Cosmic Background Radiation, Cosmology, and the James Webb Space Telescope: JWST

John C. Mather

JWST Senior Project Scientist,

NASA's Goddard Space Flight Center

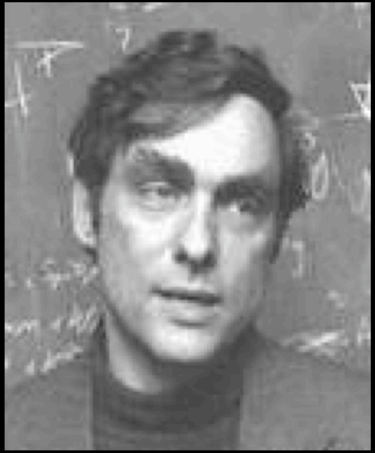
& Chief Scientist, Science Mission Directorate,

NASA HQ

August 31, 2007

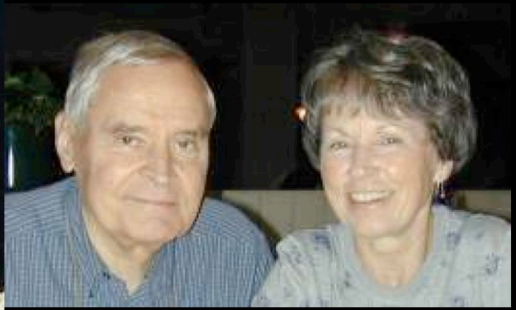
Rutgers Lusscroft Farm - Site of Early Nerds in Sussex County, N.J.

