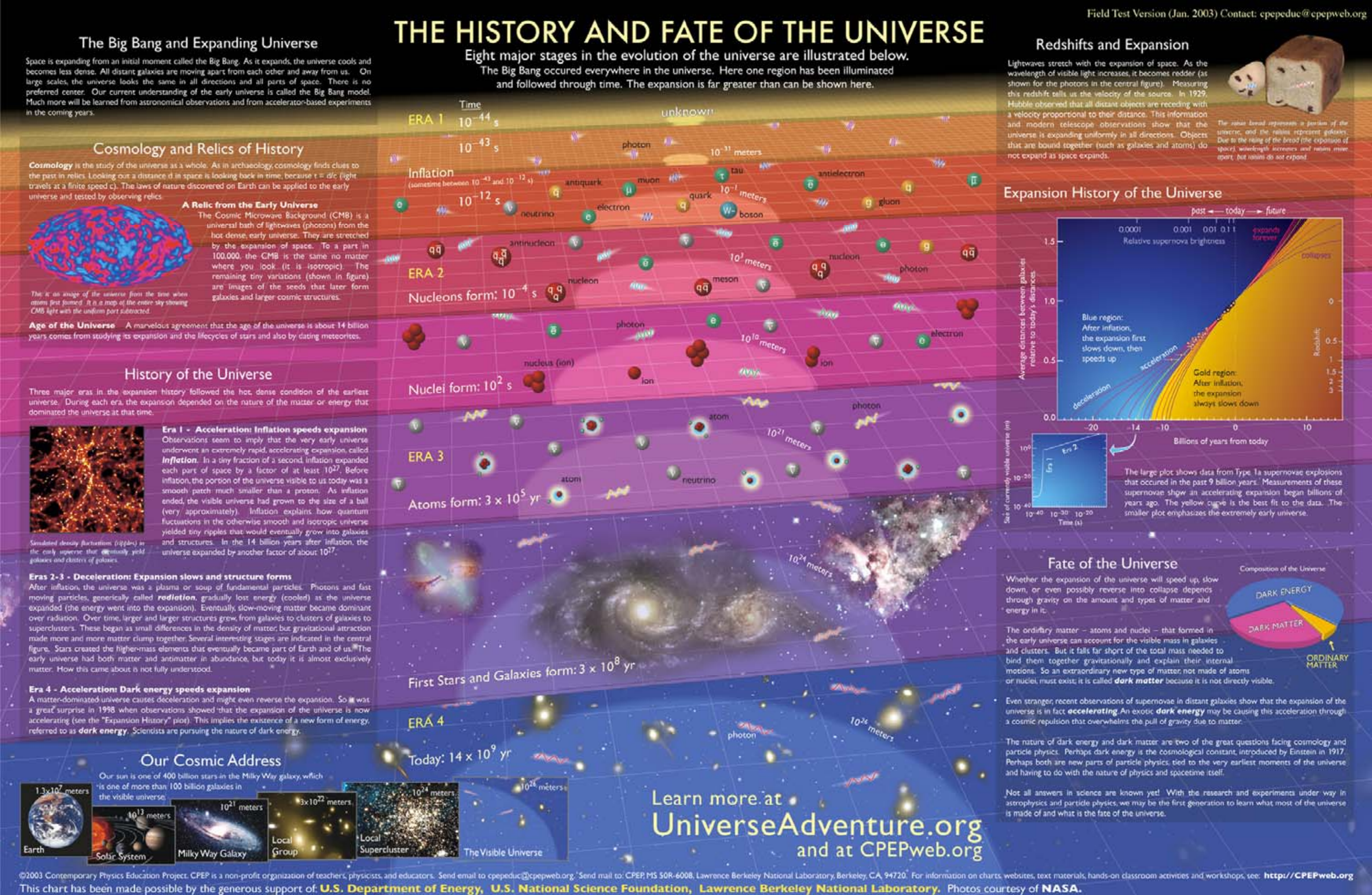
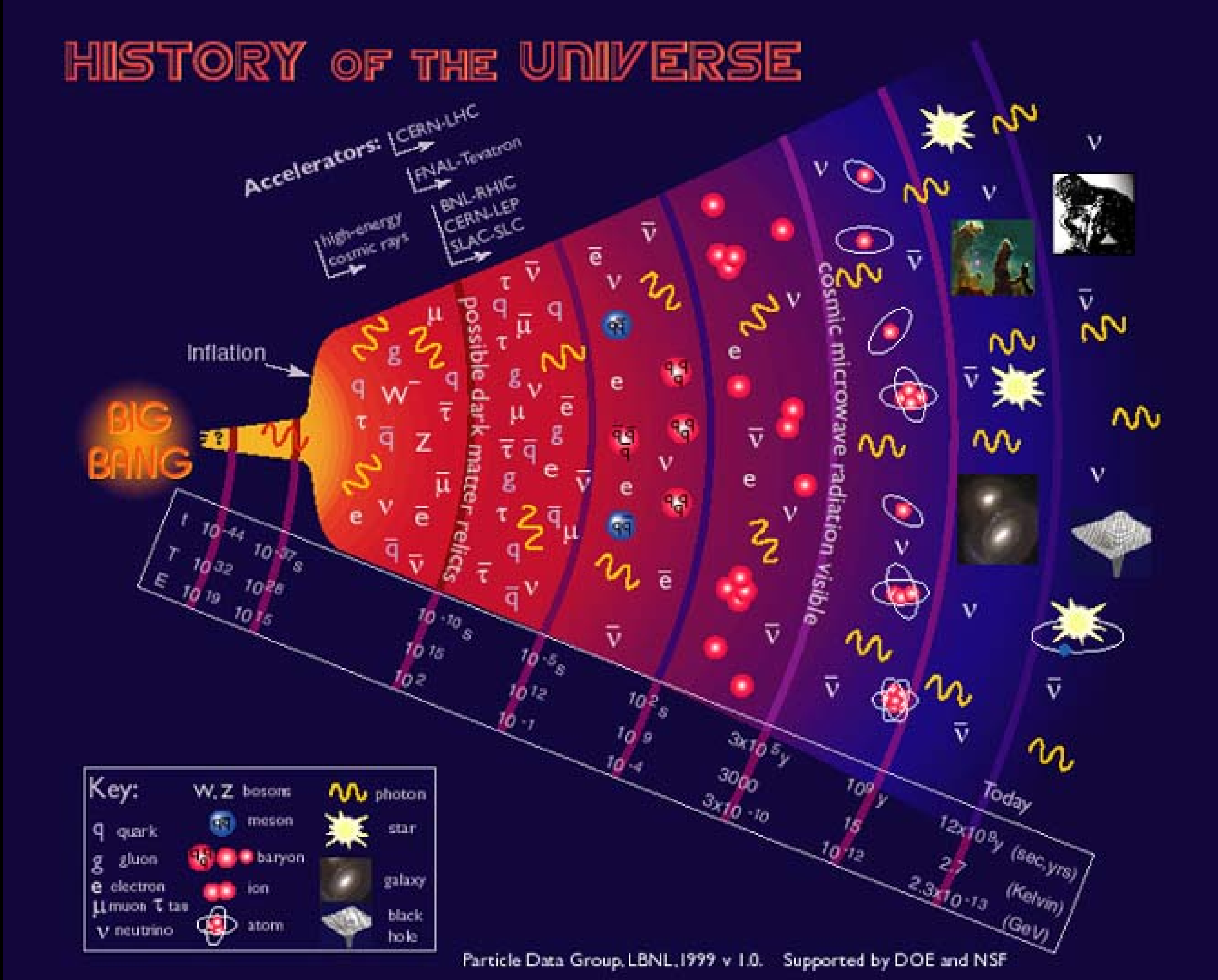


The Beginning of the Universe

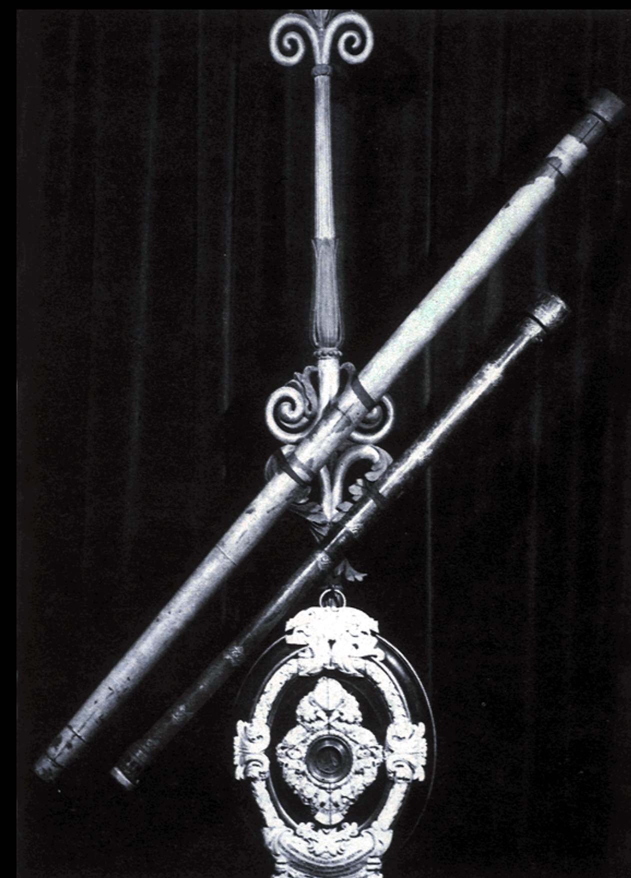
Professor George F. Smoot

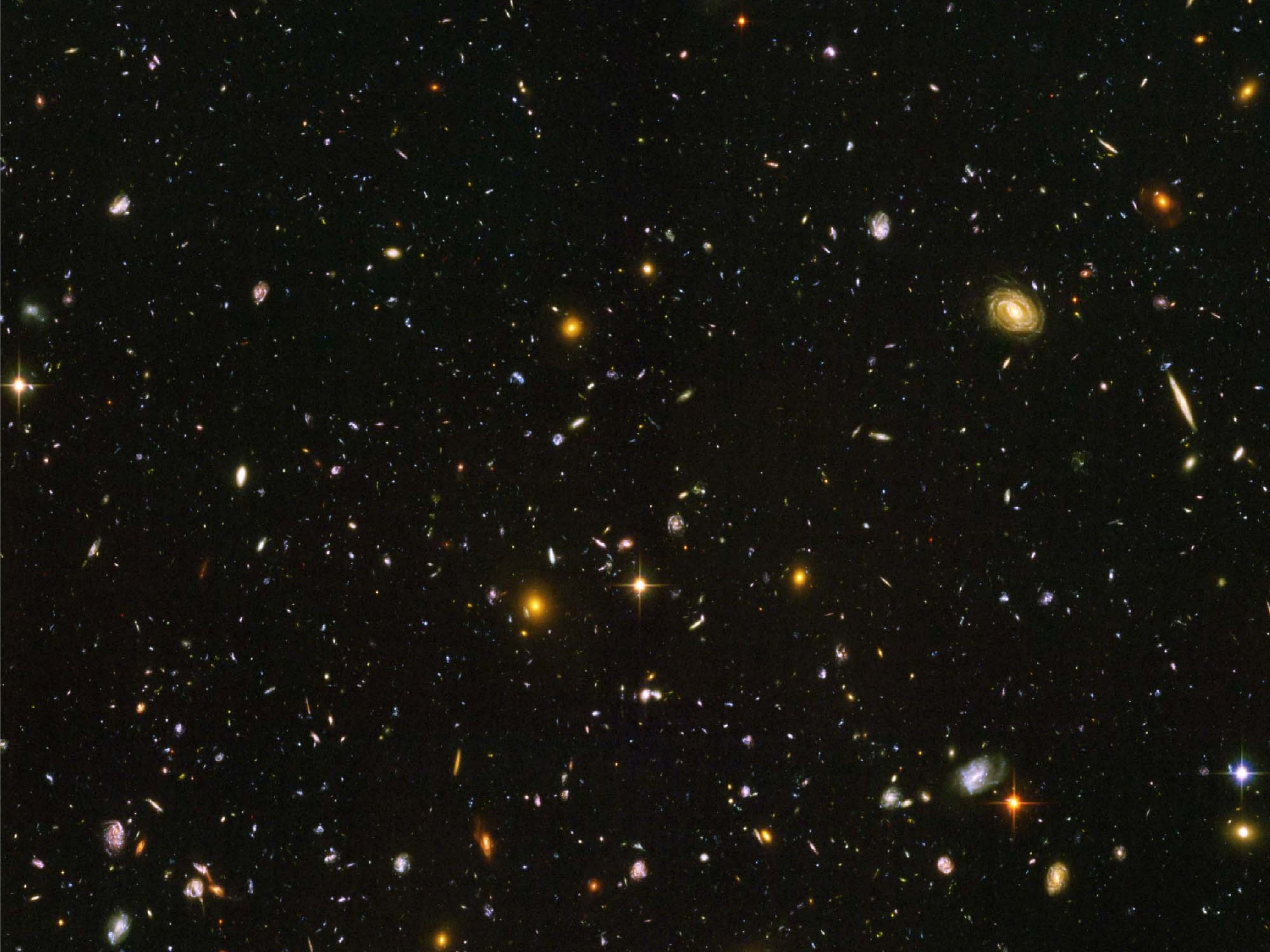
Chaire Blaise Pascal U. Paris VII, LBNL & Physics Department, University of California at Berkeley

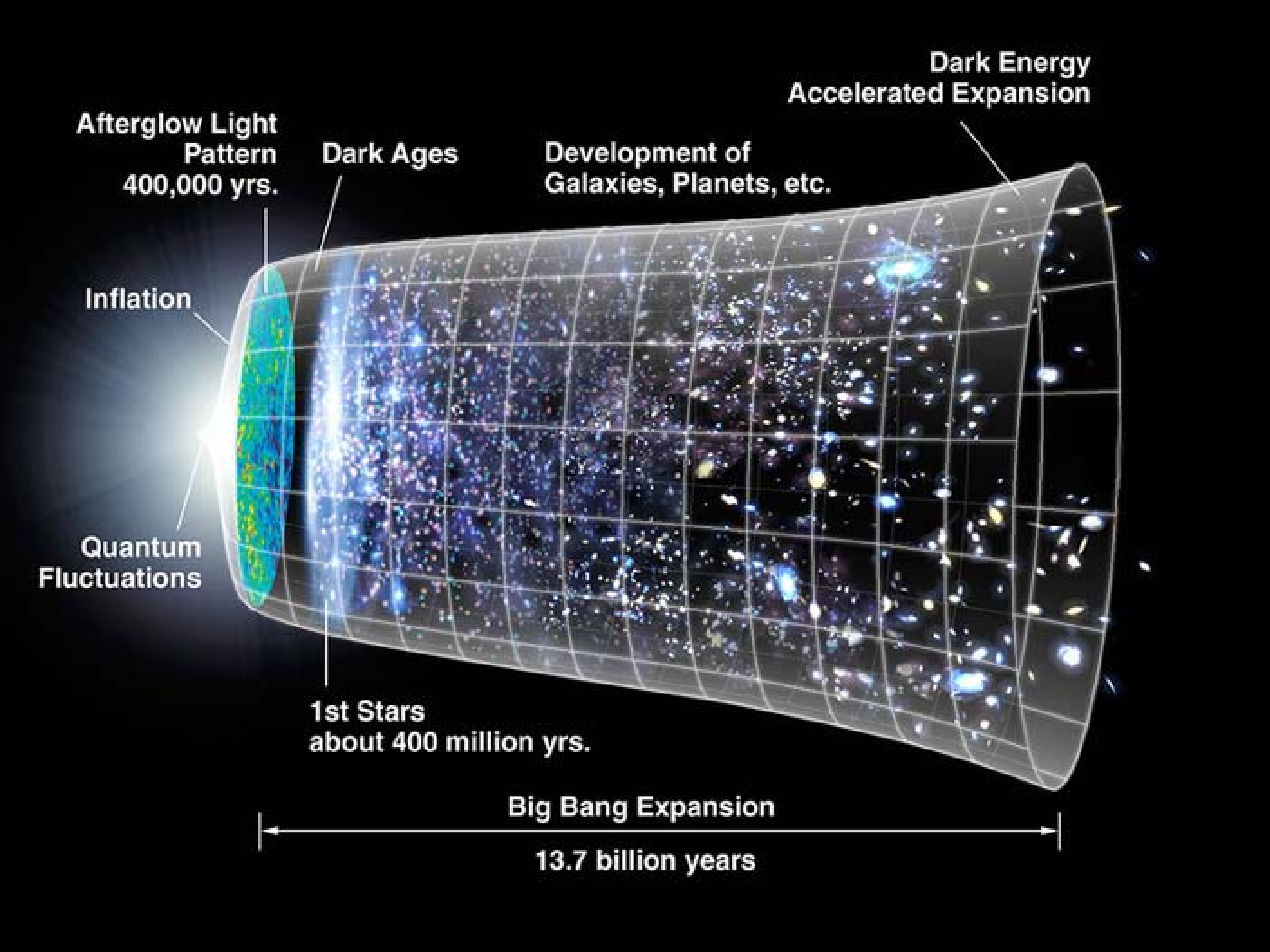

HISTORY OF THE UNIVERSE
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, 1999 v 1.0. Supported by DOE and NSF

Galileo Galilei

- Galileo created an enormous sensation when he built one of the first telescopes in 1609, pointed it at the sky, and published his discoveries in 1610 in “Sidereus Nuncius” or “Starry Messenger”. (moons of Jupiter, phases of Venus, etc.)
- Galileo’s other investigations created the foundations of modern physics and cosmology.



