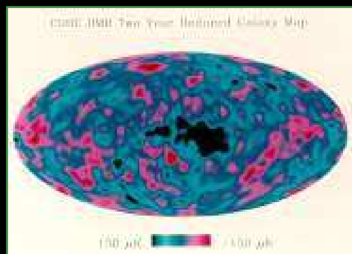
From COBE to the Nobel Prize and on to JWST

John C. Mather
NASA's Goddard Space Flight Center
March 23, 2007

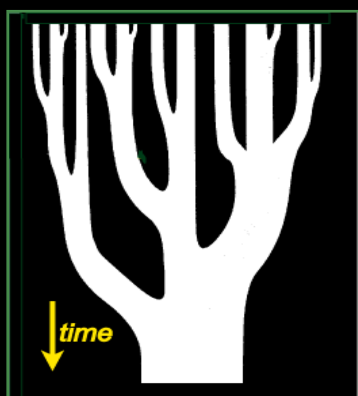
Possible History of the Universe

Big Bang seen by COBE & WMAP



?

Galaxy assembly



?

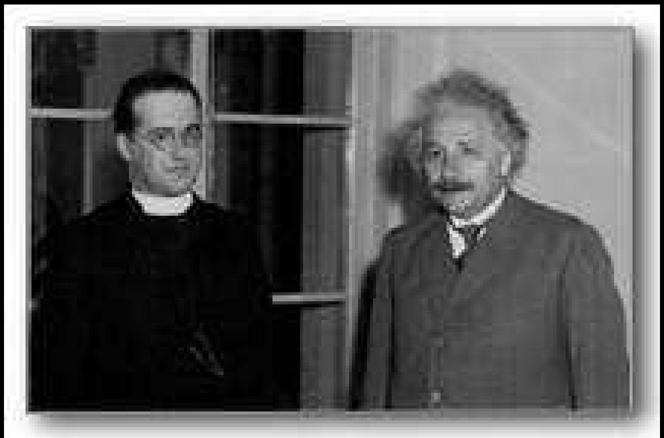
Galaxies, stars, planets, life

- Horrendous Space Kablooey - exponential expansion, primordial fluctuations, matter/antimatter, dark matter, dark energy, 13.7 ± 0.2 billion years ago
- Annihilation of antiparticles, 1 part per billion matter remaining
- Formation of Helium nuclei, 3 minutes, redshift $z = 10^9$
  - [1+z = size of universe now / size then]
- Formation of neutral gas “recombination”, 389,000 yrs, z=1089
- Population III supermassive stars, super-supernovae, and black holes, z=17 (age ~ 200 Myr)
- Galaxy formation in small parts
- Second re-ionization, z = 6 (observed)
- Star formation, merging and clustering of galaxy parts, until z~1
- Earth and Sun form, 4.5 billion years ago
- Mammals dominant, ~ 55 million years ago
- Humans, lions, tigers, mammoths, 1-2 million years ago
- Telescopes, Galileo, 1609: ~ 400 yr
- Theory of Special Relativity, 100 yr
- NASA founded, Oct. 1, 1958
- Signs of life on other planets …?
- Far future: sun goes out, universe continues to expand faster?

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 Lemaître & Albert Einstein

George Gamow

Robert Herman & Ralph Alpher

Rashid Sunyaev

Jim Peebles

Power of Hardware - CMB Spectrum

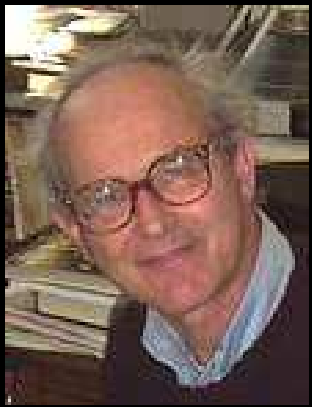
Paul Richards

Mike Werner

David Woody

Frank Low

Herb Gush

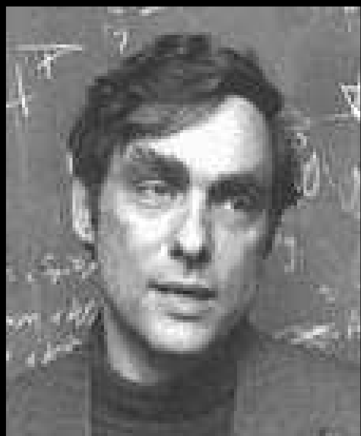


Rai Weiss

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

Starting COBE

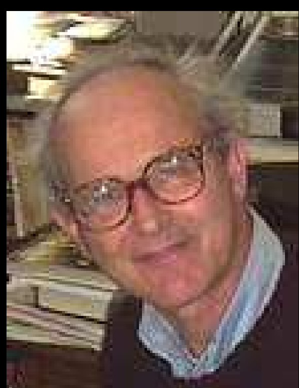


Pat Thaddeus

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 Pre-History

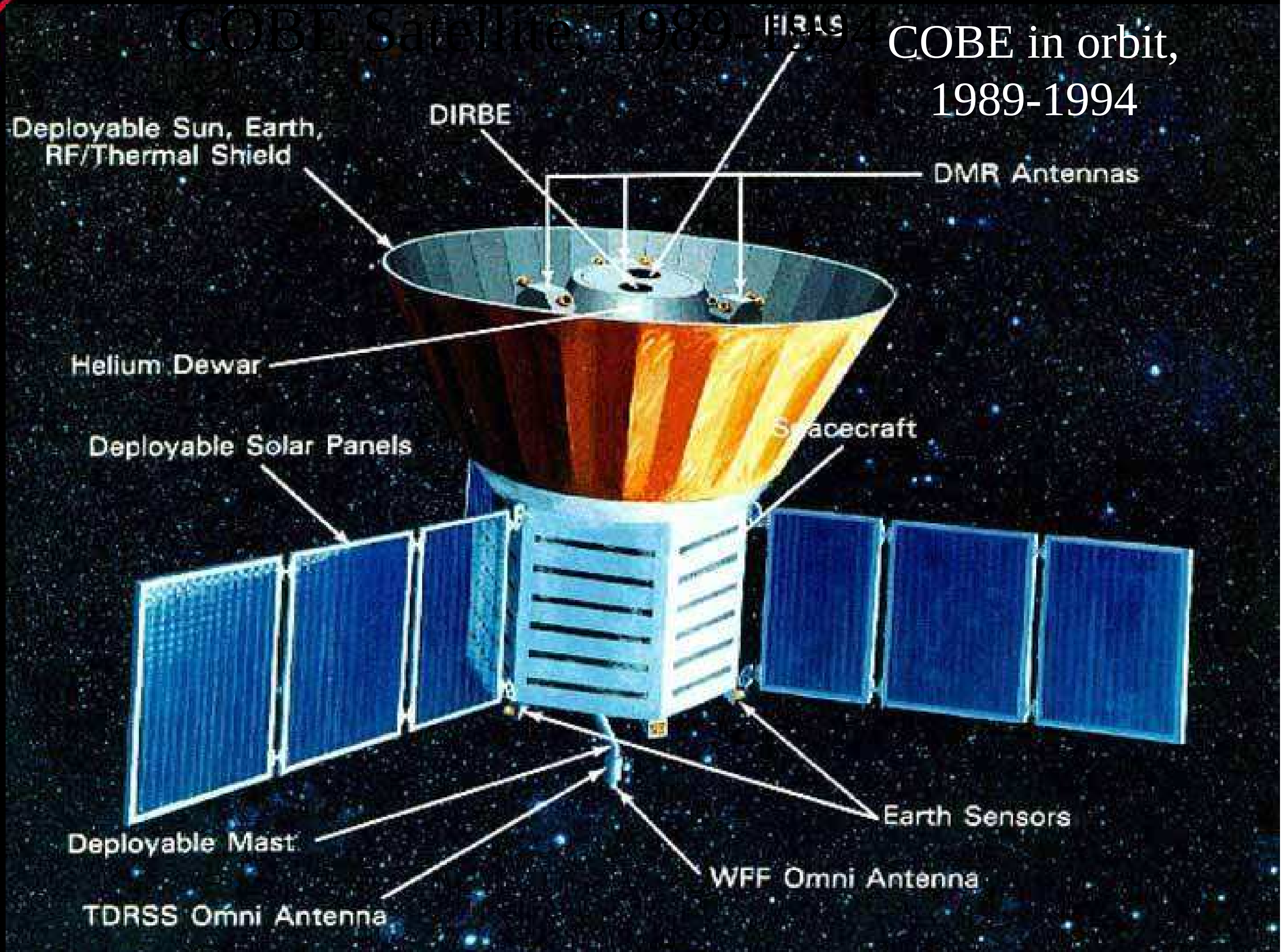
- 1974, NASA Announcement of Opportunity for Explorer satellites: ~ 150 proposals, including:
  - JPL anisotropy proposal (Gulkis, Janssen…)
  - Berkeley anisotropy proposal (Alvarez, Smoot…)
  - NASA Goddard/MIT/Princeton COBE proposal (Hauser, Mather, Muehlner, Silverberg, Thaddeus, Weiss, Wilkinson)

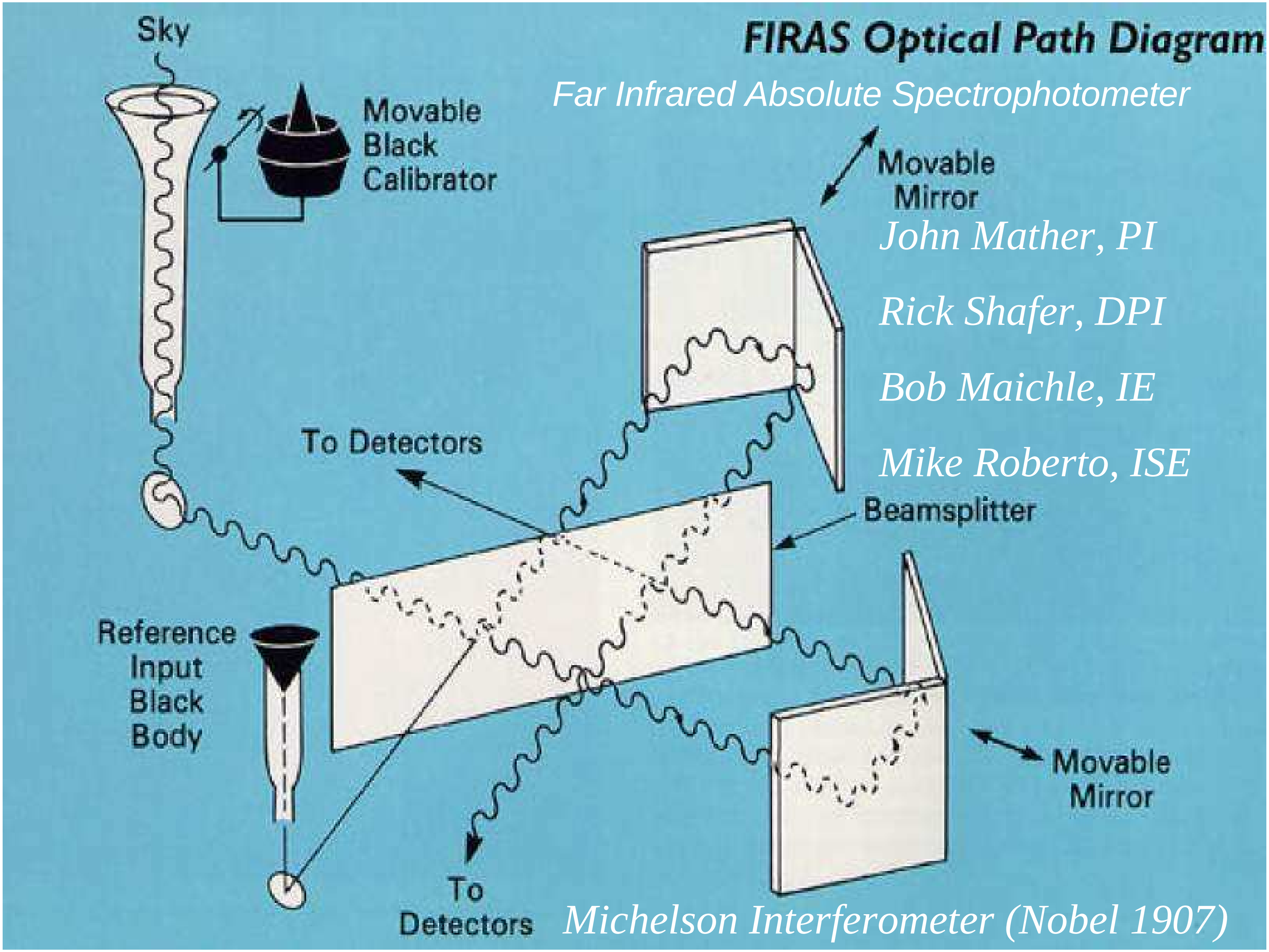
COBE History (2)

