THE COSMIC MICROWAVE BACKGROUND, COSMOLOGY & PARTICLE PHYSICS

- COSMOLOGICAL PARAMETERS from the CMB
- MAXIMA + BOOMERANG EXPERIMENT + ANALYSIS

BOOMERANG:

P. de Bernardis et al, Nature 404, 955
A.E. Lange et al, PRD submitted astro-ph/0005004

MAXIMA:

S. Hanany et al, Ap.J. Lett., submitted 0005123
A. Balbi et al, ApJ Lett, Submitted astro-ph/0005124

COMBINED ANALYSIS

A.H. Jaffe et al, PRL submitted, astro-ph/0007333

A. Jaffe, Berkeley
ICHEP, Osaka 2000

Cosmology from MAXIMA-1, BOOMERANG & COBE/DMR CMB Observations.

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Recent results from BOOMERANG-98 and MAXIMA-1, taken together with COBE-DMR, provide consistent and high signal-to-noise measurements of the CMB power spectrum at spherical harmonic multipole bands over $2 < \ell \lesssim 800$. Analysis of the combined data yields 68% (95%) confidence limits on the total density, $\Omega_{tot} \simeq 1.11 \pm 0.07$ $(^{+0.13}_{-0.12})$, the baryon density, $\Omega_b h^2 \simeq 0.032^{+0.005}_{-0.004}$ $(^{+0.009}_{-0.008})$, and the scalar spectral tilt, $n_s \simeq 1.01^{+0.09}_{-0.07}$ $(^{+0.17}_{-0.14})$. These data are consistent with inflationary initial conditions for structure formation. Taken together with other cosmological observations, they imply the existence of both non-baryonic dark matter and dark energy in the universe.

PACS numbers: 98.80.-k; 98.70.Vc; 98.80.Es; 95.85.Bh

arXiv:astro-ph/0007333 22 Jul 2000

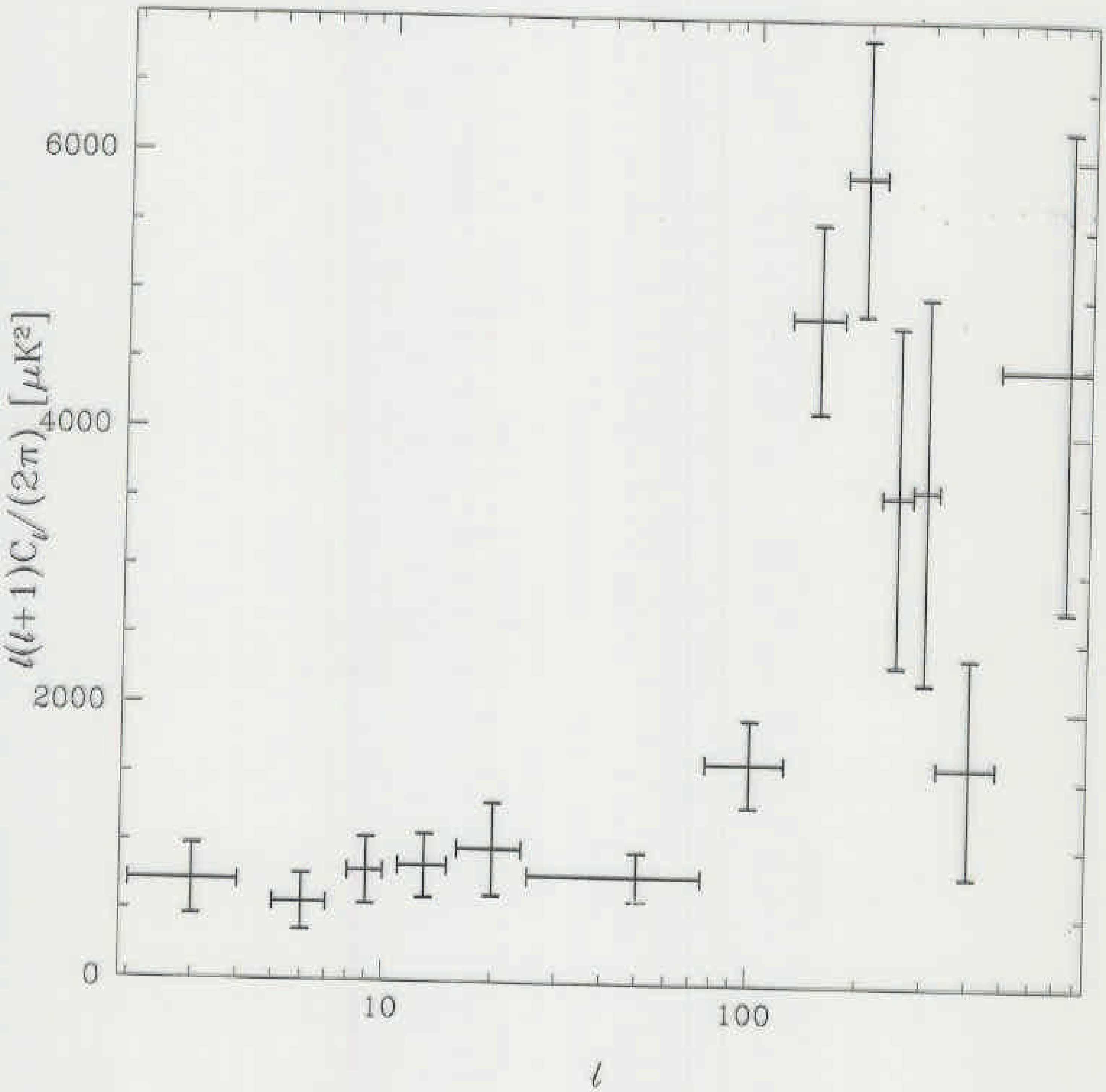
Measurements of the angular power spectrum, $\mathcal{C}_\ell$, of the Cosmic Microwave Background (CMB) have long been expected to enable precise determinations of cosmological parameters [1]. The CMB power spectrum depends on these parameters, as well as the scenario for the generation and growth of density fluctuations in the early universe. Evidence for structure in the CMB of the character predicted by adiabatic inflationary models has been mounting for the past decade and was convincingly detected in 1999 [2, 3, 4]. The recent BOOMERANG-98 (B98) [5] and MAXIMA-1 [6] CMB anisotropy data provide a significant improvement in the determination of $\mathcal{C}_\ell$. This letter jointly analyzes these two datasets, incorporating COBE-DMR [7] and other cosmological information to obtain further estimates of several cosmological parameters.

MAXIMA-1 and B98 have produced independent power spectra from patches of sky roughly 90° apart, on opposite sides of the galactic plane ([5, 6] and references therein). These data provide the first narrow-band detections of the power spectrum from $400 \lesssim \ell \lesssim 800$, where further acoustic peaks are expected in adiabatic models. Each spectrum shows a well-defined peak at multipole $\ell \sim 200$, followed by a relatively flat region extending to the highest multipoles reported (Figure 1, top). These results have been interpreted as supporting the inflationary theory of structure formation with adiabatic initial conditions, and allow the first precise CMB measurements

