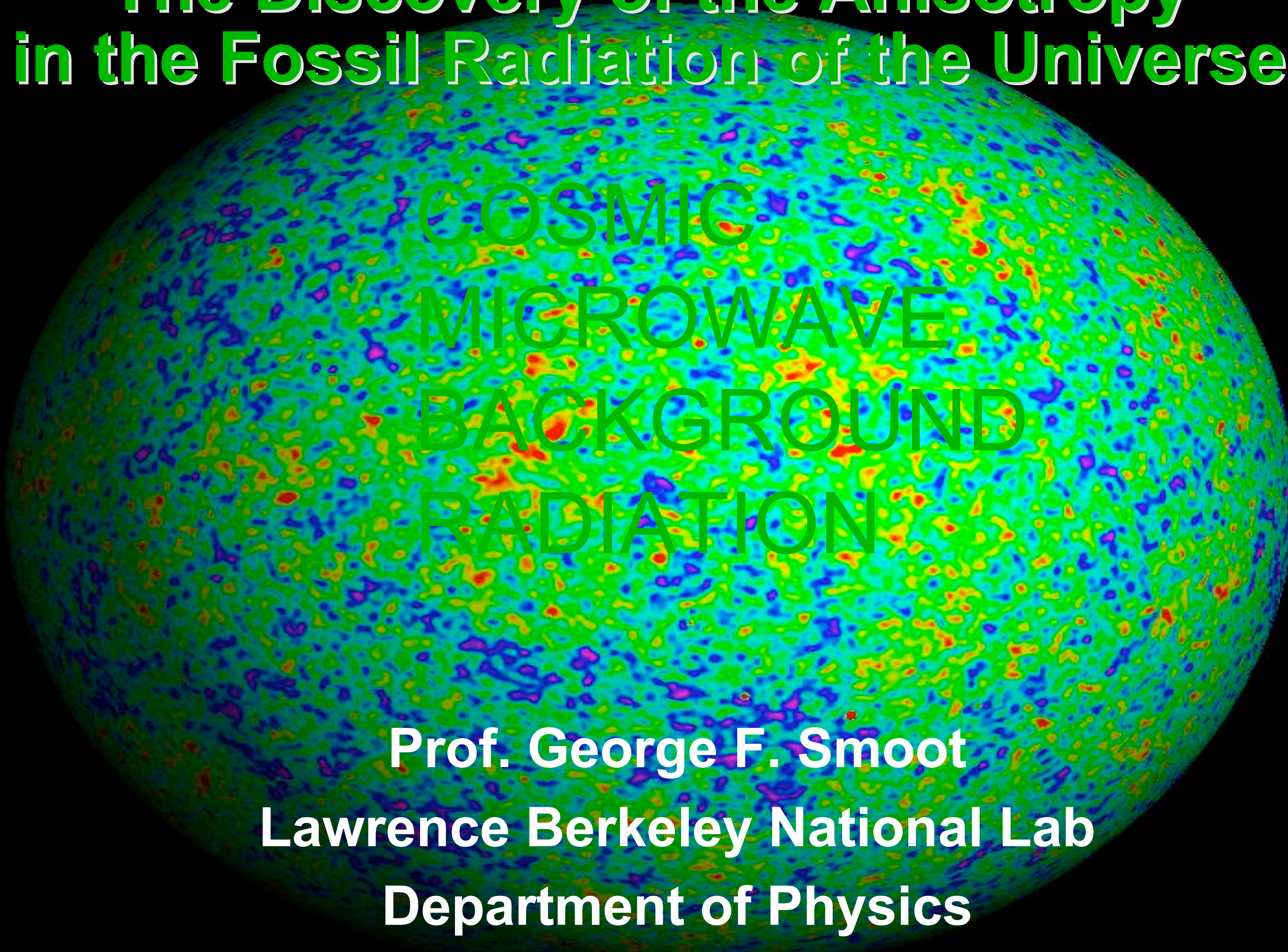
The Discovery of the Anisotropy in the Fossil Radiation of the Universe

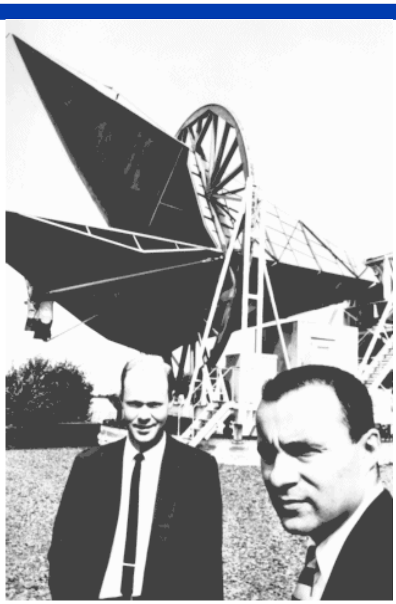


Prof. George F. Smoot
Lawrence Berkeley National Lab
Department of Physics
University of California at Berkeley

Relic Radiation from THE BIG BANG: The Story Begins

1964 Penzias & Wilson discover isotropic emission at λ=7.35 cm. If a blackbody, T=3±0.5 K. Penzias talks on the phone to Bernie Burke, who heard from Ken Turner about a talk by P.J.E. Peebles (Princeton) who had predicted the universe would be filled with a 5 K radiation.

Discovery of the Cosmic Background Radiation (CBR).

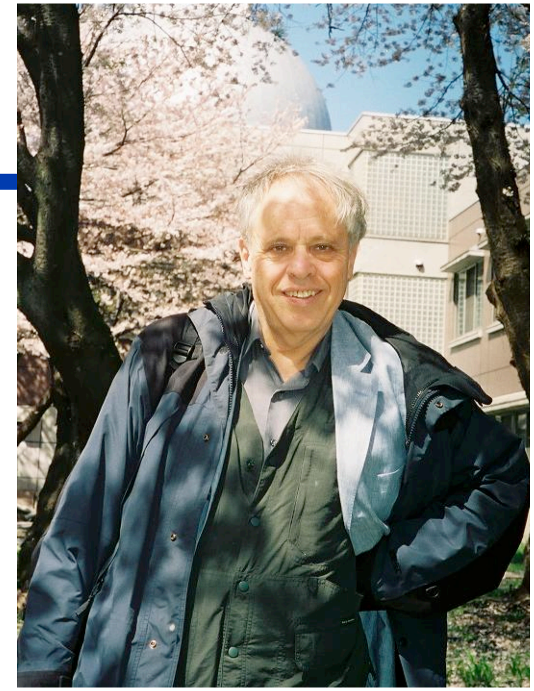


Robert Wilson & Arno Penzias
Nobel Prize (1978)

Jim Peebles

Bernie Burke

Early Exposure



Nature 215, 1155 - 1156 (09 September 1967)

Fluctuations in the Primordial Fireball

JOSEPH SILK

Harvard College Observatory, Cambridge, Massachusetts.

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible

Cosmic Microwave Background Radiation Relic Radiation from Big Bang

1970's Began Obs. Program

CMB produces $E(\nu,\theta,\vec{t})$ at observer

ν **Frequency Spectrum - predicted thermal=blackbody**

θ **Angular distribution - map the sky - seeds of structu**

$\longrightarrow$ **Polarization - linear expected - Martin Rees 1968**

t Statistics - Bose-Einstein / Planckian, 1+Z dependenc

SZ effect - Clusters scatter some CMB - faint shadow
1974 Rich Muller and I observe at Goldstone DSN wit
maser receiver

Rashid Sunyaev

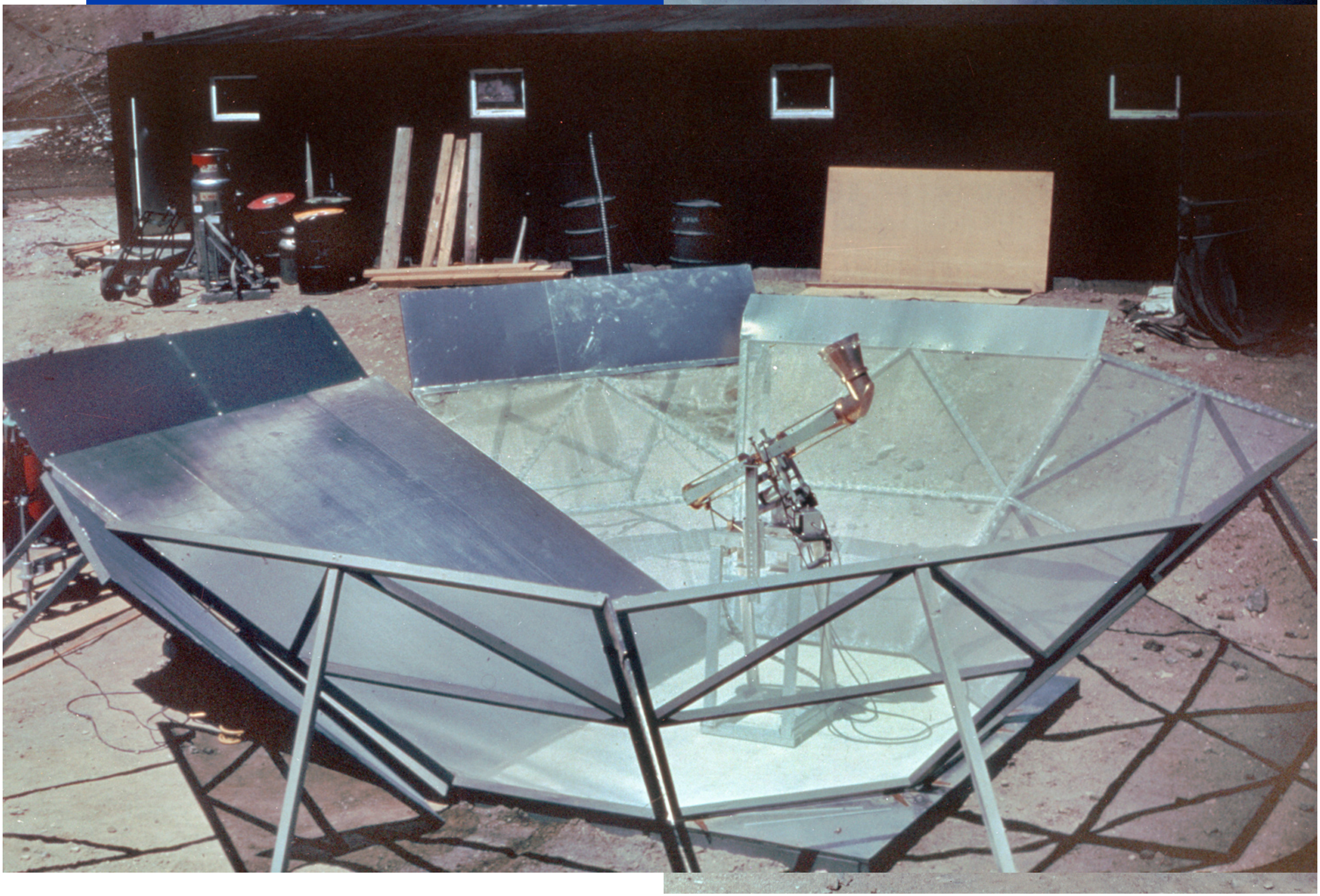
Y. B. Zel'dovich

1972 paper

CMB @ Berkeley

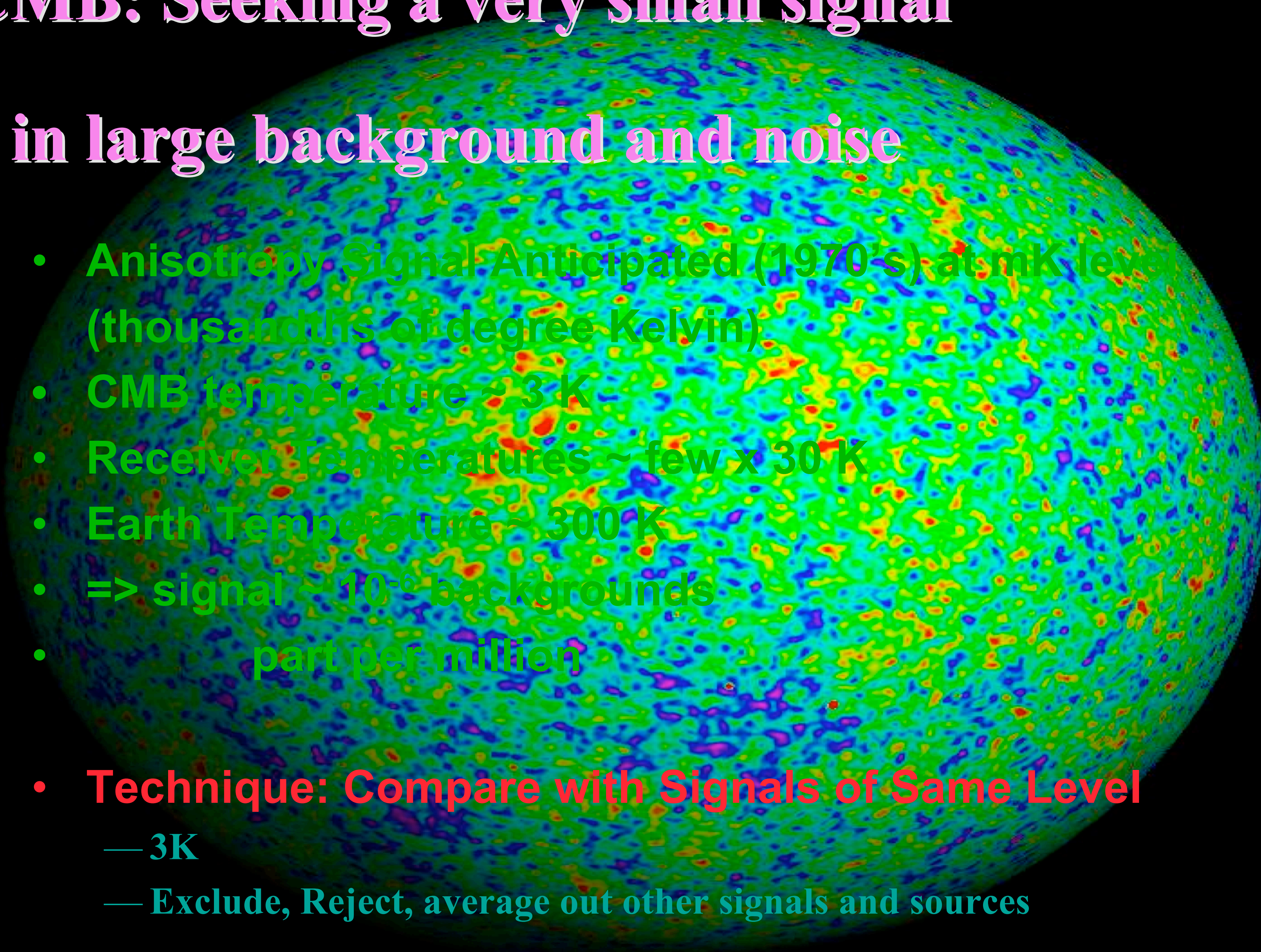
- Joe Silk - theory - 1967, start @ UCB in 1970
- Paul Richards took on graduate students John Mather & Dave Woody - beginning 1974
  - Develops bolometers and Michelson Interferometer
  - precursor for COBE FIRAS
- Anisotropy & Polarization - beginning 1974
  - Ground-based, aircraft, balloons, and spacecraft
- Berkeley-Italy spectrum collaboration joined by Haverford College - 1977
  - Long Wavelength coherent receiver observations
  - Develop reference loads
- Competition - with head start
  - Rainer Weiss & Dirk Muehlner @ MIT
  - Dave Wilkinson @ Princeton - theory & motivation Jim Peebles

Dave Wilkinson's



CMB: Seeking a very small signal

in large background and noise



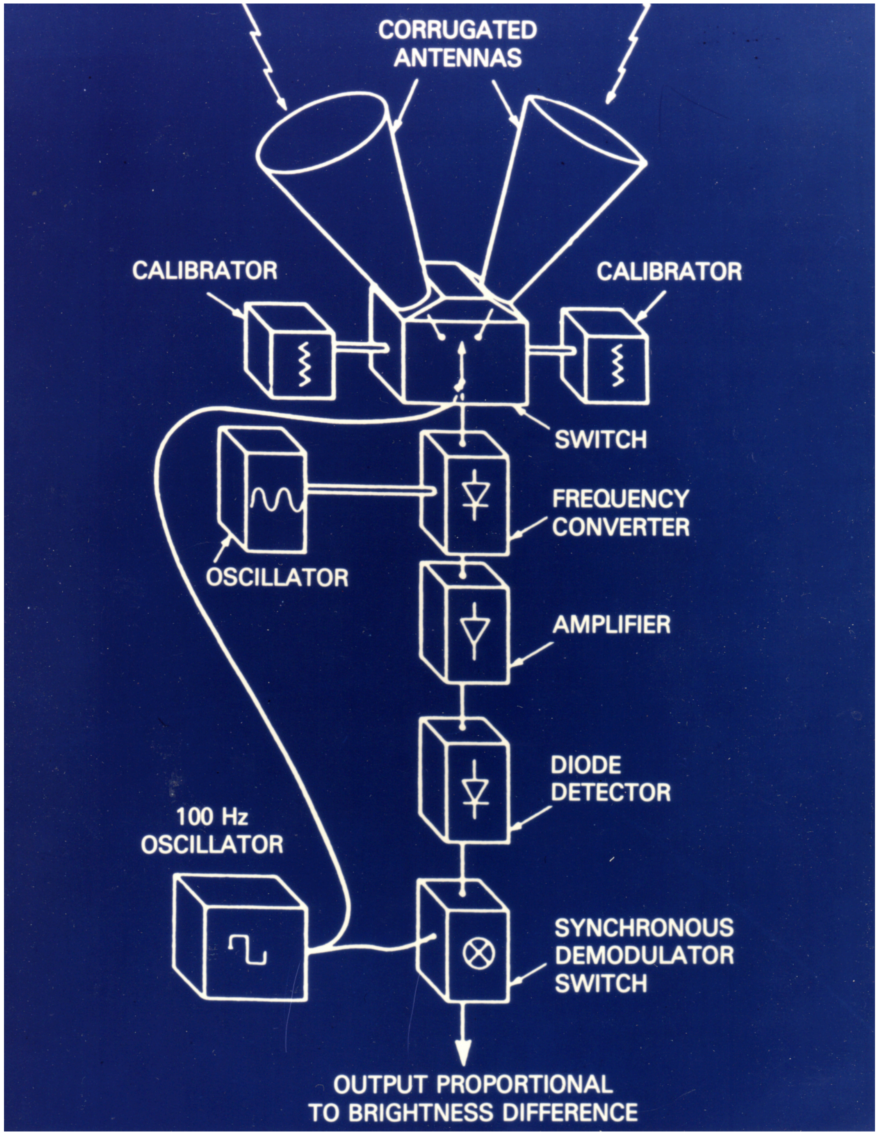
- Anisotropy Signal Anticipated (1970's) at mK level (thousandths of degree Kelvin)
- CMB temperature ~ 3 K
- Receiver Temperatures ~ few x 30 K
- Earth Temperature ~ 300 K
- => signal ~ 10^{-6} backgrounds
- part per million

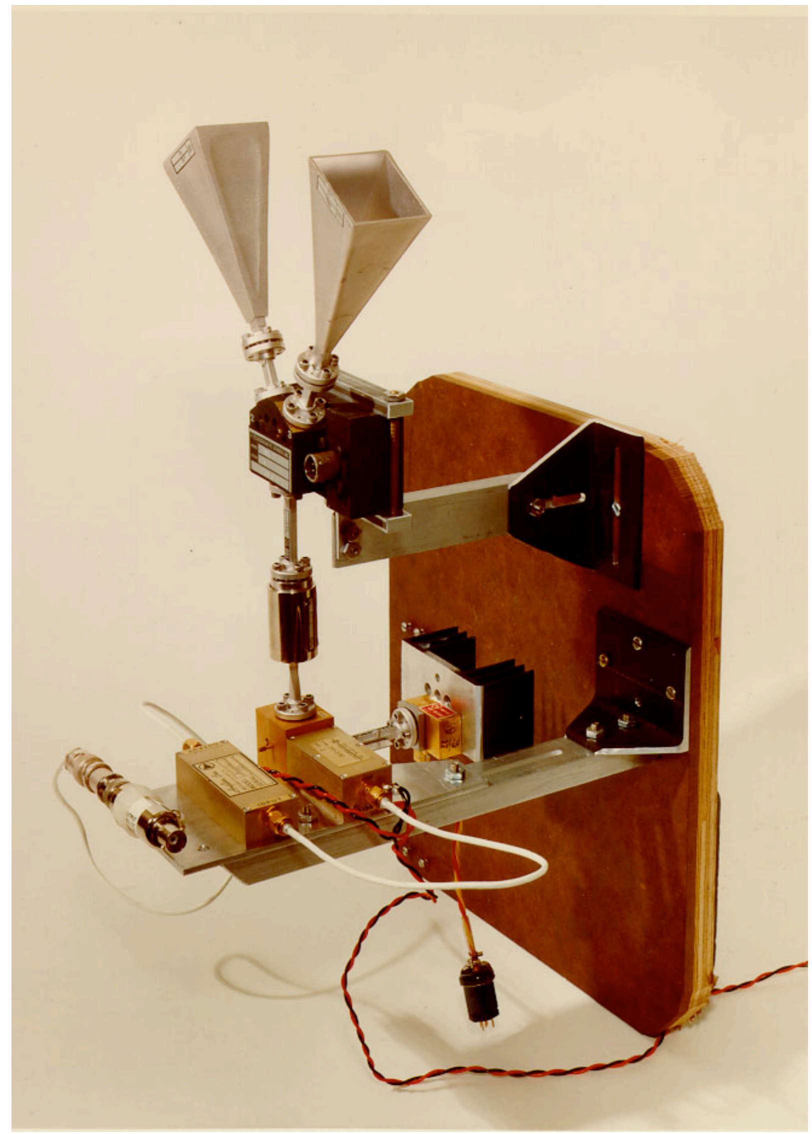
- Technique: Compare with Signals of Same Level
  - 3K
  - Exclude, Reject, average out other signals and sources

DMR

Differential Microwave Radiometer

refinement of Dicke radiometer

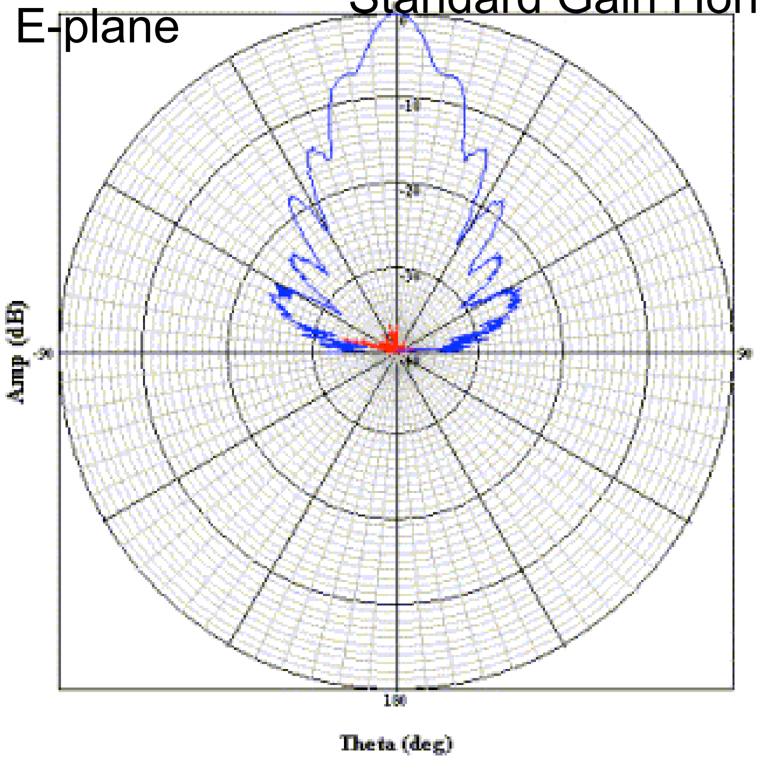




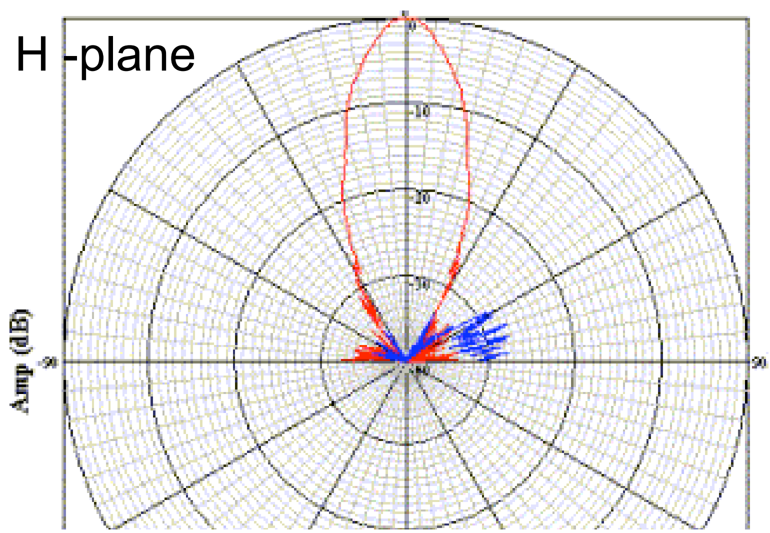
Corrugated Horn Antennas

Standard Gain Horn

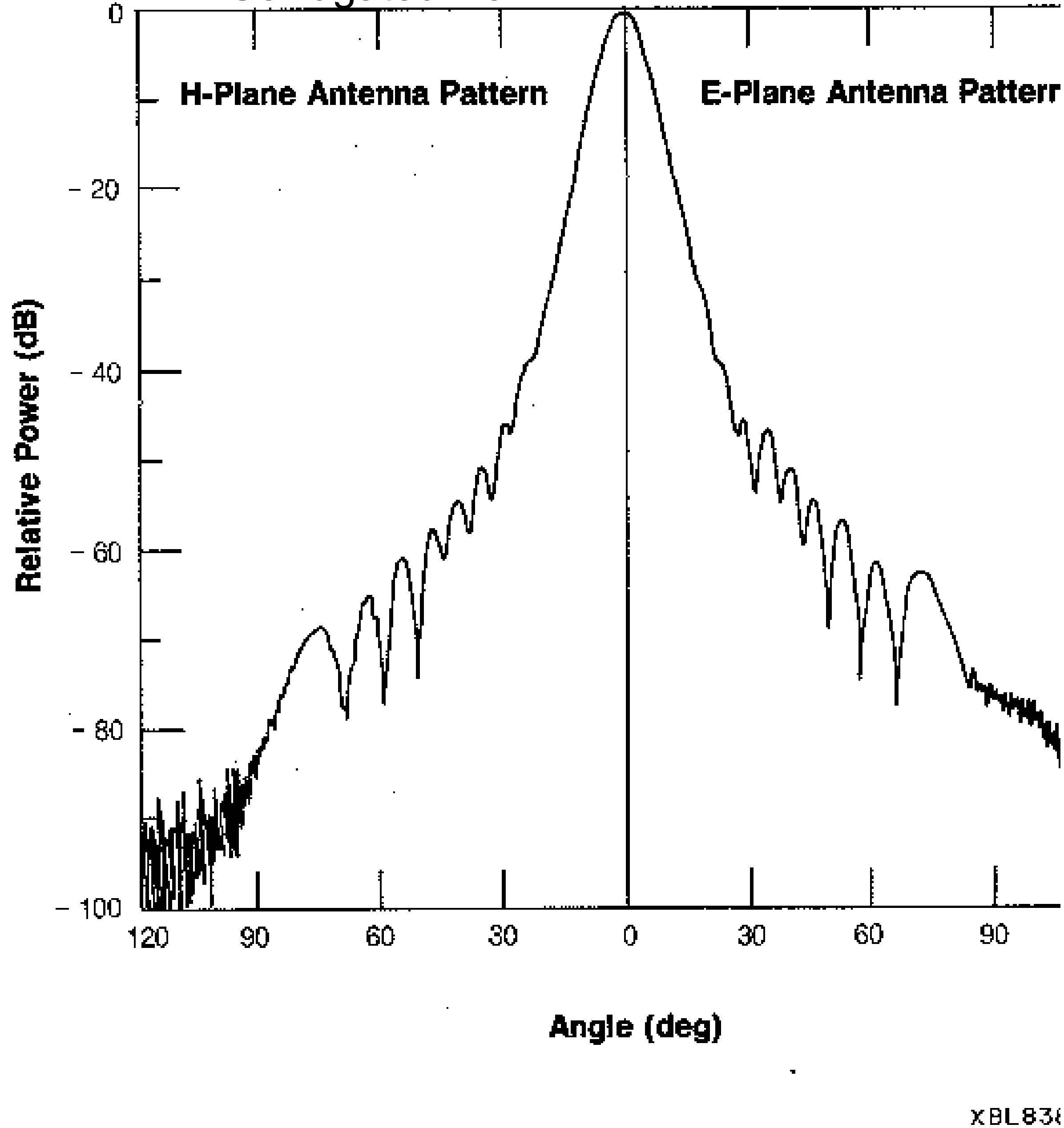
E-plane



H -plane



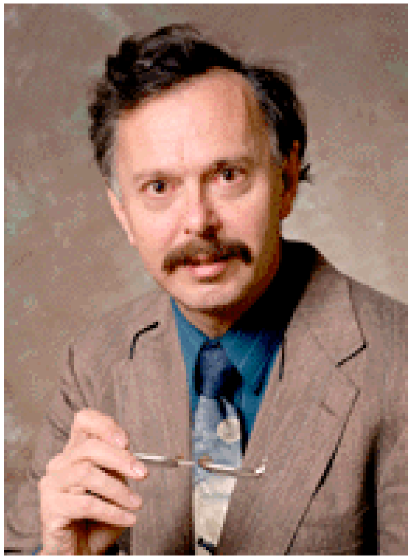
Corrugated Horn



Radiometer system to map the cosmic background radiation

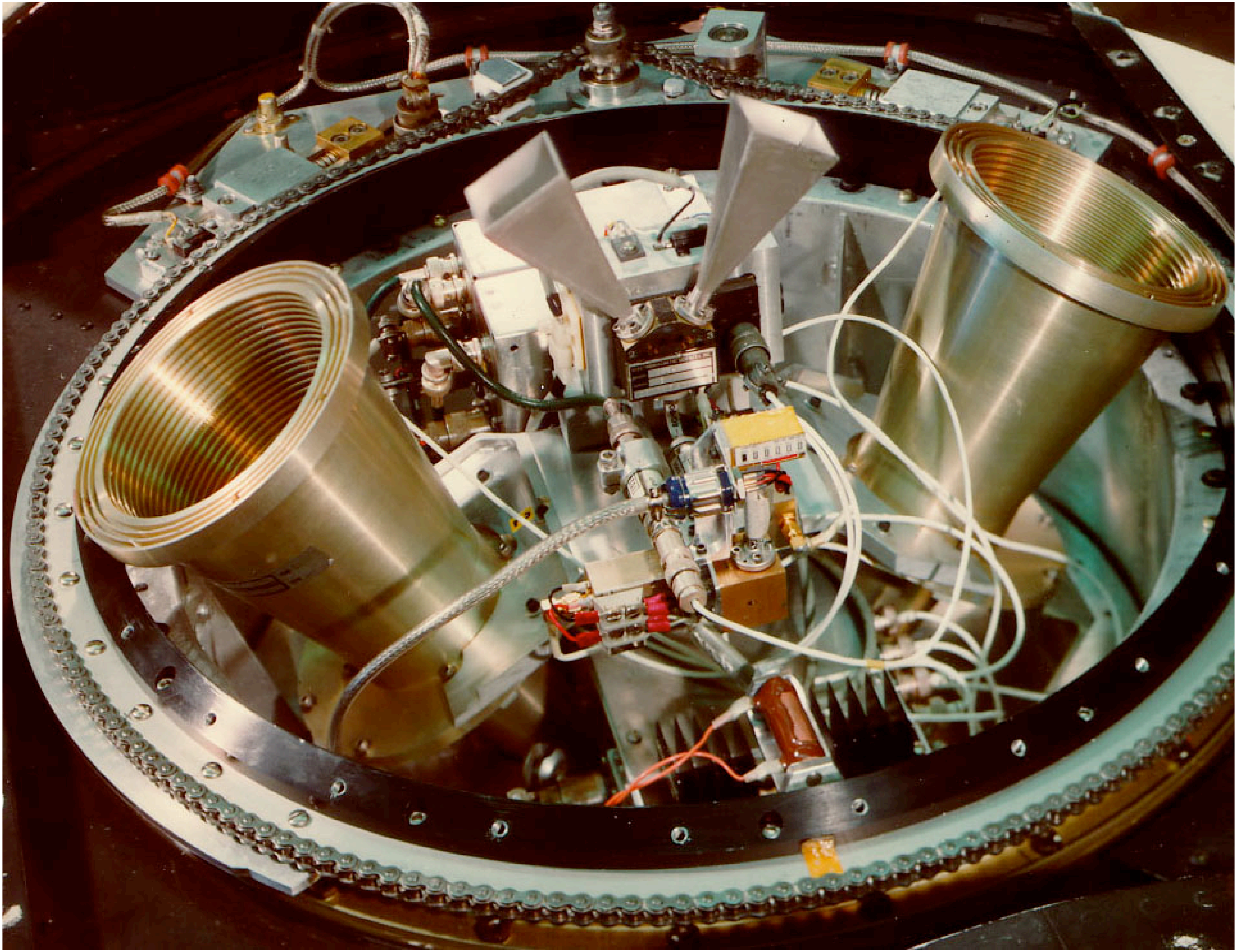
Rev. Sci. Instrum. 49, 440 (1978).

