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

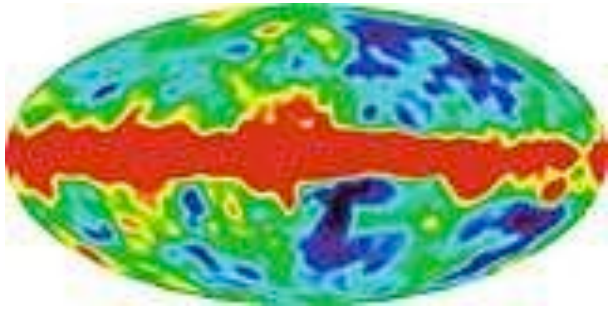
Goddard Space Flight Center Lecture

John Mather

Nov. 21, 2006

Astronomical Search For Origins

First Galaxies



Big Bang

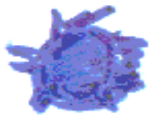
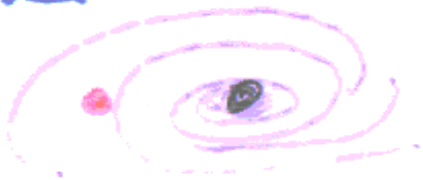
Galaxies Evolve

Life

Planets

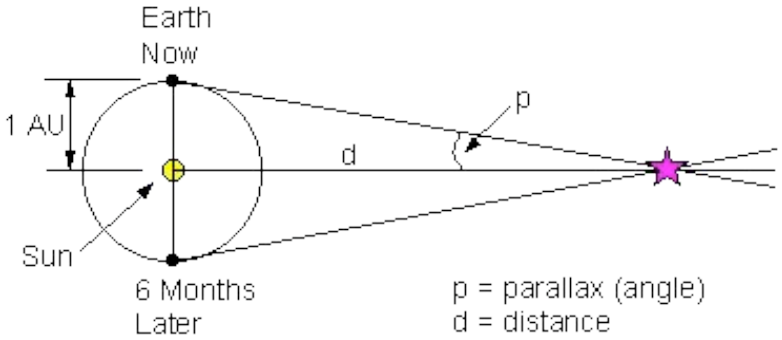
Stars

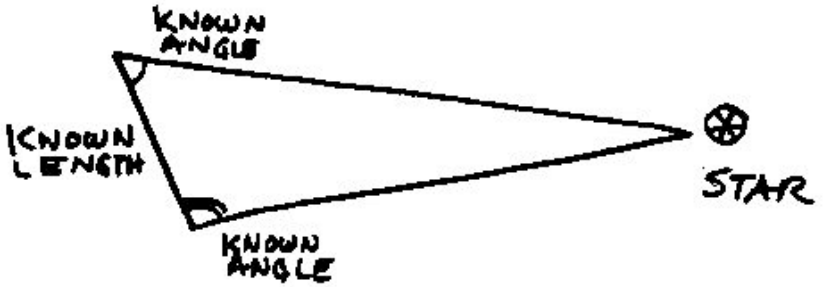
Looking Back in Time

HAND		1 m	0.000000003
EARTH		7000 km	0.02 sec
SUN		150,000,000 km	500 se
STAR			4 yrs
GALAXY			25,000 yrs
BIG BANG	?		15,000,000,000 yr

Measuring Distance

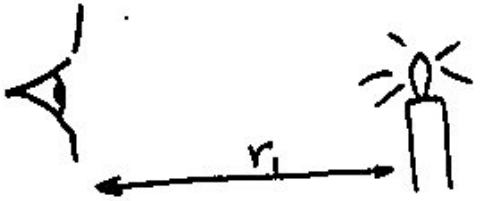
1. TRIANGLES





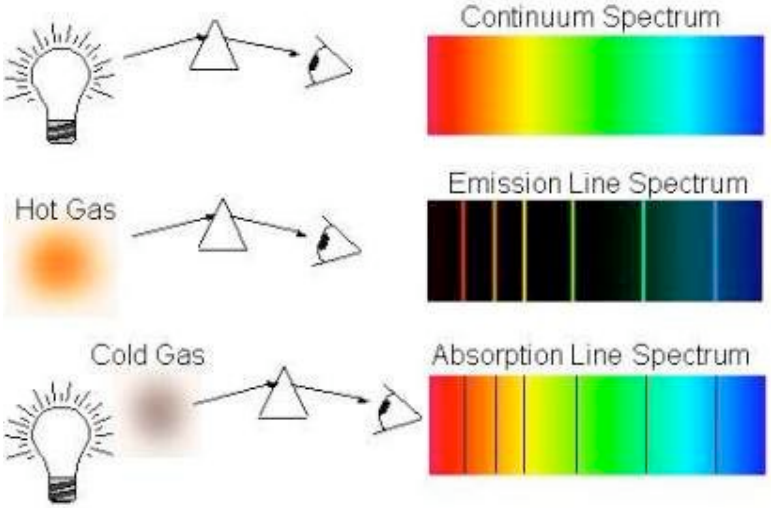
2. STANDARD CANDLES

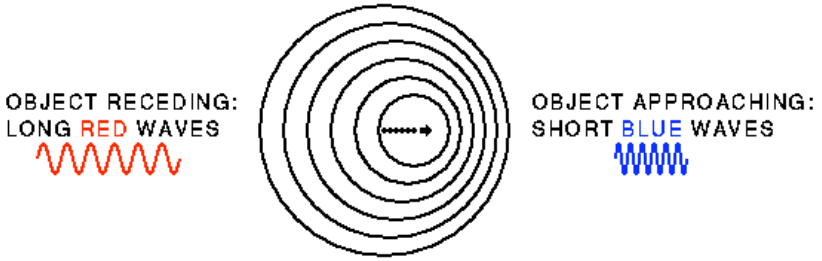
This technique enables measurement of enormous distances

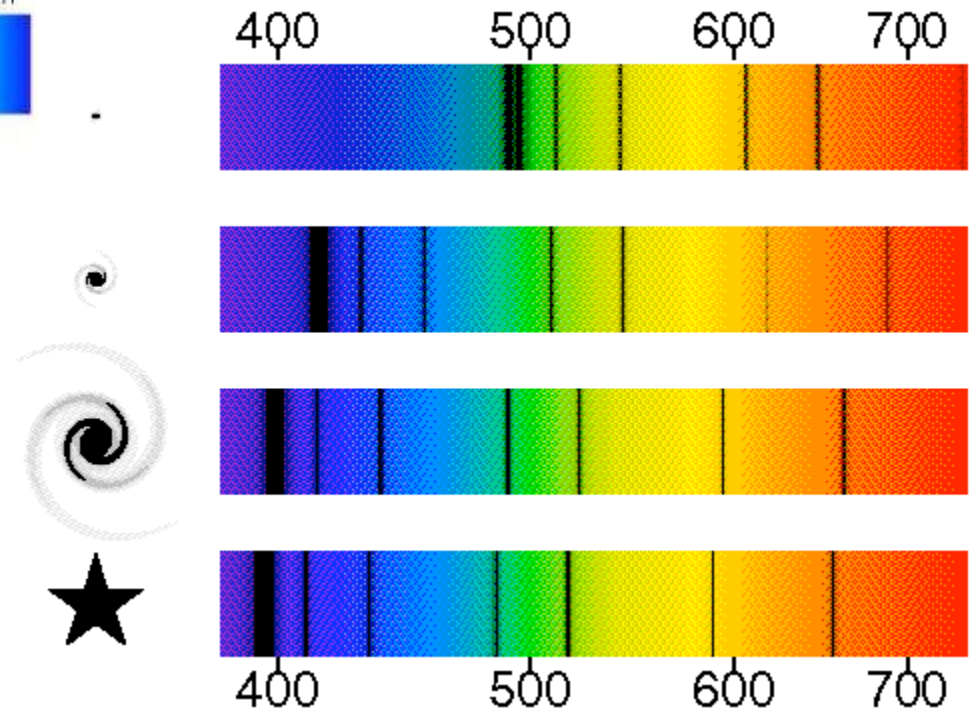


$$\frac{\text{BRIGHTNESS}_1}{\text{BRIGHTNESS}_2} = \frac{r_2^2}{r_1^2}$$

Astronomer's Toolbox #2:
Doppler Shift - Light







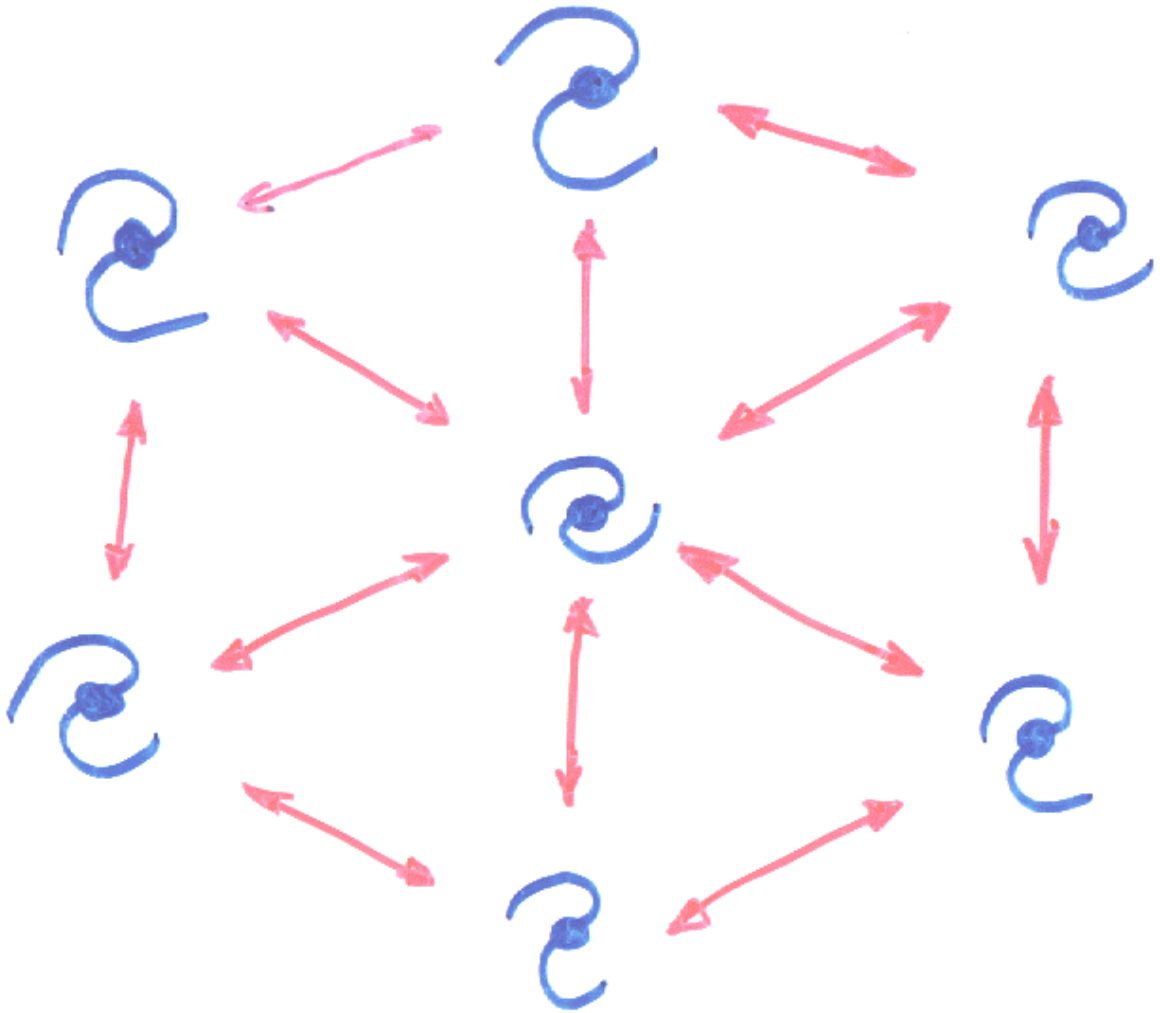
Atoms emit light at discrete wavelengths that can be seen with a spectroscope

This "line spectrum" identifies the atom and its velocity

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.



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"*.

The Power of Thought

Georges Lemaitre & Albert Einstein

George Gamow

Robert Herman & Ralph Alpher

Rashid Sunyaev

Jim Peebles

Power of Hardware - CMB Spectrum

Paul Richards

Mike Werner

David Woody

Frank Low

Herb Gush

Rai Weiss

Brief COBE History

- 1965, CMB announced - Penzias & Wilson; Dicke, Peebles, Roll, & Wilkinson
- 1974, NASA AO for Explorers: ~ 150 proposals, including:
  - JPL anisotropy proposal (Gulkis, Janssen…)
  - Berkeley anisotropy proposal (Alvarez, Smoot…)
  - Goddard/MIT/Princeton COBE proposal (Hauser, Mather, Muehlner, Silverberg, Thaddeus, Weiss, Wilkinson)

COBE History (2)

- 1976, Mission Definition Science Team selected by HQ (Nancy Boggess, Program Scientist); PI's chosen
- ~ 1979, decision to build COBE in-house at GSFC
- 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

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 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 Engineering Leadership