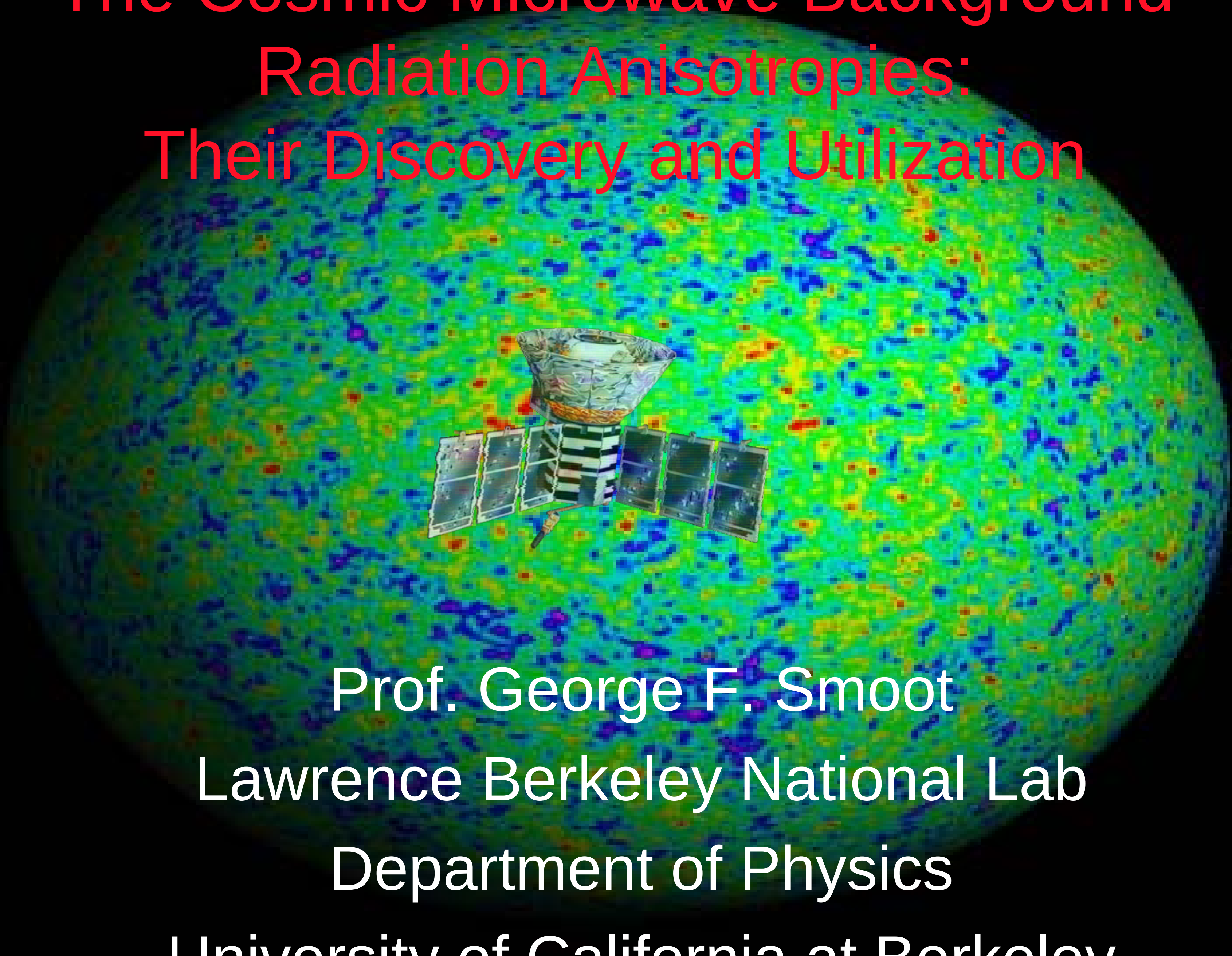



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Connections: Quarks to the Cosmos

Beyond Einstein and the Big Bang

The Cosmic Microwave Background Radiation Anisotropies: Their Discovery and Utilization

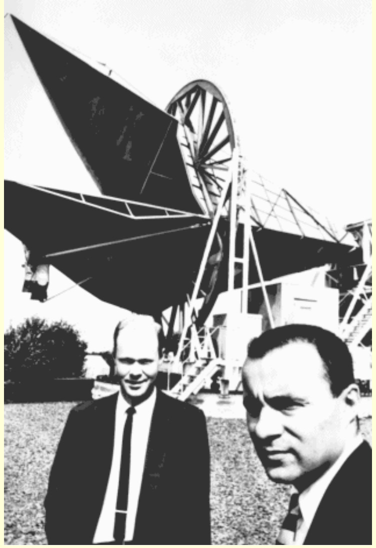


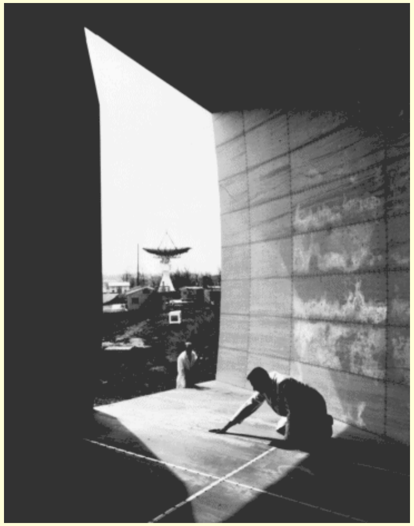
Prof. George F. Smoot
Lawrence Berkeley National Lab
Department of Physics
University of California at Berkeley

Relic Radiation from THE BIG BANG

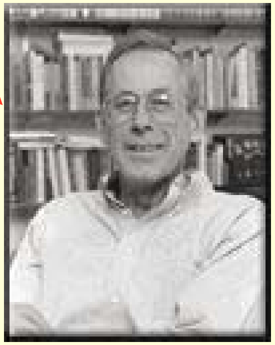
λ

±

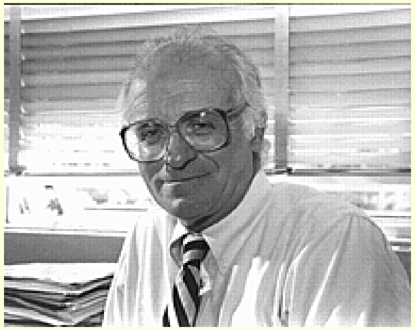




Arno Penzias & Robert Wilson Nobel Prize (1978)



Jim Peebles



Bernie Burke

Discovery of the Cosmic Background Radiation (CBR).

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

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

ν Frequency Spectrum - predicted thermal=blackbody

θ Angular distribution - map the sky

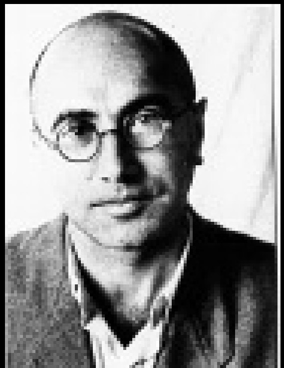
$\longrightarrow$ Polarization - low level linear expected

t Statistics - 1+z, Bose-Einstein / Planckian

SZ effect - Clusters scatter some CMB

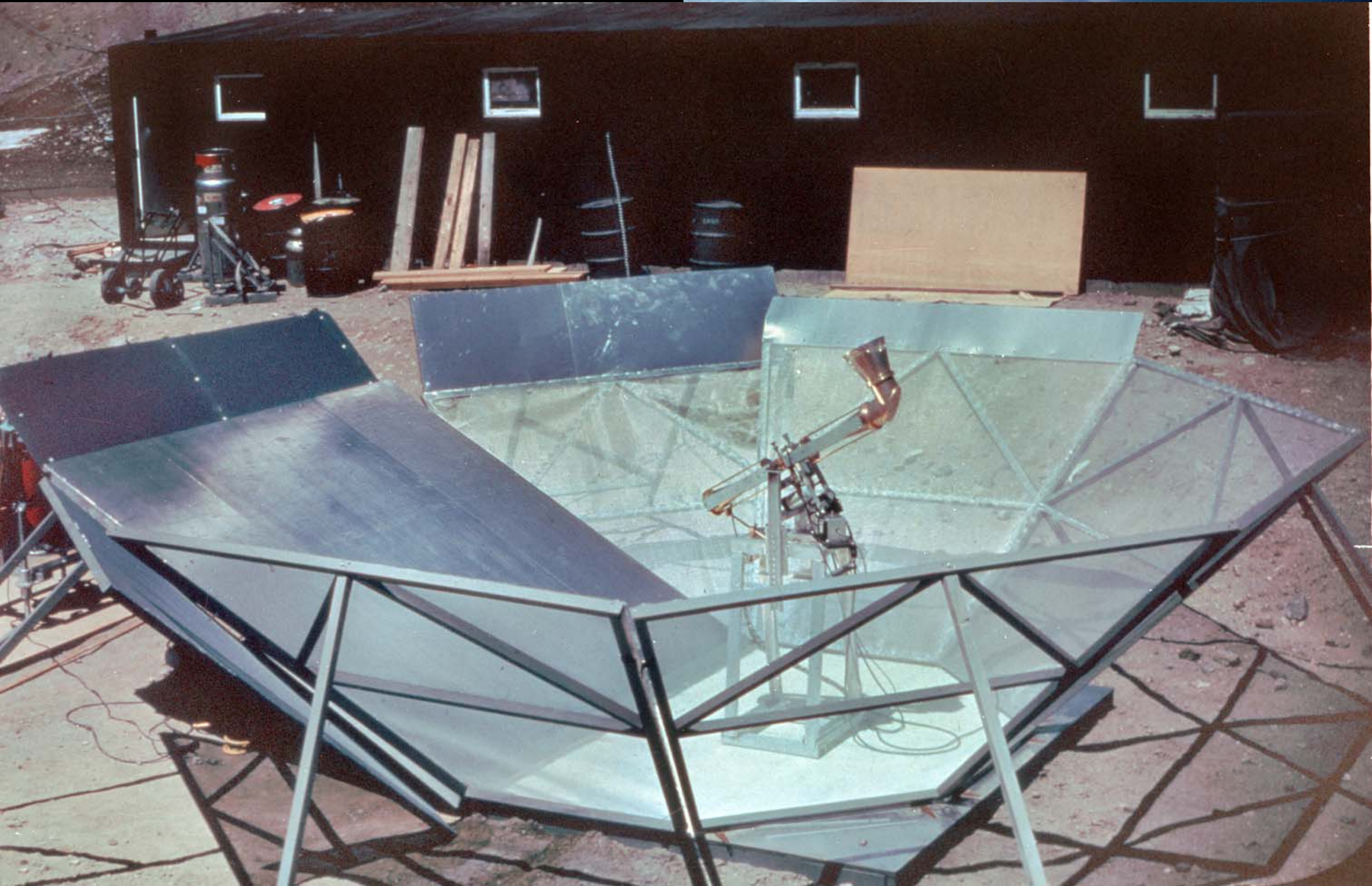
Rashid Sunyaev

Y. B. Zel'dovich

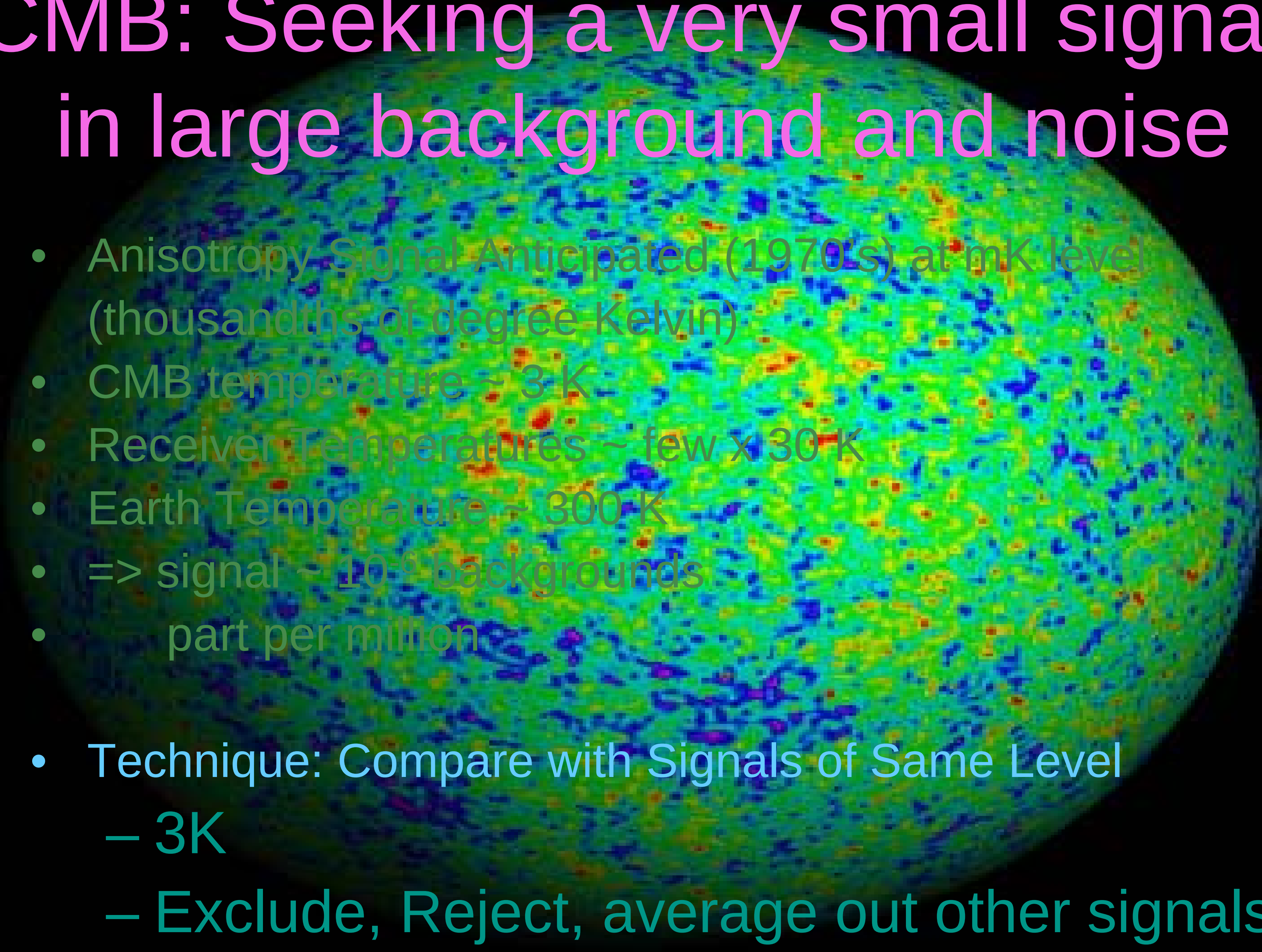


Penzias & Wilson / Bell Labs Receiver at Deutsches Museum

Dave Wilkinson's



CMB: Seeking a very small signal in large background and noise

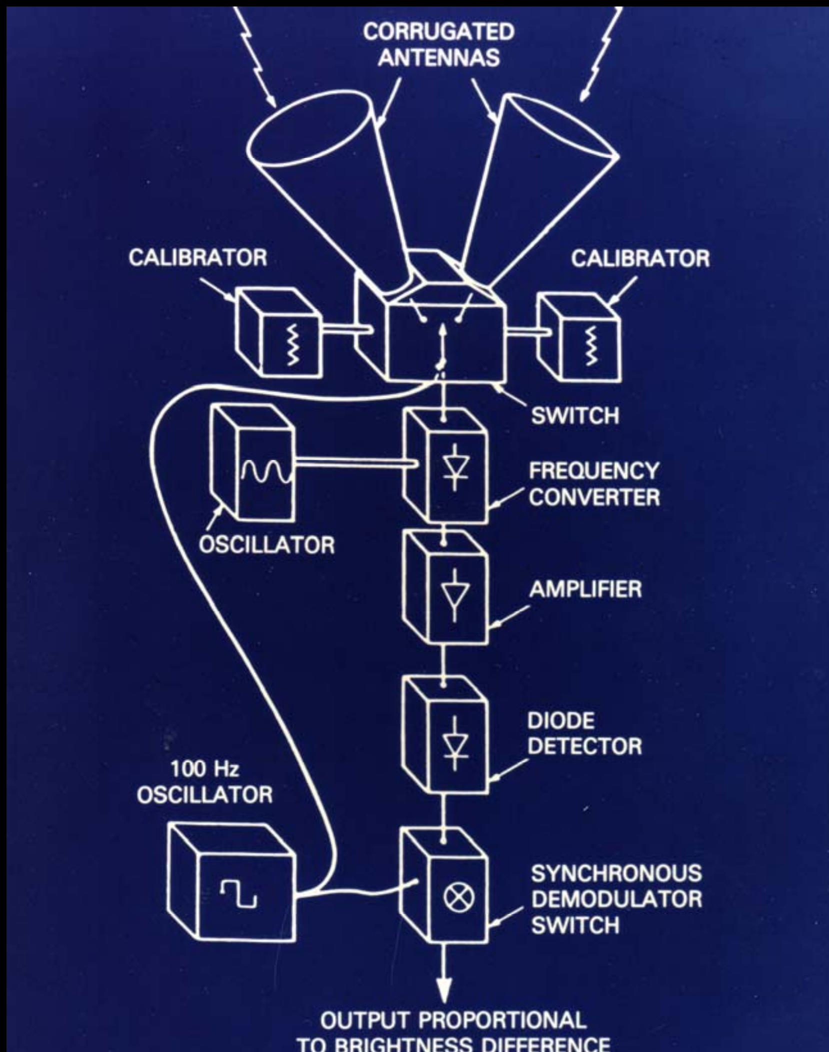


- Anisotropy Signal Anticipated (1970's) at mK level (thousandths of degree Kelvin)
- CMB temperature ~ 3 K
- Receiver Temperatures ~ few x 30 K
- Earth Temperature ~ 300 K
- => signal ~ 10^{-6} backgrounds
- part per million

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

DMR

Differential Microwave Radiometer



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Corrugated Horn Antennas

Standard Gain Horn

Corrugated Horn

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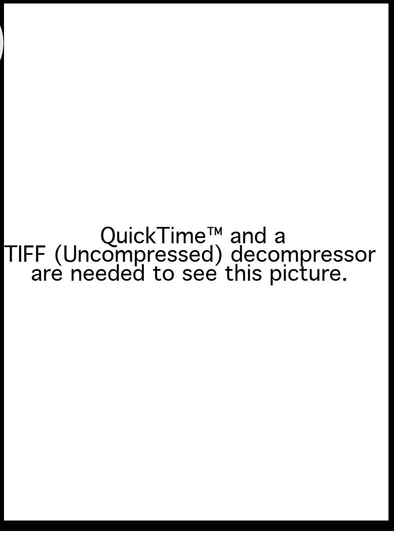
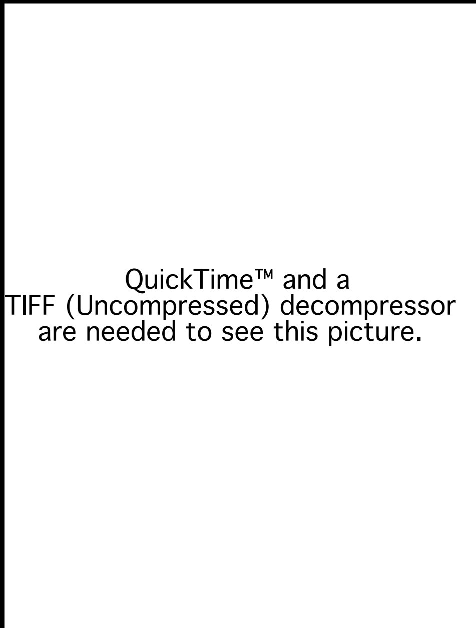
Radiometer system to map the cosmic background radiation