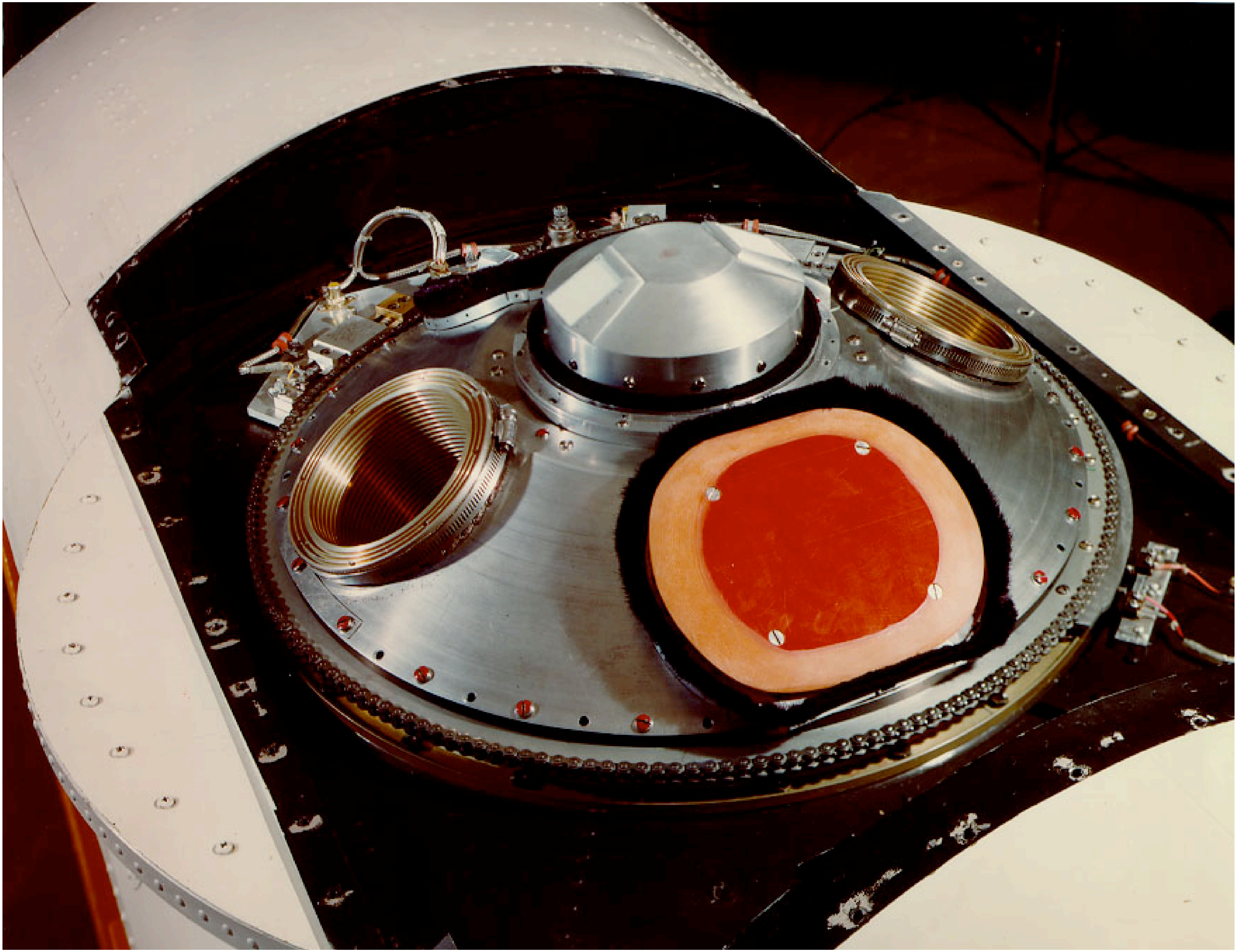
Marc V. Gorenstein, - Ph.D. on project
Richard A. Muller,
George F. Smoot, &
J. Anthony Tyson

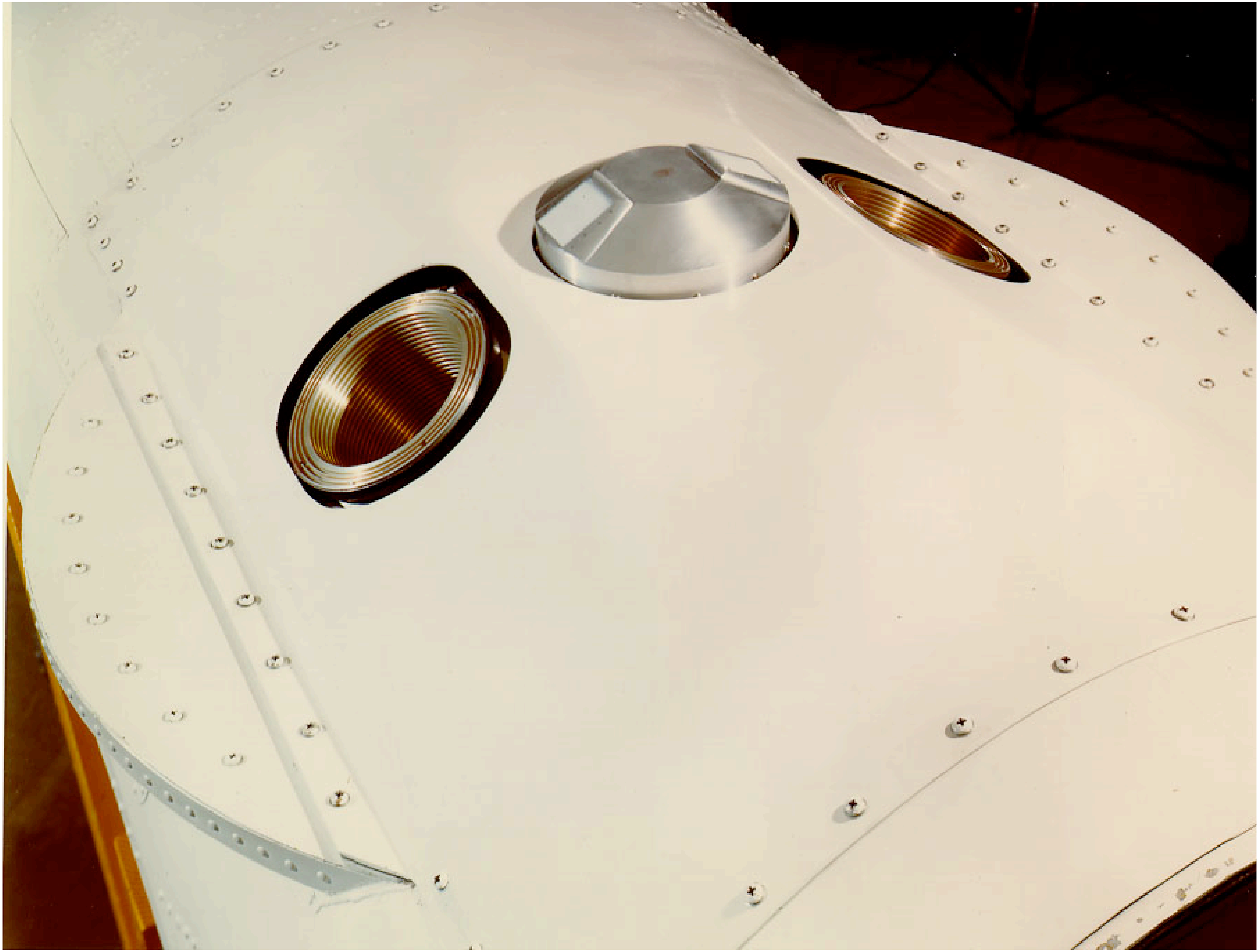


Technical and Engineering
- Jon Aymon - software
- Hal Dougherty - mechanical
- John Gibson - electronics
- Robbie Smits - rotation system
- John Yamada - tech. assembly

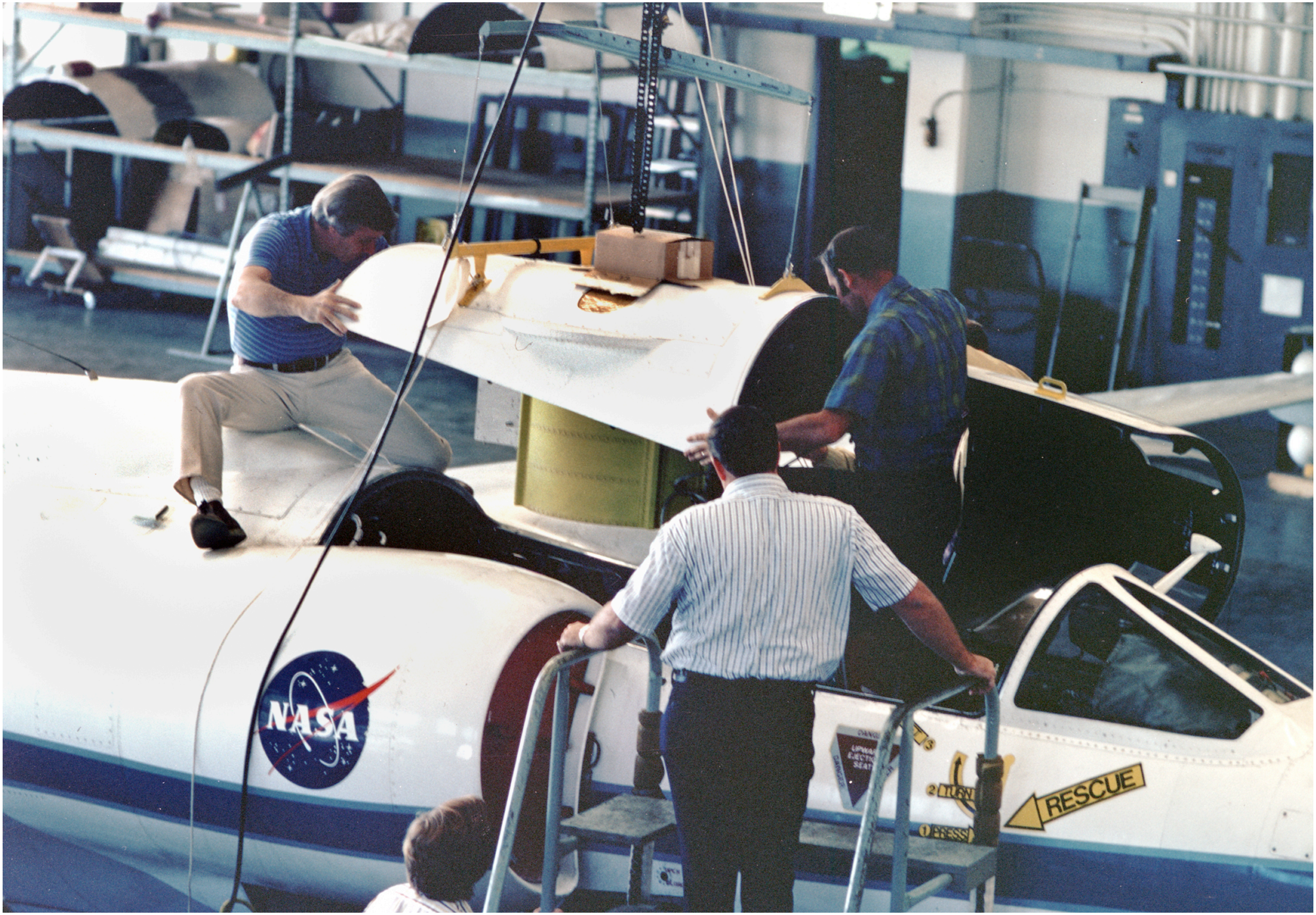
Luis Alvarez



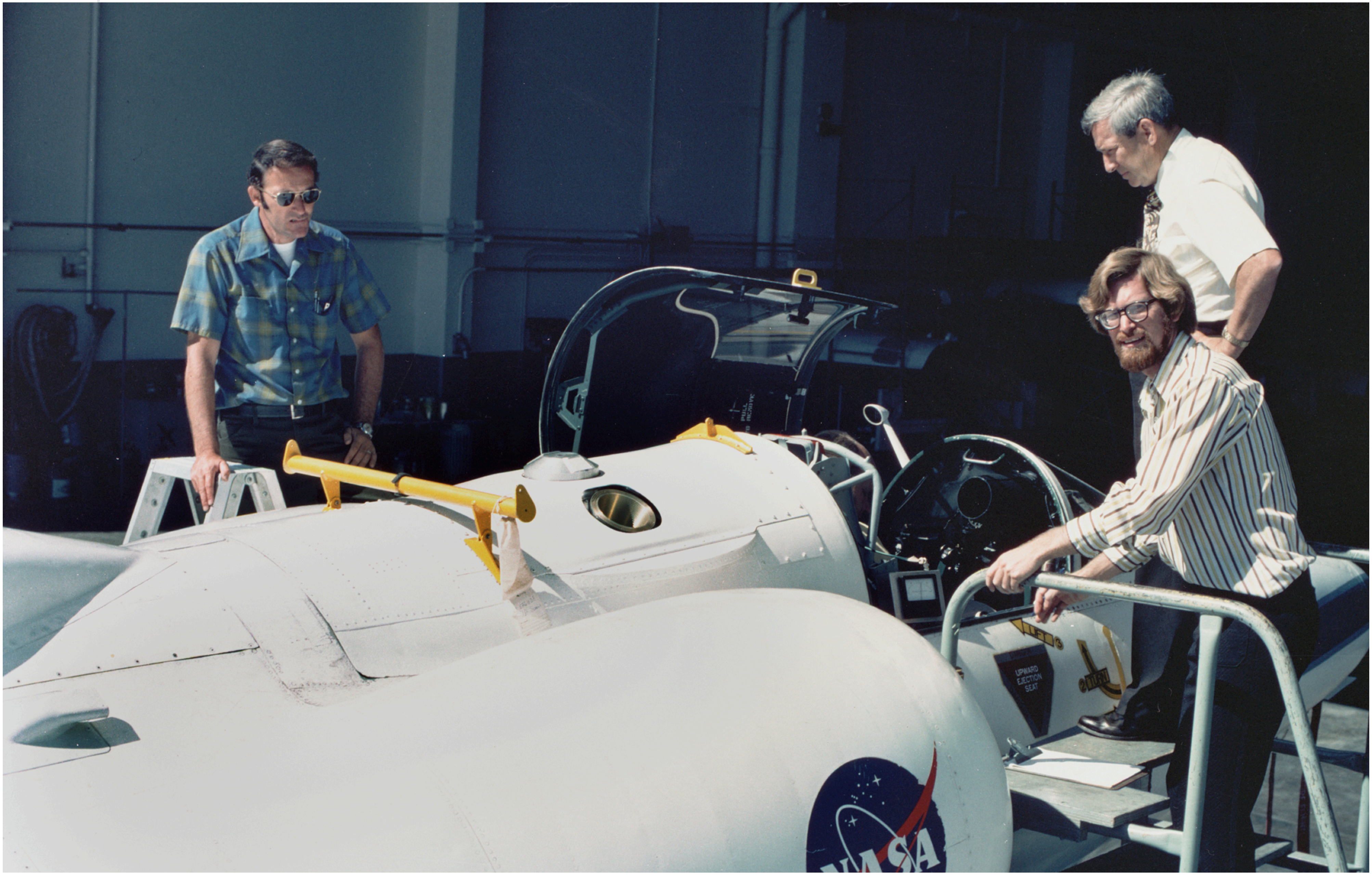


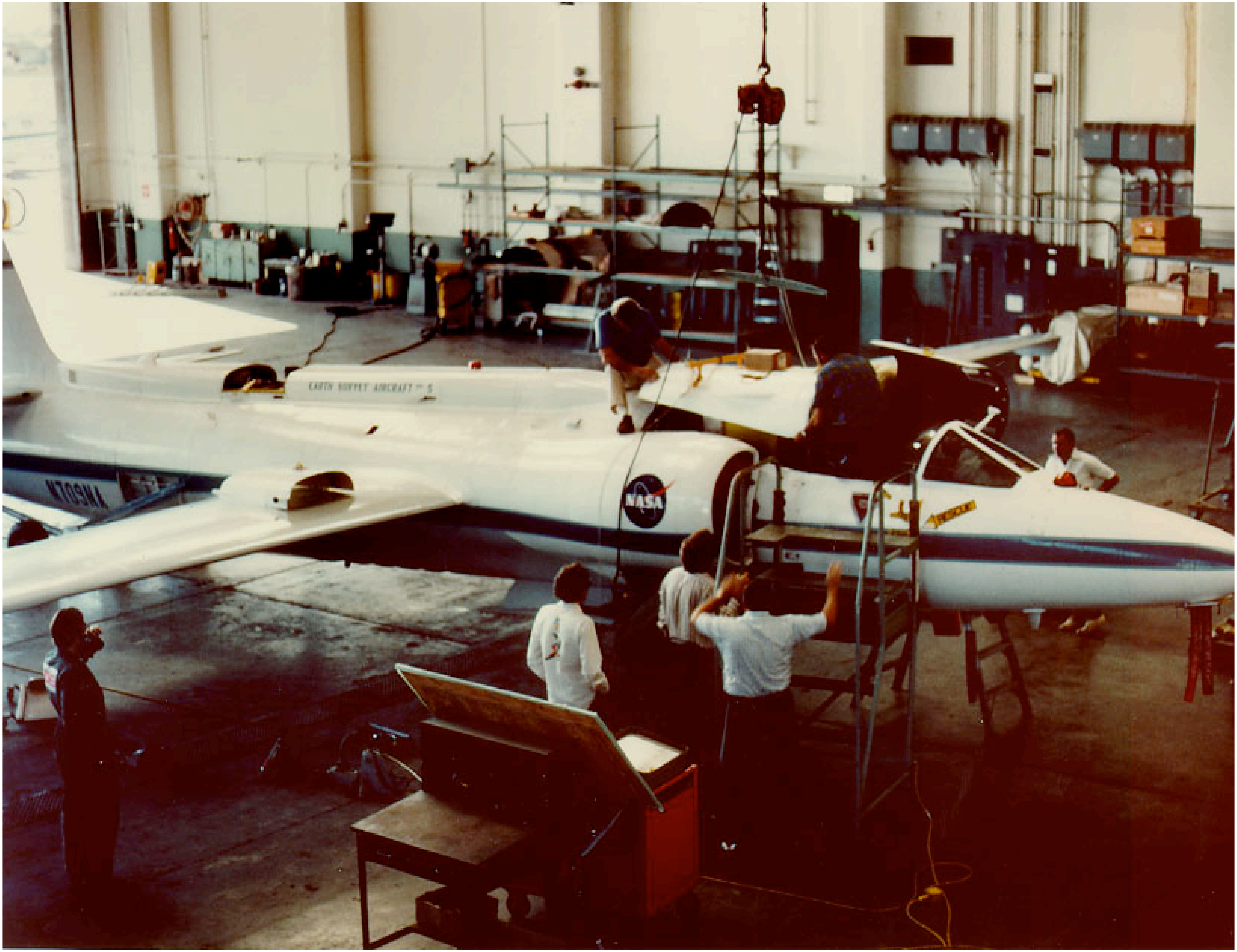


Instrument into NASA craft



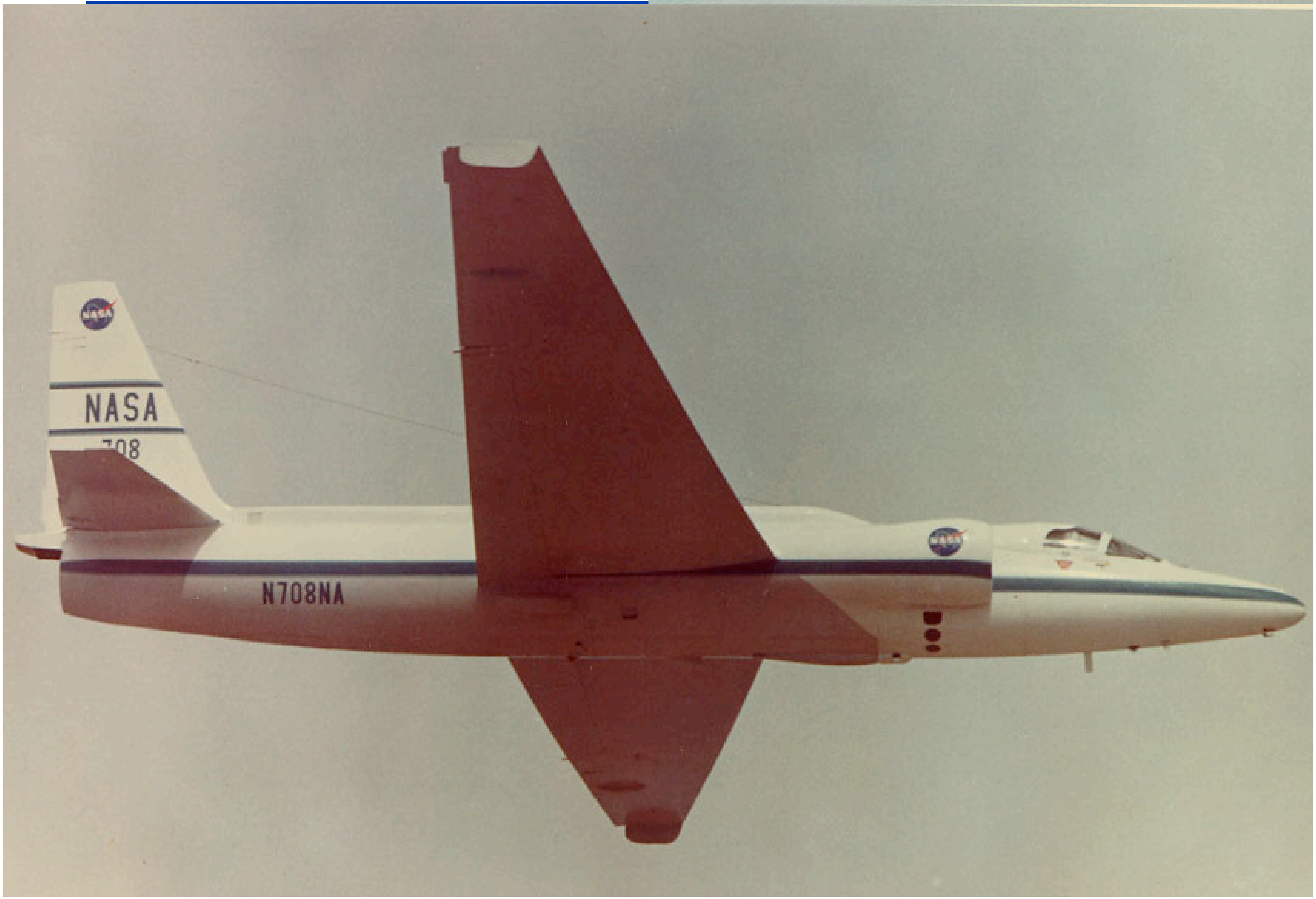
Scientists from DOE Lab puts instrument on NASA Platform

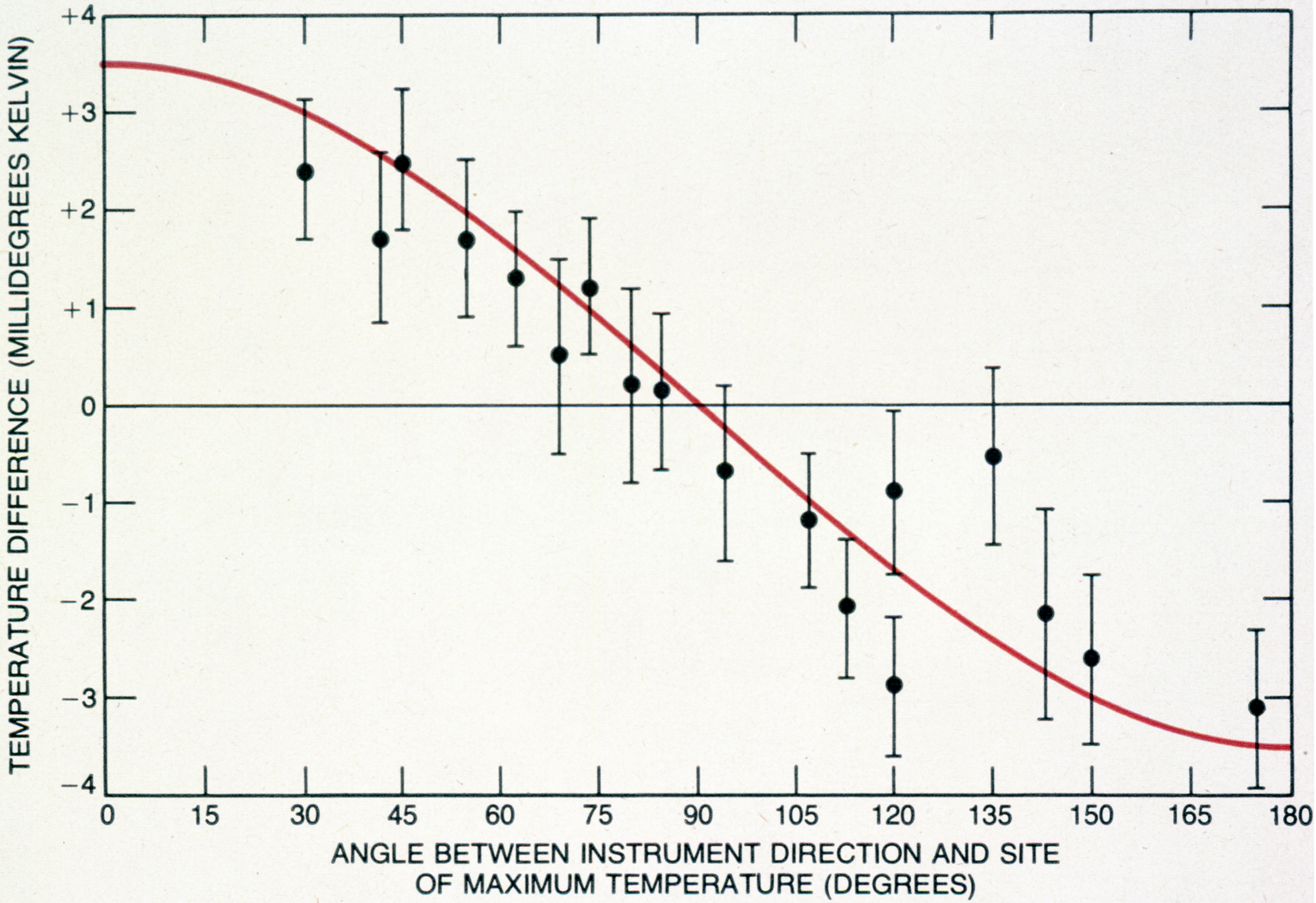



NASA


NASA
708
66681
Marc Gorenstein

U2 can find





COSINE CURVE provides the best fit for the data (averaged into 18 points) taken by the author and his colleagues in the new aether-drift experiment. The horizontal axis represents the angle made by a line connecting the two horn antennas and the direction of maximum temperature in Leo. The cosine curve is temperature distribution to be expected in the cosmic background radiation if the solar system's peculiar velocity toward Leo is 400 kilometers per second.

