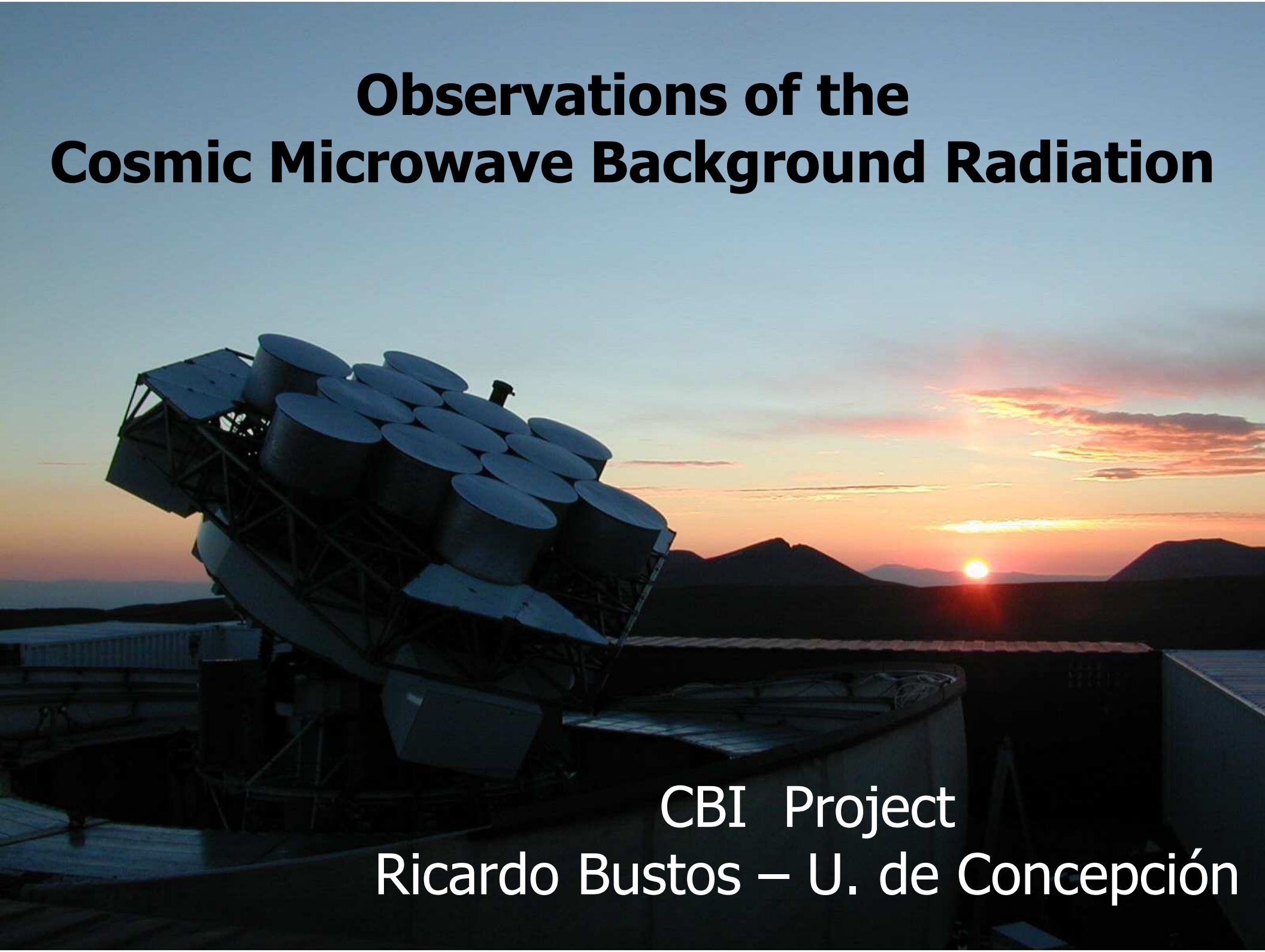
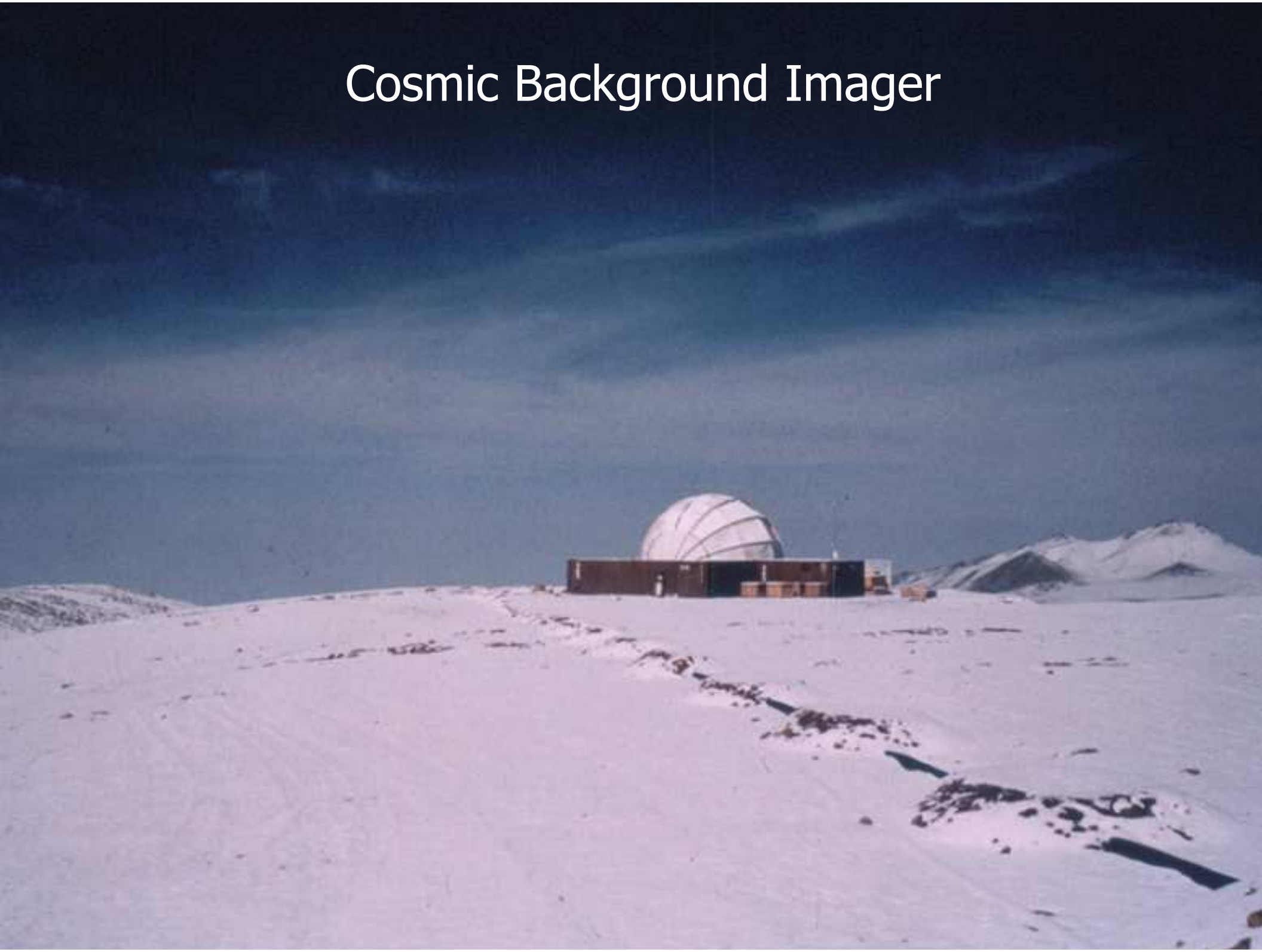
Observations of the Cosmic Microwave Background Radiation



CBI Project

Ricardo Bustos – U. de Concepción

Cosmic Background Imager



Caltech:

Dickinson
Pearson
Readhead
(principal investigator)
Shepherd

NRAO:

Mason
Myers
Pospieszalski

CITA:

Bond
Contaldi
Pen
Pogosyan
Prunet
Sievers

U. Concepción:

Bustos
Reeves
Torres

Berkeley:

Halverson
Holzapfel

U. Chile:

Achermann
Altamirano
Bronfman
Casassus
May

MSFC:

Joy

Chicago:

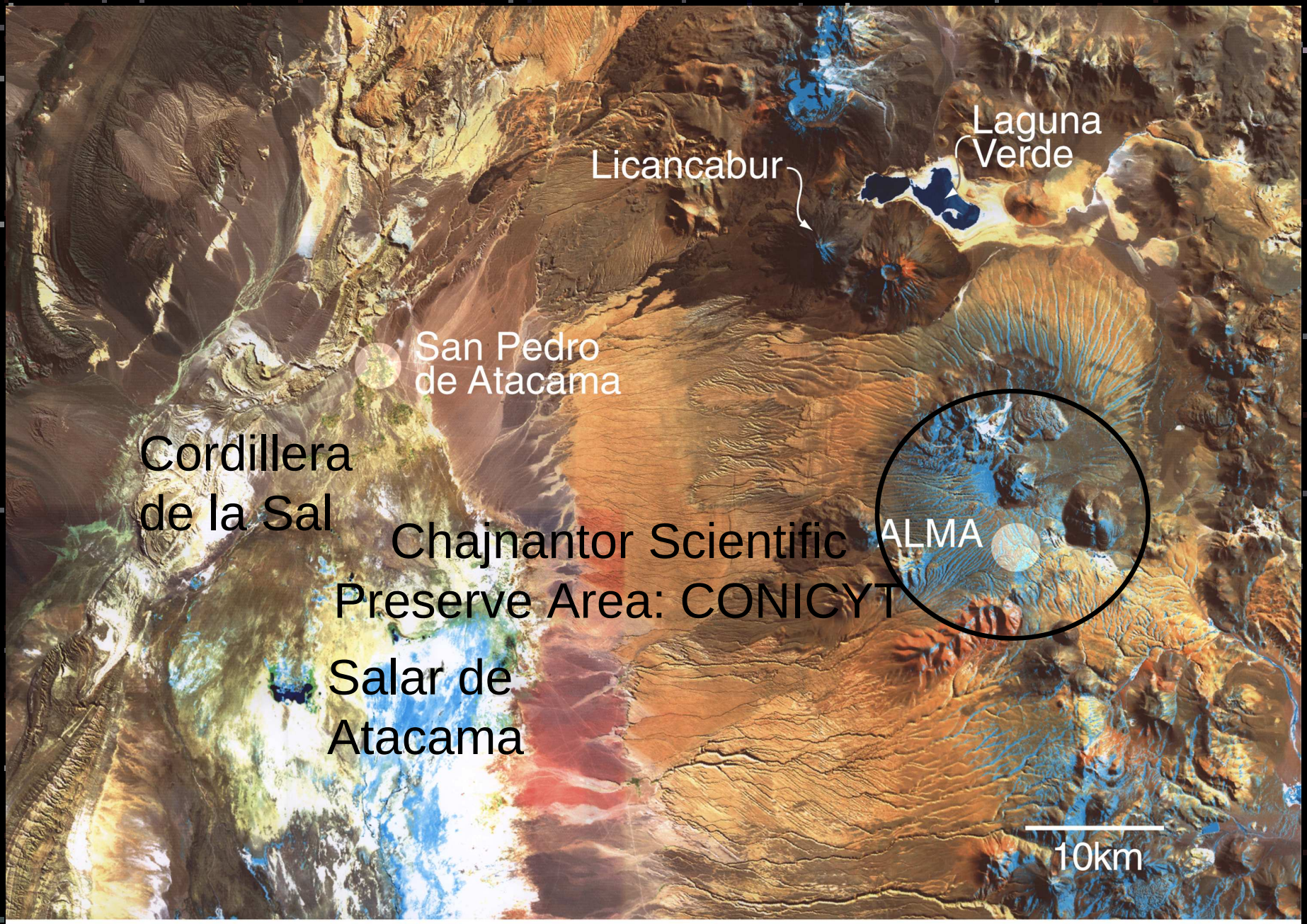
Carlstrom
Cartwright
Kovac
Leitch
Padin
Pryke

San Pedro:

Araya
Cortés
Cruz
Nail
Oyarce
Uehara

Location of CBI in northern Chile.
Extremely low level of water vapor in the atmosphere.

Llano de Chajnantor

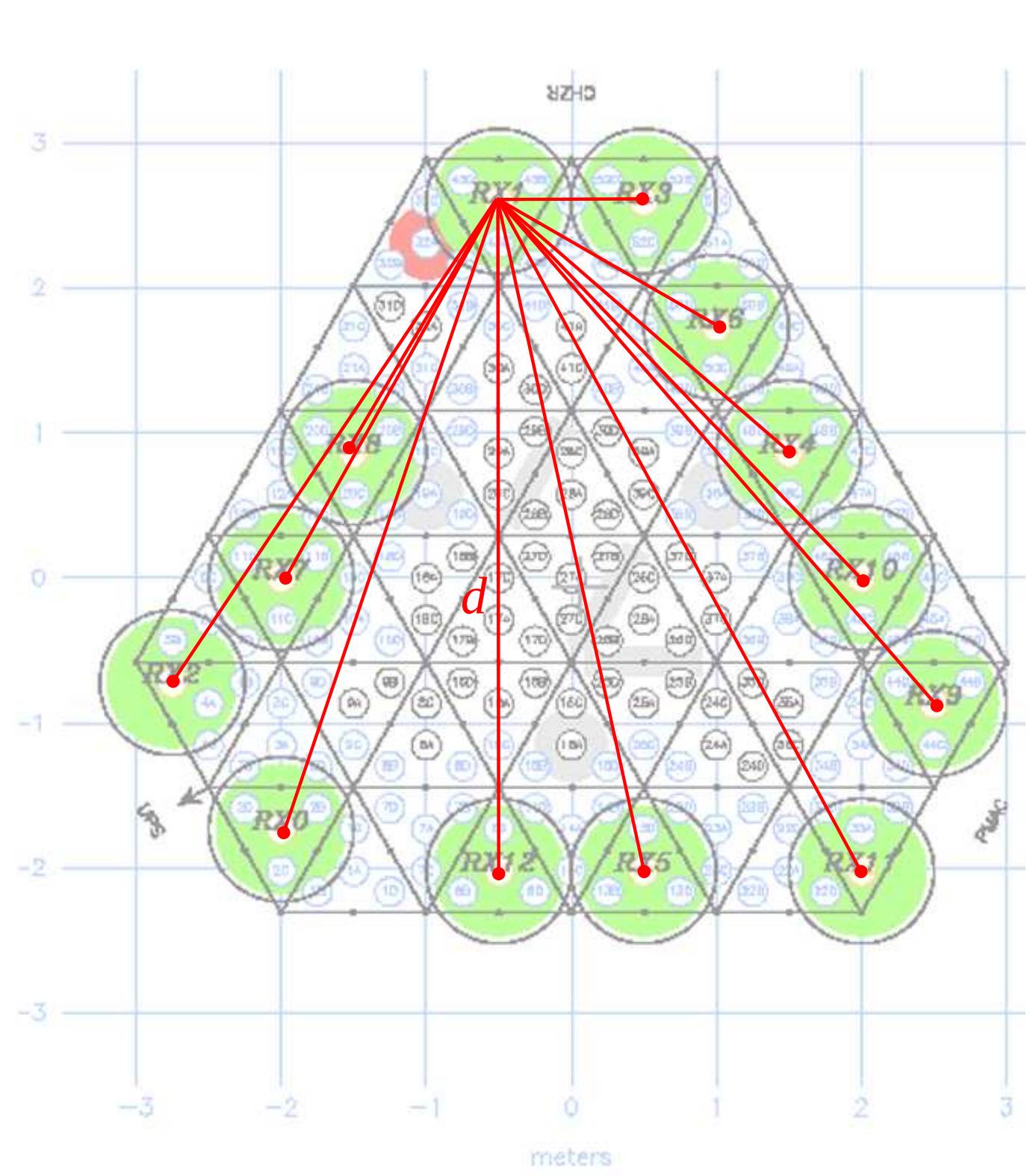


Location of the Compact Configuration of ALMA

ESO PR Photo 24c/99 (8 June 1999)

CBI Interferometer

- Array of 13 Radio Telescopes
- 0.9 m diameter of each antenna
- Detect signals between 26 - 36 GHz
- 10 Channels of 1 GHz.
- Designed to observe and to image the Cosmic Microwave Background Radiation (CMBR)
- Located in llano de Chajnantor, Chile at 5080 meters in the Andes.
- Operates since late 1999
- Reconfigured to detect polarization of CMBR from September 2002.



Number of baselines

$$N = n \cdot (n\text{-}1)/2$$

N : total baselines
n : number of antennas

If n =13, then N = 78 different baselines !