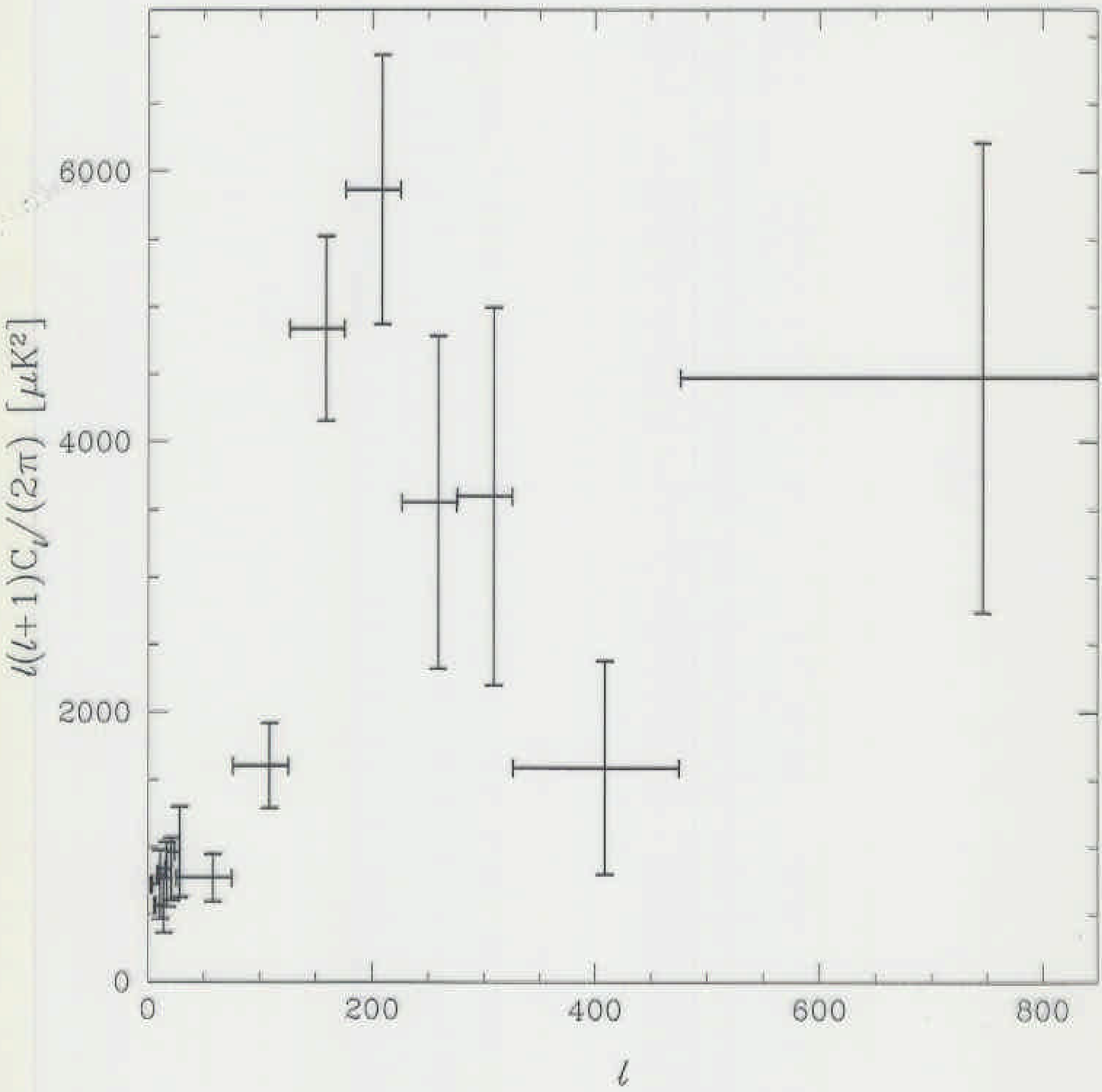
degree-scale
expts '92-99 →

← COBE/DMR →

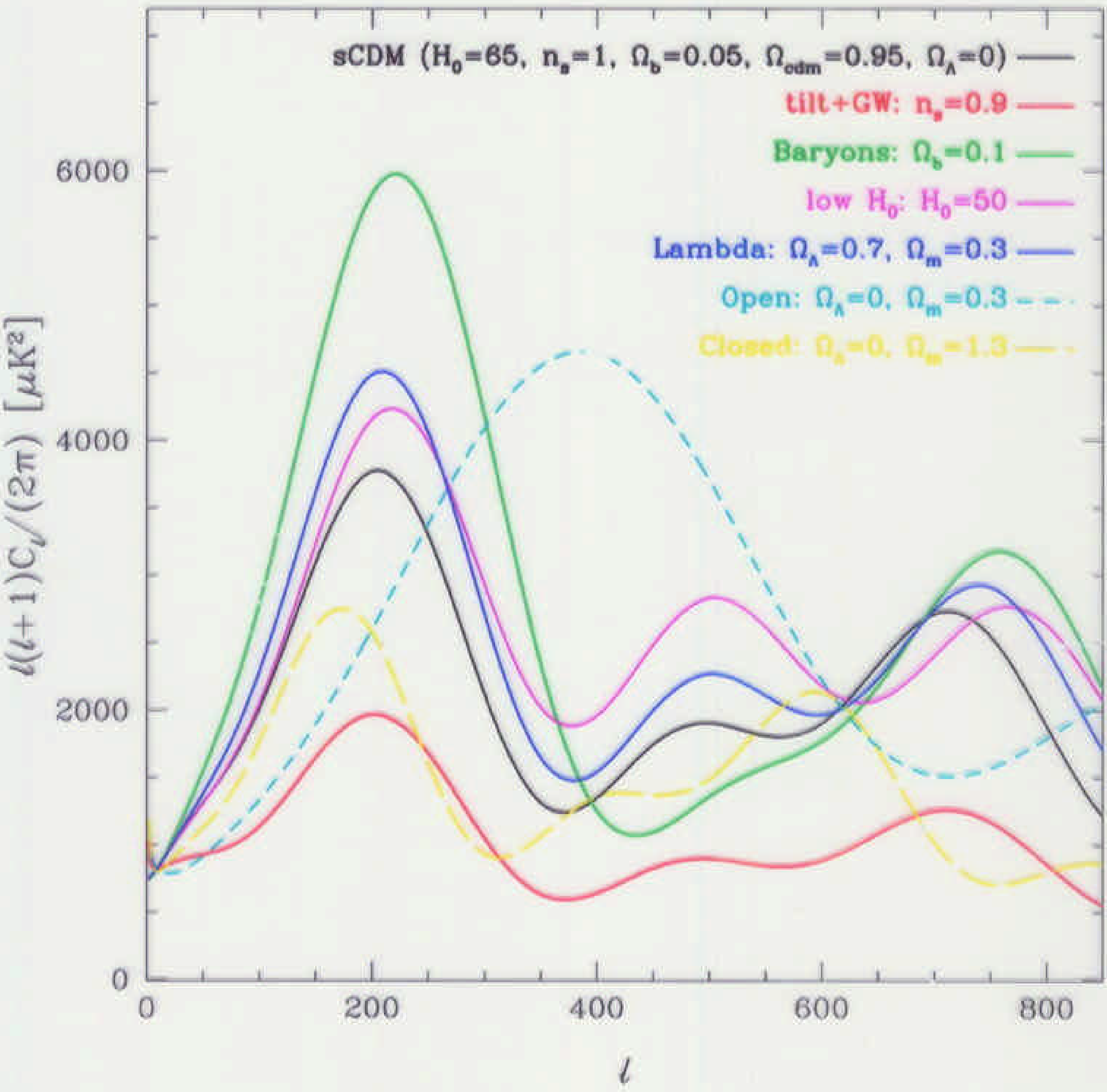
multipole ℓ ($\ell \sim 180° / \text{scale}$)



