Reminiscence of *COBE*

CMB@60 Meeting, Turin, IT, May 28-30, 2025

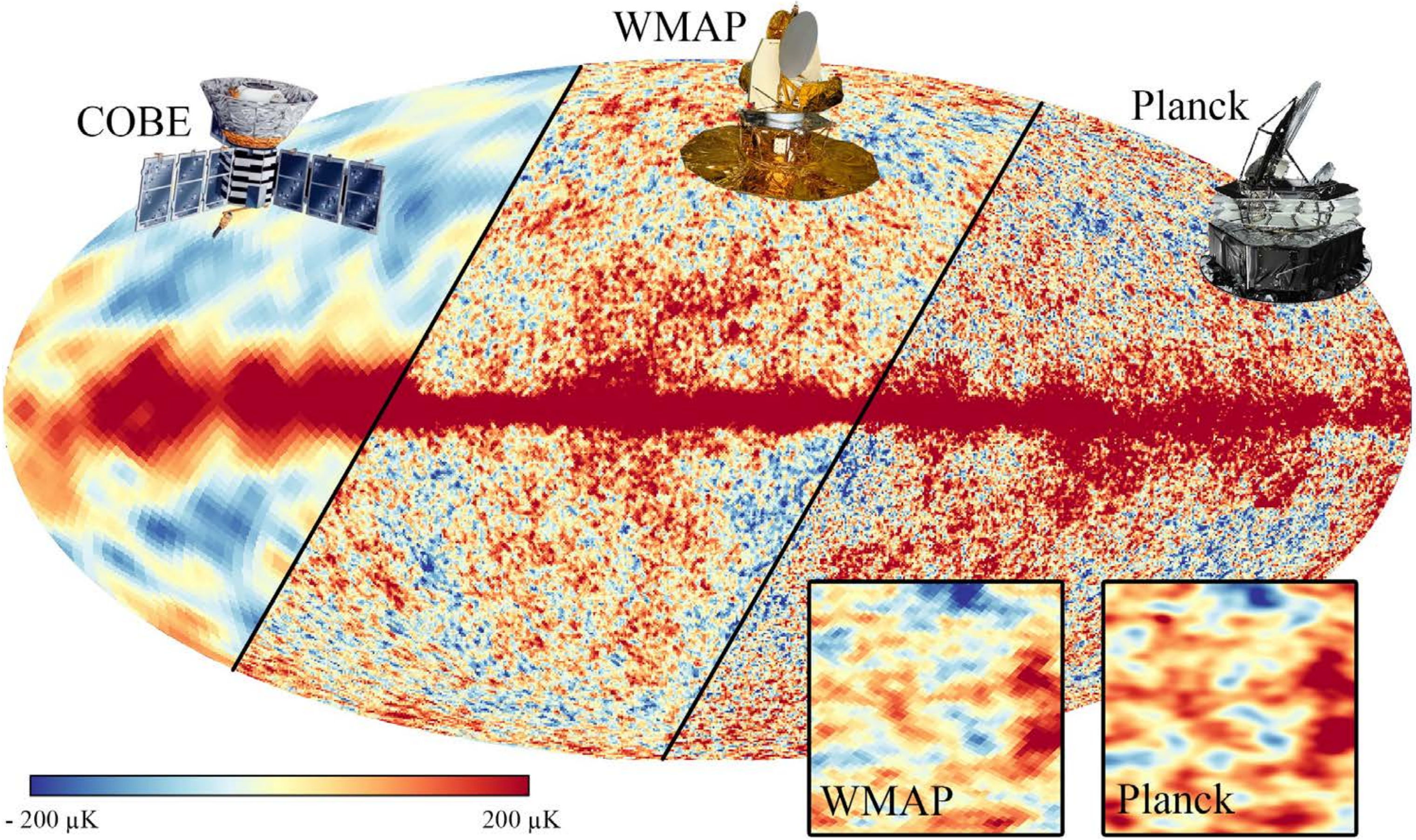
Krzysztof M. Gorski
Nicolaus Copernicus Academy
Warsaw, Poland
(on Senior Research Scientist Leave from JPL/Caltech)

2025 is the 60-th *Jubilaeus Annus* for the discovery of the Cosmic Microwave Background.

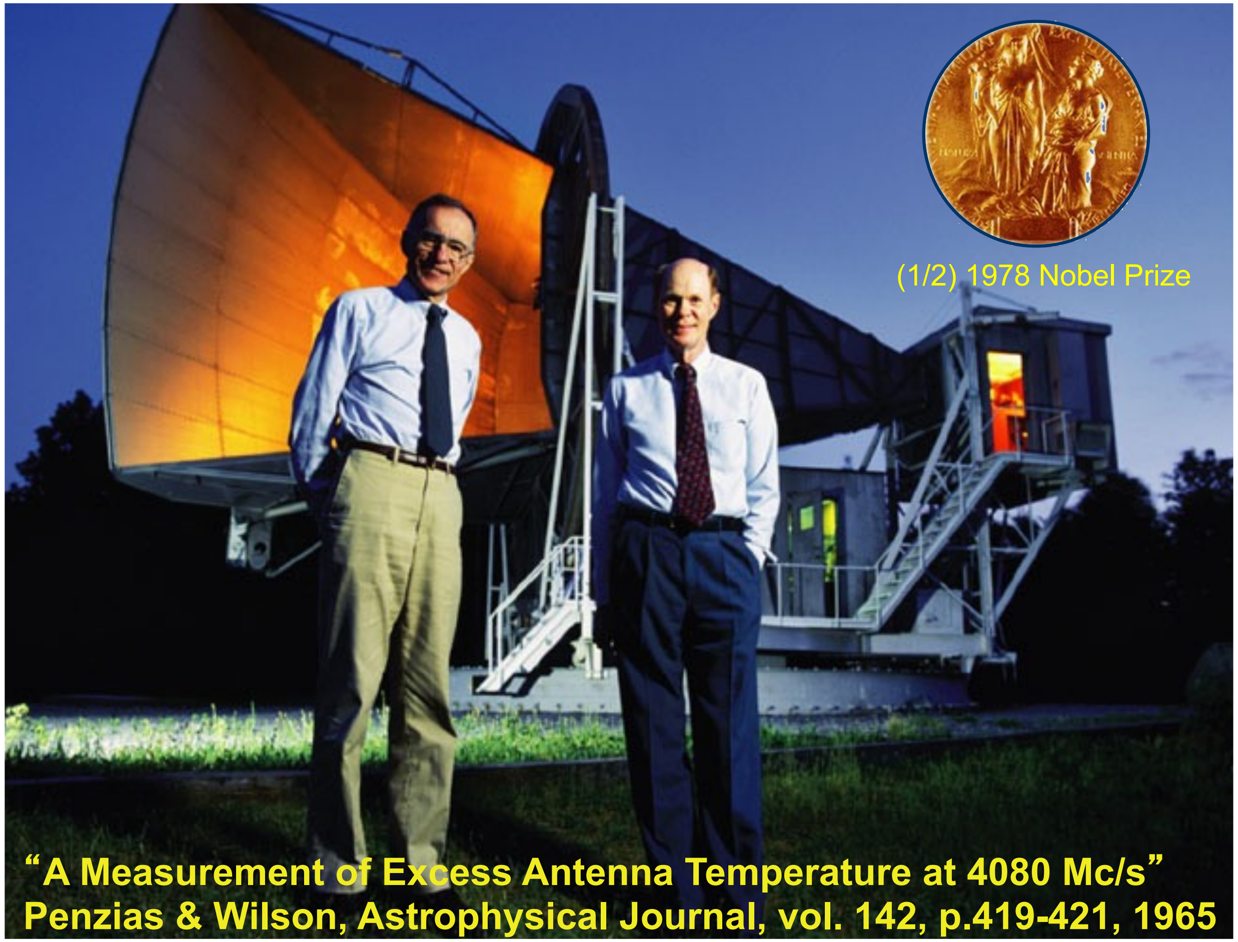
Over 6 decades a number of remarkable experiments explored the CMB sky, including 3 successful satellite missions (these in just over 2 decades of time span).

How and what have we learned?

This is the *COBE* part of the story ...



From 1965, Discovery of the CMB,   to 1978, 2*1/4 Nobel Prize (shared with P. Kapitsa)



In the meantime … a brief calendarium

- 1974 NASA releases Announcement of Opportunity for SMEX or MIDEX
  - 21 responses received, 3 proposals focused on CMB
  - All 3 Lose competition to IRAS
- 1976 – NASA forms a committee of members from those 3 CMB focused instrument proposals to develop a concept to integrate them into a single space mission
- 1977 – *COsmic Background Explorer* concept emerged (for either a Delta 5920-8 or Space Shuttle launch); integrated concept comprised
  - FIRAS – Far Infrared Absolute Spectrophotometer (PI Mather)
  - DIRBE – Diffuse Infrared Background Experiment (PI Hauser)
  - DMR – Differential Microwave Radiometer (PI Smoot)
- (1979-1980) – next page on project definition etc.
- 1988 – original Space Shuttle launch plan; Challenger tragedy delayed that; *COBE* was strongly redesigned (50% weight reduction!), and
- 1989 – on Nov. 18 *COBE* was launched on a Delta rocket

R. Weiss' master class in project definition and description

Physica Scripta. Vol. 21, 670, 1980

The COBE Project

R. Weiss

MIT, Cambridge, Mass. 02139, U.S.A.

Received September18, 1979

As described in the paper by John Mather and Tom Kelsall, the COBE (Cosmic Background Explorer) project is designed to make a substantial improvement in our knowledge of the condition in the universe at large red shifts. The focus of the mission is to study attributes of the primeval cosmic background radiation and to set limits on the universal radiation energy density at shorter wavelengths – radiation emanating from distant sources but at later times than the primeval fireball. In introducing the accompanying paper, I thought it might be worthwhile to describe the scientific strategy driving the COBE mission.

The COBE mission has been under study since 1974 by a team of scientists consisting of S. Gulkis (Jet Propulsion Laboratory), M. Hauser (NASA Goddard Space Flight Center), J. Mather (NASA), G. Smoot (University of California, Berkeley), R. Weiss (MIT), and D. Wilkinson (Princeton). The team members have been involved in ground based, balloon borne and airborne experiments to measure the background radiation and are keenly aware of limitations of these platforms and the arguments in favor of a space borne experiment. It is worth repeating these arguments:

(1) Freedom from atmospheric emission and fluctuations in the emission.

(2) Full sky coverage with a single instrument.

(3) A benign and controlled thermal environment to reduce systematic errors.

(4) The ability to perform absolute primary calibration in flight without the necessity of windows to avoid condensation of the atmosphere on calibrators and instruments.

(5) Sufficient time both to perform tests for systematic errors and to gain the increase in sensitivity permitted by extended observation time.

