



From COBE to the Nobel Prize and on to JWST

John C. Mather

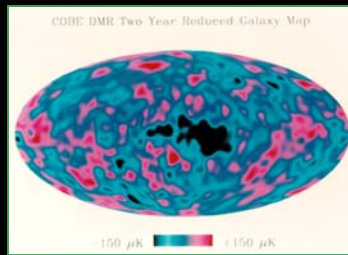
NASA's Goddard Space Flight Center

March 23, 2007



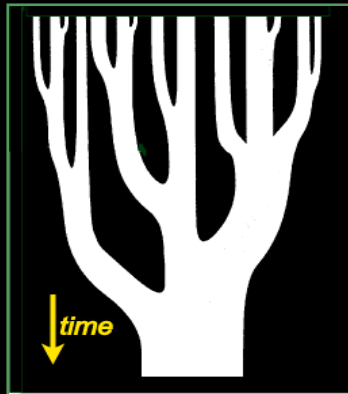
Possible History of the Universe

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 $z = 10^9$
 - $[1+z = \text{size of universe now} / \text{size then}]$
- 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 $z \sim 1$
- 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?

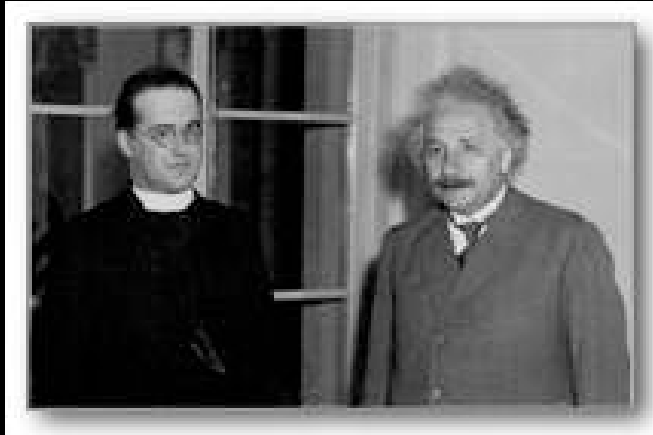


Nobel Prize Press Release

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

Mar. 23, 2007



George
Smoot

Mather UVA Physics Lecture 2007



Sam & Margie Gulkis,
Mike & Sandie Janssen



COBE Science Team



Chuck & Renee
Bennett



Nancy & Al
Boggess



Ed & Tammy Cheng



Eli & Florence
Dwek

Mar. 23, 2007



Tom & Ann
Kelsall

Mather UVA Physics Lecture 2007



Philip &
Georganne Lubin



COBE Science Team



Steve & Sharon
Meyer



Harvey & Sarah
Moseley



Tom & Jeanne
Murdock



Rick & Gwen
Shafer



Bob & Beverly
Silverberg



Ned & Pat
Wright



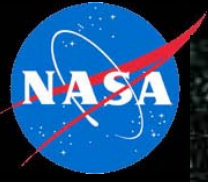
COBE Pre-History

- 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)



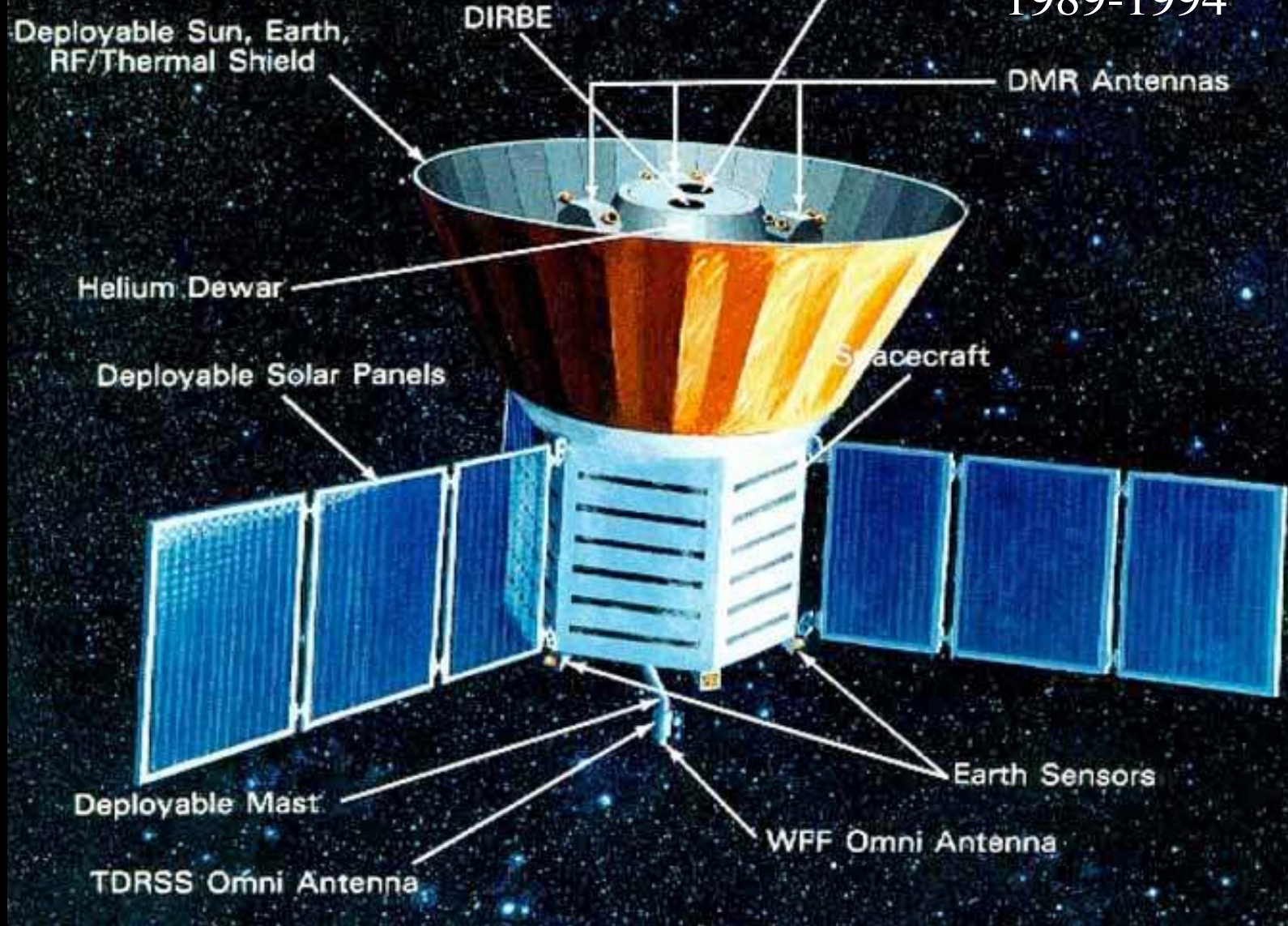
COBE History (2)