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

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

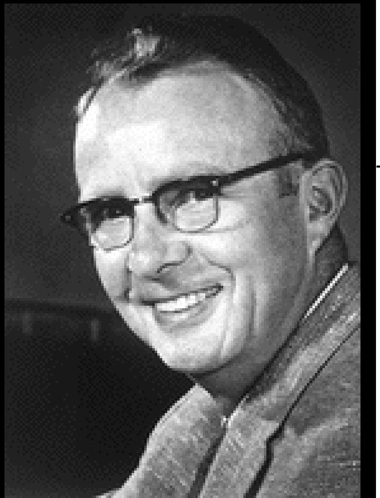




Technical and Engineering

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

Luis Alvarez



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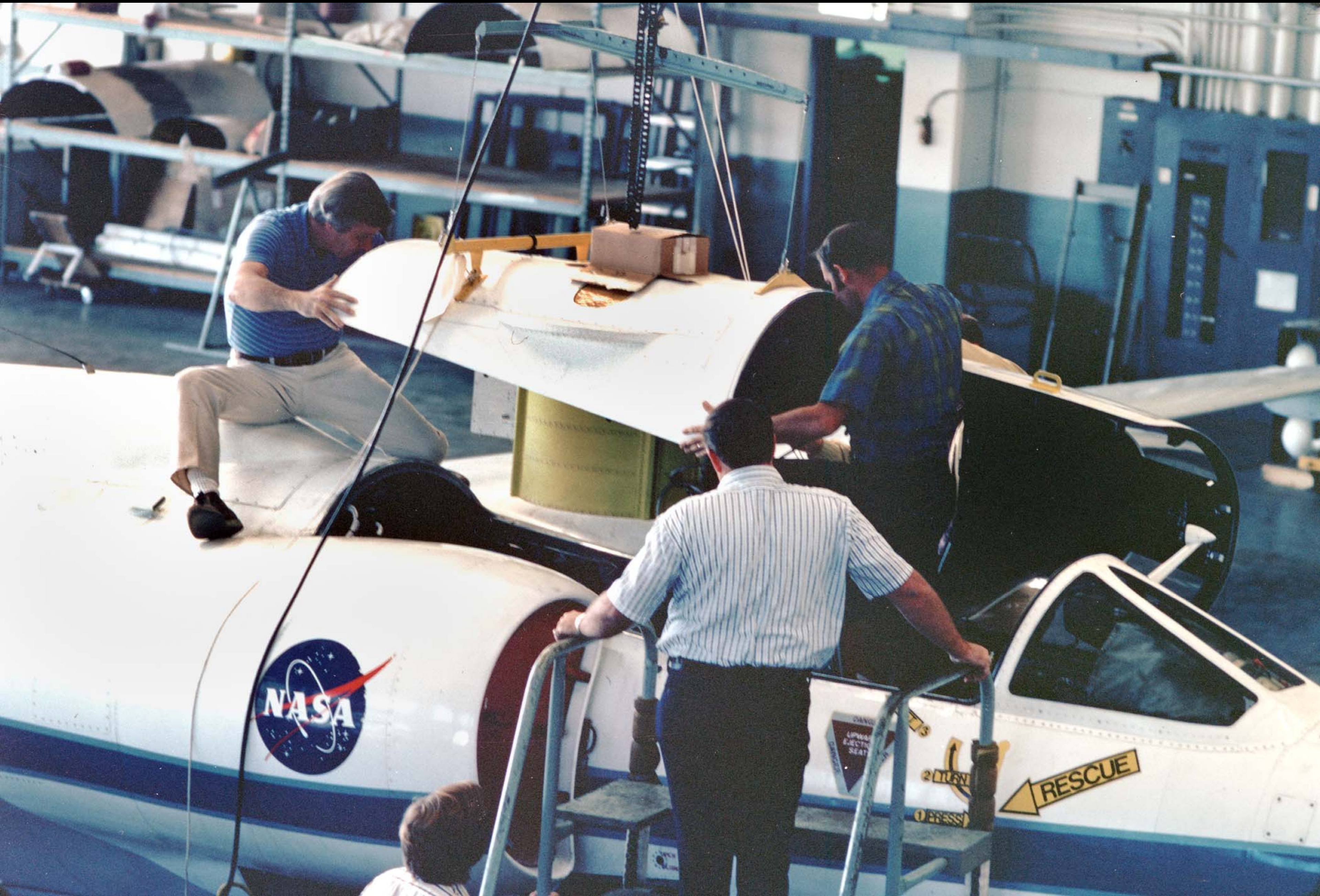
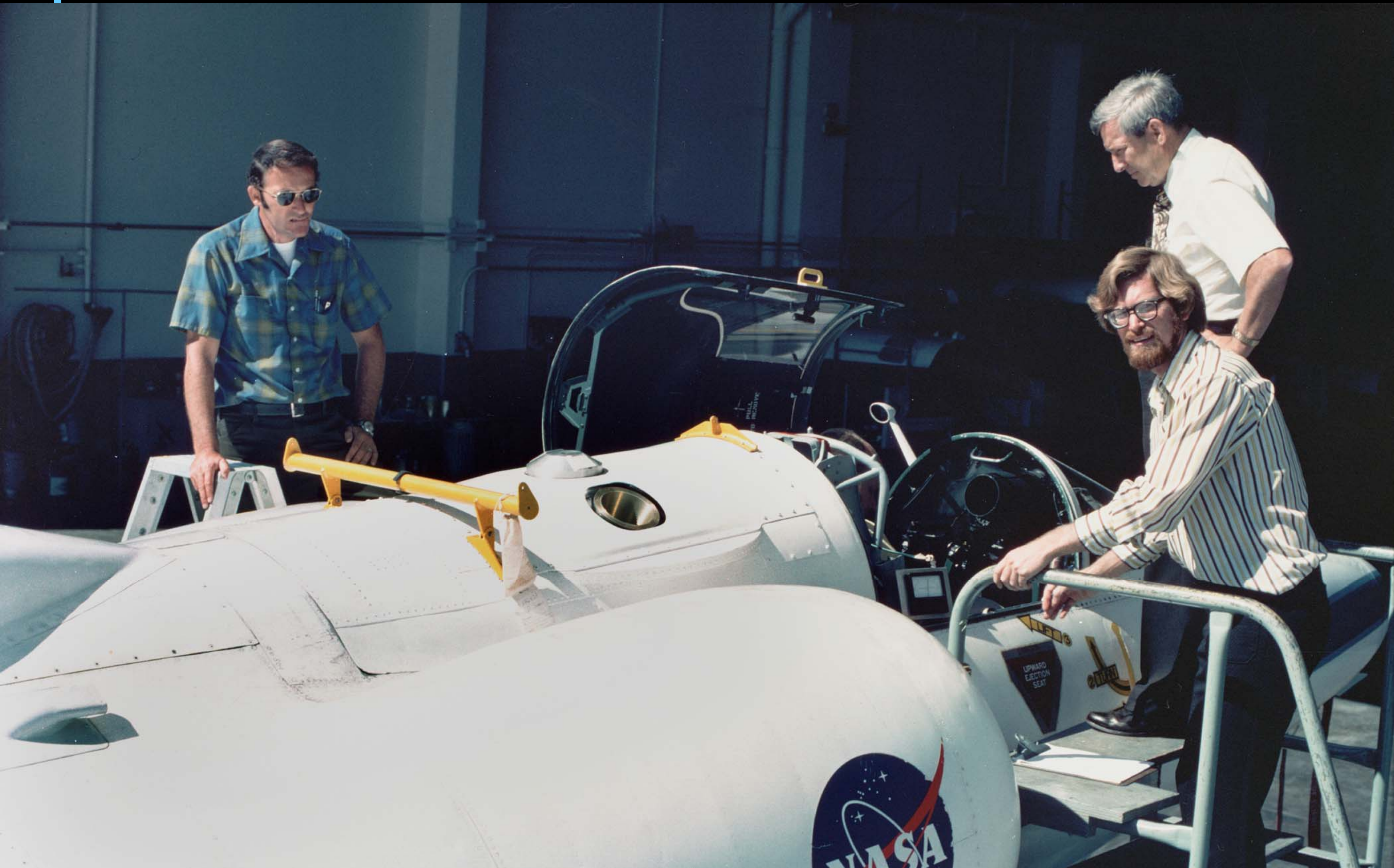
Instrument into NASA craft



Scientists from DOE Lab put instruments on NASA Platform



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NASA
708
66681
Marc Gorenstein

U2 can find

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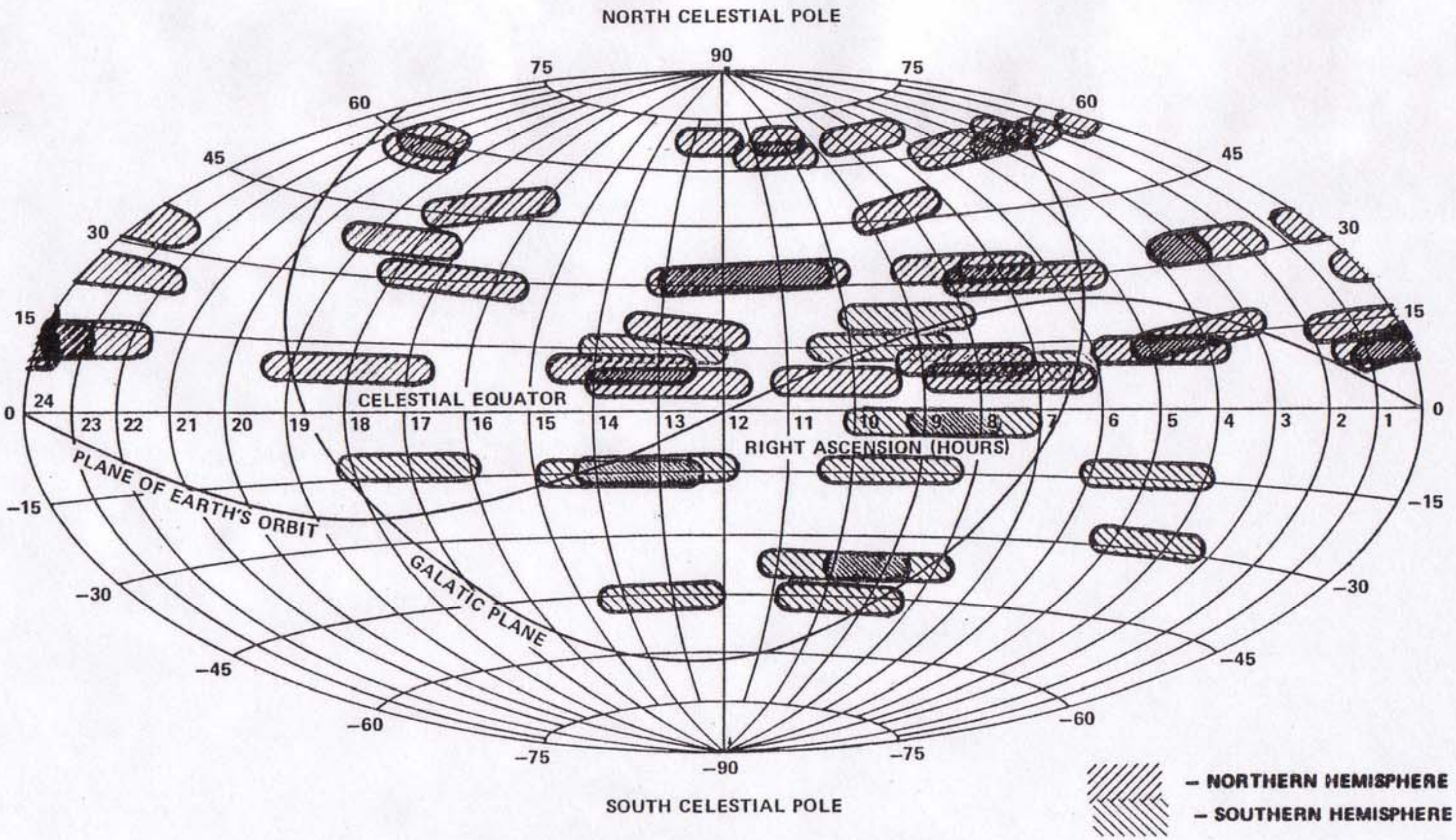
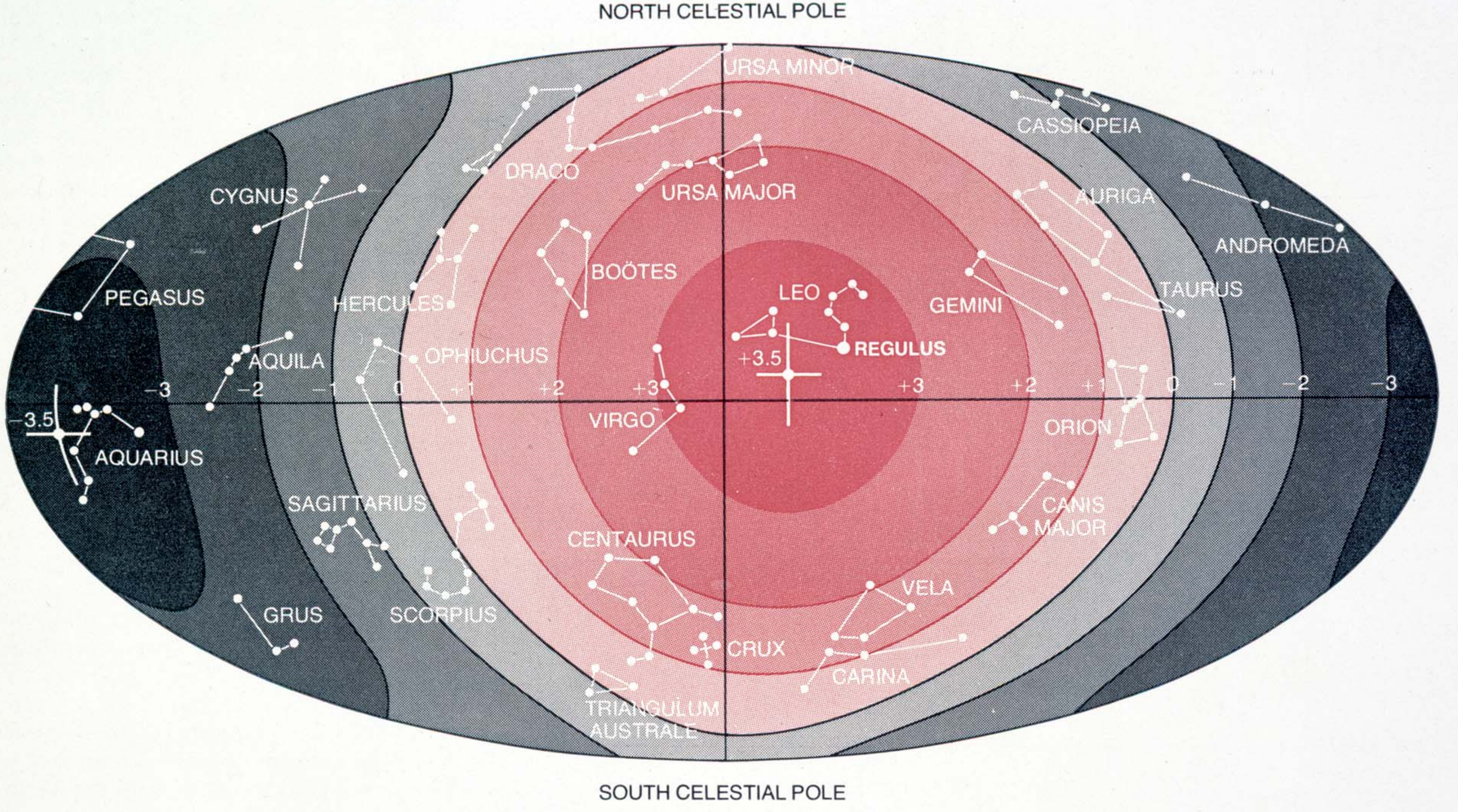


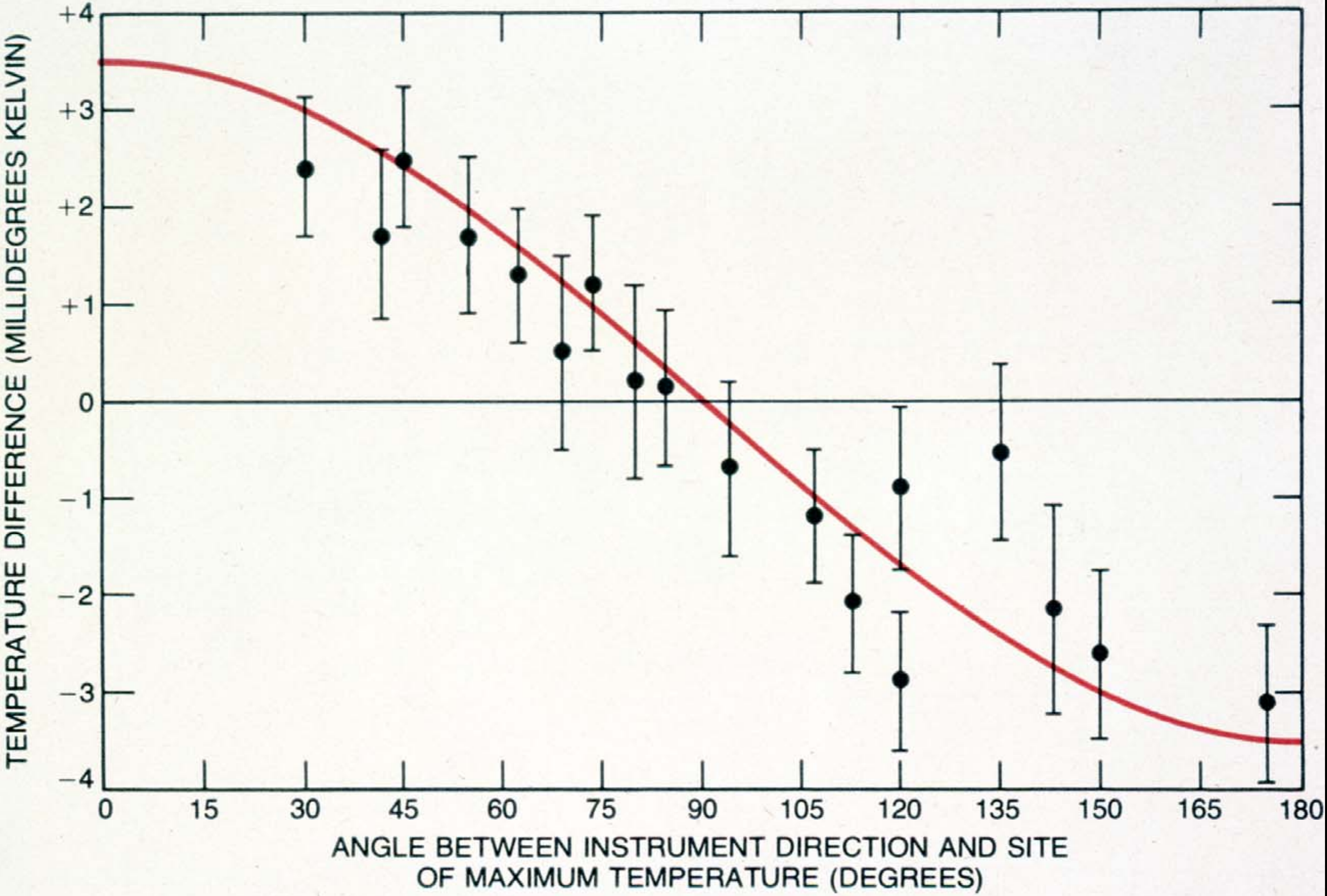
Figure 1. Plot of Sky Coverage in Celestial Coordinates. Sky coverage for the northern flights from NASA Ames in California and southern flights from Lima, Peru is indicated by the shaded regions. The width of each region is set by the 7° antenna beam widths, and the length is set by the rotation of 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