6000
4000
2000
0
10
100
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
ℓ

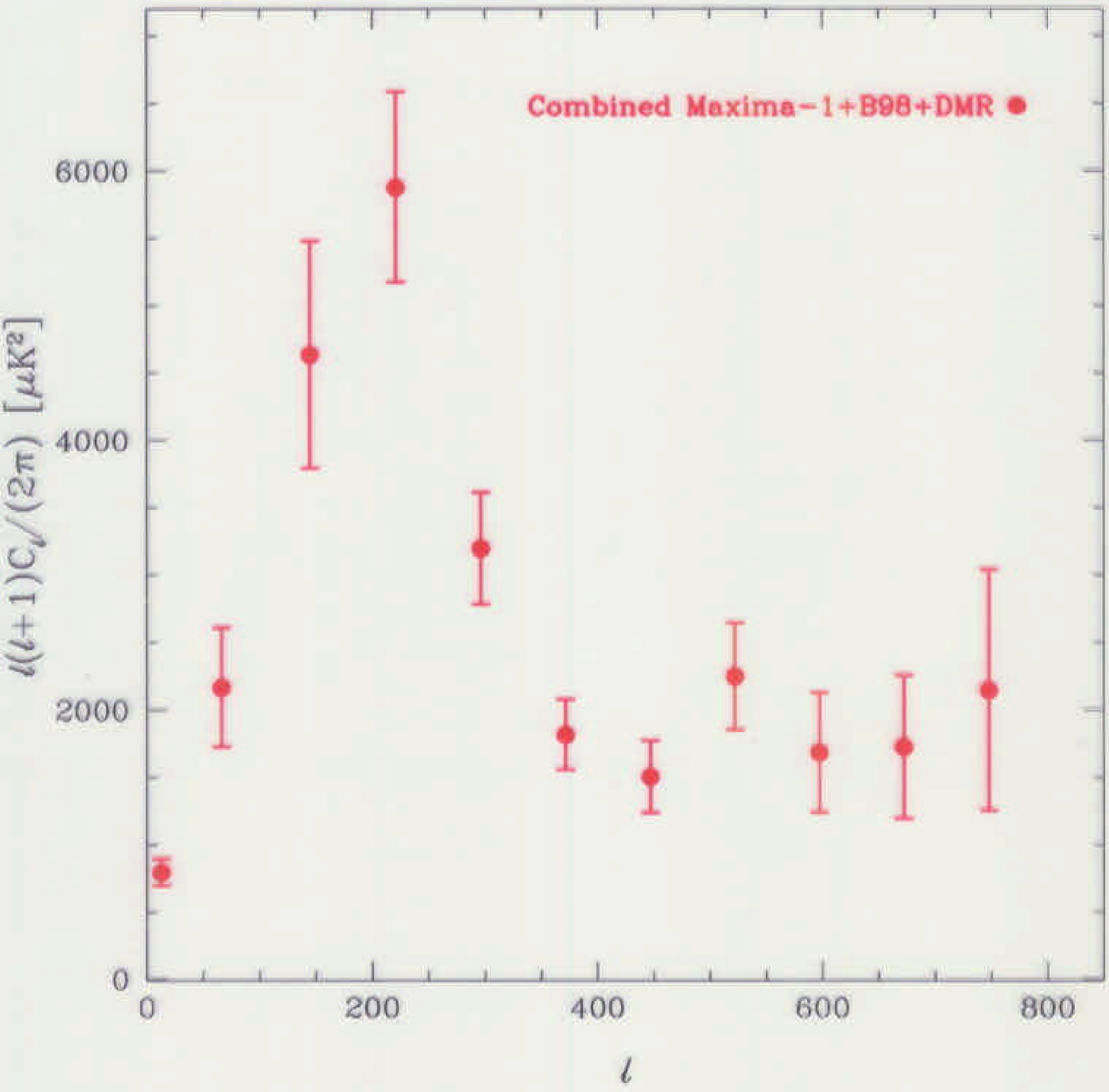


$l(l+1)C_l/(2\pi)$ [μK^2]
0
2000
4000
6000
0
200
400
600
800
l

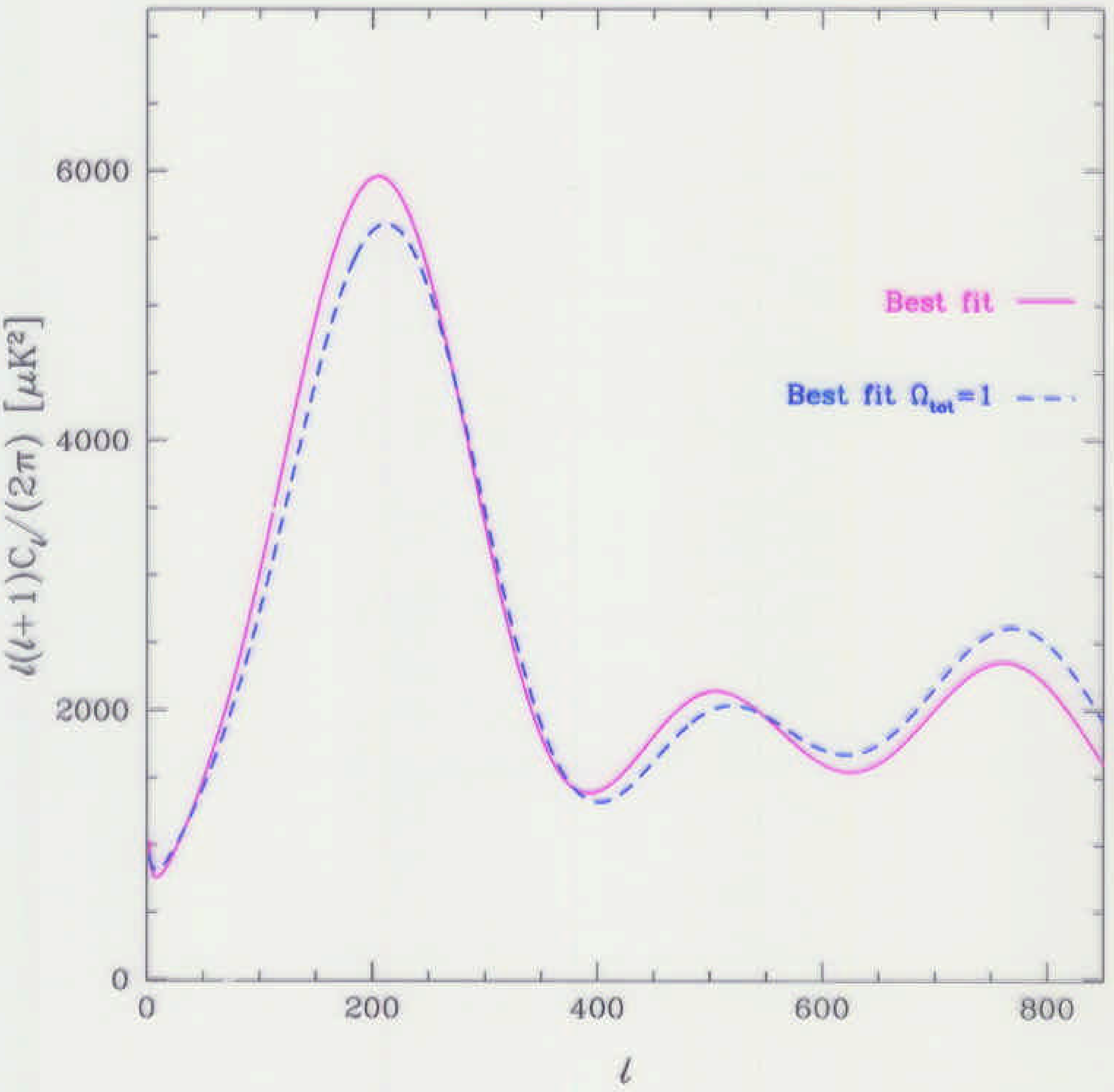

sCDM (H0=65, ns=1, Ωb=0.05, Ωcdm=0.95, ΩΛ=0)
tilt+GW: ns=0.9
Baryons: Ωb=0.1
low H0: H0=50
Lambda: ΩΛ=0.7, Ωm=0.3
Open: ΩΛ=0, Ωm=0.3
Closed: ΩΛ=0, Ωm=1.3
ℓ(ℓ+1)Cℓ/(2π) [μK²]
6000
4000
2000
0
0
200
400
600
800
ℓ

BEST FITS:

	Ω_{tot}	Ω_Λ	$\Omega_b h^2$	$\Omega_c h^2$	n_s	τ_c
	1.2	0.5	0.03	0.12	0.95	0
	1	0.7	0.03	0.17	0.98	0



Combined Maxima-1+B98+DMR
6000
4000
2000
0
0
200
400
600
800
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
ℓ


Best fit
Best fit $\Omega_{tot}=1$
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
6000
4000
2000
0
0
200
400
600
800
ℓ

Measuring Ω & Λ

- Ω_i is *defined* as a density:

$$\Omega_i = 8\pi G\rho_i/3H_0^2$$

  - i=matter, radiation, Λ, ν, curvature...

- Ω_i *determines*
  - distances [scale factor, $a(t)$]
  - kinematics [$\dot{a}(t)$]
  - curvature
  - dynamics [linear growth mode $D(a)$]
- Different cosmological tests measure different aspects of Ω
  - Difficult to get Ω_i alone
  - Instead, measure $(\Omega_m + \Omega_\Lambda)$, $(\Omega_m - \Omega_\Lambda)$, $\sigma_8\Omega_m^{0.6}$, ...

CMB statistics

z~1300: p+e→H & Universe becomes transparent.

$$\frac{\Delta T}{T}(\hat{x}) = \sum_{lm} a_{lm} Y_{lm}(\hat{x})$$

Determined by **temperature**, **velocity** and **metric** on the last scattering surface.

Power Spectrum:

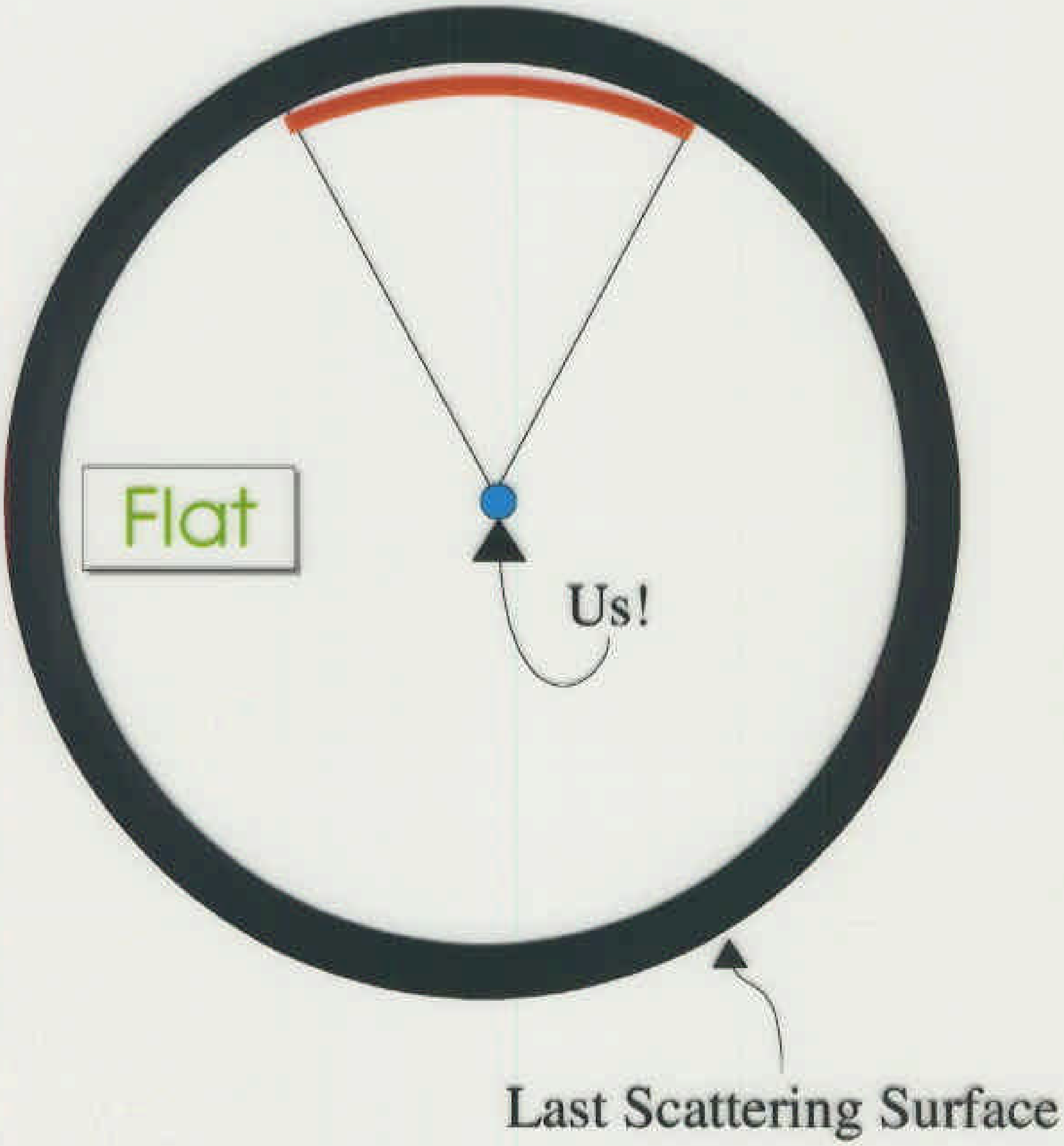
$$C_l = \langle |a_{lm}|^2 \rangle$$

Multipole $l \Leftrightarrow$ angular scale $180°/l$

For a **Gaussian** theory, C_l completely determines the statistics of the temperature.