- 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



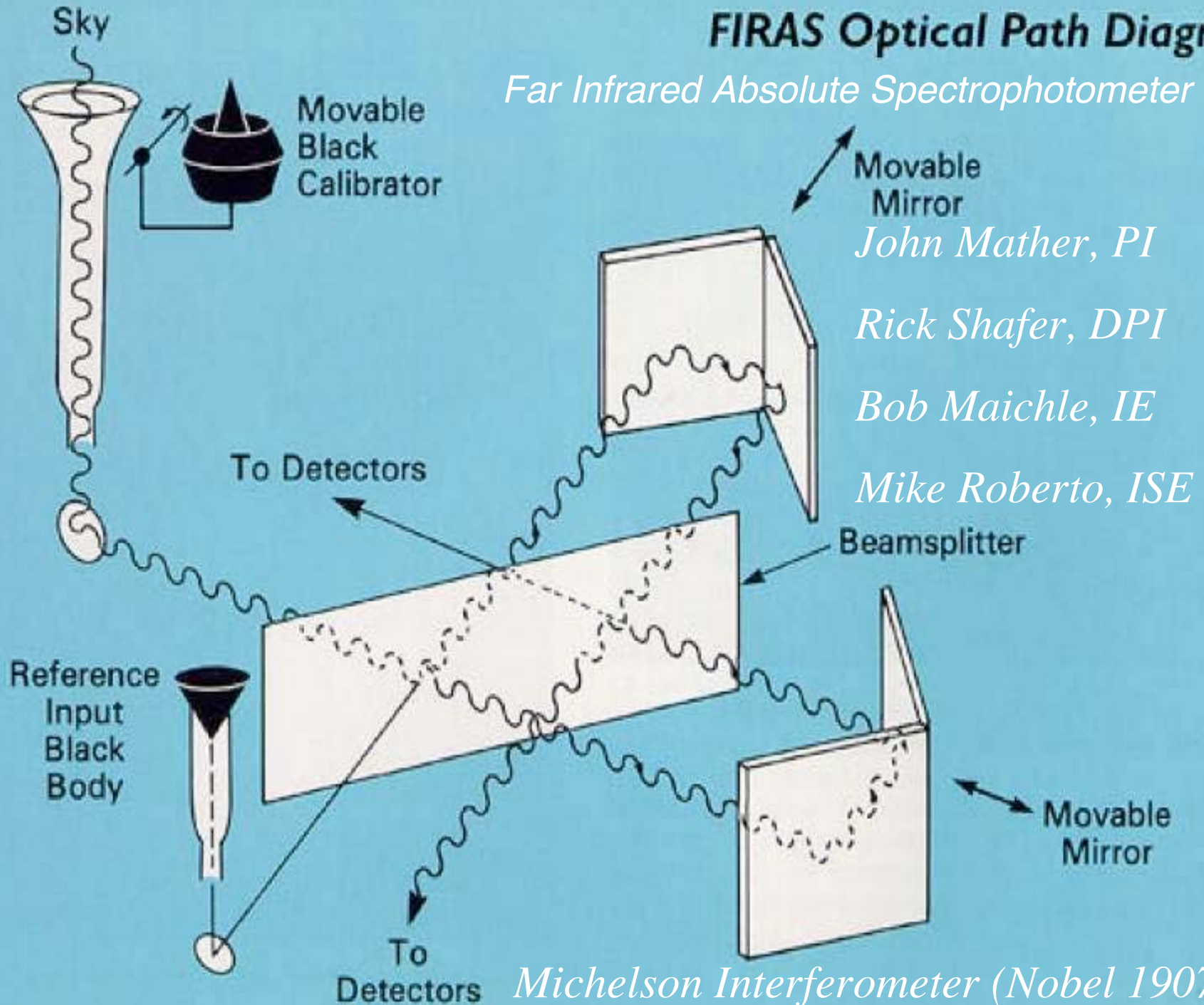
COBE Satellite, 1989-1994

COBE in orbit, 1989-1994

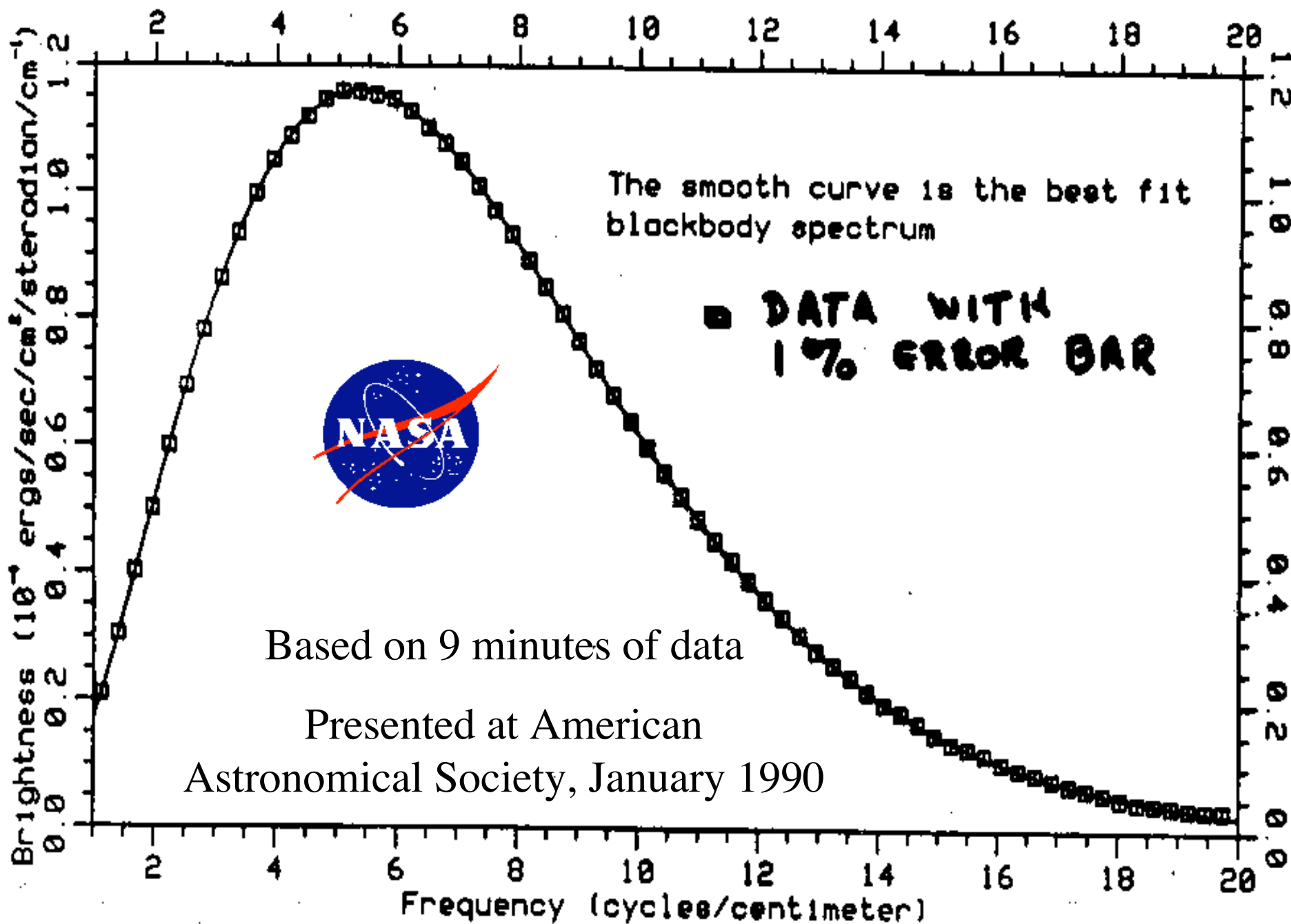


FIRAS Optical Path Diagram

Far Infrared Absolute Spectrophotometer



Cosmic Background Spectrum at the North Galactic Pole





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



Data Processing

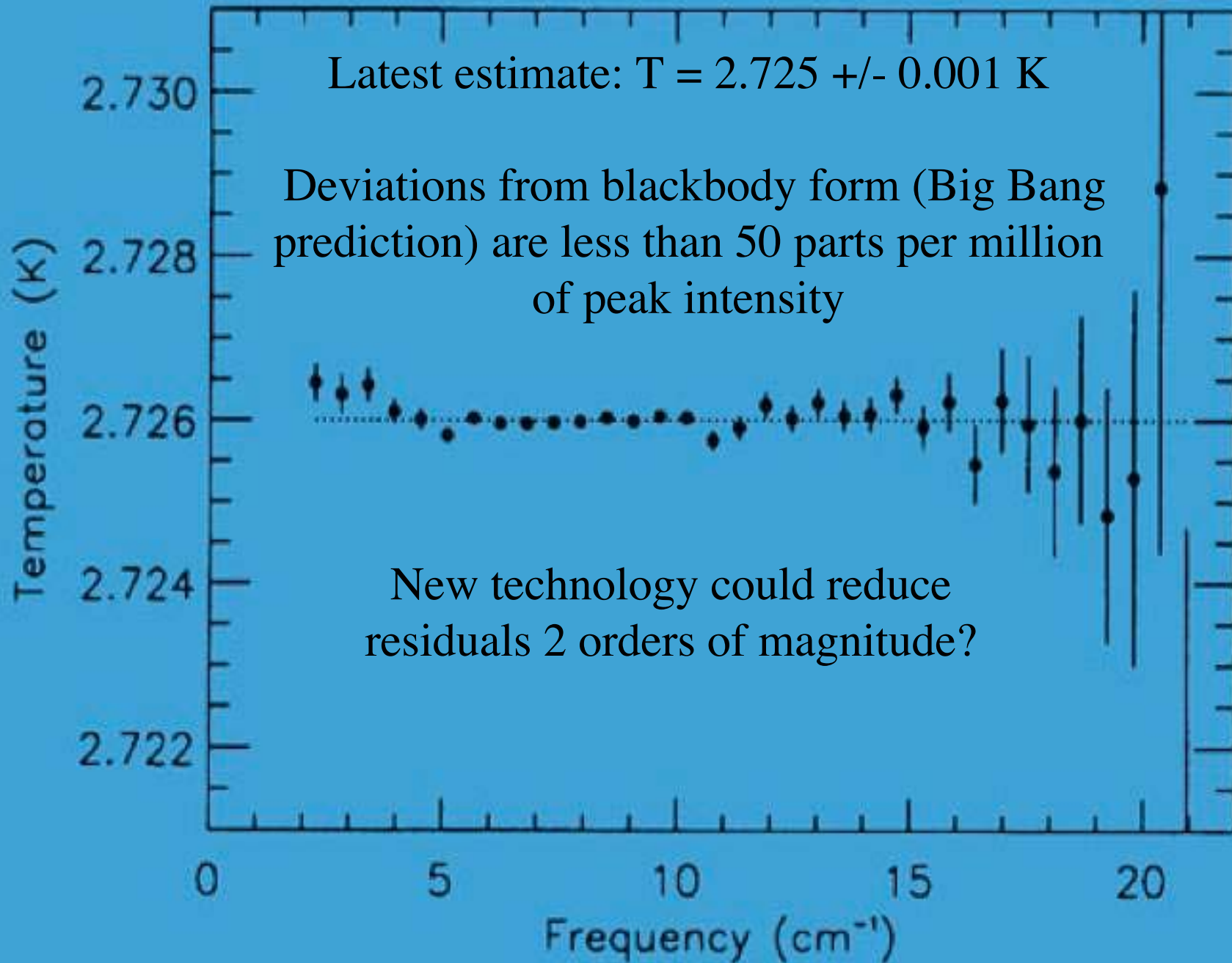
- Initial sorting and calibration - teams led by Richard Isaacman & Shirley Read
- Remove cosmic ray impulses
- Simultaneous least squares fit to all the sky and calibration data (team led by Dale Fixsen)
- Make sky maps
- Fit models of interstellar dust emission, interstellar atomic and molecular line 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 $205.3 \mu\text{m}$
- 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)

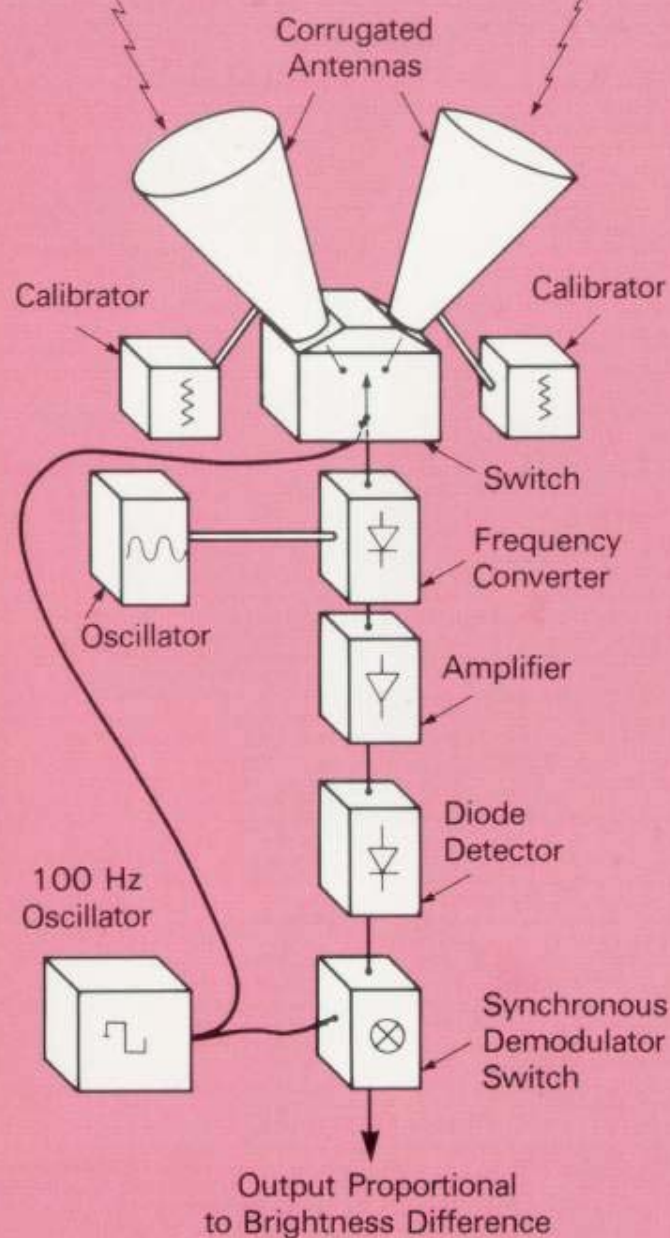
FIRAS Residual Spectrum





DMR Signal Flow Diagram

Differential Microwave Radiometers



George Smoot

Chuck Bennett

Bernie Klein

Steve Leete



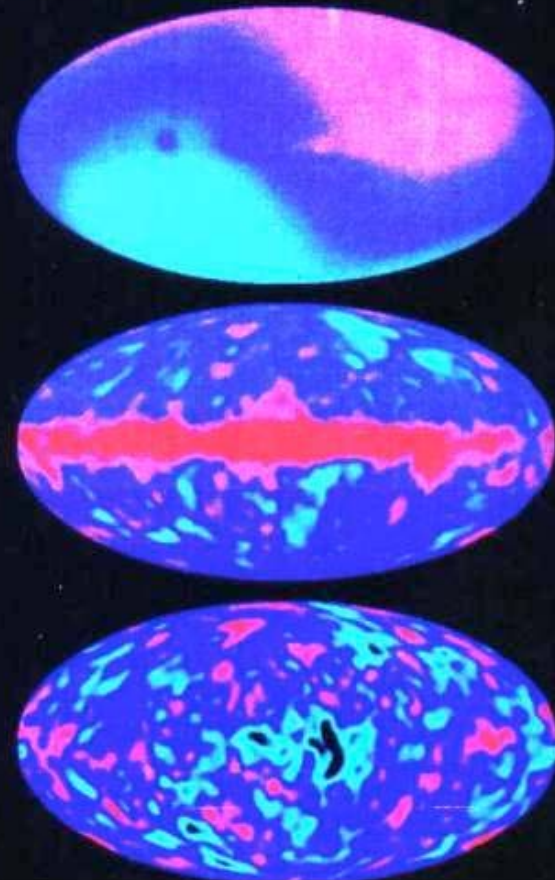
Sky map from DMR,
 $2.7 \text{ K} \pm 0.003 \text{ K}$

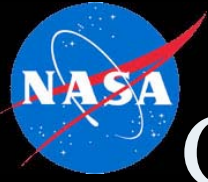
Doppler Effect of Earth's
motion removed ($v/c =$
 0.001)

