From the Big Bang to the Nobel Prize: Cosmic Background Explorer (COBE) and Beyond

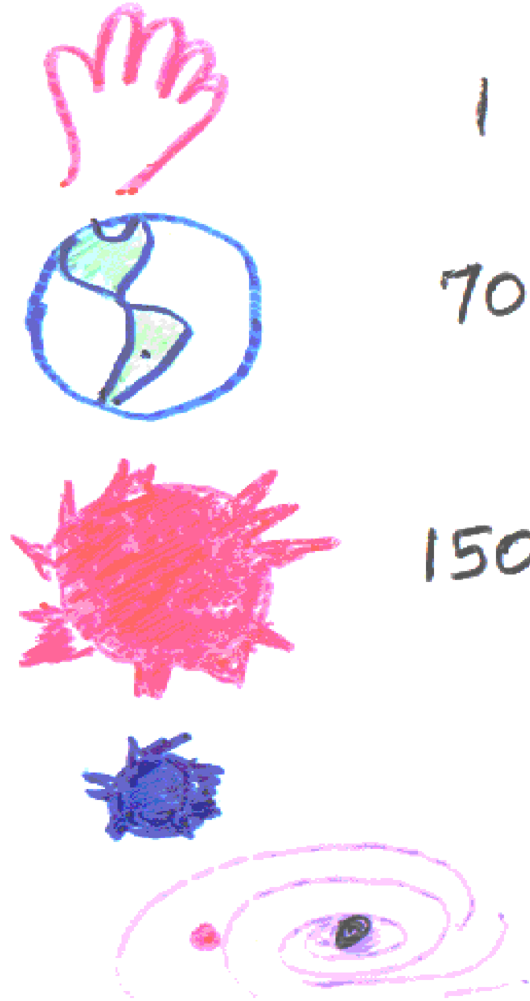
John C. Mather
NASA's Goddard Space Flight Center

Dec. 8, 2006

Nobel Prize Press Release

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2006 jointly to **John C. Mather**, NASA Goddard Space Flight Center, Greenbelt, MD, USA, and **George F. Smoot**, University of California, Berkeley, CA, USA *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*.

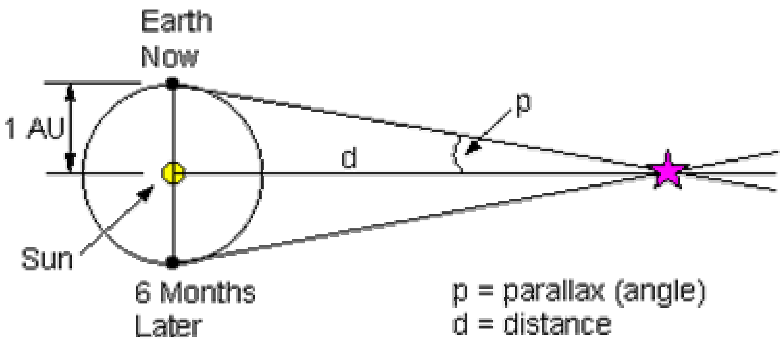
Looking Back in Time

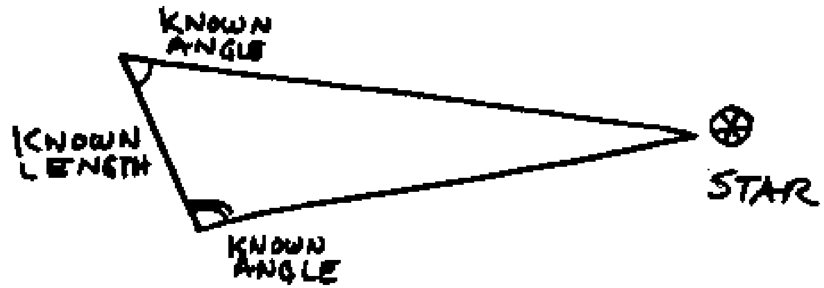


HAND	1 m	0.000 000 0003
EARTH	7000 km	0.0 2 sec
SUN	150,000,000 km	500 SE
STAR		4 YRS
GALAXY		25,000 YRS
BIG BANG ?		15,000,000,000 YI

Measuring Distance

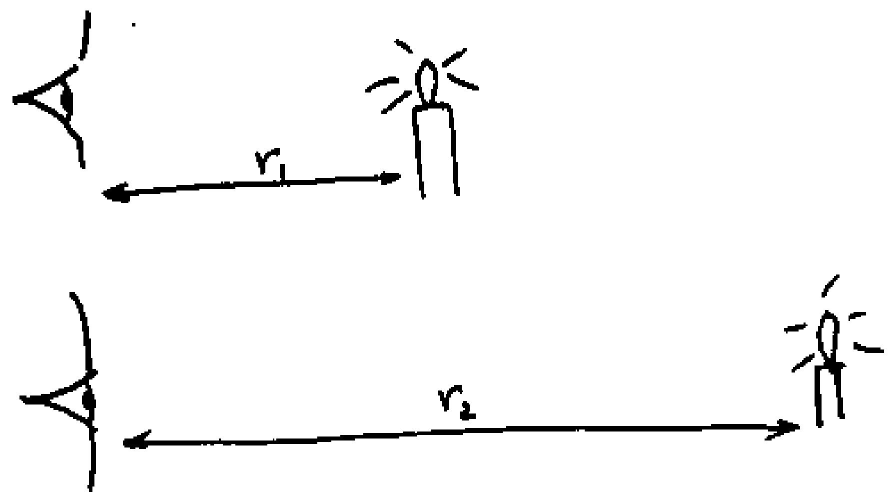
1. TRIANGLES





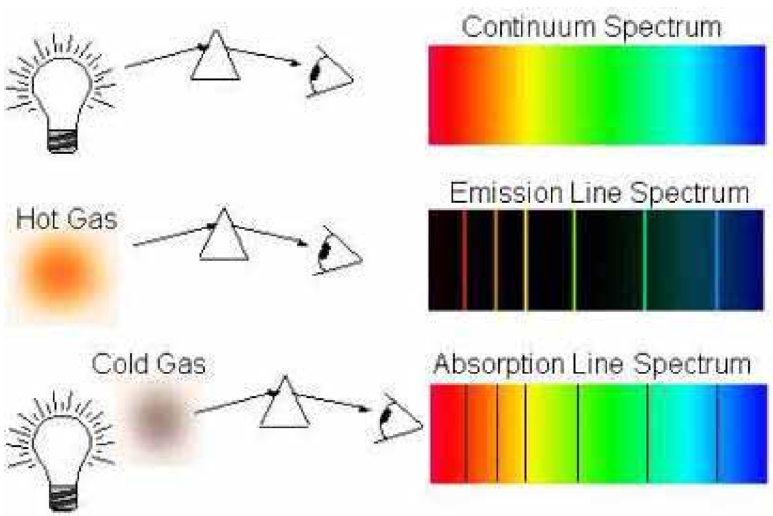
2. STANDARD CANDLES

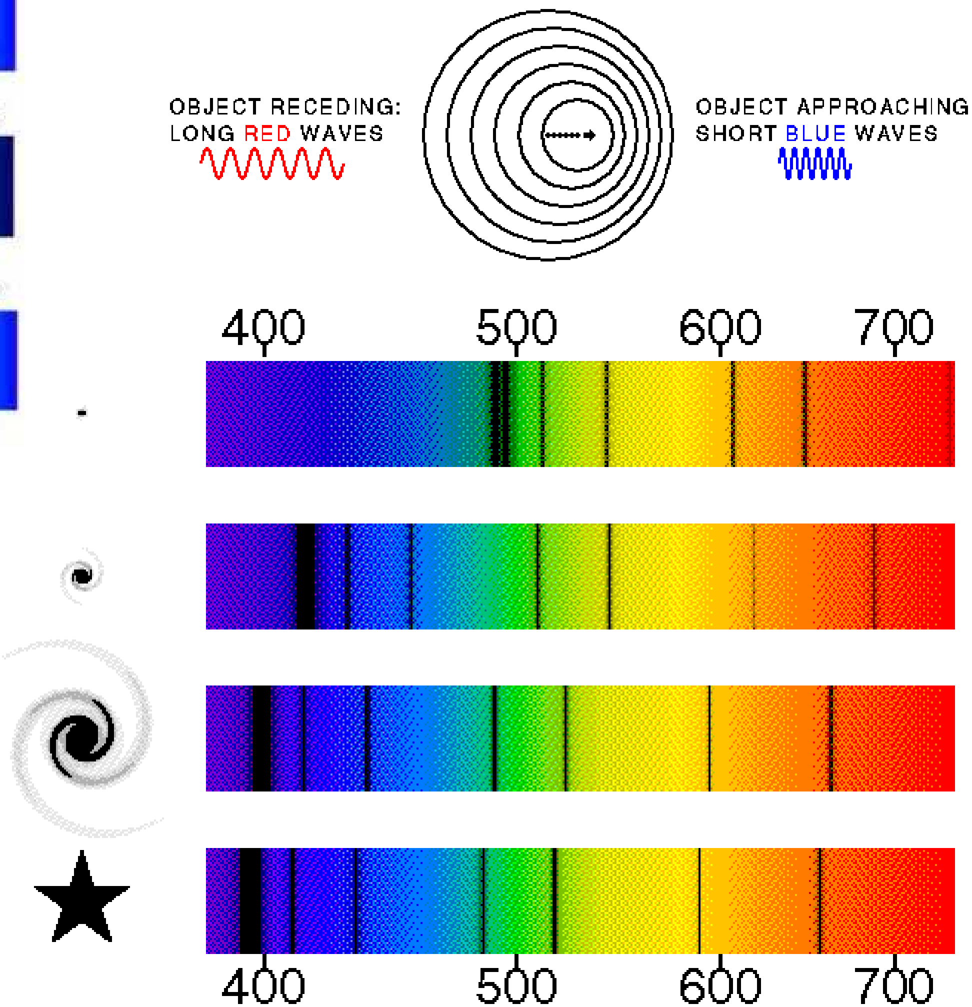
This technique enables measurement of enormous distances



$$\frac{\text{BRIGHTNESS}_1}{\text{BRIGHTNESS}_2} = \frac{r_2^2}{r_1^2}$$

Astronomer's Toolbox #2:
Doppler Shift - Light





Atoms emit light at discrete wavelengths that can be seen with a spectroscope

This "line spectrum" identifies the atom and its velocity

Hubble Discovers the Expanding Universe, 1929, confirming Lemaître's prediction of "primeval atom", 1927

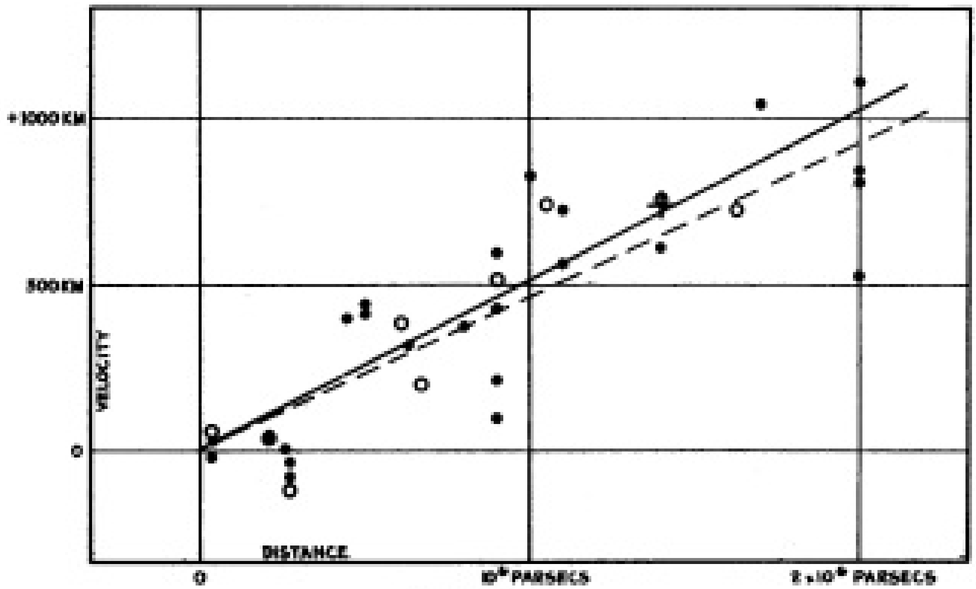


FIGURE 1

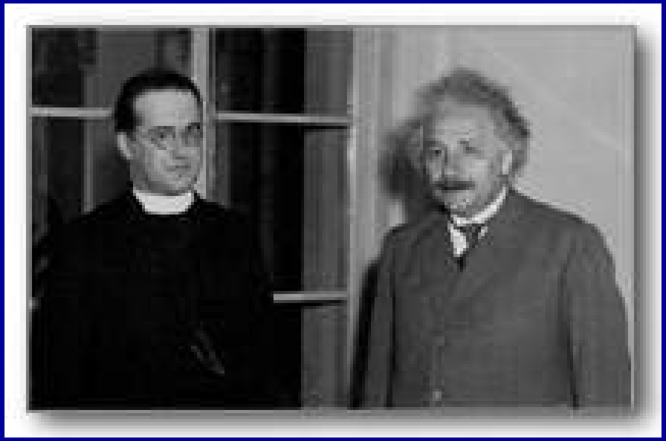
Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the

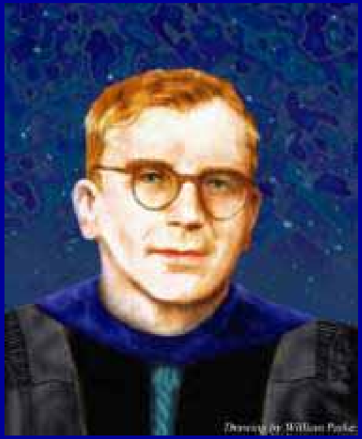
Distance/Velocity = apparent age

Linear relationship ⇒ no apparent center or edge

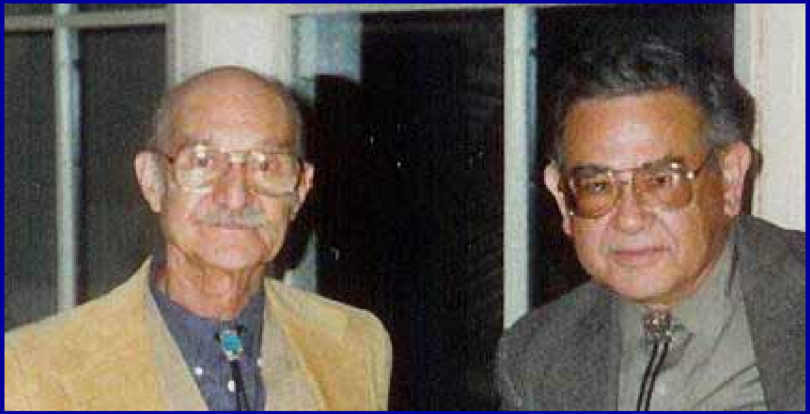
The Power of Thought



Georges Lemaître & Albert Einstein



George Gamow

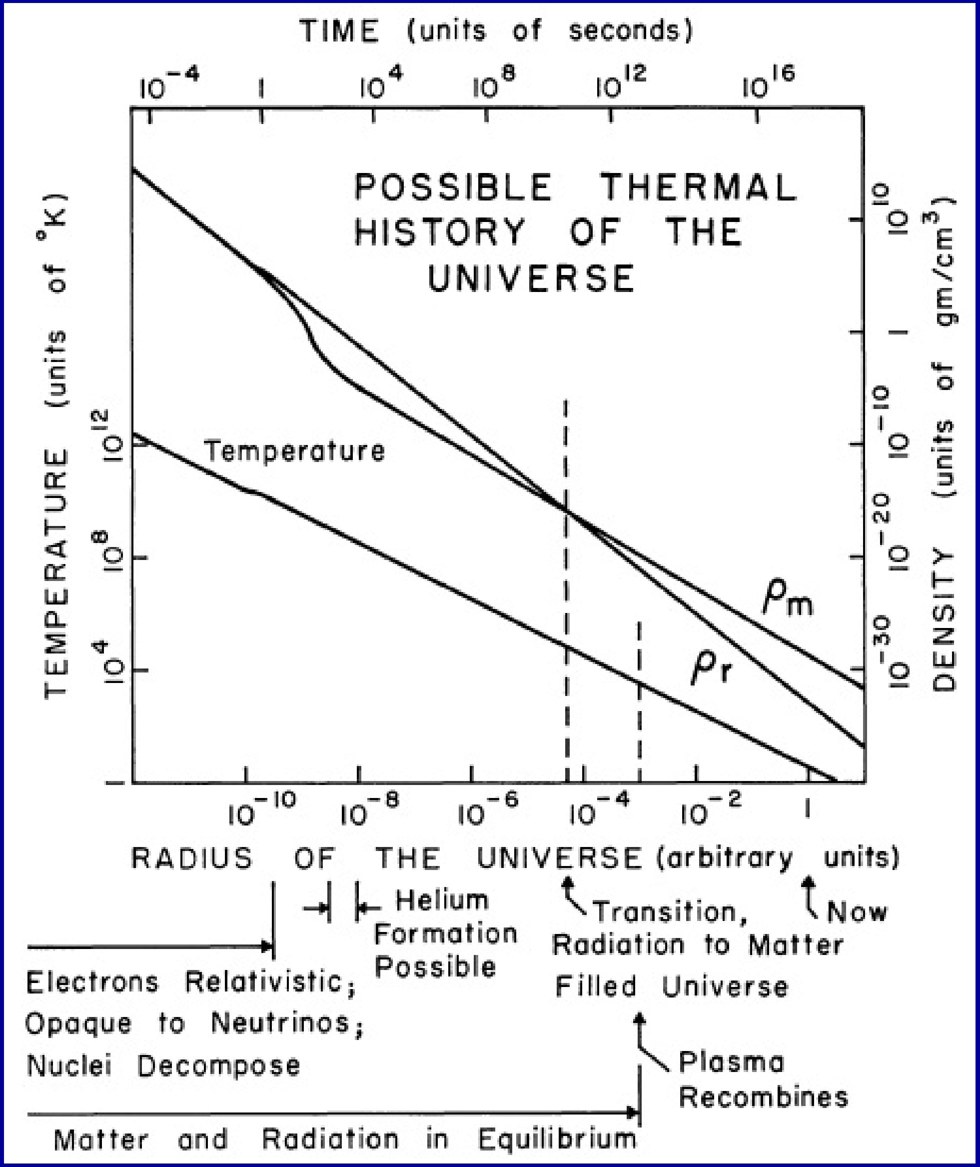


Robert Herman & Ralph Alpher

Rashid Sunyaev

Jim Peebles

History of the Universe, 1965
Dicke, Peebles, Roll, & Wilkinson



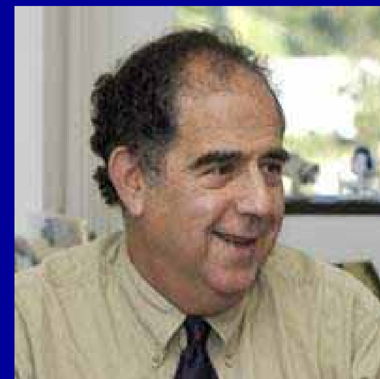
Radius = 1/(1+z),
z = redshift

Physics in 1970

- 1965, Cosmic Microwave Background discovery announced - Penzias & Wilson (Nobel 1978); Dicke, Peebles, Roll, & Wilkinson theory paper
- CMB spectrum appears wrong: 50x too much energy at short wavelengths, possible spectrum line in it
- Mather, Werner, Richards, and Woody start CMB projects
- Lockin amplifier used vacuum tubes
- Fast Fourier transform just invented, no pocket calculators yet
- PDP-11 advanced lab computer programmed by paper tape
- IR detectors made with wire saw, CP-4 etch, indium solder, and tiny wires, with tweezers