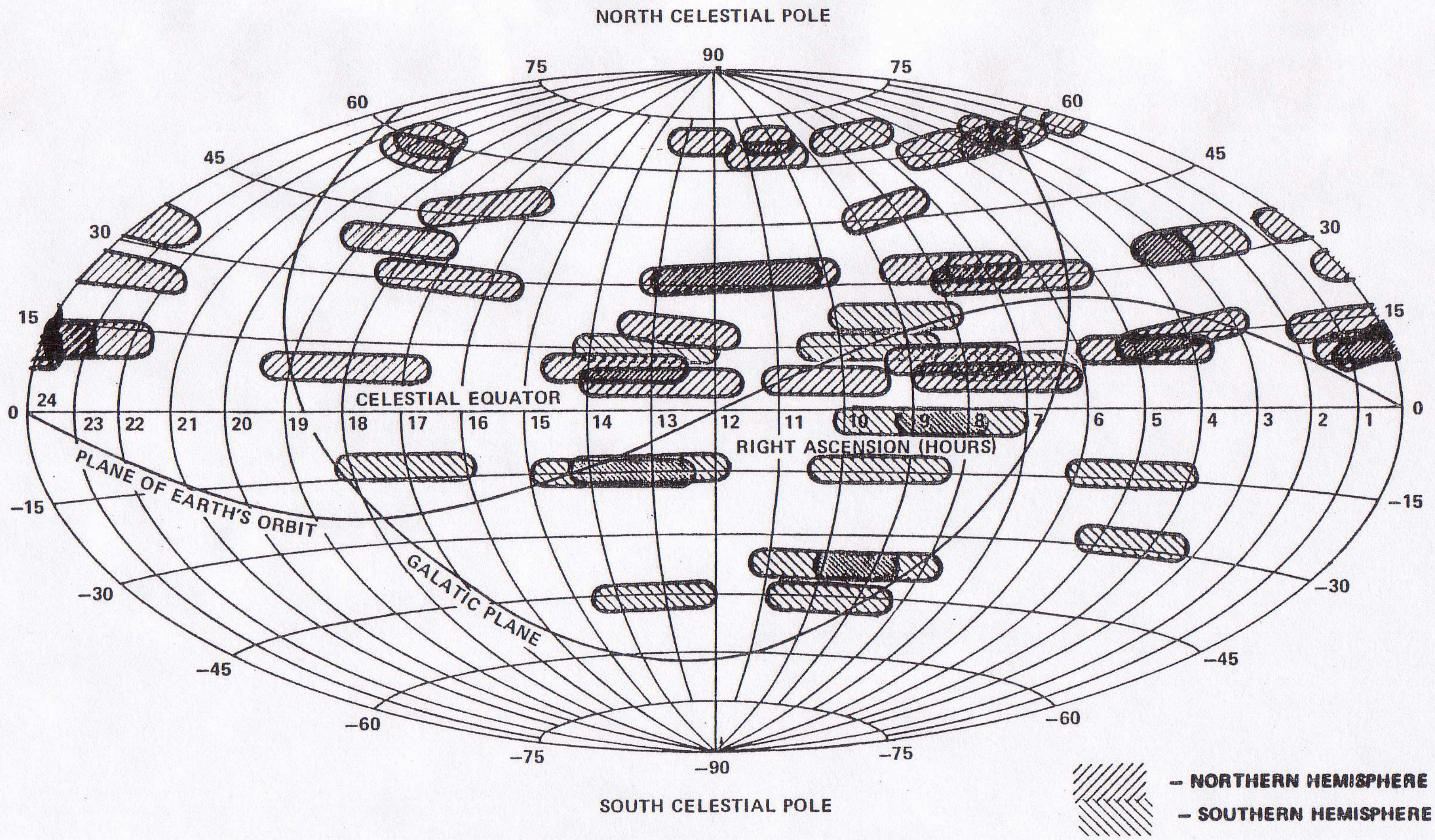
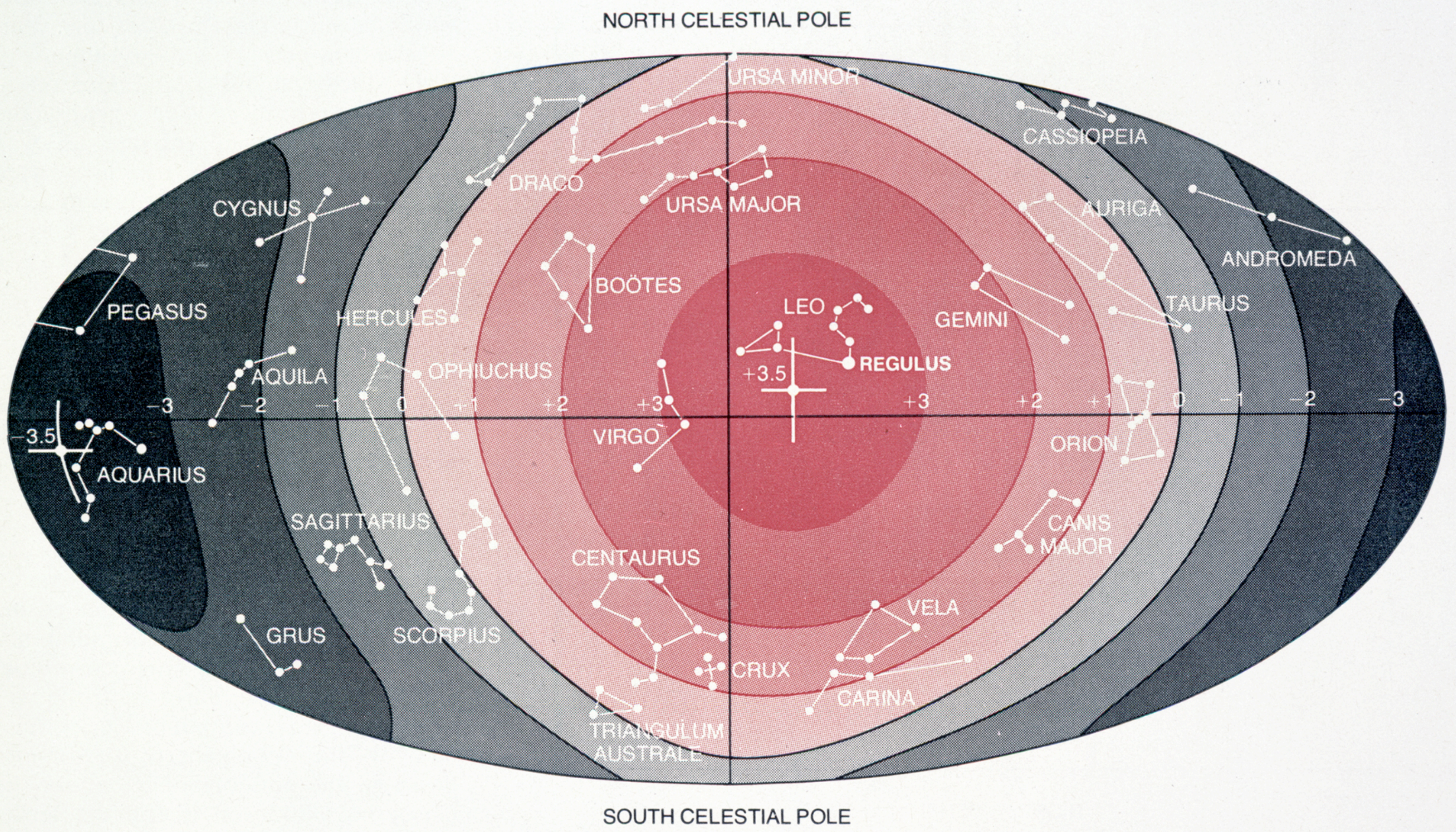


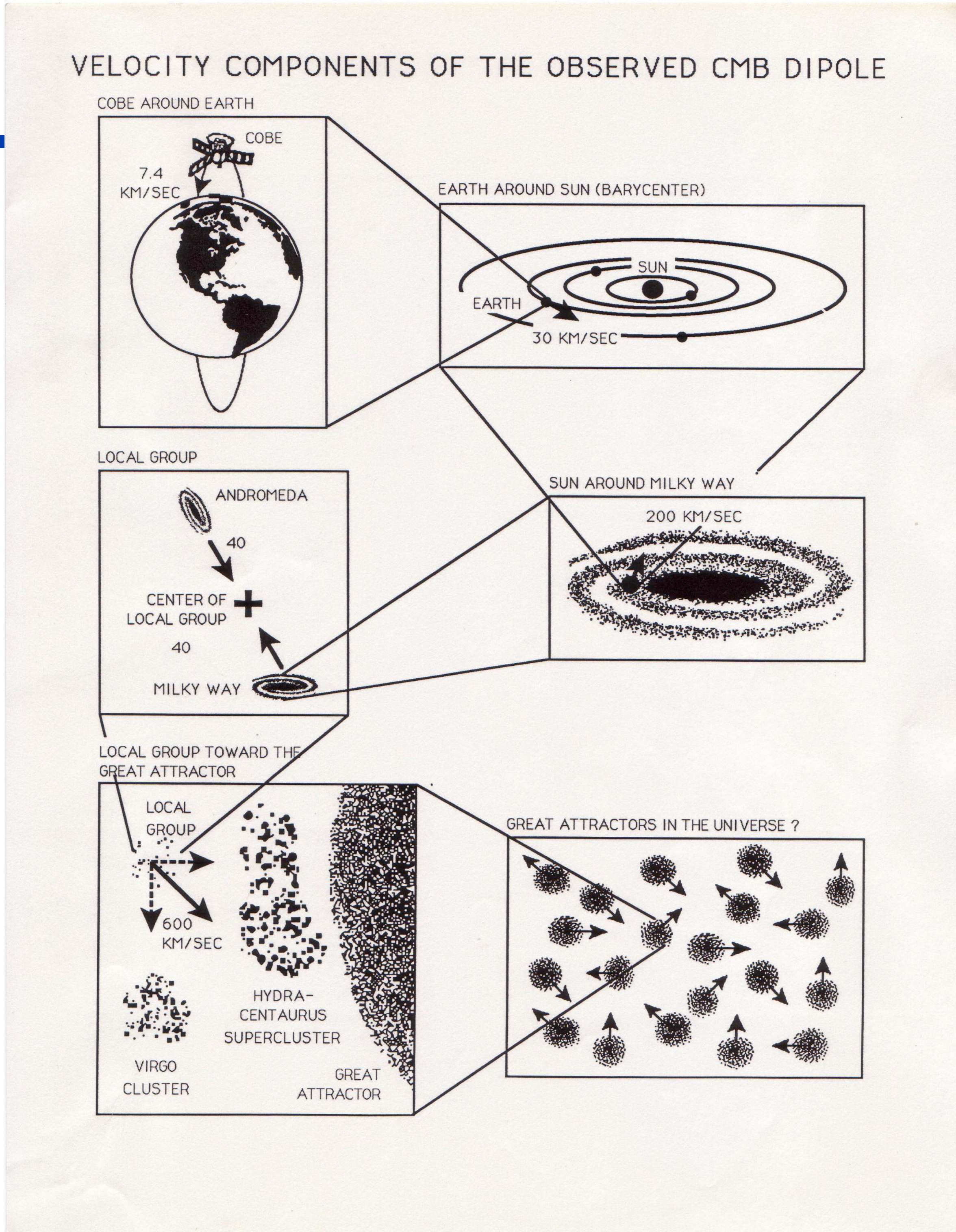
Figure 1. Plot of Sky Coverage in Celestial Coordinates. Sky coverage for the northern flights from NASA Ames in California and southern flights from Lima, Peru is indicated by the shaded regions. The width of each region is set by the 7° antenna beam widths, and the length is set by the rotation of the earth and the motion of the U2 back and forth along its flight path. The galactic and ecliptic planes are shown for reference.

Dipole Anisotropy A = 3.5 mK

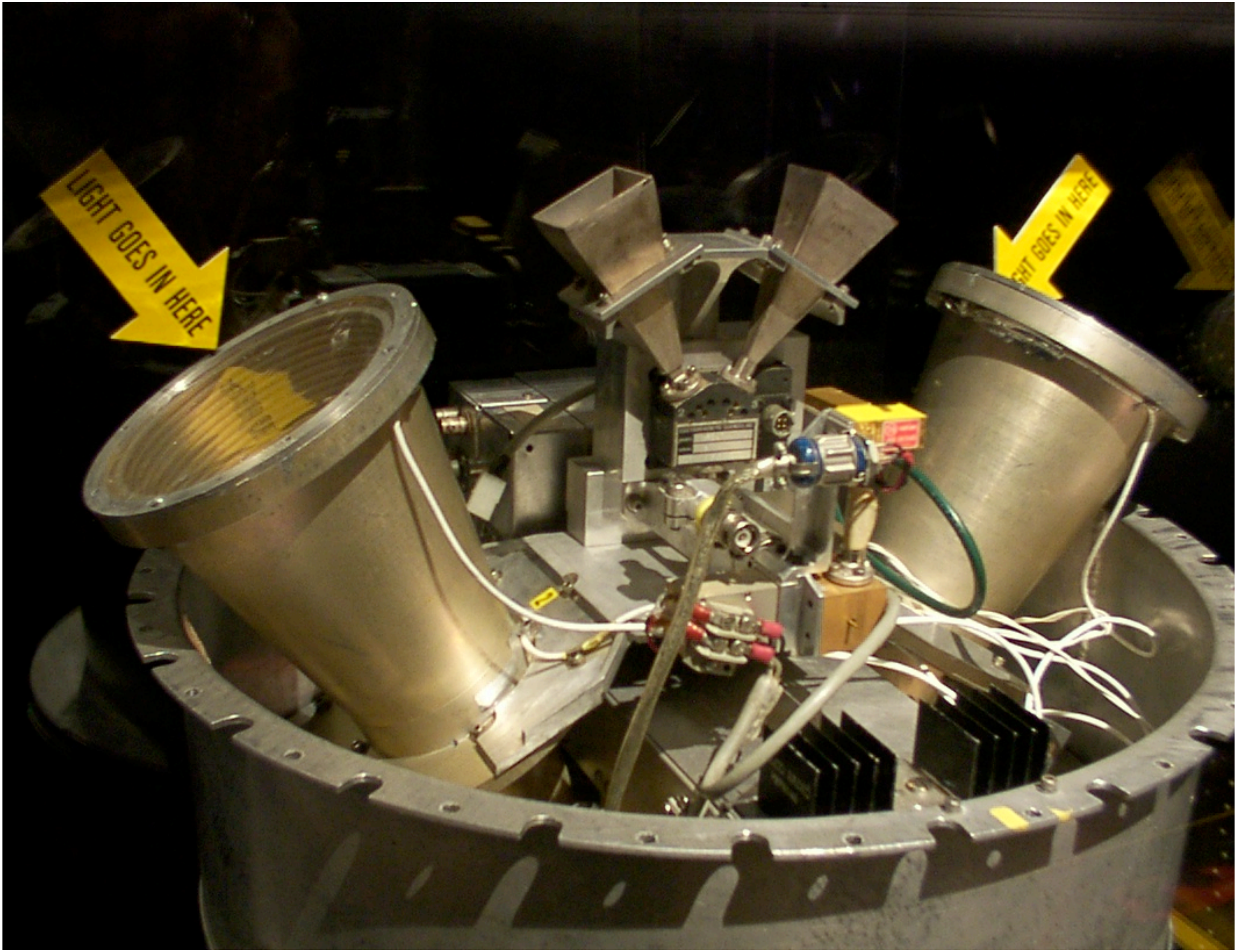


ANISOTROPY OF THE BACKGROUND RADIATION, as deduced from the U-2 survey, is plotted on the celestial sphere in contours of one millidegree K. The "hottest" spot, indicating the direc-

(±.5 hour) and latitude six degrees (±10 degrees). The "coldest" spot, the direction in which the radiation is most "reddened" by the earth's relative motion away from the incoming photons, lies 180 degrees

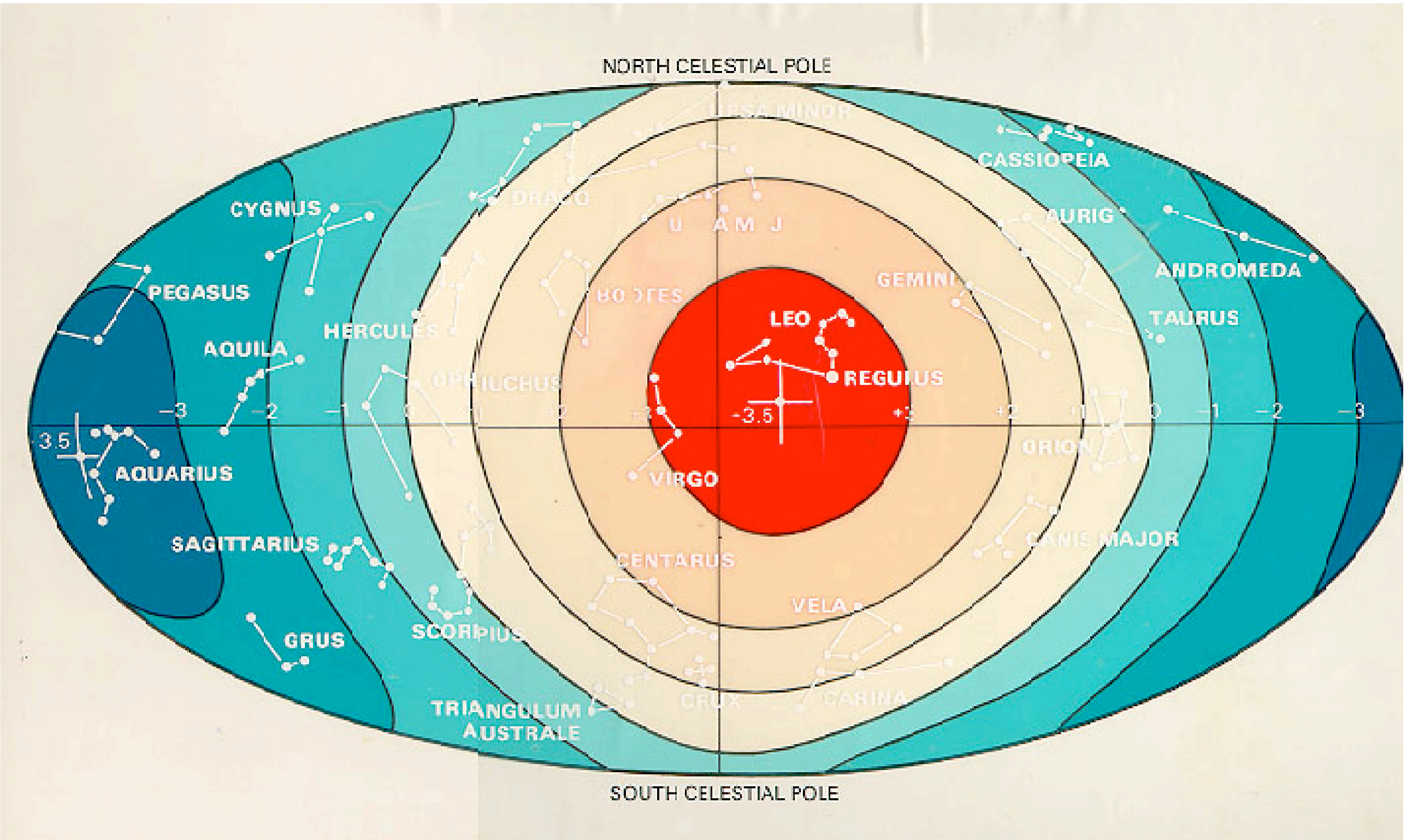


VELOCITY COMPONENTS OF THE OBSERVED CMB DIPOLE
COBE AROUND EARTH
COBE
7.4
KM/SEC
EARTH AROUND SUN (BARYCENTER)
SUN
EARTH
30 KM/SEC
LOCAL GROUP
ANDROMEDA
40
CENTER OF
LOCAL GROUP
40
MILKY WAY
SUN AROUND MILKY WAY
200 KM/SEC
LOCAL GROUP TOWARD THE
GREAT ATTRACTOR
LOCAL
GROUP
600
KM/SEC
HYDRA-
CENTAURUS
SUPERCLUSTER
VIRGO
CLUSTER
GREAT
ATTRACTOR
GREAT ATTRACTORS IN THE UNIVERSE ?