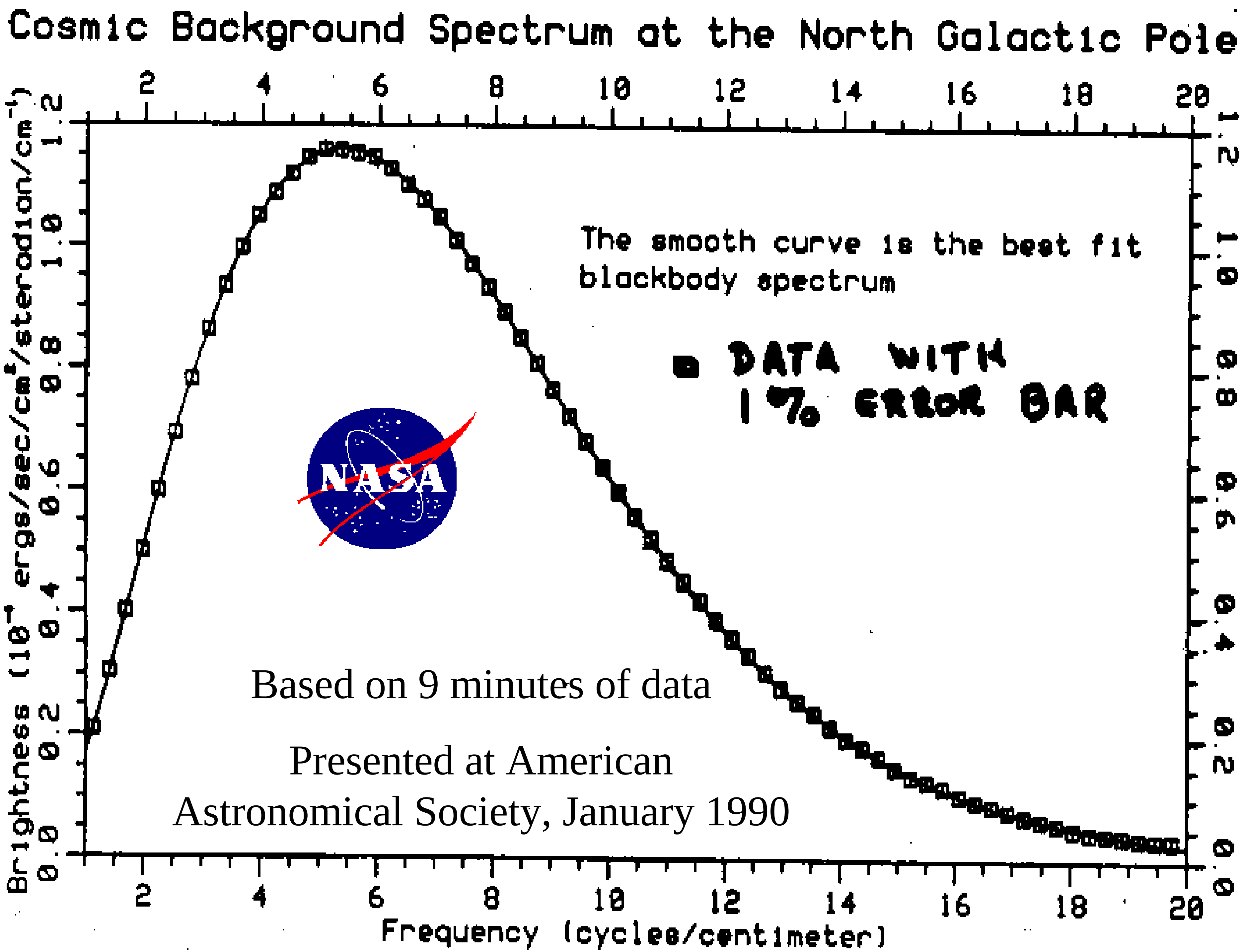
- 1976, Mission Definition Science Team selected by NASA HQ (Nancy Boggess, Program Scientist); PI's chosen
- ~ 1979, decision to build COBE in-house at Goddard Space Flight Center
- 1982, approval to construct for flight
- 1986, Challenger explosion, start COBE redesign for Delta launch
- 1989, Nov. 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 Satellite 1989-1994

COBE in orbit, 1989-1994




FIRAS Optical Path Diagram
Far Infrared Absolute Spectrophotometer
Sky
Movable Black Calibrator
Movable Mirror
John Mather, PI
Rick Shafer, DPI
Bob Maichle, IE
Mike Roberto, ISE
To Detectors
Beamsplitter
Reference Input Black Body
Movable Mirror
To Detectors
Michelson Interferometer (Nobel 1907)


Cosmic Background Spectrum at the North Galactic Pole
Brightness (10⁻⁴ ergs/sec/cm²/steradian/cm⁻¹)
Frequency (cycles/centimeter)
The smooth curve is the best fit blackbody spectrum
▪ DATA WITH 1% ERROR BAR
NASA
Based on 9 minutes of data
Presented at American Astronomical Society, January 1990

Cosmic Microwave Background matches Hot Big Bang

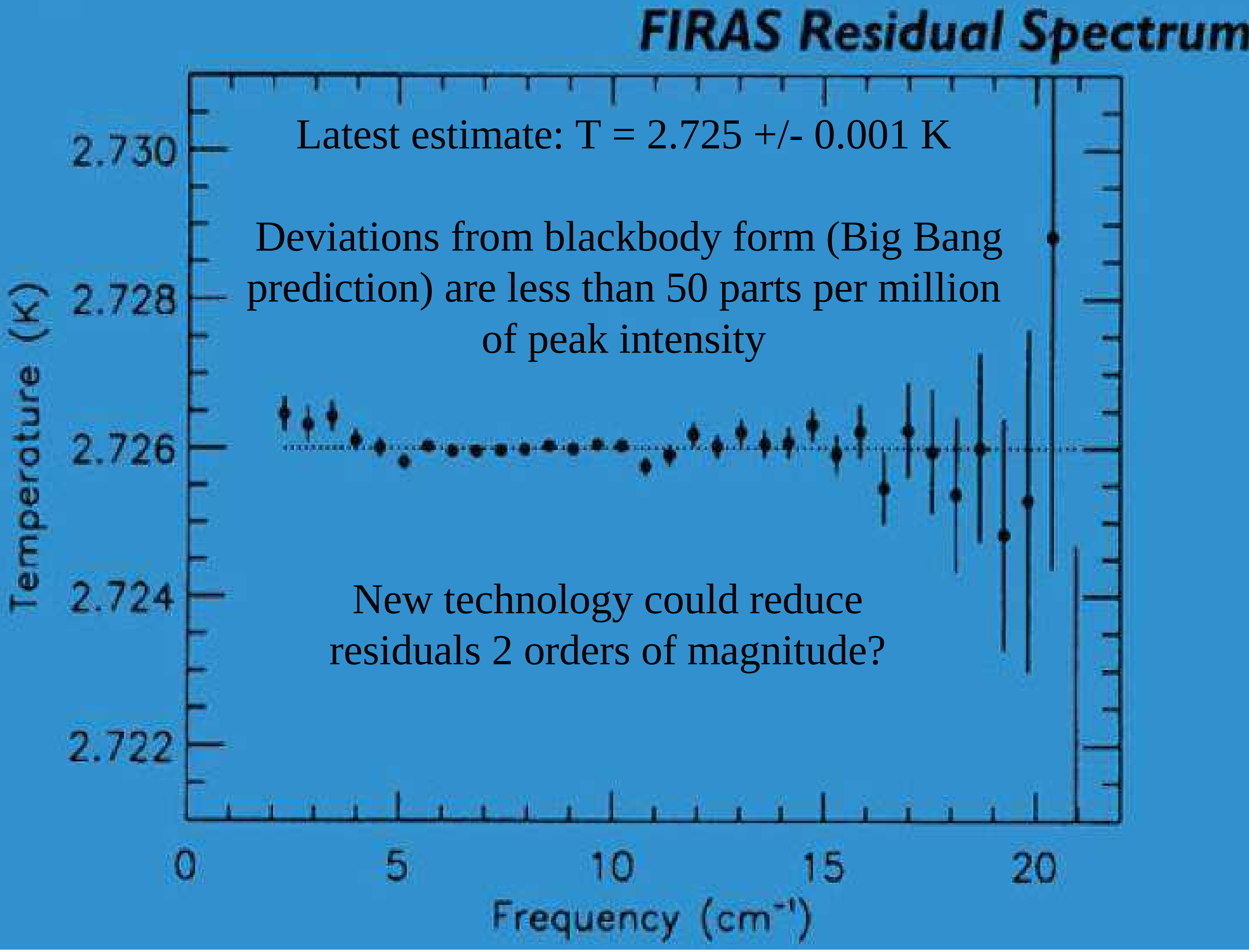
- $\delta F/F_{max}$ < 50 ppm (rms deviation)
- T = 2.725 ± 0.001 K (Fixsen & Mather 2002)
- $|y| < 15 \times 10^{-6}$, $|\mu| < 9 \times 10^{-5}$, 95% CL
- Strong limits, about 0.01%, on fraction of CMB energy due to conversion (from turbulence, proton decay, other unstable particles, decaying massive 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

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

Other FIRAS Results

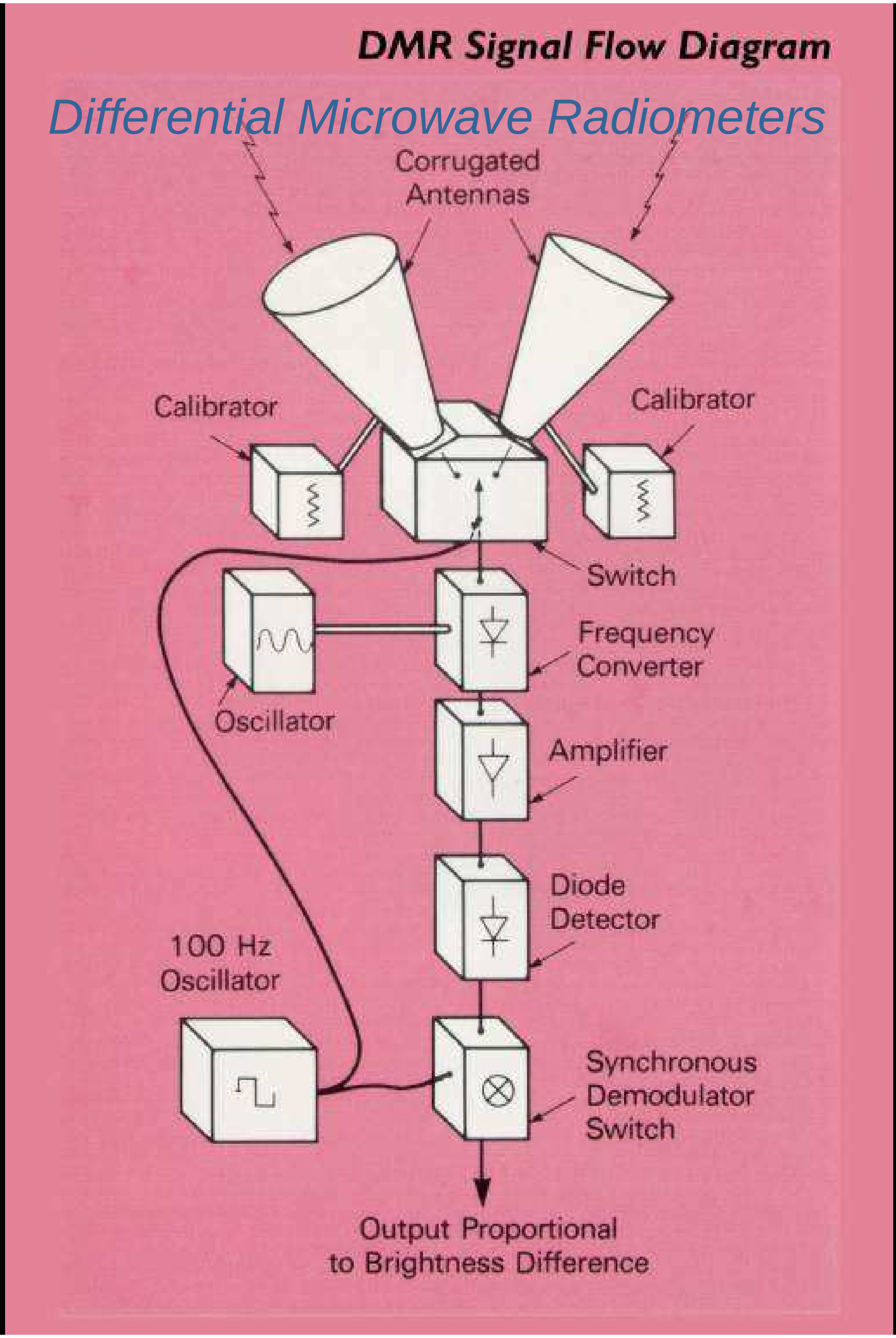
- Spectrum of far IR cosmic background radiation
- Spectrum of far IR zodiacal light
- Blackbody spectrum of cosmic dipole due to motion
- Limits on spatial variation of CMB spectrum
- Maps of dust emission of the Milky Way, with temperature, intensity, and number of types of dust (usually 2, sometimes 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)



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?



