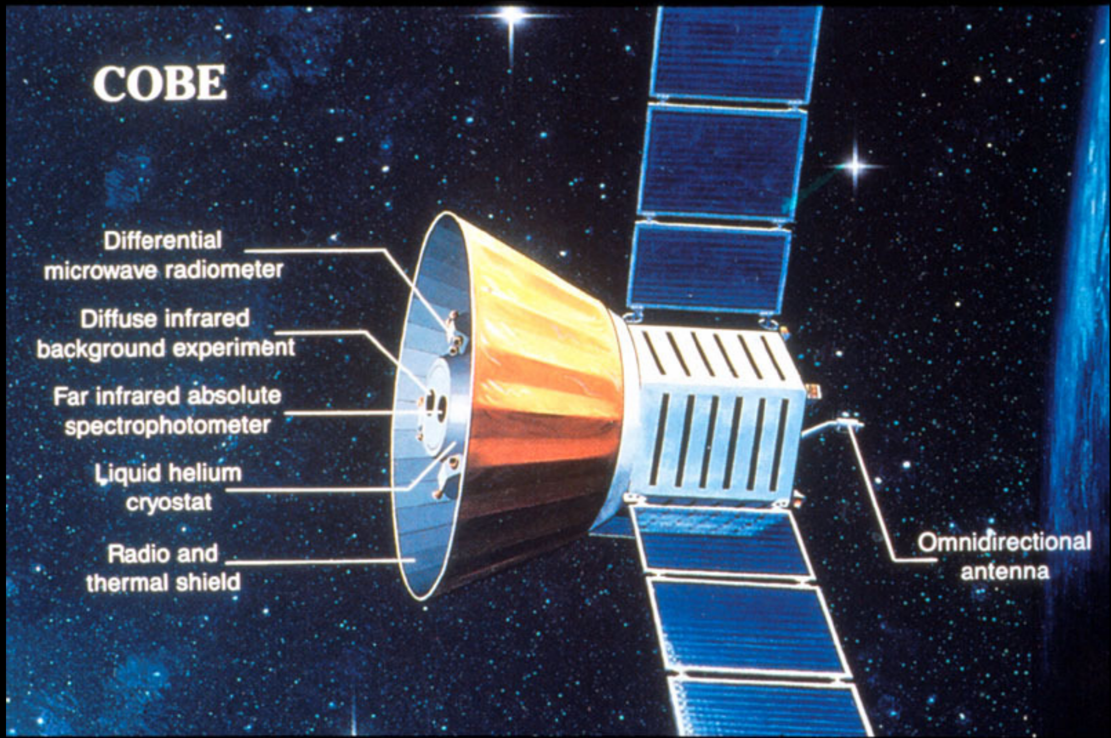
Cosmic Microwave Background Anisotropy Experiments

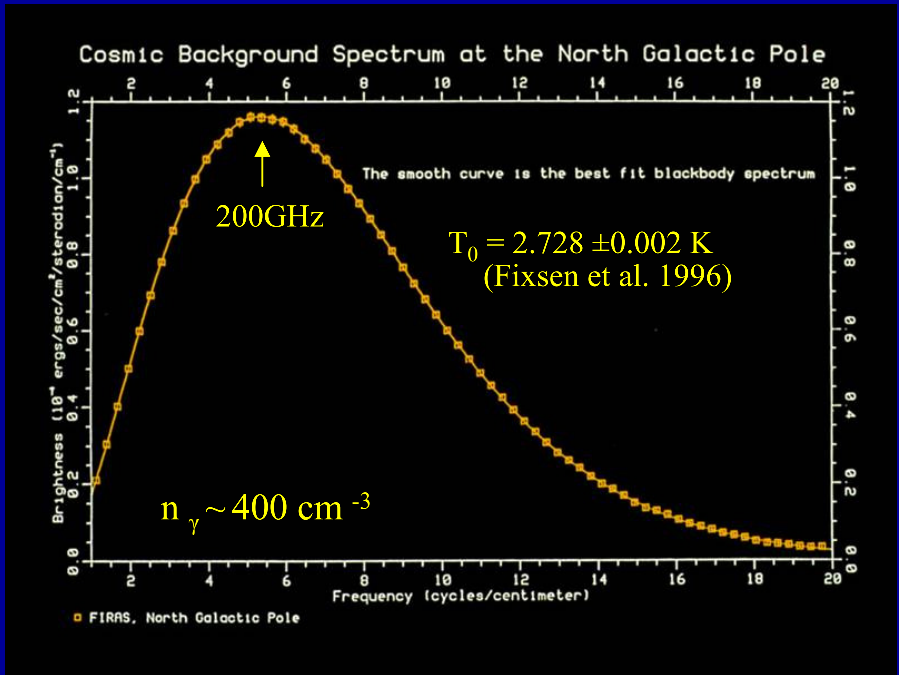


R. Rebolo (IAC)

ISAPP 2012, La Palma

The Cosmic Microwave Background

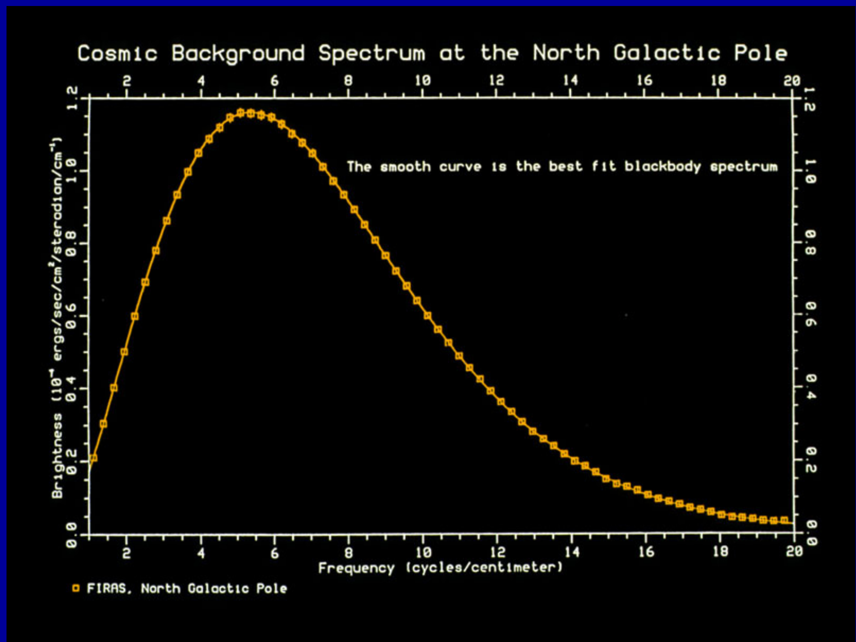
- Predicted by Gamow (1946); Doroshkevich & Novikov (1964)
- Discovered by Penzias & Wilson (1964)

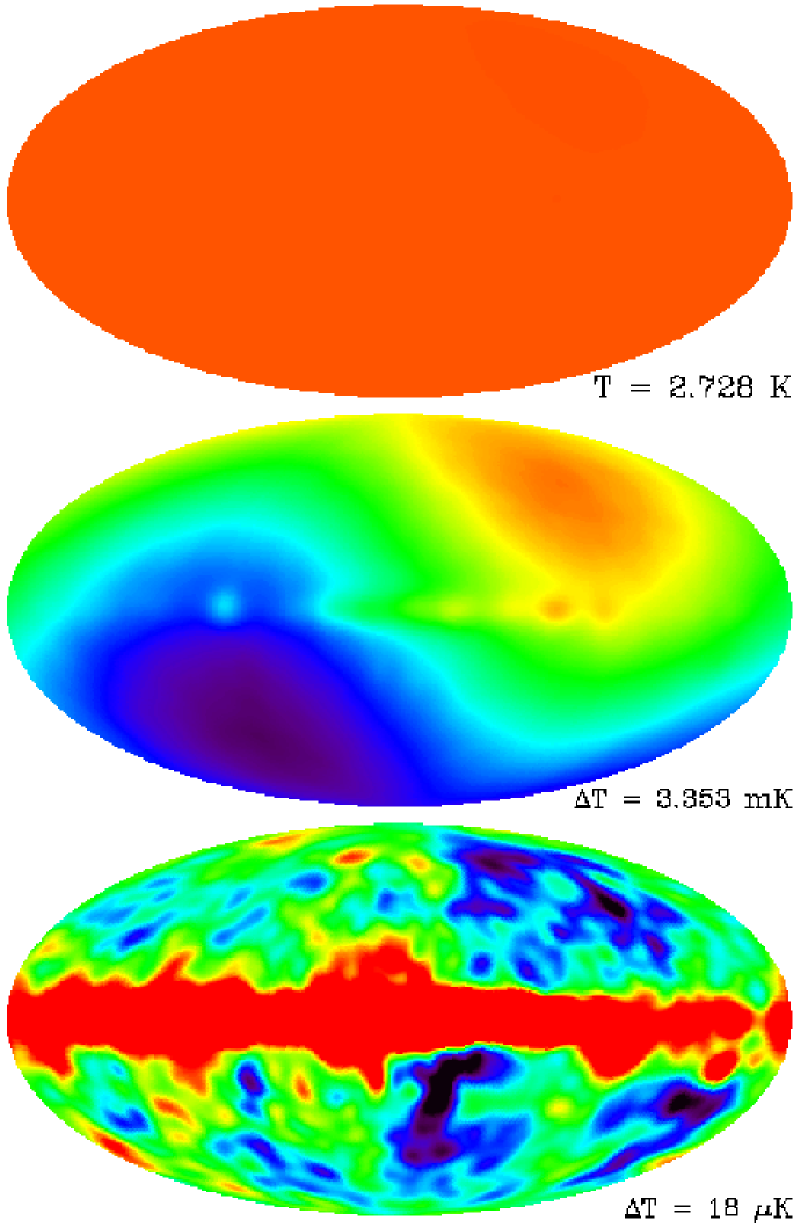


- Main properties:
  - Planckian spectrum
  - high level of isotropy (1 part in 100,000)

CMB

- Planckian distribution with remarkable precision
  T= 2.726 ± 0.002 K (95%C.L.) (COBE FIRAS, Wright et al. 1994, Fixsen et al. 1996)
- photon density n_γ~ 411 cm^{-3}
- ρ_γ= 4.64 x 10^{-34} g cm^{-31}
- CMB originates in the Last Scattering Surface (z~1000)





Dipole

$\Delta T/T = 1.23 \times 10^{-3}$

The dipole

- Caused by the motion of the solar system relative to the isotropic Planckian radiation
  - $T = T_0 (1-\beta^2)^{1/2} / (1- \beta\cos\theta)$ $\beta = v/c$
  - $\beta = 0.001237 \pm 0.000002$ (68% C.L.) or $v = 371 \pm 0.5$ km s^{-1}

    towards

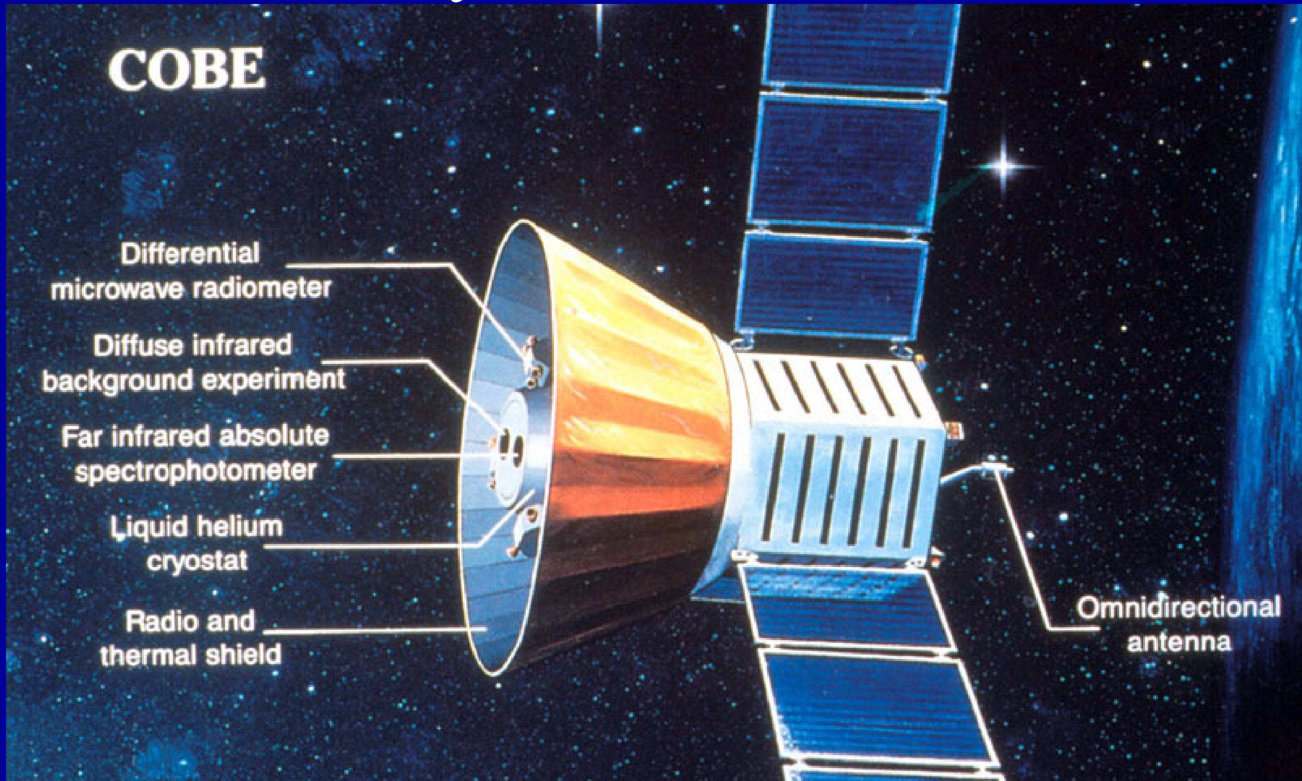
    $(\alpha,\delta) = (11.20^h \pm 0.01^h, -7.22^\circ \pm 0.08^\circ)$
  - Velocity for our Galaxy and the Local Group $V_{LG} = 627 \pm 22$ kms

    toward

    $(l,b) = (276^\circ \pm 3^\circ, 30^\circ \pm 3^\circ)$

COBE detected CMB primordial anisotropies

year 1992



COBE/DMR 4yr

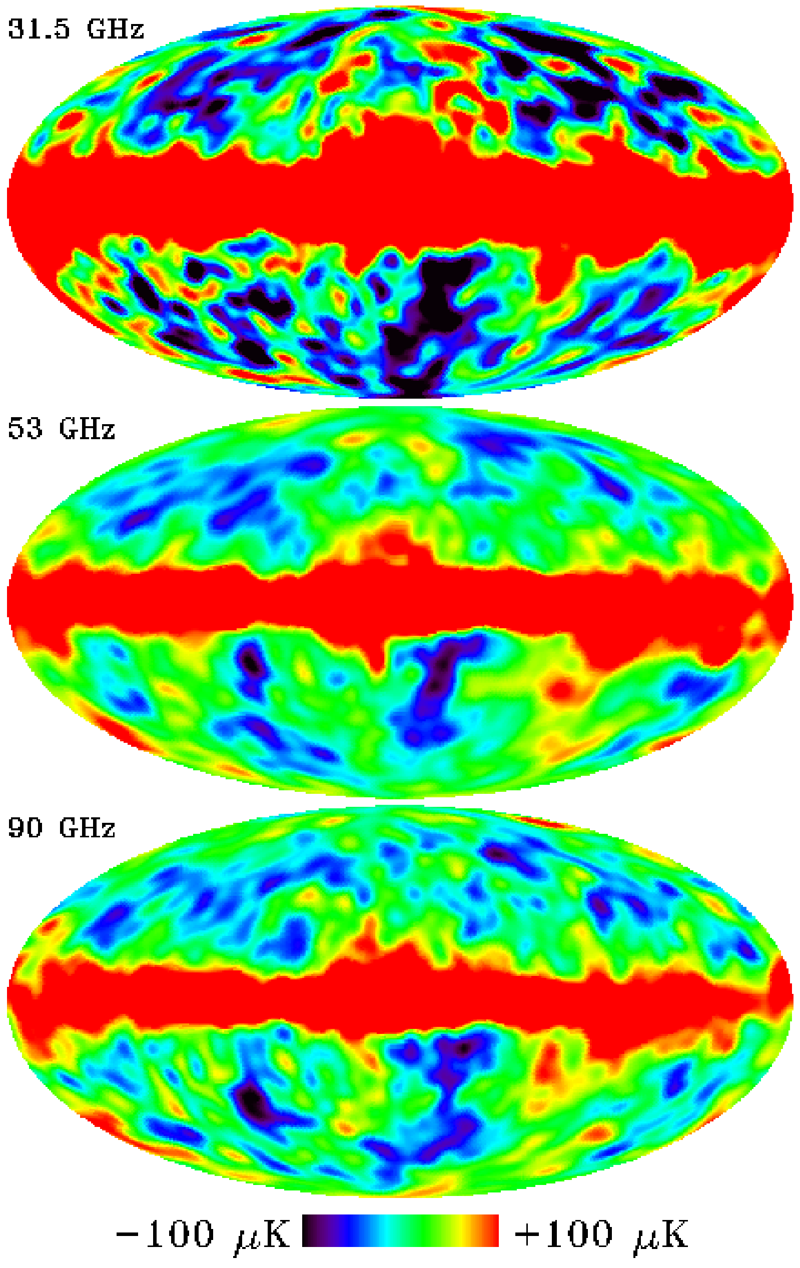
For a pure n=1 scale-invariant primordial density perturbation power spectrum

$Q_{rms\text{-}ps} = 18.4 \pm 1.6\ \mu K$

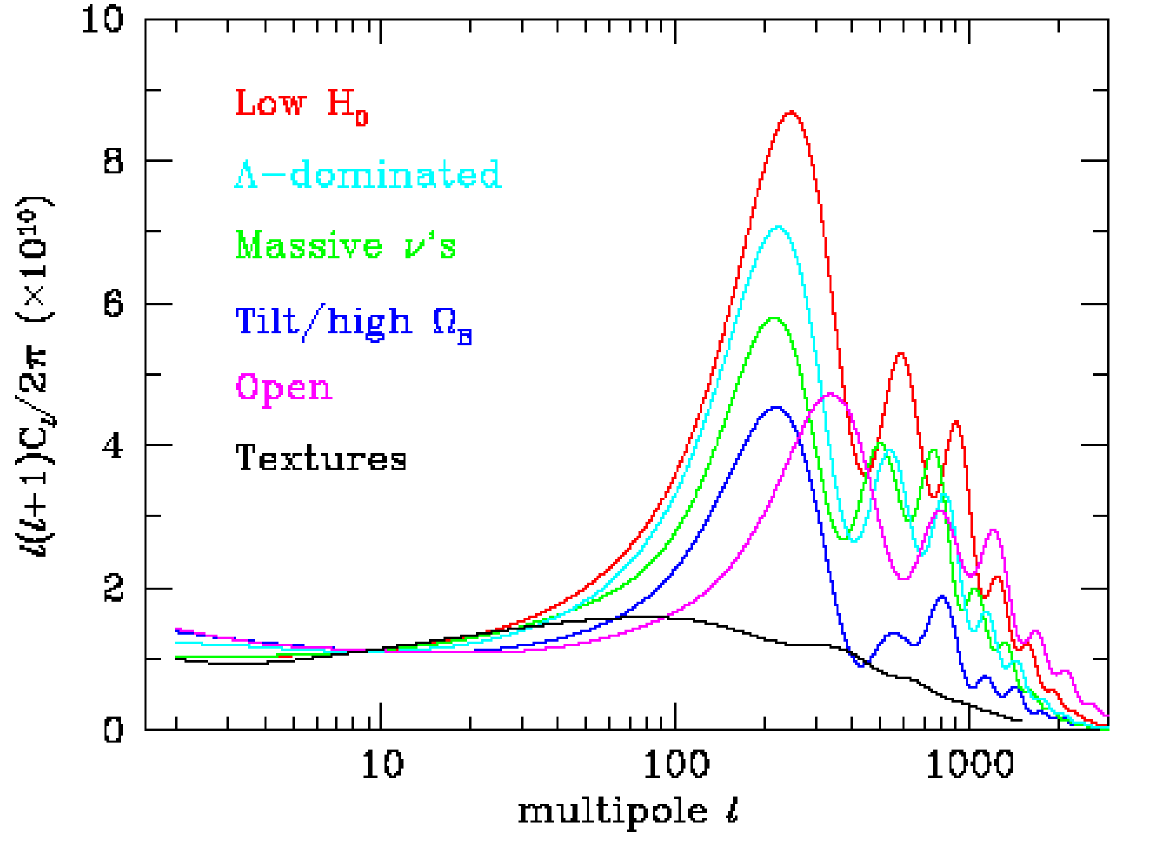
(Value of Q_{rms} predicted by the measured higher order moments of the power spectrum when a power law is assumed **Hinshaw et al. 1996, Gorski et al. 1996**)

Best-fit slope power spectrum of primordial density fluctuations

$n = 1.2 \pm 0.3$



Angular power spectrum dependence on cosmological parameters



- $P(k) = A_s\,(k/k_c)^{n_s}$

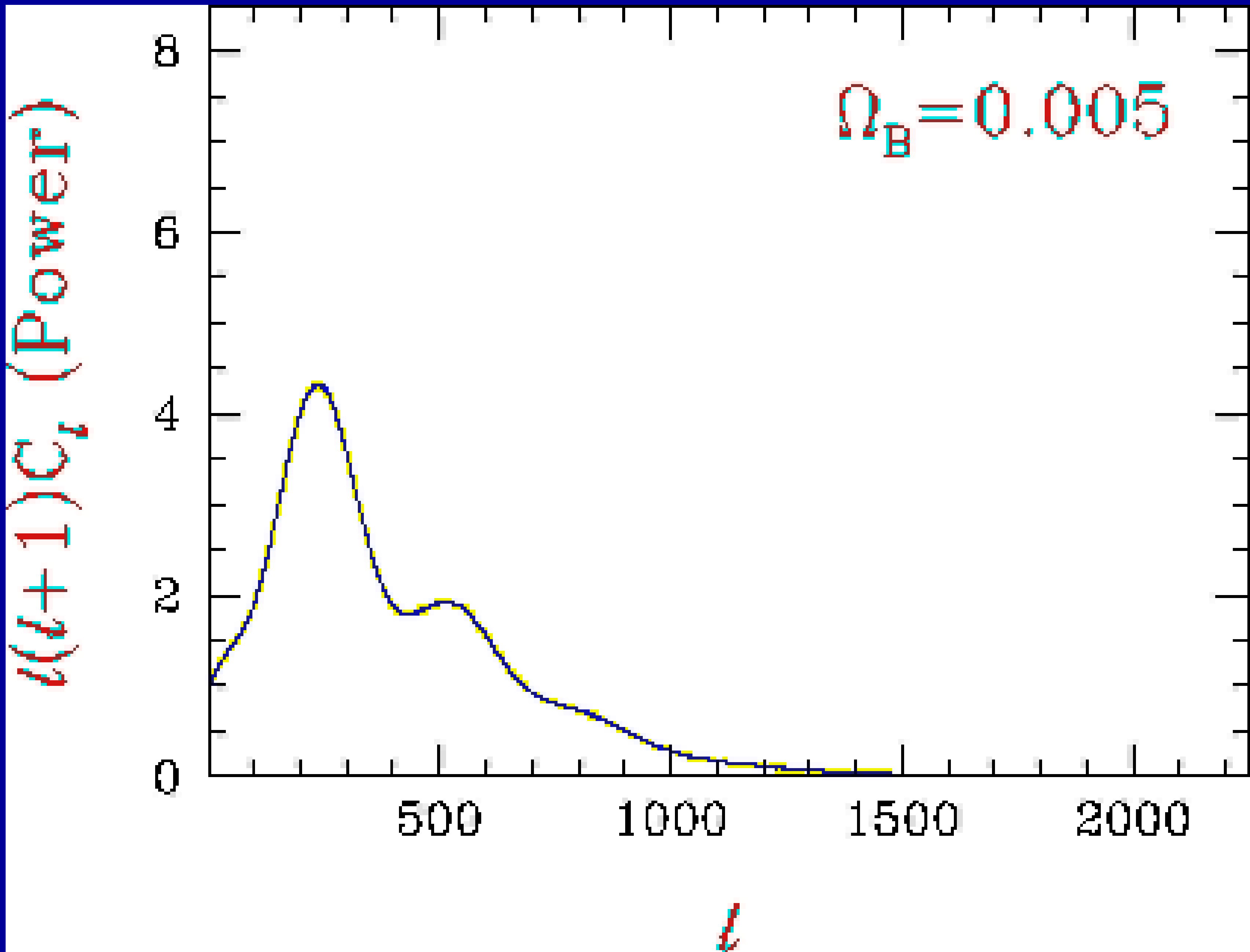
initial fluctuations spectrum

- Different model parameters give different predictions of the temperature angular power spectrum