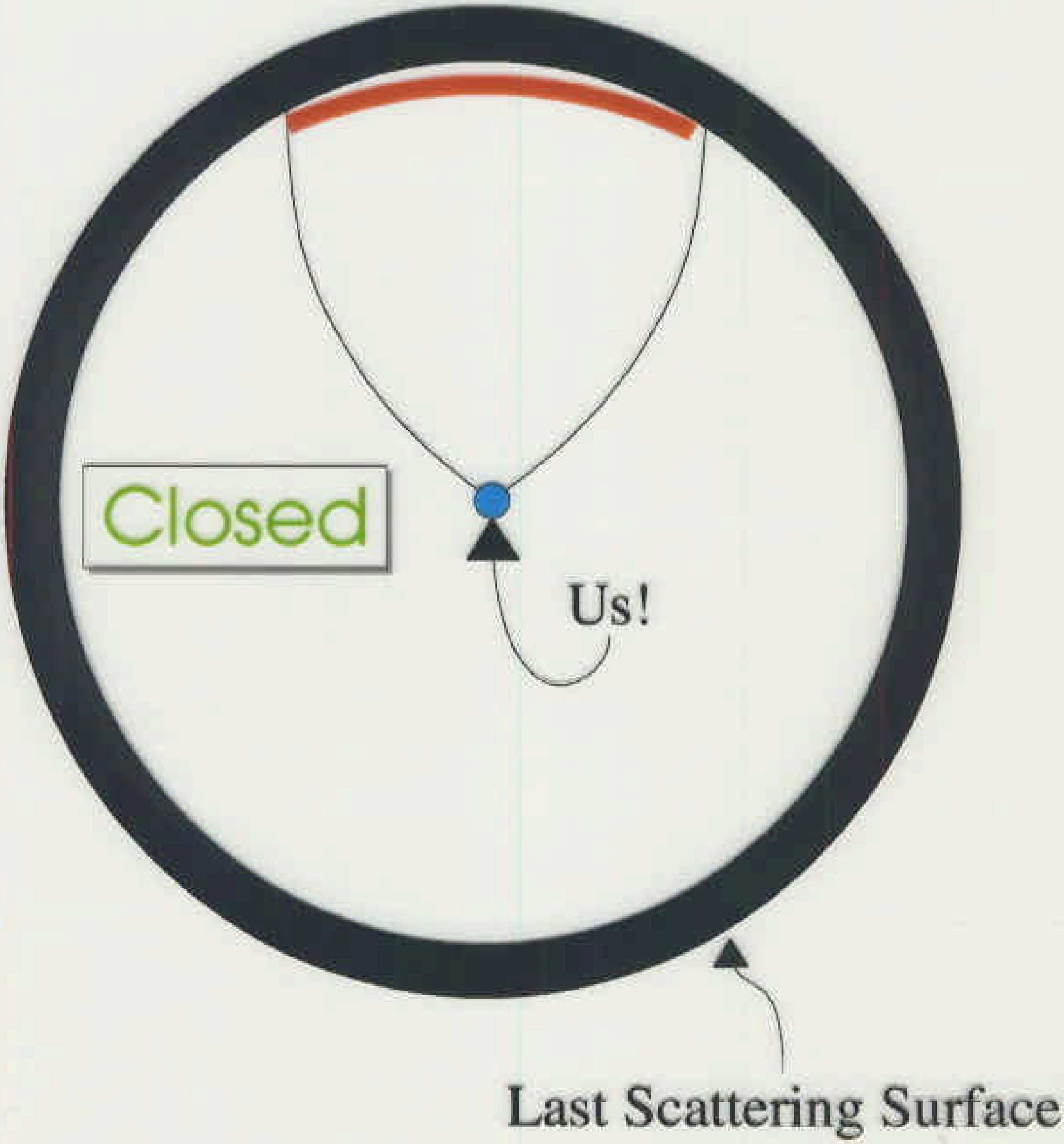
Measuring Curvature with the CMB

$$\vartheta = length / R$$



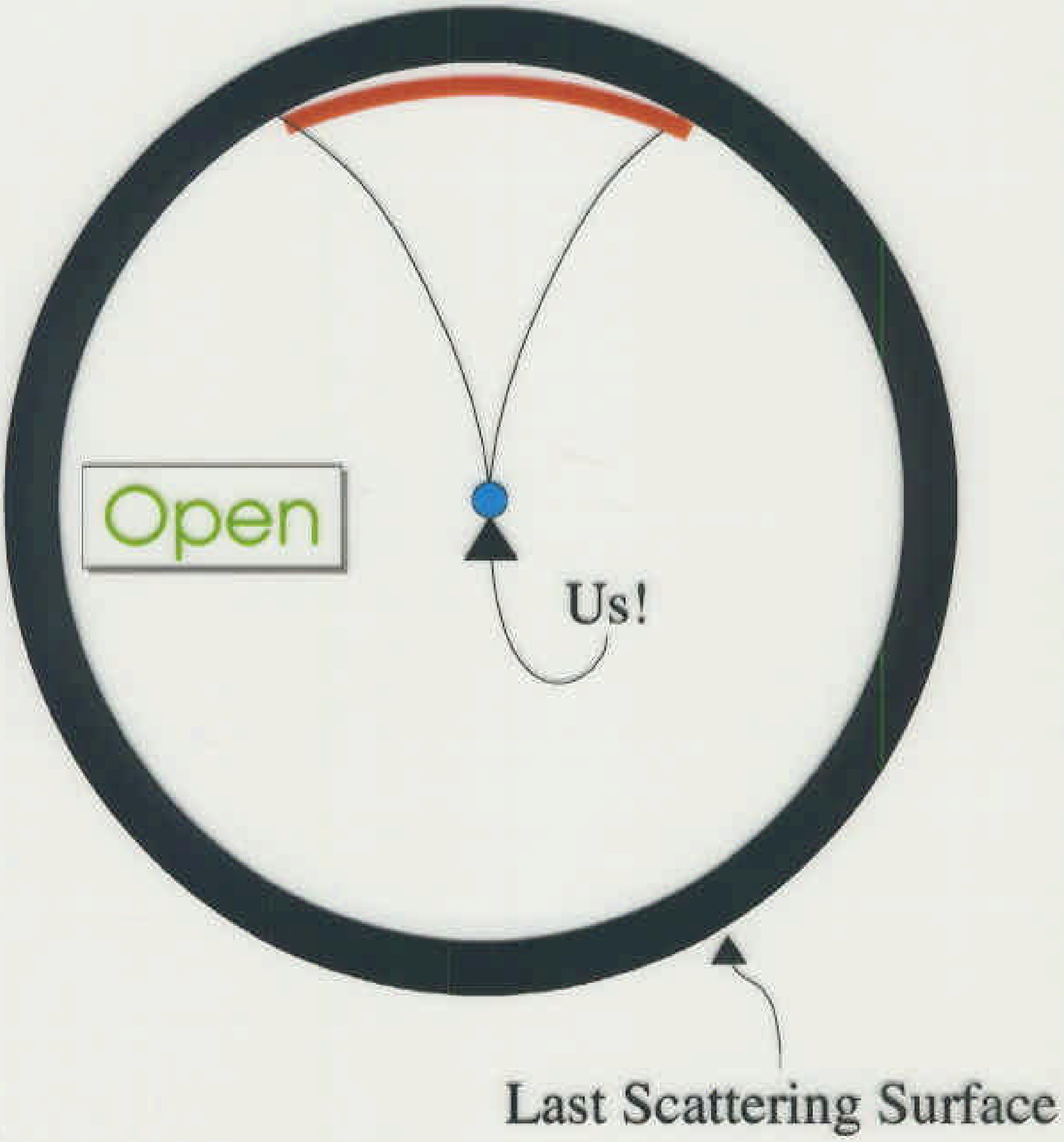
Measuring Curvature with the CMB

$\vartheta = length / R$



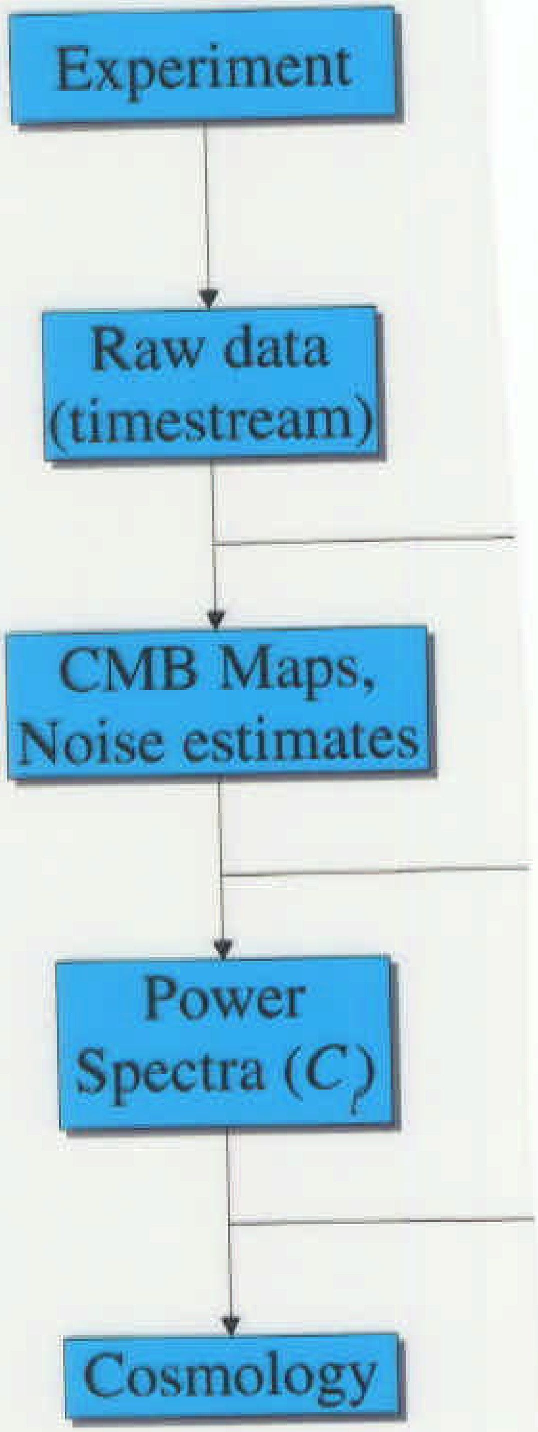
Measuring Curvature with the CMB

$$\vartheta = length / R$$



From CMB to Cosmology

Bond, Crittenden, Jaffe & Knox 99



Money, People

Repeated application of Bayes' Theorem

DMR: $N_{pix} \sim 10^3$

MAX/BOOM $10^4 - 10^5$

MAP/Planck $10^6 - 10^7$

calibration, pointing beams

(Matrix) Least Squares

$O(N_{pix}^3)$

systematic tests

foregrounds

"quadratic estimator"

- global analysis
  - all data at once!!

