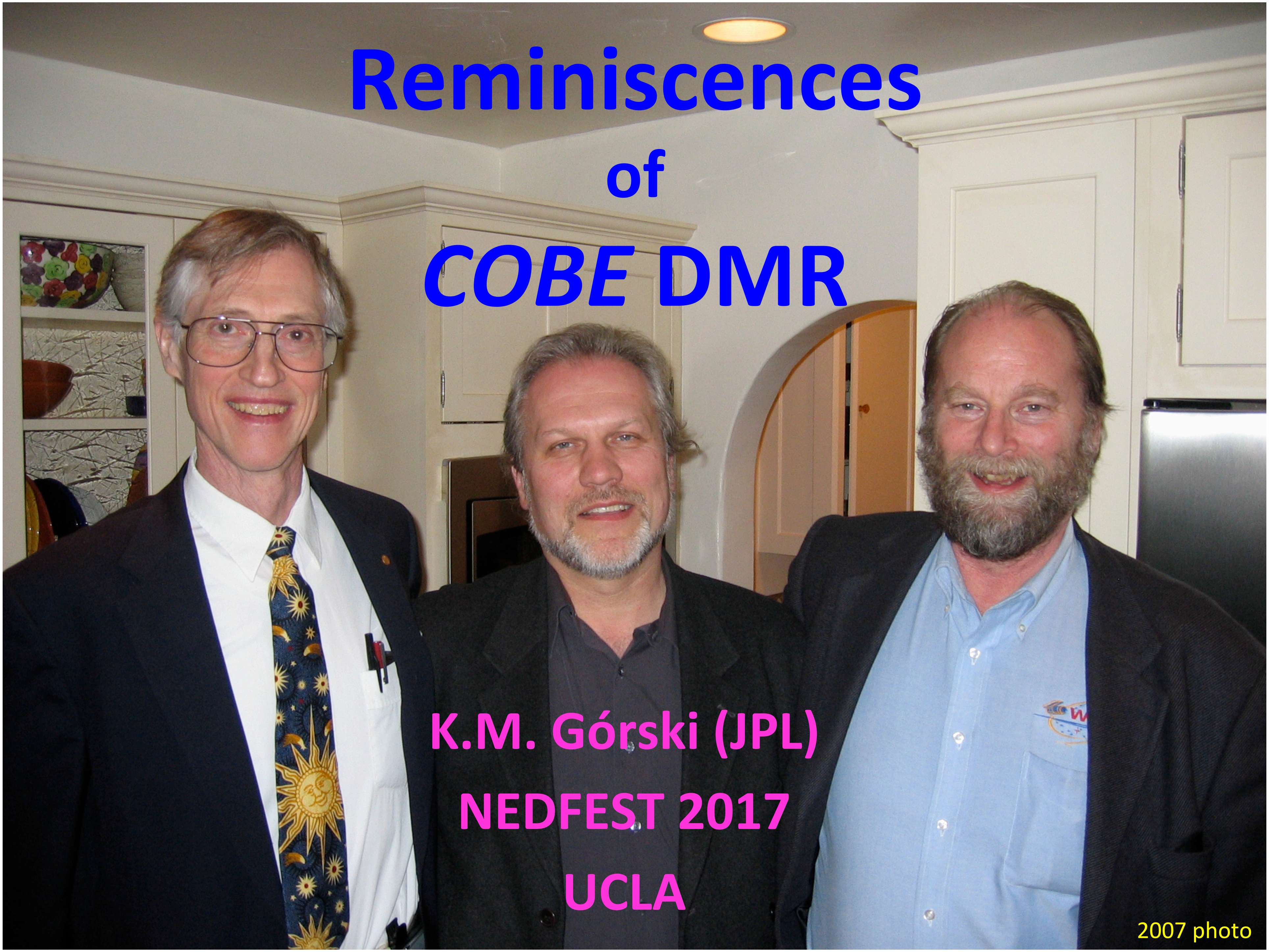


Reminiscences
of
COBE DMR

K.M. Górski (JPL)

NEDFEST 2017

UCLA

2007 photo

CO**s**mic
Background
Explorer

or (?)

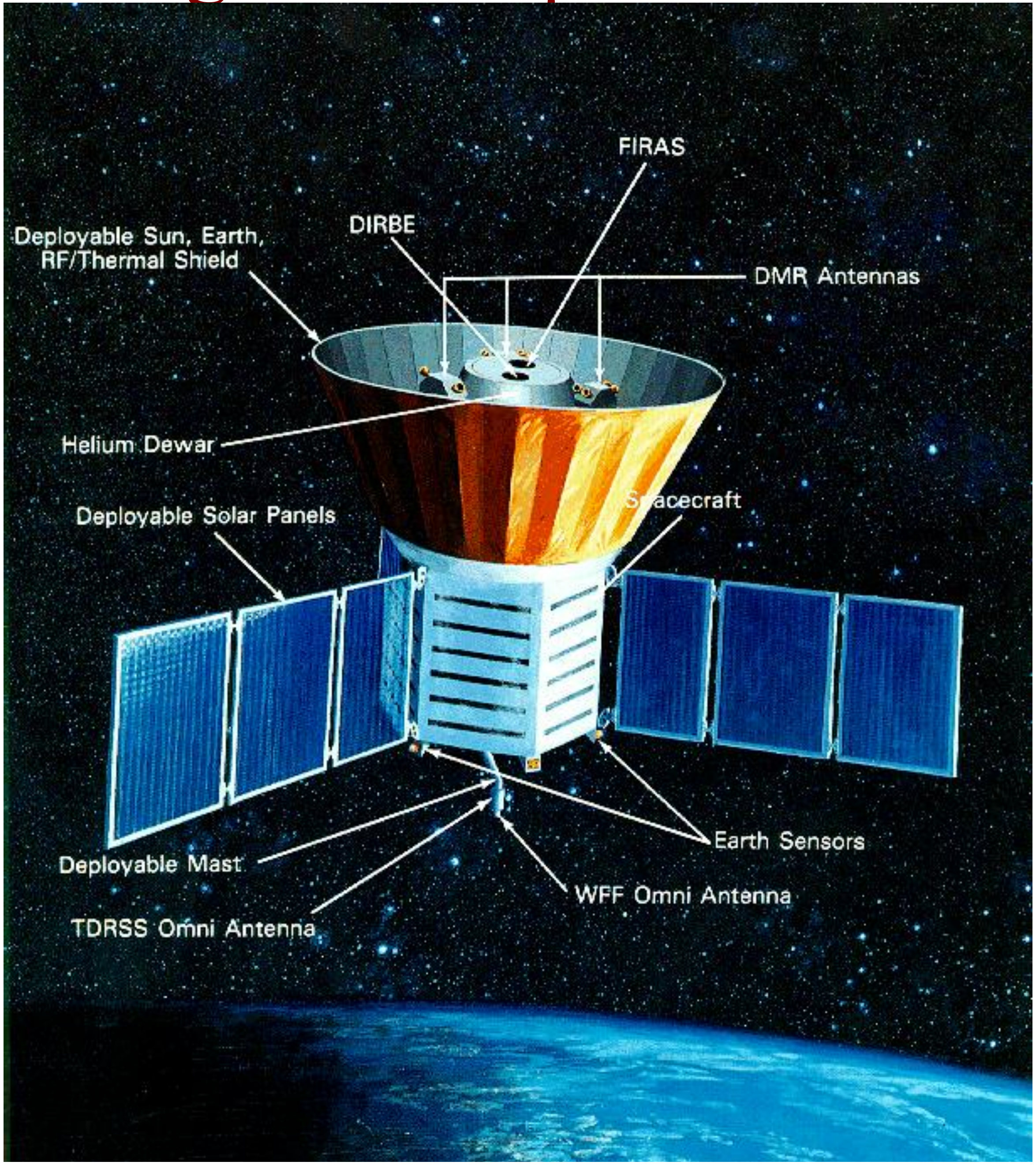
(It's been more than two decades ago, after all…)

or (?)

