Cosmic Microwave Background: limits on cosmological parameters

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Paris, 17 May 2007 Colegio de España:
Physics of the Early Universe confronts observations

Outline

- CMB anisotropies: introduction
- Overview of recent CMB experiments
  - Space, balloon-born and ground-based
- CMB and precision cosmology
  - Mapping. Peaks in the angular power spectrum
  - Analysis: methodology, priors
- Current constraints on cosmological parameters
  - Comparison with other astrophysical limits
- The future: Planck and polarization experiments
- Conclusions

Physics of the CMB anisotropies

Prior to recombination, we have strong interaction photon-electron plasma (Thomsom scattering)

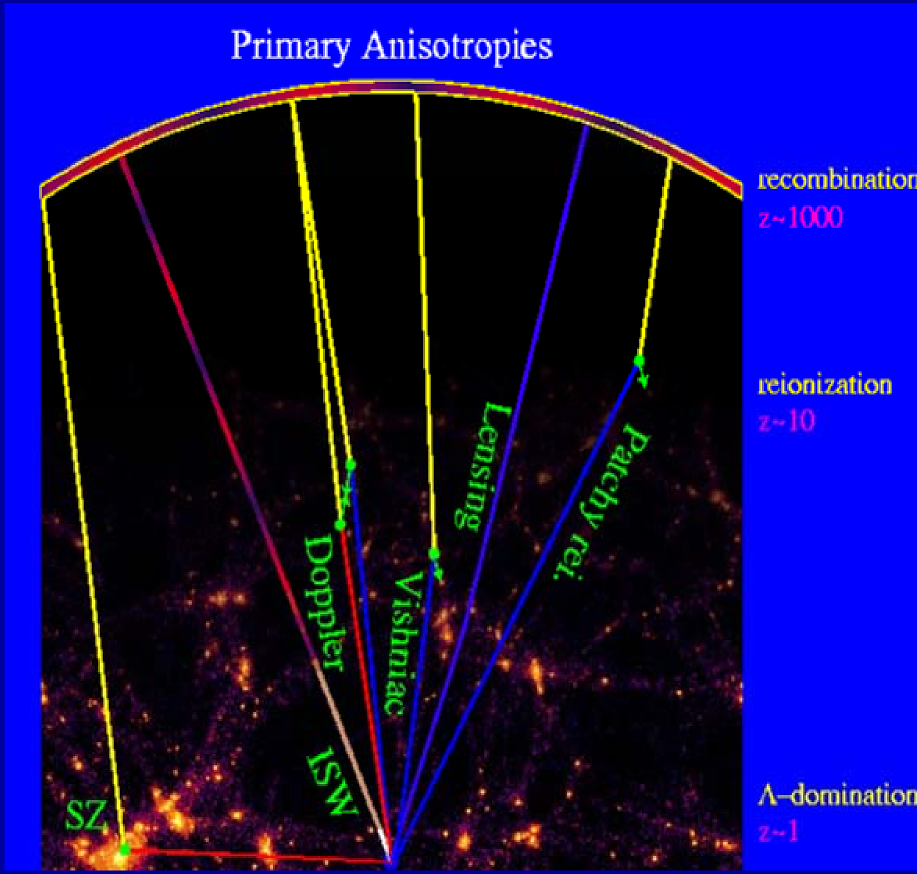
- **Primary anisotropies** (from recombination)

$$\frac{\Delta T}{T_0}(\hat{\mathbf{q}}) = \frac{1}{4}\frac{\delta n_\gamma}{n_\gamma} - \hat{\mathbf{q}} \cdot \vec{v} + \frac{1}{3}[\Phi(0) - \Phi(\vec{x}_{em})]$$

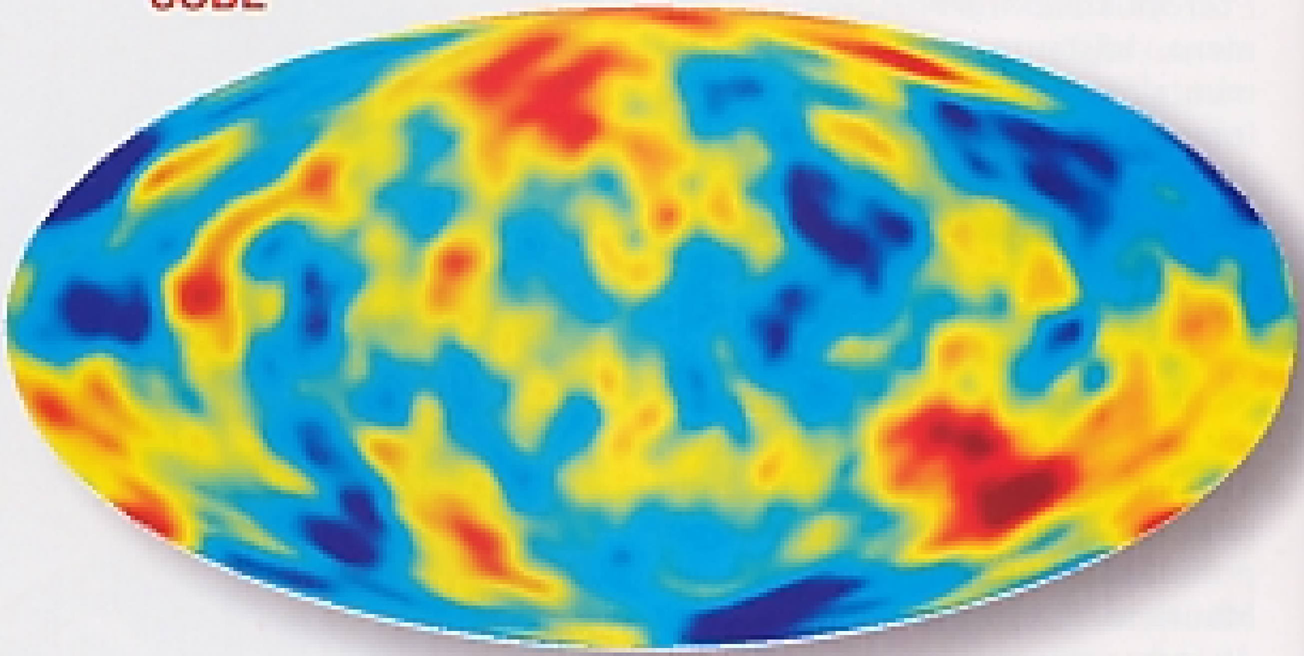
Intrinsic — Doppler — Sach-Wolfe(SW)

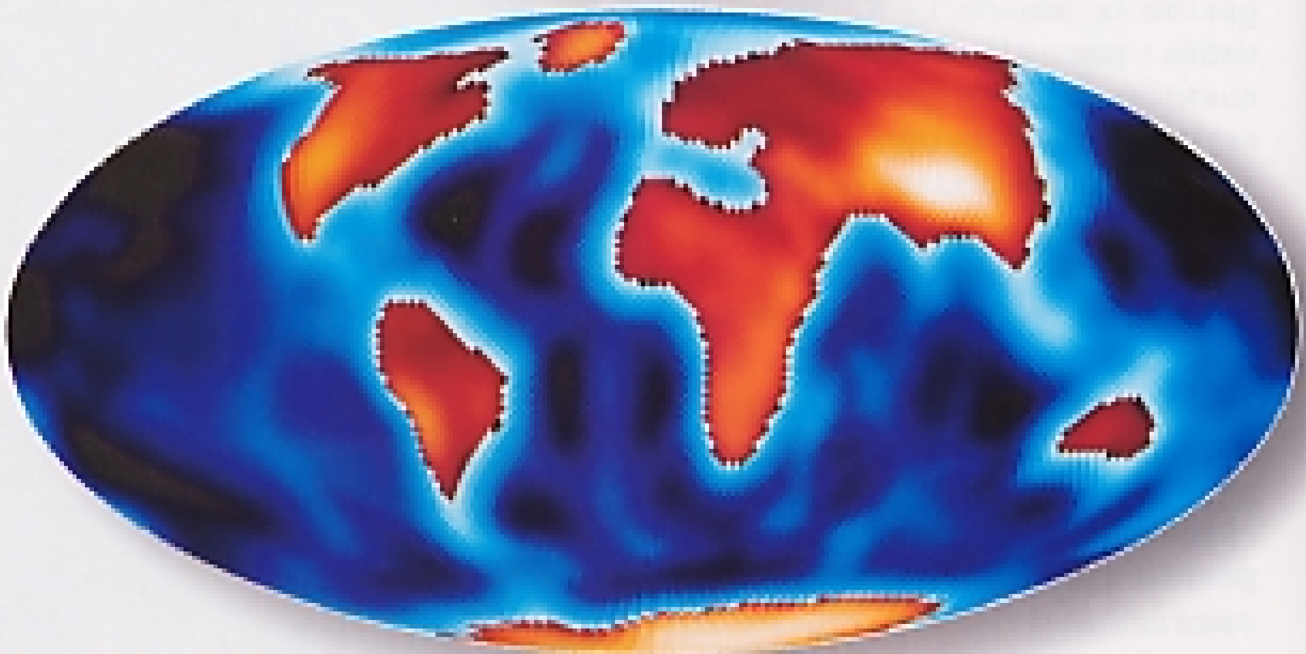
\+ Silk damping

- **Secondary anisotropies** (after recombination)
  - Integrated SW, Rees-Sciama
  - Sunyaev-Zeldovich effect
  - Reionization (global, patchy,...)
  - Lensing



COBE





Basic formalism for temperature anisotropies

- Spherical harmonic expansion

$$\Delta T/T\,(\theta,\phi) = \Sigma_{lm}\, a_{lm} Y_{lm}\,(\theta,\phi)$$

  – If the temperature anisotropies follow a Gaussian statistics then their statistical properties are measured by the angular power spectrum: a function of "multipole moments" a_{lm}:

    - $C_l \equiv < |a_{lm}|^2 > \approx 1/(2l + 1)\, \Sigma_m |a_{lm}|^2$
      – a statistically isotropic sky implies that all m´s are equivalent
      – Each coefficient a_{lm} is a random variable with mean zero and variance C_l
    - Relationship between angular scales and multipoles

$$\theta \approx 120° / l$$

    - The power at each l is $(2l + 1)\, C_l\ / (4\pi)$
    - The anisotropy amplitude is defined

$$(\Delta T_l)^2 = l\,(l + 1)\; C_l / (2\pi)$$

Polarization of the CMB

- CMB anisotropies are expected to be linearly polarized (Thomson scattering at last scattering, Rees 1968)

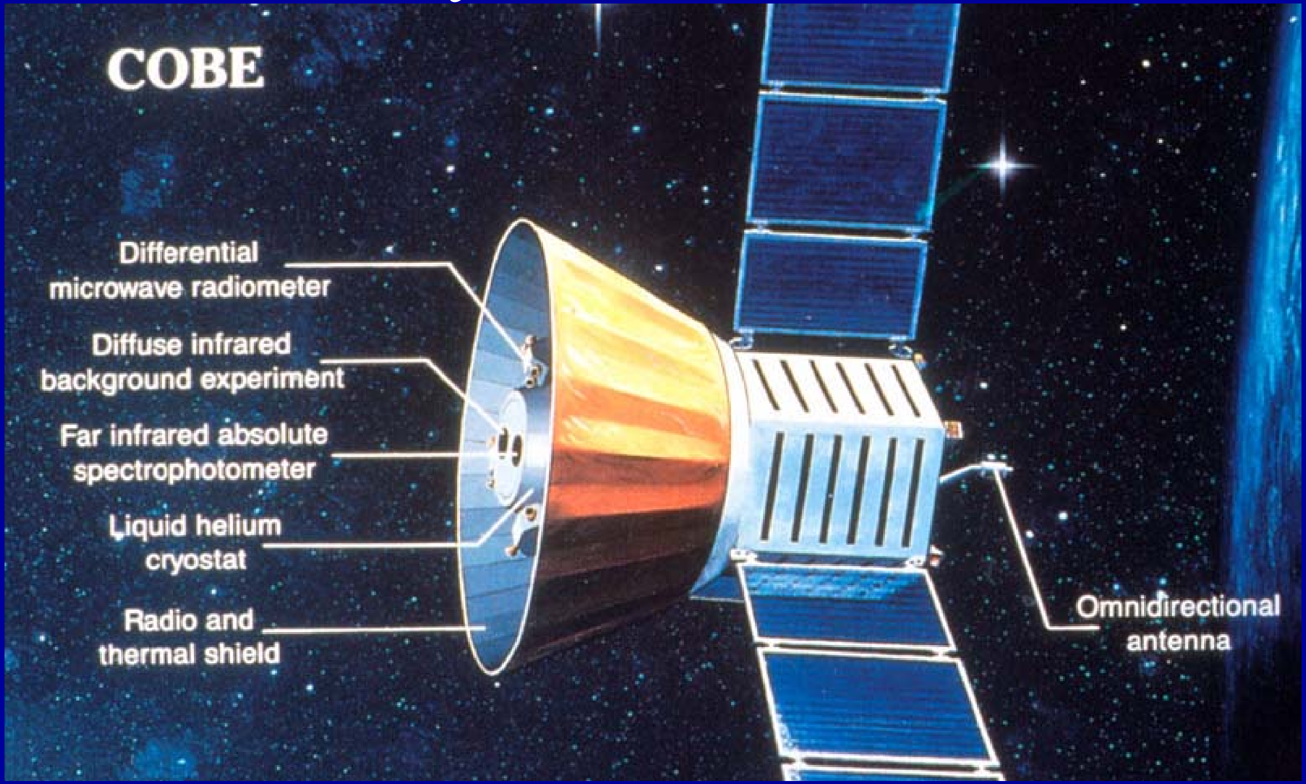
- Two other potential measurements are Q and U (Stokes parameters). Frequently decomposed in the so-called E and B modes.

- Temperature and polarization then lead to measurable:
temperatura, EE, BB power spectra (Fourier transform of the two point correlation functions) and the temperature-polarization cross correlations TE. The additional cross-correlation spectra between B and T, B and E are expected to vanish for cosmological signals.

- E and B-mode polarization can be expanded in spherical harmonics

COBE detected
CMB primordial anisotropies

year 1992



COBE/DMR 4yr

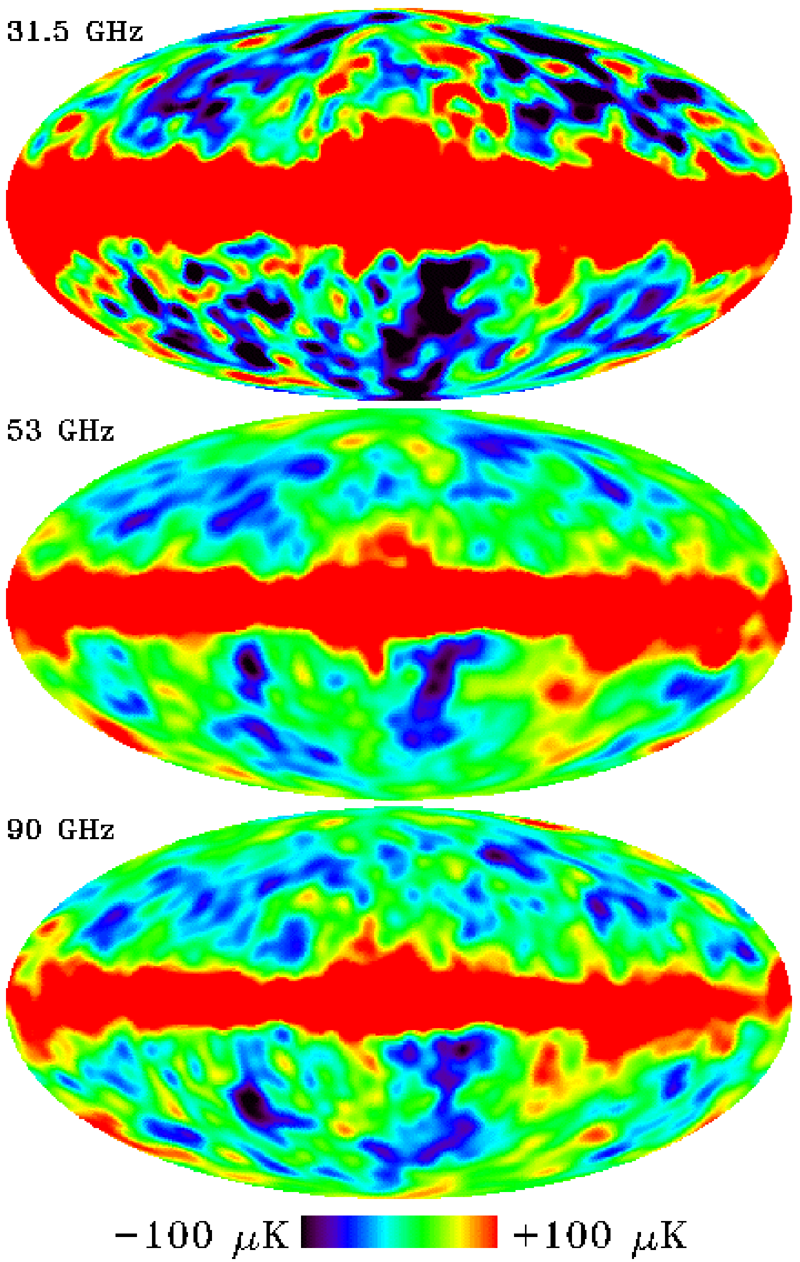
For a pure n=1 scale-invariant primordial density perturbation power spectrum

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

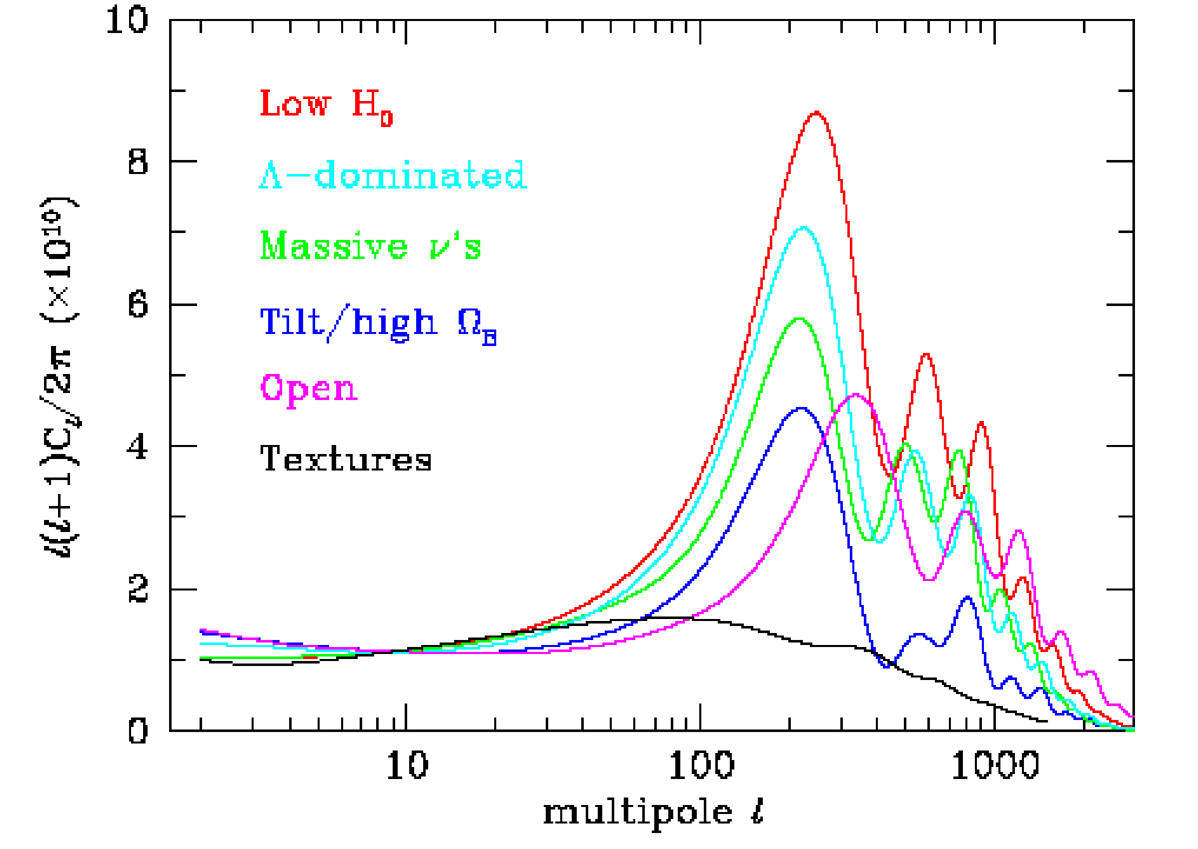
(Value of Q_{rms} predicted by the measured higher order moments of the power spectrum when a power law is assumed **Hinshaw et al. 1996, Gorski et al. 1996**)

Best-fit slope power spectrum of primordial density fluctuations

$n = 1.2 \pm 0.3$



Dependence on cosmological parameters



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

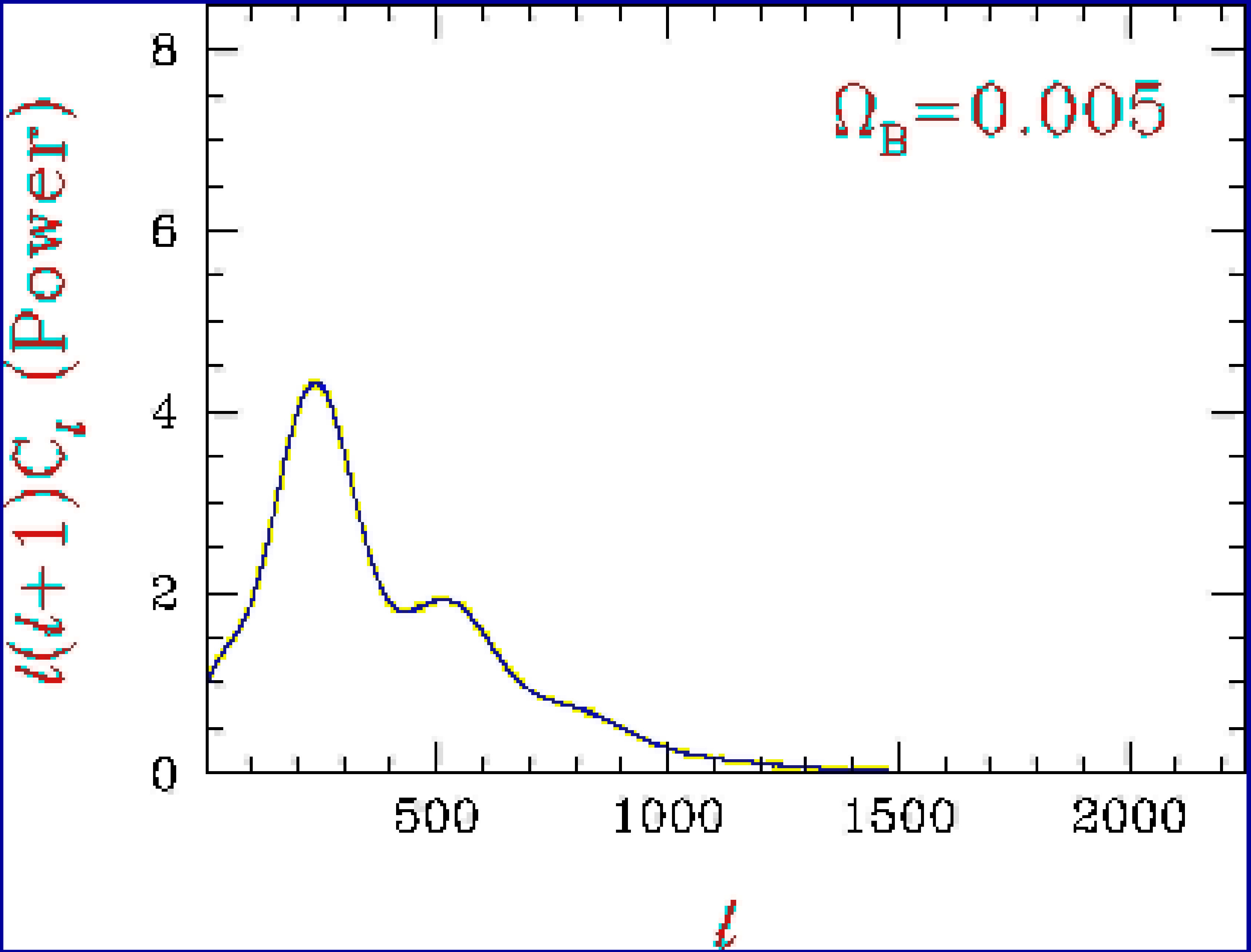
initial fluctuations spectrum

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

The parameters

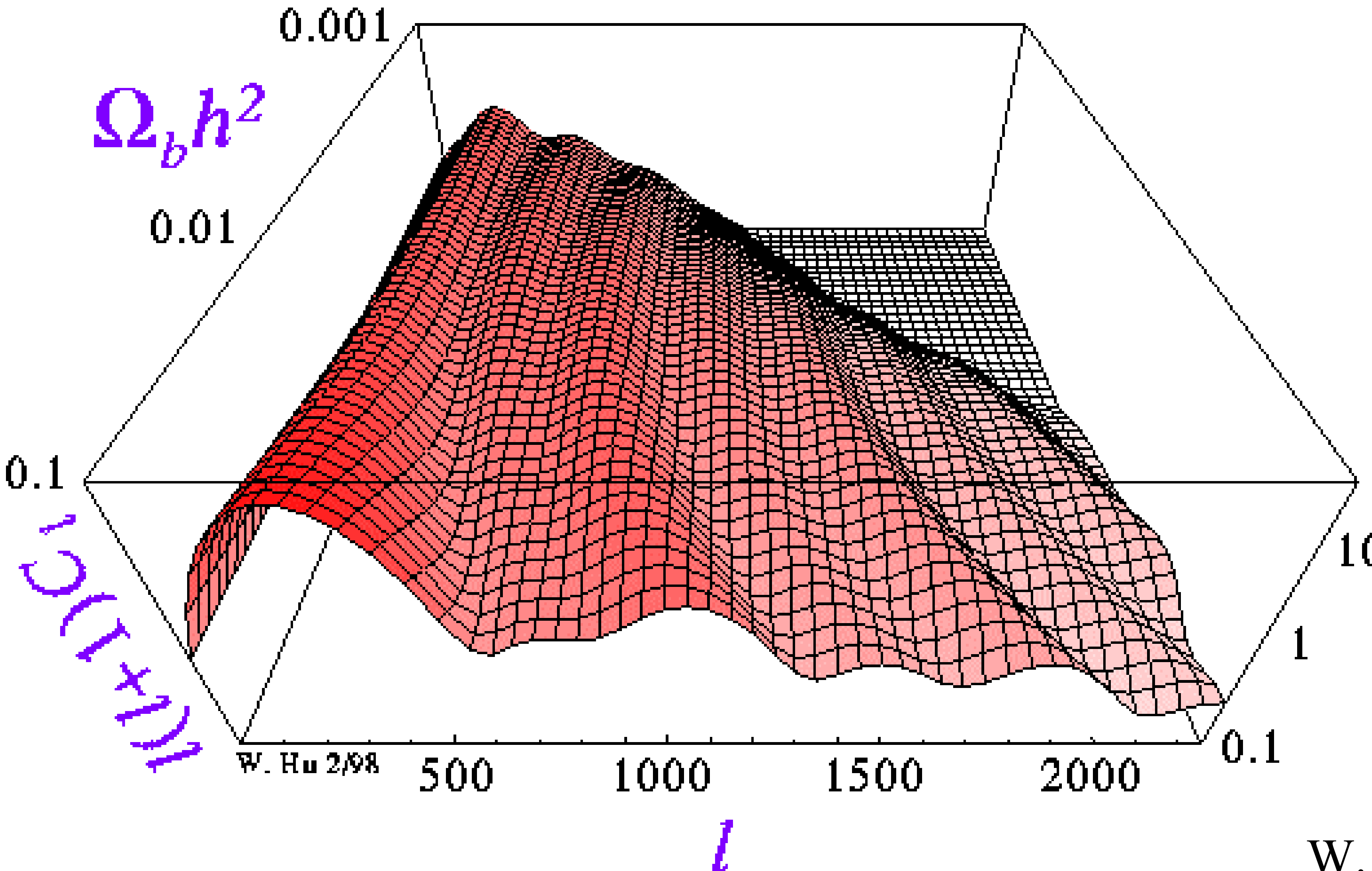
- t_0 age of the Universe
- H_0 Expansion rate at present epoch
- Total matter/energy density: Ω_0 fraction of the critical energy density contributed by all forms of matter and energy at the present epoch
- $\Omega_0 = \rho_{tot} / \rho_{crit} = \Sigma\, \Omega_i$,, $\Omega = \rho_i / \rho_{crit}$

  - $\rho_{crit} = 3\, H_0^2 / 8\pi\, G \cong 1.88 h^2 \times 10^{-29}\ gcm^{-3}$
  - 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 --- > $\Lambda / 3\, H_0^2$
  - $\rho_{tot} = \rho_m + \rho_\gamma + \rho_\Lambda$



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

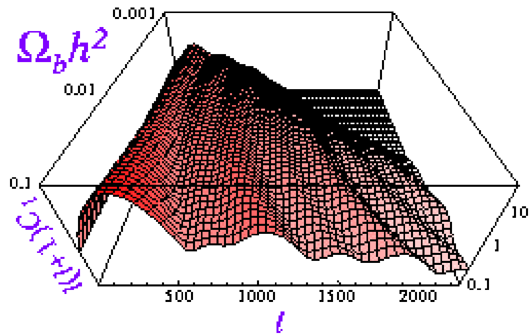
Baryon–Photon Ratio
in the CMB



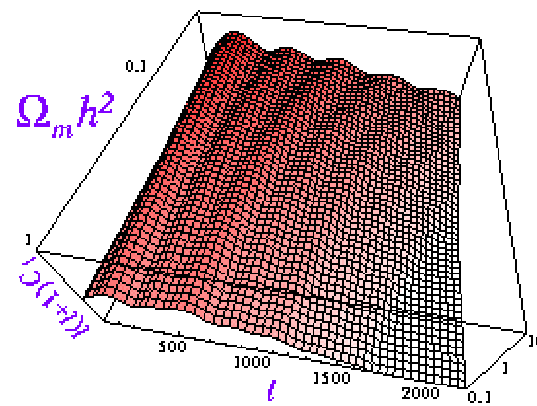
W. Hu

Cosmological Parameters in the CMB

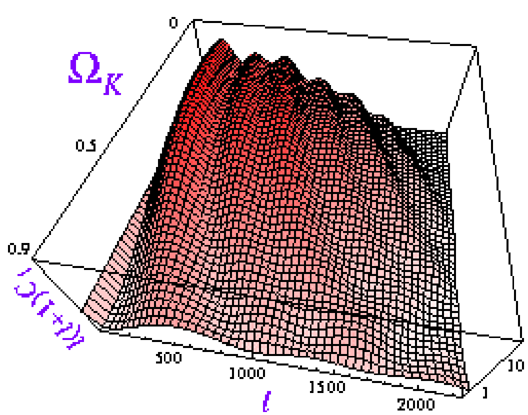
Baryon–Photon Ratio



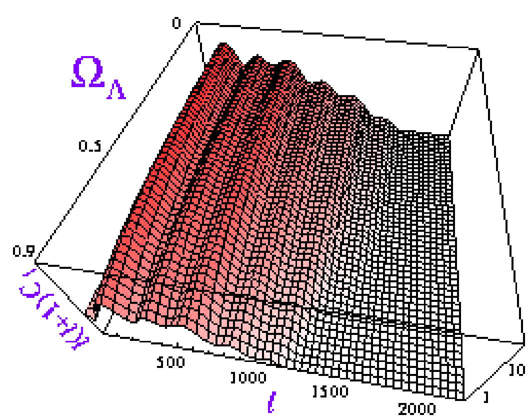
Matter–Radiation Ratio



Curvature



Cosmological Constant



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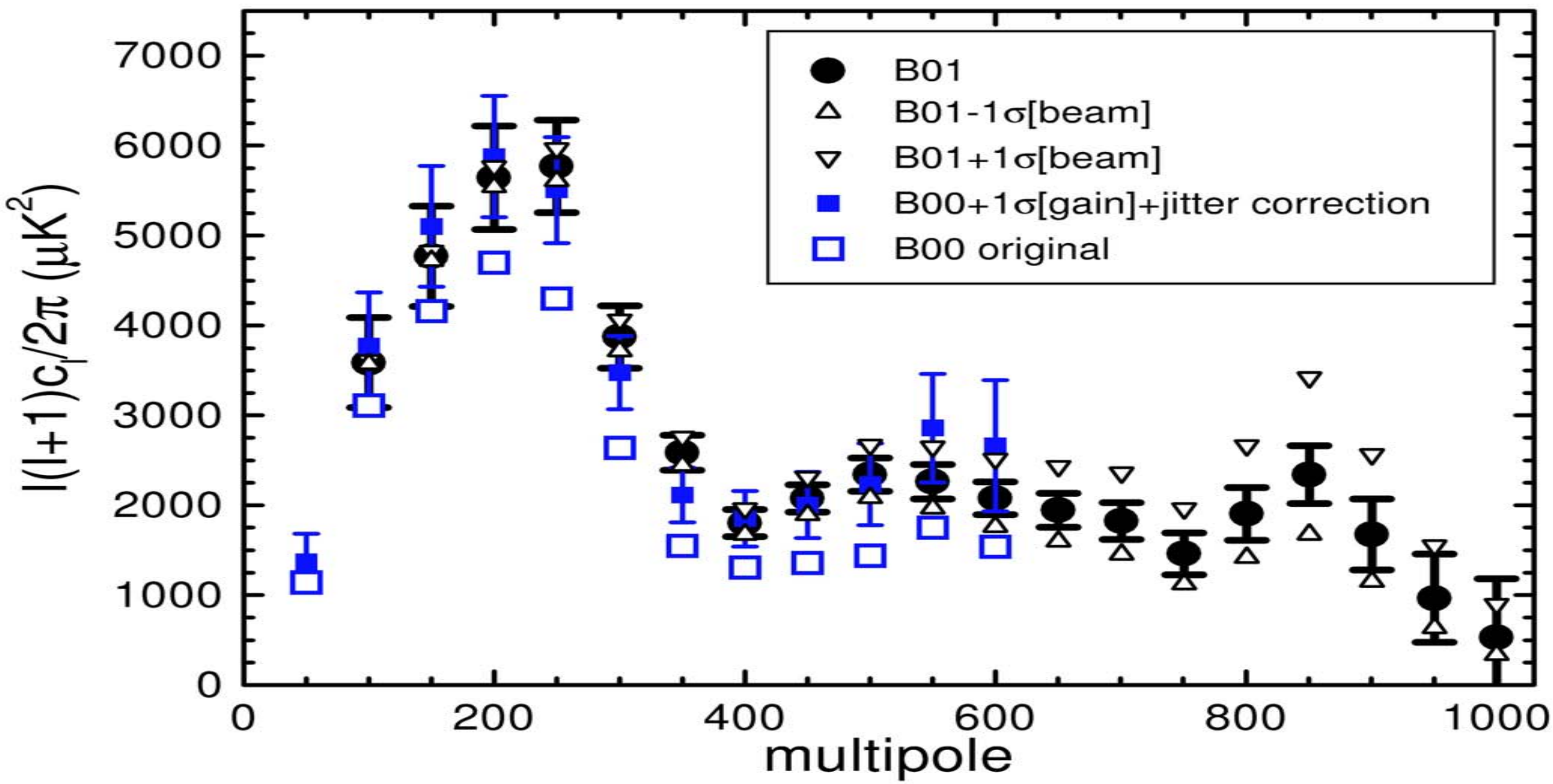
CMB experiments (after COBE)