Cosmic temperature/density
variations at 389,000 years,
 $\pm 0.00003 \text{ K}$

PHYSICS TODAY

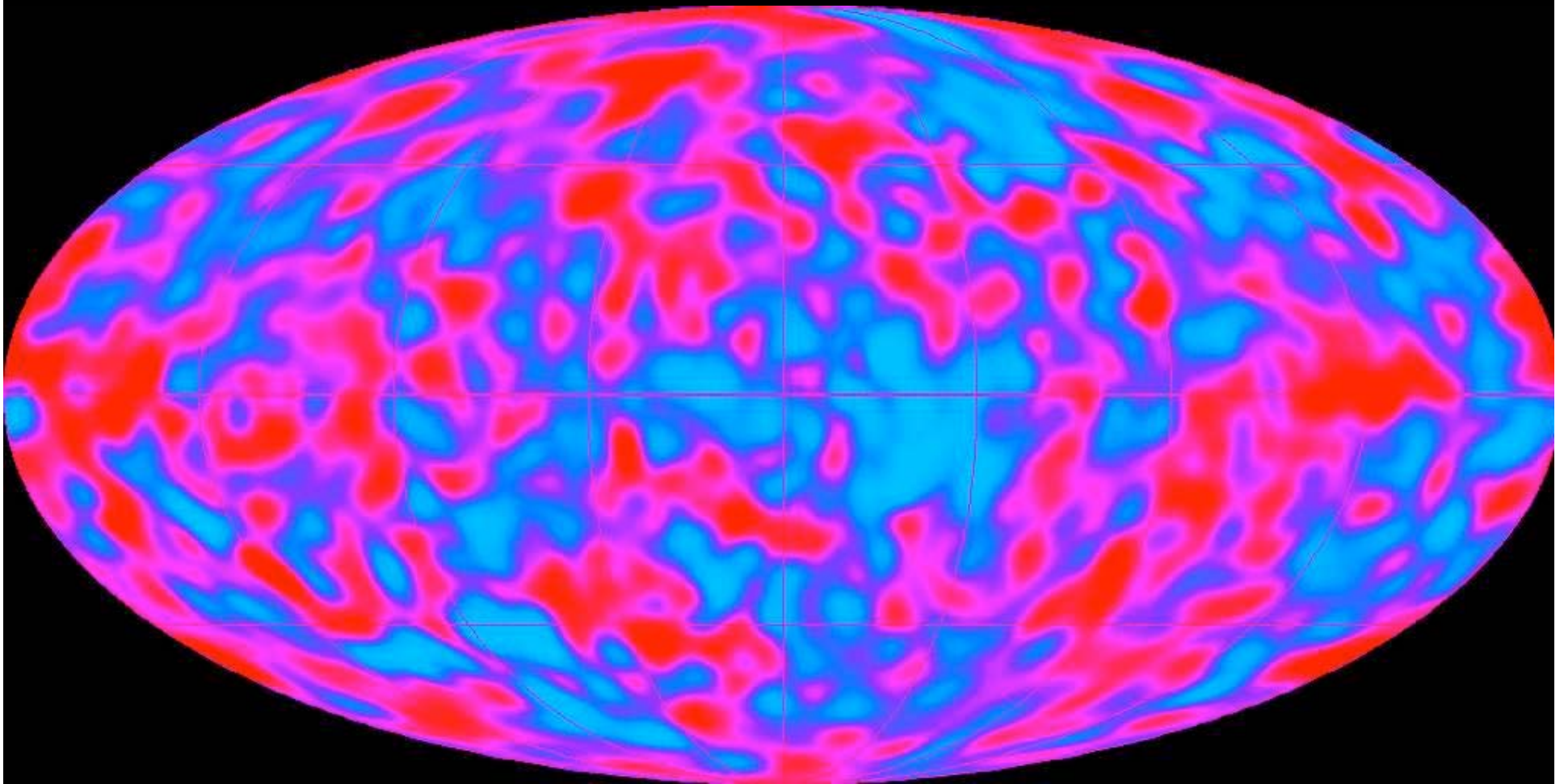
JUNE 1992

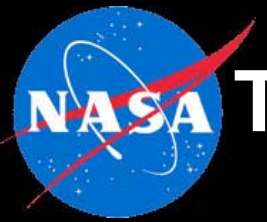




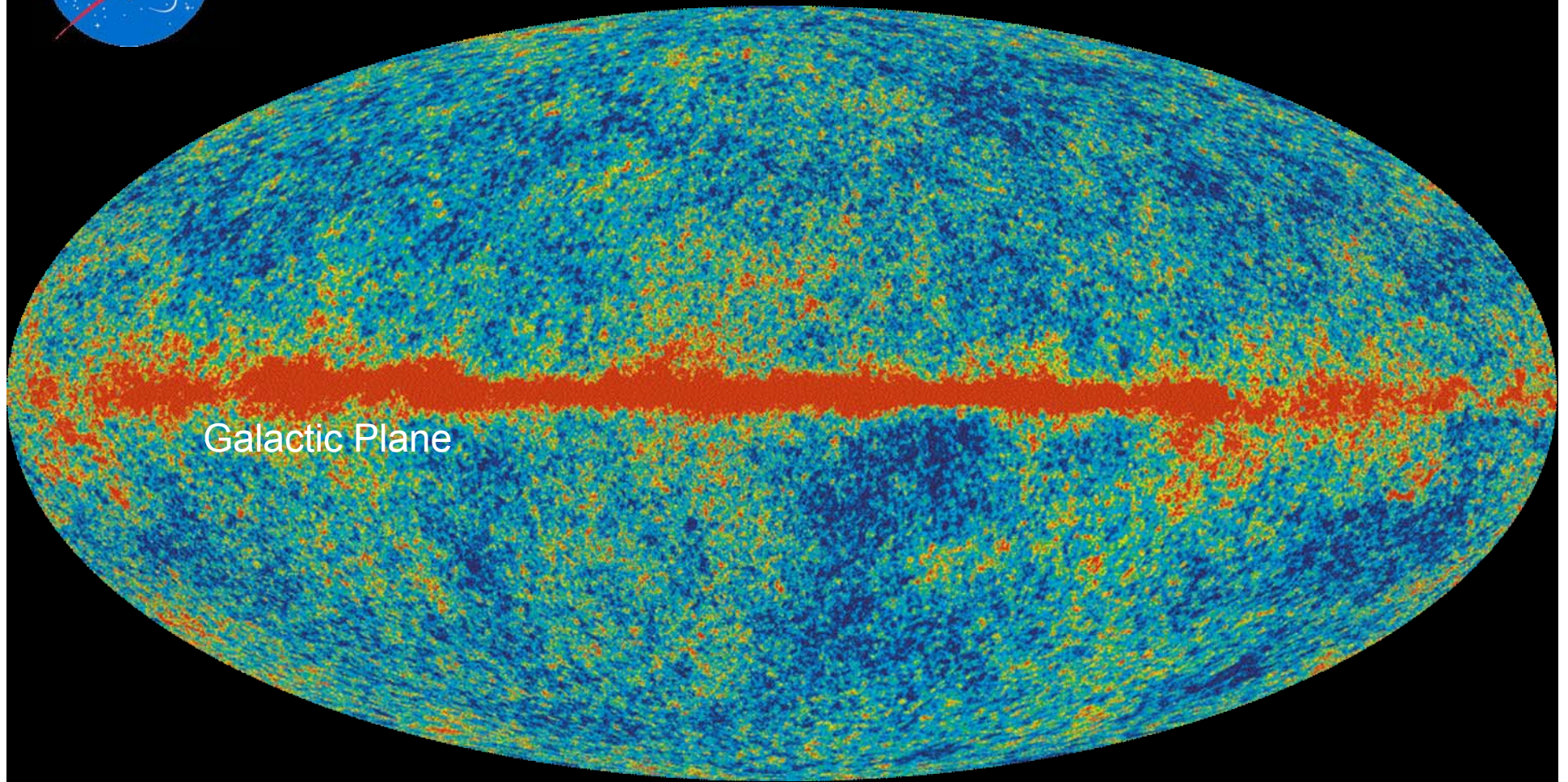
COBE Map of CMB Fluctuations

2.725 K +/- $\sim 30 \mu\text{K}$ rms, 7° beam





The Universe at age 389,000 years



Galactic Plane



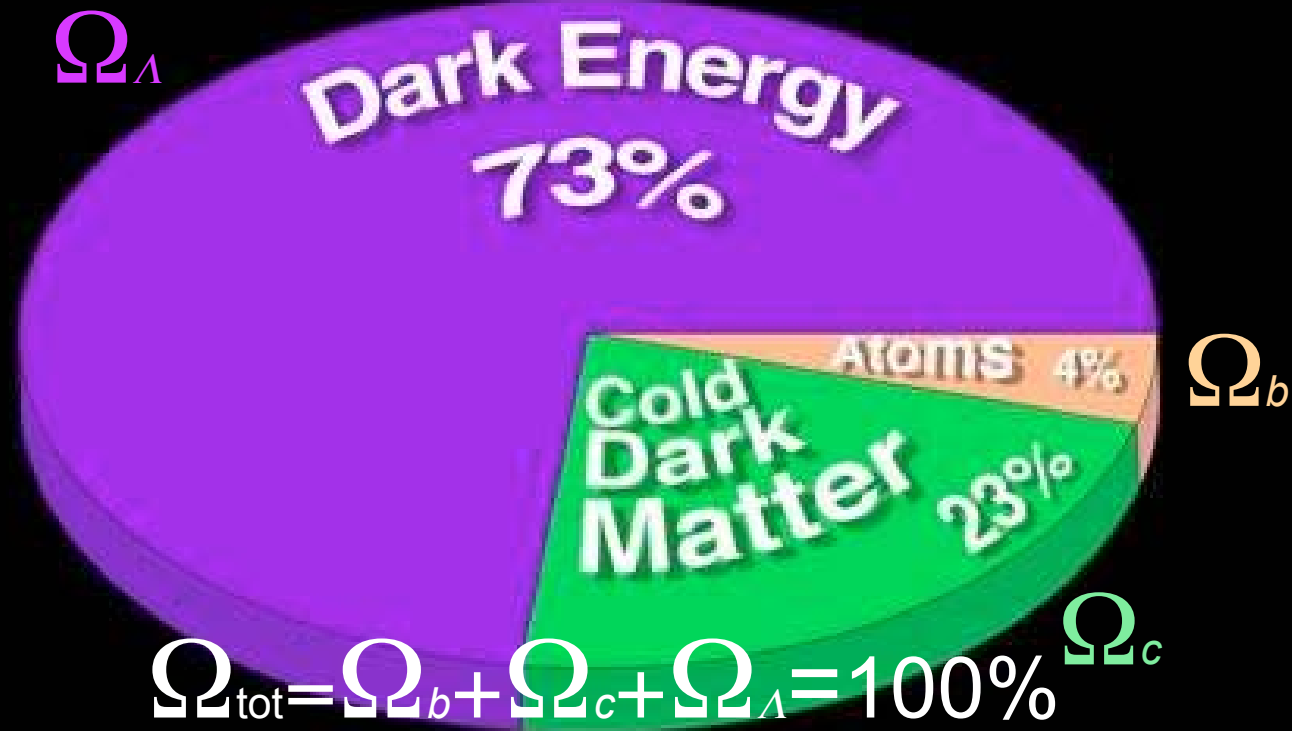
-200

+200

Temperature (μK) relative to average of 2.725 K



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

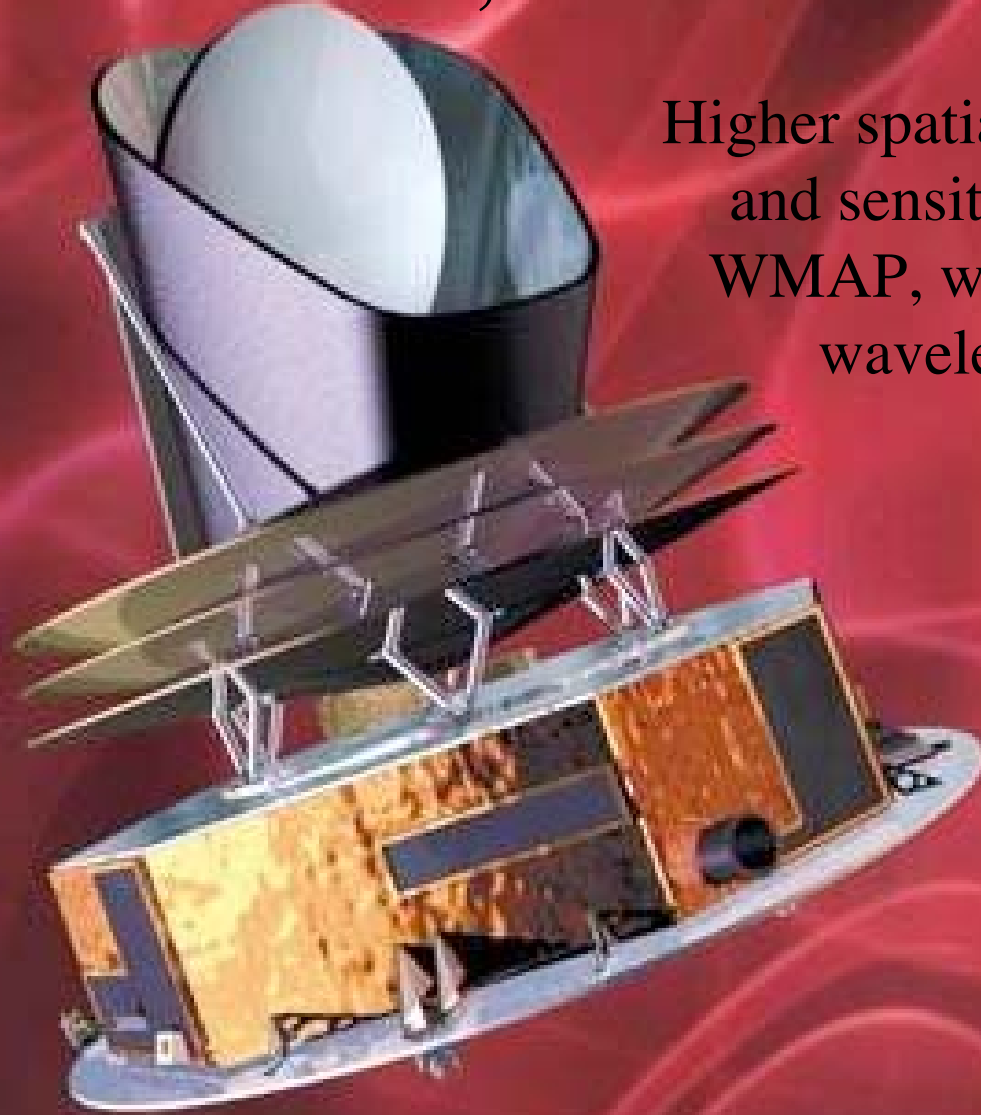


$$\Omega_{\text{tot}} = \Omega_b + \Omega_c + \Omega_\Lambda = 100\%$$

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