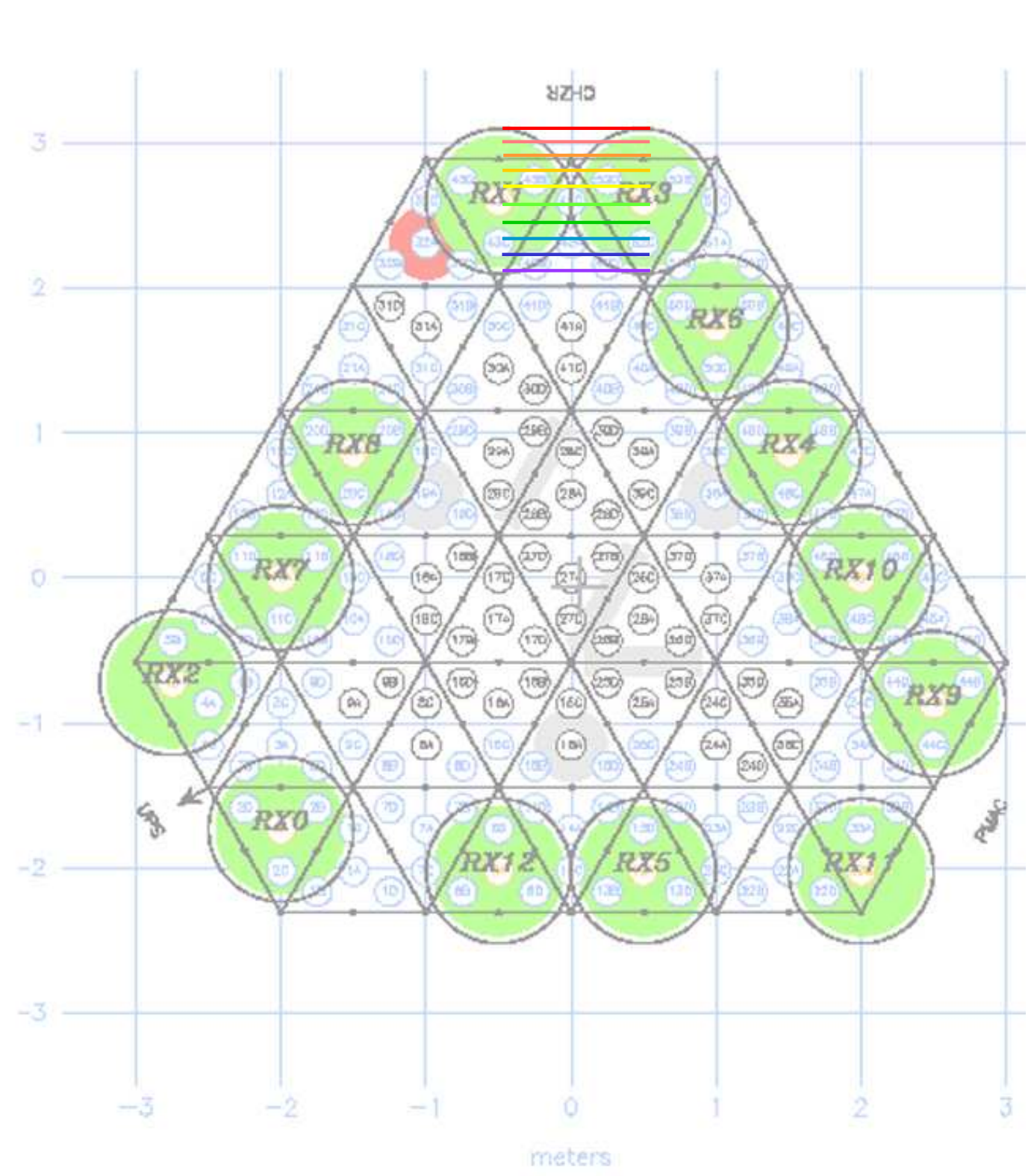
d : baseline length is sensitive to multipoles

$$l \sim 2\pi d/\lambda$$

CBI measures the spectrum between

$$300 < l < 3500$$

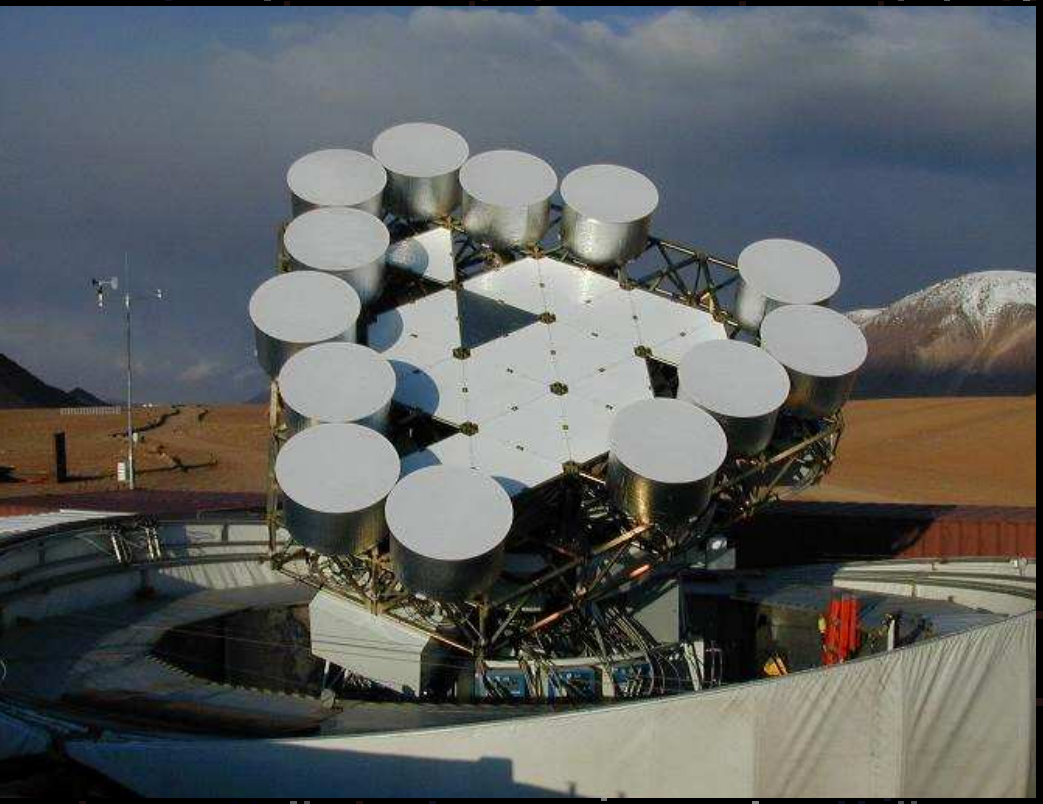
at this configuration



… adding 10 channels
per baseline,
then CBI has
780 interferometers !