$O(N_\ell \times N_{pix}^3)$!!

multi-dimensional optimization / search / marginalization

Papers, Jobs

MAXIMA & BOOMERANG

CMB ANISOTROPY EXPERIMENTS

- BALLOON-BORNE, BOLOMETER-BASED
  ~100 → ~400 GHz

BOOMERANG:

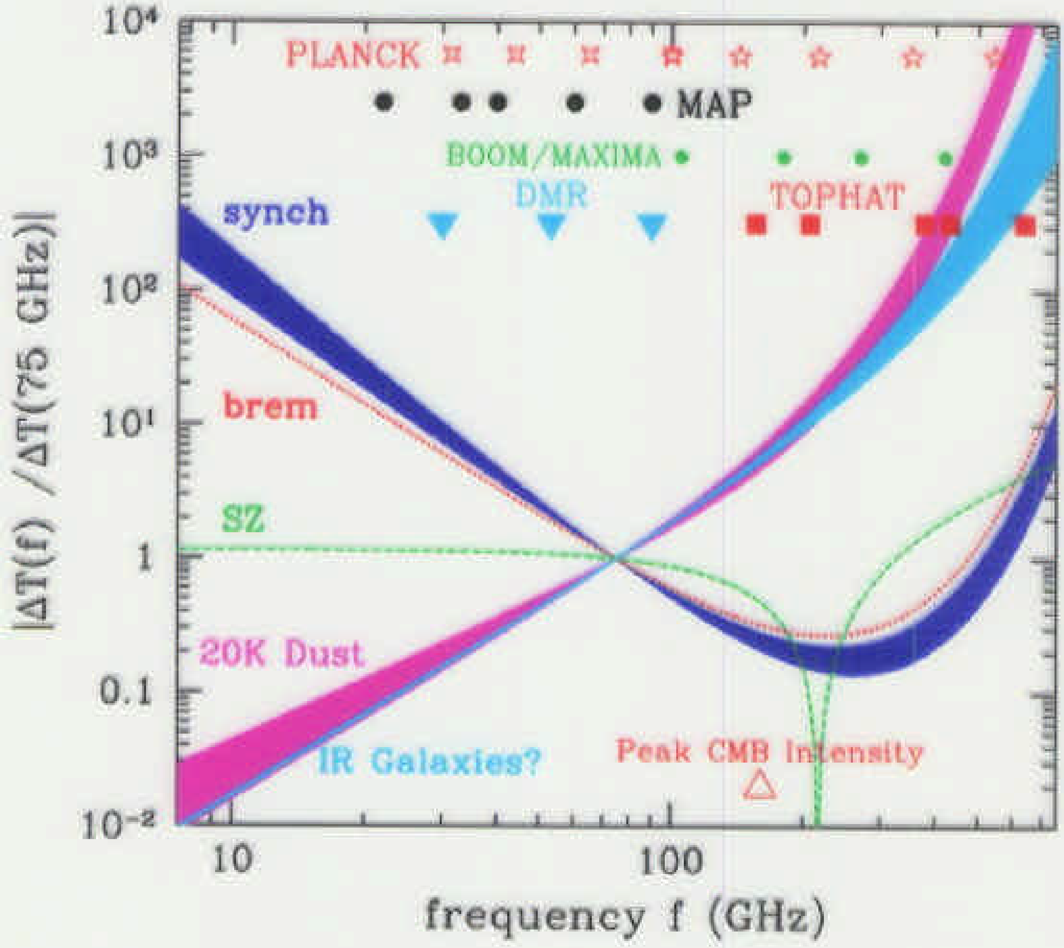
Antarctic long-duration balloon ('98)
~3% sky (1% analyzed @ 150 GHz)
10' beams at 150 GHz
single 150 GHz detector analyzed

MAXIMA

North-American single-night balloon ('98 – '99)
~0.3% sky ('98, ×2 for '98 - '99)
10' beams at 150 - 400 GHz
3 × 150 GHz + 1 × 240 GHz detectors analyzed

(More data on the disk & more to come!)

nb. calibration + beam uncertainty estimated, accounted-for.


PLANCK
MAP
BOOM/MAXIMA
DMR
TOPHAT
synch
brem
SZ
20K Dust
IR Galaxies?
Peak CMB Intensity
|ΔT(f) /ΔT(75 GHz)|
frequency f (GHz)
10
100
10^4
10^3
10^2
10^1
1
0.1
10^{-2}