(It’s been more than two decades ago, after all…)

COsmic Background Explorer

- *COBE* Satellite, 1989-1995
- FIRAS & DIRBE - < 1 year
- DMR - ~4 years
- COBE's motion => scanning the sky with DMR
  - Near-Earth orbit
  - "Bore" angle - 30 deg
  - Spin period - 73 sec
  - "Precession" angle - 86 deg
  - Precession period - 104 min



DMR scans the sky

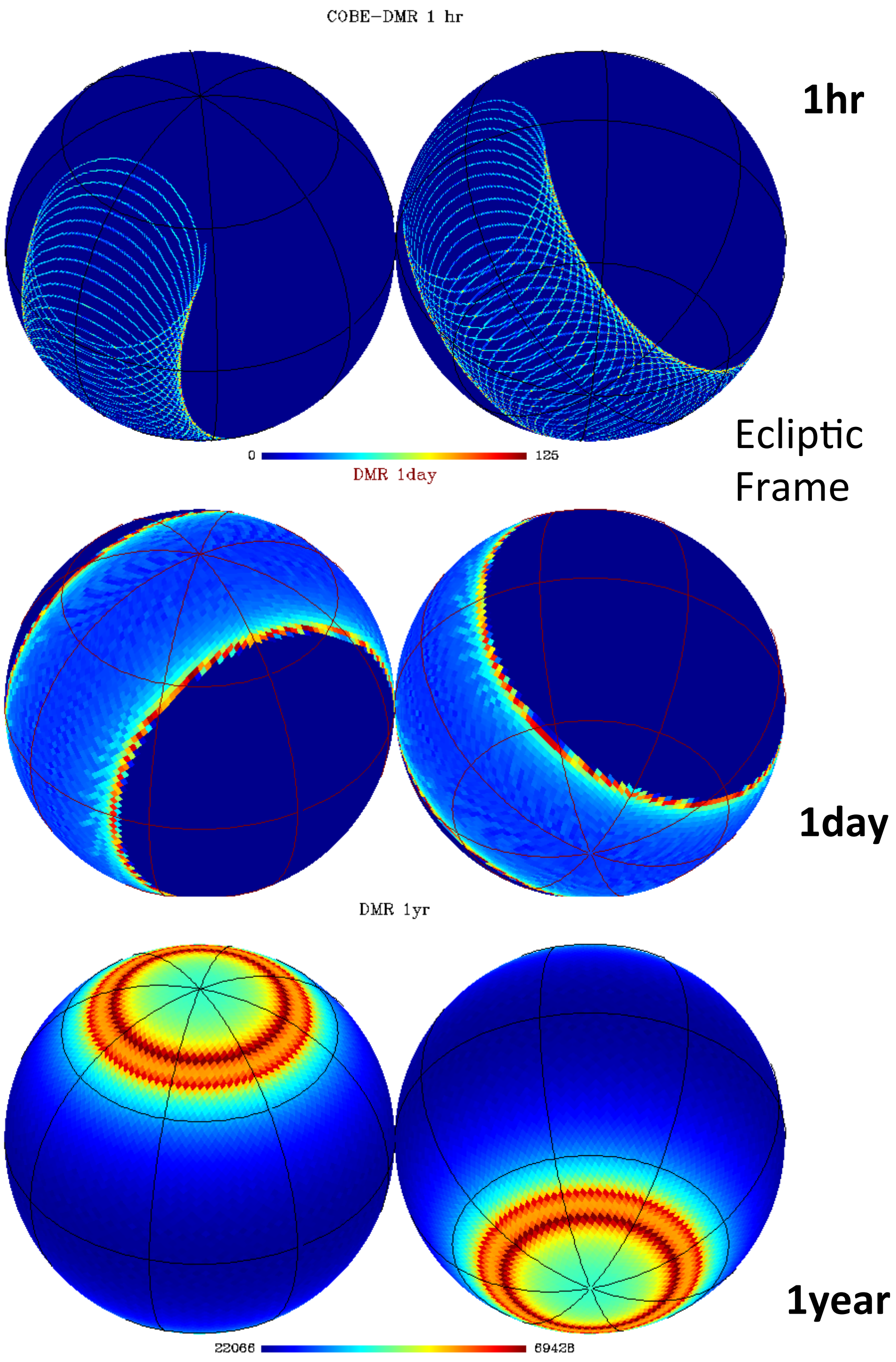
Full sky scan every ~1/2 year

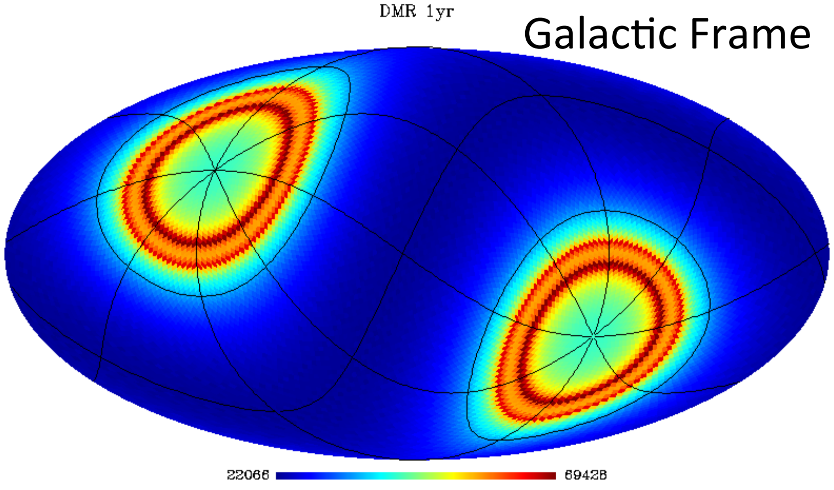
N_{obs} symmetrized full sky scan every year

Release maps made* from
1, 2 and 4 years of observations

----

*Time stream of numerous difference measurements of δT at celestial points separated by 60 deg inverted into a best fitting sky map





COBE-DMR Legacy Data

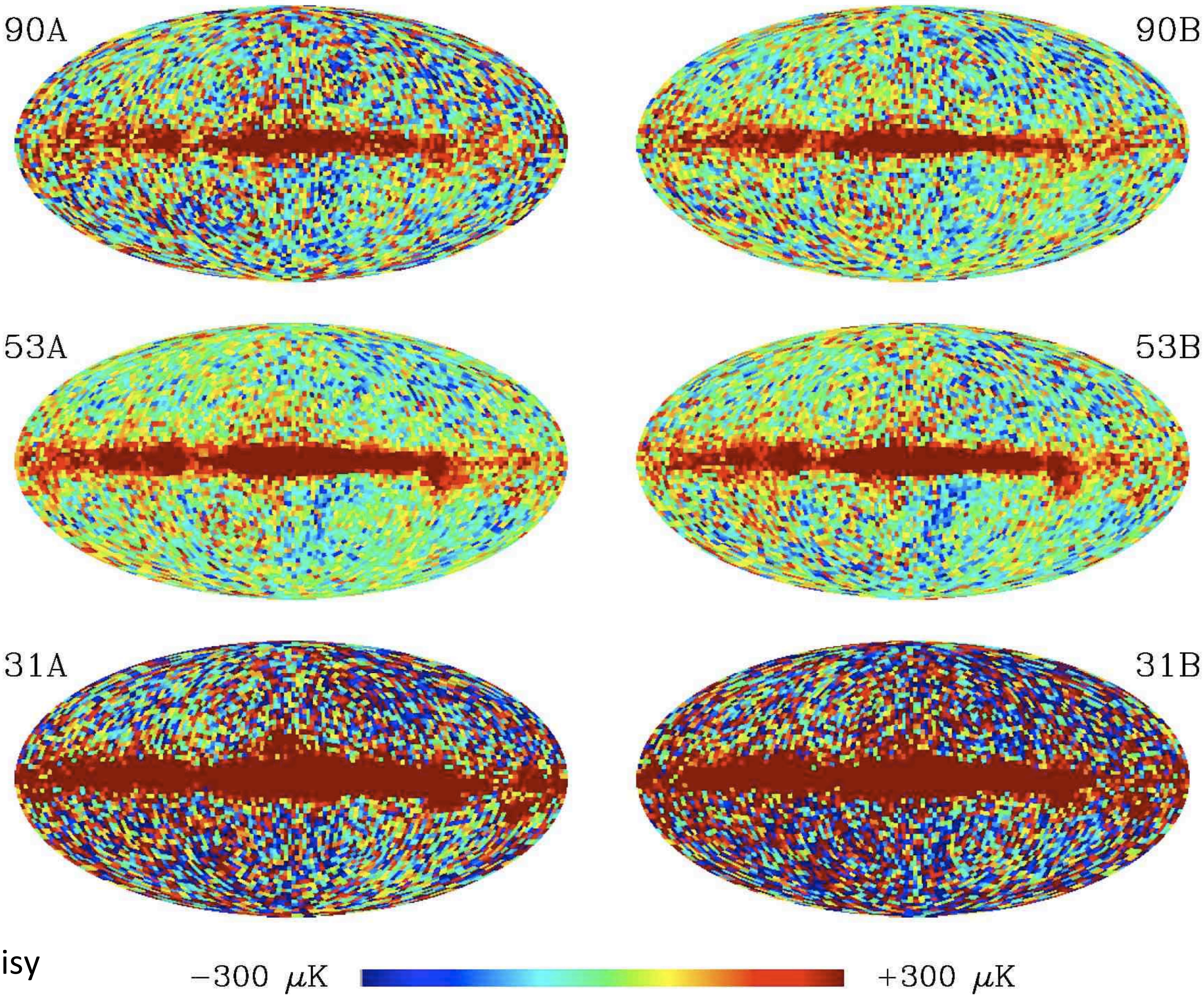
31, 53, 90 GHz
channels –
two maps
in each