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

Middle row: Don Crosby, *Roger Mattson*, Irene Ferber, Maureen Menton

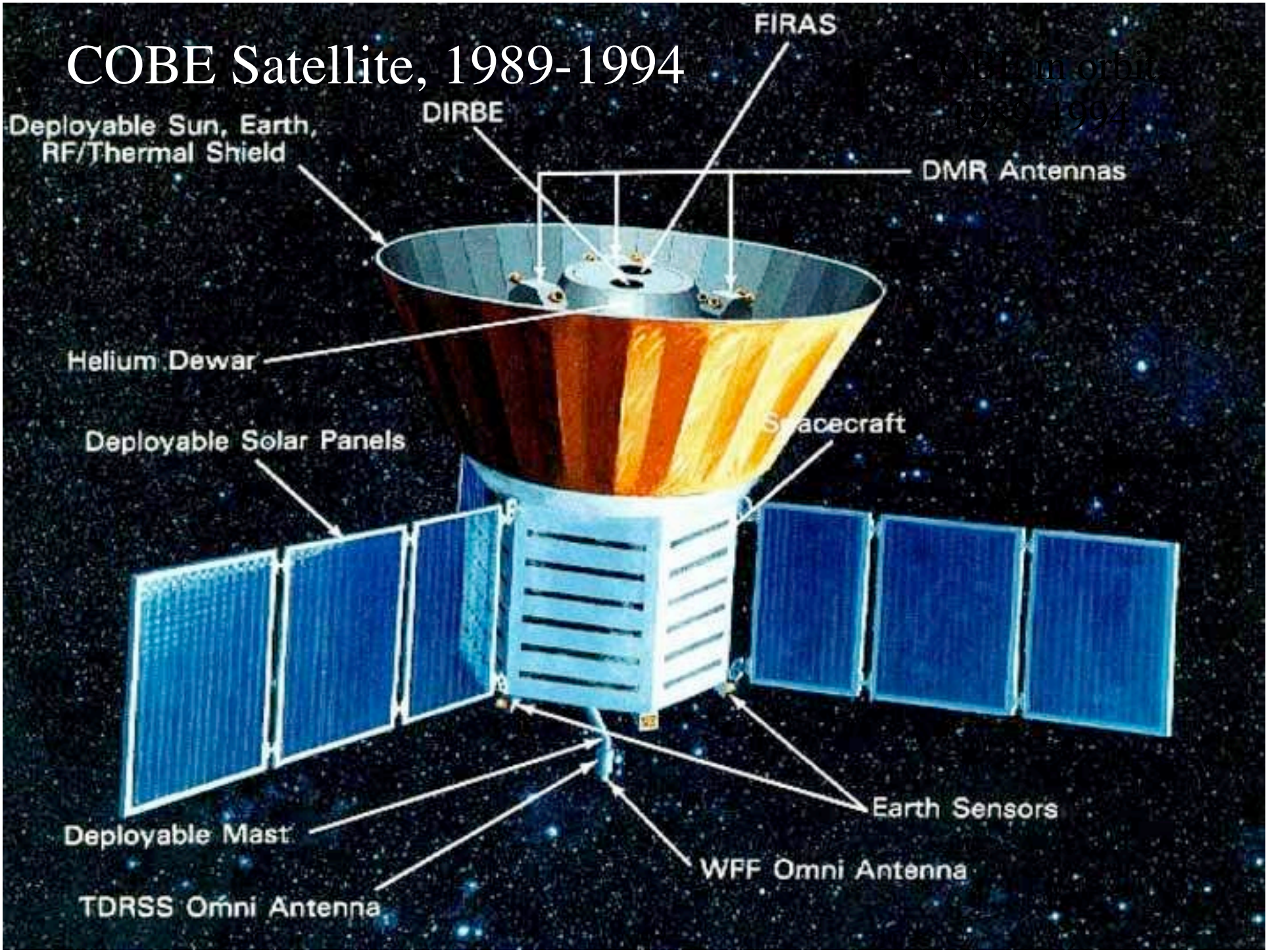
Front row: Jeff Greenwell, Ernie Doutrich, Bob Schools, Mike Roberto

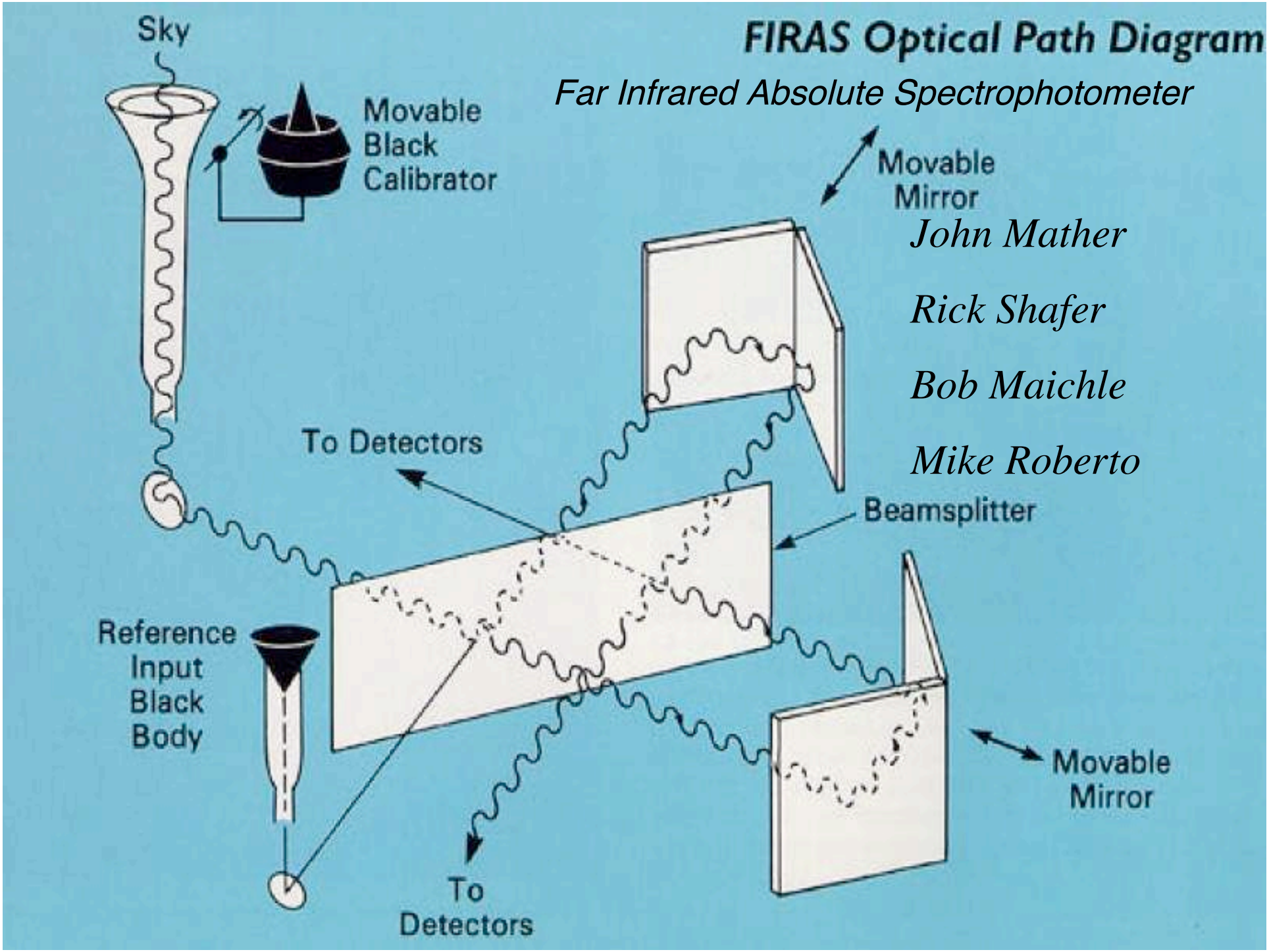
COBE Engineering Leadership

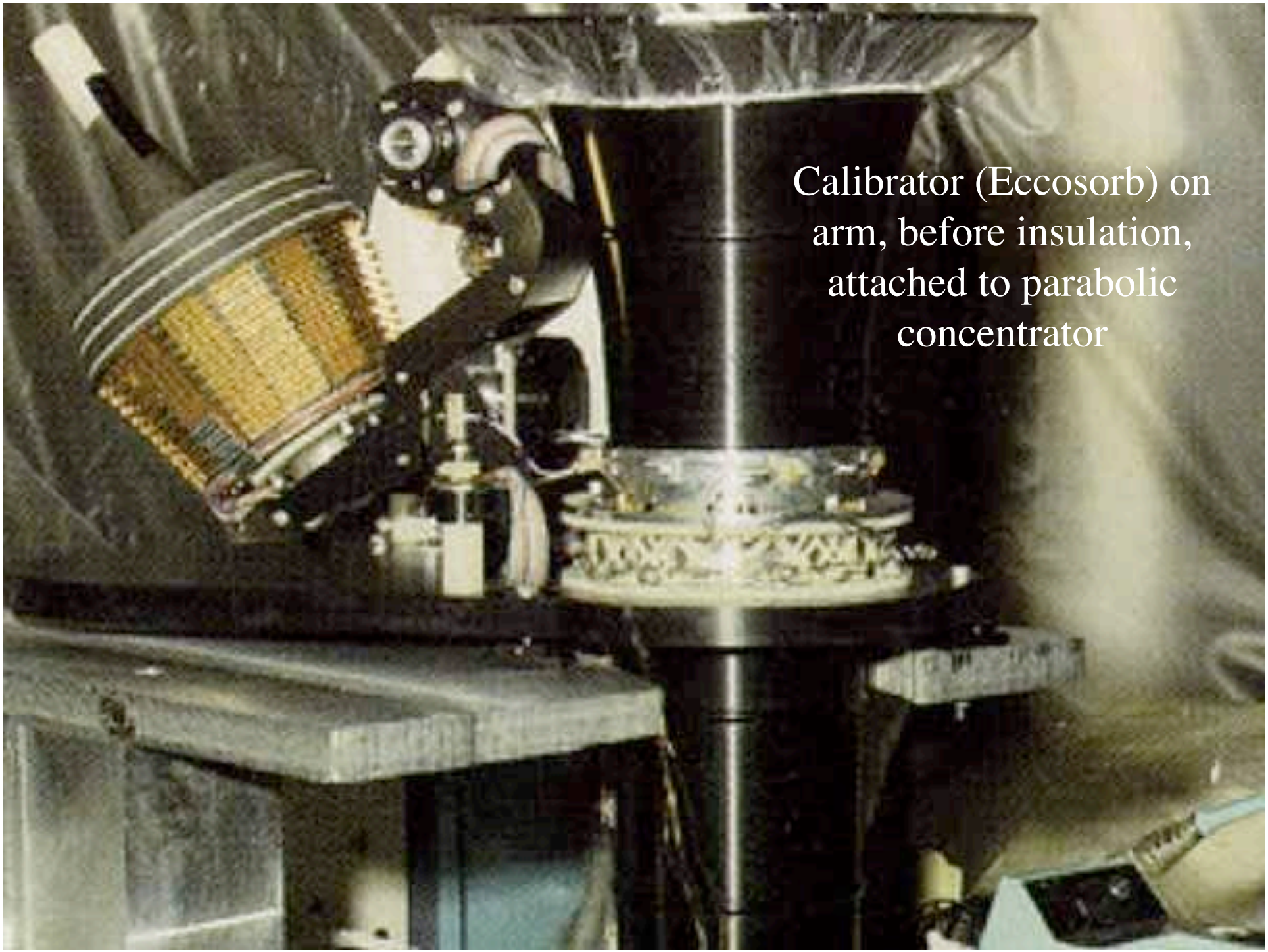
Back row: *Dennis McCarthy*, Bob Maichle, Loren Linstrom, Jack Peddicord

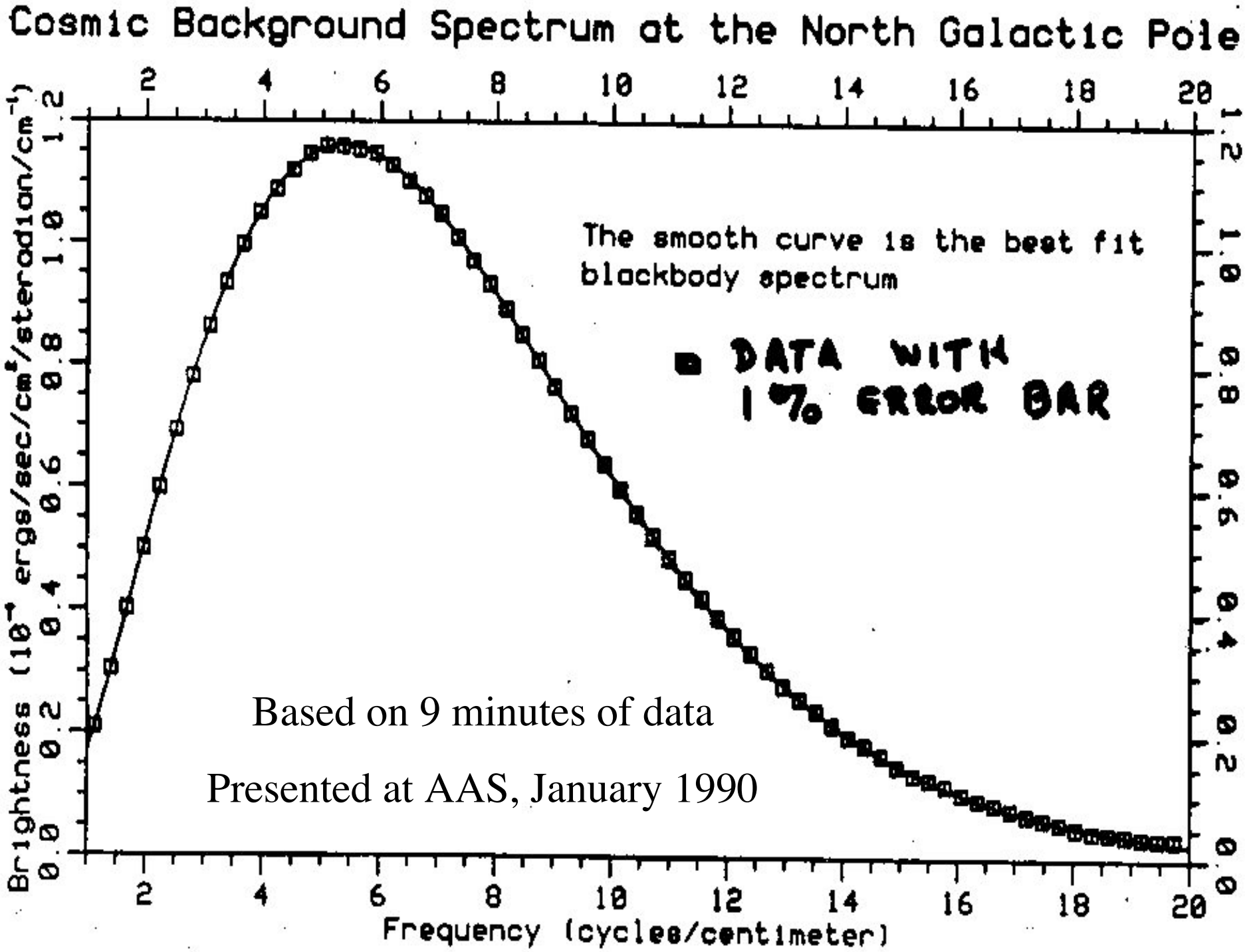
Middle row: Lee Smith, Dave Gilman, Steve Leete, Tony Fragomeni