George Smoot

Chuck Bennett

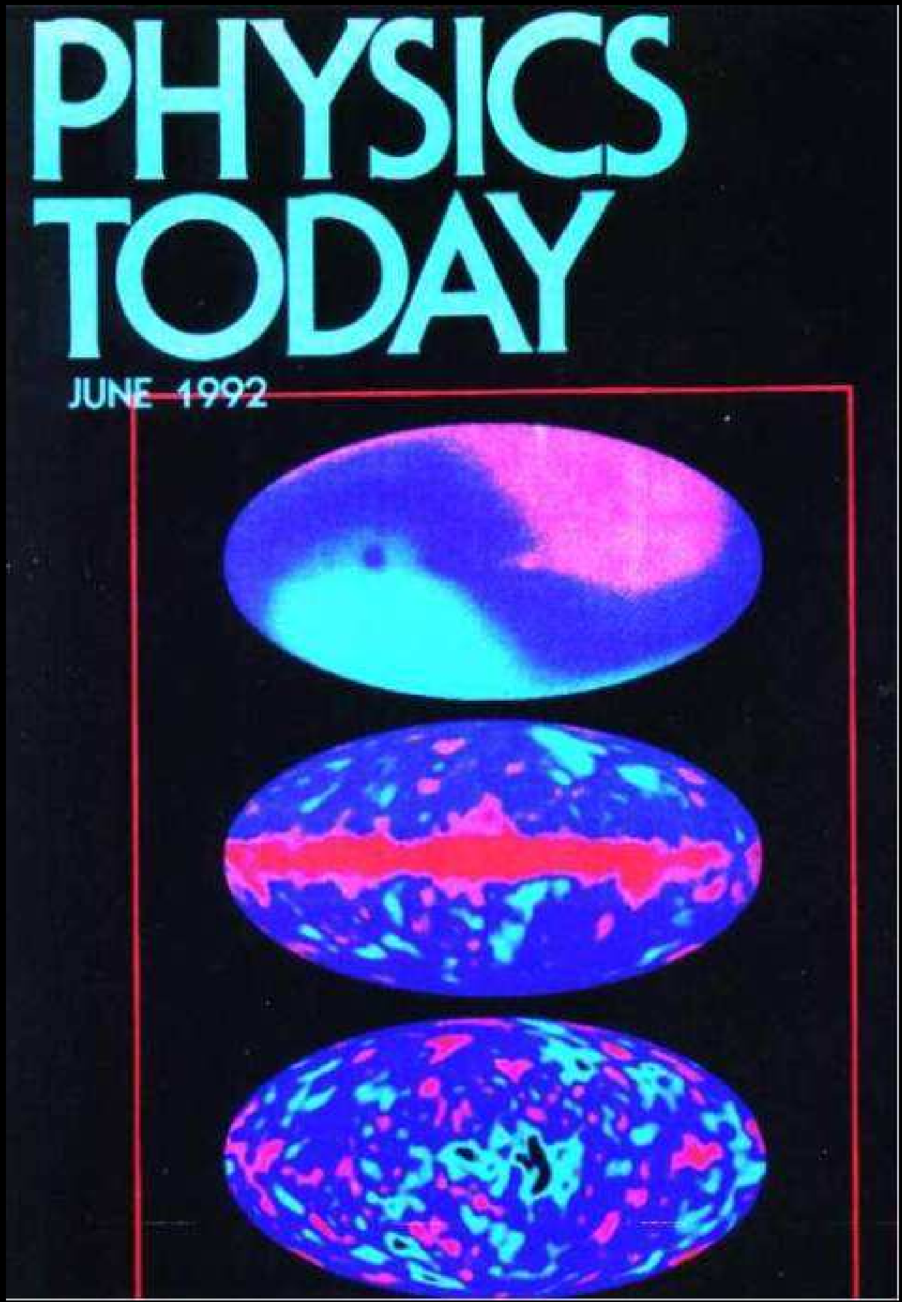
Bernie Klein

Steve Leete

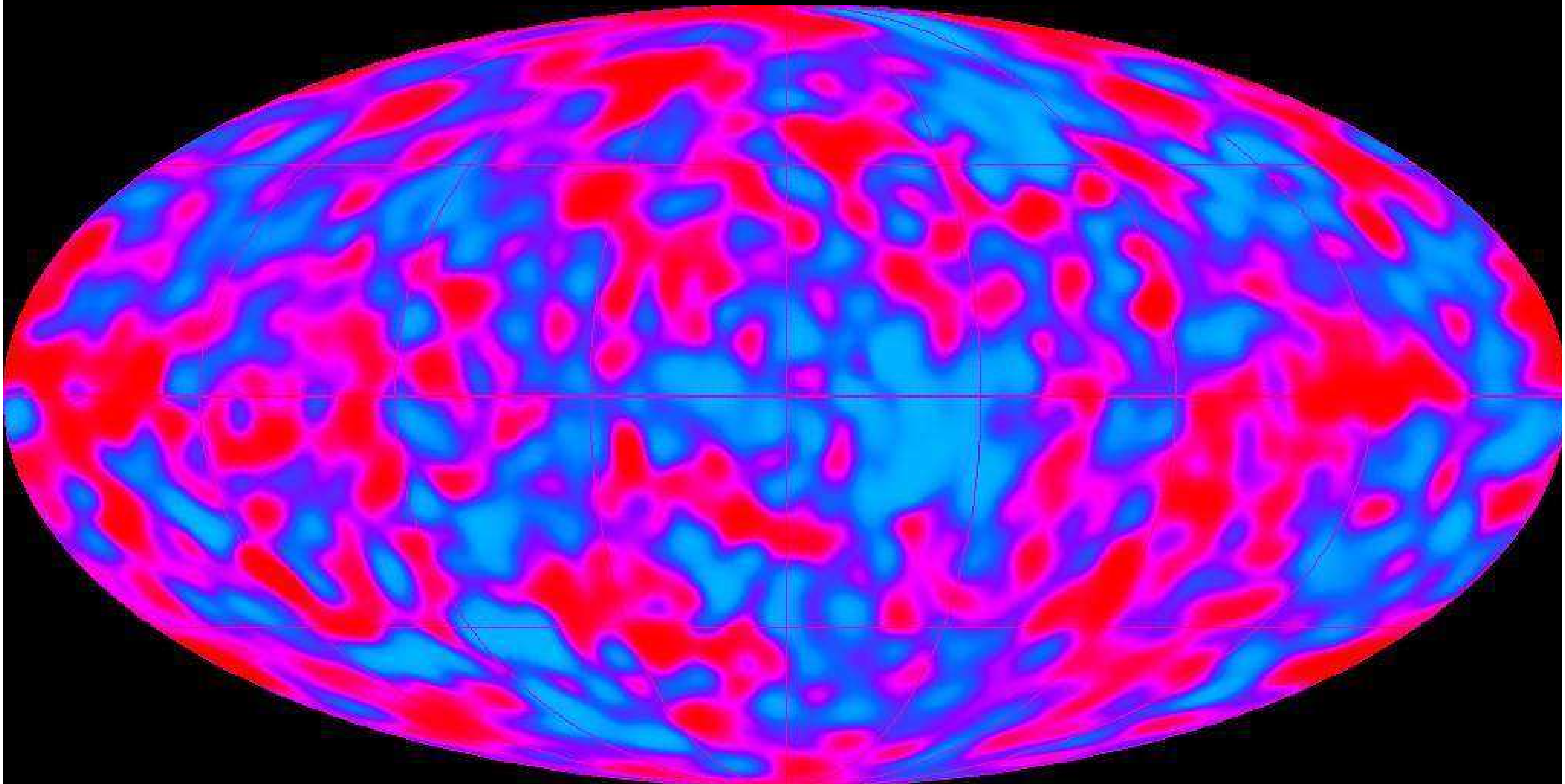
Sky map from DMR, 2.7 K +/- 0.003 K

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

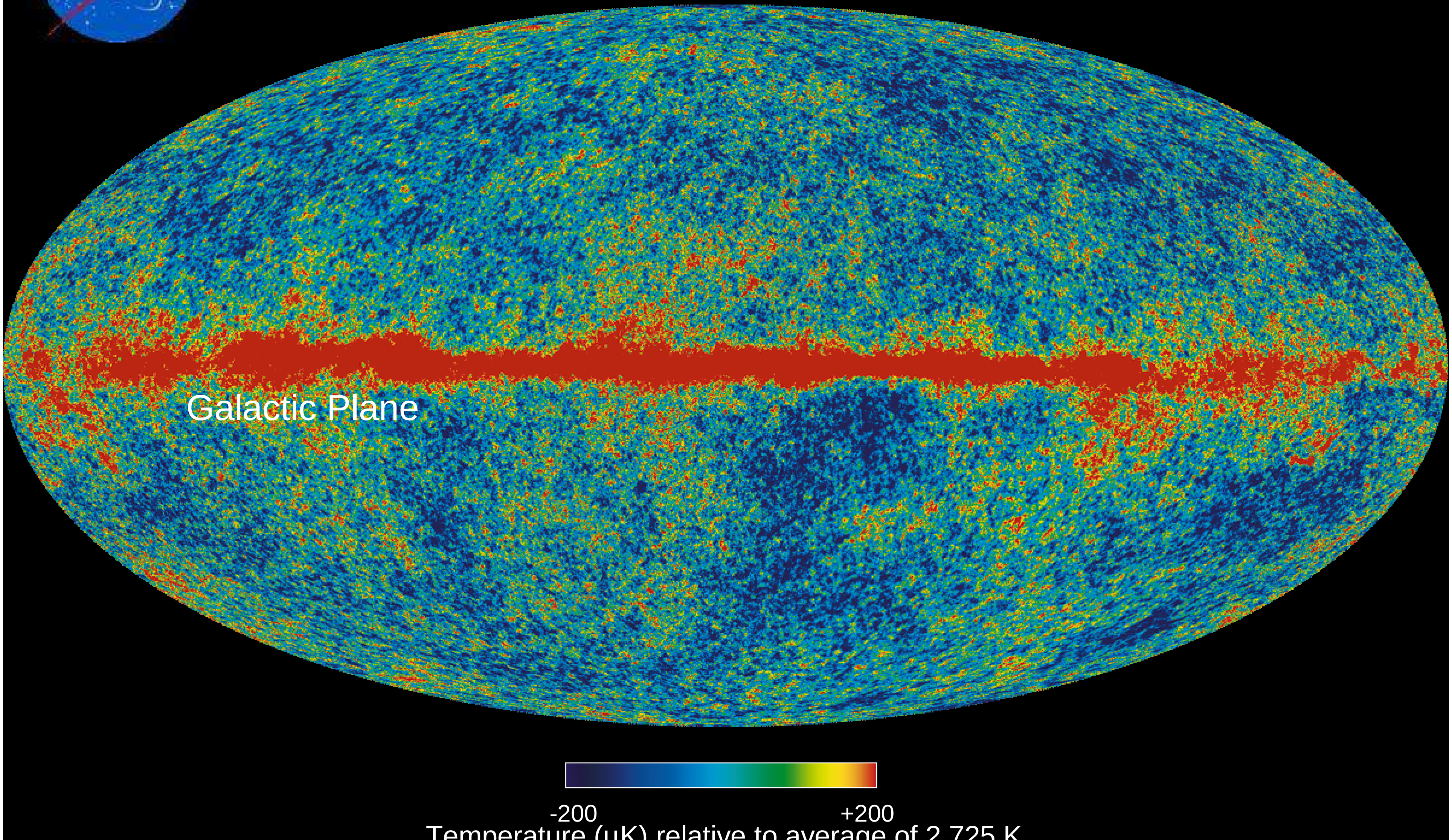
Cosmic temperature/density variations at 389,000 years, +/- 0.00003 K



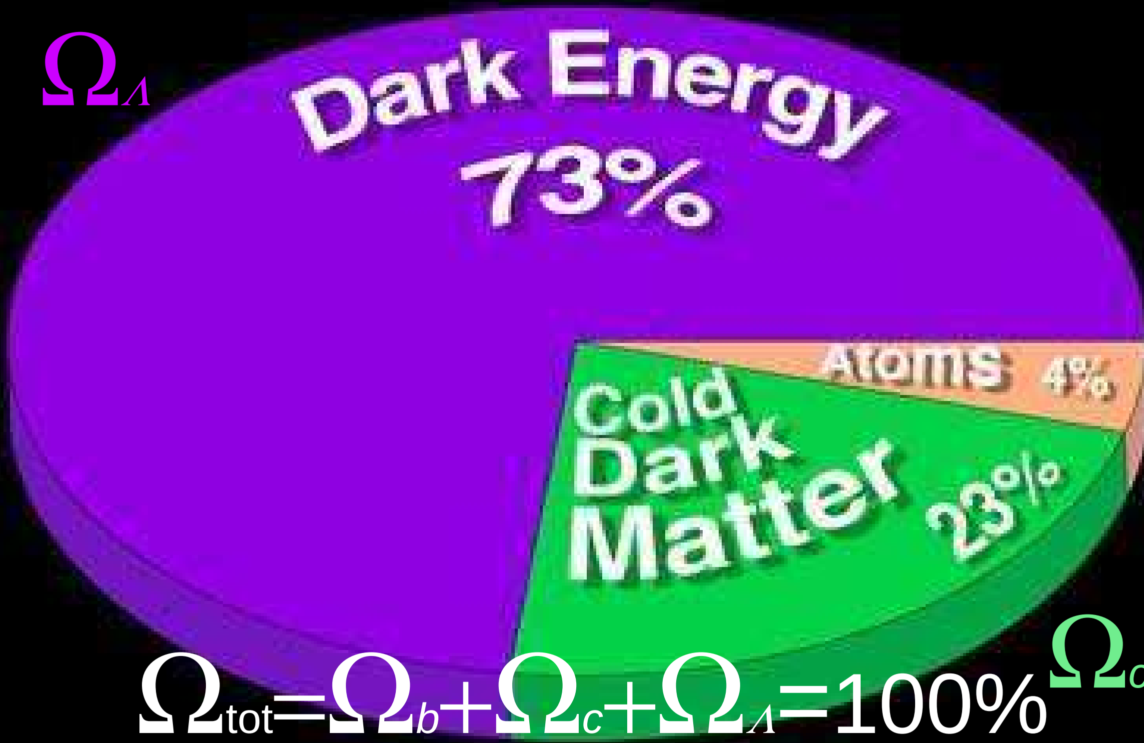
COBE Map of CMB Fluctuations
2.725 K +/- ~ 30 μK rms, 7^o beam



