\}$

"QUINTESSENCE" $w \rightarrow$ evolves . . .

"TRACKER" $w \ge -0.6$

LIMITS : SN Ia : $w \le -0.6$

HOW WELL?

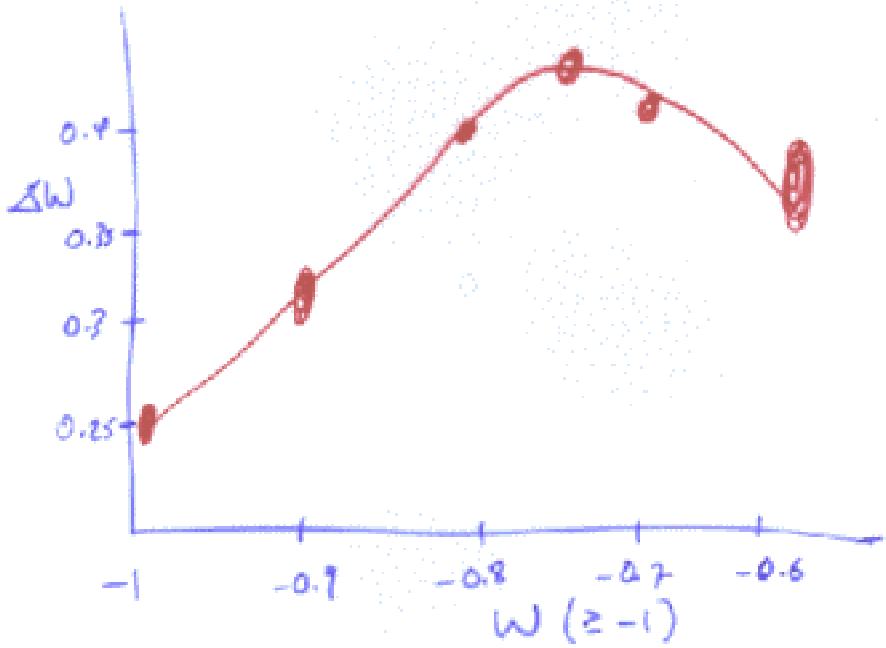
$w \le -0.7$ 100 SN $z \sim .05-1.5$

(CMK, CD '00)

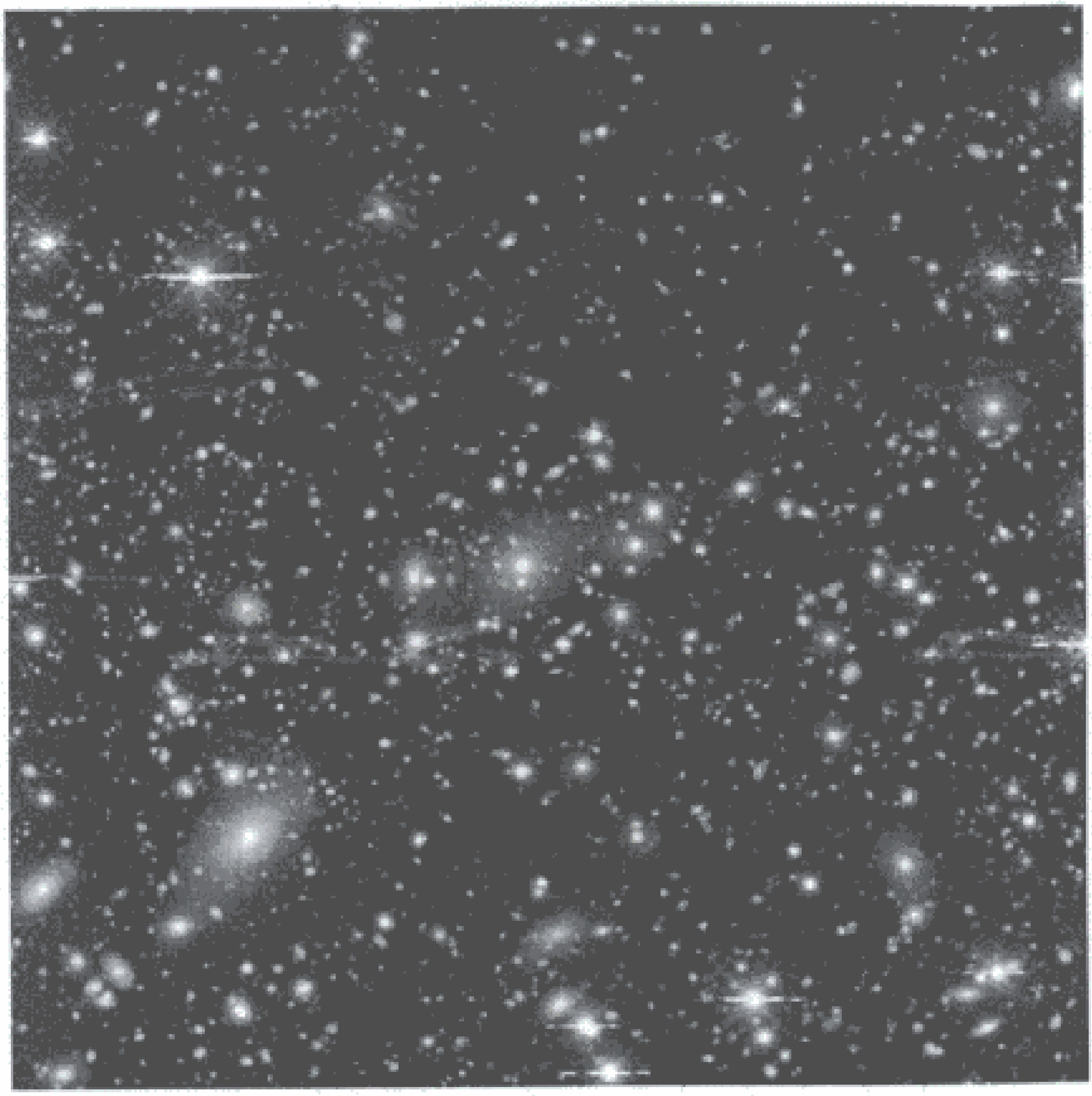
$\Delta w \sim 10\%$ 2000 SN Spec ?