In planning the COBE mission, the team came to know the peculiar difficulties of carrying out a space mission. Aside from the ever present problem of maintaining the project within an assigned budget, the mission had to be designed so that it would still be the "right thing to do" in the field after the 5 to 10 years it takes between initial planning and execution. One had to anticipate the progress that could still be made by using other platforms and blend this with the fact that in the space mission one would be dealing with technology that was 3 to 5 years behind the state of the art (to allow time for space qualification).

In an interim report to NASA in 1977, the conclusion of the team was that the technology was sufficiently advanced and the instrument systematic noise sources were well enough understood or controllable so that the major limitation in a space mission to perform precision measurements of the background would be the "noise" produced by the local astrophysical environment. The complement of instruments chosen for the mission, as well as the need for full sky coverage and extended observation time, are based primarily on the hope that the local astrophyisical "noise" can be discriminated from the cosmic background by its peculiar set of spectra and anisotropic angular distribution. In the COBE mission, the data from one instrument truly serves to enhance the value of that from another. Examples of this are discussed in the accompanying paper.

Physica Scripta

The Universe at Large Redshifts

Proceedings of the Copenhagen Symposium
June 25-29, 1979

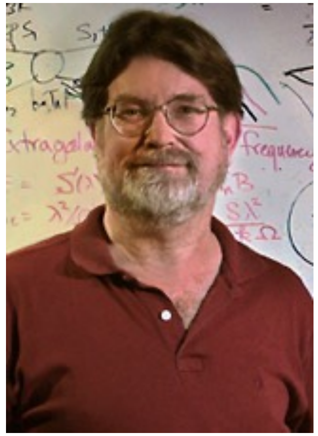
Editors: J. Kalckar, O. Ulfbeck and N. R. Nilsson.

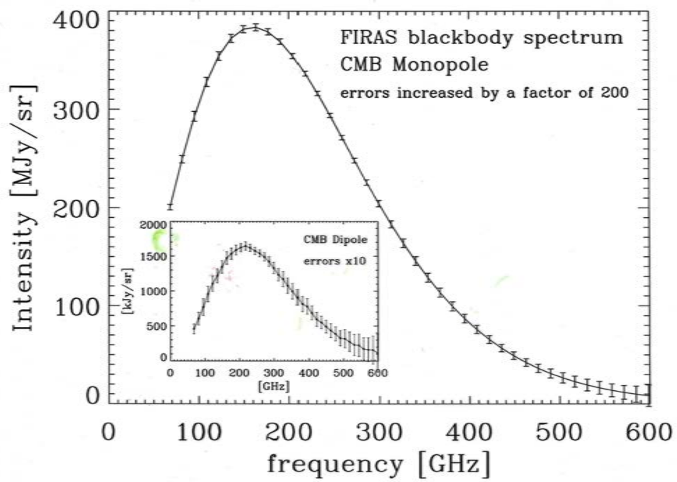
COBE Science Team early on

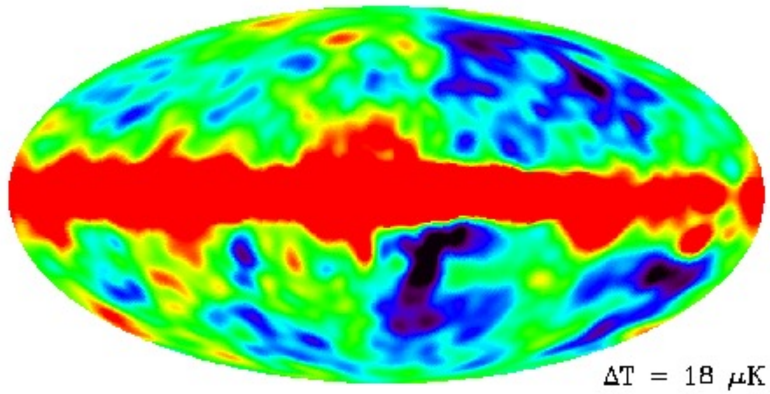
… and eventually there was *COBE's* turn …

Nobel prize in Physics, 2006, awarded to John Mather and George Smoot

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

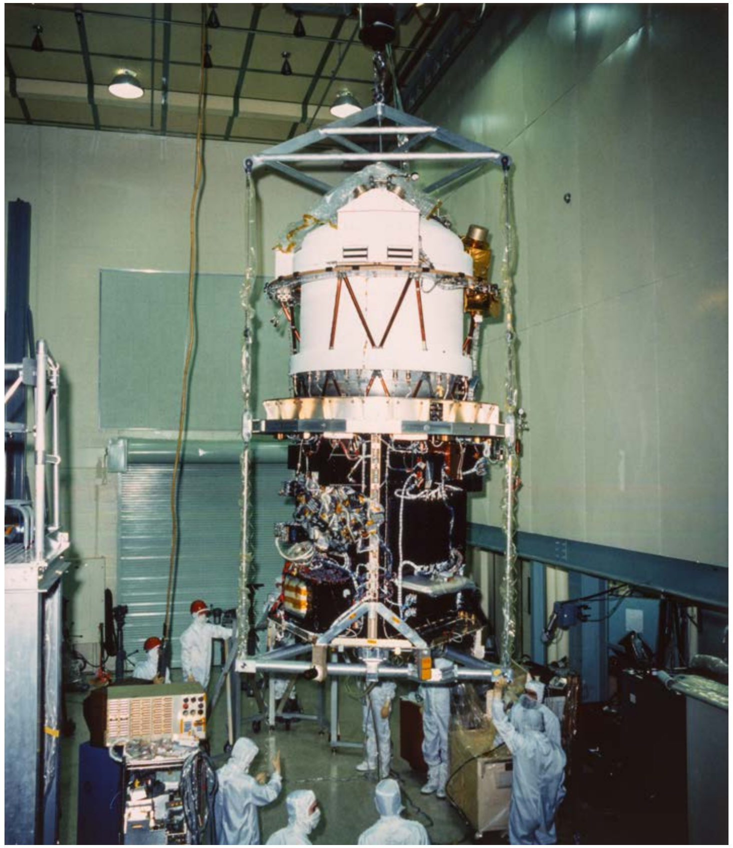


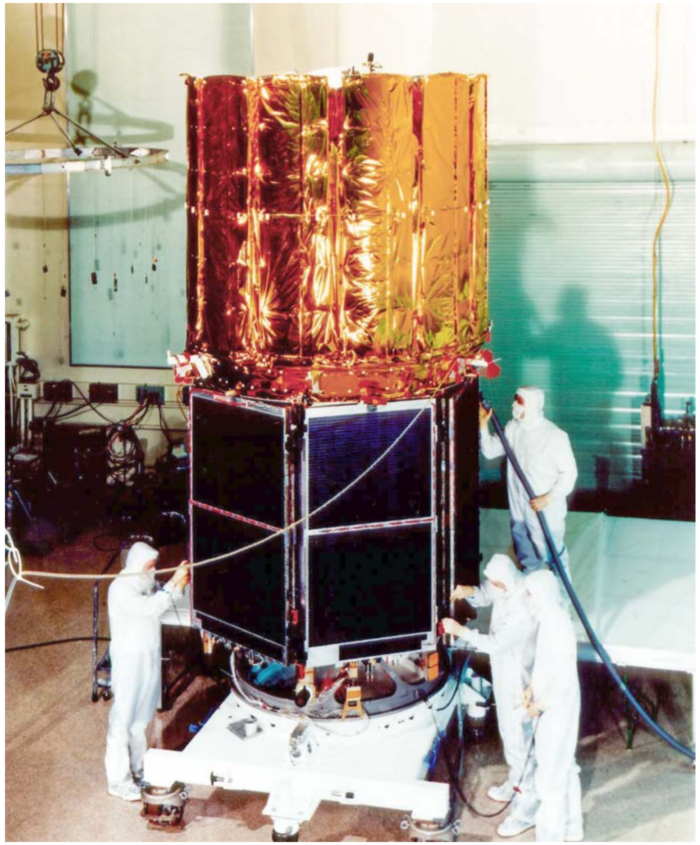




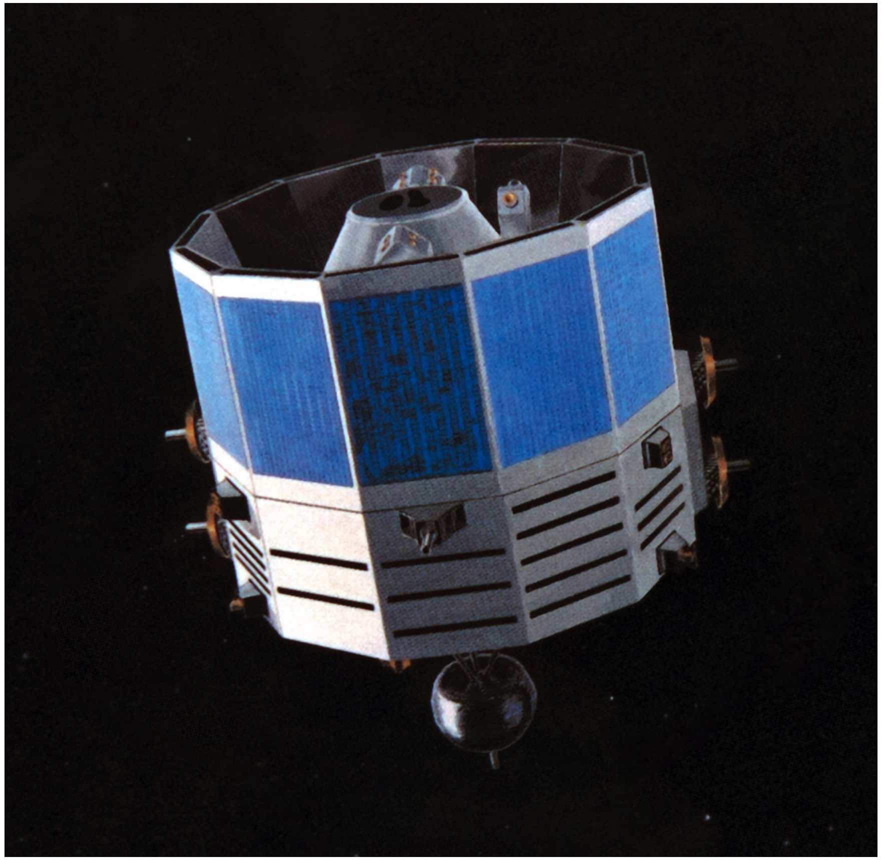
So some of it - *the COBE* Science Team – went to Stokholm