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

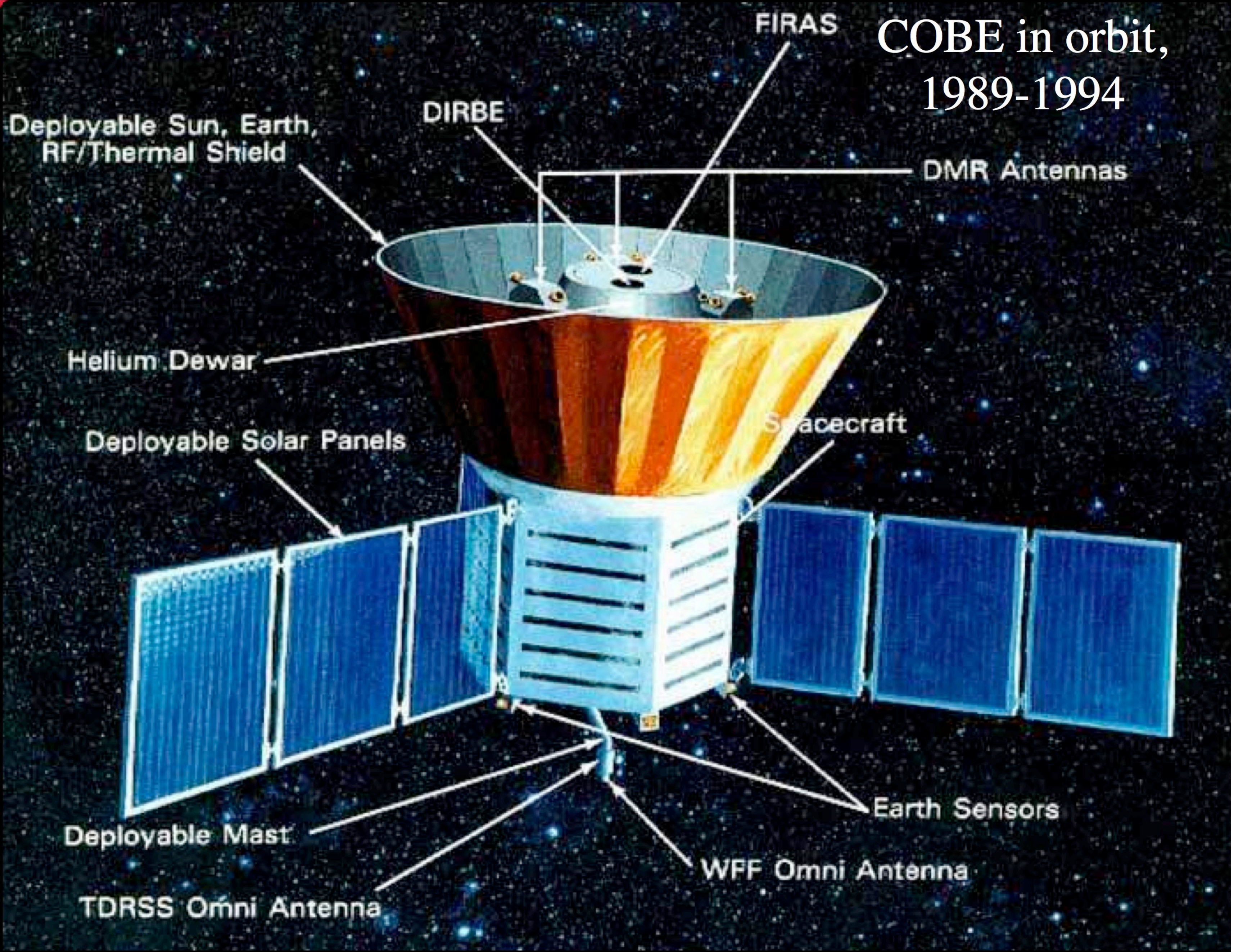
Bob & Beverly Silverberg

Ned & Pat Wright

COBE Science Team Roles

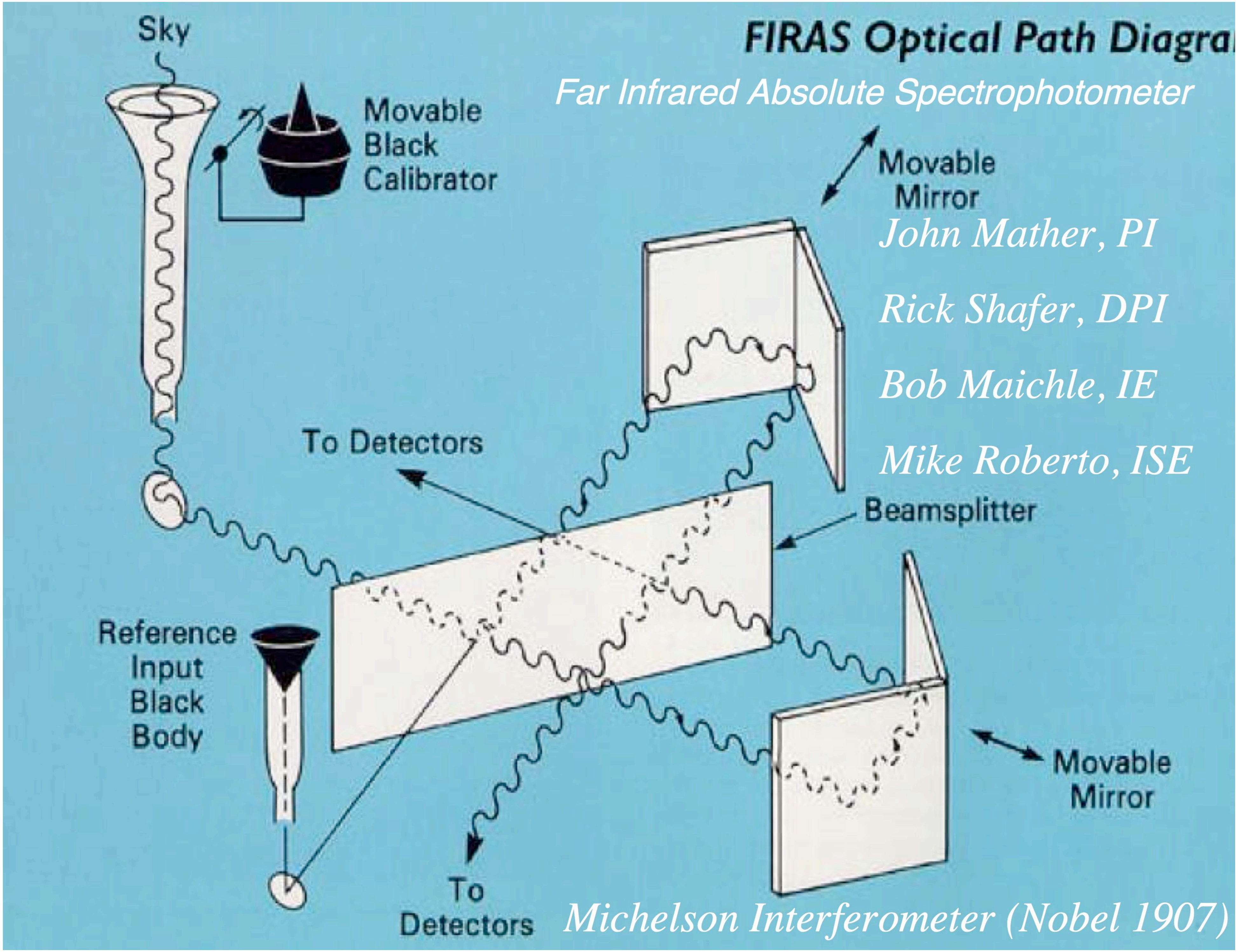
- 3 proposal teams in 1974
- Selected 6 individuals in 1976: Sam Gulkis, Mike Hauser, John Mather, George Smoot, Rai Weiss, Dave Wilkinson
- Science Working Group Chair: Weiss
- Project Scientist/Deputy: Mather/ Nancy Boggess
- DIRBE PI/Deputy: Hauser/Tom Kelsall
- DMR PI/Deputy: Smoot/Charles Bennett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