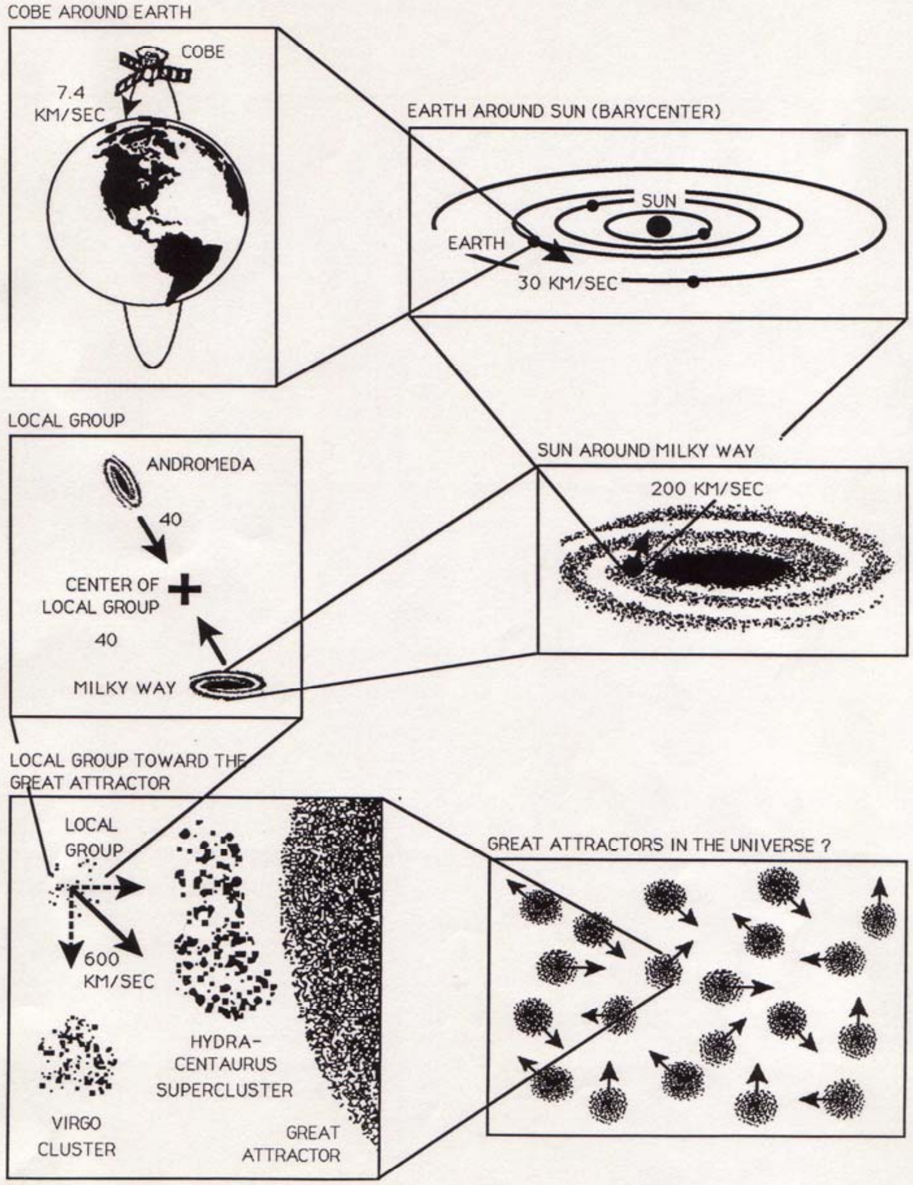
ANISOTROPY OF THE BACKGROUND RADIATION, as deduced from the U-2 survey, is plotted on the celestial sphere in contours of one millidegree K. The “hottest” spot, indicating the direc-

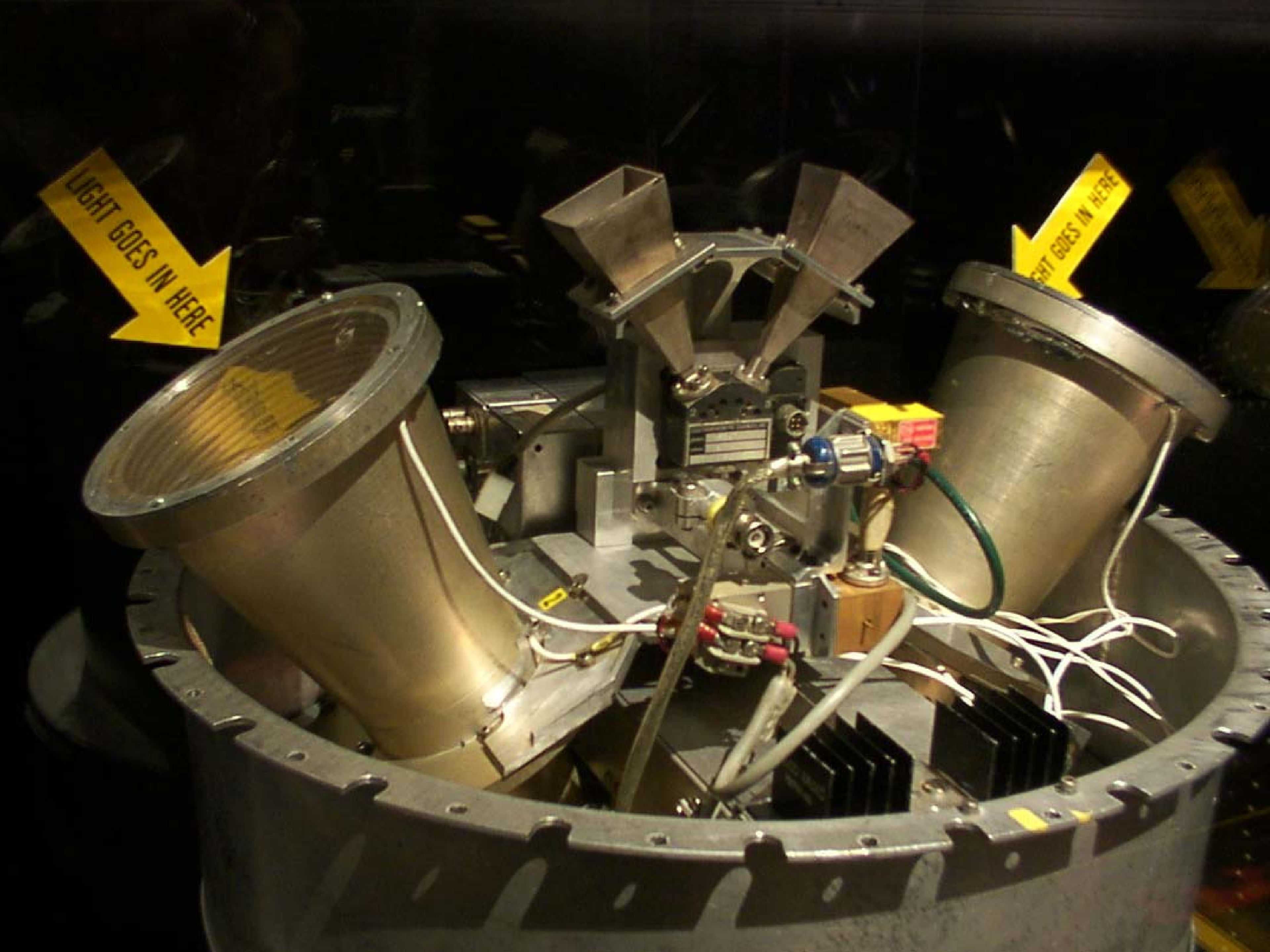
(±.5 hour) and latitude six degrees (±10 degrees). The “coldest” spot, the direction in which the radiation is most “reddened” by the earth’s relative motion away from the incoming photons, lies 180 degrees



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.

VELOCITY COMPONENTS OF THE OBSERVED CMB DIPOLE




LIGHT GOES IN HERE
GOES IN HERE

Pioneer

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TIFF (Un
are ne

QuickTime™ and a
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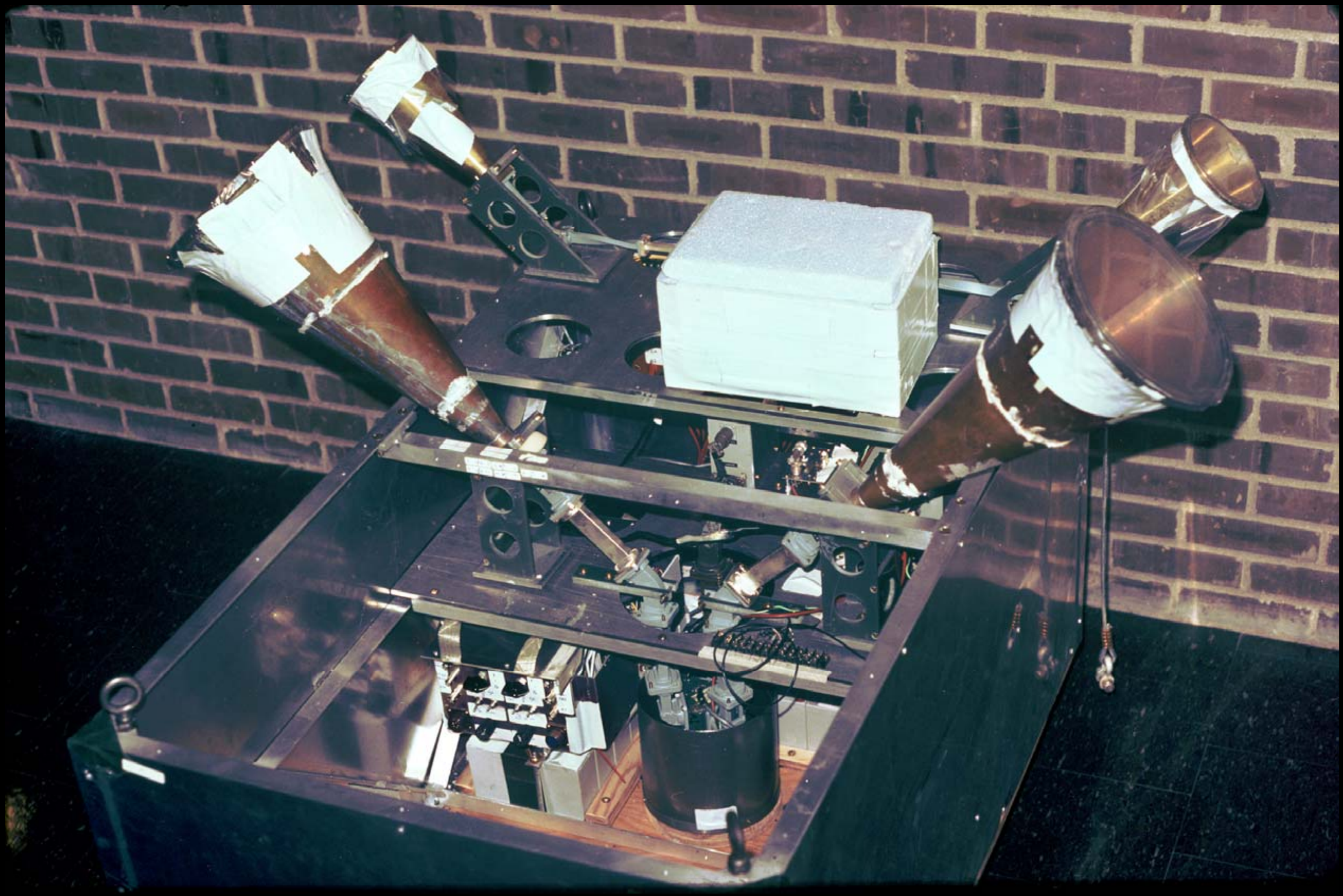
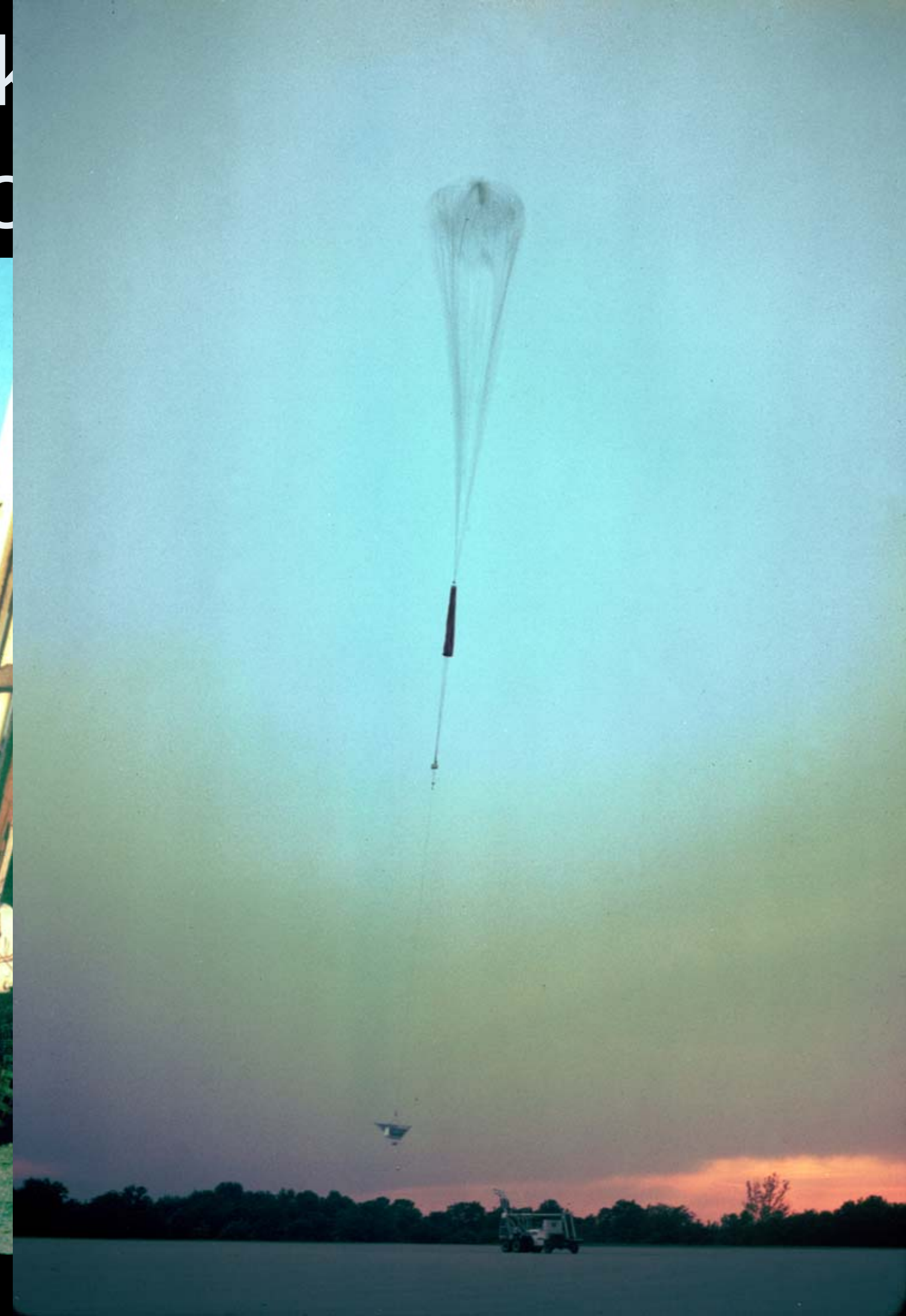
Princeton large-angular scale anisotropy
same epoch as Berkeley 3-mm



Peter Saulson & assembled payload

Princeton plus Berk
being readied fo

Peter Saulsen Dave Wilkinson



Three Balloon Flights Later- our CMB map

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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

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Spectrum of the Cosmic Background Radiation

D. P. Woody and P. L. Richards

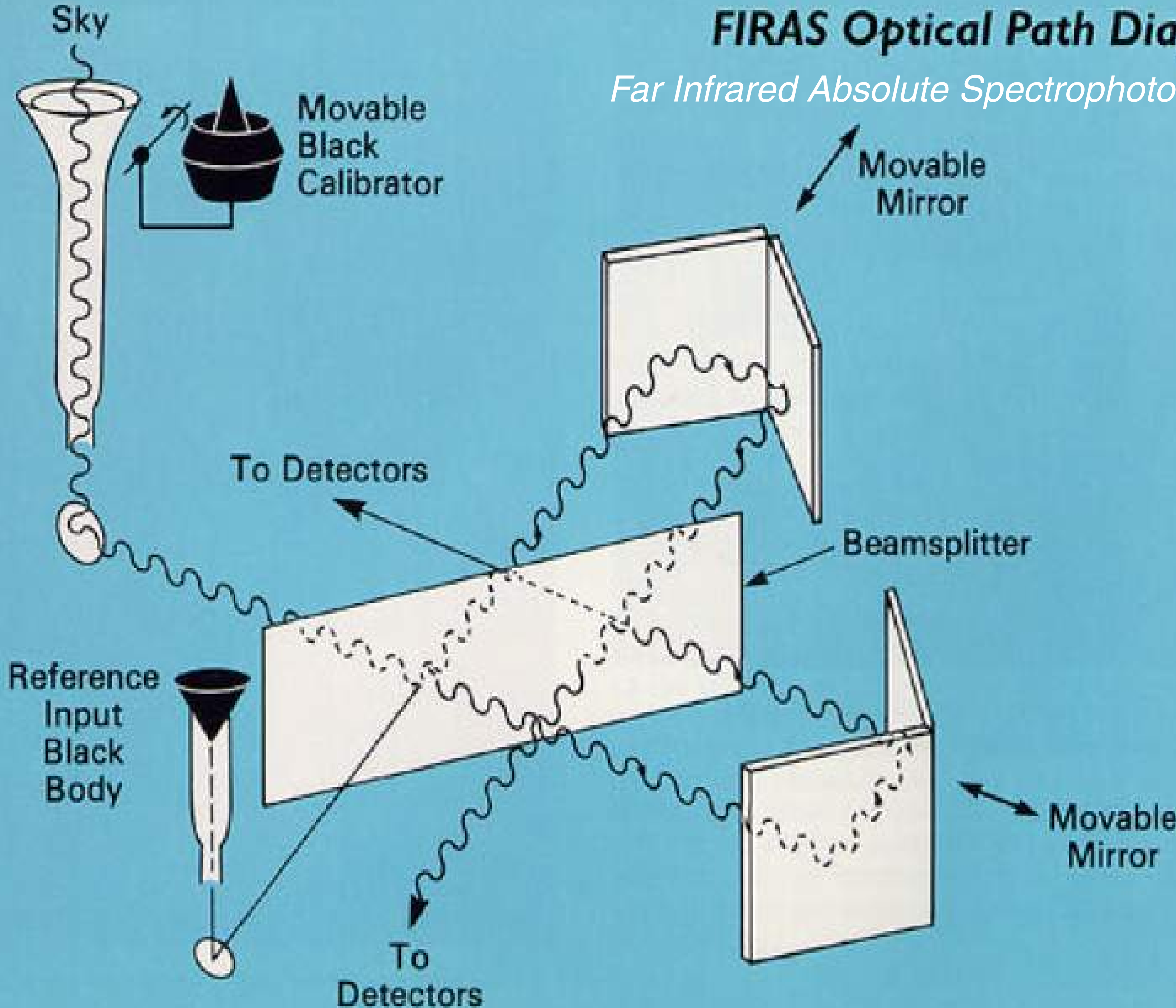
Received 15 December 1978

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.