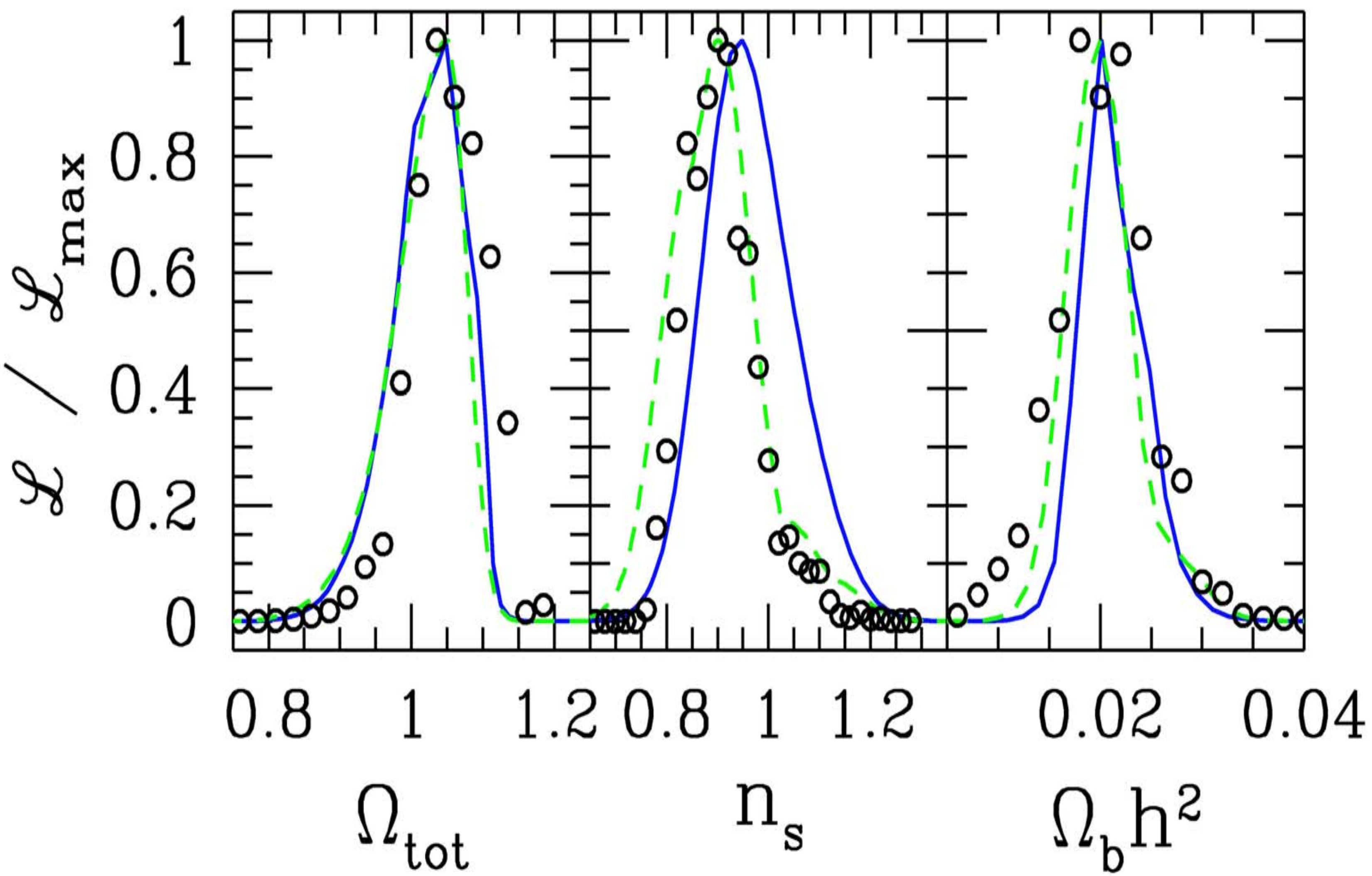
Balloon-borne experiments

- 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

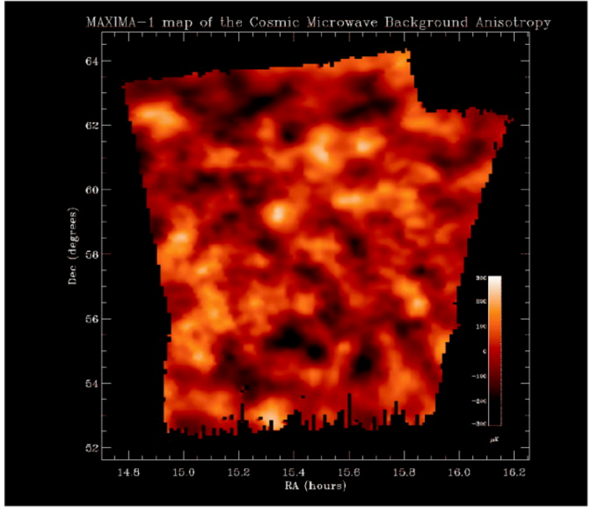


BOOMERANG results
(de Bernardis et al. 2001, astro-ph/0105296)



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 $\Delta T_{rms} = 78 \pm 6$ μK 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

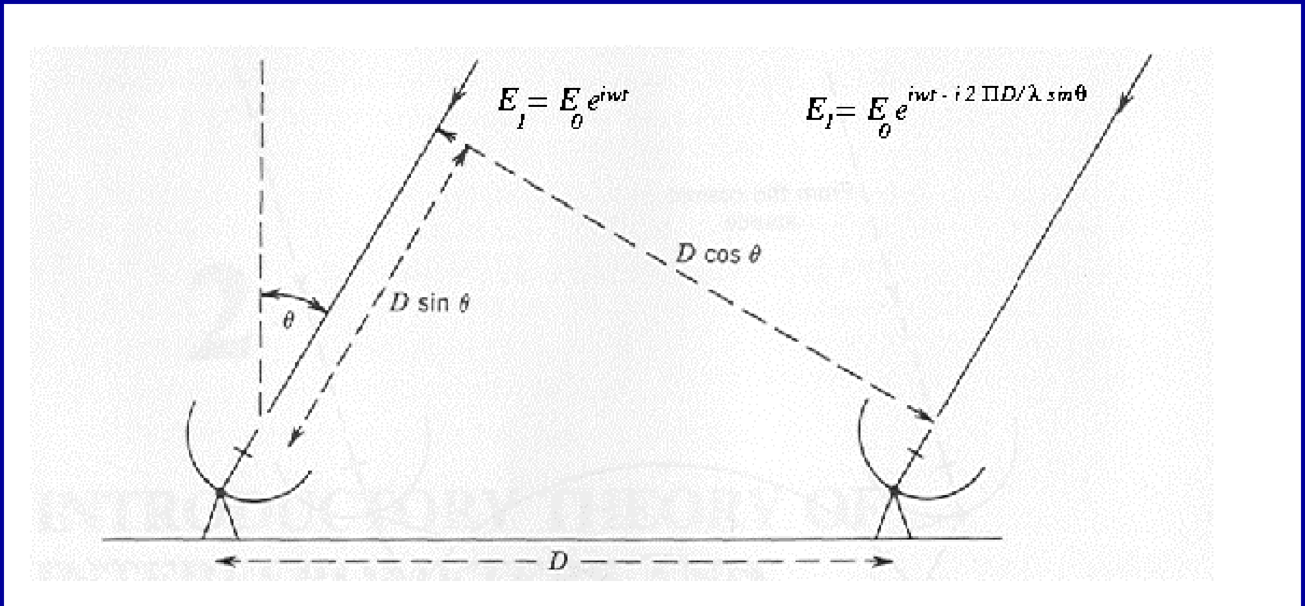
de Bernardis et al. 2001 astro-ph/0105296

- $\Omega_0 = 0.98 \pm 0.14$ 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 Antartica

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

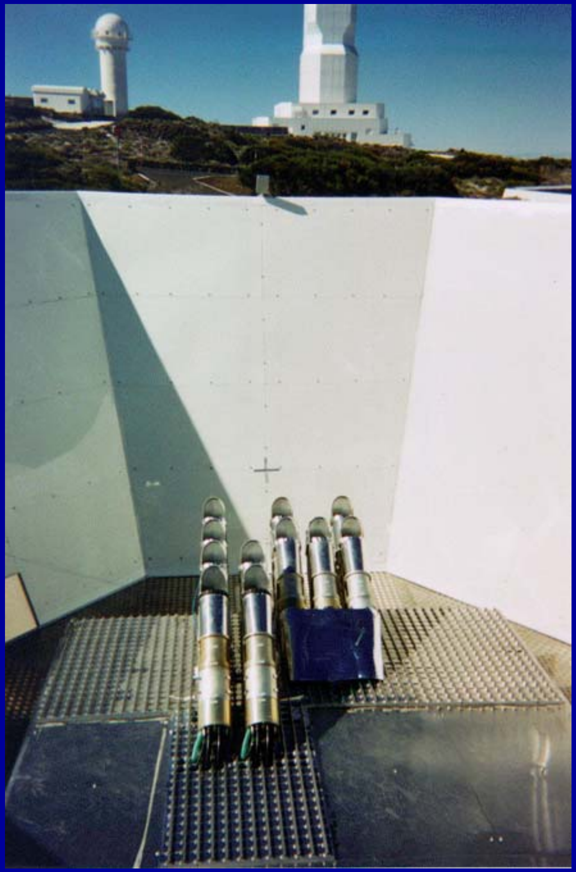
Cosmic Background Imager

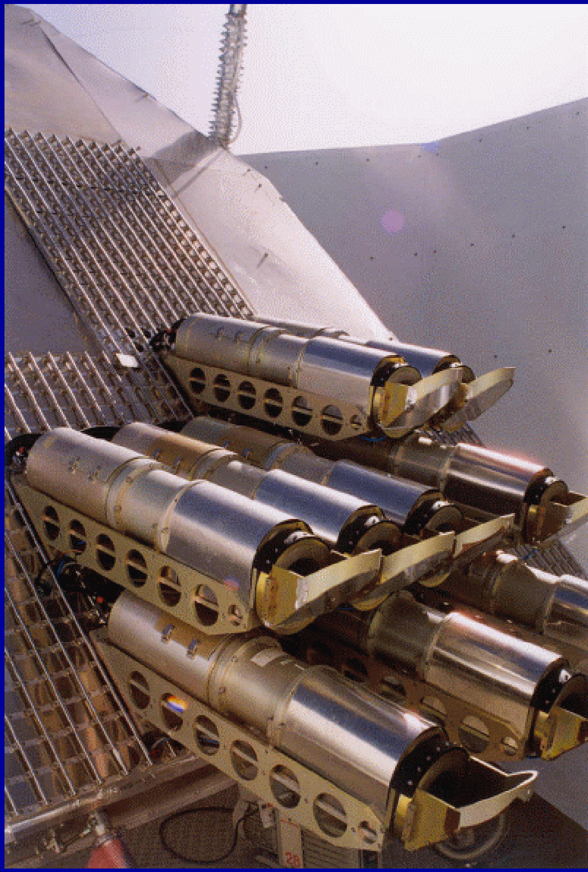
CBI Site at 5080m altitude in northern Chile

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

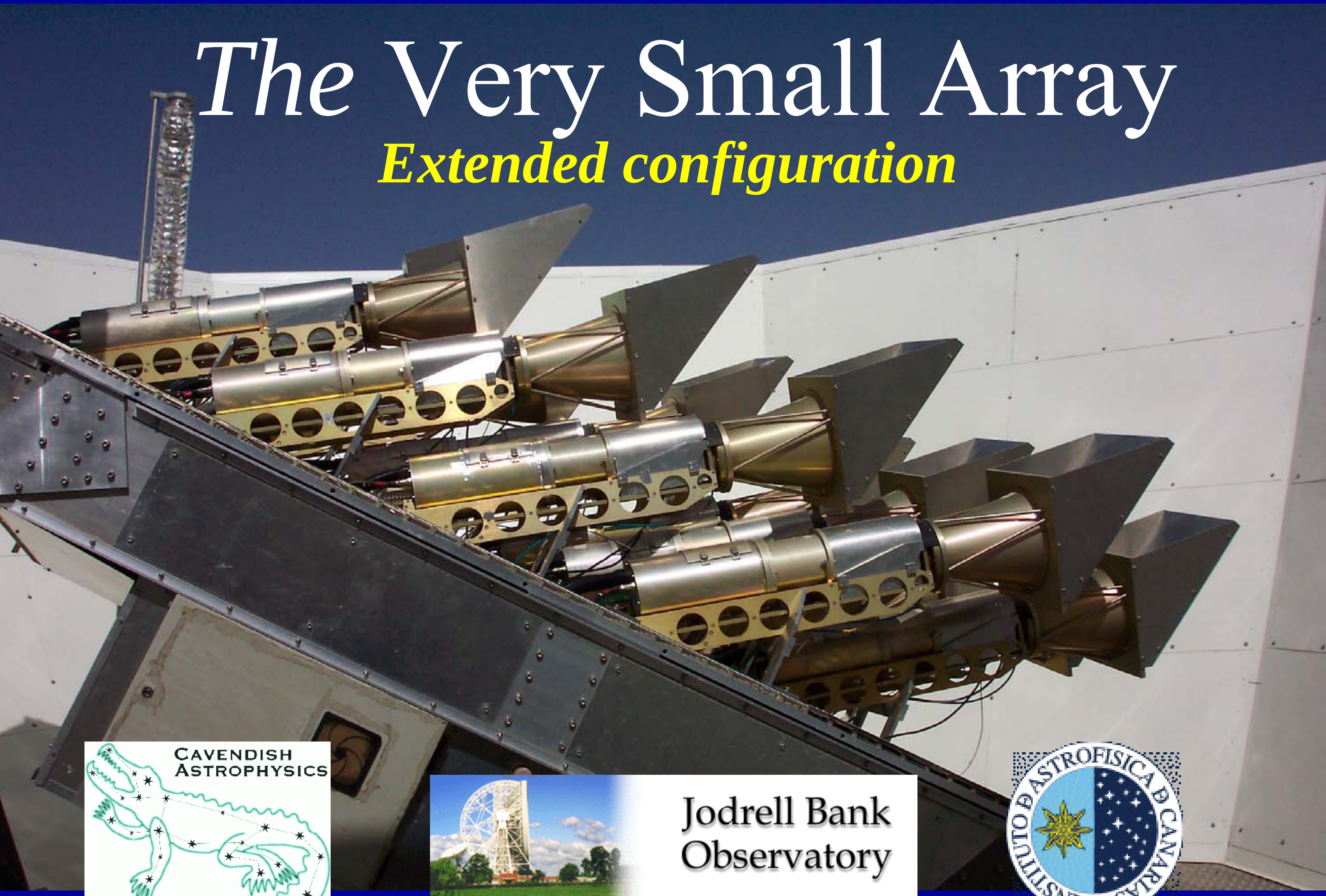
  FoV 4.5 degrees. Resolution element : 15 arcmin.





The Very Small Array

Extended configuration



CAVENDISH ASTROPHYSICS

Jodrell Bank Observatory

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

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).

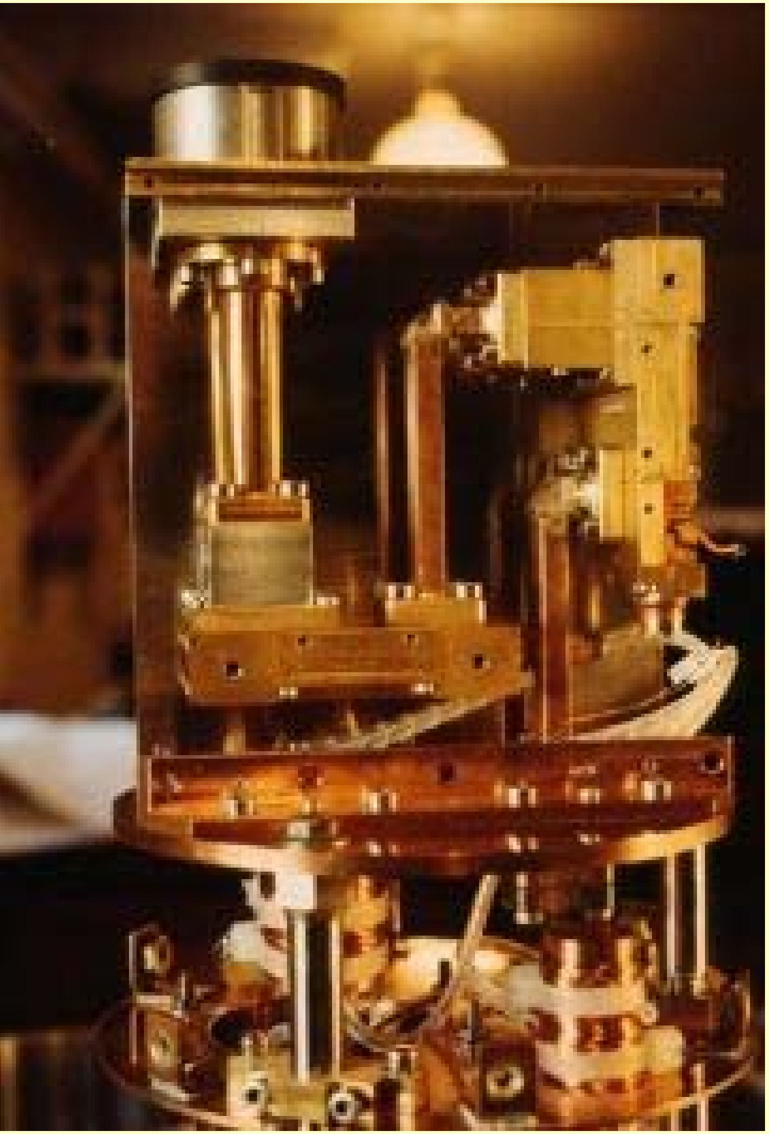
The 90º reflector gives the antennas a periscope-like property so they can be close packed like organ pipes.

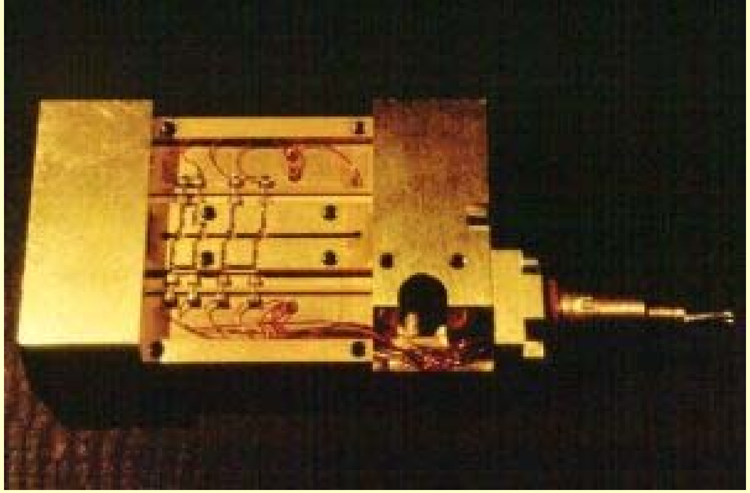
This can be rotated to give one dimension of independent tracking.

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

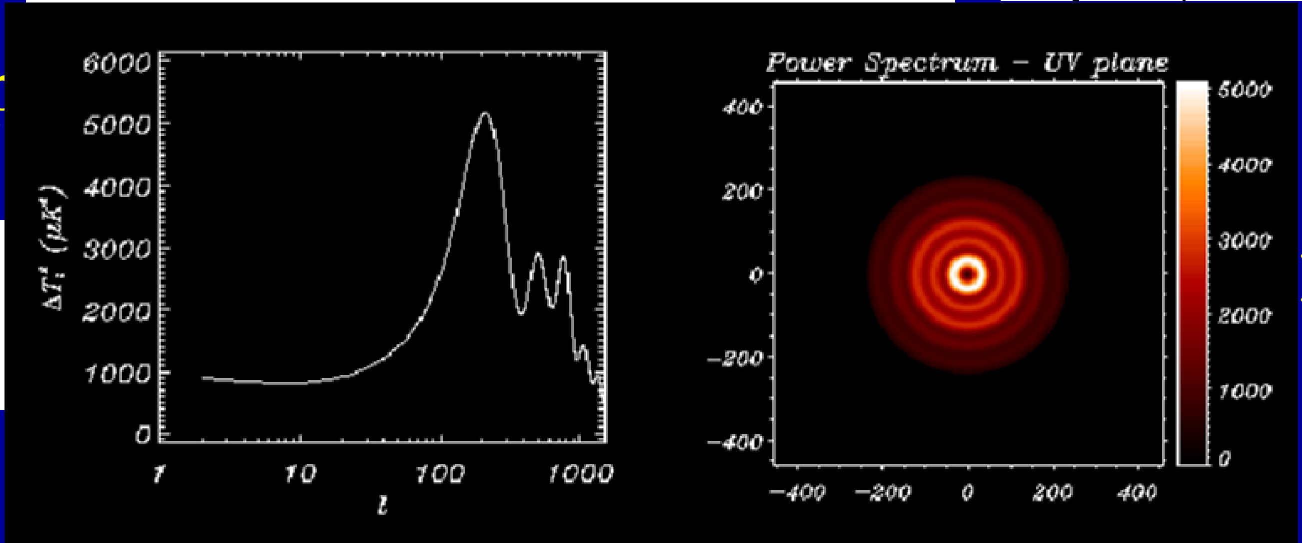
$$\frac{\Delta T}{T_0}(\vec{x}) = \sum_{\ell m} a_{\ell m} Y_{\ell m} \approx \int a(\vec{u}) e^{i2\pi \vec{u}\cdot\vec{x}} d^2\vec{u}$$

u≈ℓ/(2π)

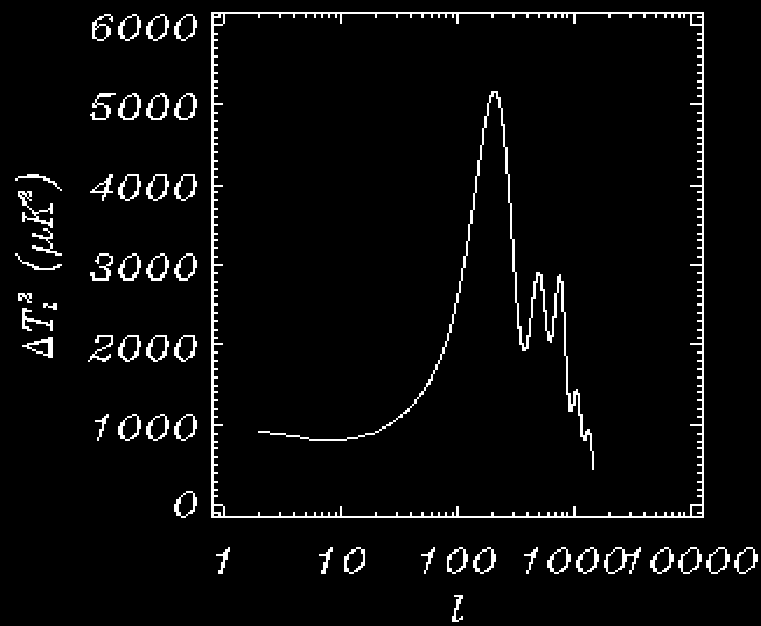
- ✓ Statistics:

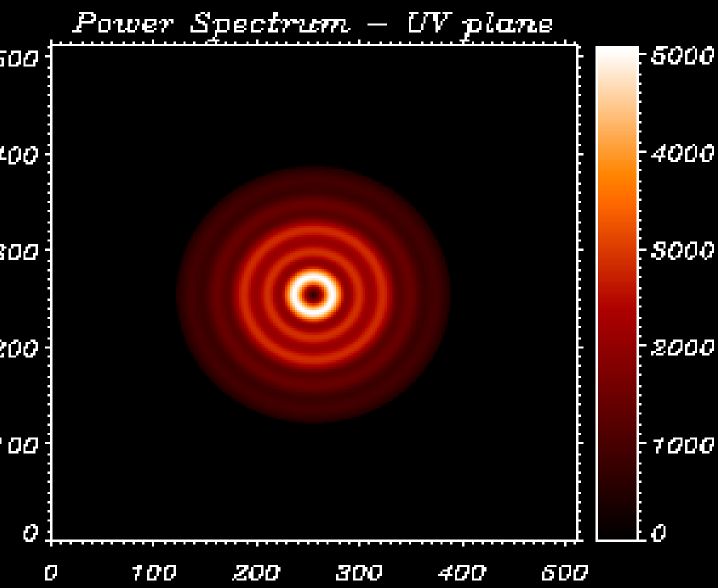
$$< a(\vec{u}) >= 0 \qquad < a^*(\vec{u}) a(\vec{u}') >= S(u)\delta^{(2)}(\vec{u}-\vec{u}'), \qquad a(-\vec{u}) = a^*(\vec{u})$$

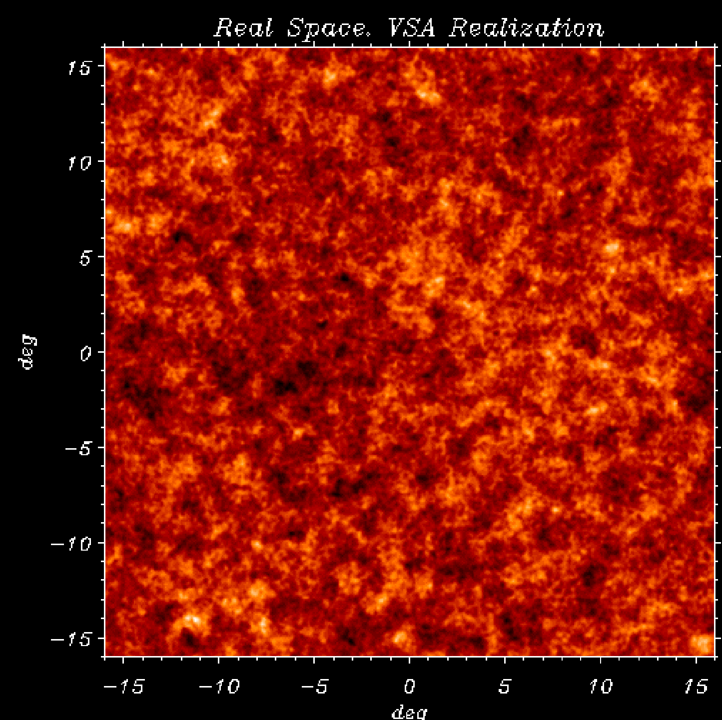
- ✓ Power sp

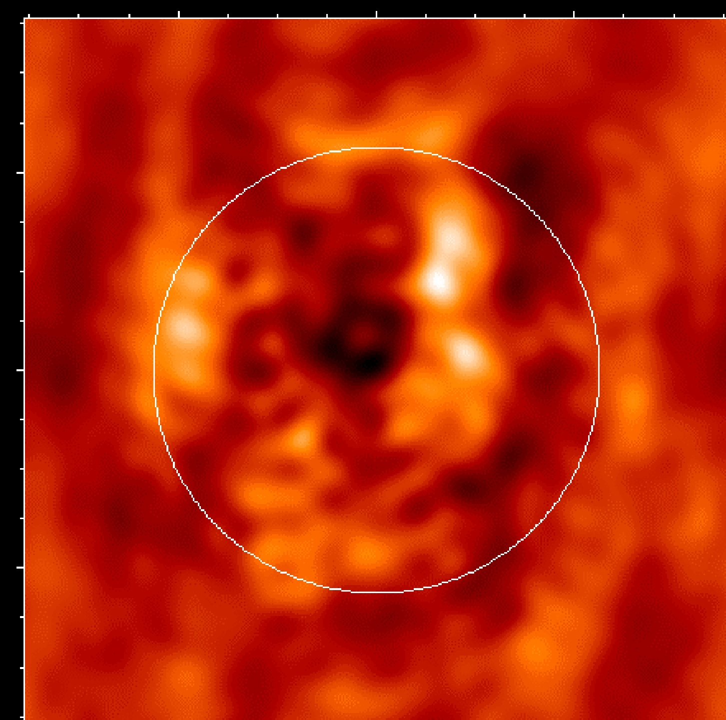


VSA simulations



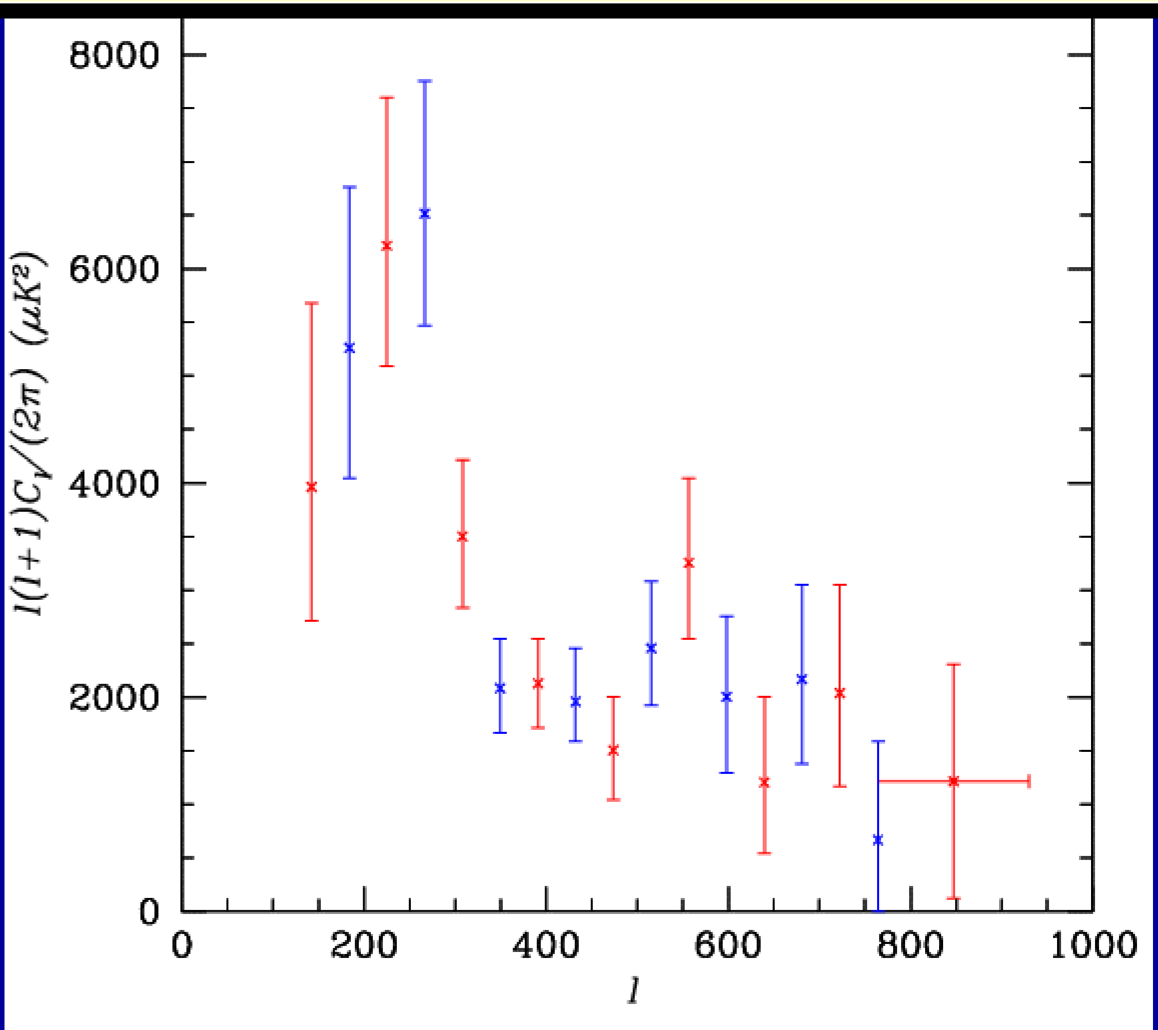






First VSA angular power spectrum (compact configuration)