COBE in orbit, 1989-1994



FIRAS Optical Path Diagra

Far Infrared Absolute Spectrophotometer



John Mather, PI

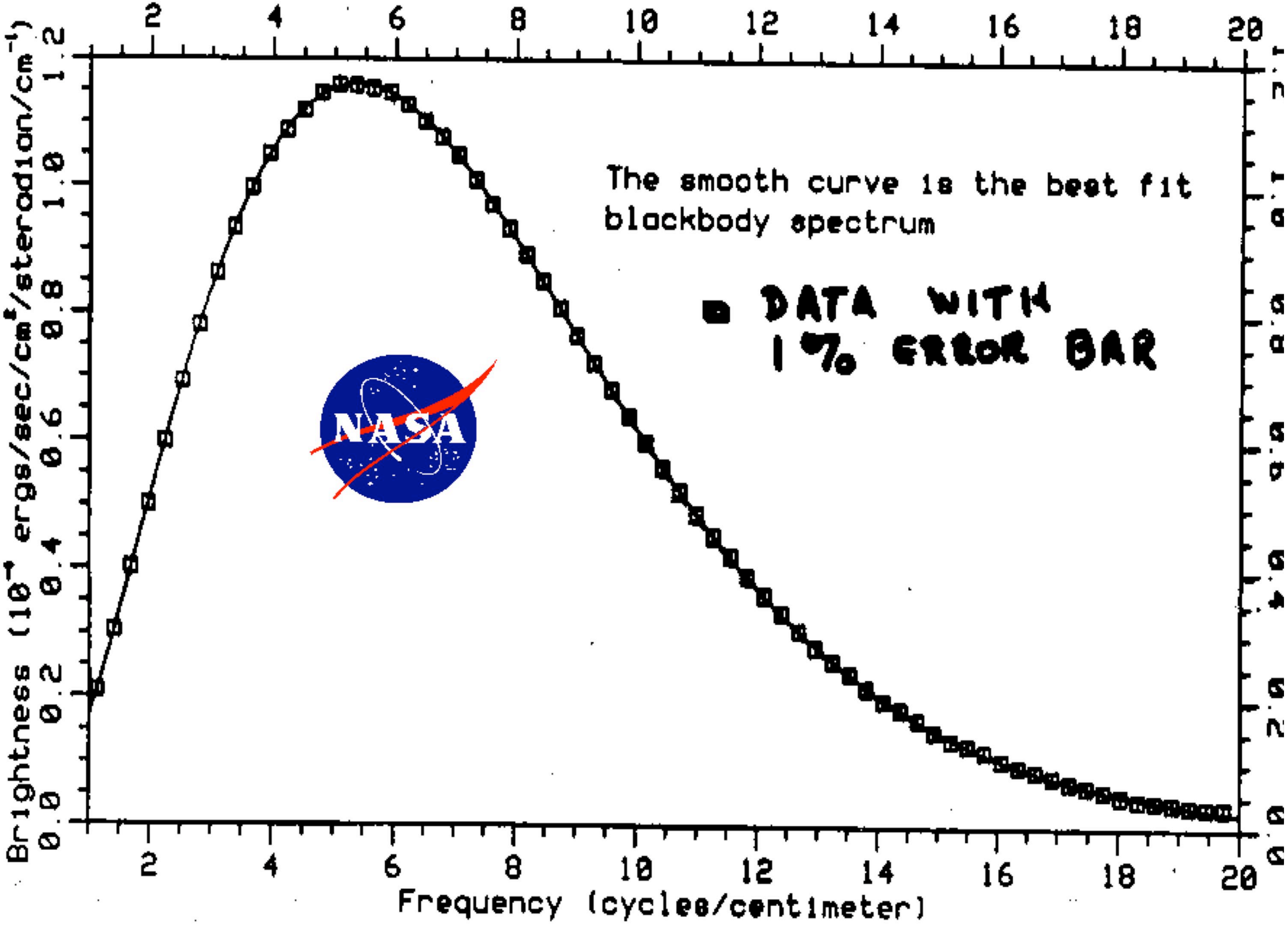
Rick Shafer, DPI

Bob Maichle, IE

Mike Roberto, ISE

Michelson Interferometer (Nobel 1907)