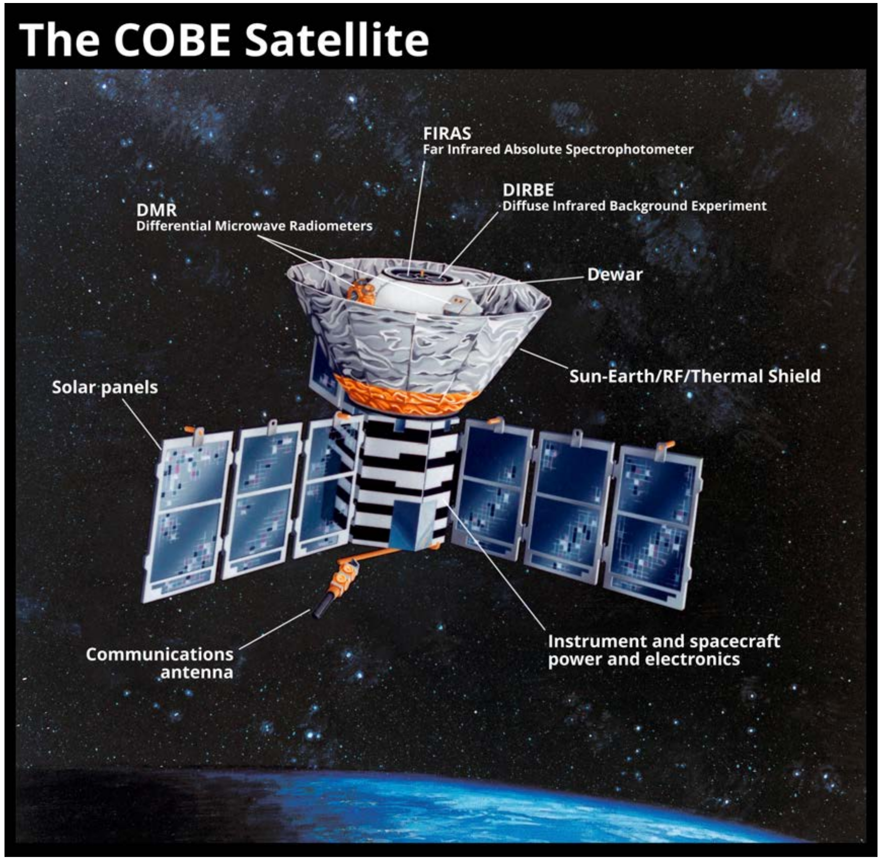
Slimmed down *COBE* readies for launch



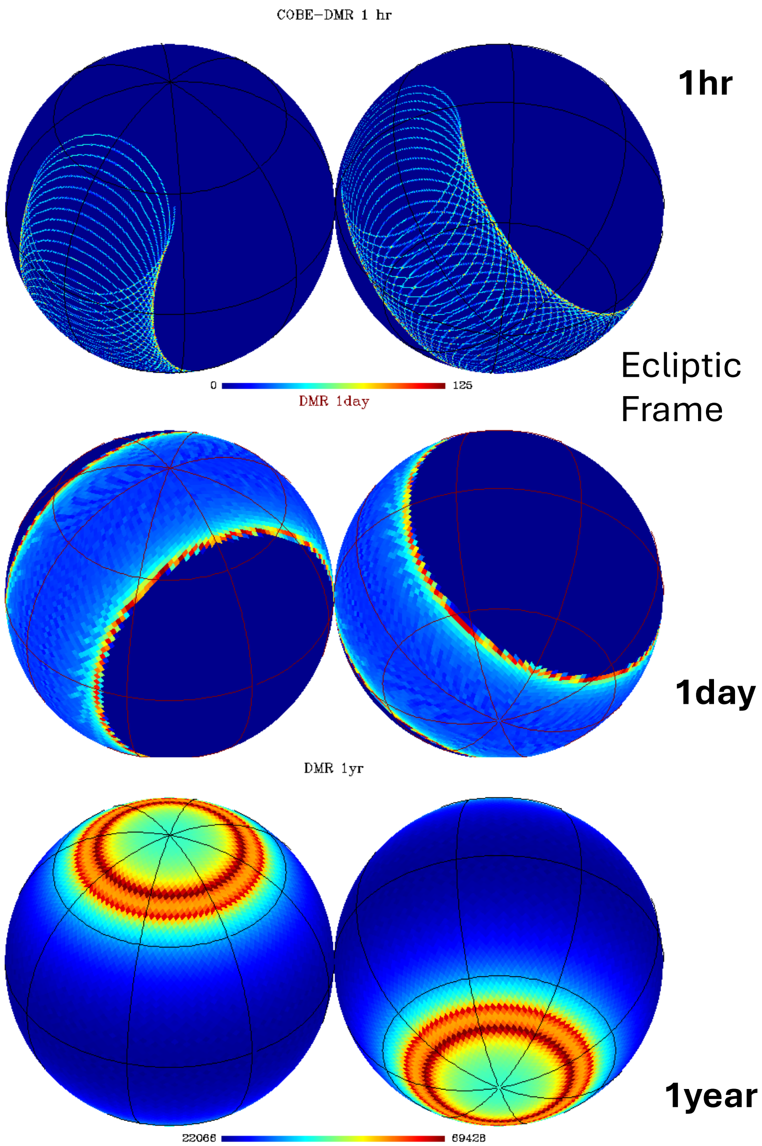


Original satellite concept, and the actual flight version





From *COBE*'s Low Earth Orbit 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

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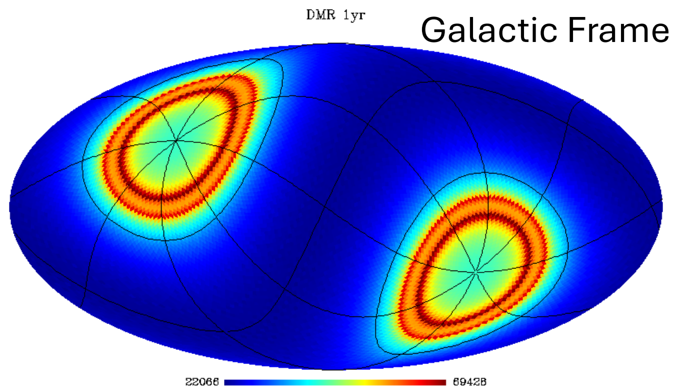
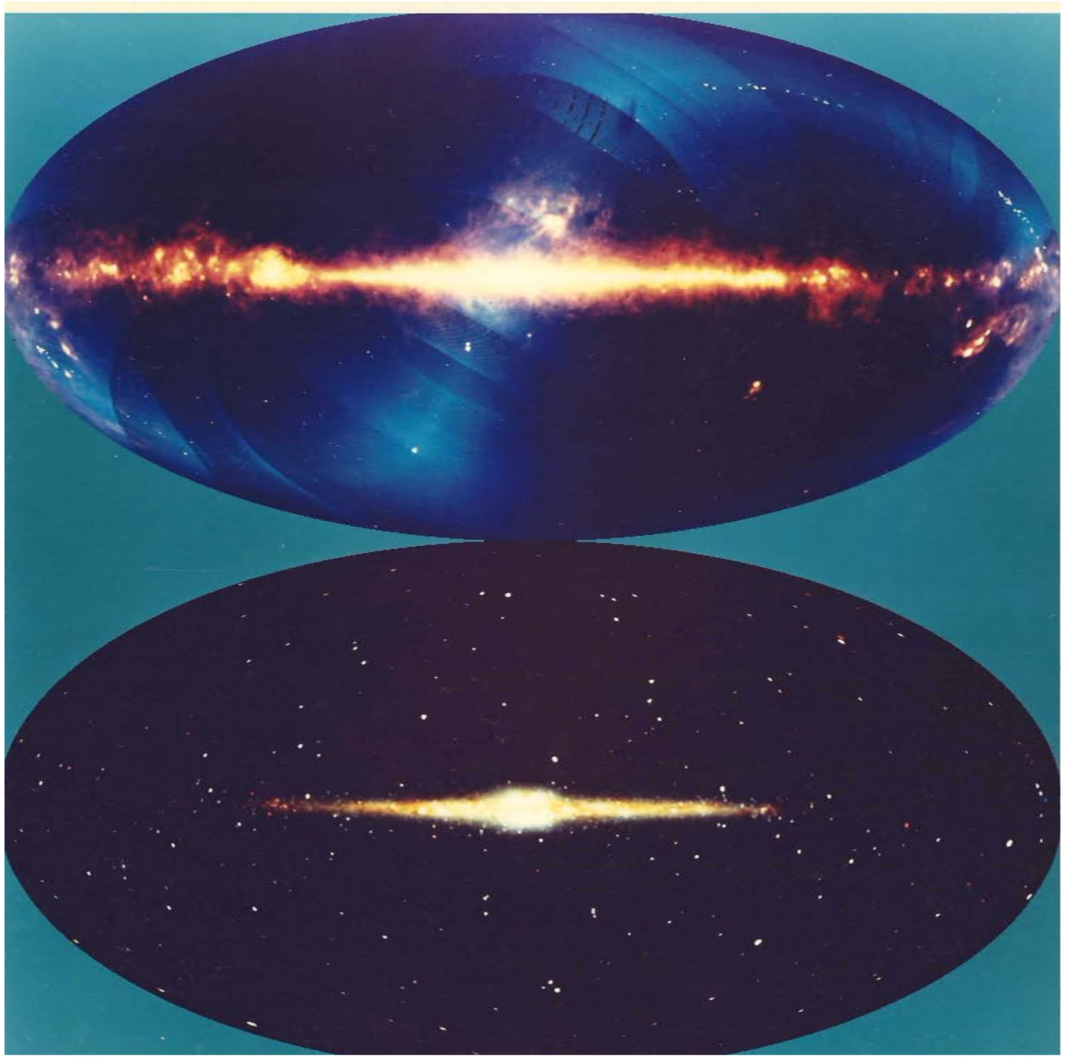
*Time stream of numerous difference measurements of δT at celestial points separated by 60 deg inverted into a best fitting sky map