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

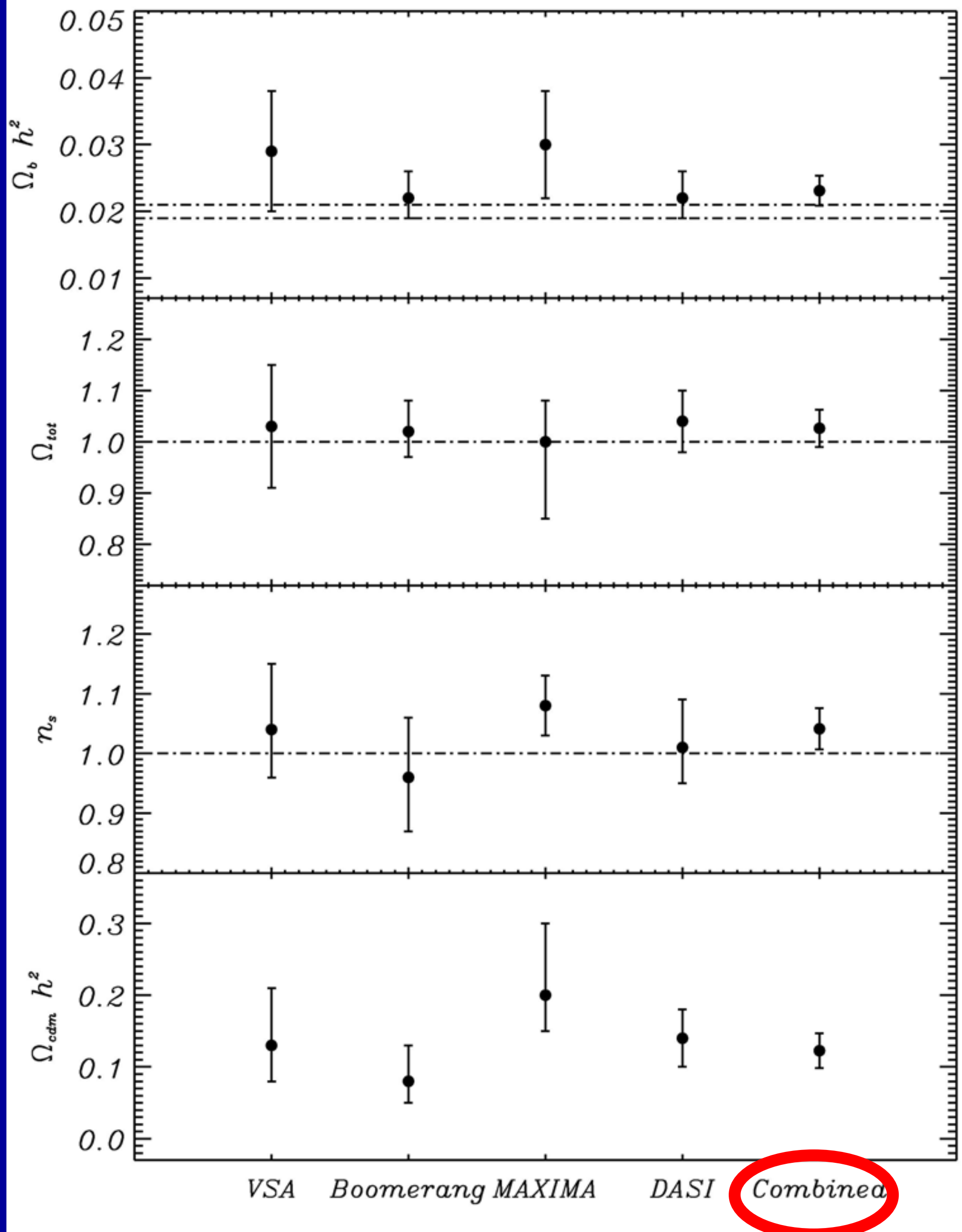


$\Omega_b\ h^2$

Ωtot

n_s

$\Omega_{cdm}\ h^2$



CMB constraints on cosmological parameters

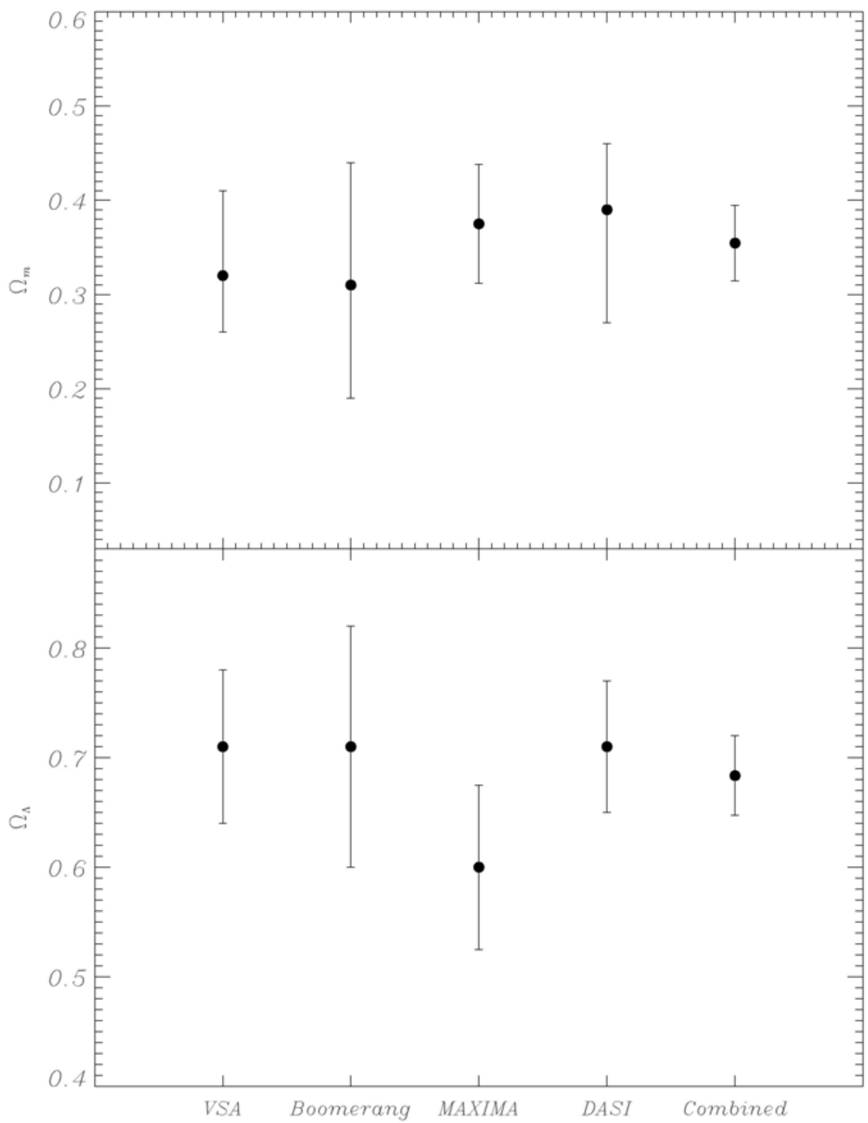
(pre-WMAP

Data)

Rubiño-Martín, Rebolo et al. 2003

Ω_m

Ω_{lambda}

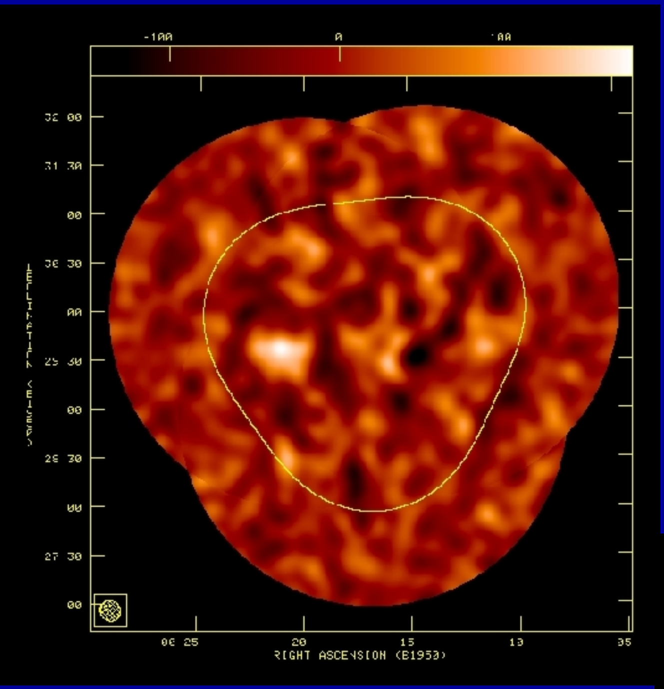


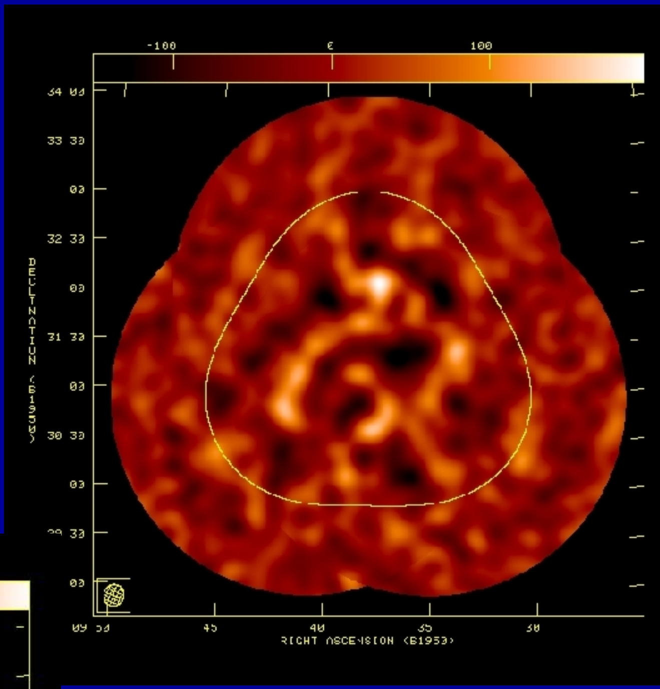
CMB constraints on cosmological parameters

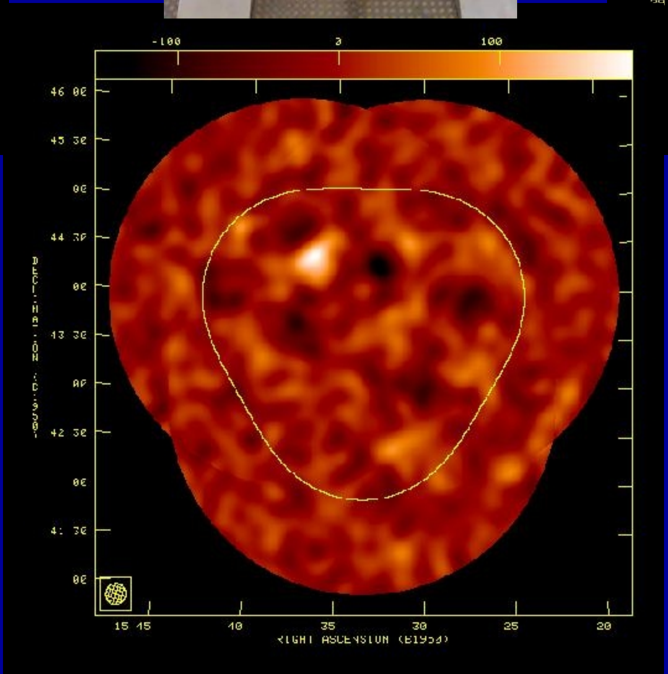
Rubiño-Martín et al. 2003, MNRAS 341, 1084

Extended configuration VSA

(December 2002)

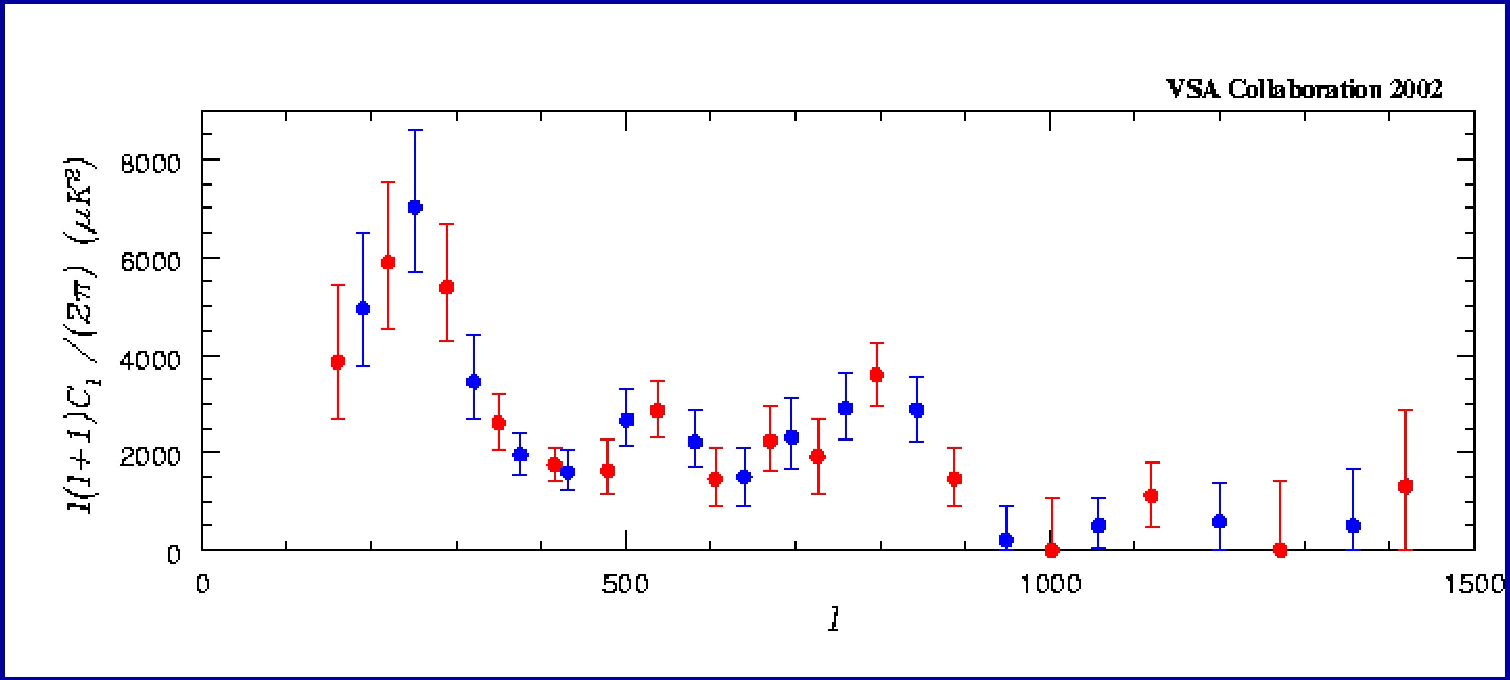






(Grainge et al.2003)

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

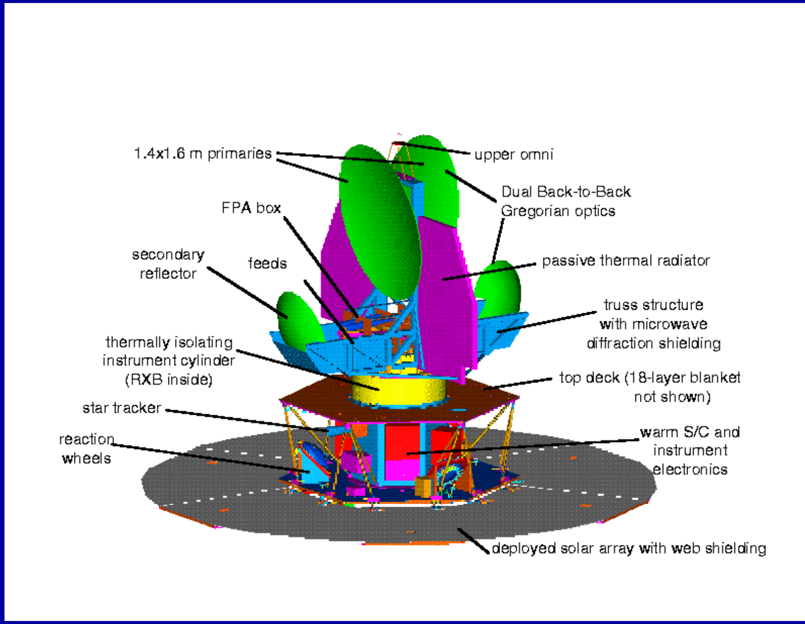
Bayesian analysis using Monte-Carlo Markov Chains.

Priors: huble constant, 2dF and SNIa

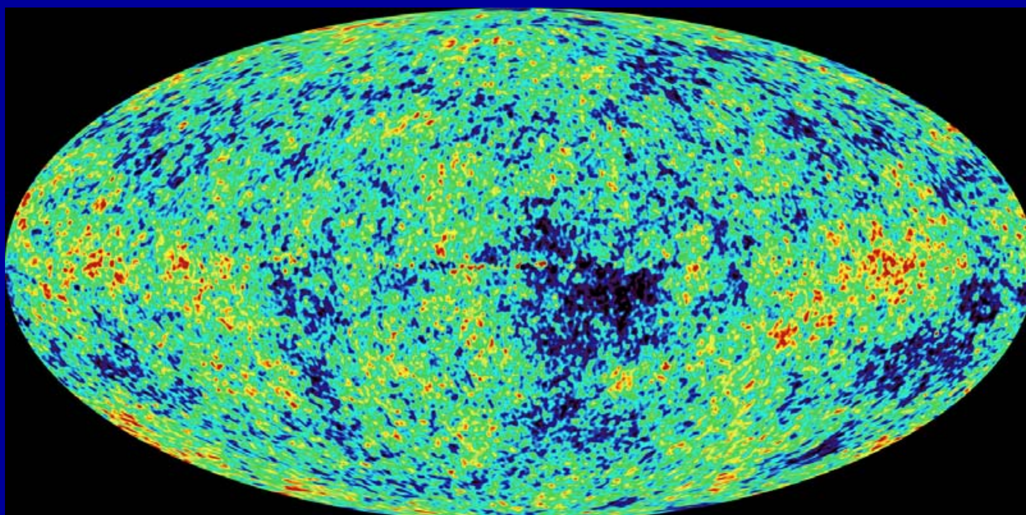
o

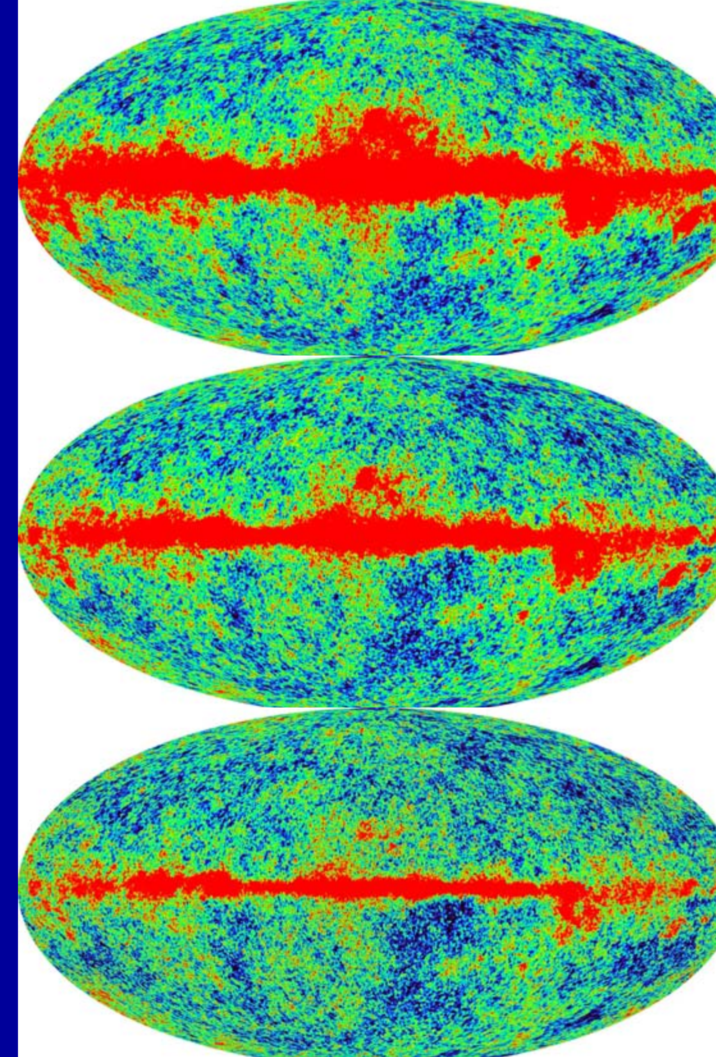
Microwave Anisotropy Probe (WMAP)

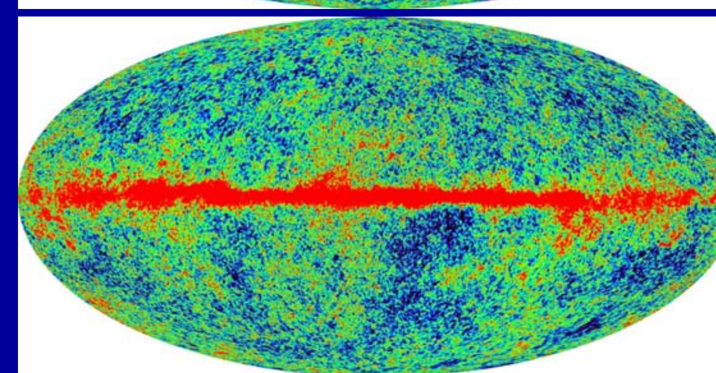
- Halo orbit about L2 Sun-Earth Lagrange point 1.5 million km from Earth
- Lifetime 27 months
- Differential pseudo-correlation with polarization
- Dual Gregorian 1.4 x 1.6 m primary reflector
- Passive radiative cooling to < 95 K
- Frequencies (GHz): 23, 33, 41, 61, 94
- FWHM (deg): .93 .68, .47, .35,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