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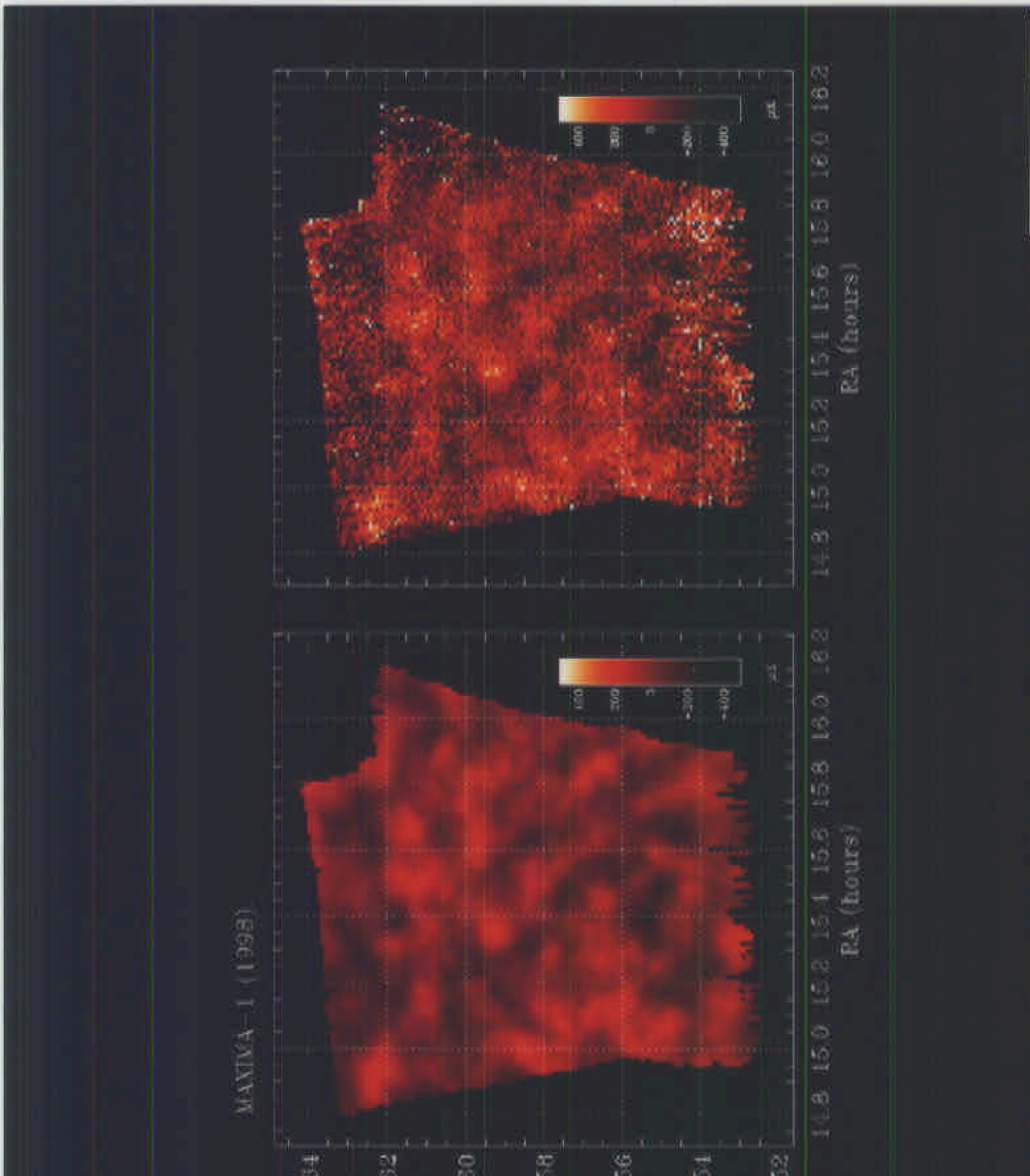
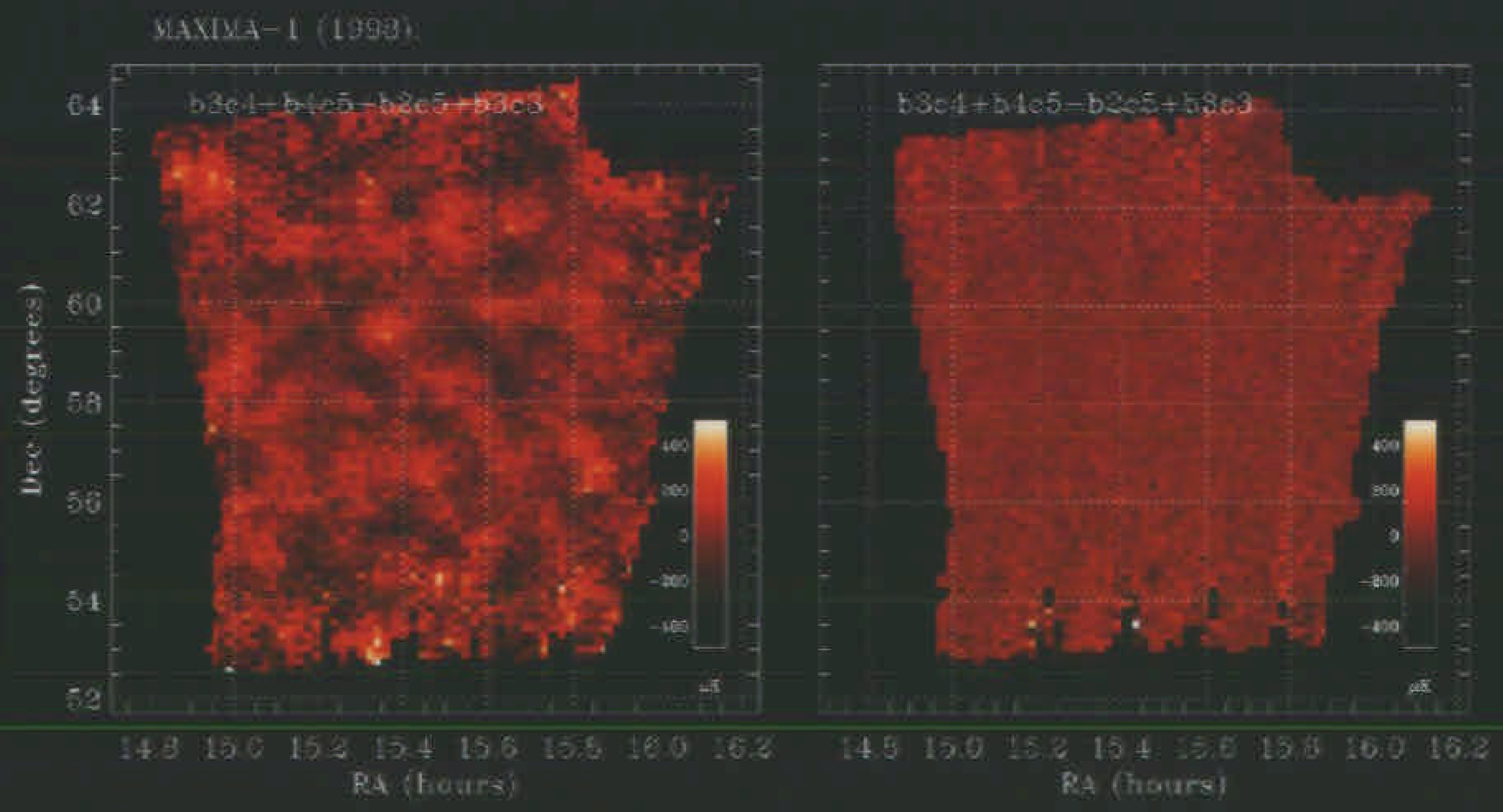
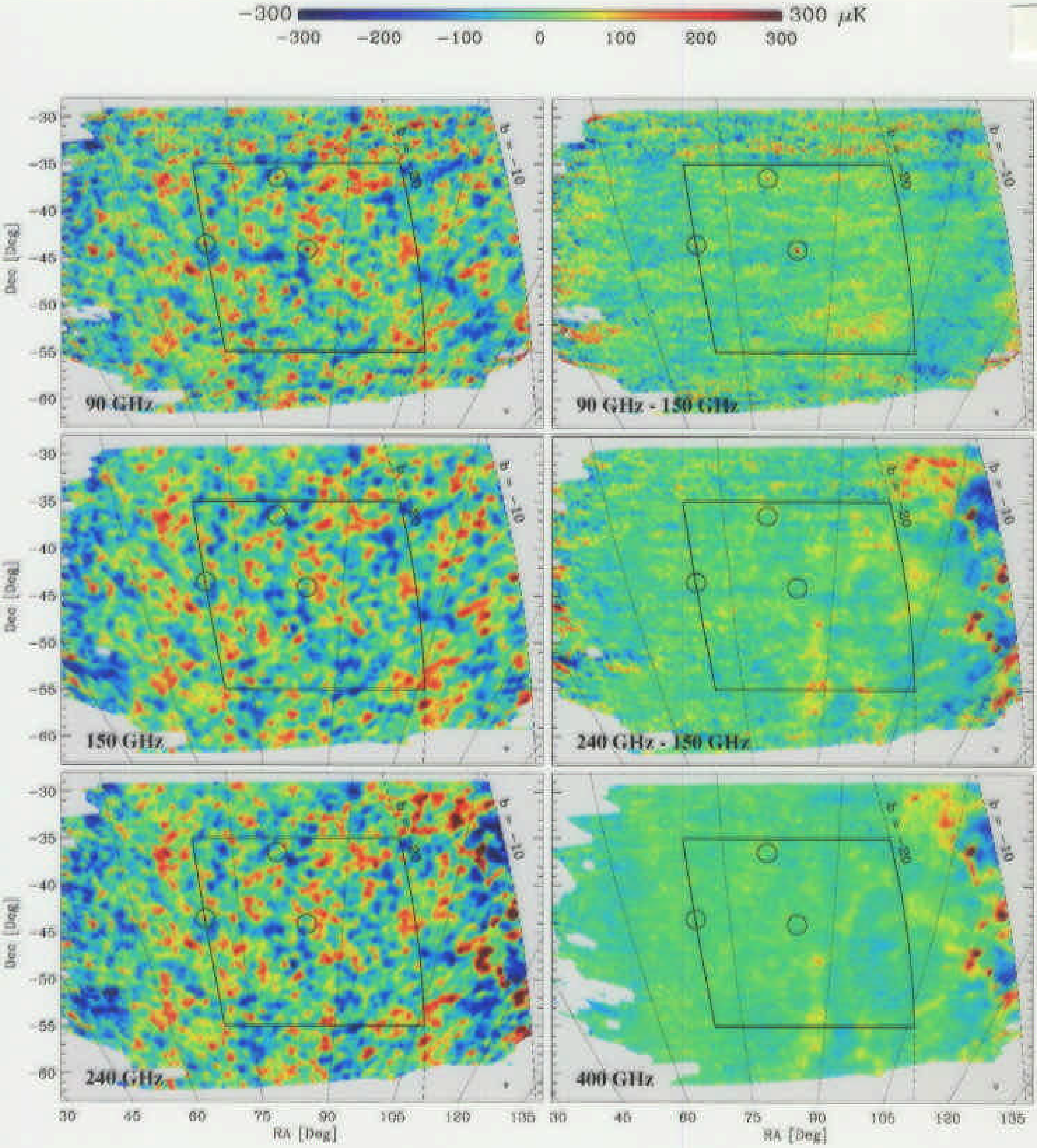
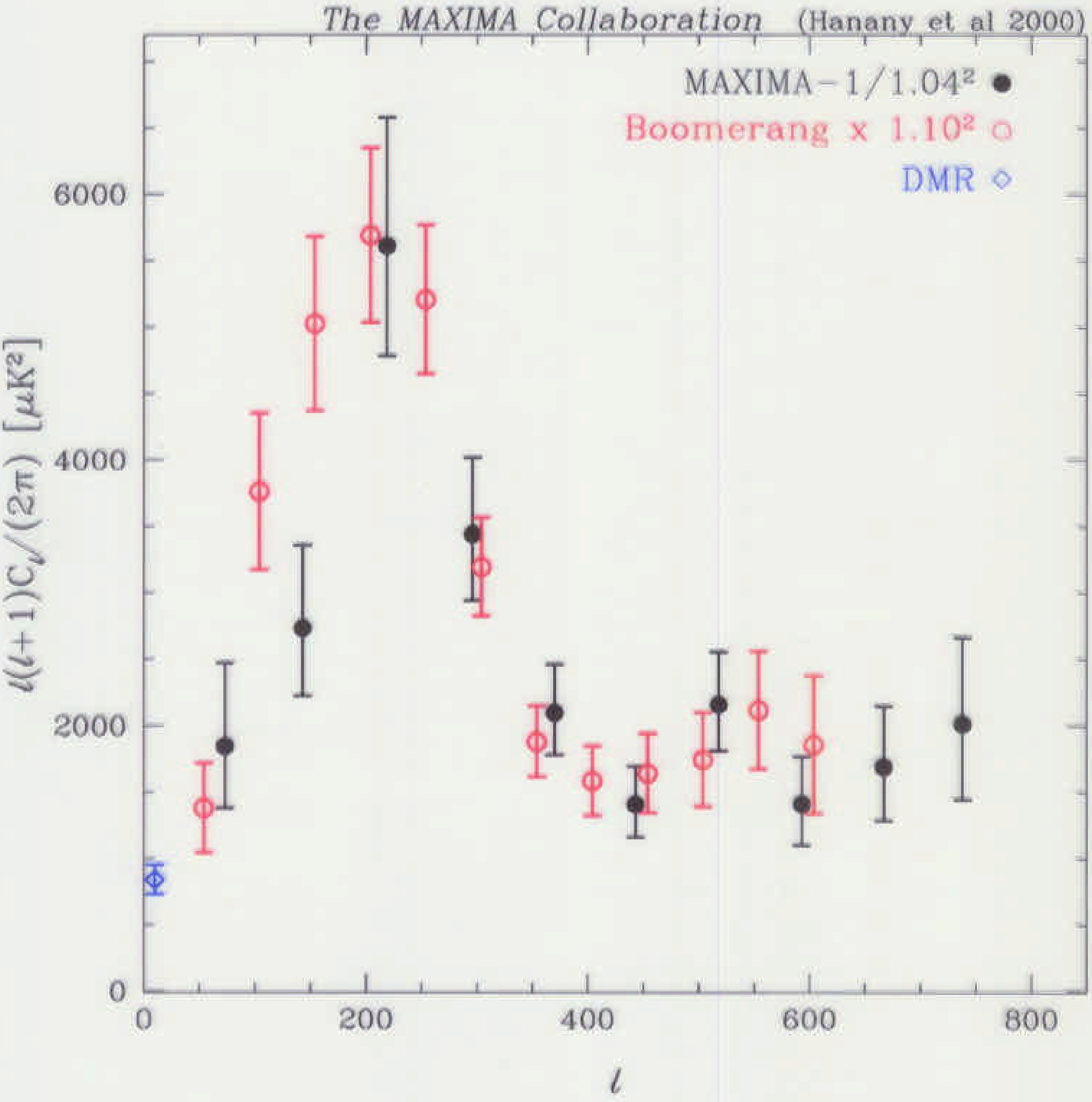


MAXIMA-1 (1998)
Dec (degrees)
RA (hours)
RA (hours)
μK


MAXIMA-1 (1999)
b3c4-b4c5-b2c5+b3c3
b3c4+b4c5-b2c5+b3c3
Dec (degrees)
RA (hours)
RA (hours)
μK
μK



−300
300 μK
-300 -200 -100 0 100 200 300
90 GHz
90 GHz - 150 GHz
150 GHz
240 GHz - 150 GHz
240 GHz
400 GHz
b = -10
b = -20
Dec [Deg]
RA [Deg]
-30 -35 -40 -45 -50 -55 -60
30 45 60 75 90 105 120 135


The MAXIMA Collaboration (Hanany et al 2000)
MAXIMA-1/1.04²
Boomerang x 1.10²
DMR
ℓ(ℓ+1)Cℓ/(2π) [μK²]
0
2000
4000
6000
0
200
400
600
800
ℓ