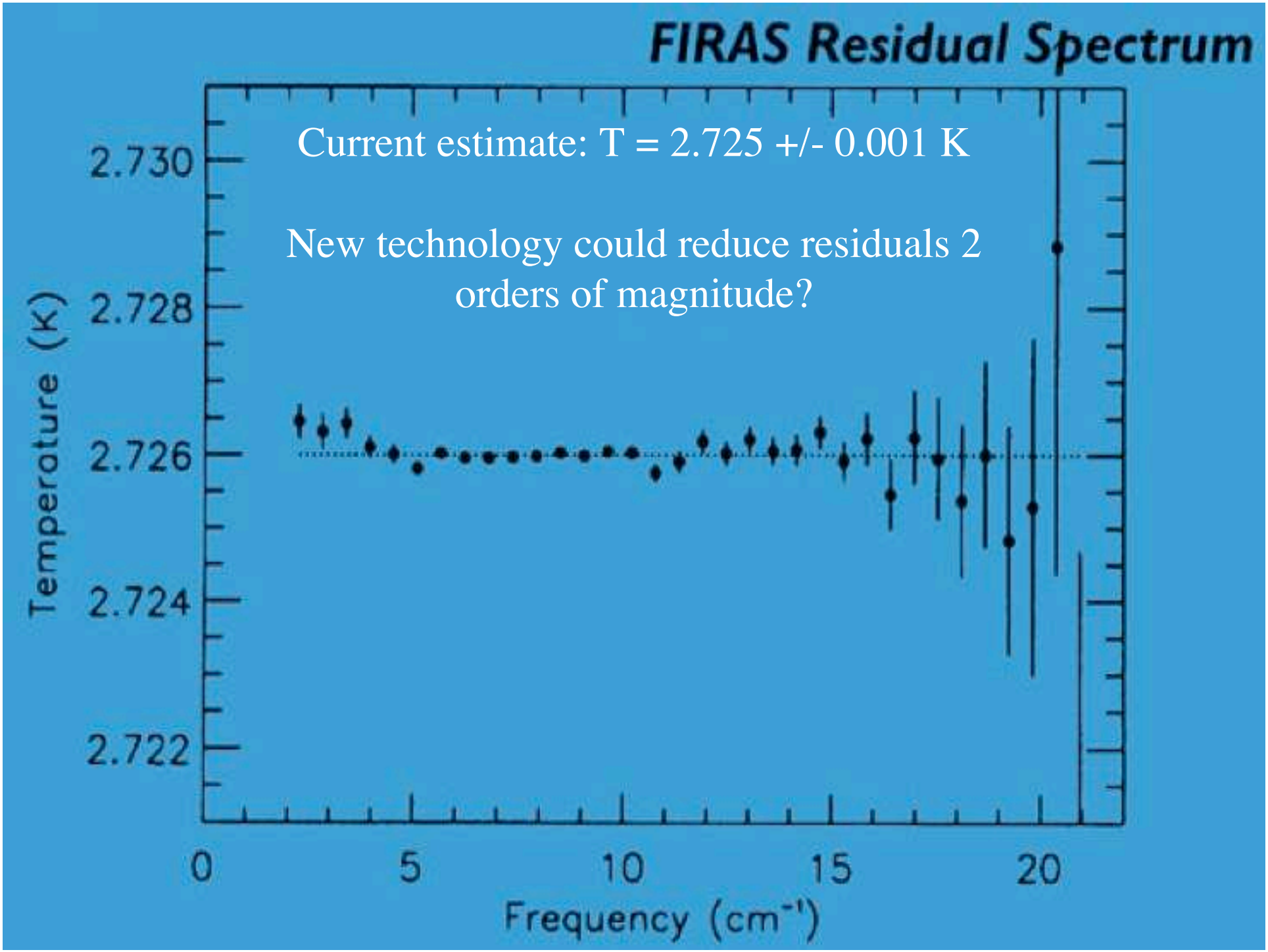
Front row: Earle Young, Chuck Katz, Bernie Klein, John Wolfgang


COBE Satellite, 1989-1994
FIRAS
DIRBE
Deployable Sun, Earth, RF/Thermal Shield
DMR Antennas
Helium Dewar
Deployable Solar Panels
Spacecraft
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna


FIRAS Optical Path Diagram
Far Infrared Absolute Spectrophotometer
Sky
Movable
Black
Calibrator
Movable
Mirror
John Mather
Rick Shafer
Bob Maichle
Mike Roberto
To Detectors
Beamsplitter
Reference
Input
Black
Body
Movable
Mirror
To
Detectors


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

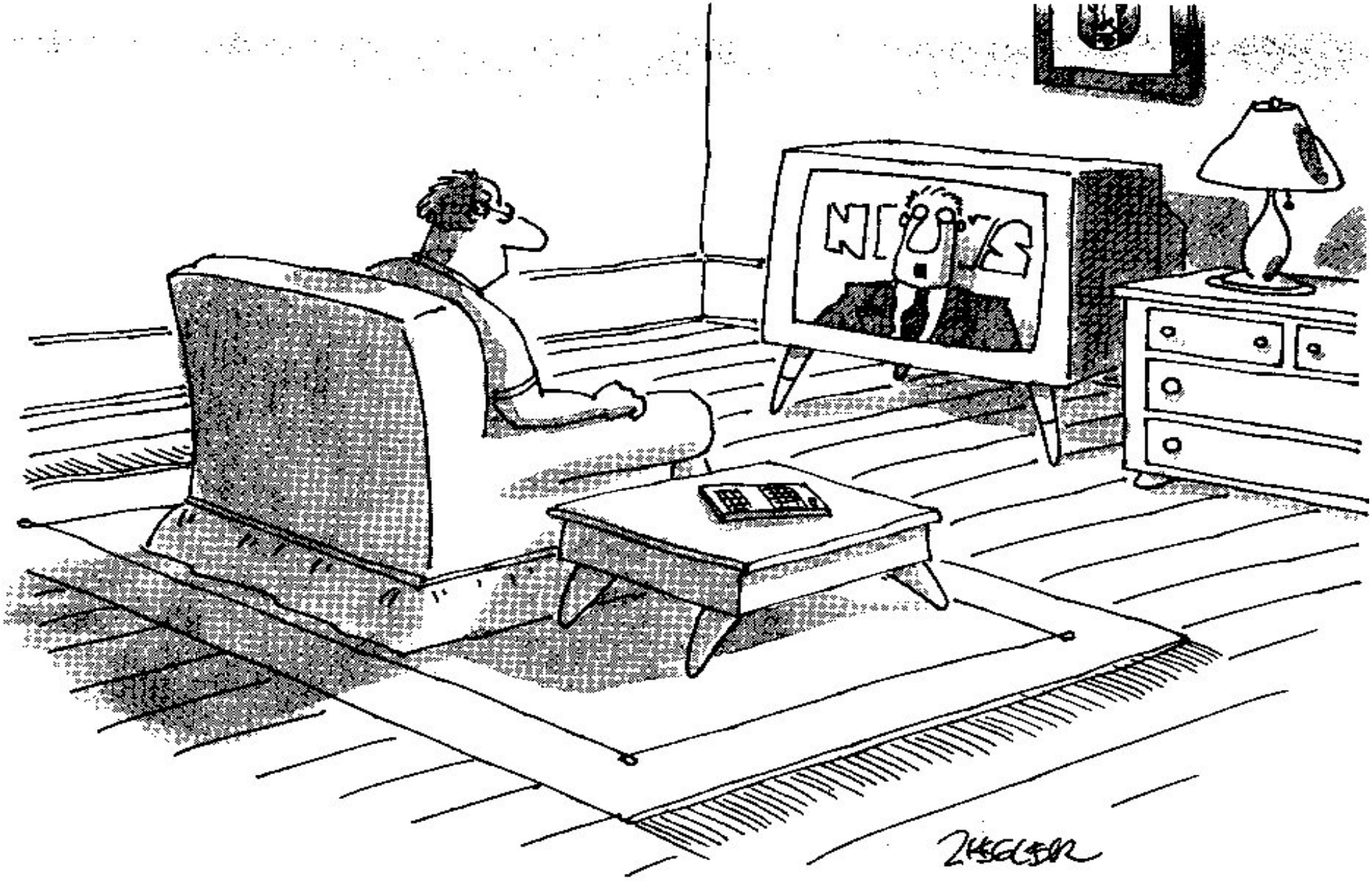

Cosmic Background Spectrum at the North Galactic Pole
The smooth curve is the best fit blackbody spectrum
= DATA WITH 1% ERROR BAR
Based on 9 minutes of data
Presented at AAS, January 1990
Brightness (10^{-4} ergs/sec/cm^2/steradian/cm^{-1})
Frequency (cycles/centimeter)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
2
4
6
8
10
12
14
16
18
20


FIRAS Residual Spectrum
Current estimate: T = 2.725 +/- 0.001 K
New technology could reduce residuals 2 orders of magnitude?
Temperoture (K)
2.730
2.728
2.726
2.724
2.722
0
5
10
15
20
Frequency (cm⁻¹)

Confirming the Big Bang Theory

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

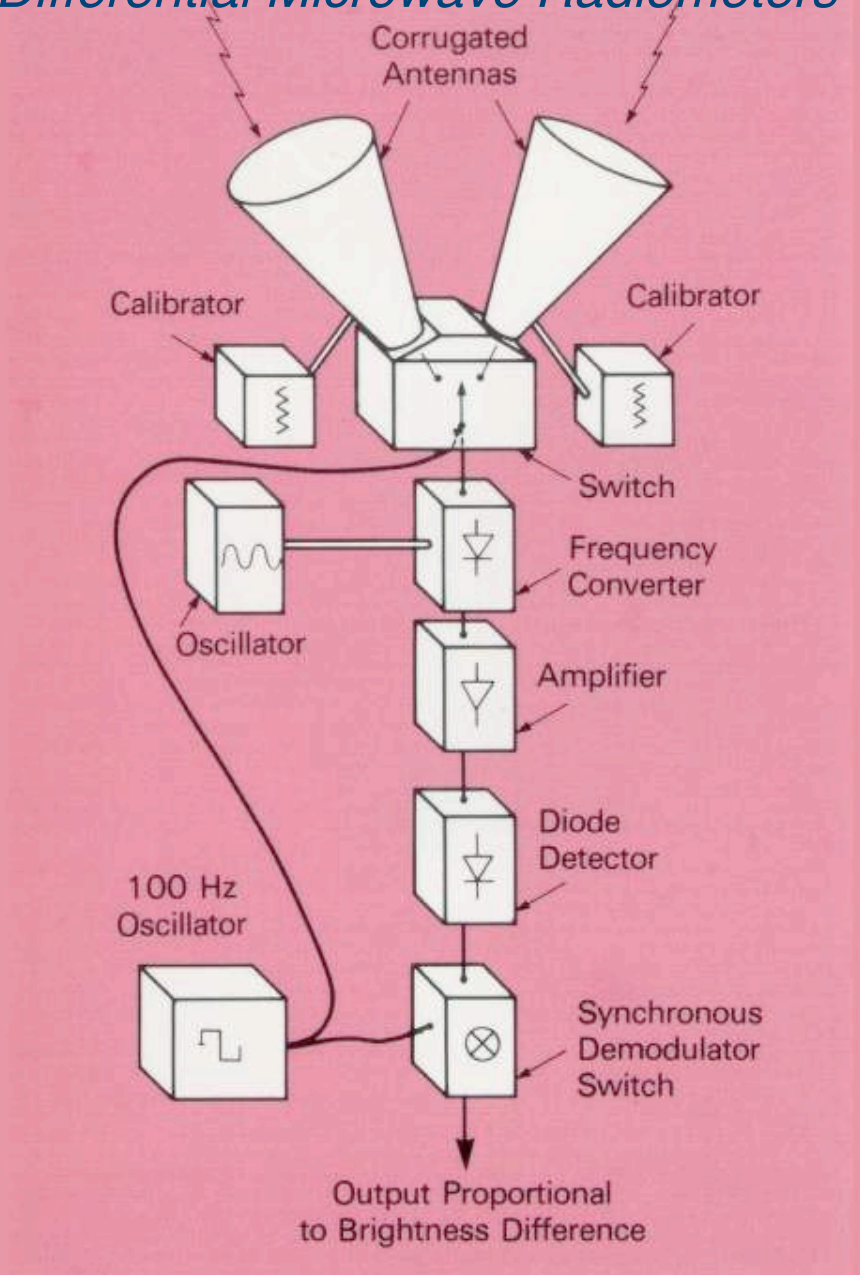
- Hot Big Bang theory is right
- No extra energy released after the first year
- No exotic events like turbulent motion