Power of Hardware - CMB Spectrum

Paul Richards

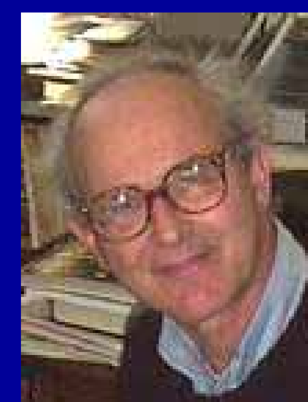


Mike Werner

David Woody

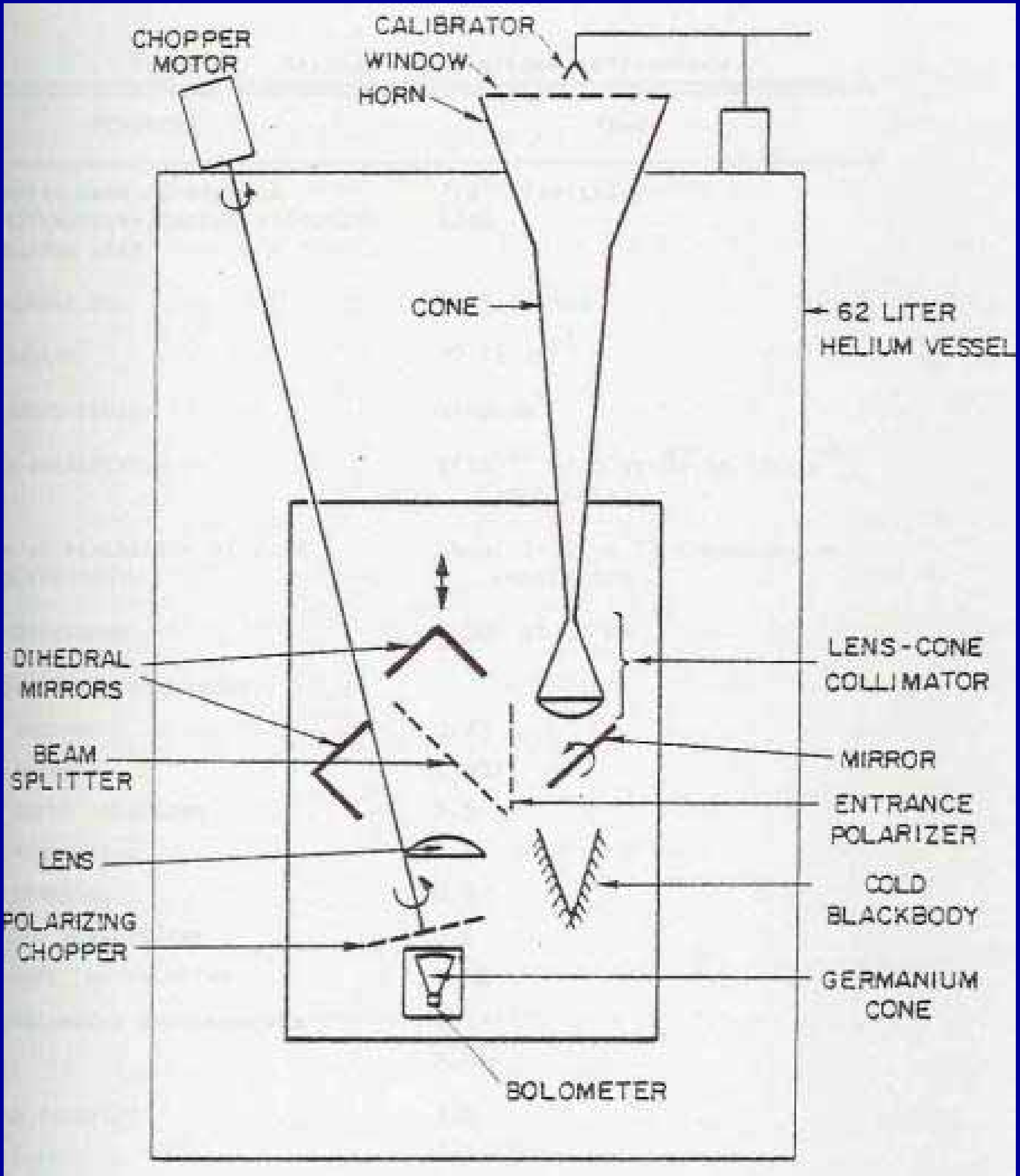
Frank Low

Herb Gush



Rai Weiss

Balloon Michelson CMB Spectrometer



Mather thesis, 1974, based on failed first flight

(Michelson Nobel Prize for instrumentation, 1907)

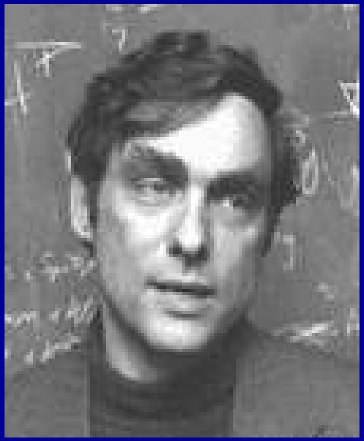
Results: Woody, Nishioka, Richards, & Mather, PRL, 1975, based on successful 2nd flight

Paul Richards giving Balloon Payload to the Air & Space Museum

COBE Pre-History

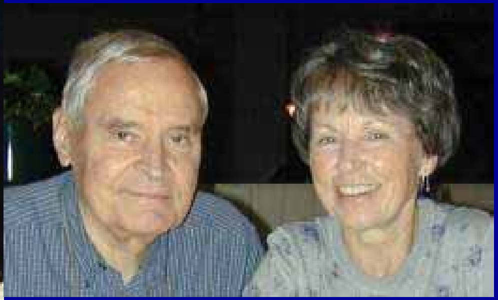
- 1974, NASA Announcement of Opportunity for Explorer satellites: ~ 150 proposals, including:
  - JPL anisotropy proposal (Gulkis, Janssen…)
  - Berkeley anisotropy proposal (Alvarez, Smoot…)
  - NASA Goddard/MIT/Princeton COBE proposal (Hauser, Mather, Muehlner, Silverberg, Thaddeus, Weiss, Wilkinson)

Starting COBE



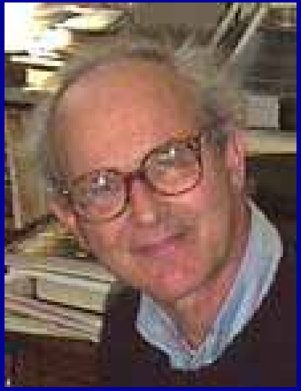
Pat Thaddeus

John & Jane Mather



Dave & Eunice Wilkinson

Mike & Deanna Hauser



Rai & Becky Weiss

George Smoot

Sam & Margie Gulkis, Mike & Sandie Janssen

COBE History (2)

- 1976, Mission Definition Science Team selected by NASA HQ (Nancy Boggess, Program Scientist); PI's chosen
- ~ 1979, decision to build COBE in-house at Goddard Space Flight Center
- 1982, approval to construct for flight
- 1986, Challenger explosion, start COBE redesign for Delta launch
- 1989, Nov. 18, launch
- 1990, first spectrum results; helium ends in 10 mo
- 1992, first anisotropy results
- 1994, end operations
- 1998, major cosmic IR background results

COBE Science Team

Chuck & Renee Bennett

Nancy & Al Boggess

Ed & Tammy Cheng

Eli & Florence Dwek

Tom & Ann Kelsall

Philip & Georganne Lubin

COBE Science Team

Steve & Sharon Meyer

Harvey & Sarah Moseley

Tom & Jeanne Murdock

Rick & Gwen Shafer

Bob & Beverly Silverberg

Ned & Pat Wright

COBE Science Team Roles

- 3 proposal teams in 1974
- Selected 6 individuals in 1976: Sam Gulkis, Mike Hauser, John Mather, George Smoot, Rai Weiss, Dave Wilkinson
- Science Working Group Chair: Weiss
- Project Scientist/Deputy: Mather/ Nancy Boggess
- DIRBE PI/Deputy: Hauser/Tom Kelsall
- DMR PI/Deputy: Smoot/Charles Bennett
- FIRAS PI/Deputy: Mather/Rick Shafer
- Data Team Lead: Ned Wright
- All Science Team members are co-investigators on all 3 instruments

COBE Engineering Leadership

Back row: Bill Hoggard, Herb Mittelman, Joe Turtil, Bob Sanford

Middle row: Don Crosby, *Roger Mattson (Project Manager)*, Irene Ferber, Maureen Menton

Front row: Jeff Greenwell, Ernie Doutrich, Bob Schools, Mike Roberto

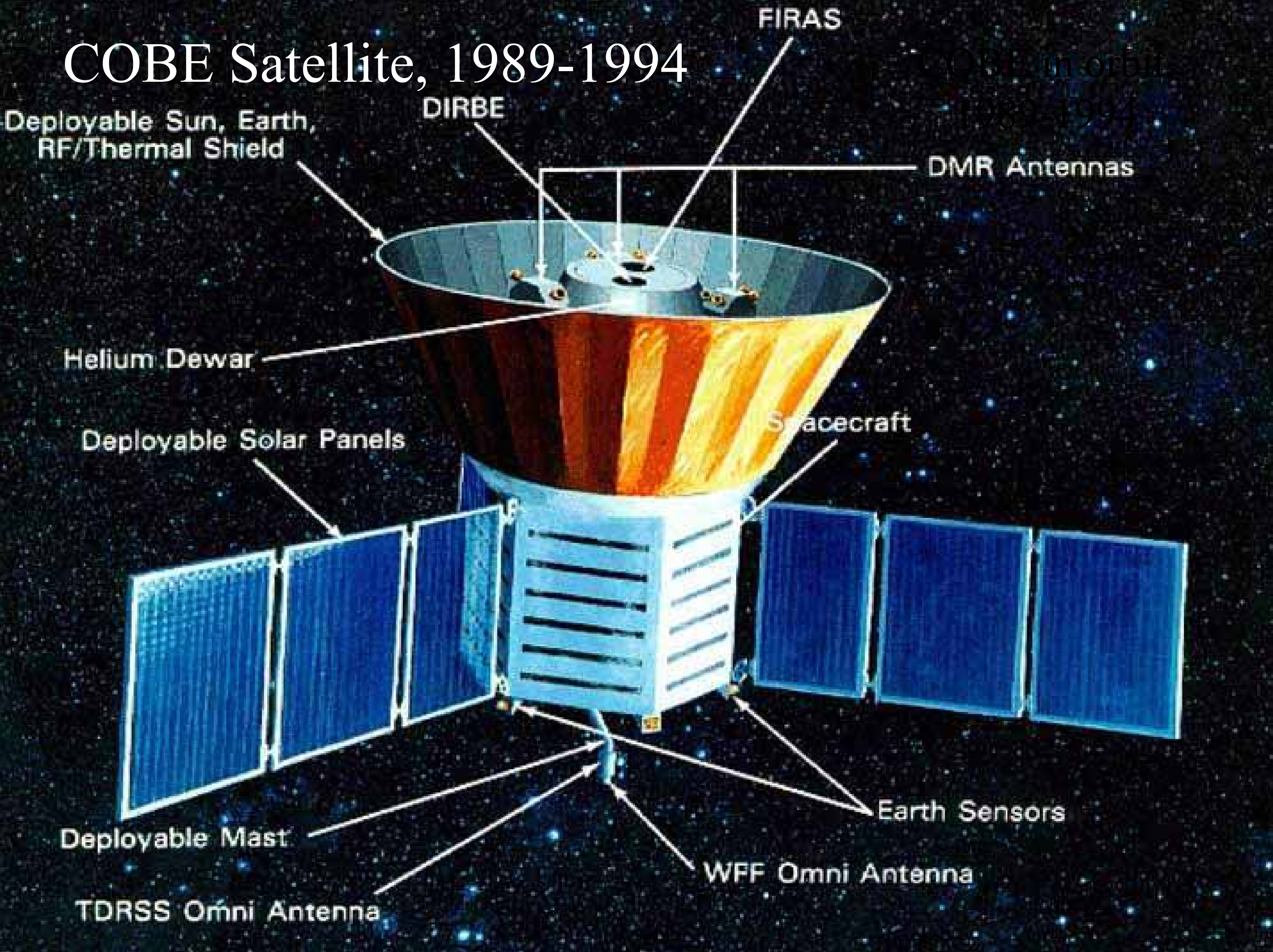
COBE Engineering Leadership

Back row: *Dennis McCarthy (Deputy Project Manager)*, Bob Maichle, Loren Linstrom, Jack Peddicord

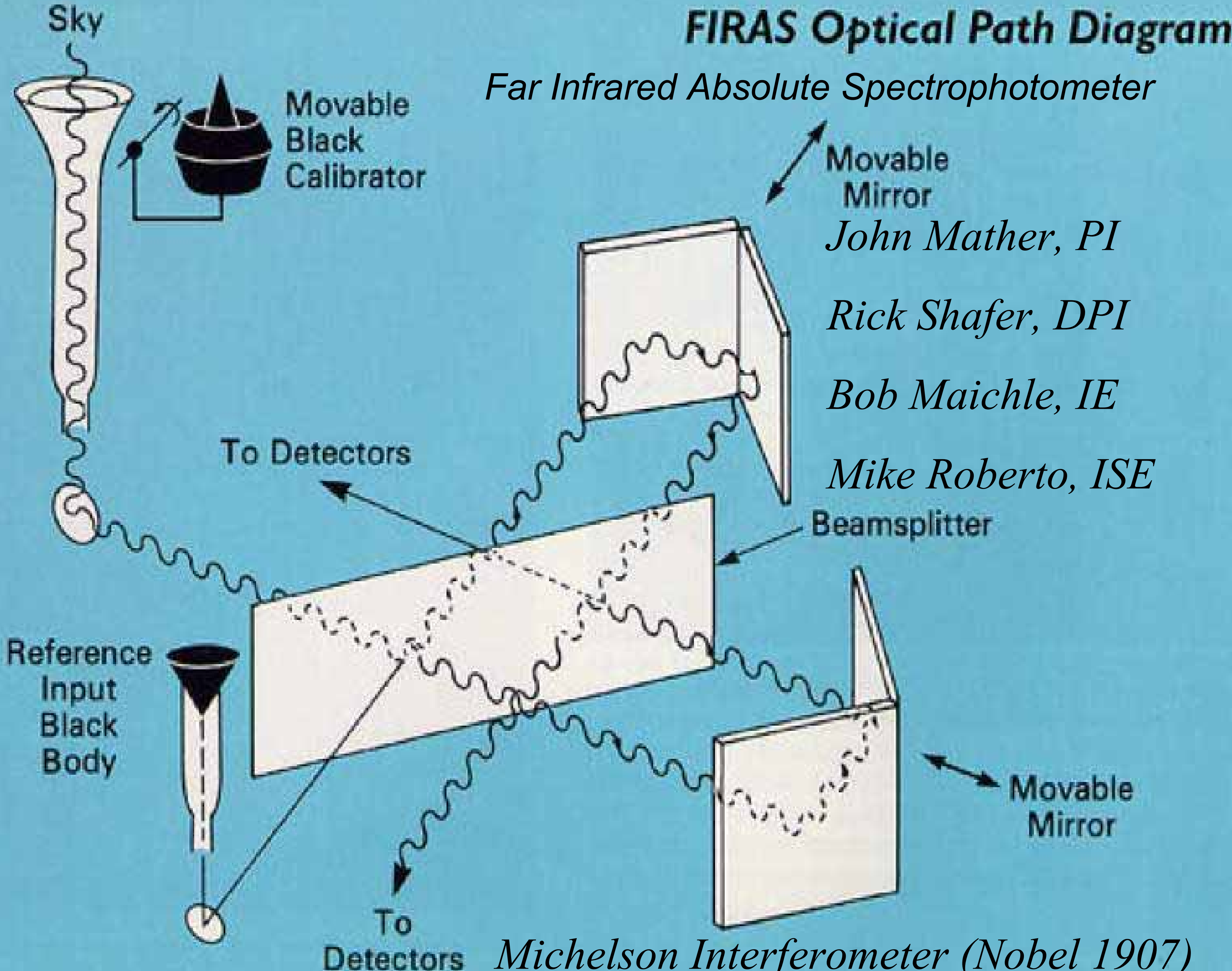
Middle row: Lee Smith, Dave Gilman, Steve Leete, Tony Fragomeni