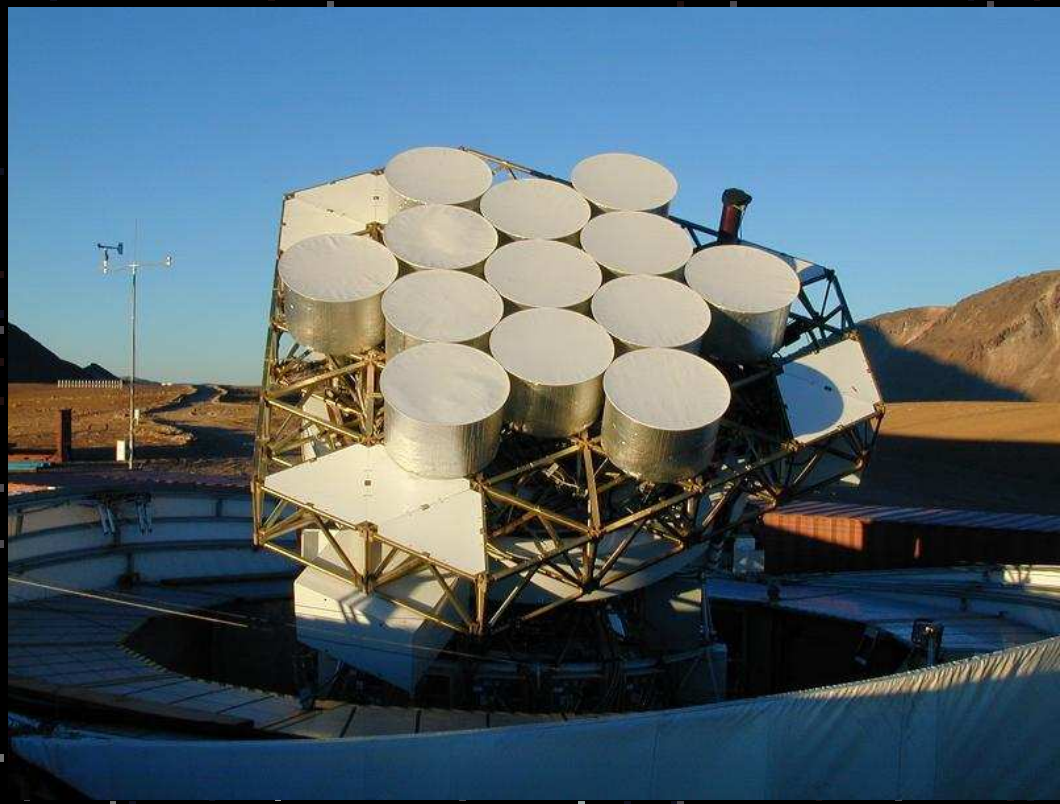
CBI Antenna Configurations

Open (Total intensity)
2000-2001



Longer baselines
Higher angular resolution

Compact (Polarization)
2002-2004

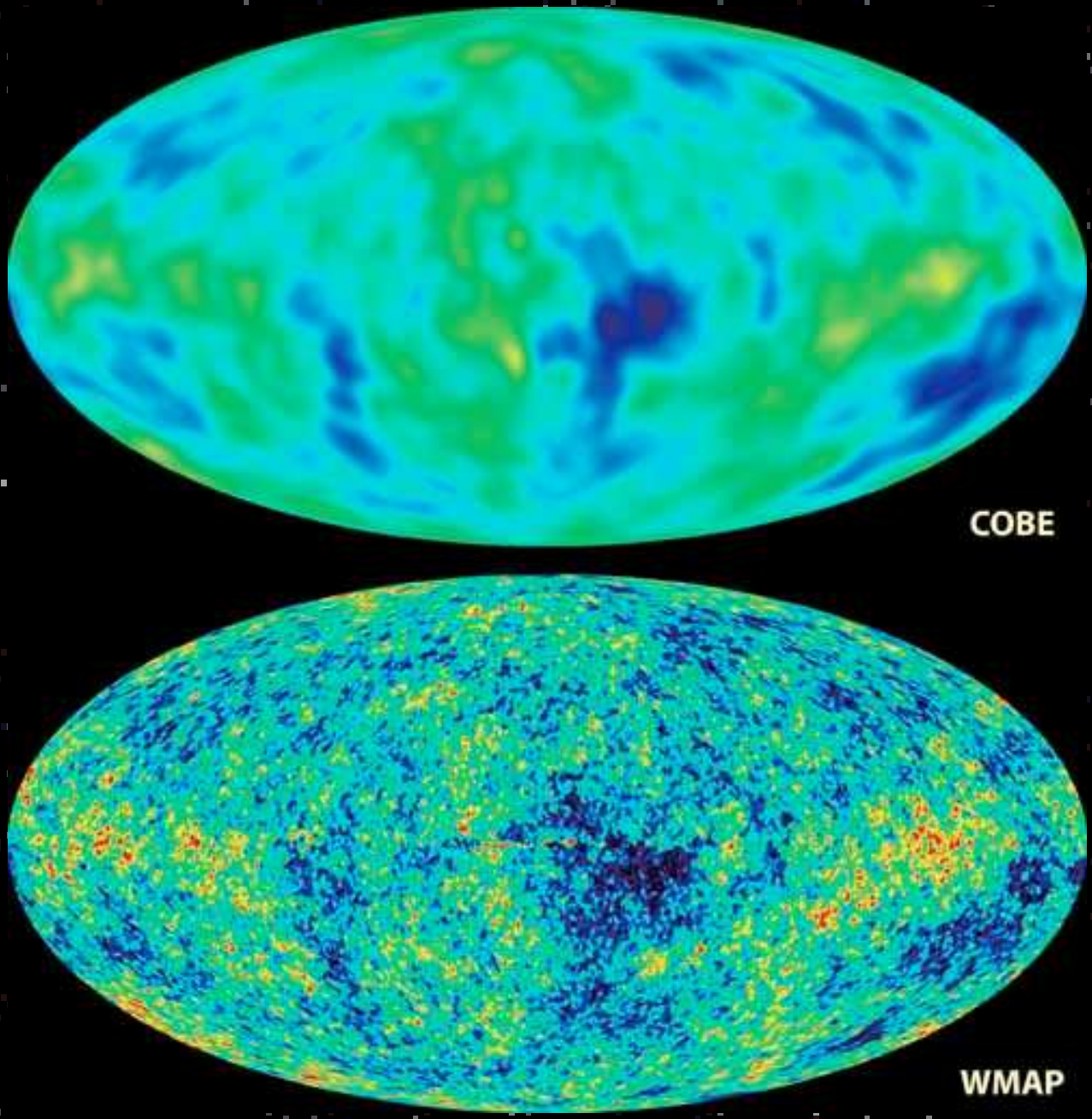


Shorter baselines
Lower angular resolution

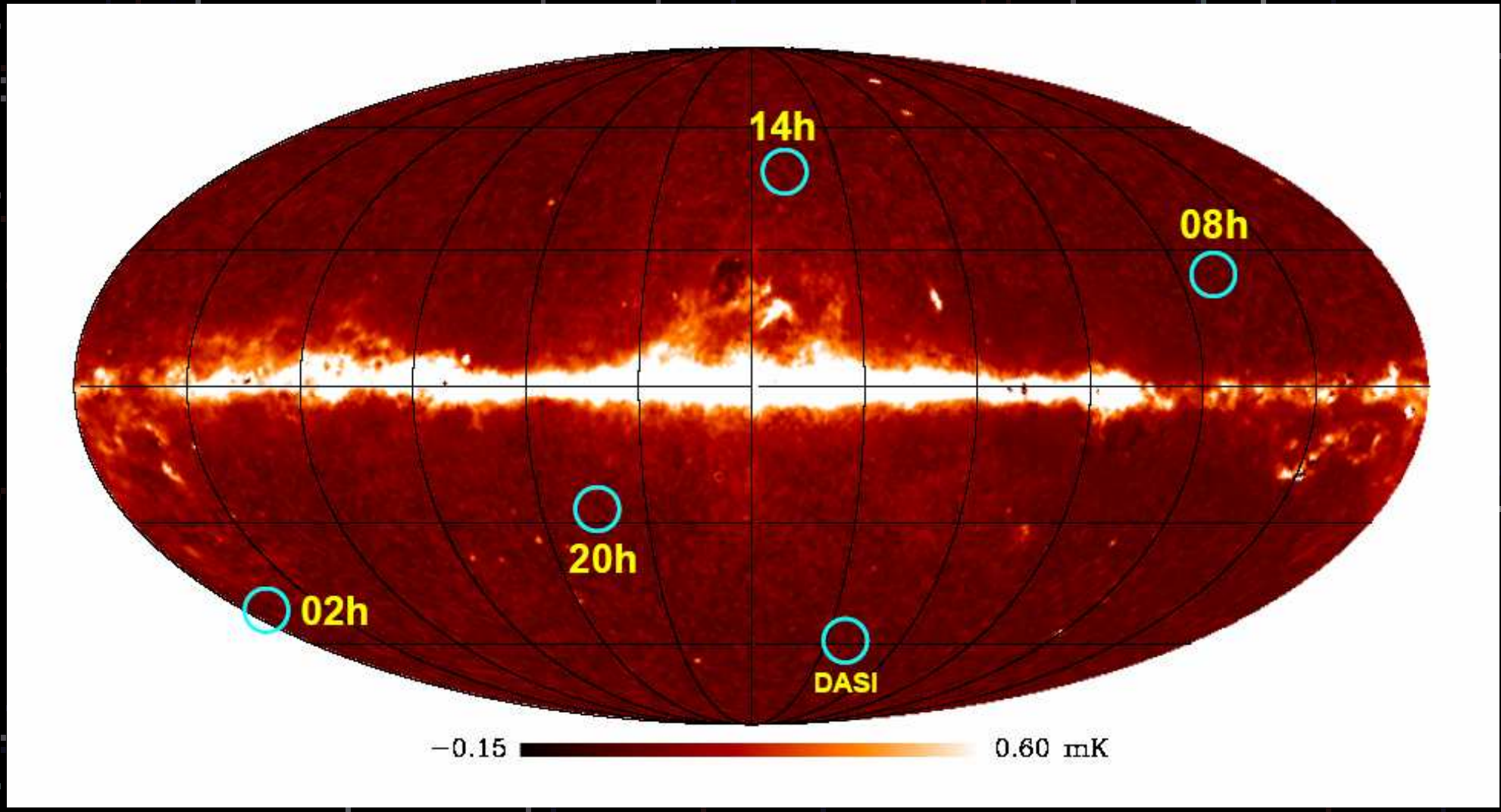
Polarization upgrade done from February to September 2002