The Universe at age 389,000 years



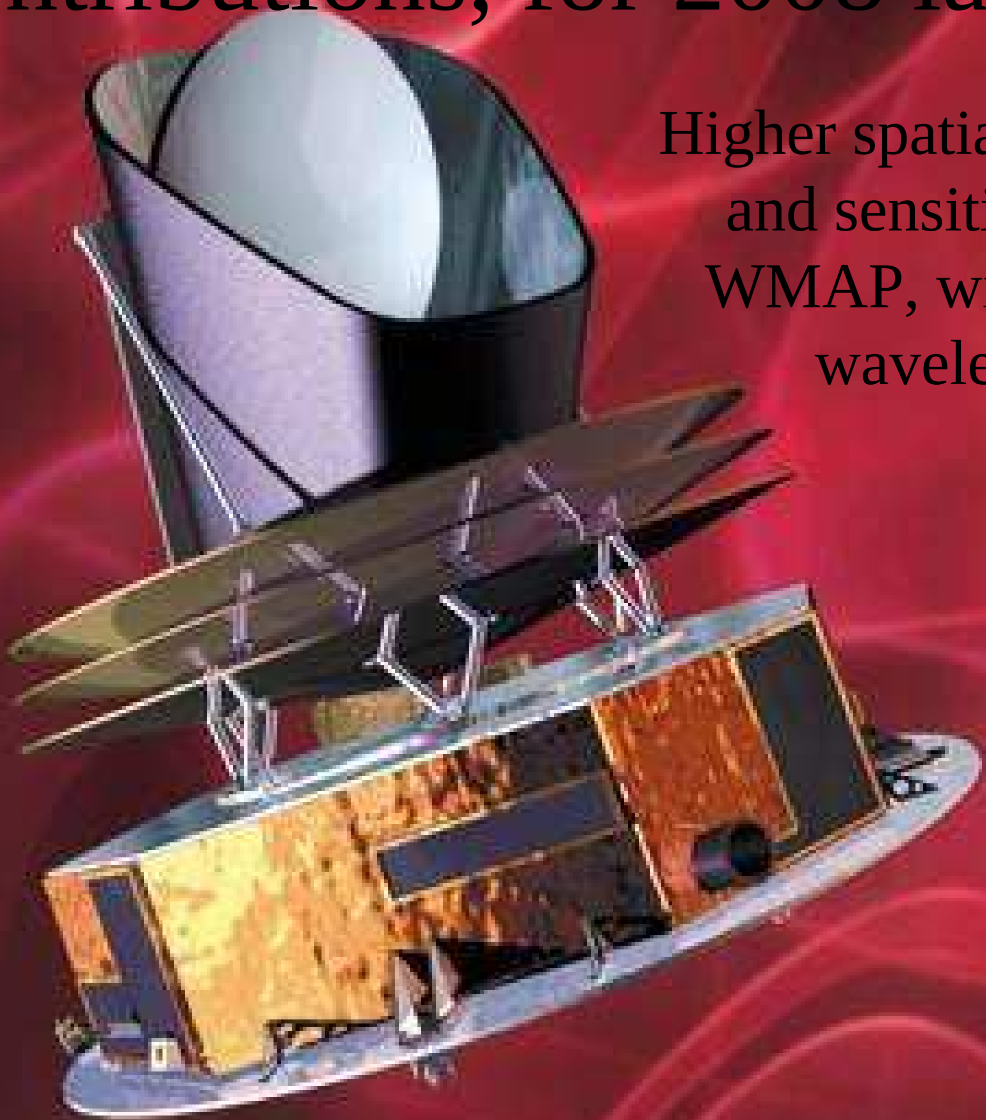
Cosmic Parameters to ~ percent accuracy from WMAP, HST, etc.



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

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

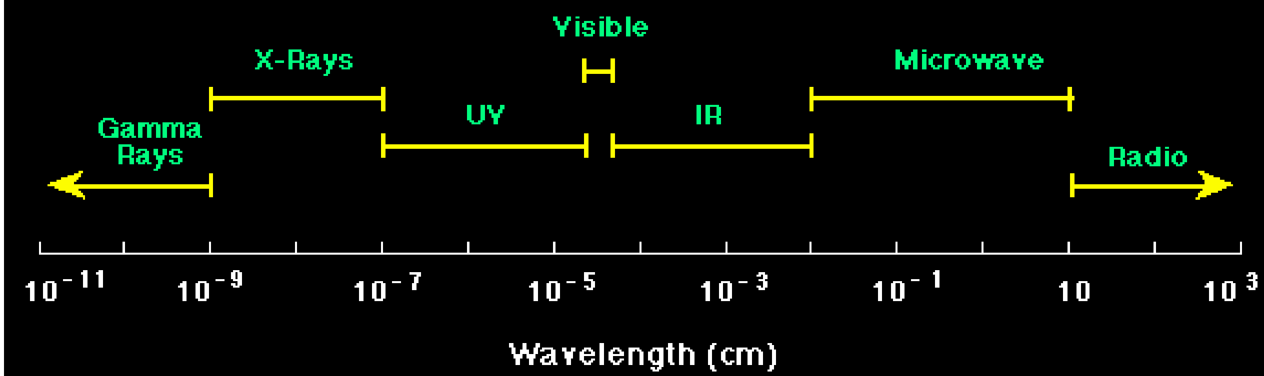
Planck Mission - ESA-led with NASA contributions, for 2008 launch

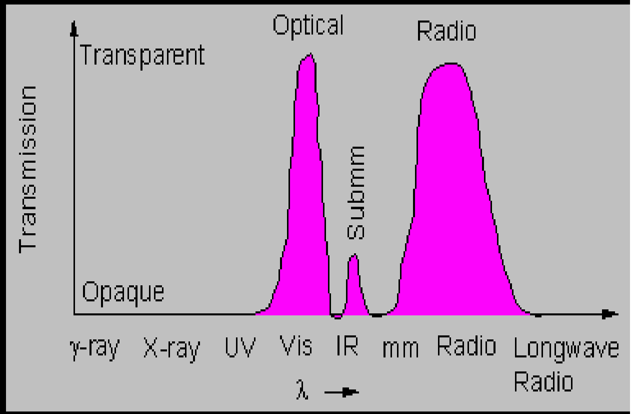


Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths

Light comes in more colors than our eyes can see

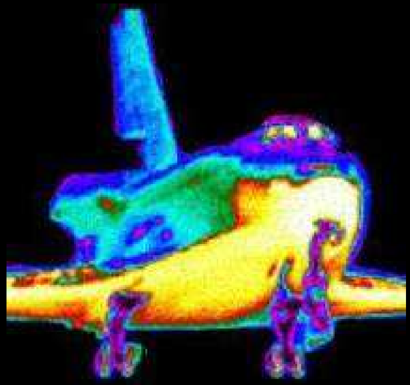
Light from the first galaxies is redshifted from the visible into the infrared.