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

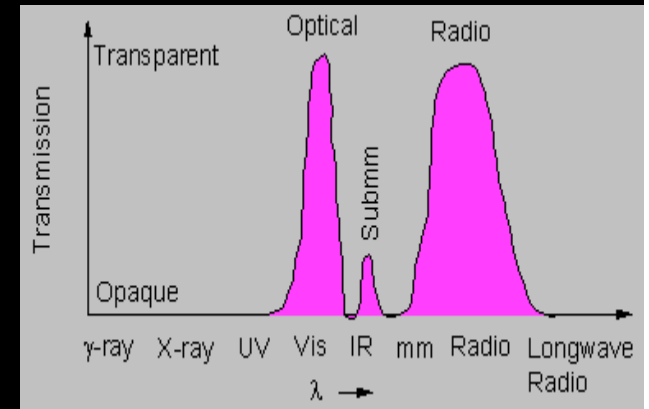
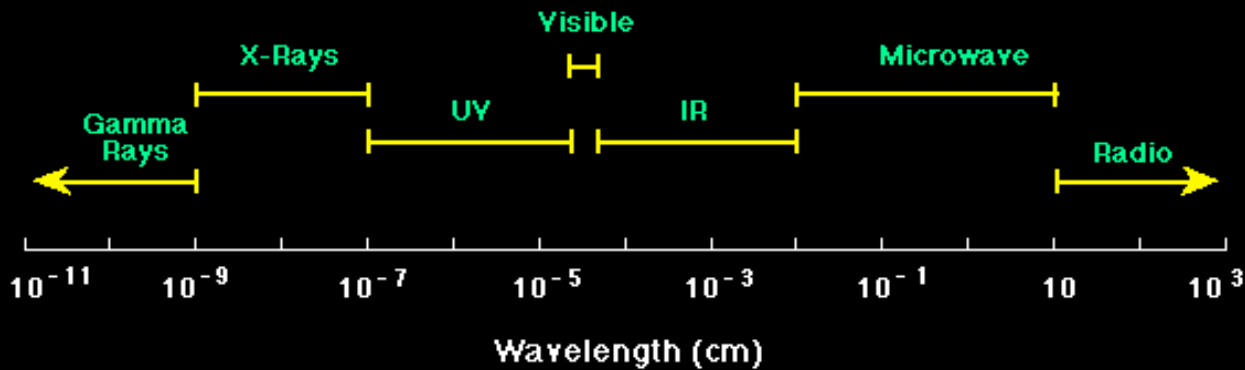
Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths



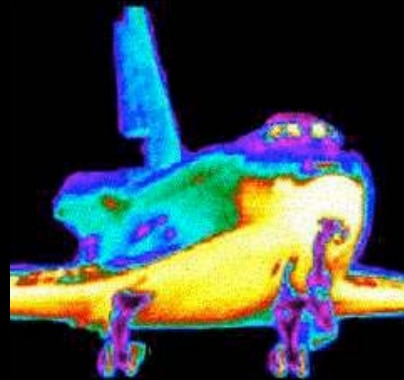


Light comes in more colors than our eyes can see

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)

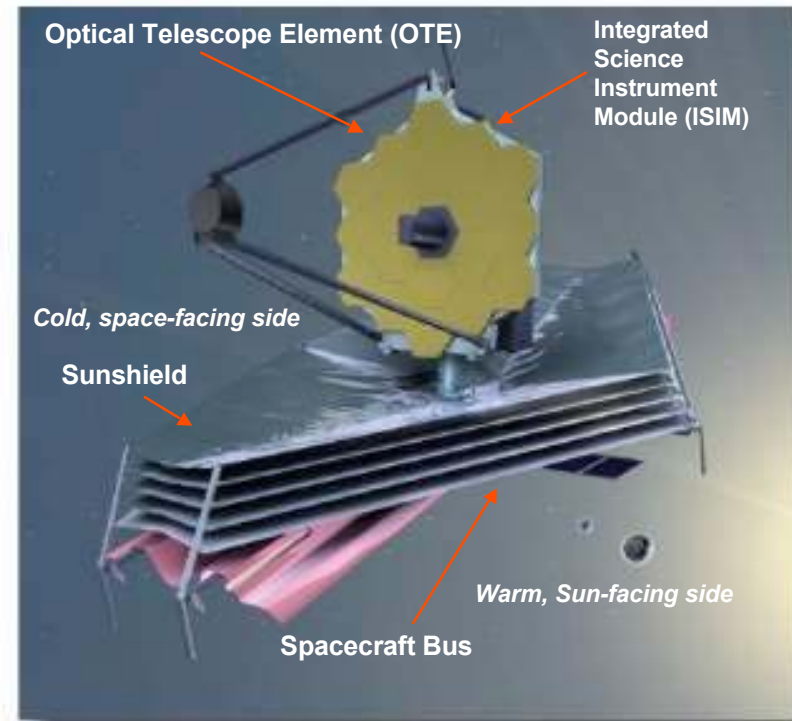
Organization

- 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



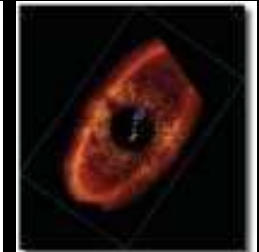
End of the dark ages: First light and reionization



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



Mar. 23,

29



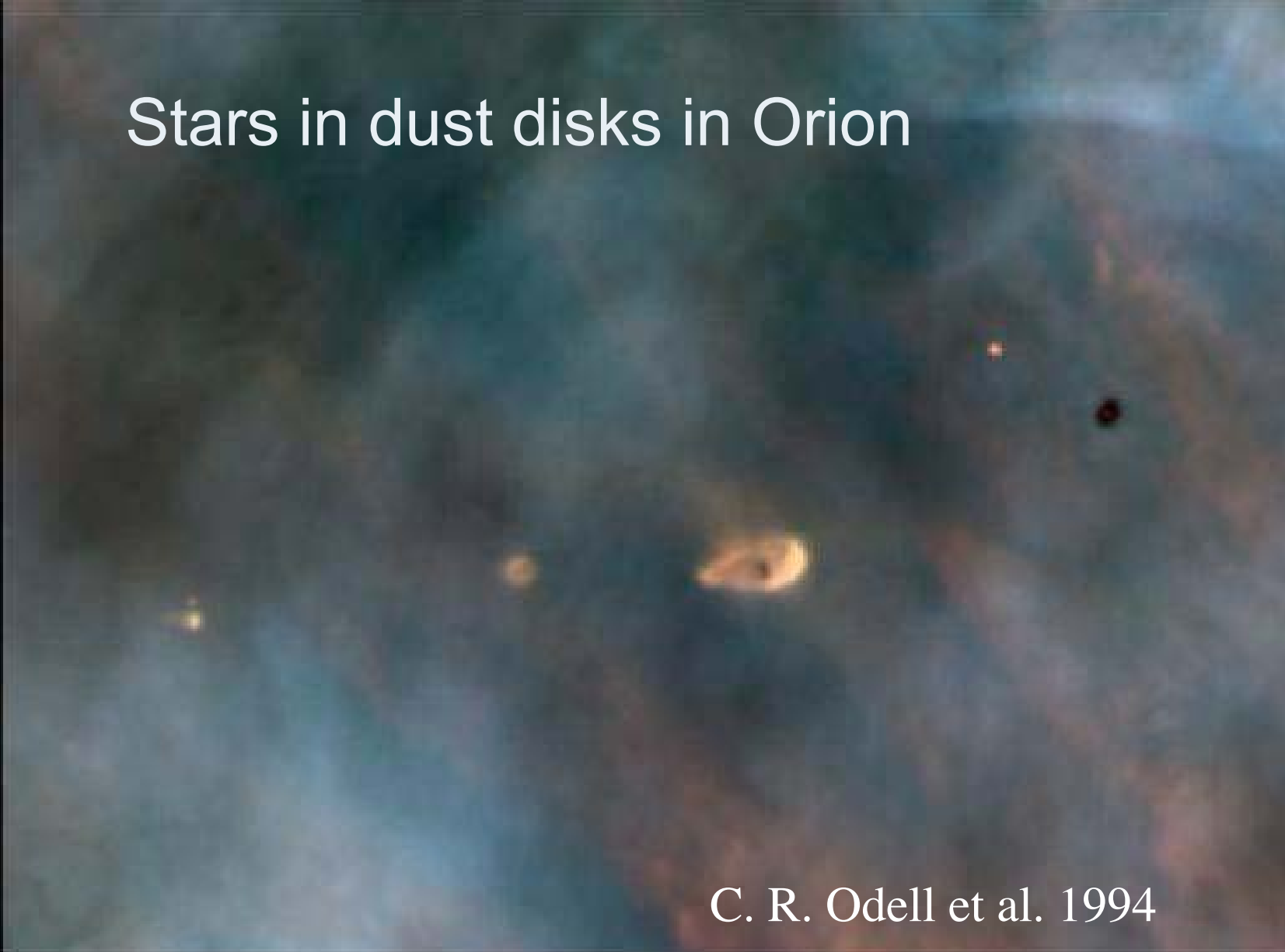
The Eagle Nebula as seen in the infrared