CMBR fluctuations. COBE and WMAP

2.725 K +/- ~ 30 μK rms, beam 7^{o}



Intrinsic fields



Synchrotron map Ka band from WMAP

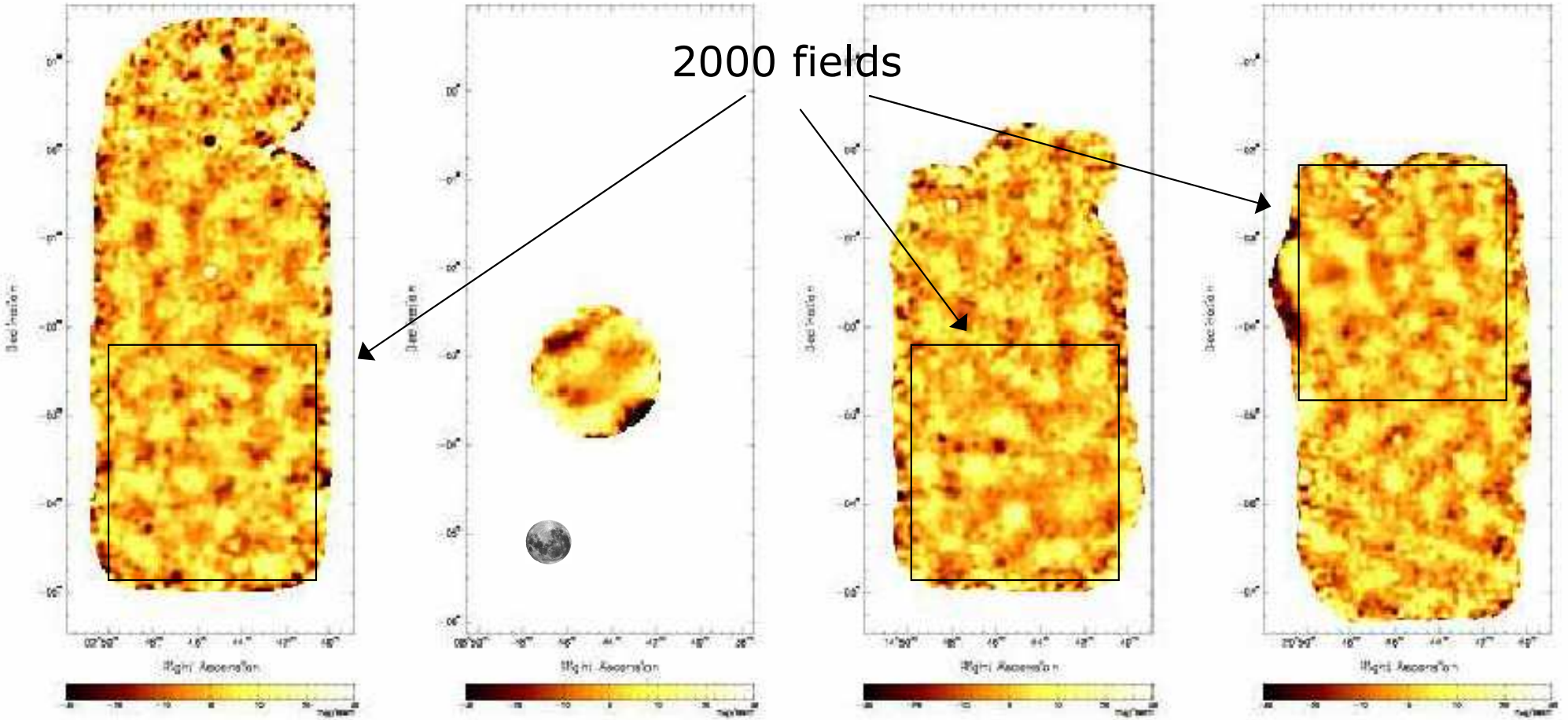
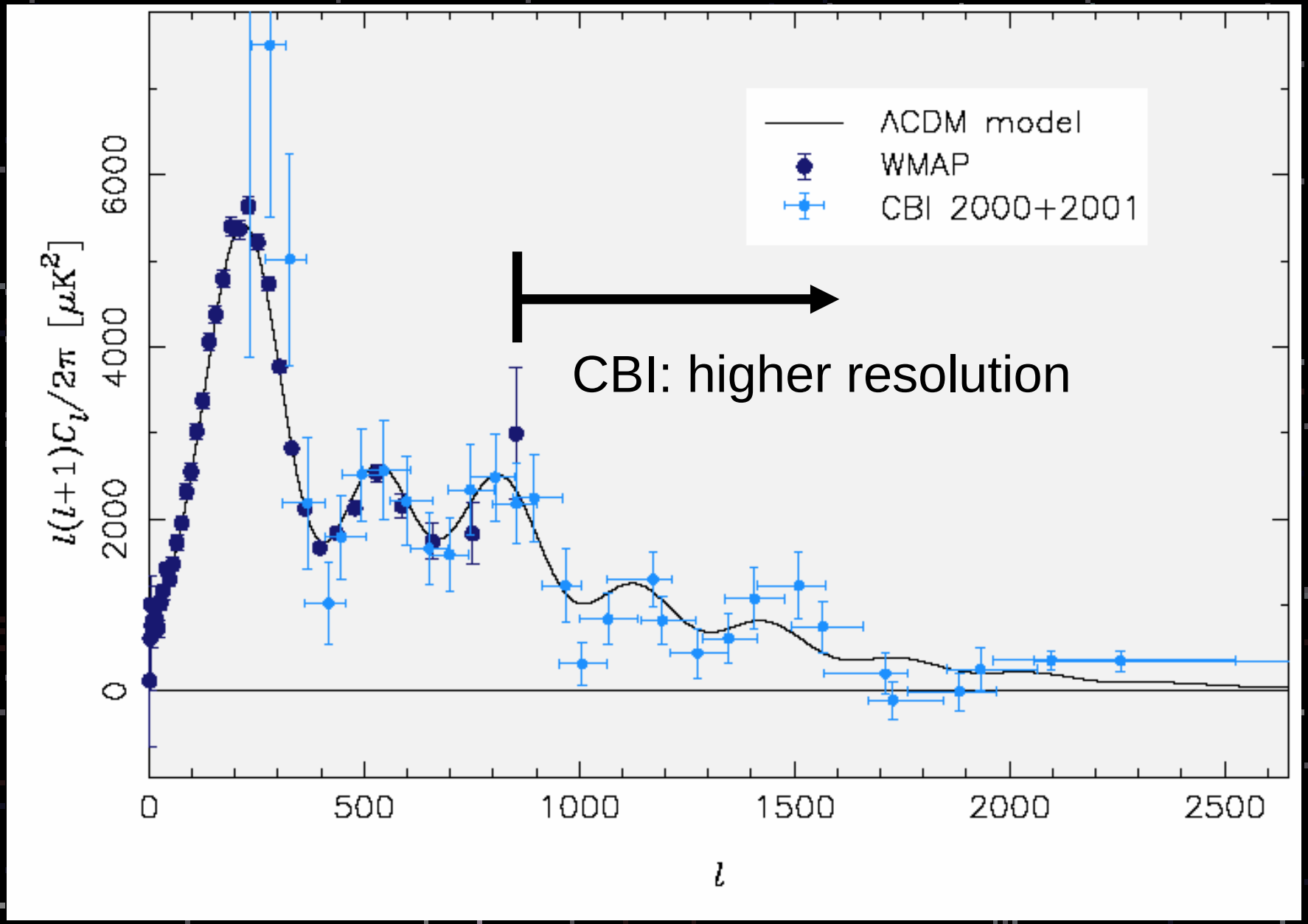


FIG. 1.— The extended mosaic images from the combined 2000+2001 observations. The angular resolution of these observations is $\sim 5'$ (FWHM).