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

DMR Signal Flow Diagram

Differential Microwave Radiometers

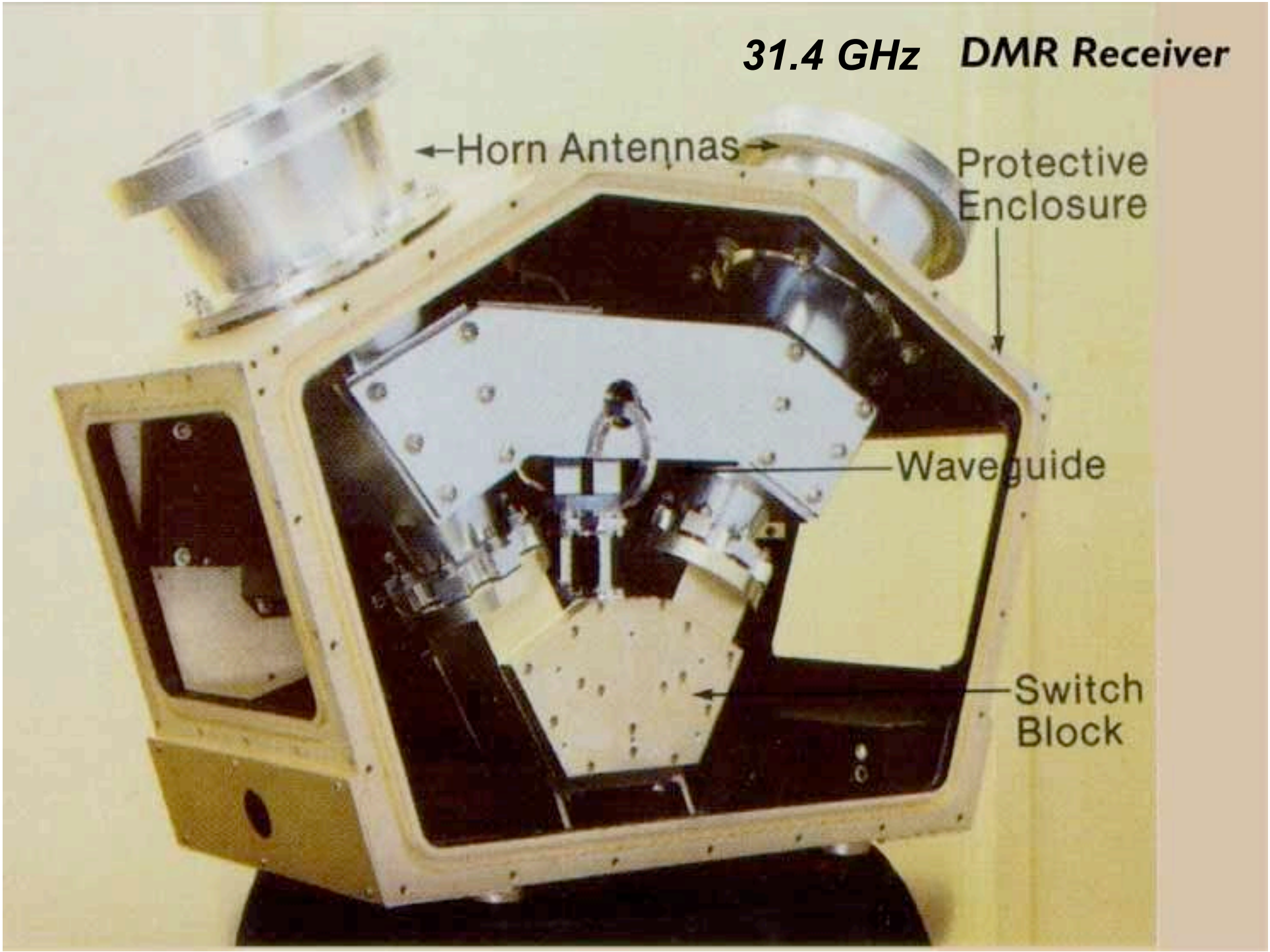


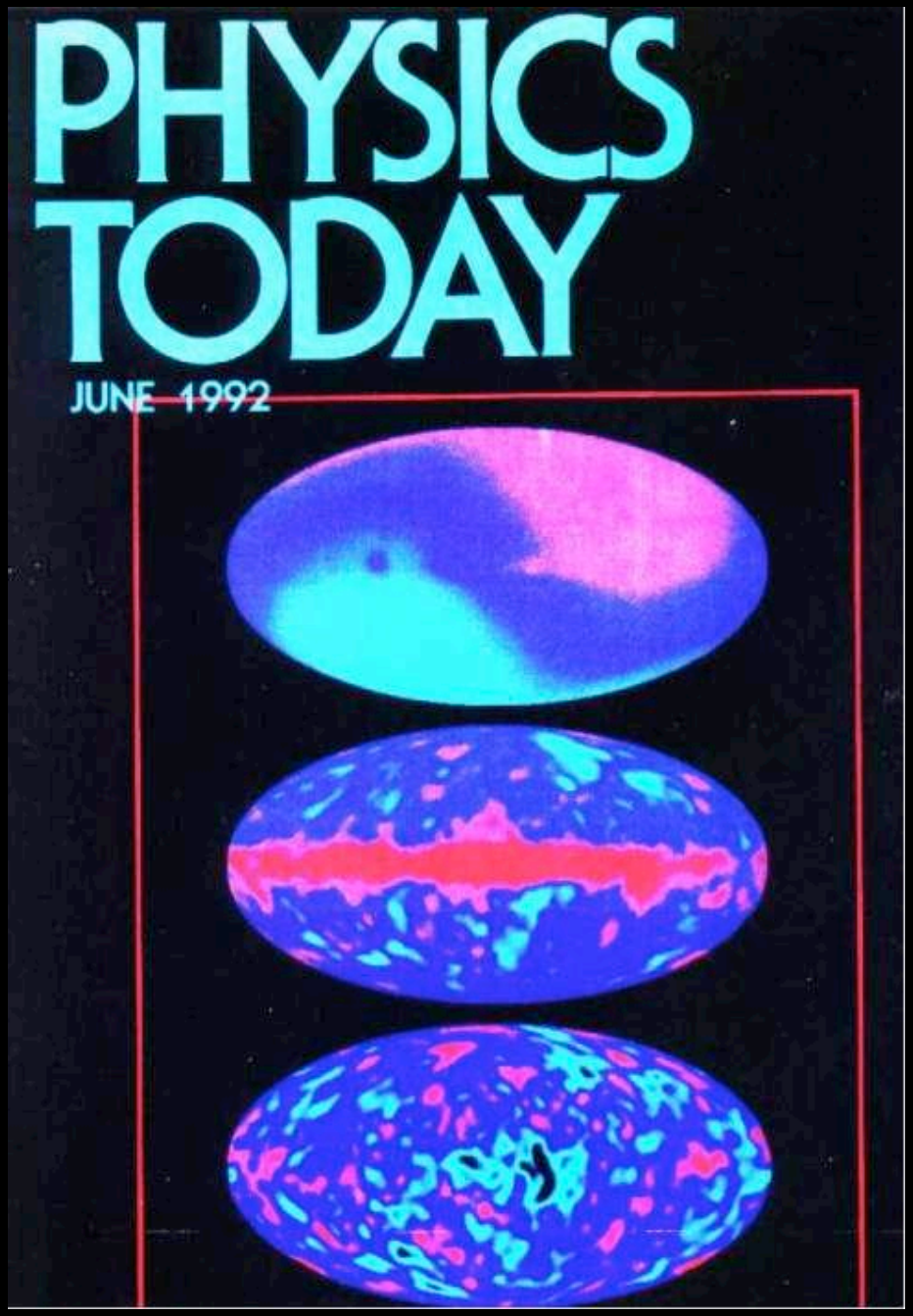
George Smoot

Chuck Bennett

Bernie Klein

Steve Leete


31.4 GHz DMR Receiver
Horn Antennas
Protective Enclosure
Waveguide
Switch Block

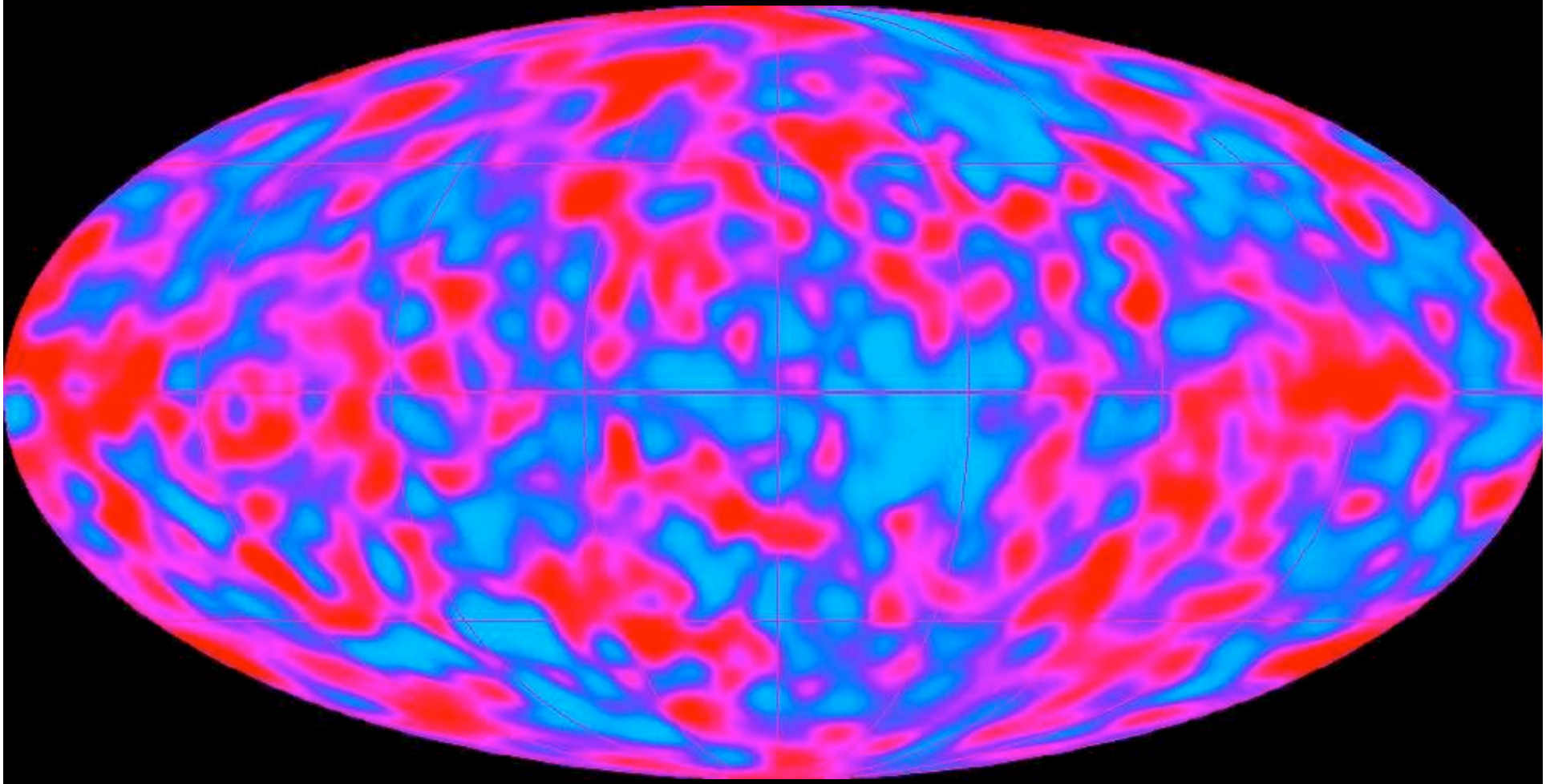


Sky map from DMR, 2.7 K +/- 0.003 K

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

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

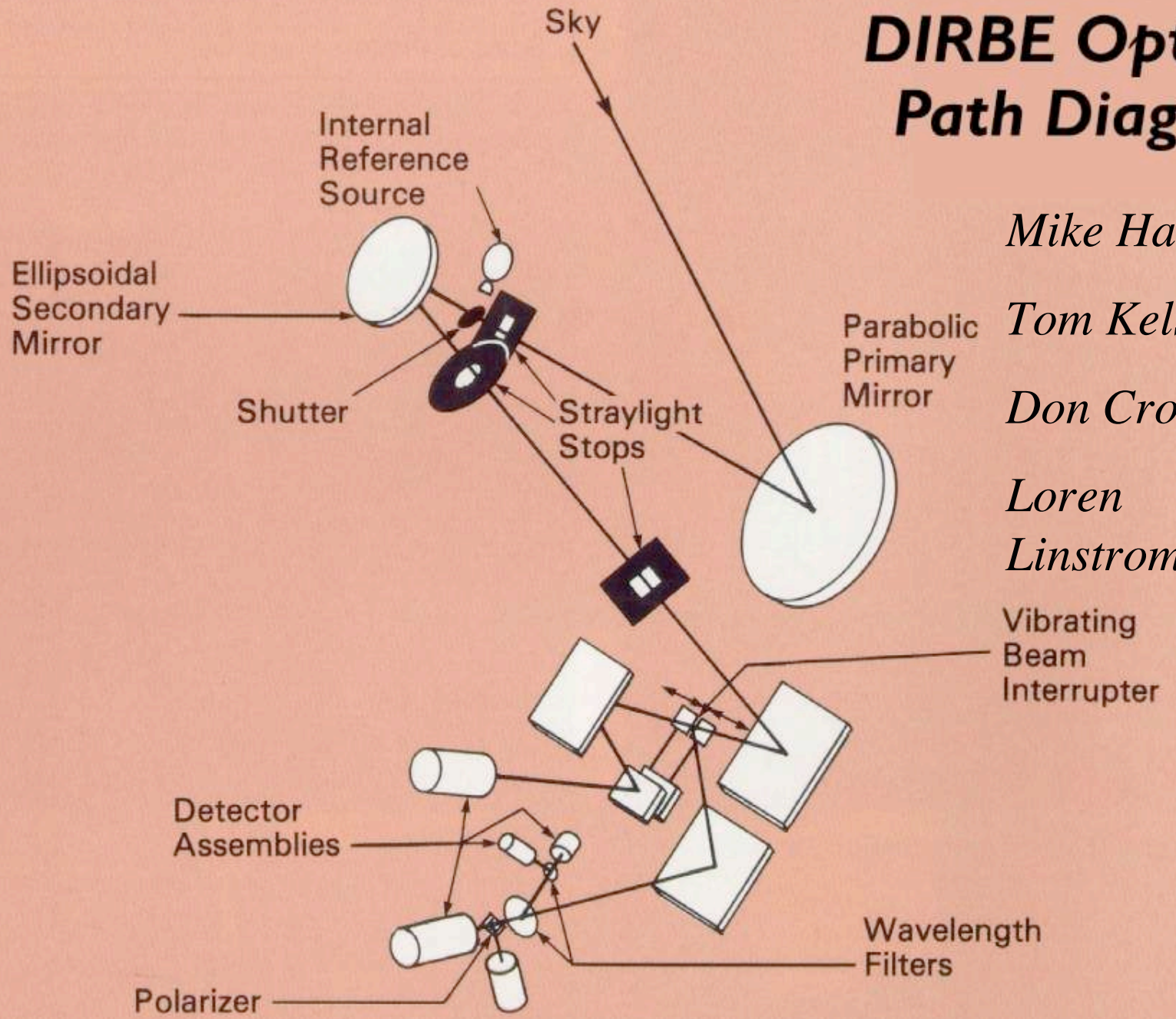
COBE Map of CMB Fluctuations
2.725 K +/- ~ 30 μK rms, 7^{o} beam