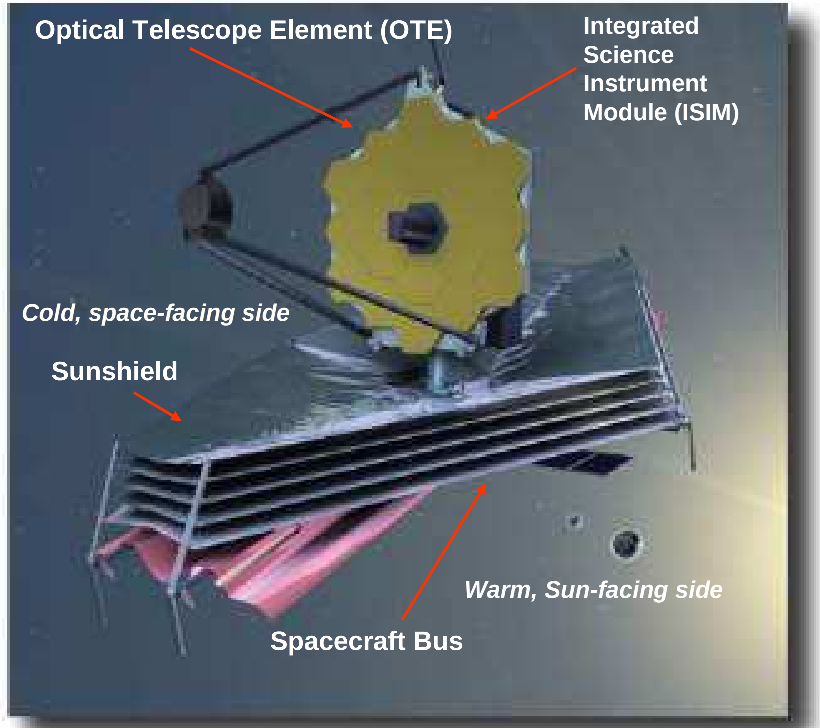


Infrared is heat radiation

Our eyes can't see it, but our skin can feel it



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)**

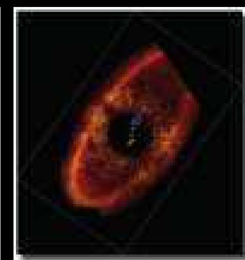
www.JWST.nasa.gov

JWST Science Themes

End of the dark ages: First light and reionization

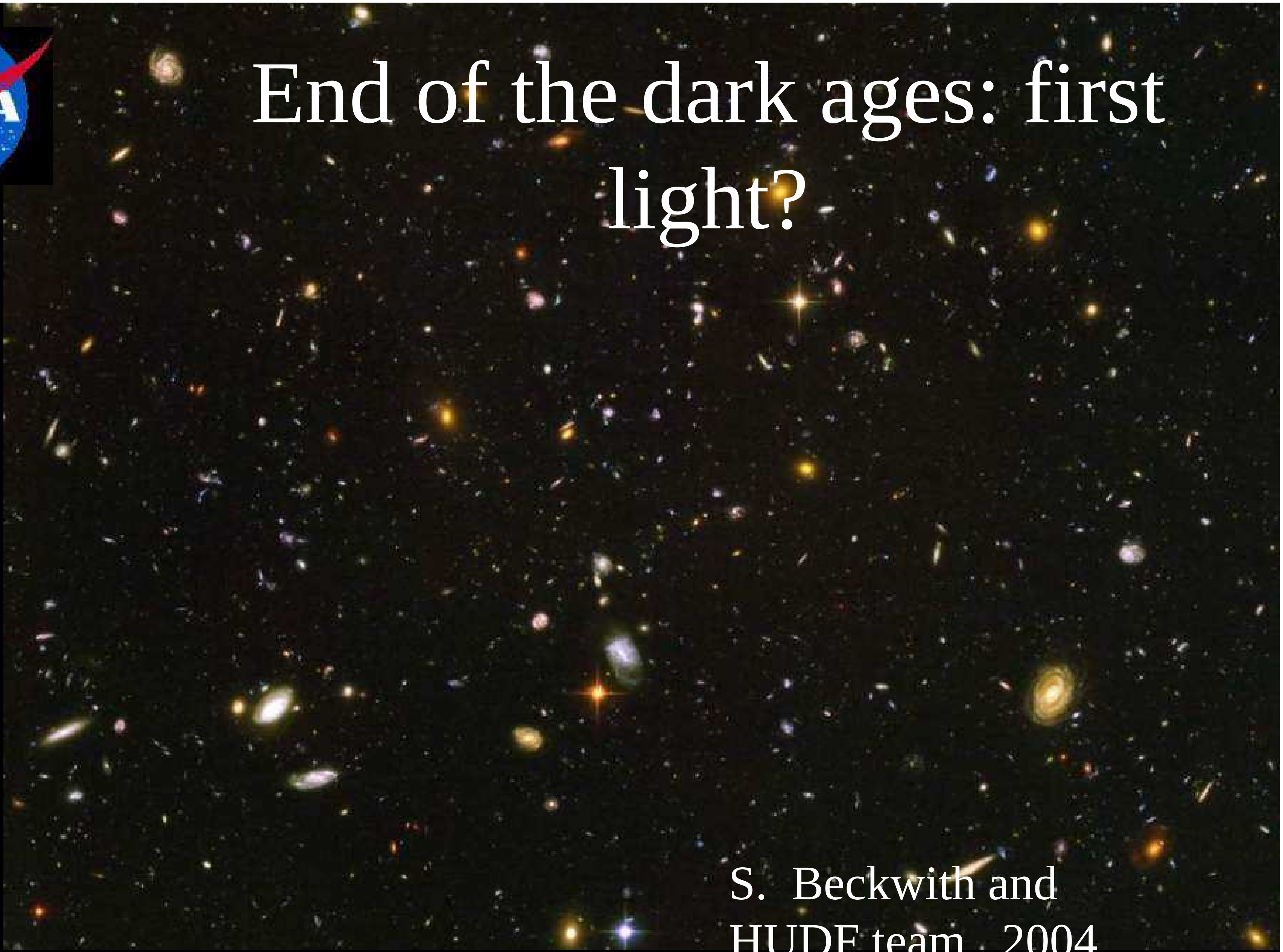
The assembly of galaxies

Birth of stars and proto-planetary systems



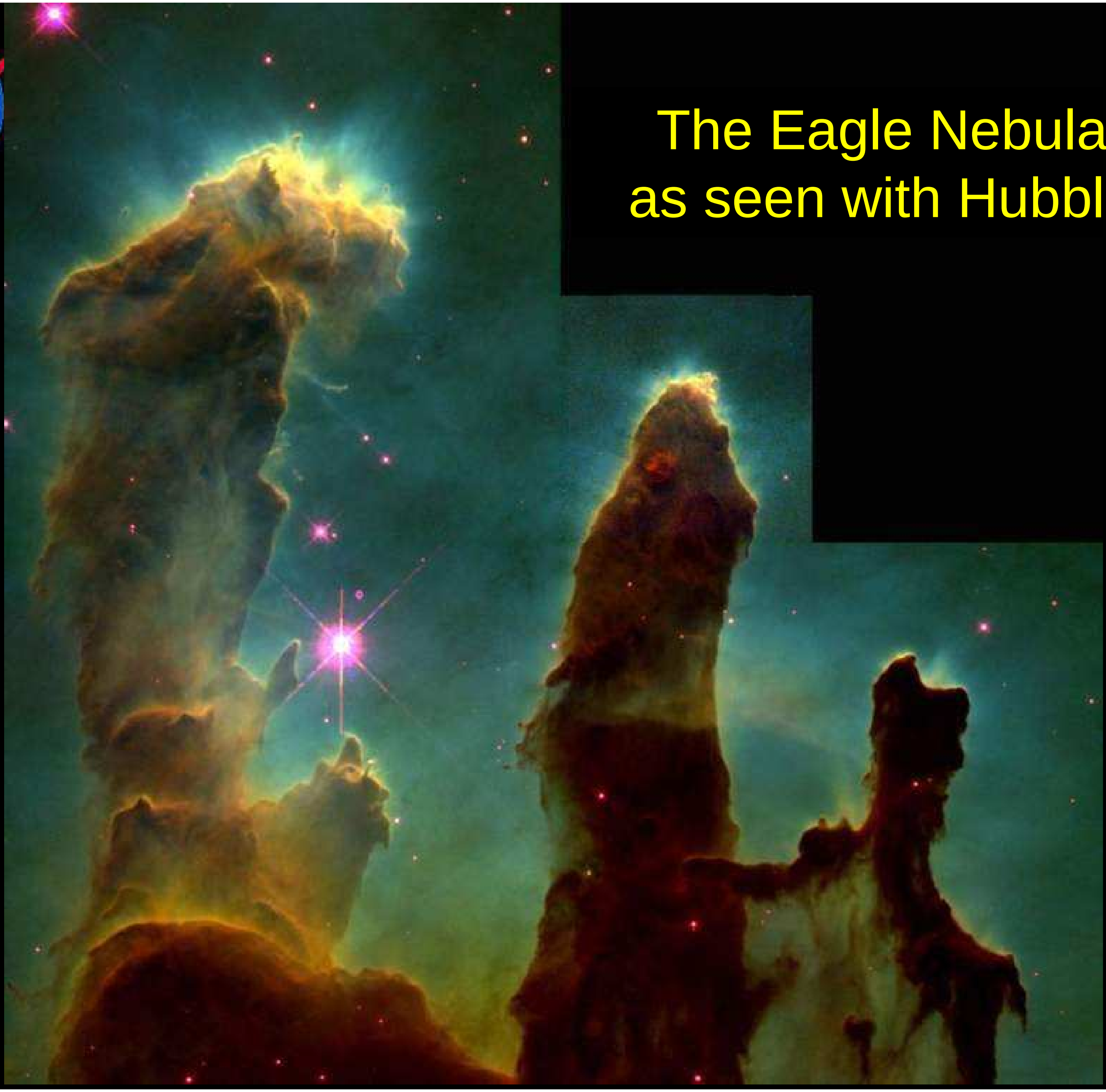
Planetary systems and the origin of life

End of the dark ages: first light?