COBE-DIRBE early on



NASA
National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

Office of Public Affairs
(301)286-8957

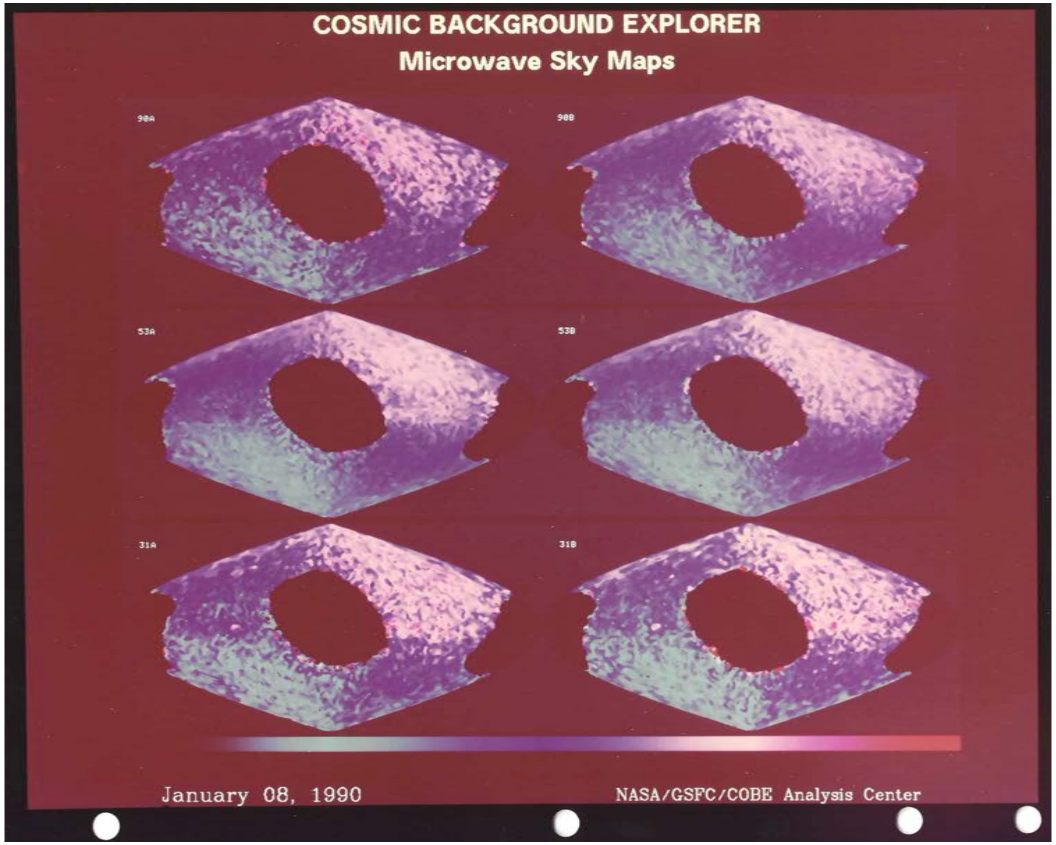
For Release:
Photo No.

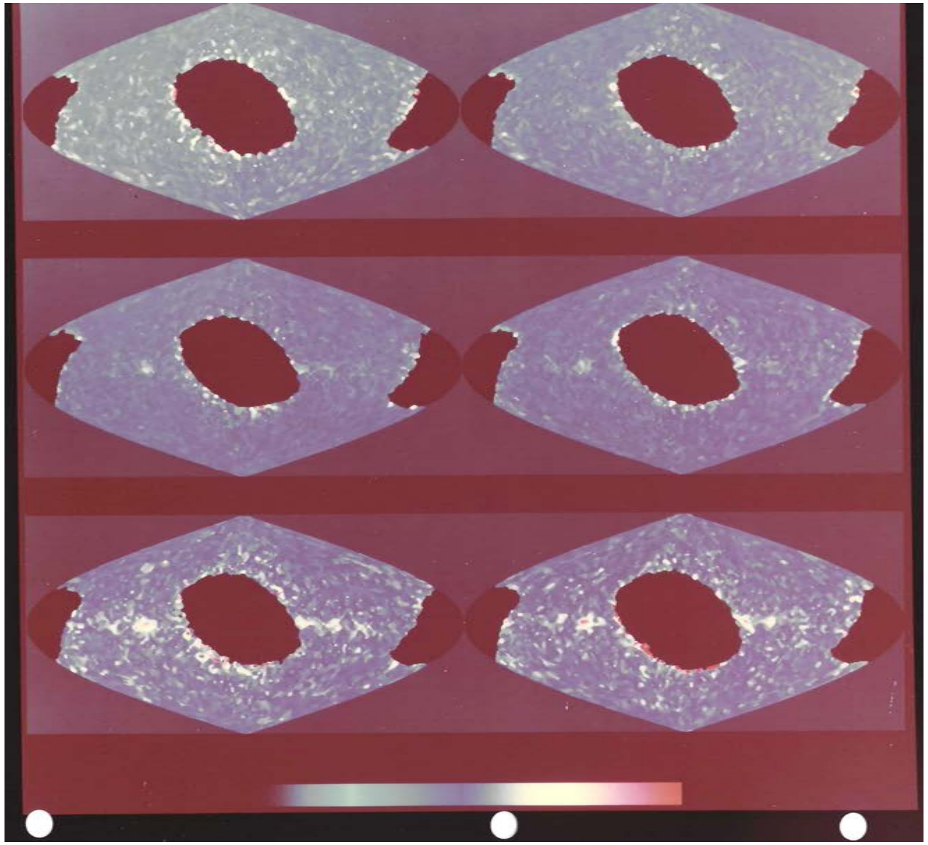
COBE IMAGES OF THE INFRARED SKY--These two all-sky images were constructed from preliminary data obtained by the Diffuse Infrared Background Experiment (DIRBE) on NASA's Cosmic Background Explorer (COBE). The top panel combines data at the far-infrared wavelengths of 25, 60 an 100 microns displayed in blue, green and red colors respectively. The image is presented in galactic coordinates, with the plane of the Milky Way Galaxy horizontal across the middle and the galactic center at the center. At these wavelengths, the dominant feature in the sky is radiation from cold dust located in vast clouds of dust and gas between the stars in our Galaxy. The S-shaped bluish band across this image is emission from interplanetary dust. Discontinuities in this band are artifacts arising from combining data obtained at different times of the year, when the Sun is in different directions. Bright sources along the blue band mostly are sightings of the Moon, which will be removed in further processing. The bottom panel combines data at the near-infrared wavelengths of 1.2, 2.2 and 3.4 microns, represented respectively as blue, green and red colors. The coordinate system is exactly the same as the top panel. The dominant sources of light at these wavelengths are stars within our Galaxy. The image shows both the thin disk and central bulge populations of stars in our spiral galaxy. Our Sun, much closer to us than any other Star, lies in the disk (which is why the disk appears edge-on to us) at a distance of about 28,000 light years from the center. The image is redder in directions where there is more dust between the stars absorbing starlight from distant stars. This absorption is so strong at visible wavelengths that the central part of the Milky Way cannot be seen. DIRBE data will facilitate studies of the content, energetics and large scale structure of the Milky Way Galaxy, as well as the nature and distribution of dust with the Solar System.
The data also will be studied for evidence of a faint, uniform infrared background, the residual radiation from the first stars and galaxies formed following the "Big Bang." COBE was launched in November 1989.

PHOTO CREDIT-NASA or National Aeronautics and Space Administration

DMR – patiently integrates the sky signals …
everyone (of those interested) – impatiently awaits

3-month worth of data integrated into these sky maps (with the dipole signal included (left) and removed (right)



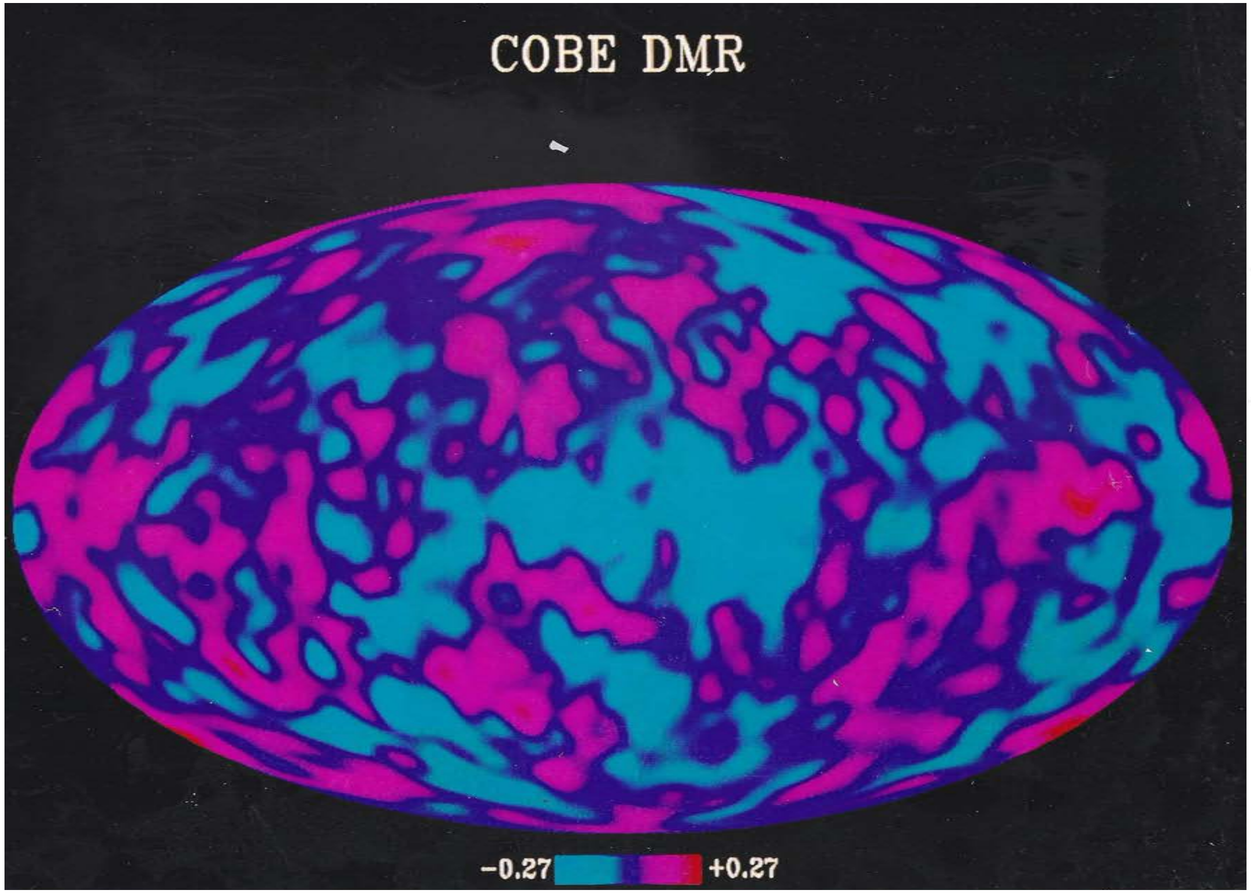


“Satellite produces 'disturbing' lack of evidence” - 17.04.1990

Rob Stein, UPI Science Editor, after “Wilkinson spoke at a news conference at an American Institute of Physics meeting about the latest results from *COBE*, an ultra sensitive satellite launched in November 1989 on a two-year mission.”