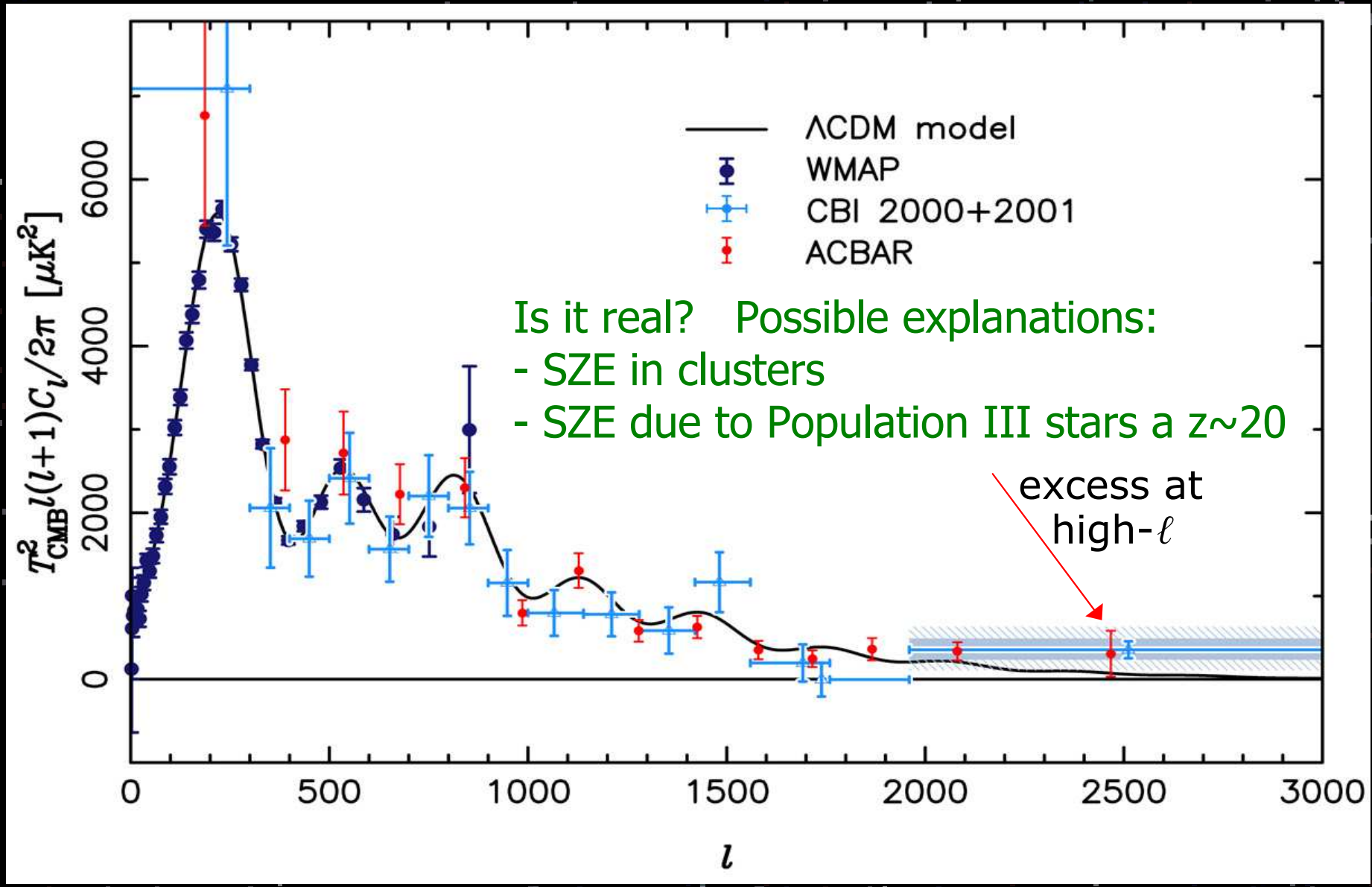
Extended intrinsic fields observed by CBI in 2000-2001. 02^h, 08^h ,14^h, 20^h fields. Angular resolution of ~ 5 arcmin, covering ~ 90 deg^2 in the sky.

Power Spectrum.



Standard Cosmological model, WMAP, and CBI 2000+2001.

Power Spectrum



Combining with high-*l* results from BIMA and ACBAR, we detect power in excess of that expected from primary anisotropy at 98% confidence.

Cosmological Parameters obtained from Total Intensity observations 2000+2001

Parameter	*WMAP* only	CBI + *WMAP*	CBI + ALL
$\Omega_b h^2$	$0.0243^{+0.0016}_{-0.0016}$	$0.0232^{+0.0012}_{-0.0012}$	$0.0228^{+0.0009}_{-0.0010}$
$\Omega_c h^2$	$0.123^{+0.017}_{-0.018}$	$0.113^{+0.014}_{-0.014}$	$0.118^{+0.010}_{-0.010}$
Ω_Λ	$0.71^{+0.08}_{-0.08}$	$0.74^{+0.06}_{-0.06}$	$0.71^{+0.05}_{-0.05}$
τ_C	$0.184^{+0.031}_{-0.057}$	$0.152^{+0.023}_{-0.041}$	$0.117^{+0.019}_{-0.033}$
n_s	$1.01^{+0.05}_{-0.05}$	$0.98^{+0.03}_{-0.03}$	$0.96^{+0.02}_{-0.02}$
$10^{10} A_S$	$27.7^{+5.5}_{-5.1}$	$24.2^{+3.5}_{-3.5}$	$22.9^{+2.4}_{-2.5}$
H_0	$72.1^{+6.4}_{-5.8}$	$72.9^{+5.2}_{-5.1}$	$70.5^{+3.7}_{-3.9}$
Age (Gyr)	$13.3^{+0.3}_{-0.3}$	$13.5^{+0.3}_{-0.2}$	$13.6^{+0.2}_{-0.2}$
Ω_m	$0.29^{+0.08}_{-0.08}$	$0.26^{+0.06}_{-0.06}$	$0.29^{+0.05}_{-0.05}$

Polarization of CMB

At z ~ 1100, the photon-baryon plasma decoupled and allowed photons to stream freely. Surface of last scattering.

CMB polarization is generated by Thomson scattering.

Intensity of polarized emission are expressed by 4 Stokes parameters *I*, *Q*, *U*, and *V*. We ignore *V*.

From *I*, *Q*, and *U*, we can generate *TT*, *EE*, *BB*, *TE*, *TB*, and *EB* power spectra. *T*: Total Intensity, *E*: Grad, *B*: Curl components of linear polarization. *E* is the component 0º or 90º from the wave vector (or interferometer baseline), *B* is ±45º.

Density perturbations generate *E* only. *B* can be generated by tensor perturbations or by gravitational lensing of *E*.

Polarization of CMB

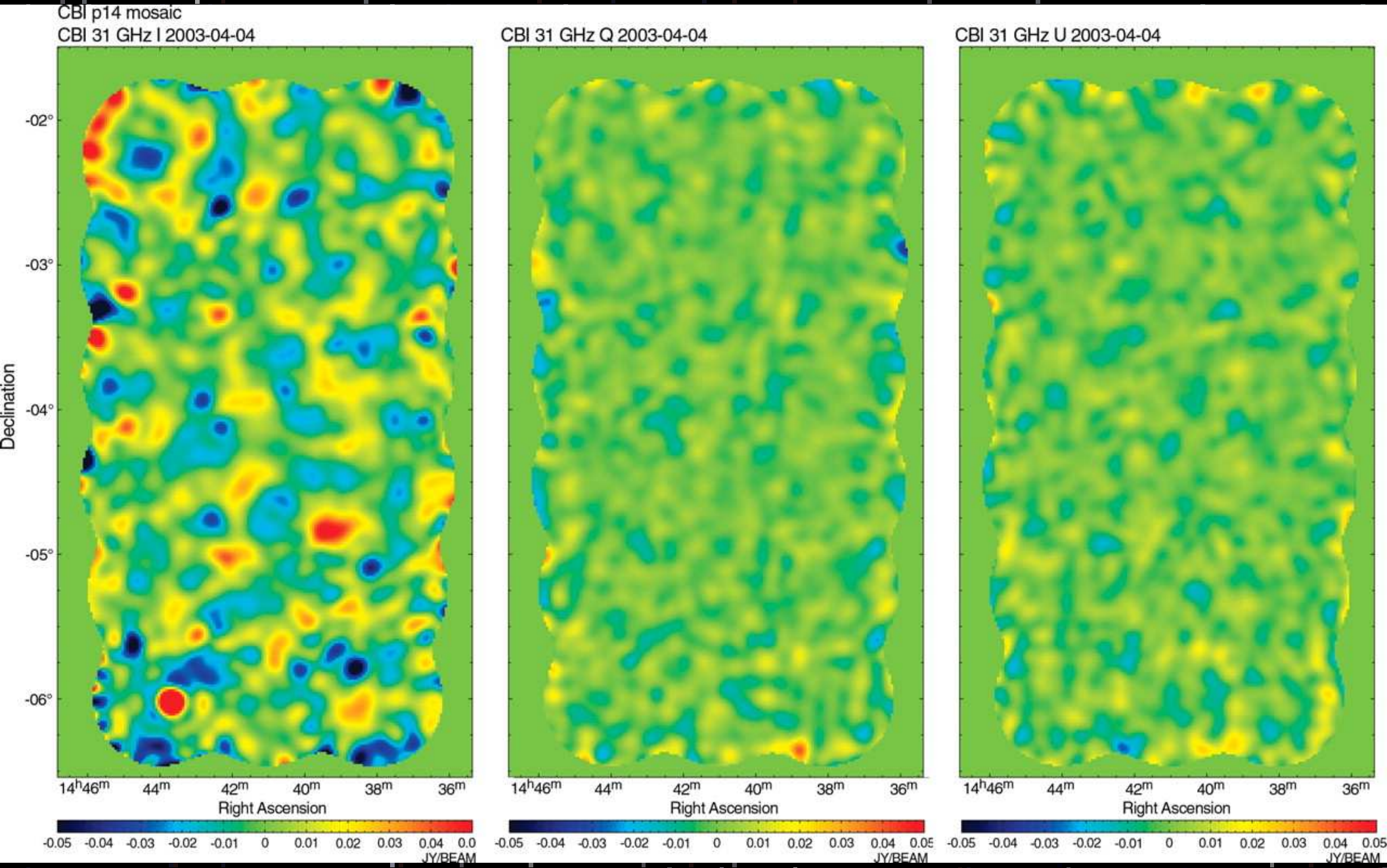
In inflation models, *B*-modes should be much weaker than *E*-modes. Confirmation that *BB* is much smaller than *EE* is a very important check of the model.