S. Beckwith and HUDF team , 2004

The Eagle Nebula as seen with Hubble

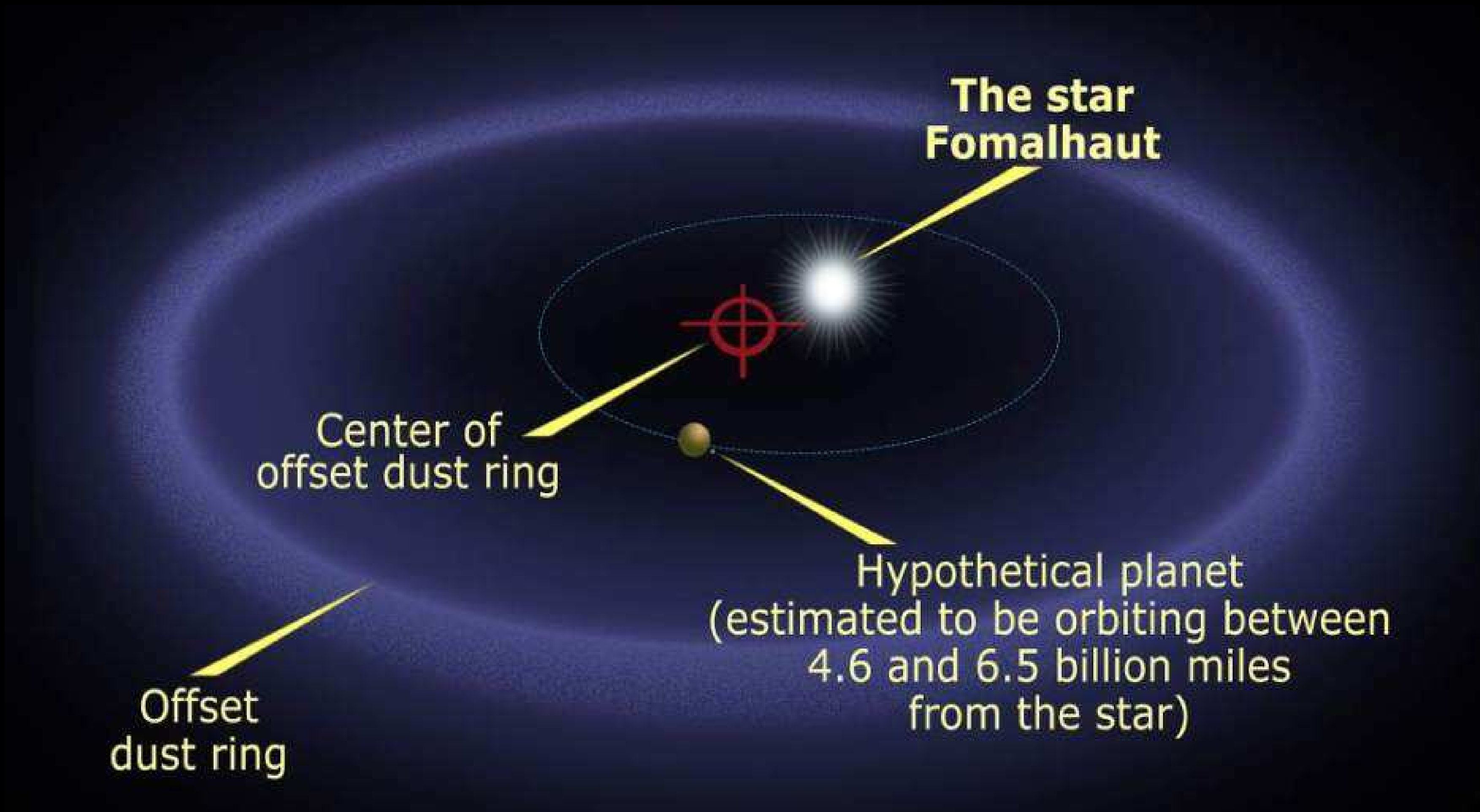


The Eagle Nebula as seen in the infrared

Stars in dust disks in Orion

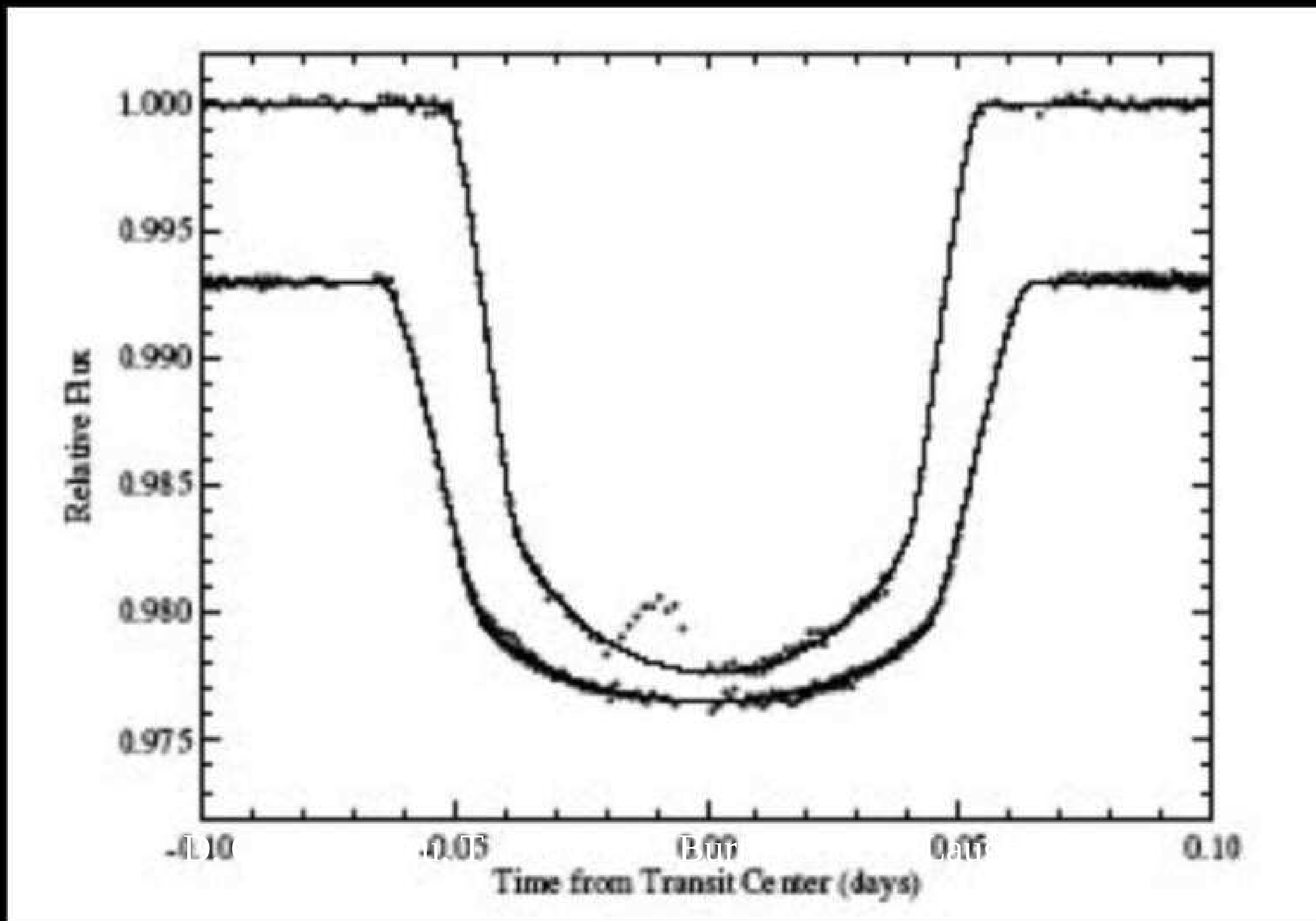
C. R. Odell et al. 1994

Planetary systems and the origins of life

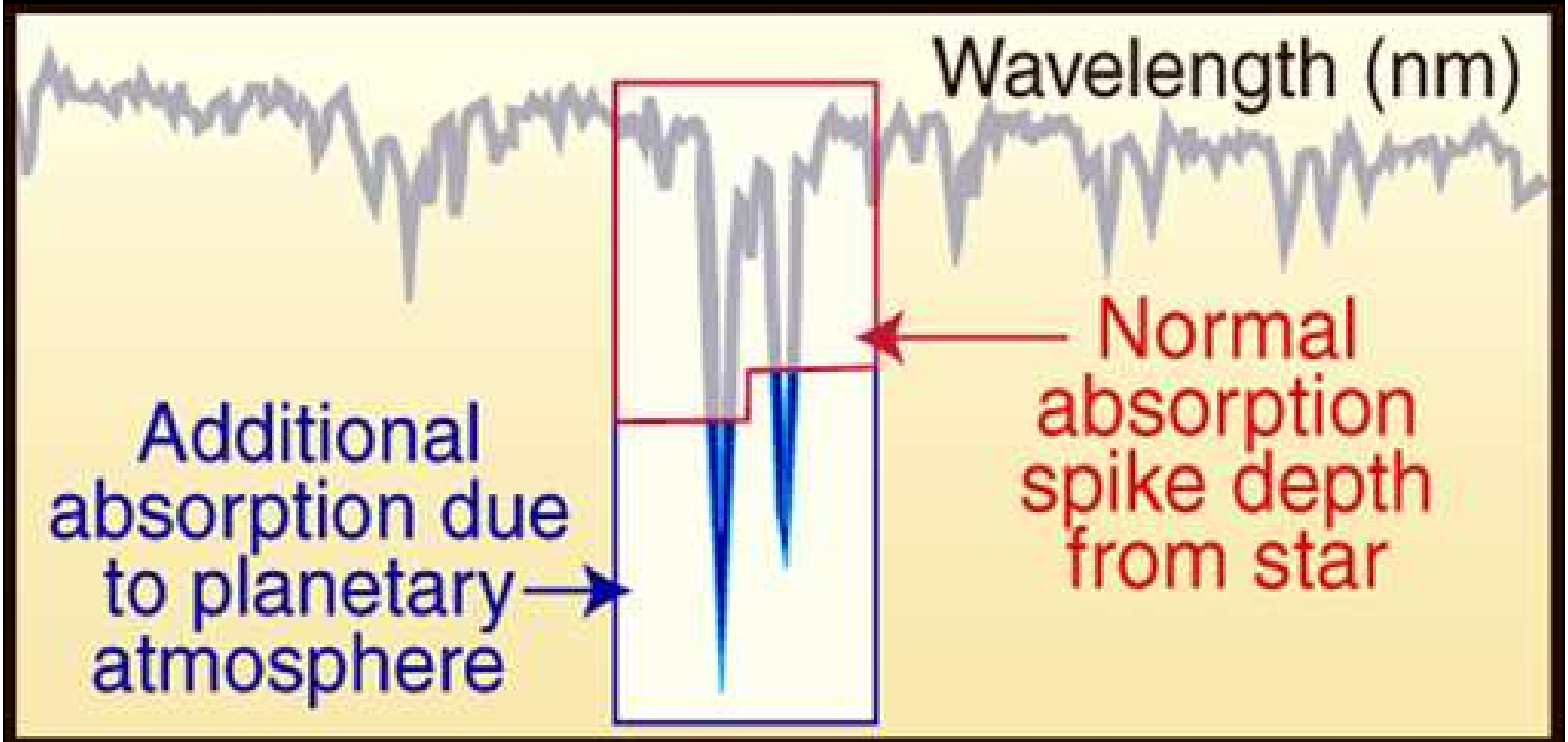


Kalas, Graham and Clampin 2005

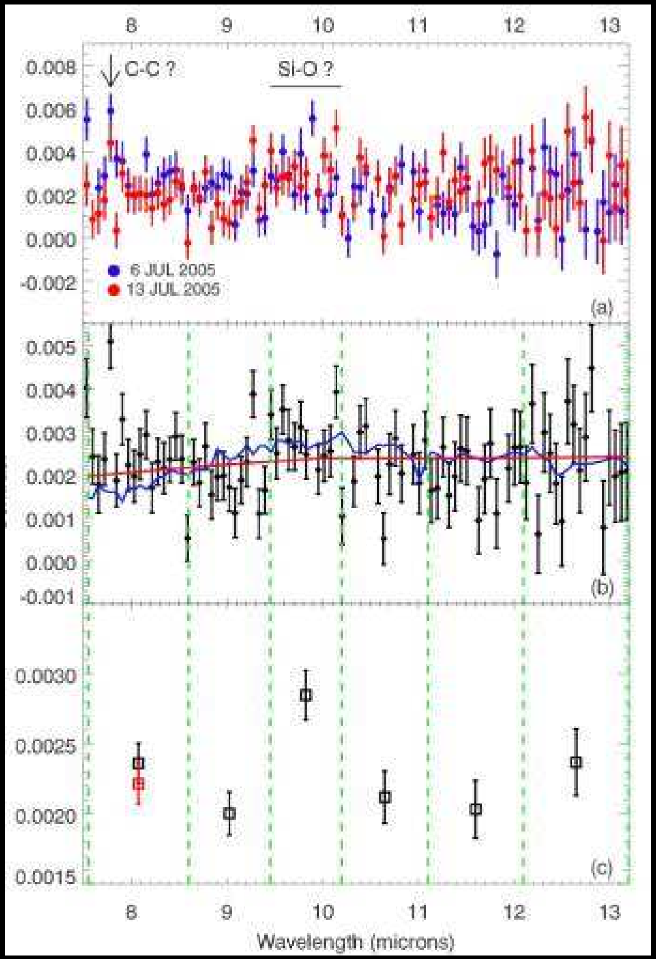
HST characterizes transiting planets; so will JWST: go find more!



Chemistry of Transiting Planets



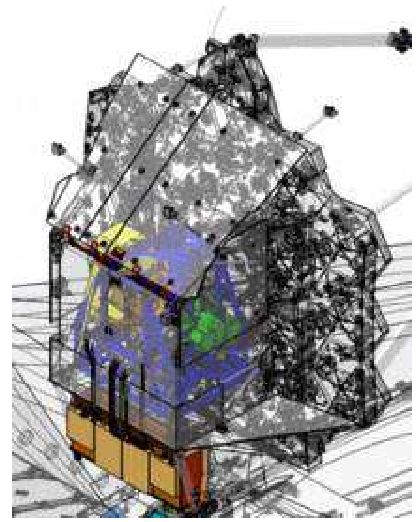
Spitzer Space Telescope sees a Dry, Dusty "Hot Jupiter"



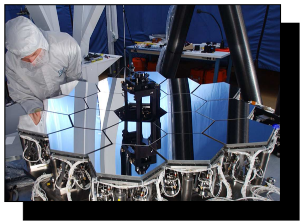
- Fractional difference between (star + planet) and (star HD 209458 b) versus wavelength
- Small bump around 9.7 µm could be due to atmospheric dust
- No indication of H_2O
- Richardson et al. Nature 2007

JWST Technology

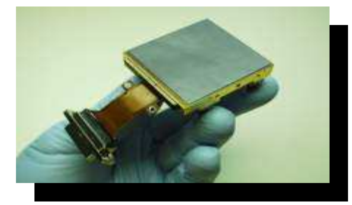
Backplane

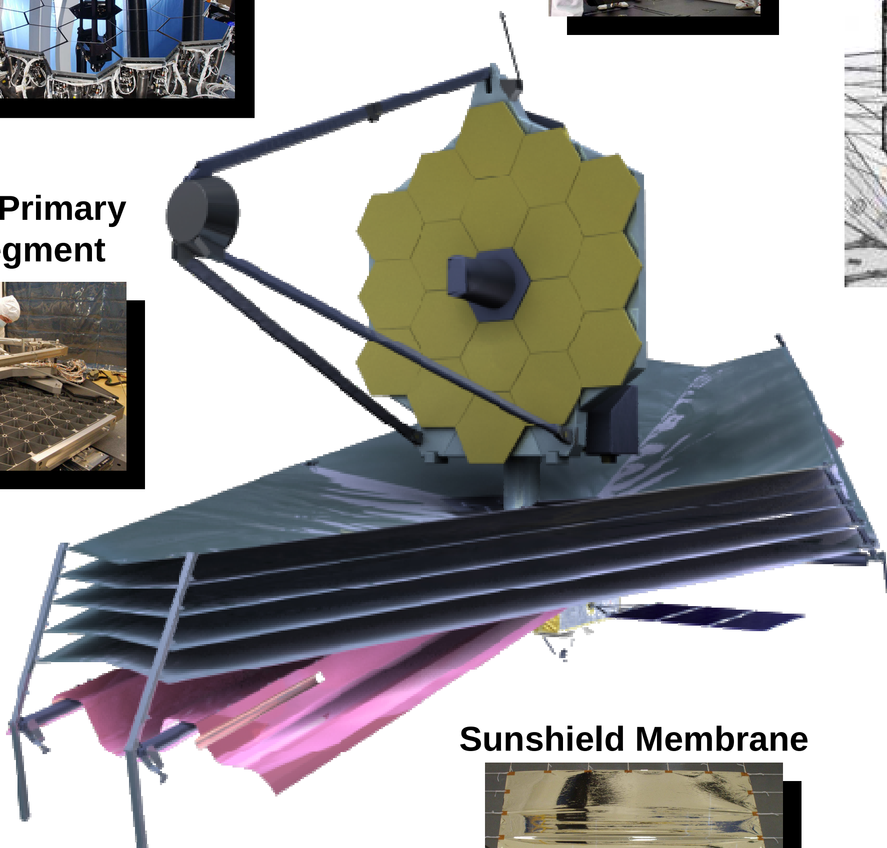


Mirror Phasing Algorithms

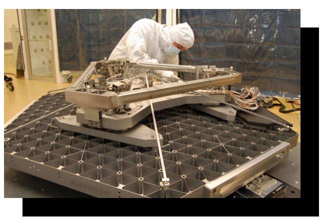


Near-Infrared Detector

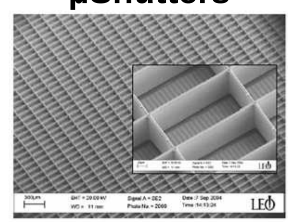




Beryllium Primary Mirror Segment

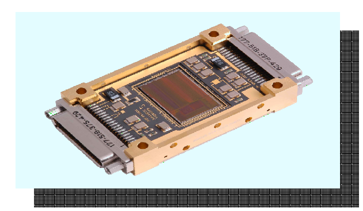


μShutters

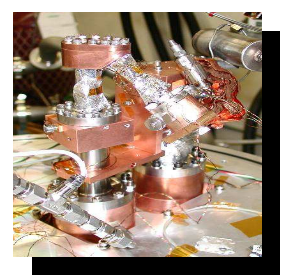


Mid-Infrared Detector

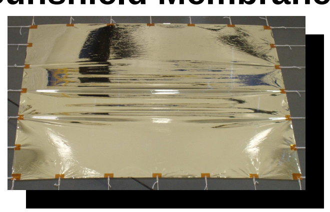
Cryogenic ASICs



Cryocooler



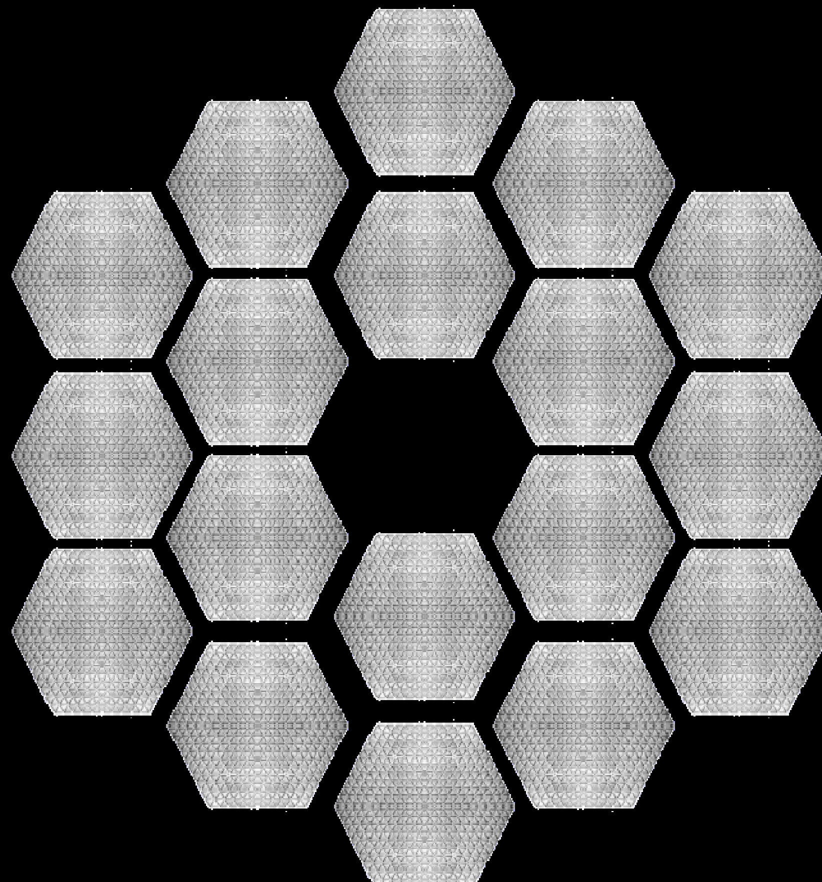
Sunshield Membrane



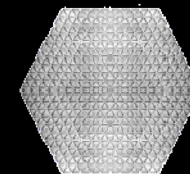
Flight Mirror Blank Fabrication Complete