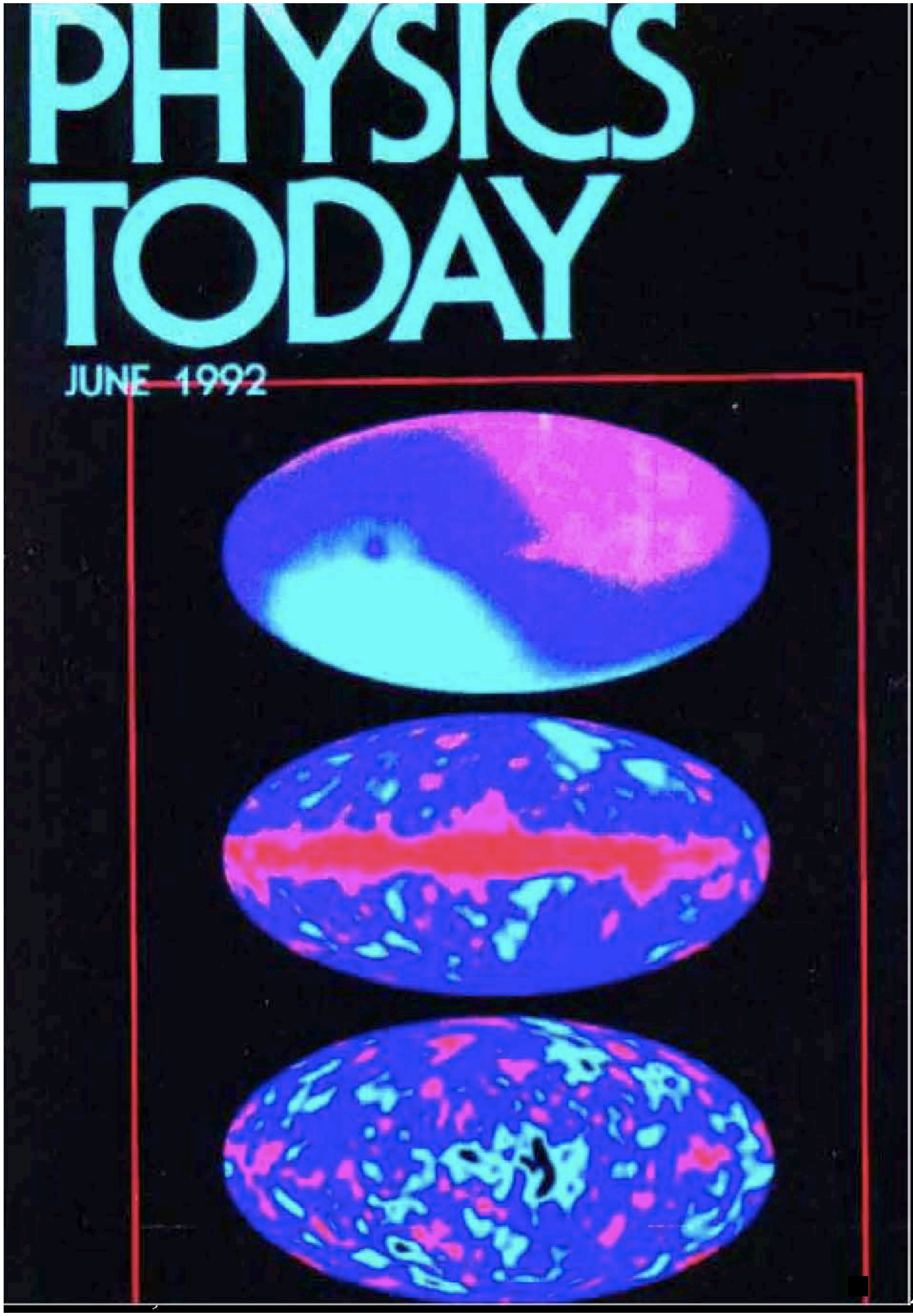
6144
2.6deg-pixels
on full sky

FWHM ~7 deg

~1000
spatially
independent
δT estimates
per map

“somewhat” noisy





COBE-DMR delivers in 1992

Sky map from DMR,
2.7 K +/- 0.003 K

Doppler Effect of Earth's
motion removed (v/c =
0.001)

Cosmic temperature/density
variations at 389,000 years,
+/- 0.00003 K

THE ASTROPHYSICAL JOURNAL, 396:L13–L18, 1992 September 1

INTERPRETATION OF THE COSMIC MICROWAVE BACKGROUND RADIATION ANISOTR DETECTED BY THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER

E. L. WRIGHT,[2] S. S. MEYER,[3] C. L. BENNETT,[4] N. W. BOGGESS,[4] E. S. CHENG,[4] M. G. HAUSER,[4] A. KOG
C. LINEWEAVER,[6] J. C. MATHER,[4] G. F. SMOOT,[6] R. WEISS,[3] S. GULKIS,[7] G. HINSHAW,[5] M. JANSSEN,[7]
T. KELSALL,[4] P. M. LUBIN,[8] S. H. MOSELEY, JR.,[4] T. L. MURDOCK,[9] R. A. SHAFER,[4]
R. F. SILVERBERG,[4] AND D. T. WILKINSON[10]

Received 1992 April 21; accepted 1992 June 12

ABSTRACT

We compare the large-scale cosmic background anisotropy detected by the *COBE* Differential Micrc Radiometer (DMR) instrument to the sensitive previous measurements on various angular scales, and t predictions of a wide variety of models of structure formation driven by gravitational instability. The obs anisotropy is consistent with all previously measured upper limits and with a number of dynamical mod structure formation. For example, the data agree with an unbiased cold dark matter (CDM) model with 50 km s^{-1} Mpc^{-1} and $\Delta M/M = 1$ in a 16 Mpc radius sphere. Other models, such as CDM plus m neutrinos [hot dark matter (HDM)], or CDM with a nonzero cosmological constant are also consistent the *COBE* detection and can provide the extra power seen on 5–10,000 km s^{-1} scales.

Subject headings: cosmic microwave background — cosmology: observations — cosmology: theory — galaxies: clustering

Ned et al. 1992, Sept. 1, ApJ(Lett)
DMR "big stuff" paper –
Interpretation of the detected CMB anisotropy

L14 WRIGHT ET AL. Vol

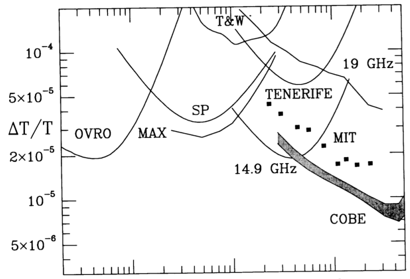


FIG. 1.—Limits on Gaussian correlation functions, $[C(0)]^{1/2}/T_0$ vs. θ_c. All are 95% confidence upper limits except for the *COBE* band which shows 2 σ upper and lower limits.

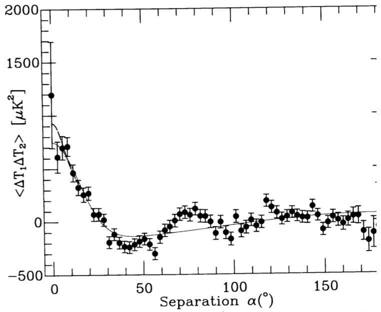
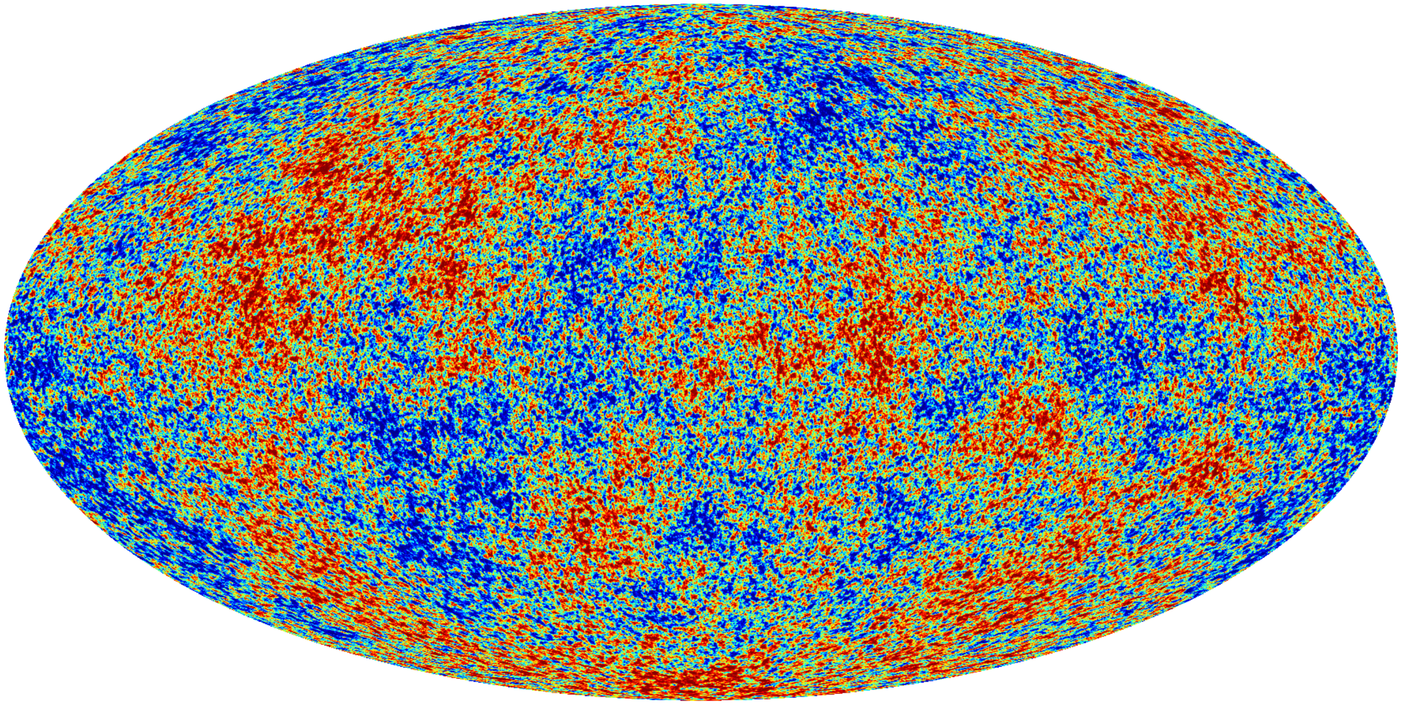


FIG. 2.—Correlation function from *COBE* data (*filled circles*) with a Gaussian model with $\theta_c = 13.^\circ5$ (*thin solid curve*) and a fit to Holtzman' lation function convolved to the DMR beam (*dashed curve*).