Front row: Earle Young, Chuck Katz, Bernie Klein, John Wolfgang

COBE Satellite, 1989-1994



Far Infrared Absolute Spectrophotometer



John Mather, PI

Rick Shafer, DPI

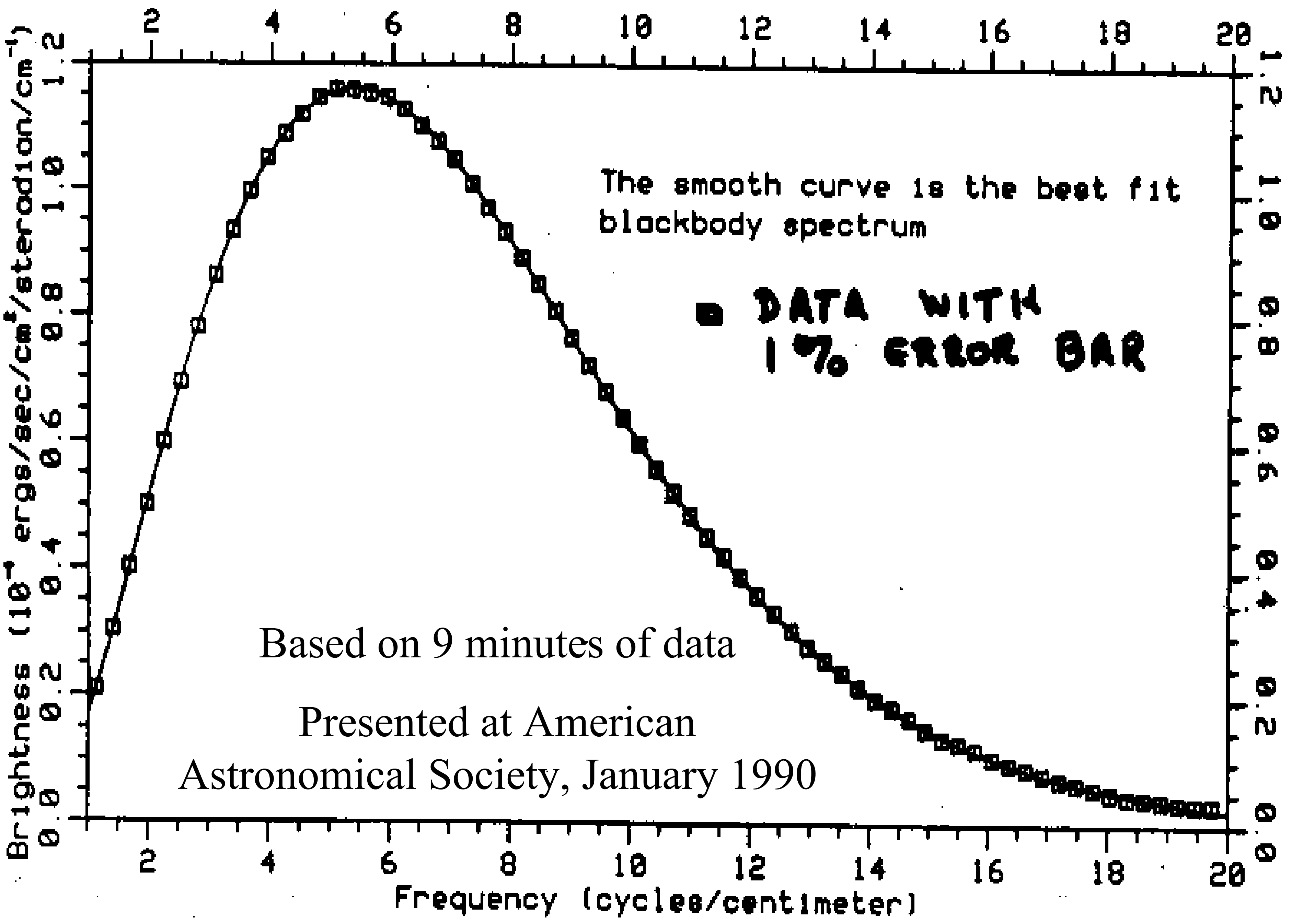
Bob Maichle, IE

Mike Roberto, ISE

Michelson Interferometer (Nobel 1907)


Calibrator (Eccosorb) on arm, before insulation, attached to parabolic concentrator
Calibrator emits same intensity as predicted Big Bang radiation

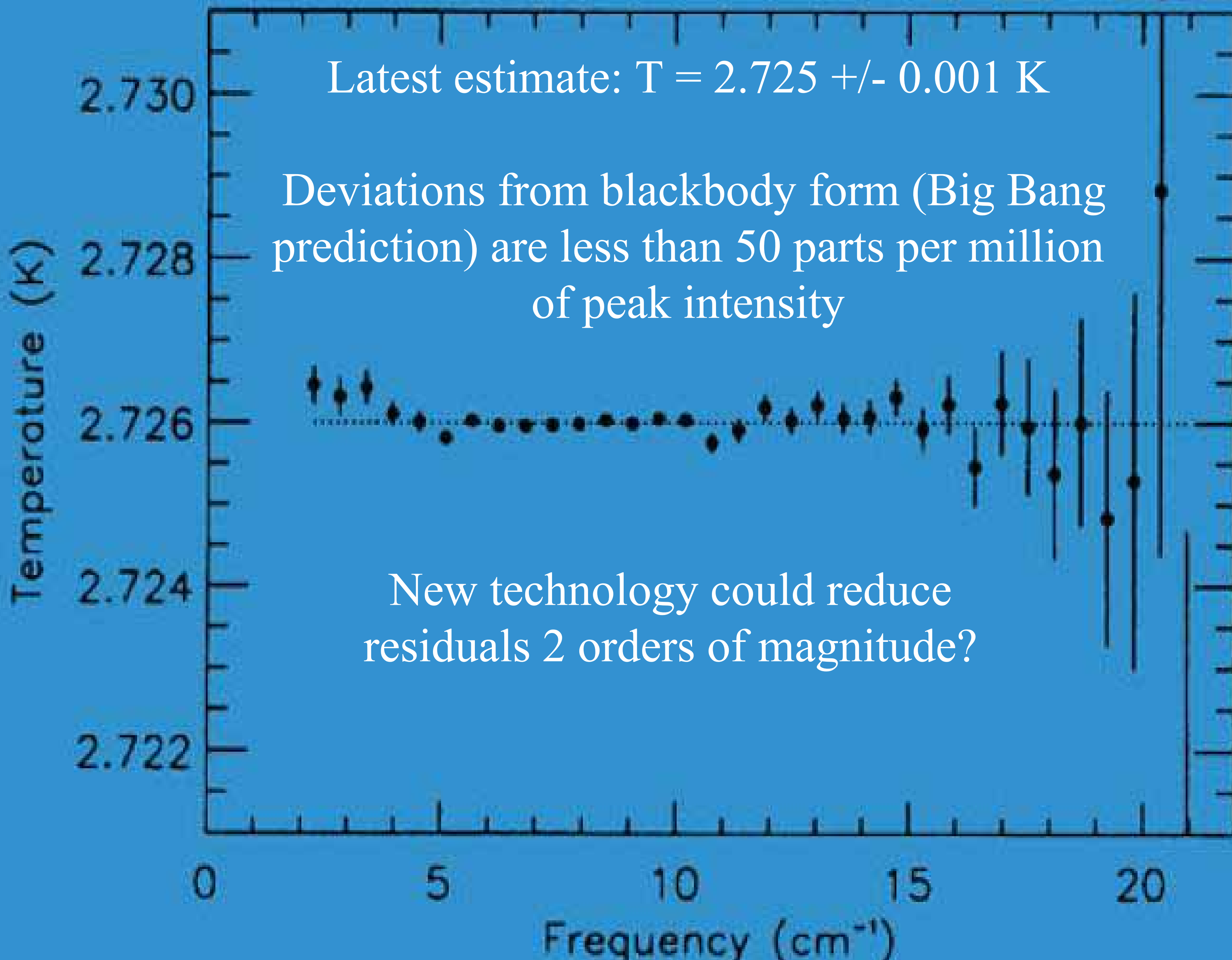
Cosmic Background Spectrum at the North Galactic Pole



Data Processing

- Initial sorting and calibration - teams led by Richard Isaacman & Shirley Read
- Remove cosmic ray impulses
- Simultaneous least squares fit to all the sky and calibration data (team led by Dale Fixsen)
- Make sky maps
- Fit models of interstellar dust emission, interstellar atomic and molecular line emission, interplanetary dust, far IR cosmic background radiation (from other galaxies?), and motion of the Earth through the universe
- Compare with models of universe: energy release versus time - Wright et al., 1994

FIRAS Residual Spectrum



Latest estimate: T = 2.725 +/- 0.001 K

Deviations from blackbody form (Big Bang prediction) are less than 50 parts per million of peak intensity

New technology could reduce residuals 2 orders of magnitude?

Bose-Einstein Distribution - 1994

Energy release or conversion in the redshift range $10^5 < z < 3 \times 10^6$ produces a Bose-Einstein distribution, where the Planck law is modified by a dimensionless chemical potential μ (Zeldovich & Sunyaev 1970):

$$S_\mu(\nu;\, T,\, \mu) = \frac{2hc^2\nu^3}{e^{x+\mu} - 1}\,, \tag{4}$$

where $x = hc\nu/kT$, and ν is measured in cm^{-1}. The linearized deviation of S_μ from a blackbody is the derivative of equation (4) with respect to μ:

$$\frac{\partial S_\mu}{\partial \mu} = \frac{-T_0}{x}\frac{\partial B_\nu}{\partial T}\,. \tag{5}$$

The current FIRAS result is $\mu = -1 \pm 4 \times 10^{-5}$, or a 95% CL upper limit of $|\mu| < 9 \times 10^{-5}$. This result and

Compton Distortion - 1994

6.3. *Compton Distortion*

Energy release at later times, $z < 10^5$, produces a Comptonized spectrum, a mixture of blackbodies at a range of temperatures. In the case of nonrelativistic electron temperatures, this spectrum is described by the Kompaneets (1957) equation, parameterized by the value of y (Zeldovich & Sunyaev 1969):

$$y = \int \frac{k(T_e - T_\gamma)}{m_e c^2} \, d\tau_e \,, \tag{6}$$

where T_e, T_γ, and τ_e are the electron temperature, the CMBR photon temperature, and the optical depth to electron Compton scattering, respectively. The distortion will be of the form (Zeldovich & Sunyaev 1969)

$$\frac{\partial S_y}{\partial y} = T_0 \left[x \coth\left(\frac{x}{2}\right) \right] - 4 \, \frac{\partial B_\nu}{\partial T} \,. \tag{7}$$

The results are $y = -1 \pm 6 \times 10^{-6}$. There is some depen-

Cosmic Microwave Background matches Hot Big Bang

- $\delta F/F_{max} < 50$ ppm (rms deviation)
- $T = 2.725 \pm 0.001$ K (Fixsen & Mather 2002)
- $|y| < 15 \times 10^{-6}$, $|\mu| < 9 \times 10^{-5}$, 95% CL
- Strong limits, about 0.01%, on fraction of CMB energy due to conversion (from turbulence, proton decay, other unstable particles, decaying massive neutrinos, late photoproduction of deuterium, explosive or normal galaxy formation, cosmic gravity waves, cosmic strings, black holes, active galactic nuclei, Population III stars, hot intergalactic medium, etc.) after t = 1 year.
- No good explanation besides Hot Big Bang

Confirming the Big Bang Theory

I wish He wouldn't keep that darn thermostat at 3 K!

Other FIRAS Results

- Spectrum of far IR cosmic background radiation
- Spectrum of far IR zodiacal light
- Blackbody spectrum of cosmic dipole due to motion
- Limits on spatial variation of CMB spectrum
- Maps of dust emission of the Milky Way, with temperature, intensity, and number of types of dust (usually 2, sometimes 3)
- First observation of N^+ line at 205.3 μm
- Maps of molecular and atomic line emissions of the Milky Way: CO, C, C^+, N^+
- Confirmation of Planck formula for blackbody spectrum (Max Planck, Nobel, 1918; Wilhelm Wien, Nobel 1913)

DIRBE (Diffuse Infrared Background Experiment)

- Map entire sky in 10 bands from 1.2 to 240 μm
- Measure, understand, and subtract for zodiacal and galactic foregrounds
- Determine small residual from early universe, primeval galaxies, etc.
- Requires absolute calibration

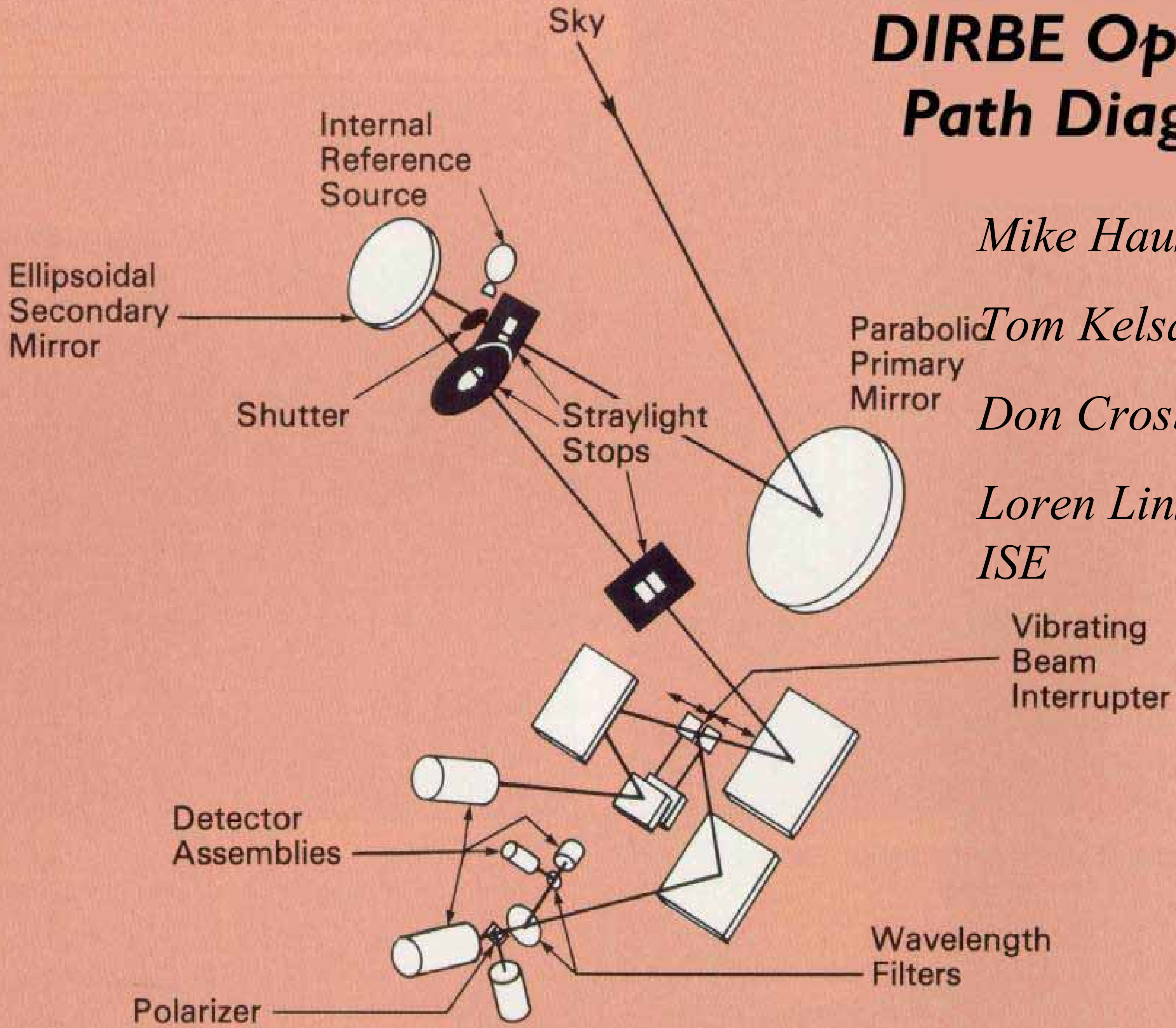
DIRBE Optical Path Diagram

Mike Hauser, PI

Tom Kelsall, DPI

Don Crosby, IE

Loren Linstrom, ISE



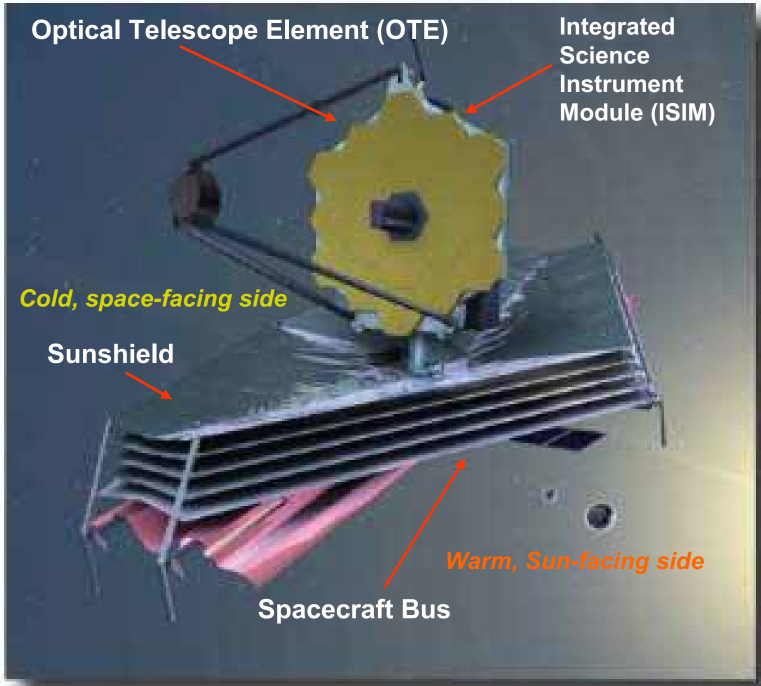
DIRBE cosmology results

- Cosmic Infrared Background has 2 parts, near (few microns) and far (few hundred microns
  - Each with brightness comparable to the known luminosity of visible & near IR galaxies
  - Luminosity of universe is ~ double expected value
  - Does not mean the CMB spectrum is distorted