- Be fabrication
- Brush-Wellman

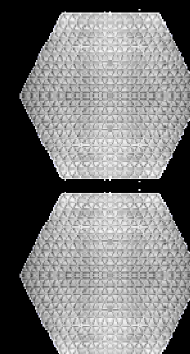
Secondary Mirror



Primary Mirror Segments



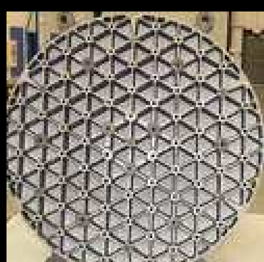
Pathfinder Mirror



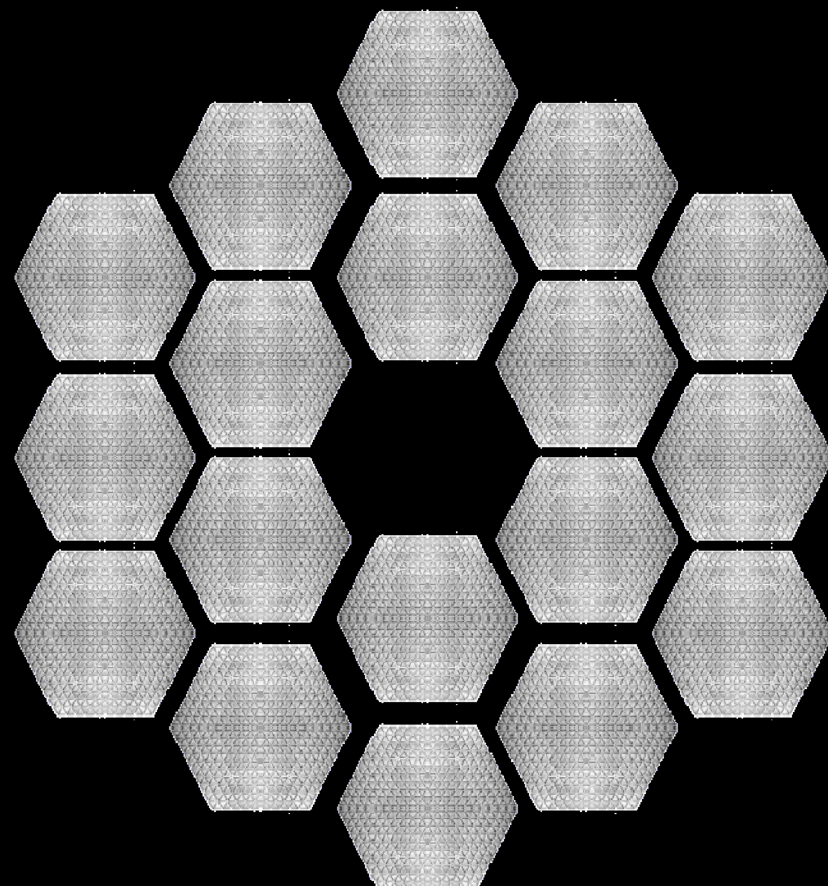
2 Flight Spares

Flight Mirror Lightweighting Complete

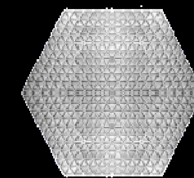
- Lightweighting
- Axsys



Secondary Mirror



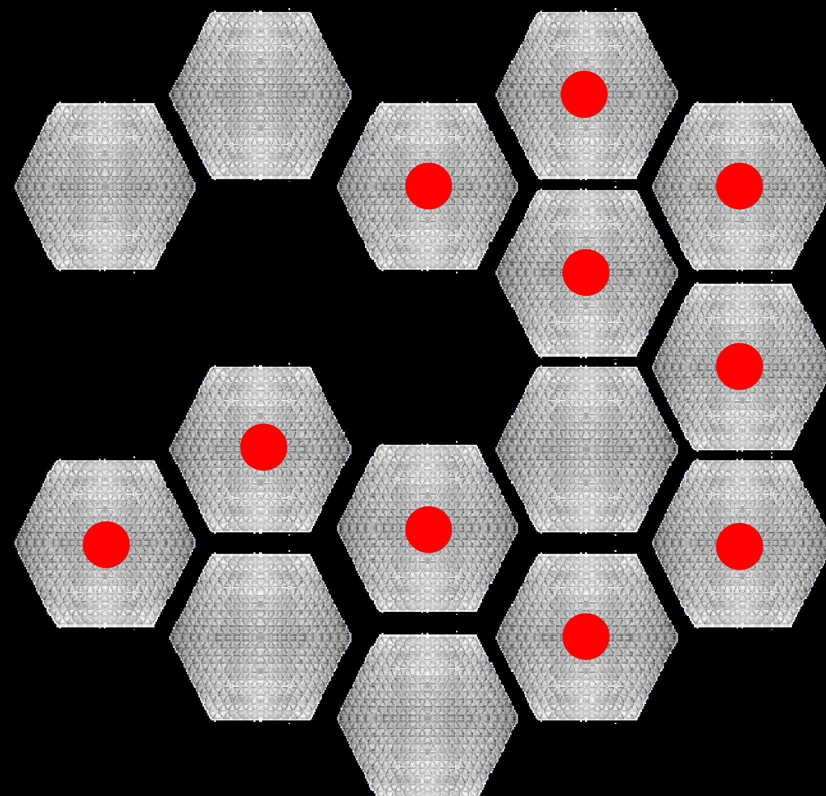
Primary Mirror Segments



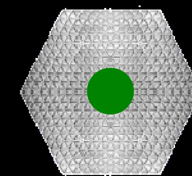
Pathfinder Mirror

Flight Mirror Polishing Started

- Mirror Polishing
- Tinsley



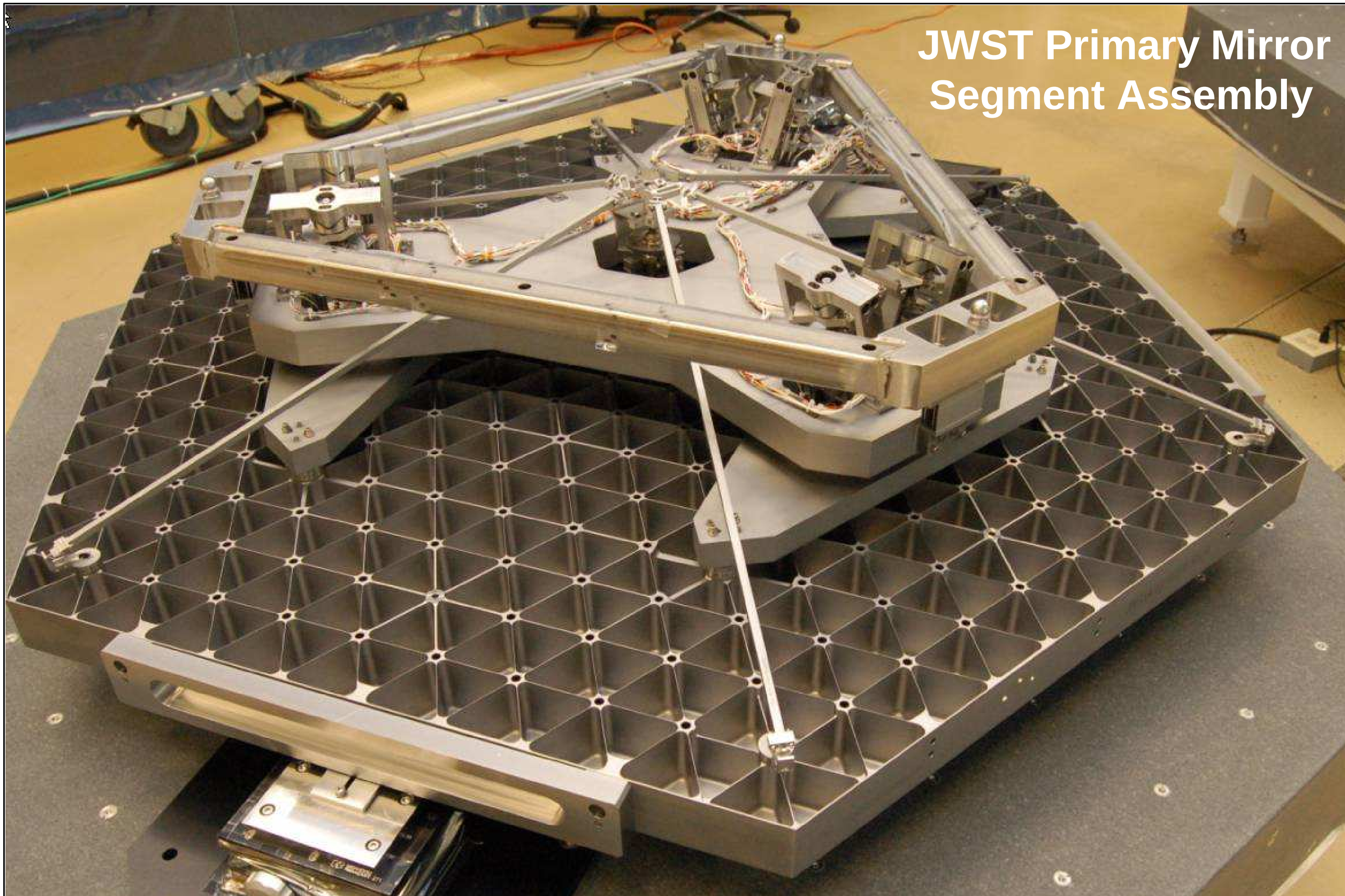
Primary Mirror Segments



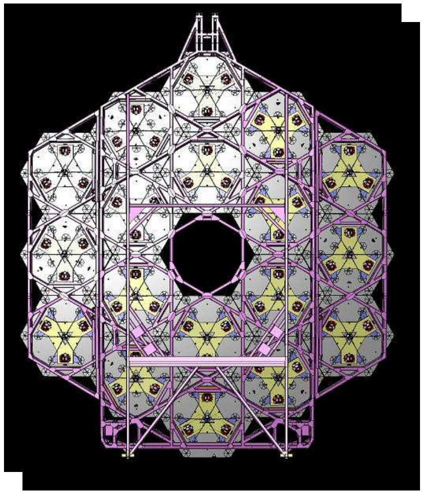
Pathfinder Mirror

- Coarse grind
- fine grind

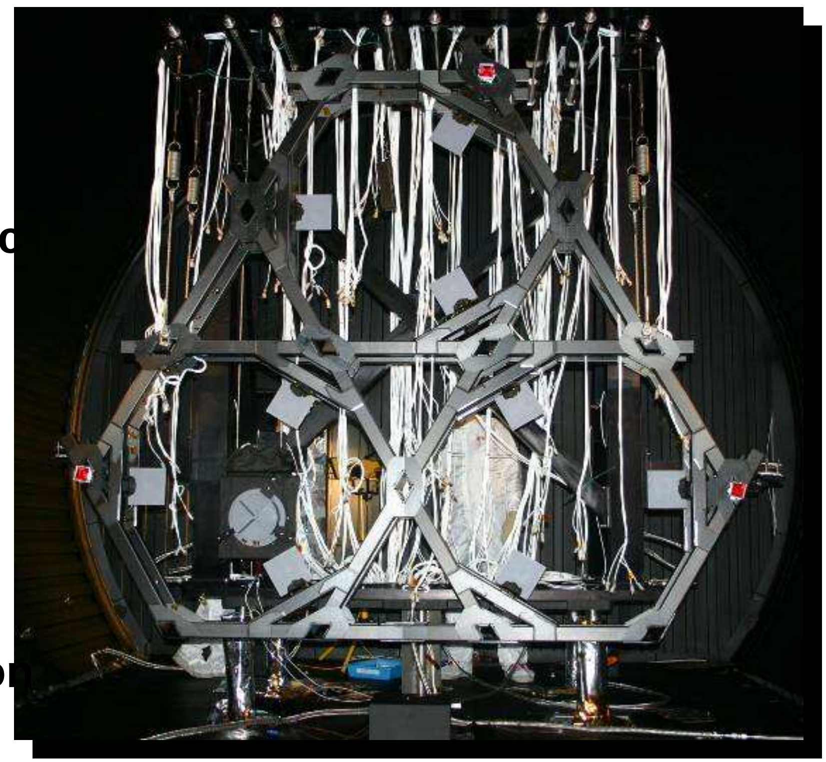
Mirror Figure Passed Launch Loads Test



Backplane Structure Model Validated



- Goal: verify the predictions of the cryogenic performance
of the primary mirror backplane structure
  - Requires precise (nm) measurements of structure at cryogenic temperatures
  - Employed speckle interferometer for precise metrology

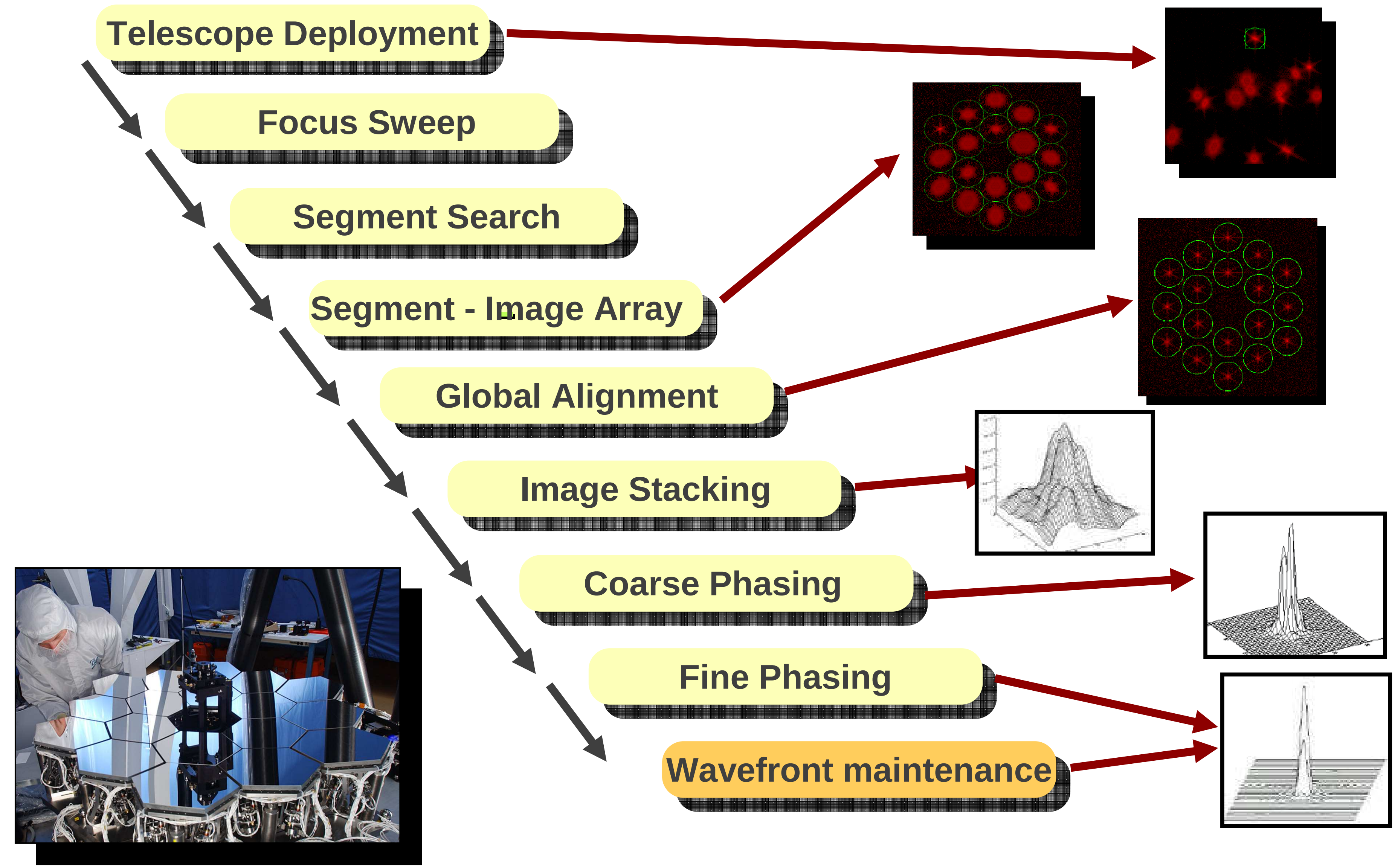


- Criteria for test requires a measurement showing that the distortion rate at cryogenic temperatures < upper 2-σ predicted value