M. J. McCaughrean
and M. Andersen, 1994



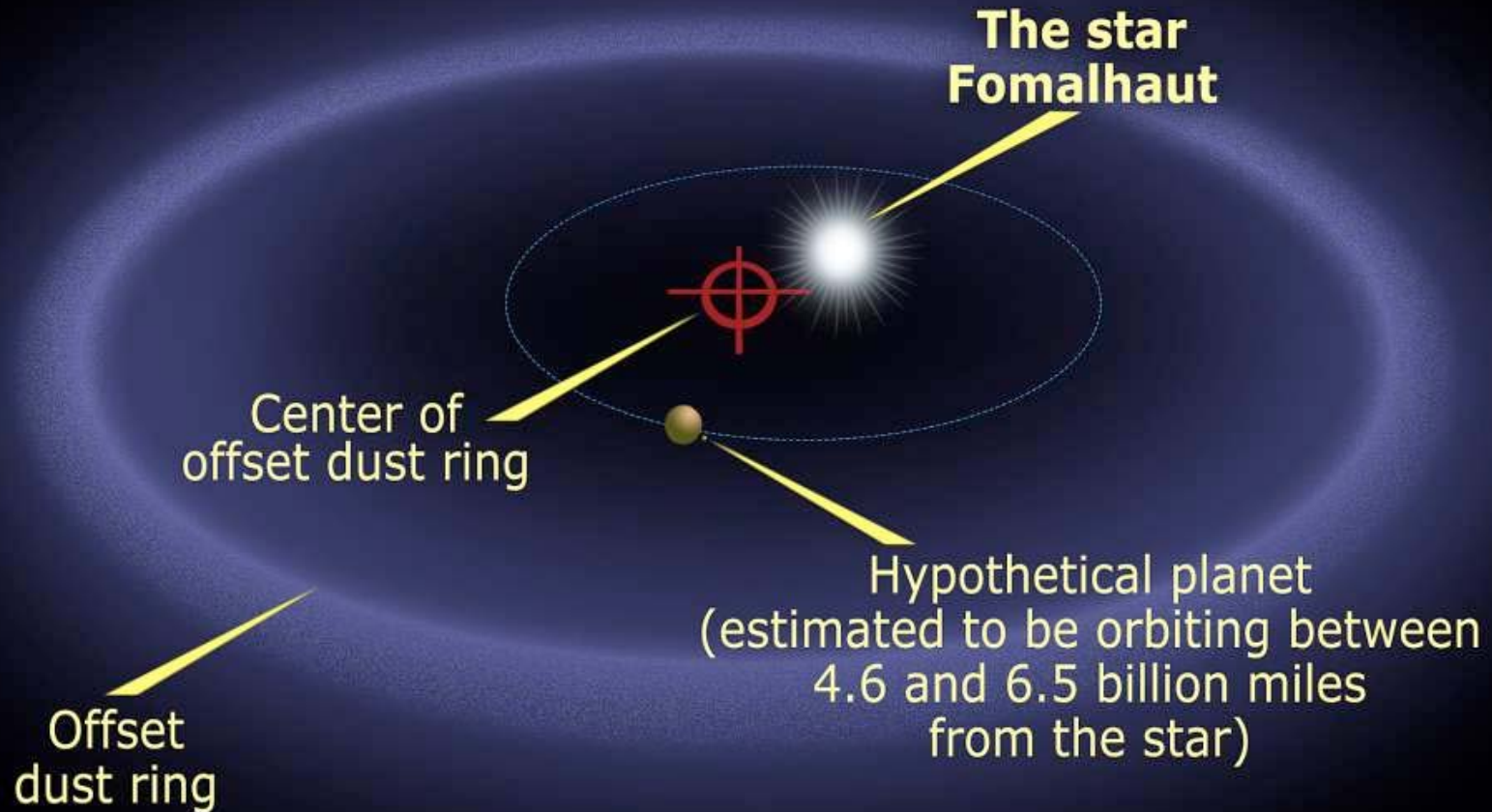
Stars in dust disks in Orion



C. R. Odell et al. 1994



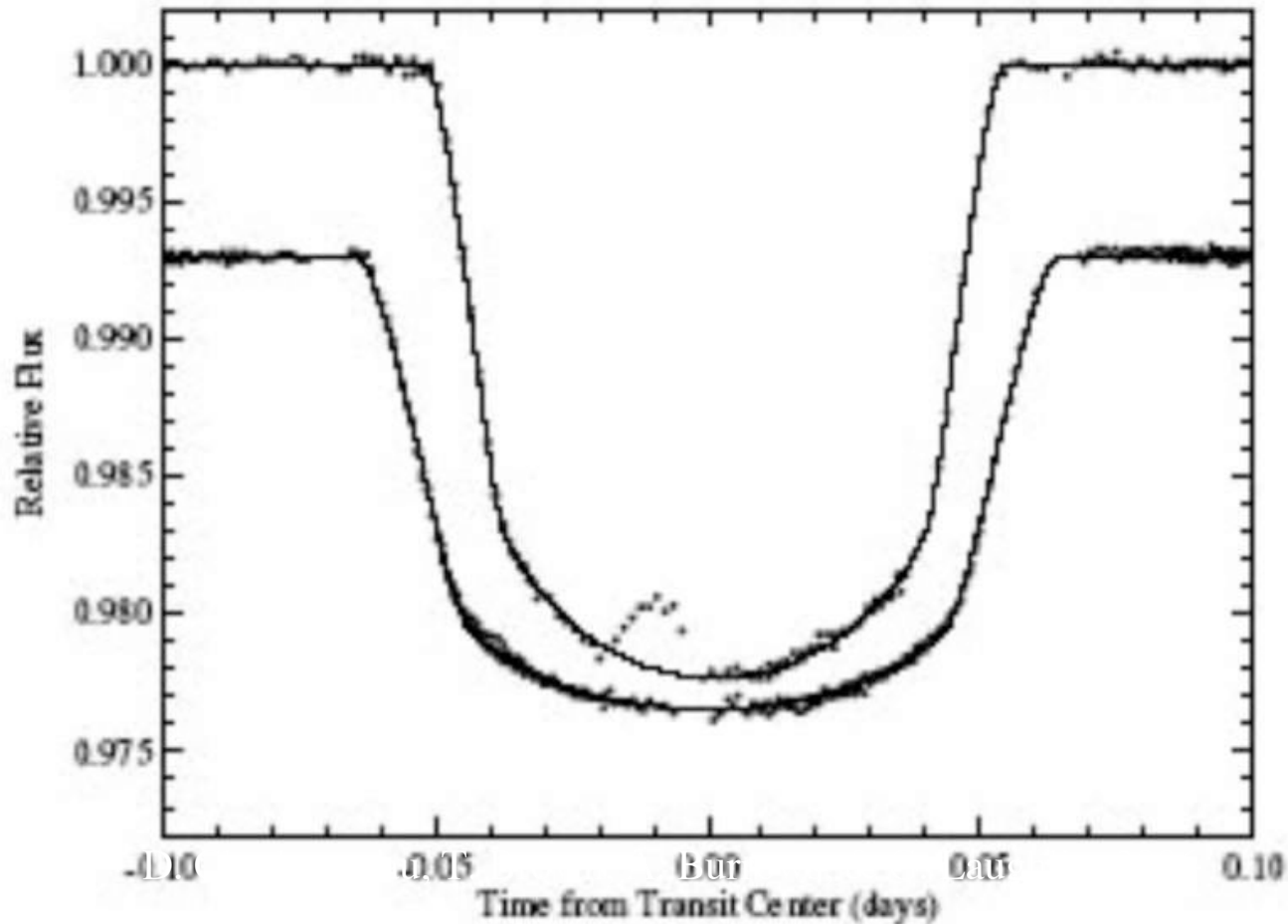
Planetary systems and the origins of life



Kalas, Graham and Clampin 2005

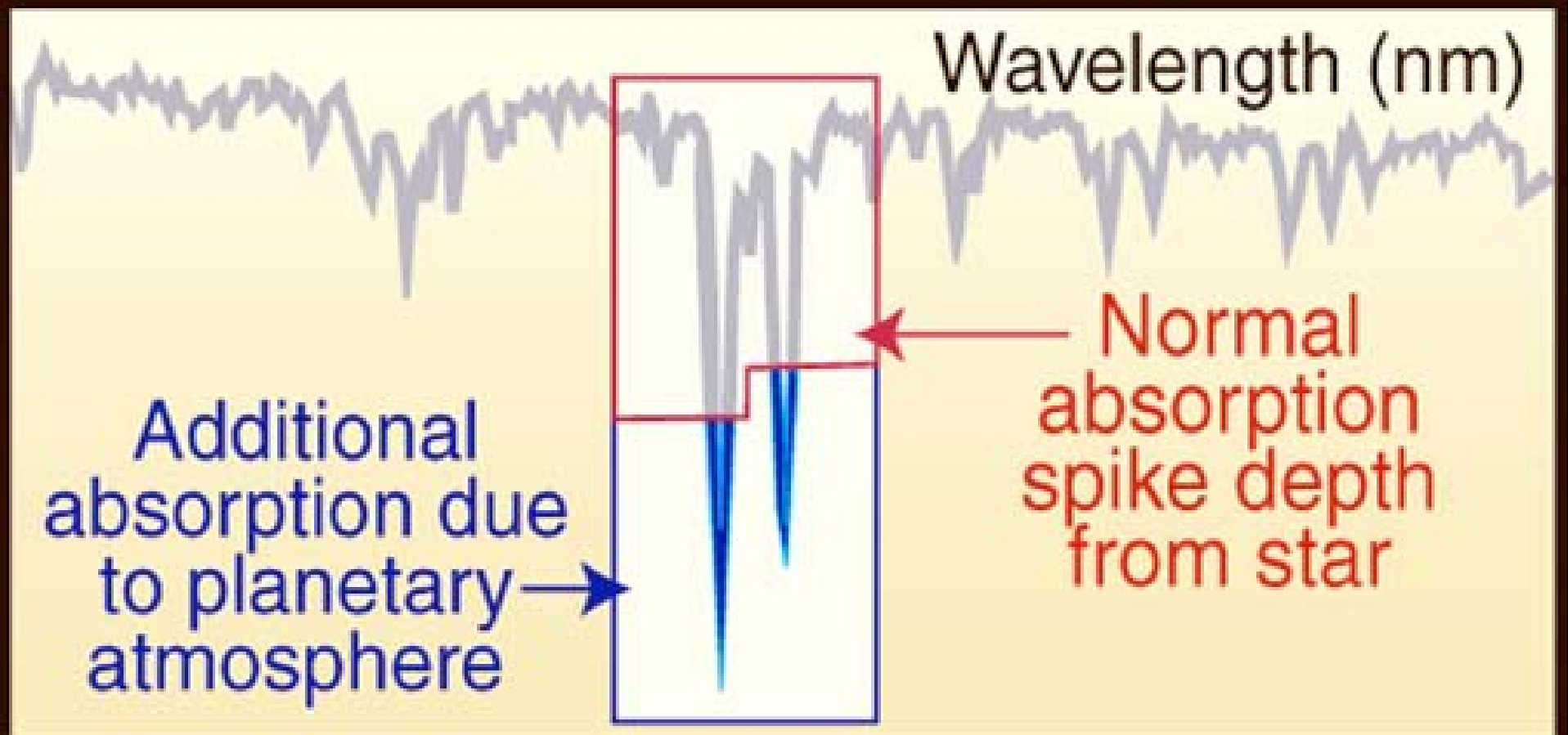


HST characterizes transiting planets; so will
JWST: go find more!