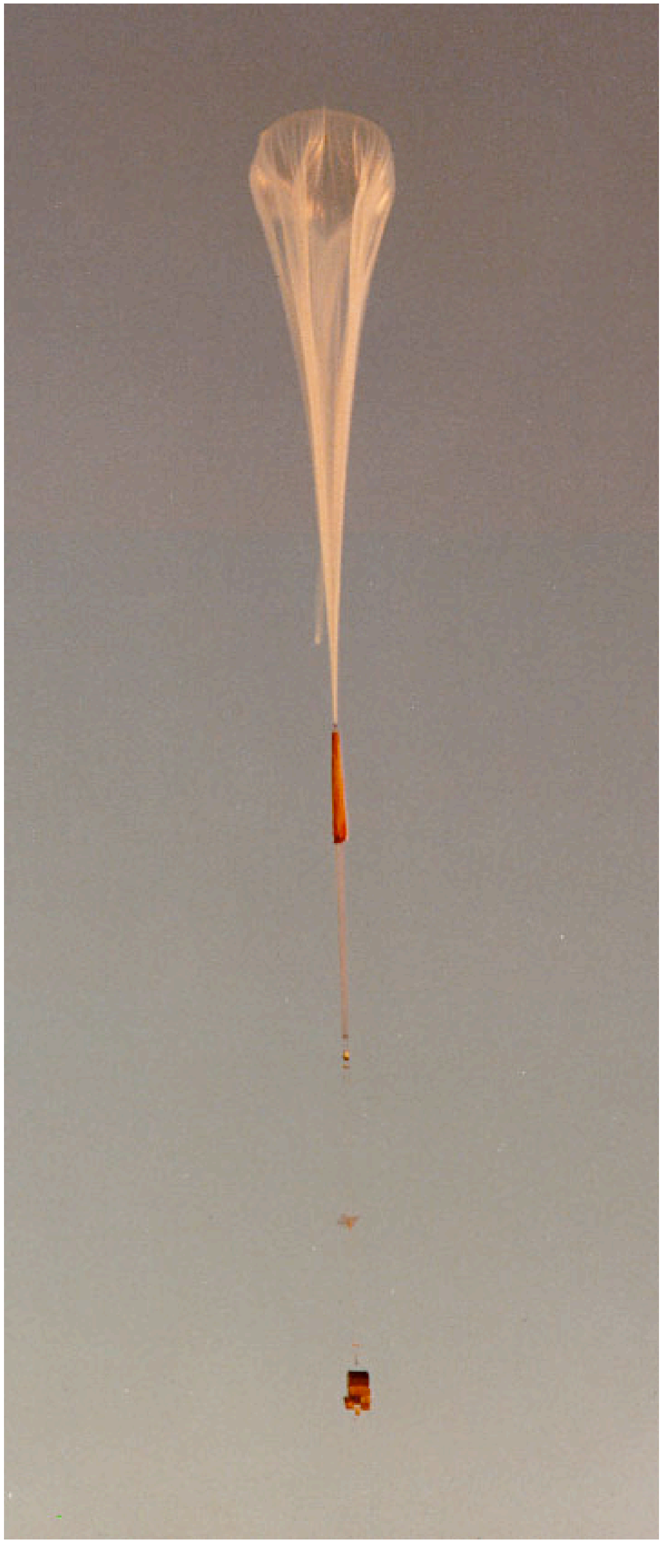

LIGHT GOES IN HERE

Best-Fitted Dipole Anisotropy

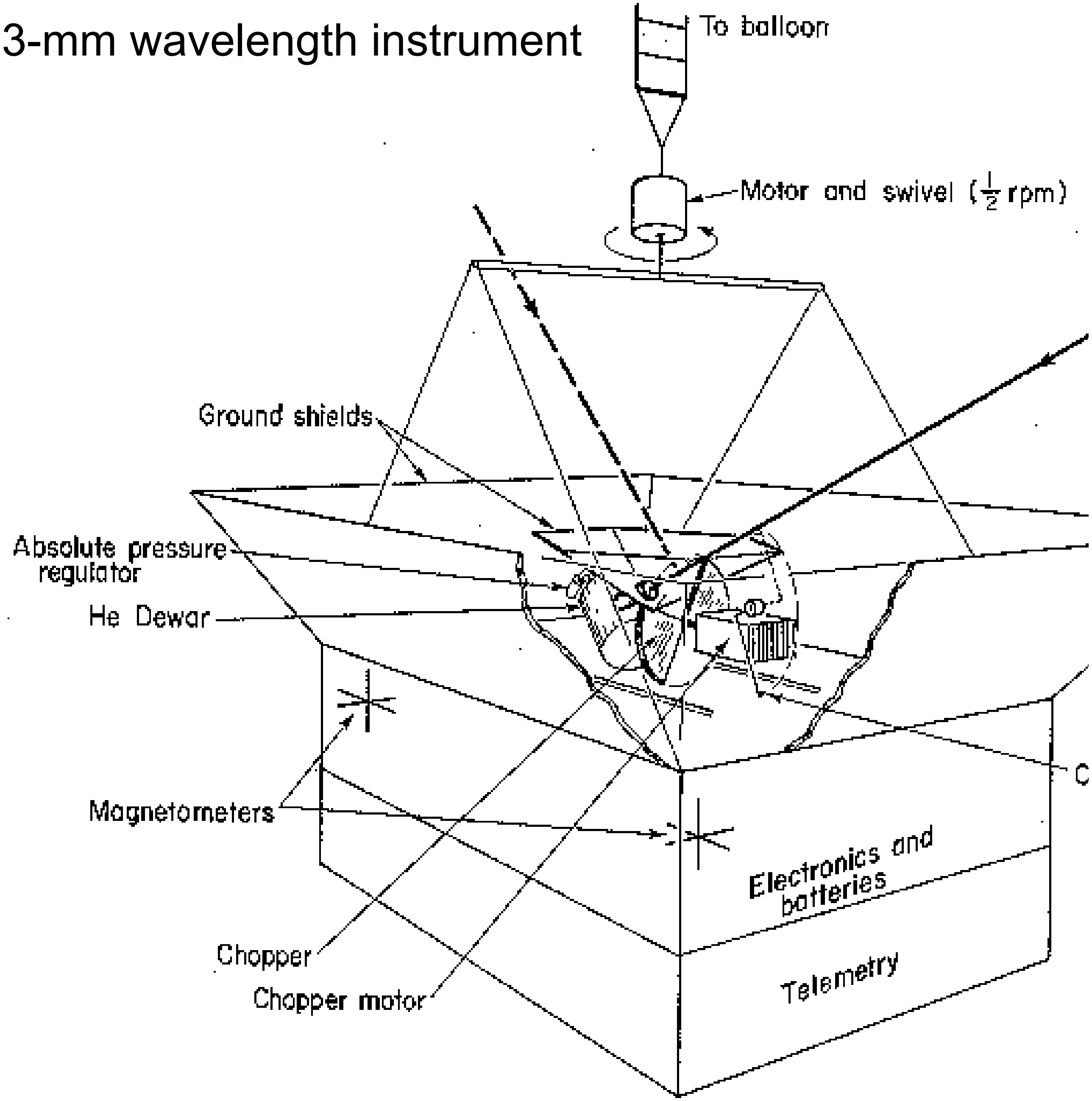
-3.5 mK to +3.5 mK

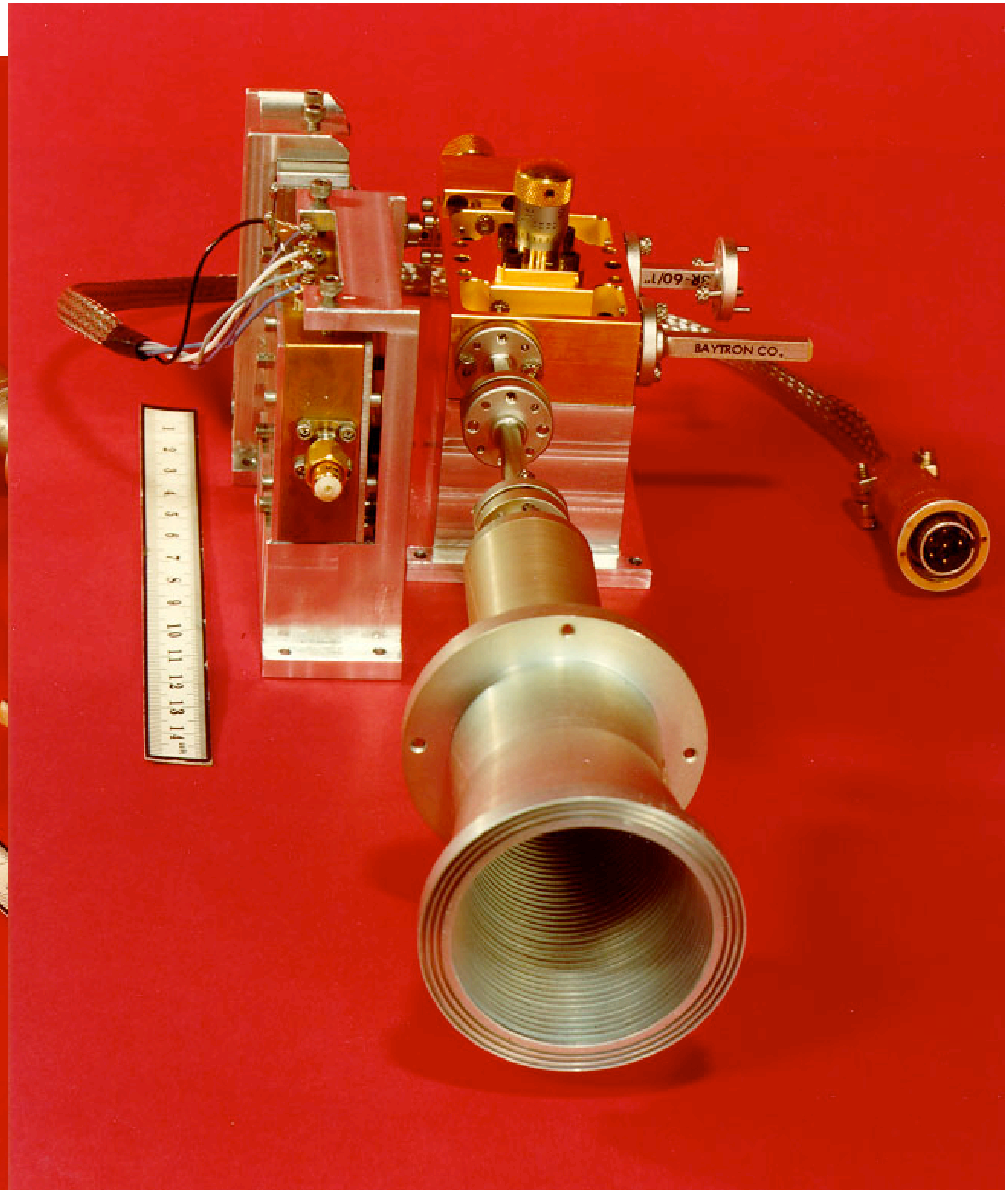


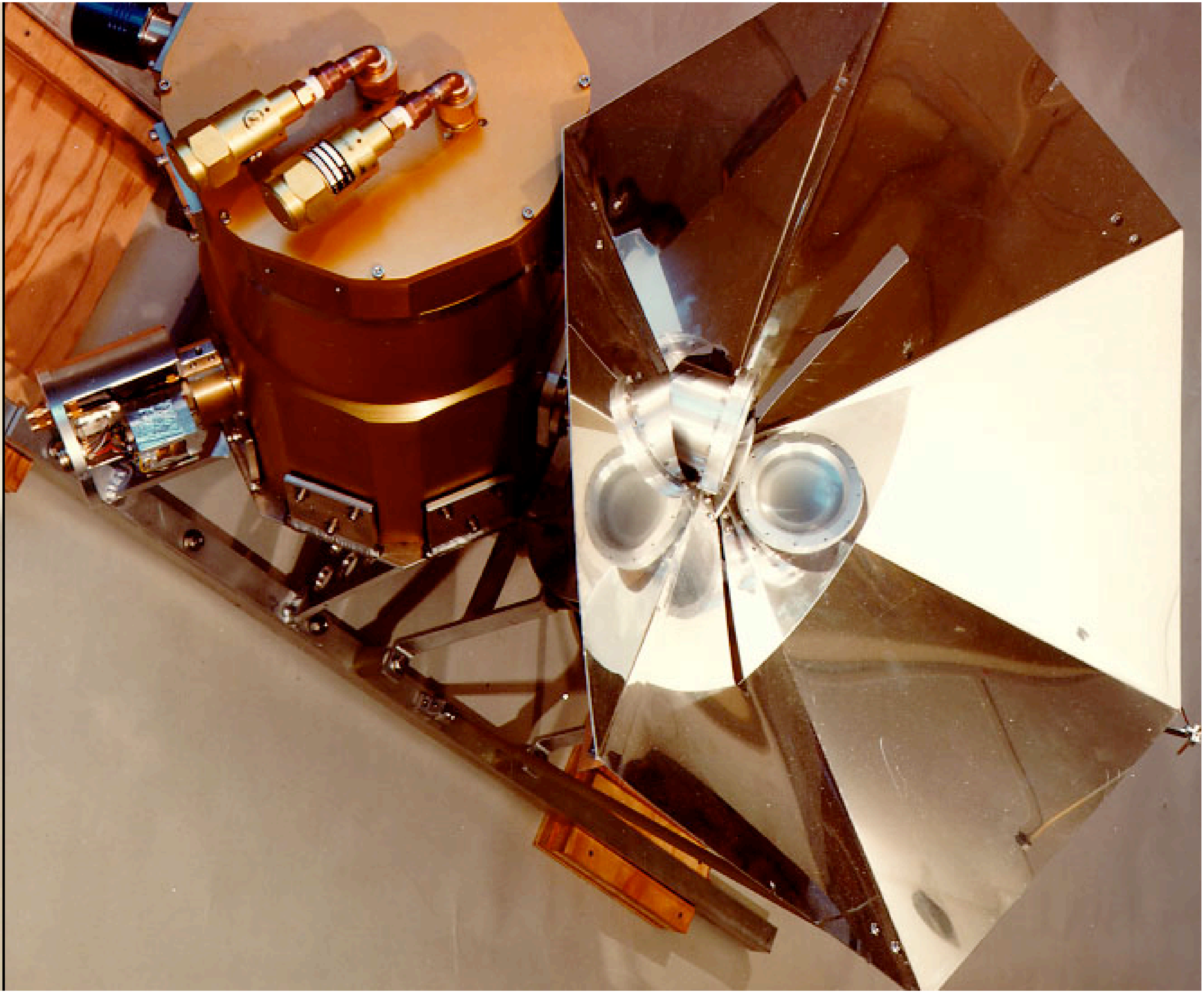
Pioneering C

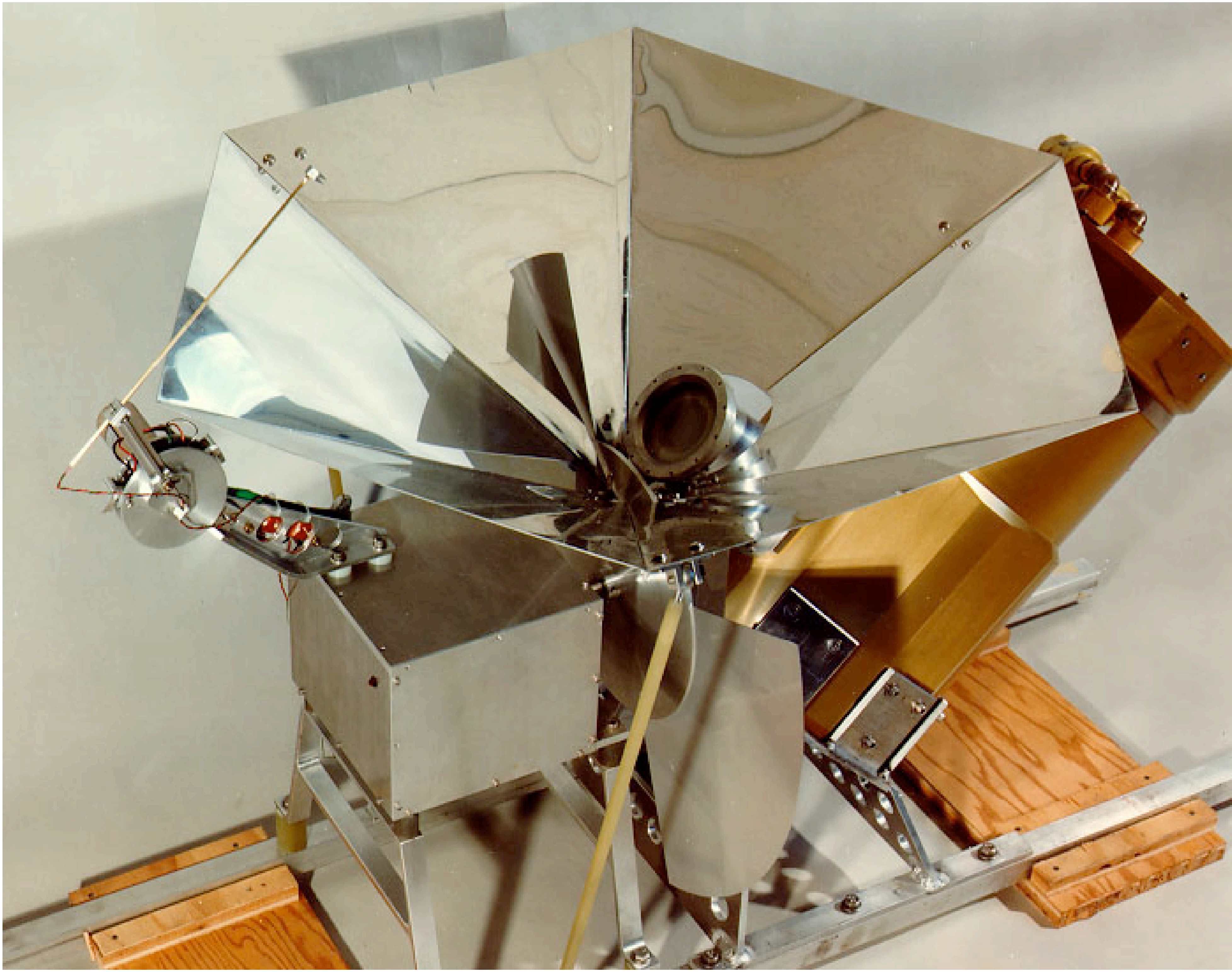


3-mm wavelength instrument



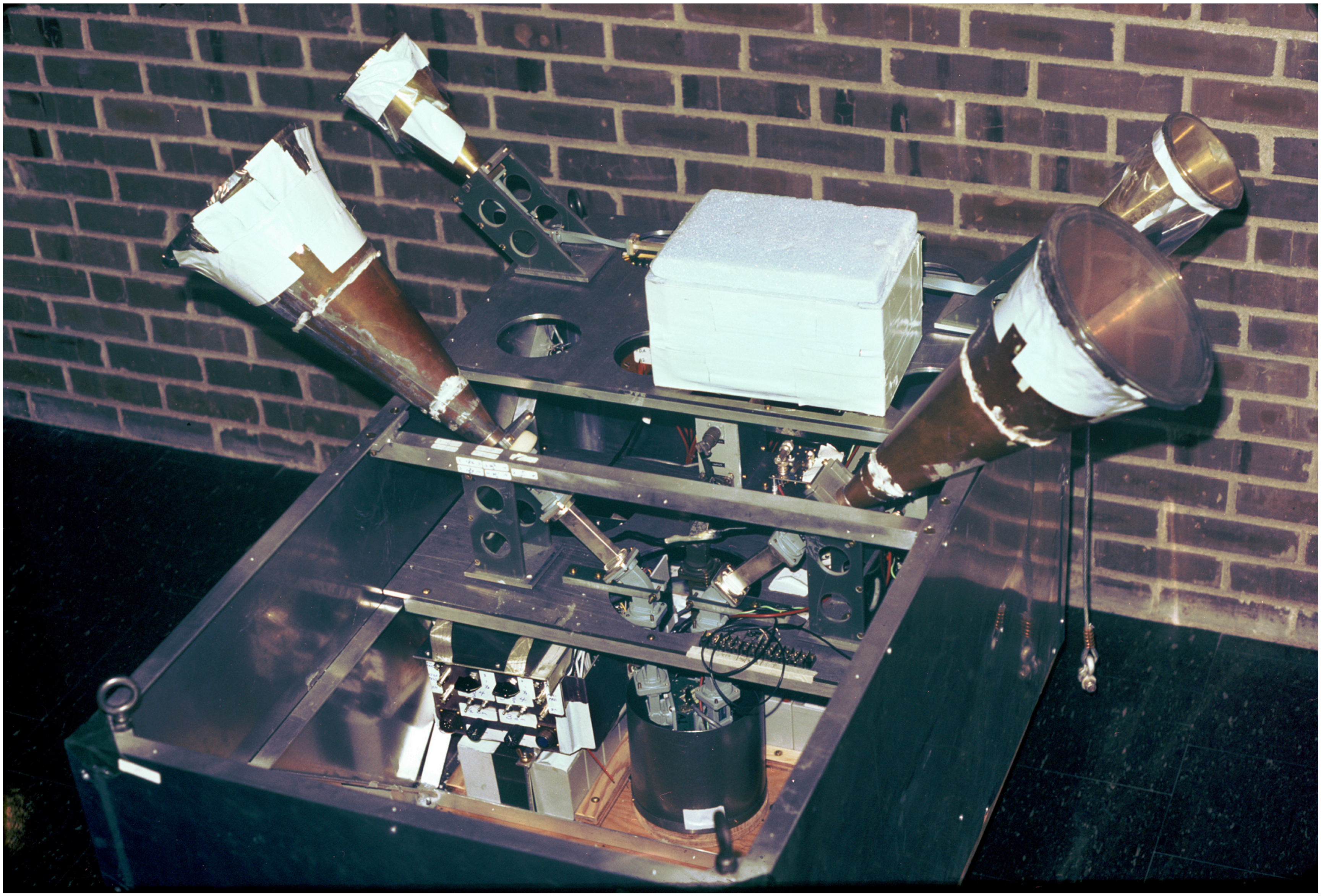

BAYTRON CO.





Princeton large-angular scale anisotropy

same epoch as Berkeley 3-mm



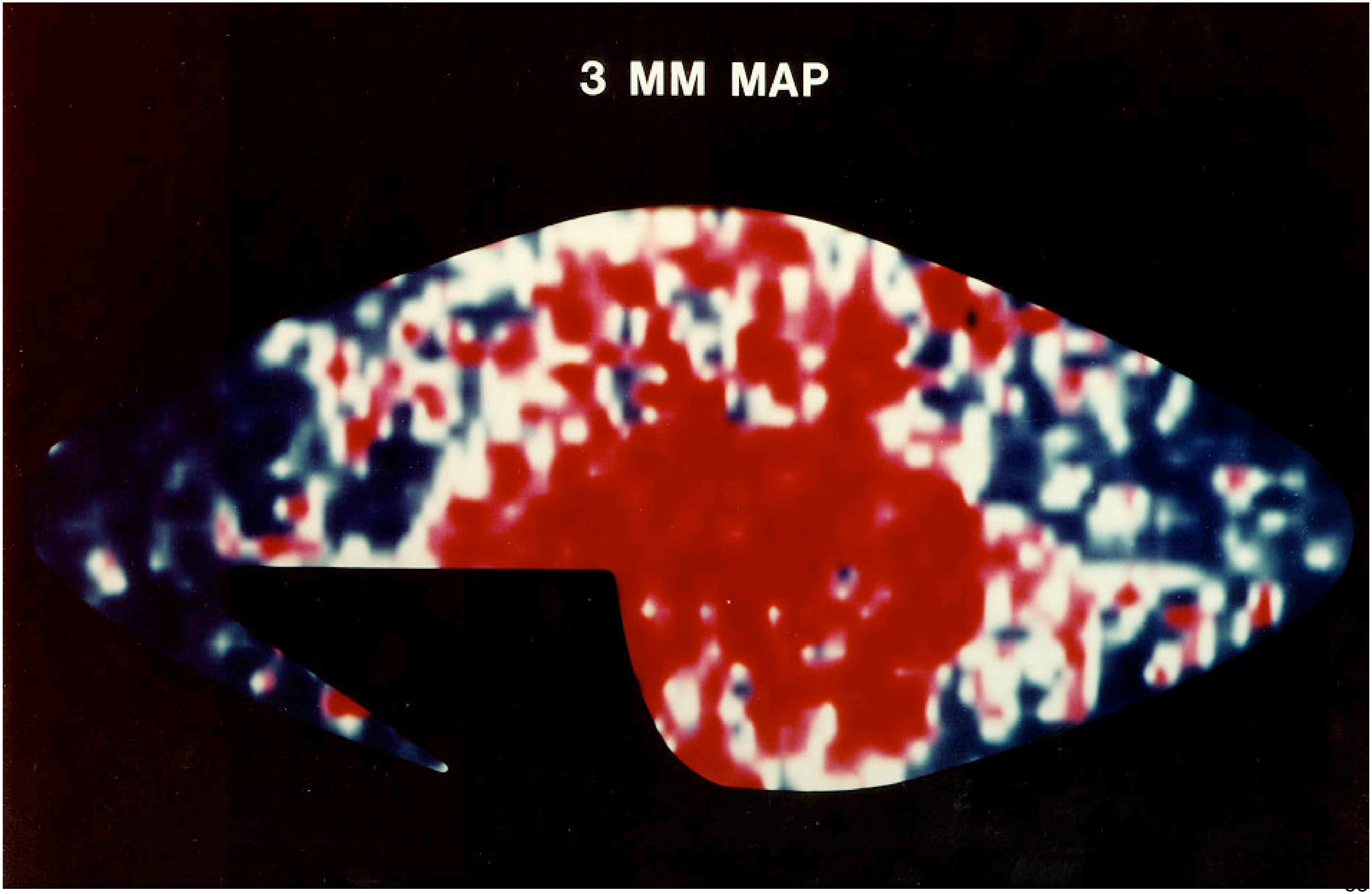
Peter Saulson & assembled payload

Princeton plus Berk

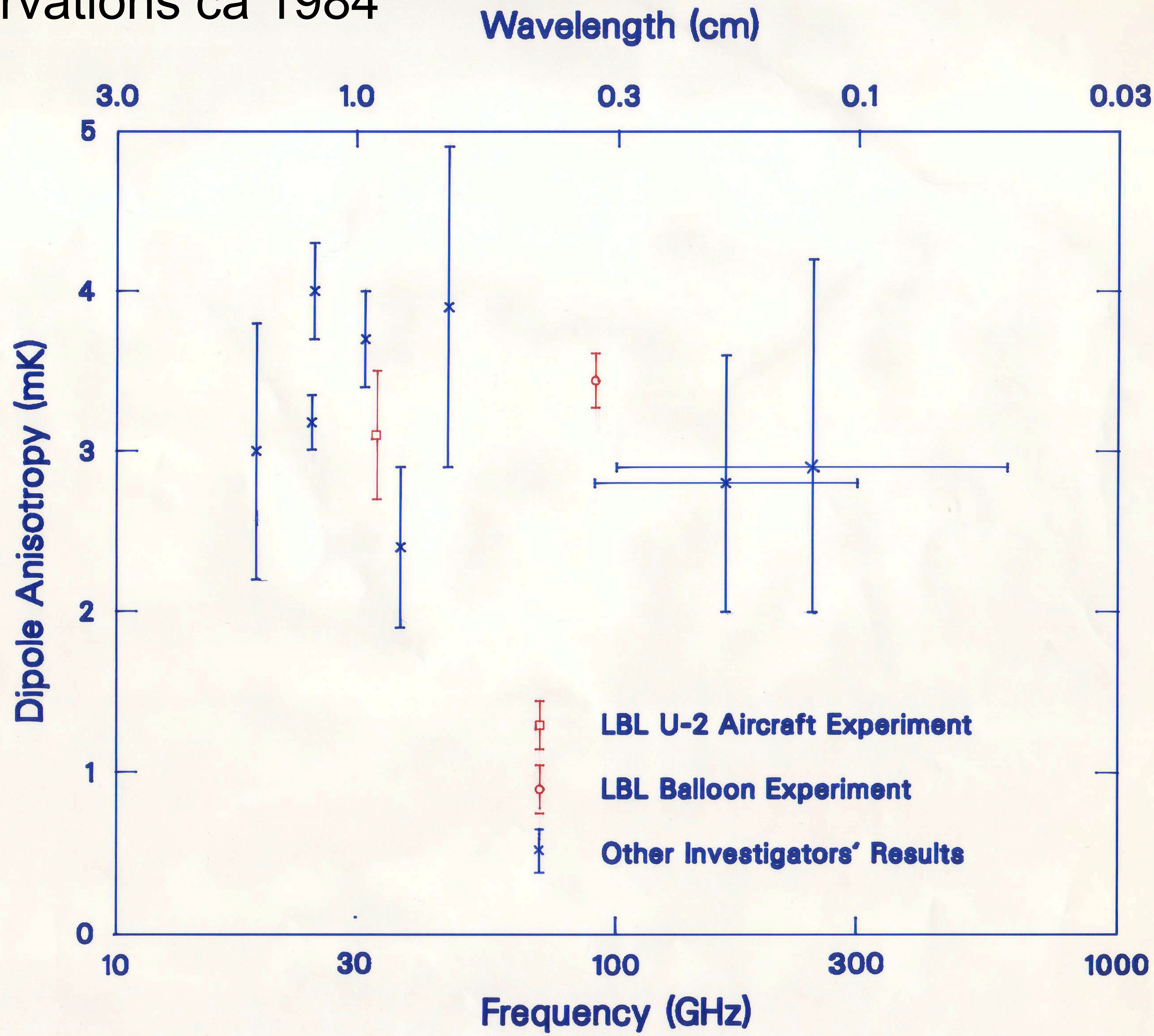
being readied fo

Peter Saulsen Dave Wilkinson

Three Balloon Flights Later- our dipole map



Observations ca 1984



COBE DMR

31.4 GHz (9-mm) Lab Breadboard

in the lab late 1970s

Spectrum : Collaboration at White Mtn.

Low-Frequency Measurement of the Spectrum of the Cosmic Background Radiation

Physical Review Letters 51, 12, 1099 (1983)

Original Team & Authors	
G.F. Smoot,	LBL/UCB
G. De Amici,	UCB
S.D. Friedman,	UCB
C. Witebsky,	UCB
N. Mandolesi*,	Bologna
R.B. Partridge,	Haverford
G. Sironi,	Milano
L. Danese &	Padua
G. De Zotti	Padua

Added Participants	
Marco Bersanelli+	Milano
Alan Kogut	UCB
Steve Levin	UCB
Marc Bensadoun	UCB
S. Cortiglioni	Bologna
G. Morigi	Bologna
G. Bonelli	Milano
J.B. Costales	UCB
Michel Limon	UCB
Yoel Rephaeli	Tel Aviv

* Planck PI

+Planck Deputy PI

Heavy Manual Operations
George Smoot, Scott Friedman, Alan Benner

South	Steve	John	Bill	Giovanni	Marc	Michele	George	Marco
Pole	Levin	Gibson	Vinje	de Amici	Bensadoun	Limon	Smoot	Bersanelli

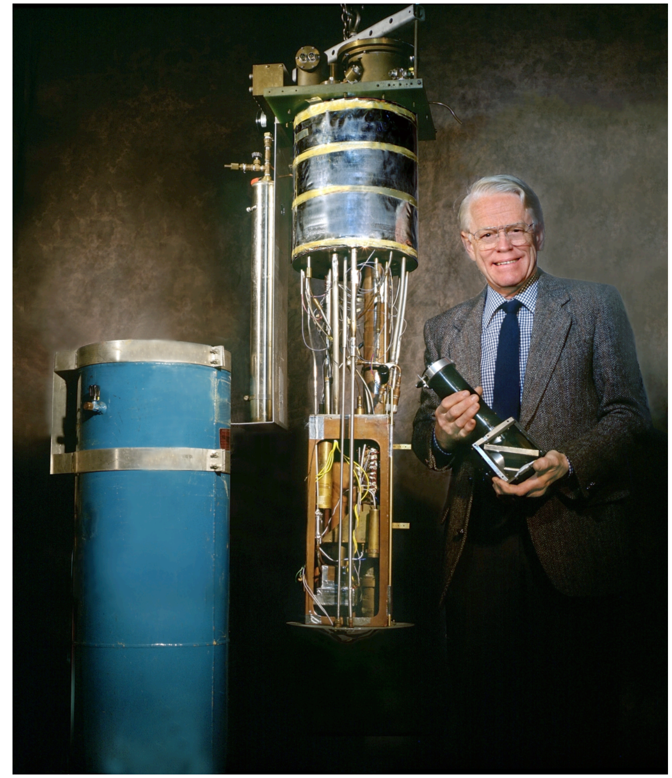

MERRY
CHRISTMAS!
X

Spectrum of the Cosmic Background Radiation

D. P. Woody and P. L. Richards

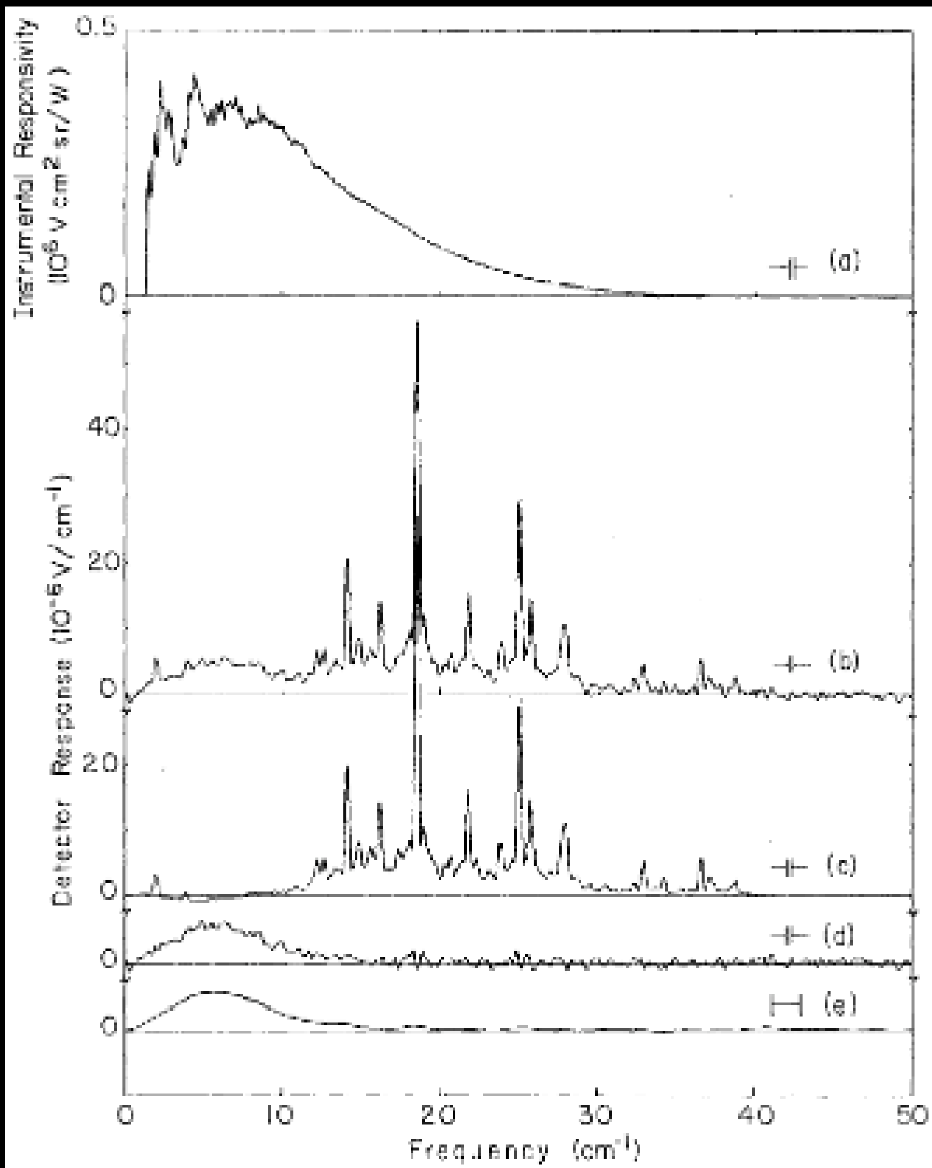
Received 15 December 1978

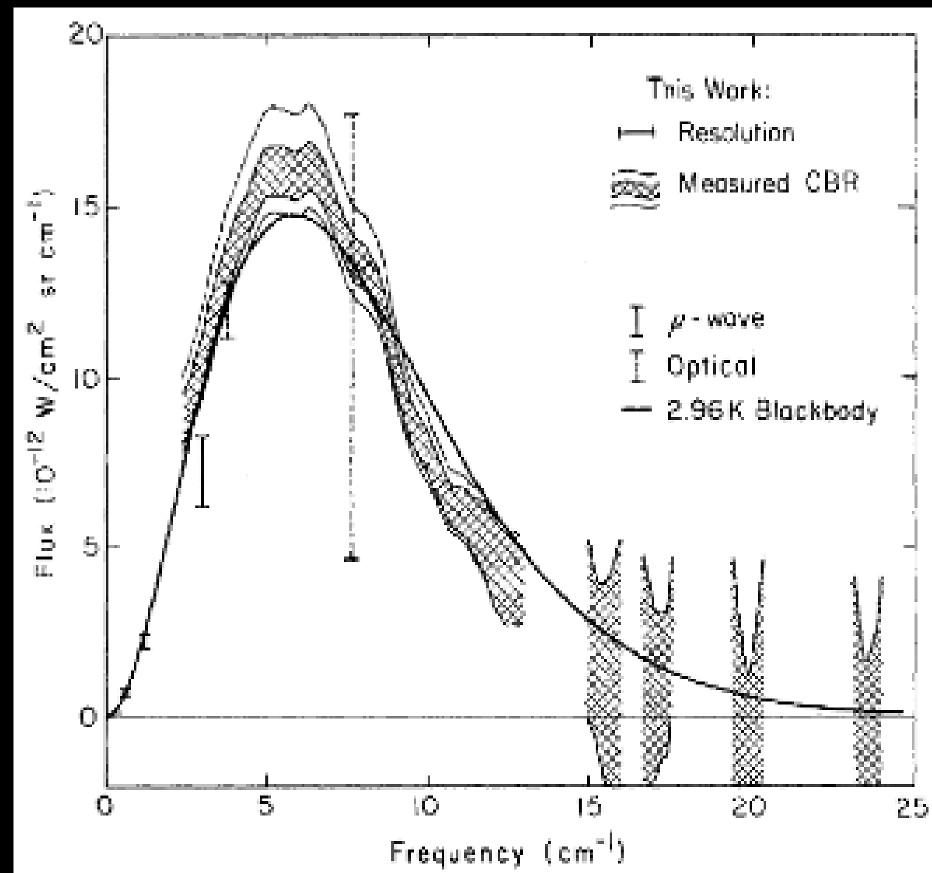
New measurements of the emission spectrum of the night sky have been made in the frequency range from 1.7 to 40 cm^{-1} using a fully calibrated, liquid-helium-cooled, balloon-borne spectrophotometer. The results show that the spectrum of the cosmic background radiation peaks at 6 cm^{-1} and is approximately that of a 3-K blackbody out to several times that frequency. However, the data show deviations from a simple blackbody curve.