WMAP
Mapa ILC del CMB



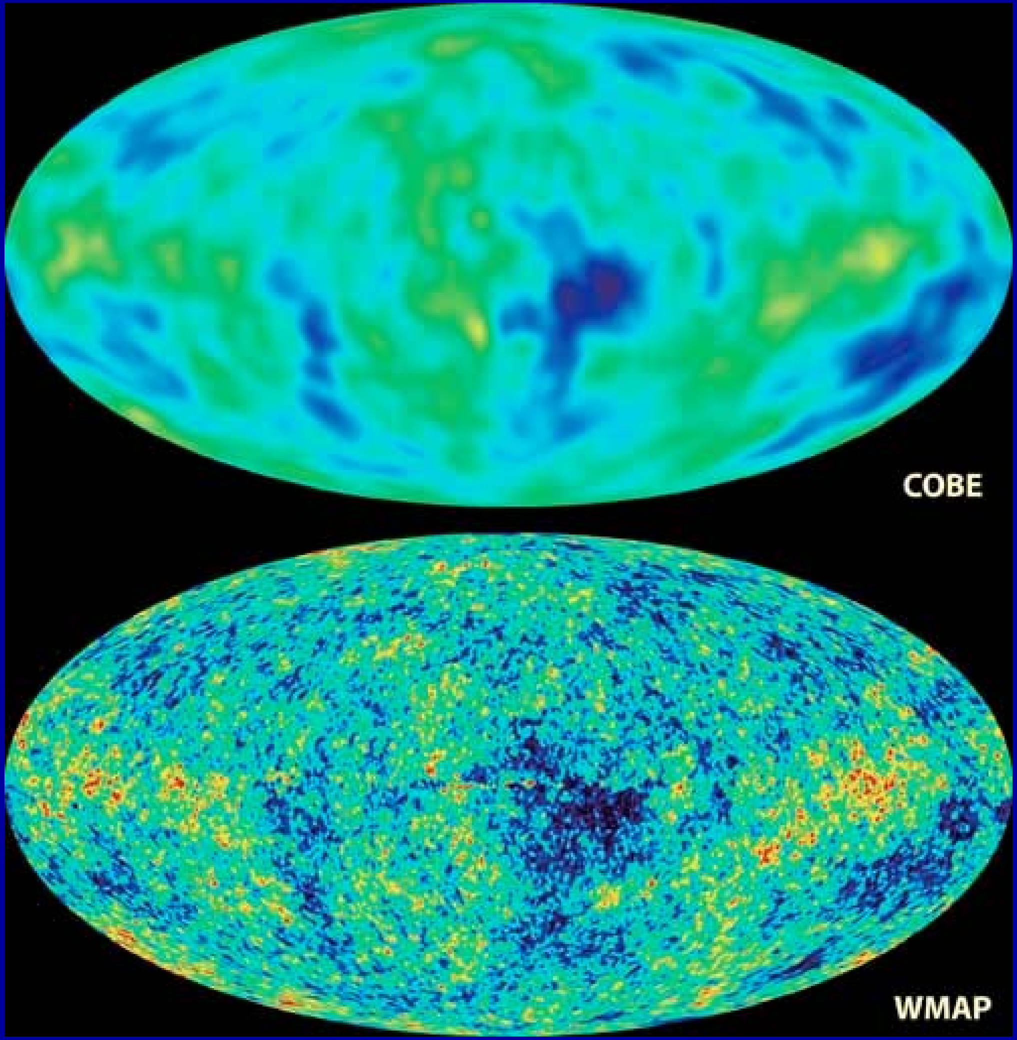


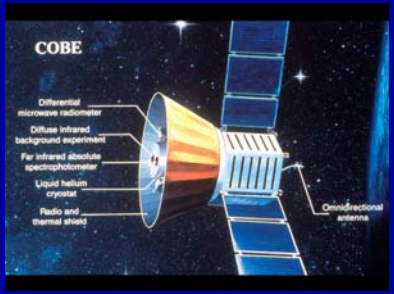


Cosmic Microwave Background

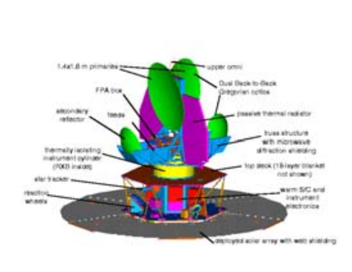
Then

Now



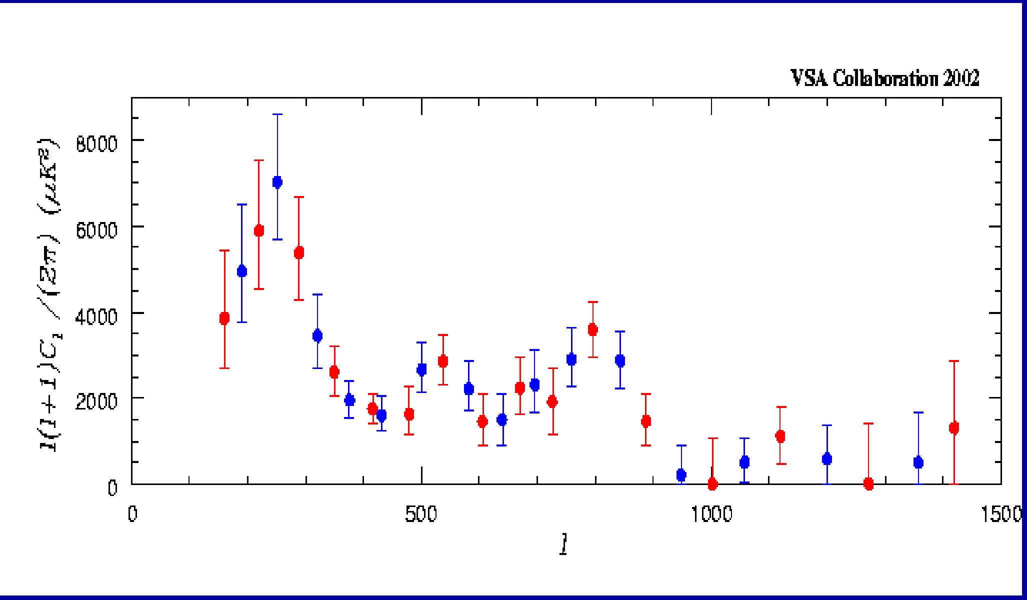


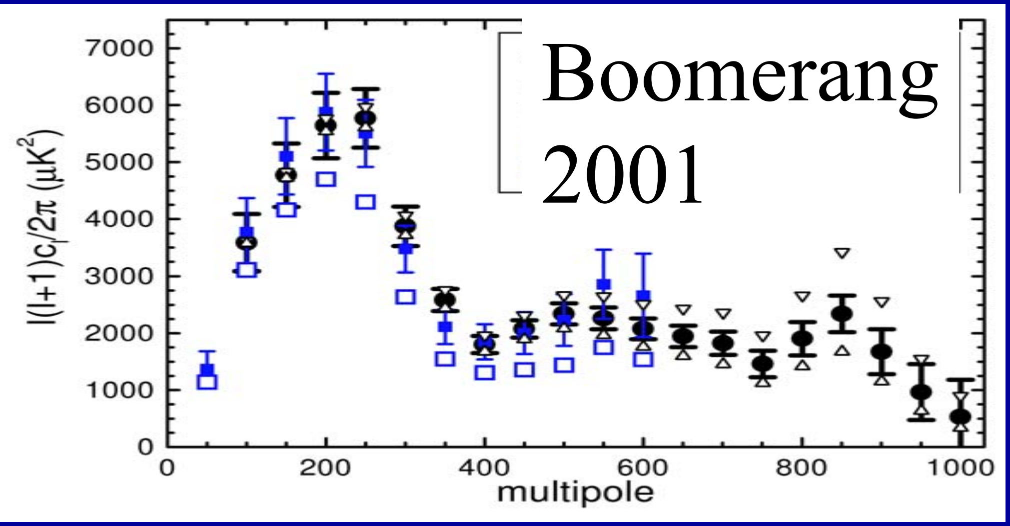
Constrains $\Omega_\Lambda + \Omega_M$

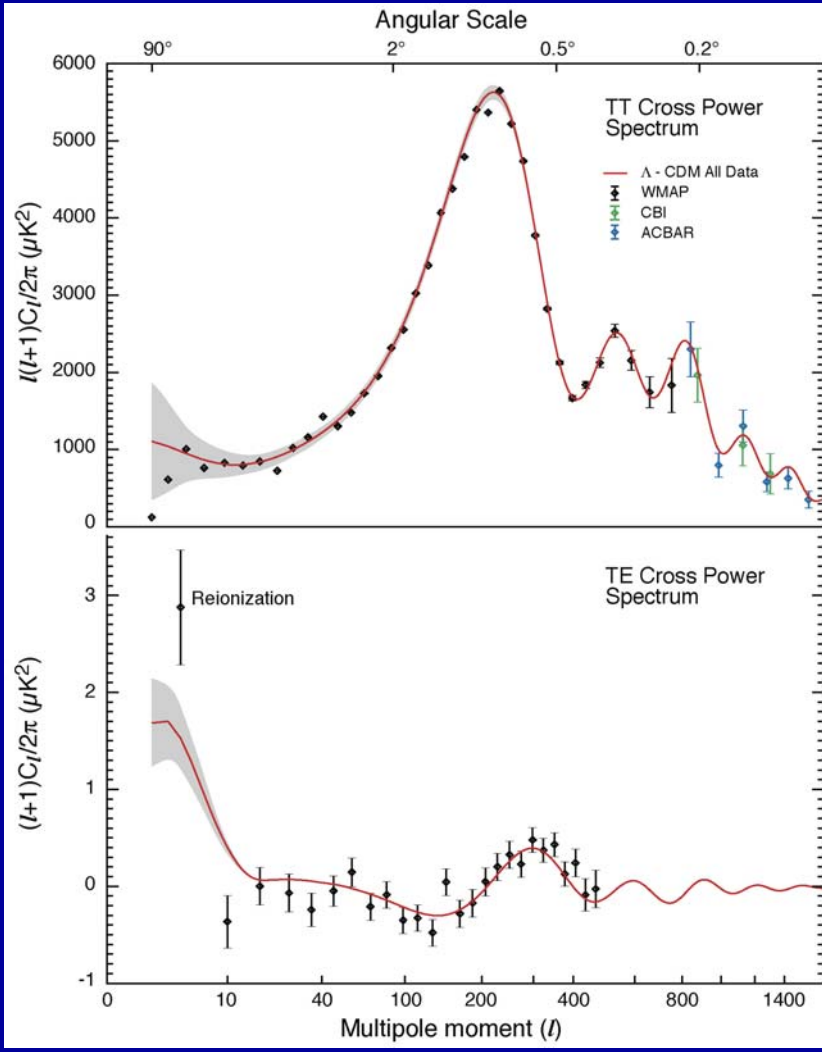


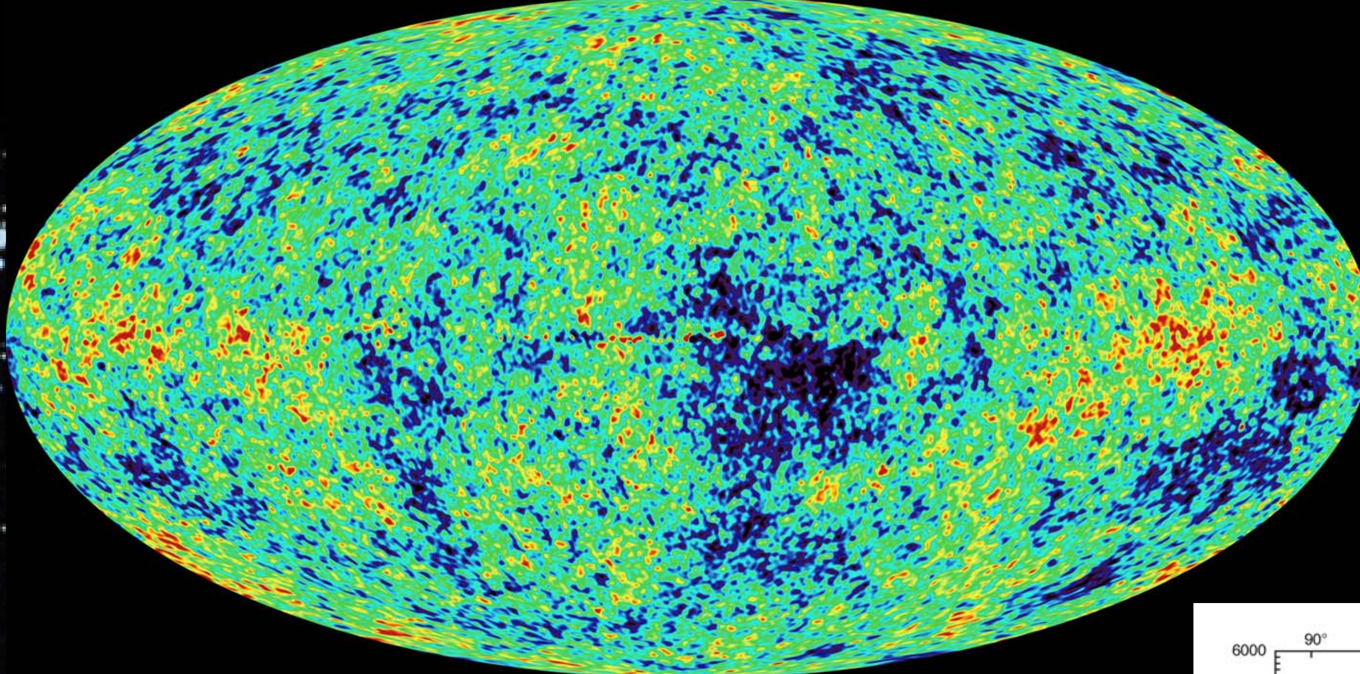
VSA December 2002

WMAP Feb. 2003









WMAP results Feb. 2003

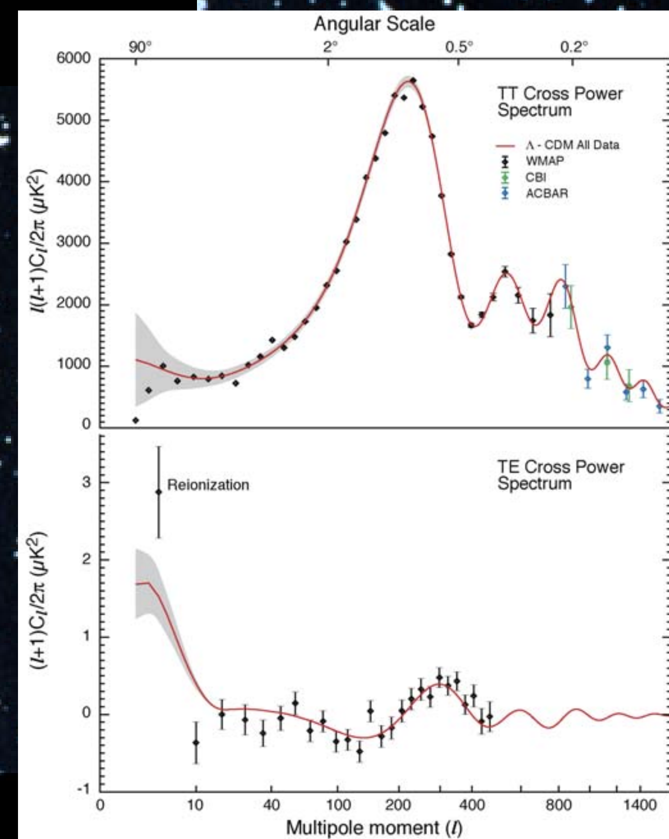


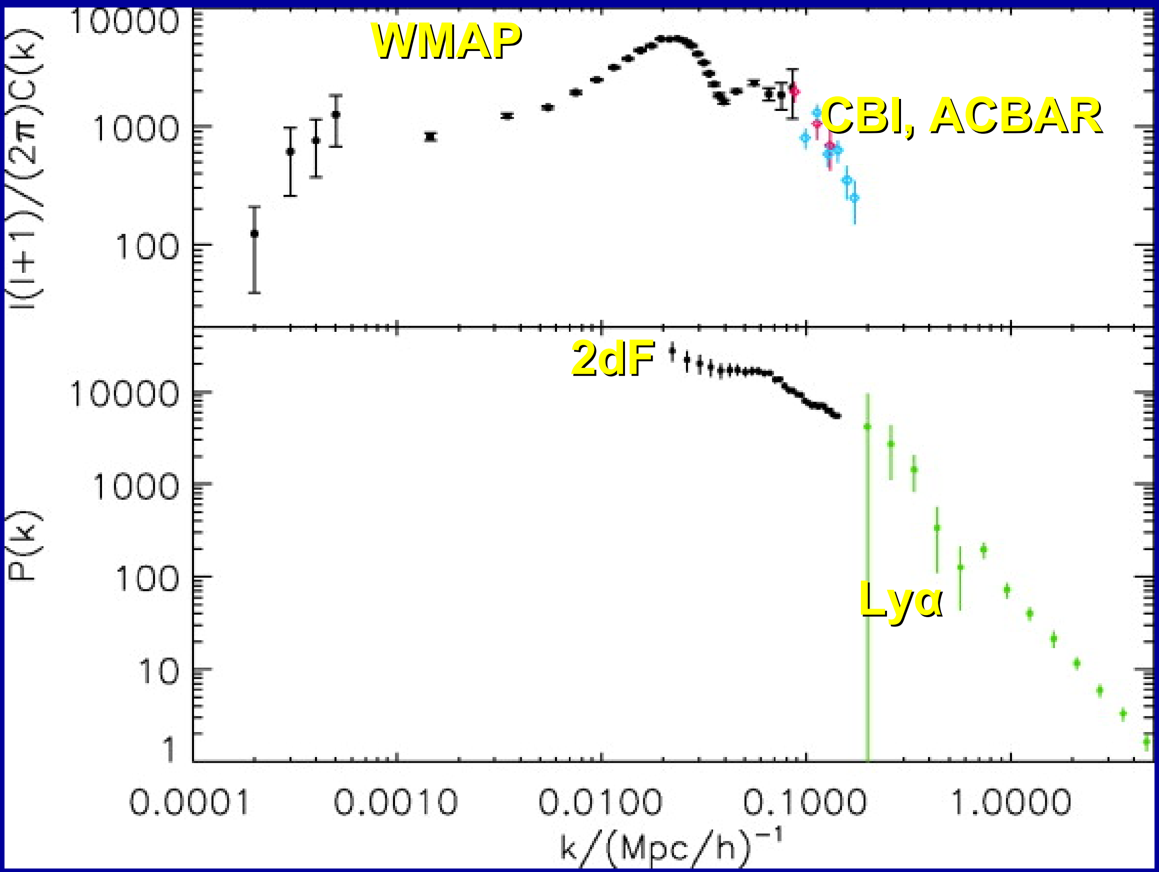
Table 2. Parameter estimates and 68% confidence limits for the standard six-parameter flat ΛCDM model.

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 1st year data



Spergel et al. 2003
ApJS 148,175

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.

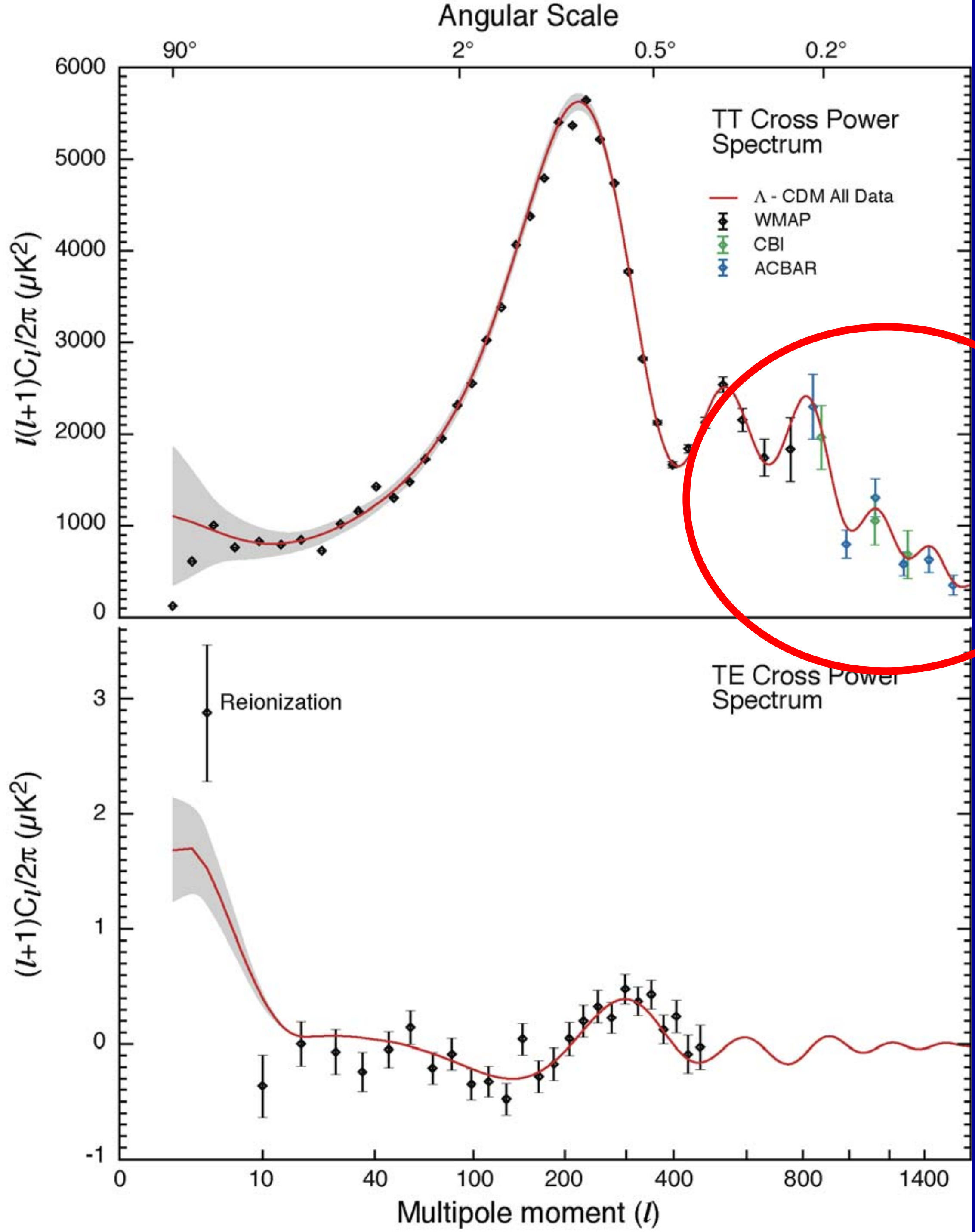
$n_{run} = -0.031 \pm 0.016$

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

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

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

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



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
- ....

The last 3 years

High Precision Cosmology (the past 3 years)

- 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.)

VSA Extended Configuration

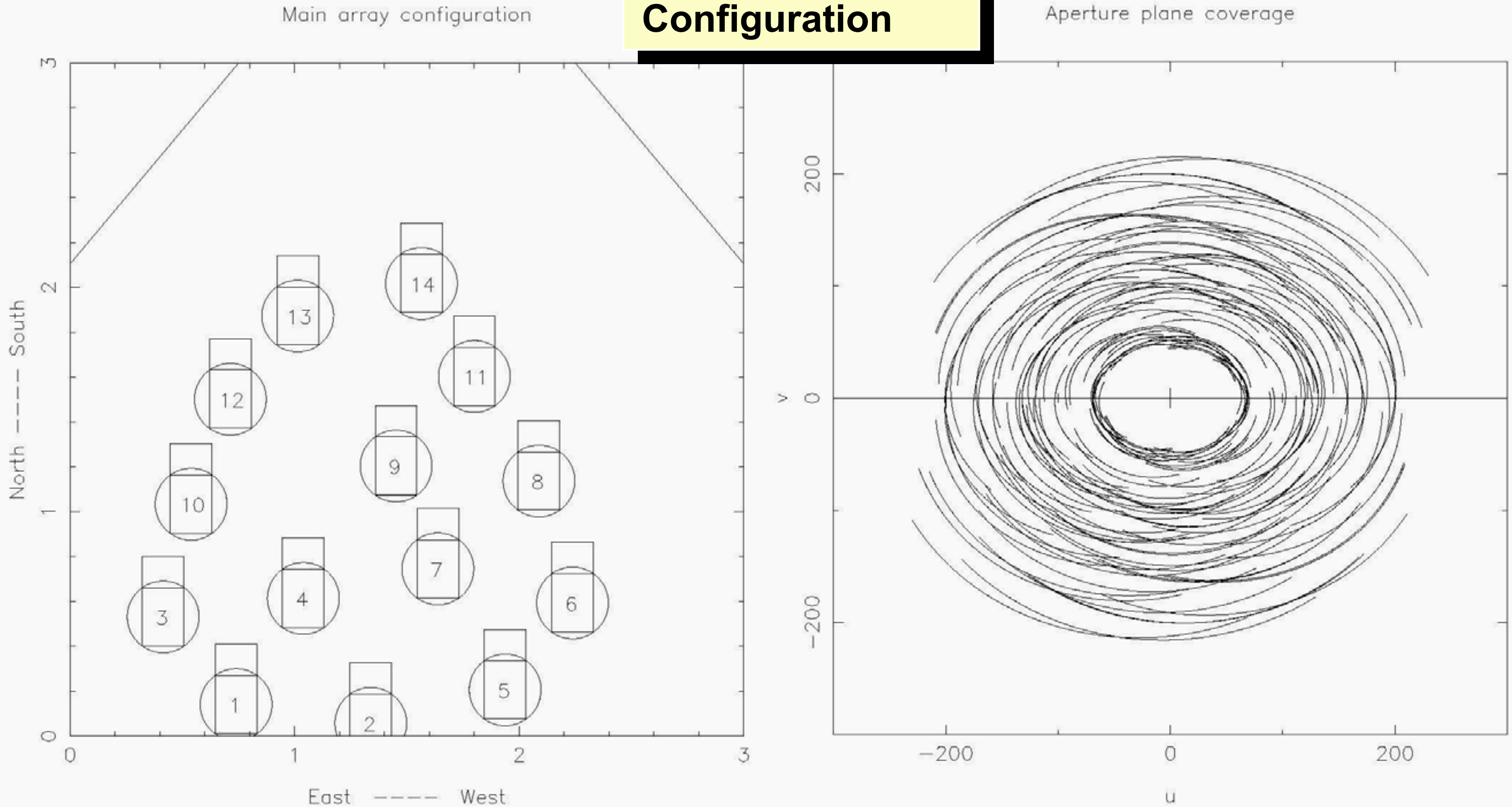
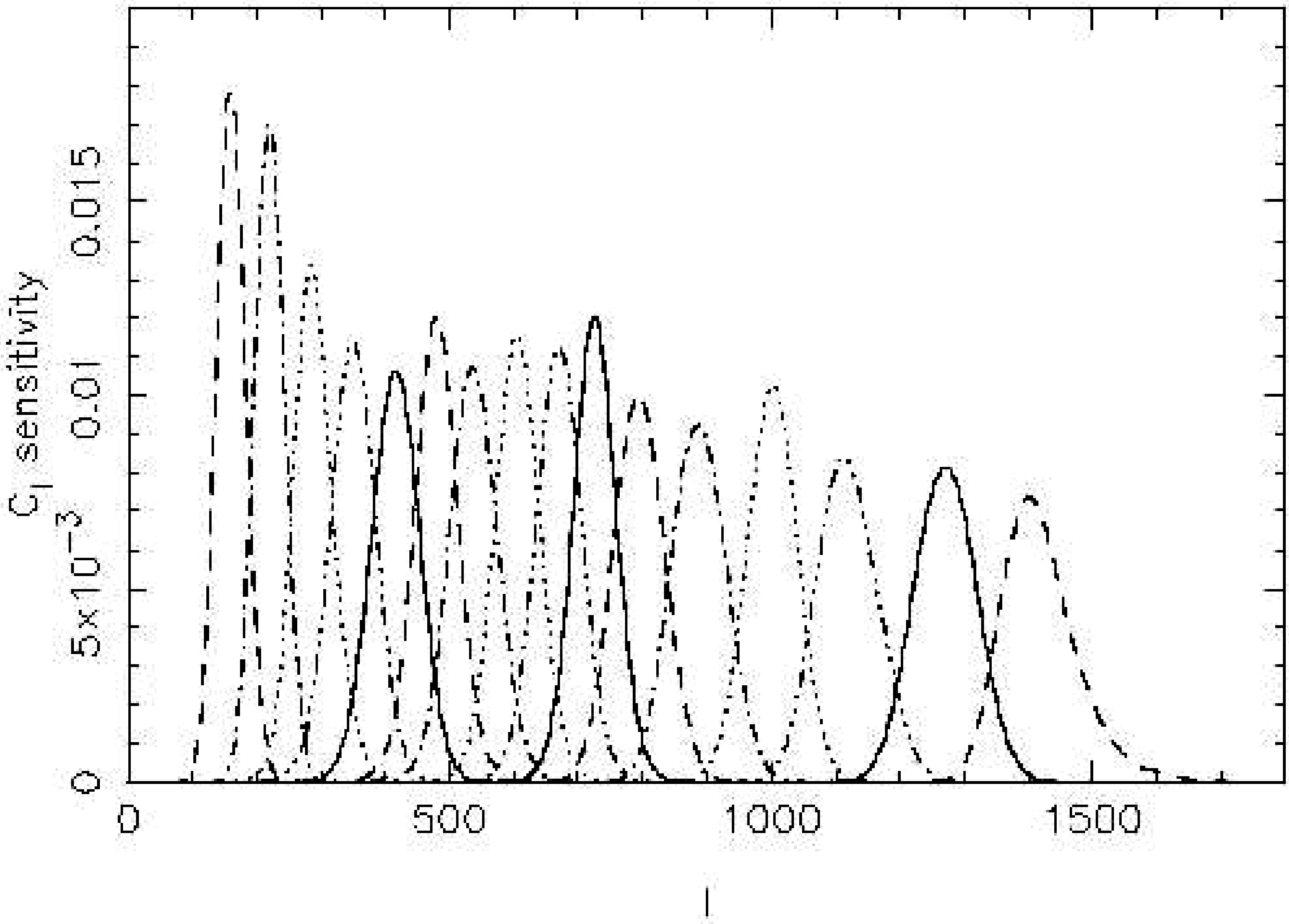
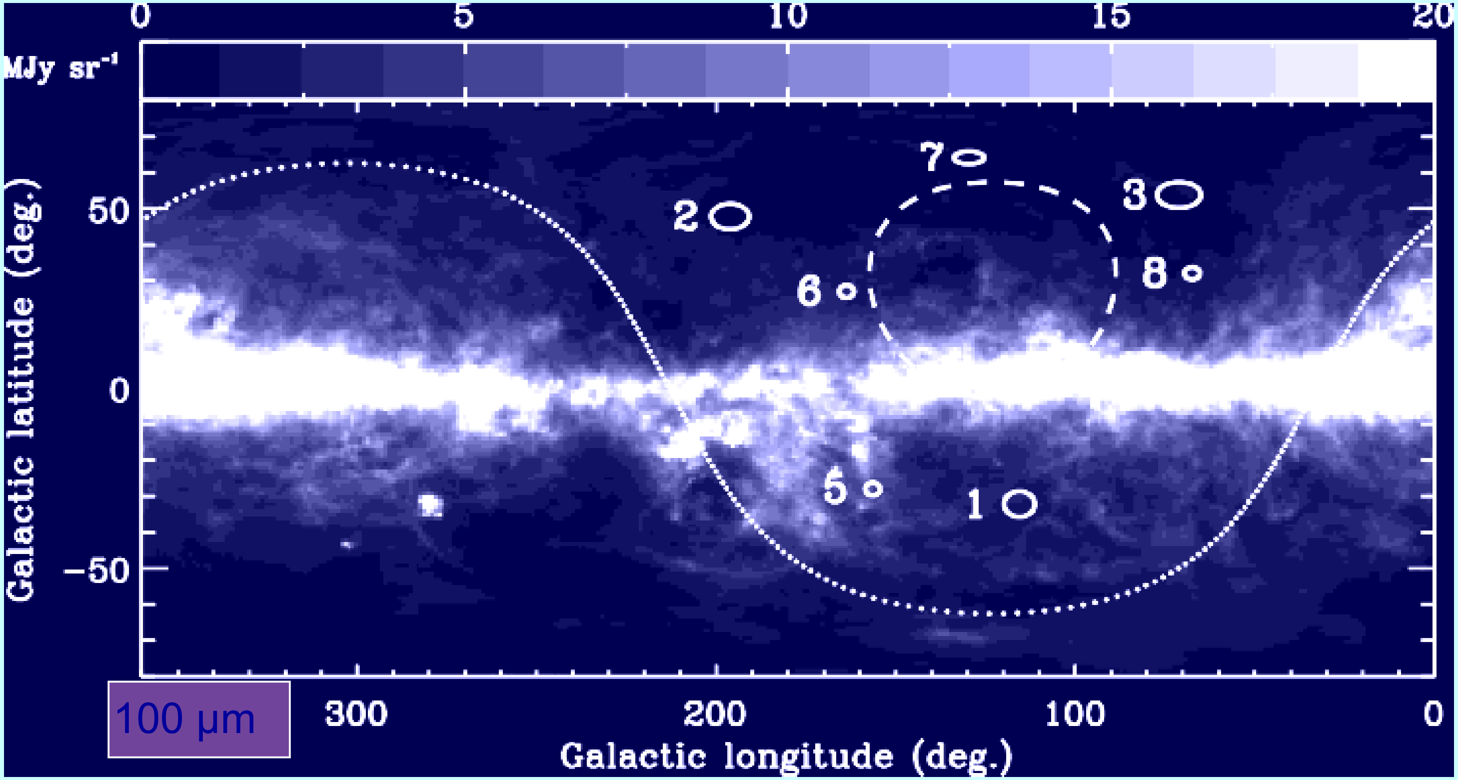


Figure 1. *Left*: Extended array configuration of the 14 antennas on the tip-tilt table. *Right*: The corresponding u, v coverage calculated for a 5 hour observation of a source at declination of $+40°$.

Window function



Selection of Fields



The 7 VSA Regions

VSA1: 7 fields
α 00^{h}19^{m}22^s δ +29°16'39"

VSA2: 7 fields
09 40 53 +31 46 21

VSA3: 7 fields
15 35 13 +42 45 05

VSA5: 3 fields
03 05 45 +27 16 35

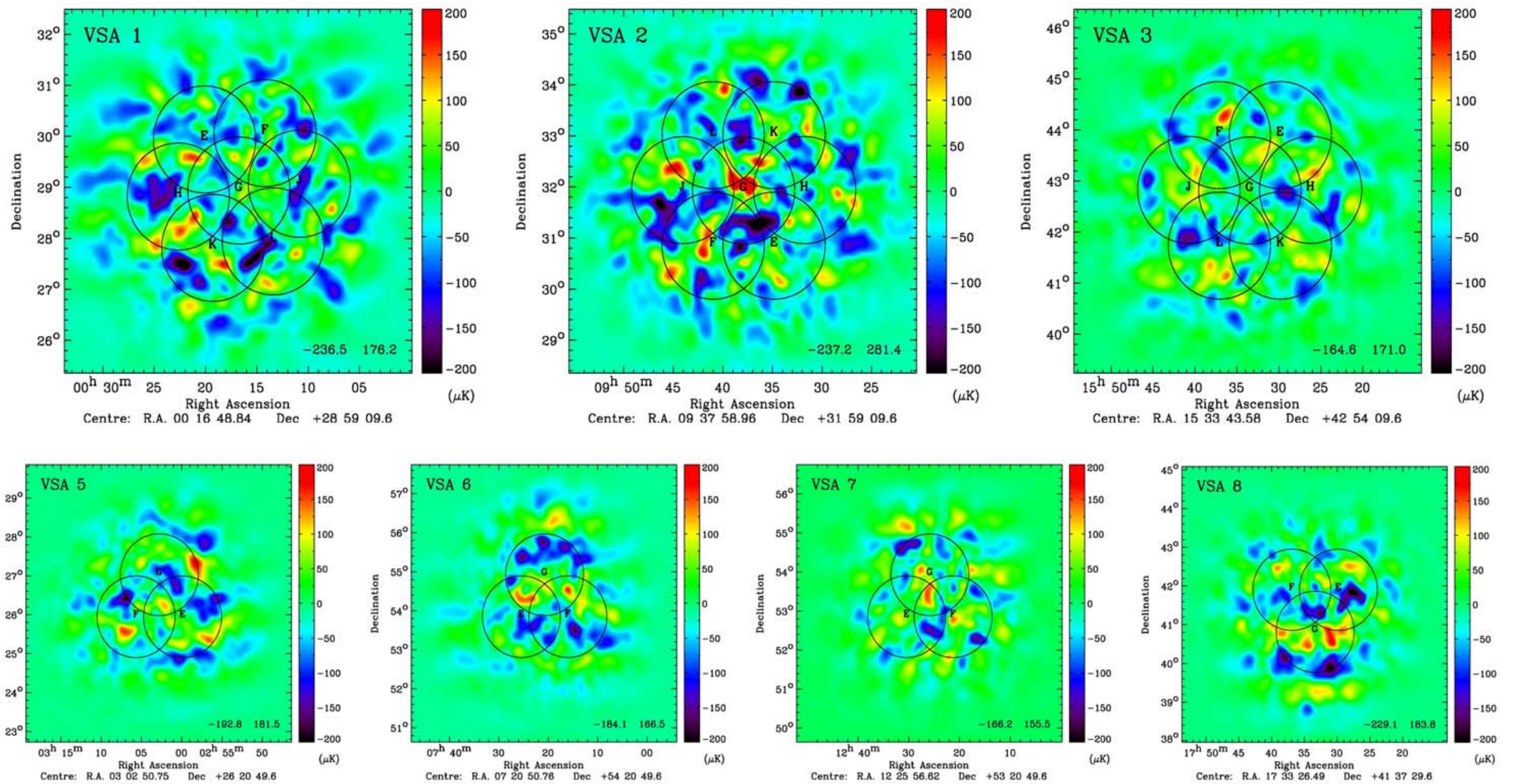
VSA6: 3 fields
07 24 48 +55 05 00

VSA7: 3 fields
12 28 14 +53 48 25

VSA8: 7 fields
17 34 58 +40 53 07

Fields chosen to limit Galactic and extragalactic emission by avoiding:

- Bright radio sources (>500 mJy) via NVSS and GB6
- Bright galaxy clusters via Ebeling et al. and Abell catalogues
- Diffuse galactic emission: Synchrotron (408 MHz Halslam et al 1981),
  Free-free (Hα WHAM Haffner et al 2003),
  Dust (100 µm Schlegel et al 1998)

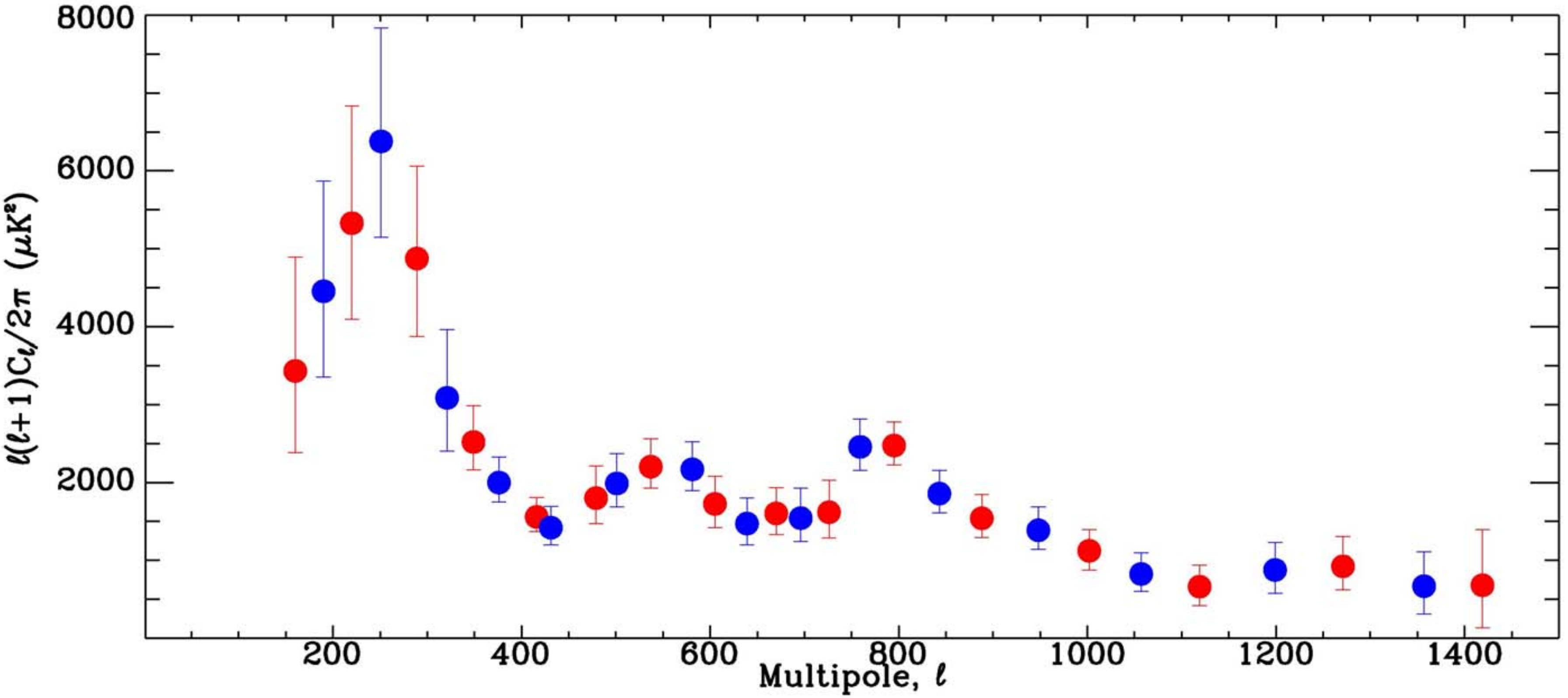


Dickinson et al. 2004 (MNRAS)

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

VSA CMB angular power spectrum (compact + extended configuration)

Dickinson et al. 2004



(two alternate binnings)