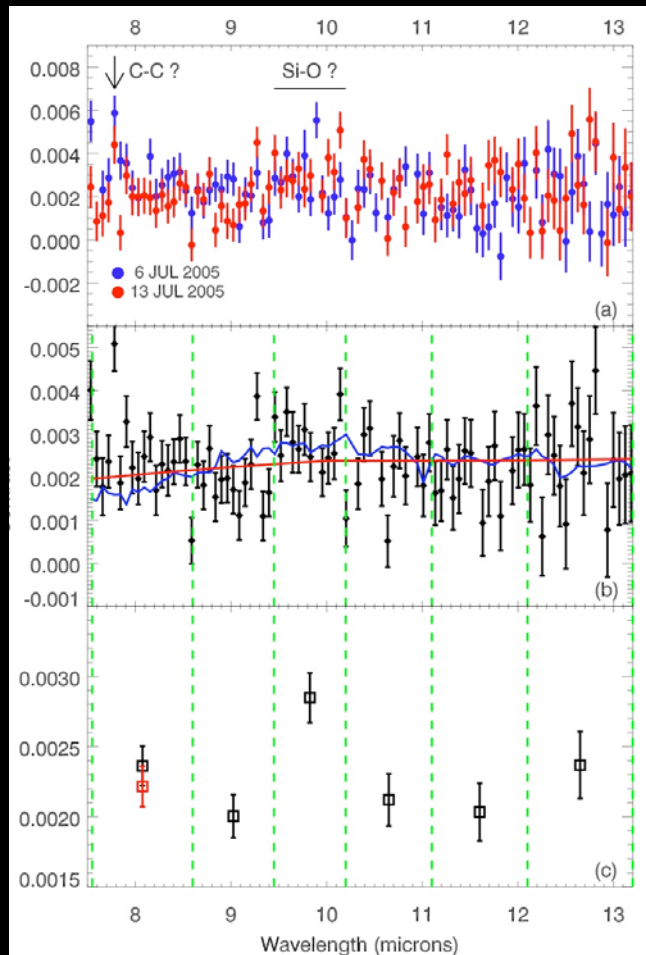


Chemistry of Transiting Planets





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



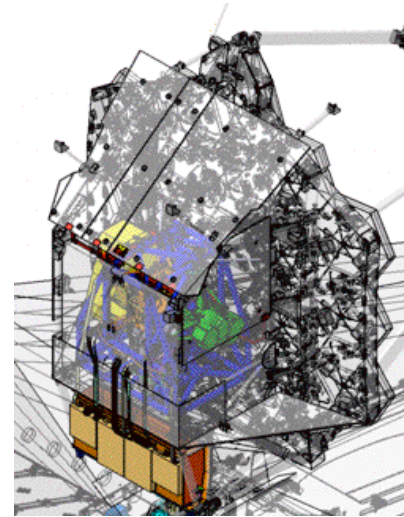
JWST Technology



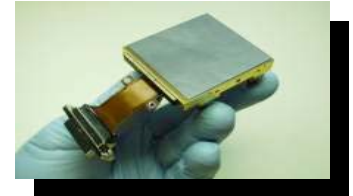
Mirror Phasing Algorithms



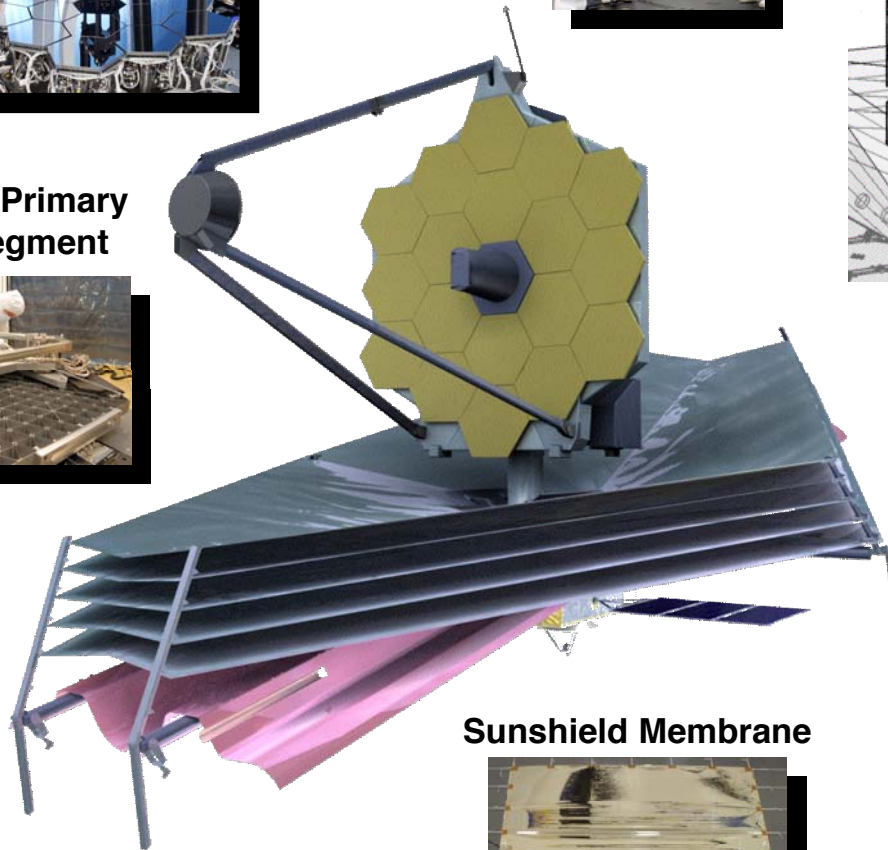
Backplane



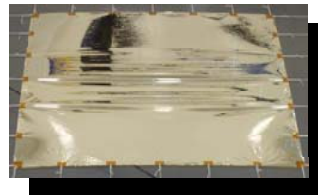
Near-Infrared Detector



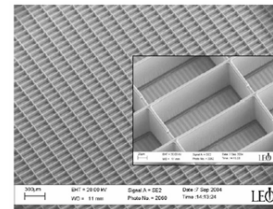
Beryllium Primary Mirror Segment



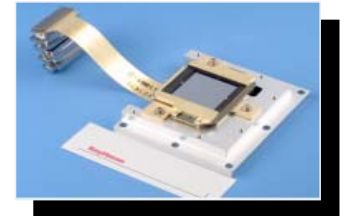
Sunshield Membrane



Shutters



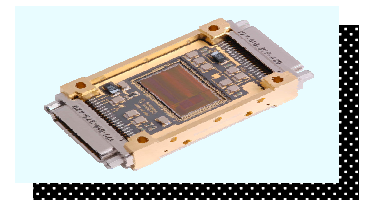
Mid-Infrared Detector



Cryocooler



Cryogenic ASICs





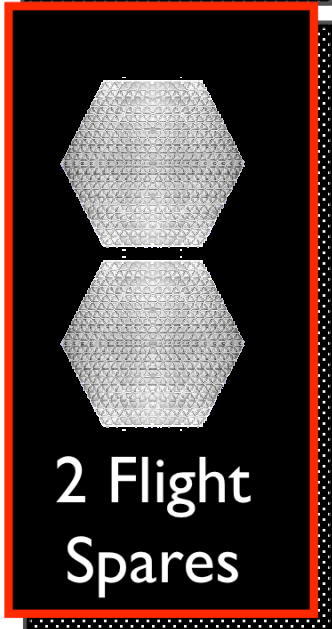
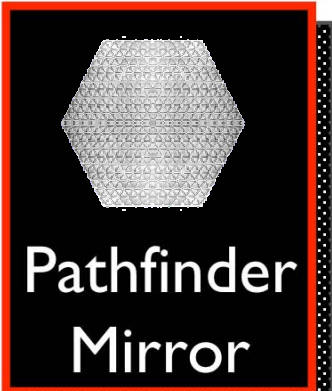
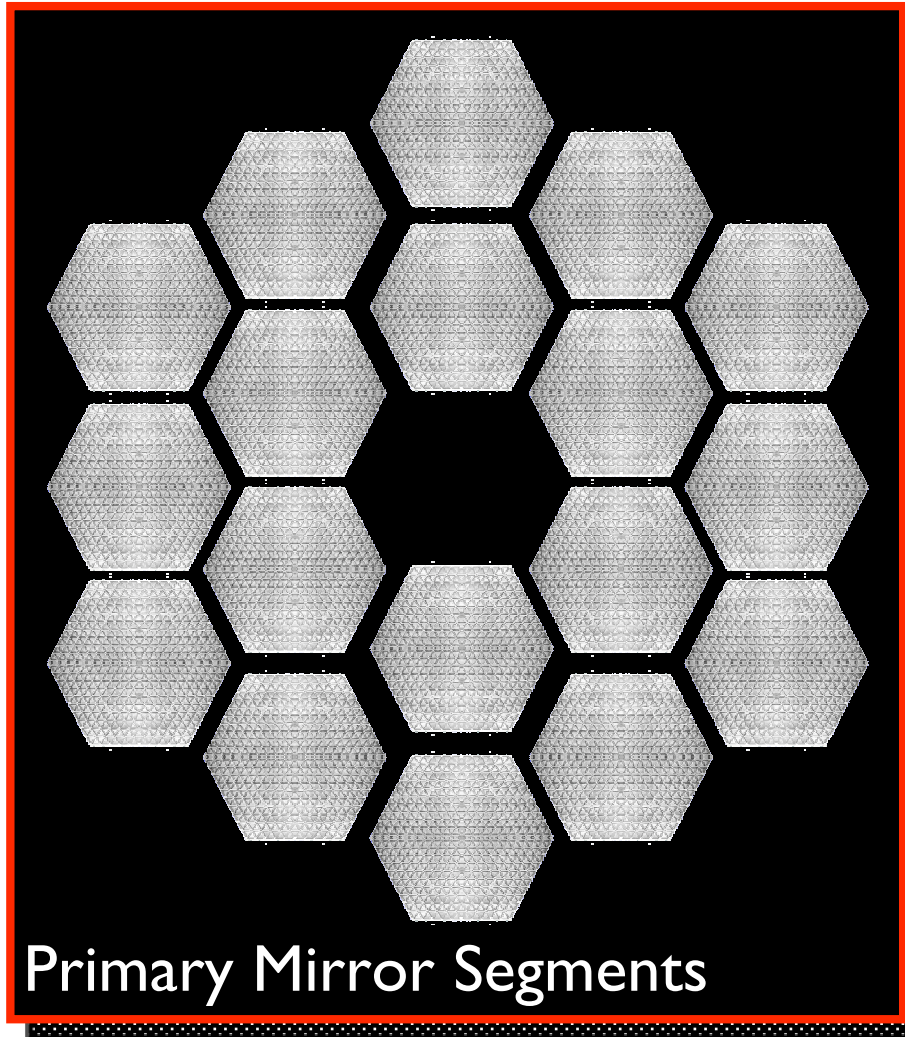
Flight Mirror Blank Fabrication Complete

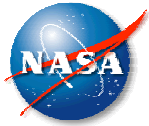


- Be fabrication
- Brush-Wellman



Secondary Mirror





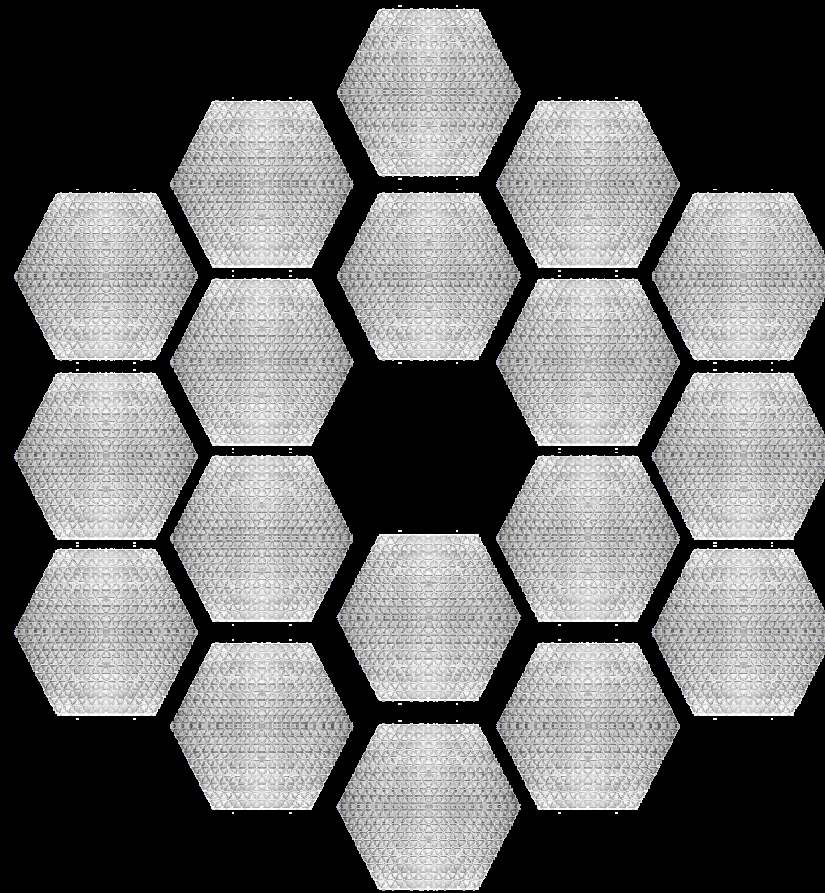
Flight Mirror Lightweighting Complete



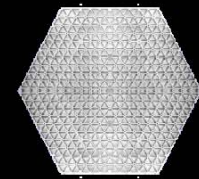
- Lightweighting
- Axsys



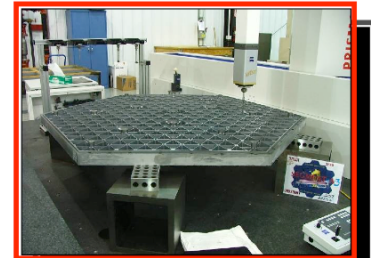
Secondary Mirror



Primary Mirror Segments



Pathfinder Mirror

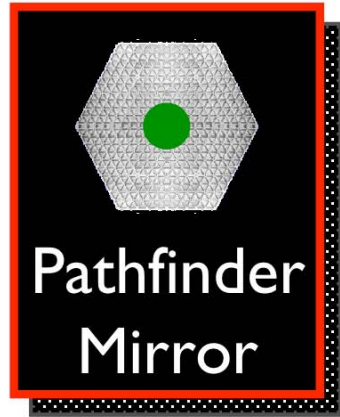
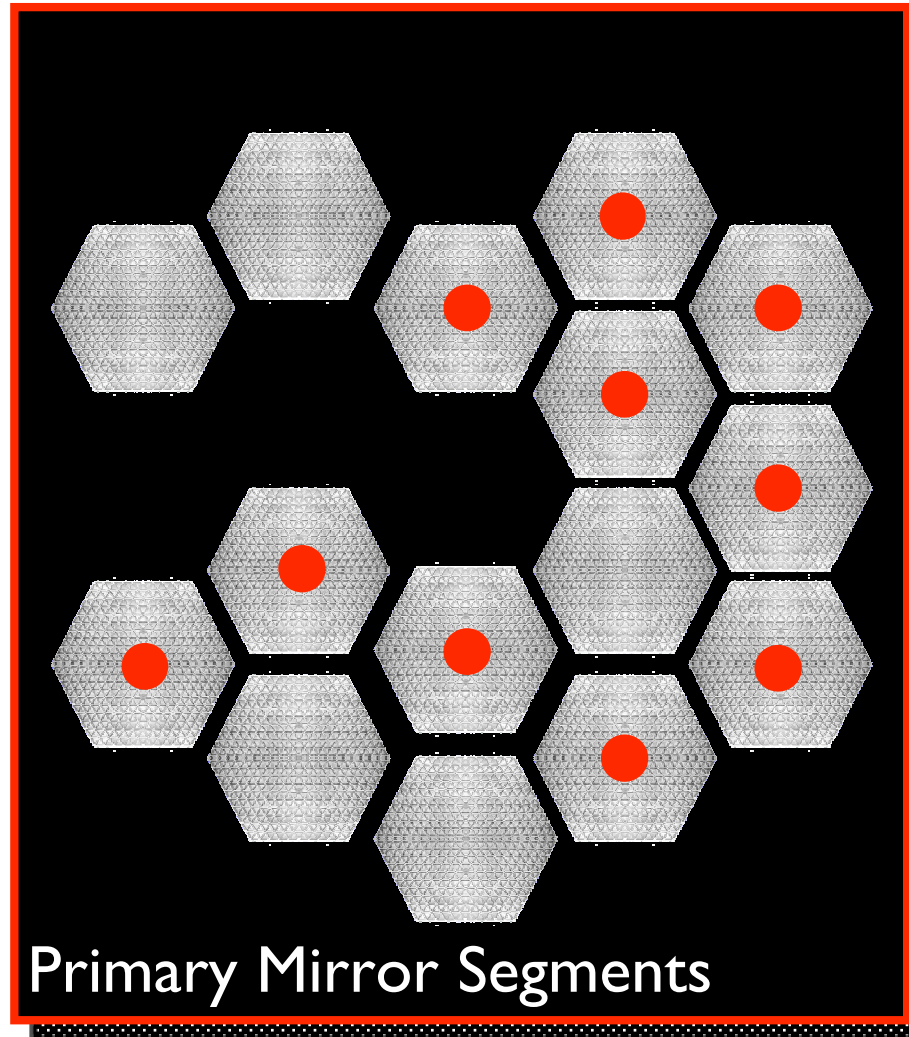