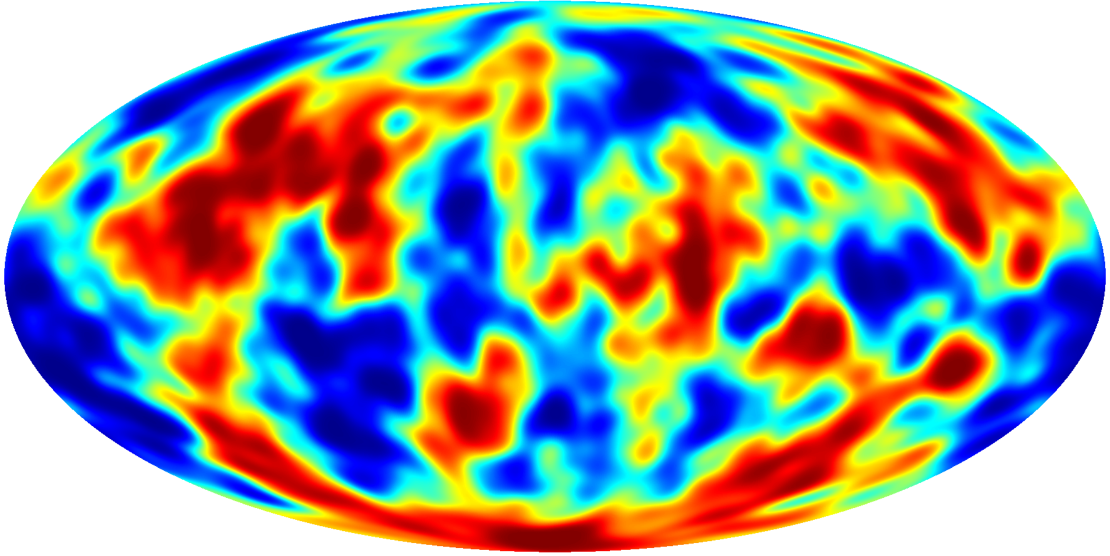
By determining the potential fluctuations at very large scales, the measurement reported by Smoot et al. (1992) will lead to much more definite models of the formation of galaxies, clusters of galaxies and superclusters. With the primordial density fluctuation spectrum specified by an assumed Harrison-Zel'dovich form and the *COBE* determined amplitude, the small-scale anisotropy experiments allow one to measure the transfer function that maps primordial perturbations into current structure. Features in the transfer function can be used to identify the nature of dark matter: for example, the mass of a neutrino corresponds to the wavenumber of a break in the transfer function. With the large-scale amplitude seen by *COBE*, and the transfer functions predicted by dark matter models of structure formation, small-scale anisotropy should be detected at levels only slightly below the current OVRO and MAX upper limits.

The case for the Harrison-Zel'dovich perturbation spectrum predicted by inflation, and dark matter-dominated scenarios for structure formation, is supported by the *COBE*–DMR results. The initial perturbations on scales of 800 km s^{-1} needed to make clusters of galaxies in the CDM model can be connected to the perturbations on scales of 10^5–10^6 km s^{-1} needed to make the anisotropy seen by *COBE*, and the slope of this connection matches the slope of the Harrison-Zel'dovich spectrum predicted by the standard inflationary scenario. Allowing for factor of 2 errors from uncertainty in b_8, one still finds that the mean slope of the primordial perturbation spectrum is $n = 1 \pm 0.23$ over three decades in scale. But the results of this paper have an even greater significance, since the ΔT observed by the DMR experiment is a direct measure of the fluctuations produced during the inflationary epoch, giving $\epsilon_H = (5.4 \pm 1.6) \times 10^{-6}$ (Abbott & Wise 1984) for $\langle Q^2_{\rm RMS}\rangle^{0.5} = 17 \pm 5$ μK, and thus provide the earliest observational information about the origin of the universe, going back to 10^{-35} s after the big bang.

Where are those primordial fluctuations in the CMB anisotropy maps that we are looking at …



For this “Planck-like”
(i.e. FWHM~5arcmin)
CMB anisotropy map
the primordial content
of only
the ~scale-invariant,
Gaussian distributed,
curvature perturbations
would lead to a dT/T
imprint shown below
(note the same phases
of the large angle dT/T



5.12 AAS Abstract, 1993

Angular Power Spectrum of the *COBE* DMR Anisotropy

E. Wright (UCLA)

The angular power spectrum estimator developed by Peebles (1973) and Hauser and Peebles (1973) has been modified and applied to the maps produced by the COBE DMR (Smoot et al 1992). The power spectrum of the real sky has been compared to the power spectra of a large number of simulated random skies produced with noise equal to the observed noise and primordial density fluctuation power spectra of power law form, with $P(k) \propto k^n$.. The ability of this technique to determine the value of n with N years of DMR data will be estimated.

The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the Cosmic Background Explorer (COBE). Scientific guidance is provided by the COBE Science Working Group. GSFC is also responsible for the development of the analysis software and for the production of the mission data sets.

The Astrophysical Journal, 436:443–451, 1994 December 1

Ned's 1994 power spectrum paper

ANGULAR POWER SPECTRUM OF THE MICROWAVE BACKGROUND ANISOTROPY SEEN BY THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER

E. L. Wright,[2] G. F. Smoot,[3] C. L. Bennett,[4] and P. M. Lubin[5]

Received 1994 January 3; accepted 1994 May 16

ABSTRACT

The angular power spectrum estimator developed by Peebles (1973) and Hauser & Peebles (1973) has been modified and applied to the 2 yr maps produced by the *COBE* DMR. The power spectrum of the real sky has been compared to the power spectra of a large number of simulated random skies produced with noise equal to the observed noise and primordial density fluctuation power spectra of power-law form, with $P(k) \propto k^n$. Within the limited range of spatial scales covered by the *COBE* DMR, corresponding to spherical harmonic indices $3 \leq l \lesssim 30$, the best-fitting value of the spectral index is $n = 1.25^{+0.4}_{-0.45}$ with the Harrison-Zel'dovich value $n = 1$ approximately 0.5 σ below the best fit. For $3 \leq l \lesssim 19$, the best fit is $n = 1.46^{+0.39}_{-0.44}$. Comparing the *COBE* DMR $\Delta T/T$ at small l to the $\Delta T/T$ at $l \approx 50$ from degree scale anisotropy experiments gives a smaller range of acceptable spectral indices which includes $n = 1$.

Subject headings: cosmic microwave background — cosmology: observations — large-scale structure of universe

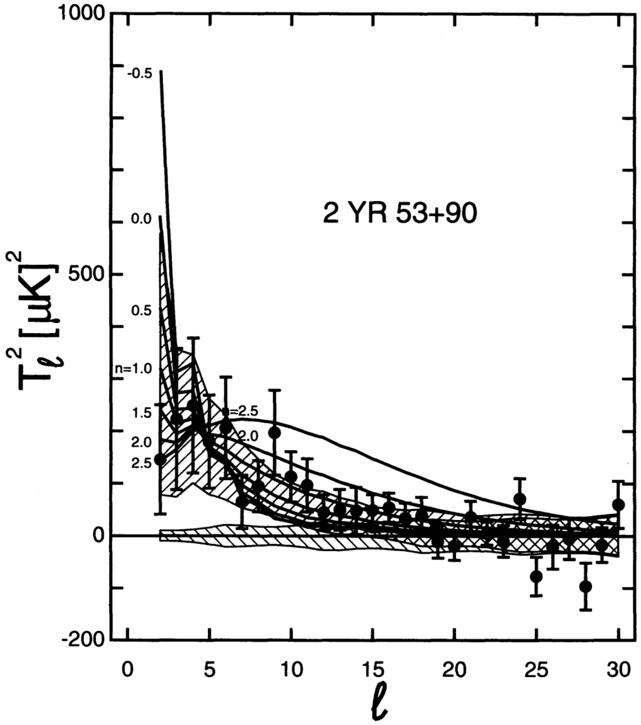


FIG. 1.—Power spectrum of the 2 yr 53+90 DMR maps (*points*) compared to the mean ±1 σ range of Monte Carlo spectra computed for Harrison-Zel'dovich (H-Z) skies with an expected $Q = 17$ μK. The lower band is the ±1 σ range for noise-only Monte Carlo spectra. The lines show the mean power spectra for Monte Carlo spectra with $n = -0.5$, 0, 0.5, 1, 1.5, 2, and 2.5 all normalized to have the same input $l = 4$ amplitude as the $Q = 17$ H-Z case.