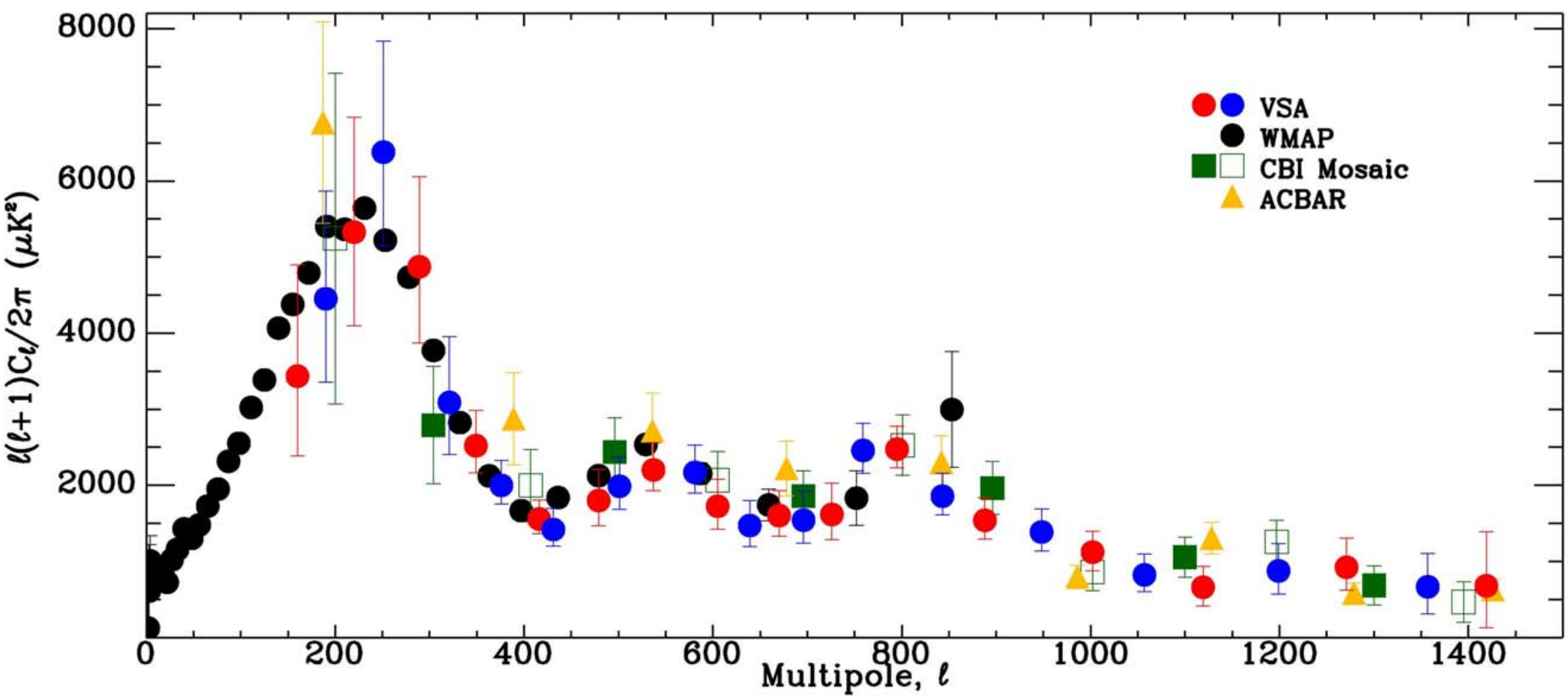

8000
6000
4000
2000
0
200
400
600
800
1000
1200
1400
$\ell(\ell+1)C_\ell/2\pi$ (μK^2)
Multipole, ℓ
VSA
WMAP
CBI Mosaic
ACBAR

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

Dark energy equation-of-state parameter

Ratio of the amplitude of Tensor to scalar fluctuations

Spectral index of tensor fluctuations

Methodology

Adiabatic models

Initial fluctuation spectrum

$$P(k) = A_{\rm S} \left(\frac{k}{k_{\rm c}} \right)^{n_{\rm S} - 1},$$

$$k_{\rm c} = 0.05 {\rm Mpc}^{-1}$$

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

CMB	External	$n_{\rm S}$	$n_{\rm run}$
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	$0.93^{+0.05}_{-0.05}$	$-0.049^{+0.035}_{-0.034}$

Constraints on tilt and Running Index in a Flat ΛCDM

Rebolo et al. 2004

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

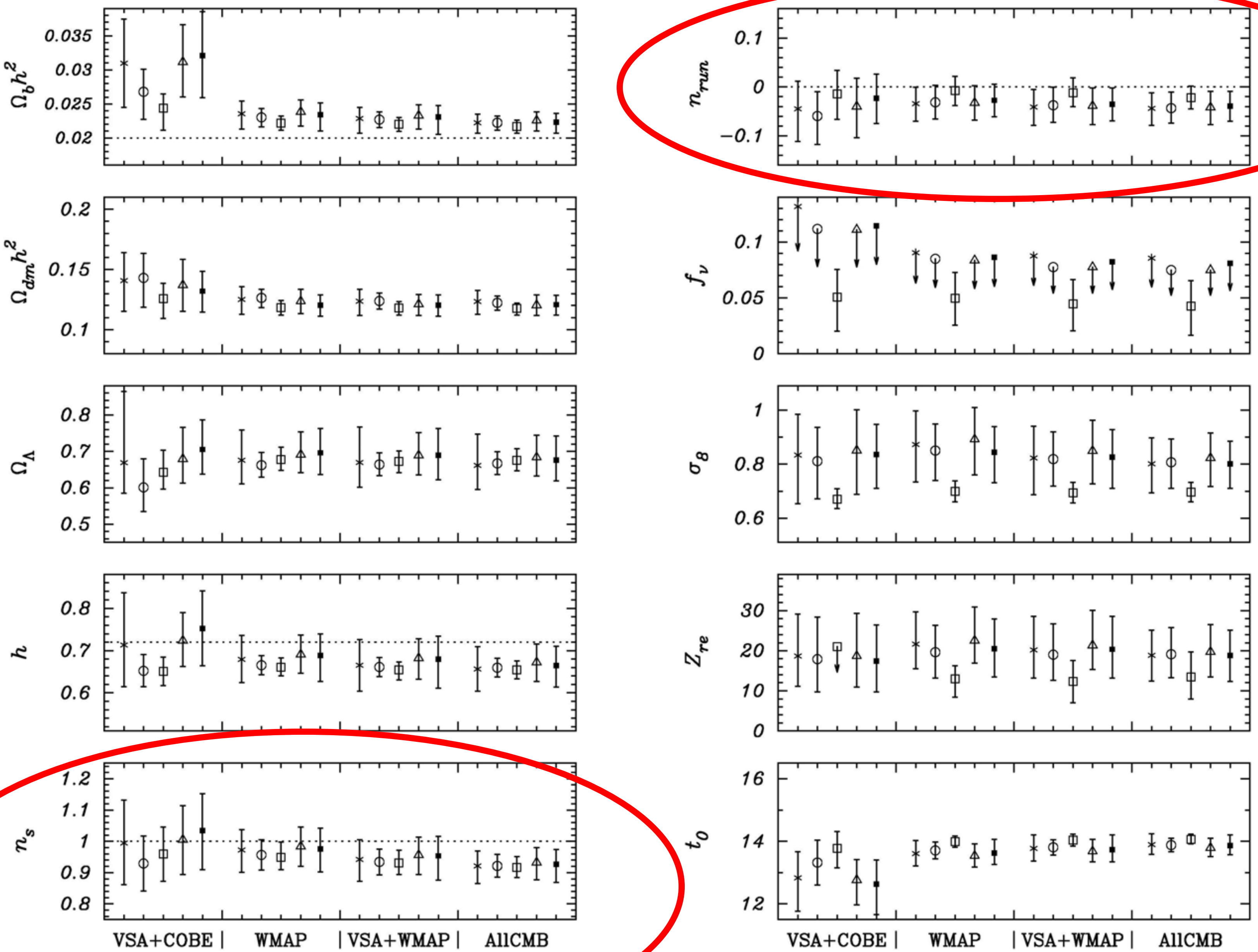
- 2dF (Percival et al. 2001, 2002)

- 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)

Flat Lambda CDM models



General Lambda CDM analysis

Priors adopted:
2dF + SNIa

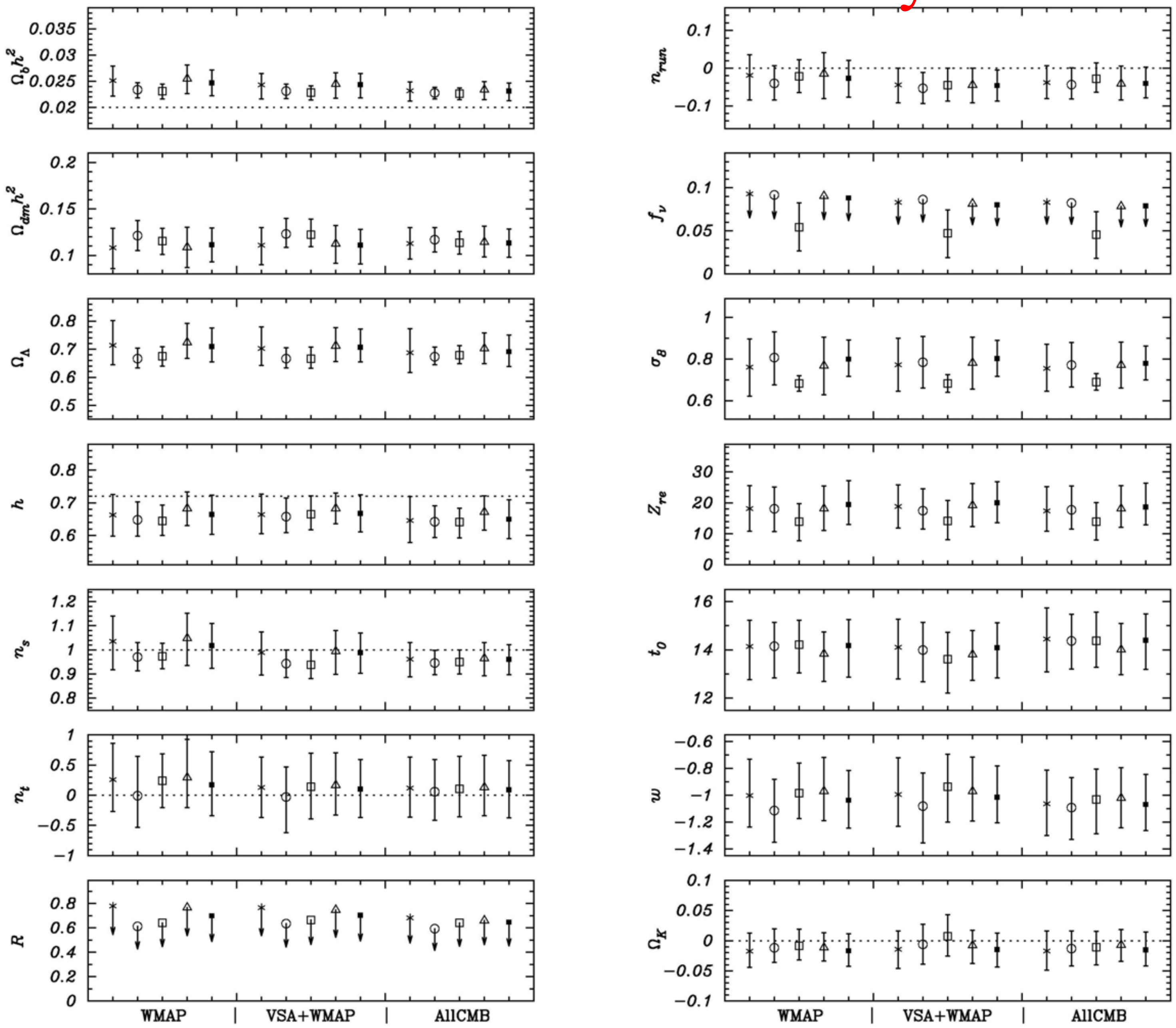
Cosmological parameters (68 %C.L.)

For neutrinos and R (95% upper limits)

Rebolo et al. 2004 (MNRAS)

	WMAP	WMAP+VSA	AllCMB
$\Omega_b h^2$	$0.025^{+0.003}_{-0.003}$	$0.024^{+0.003}_{-0.002}$	$0.023^{+0.002}_{-0.002}$
$\Omega_{dm} h^2$	$0.108^{+0.022}_{-0.021}$	$0.111^{+0.021}_{-0.019}$	$0.113^{+0.017}_{-0.017}$
h	$0.66^{+0.07}_{-0.06}$	$0.66^{+0.06}_{-0.06}$	$0.65^{+0.07}_{-0.07}$
z_{re}	18^{+7}_{-7}	19^{+7}_{-7}	17^{+7}_{-8}
Ω_k	$-0.02^{+0.03}_{-0.03}$	$-0.01^{+0.03}_{-0.03}$	$-0.02^{+0.03}_{-0.03}$
f_ν	< 0.093	< 0.083	< 0.083
w	$-1.00^{+0.24}_{-0.27}$	$-0.99^{+0.24}_{-0.27}$	$-1.06^{+0.24}_{-0.25}$
n_S	$1.04^{+0.12}_{-0.11}$	$0.99^{+0.09}_{-0.09}$	$0.96^{+0.07}_{-0.07}$
n_T	$0.26^{+0.53}_{-0.60}$	$0.13^{+0.49}_{-0.51}$	$0.12^{+0.48}_{-0.51}$
n_{run}	$-0.02^{+0.07}_{-0.05}$	$-0.04^{+0.05}_{-0.04}$	$-0.04^{+0.04}_{-0.05}$
$10^{10} A_S$	27^{+8}_{-5}	26^{+9}_{-5}	25^{+6}_{-5}
R	< 0.78	< 0.77	< 0.68
Ω_Λ	$0.71^{+0.07}_{-0.09}$	$0.70^{+0.06}_{-0.08}$	$0.69^{+0.07}_{-0.09}$
t_0	$14.1^{+1.4}_{-1.1}$	$14.1^{+1.3}_{-1.2}$	$14.4^{+1.4}_{-1.3}$
Ω_m	$0.31^{+0.09}_{-0.07}$	$0.31^{+0.08}_{-0.06}$	$0.33^{+0.10}_{-0.07}$
σ_8	$0.76^{+0.14}_{-0.14}$	$0.77^{+0.13}_{-0.13}$	$0.76^{+0.11}_{-0.12}$
τ	$0.20^{+0.13}_{-0.11}$	$0.20^{+0.15}_{-0.10}$	$0.17^{+0.12}_{-0.10}$

General Lambda CDM analysis



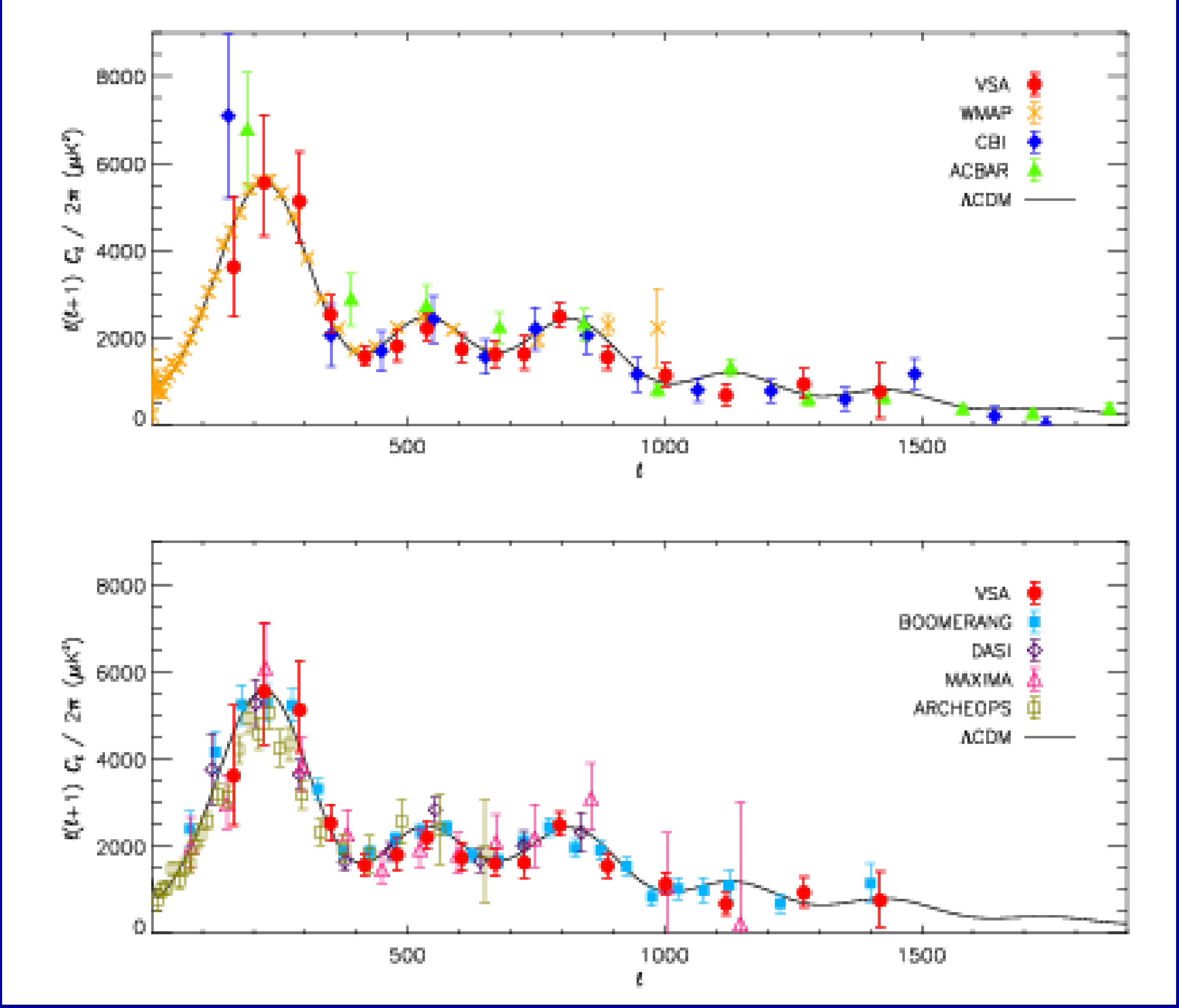
WMAP 3rd year

Spergel et al. 06

WMAP Cosmological Parameters Model: lcdm Data: wmap	
$10^2\Omega_b h^2$	$2.230^{+0.075}_{-0.073}$
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.7 \pm 1.4) \times 10^{-10}$
h	0.735 ± 0.032
H_0	73.5 ± 3.2 km/s/Mpc
$n_s(0.002)$	0.951 ± 0.016
$\Omega_b h^2$	$0.02230^{+0.00075}_{-0.00073}$
Ω_Λ	0.763 ± 0.034
Ω_m	0.237 ± 0.034
$\Omega_m h^2$	$0.1265^{+0.0081}_{-0.0080}$
σ_8	0.742 ± 0.051
A_{SZ}	1.00 ± 0.64
t_0	$13.73^{+0.16}_{-0.15}$ Gyr
τ	$0.088^{+0.029}_{-0.030}$
θ_A	$0.5948^{+0.0021}_{-0.0022}$ °
z_r	10.9 ± 2.5

WMAP Cosmological Parameters Model: lcdm Data: wmap+cbi+vsa	
$10^2\Omega_b h^2$	2.208 ± 0.071
$\Delta^2_{\mathcal{R}}(k=0.002/\mathrm{Mpc})$	$(23.5^{+1.3}_{-1.4}) \times 10^{-10}$
h	0.742 ± 0.031
H_0	74.2 ± 3.1 km/s/Mpc
$n_s(0.002)$	0.947 ± 0.015
$\Omega_b h^2$	0.02208 ± 0.00071
Ω_Λ	0.774 ± 0.031
Ω_m	0.226 ± 0.031
$\Omega_m h^2$	$0.1233^{+0.0075}_{-0.0074}$
σ_8	$0.721^{+0.047}_{-0.046}$
A_{SZ}	$0.85^{+0.62}_{-0.58}$
t_0	13.76 ± 0.15 Gyr
τ	0.087 ± 0.029
θ_A	0.5942 ± 0.0020 °
z_r	10.8 ± 2.4

Current CMB data



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

Σm_ν <0.17 eV

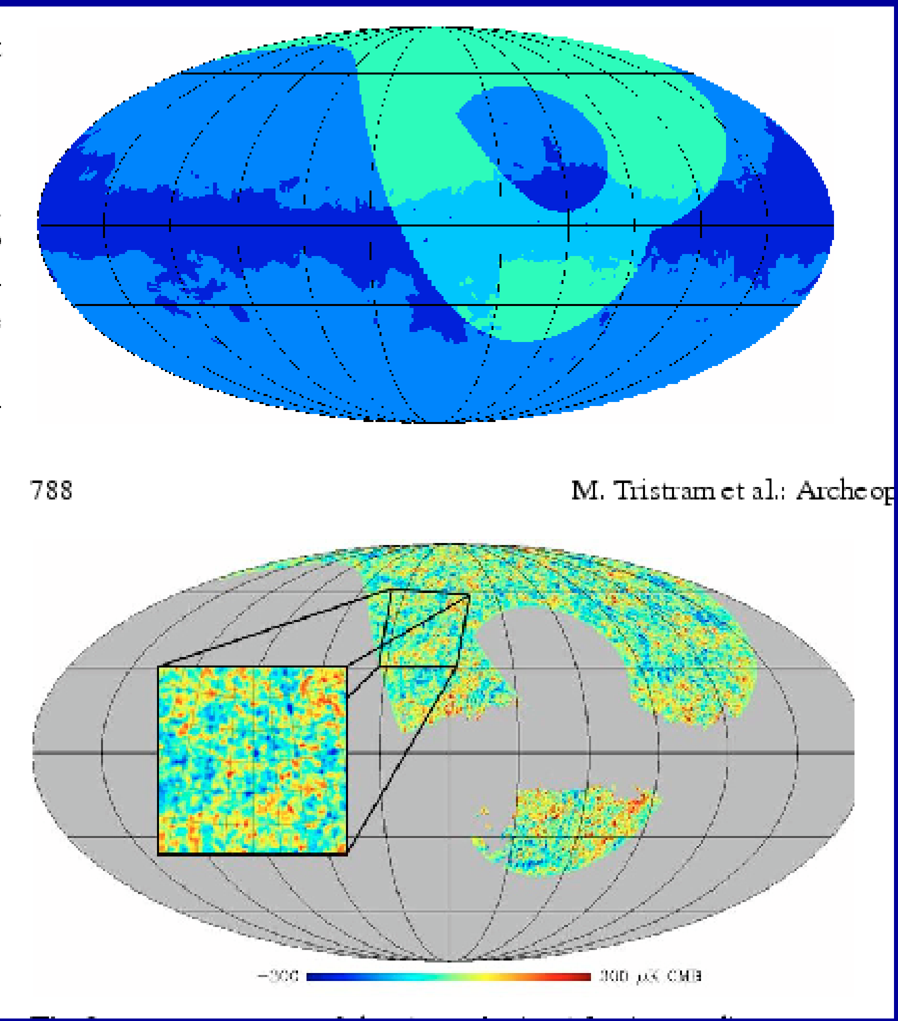
Upp. Limit 95 %

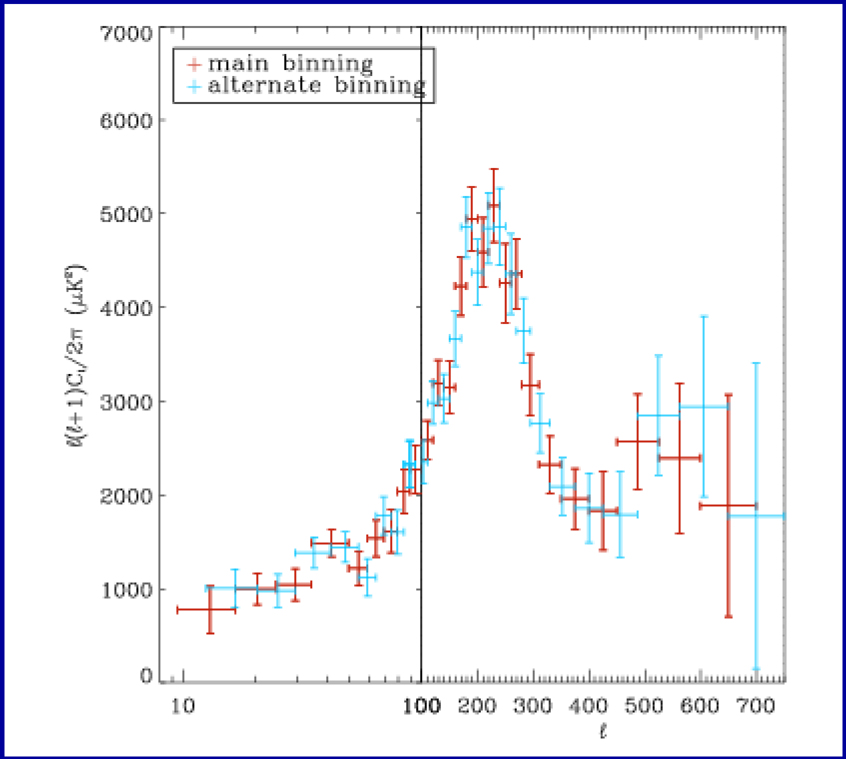
CMB constraints on cosmological parameters

without WMAP?

control on systematics

ARCHEOPS



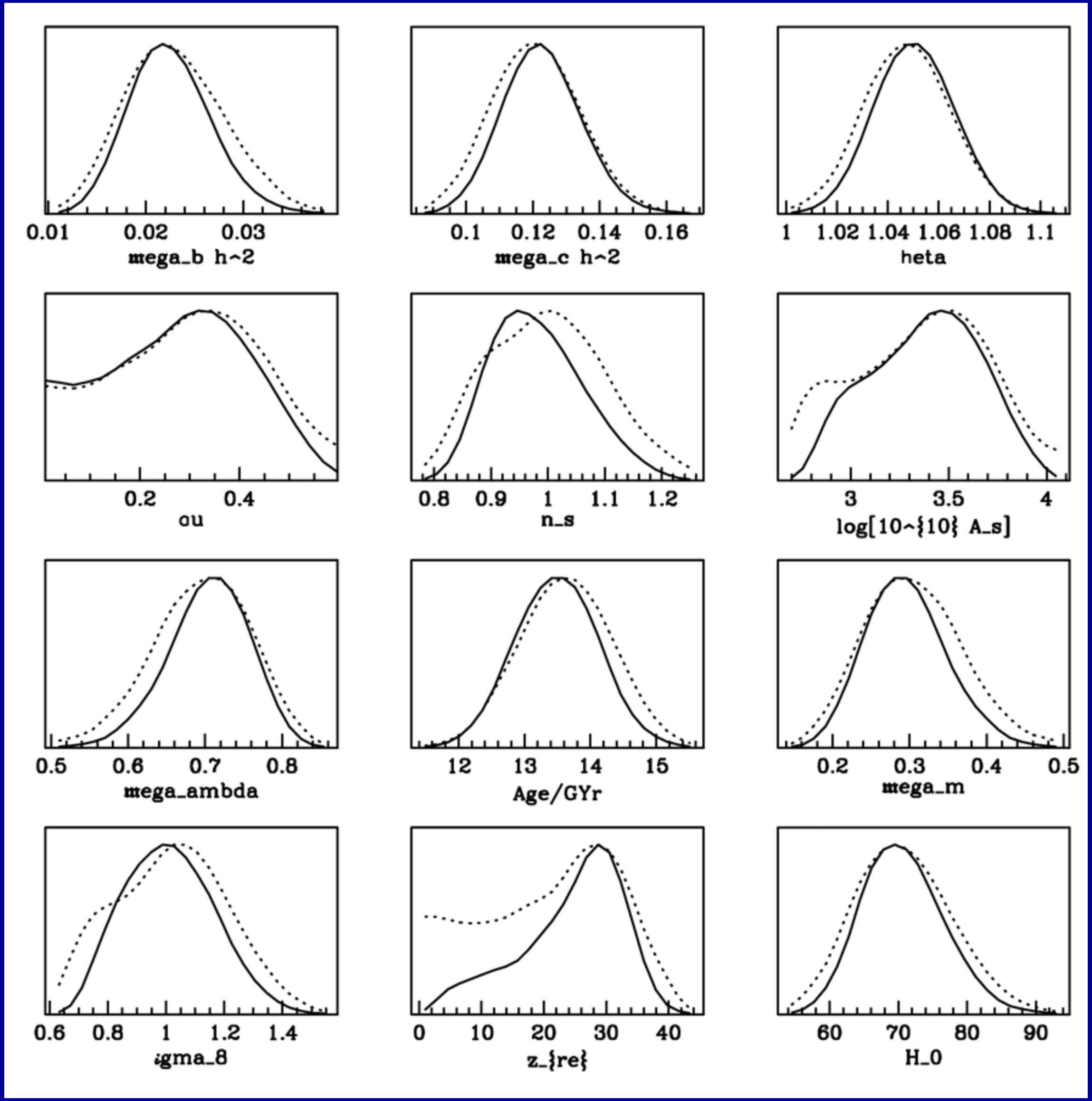


Tristram et al. 05

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.