The parameters

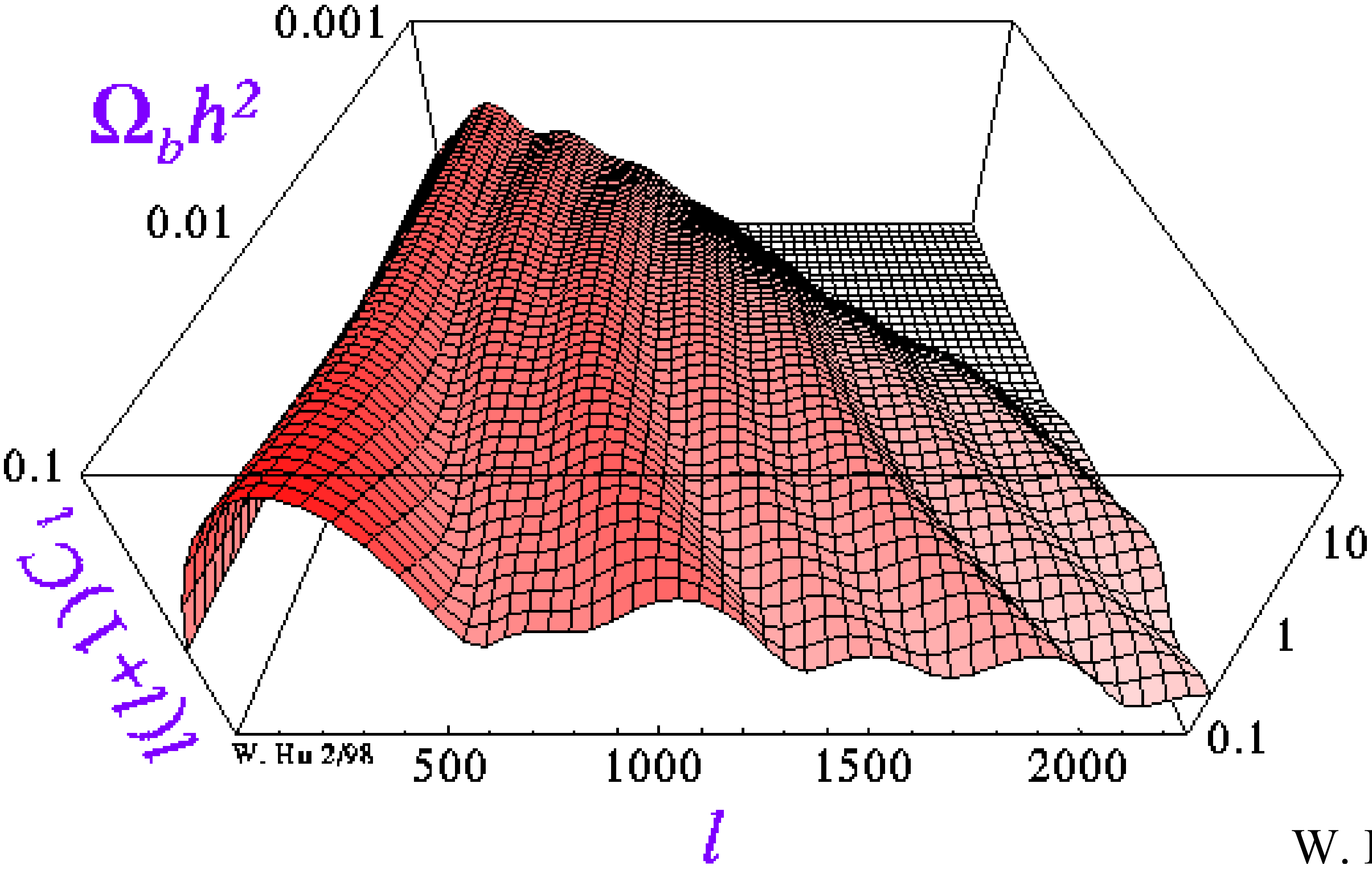
- t_0 age of the Universe
- H_0 Expansion rate at present epoch
- Total matter/energy density: Ω_0 fraction of the critical energy density contributed by all forms of matter and energy at the present epoch
- $\Omega_0 = \rho_{tot} / \rho_{crit} = \Sigma\, \Omega_i$,, $\Omega_i = \rho_i / \rho_{crit}$

  - $\rho_{crit} = 3\, H_0^2 / 8\pi\, G \cong 1.88 h^2 \times 10^{-29}\ gcm^{-3}$
  - ρ_b barionic density
  - ρ_ν neutrino density
  - ρ_{dm} cold dark matter density
  - ρ_m matter density $(\rho_b + \rho_\nu + {}_{dm})$
  - ρ_γ photon energy density
  - ρ_Λ vacuum energy density ---> $\Lambda / 3\, H_0^2$
  - $\rho_{tot} = \rho_m + \rho_\gamma + \rho_\Lambda$



$\Omega_B = 0.005$
$\ell(\ell+1)C_\ell$ (Power)
ℓ
0
2
4
6
8
500
1000
1500
2000

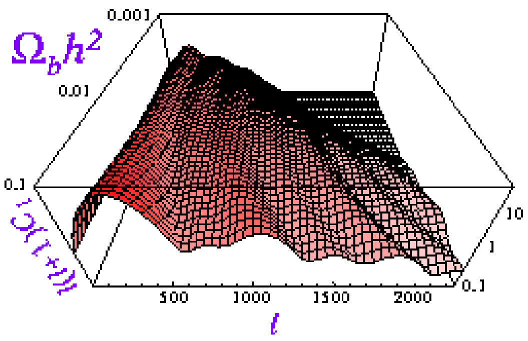
Baryon–Photon Ratio
in the CMB



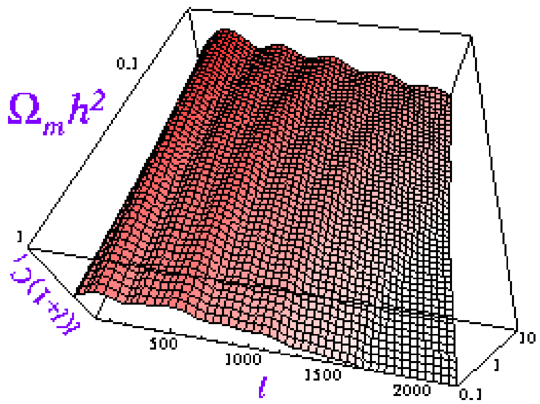
W. Hu

Cosmological Parameters in the CMB

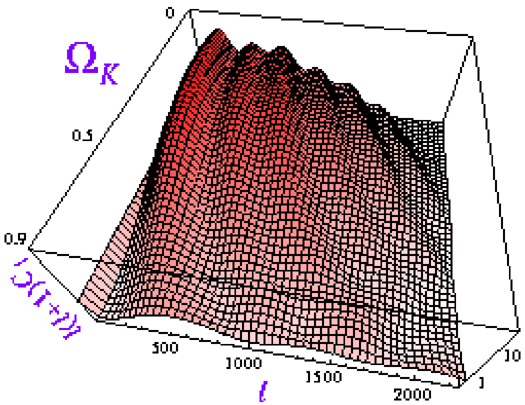
Baryon–Photon Ratio



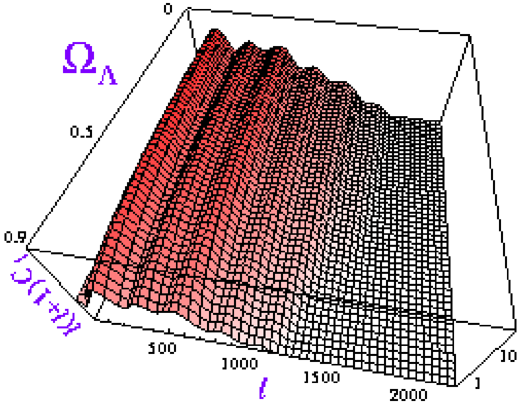
Matter–Radiation Ratio



Curvature



Cosmological Constant



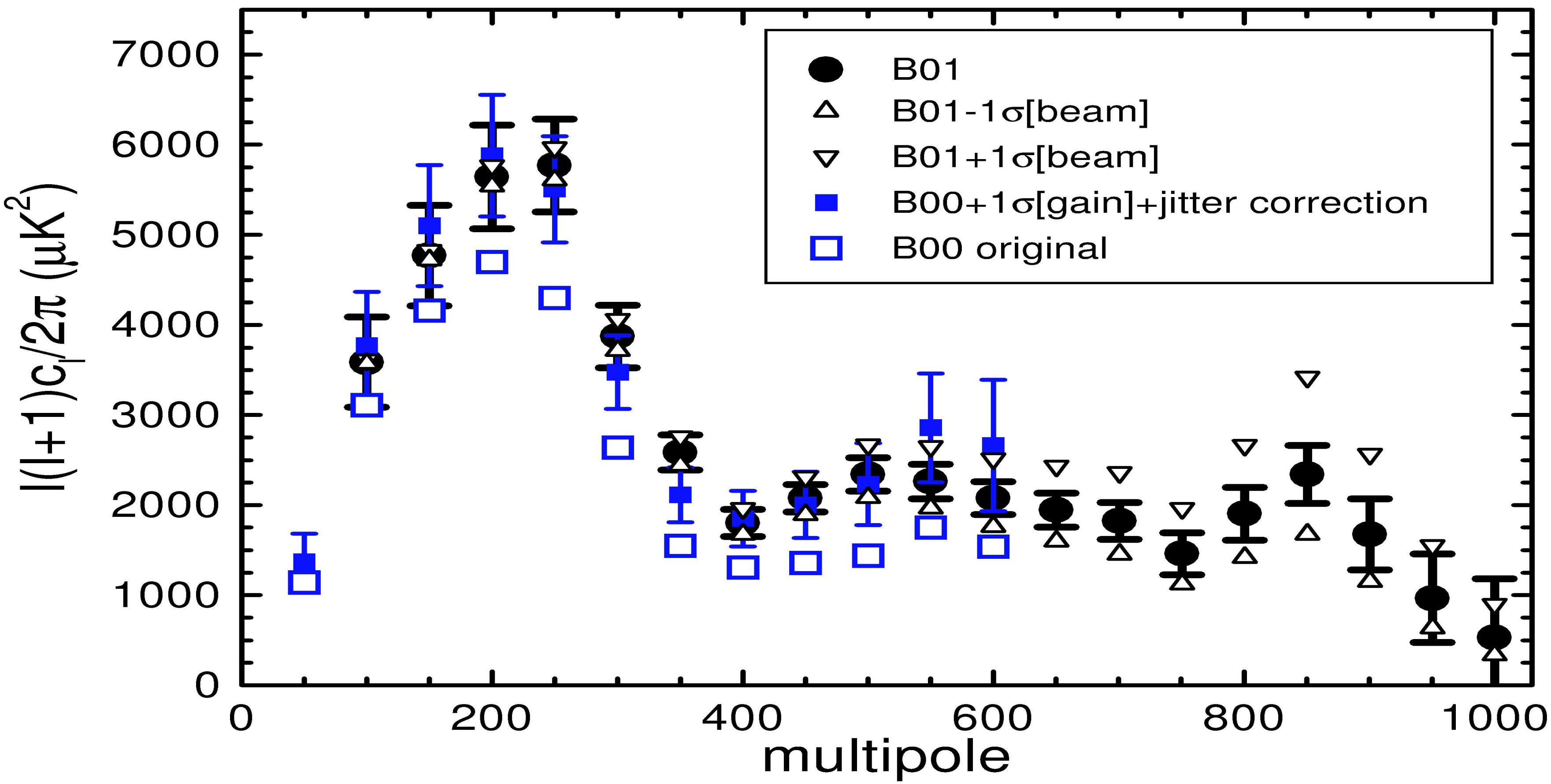
W.Hu 2/98

CMB experiments (after COBE)

Balloon-borne experiments

- ARGO
- MAX
- MSAM
- BAM
- QMAP
- BOOMERANG
- MAXIMA
- TOP HAT
- HACME
- ACE
- ARCHEOPS
- BEAST
- .

BOOMERANG: Analysis of the complete data set
Netterfield et al. 2001, de Bernardis et al. 2001

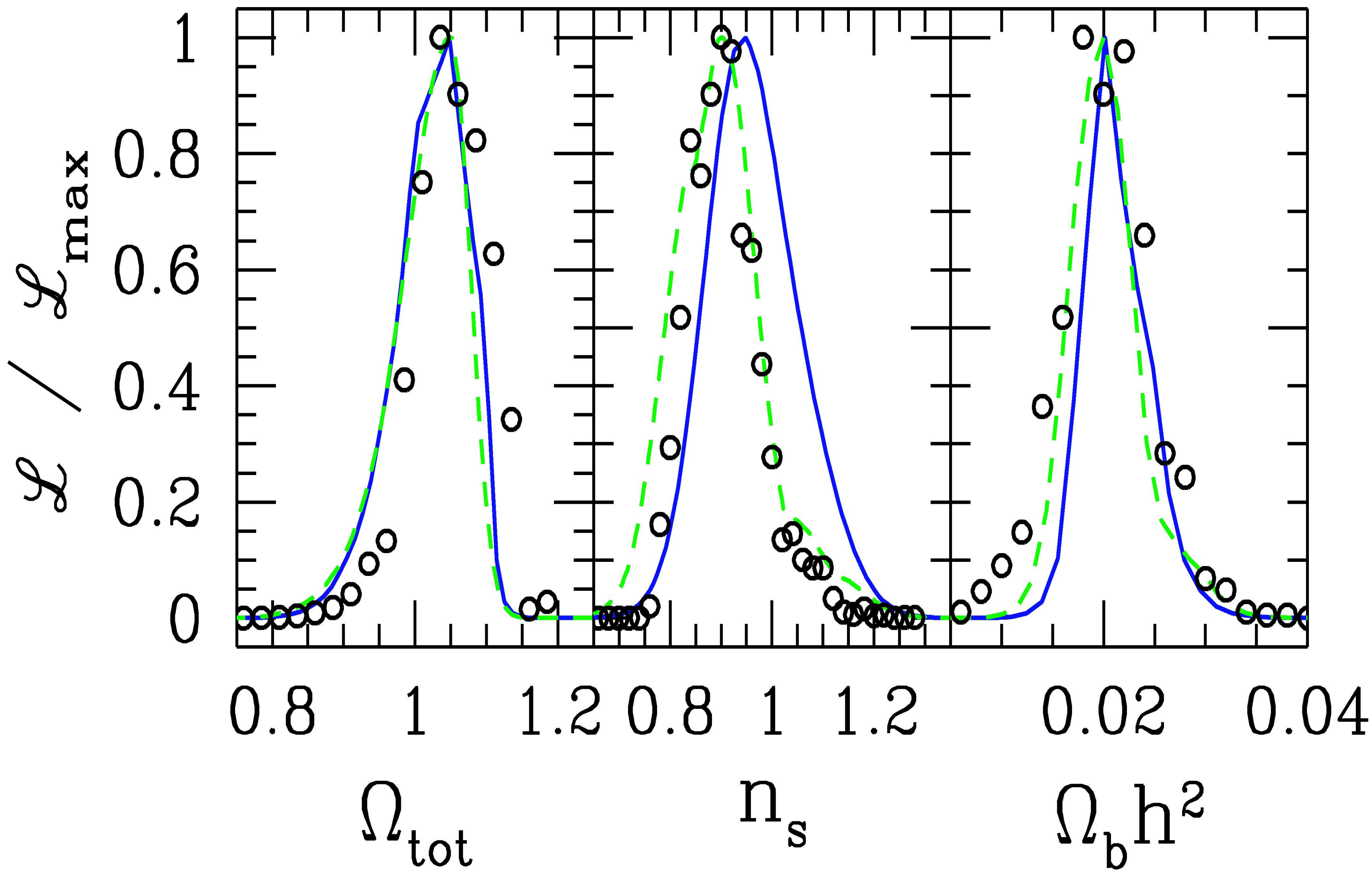


High Precision Cosmology

- High quality data
  - better control of systematics
- Methodology
  - Models and priors
  - Bayesian analysis
  - Monte Carlo Markov Chains*

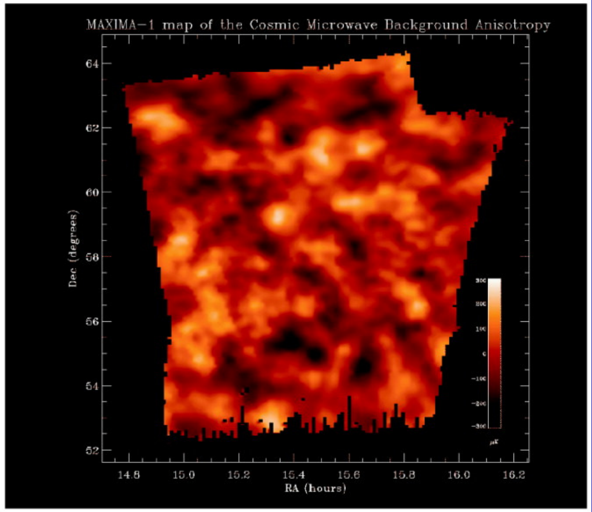
(* see Lewis and Bridle 2002, the appendix
of Tegmark et al. 2004 Phys Rev D 69, 103512,
or Verde et al.)

BOOMERANG results
(de Bernardis et al. 2001, astro-ph/0105296)



MAXIMA

Hanany et al. 2000



- Off-axis Gregorian telescope with a 1.3 m primary mirror mounted on an altitude controlled balloon-borne platform
- Array of 16 bolometric photometers operated at 100 mK
- Observed a region of 124 deg^2 of the sky
- FWHM 10 arcmin at frequencies 150, 240 and 410 GHz
- Scale range $36 < l < 785$
- Calibrator : dipole
- Peak with amplitude $\Delta T_{rms} = 78 \pm 6\ \mu K$ at $l = 220$
- Amplitude varying between 40 and 50 μK for $400 < l < 785$

Total matter/energy density from CMB anisotropies

- $\Omega_0 = 1.02 \pm 0.06$,   BOOMERANG

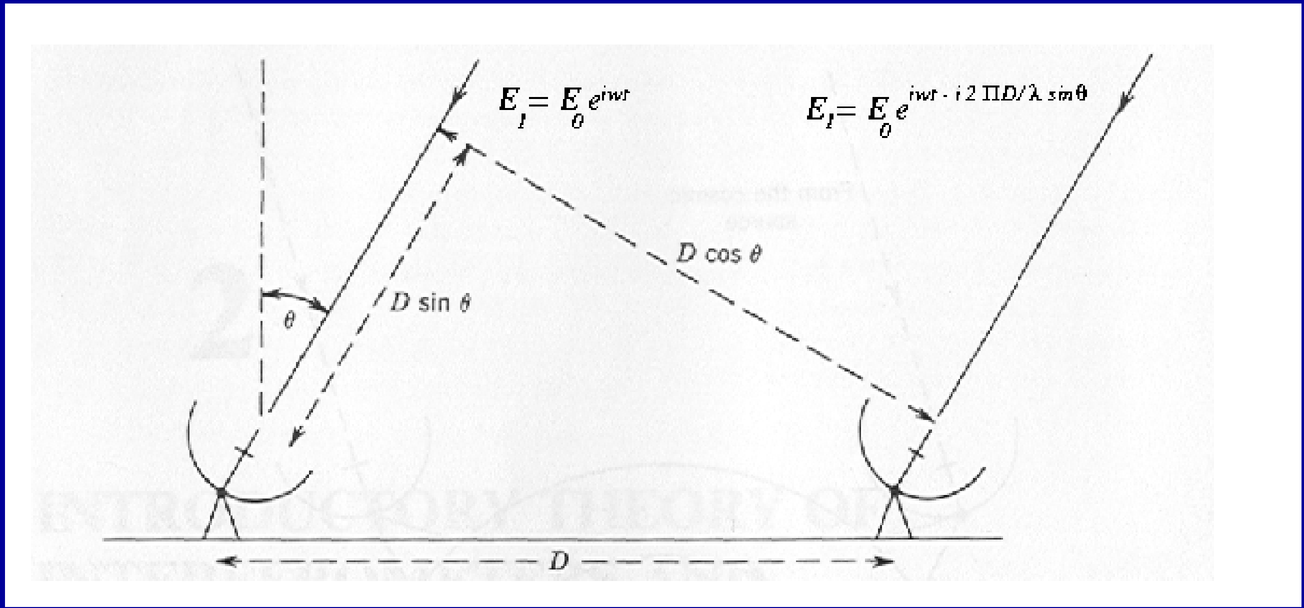
de Bernardis et al. 2001 astro-ph/0105296

- $\Omega_0 = 0.98 \pm 0.14$ MAXIMA

Abroe et al. 2001, astro-ph/0111010

Interferometry

- CAT
- Tenerife 33 GHz
- Very Small Array
- CBI
- DASI
- OVRO
- VLA
- Ryle
- ATCA
- BIMA
- ACBAR



DASI in Antarctica

Total matter/energy density from CMB anisotropies

- $\Omega_0 = 1.02 \pm 0.06$, BOOMERANG

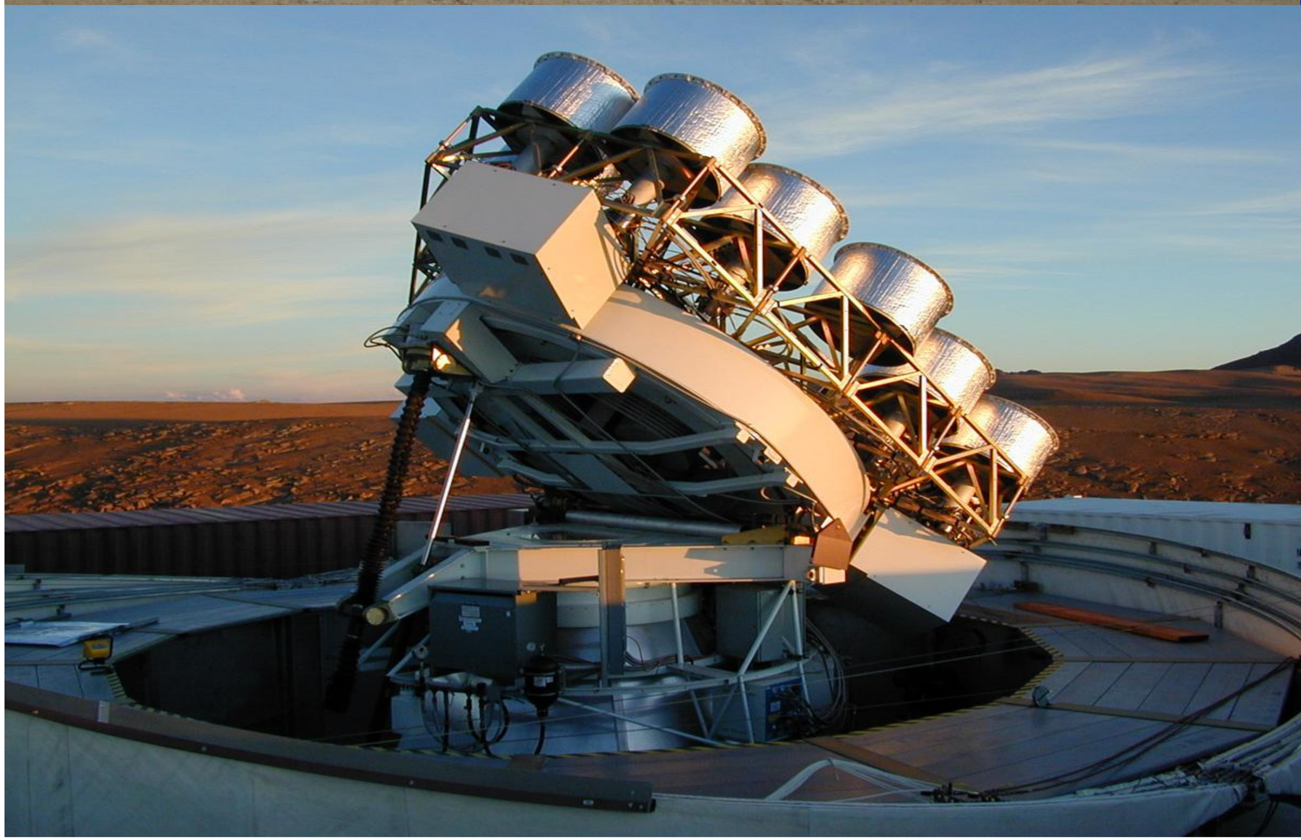
  de Bernardis et al. 2001 astro-ph/0105296