FIRAS Optical Path Diagram

Far Infrared Absolute Spectrophotometer

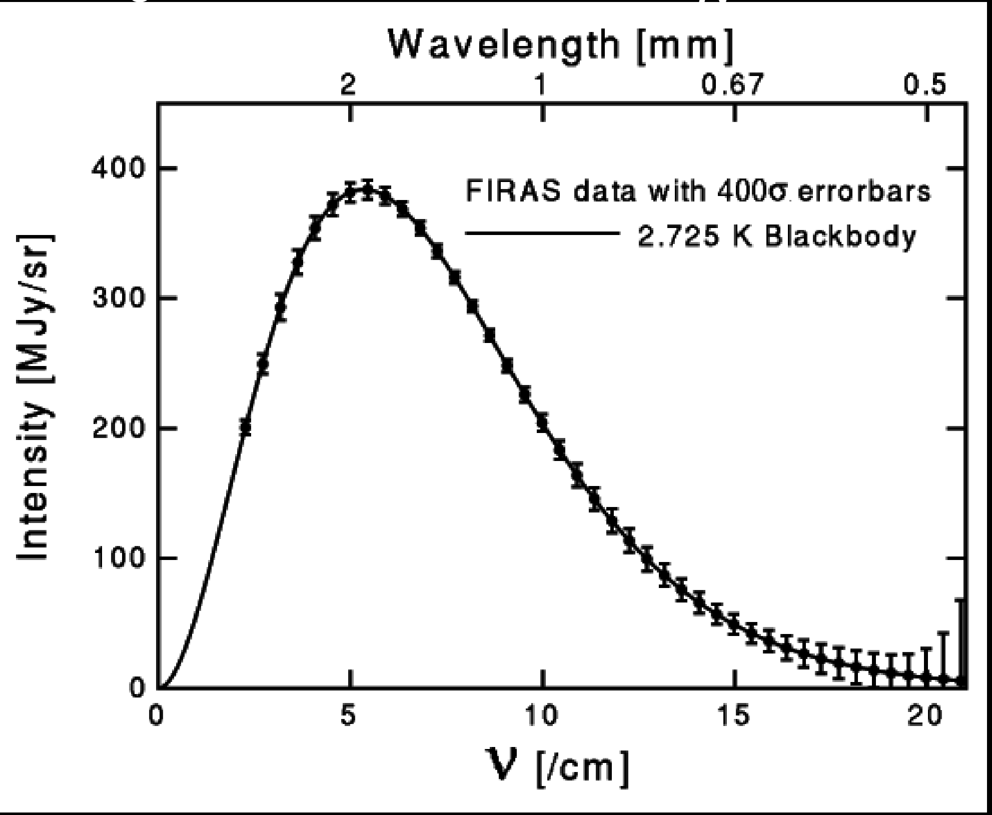


FIRAS Horn & External Calibrator

COBE Spectrum of the Universe

-first 9 minutes of data

Jan 1990 AAS meeting



Frequency Spectrum

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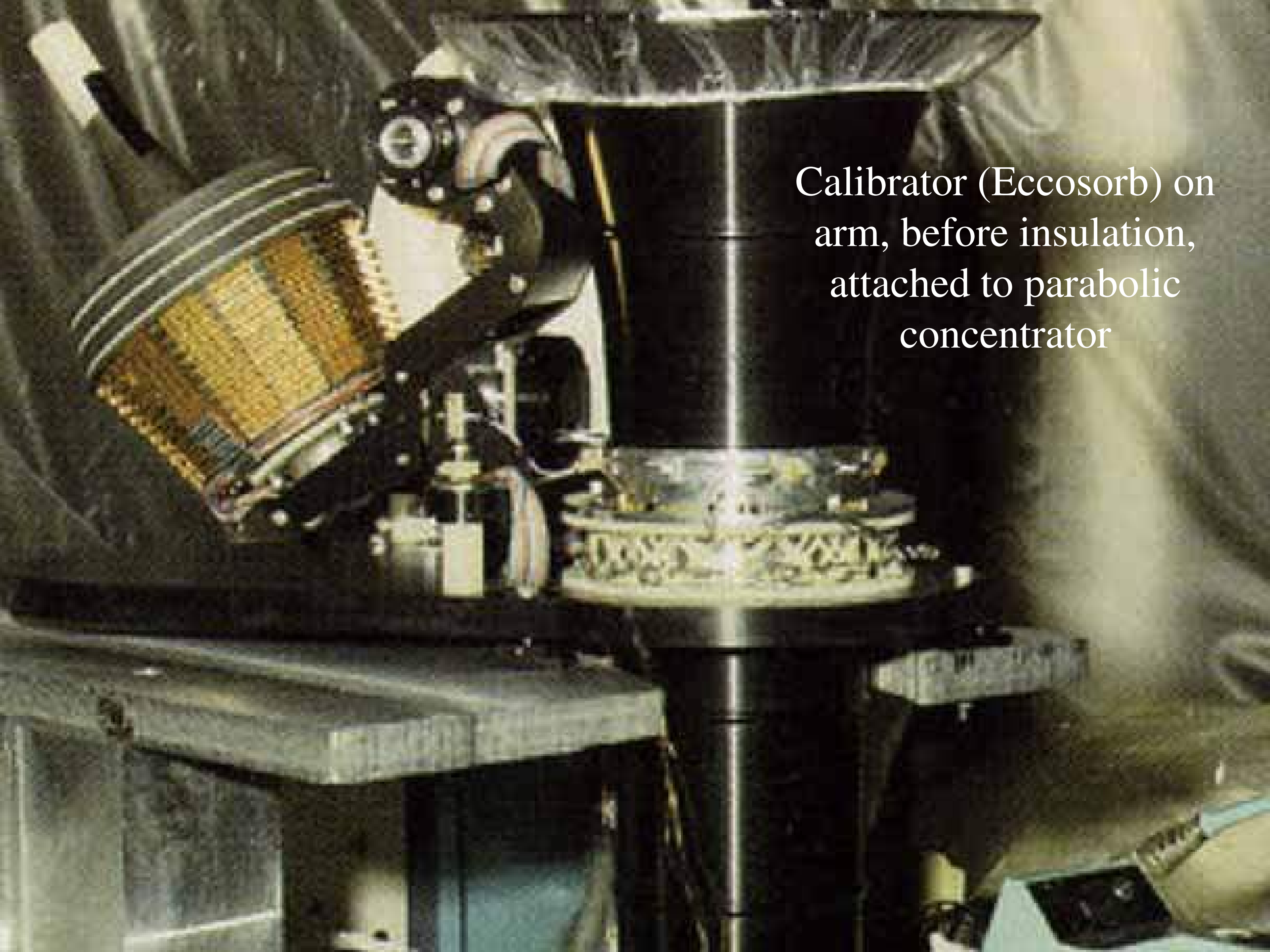
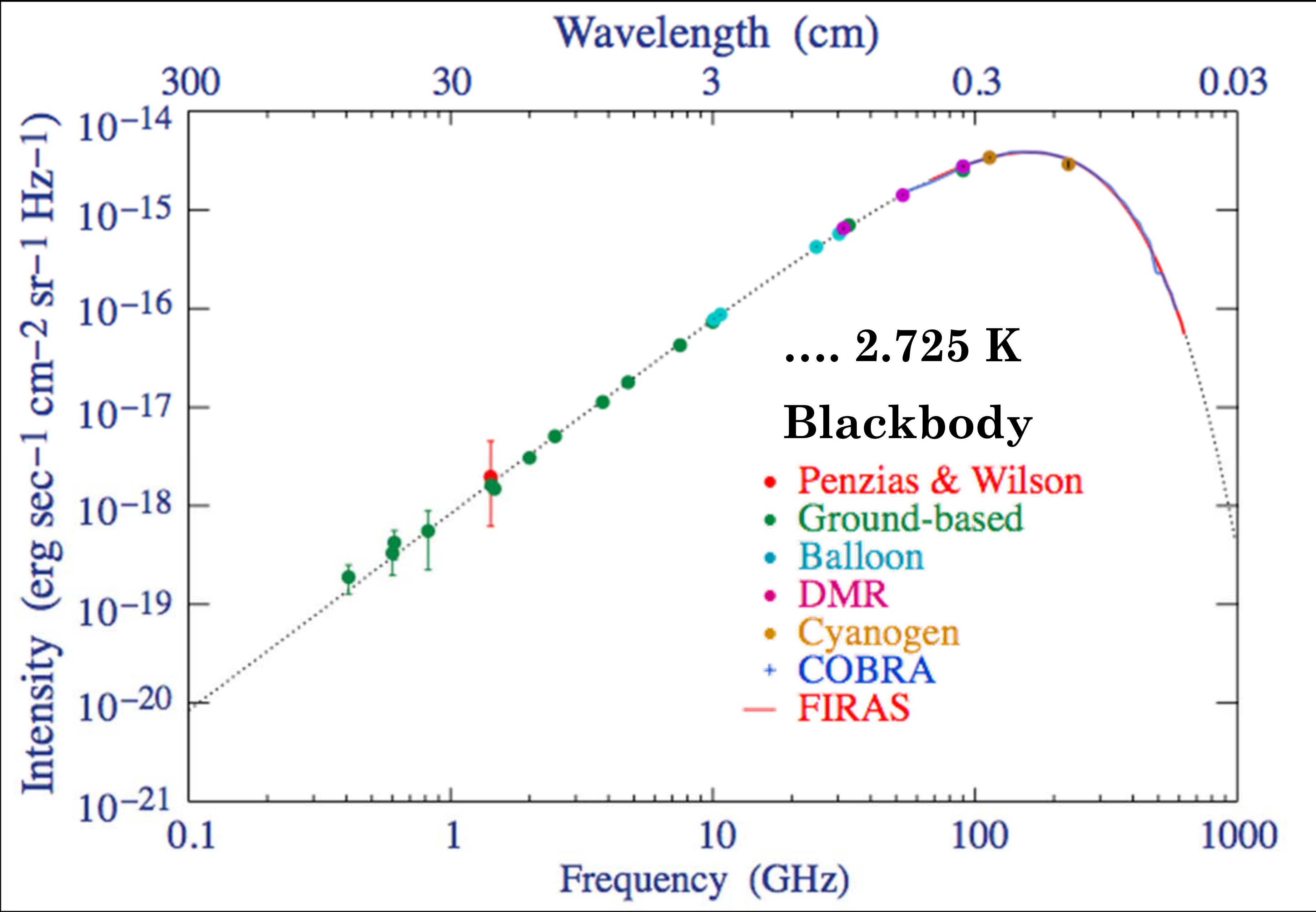
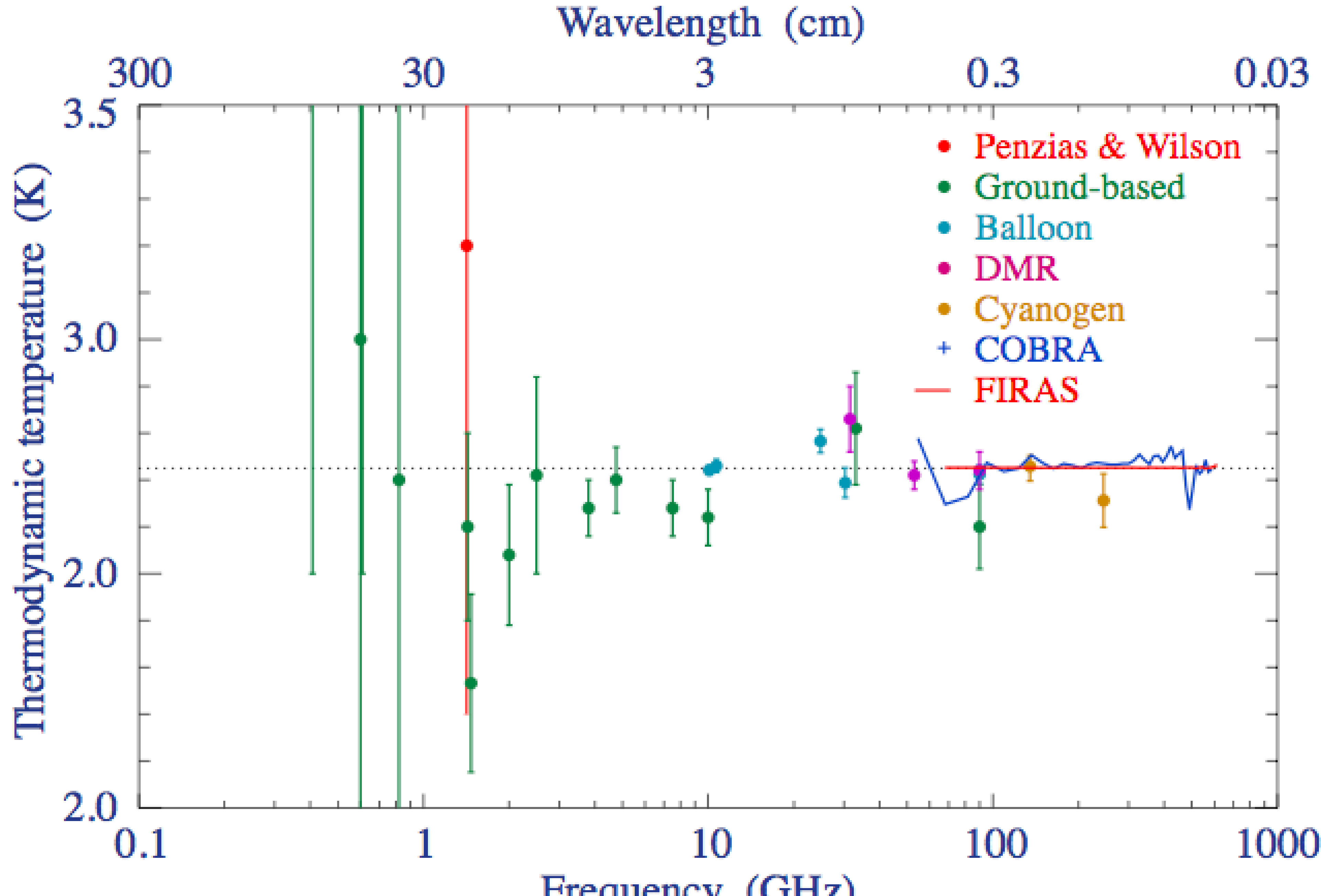

Calibrator (Eccosorb) on
arm, before insulation,
attached to parabolic
concentrator