- A space probe exploring the evolution of the universe has produced a 'disturbing' lack of evidence to explain the uneven distribution of galaxies through the cosmos, scientists said Tuesday.
- While preliminary data from *COBE* continues to support the 'big bang' theory of the universe's creation, the information gathered so far has failed to explain its current 'lumpy’ formation.
- 'The smoothness is disturbing us a lot. At this point we're beginning to expect little warts and dimples to appear,' said David Wilkinson, a professor of physics at Princeton University.
- The $160 million orbiting space probe was designed to answer fundamental questions about the formation and evolution of the universe by collecting data about faint radiation left over from the big bang explosion.
- Scientists theorize the universe exploded into existence 15 billion years ago in a hot, dense fireball that instantly began expanding in all directions.
- ... scientists ... said the data collected so far by COBE appears consistent with those theories.
- BTW: ... scientists also released a new color photograph of the Earth's home galaxy, the Milky Way ... 'This thing ... is spectacular. I mean that's wonderful,' said Wilkinson ... 'My God, it's as though you were in Andromeda taking a picture of our galaxy.’ (- the DIRBE pictures of the Galaxy)
- 'One year or two years from now, if those pictures are still looking smooth at the accuracies we'll have then, then there's real trouble. Then there's real big trouble,' said Wilkinson.

Finally, one year of measurements yielded sky maps that allowed to render this priceless *COBE*-DMR discovery picture of CMB anisotropy released by NASA in April, 1992



Kris,
To my friend and colleague -
I hope to see you frequently
for good times & cosmology
- Chuck Bennett

NASA
National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

Office of Public Affairs
(301)286-8957

For Release: APRIL 23, 1992
Photo No.

Pictured is a microwave map of the whole sky made from one year of data taken by NASA's Cosmic Background Explorer (COBE) Differential Microwave Radiometers (DMR). The map is in galactic coordinates with the position of the Milky Way Galaxy horizontal across the middle of the map, and with the center of our galaxy at the map center. The data from all three DMR frequencies have been used to model and remove microwave emission from our galaxy. Red indicates one hundredth of one percent (0.01%) warmer and blue indicates one hundredth of one percent colder than the average sky temperature of 2.73 degrees above absolute zero. Most of the red and blue patches are the result of instrument noise, but computer analyses indicate that faint cosmic signals also are present.

The DMR instrument was designed to search for temperature variations in the relic cosmic microwave background radiation from the Big Bang. The COBE data revealed for the first time this 15-billion-year-old fossil of conditions of the early Universe.

Computer analysis of the data shows that the pattern of fluctuations supports predictions from the "inflationary Big Bang" theory. The amplitudes of the fluctuations are consistent with explaining the birth and growth of galaxies using large amounts of invisible "dark matter."

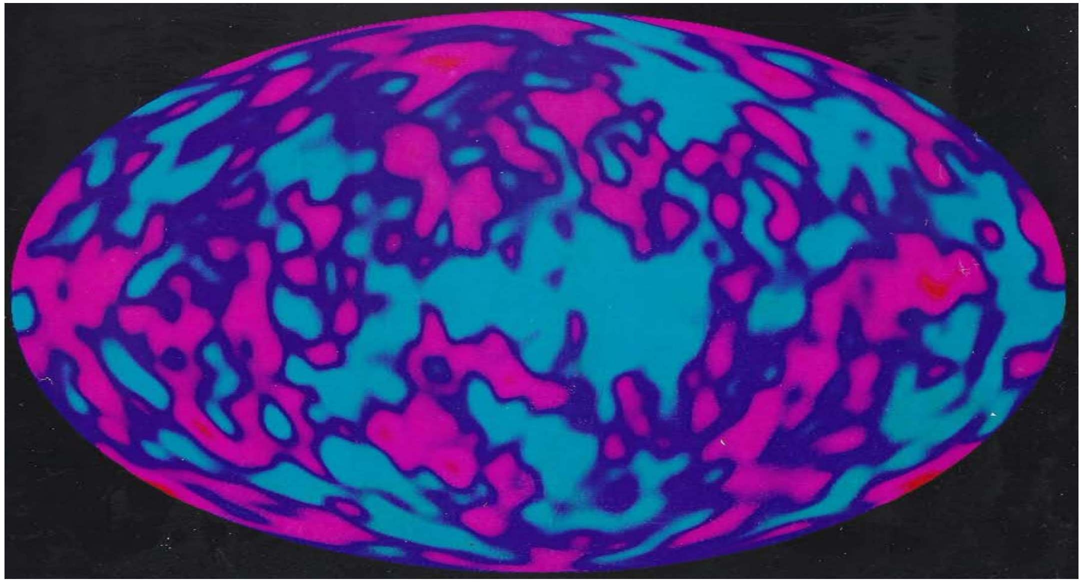
COBE was launched in November 1989, from Vandenberg Air Force Base, California, aboard a Goddard-managed Delta launch vehicle. The Goddard Space Flight Center, Greenbelt, Maryland, manages COBE for NASA's Office of Space Science and Applications, Astrophysics Division, Washington, DC.

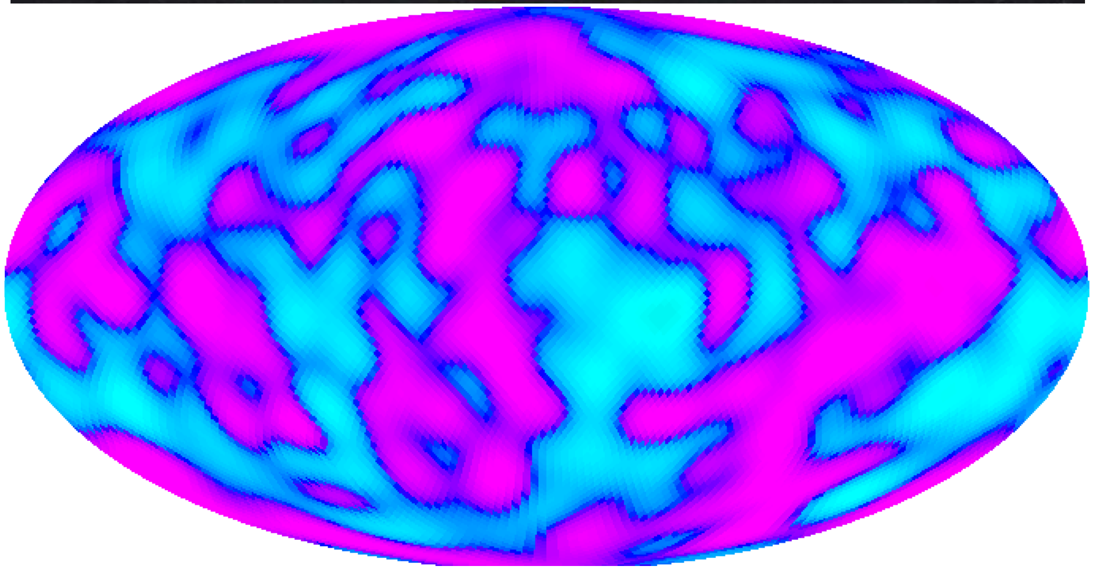
PHOTO CREDIT: NASA/GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

Kris,
Good luck in Paris -
figure out what it all
means

Chris
Best wishes for your
future cosmology research,
Nancy Boggess

Kris G,
Glad you could come.
Referenced your work. George Smoot





COBE-DMR

- 1 year of data, CMB anisotropy extracted by 3 frequency band Internal Linear Combination
- Very noisy, hence heavily smoothed – and still noisy
- Allegedly:
  - “most discernible patterns not real structures, but noise features”,
  - “only statistical assessment of signal reliable”

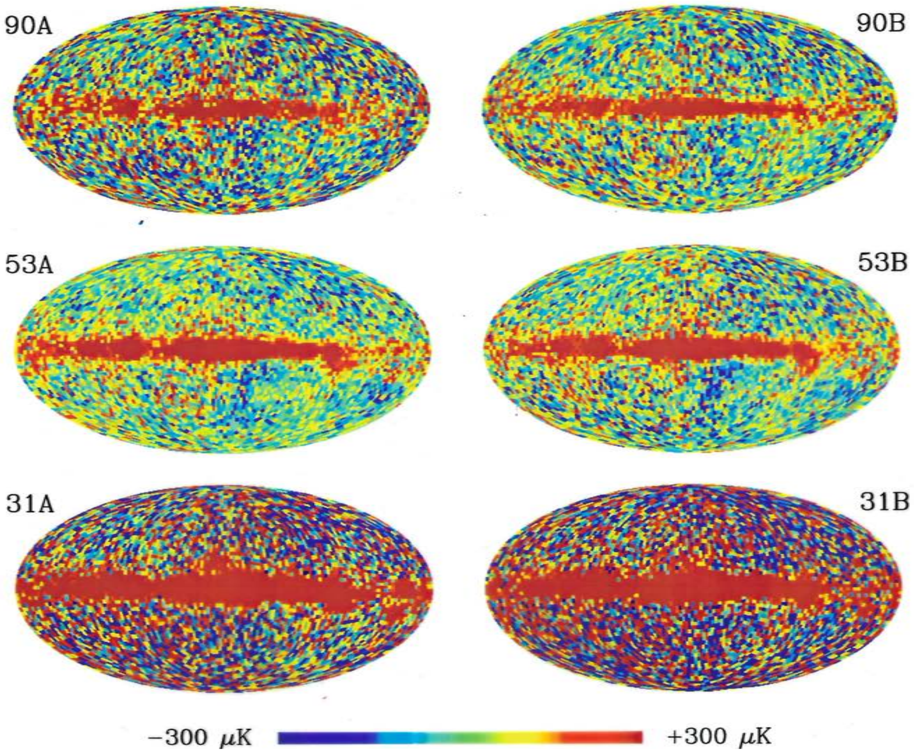
Planck

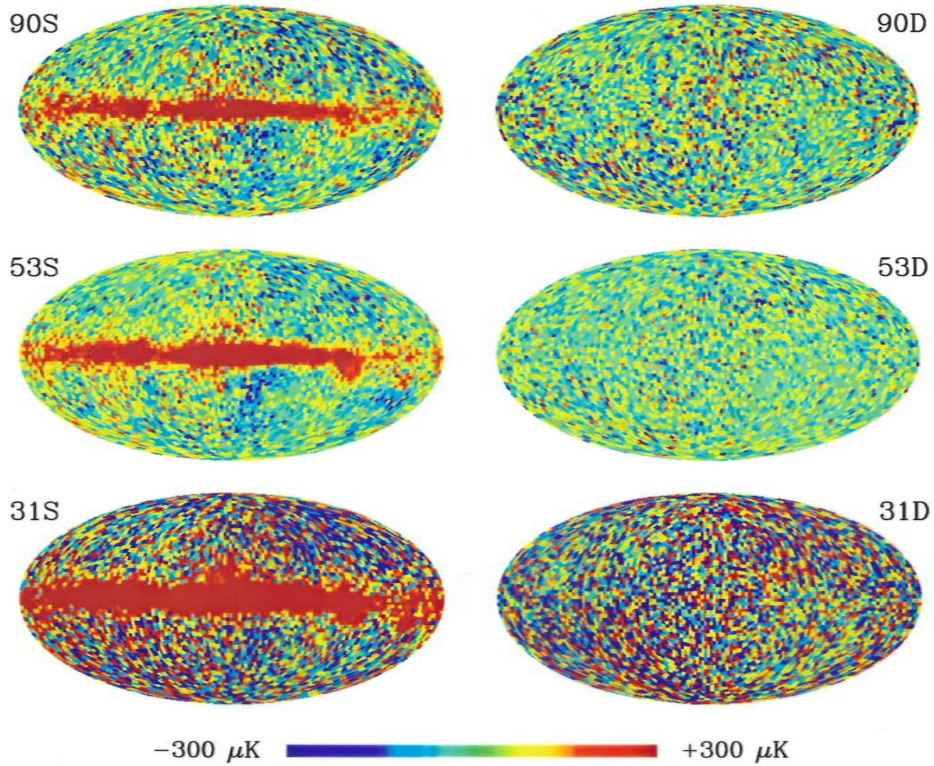
- Full data set, CMB anisotropy extracted from component separation of all 9 frequency maps
- Heavily smoothed to match (approximately) the DMR picture above
- Hence – essentially noiseless