Flight Mirror Polishing Started



- Mirror Polishing
- Tinsley

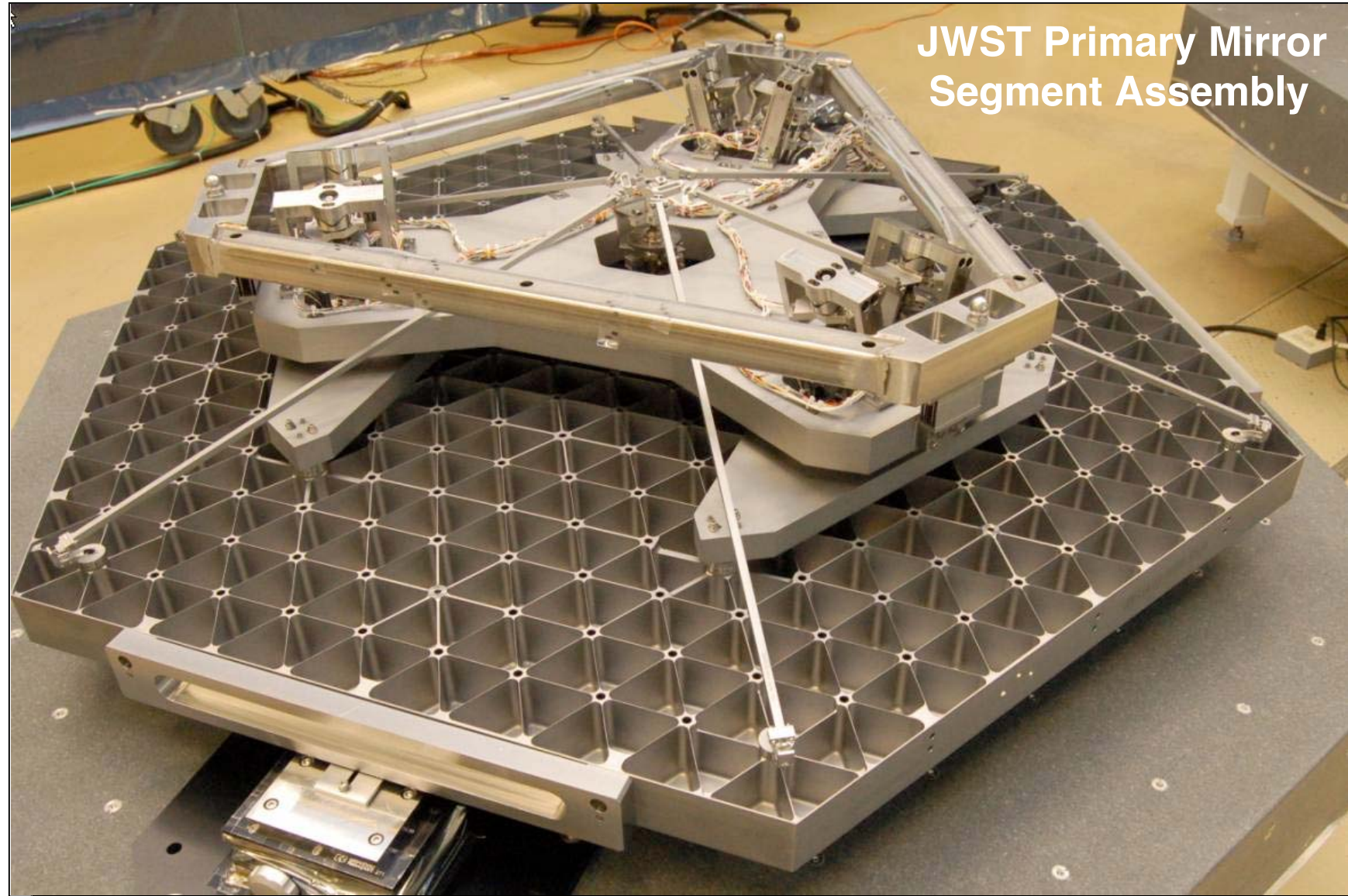


- Coarse grind
- fine grind



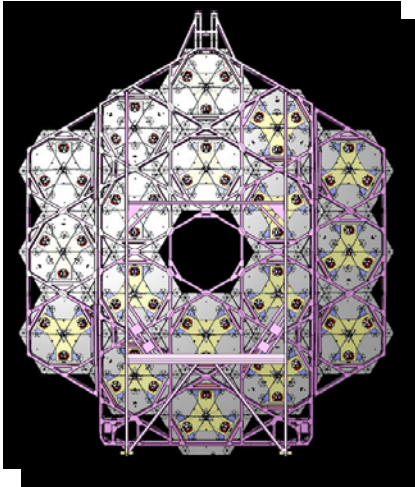


Mirror Figure Passed Launch Loads Test



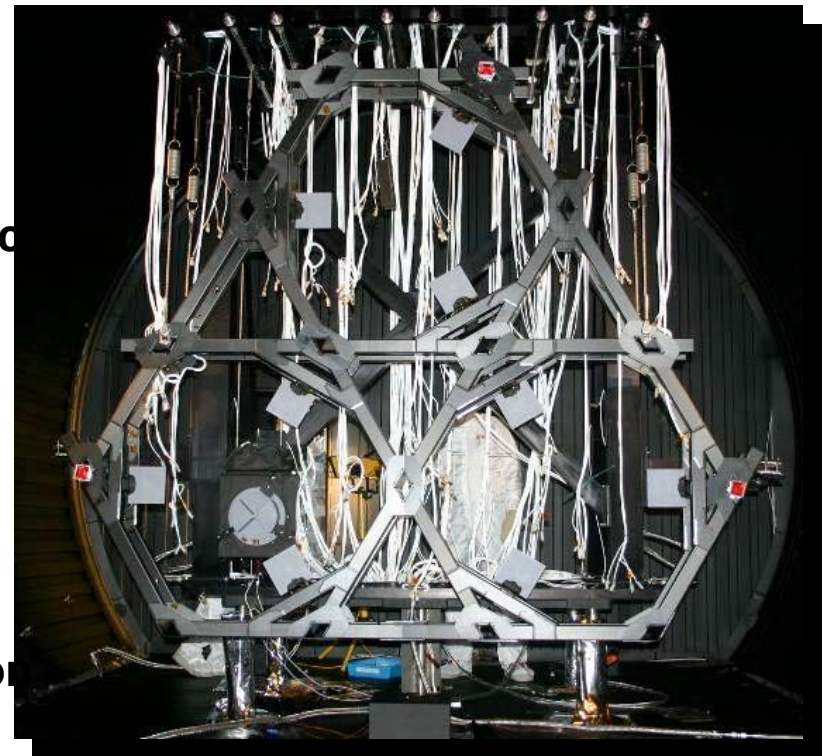


Backplane Structure Model Validated



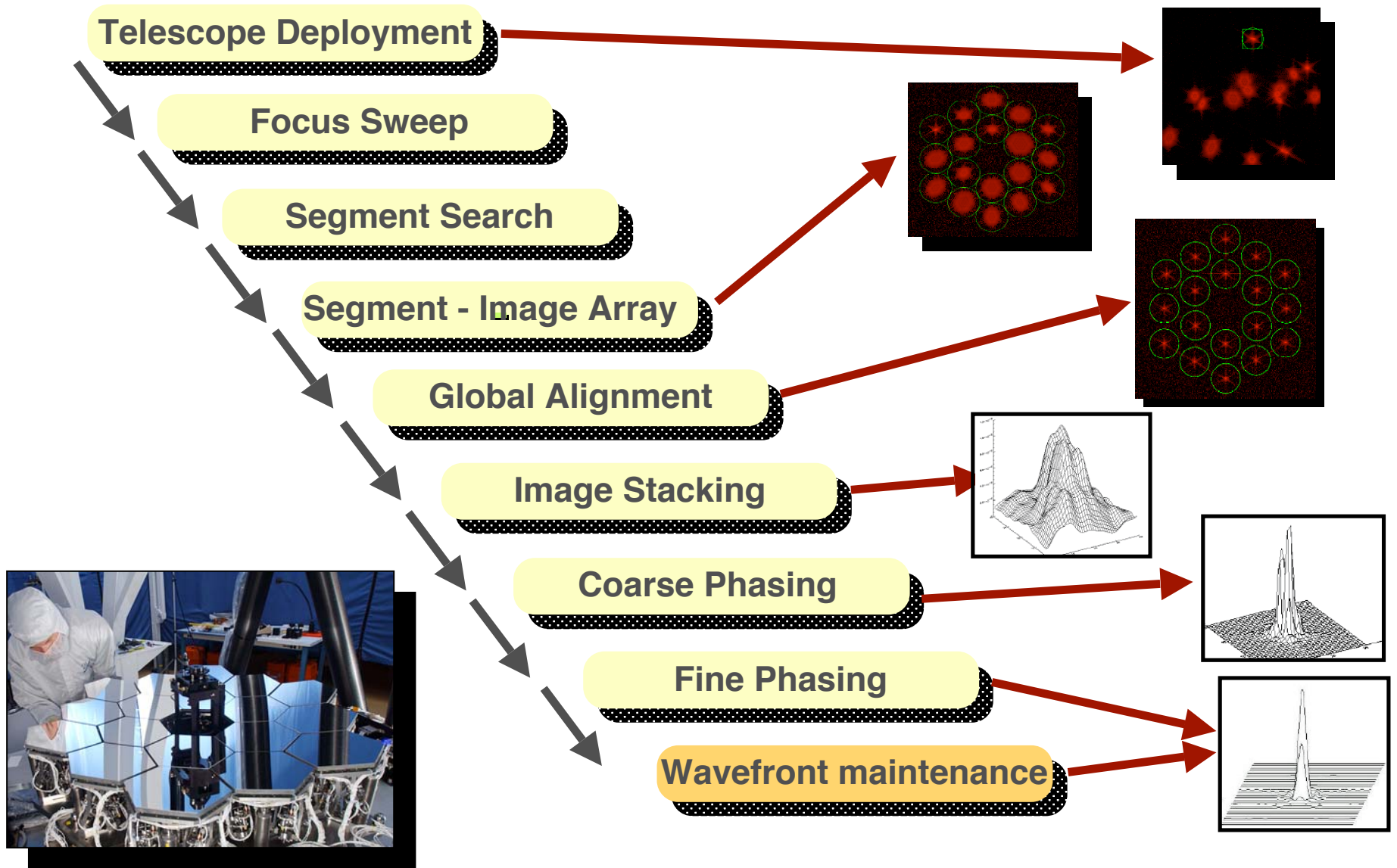
- Goal: verify the predictions of the cryogenic performance of the primary mirror backplane structure
 - Requires precise (nm) measurements of structure at cryogenic temperatures
 - Employed speckle interferometer for precise metrology