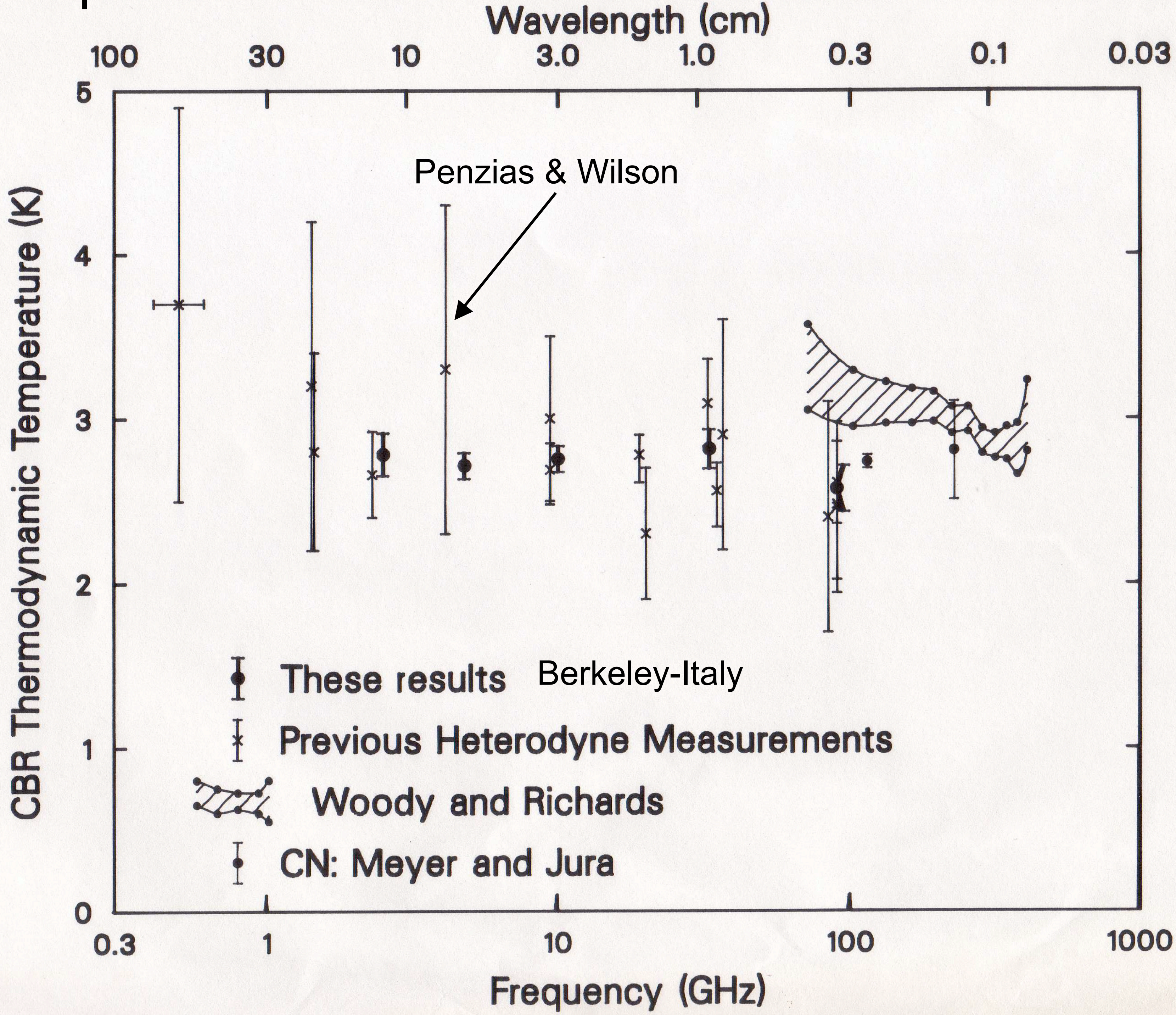
Paul Richards stands with elements of the Woody-Richards cosmic microwave background instrument package, an historic balloon-borne experiment that now resides in the Smithsonian Museum's permanent national collection.

Woody and Richards 1978



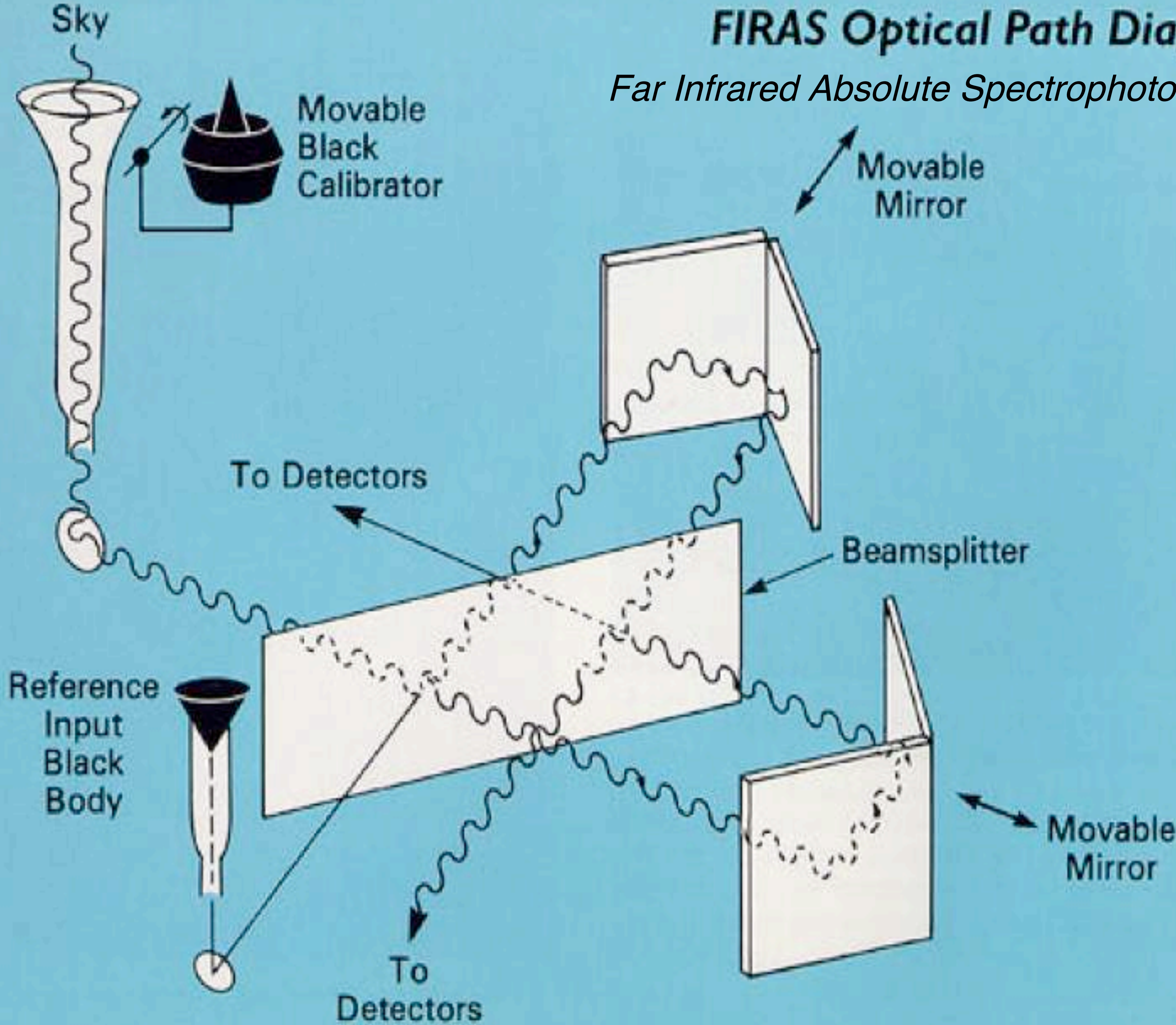


CMB Spectrum ca 1984



FIRAS Optical Path Diagram

Far Infrared Absolute Spectrophotometer

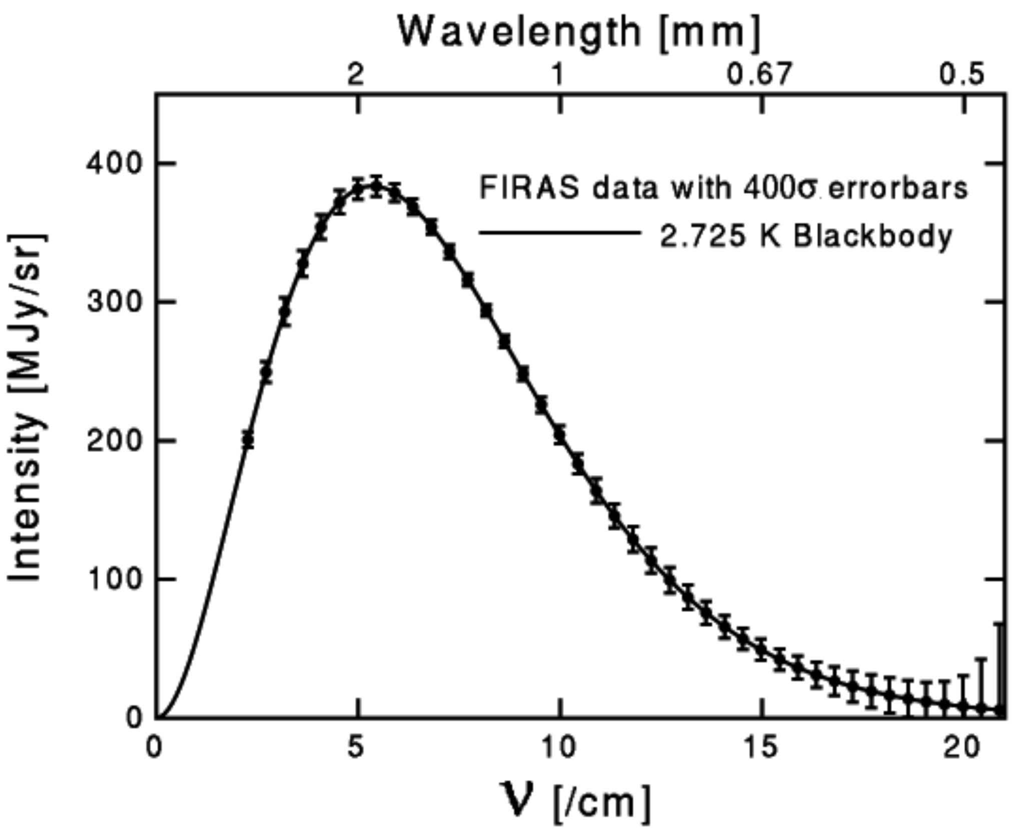


FIRAS Horn & Ext. Calibrator

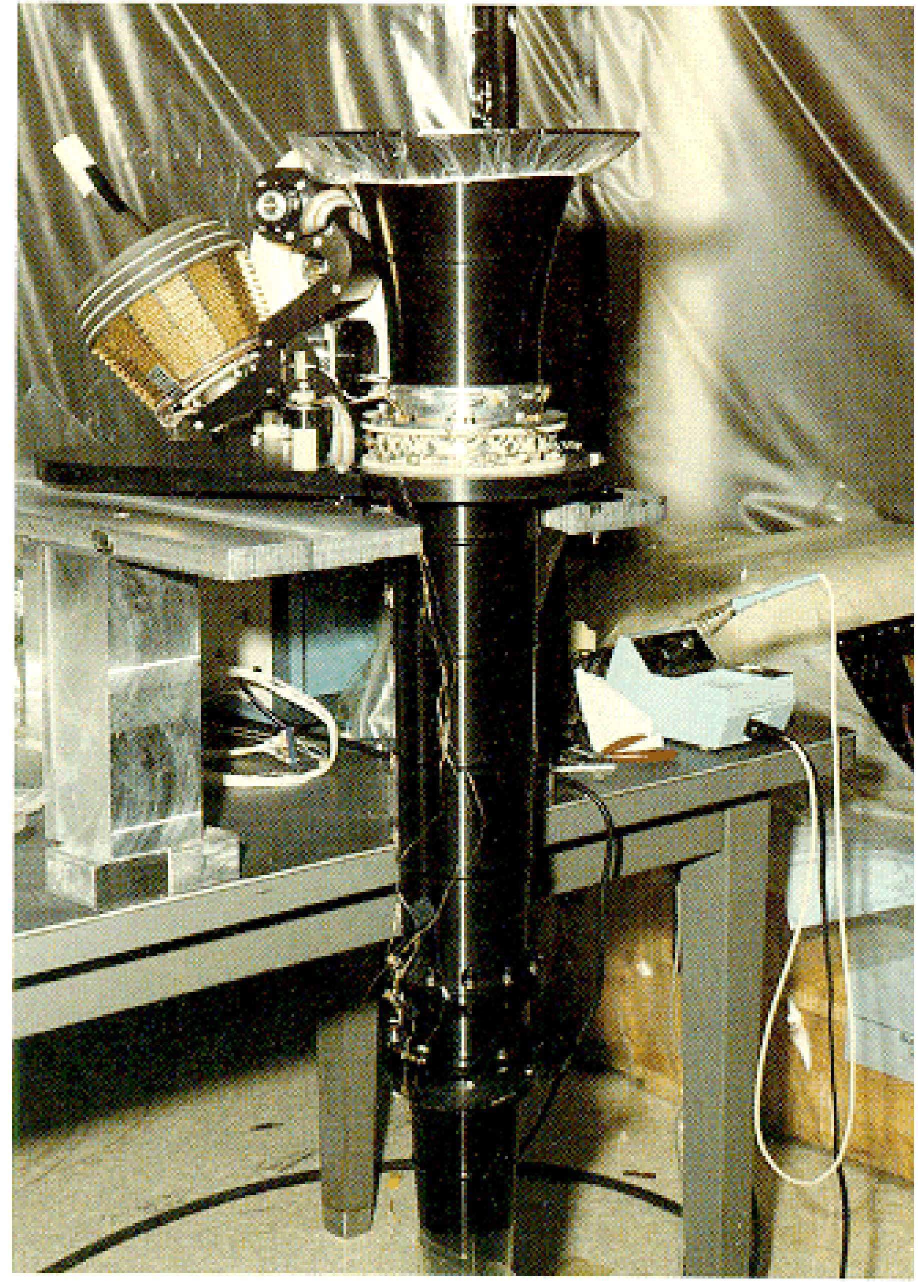
COBE Spectrum of the Universe

-first 9 minutes of data

-Jan 1990 AAS meeting

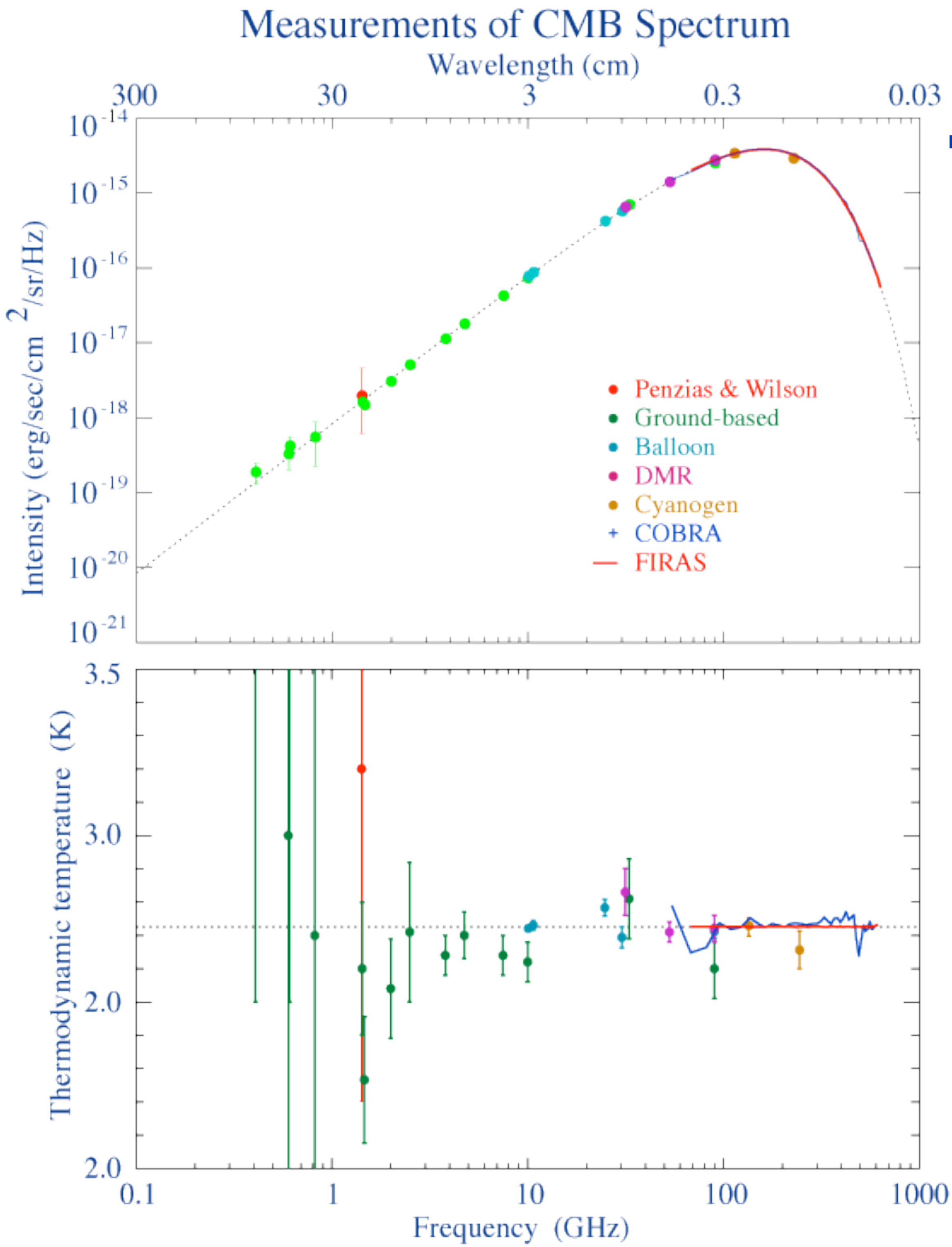


Frequency Spectrum



Horn antenna with movable calibrator. Protective plastic covers will be removed.

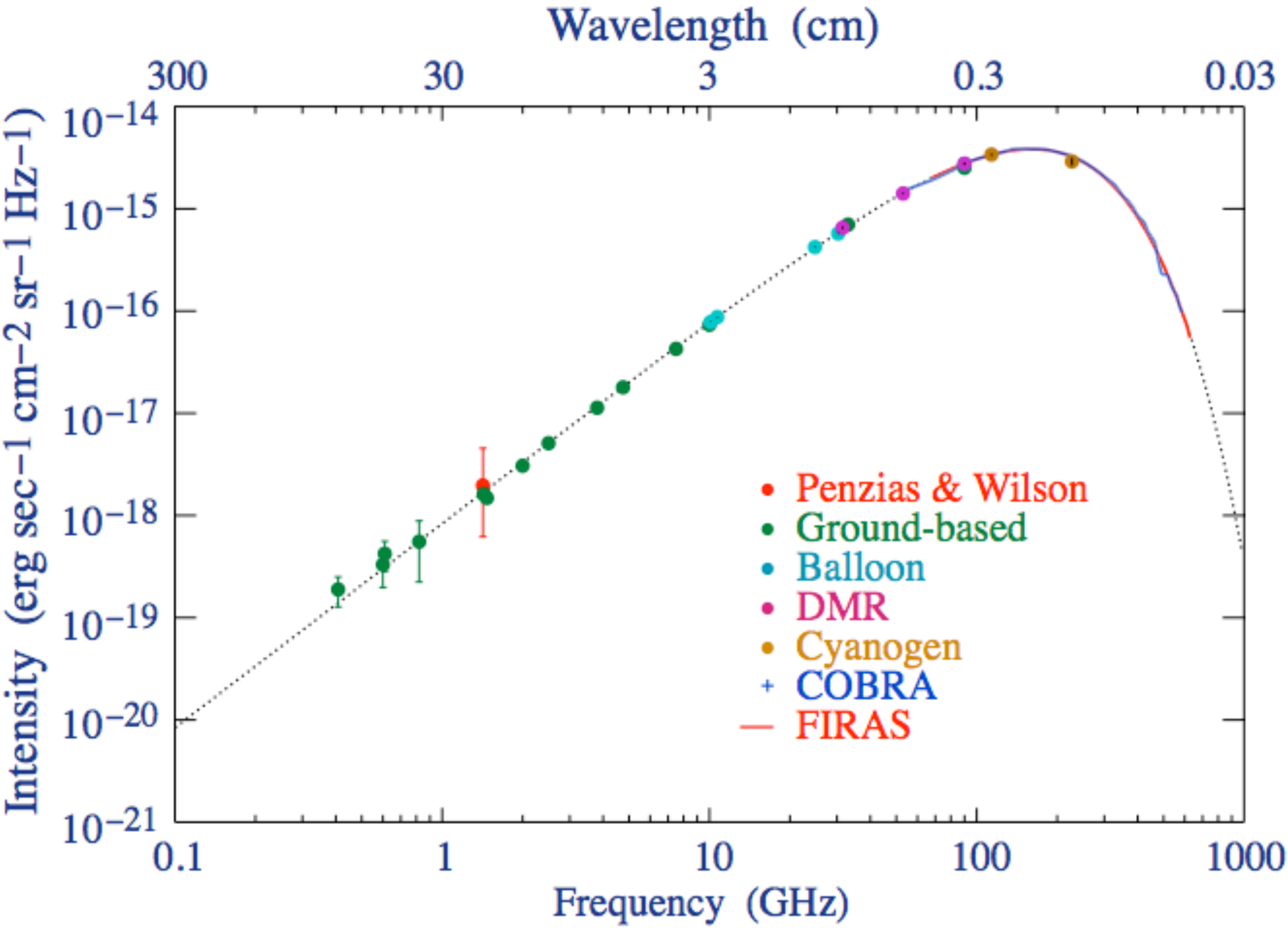

Calibrator (Eccosorb) on
arm, before insulation,
attached to parabolic
concentrator



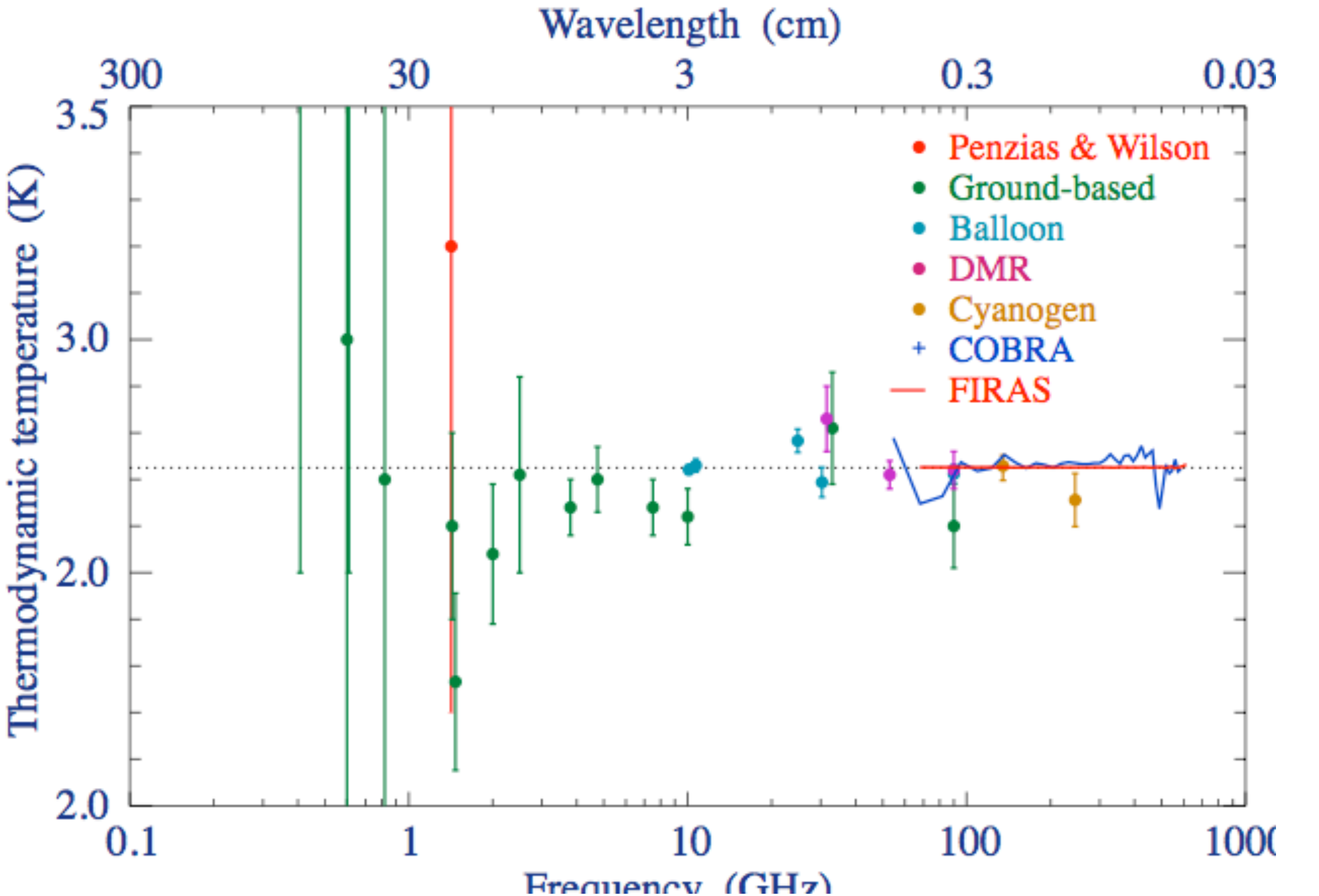
Measurements of CMB Spectrum
Wavelength (cm)
300
30
3
0.3
0.03
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
Intensity (erg/sec/cm ^{2}/sr/Hz)
Penzias & Wilson
Ground-based
Balloon
DMR
Cyanogen
COBRA
FIRAS
3.5
3.0
2.0
2.0
Thermodynamic temperature (K)
0.1
1
10
100
1000
Frequency (GHz)