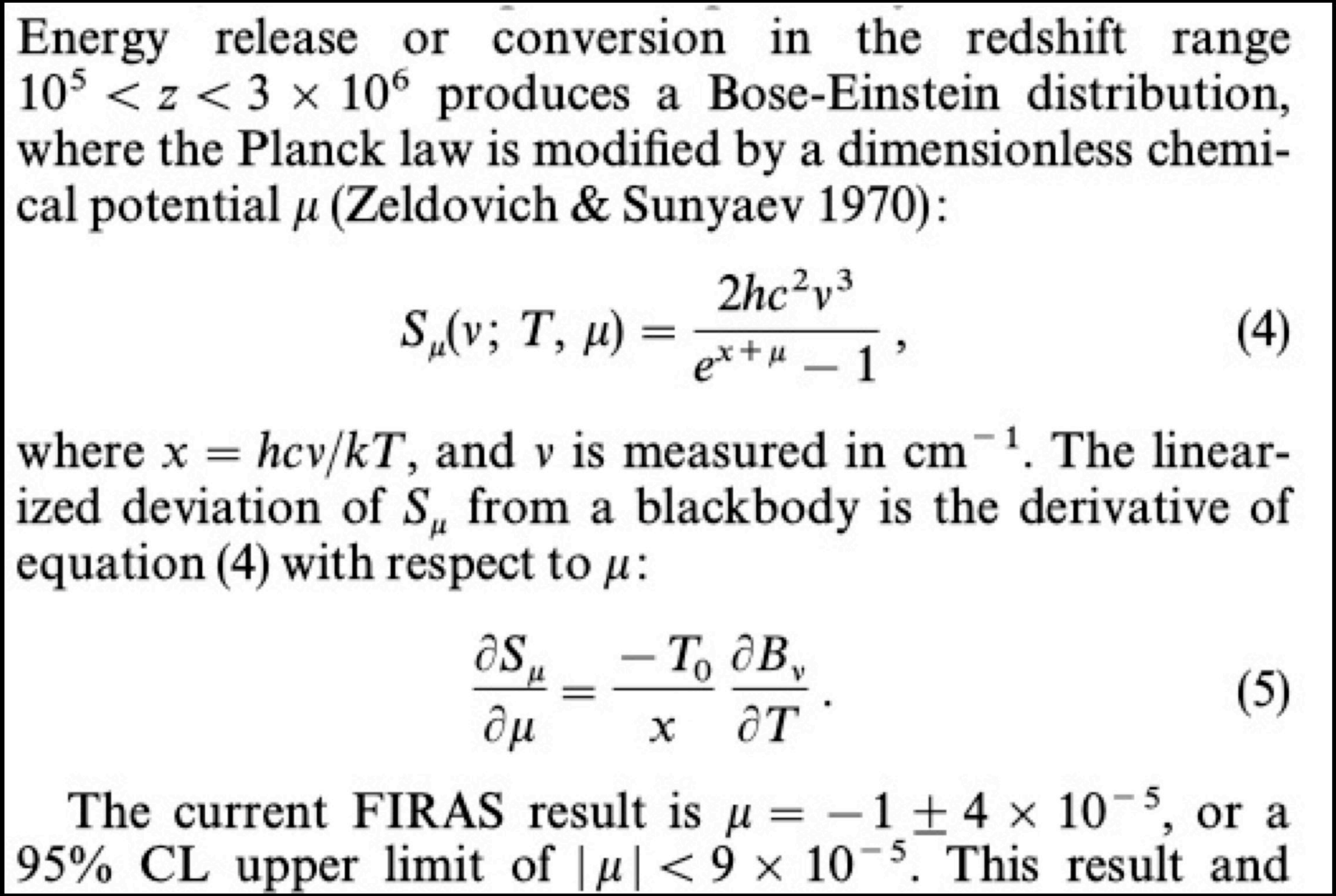
Cosmic Background Spectrum at the North Galactic Pole



The smooth curve is the best fit blackbody spectrum

■ DATA WITH 1% ERROR BAR

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):