James Webb Space Telescope (JWST)

Organization

- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA
- Operations: Space Telescope Science Institute



Description

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch June 2013 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission (10-year goal)

www.JWST.nasa.gov

JWST Science Themes


End of the dark ages: First light and reionization

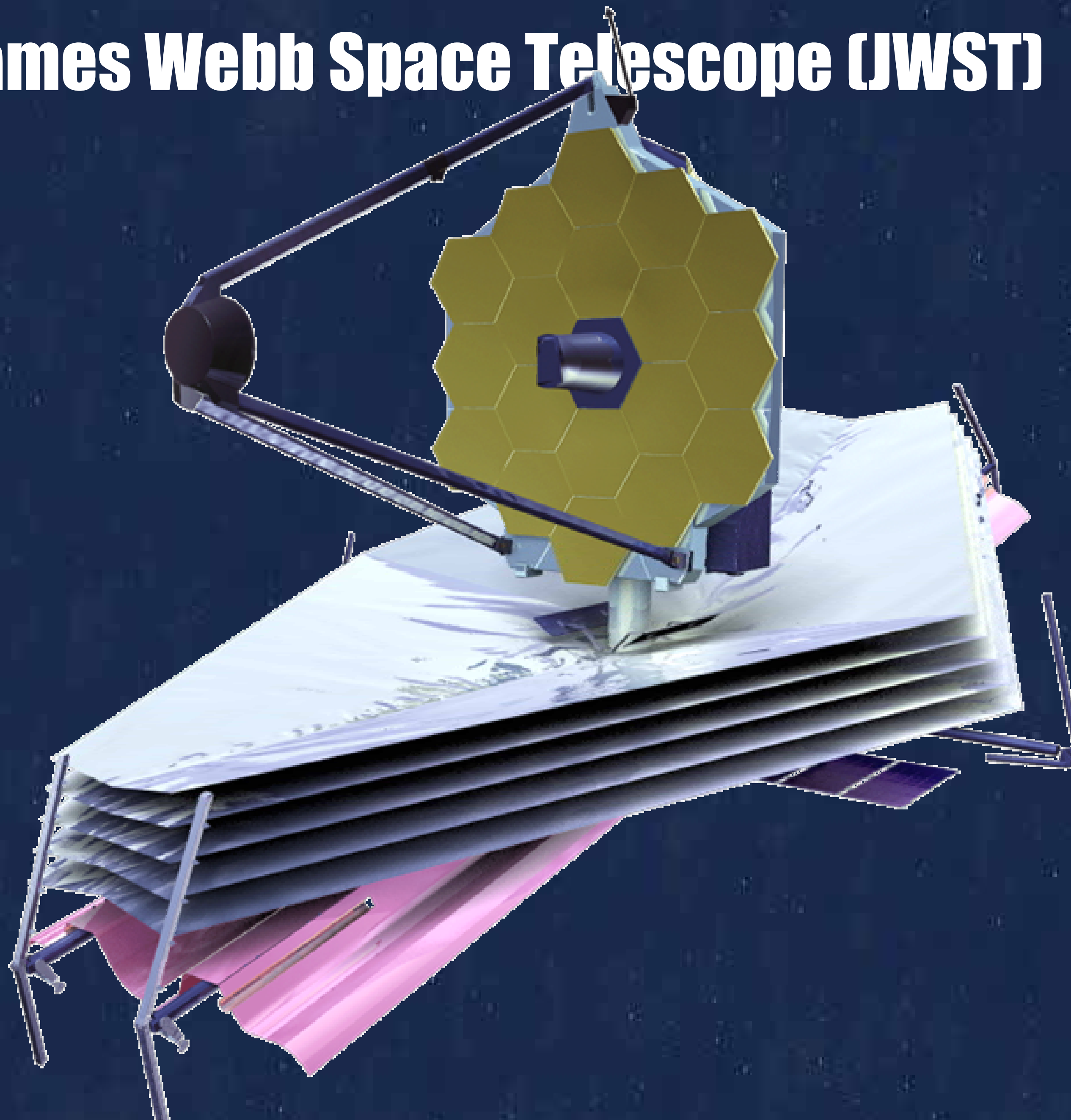

The assembly of galaxies


Birth of stars and proto-planetary systems


Planetary systems and the origin of life

The End

James Webb Space Telescope (JWST)



Summary of JWST

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and 4 instruments for infrared performance, covering 0.6 to 29 μm
- Launch June 2013 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2: 1.5 million km away in deep space (needed for cooling)
- 5-year science mission (10-year goal)

James Webb Space Telescope

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- Instruments:
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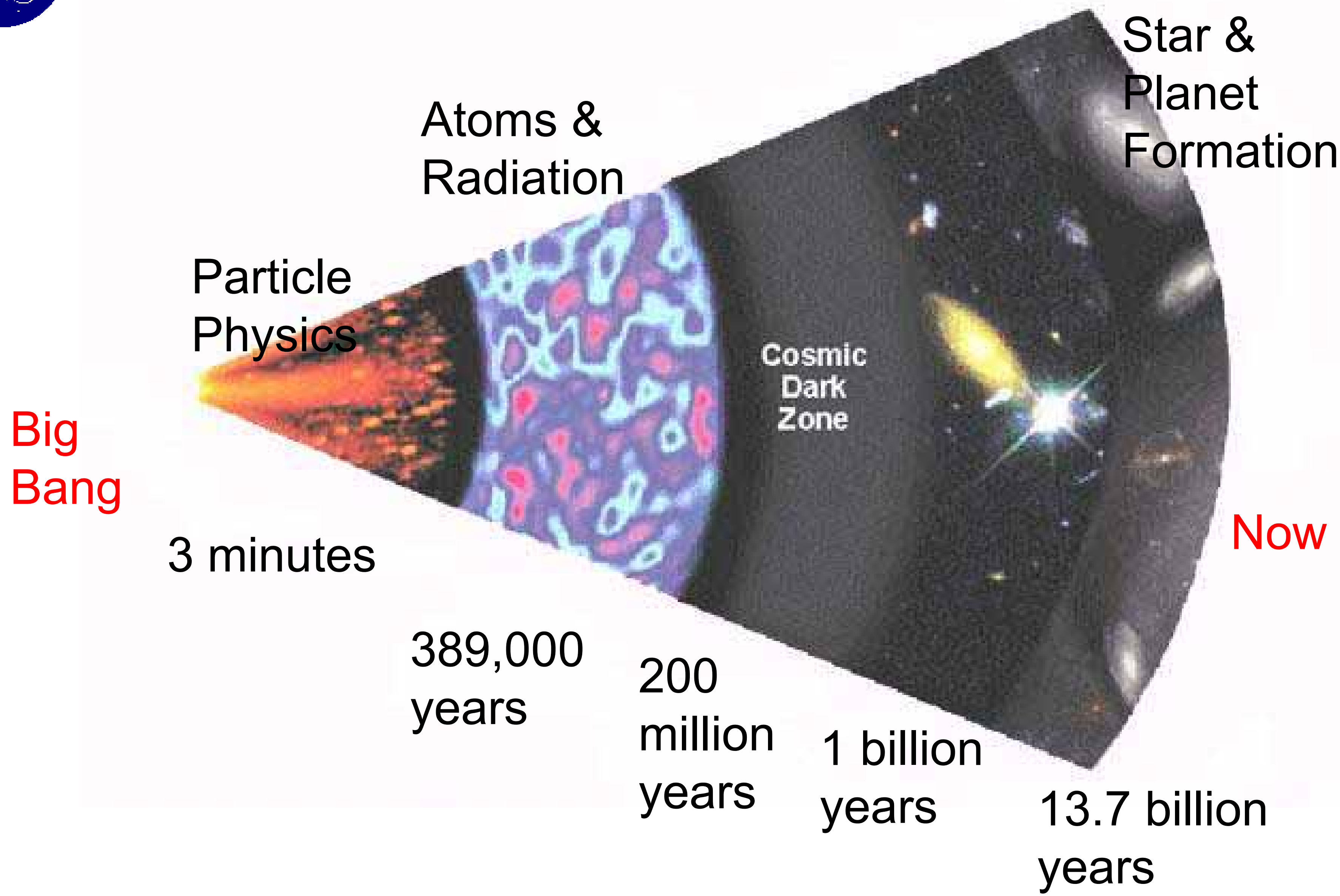
Four Scientific Themes

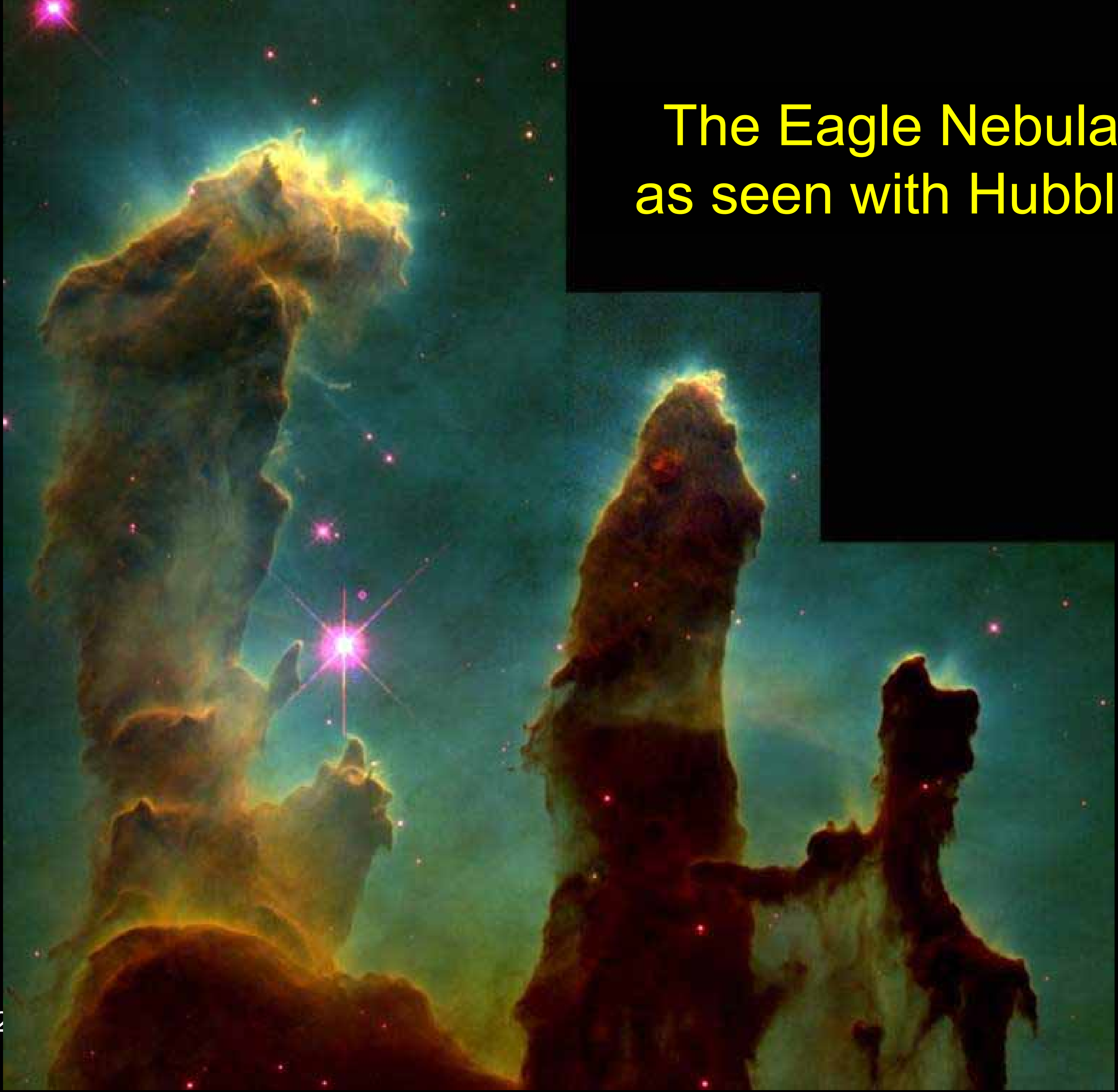
- First objects formed after Big Bang
  - Super-stars?
  - Super-supernovae?
  - Black holes?
- Assembly of galaxies (from small pieces?)
- Formation of stars and planetary systems
  - Hidden in dust clouds
- Planetary systems and conditions for life

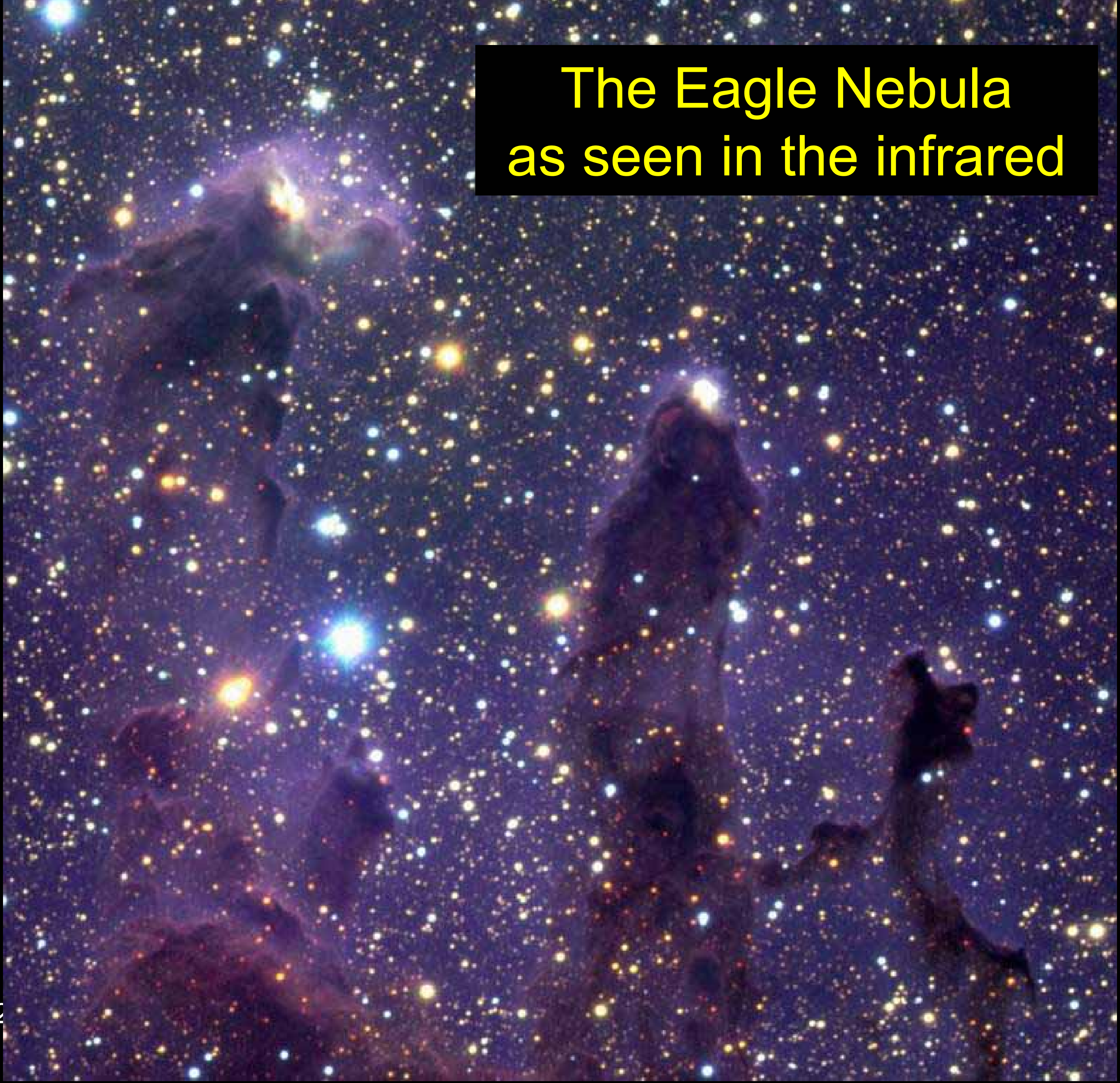
JWST Science Objectives versus Cosmic History



End of the dark ages: first light?