The dominant source of the *E* mode is caused by velocity effects in the acoustic waves at the surface of last scattering, introducing a shift of one-half cycle in phase between the maxima in the *TT* and *EE* spectra.

Each CBI receiver is sensitive to right (*R*) or left (*L*) circular polarization. Co-polar baselines *RR* or *LL* are sensitive to Stokes $I \pm V \approx I$. Cross-polar *RL* or *LR* are sensitive to linear polarization, Stokes $Q \pm iU$.

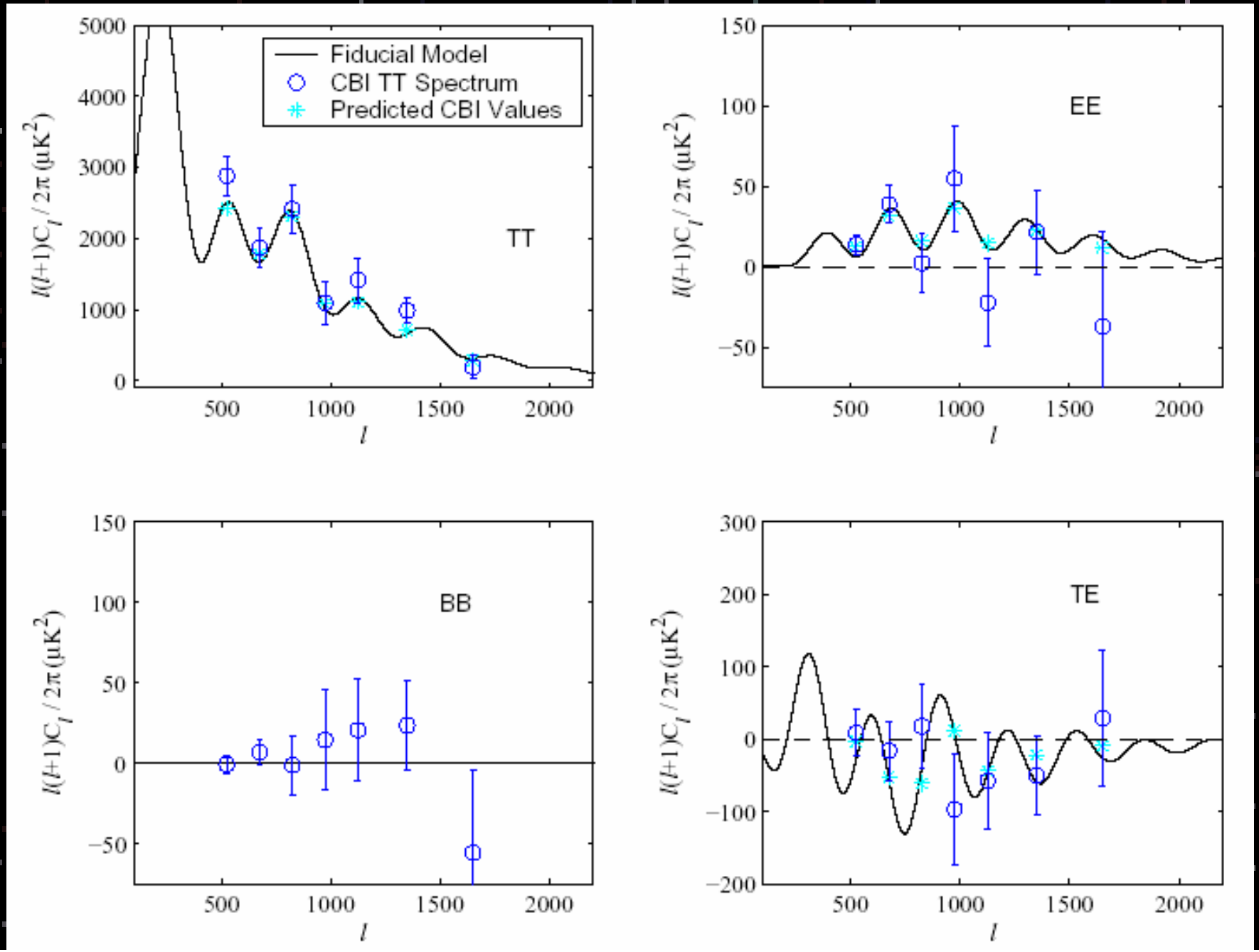
Polarization spectrum is no more than 10% than total intensity.

14^h field image: *I*, *Q*, and *U*.