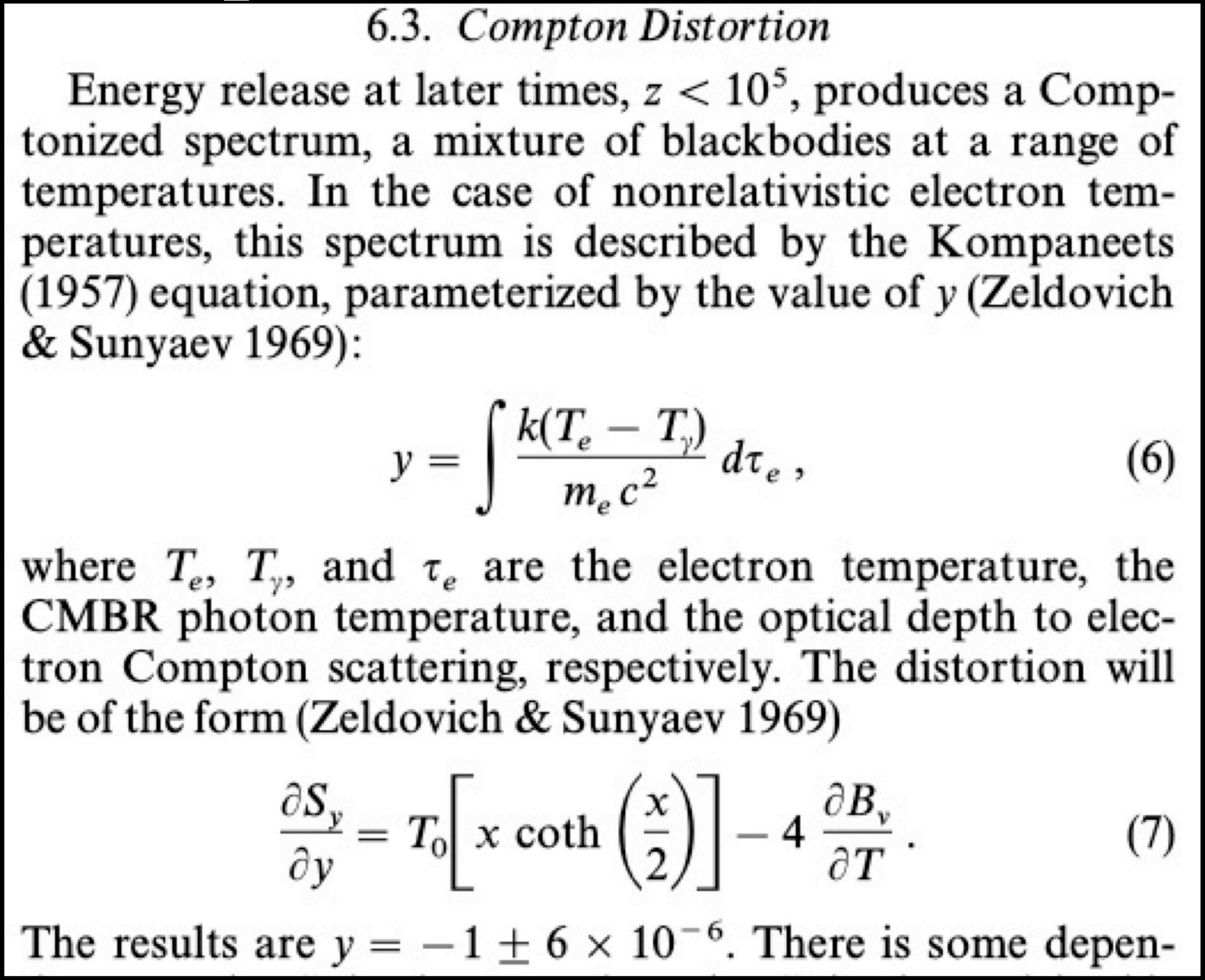
$$S_\mu(\nu;\, T,\, \mu) = \frac{2hc^2\nu^3}{e^{x+\mu} - 1}\,, \tag{4}$$