Comparison with other astrophysical constraints on cosmological parameters

Baryonic density from Primordial nucleosynthesis

- Baryon density based on abundances of light elements
- $\Omega_b\ h^2 = 0.020 \pm 0.002$ (95% C.L.) Burles et al. 2001
- $\rho_b = 6.88\eta \times 10^{-22}\ \mathrm{g cm^{-3}}$
- $\Omega_b = 0.045 \pm 0.025$

- To be also compared with

Density of luminous matter in galaxies

- $\Omega_{lum} \sim 0.003$

(Persic and Salucci, 1992)

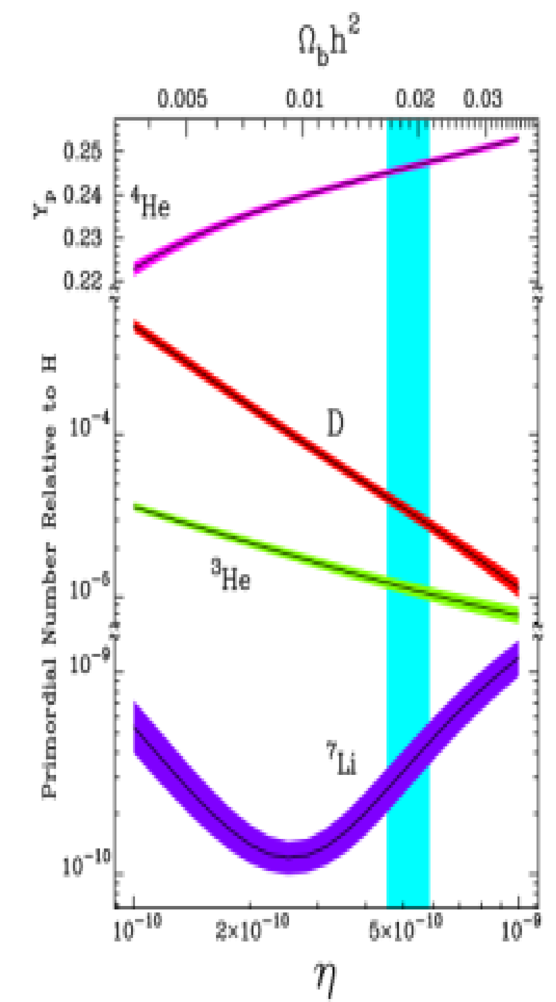


FIGURE 3. Predicted abundances of ^{4}He (mass fraction), D, ^{3}He, and ^{7}Li (number relative to hydrogen) as a function of the baryon density; widths of the curves indicate "2σ" theoretical uncertainty. The dark band highlights the determination of the baryon density based upon

Lithium versus metallicity in old stars

Rebolo et al. 1988 A&A

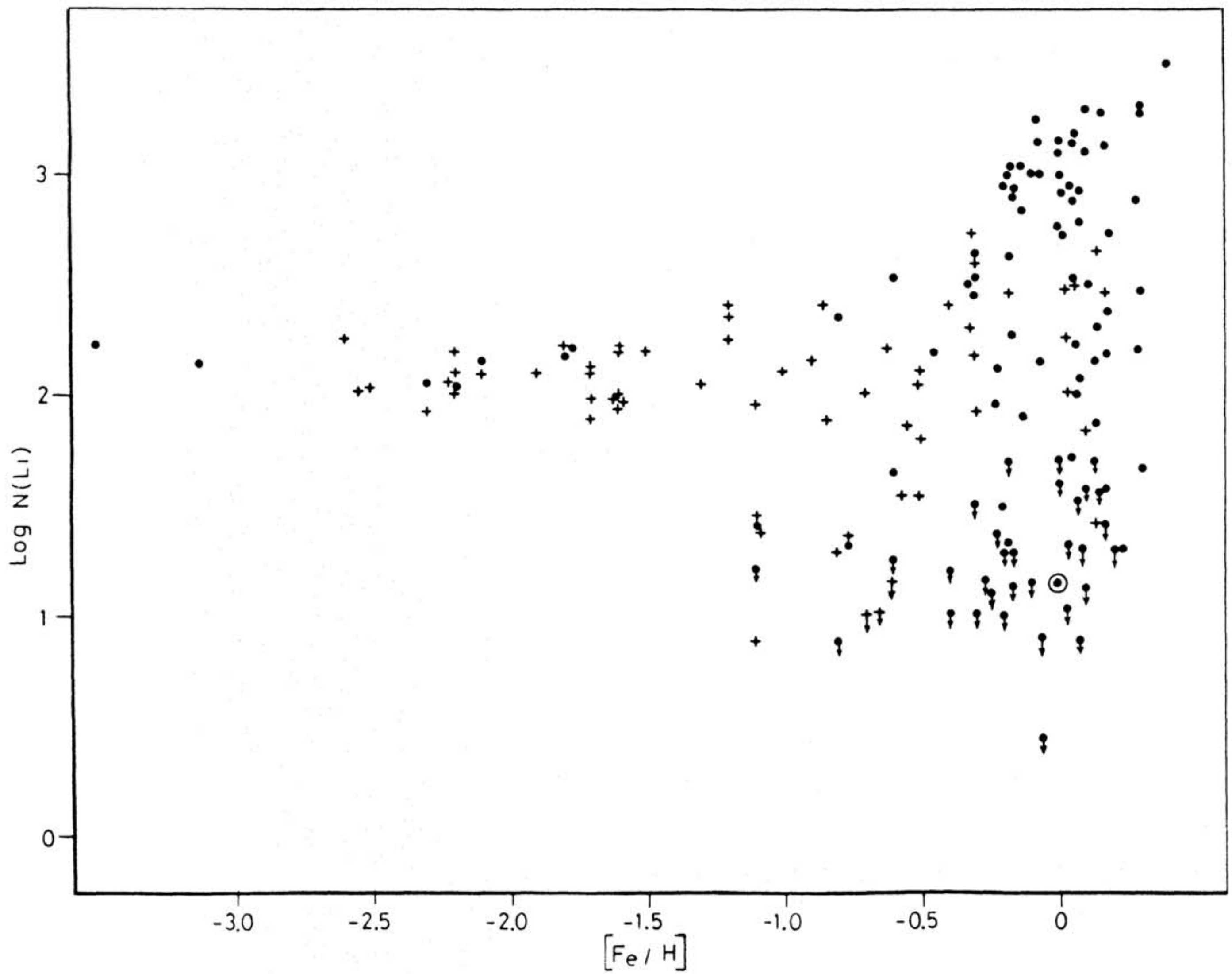
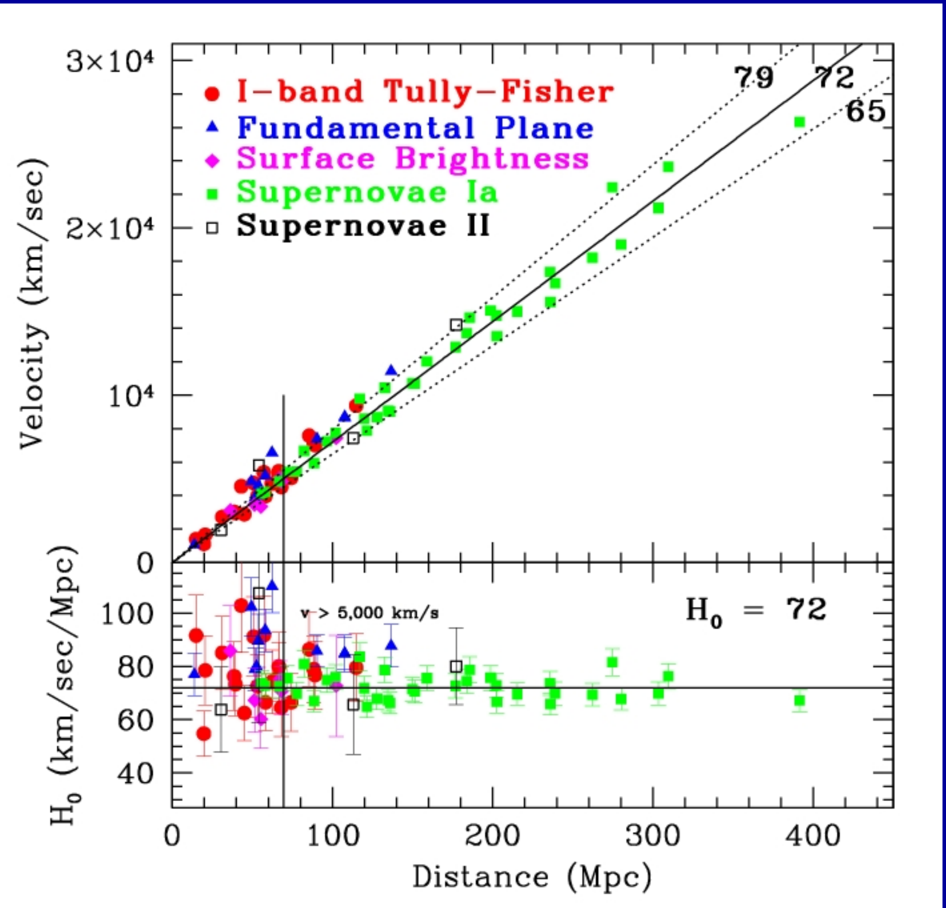


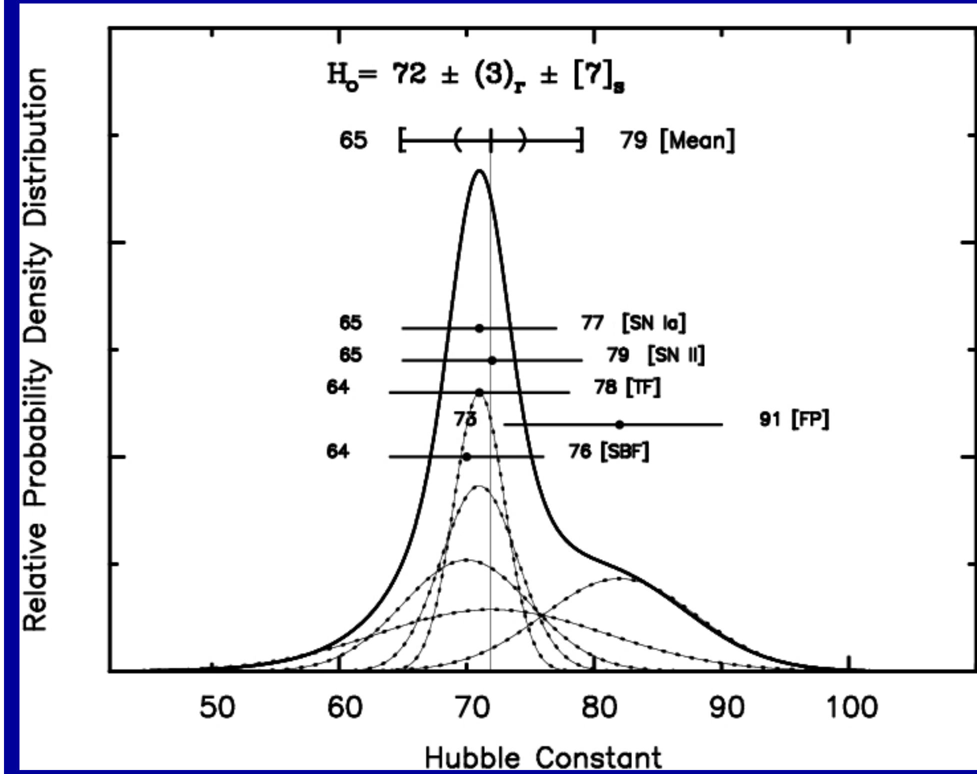
Fig. 3. Lithium abundance against metallicity for stars with $T_{eff} > 5500$ K. Typical error bars for $\log N(\mathrm{Li})$ and [Fe/H] are 0.1 − 0.2 dex. Temperature ranges: • $T_{eff} > 6000$ K: + 6000 K < T_{eff} < 5500 K. Sources of data: Spite and Spite (1982, 1986); Spite et al. (1984); Boesgaard and Trippico (1986a, b); Rebolo et al. (1987b). This work

The Expansion of the Universe

HST-Key project

Based on Cepheid luminosity distances to 25 galaxies within 25 Mpc





H_0 = 72 ± 3 (stat.)
7 (sys.)
km/sec/Mpc

Freedman et al. 2001

Sunyaev-Zeldovich Effect

Shift in the CMB spectrum as radiation passes clusters of galaxies: Compton scattering of electrons on CMB photons

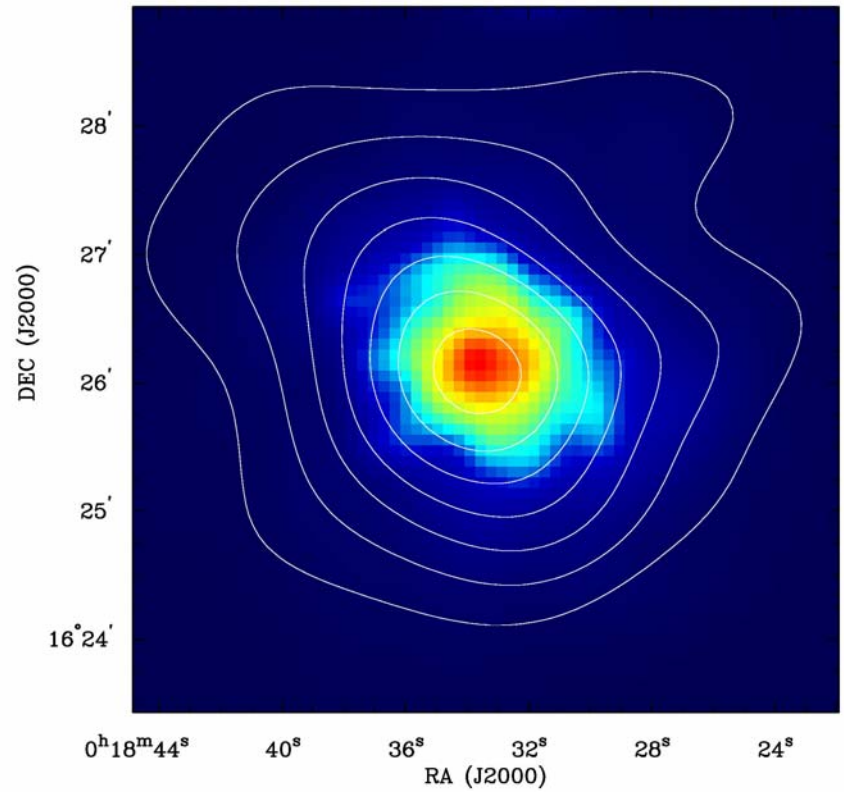
Temp. of electron gas ~ keV
Thermal emission in X-rays

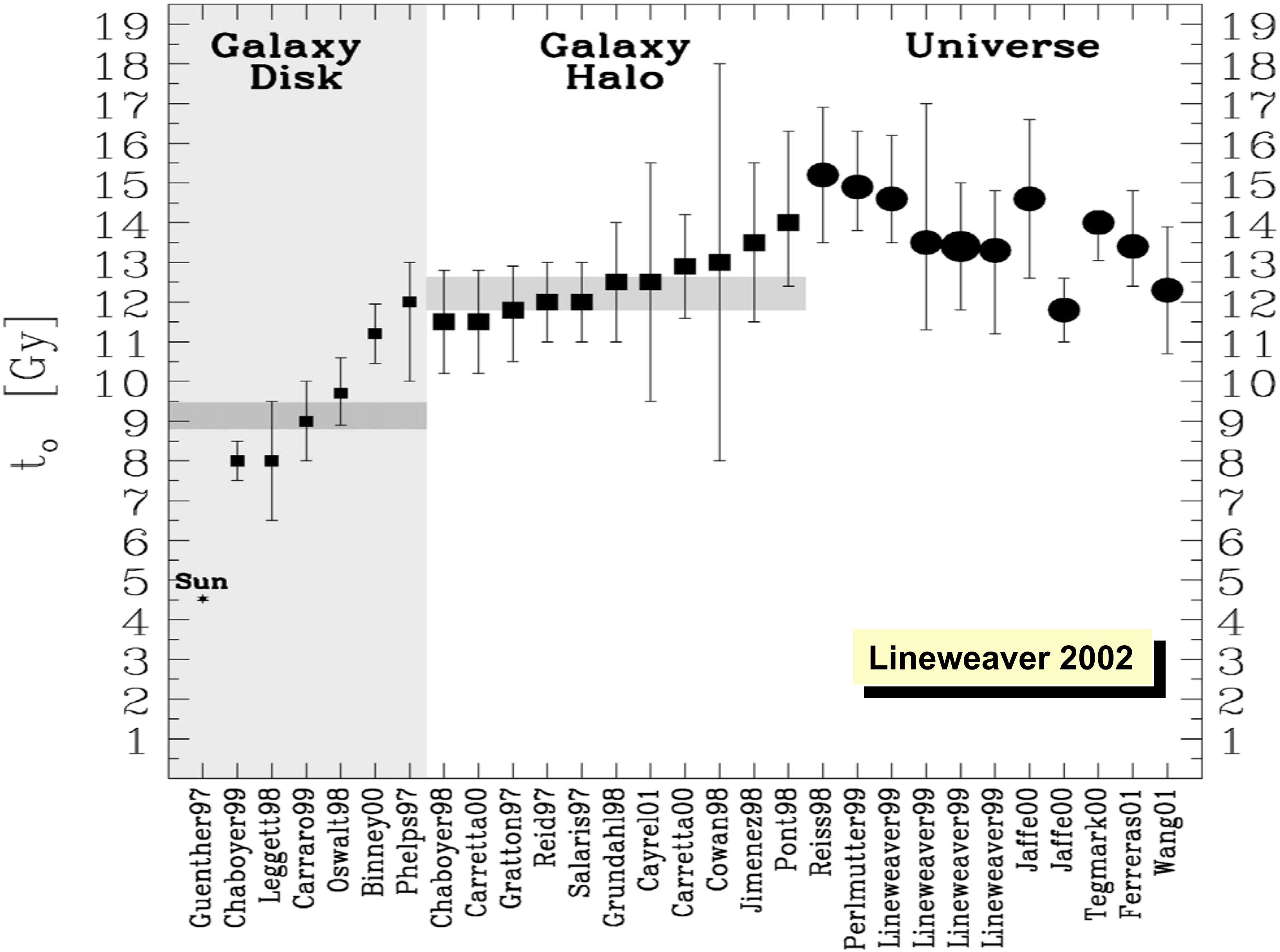
$$SZ : \Delta T \sim \int dl \; n_e T_e \sigma_T$$

$$\text{X-ray} \sim \int n_e^2 \, dl$$

Birkinshaw (1999) :
H_0= 60 ± 10 km/sec/Mpc

Carlstrom et al. (2001)
33 clusters
H_0 = 63 ± 3 (statistical) km/sec/Mpc
30% (systematic)





Conclusion $t_0 = 13.2 \pm 1.2$ Gyr

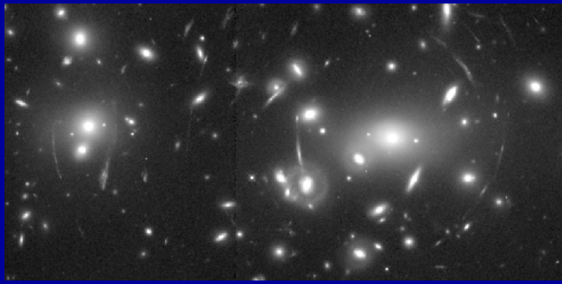
Dark matter density

Use clusters of galaxies as a tracer of the total clustered mass of the Universe. Problem: determine Gas to total mass ratio

Gas is determined by :

measuring the x-ray flux from the intracluster gas

or by Sunyaev-Zeldovich effect



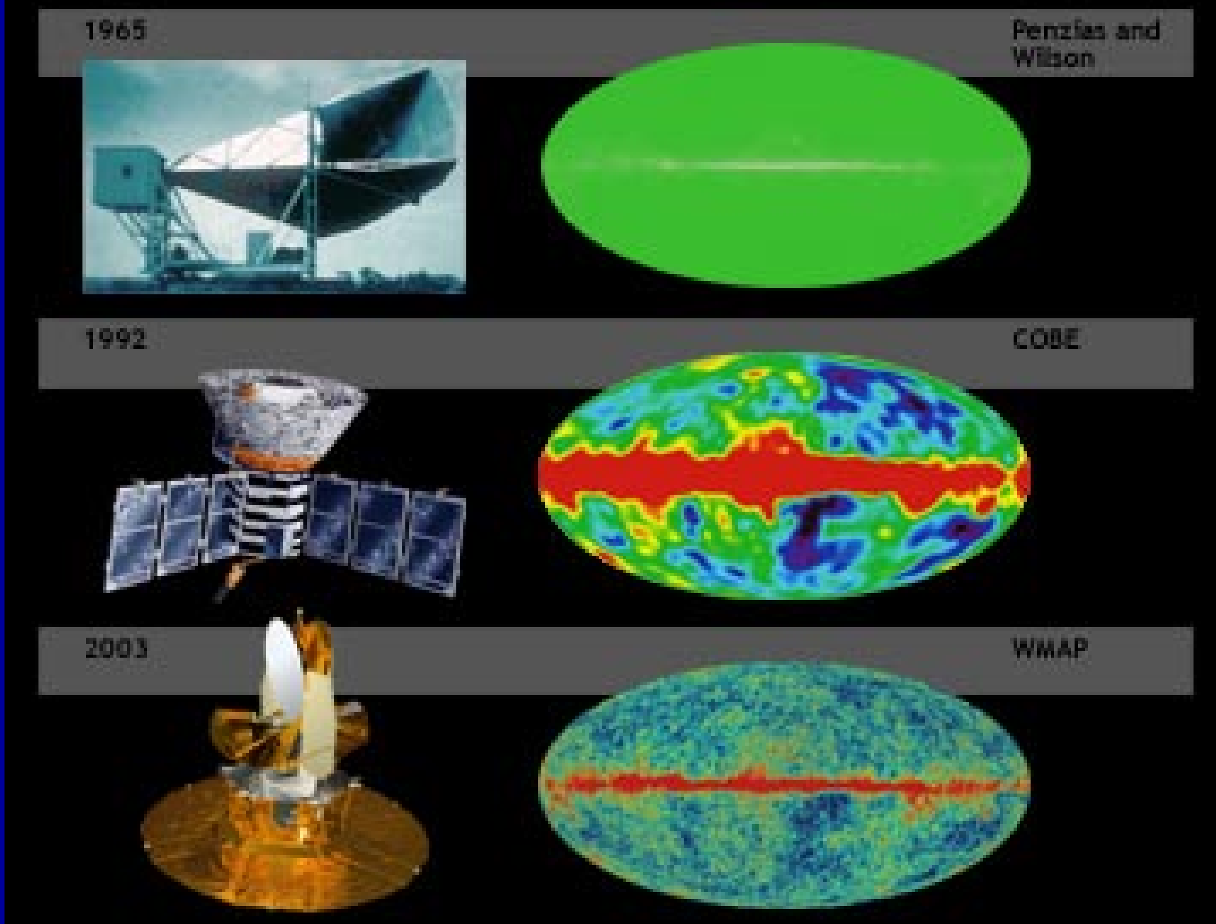
The total cluster mass can be determined:

1) virial theorem
2) assuming that the gas is in hydrostatic equilibrium
3) by gravitational lensing

$$f_b = \frac{M_{gas}}{M_{TOT}} = \frac{M_b}{M_{TOT}} = \frac{\Omega_b}{\Omega_m}$$

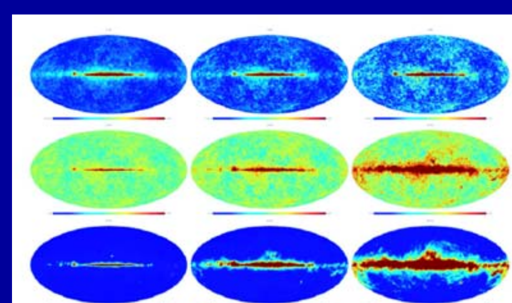
f=10-20% $\Omega_M \sim 0.2\text{-}0.4$

Planck and future polarization experiments

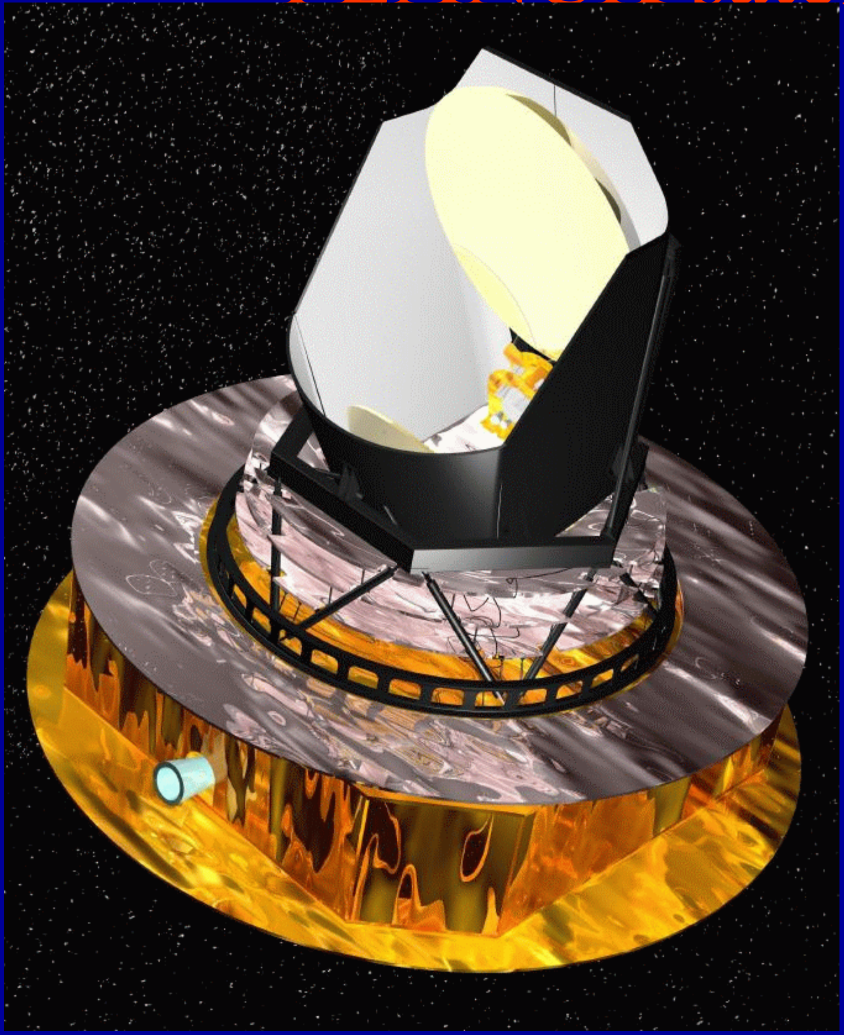


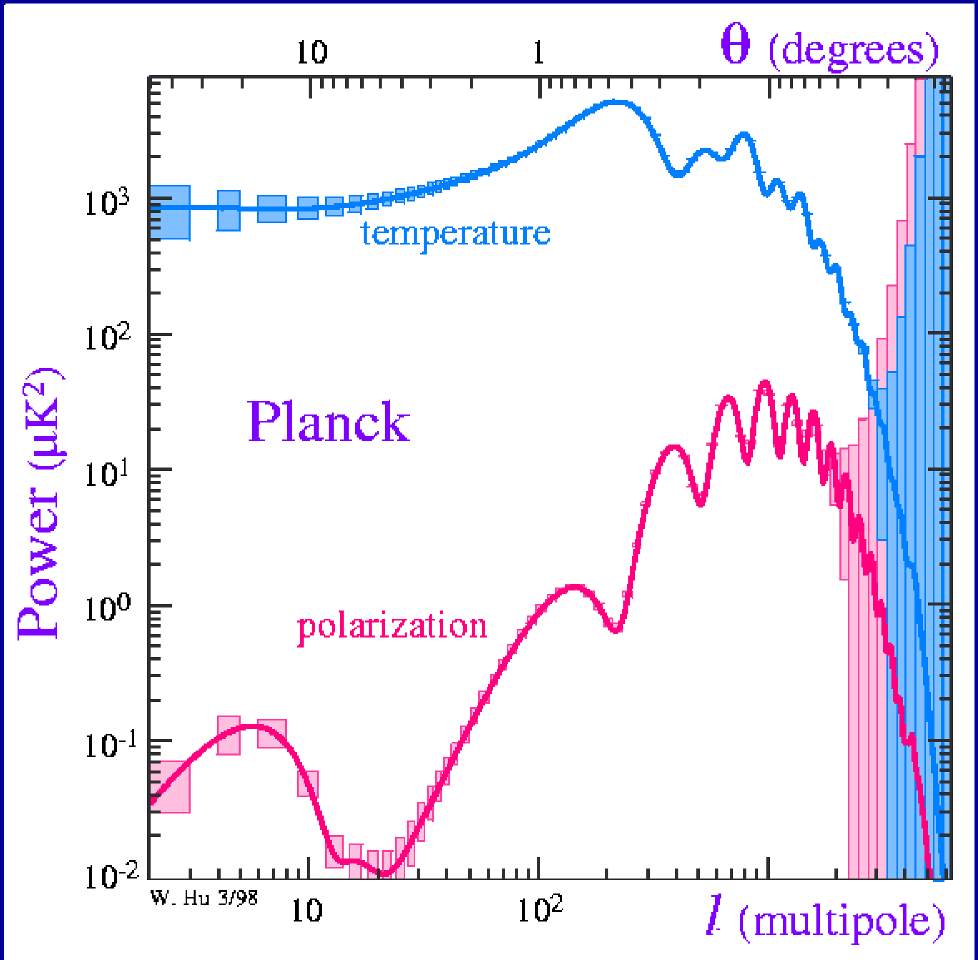
Planck: 3rd Generation CMB space experiment

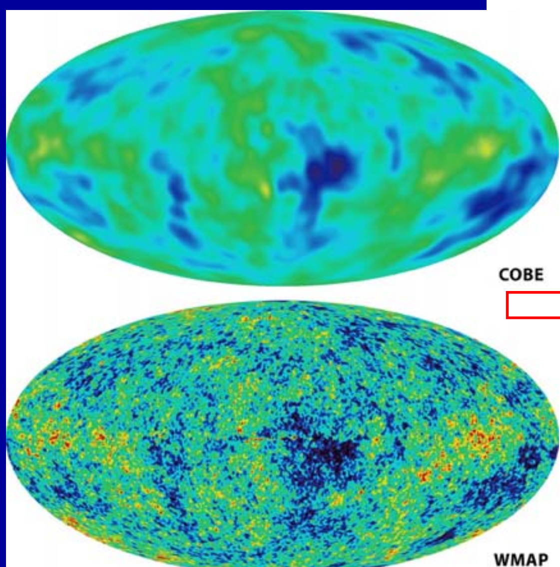
2

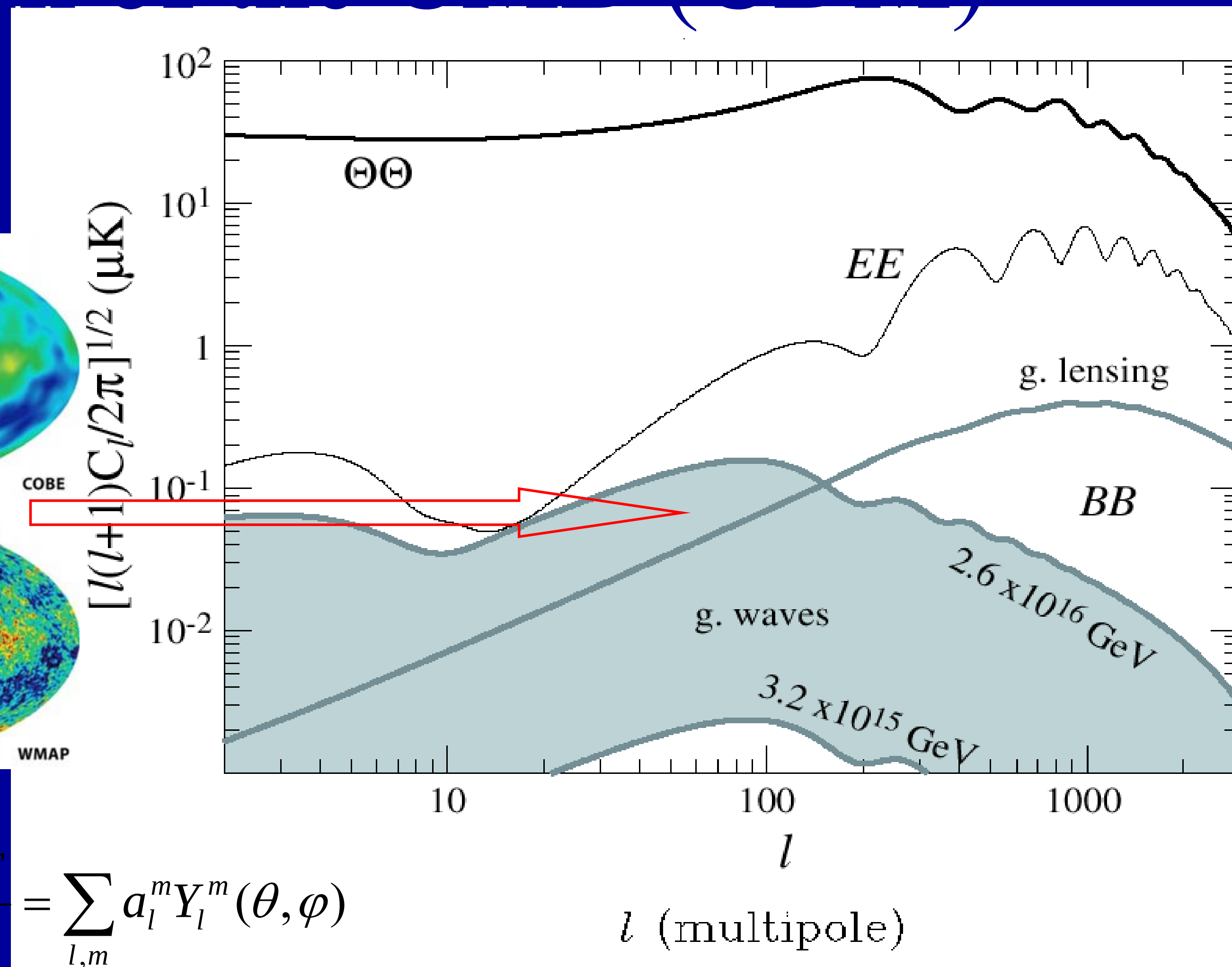


PLANCK satellite (launch 2008)







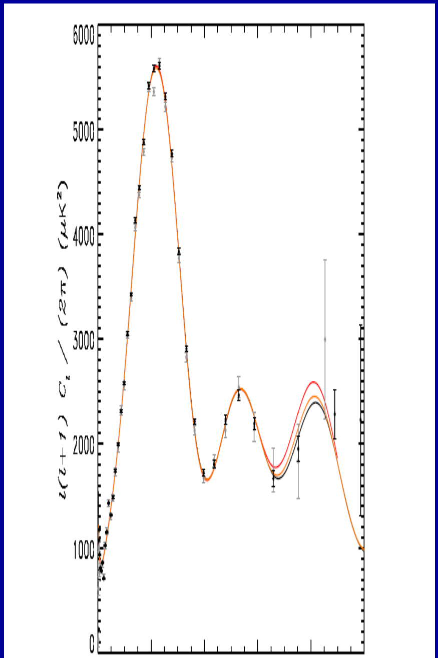


$$\frac{\Delta T}{T} = \sum_{l,m} a_l^m Y_l^m(\theta,\varphi)$$

$$C_l = \langle |a_l^m|^2 \rangle$$

WMAP 3-year TT spectru

Spergel et al. 2006



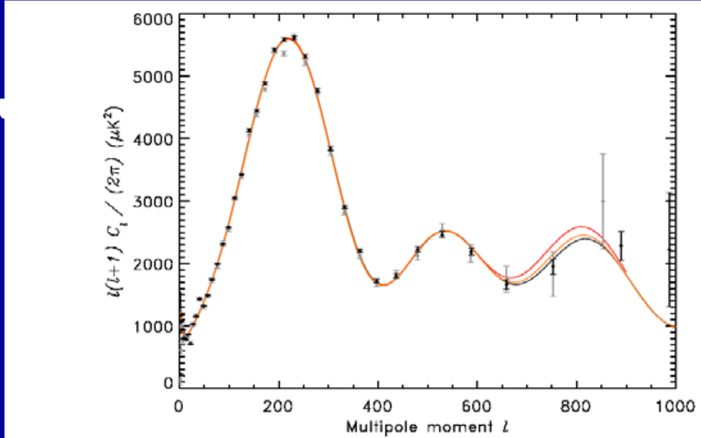
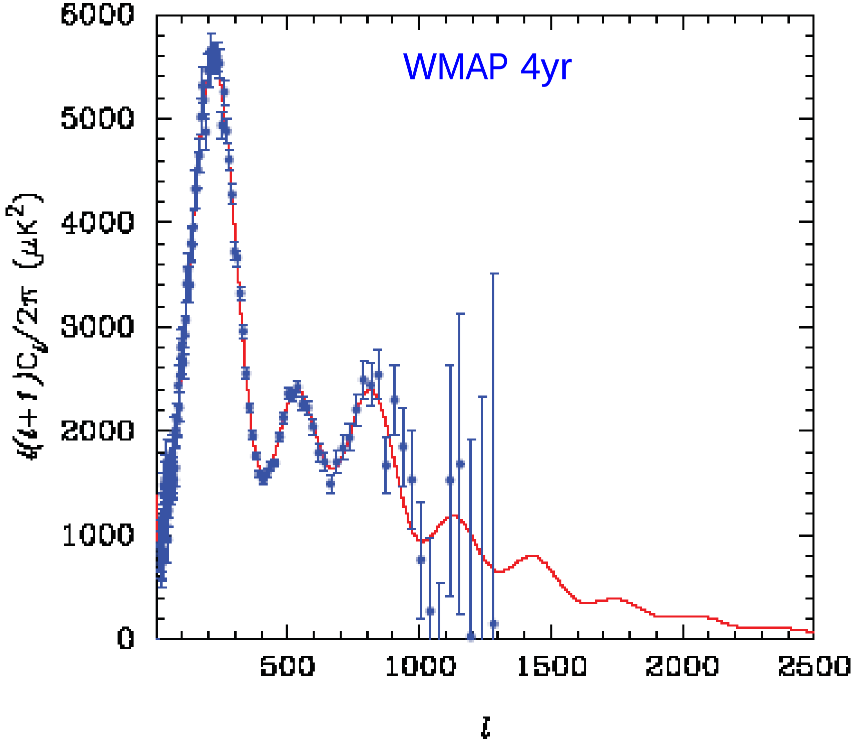
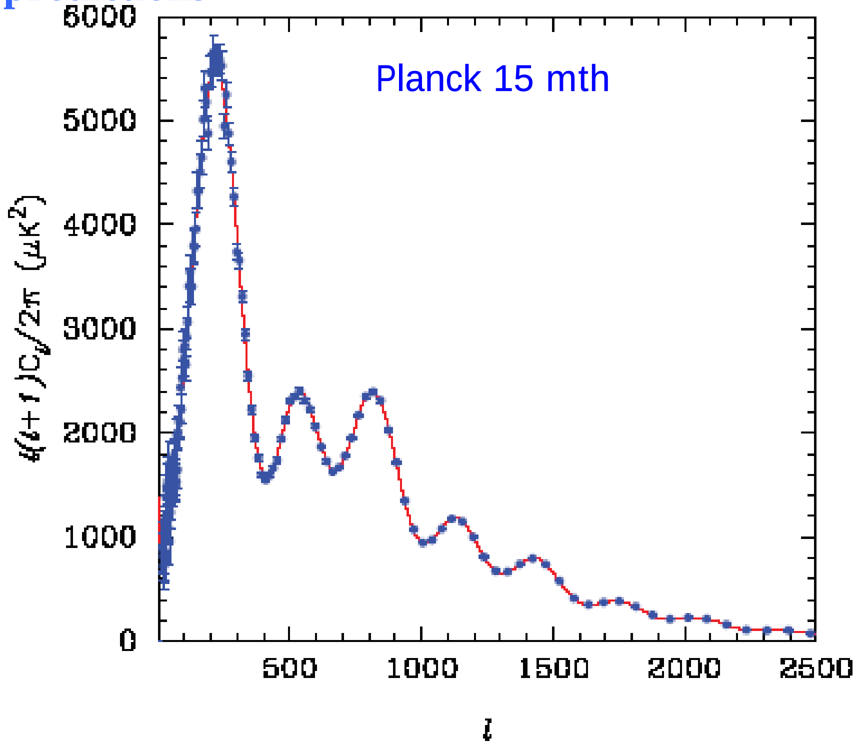


Fig. 2.— Comparison of the predictions of the different best fit models to the data. The *black* line is the angular power spectrum predicted for the best fit three-year WMAP only ΛCDM model. The *red* line is the best fit to the 1-year WMAP data. The *orange* line is the best fit to the combination of the 1-year WMAP data, CBI and ACBAR (WMAPext in Spergel et al. (2003)). The solid data points are for the 3 year data and the light gray data points are for the first year data.