COBE-DMR data set, (multiple versions of) 6 full sky maps

31, 53, 90 GHz channels with FWHM ~7 deg bams – two maps in each; 6144 2.6deg-pixels on full sky

~1000 spatially independent δT estimates per map; “somewhat” noisy





Emergence of *COBE*-DMR measurements in the form of multi-frequency, digitized full sky maps forced a rapid modernization of CMB data analysis techniques (scans of my "historical" transparencies from ~30 years ago)

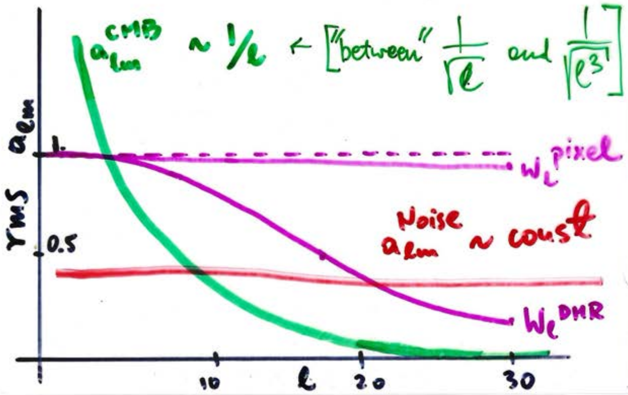
Fourier decomposition of a COBE-DMR Map

$(\theta_p,\varphi_p)_{6144 \text{ pixels}}$

$$\frac{\delta T}{T}(p) = \Delta_{CMB}(p) + \Delta_{Galaxy}(p) + \Delta_{Noise}(p)$$

$$= \sum_{\ell=0}^{\ell_{max}} \sum_{m=-\ell}^{\ell} \left\{ \left[a_{\ell m}^{CMB} + a_{\ell m}^{Galaxy} \right] W_\ell^{DMR} + a_{\ell m}^{Noise} \right\} W_\ell^{pixel} Y_{\ell m}(\theta_p,\varphi_p)$$

(+ foregrounds + systematics)



$$\underline{c} = \underline{s} + \underline{n}$$

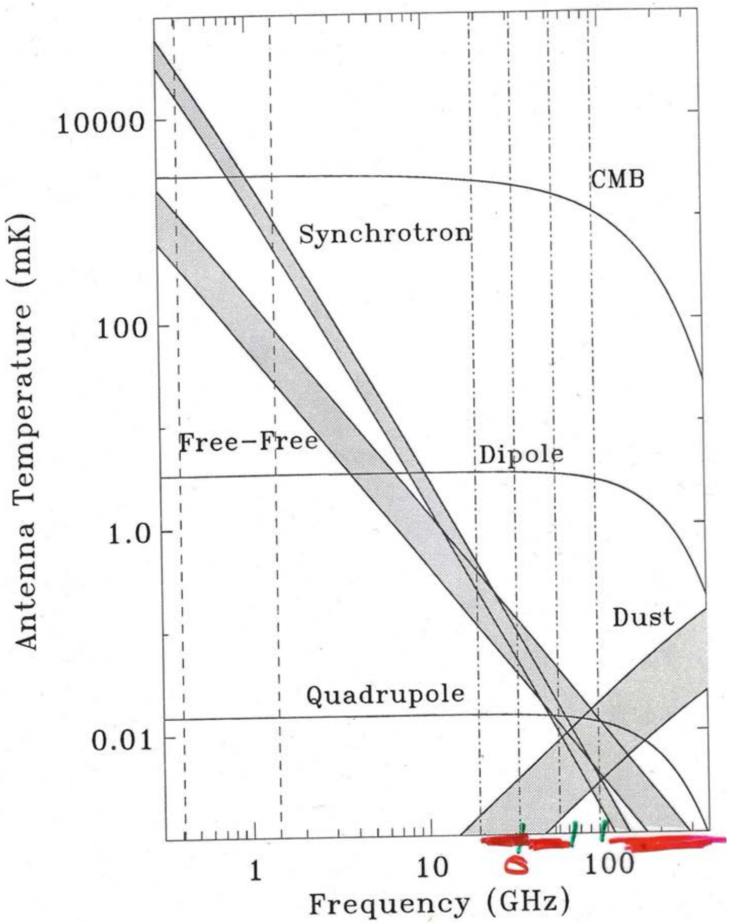
$$c_i = \int_{\text{cut-sky}} d\Omega \, \frac{\delta T}{T}(\Omega) \, \Psi_i(\Omega)$$

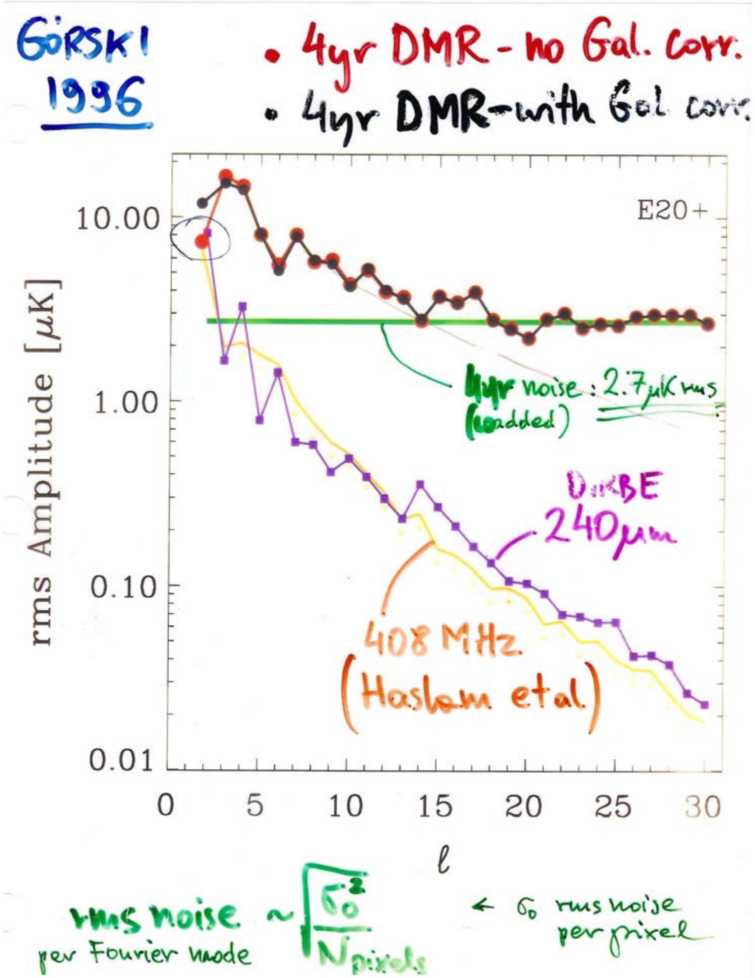
$$P(\underline{c})\, d\underline{c} = \frac{d\underline{c}}{(2\pi)^{N/2}\sqrt{\det(\underline{\underline{S}}+\underline{\underline{N}})}} \, e^{-\frac{1}{2}\underline{c}^T \cdot (\underline{\underline{S}}+\underline{\underline{N}})^{-1} \cdot \underline{c}}$$

$$\langle s \cdot s^T \rangle = \underline{\underline{S}} \qquad \langle n \cdot n^T \rangle = \underline{\underline{N}}$$

$$\underline{\underline{S}} = \underline{\underline{S}}(\underline{\underline{A}}) \qquad \underline{\underline{A}} = \mathrm{diag}\Big[\underbrace{C_2 \ldots C_2}_{5\times}, \underbrace{C_3 \ldots C_3}_{7\times}, \ldots \underbrace{}_{(2\ell+1)\times}$$

"Astrophysical Noise" from Ray's 1979/80 piece – DMR's CMB temperature anisotropy foregrounds





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.

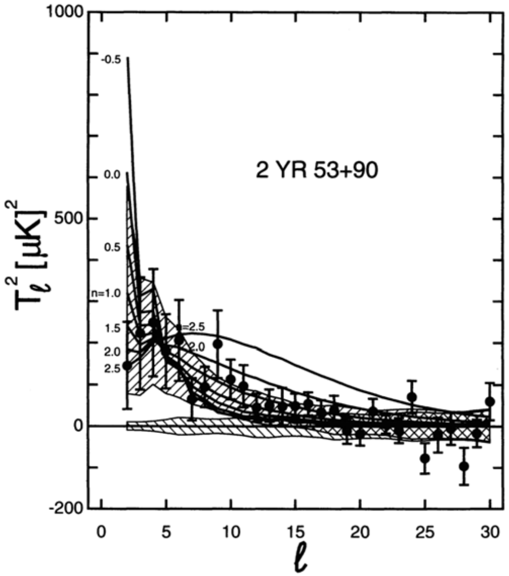


FIG. 1.—Power spectrum of the 2 yr 53+90 DMR maps (*points*) compared to the mean $\pm 1\ \sigma$ range of Monte Carlo spectra computed for Harrison-Zel'dovich (H-Z) skies with an expected $Q = 17\ \mu$K. The lower band is the $\pm 1\ \sigma$ range for noise-only Monte Carlo spectra. The lines show the 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.