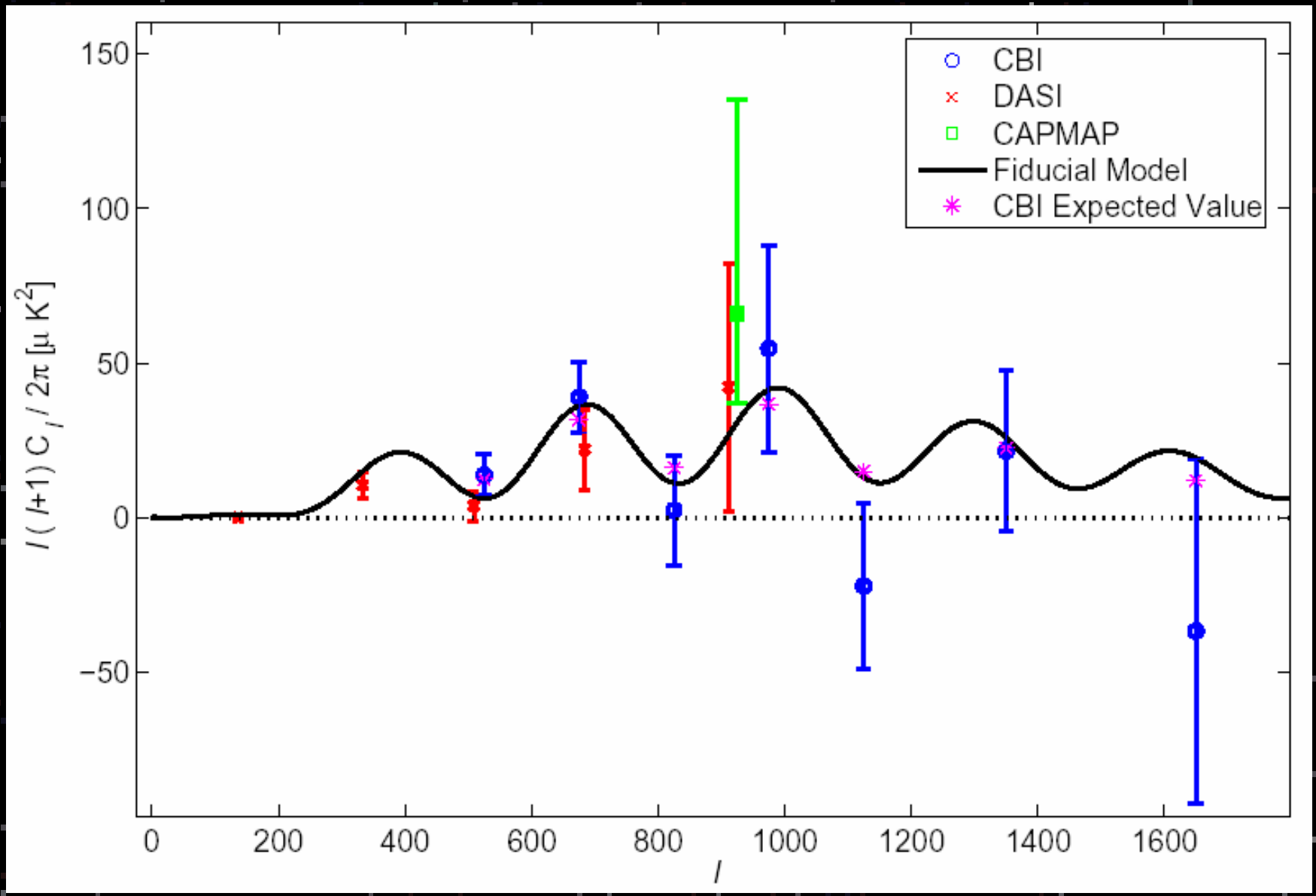


Ground pickup removed

CMB Polarization Angular Spectrum
CBI Observations 2002-2004



Comparison of EE measurements from CBI, DASI , and CAPMAP



Cosmological Parameters obtained from Polarization observations 2002+2004

	WMAP1	CBIpol+WMAP1	CBIpol+CBIext+WMAP1
$\Omega_b h^2$	$0.0243^{+0.0019}_{-0.0017}$	$0.0240^{+0.0018}_{-0.0016}$	$0.0233^{+0.0013}_{-0.0013}$
$\Omega_c h^2$	$0.119^{+0.016}_{-0.016}$	$0.113^{+0.014}_{-0.015}$	$0.109^{+0.012}_{-0.013}$
θ	$1.049^{+0.007}_{-0.008}$	$1.048^{+0.006}_{-0.006}$	$1.044^{+0.005}_{-0.005}$
τ_c	$0.188^{+0.037}_{-0.065}$	$0.190^{+0.044}_{-0.067}$	$0.164^{+0.027}_{-0.053}$
n_s	$1.01^{+0.06}_{-0.05}$	$1.00^{+0.06}_{-0.05}$	$0.98^{+0.04}_{-0.04}$
$\log[10^{10} A_S]$	$3.3^{+0.2}_{-0.2}$	$3.3^{+0.2}_{-0.2}$	$3.2^{+0.2}_{-0.2}$
Ω_Λ	$0.72^{+0.08}_{-0.07}$	$0.74^{+0.07}_{-0.07}$	$0.75^{+0.06}_{-0.06}$
Age (Gyr)	$13.3^{+0.4}_{-0.4}$	$13.4^{+0.3}_{-0.4}$	$13.5^{+0.3}_{-0.3}$
Ω_m	$0.28^{+0.07}_{-0.08}$	$0.26^{+0.07}_{-0.07}$	$0.25^{+0.06}_{-0.06}$
σ_8	$0.94^{+0.13}_{-0.13}$	$0.91^{+0.10}_{-0.10}$	$0.85^{+0.08}_{-0.08}$
z_{re}	$17.5^{+6.7}_{-6.2}$	$17.5^{+6.7}_{-6.2}$	$16.0^{+6.0}_{-5.5}$
H_0	$73.3^{+7.1}_{-6.4}$	$74.5^{+7.7}_{-6.5}$	$74.2^{+6.1}_{-5.5}$

Conclusions – Total Intensity

Two years of CMBR observations with the CBI have been combined to give a sensitive, high-resolution angular power spectrum over the range $400 < l < 3500$.

CBI 2000+2001 observations combined with *WMAP* gives the most precise cosmological parameters ever published.

These results are consistent with the key predictions of structure formation and inflationary theories.

A marginal detection of a running of the scalar spectral index.

Detection of an excess of power of that expected from primary anisotropy at $\ell > 2000$ with a 98 % confidence.

Conclusions – Polarization

High significant detection of the *E*-mode polarization. First to detect and measure the 2nd and 3rd peaks in the *EE* spectrum.

Determined a *TT*-*EE* phase-shift of π, as expected if acoustic waves are the origin of the features in the *TT* and *EE* spectra.

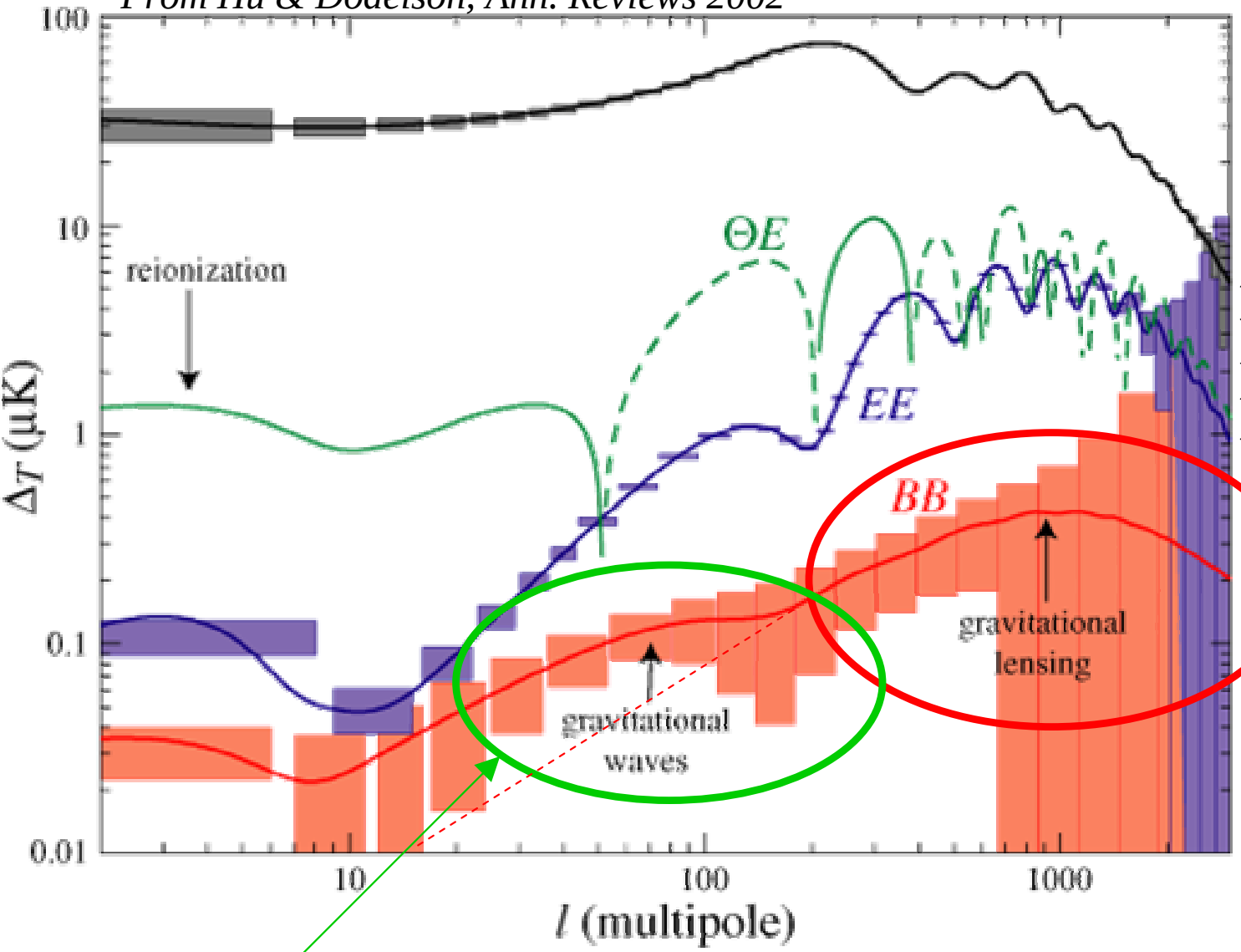
Powerful confirmation of the standard model of cosmology:

- Dark energy (~75%) and non-baryonic "cold dark matter" (~20%) are the dominant constituents of the Universe. ~5% are conventional "baryonic" matter.
- Geometry is close to flat (Euclidean).
- Primordial density fluctuations are predominantly adiabatic.

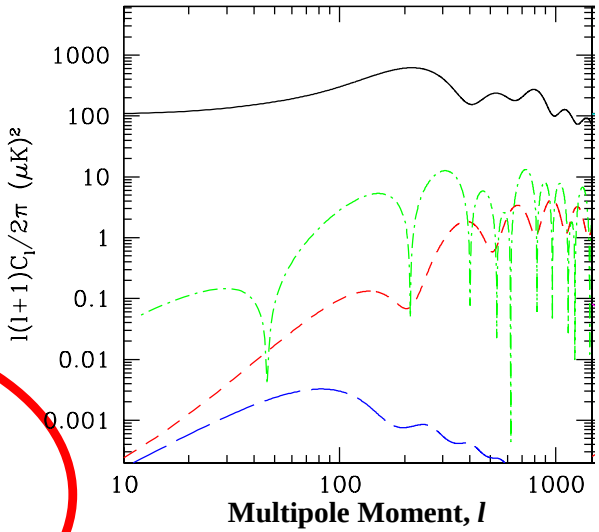
We expect by the end of 2005 to have more than doubled the data set, decreasing by a factor of 2 the uncertainties of C_l.

Science Target: CMB Polarization B-modes

From Hu & Dodelson, Ann. Reviews 2002



Errors shown are for Planck...



Lensing B-modes (a foreground)

Primordial B-modes, fingerprint of Inflation.
(Shown for T/S = 0.1, a high value)


http://www.astro.caltech.edu/~tjp/CBI/