CMB Intensity vs. Frequency or wavelength

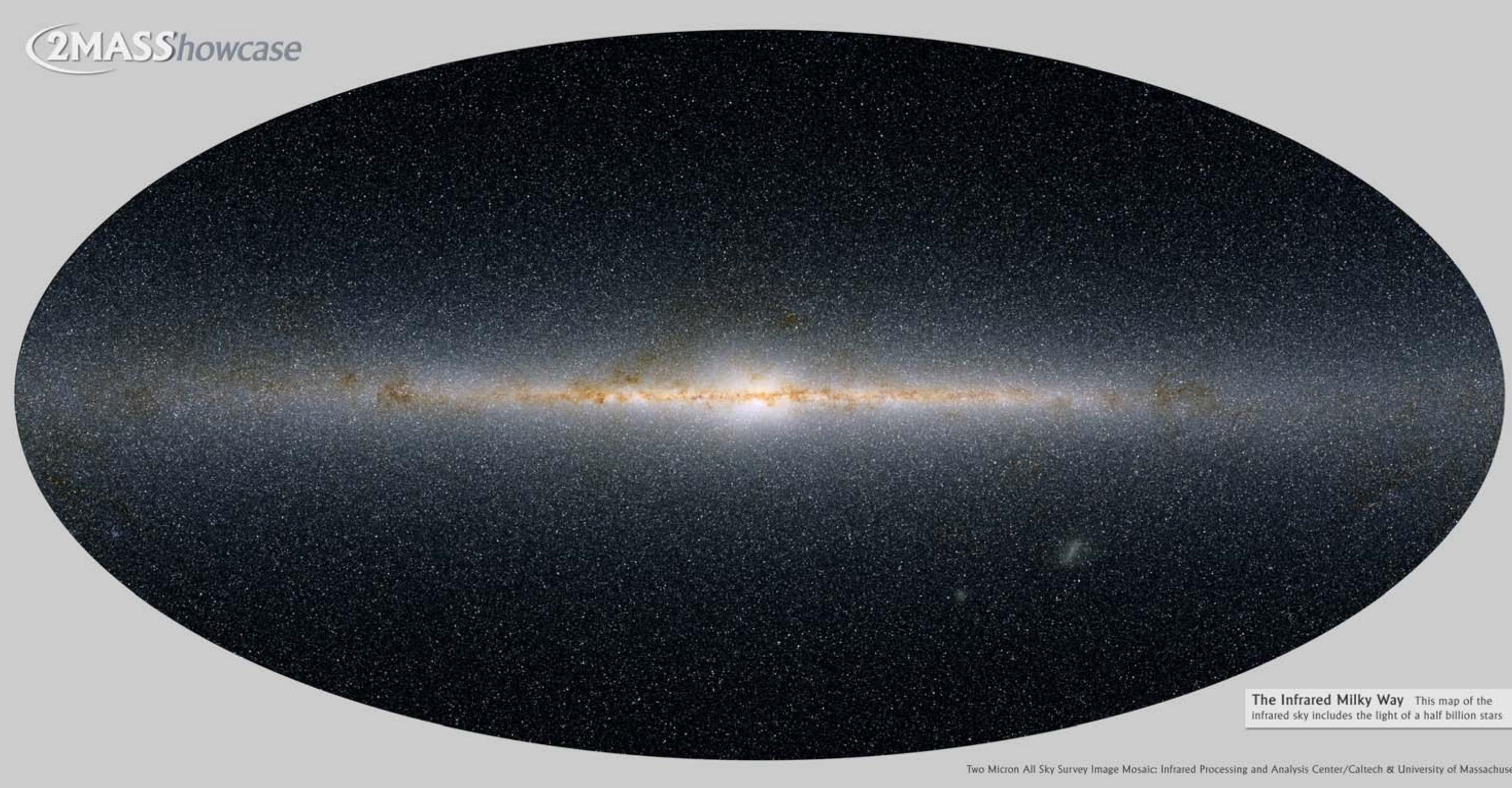


CMB Temperature vs Frequency/wavelength

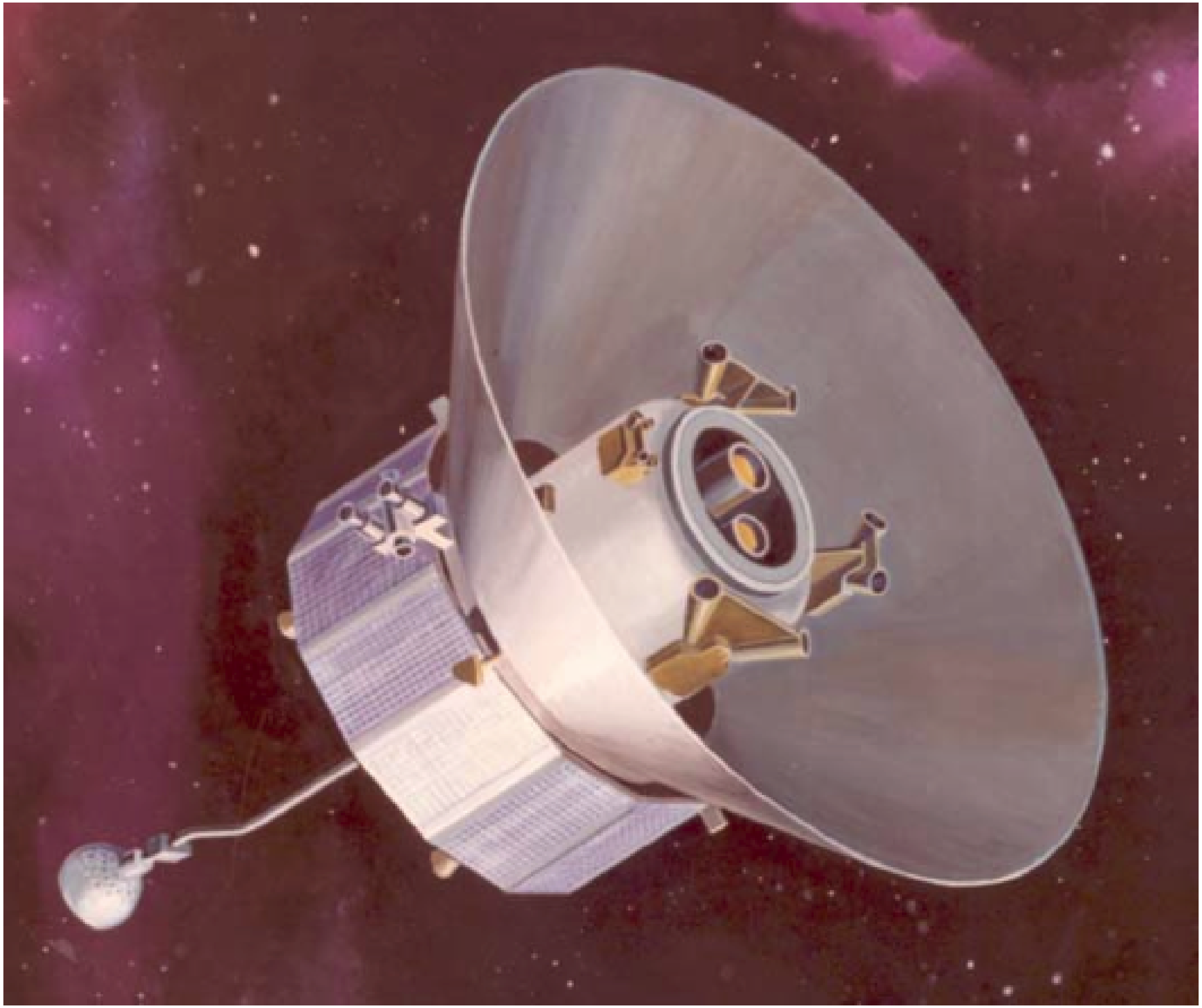


Diffuse Infrared Background Experiment

DIRBE 1.25, 2.2, 3.5 μm Composite



Cosmic Background Explorer: COBE - artist concept



COBE DMR Hardware Effort

- Huge List of People
- Here are a few photos

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TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
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are needed to see this picture.

John Maruschak

Roger Ratliff

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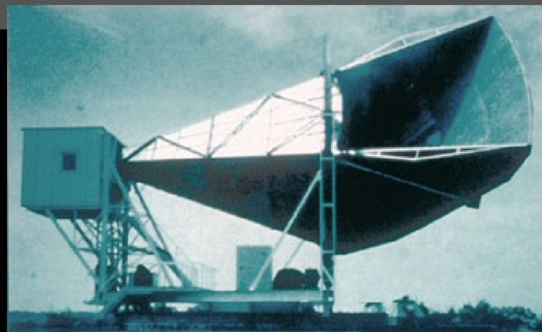
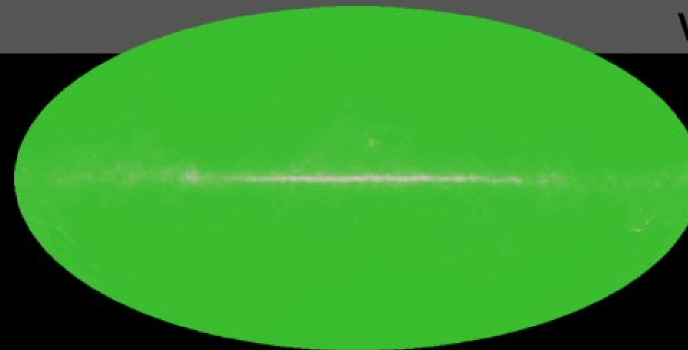
1965

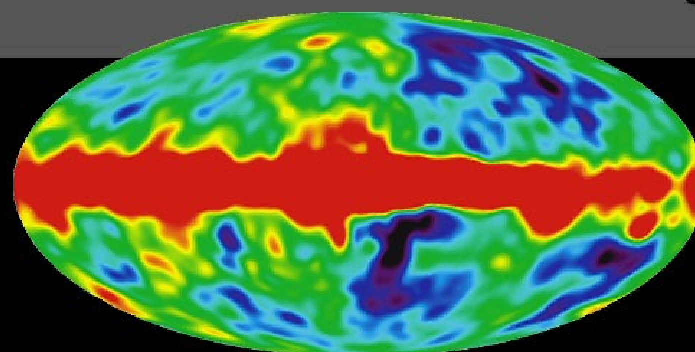
Penzias and Wilson





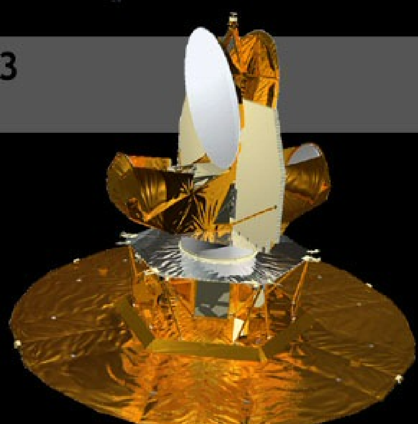
1992

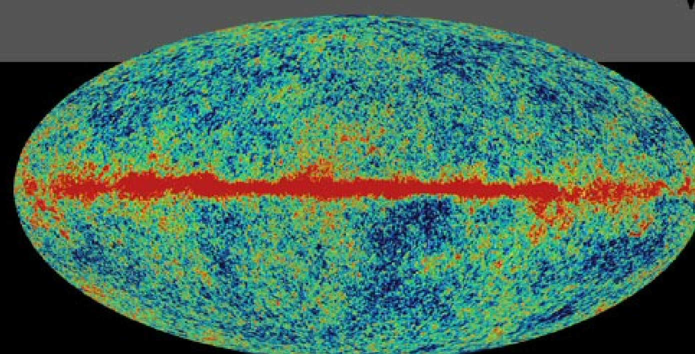
COBE



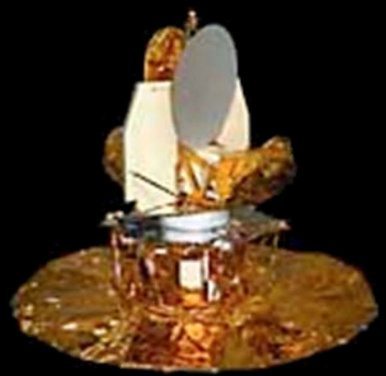
2003

WMAP

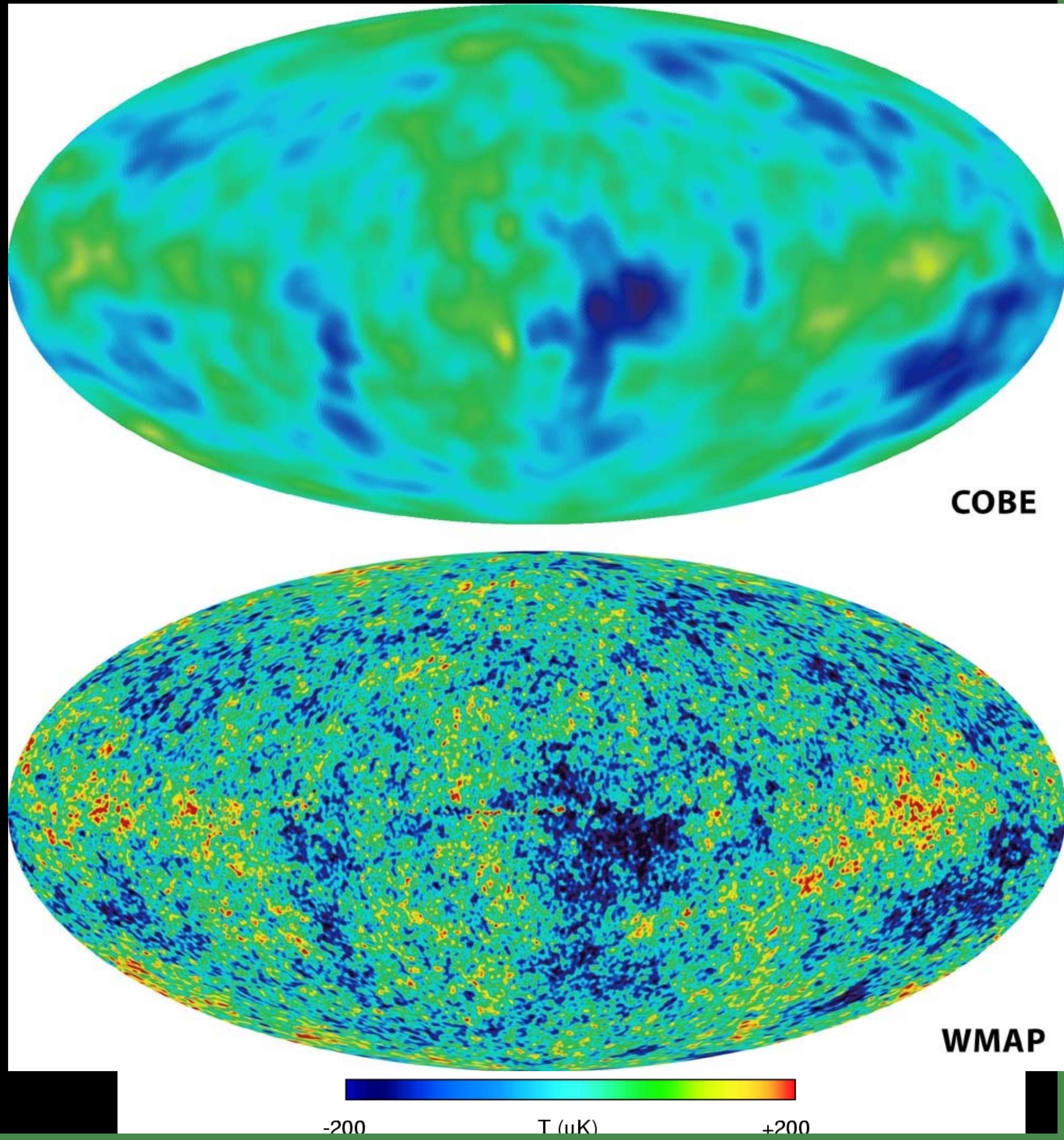




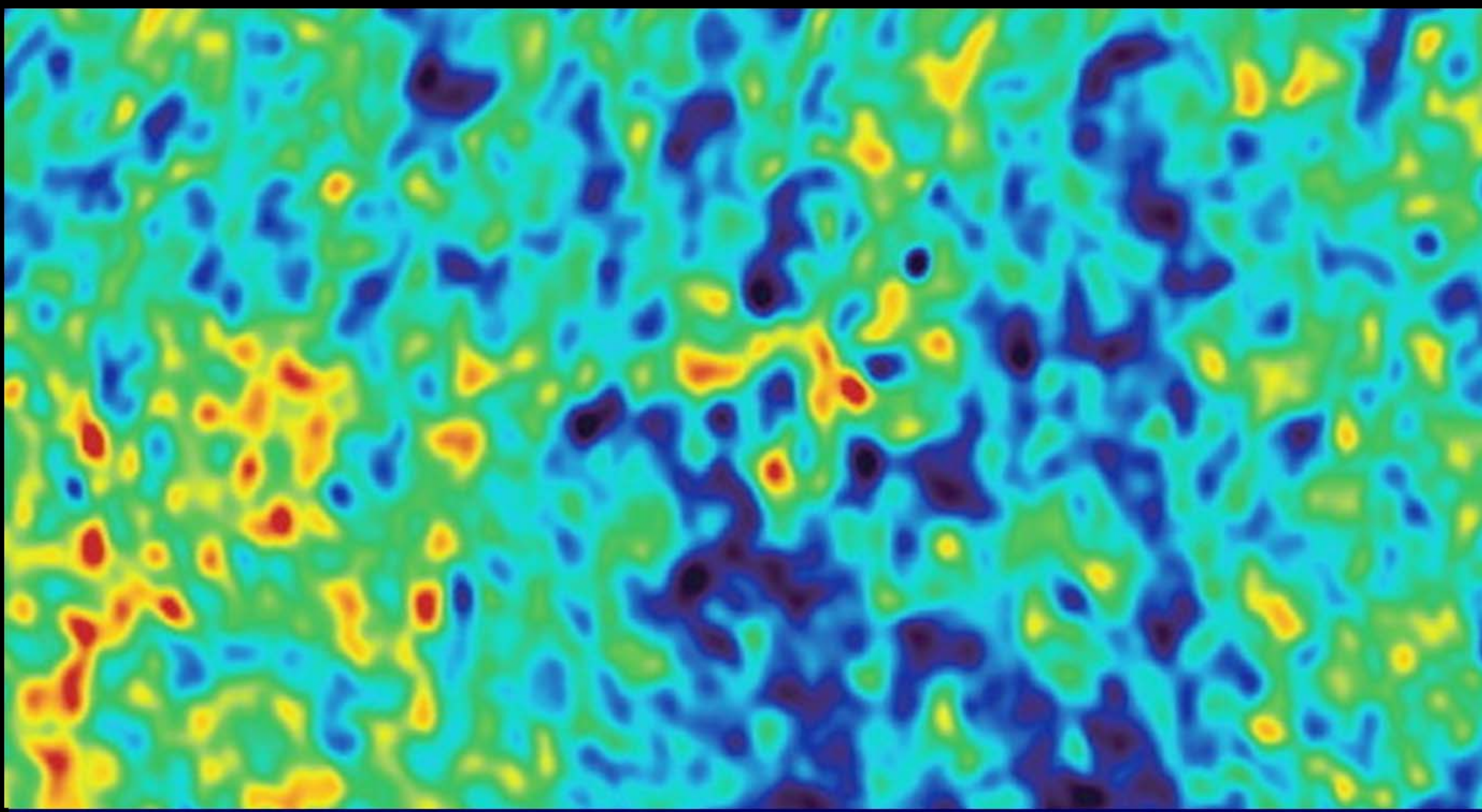
COBE 1992



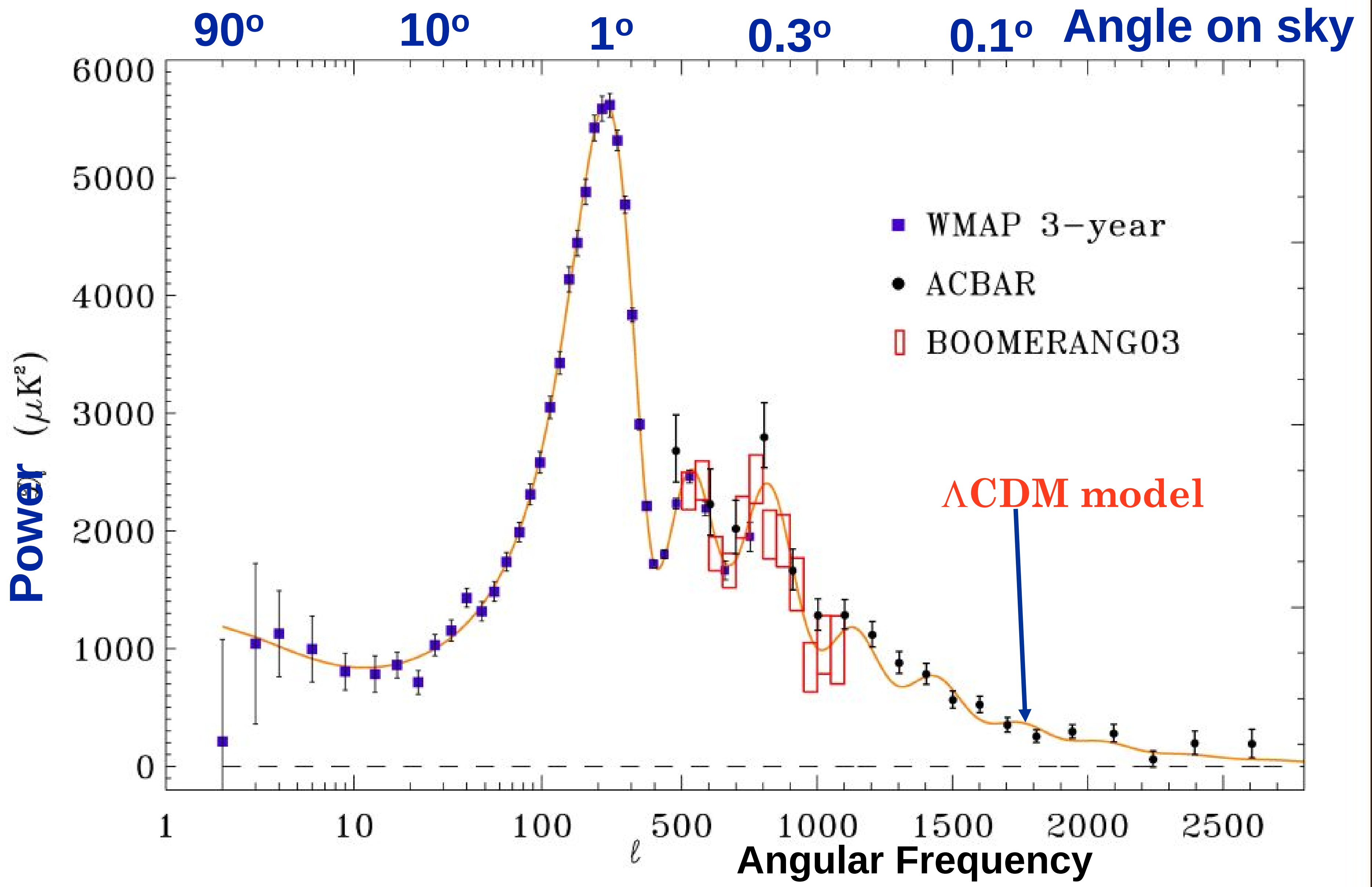
WMAP 2003



An image of quantum fluctuations blown up to the size of the universe.