- $\Omega_0 = 0.98 \pm 0.14$ MAXIMA

  Abroe et al. 2001, astro-ph/0111010

- $\Omega_0 = 1.04 \pm 0.06$ DASI

  Pryke et al. 2001, astro-ph/0104490



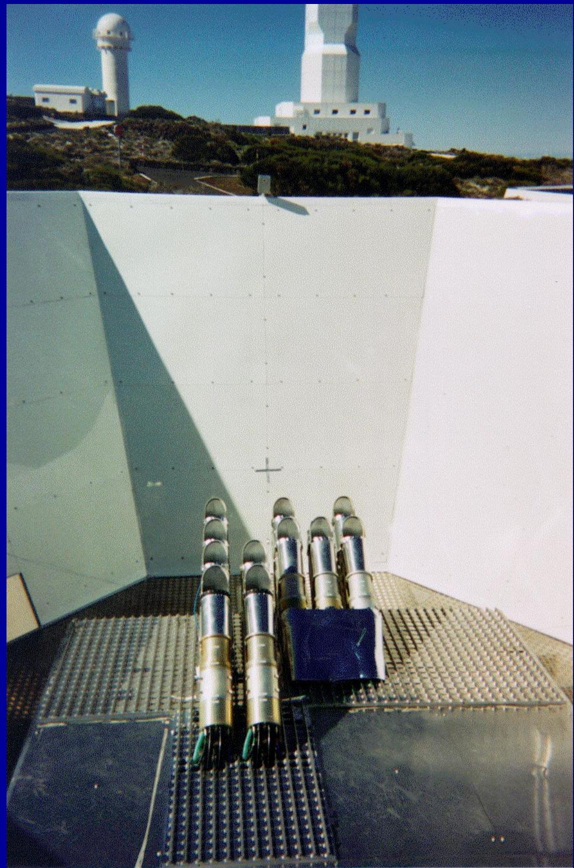
Cosmic Background Imager

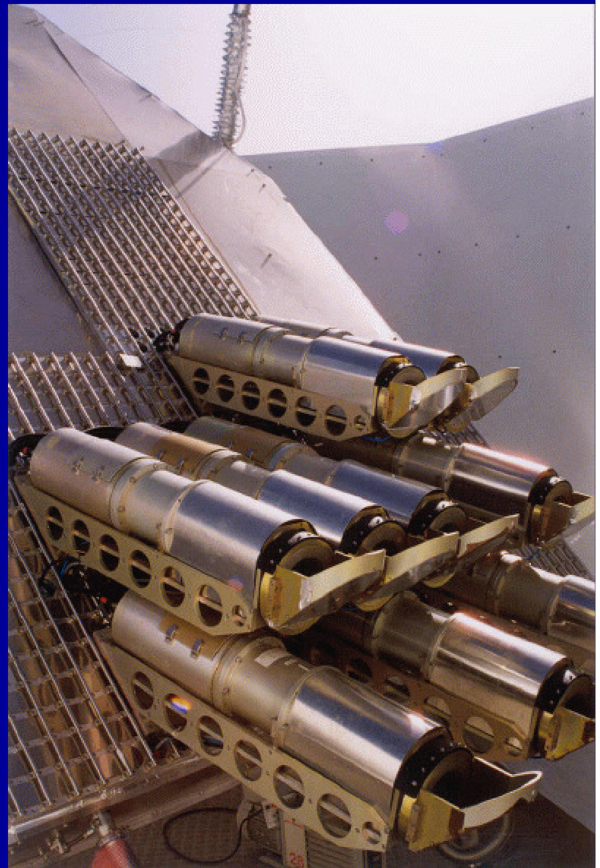
CBI Site at 5080m altitude in northern Chile

Very Small Array (VSA)

- Array of 14 conical horn antennas located at Tenerife
- HEMT based receivers working in the range 26 - 36 GHz
- Single-channel analogue phase-switched correlator 1.5 GHz bandwidth.
- Horn reflectors mounted on a tip table. Close packing
- Compact configuration

  FoV 4.5 degrees. Resolution element : 15 arcmin.





The Very Small Array

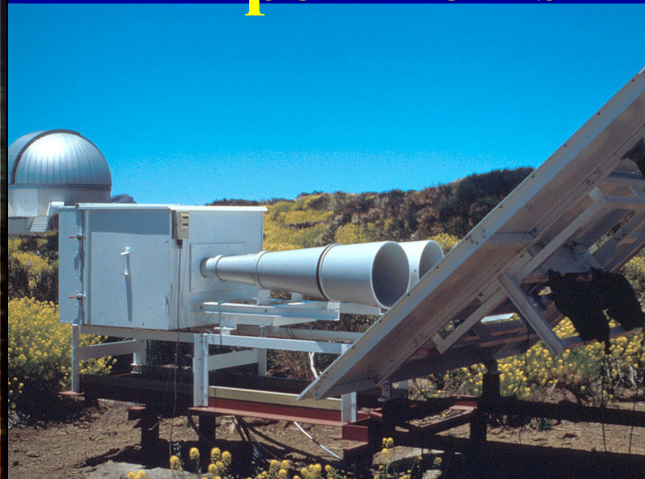
Extended configuration

CAVENDISH ASTROPHYSICS

Jodrell Bank Observatory

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

Tenerife CMB Experiments



The VSA consortium

Cambridge Astrophysics Group

Mike Hobson (PI)	Keith Grainge(PM)	Paul Scott	Anthony Lasenby
Mike Jones	Richard Saunders	Angela Taylor	Rüdiger Kneissl
Klaus Maisinger	Anze Slosar	Richard Savage	Katy Lancaster
Nutan Rajguru	Anna Scaife	Dave Titterington	Guy Pooley
Roger Boysen	Mike Crofts	Liz Waldram	Roger Dace
Tony Brown	Jerry Czeres	Ian Northrop	Clive Shaw

Jodrell Bank Observatory

Richard Davis	Rod Davies	Clive Dickinson
Bob Watson	Kieran Cleary	Richard Battye
Colin Baines	Jason Marshall	Eddie Blackhurst
Althea Wilkinson	J. P. Leahy	Yasser Hafez

Instituto de Astrofísica de Canarias

Rafa Rebolo	Jose Alberto Rubiño	Carlos Gutierrez	Ricardo Genova	Jose Luis Salazar Carmen Padilla

The Antennas

- Efficient, unblocked with a clean aperture
- Compact for close packing (small aperture)
- Low cross-coupling
- Can track independently (fringe rate tracking)

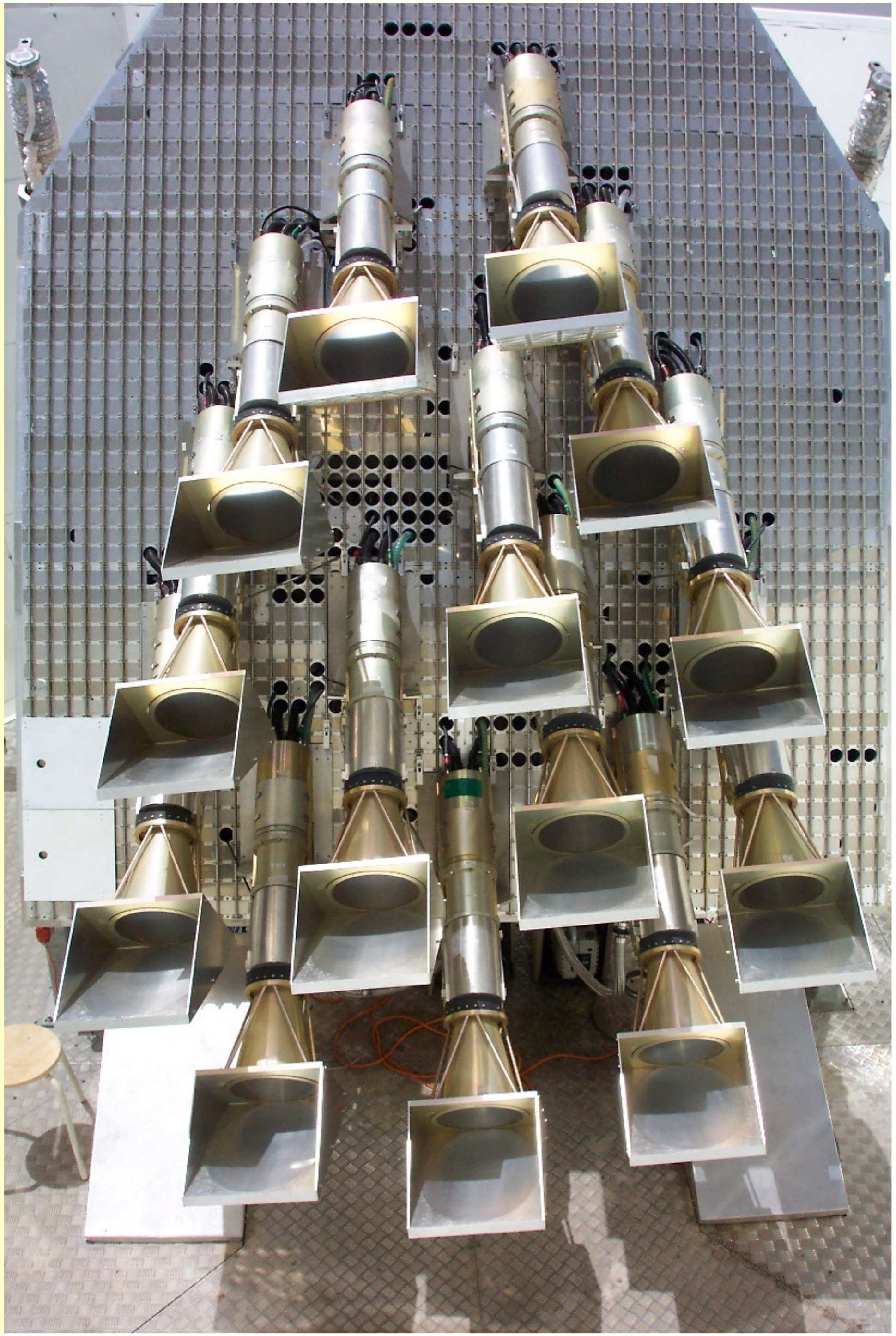
These conditions are met by conical horn reflector antennas (CHRA).

The 90º reflector gives the antennas a periscope-like property so they can be close packed like organ pipes.

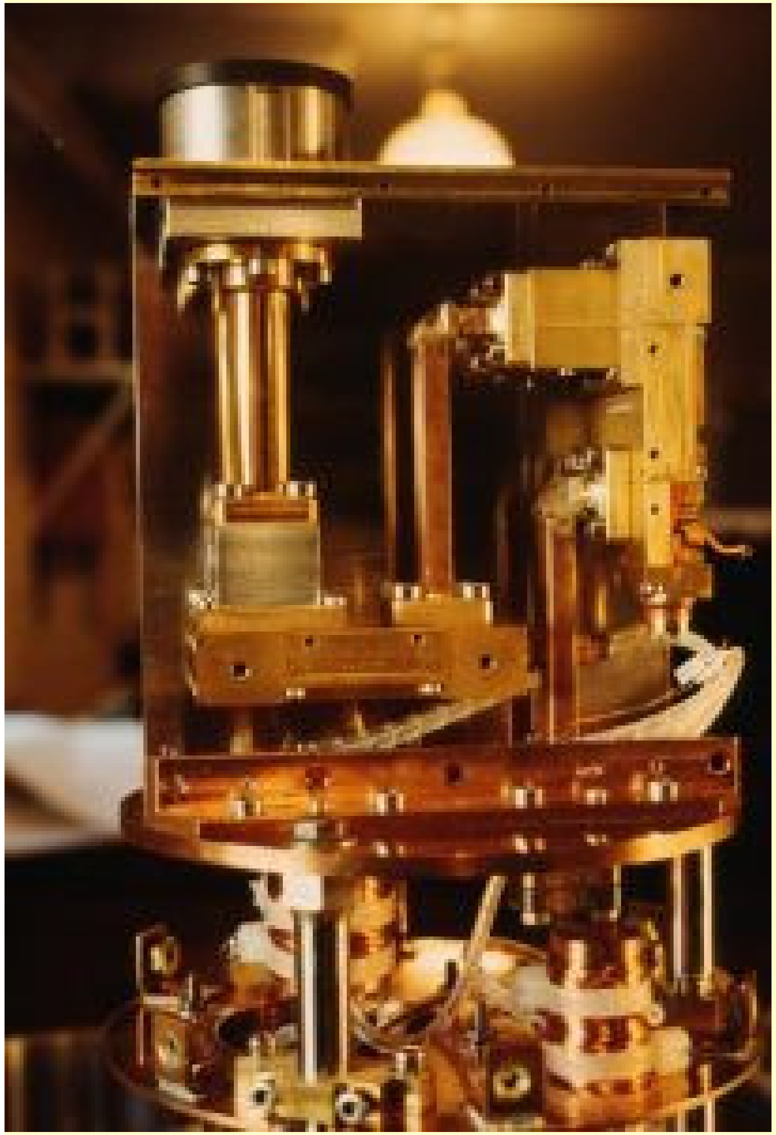
This can be rotated to give one dimension of independent tracking.

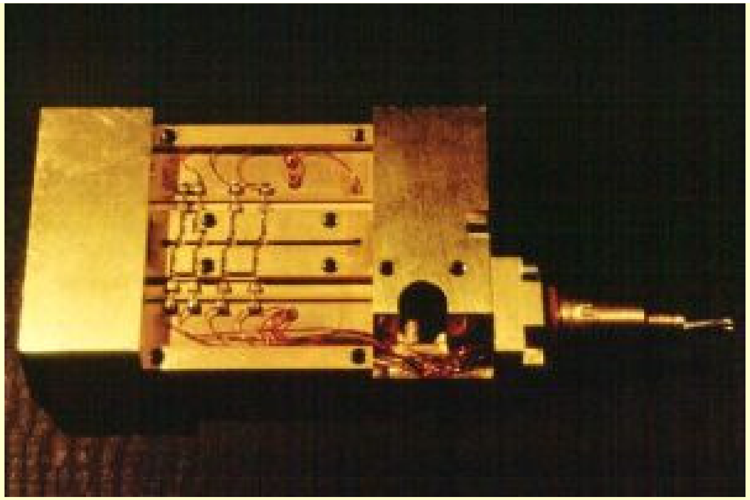
Side blinders are required to block cross Coupling

Primary beam 2 degrees FWHM , Synthetized beam approx. 11 arcmin



The Receivers





The amplifiers are based on the 26-36 GHz Pospieszalski NRAO design were built and modified by Eddie Blackhurst at the Jodrell Bank Observatory, and use unpassivated InP HEMTs from Hughes and Fujitsu.

The bias supplies are fed from a battery pack to give a low noise protected voltage free from switch transients which can cause damage to the HEMTs.

Each antenna has a 4-stage (Hughes) and a 2-stage (Fijitsu) amps. Bias conditions can be set individually for each transistor to optimize sensitivity.

Noise temperatures of 25 K (including horn) are achieved across the band which is flat to 1dB.

CMB interferometry

- ✓ CMB anisotropies in small fields

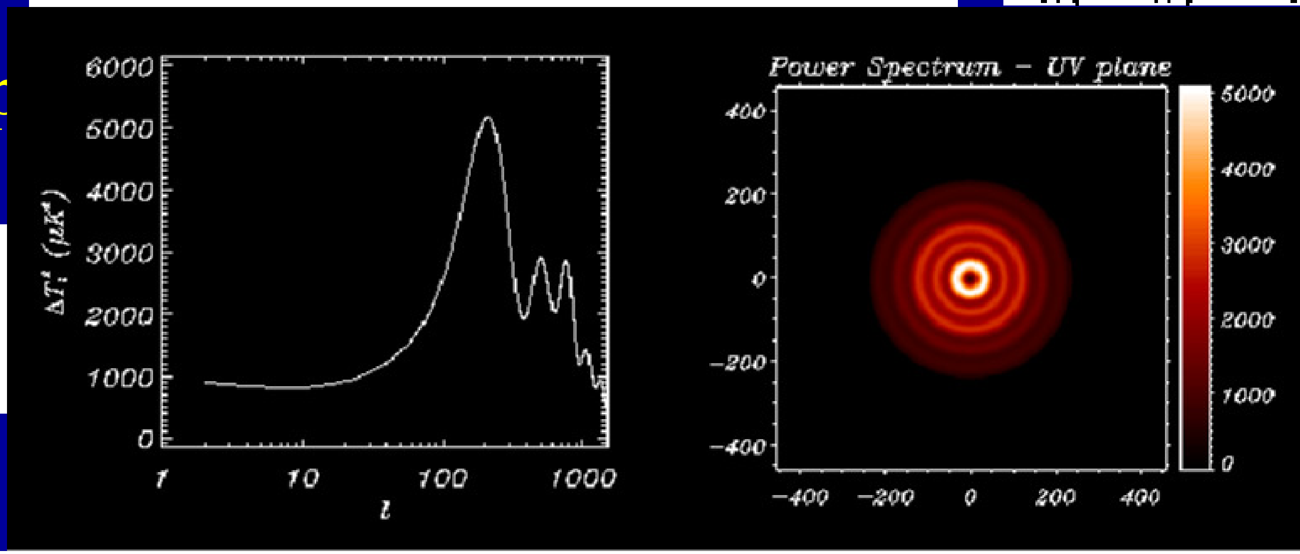
$$\frac{\Delta T}{T_0}(\vec{x}) = \sum_{\ell m} a_{\ell m} Y_{\ell m} \approx \int a(\vec{u}) e^{2\pi i \vec{u}\cdot\vec{x}} d^2\vec{u}$$

u≈ℓ/(2π)

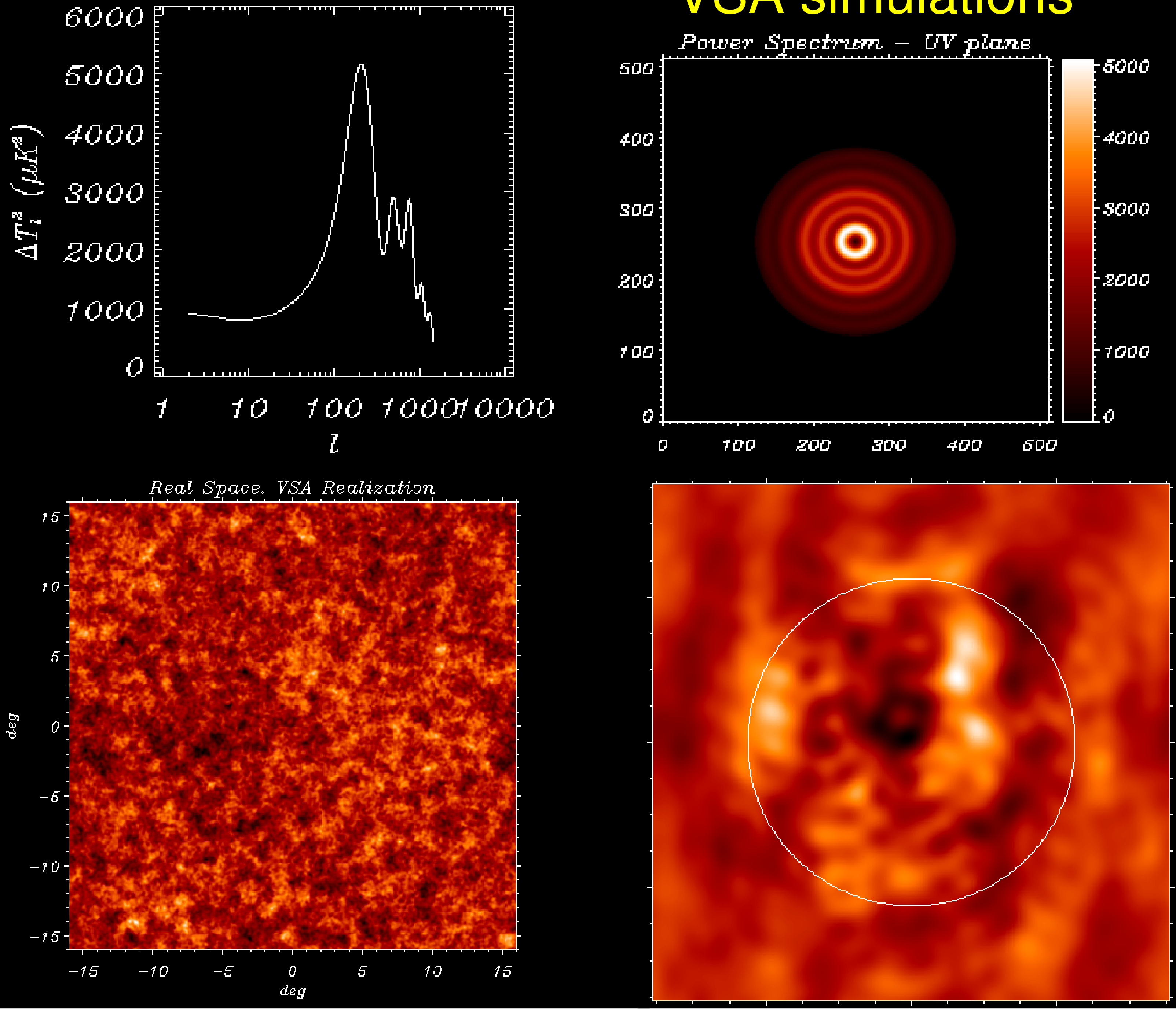
- ✓ Statistics:

$$< a(\vec{u}) >= 0 \qquad < a^*(\vec{u}) a(\vec{u}') >= S(u)\delta^{(2)}(\vec{u}-\vec{u}'), \qquad a(-\vec{u}) = a^*(\vec{u})$$