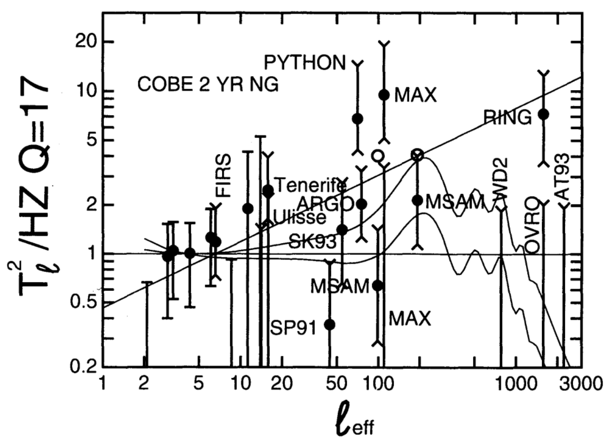


FIG. 4.—Power spectra normalized to the mean of 17 μK Harrison-Zel'dovich Monte Carlo skies. *COBE* data points from the 2 yr NG DMR maps. Models shown as thin curves: $n = 1$, $Q = 17$ μK is the horizontal line, the best-fit $n = 1.4$ power law is the slanted line, and tilted CDM including the effects of gravitational waves with the long dashed curve showing $n = 0.96$ (predicted by ϕ^4 chaotic inflation), and the short dashed curve showing $n = 0.85$, where the tensor and scalar quadrupoles are equal (Crittenden et al. 1993). Points with "bent" ends on their error bars are from other experiments: FIRS (Ganga et al. 1993), (*left to right*) ULISSE (de Bernardis et al. 1992), Tenerife (Watson et al. 1992 and Hancock et al. 1994), the South Pole (Schuster et al. 1993), Saskatoon (Wollack et al. 1993), the Python experiment (Dragovan et al. 1994), ARGO (de Bernardis et al. 1994), MSAM single subtracted (Cheng et al. 1994), MAX (Gunderson et al. 1993 and Meinhold et al. 1993), MSAM double subtracted, White dish second harmonic (Tucker et al. 1993), OVRO (Readhead et al. 1989, OVRO RING (Myers et al. 1993), and the Australia Telescope (Subrahmayan et al. 1993. The open circles above the MSAM points show the effects of not removing sources.

THE ASTROPHYSICAL JOURNAL, 464:L21–L24, 1996 June 10

ANGULAR POWER SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND ANISOTROPY SEEN BY THE *COBE*[1] DMR

E. L. WRIGHT,[2] C. L. BENNETT,[3] K. GÓRSKI,[4,5] G. HINSHAW,[4] AND G. F. SMOOT[6]
Received 1996 January 11; accepted 1996 March 21

ABSTRACT

The angular power spectrum estimator developed by Peebles and Hauser & Peebles has been modified and applied to the 4 yr maps produced by the *COBE* DMR. The power spectrum of the observed sky has been compared to the power spectra of a large number of simulated random skies produced with noise equal to the observed noise and primordial density fluctuation power spectra of power-law form, with $P(k) \propto k^n$. The best-fitting value of the spectral index in the range of spatial scales corresponding to spherical harmonic indices $3 \leq \ell \lesssim 30$ is an apparent spectral index $n_{\rm app} = 1.13^{+0.3}_{-0.4}$ which is consistent with the Harrison-Zeldovich primordial spectral index $n_{\rm pri} = 1$. The best-fitting amplitude for $n_{\rm app} = 1$ is $\langle Q^2_{\rm rms}\rangle^{0.5} = 18$ μK.

Subject headings: cosmic microwave background — cosmology: observations

Ned's 1996 ultimate DMR power spectrum paper

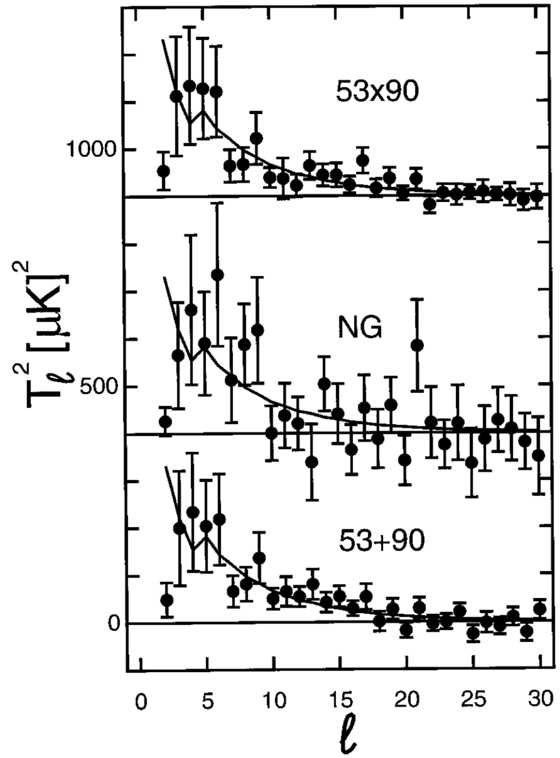


FIG. 1.—Cross-power spectra for the 53 + 90 $A \times B$, 53 × 90, and NG $A \times B$ maps. T_ℓ^2 measures the variance of the sky due to order ℓ harmonics for full sky coverage, but partial sky coverage changes the expected value as seen in the curves showing the average power spectrum of $Q = 17$ μK, $n = 1$ Monte Carlo models in the cut sky. Values are shifted upward by 400 for NG and 900 for 53 × 90, as shown by the horizontal lines marking zero power.

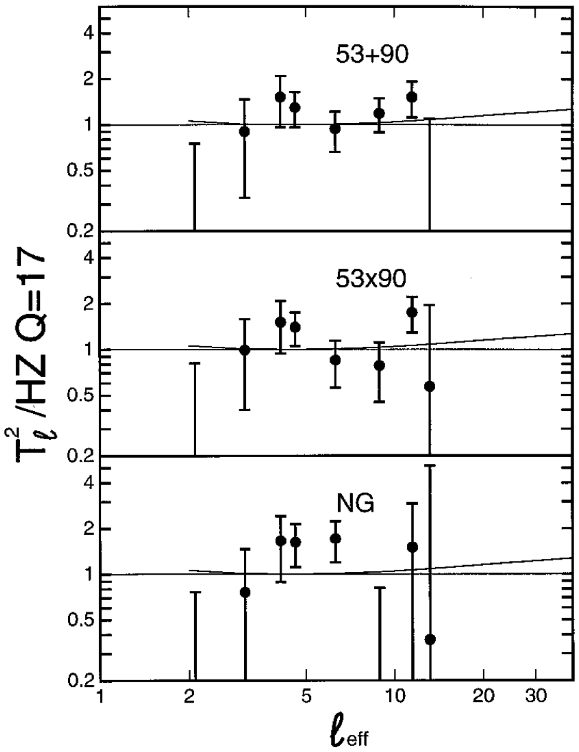


FIG. 2.—Binned cross-power spectra for the 53 + 90 $A \times B$, 53 × 90, and NG $A \times B$ maps, normalized to the mean power spectrum of $Q = 17$ μK, $n = 1$ simulations, plotted on a logarithmic scale. $\ell_{\rm eff}$ is the effective wavenumber of the bin for $n = 1$. The thin curves show a CDM model with $n_{\rm pri} = 0.96$ including the effect of gravitational waves derived from Crittenden et al. (1993).

DMR CMB anisotropy
2-parameter likelihood surface

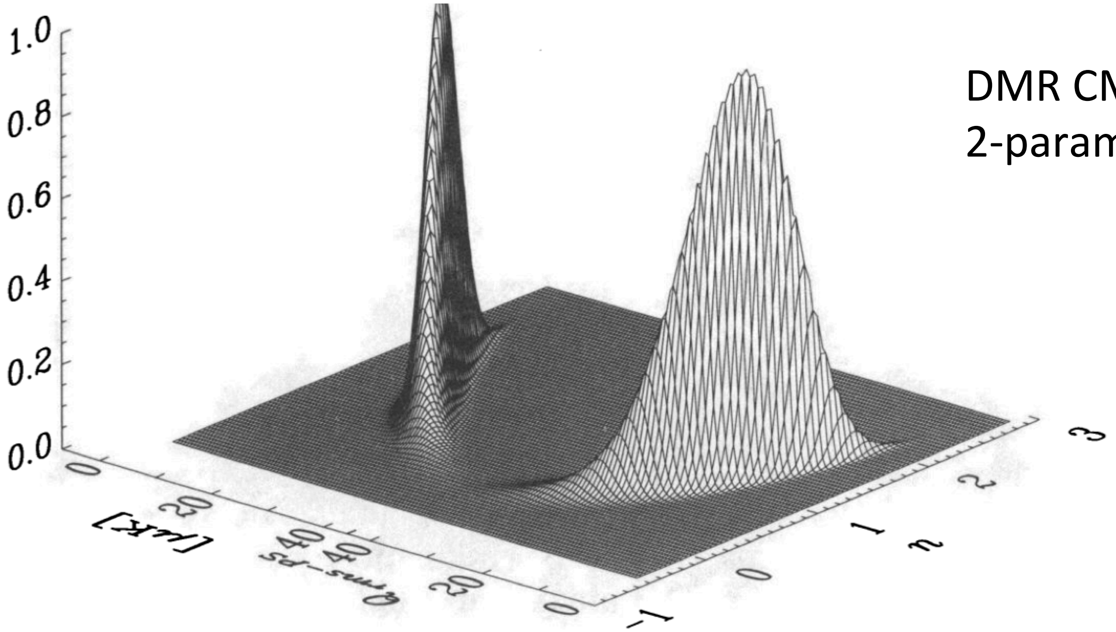


FIG. 1.—Two views of the likelihood function, $P(Q_{\rm rms-PS}, n)$ derived in a simultaneous analysis of the 53 and 90 GHz *COBE*-DMR two-year data including harmonic amplitudes from the range $\ell \in [2, 30]$.