CMB PARAMETER ESTIMATION

Calculate LIKELIHOOD FUNCTION $P(\hat{C}_\ell | \text{model})$ OVER A GRID OF COSMOLOGICAL MODELS PARAMETRIZED BY

Ω_{tot} Ω_Λ $\Omega_b h^2$ $\Omega_{cdm} h^2$

n_s τ_c (amplitude of fluctuations)

- τ_c → reionization optical depth
- n_s → scalar tilt $P(k) \propto k^{n_s}$

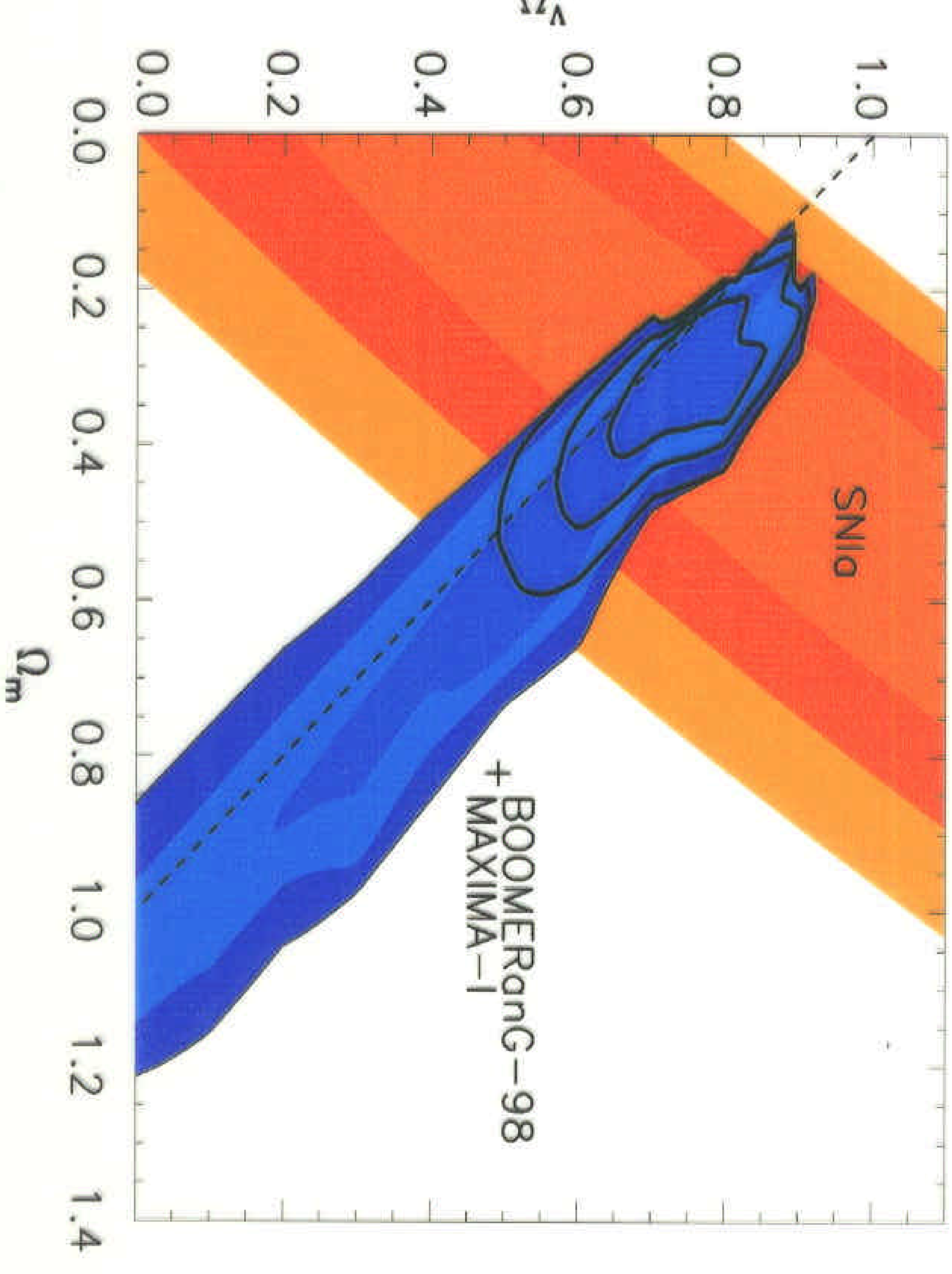
and experimental beam + calibration uncertainty

- When reporting one parameter, we marginalize over all others.
- Detailed results sensitive to parameter ranges and prior probabilities

e.g. "weak prior"

$t_0 > 10\,\text{Gyr}$ $\quad 0.4 < h < 0.9 \quad$ $\Omega_m > 0.1$

(+ of course only valid w/in this class of models!)



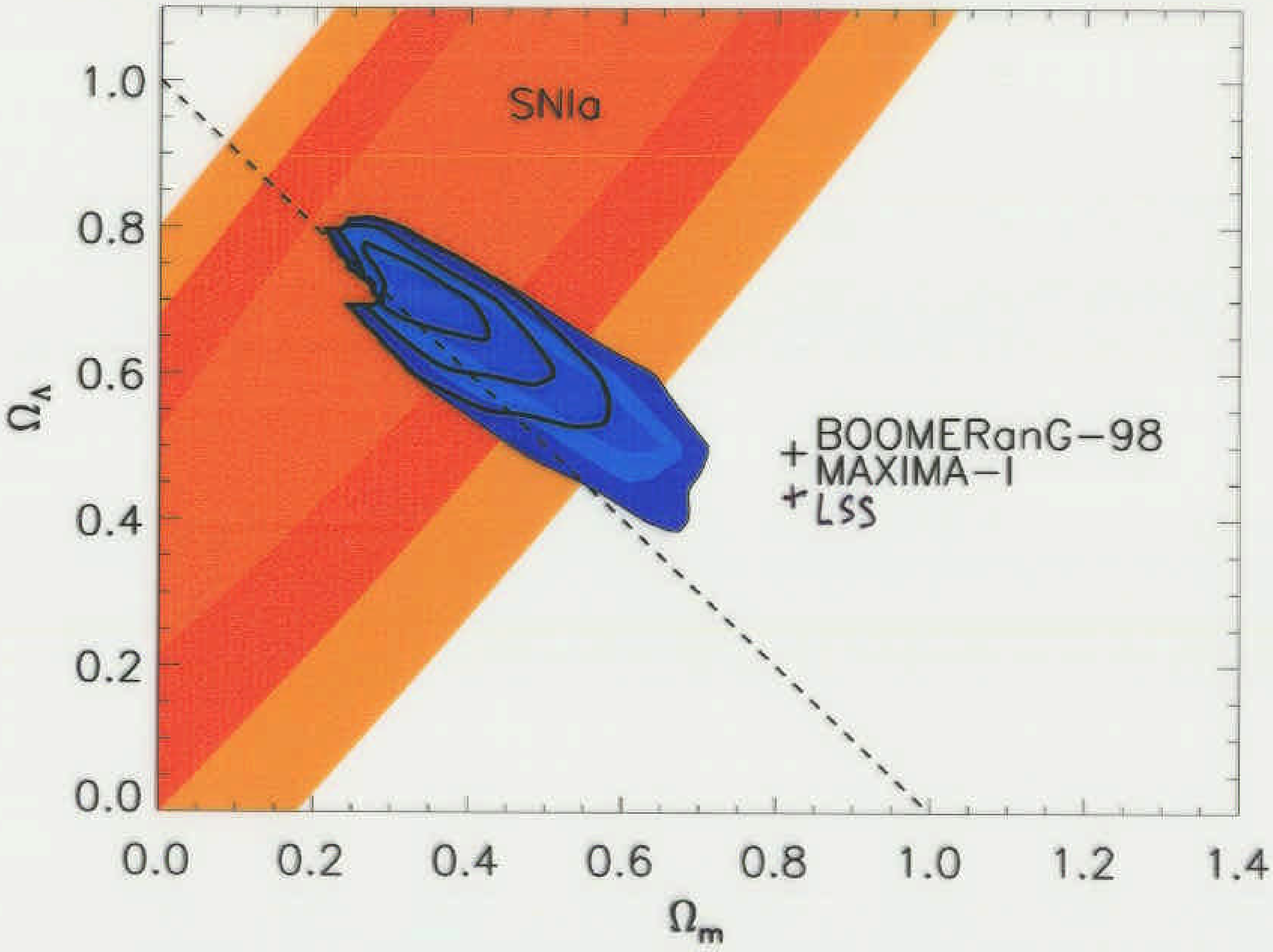
Ω_Λ
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Ω_m
SNIa
BOOMERanG−98
+MAXIMA−I

add prior information: amplitude & shape of the matter power spectrum

$\beta \simeq \Omega_M^{0.6}\sigma_8 \simeq 0.55 \pm 0.02\,^{+.11}_{-.08}$

$\Gamma + \frac{1}{2}(n_s - 1) \simeq 0.22^{+.07+.08}_{-.04-.07}$

$\hookrightarrow \sim \Omega_m h$


SNIa
+ BOOMERanG-98
+ MAXIMA-I
+ LSS
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