- ✓ Power sp

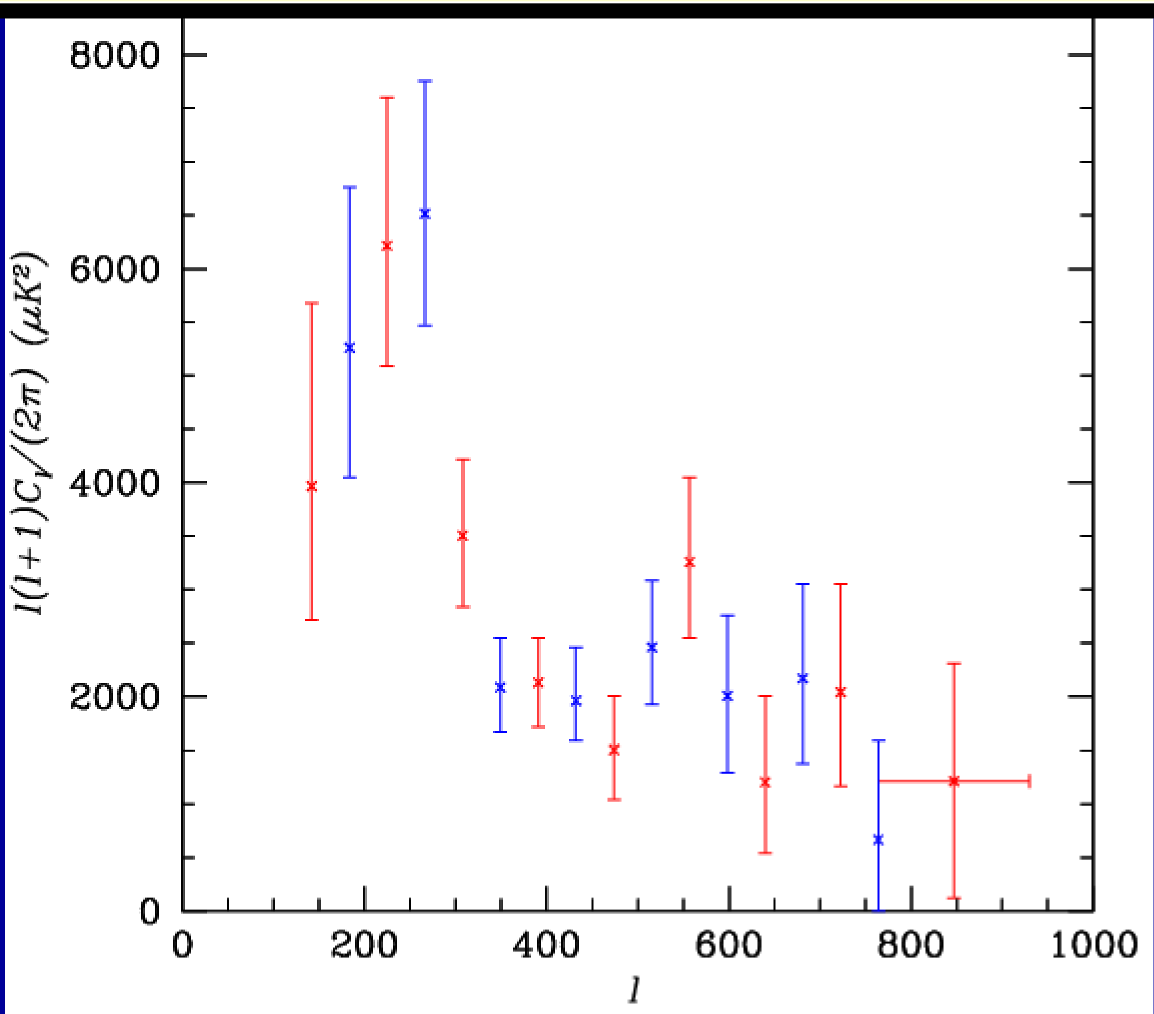


VSA simulations



First VSA angular power spectrum (compact configuration)

Scott et al. astro-ph/0205380
MNRAS 341, 1076 (2003)

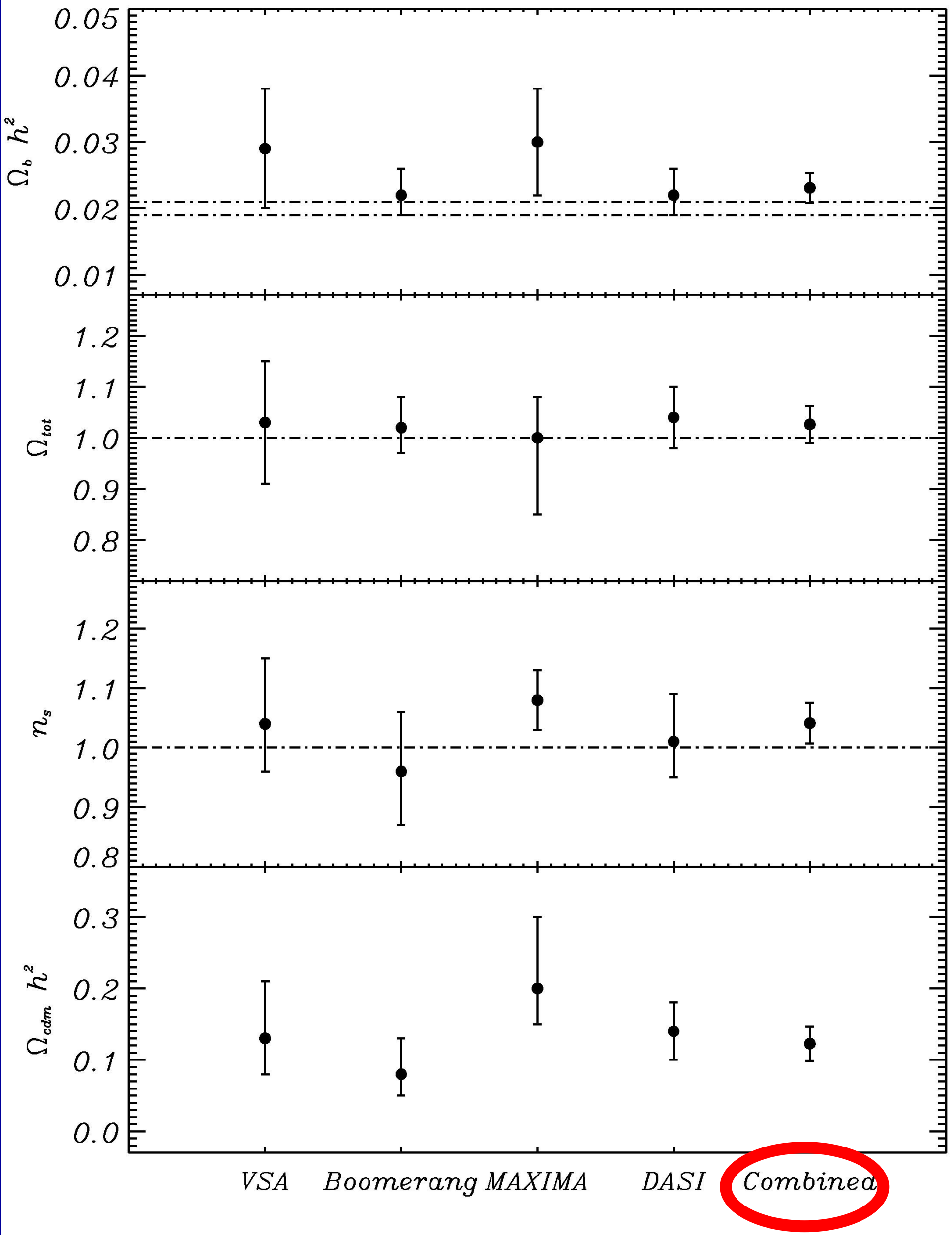


$\Omega_b\ h^2$

Ωtot

n_s

$\Omega_{cdm}\ h^2$



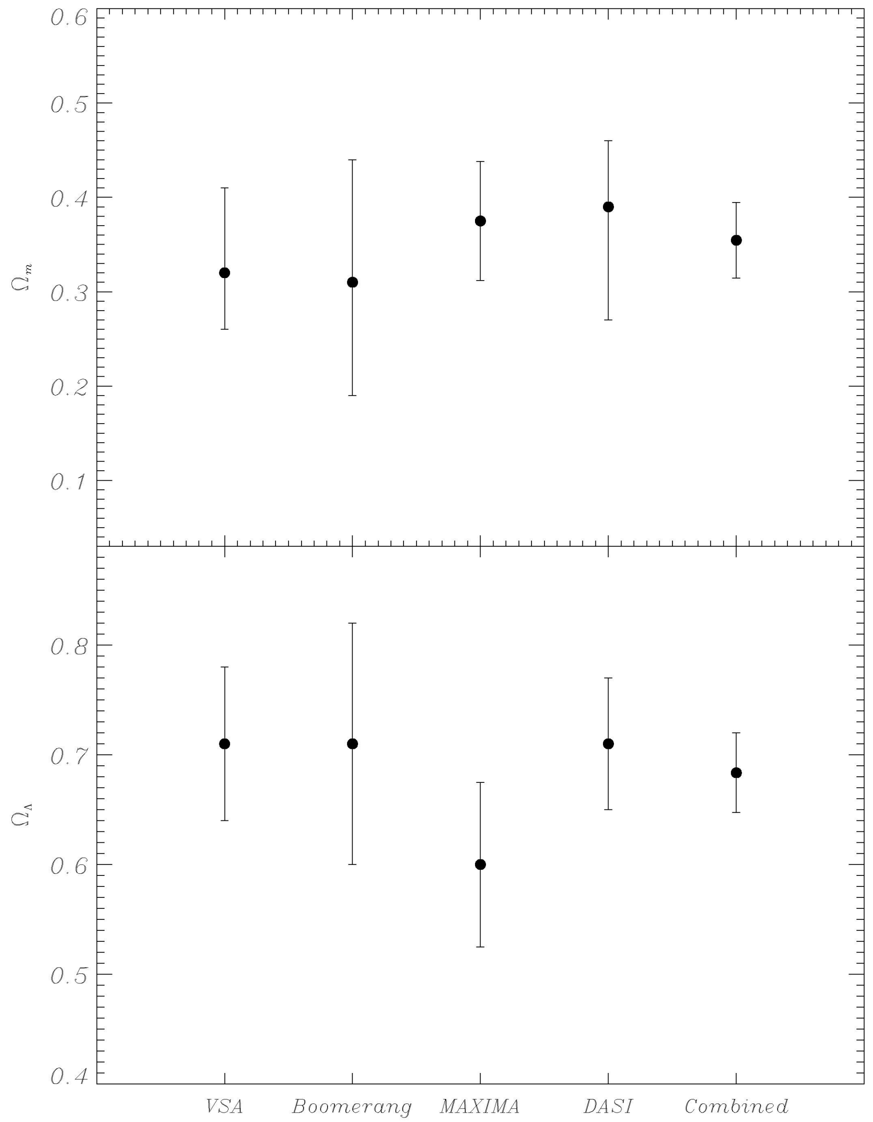
CMB constraints on cosmological parameters

(pre-WMAP Data)

Rubiño-Martín, RRL et al. 2003

Ω_m

Ω_{lambda}

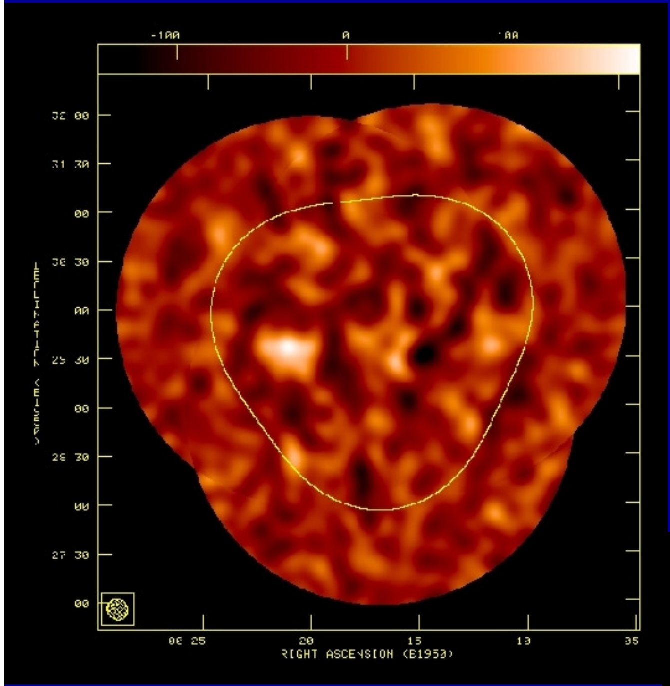


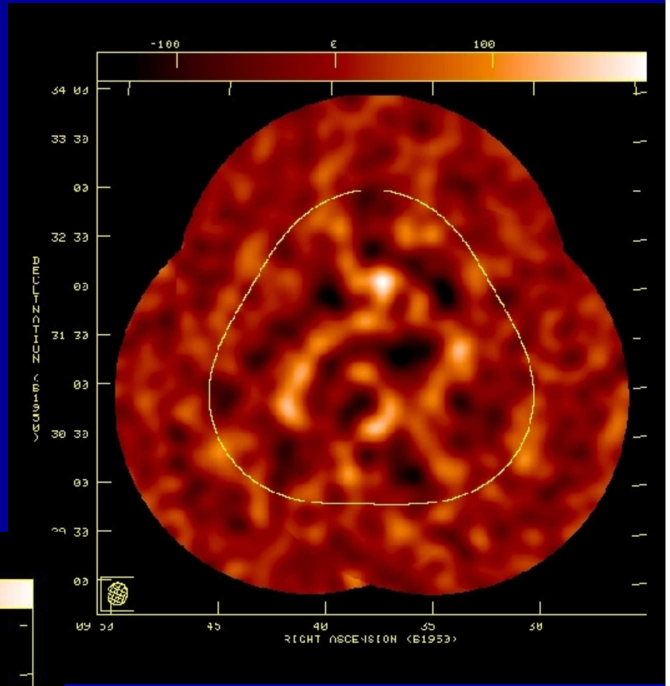
CMB constraints on cosmological parameters

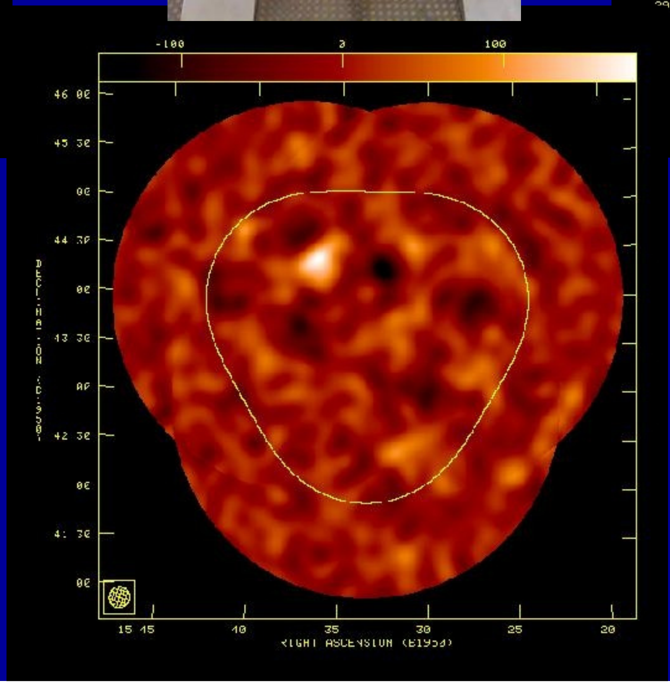
Rubiño-Martín et al. 2003, MNRAS 341, 1084

Extended configuration VSA

(December 2002)

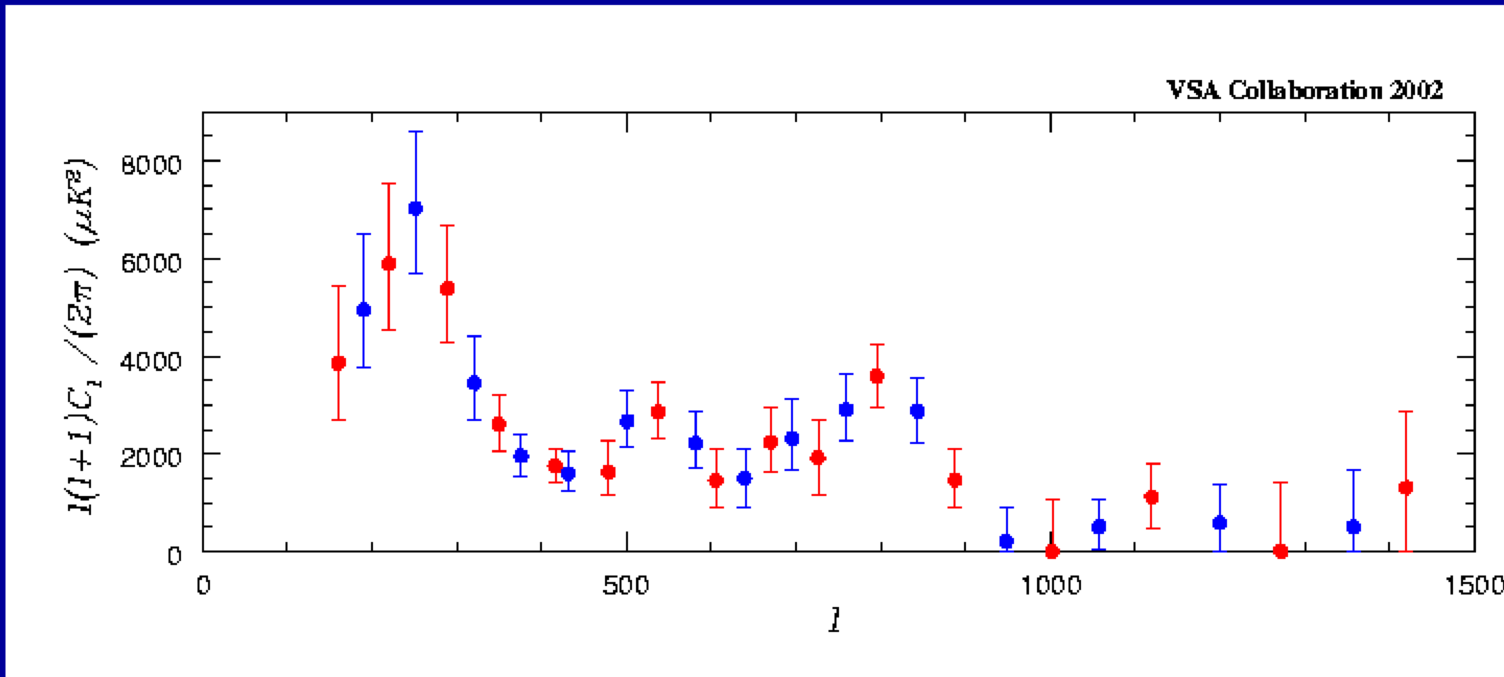






(Grainge et al.2003)

MNRAS 341, L23



$\Omega_b h^2$	0.0219 ±0.0014
Ωtot	0.99± 0.03
n	1.01± 0.05
$\Omega_{cdm} h^2$	0.128± 0.02
h	0.68 ± 0.05
Ω_m	0.32 ± 0.06
Ω_{lambda}	0.66± 0.05
Age	13.6± 0.9 Gyr

(Grainge et al.2003)

Slosar et al.2003

MNRAS 341, L29

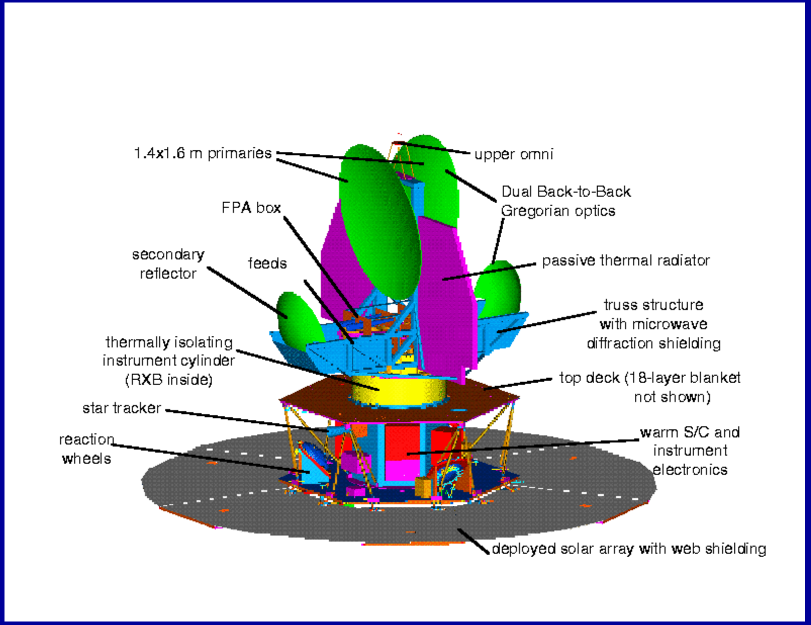
Bayesian analysis using Monte-Carlo Markov Chains.

Priors: huble constant, 2dF and SNIa

o

Microwave Anisotropy Probe (WMAP)

- Halo orbit about L2 Sun-Earth Lagrange point 1.5 million km from Earth
- Lifetime 27 months
- Differential pseudo-correlation with polarization
- Dual Gregorian 1.4 x 1.6 m primary reflector
- Passive radiative cooling to < 95 K
- Frequencies (GHz): 23, 33, 41, 61, 94
- FWHM (deg): .93 .68, .47, .35, .21
- Sensitivity better than 20 μK per 0.3 degree square



WMAP at Lagrange 2 (L2) Point

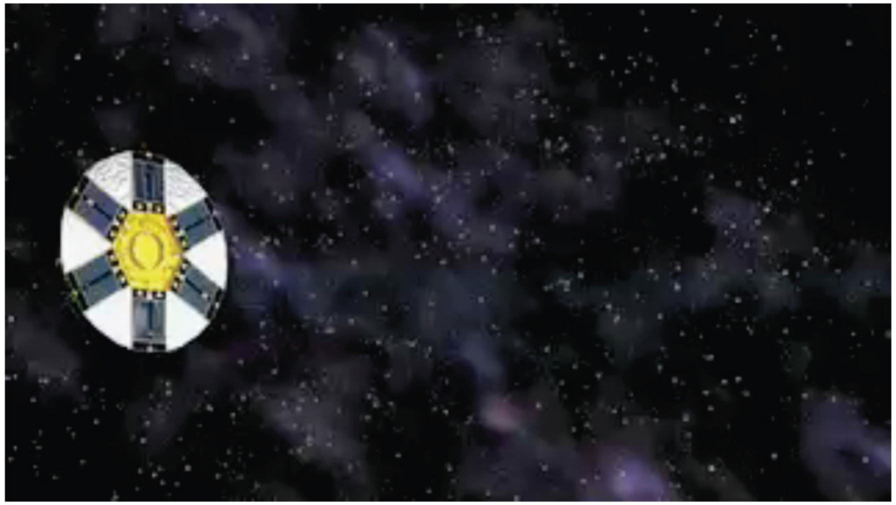
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

**January 2010:
The seven-year
data release**

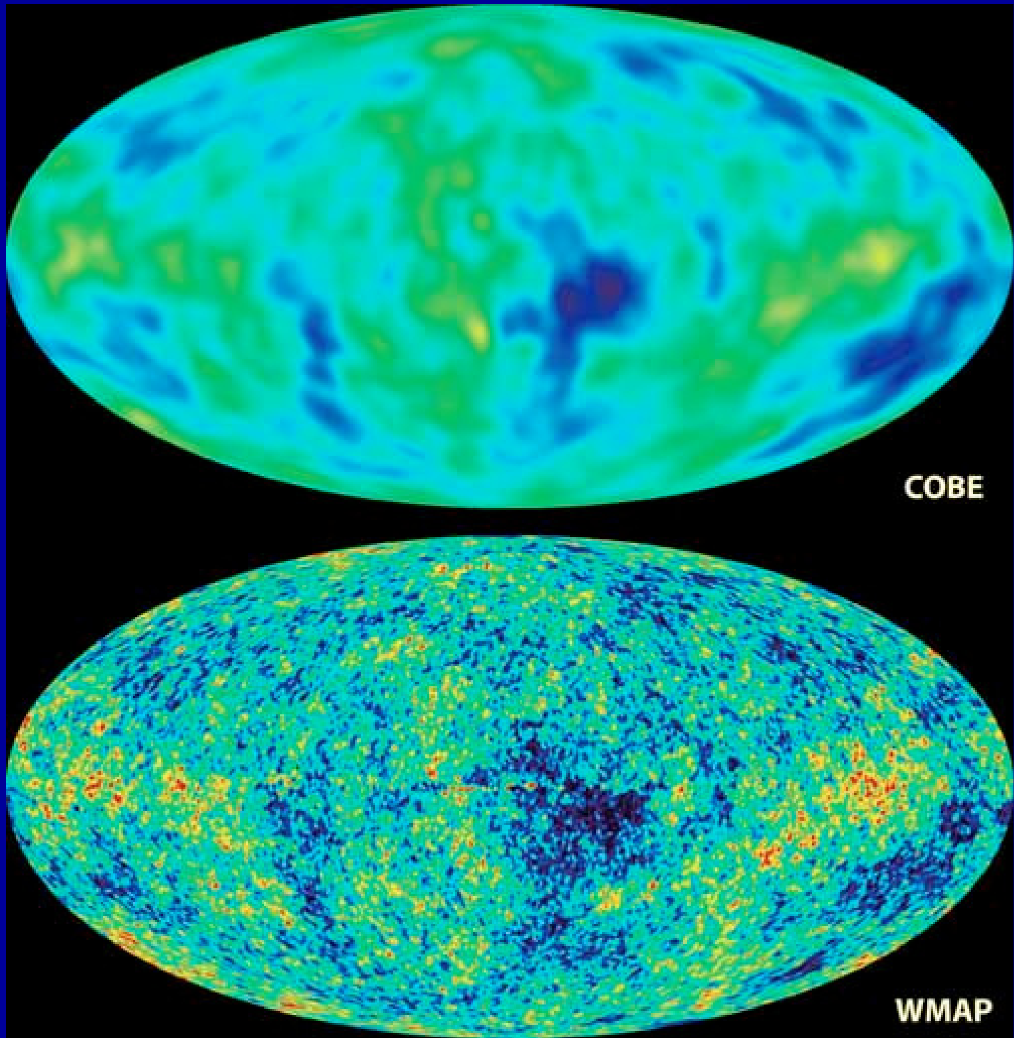


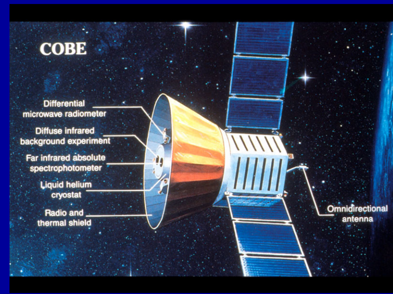
- L2 is 1.6 million kilometers from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