THE ASTROPHYSICAL JOURNAL, 464:L11–L15, 1996 June 10

My 1996 ultimate
DMR power spectrum
paper

POWER SPECTRUM OF PRIMORDIAL INHOMOGENEITY DETERMINED FROM THE FOUR-YEAR *COBE*[1] DMR SKY MAPS

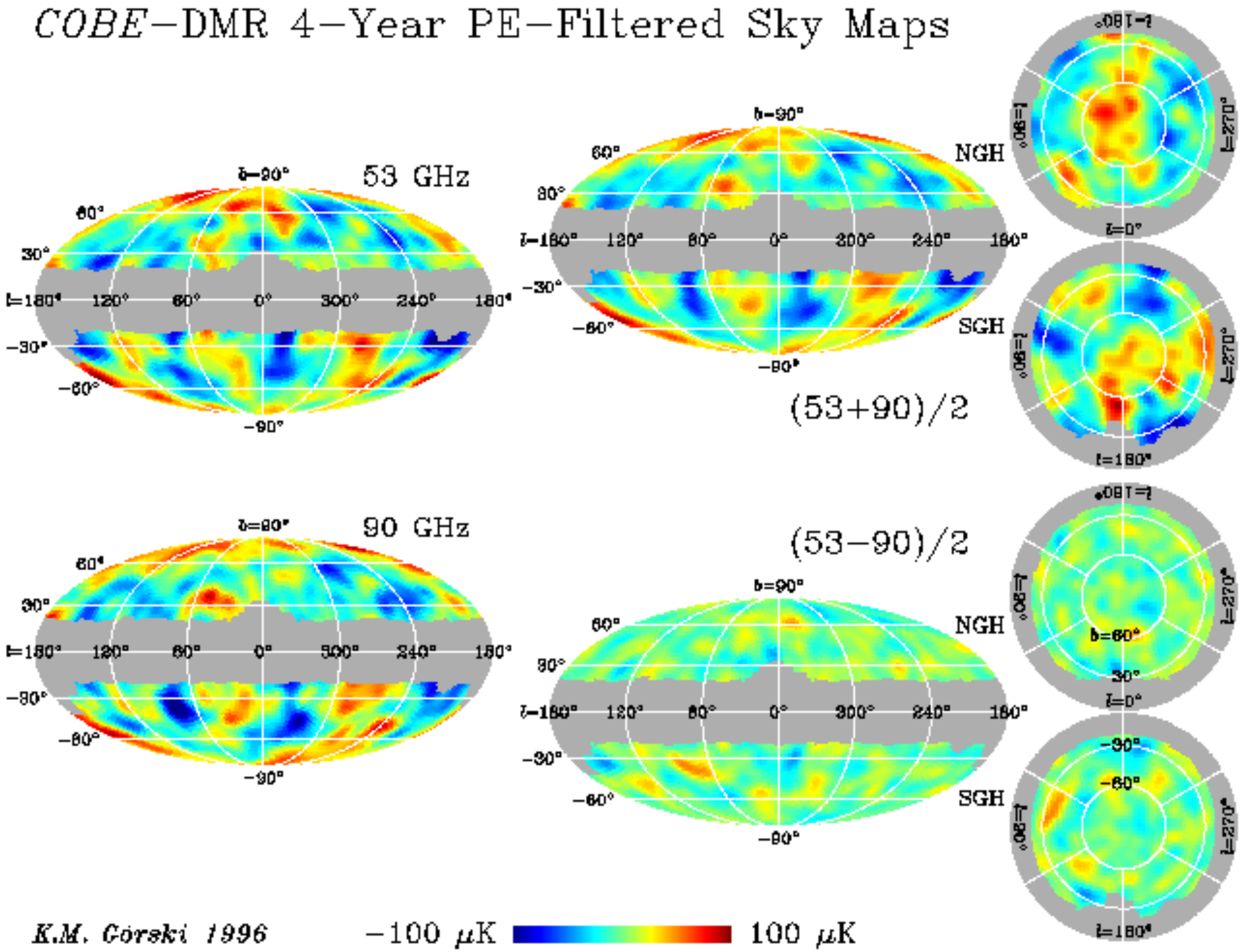
K. M. GÓRSKI,[2, 3, 4] A. J. BANDAY,[2, 5] C. L. BENNETT,[6] G. HINSHAW,[2] A. KOGUT,[2] G. F. SMOOT,[7] AND E. L. WRIGHT[8]

Received 1996 January 9; accepted 1996 March 21

power spectrum estimation from the foreground-corrected 4 yr *COBE* DMR data renders $n \sim 1.2 \pm 0.3$ and $Q_{\rm rms-PS} \sim 15.3^{+3.7}_{-2.8}$ μK (projections of the two-parameter likelihood). The results are consistent with the Harrison-Zeldovich $n = 1$ model of amplitude $Q_{\rm rms-PS} \sim 18$ μK detected with significance exceeding 14 σ

After this having been settled we could go back to the maps to squeeze out a little bit more …

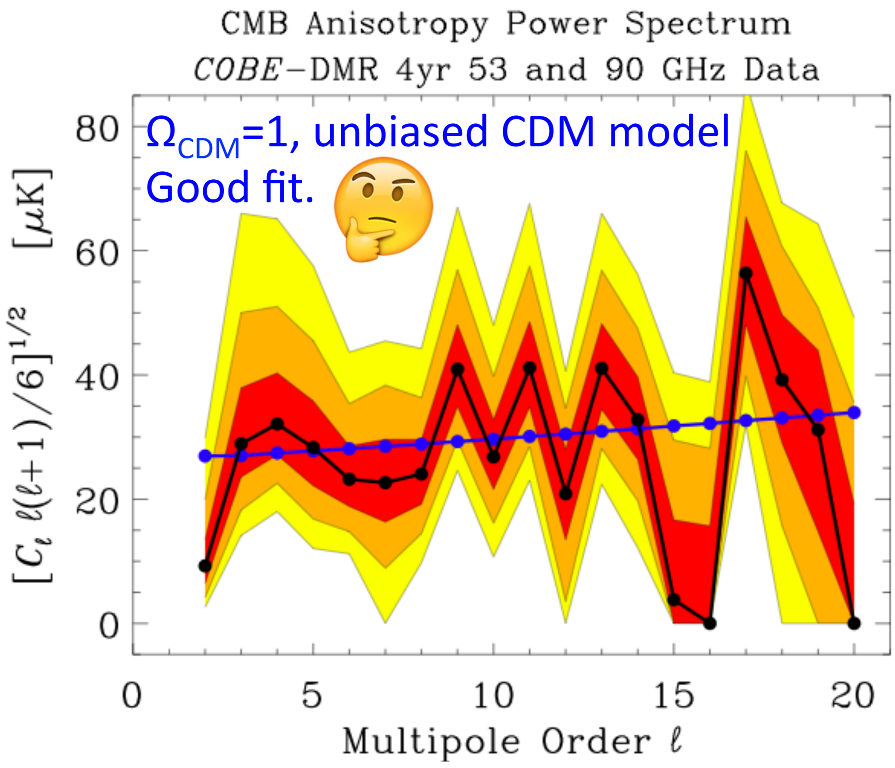
Last scattering surface according to COBE-DMR