- 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





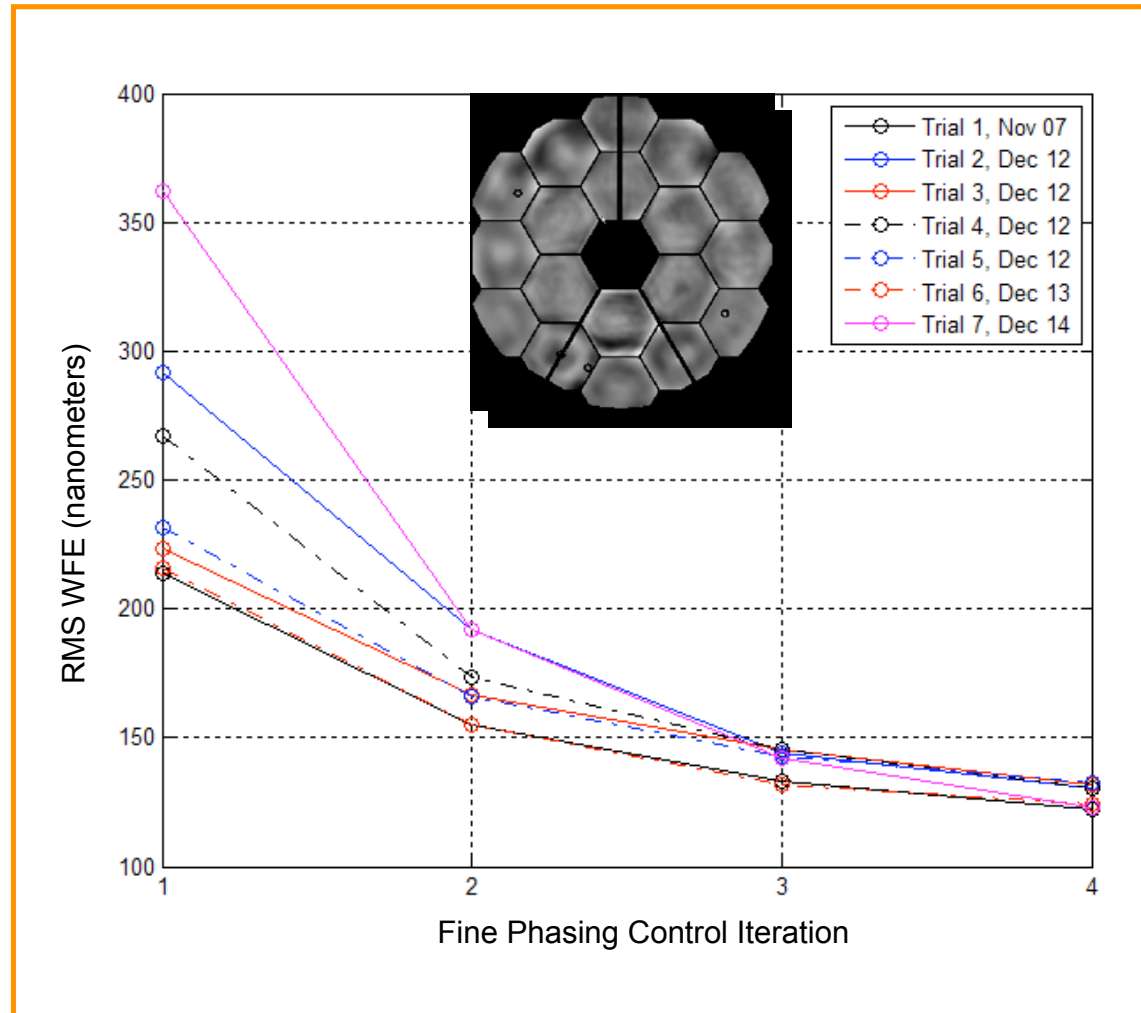
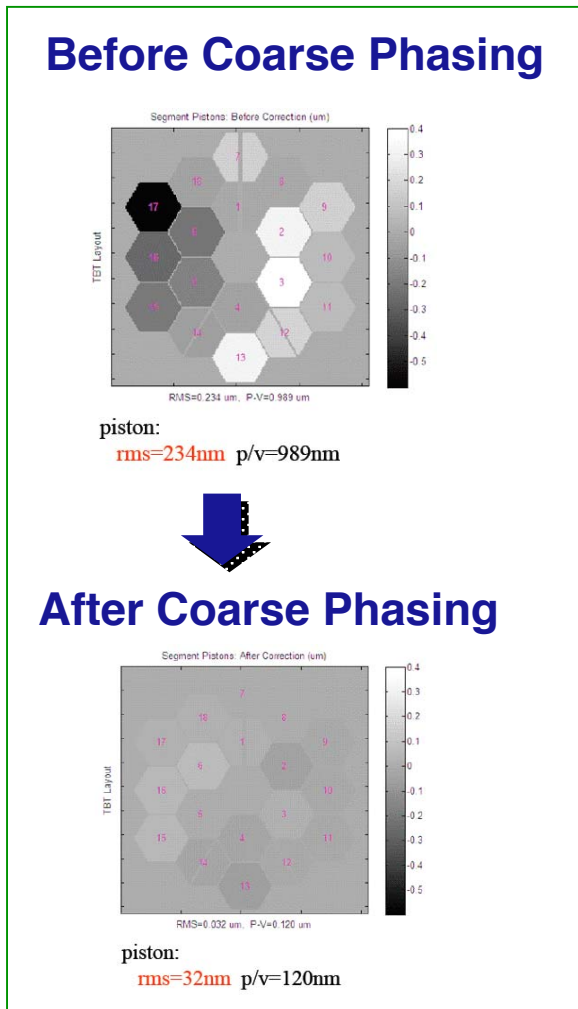
JWST Phasing Algorithms Demonstrated

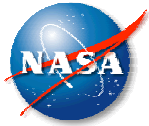


Coarse Phasing
(Segment to segment piston)



Fine Phasing





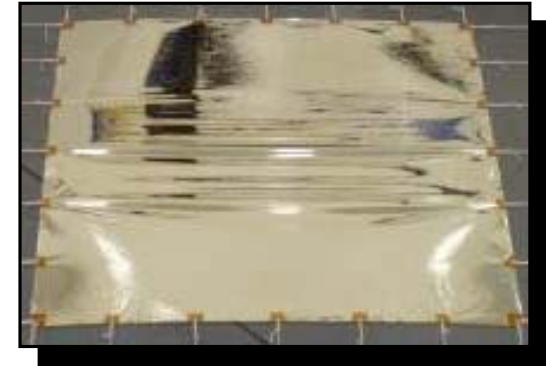
Sunshield Material Validated



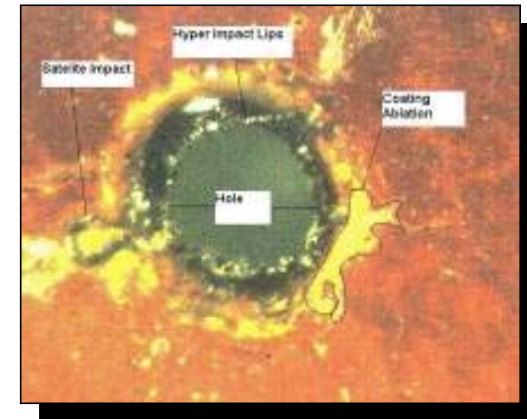
- Sunshield material has reached technical maturity
 - Thermal performance
 - Micro-meteoroid impacts
 - Material strength (deployments)



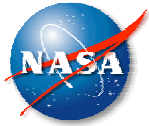
- Sunshield pathfinder: membrane folding test in progress



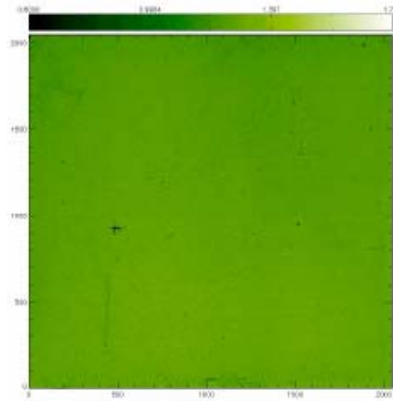
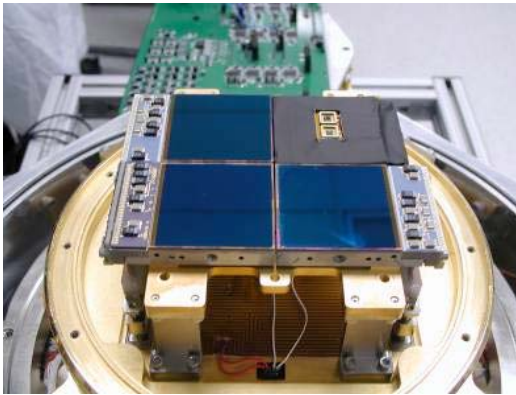
Material strength Test



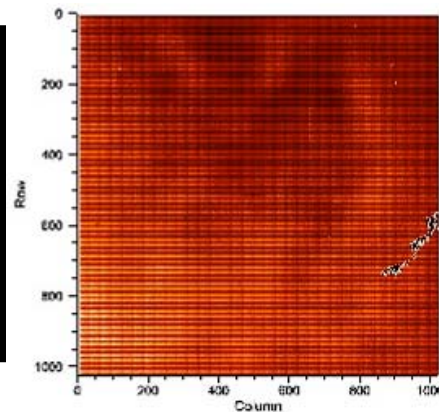
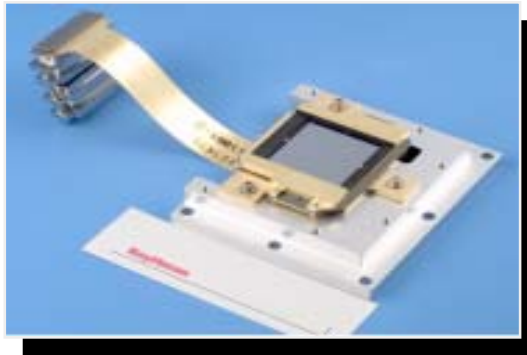
Micro-meteoroid Test



JWST Flight Detectors in Production



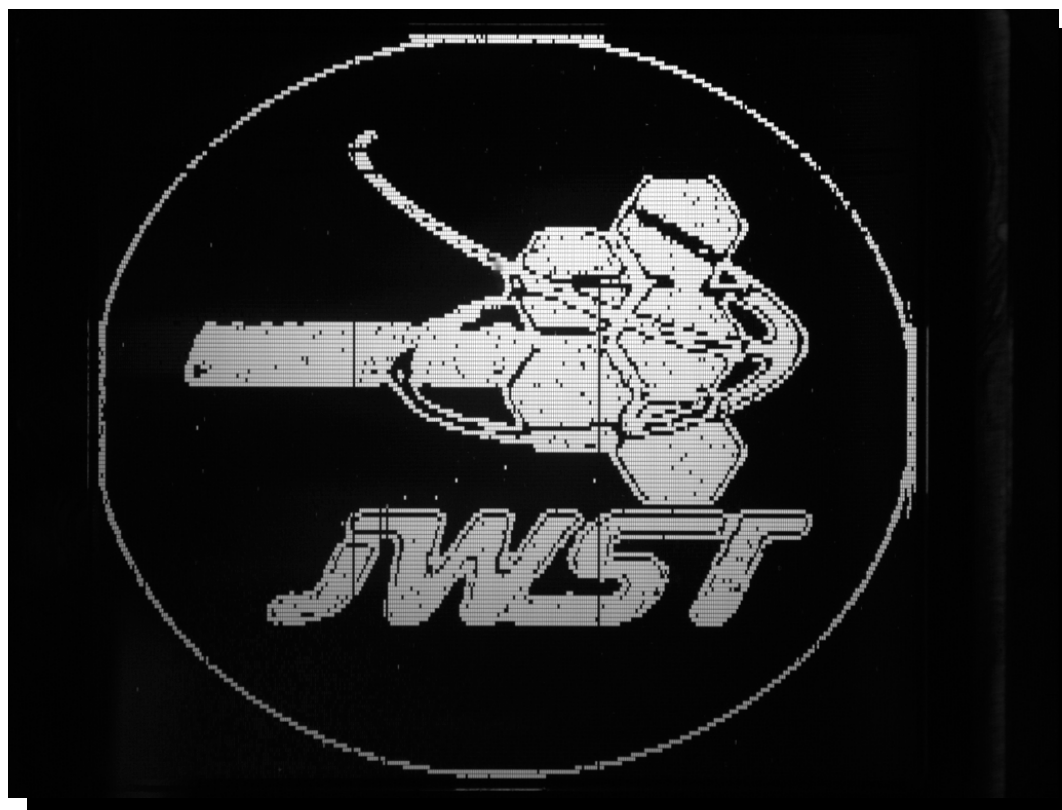
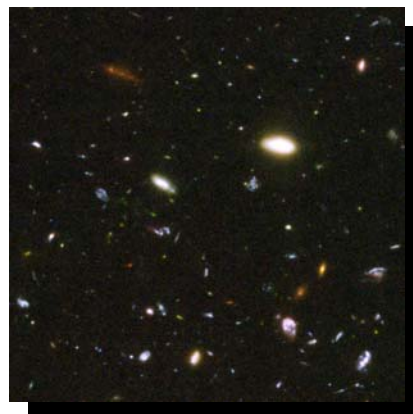
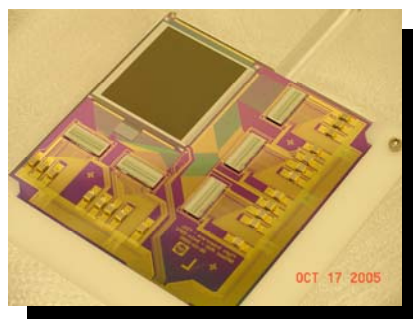
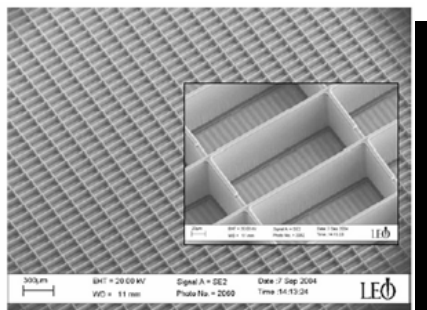
- NIRCam detectors and their packages have reached technical maturity
- Flight detectors are in production and meet specifications



- Mid-Infrared detectors have reached 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 \neq success**
- **If it's tested, it won't work the first time either - plan to rehearse, test, rework, retest**
- **Elementary things fail: simple \neq successful**
- **It's worth all this work: no substitute for major space missions**



The End