Cosmic Microwave Background

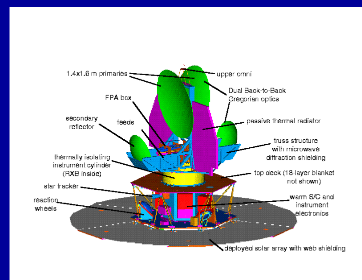
Then

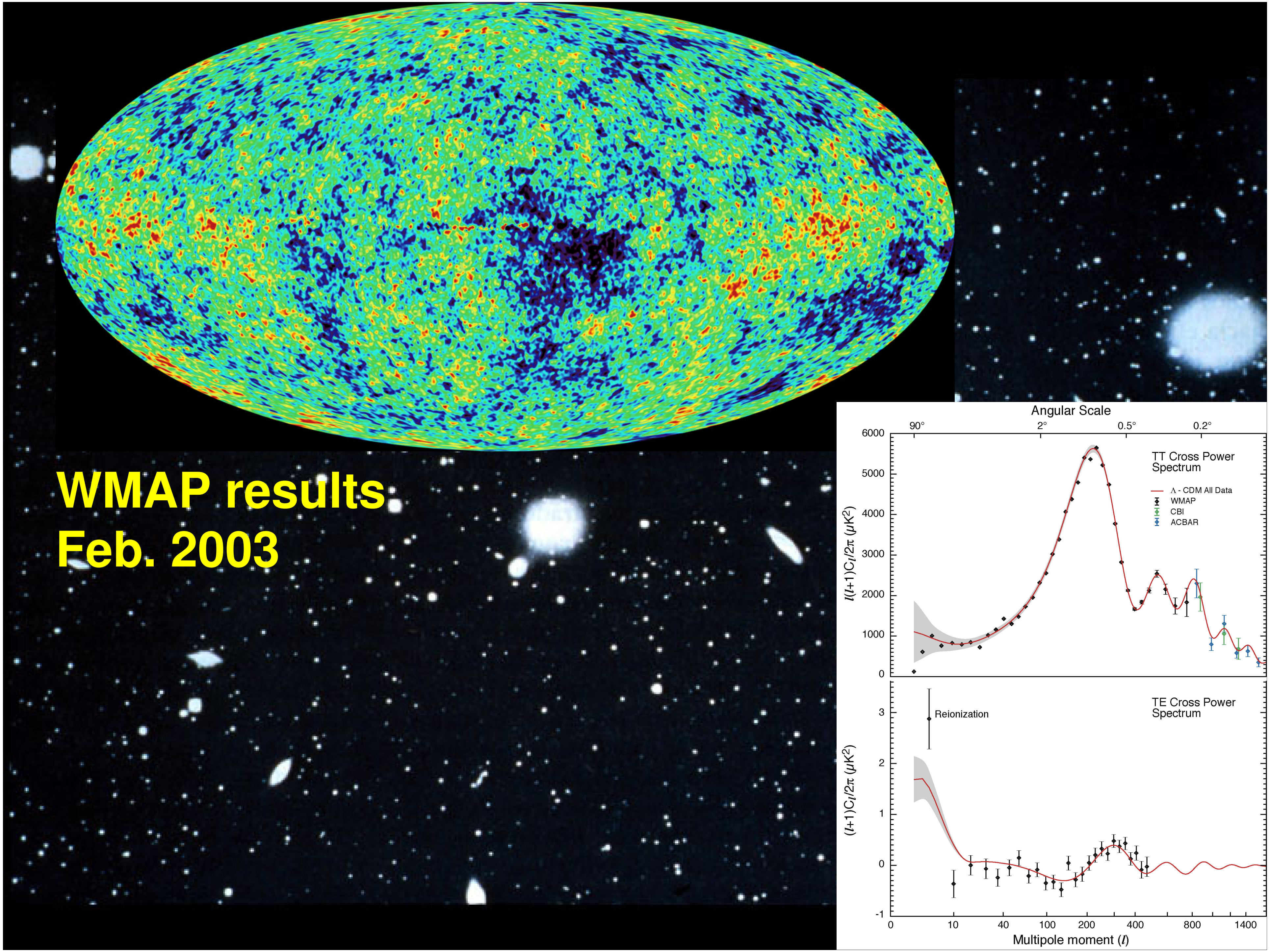
Now





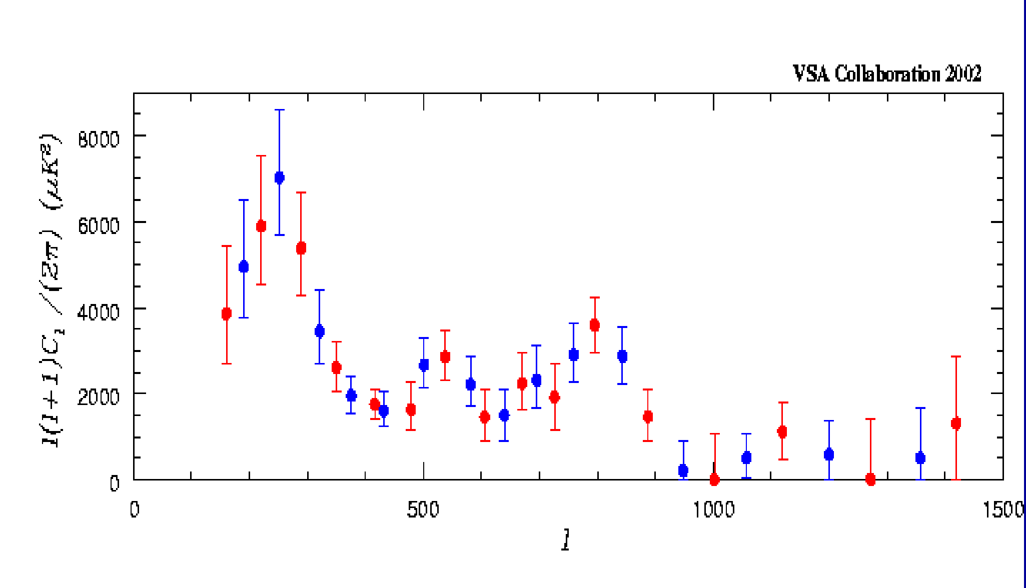
Constrains $\Omega_\Lambda + \Omega_M$

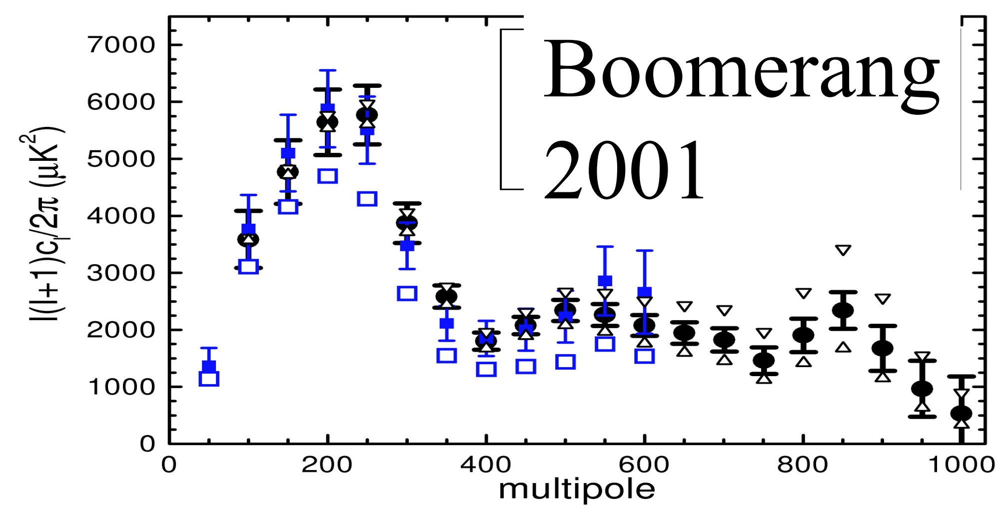



WMAP results
Feb. 2003
Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK²)
6000
5000
4000
3000
2000
1000
0
TE Cross Power Spectrum
Reionization
(l+1)C_l/2π (μK²)
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)

VSA December 2002

WMAP Feb. 2003





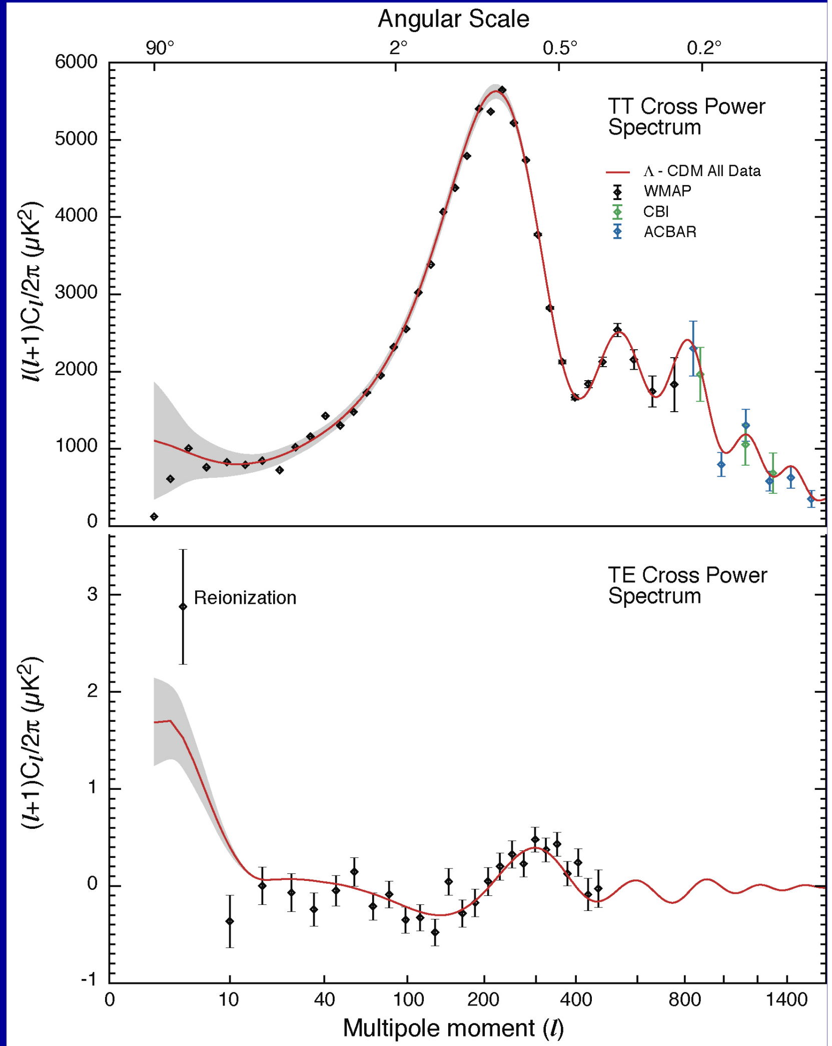
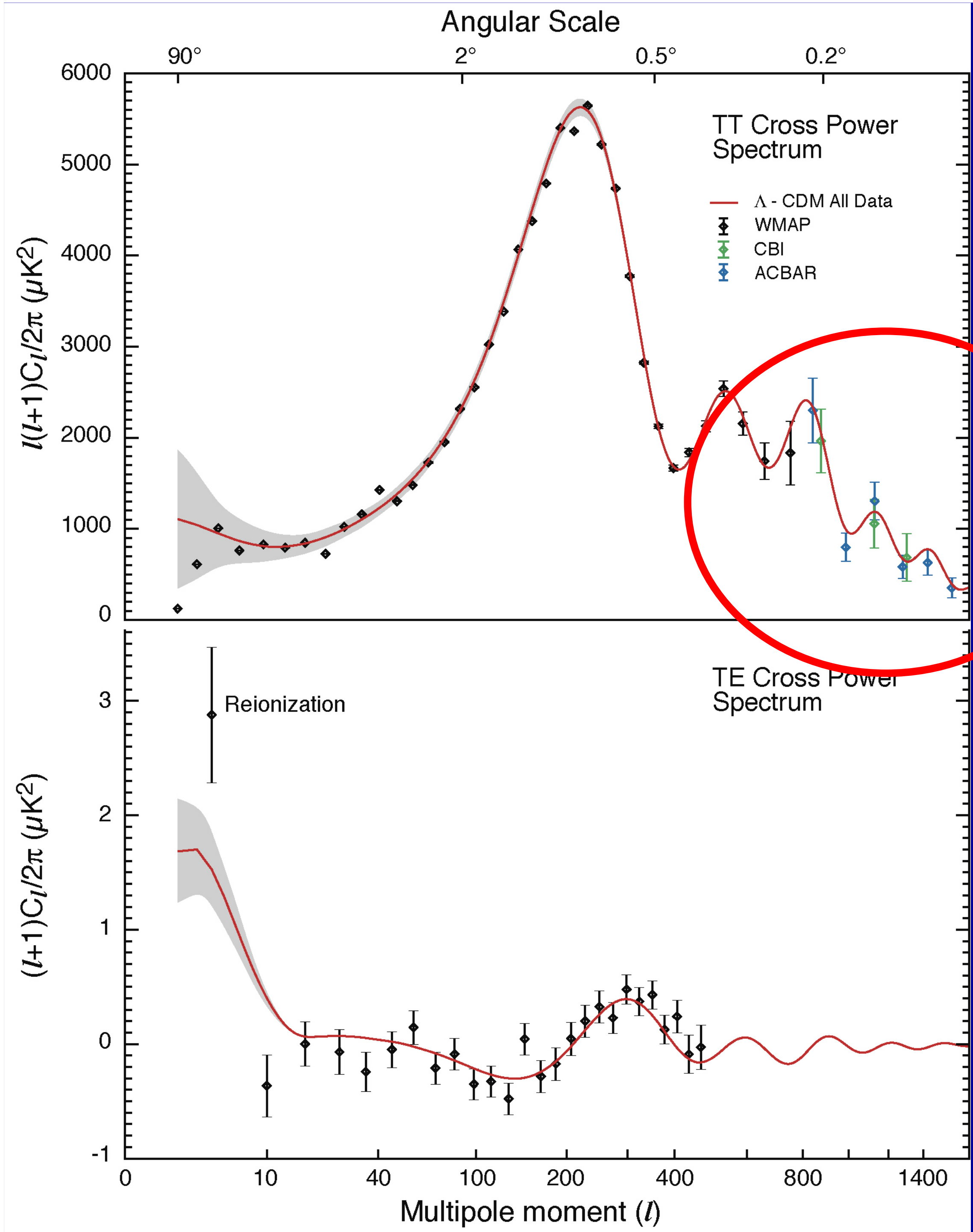


Table 2. Parameter estimates and 68% confidence limits for the standard six-parameter flat ΛCDM model.

1st year

Parameter	WMAP	WMAP+VSA
$\omega_{\rm b}$	$0.0240^{+0.0027}_{-0.0016}$	$0.0234^{+0.0019}_{-0.0014}$
$\omega_{\rm dm}$	$0.117^{+0.018}_{-0.018}$	$0.111^{+0.014}_{-0.016}$
h	$0.73^{+0.10}_{-0.06}$	$0.73^{+0.09}_{-0.05}$
$n_{\rm S}$	$1.00^{+0.09}_{-0.04}$	$0.97^{+0.06}_{-0.03}$
$10^{10}A_{\rm S}$	27^{+9}_{-5}	23^{+7}_{-3}
τ	$0.18^{+0.16}_{-0.08}$	$0.14^{+0.14}_{-0.07}$

$$z_{\rm reion} \approx 92\,(0.03\,h\,\tau\,/\,\Omega_b h^2)^{2/3}\,\Omega_m^{\;1/3}$$

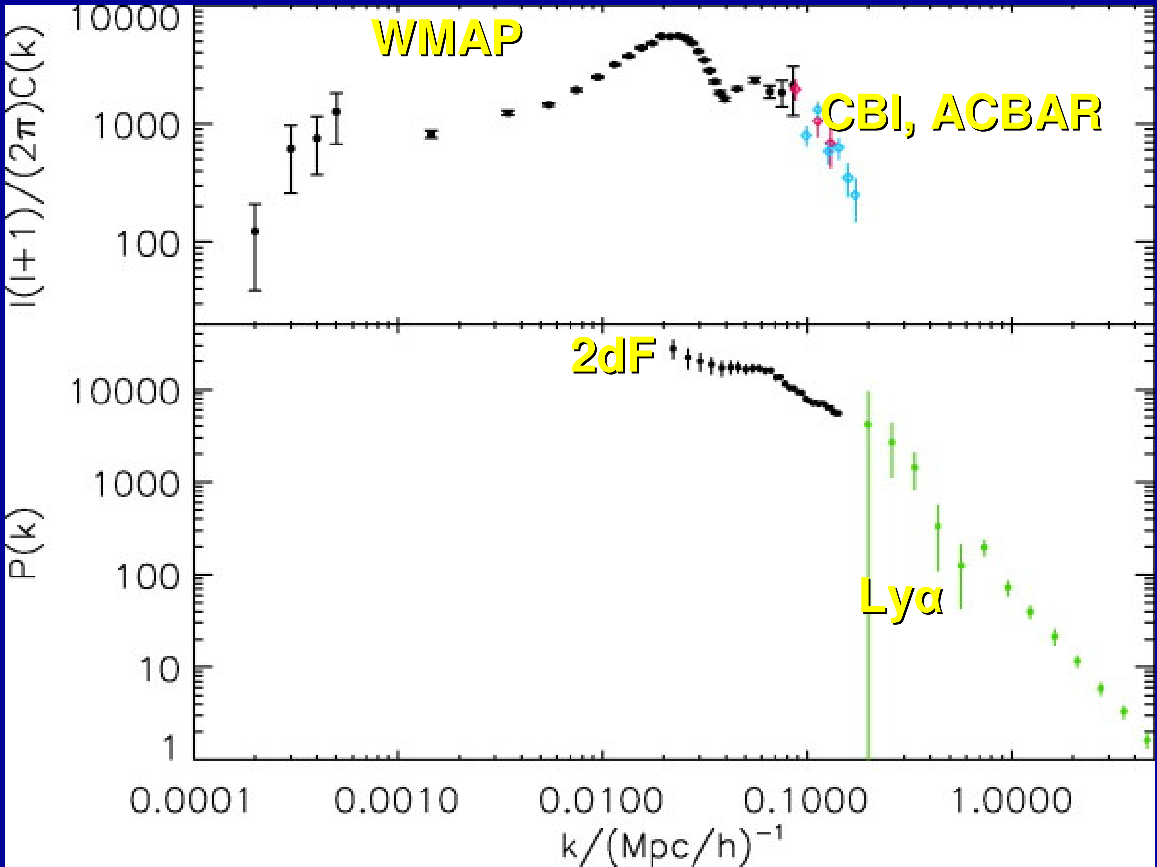


WMAP
CMB power
spectrum

High l multipoles
bring information on :

- Initial spectrum of fluctuations
- Inflationary scenarios
- Neutrino contribution to the matter content of the Universe
- ....