COBE−DMR 4−Year PE−Filtered Sky Maps

K.M. Górski 1996

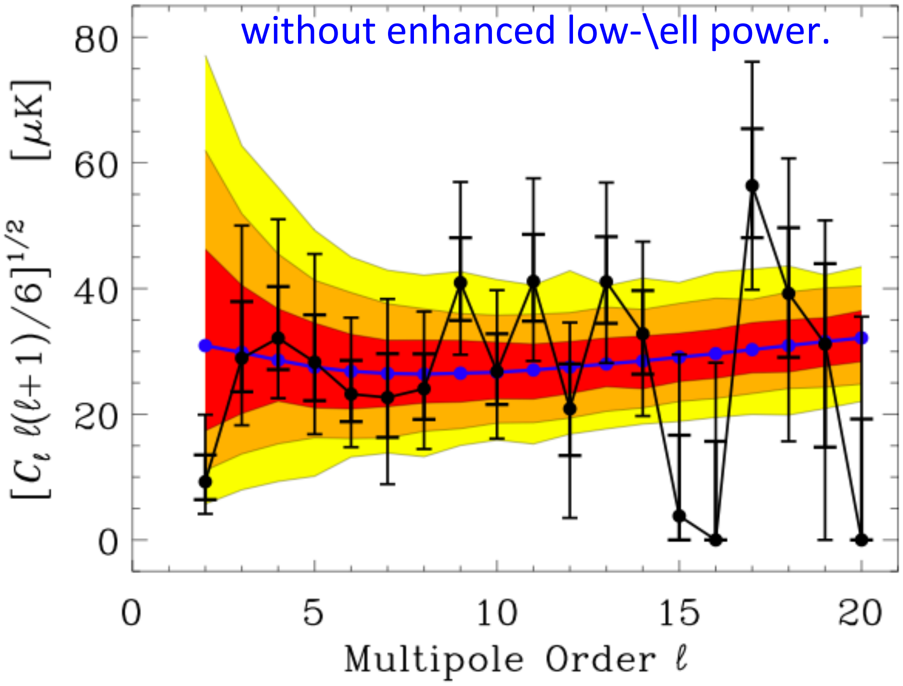
Proceedings of the XXXIst Recontres de Moriond

ℓ-by-ℓ CMB Anisotropy Spectrum from the 4yr COBE-DMR data

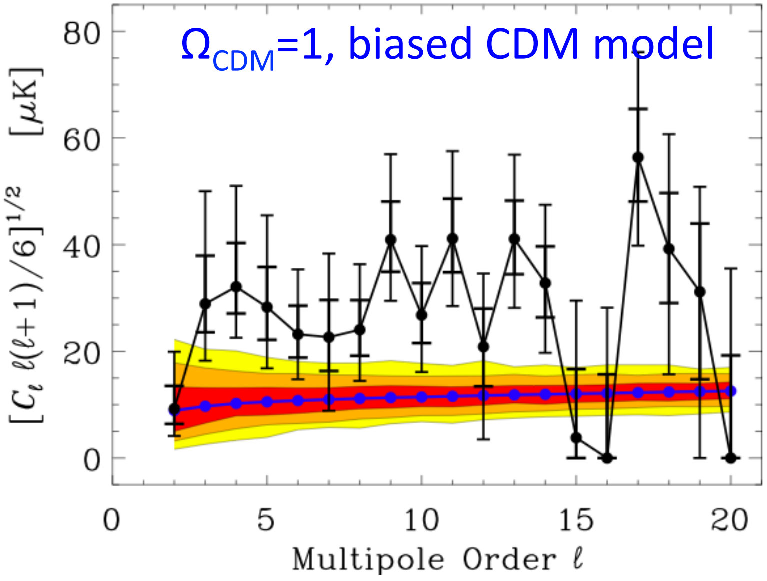


Ω_{CDM}=1, unbiased CDM model
Good fit. 🤔

Example of CDM+Λ model;
Fitted DMR OK, but worse than those
without enhanced low-\ell power.

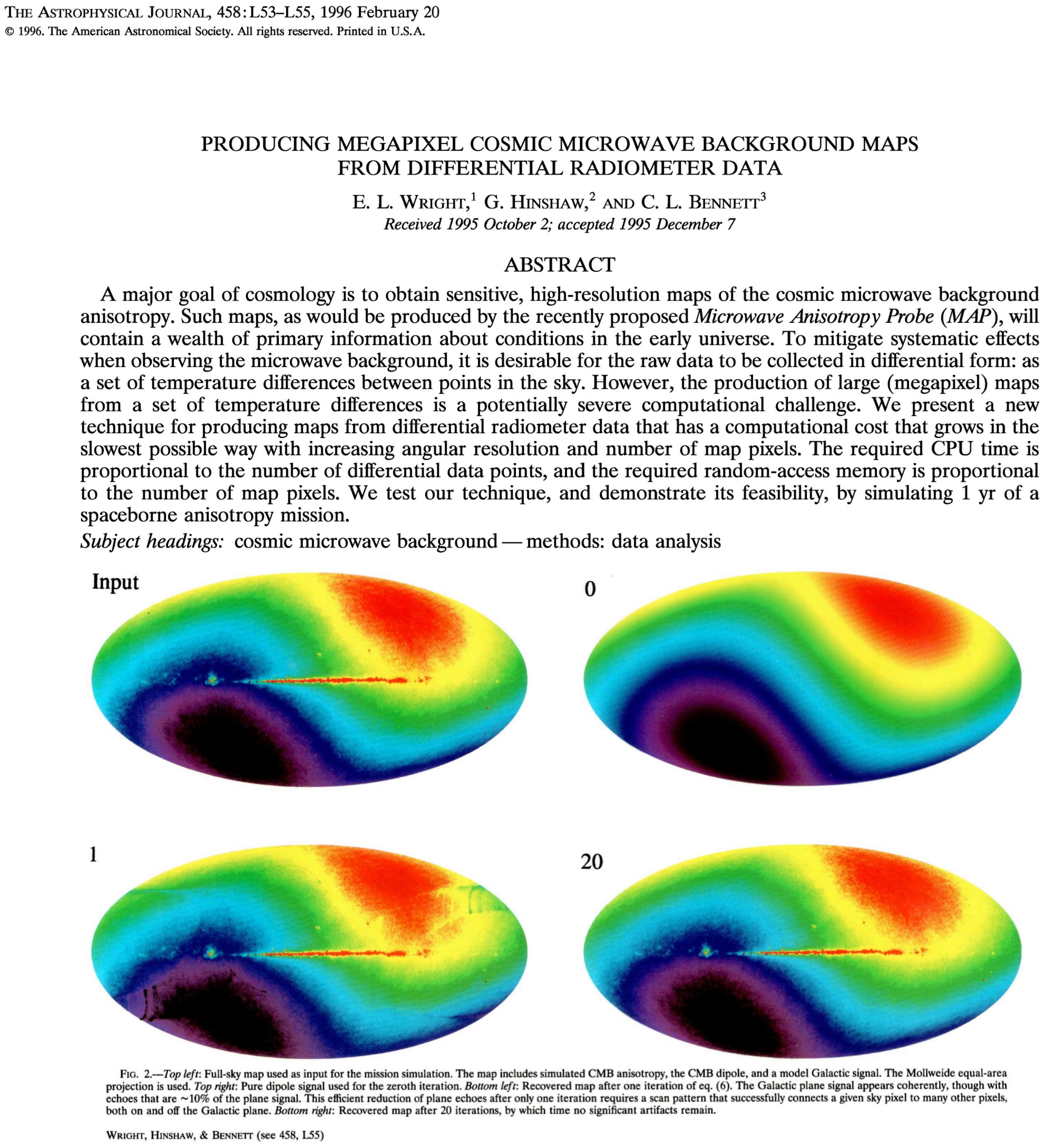


This model was vetoed.
DMR brought about the days
when
“Biased Cold Dark Matter Model”
died.



Ω_{CDM}=1, biased CDM model

“Necessity is the mother of invention”



The Astrophysical Journal, 458:L53–L55, 1996 February 20

PRODUCING MEGAPIXEL COSMIC MICROWAVE BACKGROUND MAPS FROM DIFFERENTIAL RADIOMETER DATA

E. L. Wright,[1] G. Hinshaw,[2] and C. L. Bennett[3]

Received 1995 October 2; accepted 1995 December 7

ABSTRACT

A major goal of cosmology is to obtain sensitive, high-resolution maps of the cosmic microwave background anisotropy. Such maps, as would be produced by the recently proposed *Microwave Anisotropy Probe* (*MAP*), will contain a wealth of primary information about conditions in the early universe. To mitigate systematic effects when observing the microwave background, it is desirable for the raw data to be collected in differential form: as a set of temperature differences between points in the sky. However, the production of large (megapixel) maps from a set of temperature differences is a potentially severe computational challenge. We present a new technique for producing maps from differential radiometer data that has a computational cost that grows in the slowest possible way with increasing angular resolution and number of map pixels. The required CPU time is proportional to the number of differential data points, and the required random-access memory is proportional to the number of map pixels. We test our technique, and demonstrate its feasibility, by simulating 1 yr of a spaceborne anisotropy mission.

Subject headings: cosmic microwave background — methods: data analysis

Fig. 2.—*Top left*: Full-sky map used as input for the mission simulation. The map includes simulated CMB anisotropy, the CMB dipole, and a model Galactic signal. The Mollweide equal-area projection is used. *Top right*: Pure dipole signal used for the zeroth iteration. *Bottom left*: Recovered map after one iteration of eq. (6). The Galactic plane signal appears coherently, though with echoes that are ~10% of the plane signal. This efficient reduction of plane echoes after only one iteration requires a scan pattern that successfully connects a given sky pixel to many other pixels, both on and off the Galactic plane. *Bottom right*: Recovered map after 20 iterations, by which time no significant artifacts remain.