Bluebook predictions





Inflation requires accuracy

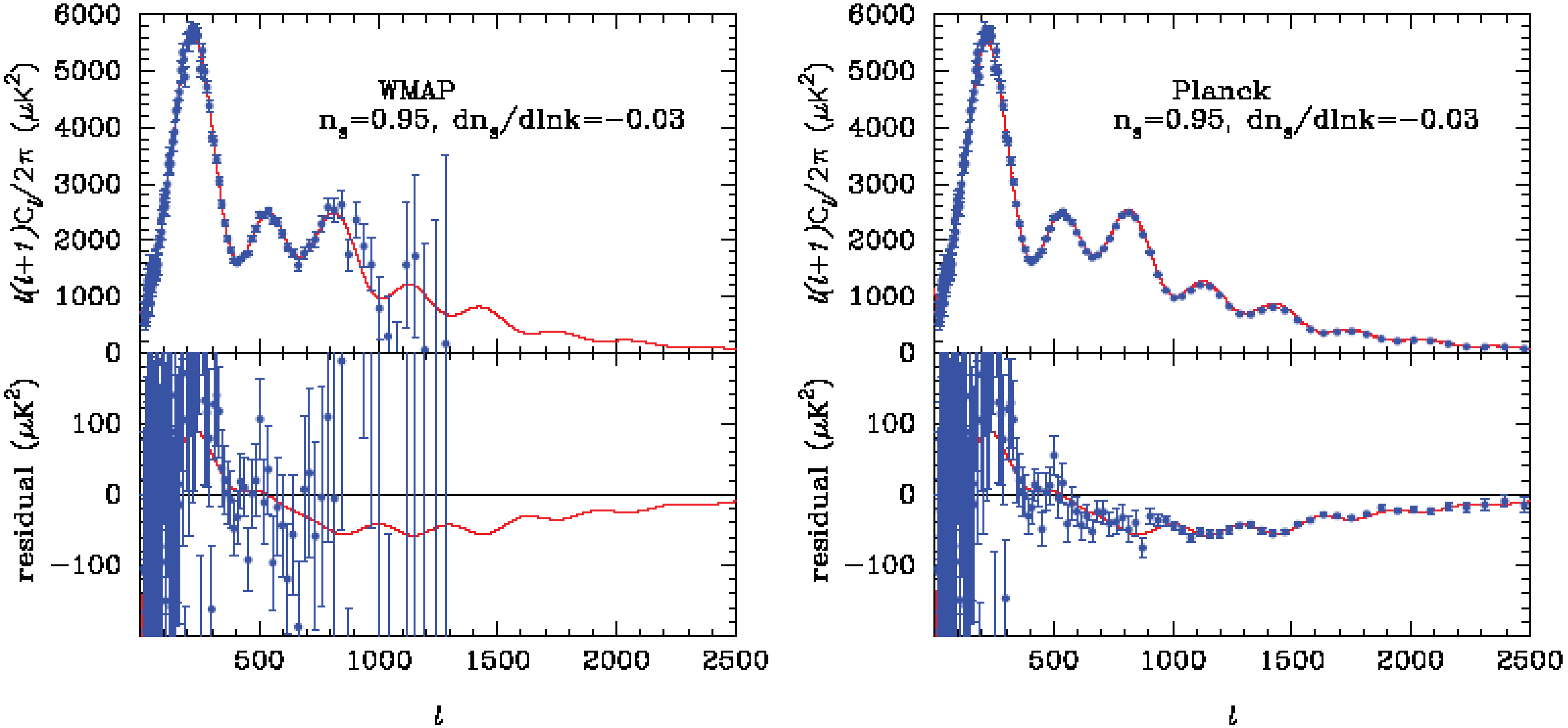


FIG 2.12.—Same as Figure 2.11, but now comparing the concordance ΛCDM model, having $n_S = 0.95$ and zero run (solid line), with a realisation of a model having with $n_S = 0.95$ (at a fiducial wavenumber of $k_0 = 0.05$ Mpc^{-1}) and a run of $dn_S/d\ln k = -0.03$.

B-mode polarization

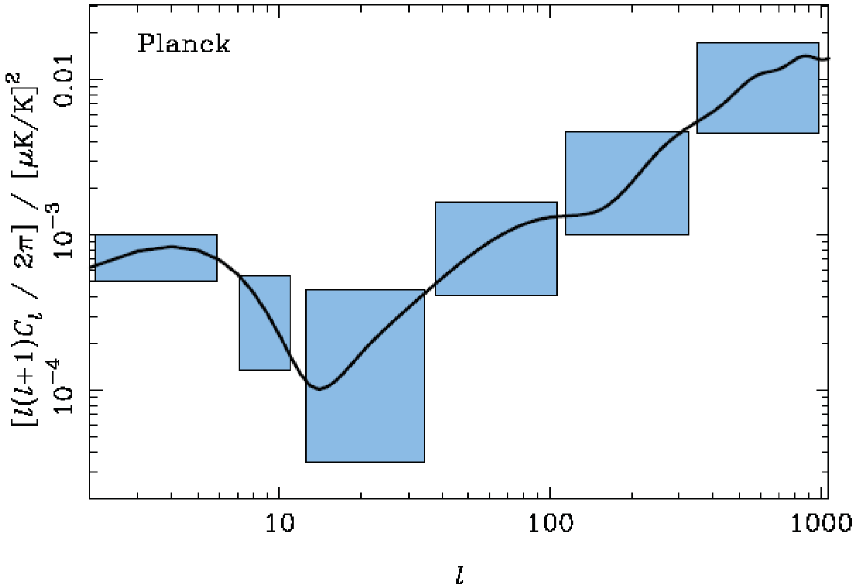


FIG 2.17.—Forecasts for the $\pm1\sigma$ errors on the B-mode polarization power spectrum C_ℓ^B from *Planck* (for $r = 0.1$ and $\tau = 0.17$). Above $\ell \sim 150$ the primary spectrum is swamped by weak gravitational lensing of the E-polarization produced by the dominant scalar perturbations. The cosmological model, and the assumptions about instrument characteristics, are the same as in Figure 2.13.

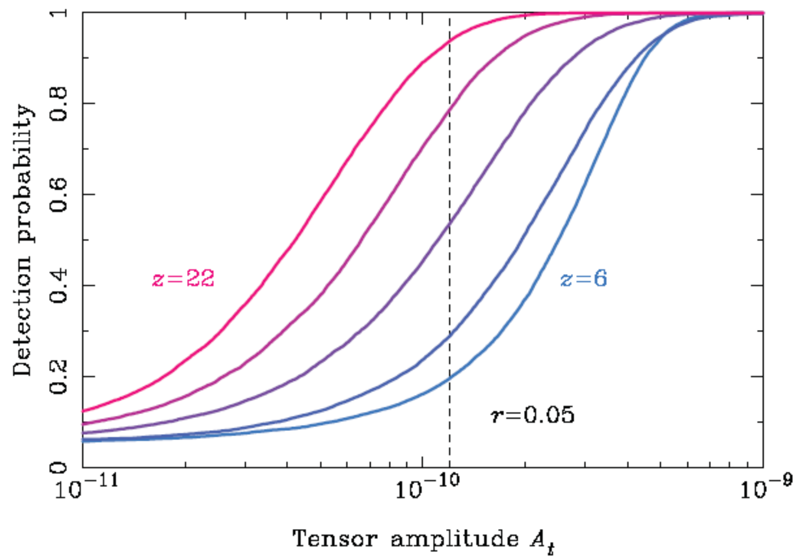


FIG 2.16.—The probability of detecting B-mode polarization at 95% confidence as a function of A_T, the amplitude of the primordial tensor power spectrum (assumed scale-invariant), for *Planck* observations using 65% of the sky. The curves correspond to different assumed epochs of (instantaneous) reionization: $z = 6$, 10, 14, 18 and 22. The dashed line corresponds to a tensor-to-scalar ratio $r = 0.05$ for the best-fit scalar normalisation, $A_S = 2.7\times10^{-9}$, from the one-year *WMAP* observations.

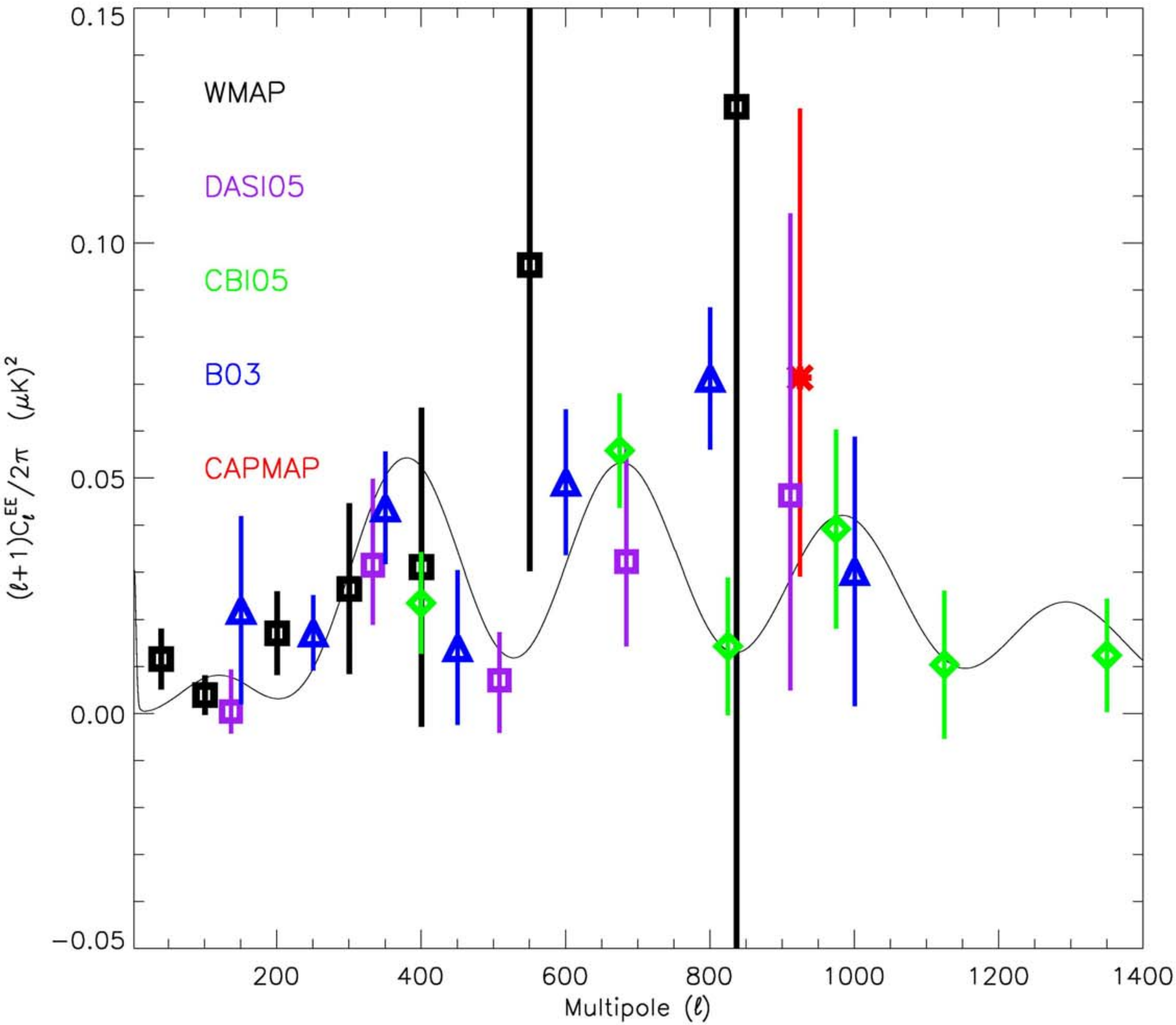
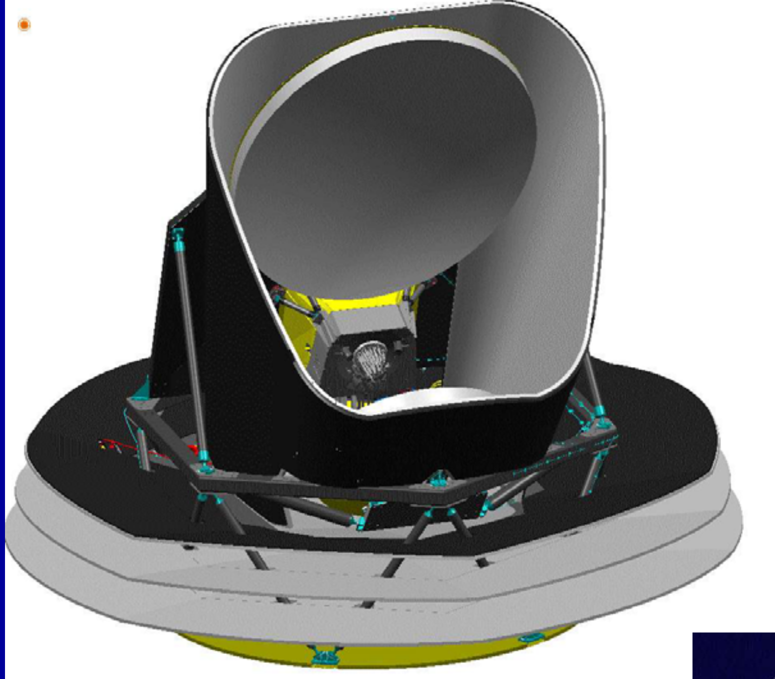
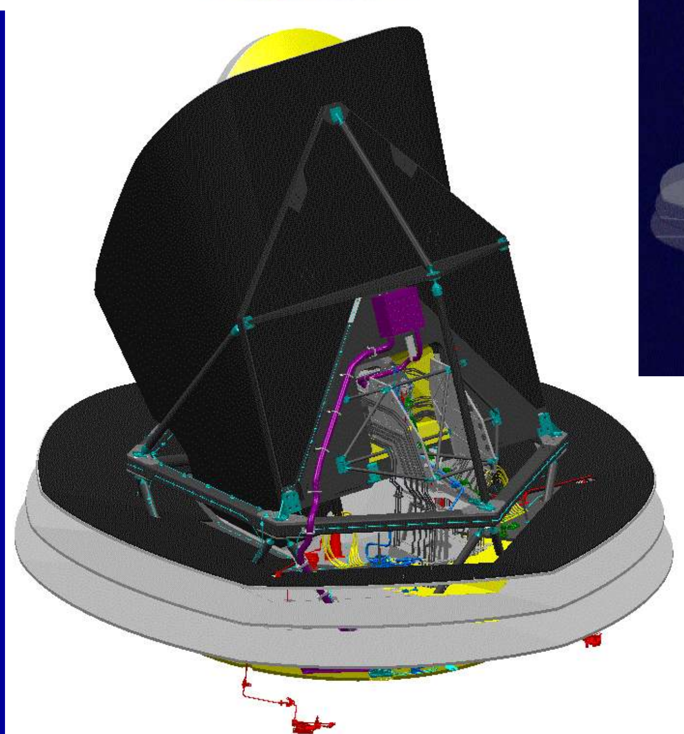
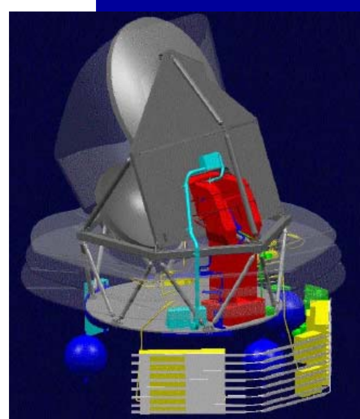


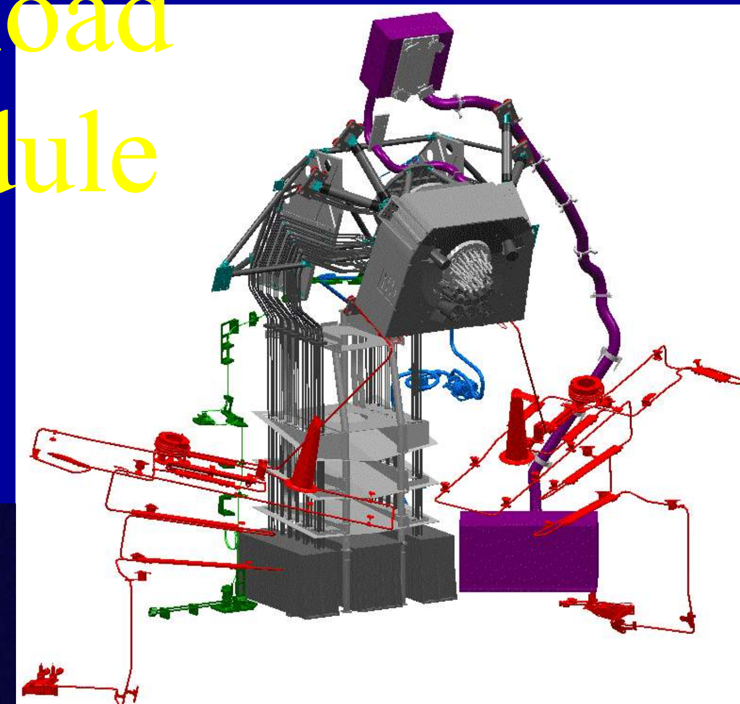
FIG. 22.— The EE spectrum at $\ell > 40$ for all measurements of the CMB polarization. The curve is the best fit EE spectrum. Note that the y axis has only one power of ℓ. The black boxes are the *WMAP* data; the triangles are the BOOMERanG data; the squares are the DASI data; the diamonds are the CBI data; and the asterisk is the CAPMAP data. The *WMAP* data are the QVW combination. For the first point, the cleaned value is used. For other values, the raw values are used. The data are given in Table 8

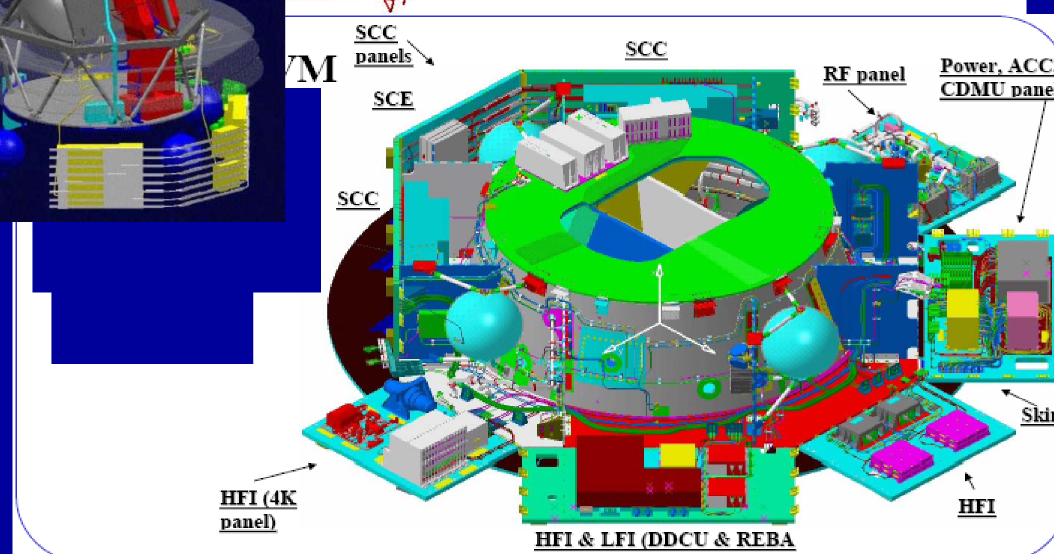
Payload module



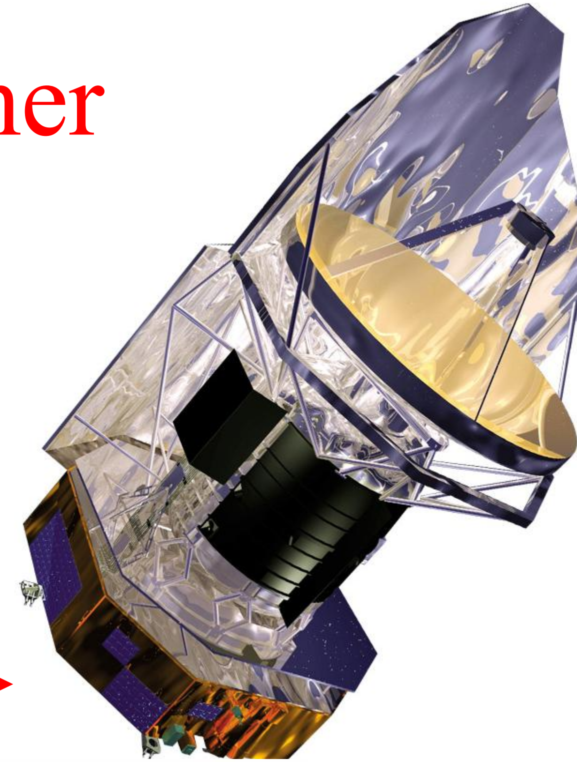






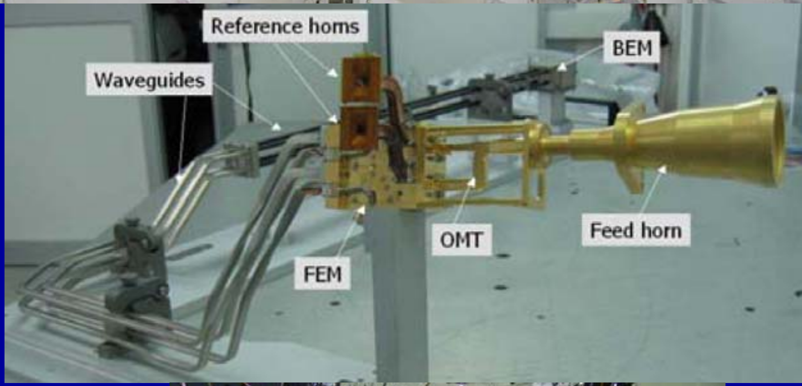


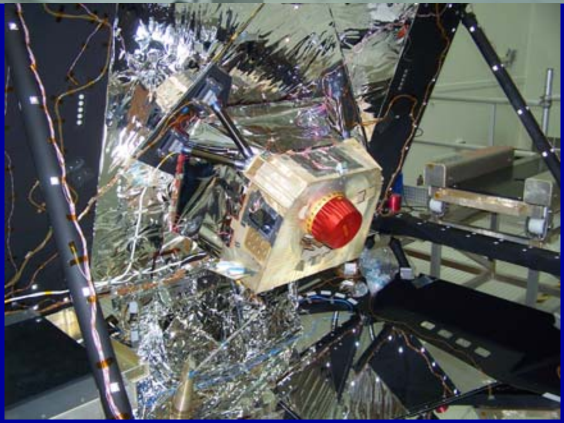
Launch in summer 2008



Planck status

- Spacecraft:
  - cryo-qualification tests at Centre Spatial de Liège successfully completed
  - Flight Service Model completed and delivered
- LFI:
  - FM testing completed (Sept 2006)
  - Delivered for integration October 2006
- HFI:
  - FM tested and delivered (August 2006)
  - Integration with LFI starting October 2006
- Telescope:
  - flight reflectors delivered to Alcatel
  - reflectors tested at cryo T
  - radio-freq model test campaign on-going

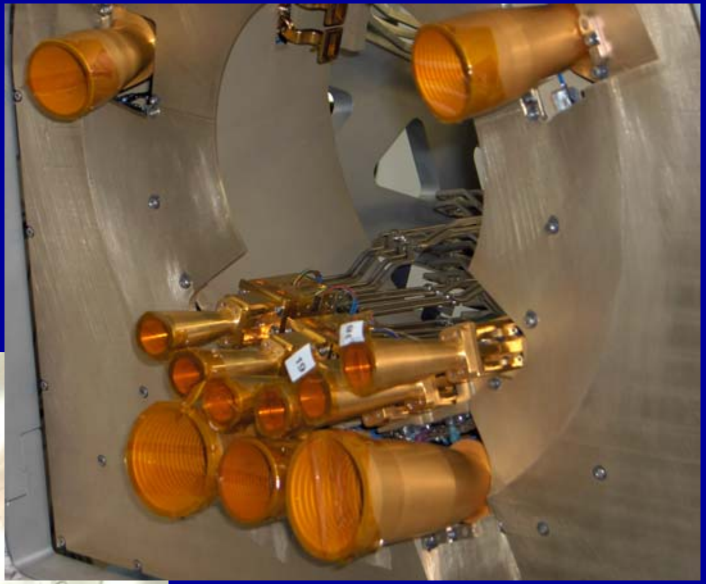


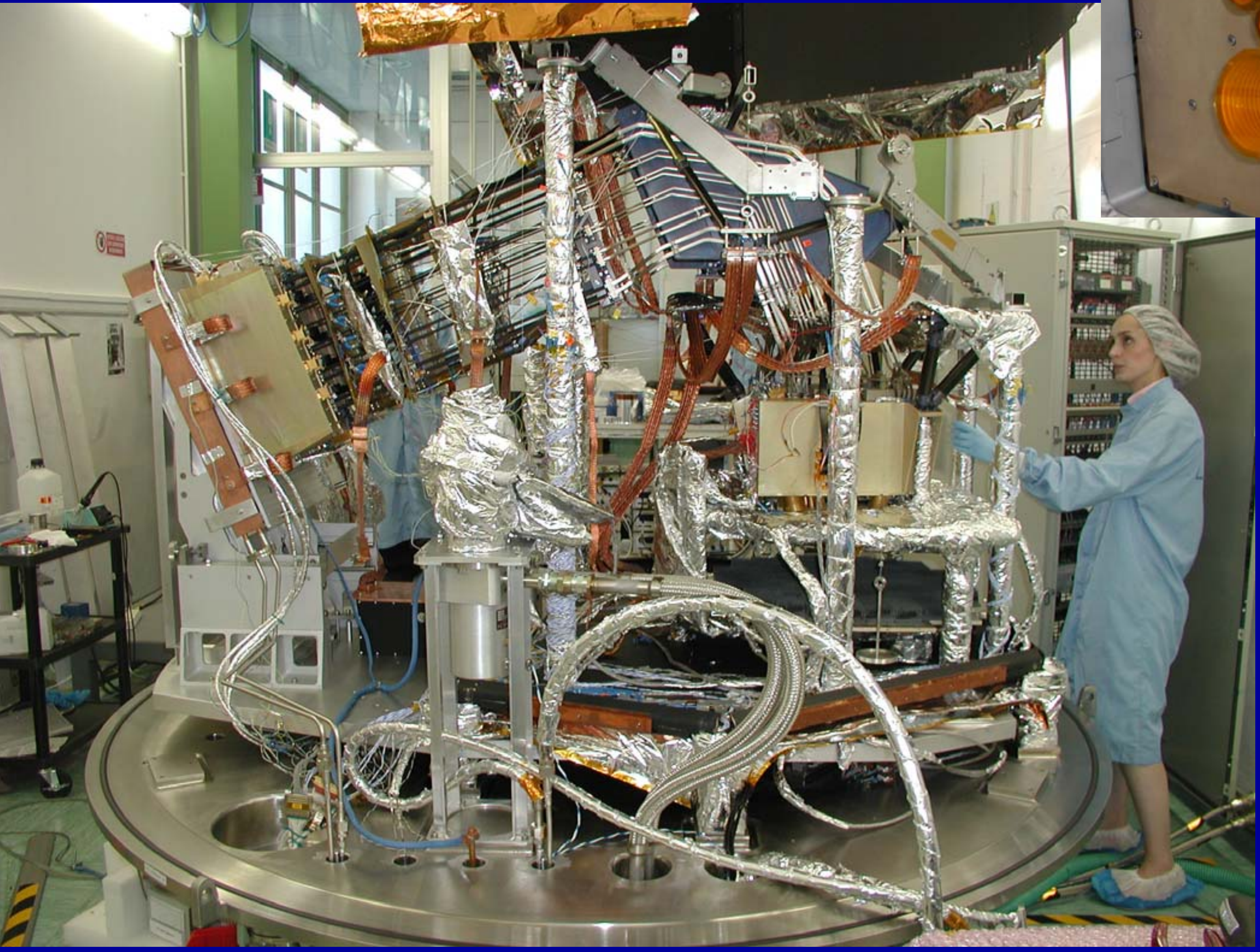


Next Major Milestone: Full flight satellite cryogenic test (October 2007)