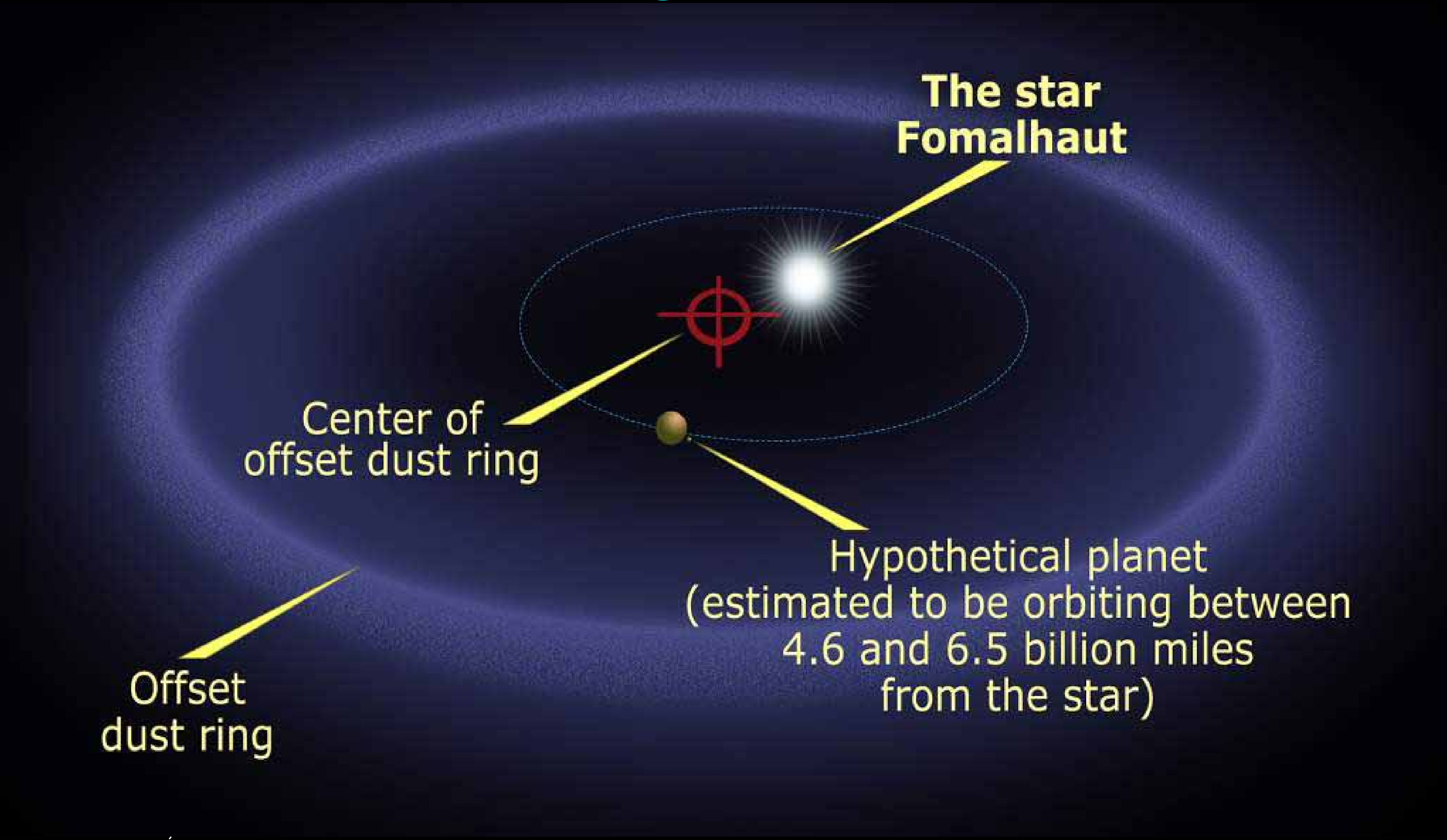
The Eagle Nebula
as seen with Hubble



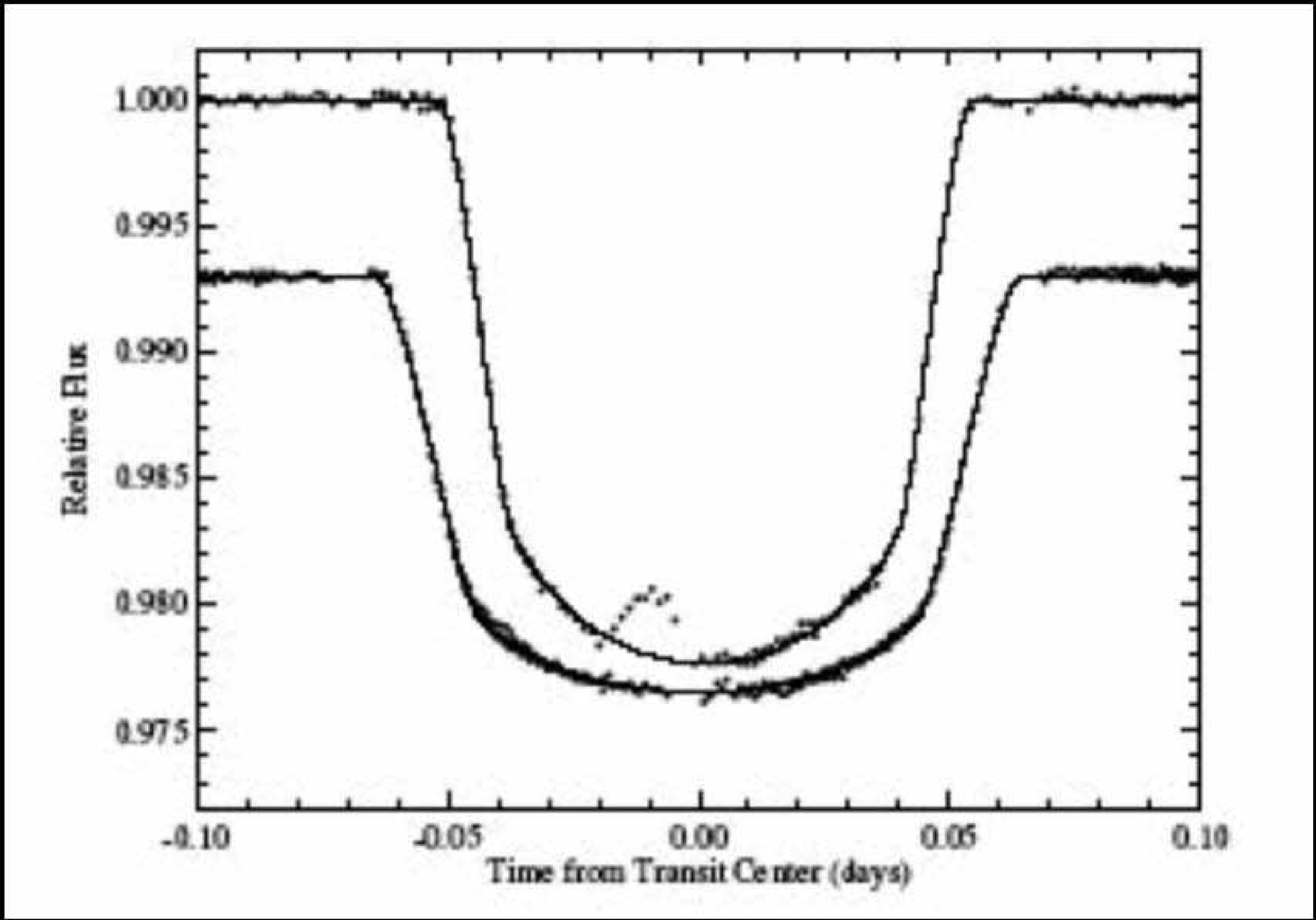

The Eagle Nebula
as seen in the infrared

Stars in dust disks in Orion

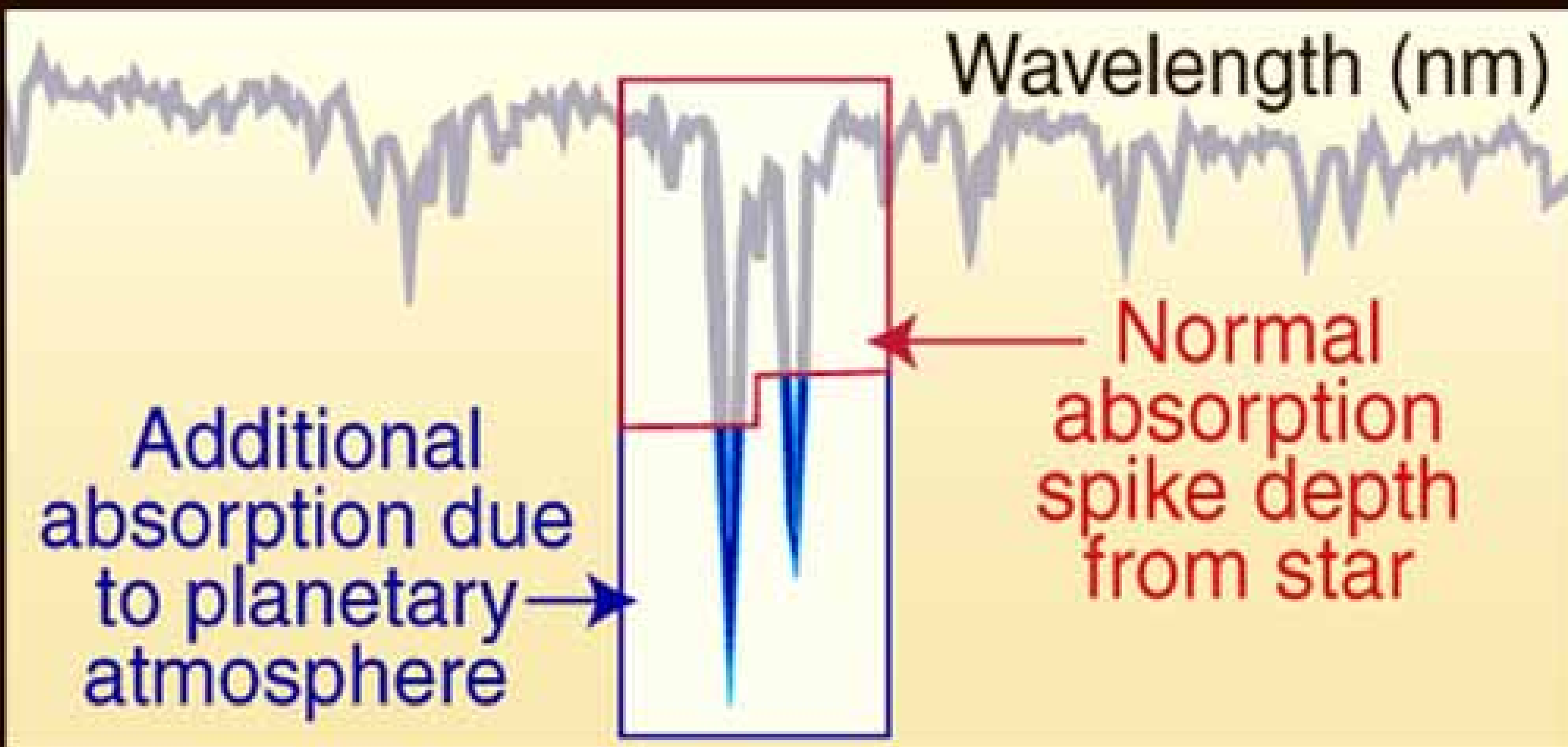
Planetary systems and the origins of life



HST characterizes transiting planets; so will JWST



Chemistry of Transiting Planets



What happened before the Big Bang?

What's at the center of a black hole?

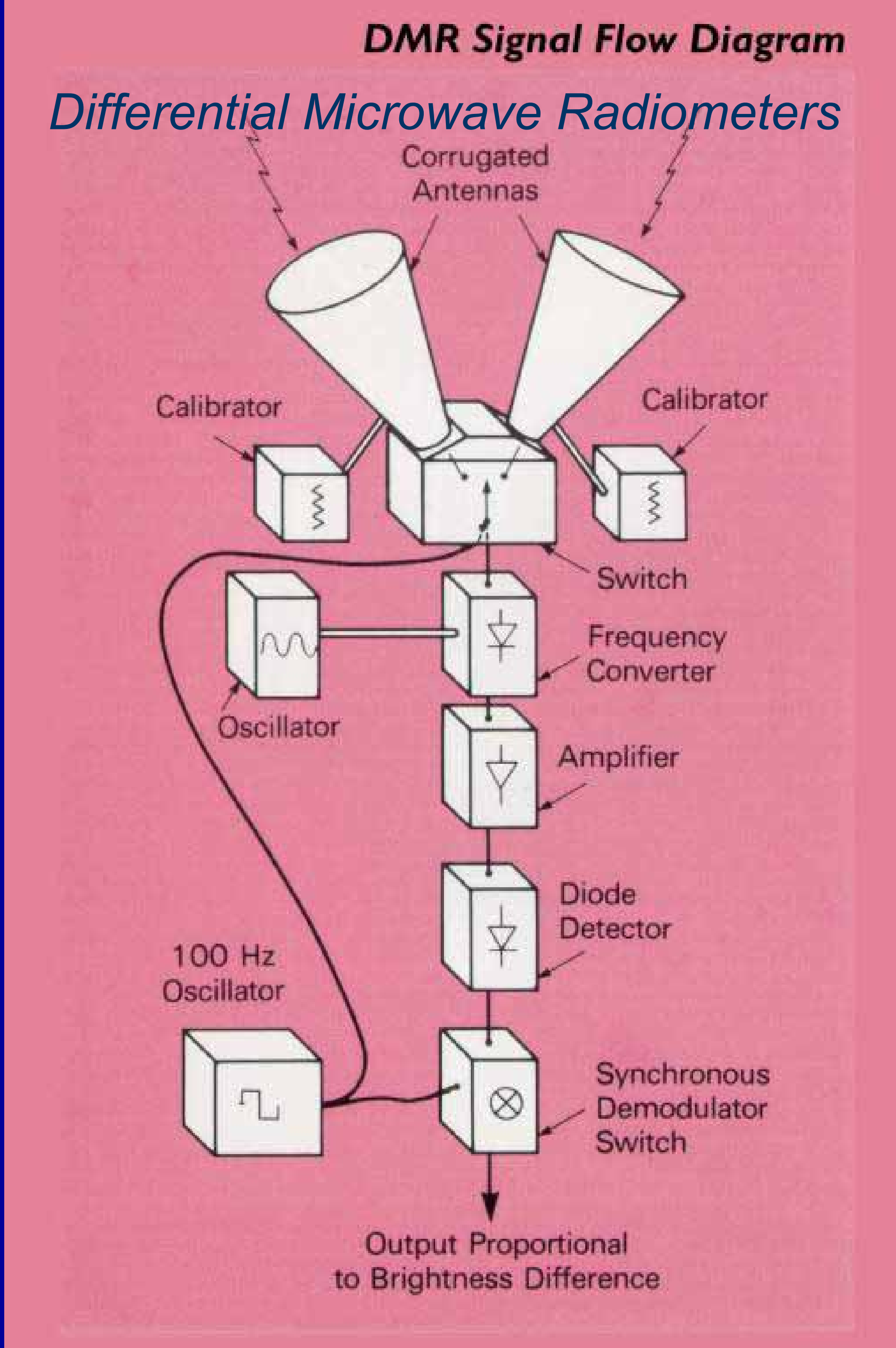
How did we get here?

What is our cosmic destiny?

What are space and time?