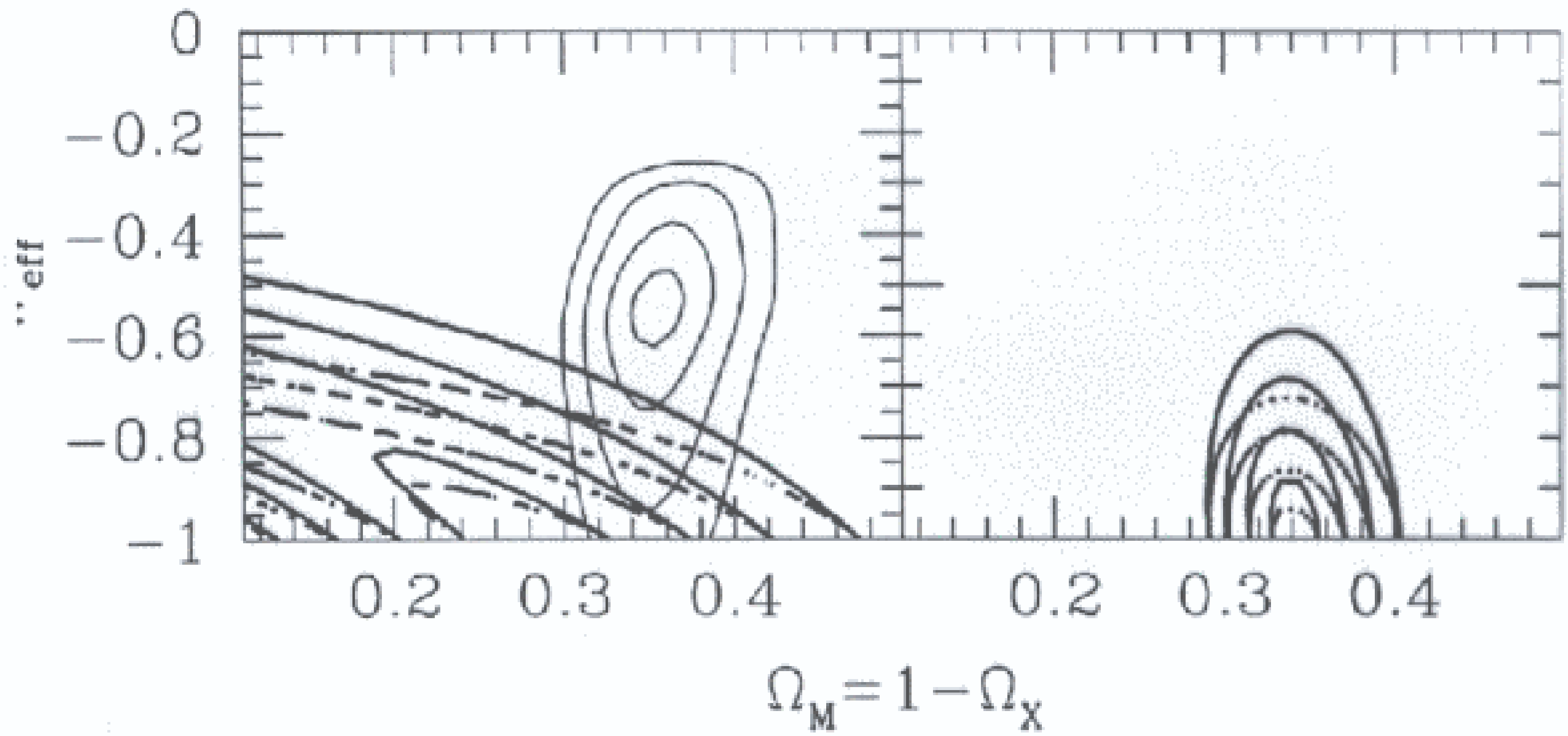
$\Delta w \sim 10\%$ Galaxy evolution ?

(Ω_m)



LMK, EL, CD





ontours of likelihood, from 0.5σ to 2σ, in the Ω_M–$w_{\rm eff}$ plane. Left: The thin solid lines are the const
CMB. The heavy lines are the SN Ia constraints (using the Fit C supernovae of Ref. [1]) for constan
) and for a scalar-field model with an exponential potential (broken curves; quadratic and quartic pote
SN Ia constraints). Note that the SN Ia contours for dynamical scalar-field models and constant w
t (see text). Right: The likelihood contours from all of our cosmological constraints for constant w mo
al scalar-field models (broken).

CONCLUSIONS:

IT DOESN'T REALLY MATTER:

NO SET OF MEASUREMENTS OF COSMOLOGICAL PARAMETERS WILL EVER ALLOW A DETERMINATION OF THE ULTIMATE DESTINY OF THE UNIVERSE!

LMK + MST