WMAP 1st year data



WMAP data is combined with CMB experiments probing the high-l region of spectrum.
In addition, they also consider information from large scale structure (2dF) and Lyα forest.

$$n_{run} = -0.031 \pm 0.016$$

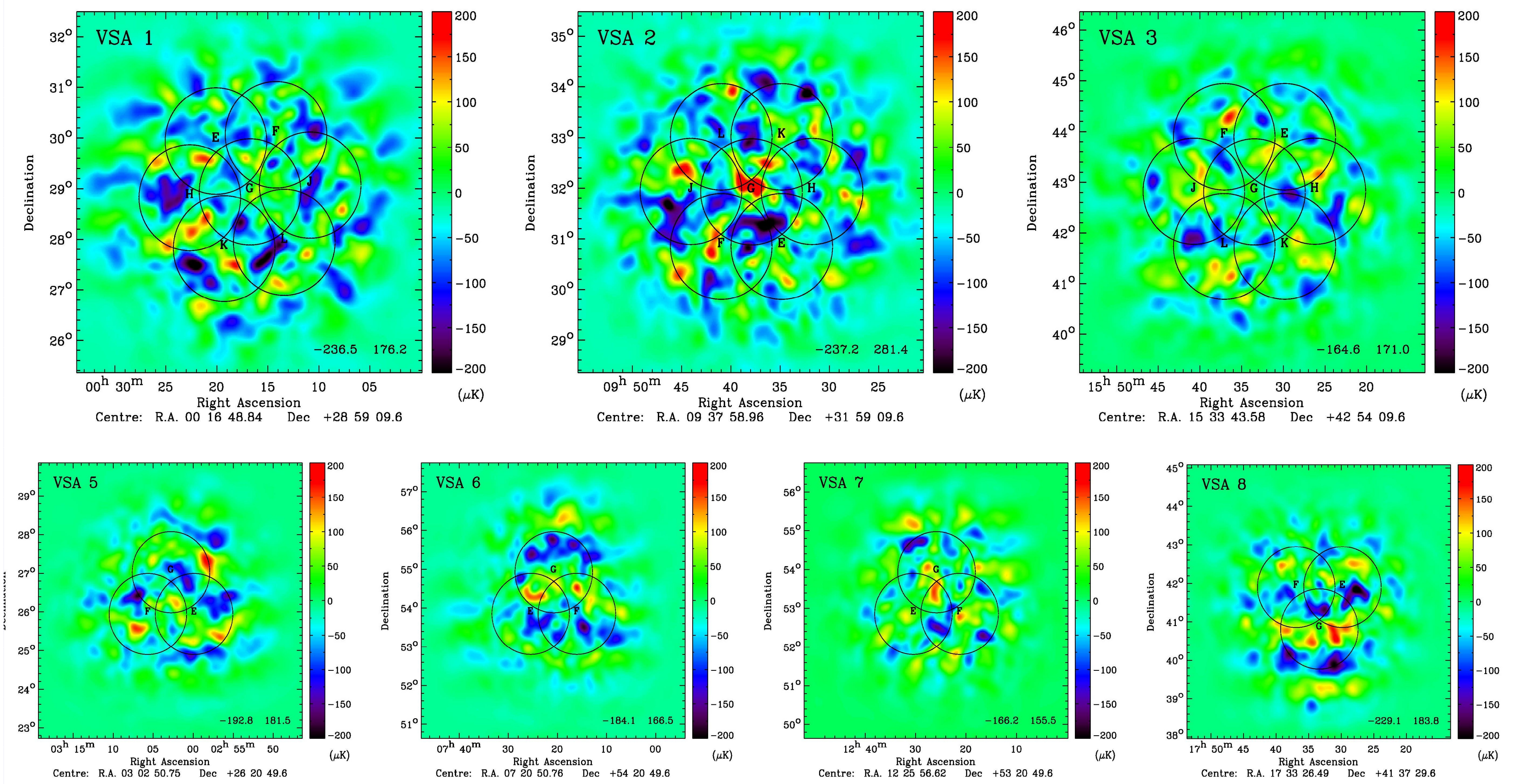
$$n_S = n_S(k_0) + n_{run} \ln(k/k_0)$$

$$\Omega_\nu h^2 < 0.0076 \; (95\%)$$

$$f_\nu = \Omega_\nu / \Omega_{dm}$$

$$\Omega_\nu h^2 = \Sigma m_i / 94\text{eV}$$

Spergel et al. 2003
ApJS 148,175

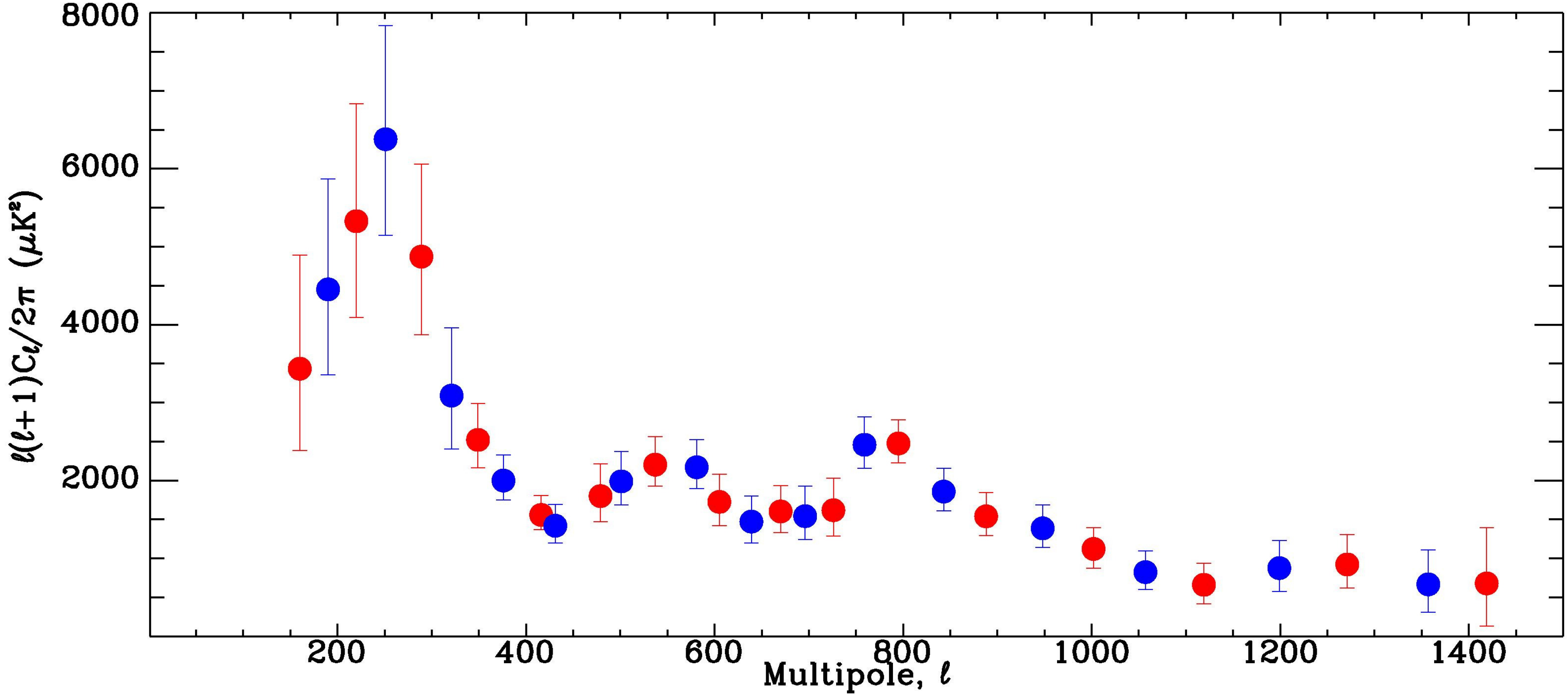


VSA extended: Dickinson et al. 2004 (MNRAS)

Typical rms values of 5-25 microK beam^{-1}

VSA CMB angular power spectrum (compact + extended configuration)

Dickinson et al. 2004



(two alternate binnings)

Table 1. Priors used on each cosmological parameter when it is allowed to vary. The notation (a, b) for parameter x denotes a top-hat prior in the range $a \leqslant x \leqslant b$.

Basic Parameter	Prior
ω_{b}	(0.005,0.10)
ω_{dm}	(0.01, 0.99)
h	(0.4,1.0)
n_{S}, n_1, n_2	(0.5,1.5)
z_{re}	(4,30)
$10^{10} A_{\mathrm{S}}$	(10,100)
n_{run}	(−0.15,0.15)
$A_{\mathrm{X}}/(\mu\mathrm{K})^2$	(−500,500)
f_ν	(0,0.2)
Ω_{k}	(−0.25,0.25)
w	(−1.5,0)
R	(0,2)
n_{T}	(−1.5,3)

Dark energy equation-of-state parameter

Ratio of the amplitude of Tensor to scalar fluctuations

Spectral index of tensor fluctuations

Constraints on tilt and Running Index in a Flat ΛCDM

Rebolo et al. MNRAS (2004)

Table 3. Limits on n_S and n_{run} in the flat ΛCDM model with a running spectral index for different CMB data sets and external priors.

CMB	External	n_S	n_{run}
COBE+VSA	None	$0.93^{+0.13}_{-0.12}$	$-0.081^{+0.049}_{-0.049}$
WMAP	None	$0.94^{+0.07}_{-0.06}$	$-0.060^{+0.037}_{-0.036}$
WMAP+VSA	None	$0.96^{+0.07}_{-0.07}$	$-0.069^{+0.032}_{-0.032}$
COBE+VSA	HST	$0.92^{+0.11}_{-0.12}$	$-0.081^{+0.048}_{-0.048}$
WMAP	HST	$0.95^{+0.06}_{-0.07}$	$-0.060^{+0.037}_{-0.037}$
WMAP+VSA	HST	$0.93^{+0.06}_{-0.05}$	$-0.069^{+0.036}_{-0.036}$
COBE+VSA	2dF	$1.00^{+0.12}_{-0.13}$	$-0.044^{+0.058}_{-0.061}$
WMAP	2dF	$0.95^{+0.05}_{-0.06}$	$-0.038^{+0.025}_{-0.037}$
WMAP+VSA	2dF	$0.93^{+0.05}_{-0.05}$	$-0.049^{+0.035}_{-0.034}$

For slow-roll inflation,

$$r = 16\varepsilon_1 \text{ and } 1 - n_s = 2\,\varepsilon_1 + \varepsilon_2$$

where ε_1 and ε_2 relate to the shape of the inflationary potential:

$$\epsilon_1 = \frac{M_{Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2$$

$$\epsilon_2 = \frac{M_{Pl}^2}{4\pi}\left[\left(\frac{V'}{V}\right)^2 - \frac{V''}{V}\right].$$

Here, M_{Pl} is the Planck mass. The quantity $1 - n_s$ can also be expressed as

$$1 - n_s = \frac{M_{Pl}^2}{16\pi}\left[6\left(\frac{V'}{V}\right)^2 - 2\left(\frac{V''}{V}\right)\right]$$

To relate r and $1 - n_s$, we need to know how V'' and V' relate. It is often assumed that $V'' << V'$, or $\varepsilon_2 << \varepsilon_1$, in which case $r \sim 8\,(1 - n_s)$. Now we see the importance of a precise value of n_s. Using the best available estimate from WMAP, $n_s = 0.95 \pm .02$ (section 3.4.4.8, we find $r \sim 0.4 \pm .2$ in the simplest case.

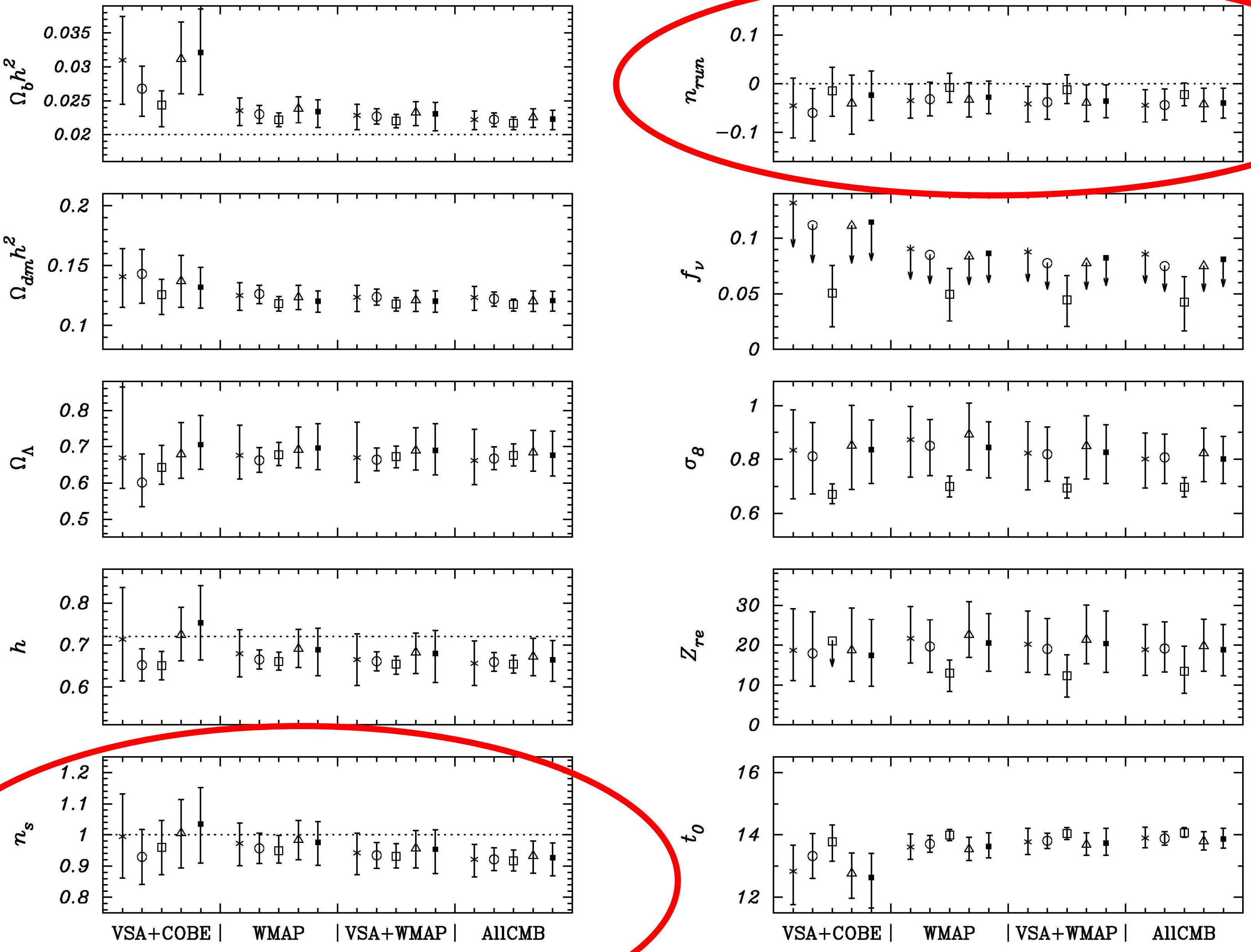
The value of r translates directly into an expected amplitude of B-mode

Partridge 2008

What is the role of external priors on the imposed limits ?

- 2dF (Percival et al. 2001, 2002)
- 2df + fgas (gas fraction in dynamically relaxed clusters of galaxies Allen et al. 2002)
- 2df+fgas+XLF (observed local X-ray luminosity function of clusters of galaxies, Allen et al. 2003)
- 2dF+HST (Key project Freedman et al. 2001)
- 2dF+ Cosmic Shear (Hoekstra et al. 2002)

Flat Lambda CDM models

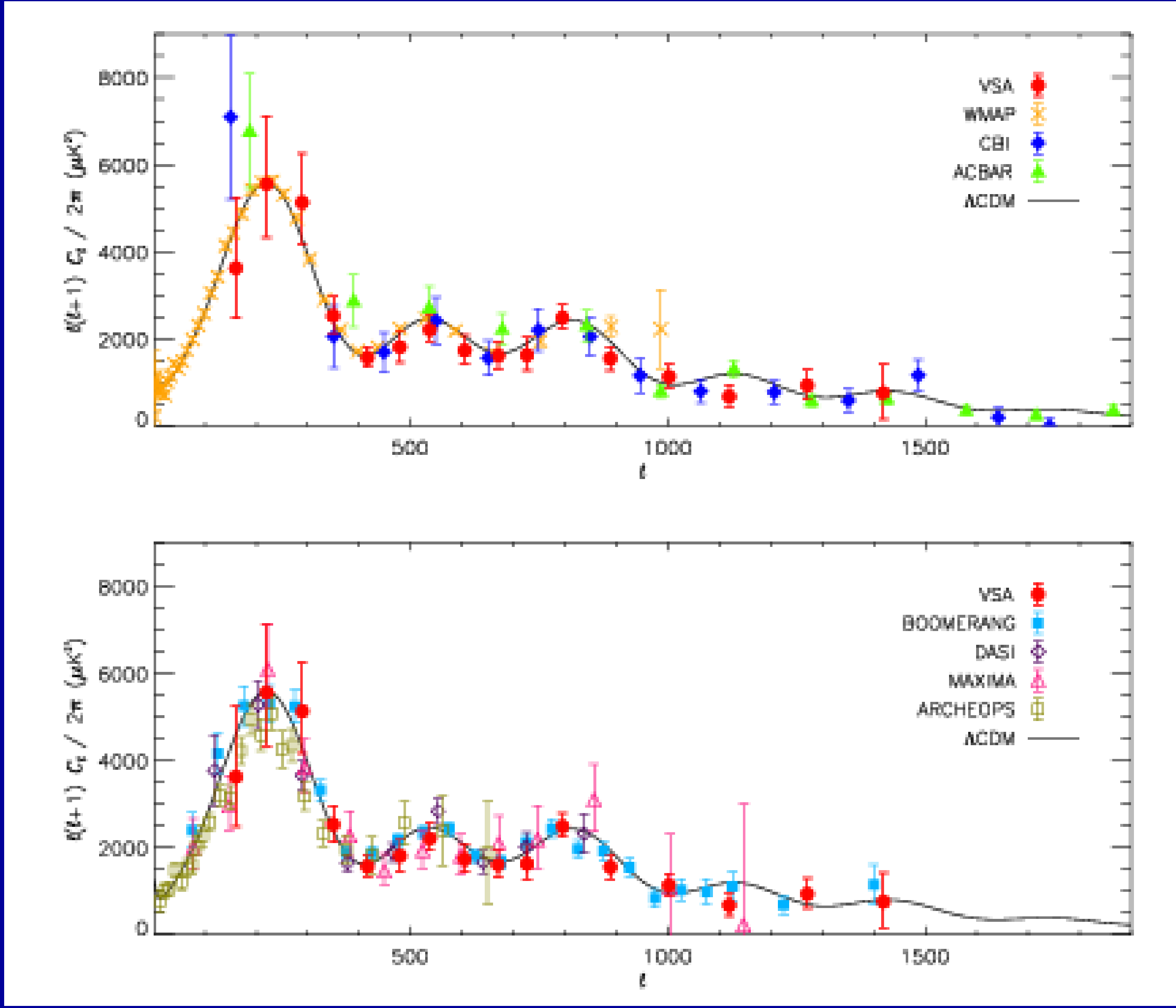


WMAP 3rd year

Spergel et al. 06

WMAP Cosmological Parameters Model: lcdm Data: wmap		WMAP Cosmological Parameters Model: lcdm Data: wmap+cbi+vsa	
$10^2\Omega_b h^2$	$2.230^{+0.075}_{-0.073}$	$10^2\Omega_b h^2$	2.208 ± 0.071
$\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$	$(23.7 \pm 1.4) \times 10^{-10}$	$\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$	$(23.5^{+1.3}_{-1.4}) \times 10^{-10}$
h	0.735 ± 0.032	h	0.742 ± 0.031
H_0	73.5 ± 3.2 km/s/Mpc	H_0	74.2 ± 3.1 km/s/Mpc
$n_s(0.002)$	0.951 ± 0.016	$n_s(0.002)$	0.947 ± 0.015
$\Omega_b h^2$	$0.02230^{+0.00075}_{-0.00073}$	$\Omega_b h^2$	0.02208 ± 0.00071
Ω_Λ	0.763 ± 0.034	Ω_Λ	0.774 ± 0.031
Ω_m	0.237 ± 0.034	Ω_m	0.226 ± 0.031
$\Omega_m h^2$	$0.1265^{+0.0081}_{-0.0080}$	$\Omega_m h^2$	$0.1233^{+0.0075}_{-0.0074}$
σ_8	0.742 ± 0.051	σ_8	$0.721^{+0.047}_{-0.046}$
A_{SZ}	1.00 ± 0.64	A_{SZ}	$0.85^{+0.62}_{-0.58}$
t_0	$13.73^{+0.16}_{-0.15}$ Gyr	t_0	13.76 ± 0.15 Gyr
τ	$0.088^{+0.029}_{-0.030}$	τ	0.087 ± 0.029
θ_A	$0.5948^{+0.0021}_{-0.0022}$ °	θ_A	0.5942 ± 0.0020 °
z_r	10.9 ± 2.5	z_r	10.8 ± 2.4

CMB data (in 2006)



CMB+ Lyman-alpha forest + galaxy clustering + SN constraints

Seljak et al. 2006

$\Omega_b h^2$	0.0230 ±0.0006
n	0.964± 0.012
n_run	-0.015± 0.012
$\Omega_{cdm} h^2$	0.117± 0.003
h	0.705 ± 0.013
Ω_0	1.003 ± 0.006
σ_8	0.847± 0.022 Gyr

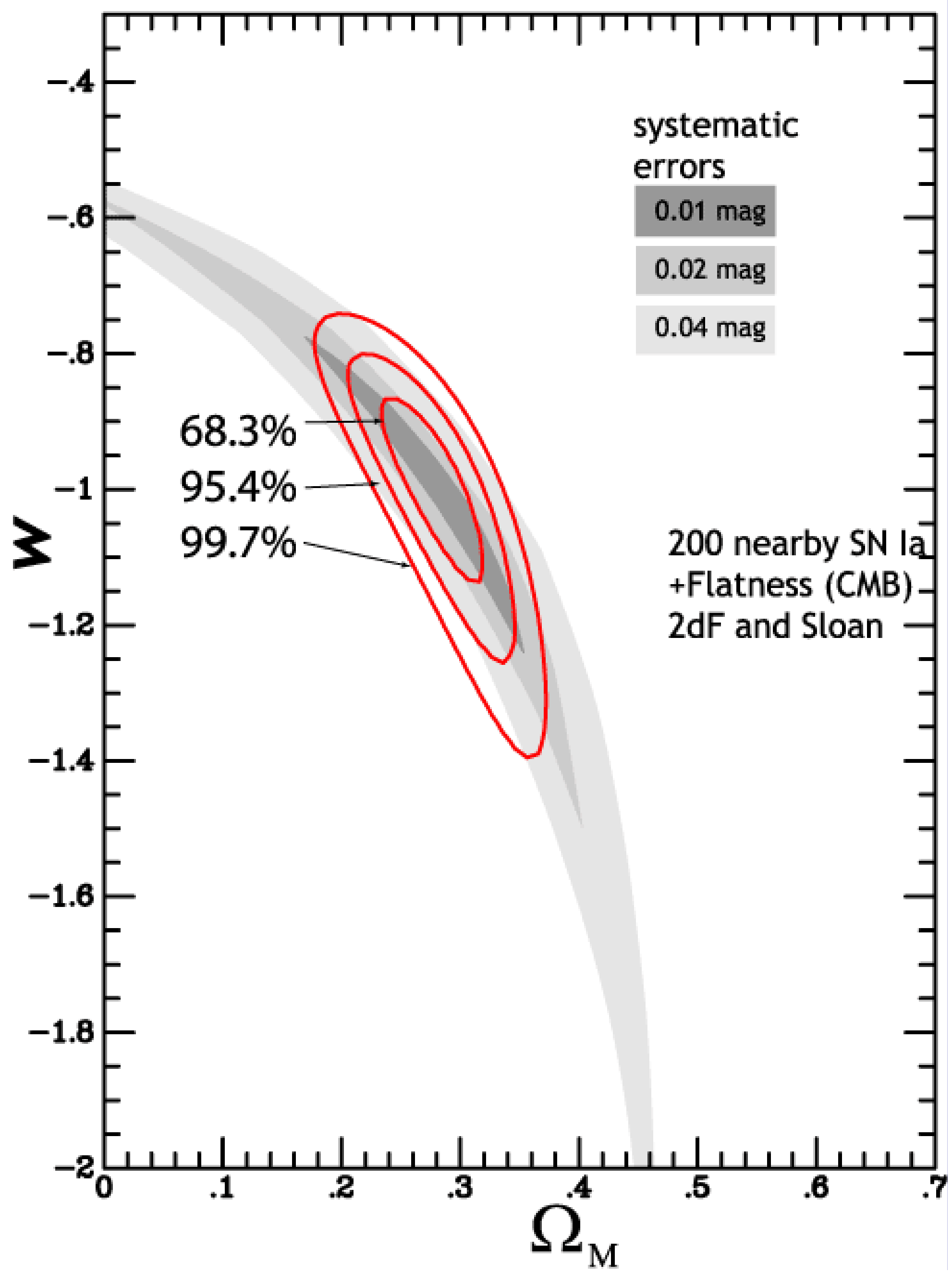
68% C.L.