CMB Angular Power Spectrum
Current Best Observations as of Nov 2006



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

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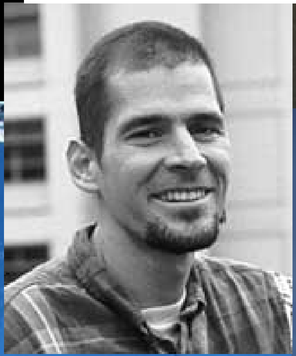
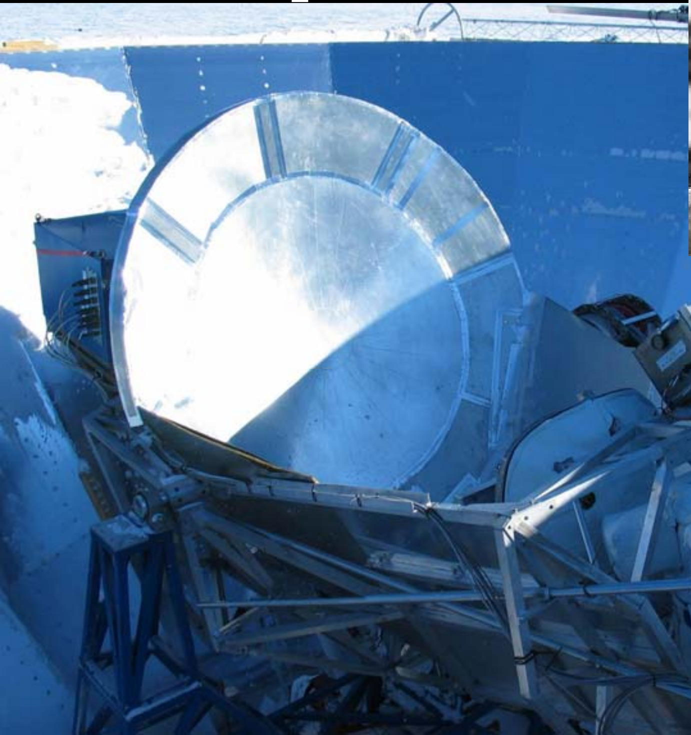
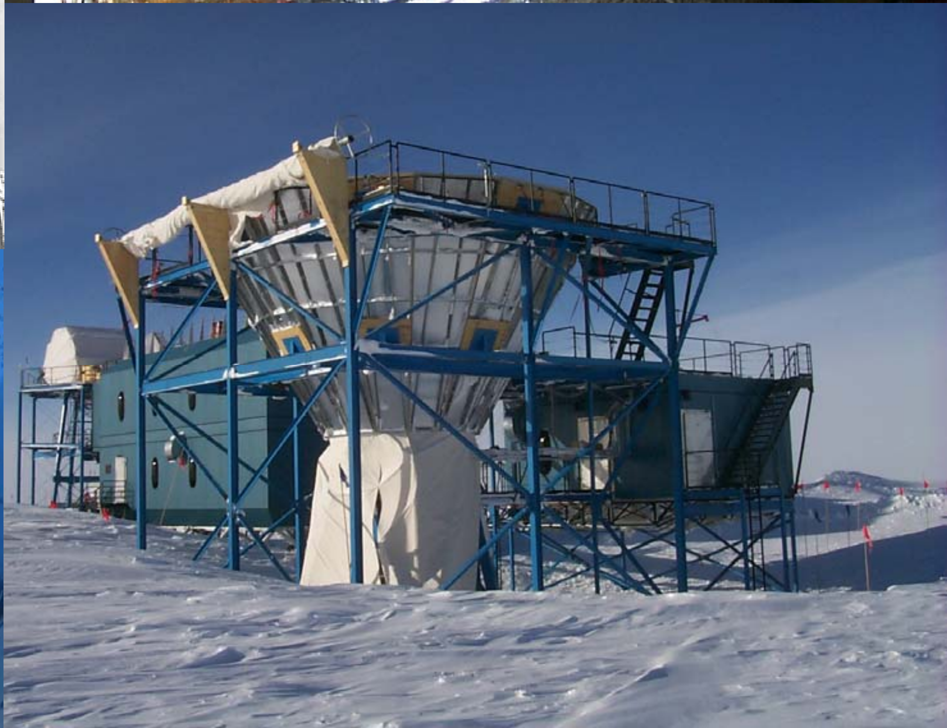
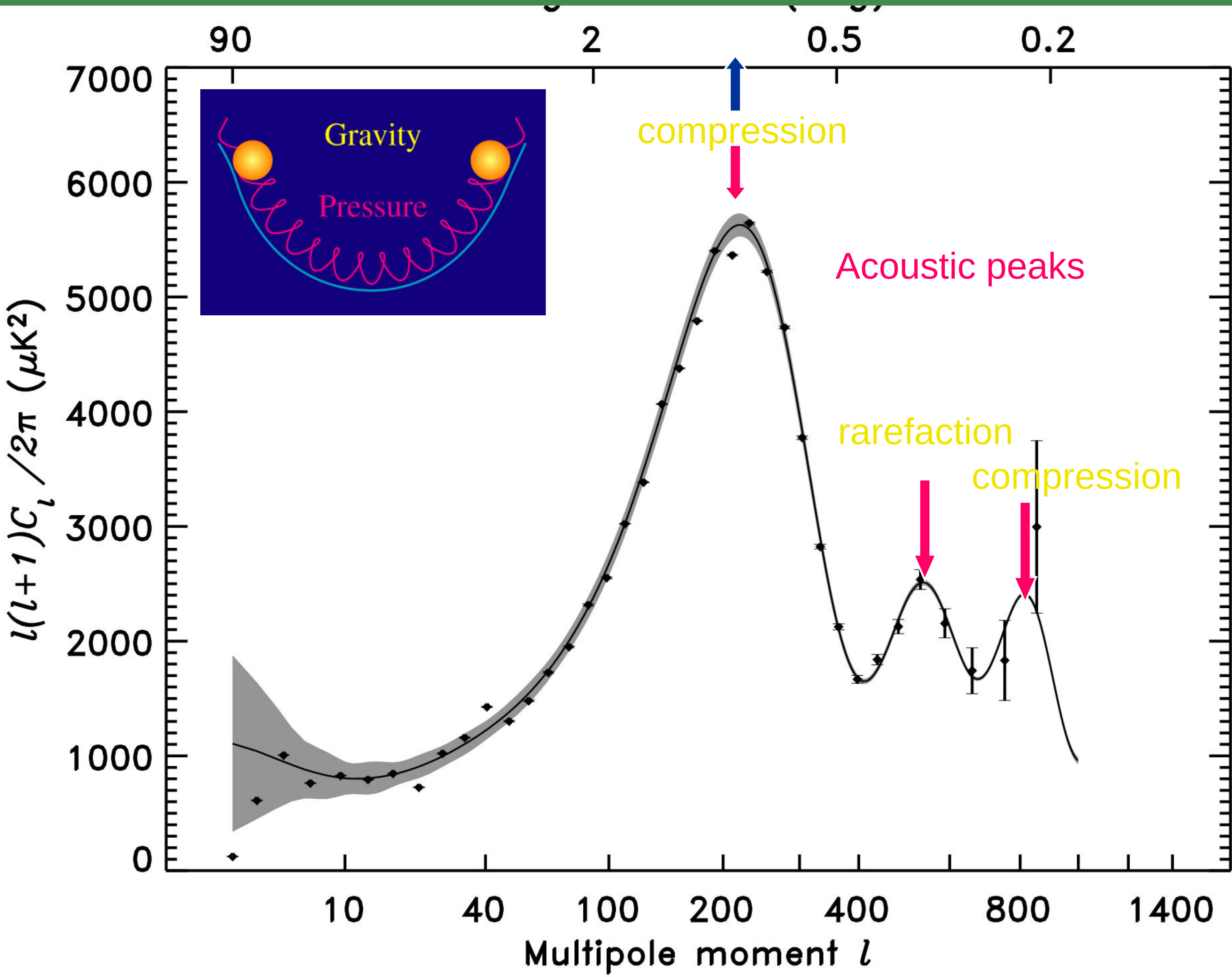
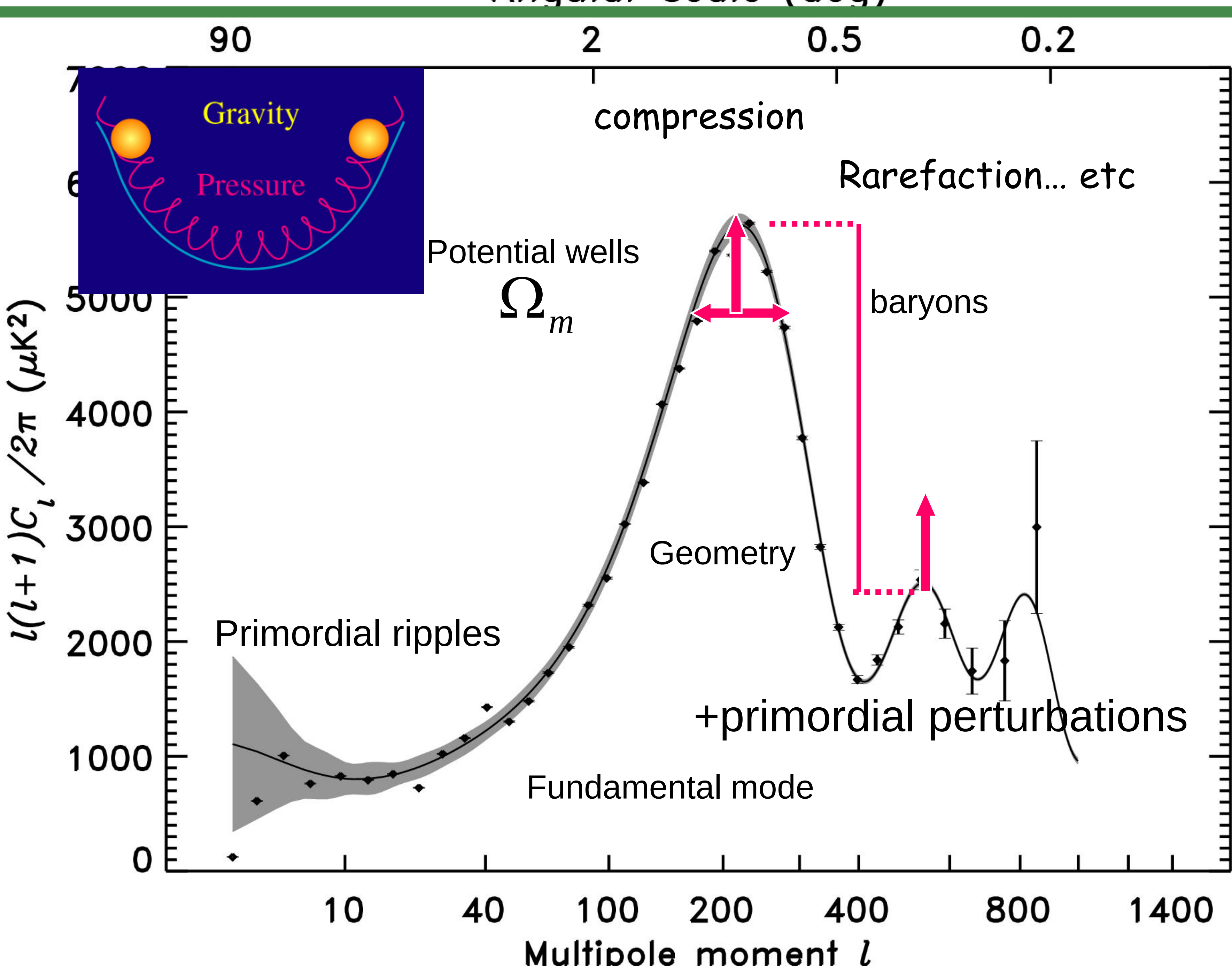








90
2
0.5
0.2
Gravity
Pressure
compression
Acoustic peaks
rarefaction
compression
7000
6000
5000
4000
3000
2000
1000
0
l(l+1)C_l /2π (μK²)
10
40
100
200
400
800
1400
Multipole moment l



Jungman, Kamionkowski, Kosowsky, Spergel, 1996

State-of-the-Art of the Universe 2003 Data

13.7 billion years old, expanding
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

State-of-the-Art of the Universe 2006 Data

13.8 billion years old, accelerating expansion rate

Composition: 74% dark energy, 22% dark matter, 4% ordinary matter

3-yr WMAP, 2df, SDSS, BOOMERanG,
ACBAR, CBI, VSA, SN astier, SN gold, WL and BAO

Quantity		Significance	Value
Hubble Expansion Rate	H_0	Current Expansion Rate of Universe	70.8±1.5 km/s/Mp
Density Parameter	Ω_0	Total energy density / critical density	1.01 ± 0.015
Mass Density Parameter	Ω_m	Total matter density / critical density	0.262 ± 0.016
Ordinary Matter Density	Ω_b	Ordinary matter density /critical density	0.044 ± 0.002
Dark Energy density	Ω_Λ	Dark Energy density / critical density	0.738 ± 0.016
Age of Universe Now Age of Universe at recomb Redshift of recombination	t_0 t_{ls} $1+z_{ls}$	Elapsed time from Big Bang to now Elasped time Big Bang to last scattering Ratio of size of universe now / size then	13.84±0.14 Gyr 0.379±0.007 Myr 1089 ± 1
Scalar spectral index Scalar amplitude $\Delta\rho/\rho$ on 8 h^{-1} Mpc scale	n_s $\Delta\phi/c^2$ σ_8	Index of amplitude power law 1=invariant ; no scale dependence matter fluctuations on ~10Mpc scale	0.938 ± 0.015 10^{-5} 0.751 ± 0.032
Reionization Optical Depth	τ	Fraction CMB scattered	0.070 ± 0.028

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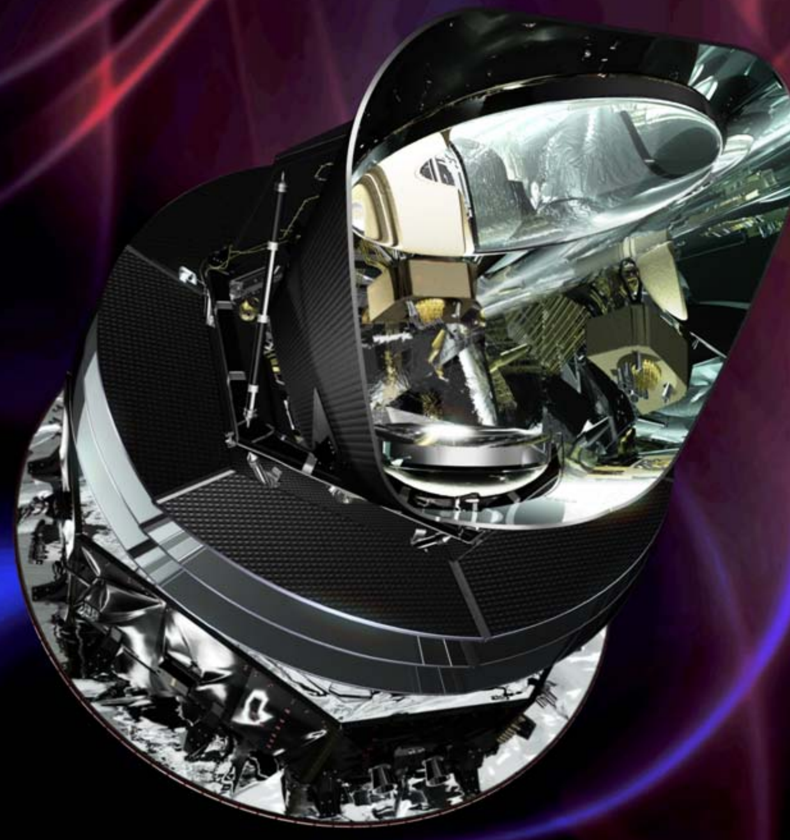
Looking back to the dawn of time