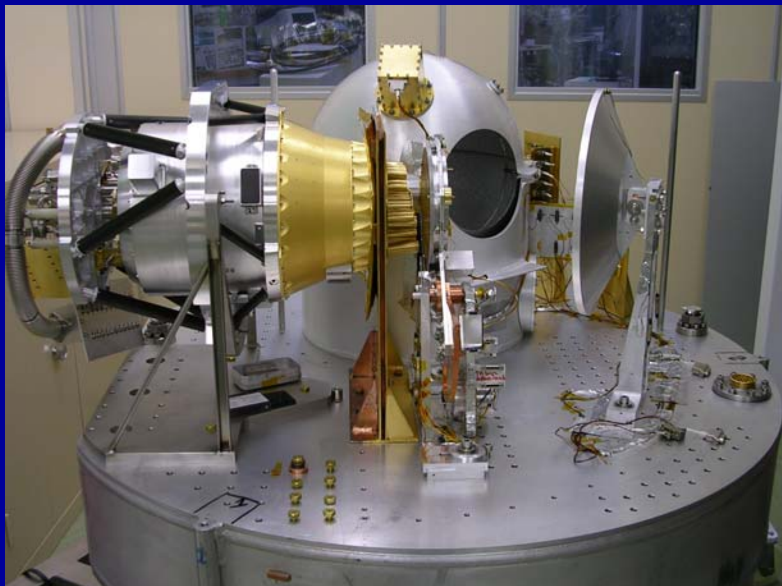
Telescope

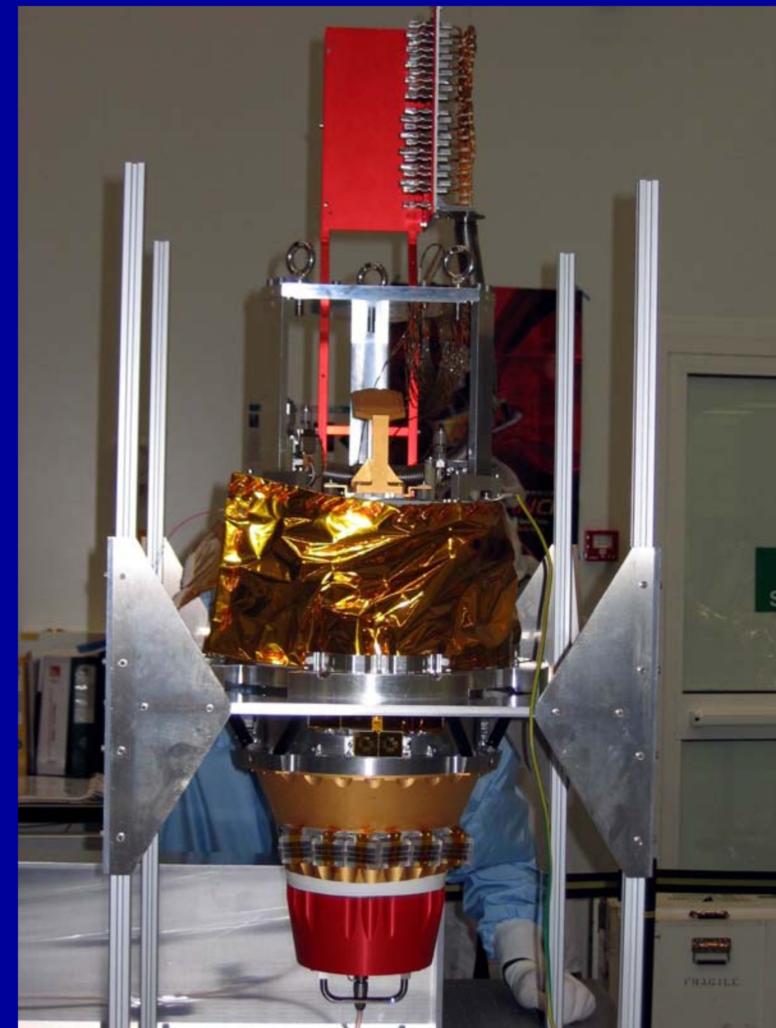
LFI



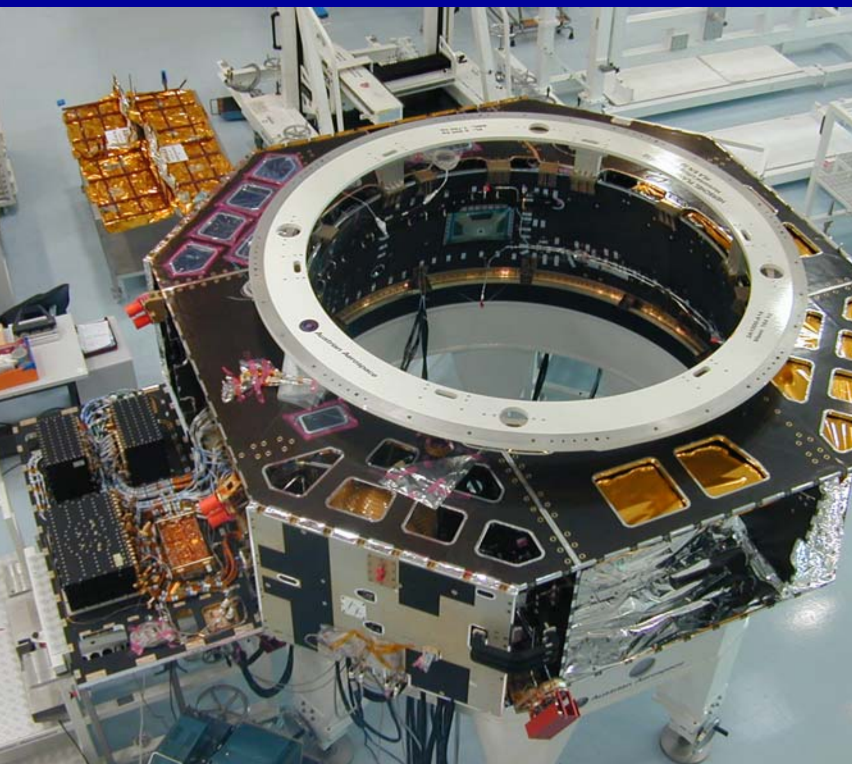


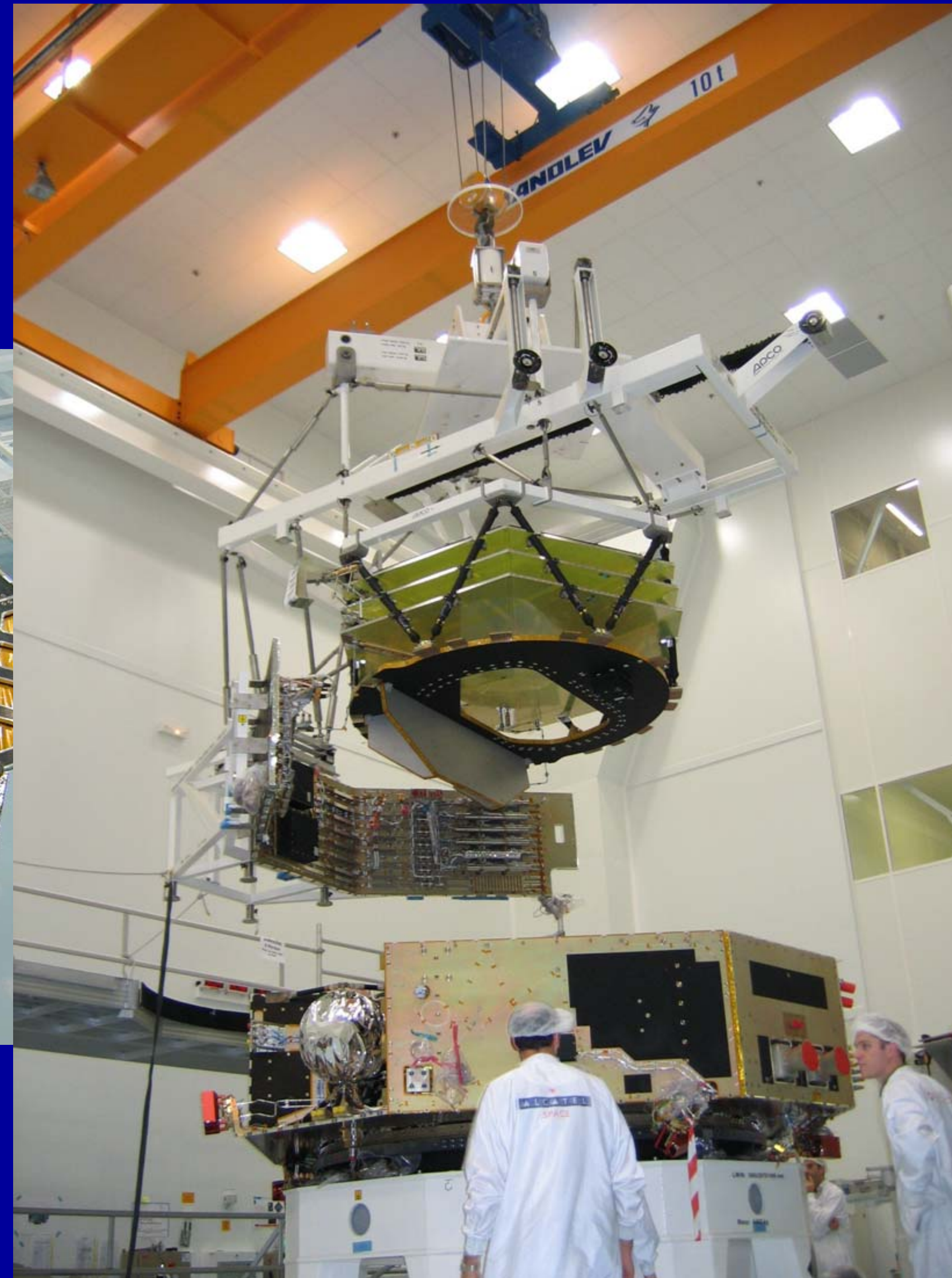
HFI



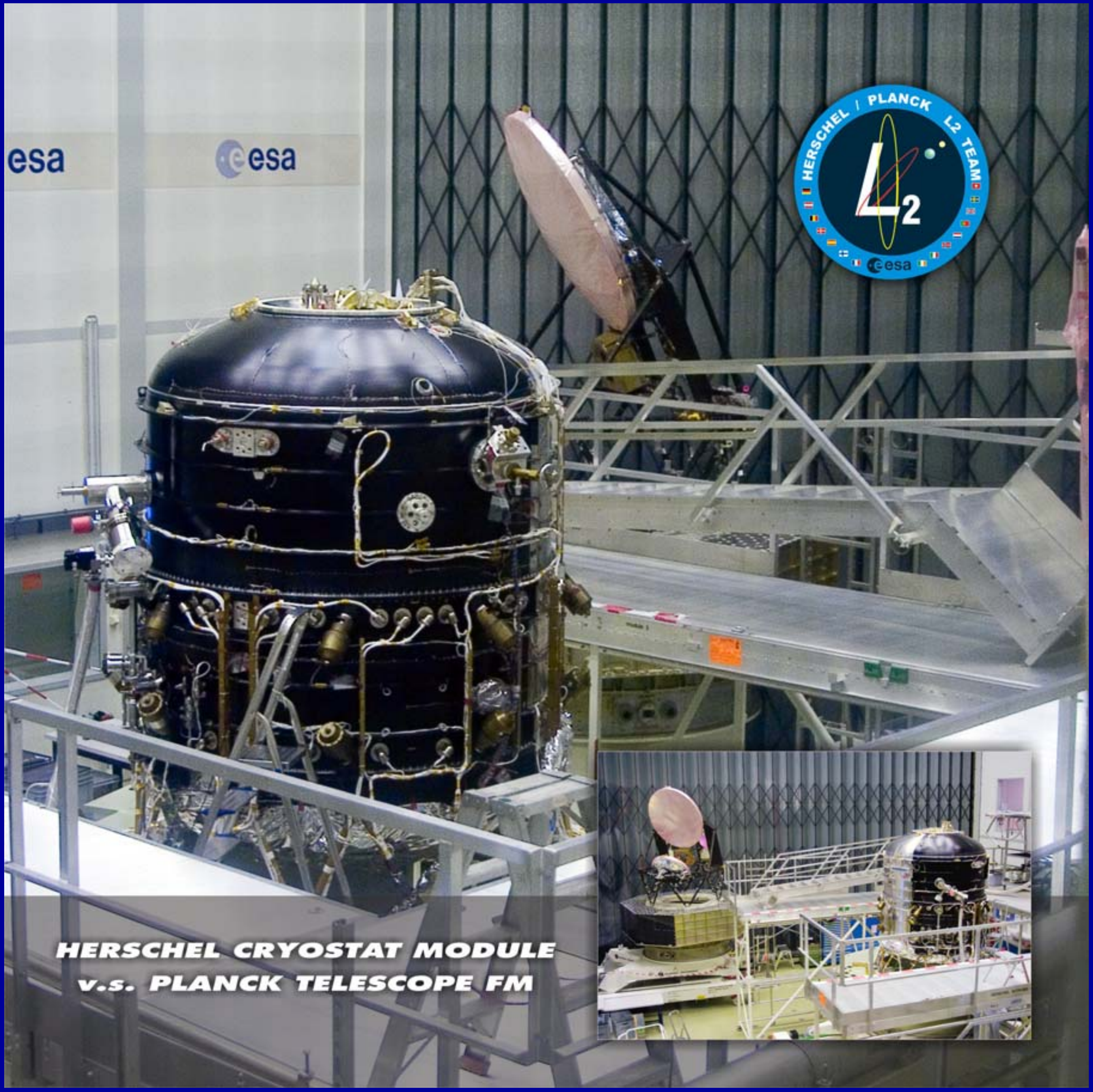


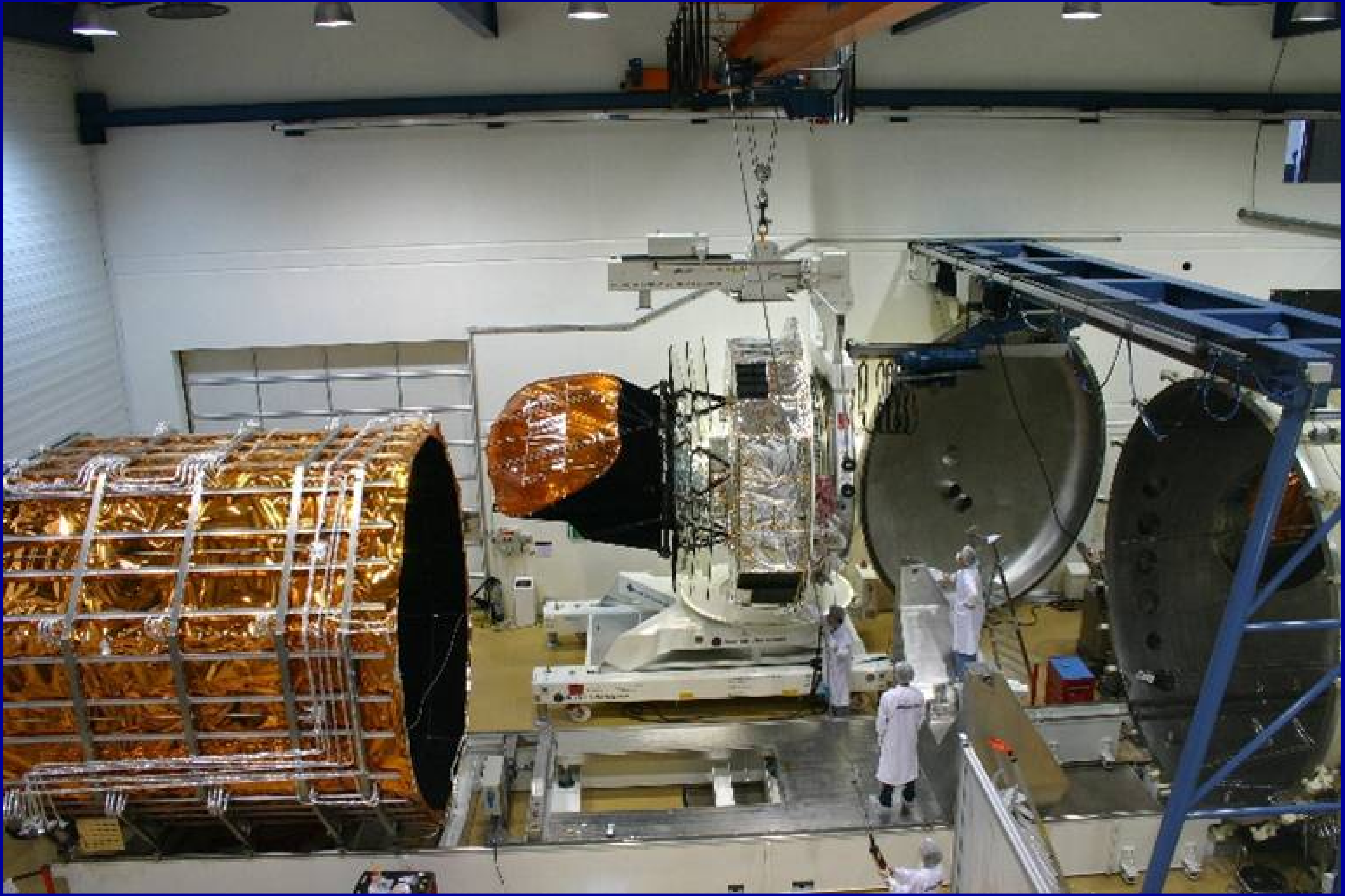
Satellite assembly

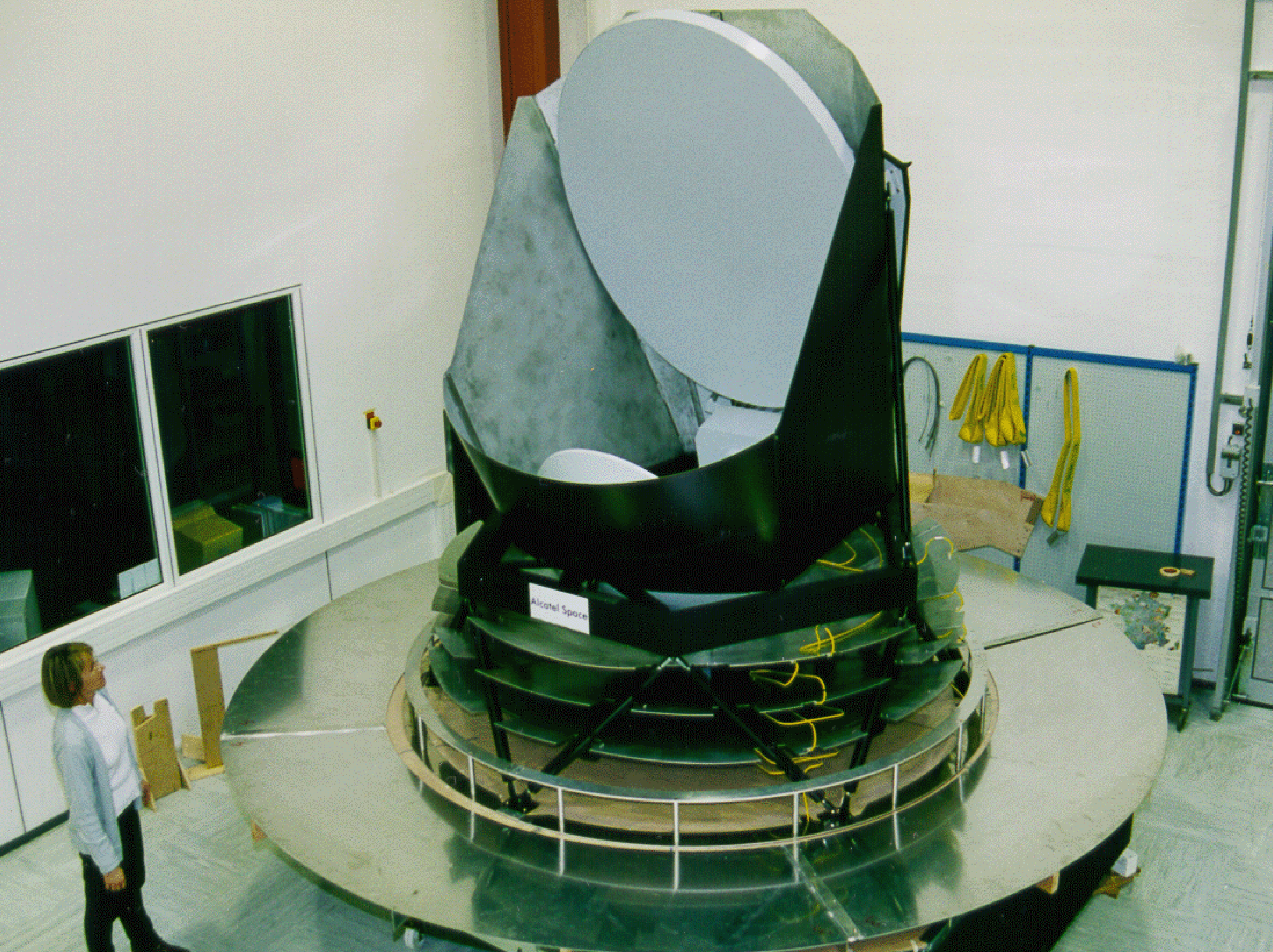




H+P


esa
esa
HERSCHEL / PLANCK L2 TEAM
L2
esa
HERSCHEL CRYOSTAT MODULE
v.s. PLANCK TELESCOPE FM




Alcatel Space

QUIJOTE CMB experiment

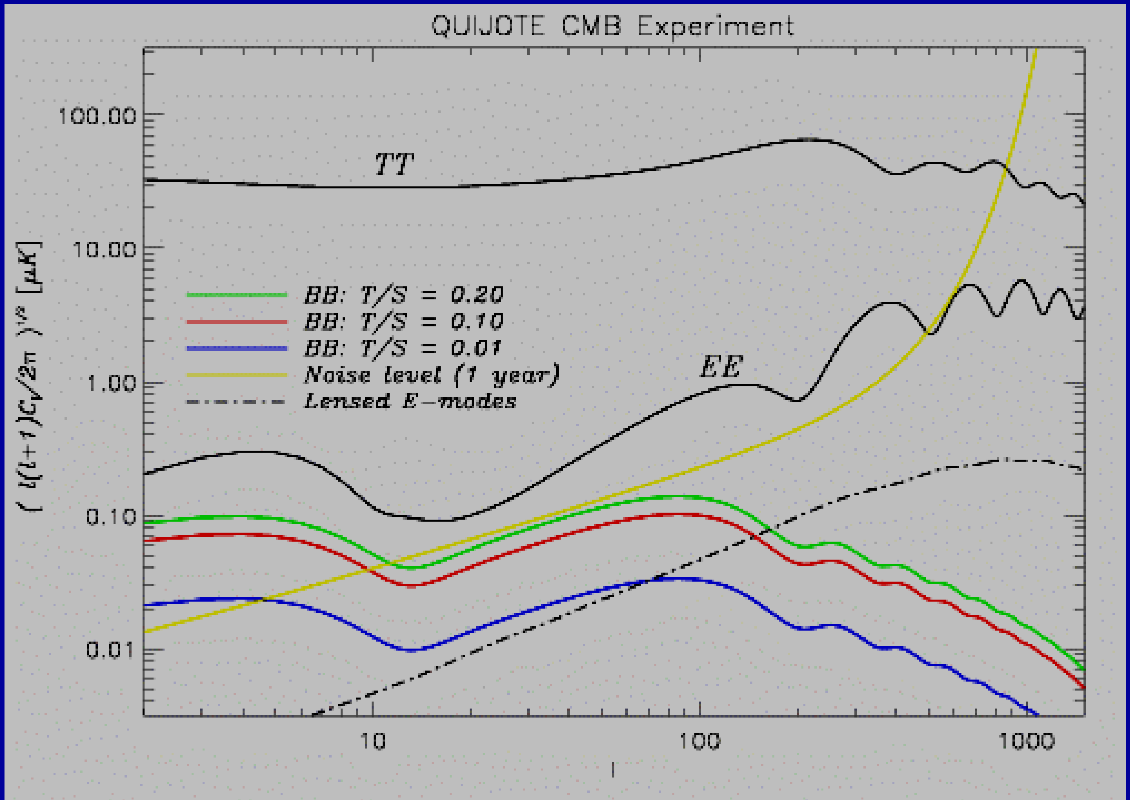
- Aim : perform high sensitivity observations of the polarization of the CMB and Galactic foregrounds in the frequency range 10-30 GHz at large angular scales
- Collaboration: IAC, IFCA, Univ. Manchester and Cambridge

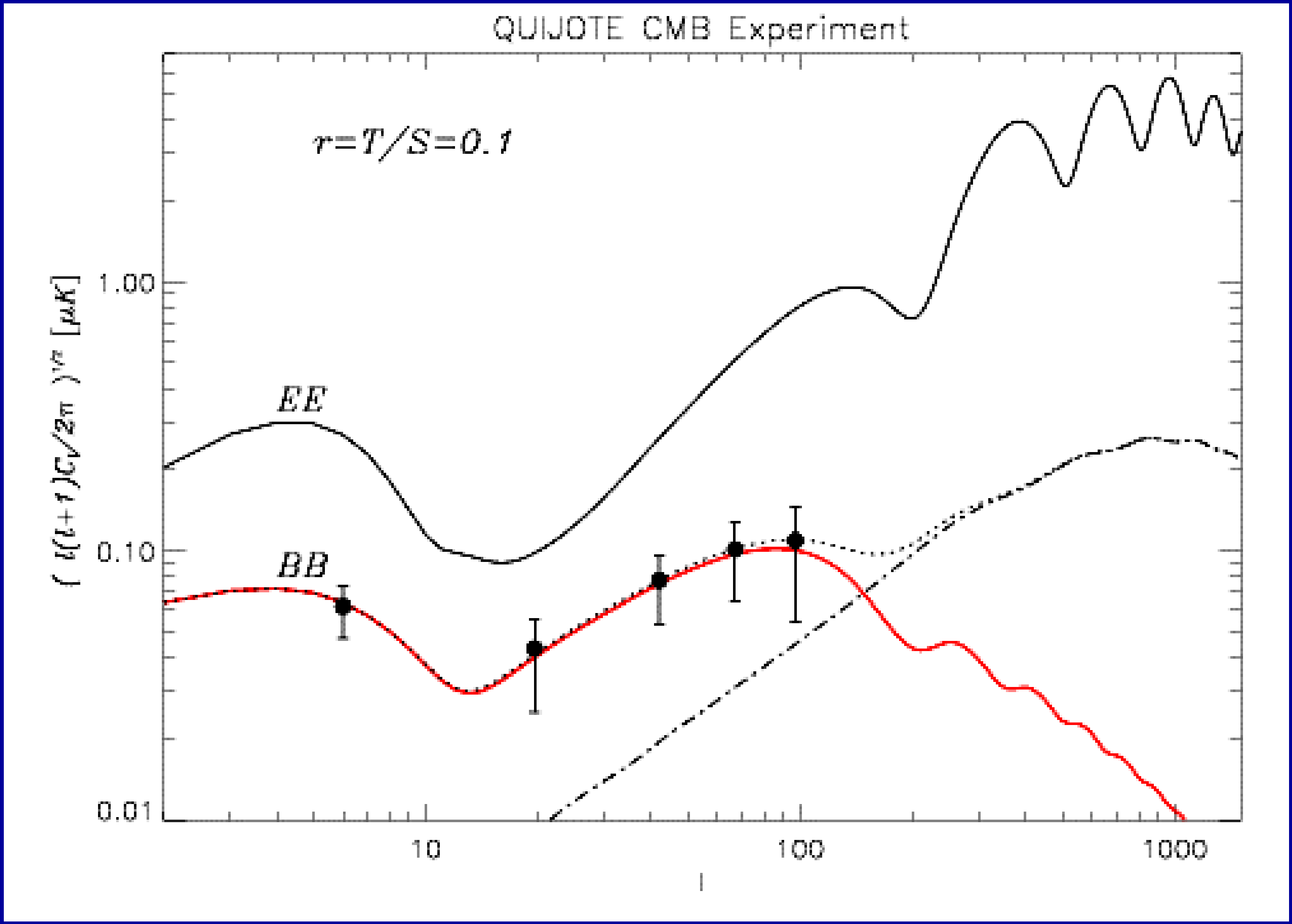
QUIJOTE CMB experiment

- Basic features:
  - Site: Teide Observatory
  - Frequencies: 11, 13, 17 and 30 GHz. Receiver (see Roger´s talk)
  - Angular resolution: ~1 degree
  - Antennas: 3 independent antennas
  - Observing strategy: each antenna mounted on a fast spinning system (1-0.2 Hz) . Earth rotation provides daily sky coverage of several thousand sq degrees. Each antenna operates with an indepenedet cryocooled multi-channel receiver.
  - Sensitivity: adequate to measure tensor modes of amplitude r=0.10 at 30 GHz after two years of data. Complement Planck at low-frequency

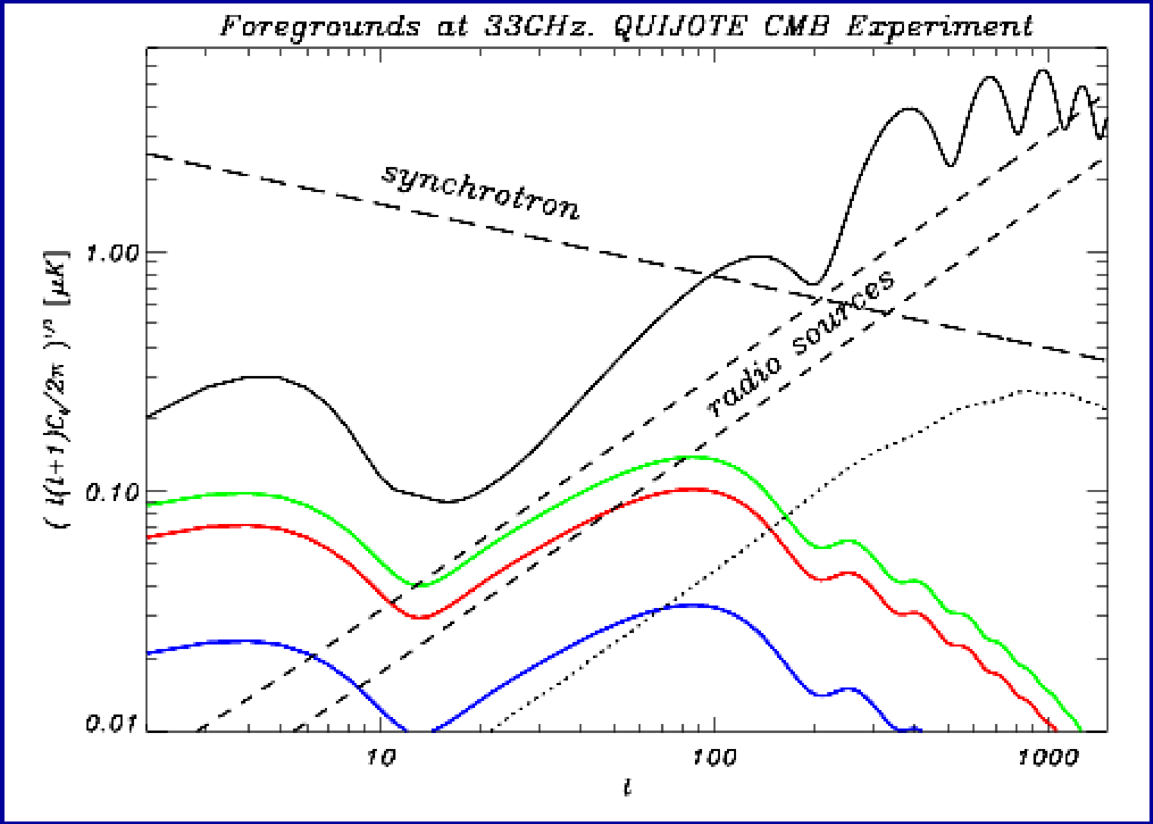
SCIENCE

The goal for QUIJOTE is to provide at 10-30 GHz
a sensitivity 1-2 microK per 1 degree beam over 10000 sq deg. after one year of operation.





Sensitivity of the proposed experiment as compared with theoretical predictions for B-mode component of r=T/S=0.1.



Foreground contamination at 33 GHz as compared with BB modes.
The synchrotron signal (large dashed line) corresponds to the total expected contribution in polarization based on La Porta et al. (2006).
Radio source contribution (short dashed line) for the case of subtracting sources down to 1 Jy in total intensity (upper line) and 300 mJy (lower line)).

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 1%)
- Dark energy density and for the parameter of the equation of state (consistent with cosmological constant w = -1 ± 0.06)

... However, not so good agreement among the various estimates on the Hubble constant (discrepancies at the level of few per cent, larger than claimed statistical errors)

Conclusions (ii)

Parameters of inflationary models:

Increasing evidence for a tilted scalar spectral index n_s in the range 0.95-0.96.

...but not so clear evidence for a non-zero value of the running index.

Strong upper limits on the ratio of tensor to scalar perturbations $r < 0.22$

Conclusions (III)

Neutrinos:
Stringent upper limits on neutrino masses appear to imply the masses are not degenerated.

Amplitude of fluctuations:
The values estimated for σ_8 appear to converge in the range 0.80-0.85