… Big Questions, Ripe to Answer

Differential Microwave Radiometers



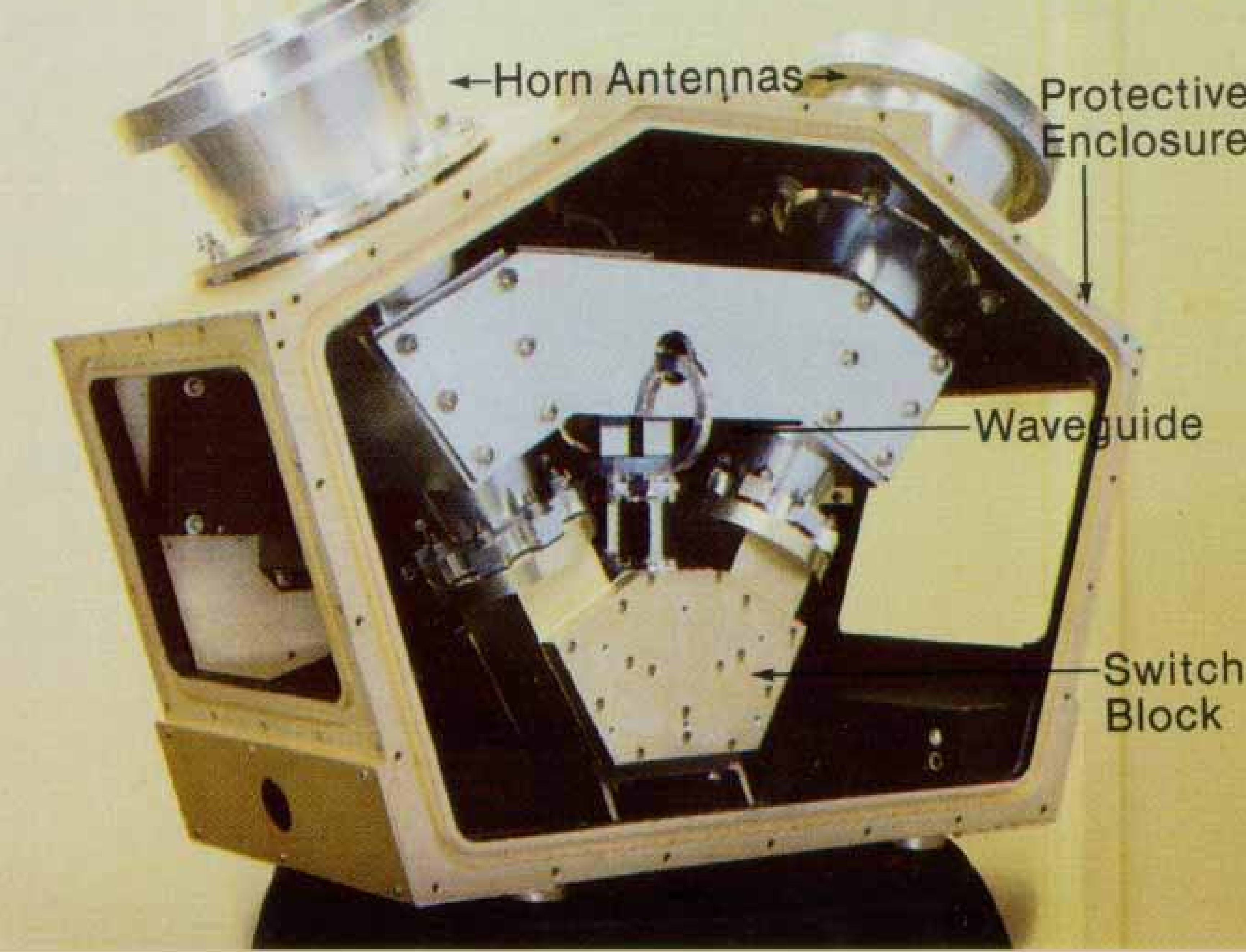
George Smoot

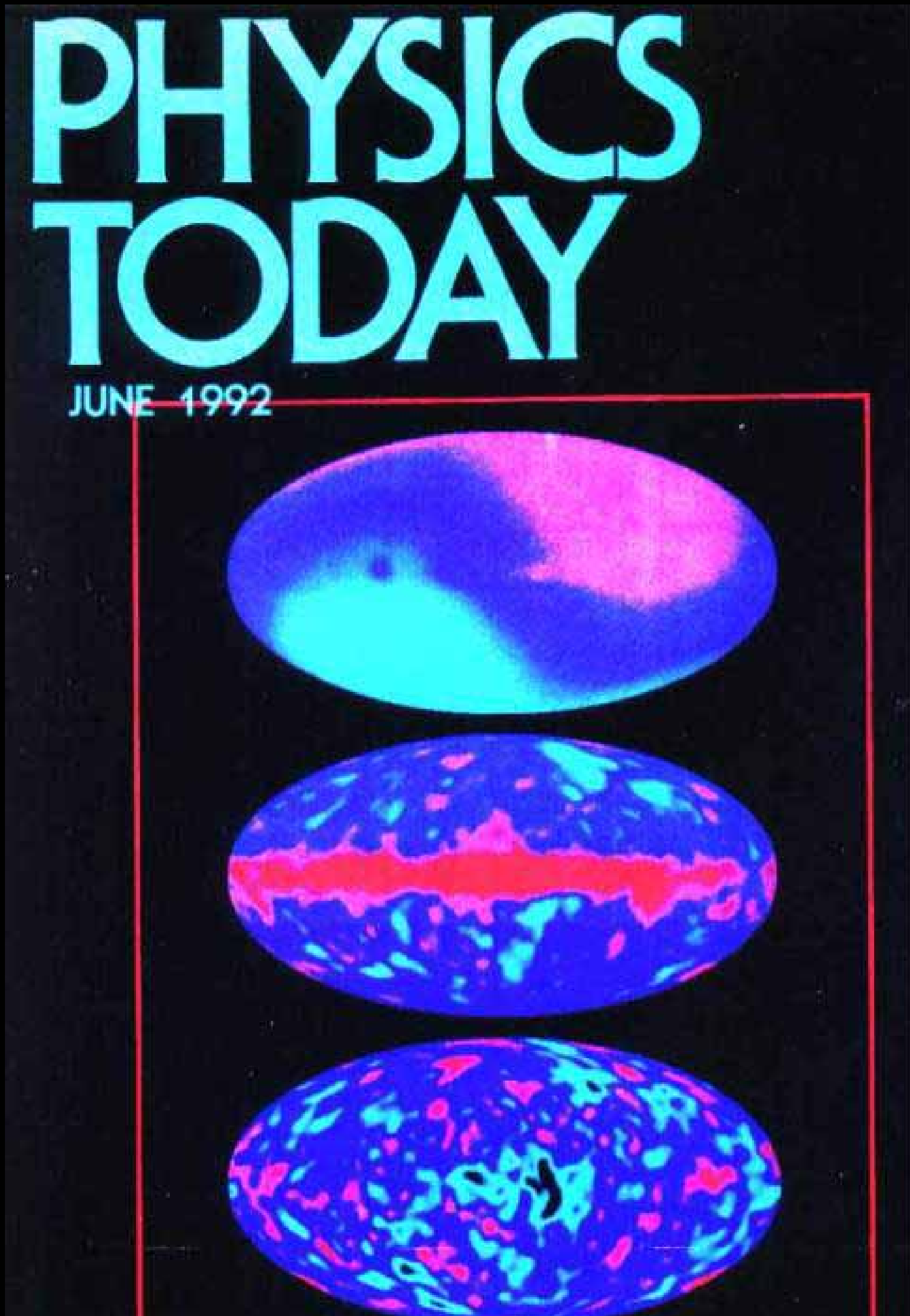
Chuck Bennett

Bernie Klein

Steve Leete

31.4 GHz DMR Receiver



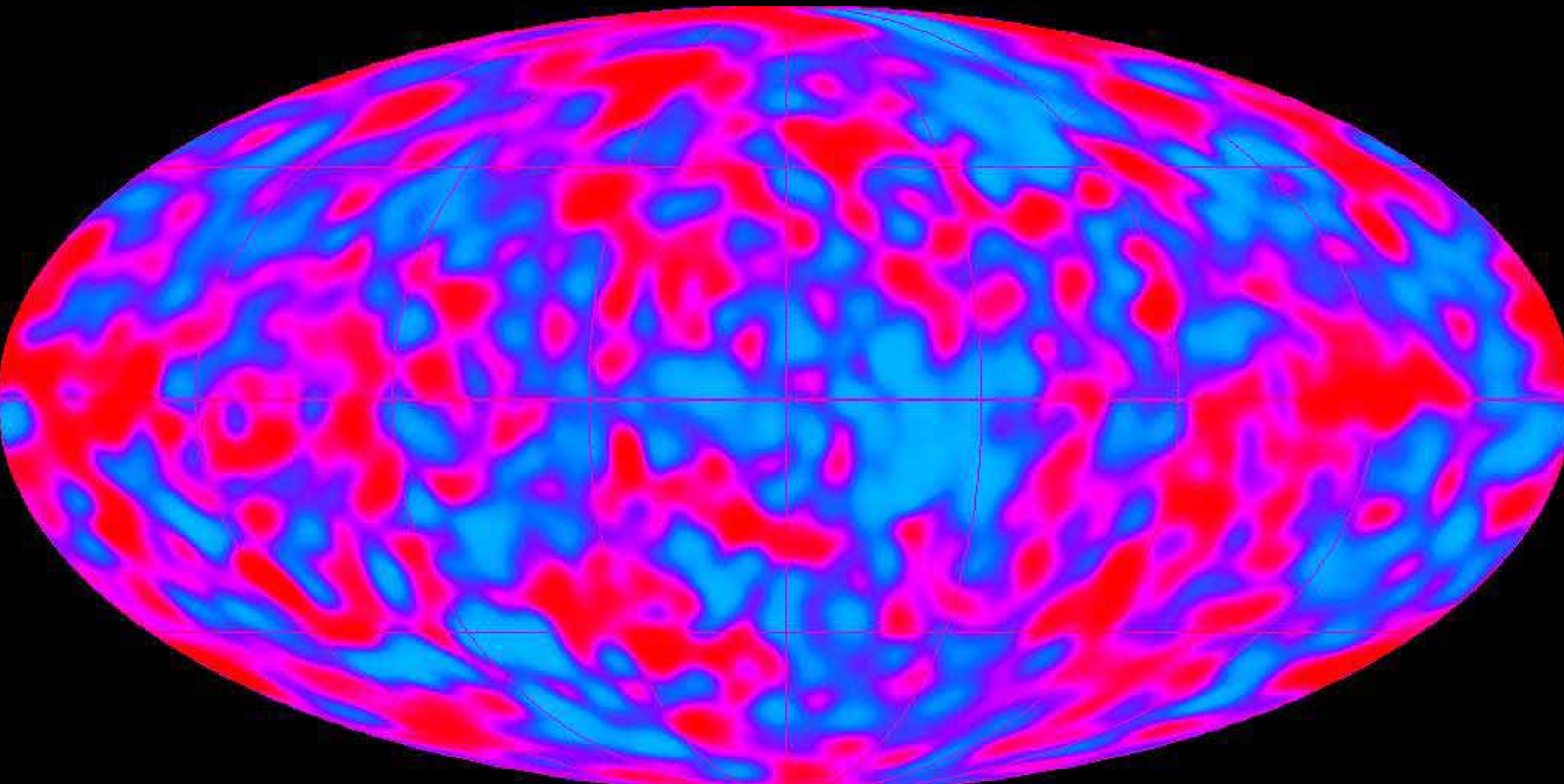


Sky map from DMR,
2.7 K +/- 0.003 K

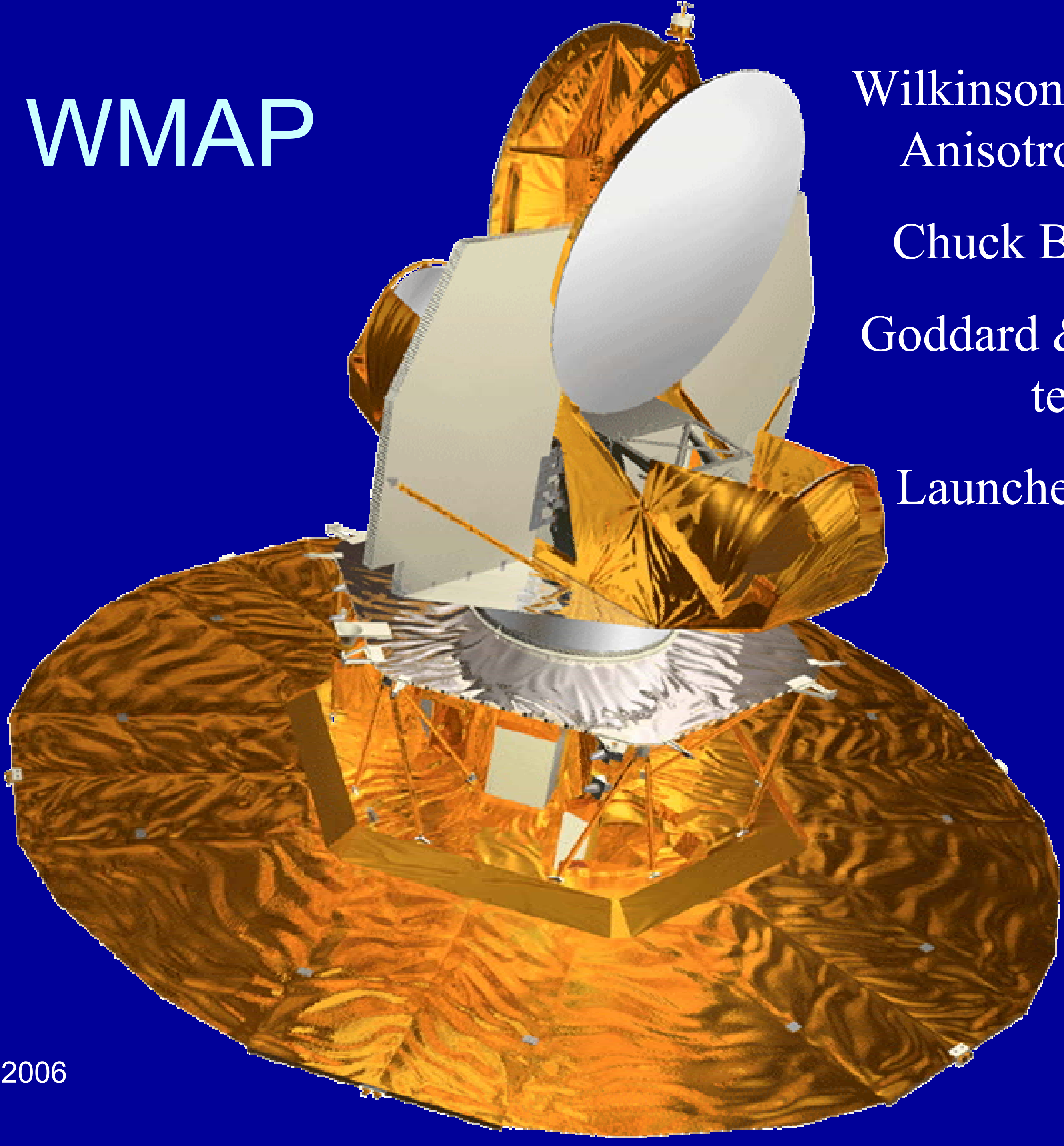
Doppler Effect of Earth's motion removed (v/c = 0.001)