European Space Agency
Agence spatiale européenne

More information can be found on:
http://www.esa.int/science/planck

CMB Missions Revolutionise Our Understanding of the Universe

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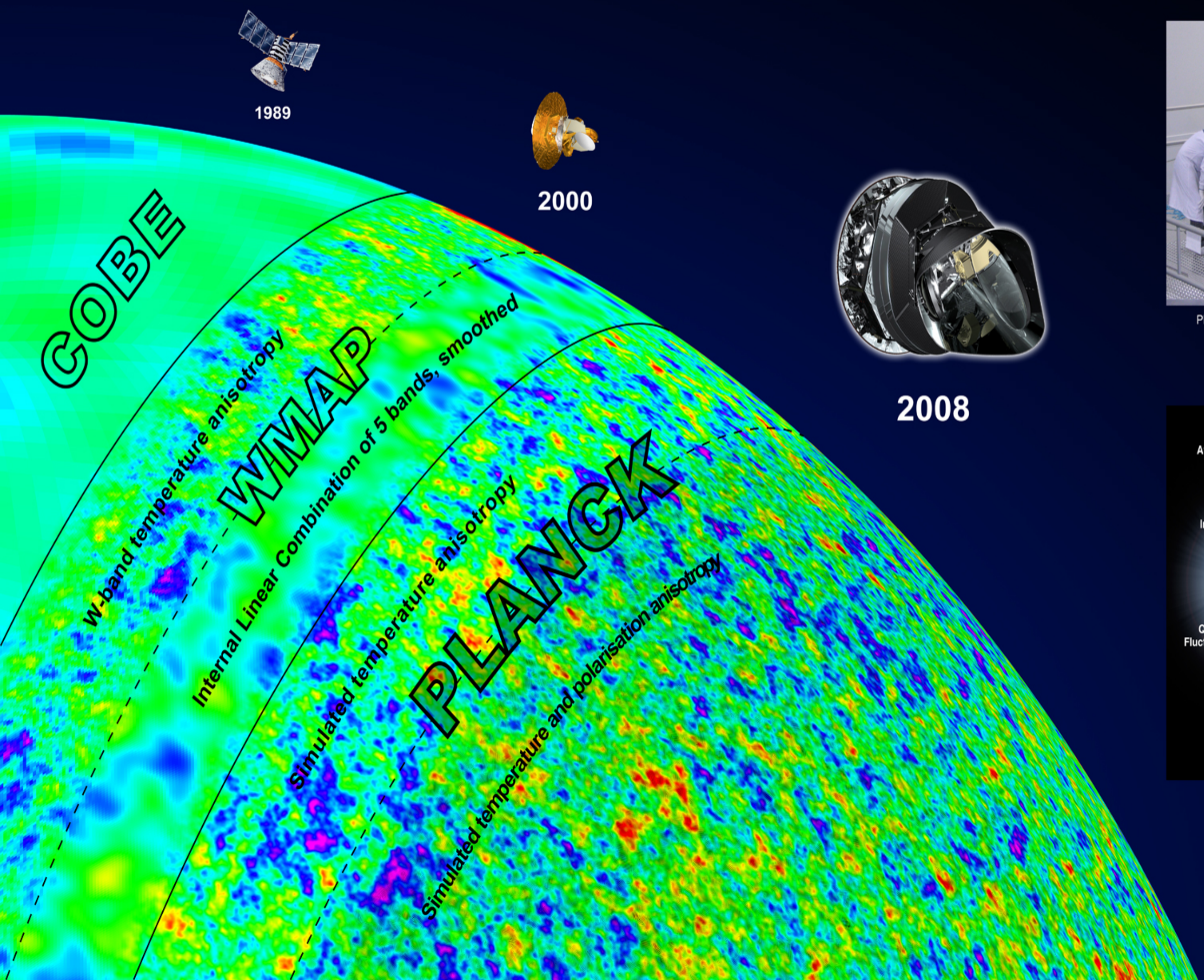
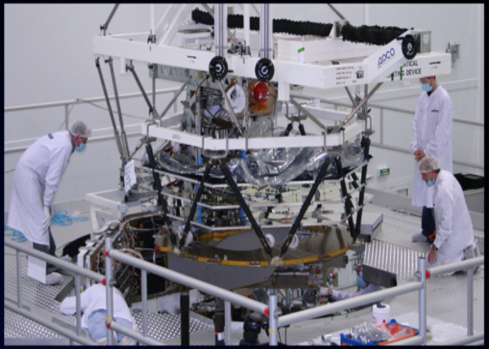
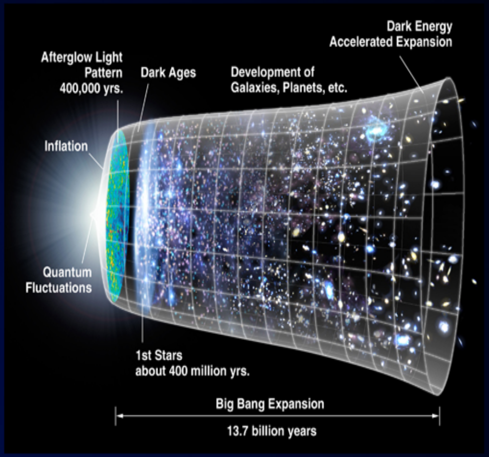




Planck spacecraft in clean assembly at Alcatel Alenia Space in January 2007



NASA esa ALCATEL ALENIA SPACE An Alcatel/Finmeccanica company

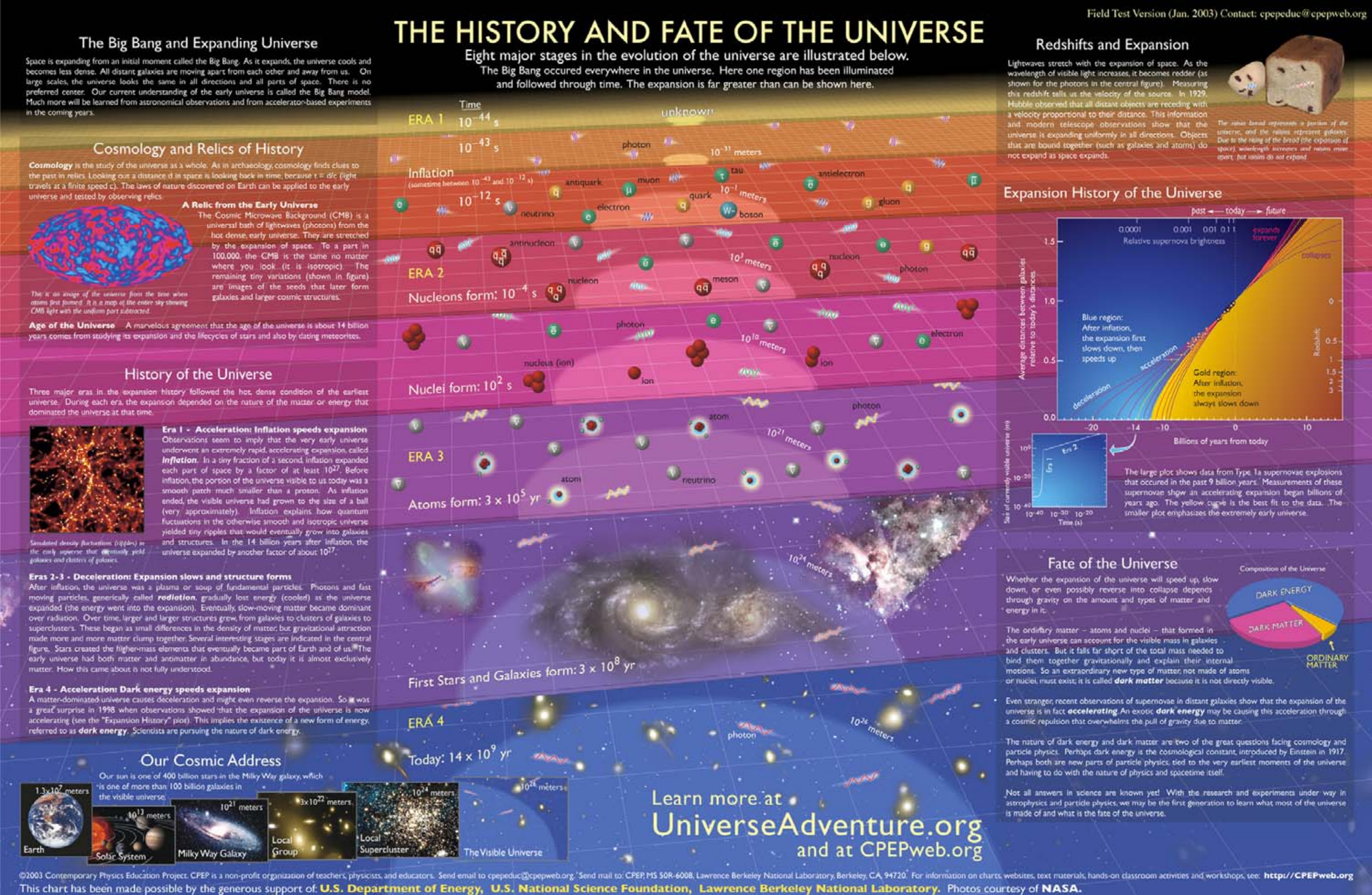
Golden Age of Cosmology

- Tremendous opportunities
- Intellectual Understanding of Universe
- Probe of Potential New Physics
- Strong Tests of our Knowledge
- Very Attractive and Exciting to public and for bringing next generation along.

Big questions: Seeking Answers

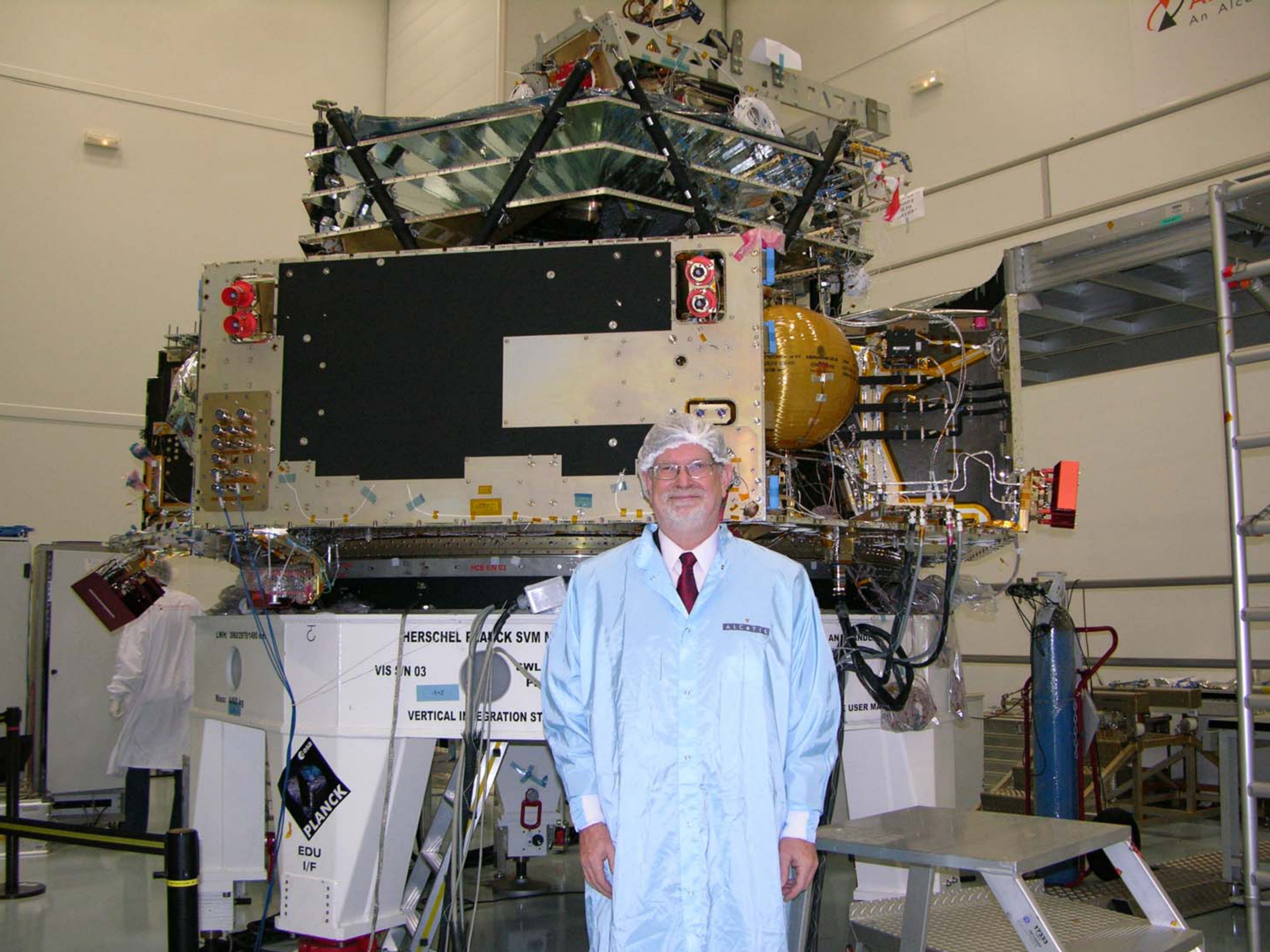
What is the right physics to describe the Universe?

1. Did inflation happen? How?
2. What is the dark matter?
3. What is the dark energy?
4. What generated the matter-antimatter asymmetry?
5. Are there other relics to be found (e.g. cosmic strings)?
6. Are there extra dimensions?
7. Do fundamental constants vary?
8. What other exotic forces might come in play?



Echoes of Creation Professor George F. Smoot

LBNL & Physics Department, University of California at Berkeley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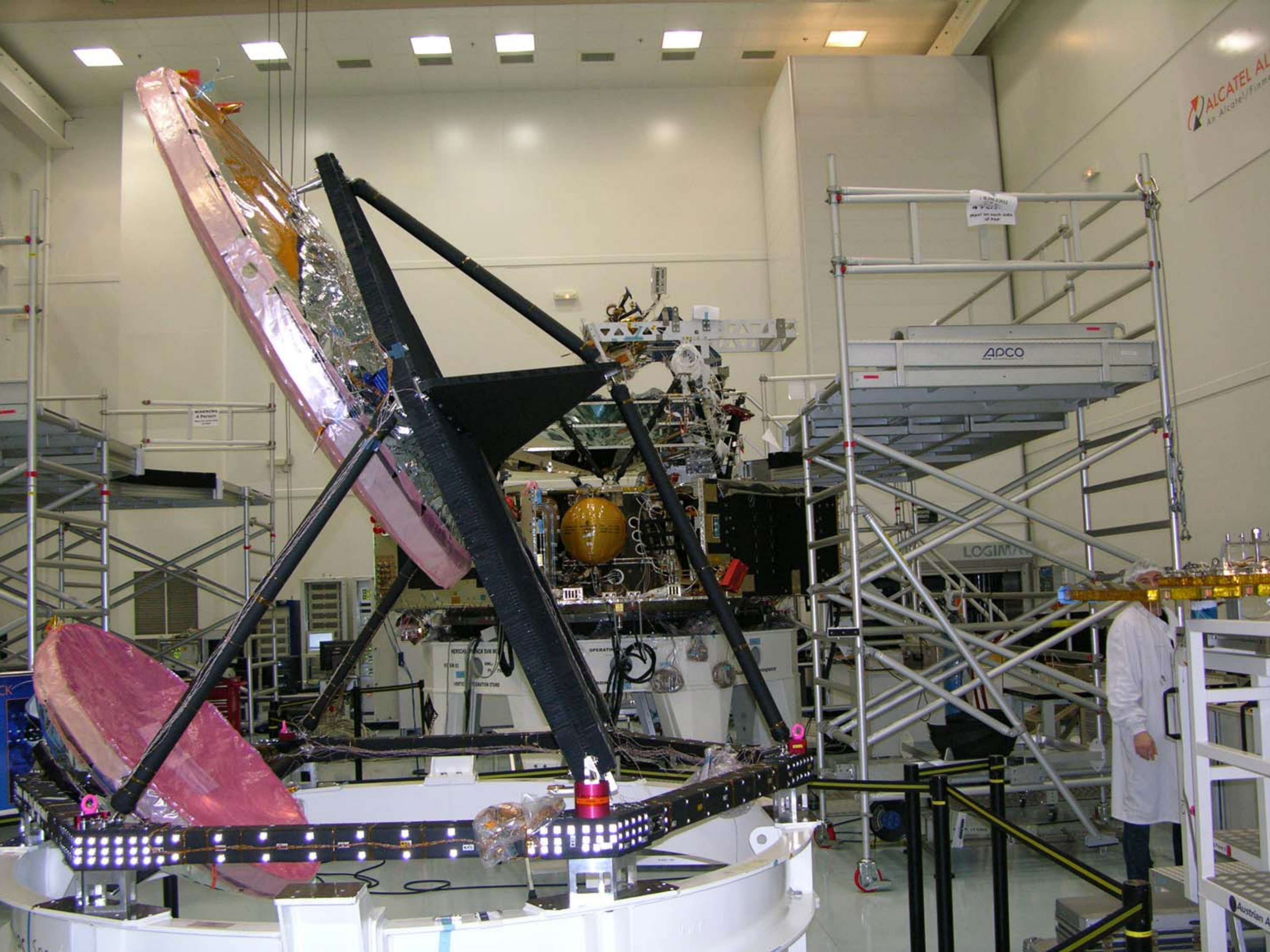
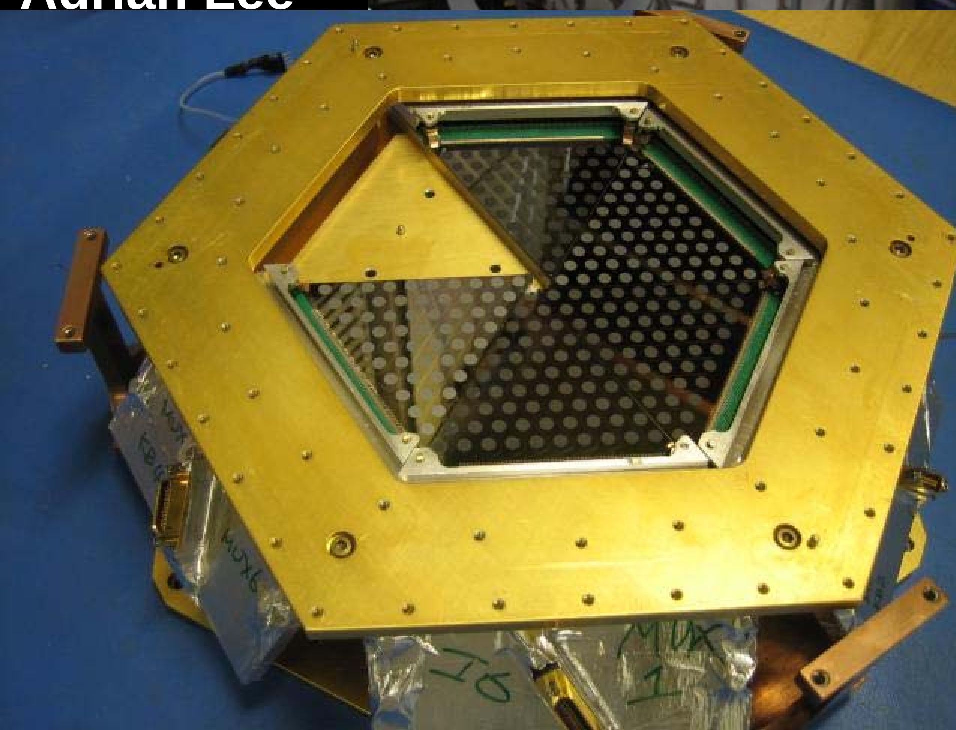

ALCATEL
APCO

APEX-SZ

Receiver being Installed for engineering run

First Science In Spring 07

Adrian Lee



SPT began observations from the Pole this February