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

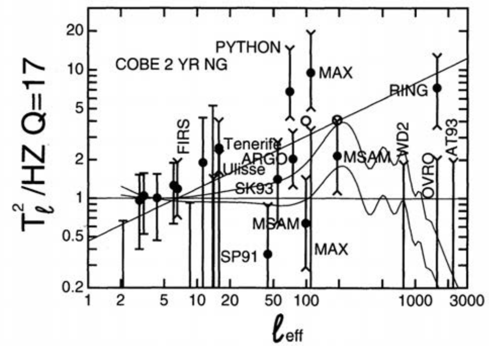


FIG. 4.—Power spectra normalized to the mean of 17 μK Harrison-Zel'dovich Monte Carlo skies. *COBE* data points from the 2 yr NG DMR maps. Models shown as thin curves: $n = 1$, $Q = 17\ \mu$K is the horizontal line, the best-fit $n = 1.4$ power law is the slanted line, and tilted CDM including the effects 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

Finally giving up on the "blue" DMR power spectrum

Ned's 1996 ultimate DMR power spectrum paper

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 $3 \le \ell \lesssim 30$ is an apparent spectral index $n_{app} = 1.13^{+0.3}_{-0.4}$ which is consistent with the Harrison-Zeldovich primordial spectral index $n_{pri} = 1$. The best-fitting amplitude for $n_{app} = 1$ is $\langle Q^2_{rms} \rangle^{0.5} = 18\ \mu$K.

Subject headings: cosmic microwave background — cosmology: observations

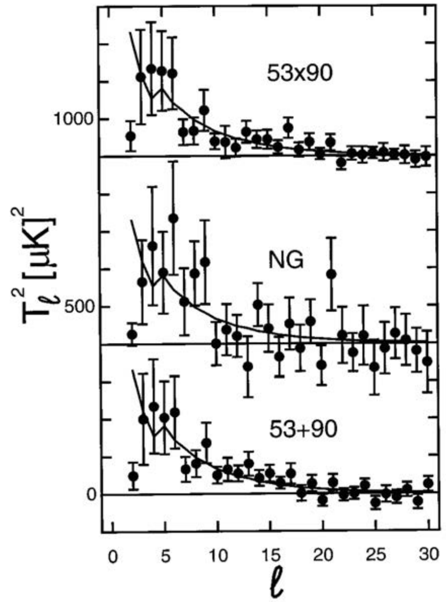


Fig. 1.—Cross-power spectra for the 53 + 90 $A \times B$, 53 × 90, and NG $A \times B$ maps. T_ℓ^2 measures the variance of the sky due to order ℓ harmonics for full sky coverage, but partial sky coverage changes the expected value as seen in the curves showing the average power spectrum of $Q = 17\ \mu$K, $n = 1$ 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.

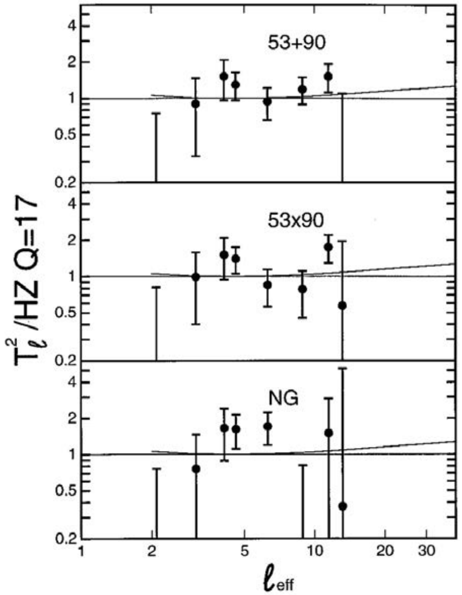
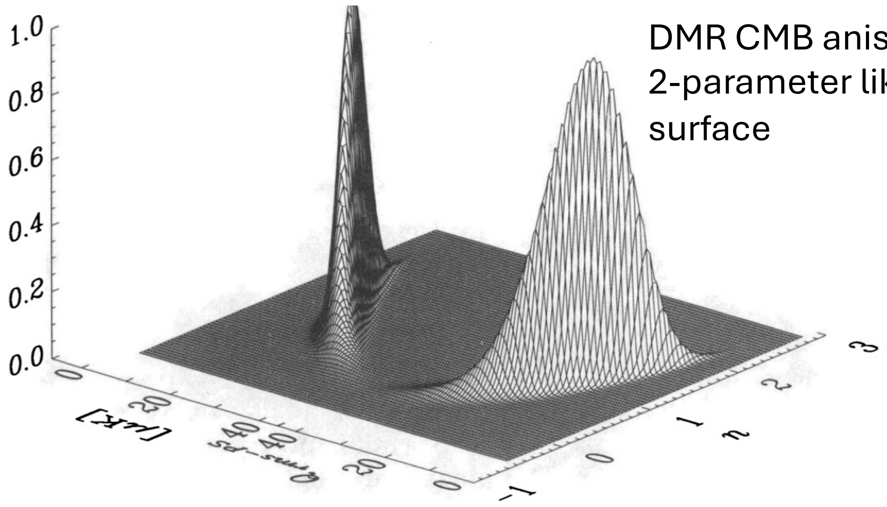
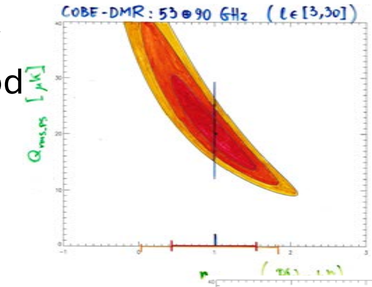


Fig. 2.—Binned cross-power spectra for the 53 + 90 $A \times B$, 53 × 90, and NG $A \times B$ maps, normalized to the mean power spectrum of $Q = 17\ \mu$K, $n = 1$ simulations, plotted on a logarithmic scale. ℓ_{eff} is the effective wavenumber of the bin for $n = 1$. The thin curves show a CDM model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



DMR CMB anisotropy
2-parameter likelihood
surface



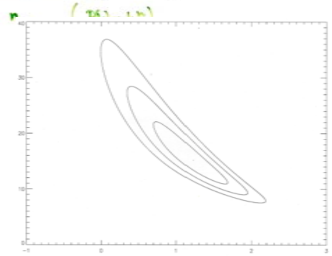


FIG. 1.—Two views of the likelihood function, $P(Q_{\mathrm{rms-PS}}, n)$ derived in a simultaneous analysis of the 53 and 90 GHz *COBE*-DMR two-year data including harmonic amplitudes from the range $\ell \in [2, 30]$.

My 1996 ultimate
DMR power spectrum paper

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

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]

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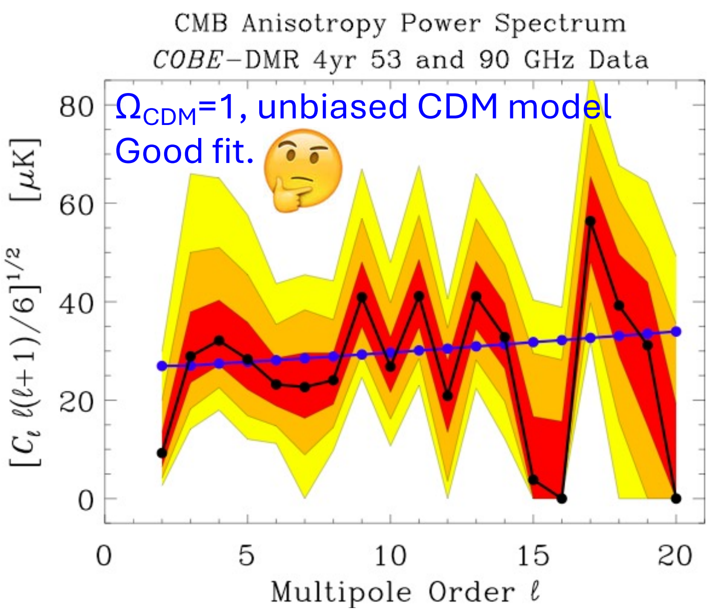
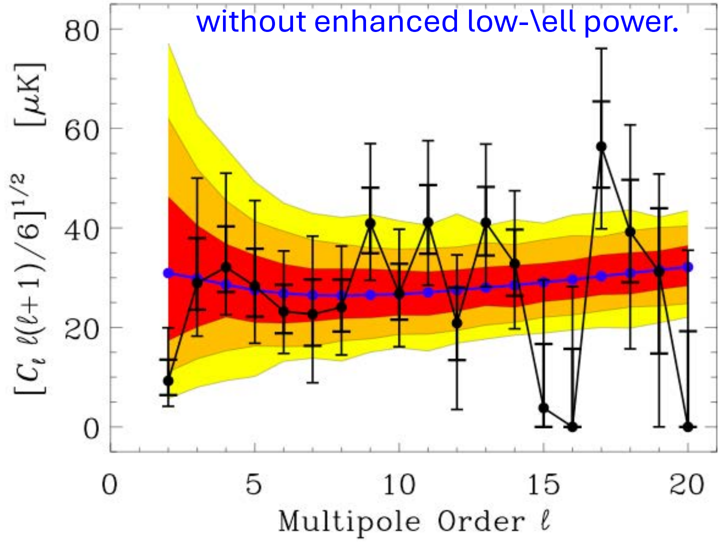
power spectrum estimation from the foreground-corrected 4 yr *COBE* DMR data renders $n \sim 1.2 \pm 0.3$ and $Q_{\mathrm{rms-PS}} \sim 15.3^{+3.7}_{-2.8}$ μK (projections of the two-parameter likelihood). The results are consistent with the Harrison-Zeldovich $n = 1$ model of amplitude $Q_{\mathrm{rms-PS}}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

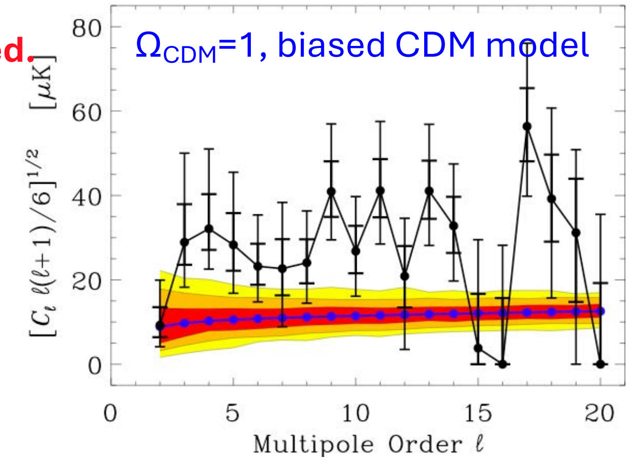
l-by-l CMB Anisotropy Spectrum from the 4yr COBE-DMR data