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



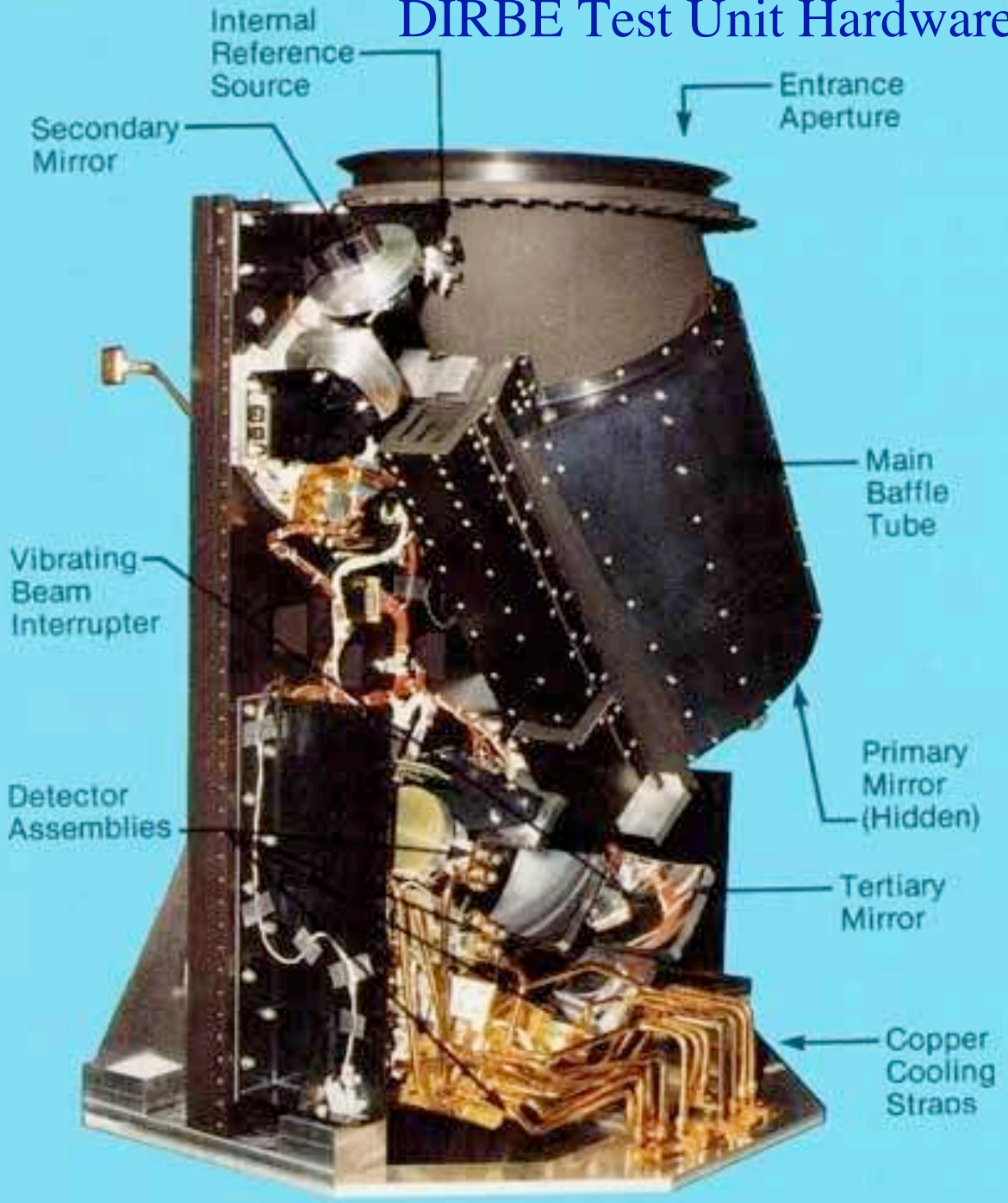
Mike Hauser

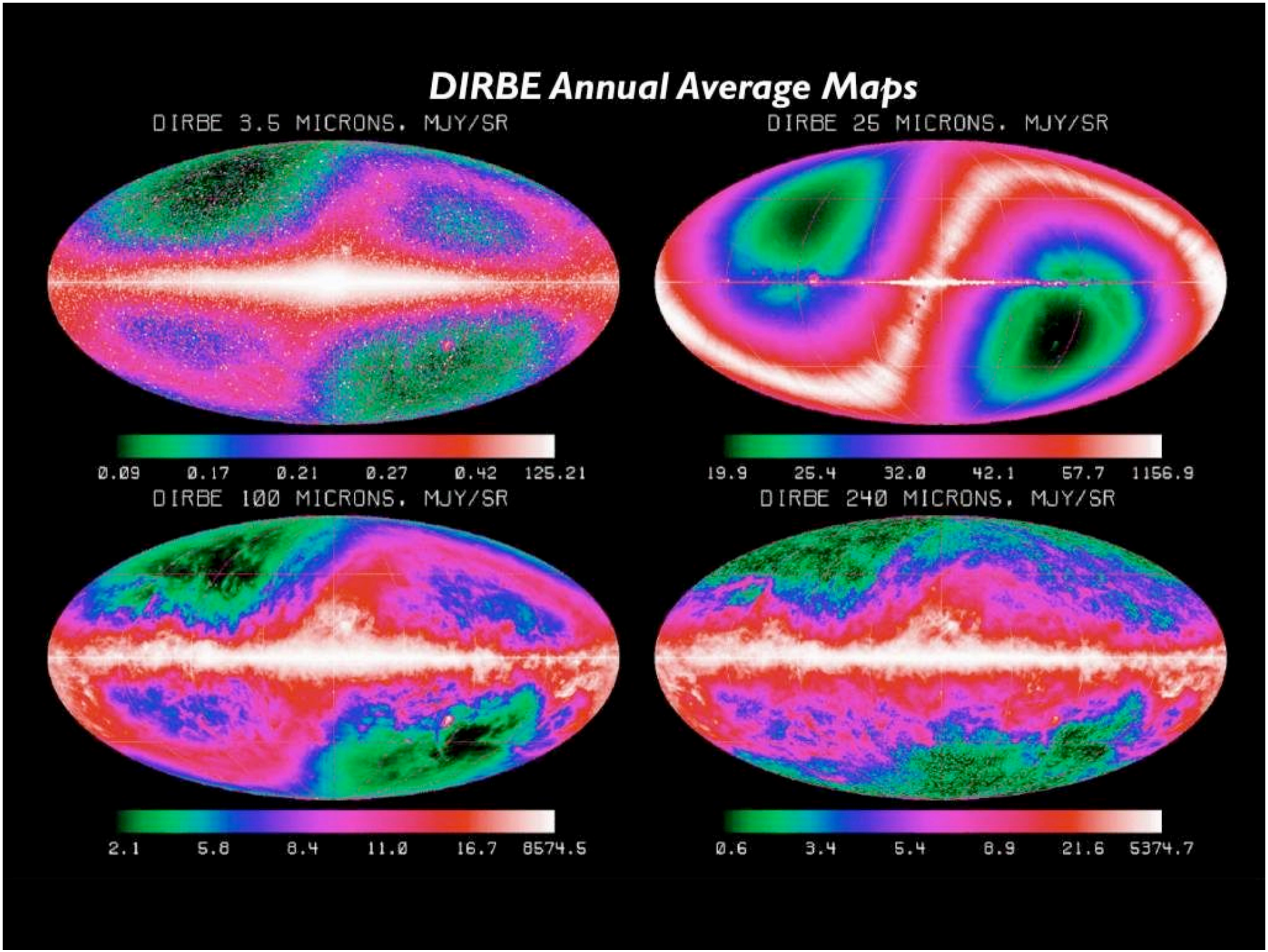
Tom Kelsall

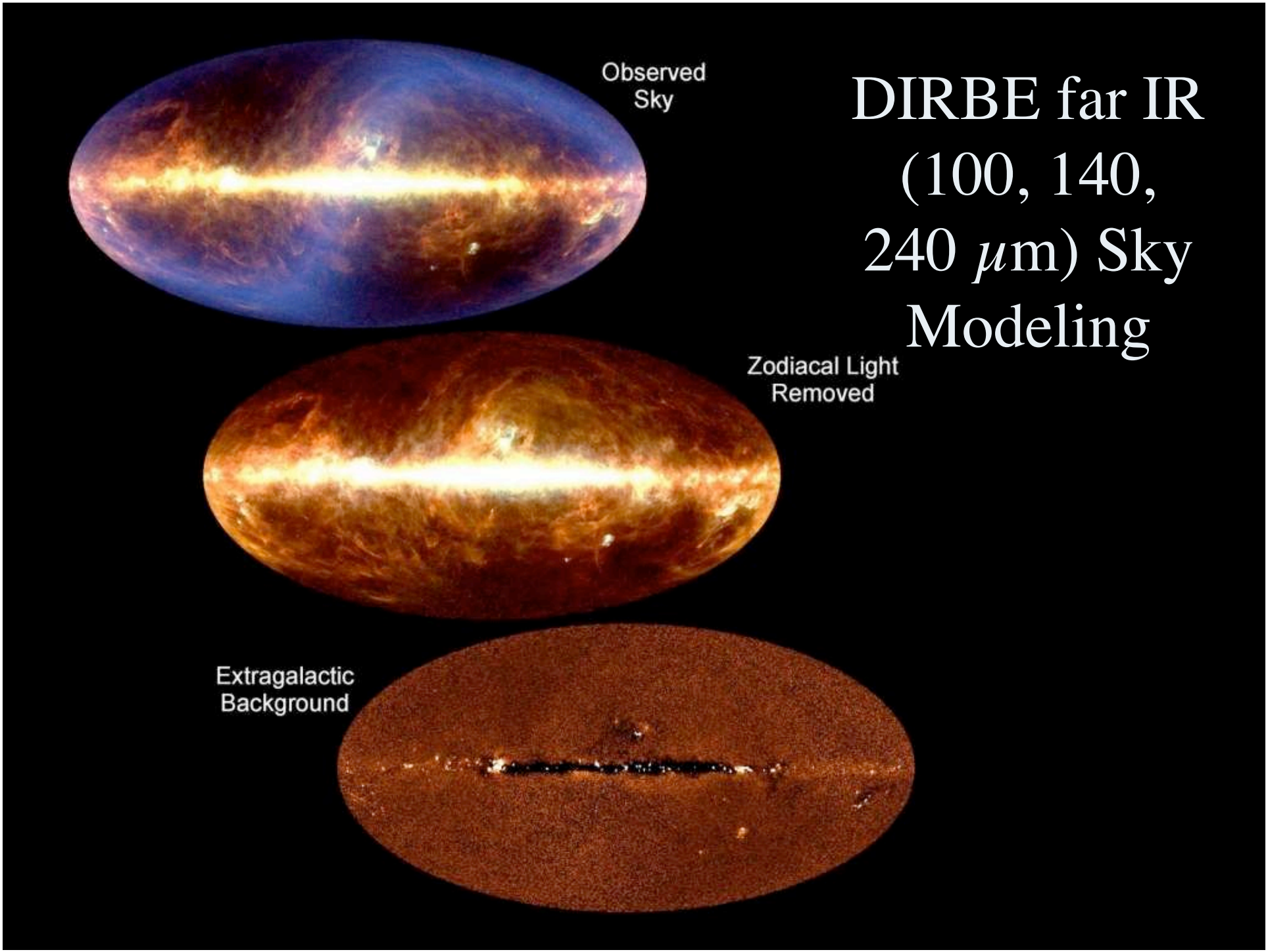
Don Crosby

Loren Linstrom

DIRBE Test Unit Hardware




DIRBE Annual Average Maps
DIRBE 3.5 MICRONS. MJY/SR
0.09 0.17 0.21 0.27 0.42 125.21
DIRBE 25 MICRONS. MJY/SR
19.9 25.4 32.0 42.1 57.7 1156.9
DIRBE 100 MICRONS. MJY/SR
2.1 5.8 8.4 11.0 16.7 8574.5
DIRBE 240 MICRONS. MJY/SR
0.6 3.4 5.4 8.9 21.6 5374.7

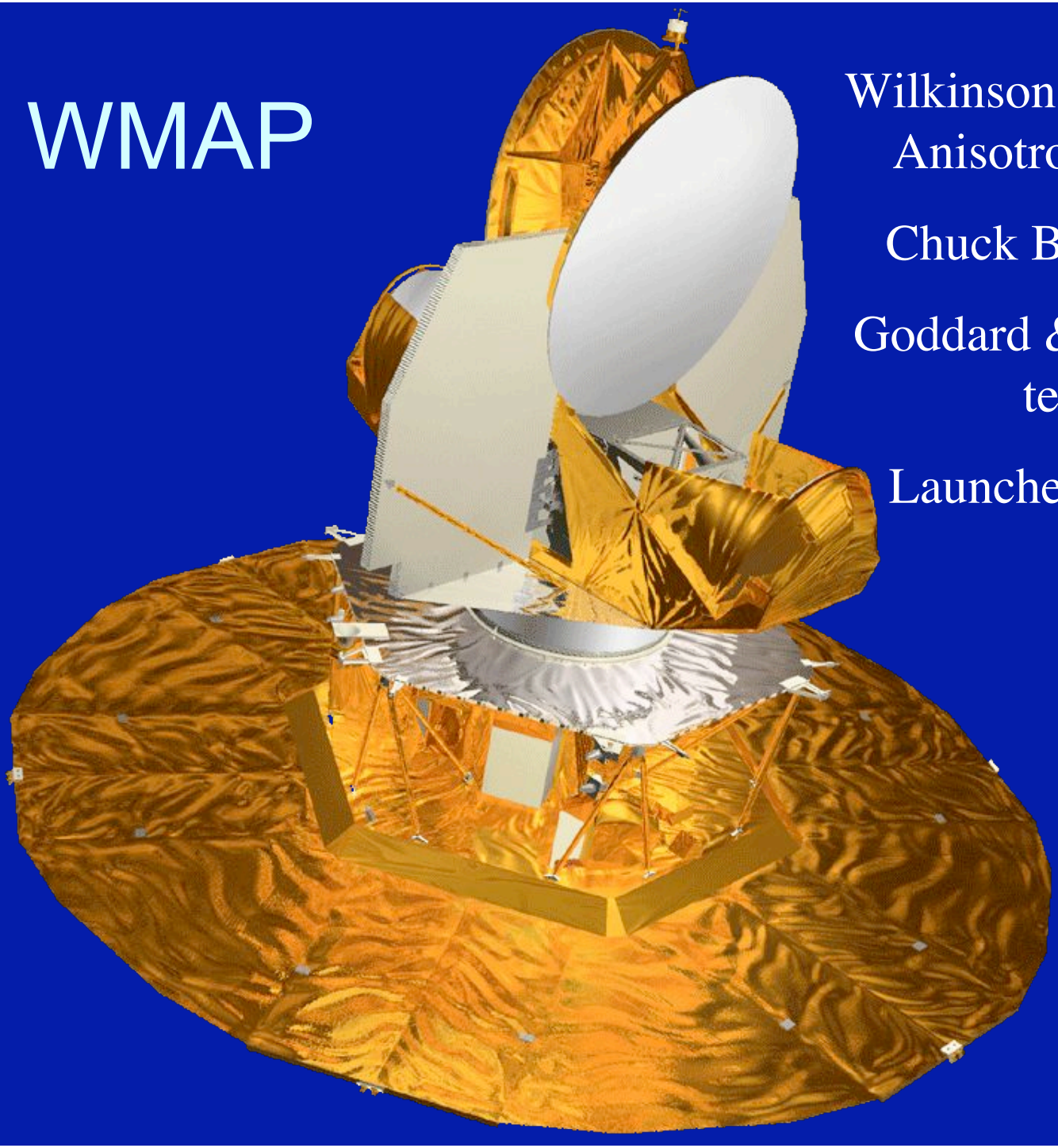


DIRBE far IR (100, 140, 240 μm) Sky Modeling

COBE Cosmology

- CMB has blackbody spectrum, $\delta F/F_{max}$ <50 ppm. Strong limits, about 0.01%, on energy conversion (from turbulence, unstable particles, etc.) after t = 1 year. No good explanation besides Hot Big Bang.
- CMB has spatial structure, 0.001% on scales > 7^{o}, consistent with scale-invariant predictions and inflation, dark matter and dark energy or Λ constant, and formation of galaxies and clusters by gravity.
- CIBR has 2 parts, near (few microns) and far (few hundred microns), each with brightness comparable to the known luminosity of visible & near IR galaxies: L of universe is ~ double expected value.