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*

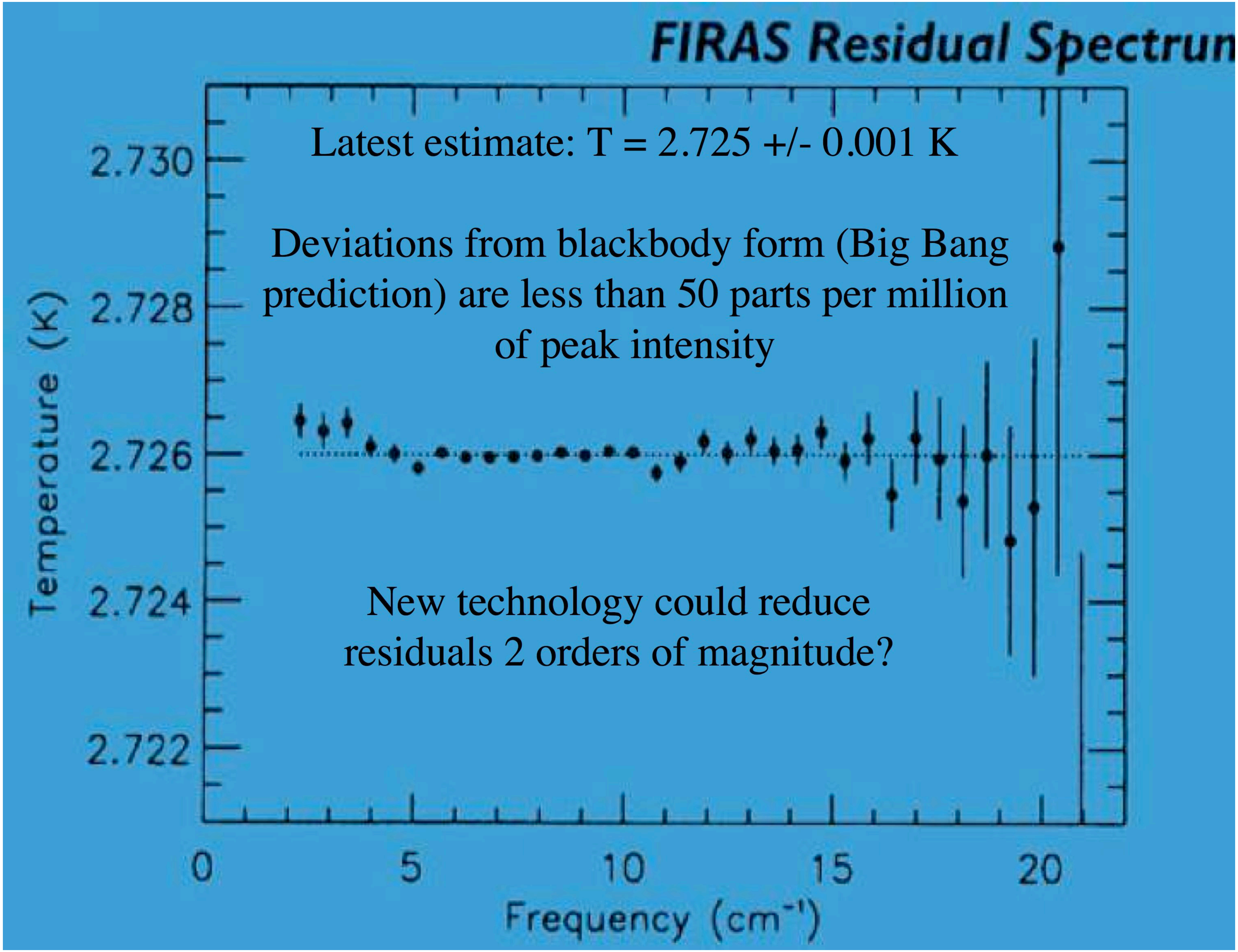
Energy release at later times, $z < 10^5$, produces a Comptonized spectrum, a mixture of blackbodies at a range of temperatures. In the case of nonrelativistic electron temperatures, this spectrum is described by the Kompaneets (1957) equation, parameterized by the value of y (Zeldovich & Sunyaev 1969):