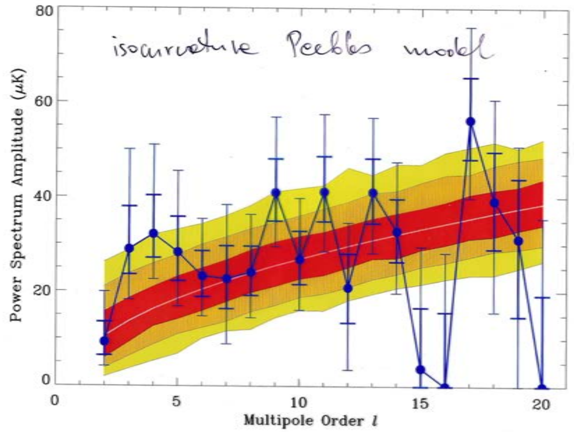


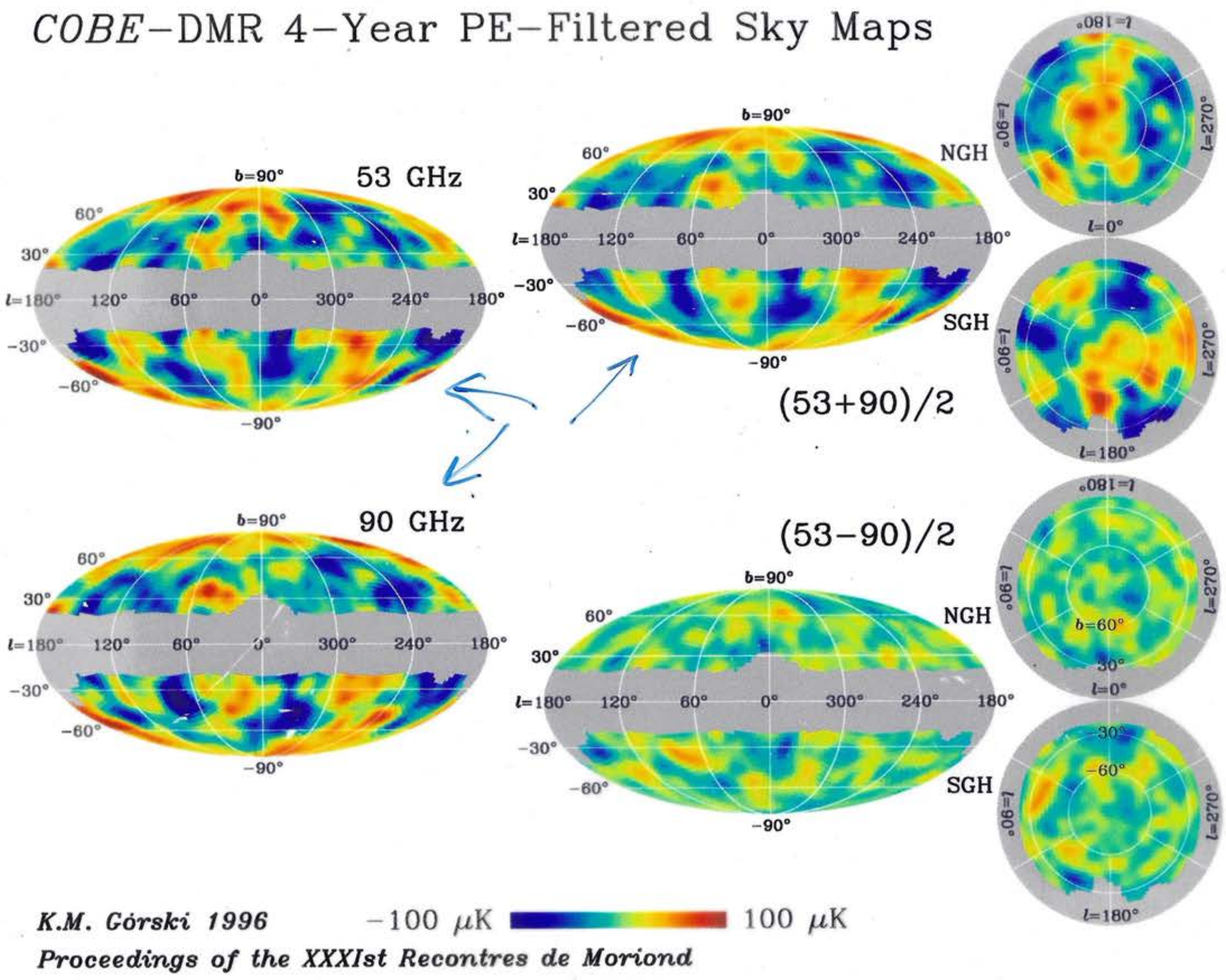
Example of CDM+Λ model;
Fitted DMR OK, but worse than those without enhanced low-\ell power.



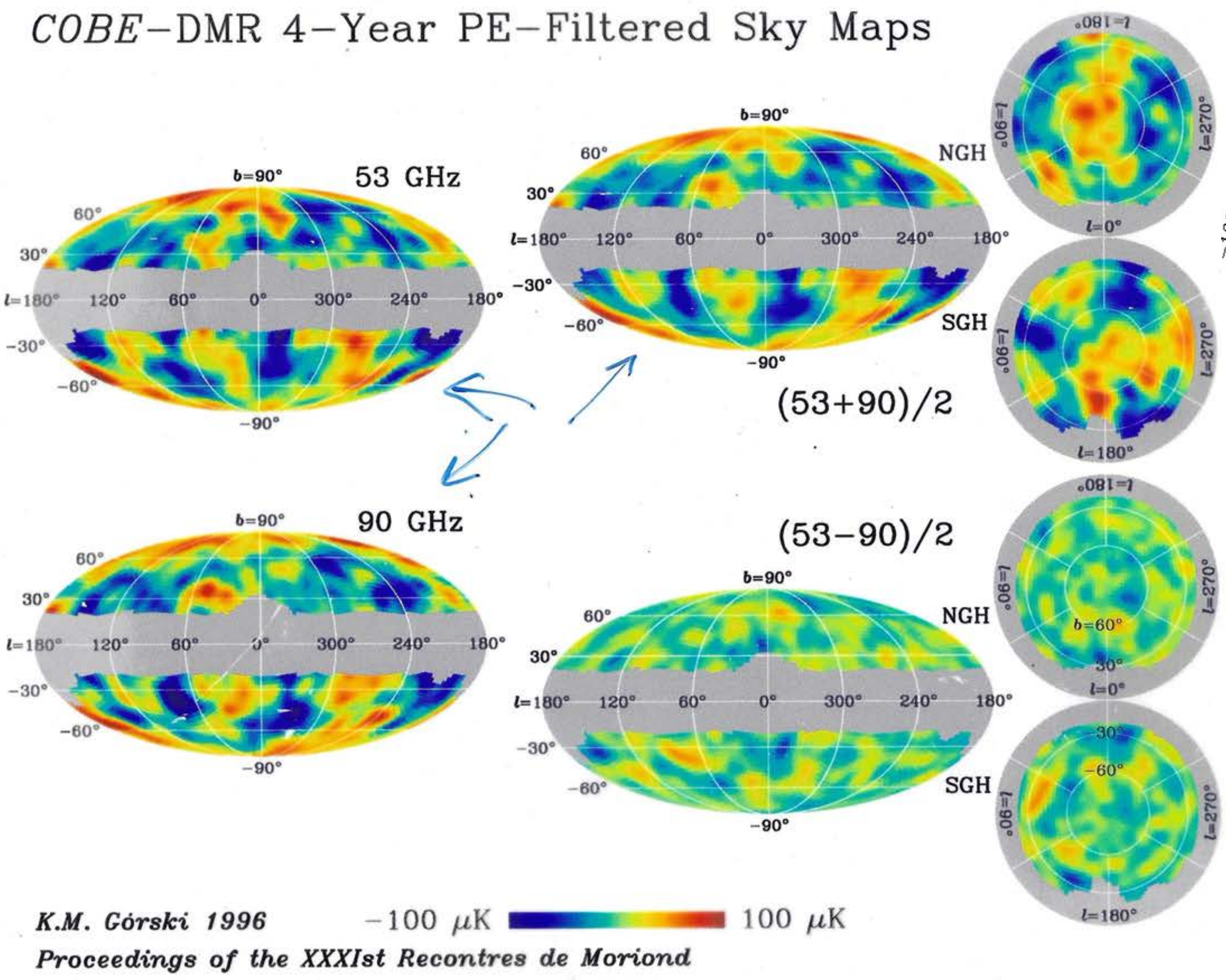
These models were vetoed.
DMR killed the (b~2.5) "Biased Cold Dark Matter Model".



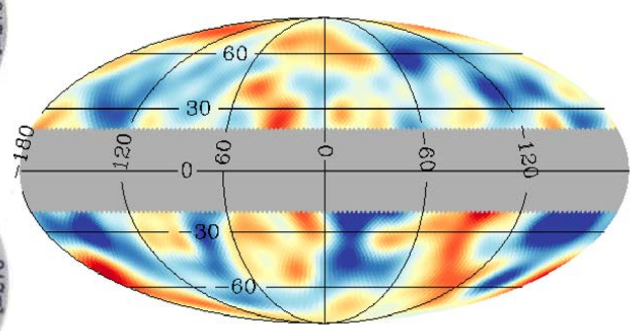




The best picture of the last scattering surface that we obtained based on the full 4-year DMR data set



A few years later,
WMAP and Planck revealed this



This is the low angular resolution part of the component separated Planck data

The best picture of the last scattering surface that we obtained based on the full 4-year DMR data set

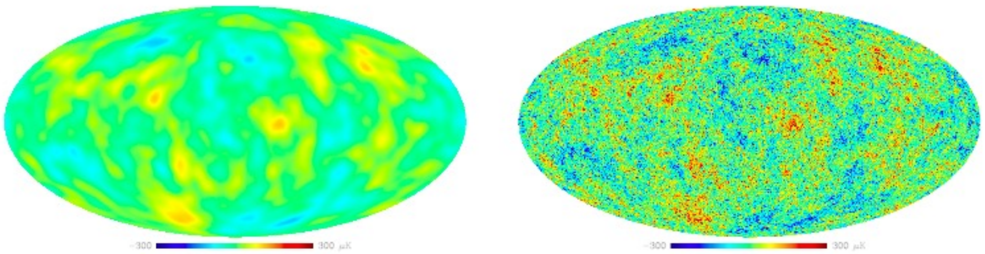
After *COBE* …

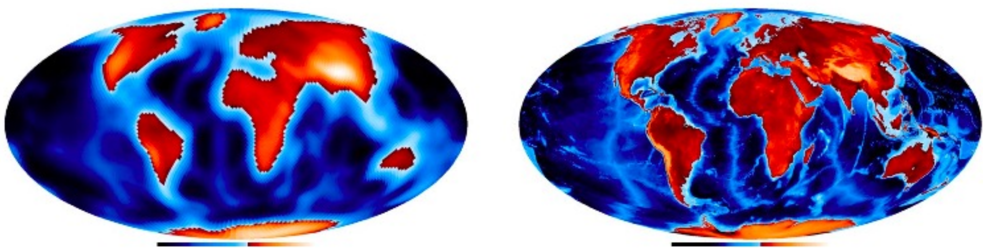
To make progress we needed measurements with much better angular resolution, less noise, colder environment and instruments, etc., etc., …

… and we got them!

… TBC with the next speakers …

~10+ years of CMB sky exploration





~500+ years of Earth exploration