Dr. Al Kogut

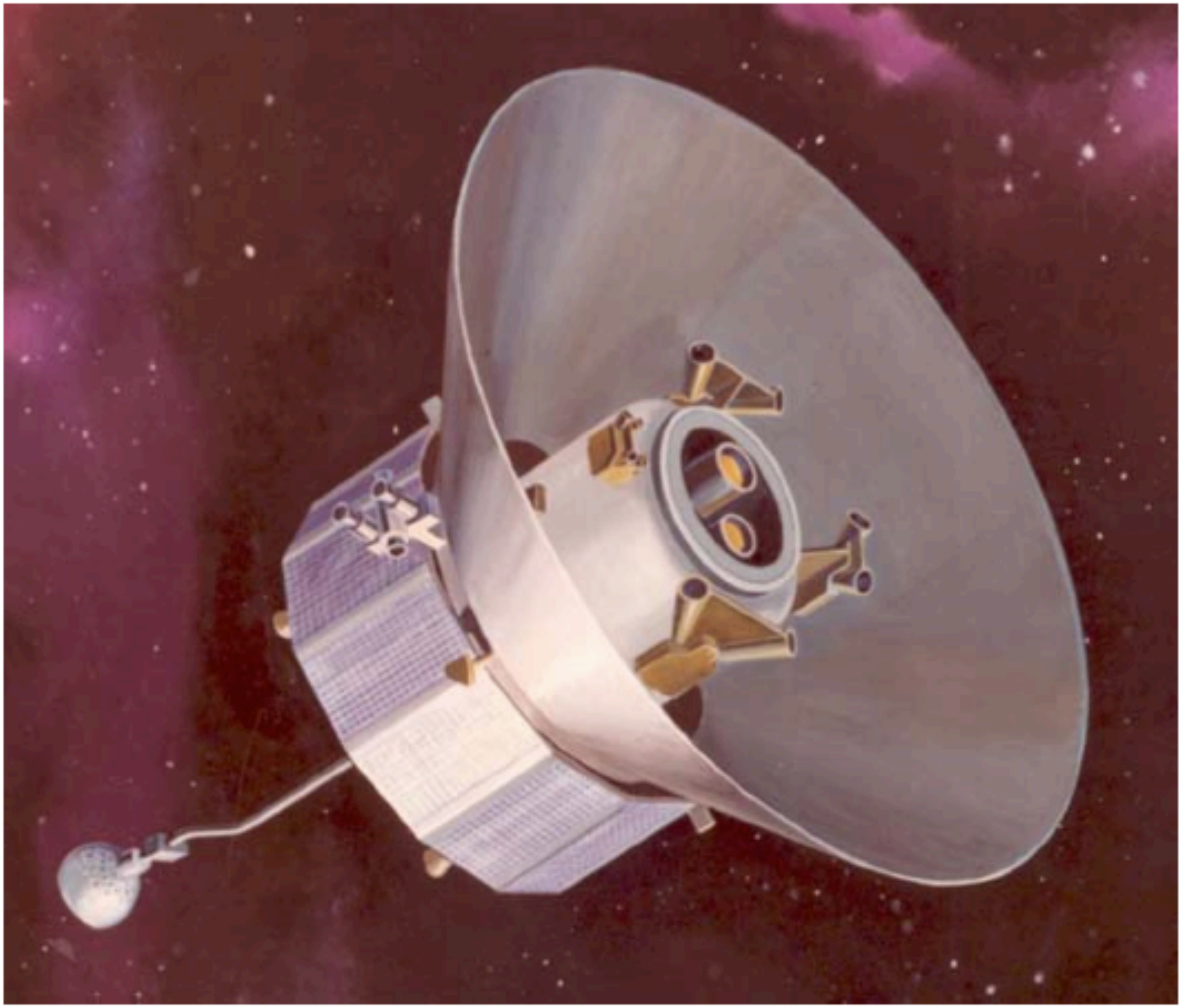
CMB Intensity vs ν or λ



CMB Temperature vs ν or λ

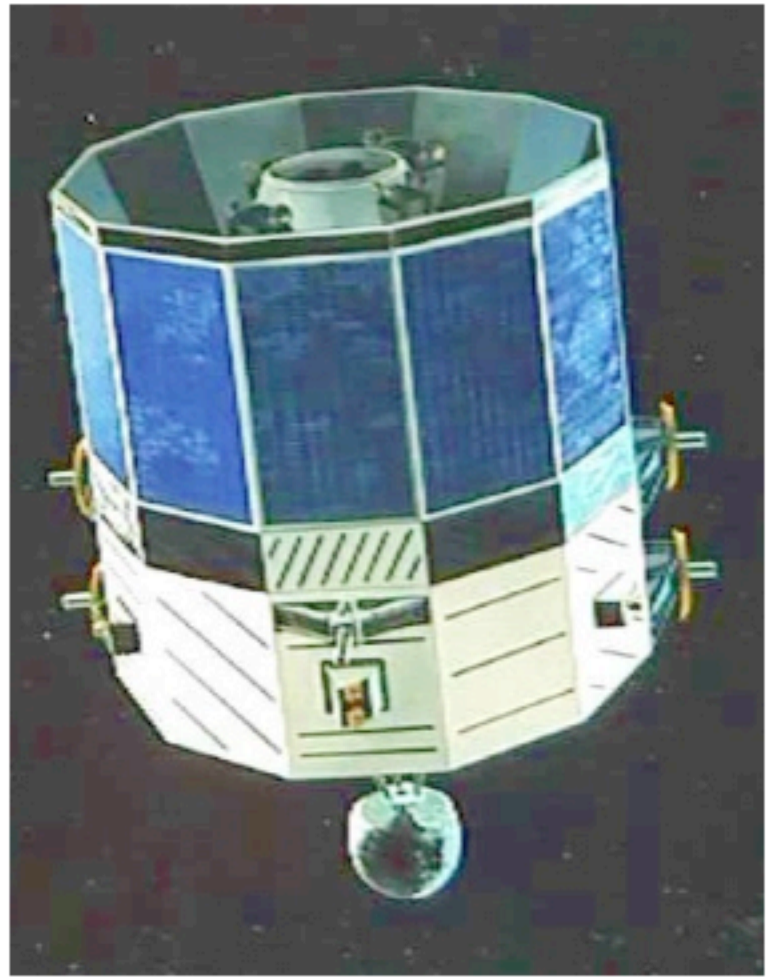


Original COBE was for a Delta



COBE was directed to use the Shuttle

- This picture is the shuttle launched version of COBE which was actually nearly completed in Jan 1986.
- Then the Challenger blew up on launch…



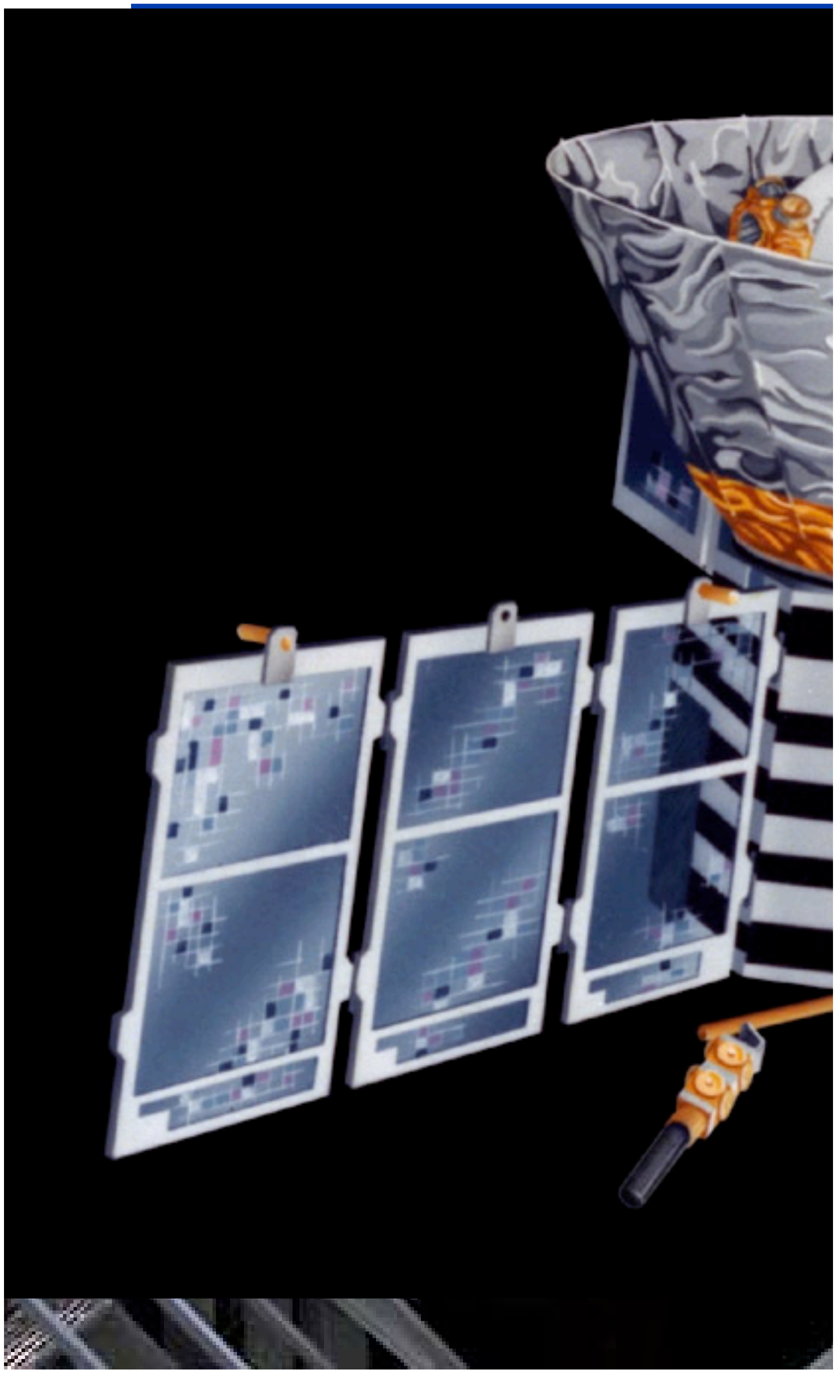
COBE DMR Hardware Effort

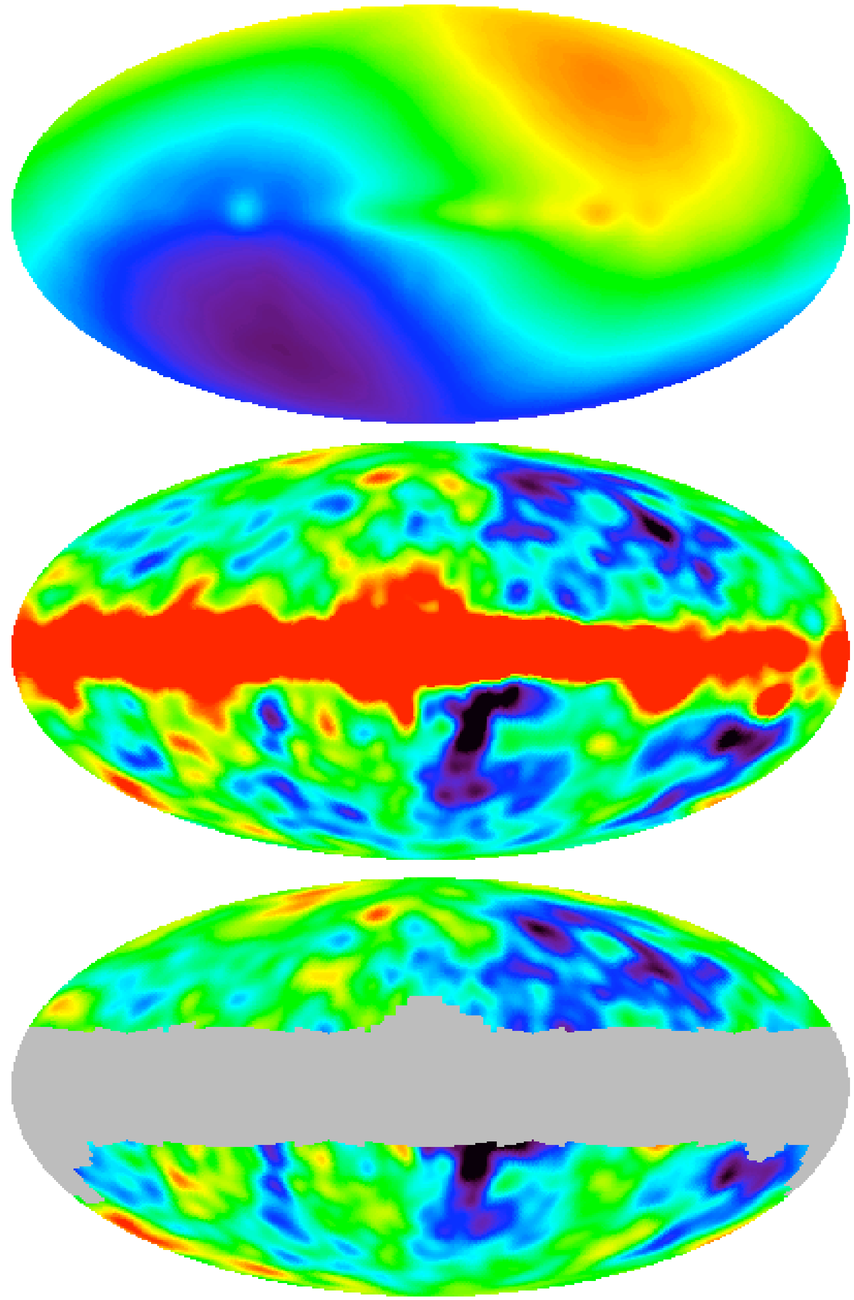
Huge List of People

Here are a few photos

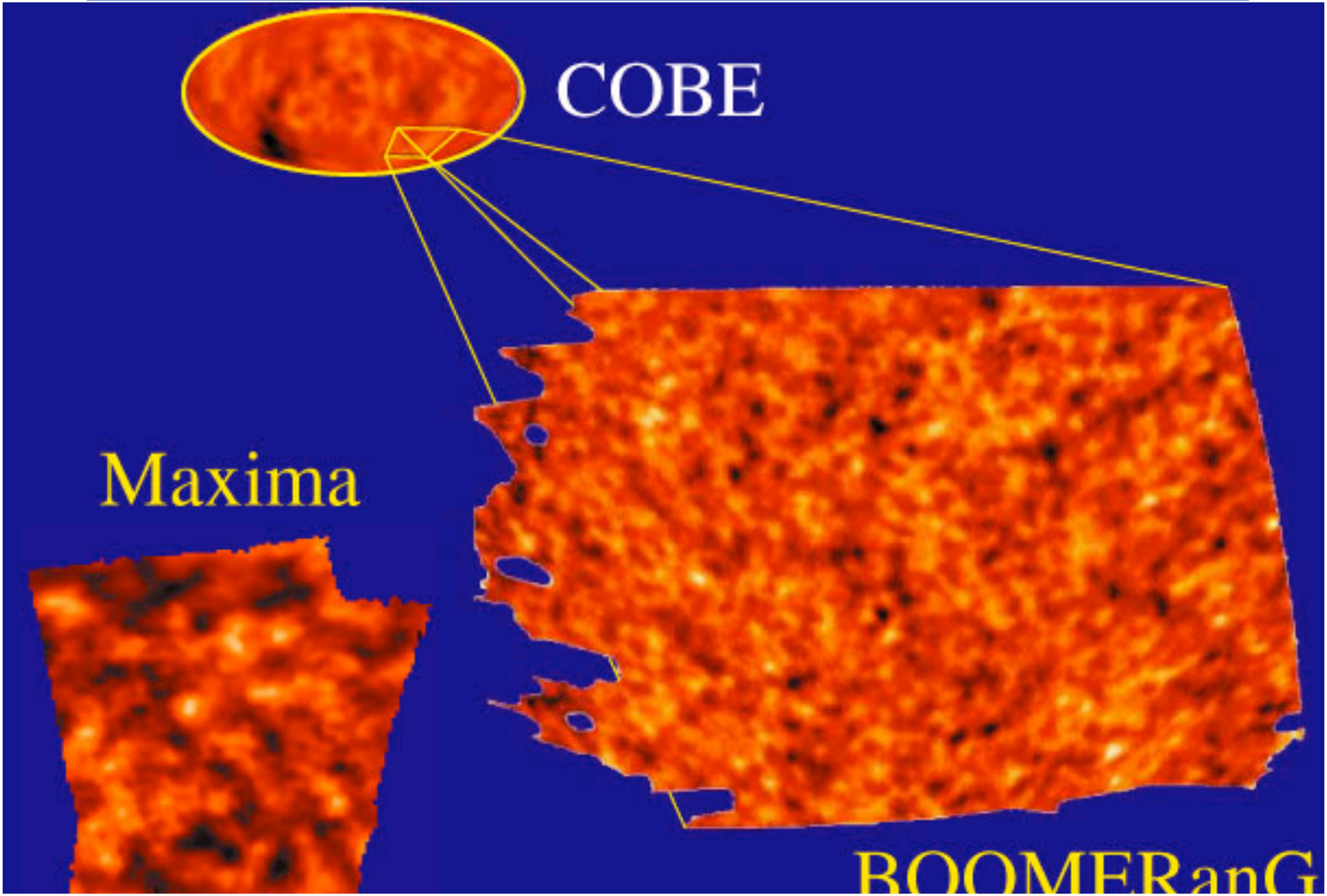
Bobby Patschke | Peter Young | Maria Lecha | Rick Mills | Larry Hillard

COBE DM





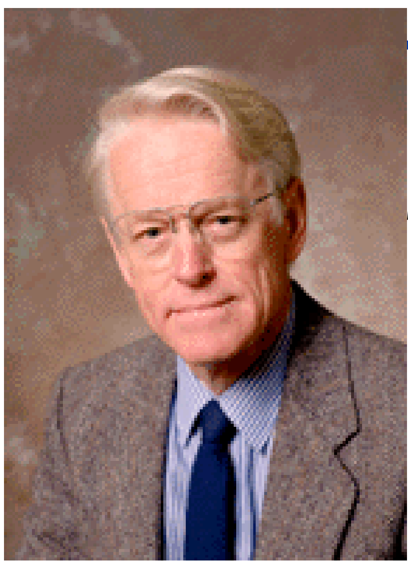
COBE plus Balloons

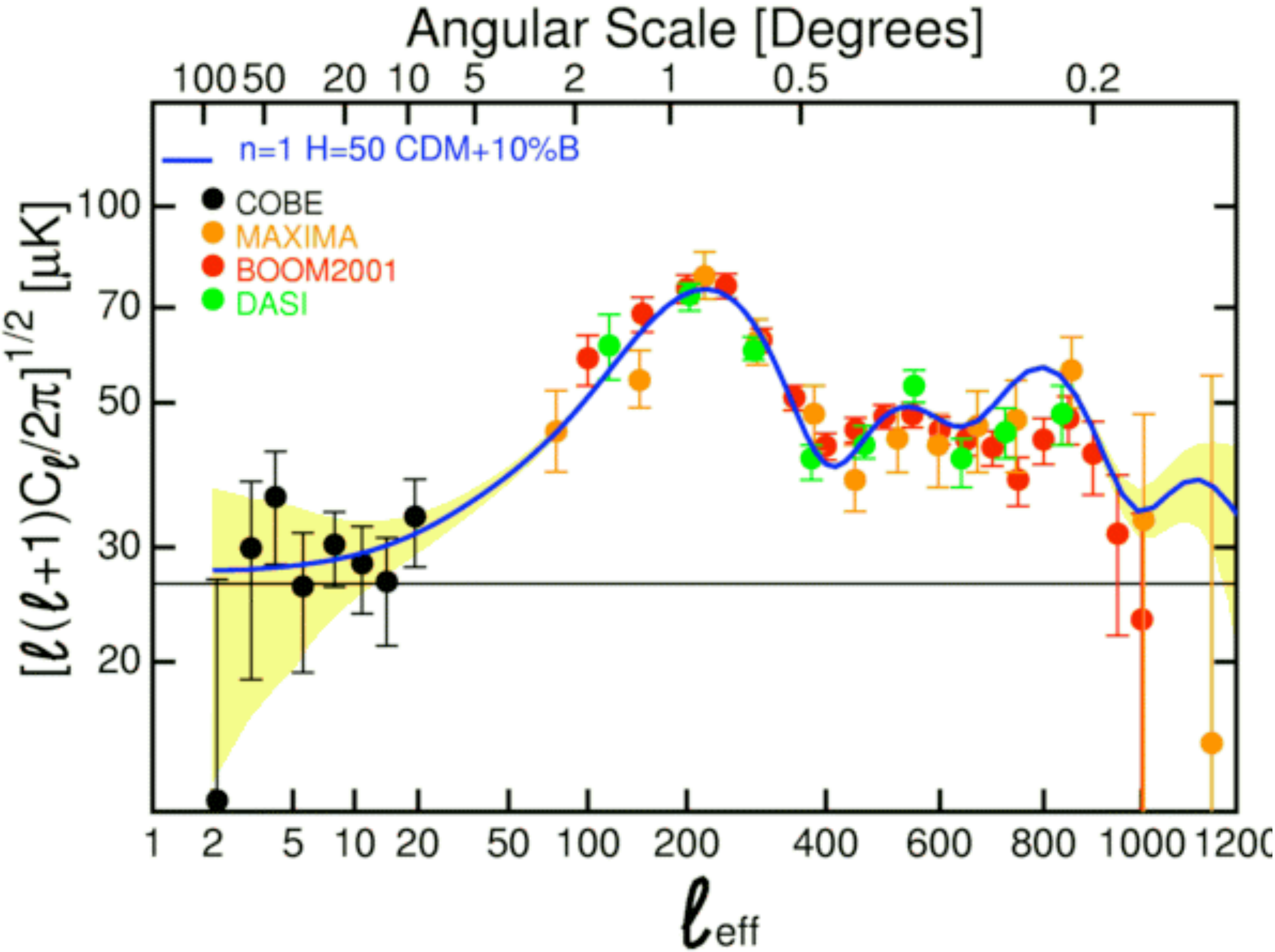


MAXIMA: Millimeter-wave anisotropy experiment imaging array

October 15, 2001 Volume 586, pp. 214-216
RELATIVISTIC ASTROPHYSICS: 20th Texas Symposium

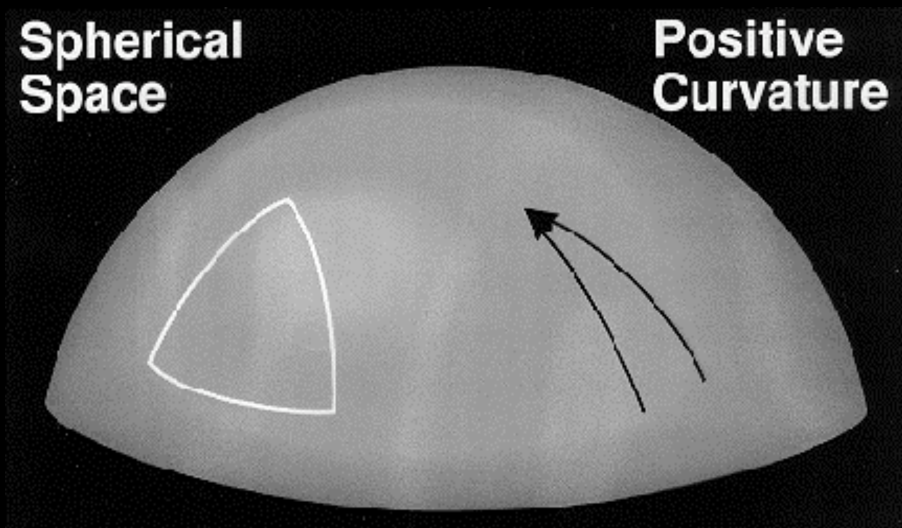
C. Winant,[1] M. Abroe,[2] P. Ade,[3] A. Balbi,[4,5] D. Barbosa,[6] J. Bock,[7,8] J. Borrill,[4,6] A. Boscaleri,[9] J. Collins,[4] P. de Bernardis,[10] P. Ferreira,[11] S. Hanany,[2] V. Hristov,[7] A. H. Jaffe,[4] B. Johnson,[2] A. E. Lange,[7] A. T. Lee,[4,6] P. D. Mauskopf,[12] C. B. Netterfield,[13] S. Oh,[6] E. Pascale,[9] B. Rabii,[4] P. L. Richards,[4,6] R. Stompor,[4] G. F. Smoot,[4,6] and J. H. P. Wu[4]

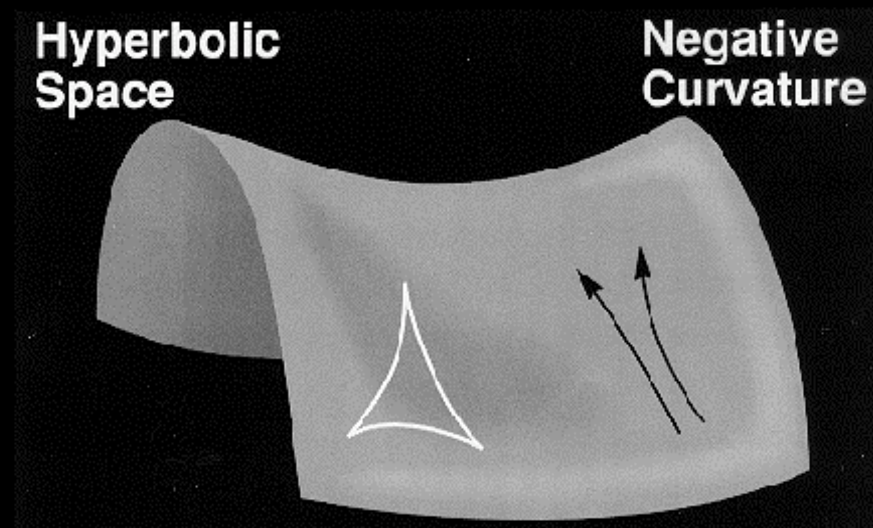


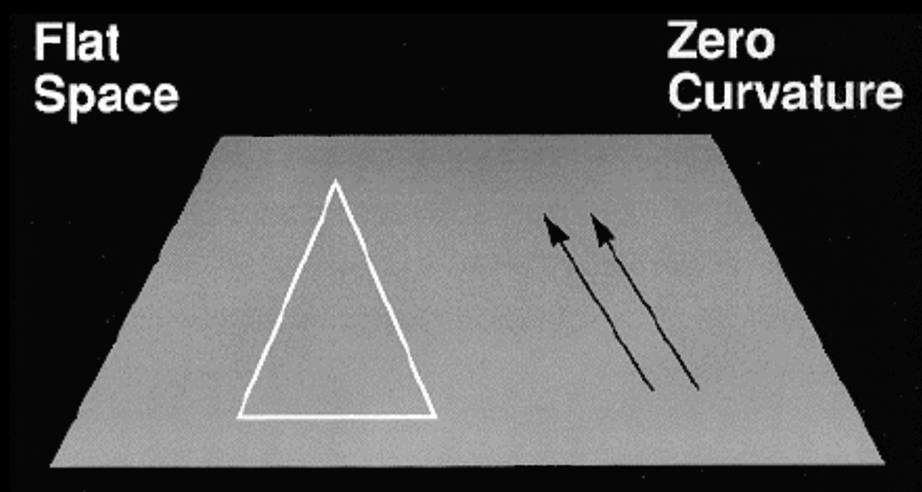


Angular Scale [Degrees]
100 50 20 10 5 2 1 0.5 0.2
n=1 H=50 CDM+10%B
COBE
MAXIMA
BOOM2001
DASI
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
100
70
50
30
20
1 2 5 10 20 50 100 200 400 600 800 1000 1200
$\ell_{\rm eff}$