WMAP



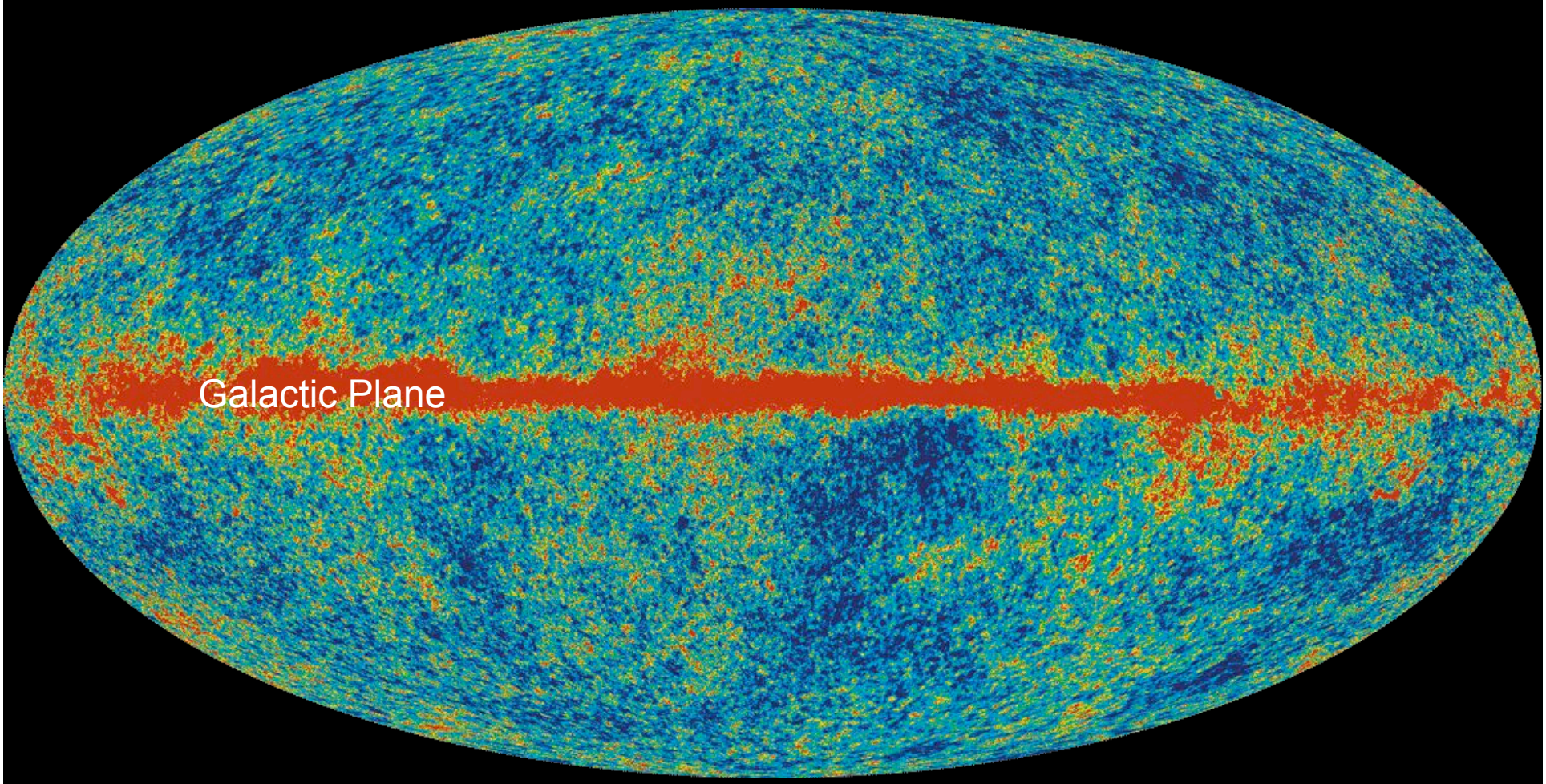
Wilkinson Microwave Anisotropy Probe

Chuck Bennett, PI

Goddard & Princeton team

Launched in 2001

The Universe at age 389,000 years

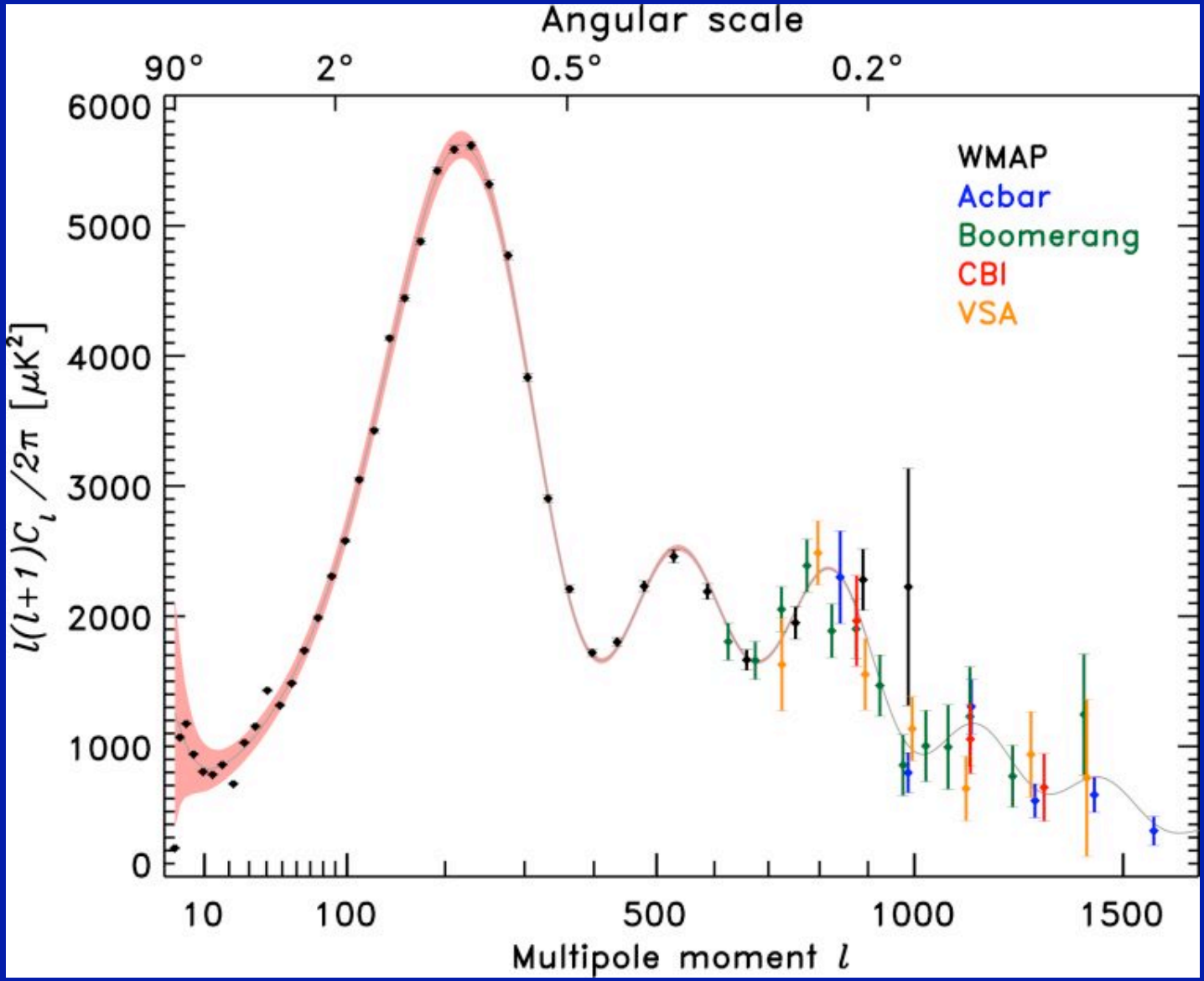


Cosmic Parameters to ~ percent accuracy

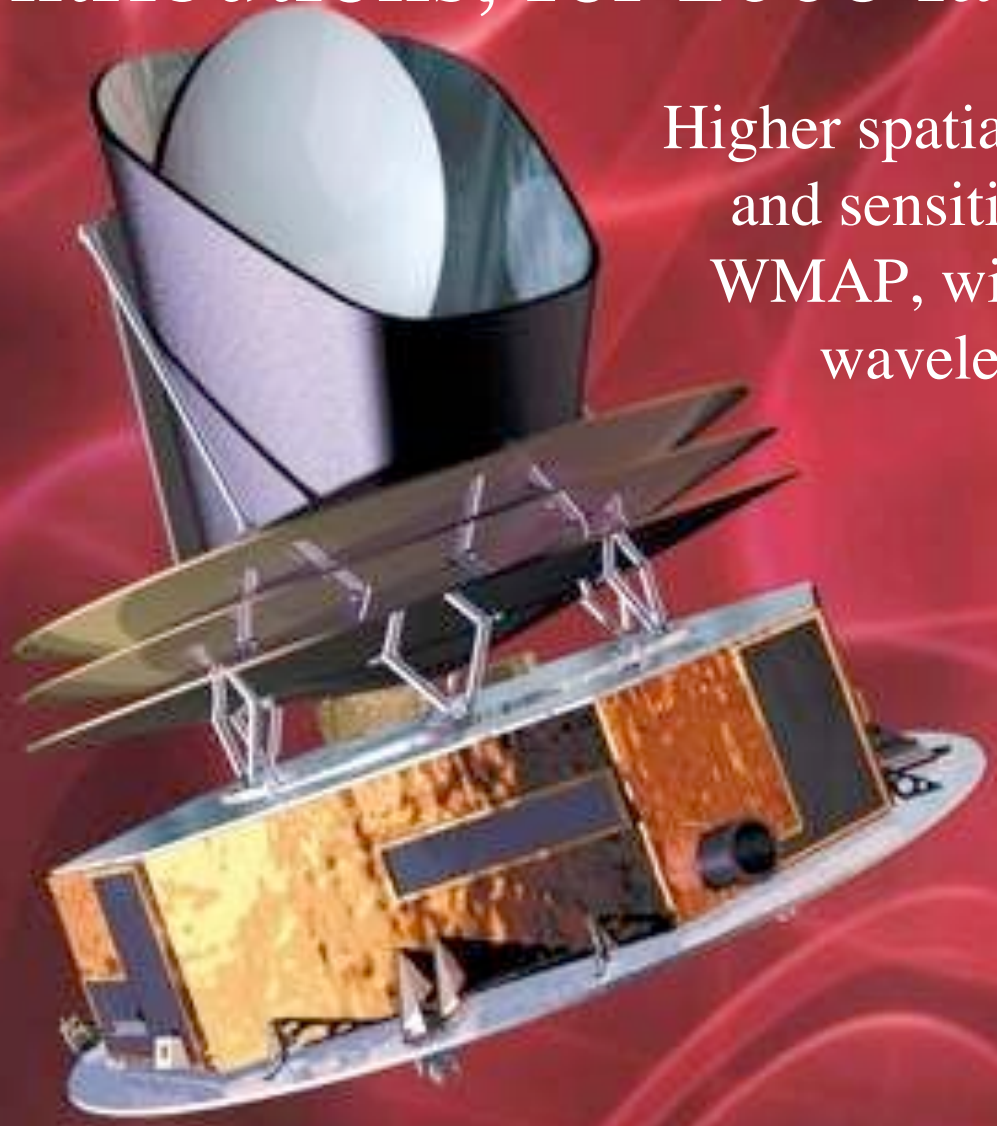
$$\Omega_{tot}=\Omega_b+\Omega_c+\Omega_\Lambda=100\%$$

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

CMB Angular Power Spectrum

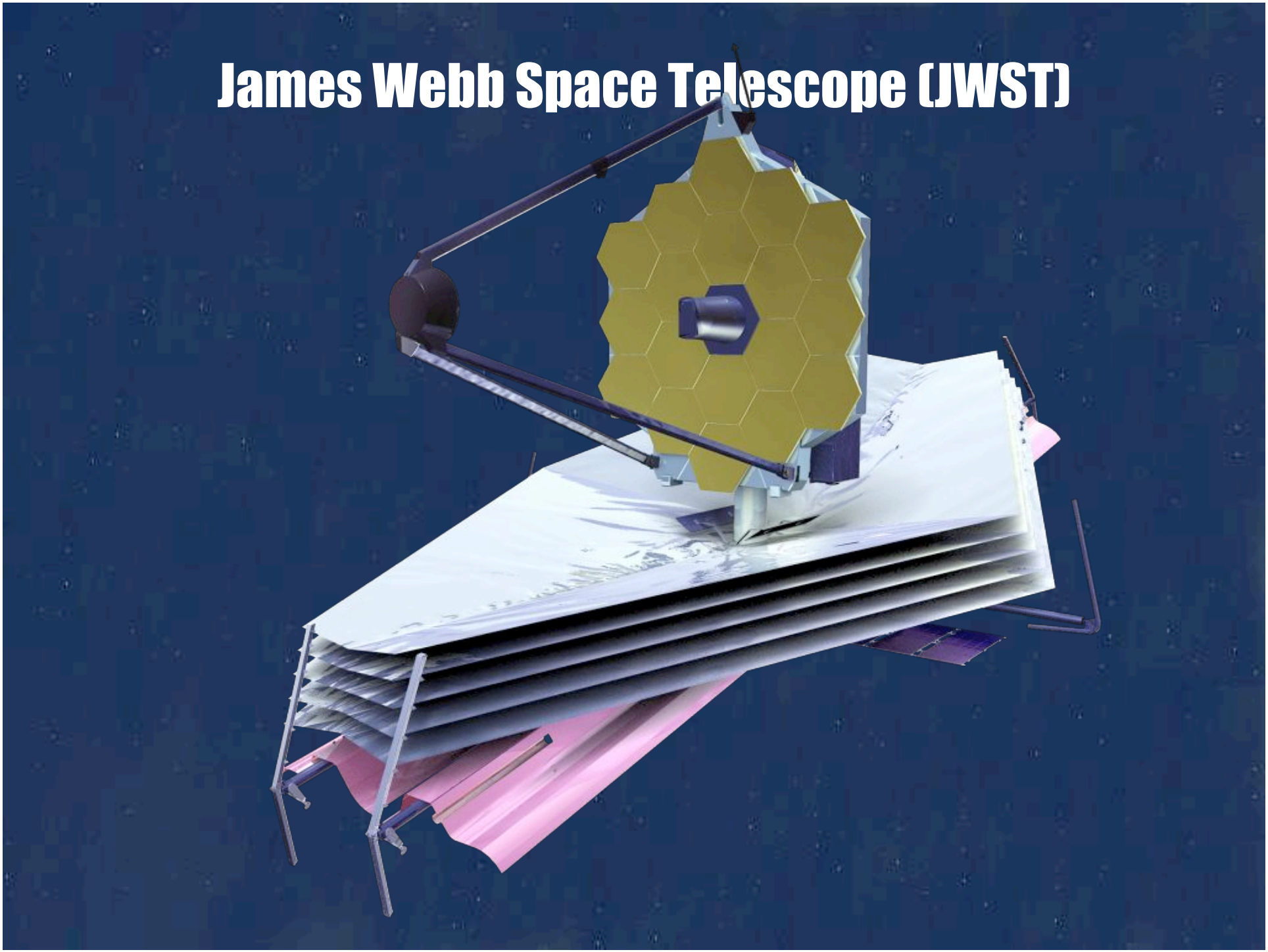


Planck Mission - ESA-led with NASA contributions, for 2008 launch



Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths

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)