$r < 0.22$

$\Sigma m_\nu < 0.17$ eV

Upp. Limit 95 %

Dark energy constraints

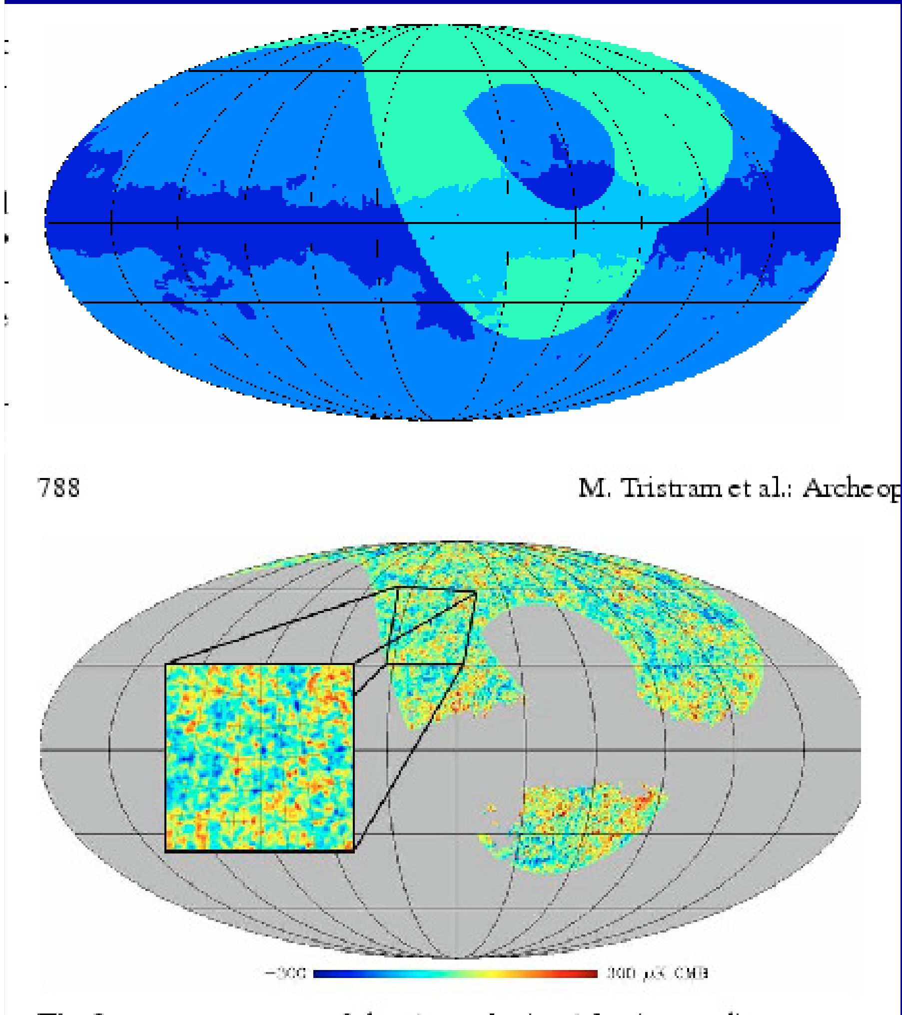


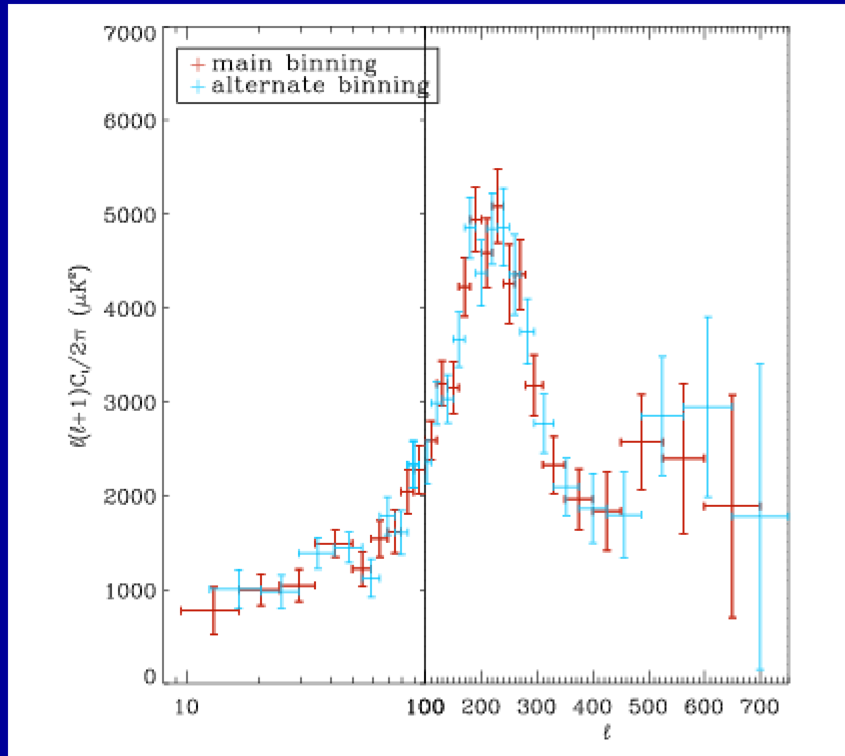
CMB constraints on cosmological parameters

without WMAP?

control on systematics

ARCHEOPS

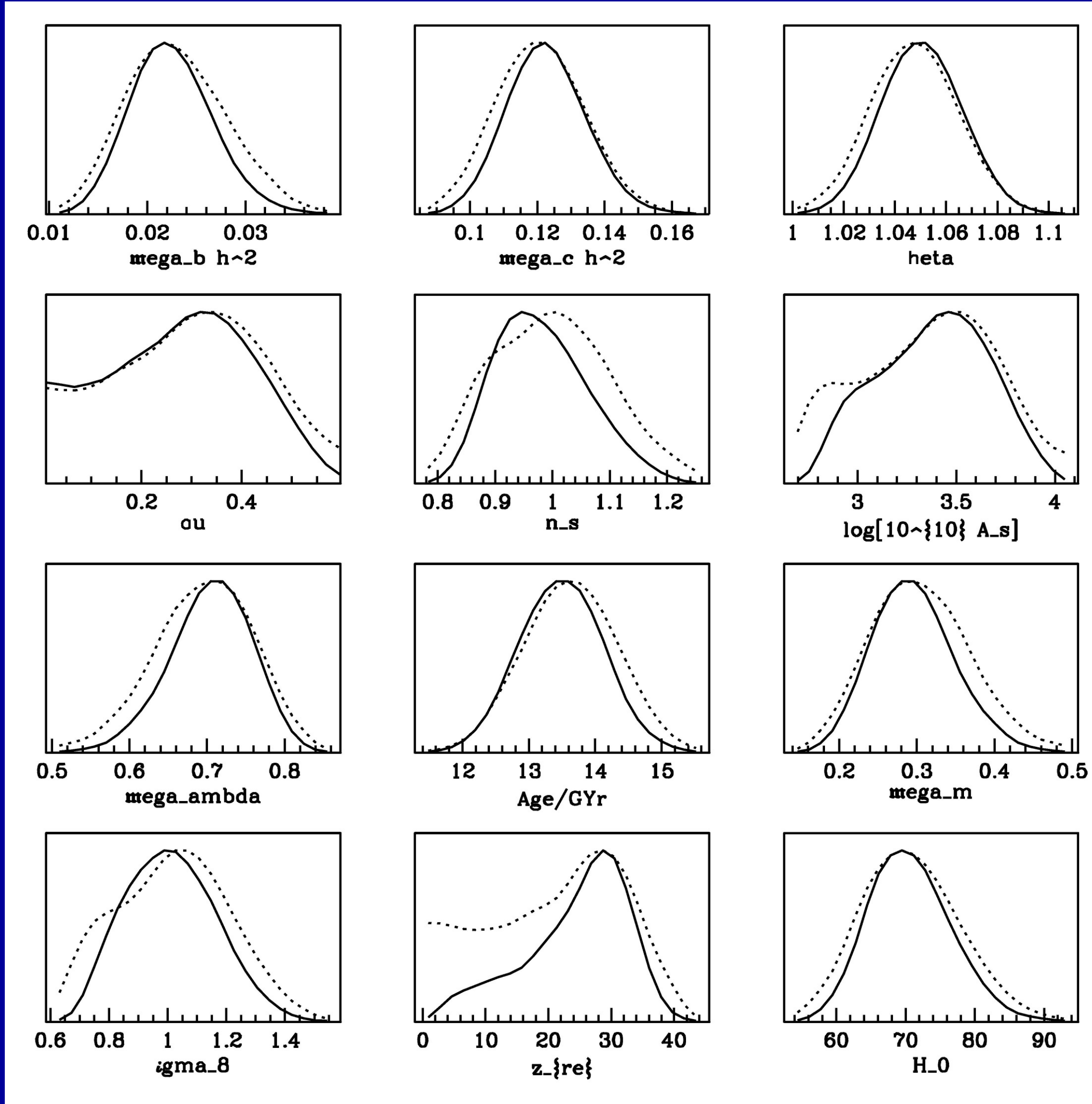




Tristram et al. 05

ARCHEOPS + VSA

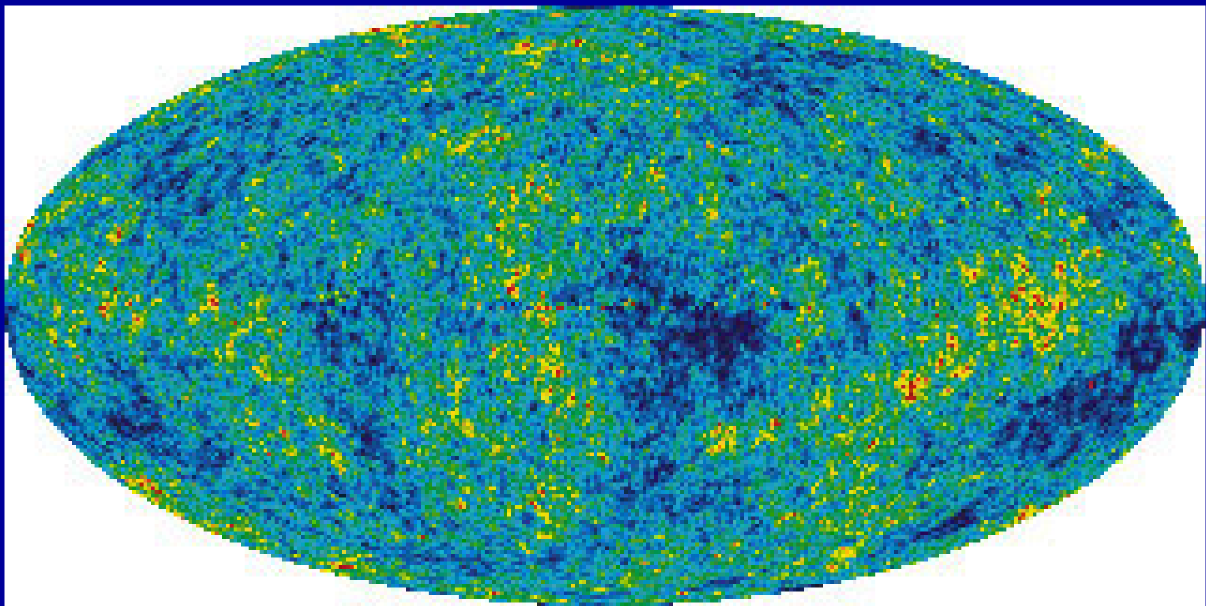
$\Omega_b h^2$	0.0217 ±0.004
n	0.95± 0.09
$\Omega_{cdm} h^2$	0.128± 0.02
h	0.69 ± 0.06
Ω_m	0.29 ± 0.05
Ω_{lambda}	0.71± 0.05
Age	13.5± 0.6 Gyr
σ_8	1.00 ±0.15



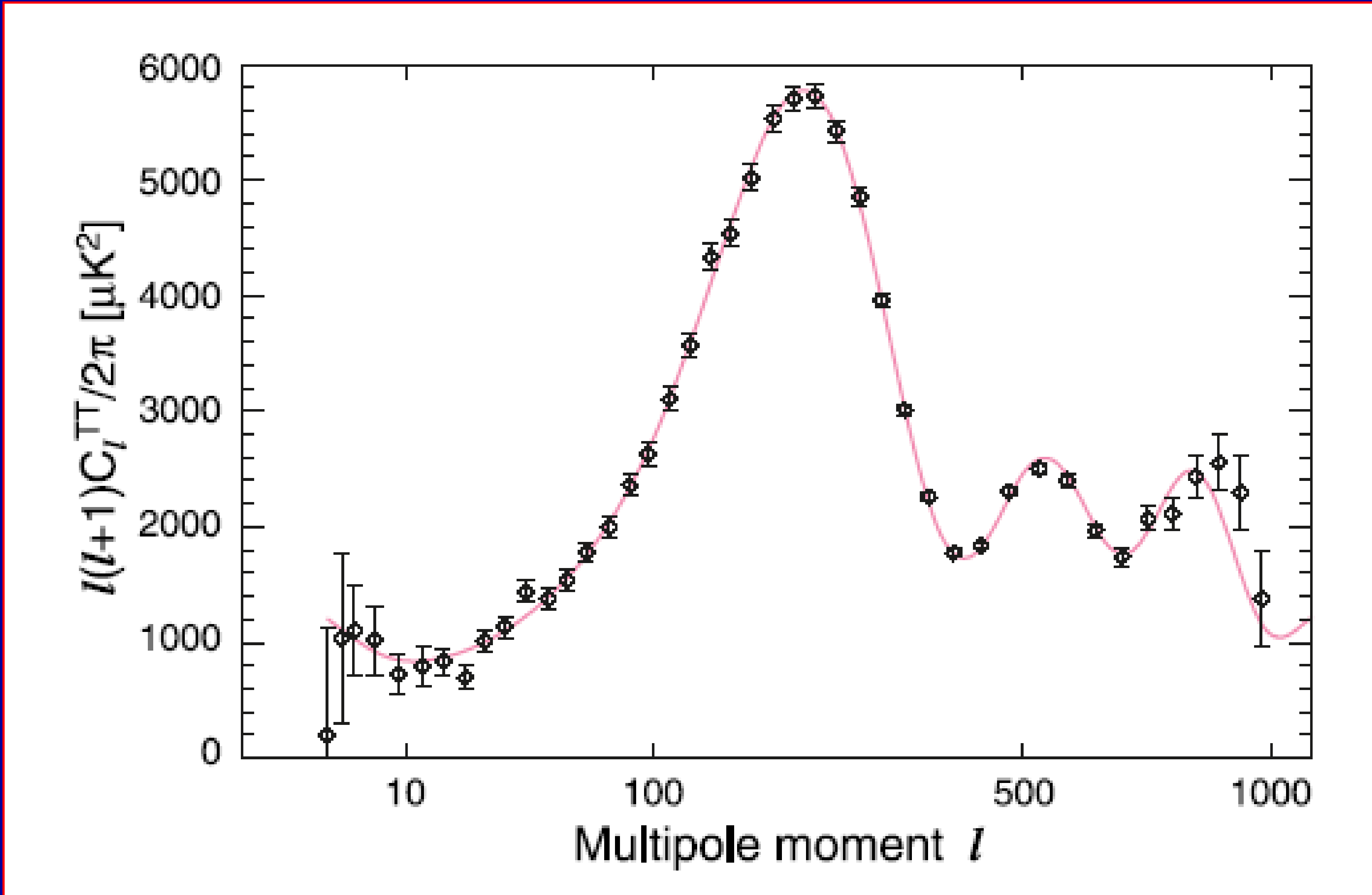
Assuming
Flat model
SNIa+2dF priors

Rubiño et al.

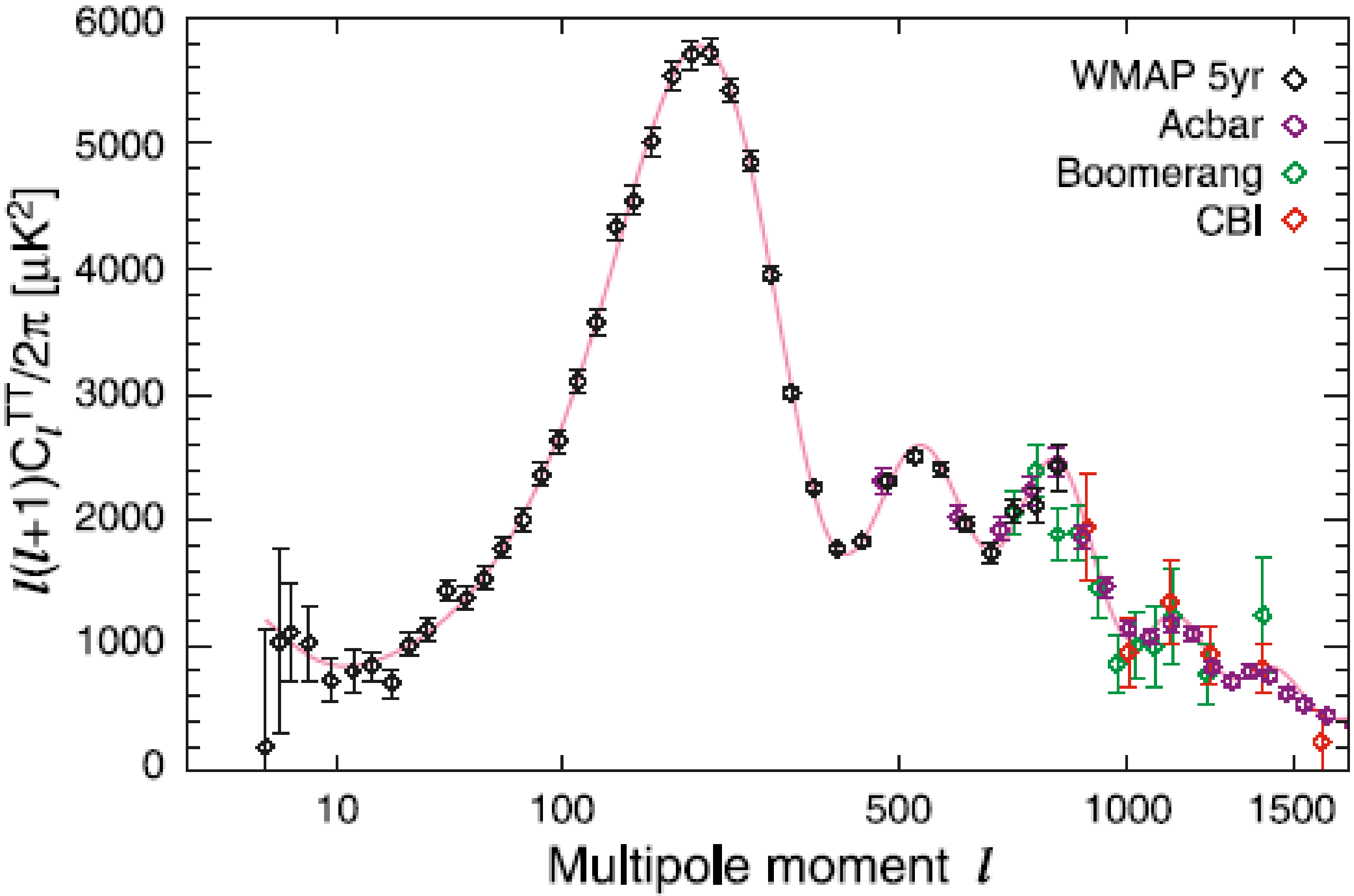
Results from WMAP 5yr



WMAP 5-yr

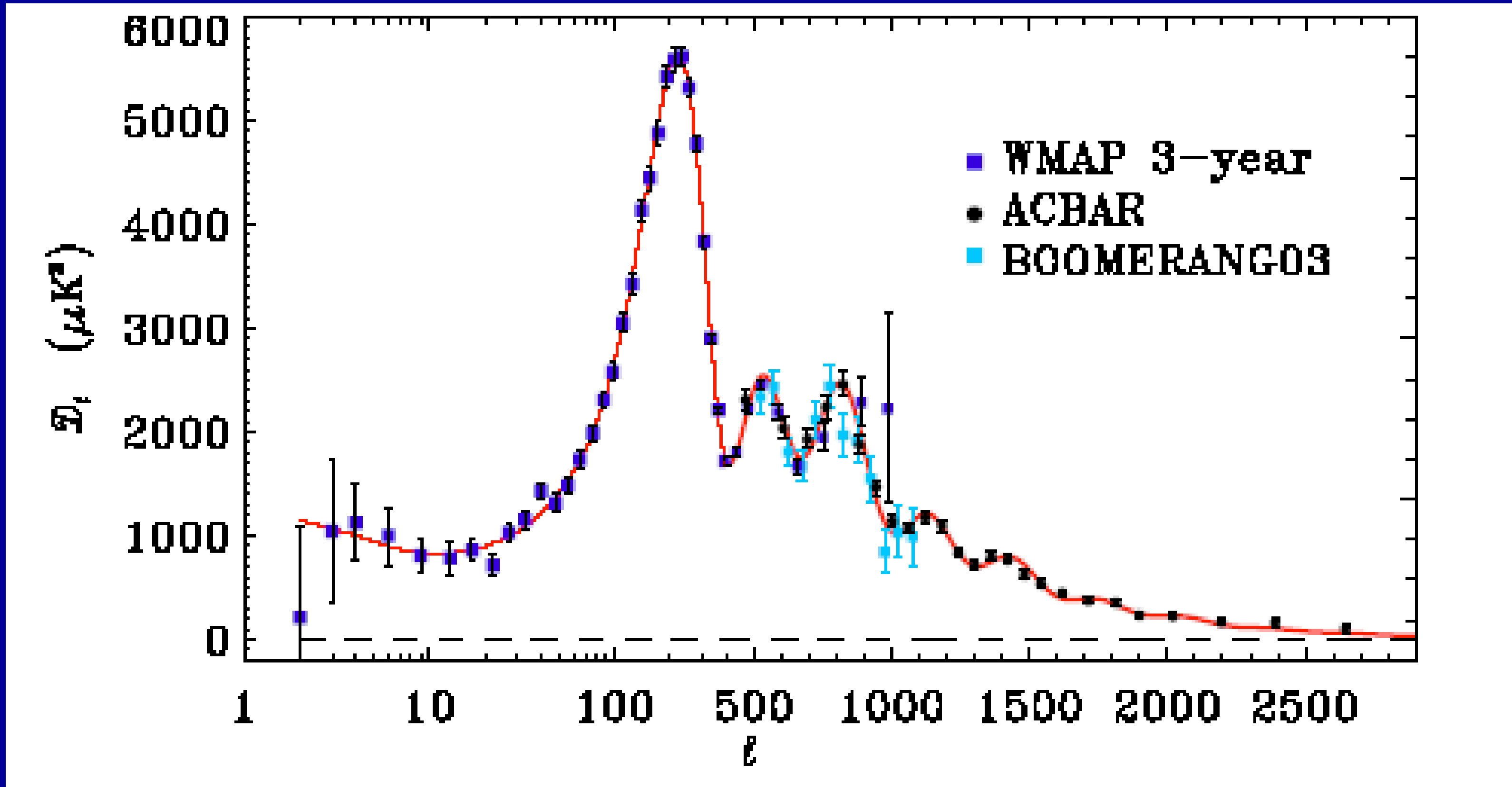


Hinshaw et al. 2008
Nolta et al. 2008



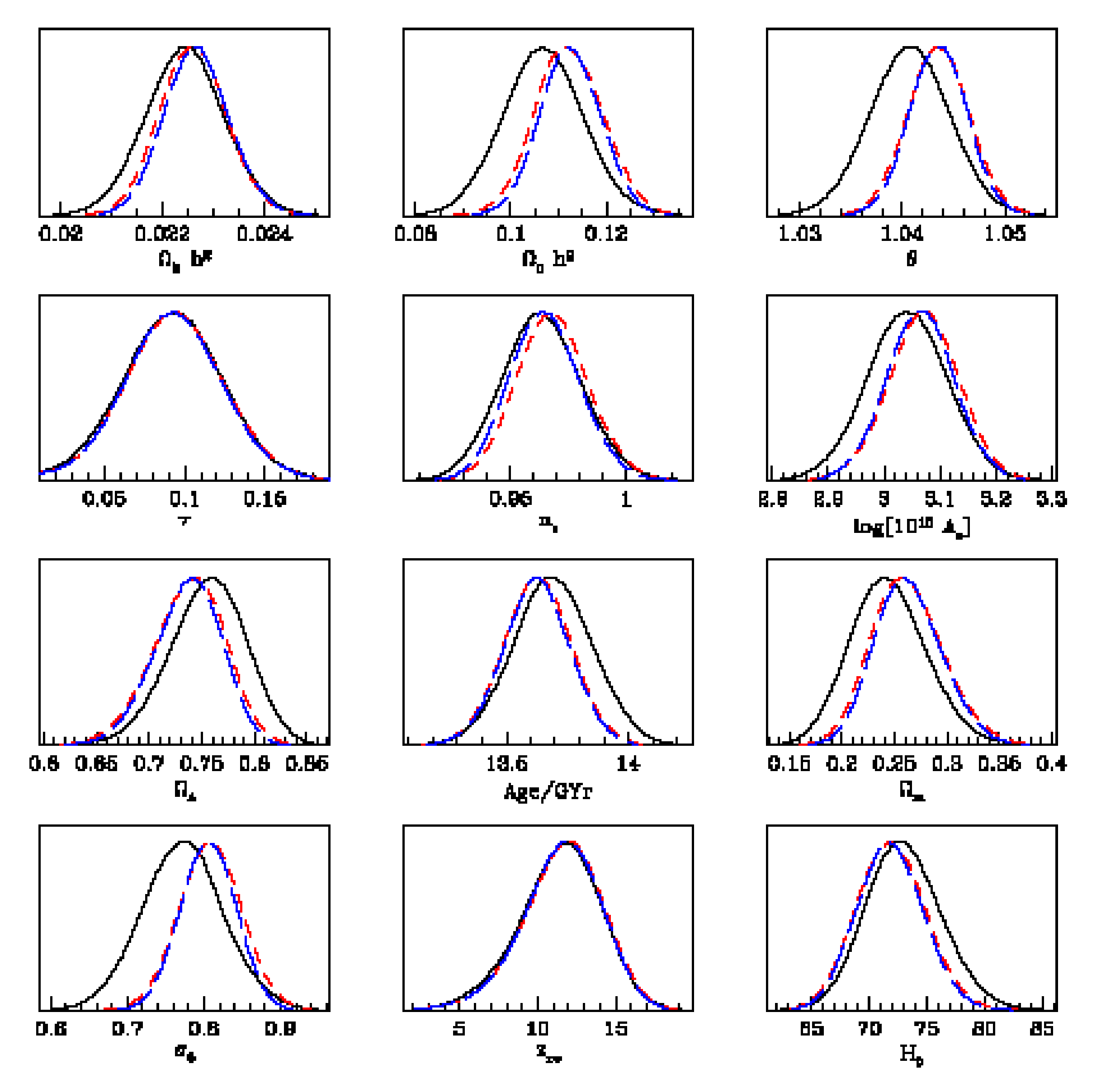
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
l(l+1)C_l^TT/2π [μK²]
Multipole moment l
WMAP 5yr
Acbar
Boomerang
CBI