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

COBE Map of CMB Fluctuations
2.725 K +/- ~ 30 μK rms, 7^o beam



WMAP



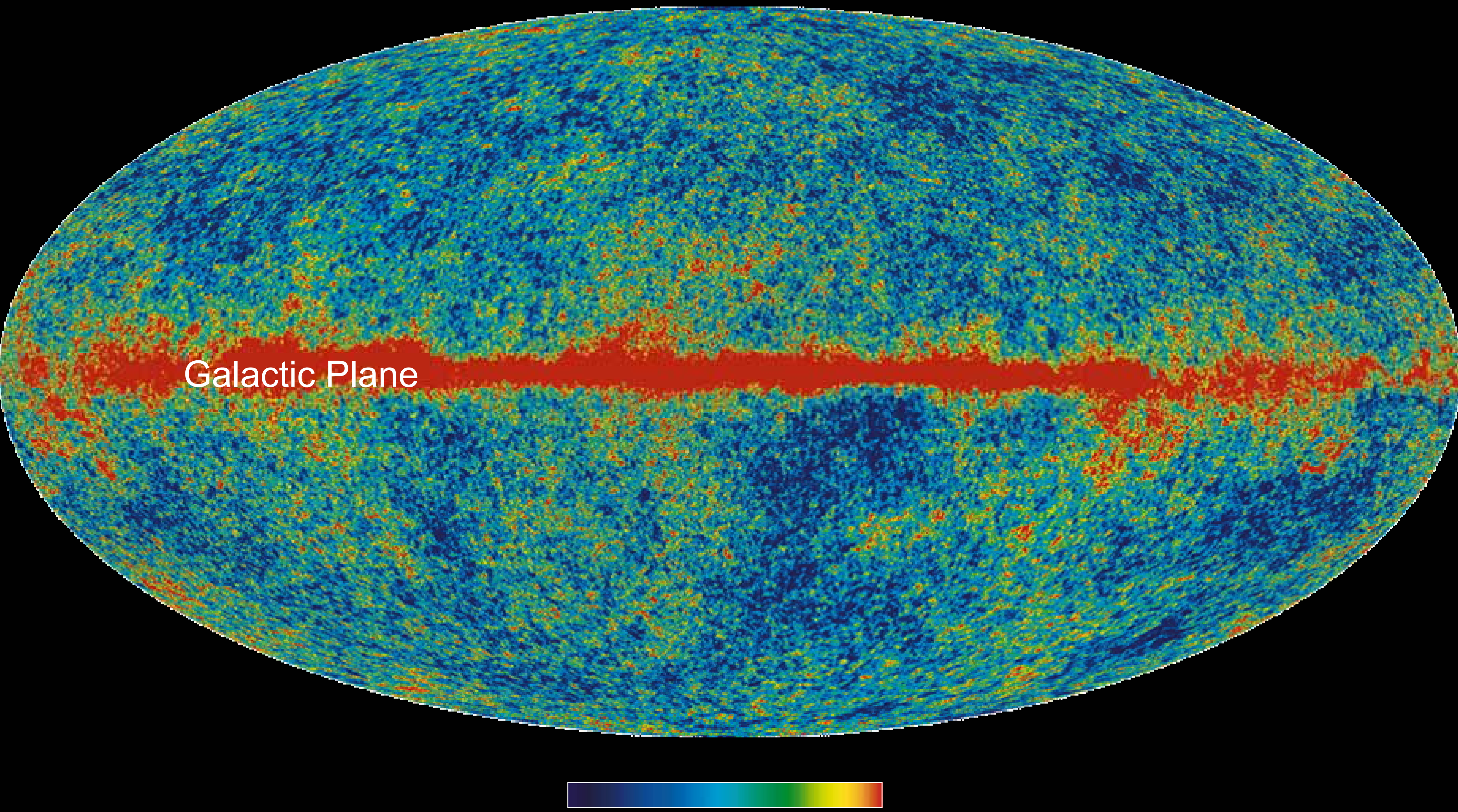
Wilkinson Microwave Anisotropy Probe

Chuck Bennett, PI

Goddard & Princeton team

Launched in 2001

The Universe at age 389,000 years



-200 +200

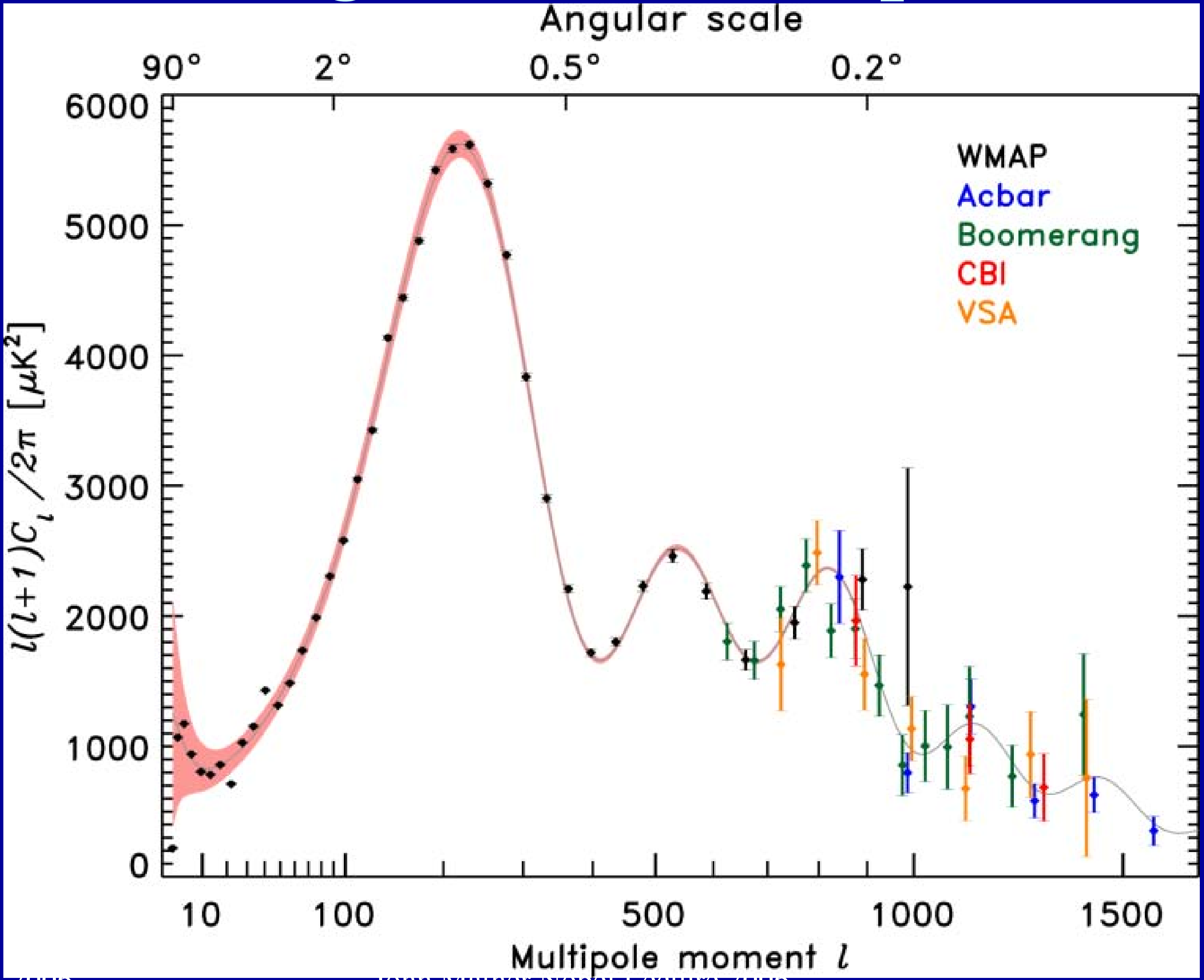
Temperature (µK) relative to average of 2.725 K

Cosmic Parameters to ~ percent accuracy

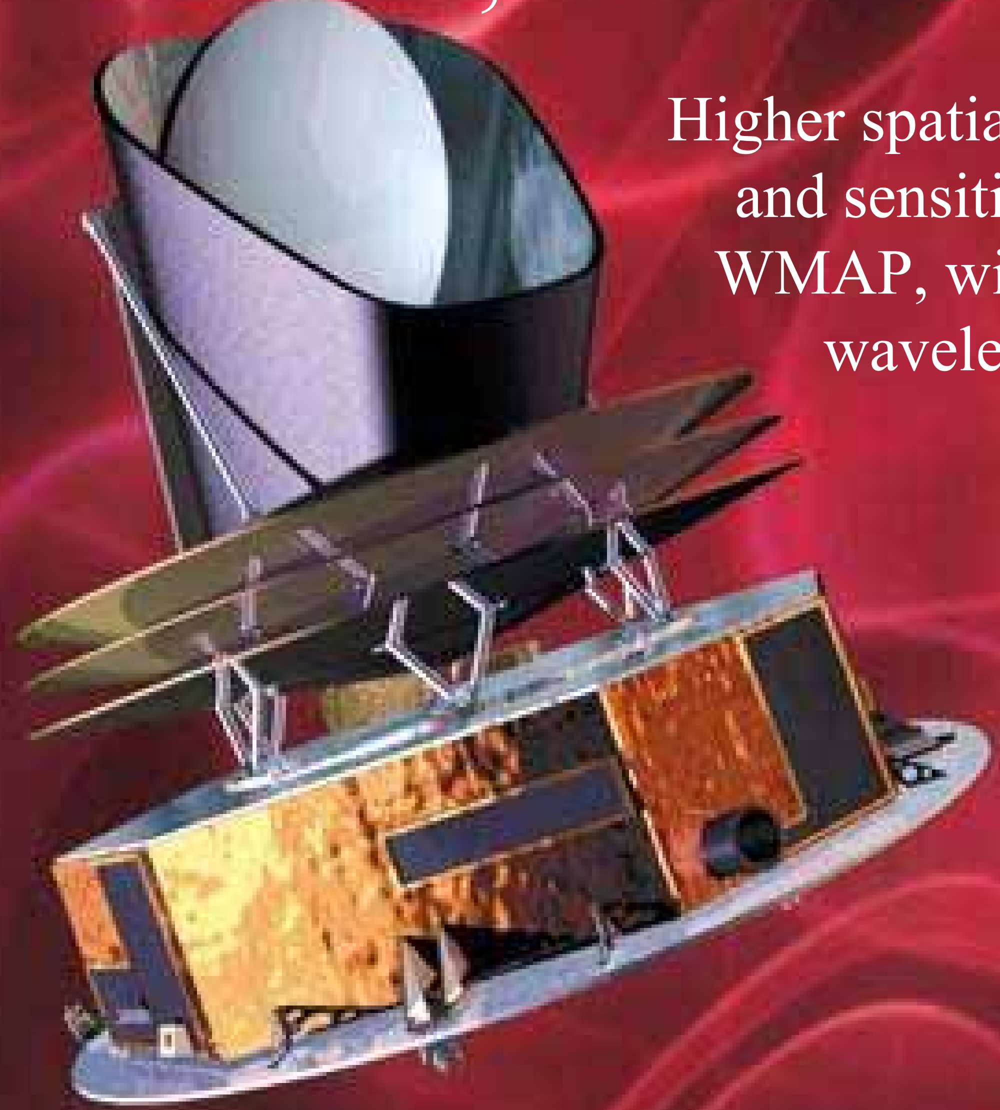
$$\Omega_{tot} = \Omega_b + \Omega_c + \Omega_\Lambda = 100\%$$

$$\Omega_m = \Omega_b + \Omega_c = 27 \pm 4\%$$

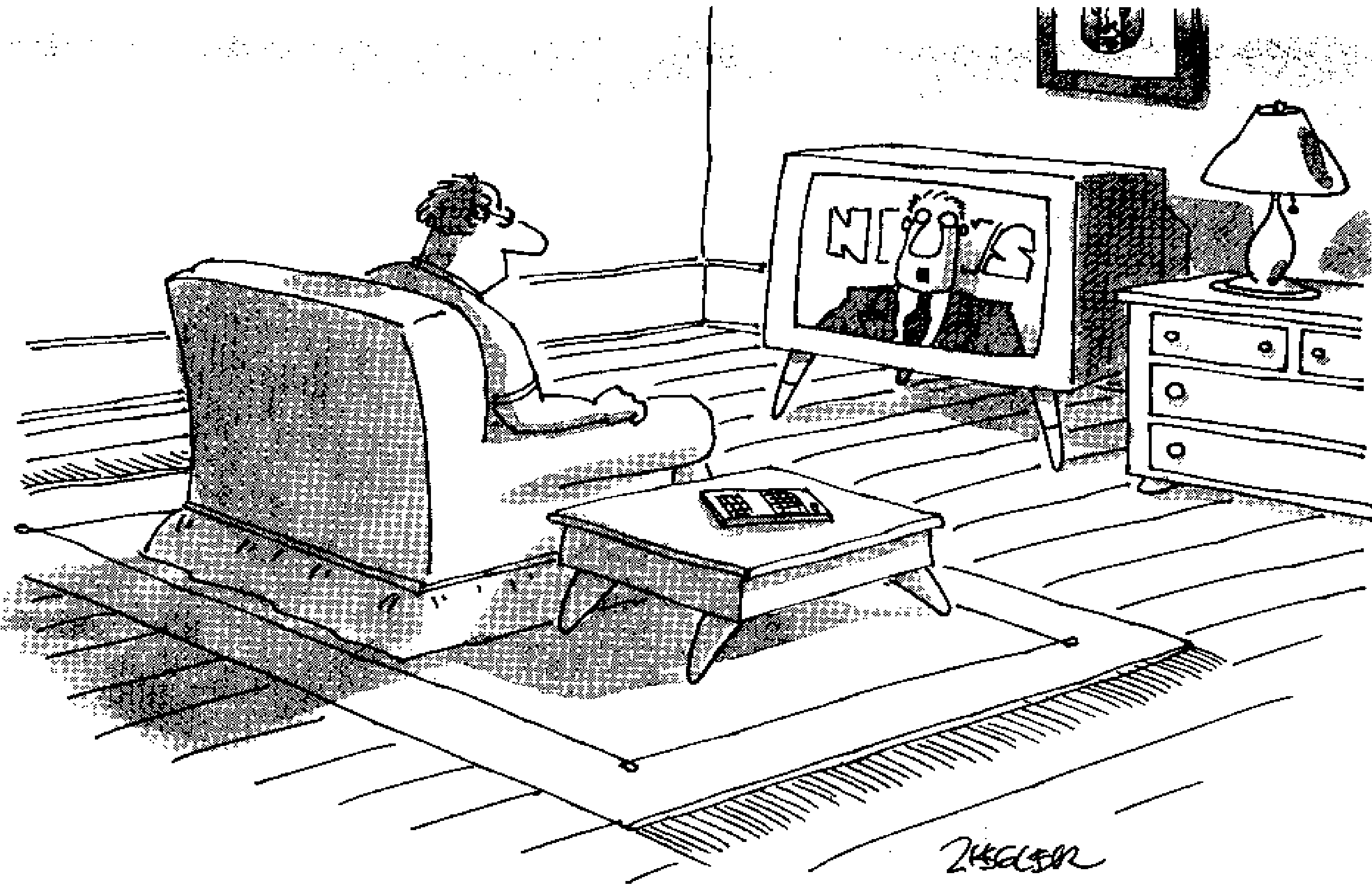
CMB Angular Power Spectrum



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



Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths

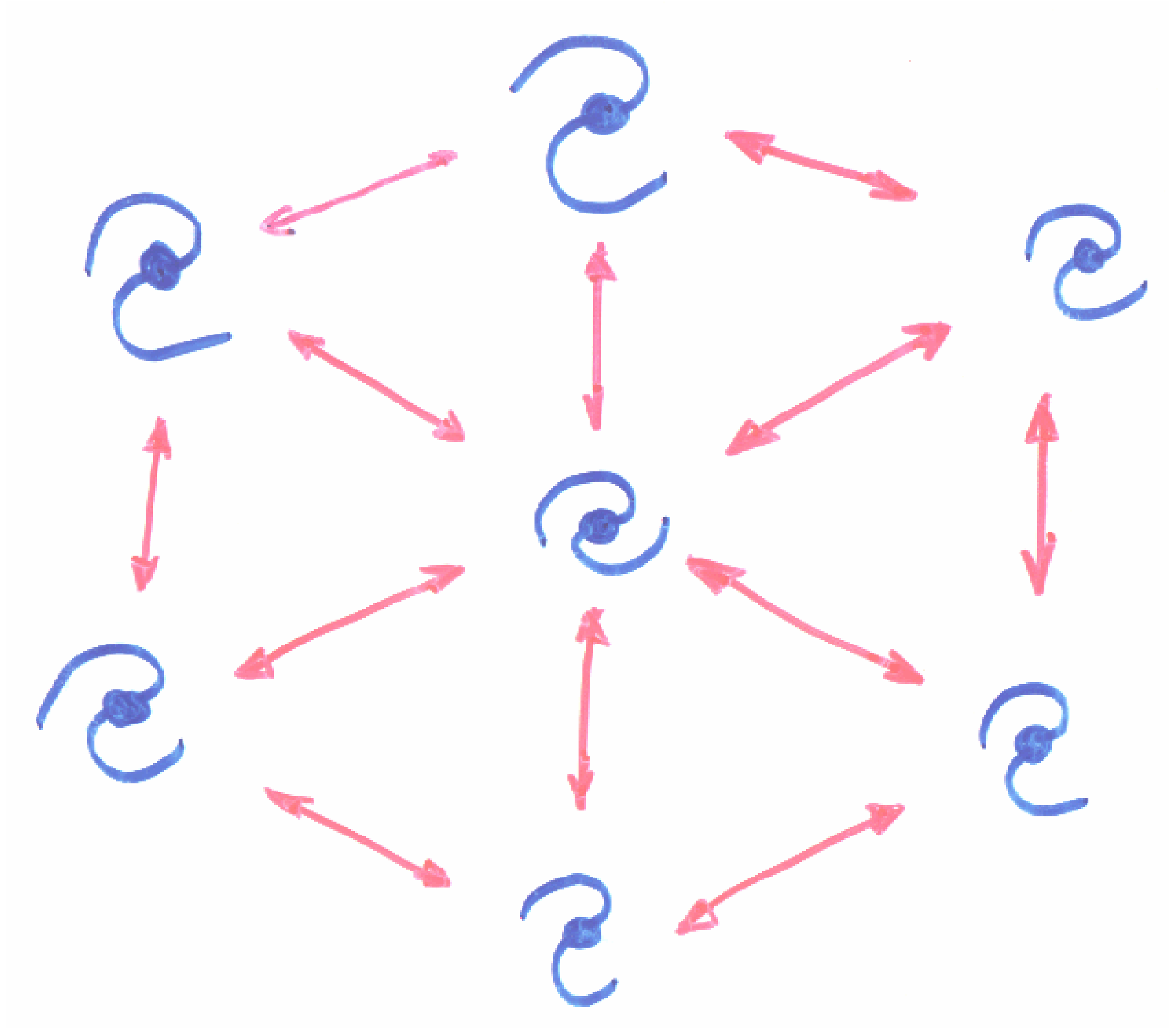


"Scientists confirmed today that everything we know about the structure of the universe is wrongedy-wrong-wrong."

Galaxies attract each other, so the expansion should be slowing down -- Right??

To tell, we need to compare the velocity we measure on nearby galaxies to ones at very high redshift.

In other words, we need to extend Hubble's velocity vs distance plot to much greater distances.