Wright, Hinshaw, & Bennett (see 458, L55)

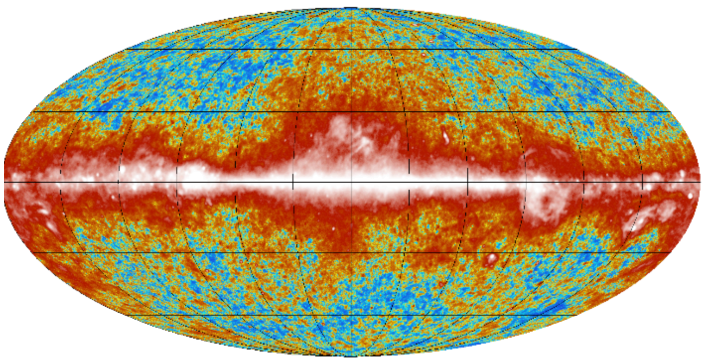
Before *COBE*-DMR was over, Ned moved on, and (surprise?) hit the nail right on the head …

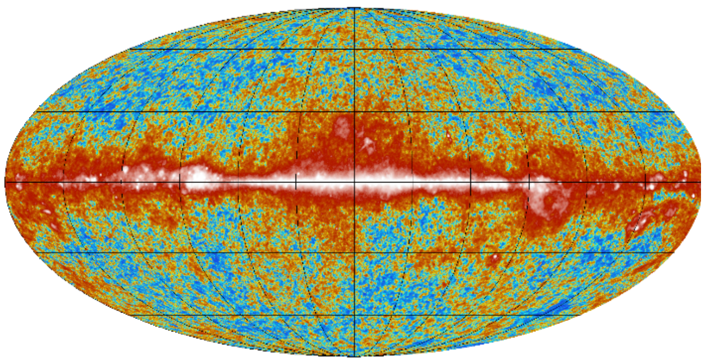
Wright, Hinshaw, Bennett 1996 paper demonstrated feasibility of making multi-million pixel CMB anisotropy maps from massively scaled up measurements conducted a la DMR.

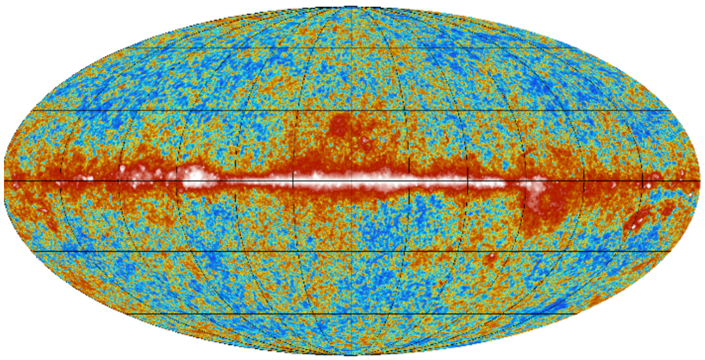
This was essential for supporting the bid for high resolution CMB anisotropy instrument to follow *COBE*-DMR in space.

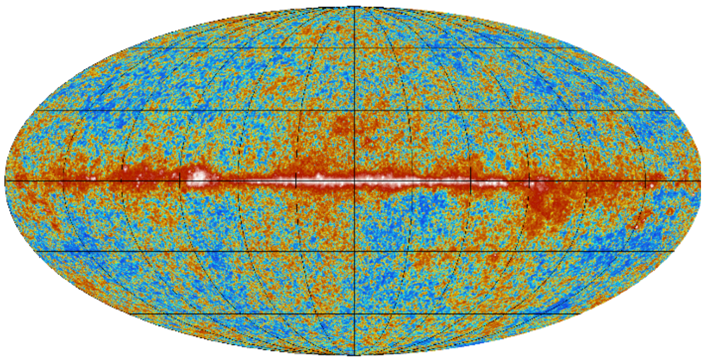
That proposed instrument was MAP, to become later WMAP.

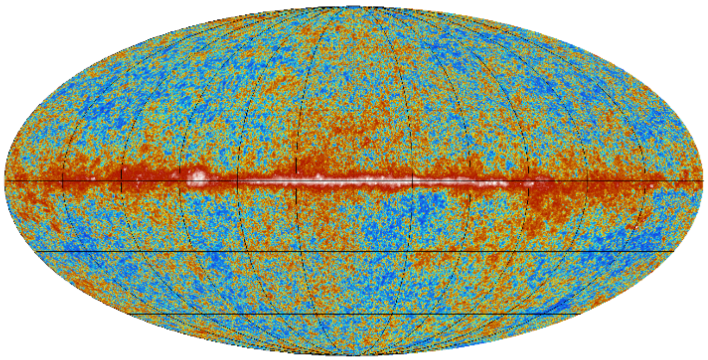
But that’s another story …

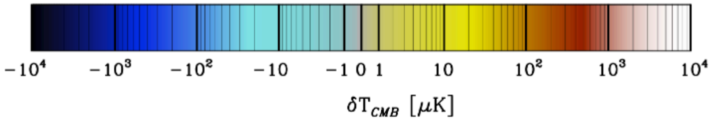

WMAP 9yrs K-band


WMAP 9yrs Ka-band


WMAP 9yrs Q-band


WMAP 9yrs V-band

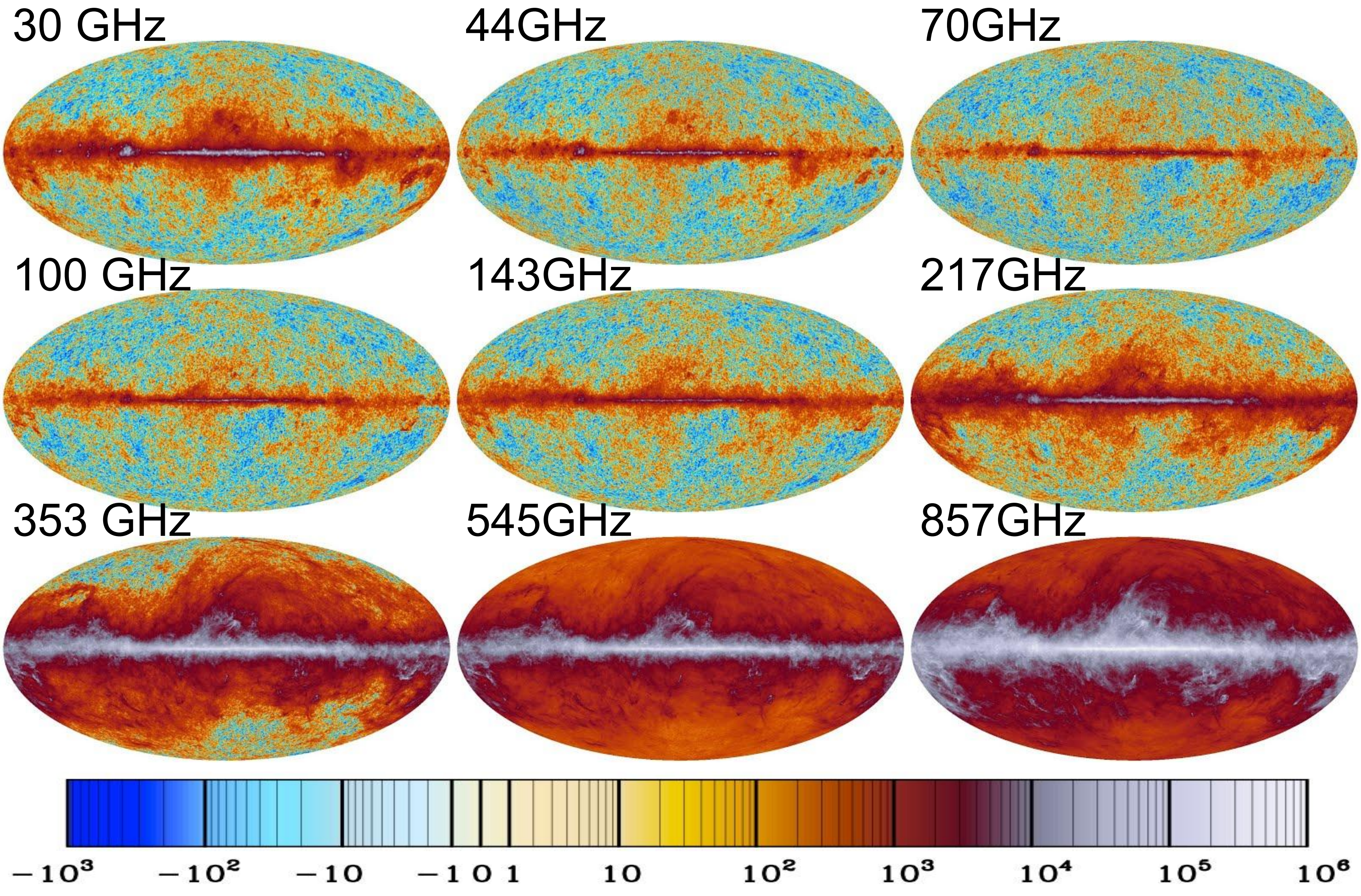

WMAP 9yrs W-band



Post-2003
Pre-Planck
microwave sky

the great WMAP
mission
and its
sky maps
at
22-94 GHz

Planck 2013 Maps of the microwave and sub-mm Sky



30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

So, needless to say, I got very excited when I found this on the web …

Photo by Steven Limentani

FESTIVAL LINEUPS

Oteil Burbridge To Lead Super Jam At NedFest 2017

Sadly, it is (was) not this event …

So, Ned –

May Your “SOUND OF SILENCE”
Be
Thunderous,
Long,
and
Better than Ever!