ACBAR

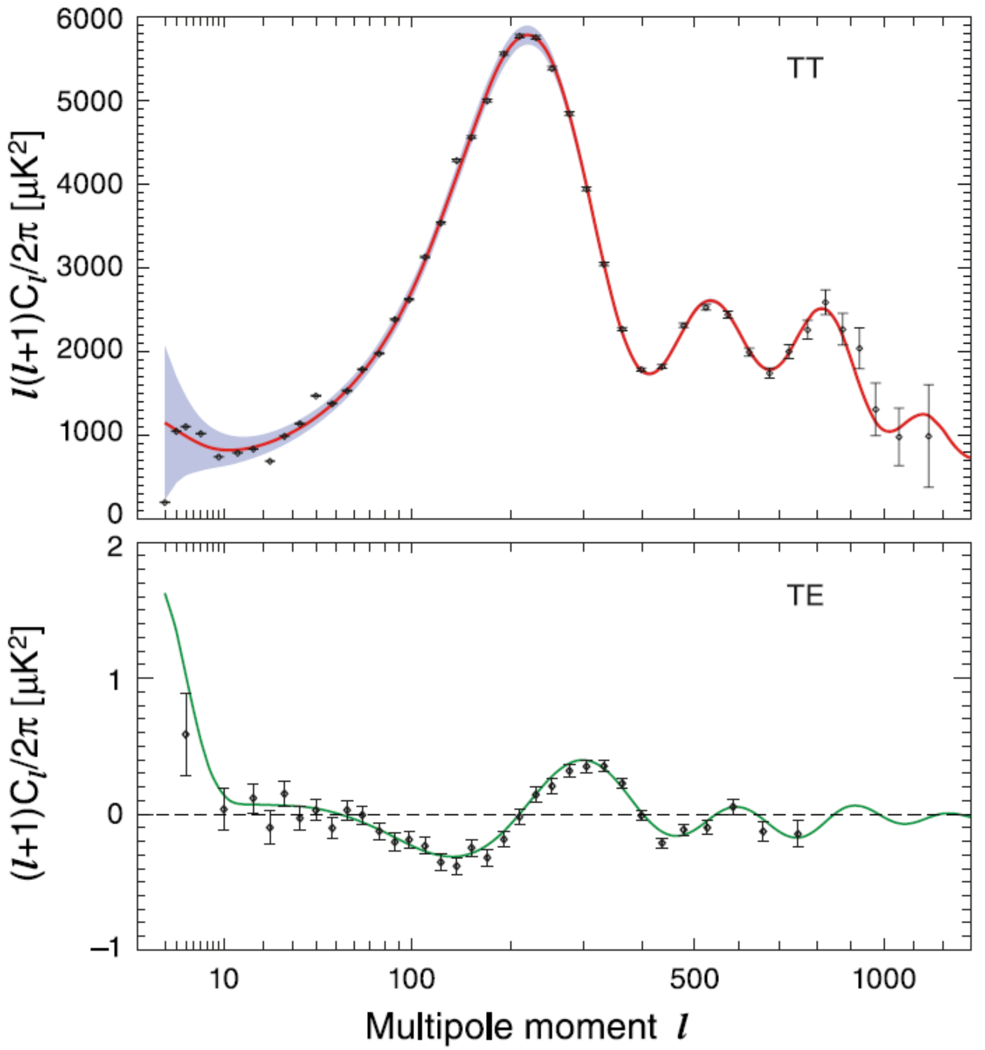


Reichardt et al. 2008

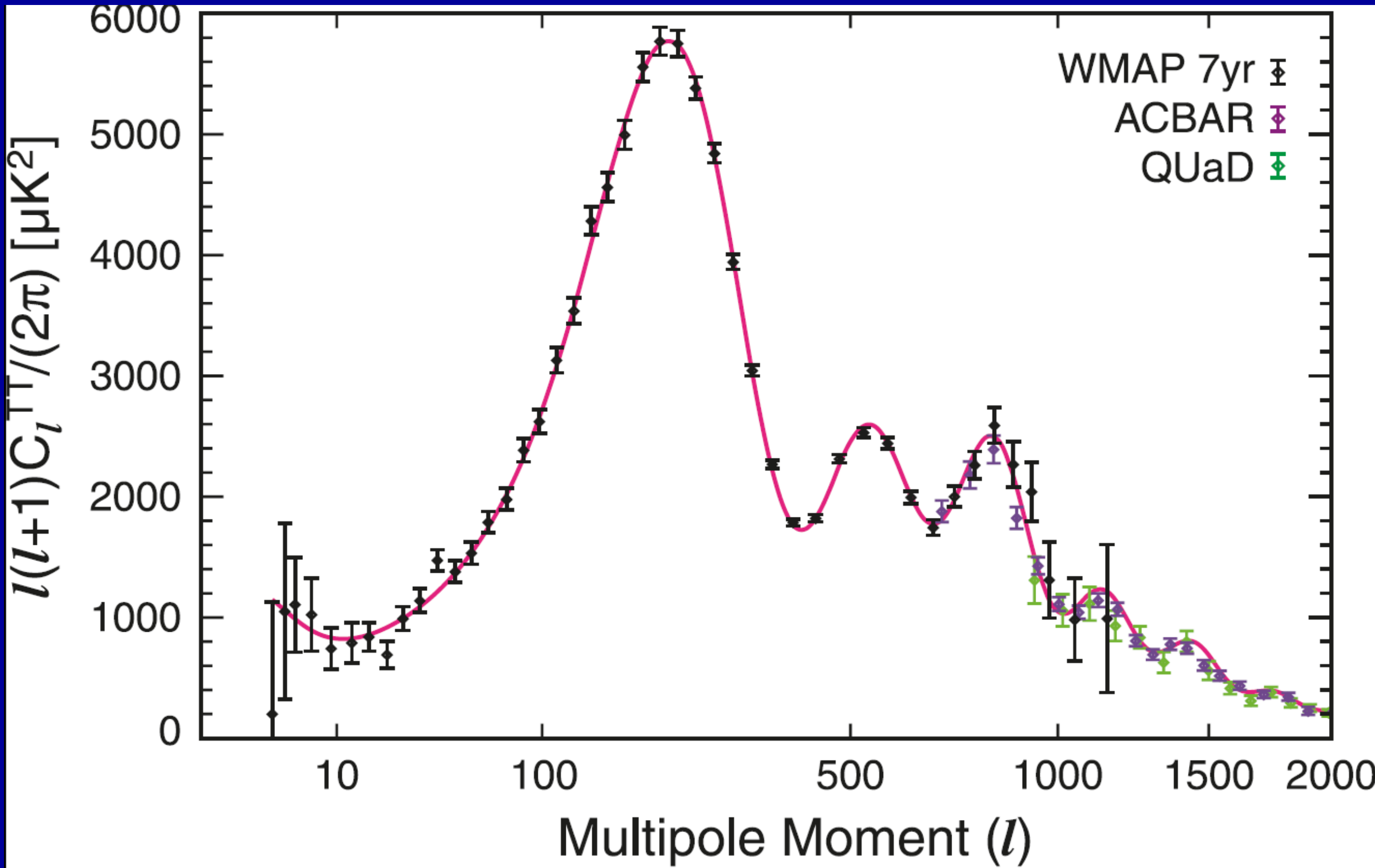
Ωtot	0.97± 0.05
n	0.968± 0.015
Ω_m	0.26 ± 0.03
Ω_{lambda}	0.71± 0.05



WMAP 7-yr



TT
TE
6000
5000
4000
3000
2000
1000
0
2
1
0
−1
10
100
500
1000
$l(l+1)C_l/2\pi$ [μK²]
$(l+1)C_l/2\pi$ [μK²]
Multipole moment l



6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
WMAP 7yr
ACBAR
QUaD
10
100
500
1000
1500
2000
Multipole Moment (l)

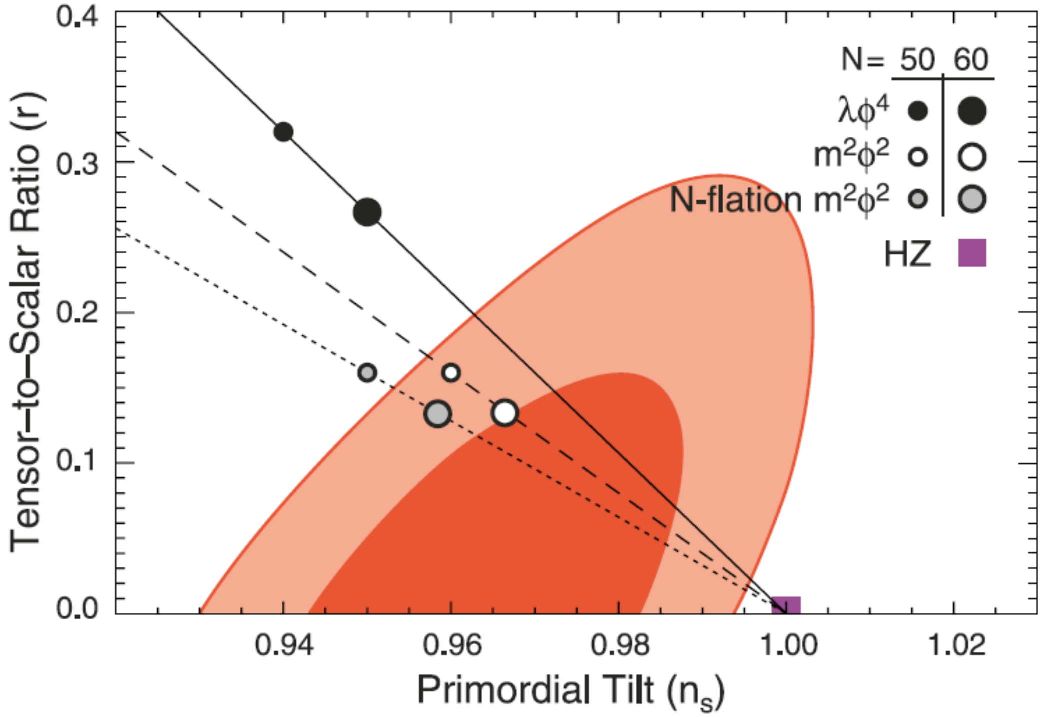
Table 1

Summary of the Cosmological Parameters of ΛCDM Model[a]

Parameter	*WMAP* Seven-year ML[b]	*WMAP*+BAO+H_0 ML	*WMAP* Seven-year Mean[c]	*WMAP*+BAO+H_0 Me
$100\Omega_b h^2$	2.227	2.253	$2.249^{+0.056}_{-0.057}$	2.255 ± 0.054
$\Omega_c h^2$	0.1116	0.1122	0.1120 ± 0.0056	0.1126 ± 0.0036
Ω_Λ	0.729	0.728	$0.727^{+0.030}_{-0.029}$	0.725 ± 0.016
n_s	0.966	0.967	0.967 ± 0.014	0.968 ± 0.012
τ	0.085	0.085	0.088 ± 0.015	0.088 ± 0.014
$\Delta^2_{\mathcal{R}}(k_0)$[d]	2.42×10^{-9}	2.42×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.430 \pm 0.091) \times 10$
σ_8	0.809	0.810	$0.811^{+0.030}_{-0.031}$	0.816 ± 0.024
H_0	$70.3\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.4 \pm 2.5\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.2 \pm 1.4\ \mathrm{km\ s^{-1}}$ Mp
Ω_b	0.0451	0.0455	0.0455 ± 0.0028	0.0458 ± 0.0016
Ω_c	0.226	0.226	0.228 ± 0.027	0.229 ± 0.015
$\Omega_m h^2$	0.1338	0.1347	$0.1345^{+0.0056}_{-0.0055}$	0.1352 ± 0.0036
$z_{\rm reion}$[e]	10.4	10.3	10.6 ± 1.2	10.6 ± 1.2
t_0[f]	13.79 Gyr	13.76 Gyr	13.77 ± 0.13 Gyr	13.76 ± 0.11 Gyr

[redacted]

Probing Inflation (Power Spectrum)



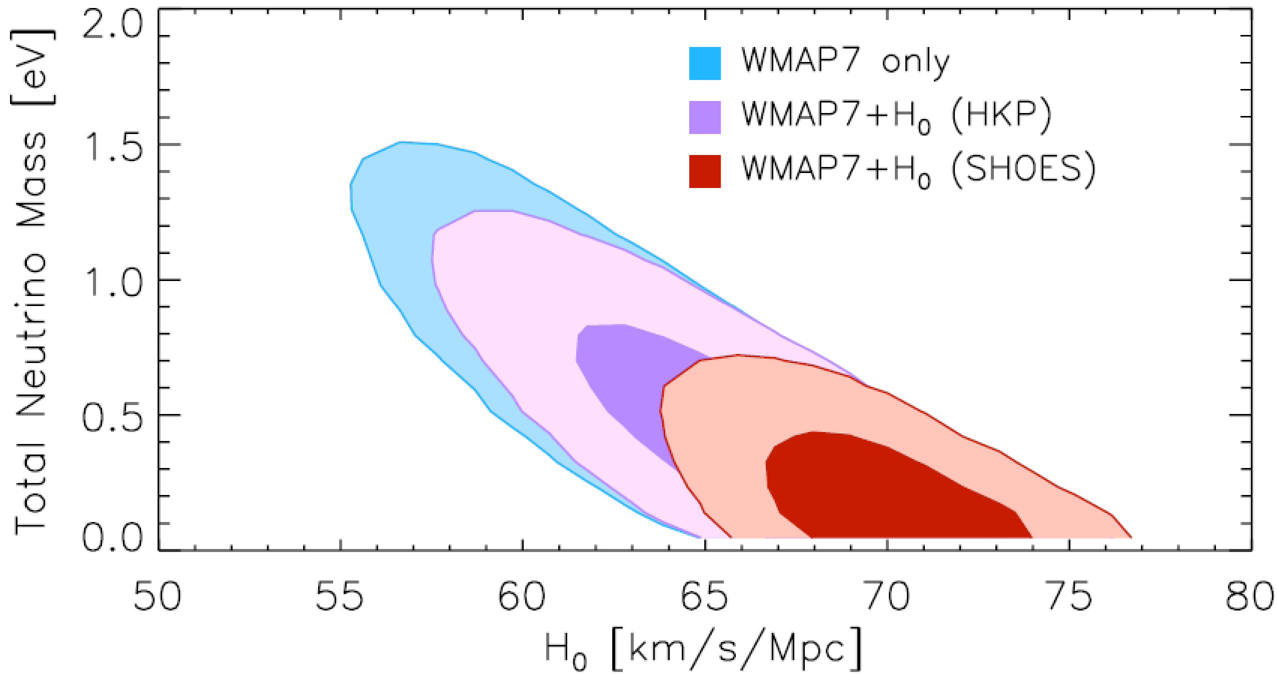
- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)

Komatsu et al. 2011

Table 7
Primordial Tilt n_s, Running Index $dn_s/d\ln k$, and Tensor-to-scalar Ratio r

Model	Parameter[a]	Seven-year *WMAP*[b]	*WMAP*+ACBAR+QUaD[c]	*WMAP*+BAO+H_0
Power-law[d]	n_s	0.967 ± 0.014	$0.966^{+0.014}_{-0.013}$	0.968 ± 0.012
Running	n_s	$1.027^{+0.050}_{-0.051}$ [e]	$1.041^{+0.045}_{-0.046}$	1.008 ± 0.042[f]
	$dn_s/d\ln k$	-0.034 ± 0.026	$-0.041^{+0.022}_{-0.023}$	-0.022 ± 0.020
Tensor	n_s	$0.982^{+0.020}_{-0.019}$	$0.979^{+0.018}_{-0.019}$	0.973 ± 0.014
	r	<0.36 (95% CL)	<0.33 (95% CL)	<0.24 (95% CL)
Running +tensor	n_s	1.076 ± 0.065		1.070 ± 0.060
	r	<0.49 (95% CL)	N/A	<0.49 (95% CL)
	$dn_s/d\ln k$	-0.048 ± 0.029		-0.042 ± 0.024

And, the mass of neutrinos



- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

Komatsu et al. 2011

Latest results: CMB+ BOSS (SDSS·3)

Sánchez, et al. 2012 astroph

ABSTRACT

We obtain constraints on cosmological parameters from the spherically averaged redshift-space correlation function of the CMASS Data Release 9 (DR9) sample of the Baryonic Oscillation Spectroscopic Survey (BOSS). We combine this information with additional data from recent CMB, SN and BAO measurements. Our results show no significant evidence of deviations from the standard flat-ΛCDM model, whose basic parameters can be specified by $\Omega_{\rm m} = 0.285 \pm 0.009$, $100\,\Omega_{\rm b} = 4.59 \pm 0.09$, $n_{\rm s} = 0.961 \pm 0.009$, $H_0 = 69.4 \pm 0.8\,{\rm km\,s^{-1}\,Mpc^{-1}}$ and $\sigma_8 = 0.80 \pm 0.02$. The CMB+CMASS combination sets tight constraints on the curvature of the Universe, with $\Omega_k = -0.0043 \pm 0.0049$, and the tensor-to-scalar amplitude ratio, for which we find $r < 0.16$ at the 95 per cent confidence level (CL). These data show a clear signature of a deviation from scale-invariance also in the presence of tensor modes, with $n_{\rm s} < 1$ at the 99.7 per cent CL. We derive constraints on the fraction of massive neutrinos of $f_\nu < 0.049$ (95 per cent CL), implying a limit of $\sum m_\nu < 0.51{\rm eV}$. We find no signature of a deviation from a cosmological constant from the combination of all datasets, with a constraint of $w_{\rm DE} = -1.033 \pm 0.073$ when this parameter is assumed time-independent, and no evidence of a departure from this value when it is allowed to evolve as $w_{\rm DE}(a) = w_0 + w_a(1 - a)$. The achieved accuracy on our cosmological constraints is a clear demonstration of the constraining power of current cosmological observations.

Conclusions (I)

- Good agreement on the constraints imposed using CMB and various data sets for:

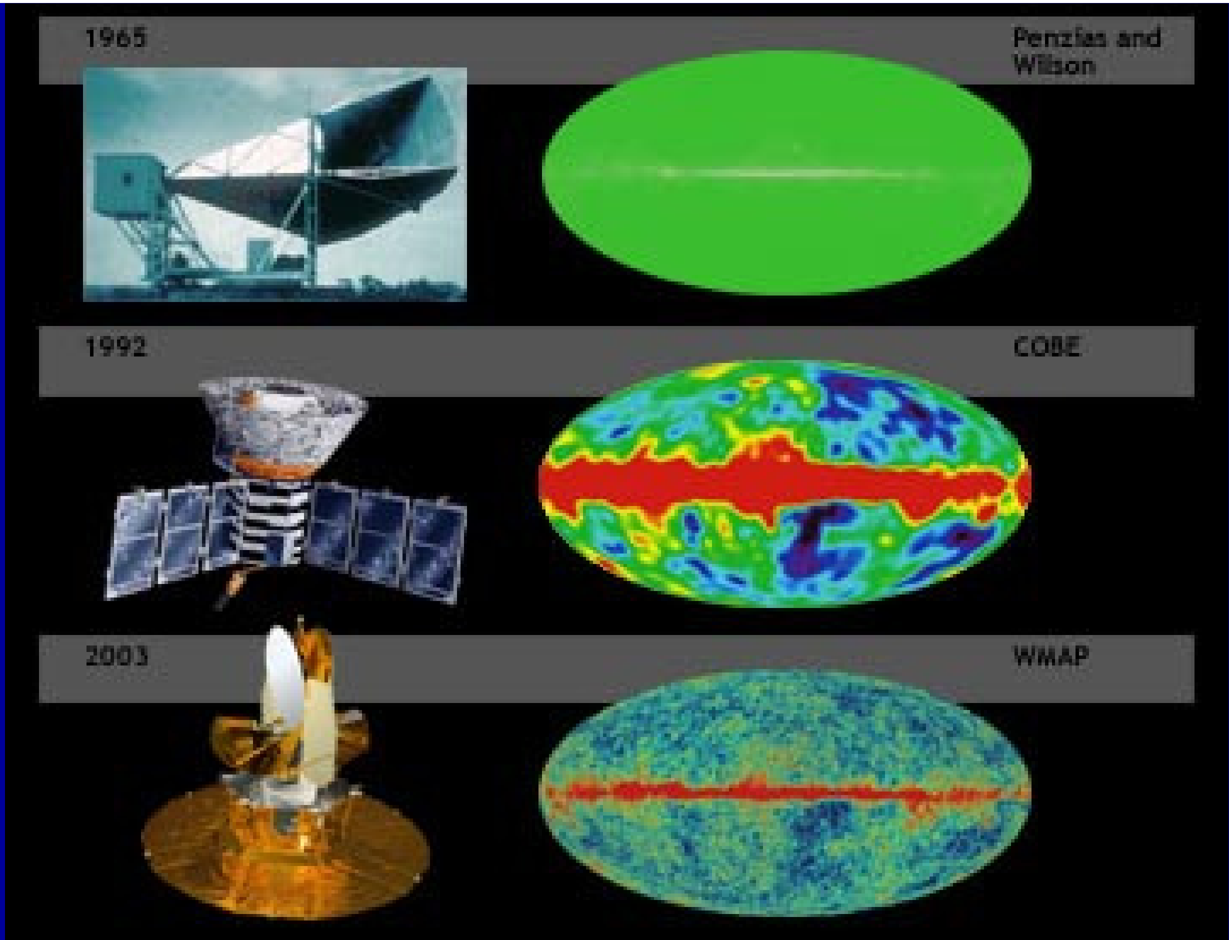
- Baryonic density,
- Cold dark matter density,
- Curvature parameter (flat within less than 0.4%)
-Dark energy density and for the parameter of the equation of state (consistent with cosmological constant $w = -1 \pm 0.06$)
- Index of scalar perturbations $n\_s=0.961 \pm 0.009$

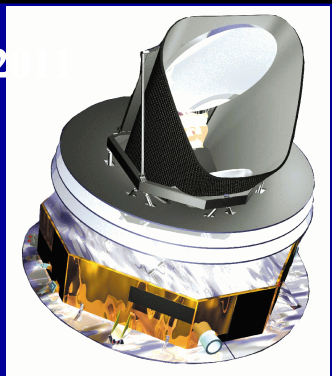
Conclusions (II)

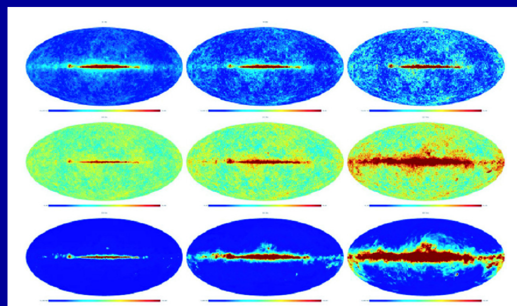
Parameters of inflationary models:

Increasing evidence for a tilted scalar spectral index $n_s = 0.96$
...but not so clear evidence when a non-zero value of the running index is allowed.

Strong upper limits on the ratio of tensor to scalar perturbations $r < 0.16$ for flat lambda cdm models.







Planck: 3rd Generation CMB space experiment

Follow cosmological results early 2013 and J. Tauber´s talk tomorrow

Dark energy constraints