2-D Examples of Curved Spaces

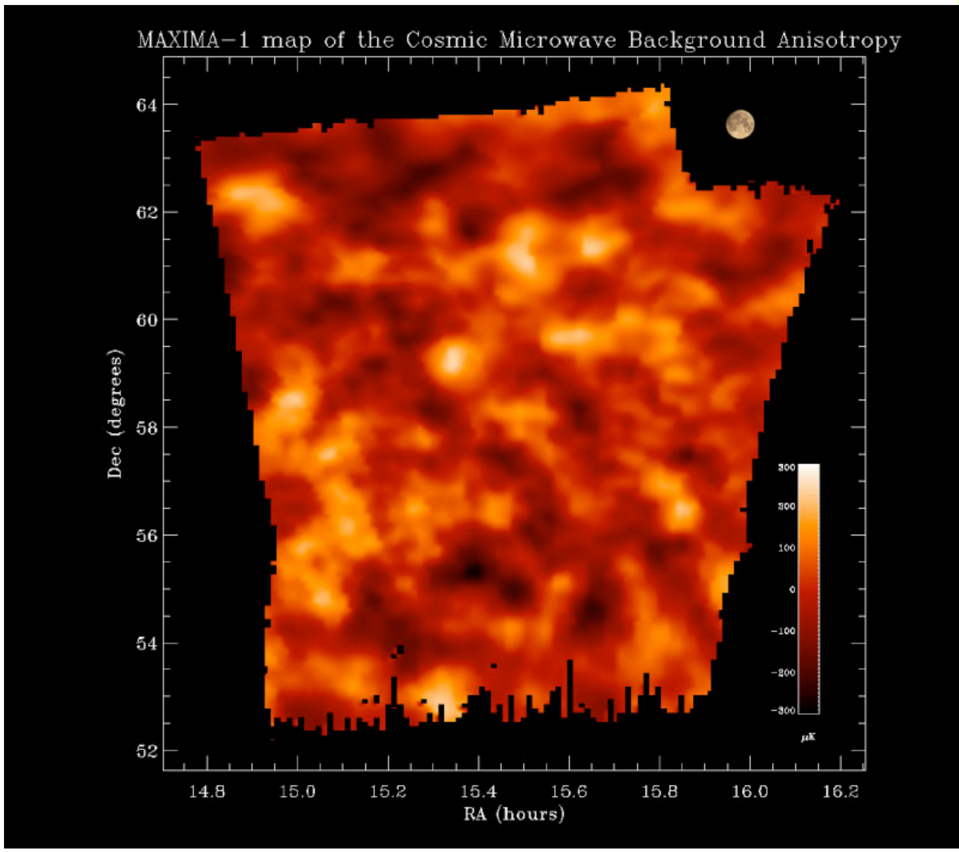


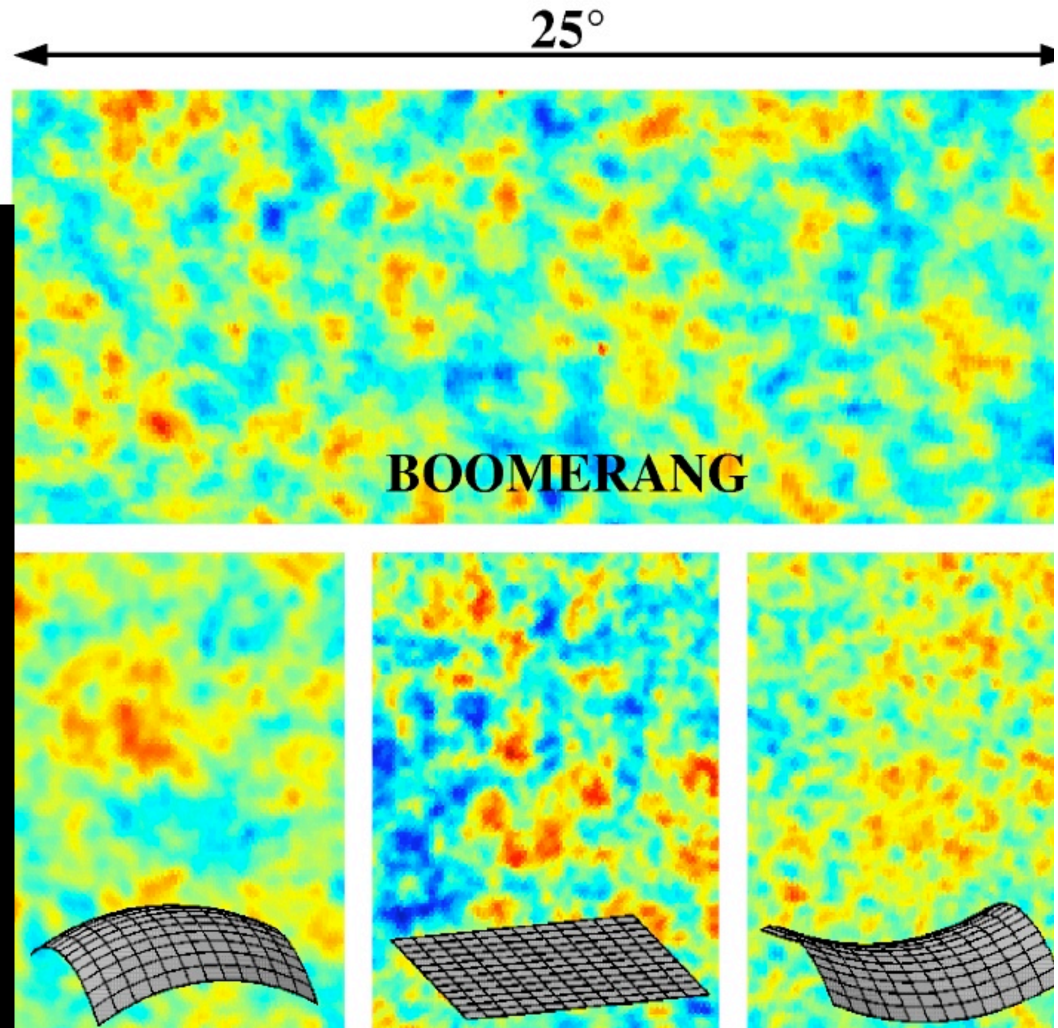




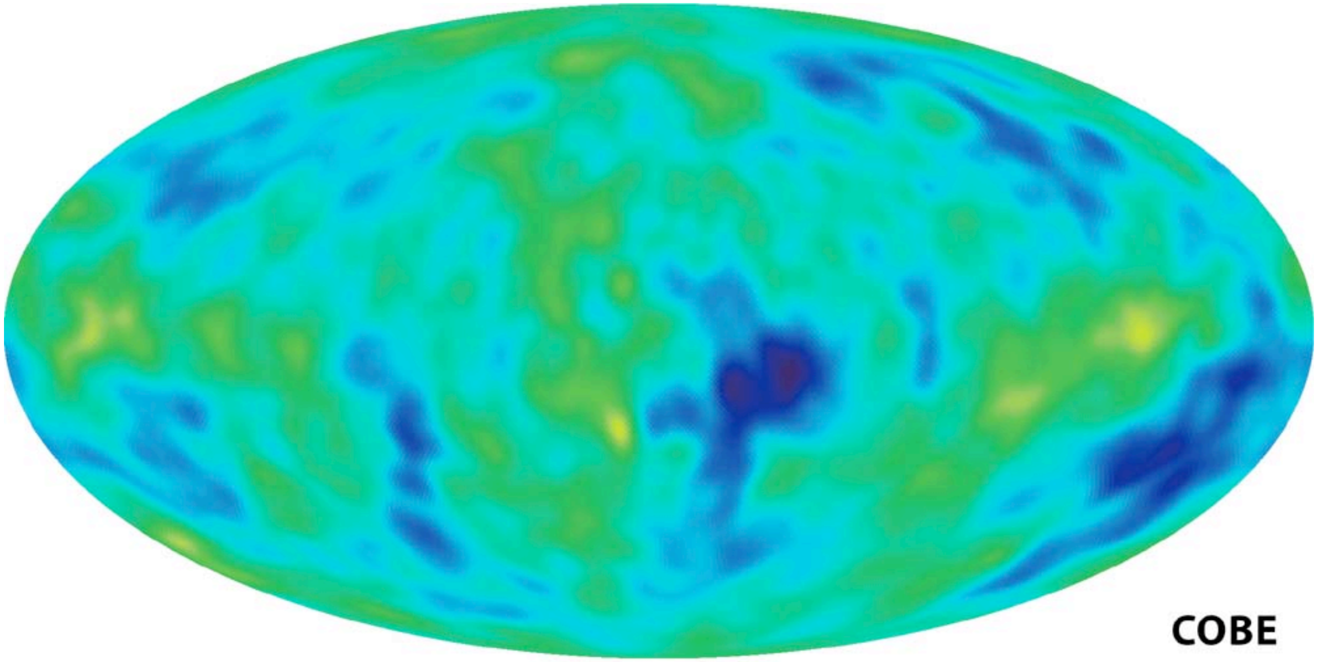
60

Measuring the Curvature of the Universe Using the CMB

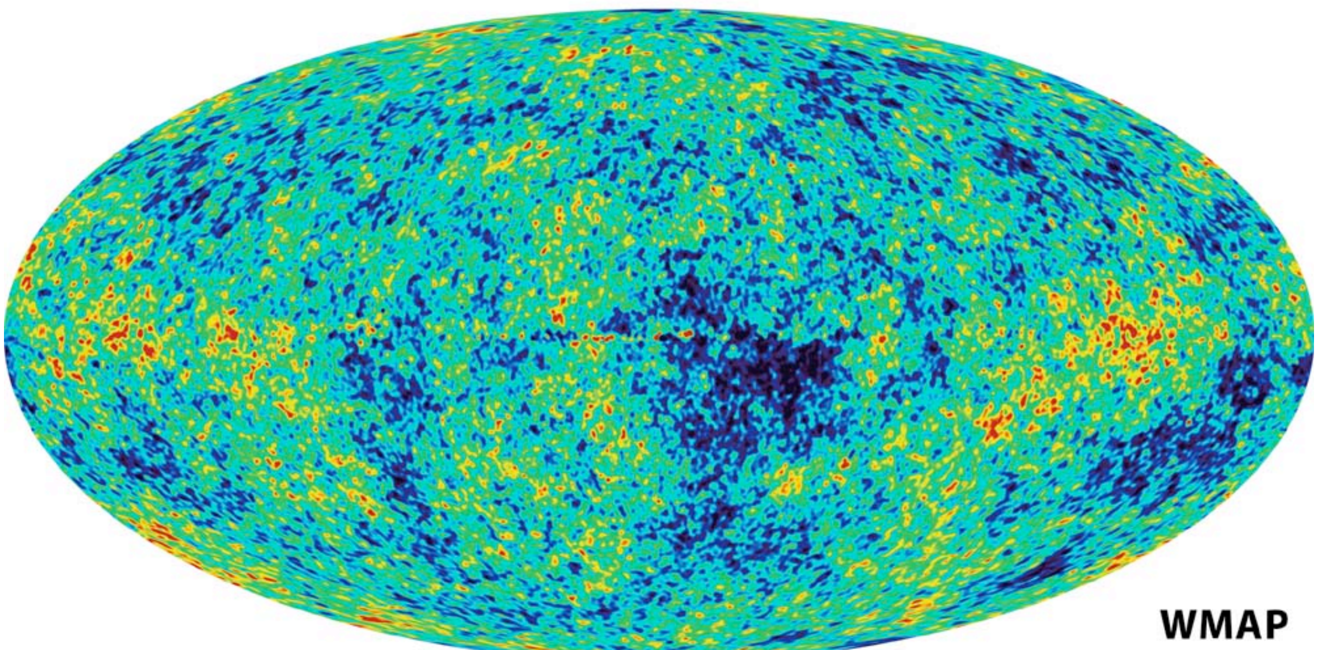




WMAP Continues Effort

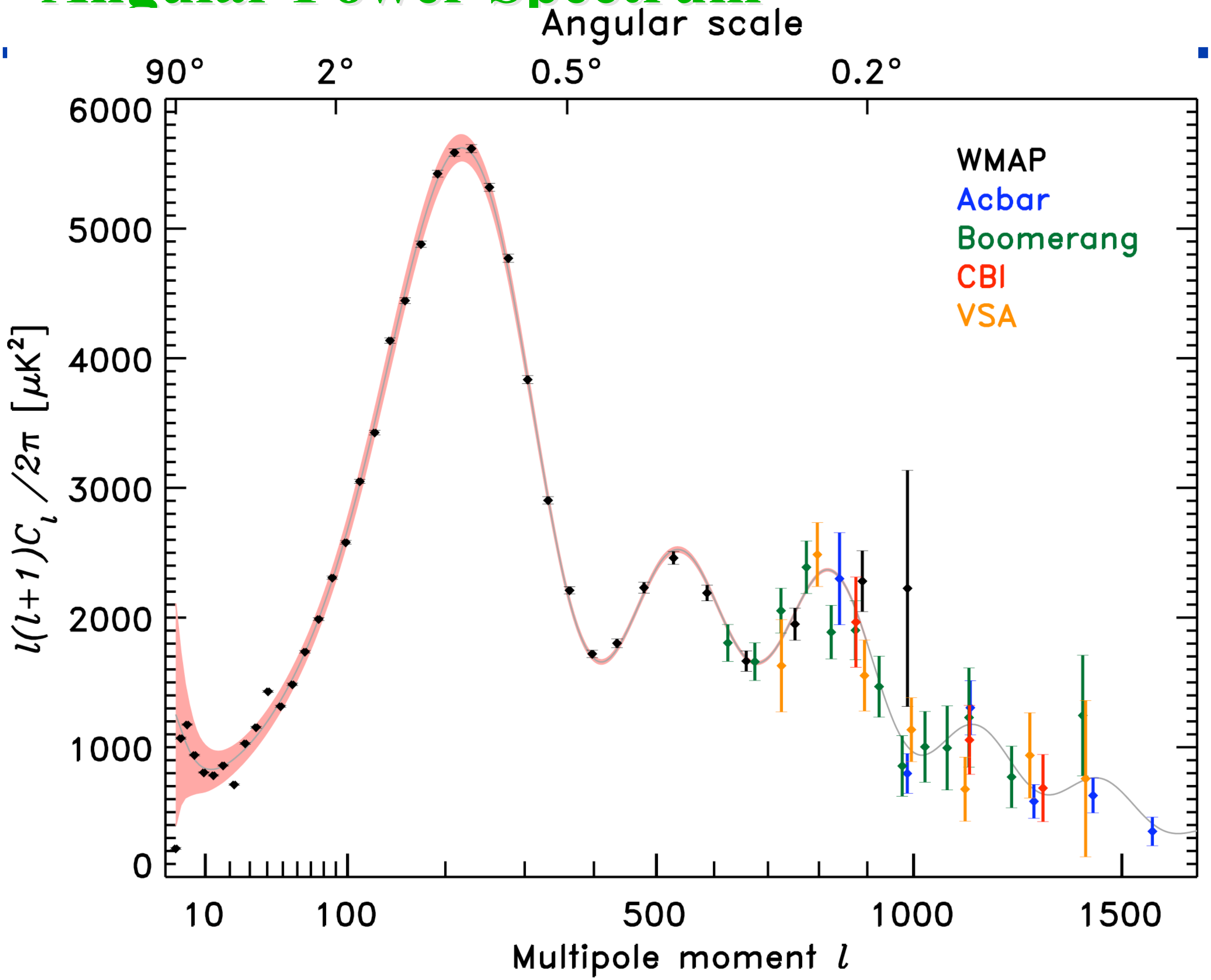


COBE

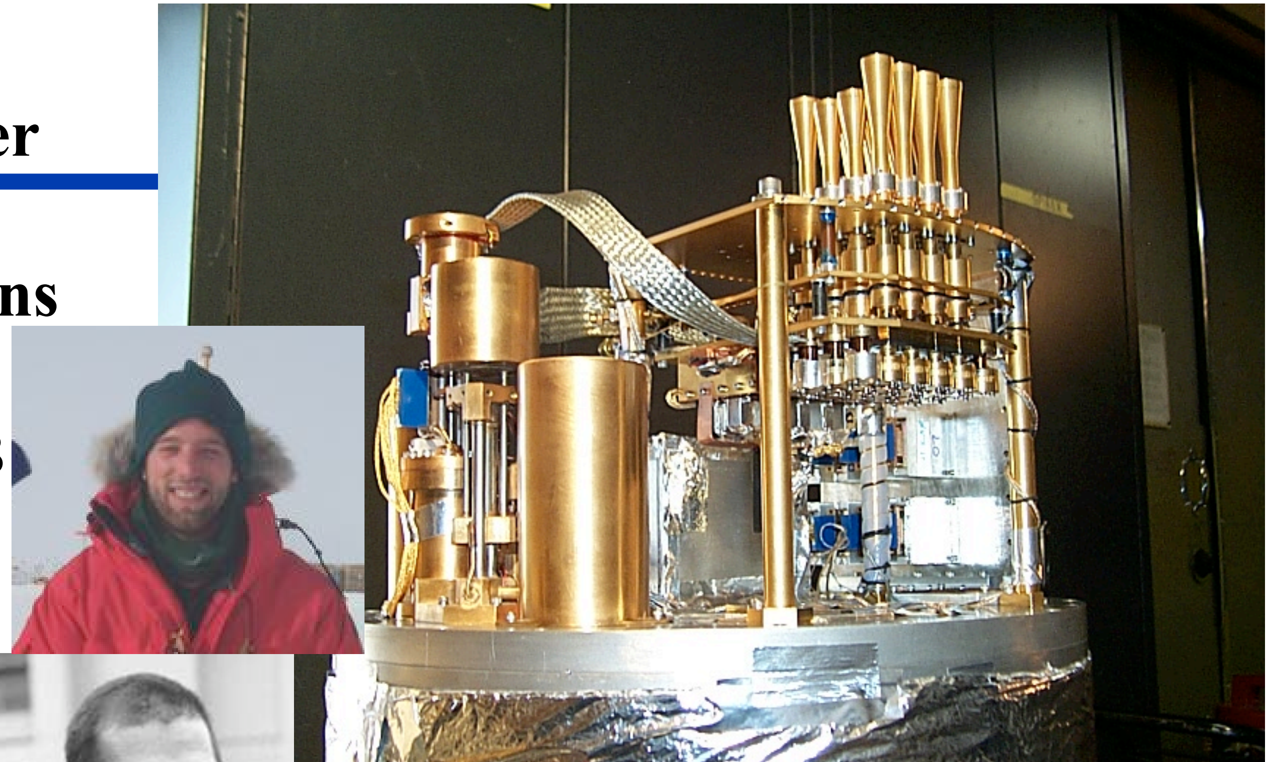


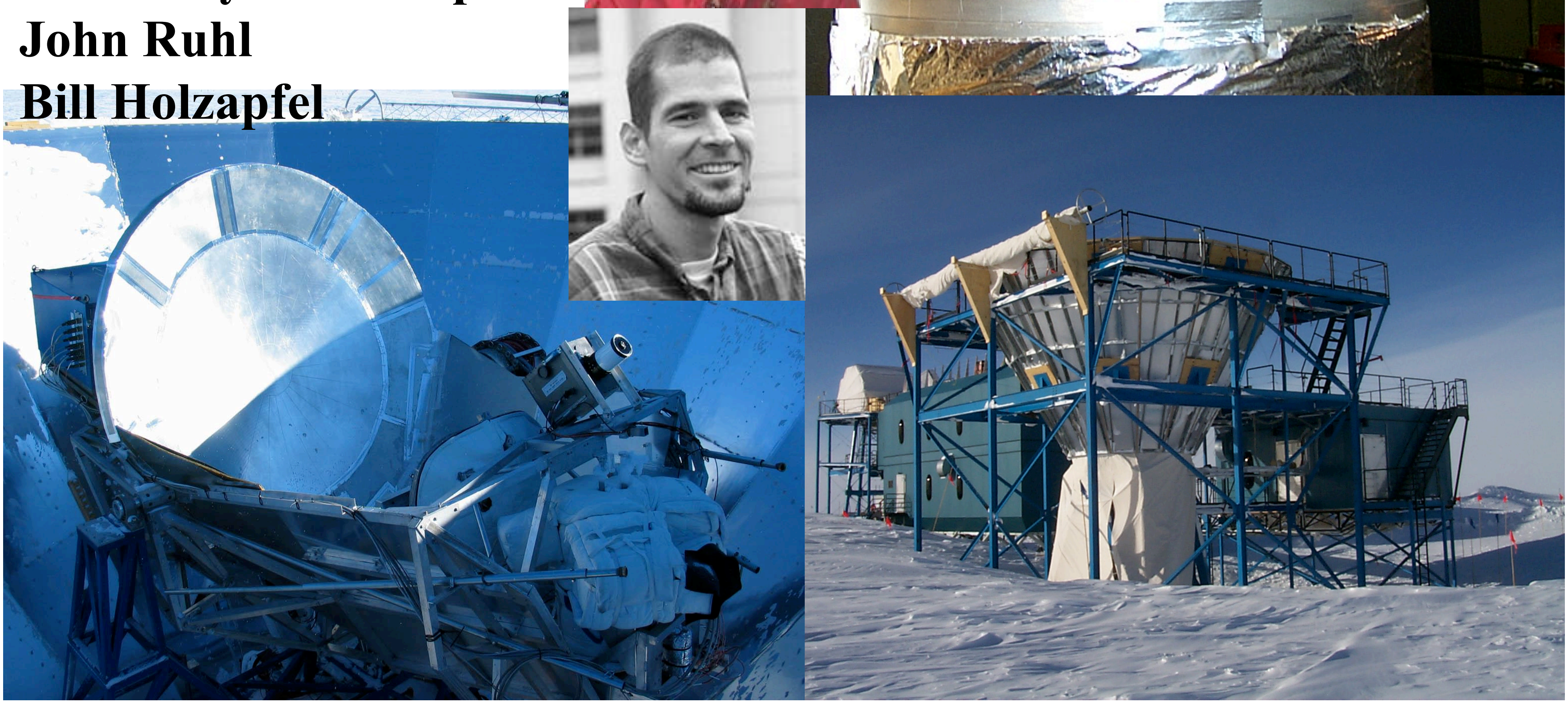
WMAP

Angular Power Spectrum



Arcminute Cosmology
Bolometer Array Receiver
(ACBAR)
2005 Finished observations
at South Pole
New constraints on CMB
Damping tail and
secondary Anisotropies
John Ruhl
Bill Holzapfel

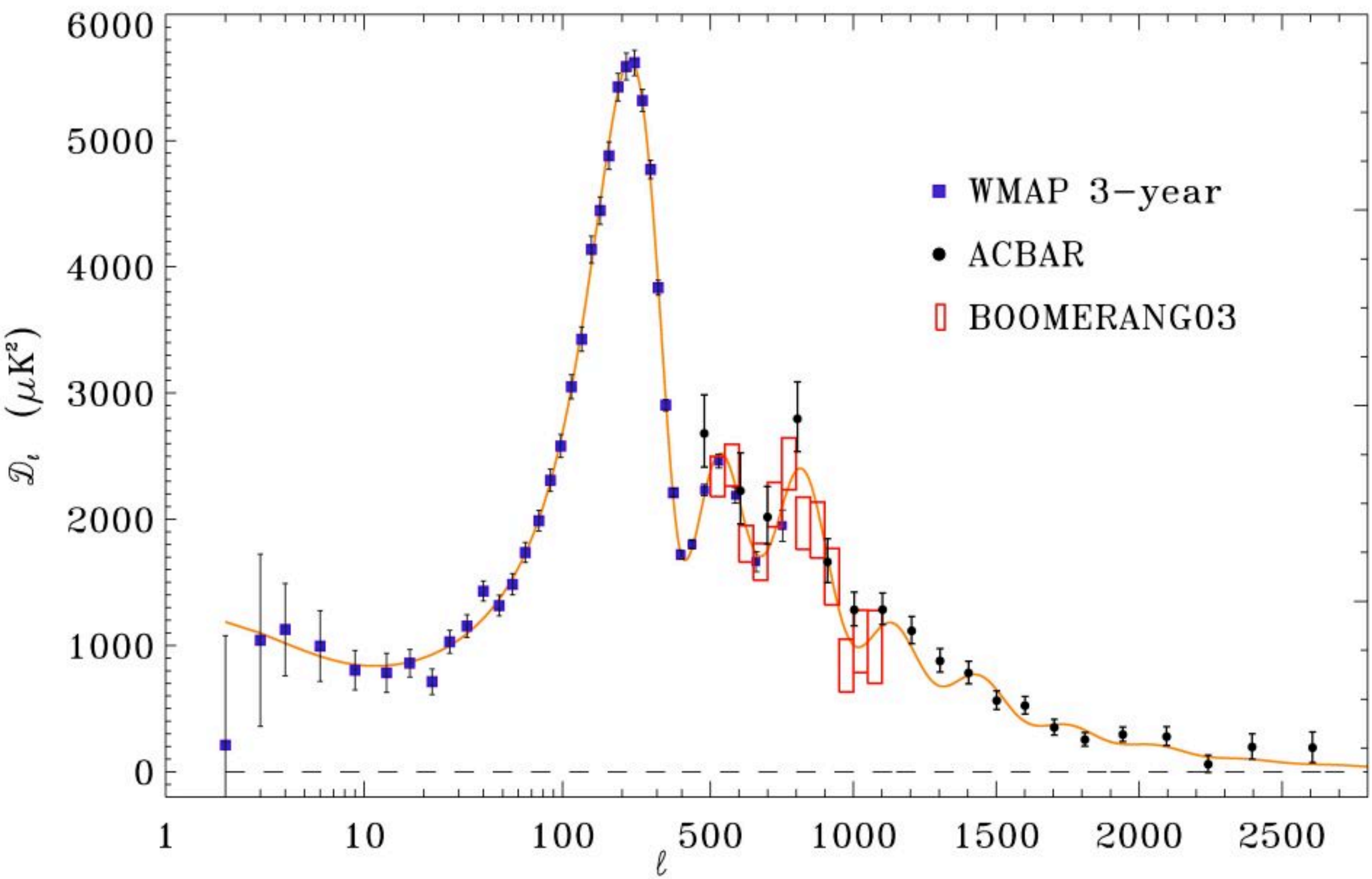




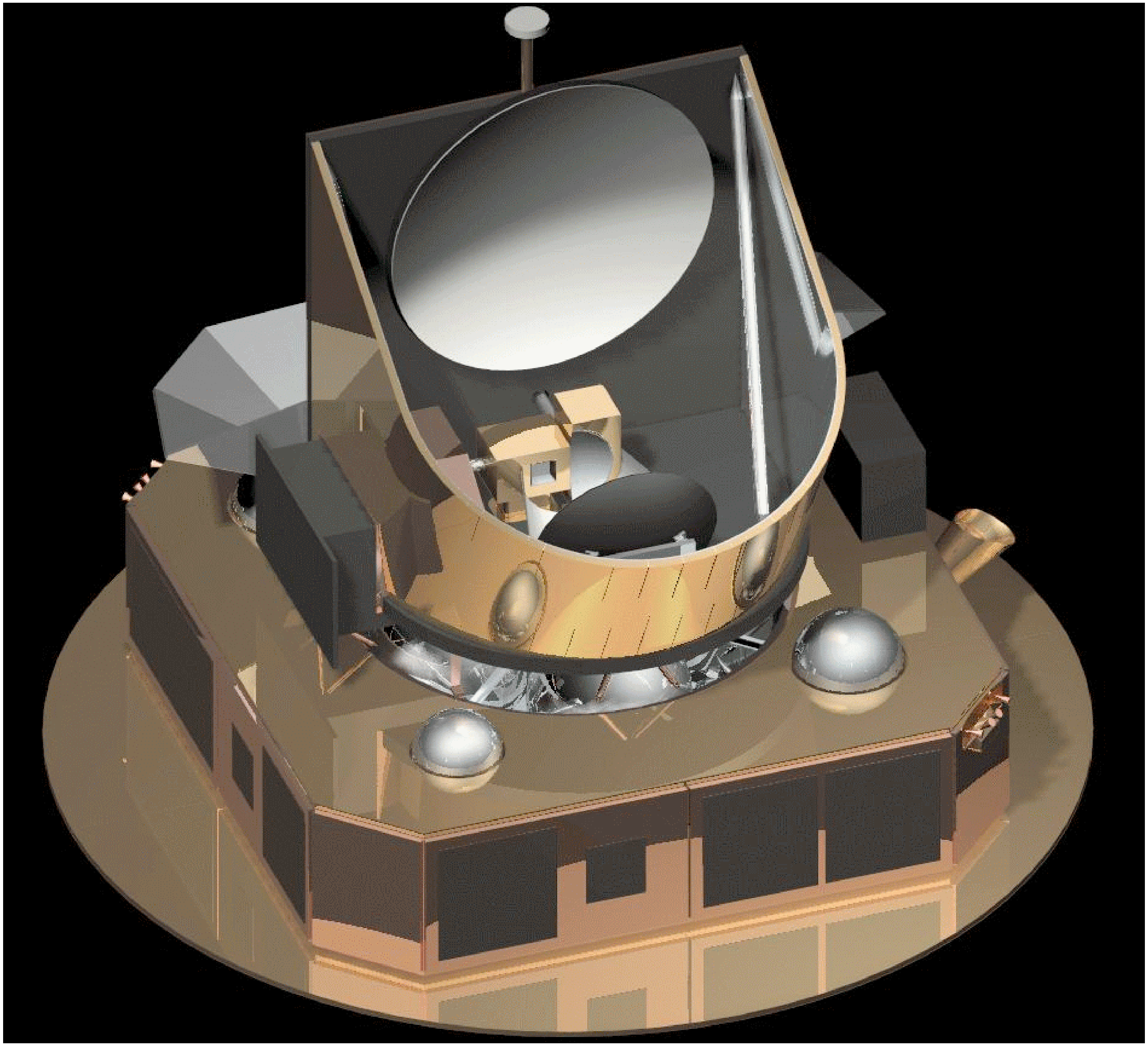
Power spectrum from first 2 years of ACBAR observations

Kuo et al. astro-ph/0611198

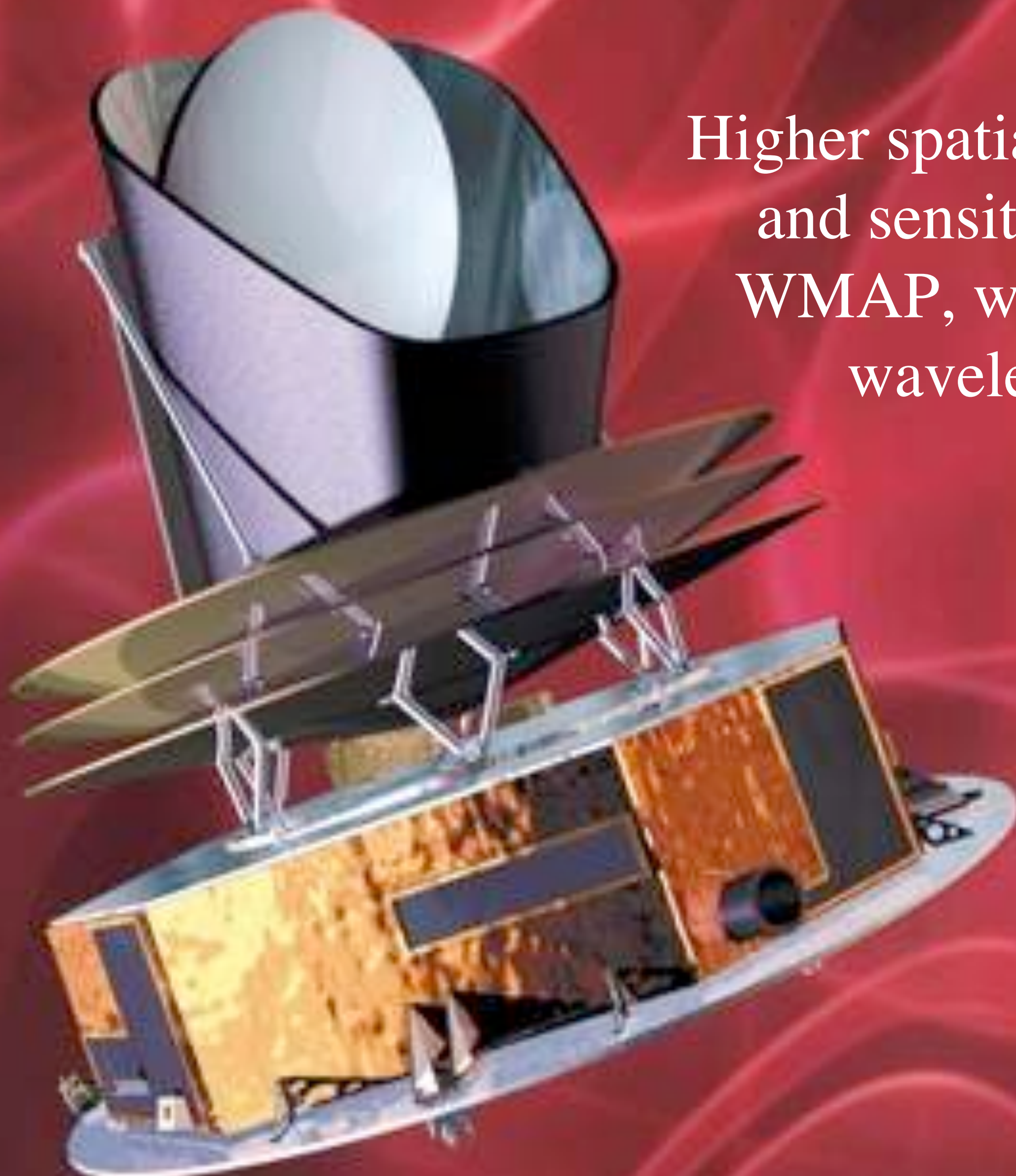
Analysis of final power spectrum with 4x more data in progress