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

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-

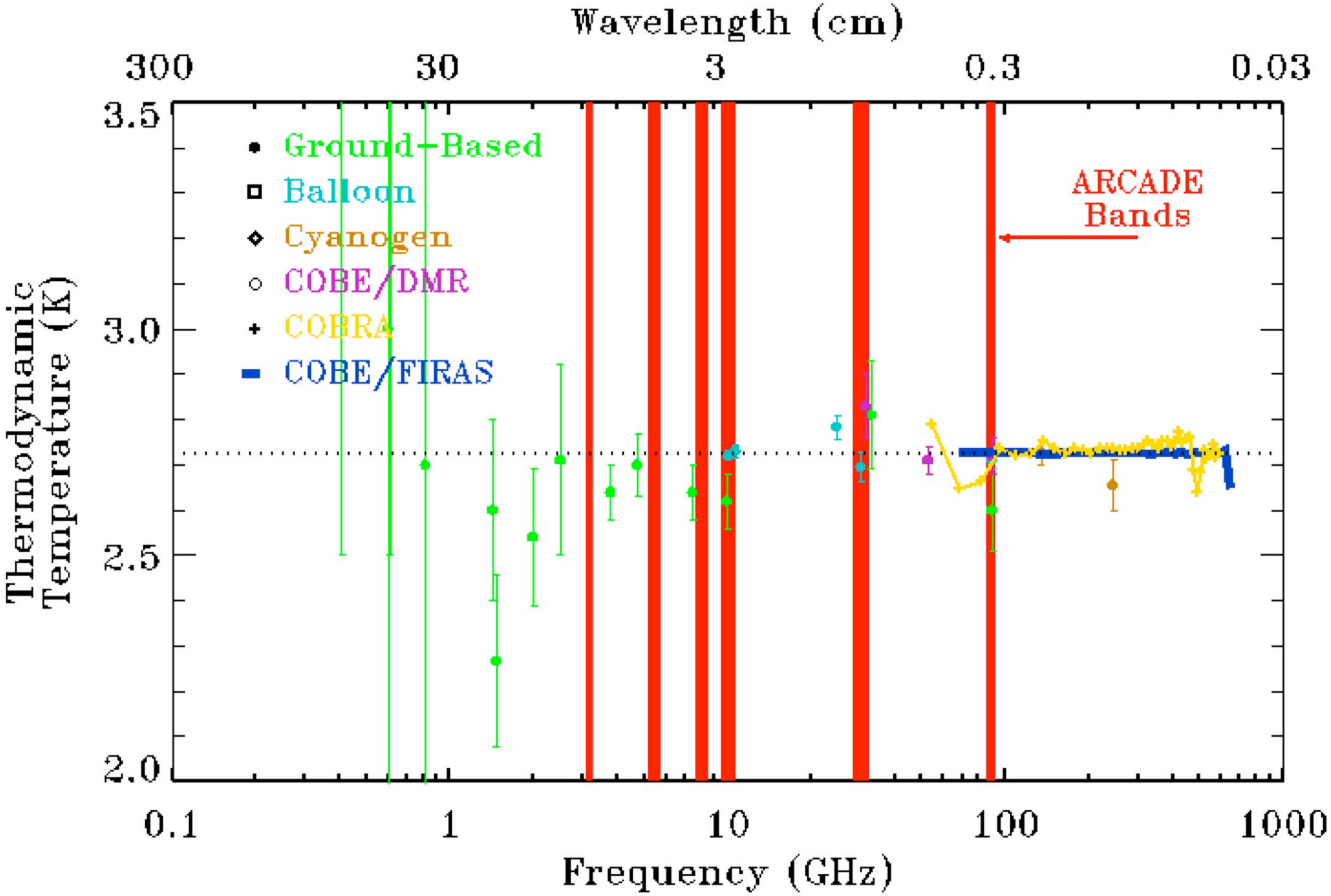


Latest estimate: T = 2.725 +/- 0.001 K

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

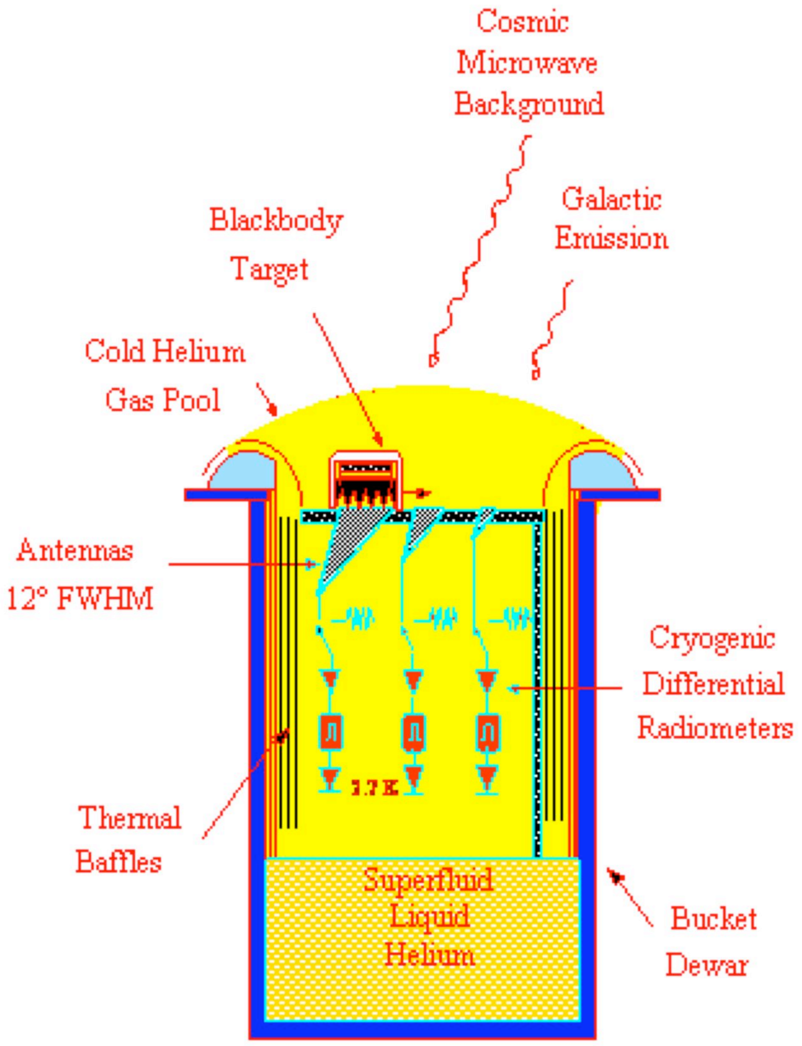
New technology could reduce residuals 2 orders of magnitude?