	Ω_{tot}	$\Omega_b h^2$	n_s	$\Omega_{CDM} h^2$	Ω_M	Ω_Λ
B97+M1+DMR	1.11 ± 0.07	0.032 ± 0.005	$1.01^{+0.04}_{-0.08}$	$0.14^{+0.06}_{-0.05}$		
$+\Omega_{tot}=1$	1	0.030 ± 0.004	$0.99^{+0.07}_{-0.06}$	$0.14^{+0.06}_{-0.05}$		
CMB + LSS	1.11 ± 0.05	0.032 ± 0.004	$1.00^{+0.09}_{-0.06}$	$0.13^{+0.02}_{-0.01}$	0.49 ± 0.13	$0.63^{+0.09}_{-0.09}$
CMB + SN1a	$1.04^{+0.06}_{-0.05}$	0.032 ± 0.005	$1.00^{+0.09}_{-0.08}$	0.10 ± 0.04	0.35 ± 0.07	$0.75^{+0.06}_{-0.07}$
CMB+LSS+SN1a	1.06 ± 0.04	$0.033^{+0.005}_{-0.004}$	$1.03^{+0.04}_{-0.07}$	$0.14^{+0.03}_{-0.02}$	0.37 ± 0.07	0.71 ± 0.05

also: CMB + $h = 0.71 \pm 0.08 \implies \Omega_{tot} = 1.05 \pm 0.04$

THE FUTURE OF THE CMB

- Still more MAXIMA + BOOMERANG DATA !
  - higher ℓ, smaller sample variance

    higher sensitivity, better spectral resolution

Interferometers on-line + taking data
- DASI, CBI, VSA

POLARIZATION MEASUREMENTS coming soon

POLAR, PIQUE, MAXIPOL, B2K

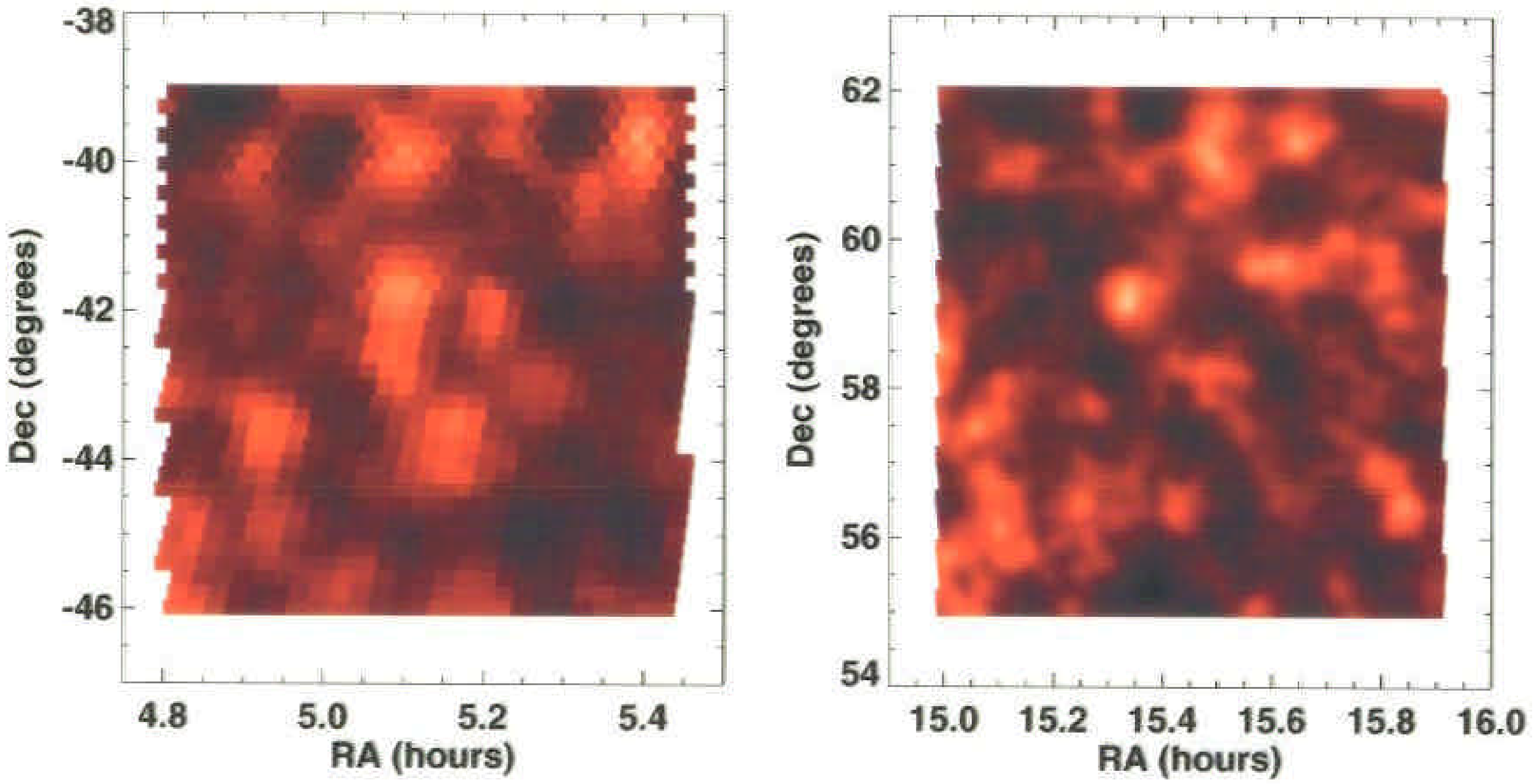
(confirmation of paradigm; info on inflation)

- Sattellites coming soon

  MAP launch in April 2000

  Planck in 2007

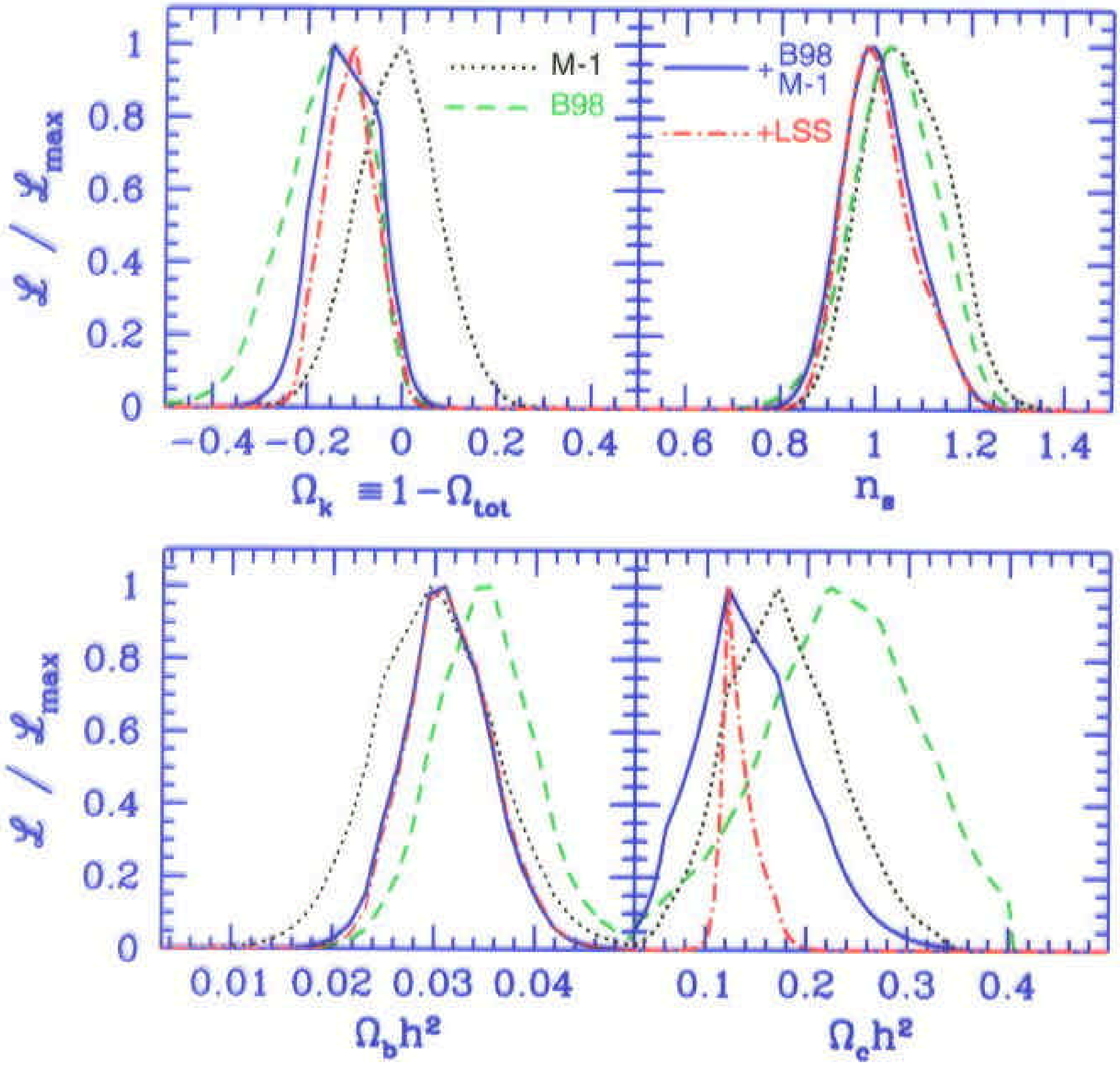
(iii) A $7^\circ \times 7^\circ$ patch of each map (977 & 7144 pixels respectively).



curvature + tilt consistent w/ Inflation

there are baryons!

CMB: there is probably CDM



$\mathcal{L} / \mathcal{L}_{max}$
M-1
B98
+B98 M-1
+LSS
$\Omega_k \equiv 1-\Omega_{tot}$
n_s
$\Omega_b h^2$
$\Omega_c h^2$

CONCLUSIONS:

THE CMB & PARTICLE PHYSICS

- $\Omega_{tot} \approx 1$, $n_s \simeq 1$
  $\Rightarrow$ Inflation

$\Omega_b h^2 \simeq 0.03$

$\Rightarrow$ $\exists$ dark baryons, some non-baryons
(CDM? "Dark energy"? Λ?)

very close to BBN measurement (~ 0.02)
(small worries but early days yet)

+ other cosmology: SNIa or Large-Scale Structure

$\Omega_M \sim 0.3$, $\Omega_\Lambda \sim 0.7$

$\Rightarrow$ non-baryonic dark matter
$\Rightarrow$ cosmological constant? / scalar field?
(it's not "natural" -- it's just the data!)

Ω_ν needs Large-scale Structure (spectral shape)

+ Simplest COSMIC STRING models ruled out

(active sources prefer wide first peak)