More in the Future
e.g. Max Planck Surveyor Mission, launch 2008

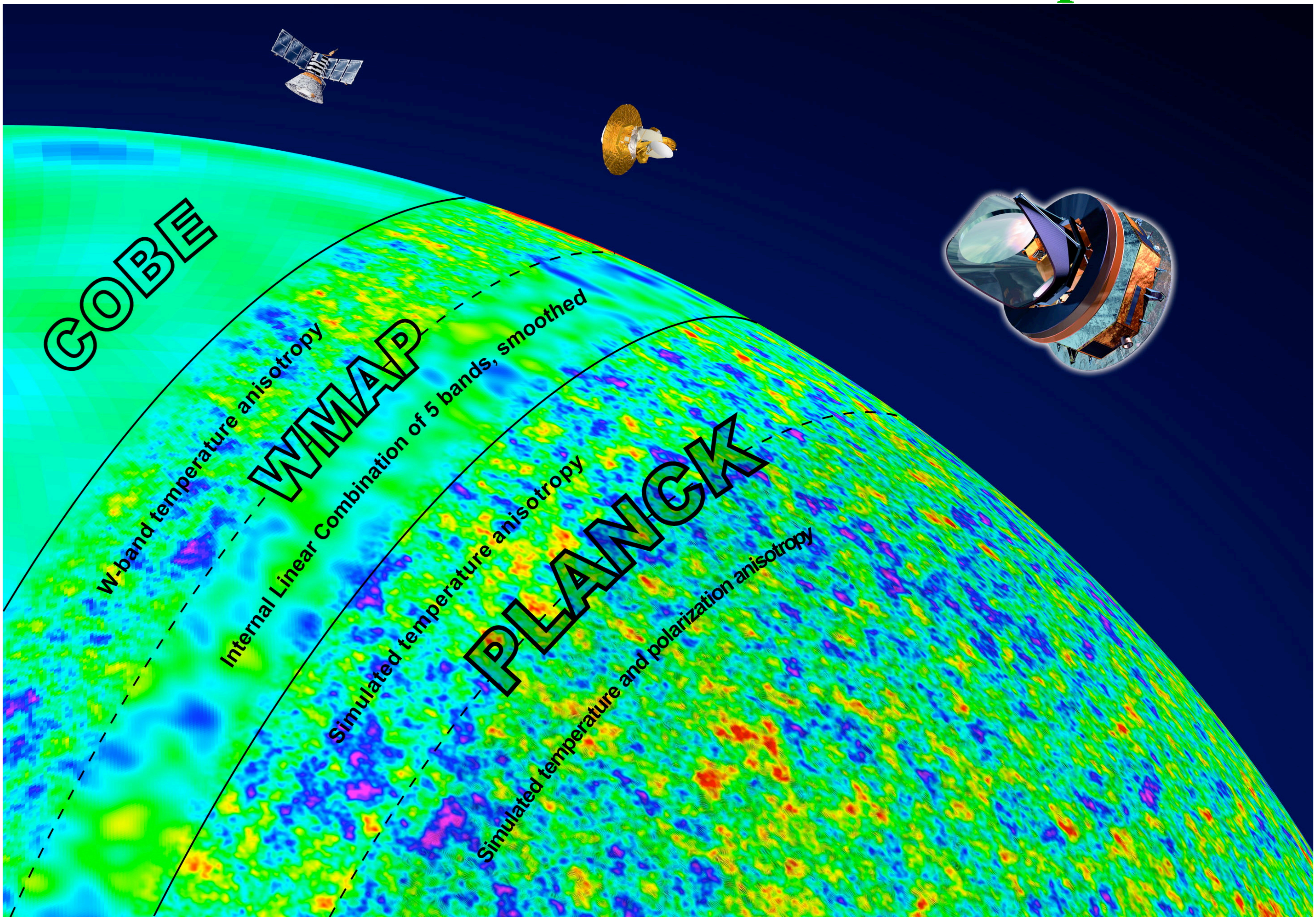


Planck Mission - ESA-led with NASA contributions, for 2008 launch



Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths

Evolution Of CMB Satellite Maps

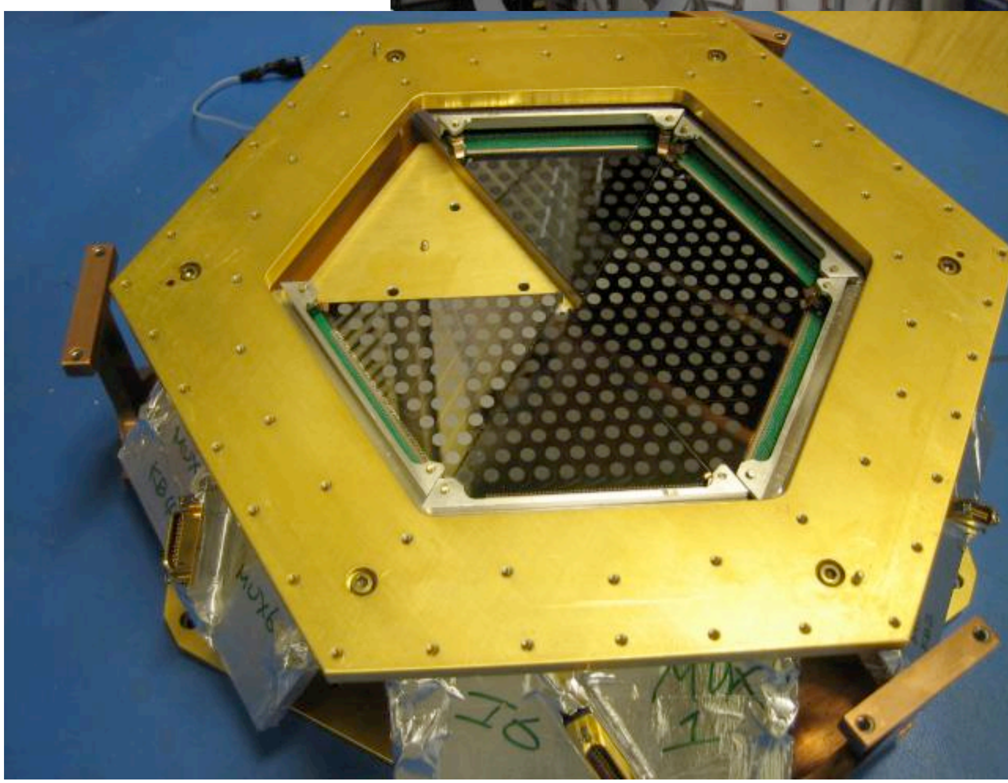


APEX-SZ

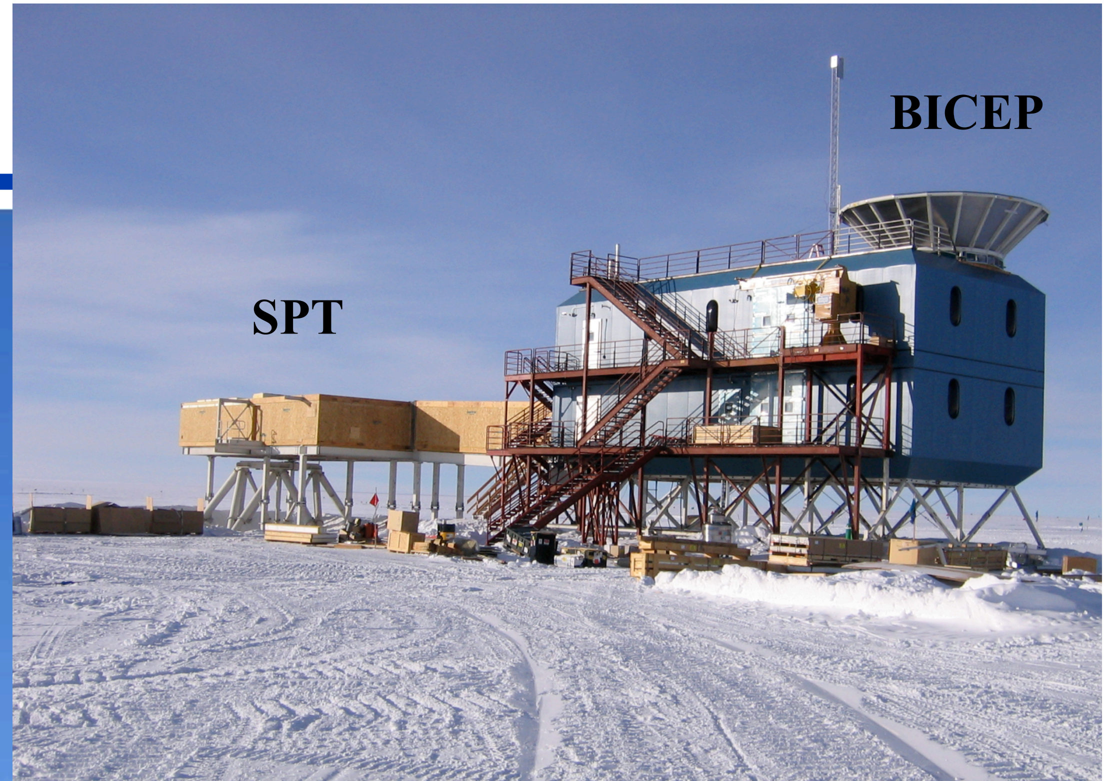
Receiver being Installed for engineering run

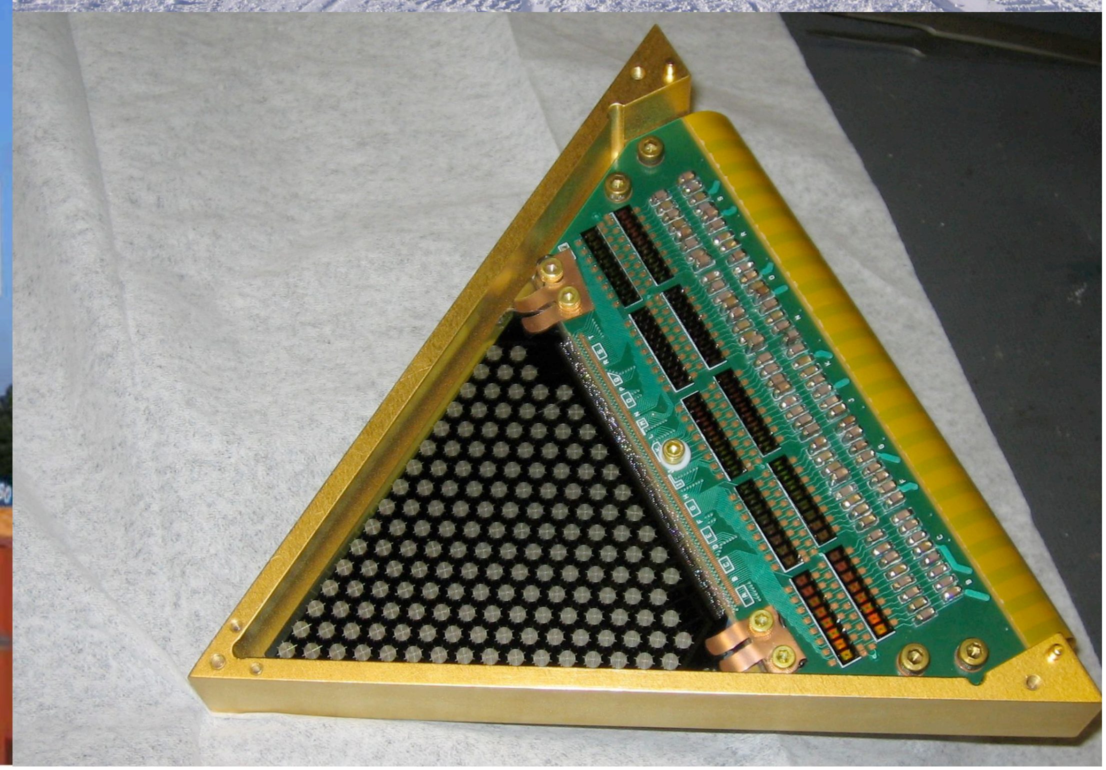
First Science In Spring 07

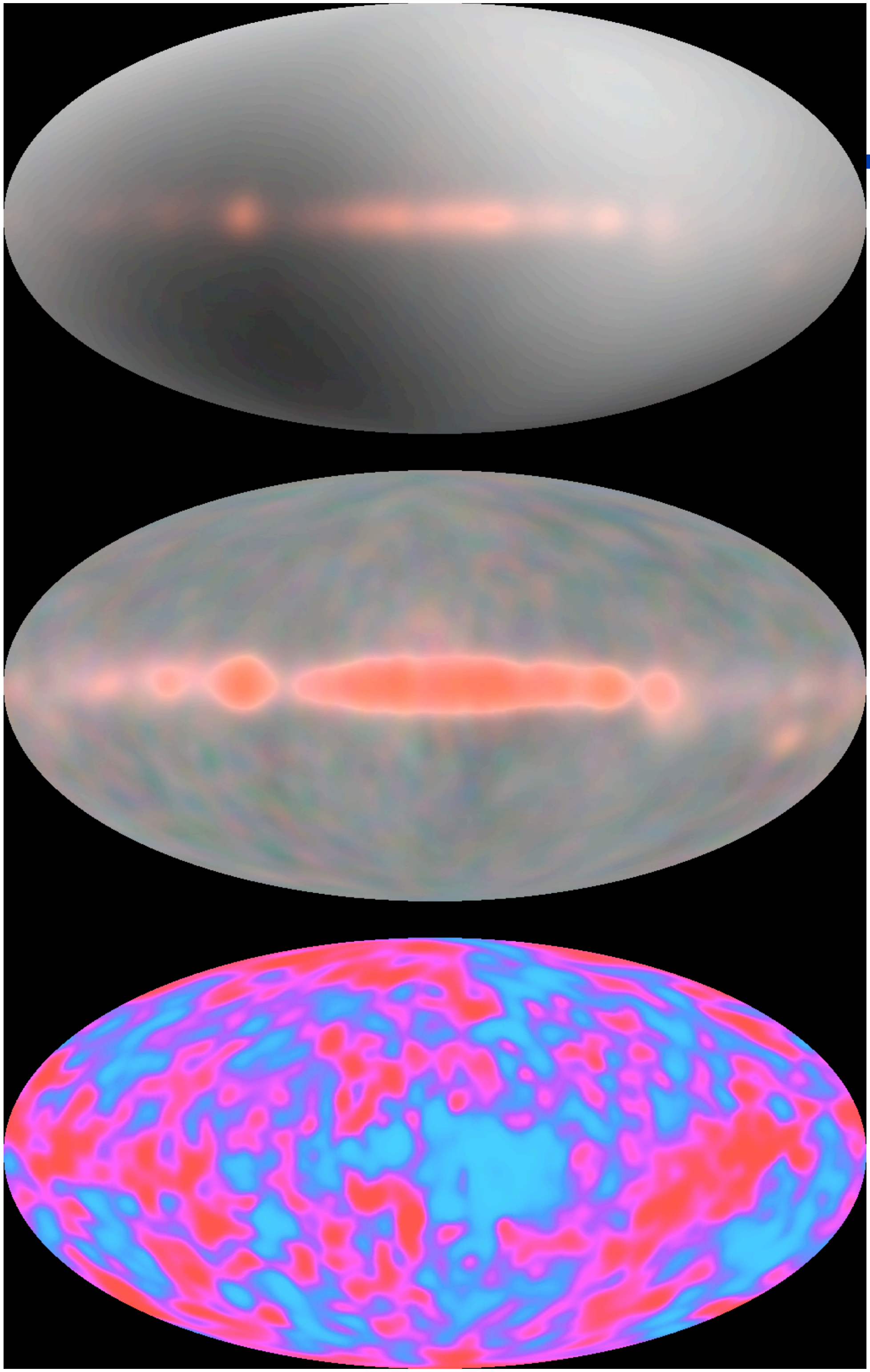
Adrian Lee



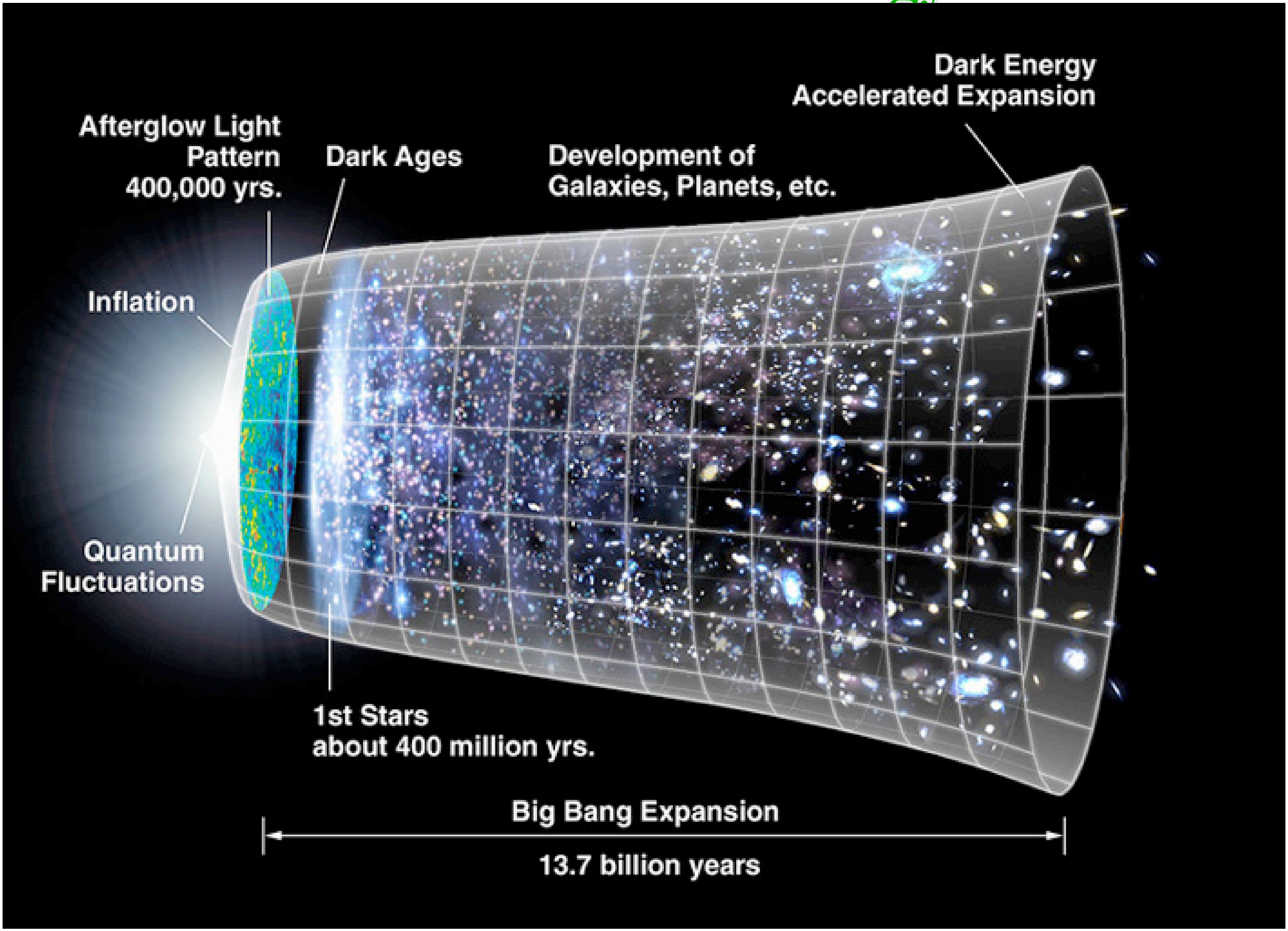
SPT will begin observations from the Pole this February





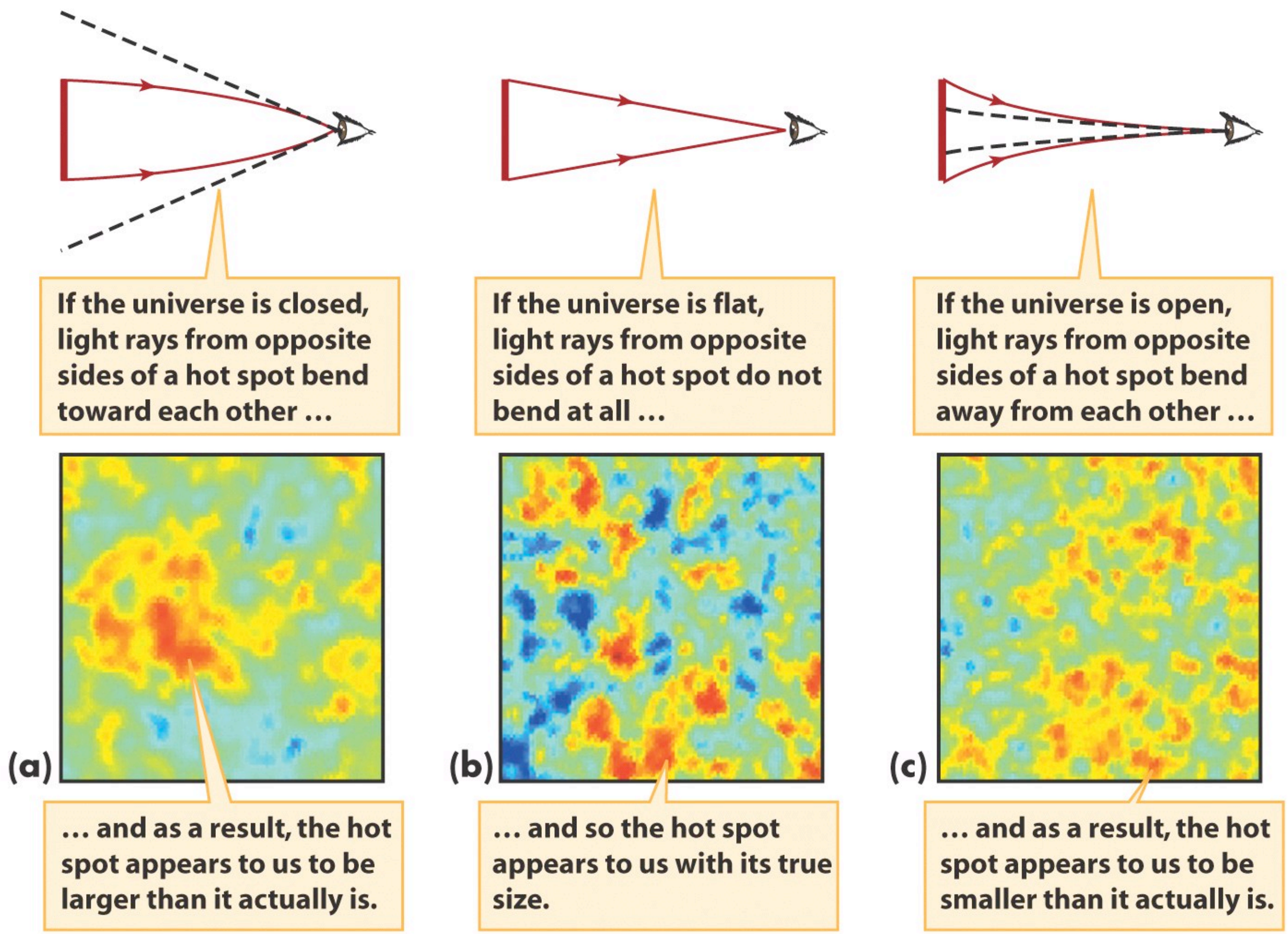


Current Cosmology



Our Universe is flat

- The theoretically predicted hot spot size (about 1 degree) is very close to what is observed
- Therefore, our universe is flat, or density parameter is 1.0

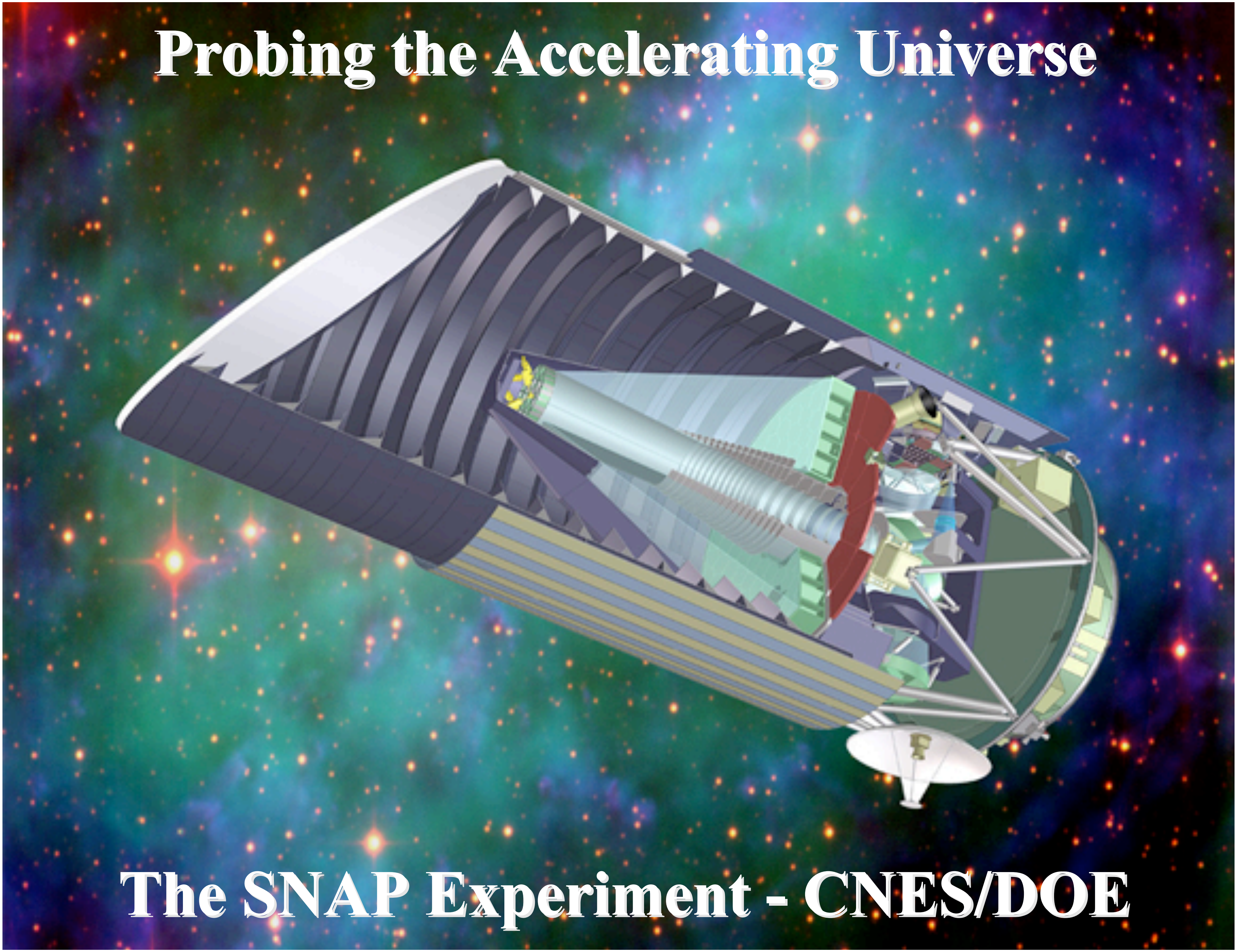


State-of-the-Art of the Universe

- Age: 13.7 billion years
- Composition: 73% dark energy, 23% dark matter, 4% ordinary matter

table 28-2 Some Key Properties of the Universe

Quantity	Significance	Value*
Hubble constant, H_0	Present-day expansion rate of the universe	71^{+4}_{-3} km/s/Mpc
Density parameter, Ω_0	Combined mass density of all forms of matter *and* energy in the universe, divided by the critical density	1.02 ± 0.02
Matter density parameter, Ω_m	Combined mass density of all forms of matter in the universe, divided by the critical density	0.27 ± 0.04
Density parameter for ordinary matter, Ω_b	Mass density of ordinary atomic matter in the universe, divided by the critical density	0.044 ± 0.004
Dark energy density parameter, Ω_Λ	Mass density of dark energy in the universe, divided by the critical density	0.73 ± 0.04
Age of the universe, T_0	Elapsed time from the Big Bang to the present day	$(1.37 \pm 0.02) \times 10^{10}$ years
Age of the universe at the time of recombination	Elapsed time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation	$(3.79^{+0.08}_{-0.07}) \times 10^5$ years
Redshift z at the time of recombination	Since the cosmic background radiation was released, the universe has expanded by a factor $1 + z$	1089 ± 1


Probing the Accelerating Universe
The SNAP Experiment - CNES/DOE