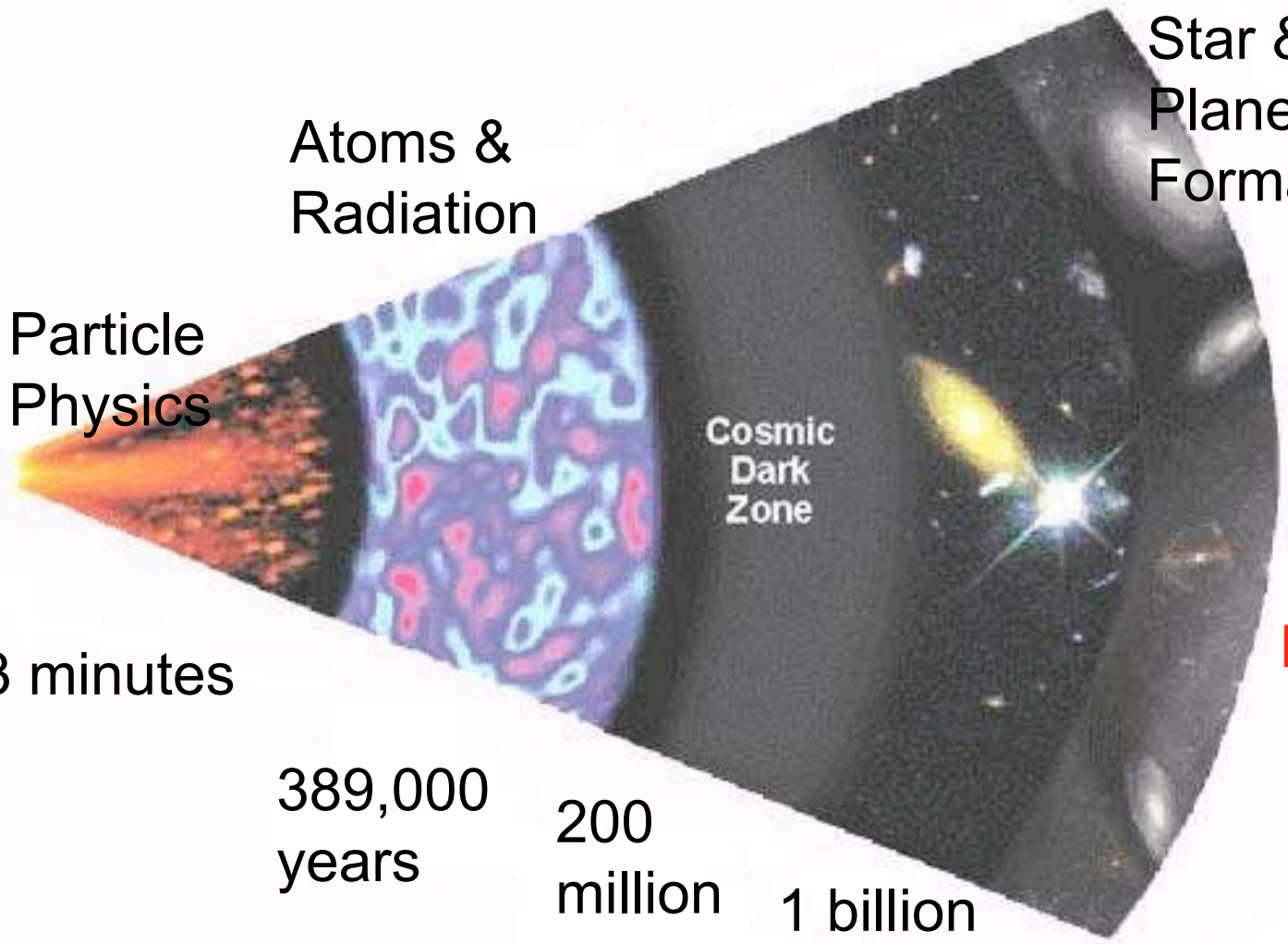
James Webb Space Telescope

- 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

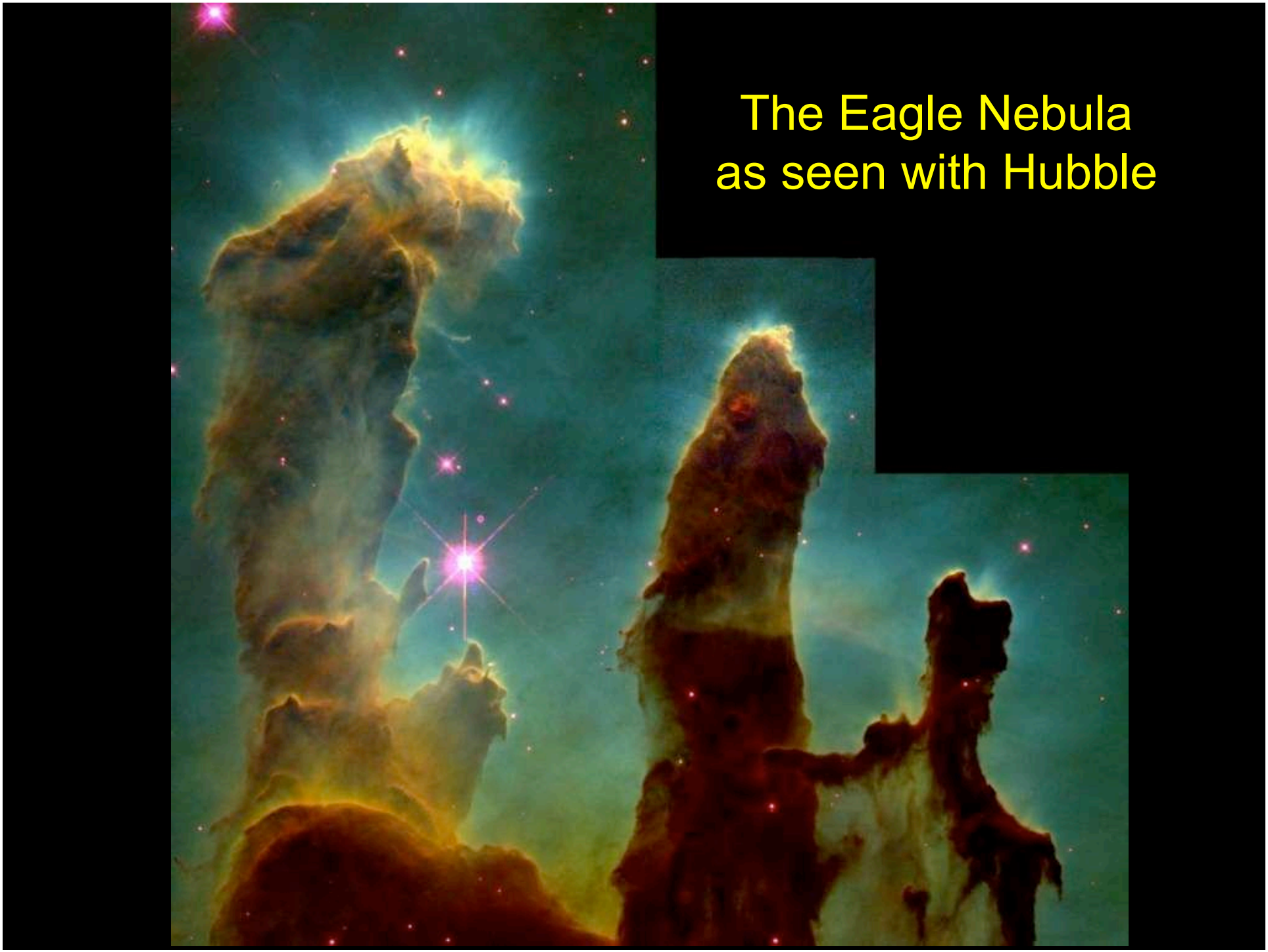
Four Scientific Themes

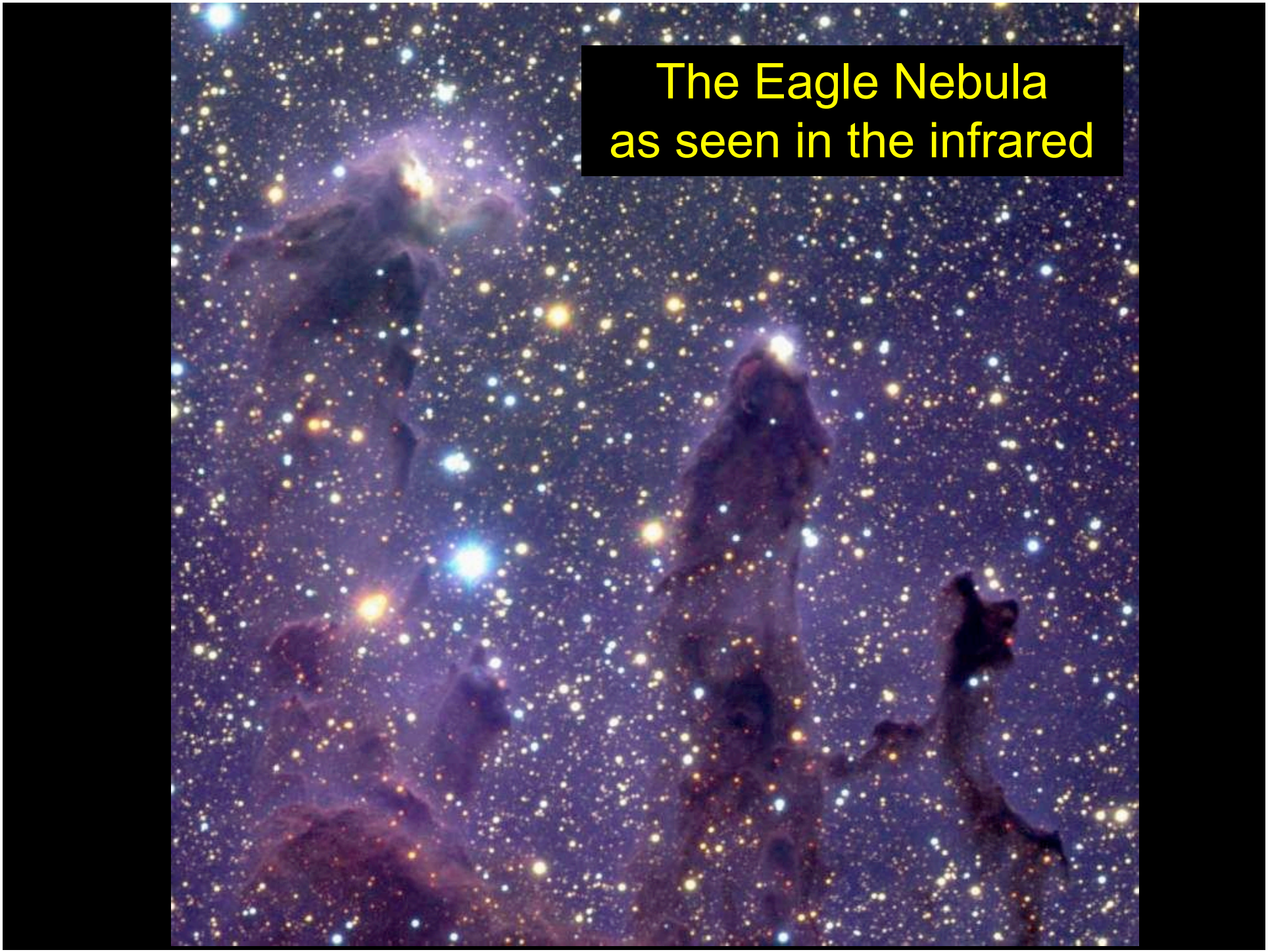
- First objects formed after Big Bang
  - Super-stars?
  - Super-supernovae?
  - Black holes?
- Assembly of galaxies (from small pieces?)
- Formation of stars and planetary systems
  - Hidden in dust clouds
- Planetary systems and conditions for life