- Requirements have been met
  - Measured 25.2 nm-rms/K
  - Model prediction of 36.8 nm-rms/K (95% upper confidence limit)

- Validates backplane stability predictions on orbit and during integration and test

JWST Mirror Phasing



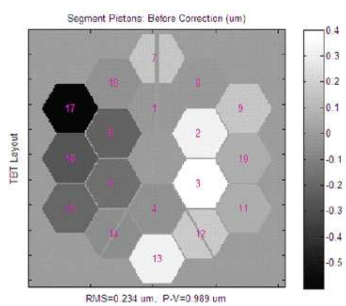
JWST Phasing Algorithms Demonstrated

Coarse Phasing

(Segment to segment piston)

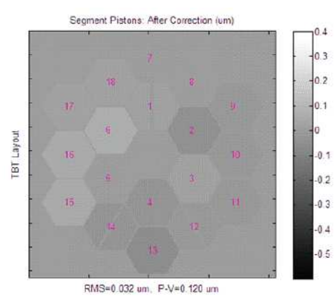
Fine Phasing

Before Coarse Phasing

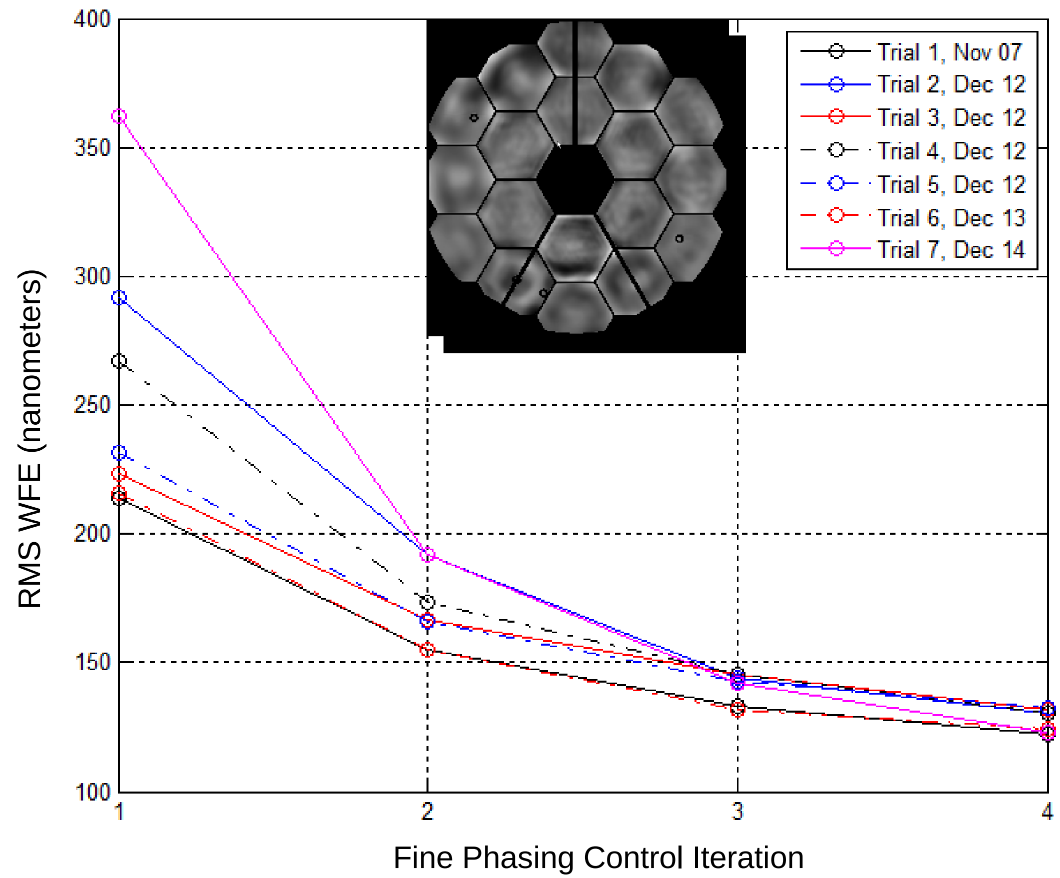


piston:
rms=234nm p/v=989nm

After Coarse Phasing



piston:
rms=32nm p/v=120nm

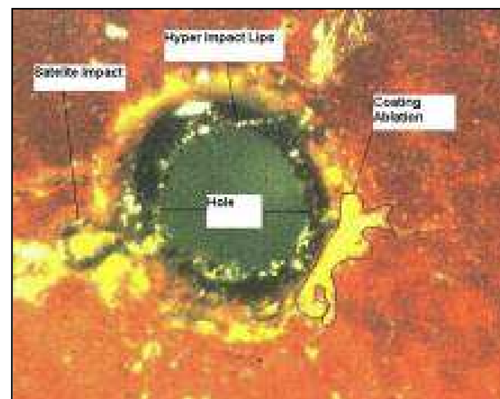


Sunshield Material Validated

- Sunshield material has reached technical maturity
  - Thermal performance
  - Micro-meteoroid impacts
  - Material strength (deployments)

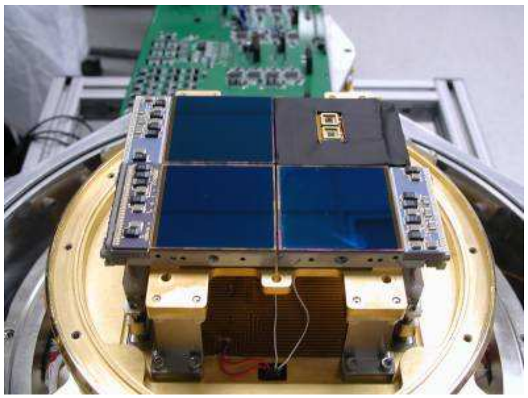
Material strength Test

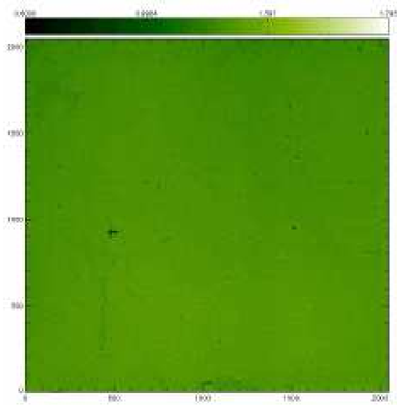
- Sunshield pathfinder: membrane folding test in progress



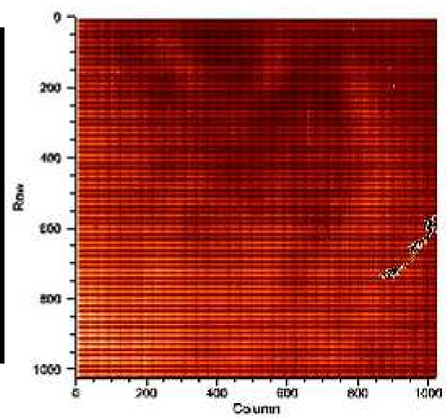
Micro-meteoroid Test

JWST Flight Detectors in Production



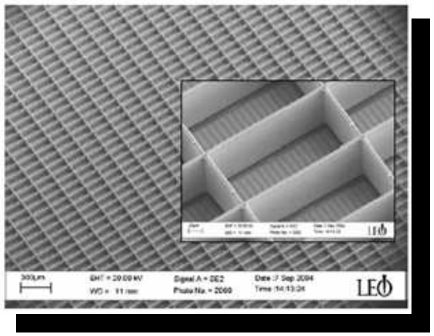


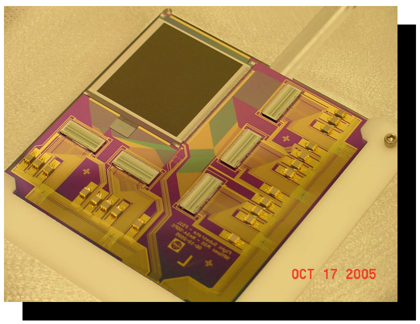
- NIRCam detectors and their packages have reached technical maturity
- Flight detectors are in production and meet specifications

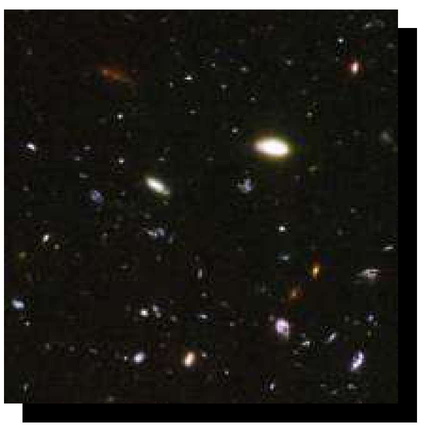


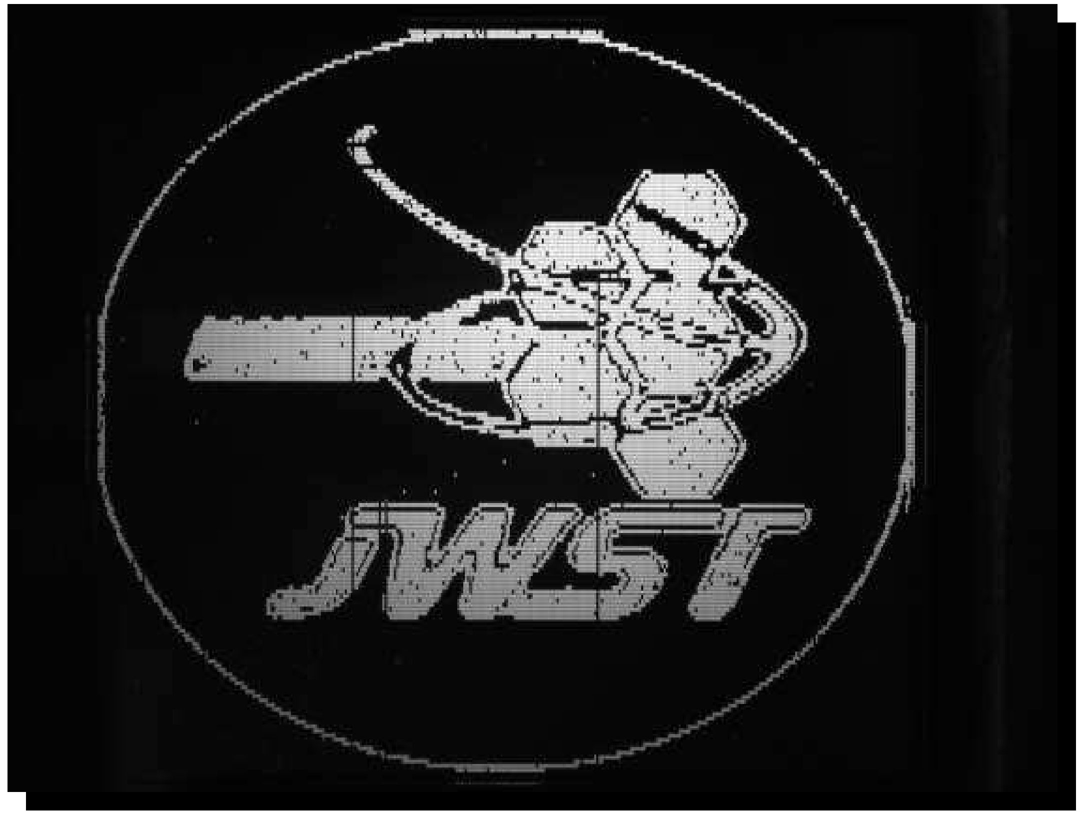
- Mid-Infrared detectors have reached have reached technical maturity
- Flight detectors are in production and currently being hybridized.
- Detectors meet performance specifications

MicroShutter Array Achieved Flight Performance









NIRSpec Microshutter array configured to specific pattern of open and closed shutters .

JWST Lessons from COBE

- **Aim high - the world will change in 20 yrs.**
- **Do only what can't be done any other way**
- **If there's no law of nature against it, maybe it can be done: don't be intimidated**
- **If it's not forbidden, it's required: physics & astronomy**
- **Mather's Principle of Management: If it's not required, it's forbidden (but what *IS* required?)**
- **If it's not tested, it won't work: confidence ≠ success**
- **If it's tested, it won't work the first time either - plan to rehearse, test, rework, retest**
- **Elementary things fail: simple ≠ successful**
- **It's worth all this work: no substitute for major space missions**

The End