COBE Starts Precision Cosmology

- CMB has spatial structure
  - 0.001% on scales > 7^{o}
  - Consistent with scale-invariant predictions and inflation
  - Fits dark matter and dark energy or Λ constant
  - Supports formation of galaxies and clusters by gravity
- Cosmic Infrared Background has 2 parts, near (few microns) and far (few hundred microns
  - Each with brightness comparable to the known luminosity of visible & near IR galaxies
  - Luminosity of universe is ~ double expected value
  - Does not mean the CMB spectrum is distorted

White Mountain CMB Fabry-Perot Spectrometer with Werner & Richards

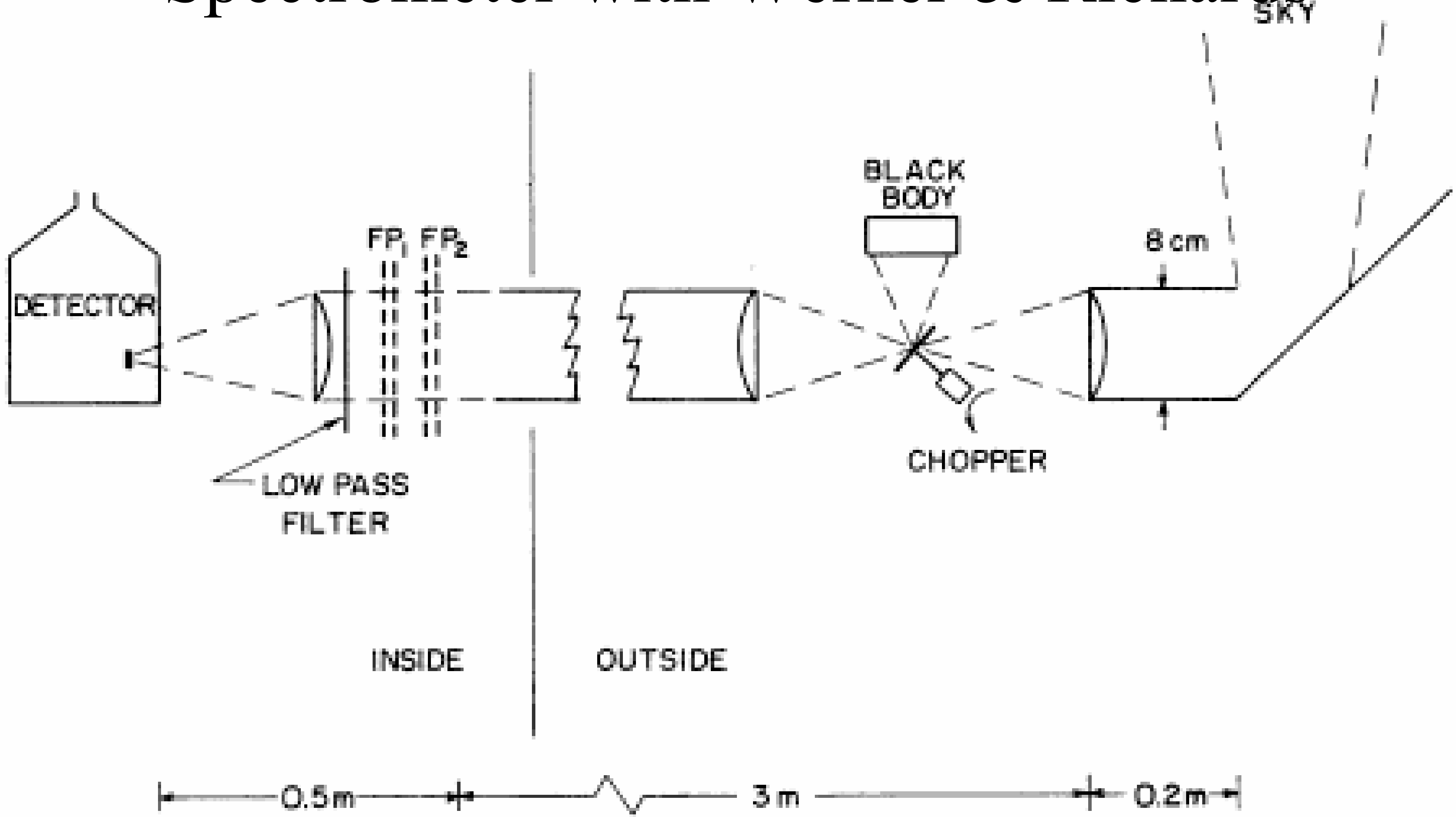
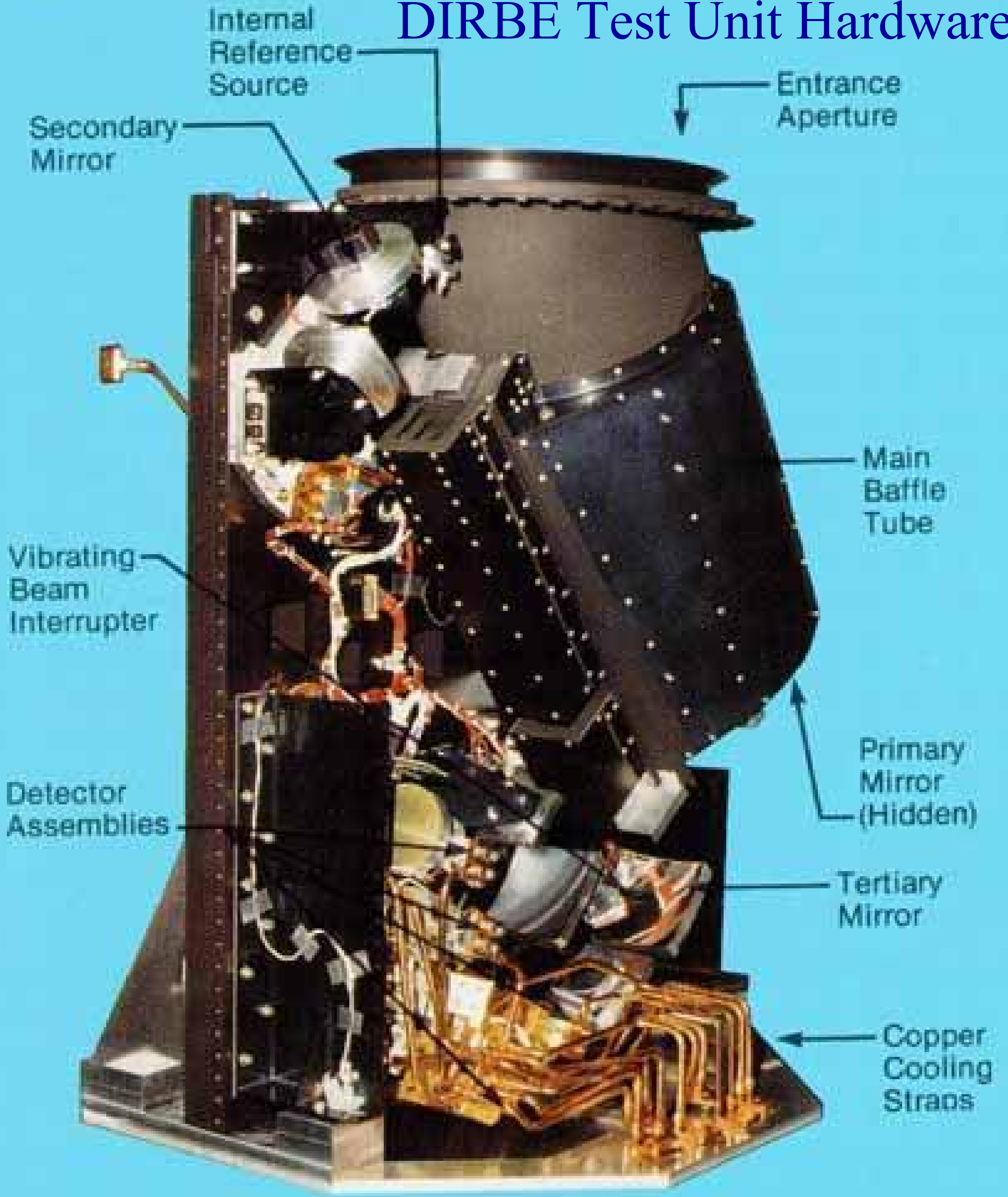
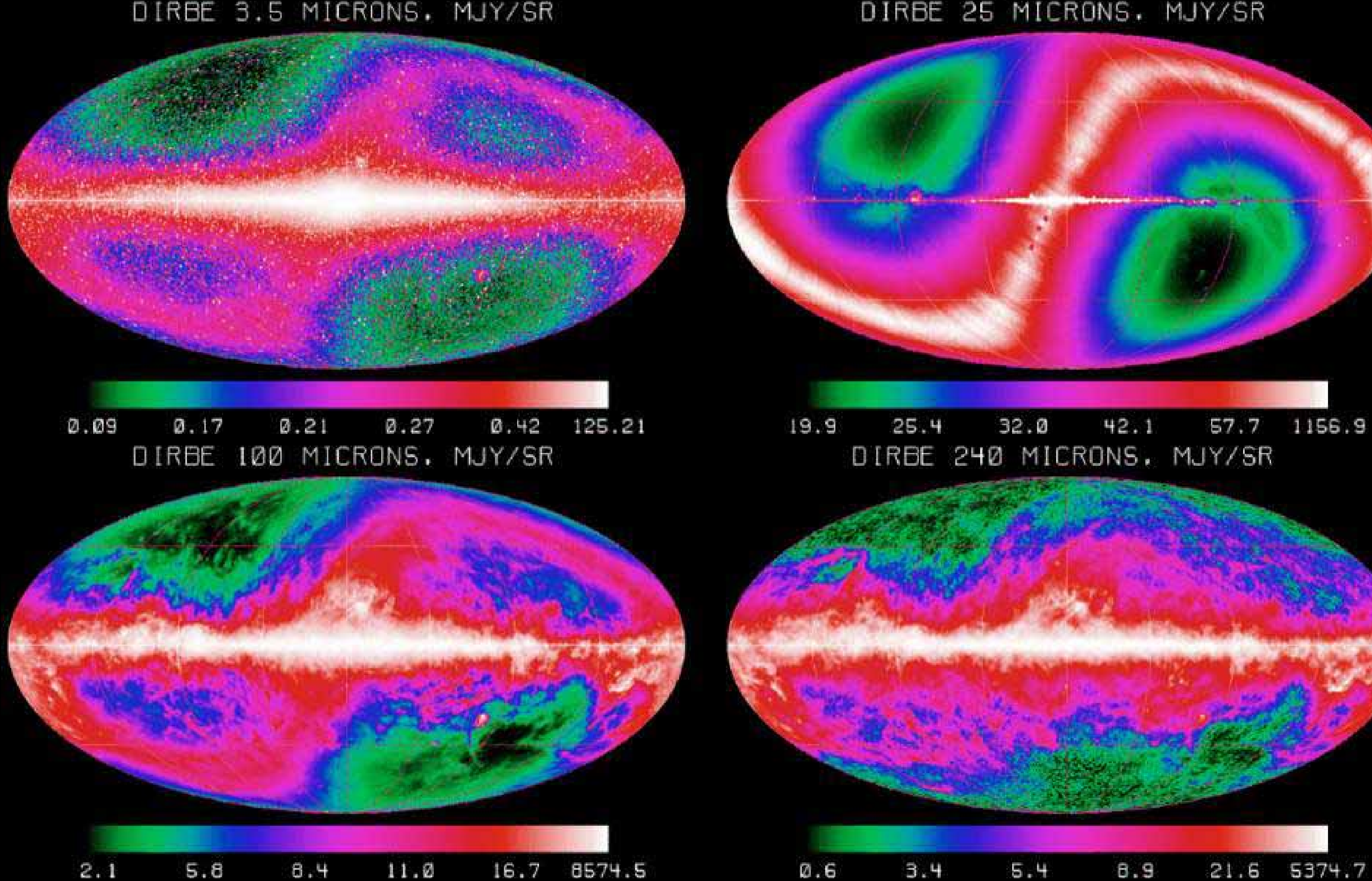


FIG. 1.—Submillimeter Fabry-Perot spectrometer, described in detail in the text. FP_1 and FP_2 are high- and low-finesse Fabry-Perot etalons.

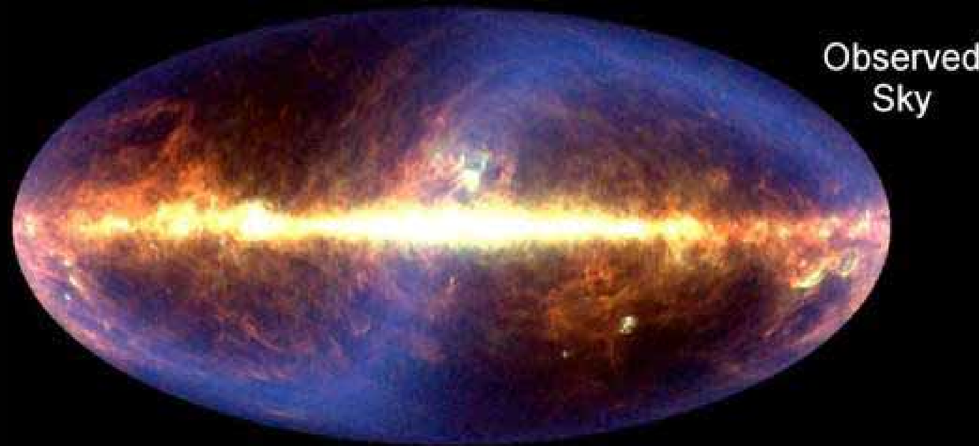
DIRBE Test Unit Hardware

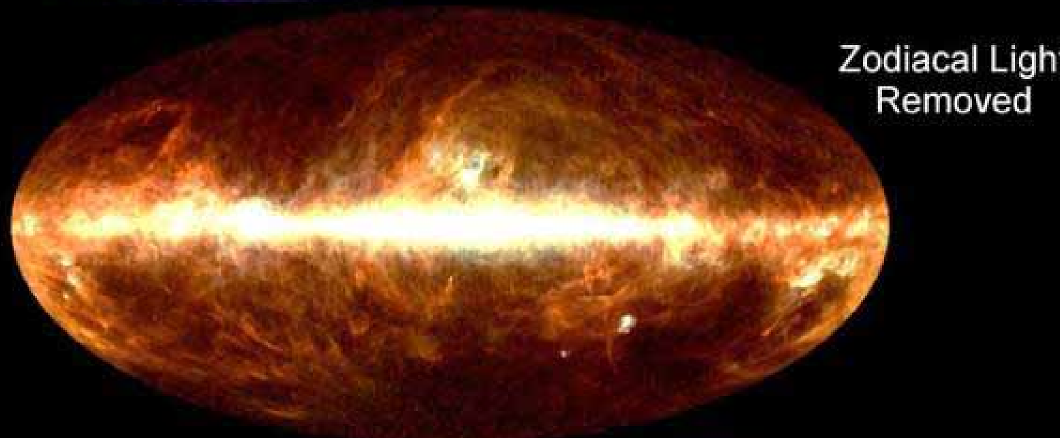


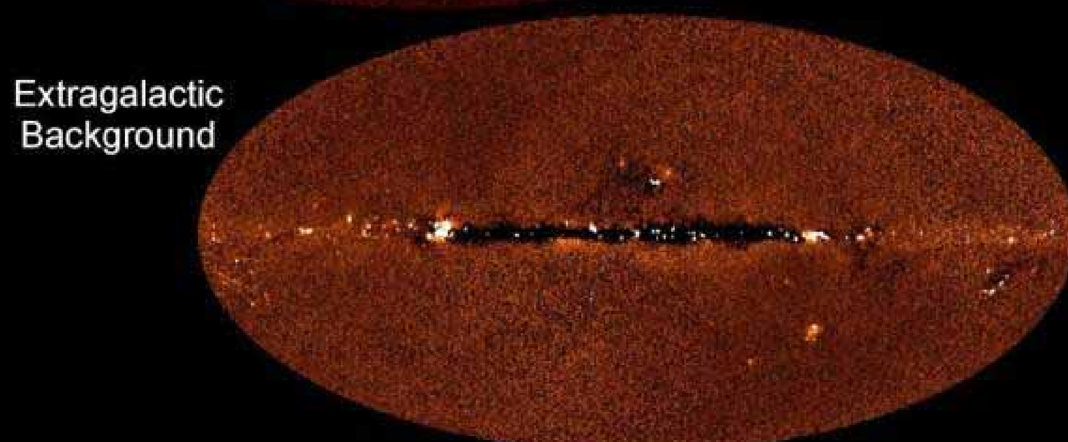
DIRBE Annual Average Maps



DIRBE far IR (100, 140, 240 μm) Sky Modeling

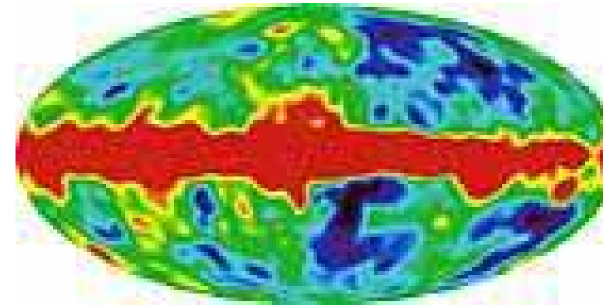




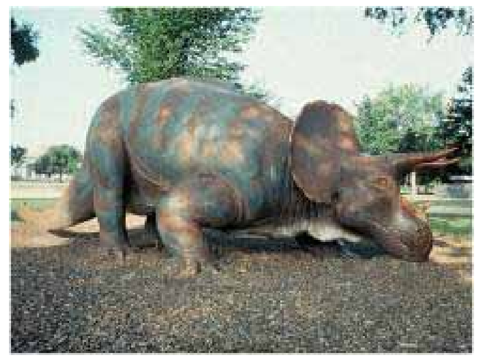


Astronomical Search For Origins

First Galaxies



Big Bang



Life

Galaxies Evolve

Planets

Stars