JWST Science Objectives versus Cosmic History



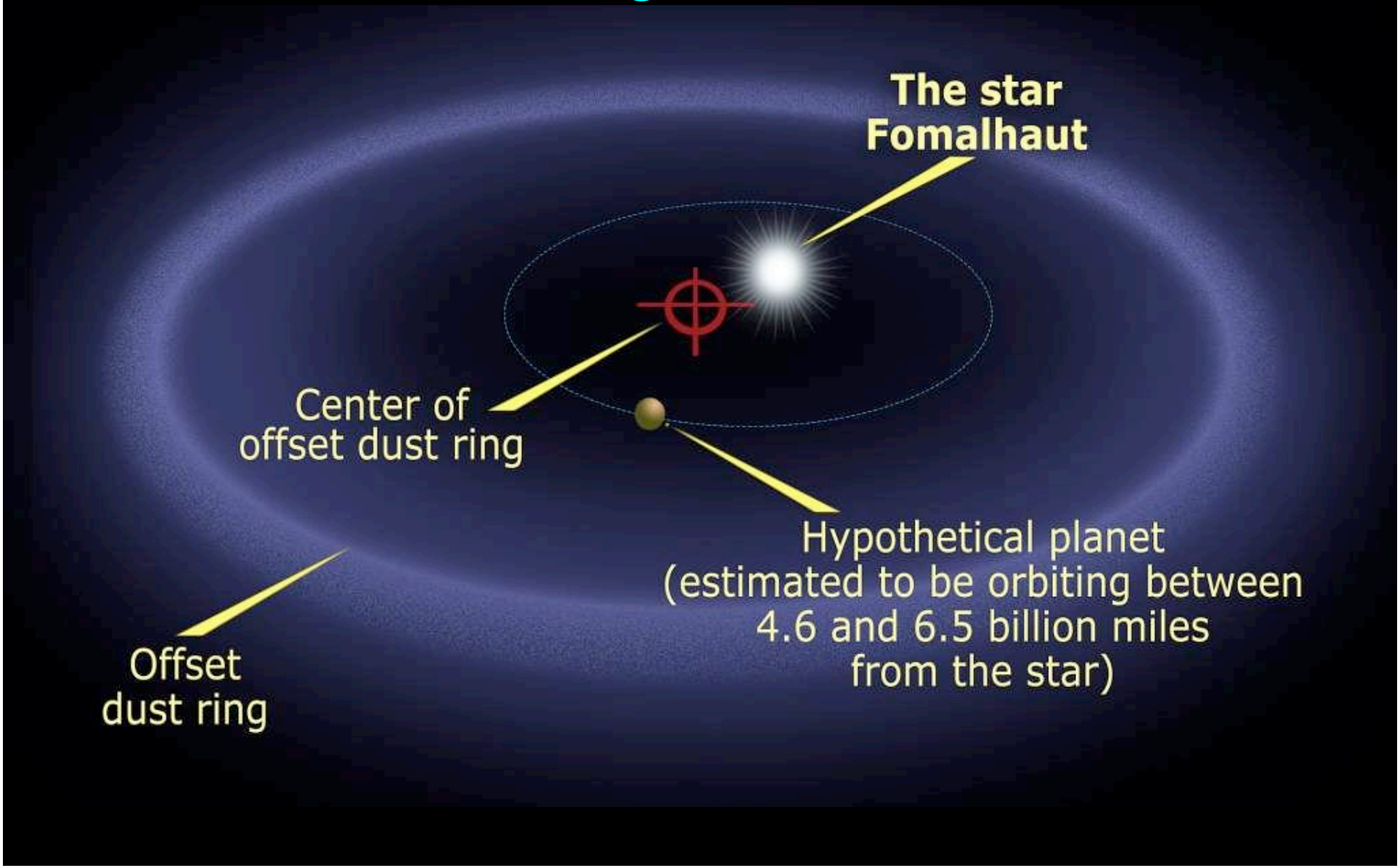

End of the dark ages: first light?


The Eagle Nebula
as seen with Hubble

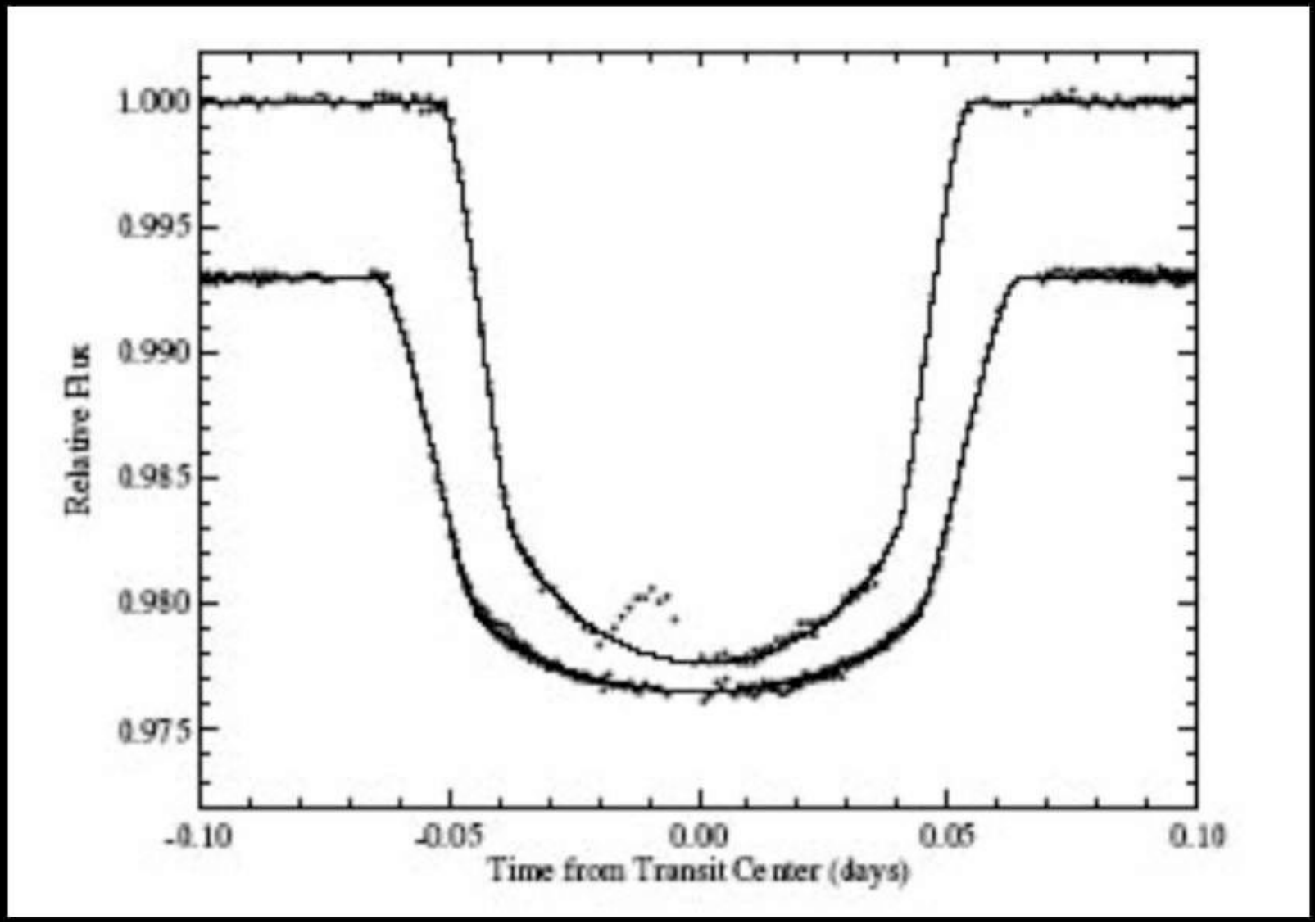

The Eagle Nebula
as seen in the infrared


Stars in dust disks in Orion

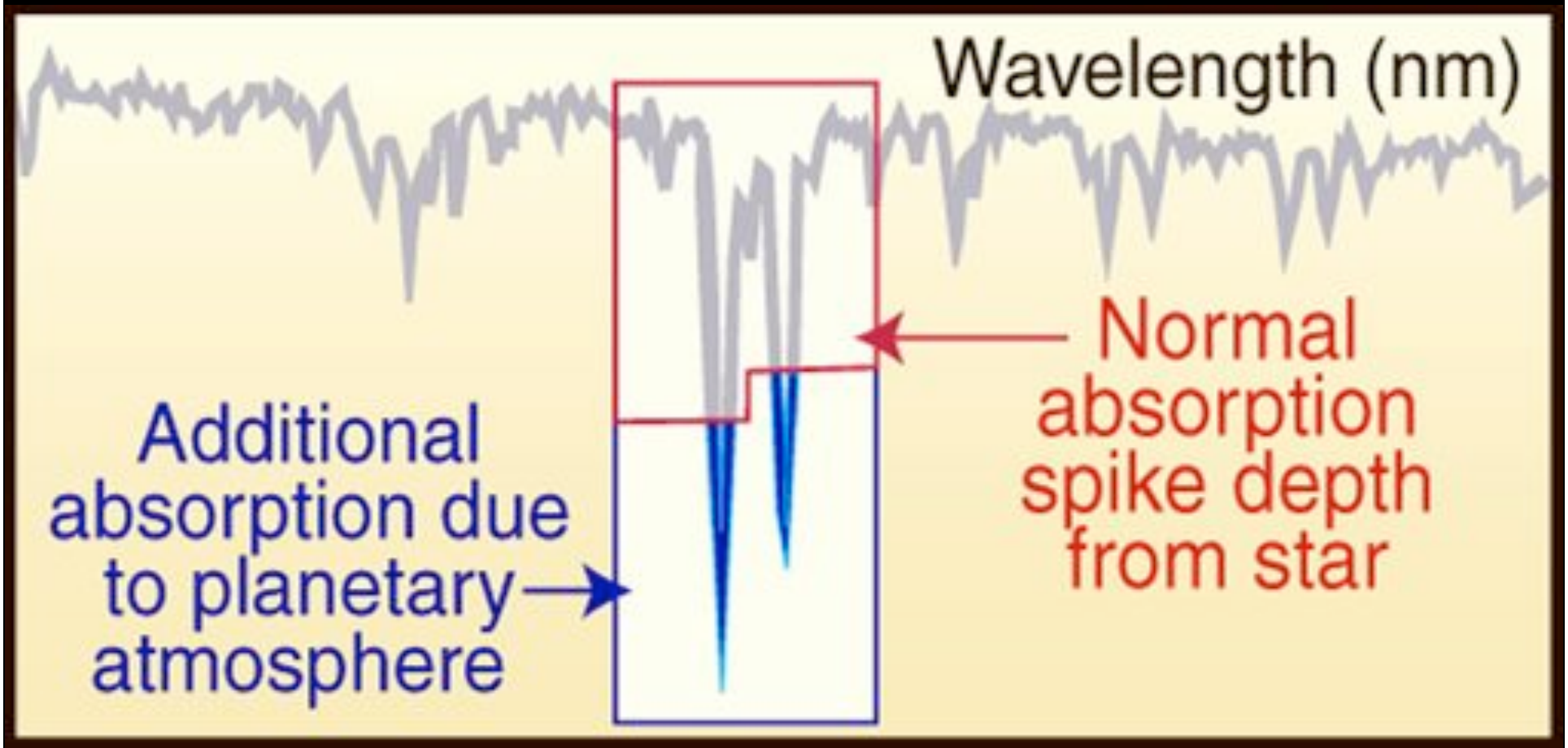
Planetary systems and the origins of life

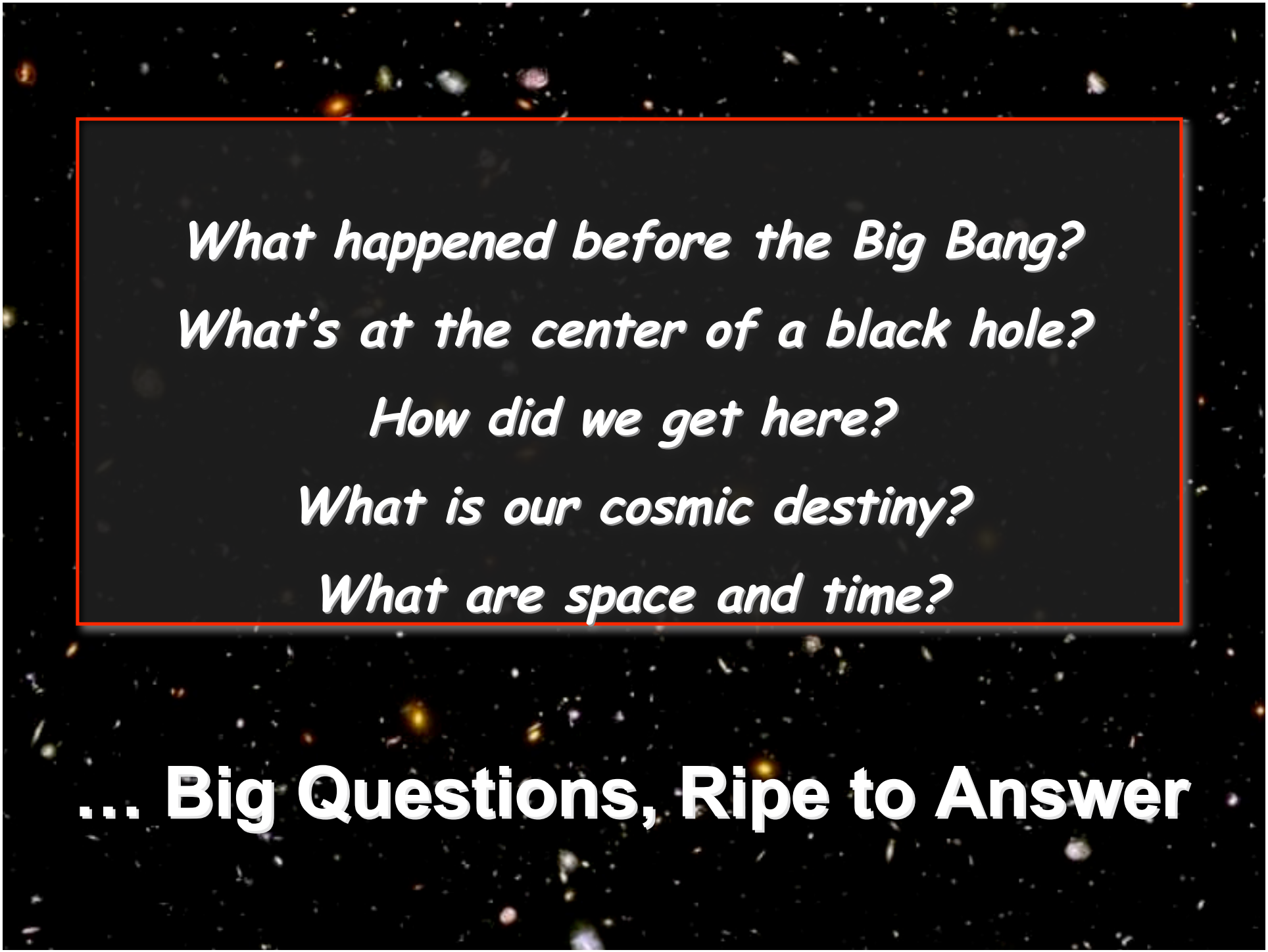


HST characterizes transiting planets; so will JWST



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