CMBR at Other Wavelengths



ARCADE

- Al Kogut, PI
- 3 to 90 GHz, with microwave technology
- Absolutely calibrated by full beam blackbody, mK accuracy
- Balloon payload, open helium bucket, helium outflow keeps equipment clean
- 4 flights completed
- Measurement sensitivity Y_ff < 10^{-6}, $\mu < 2\times10^{-5}$
- http://arcade.gsfc.nasa.gov



FIRAS 2: Was recombination era out of equilibrium?

Decay of Primordial Particles?

Sunyaev et al. predictions?

Etc.?

Improvements over FIRAS

- Totally symmetrical instrument
- Totally isothermal instrument, matching CMB temperature
- 1000x better detectors, possibly post-dispersed for better sensitivity: photon noise allows ppb (few nK)
- Isolators between (colder) detectors and instrument; alternatively, kinematic inductance thermometers for detectors without self-heating
- Possibly, use of paraboloid reflector for smaller beamwidth, to see through holes in local dust clouds
- Far from Earth, for better sidelobe control
- Better thermometers, for comparison with other instruments

Foreground Issues

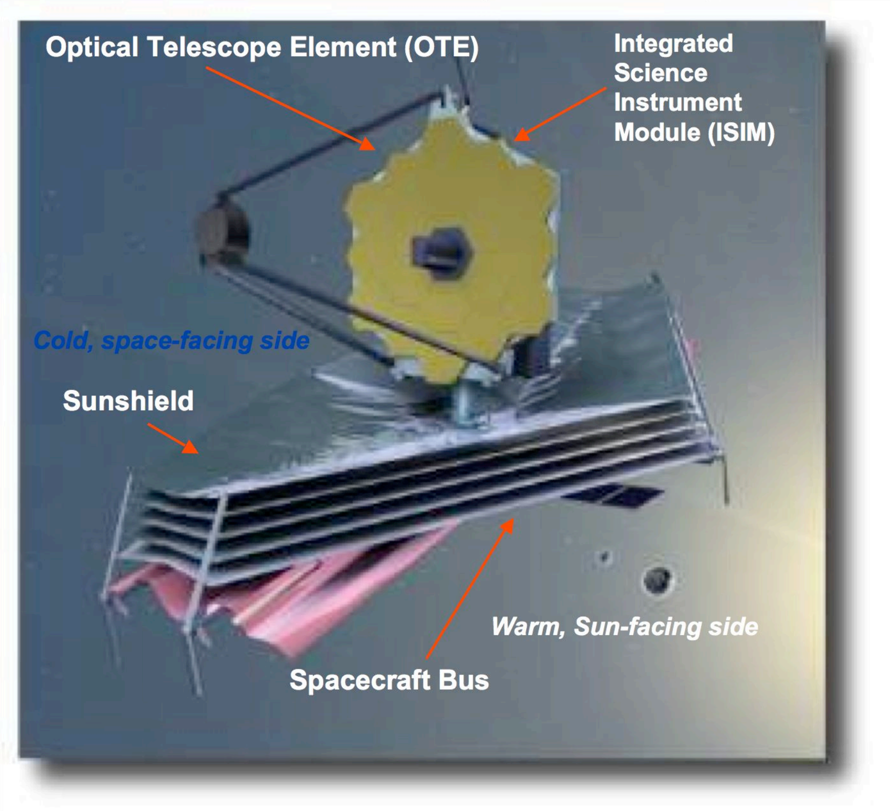
- Dust at various temperatures in Milky Way
- Spinning dust grains
- Electrons: synchrotron and brehmsstrahlung
- Atomic and molecular line emissions
- All the same processes in other galaxies
- Probably, none of these match predicted narrow frequency patterns of H recombination line series

- Conclusion: ppb measurements of H recombination series may not be impossible

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**

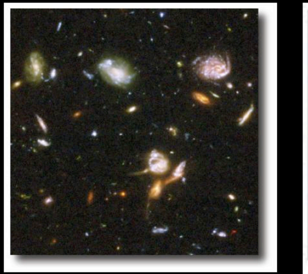


Description

- **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

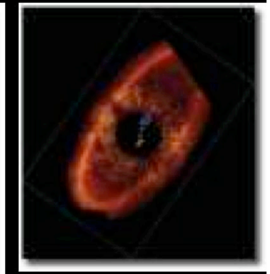
JWST Science Themes



End of the dark ages: First light and reionization

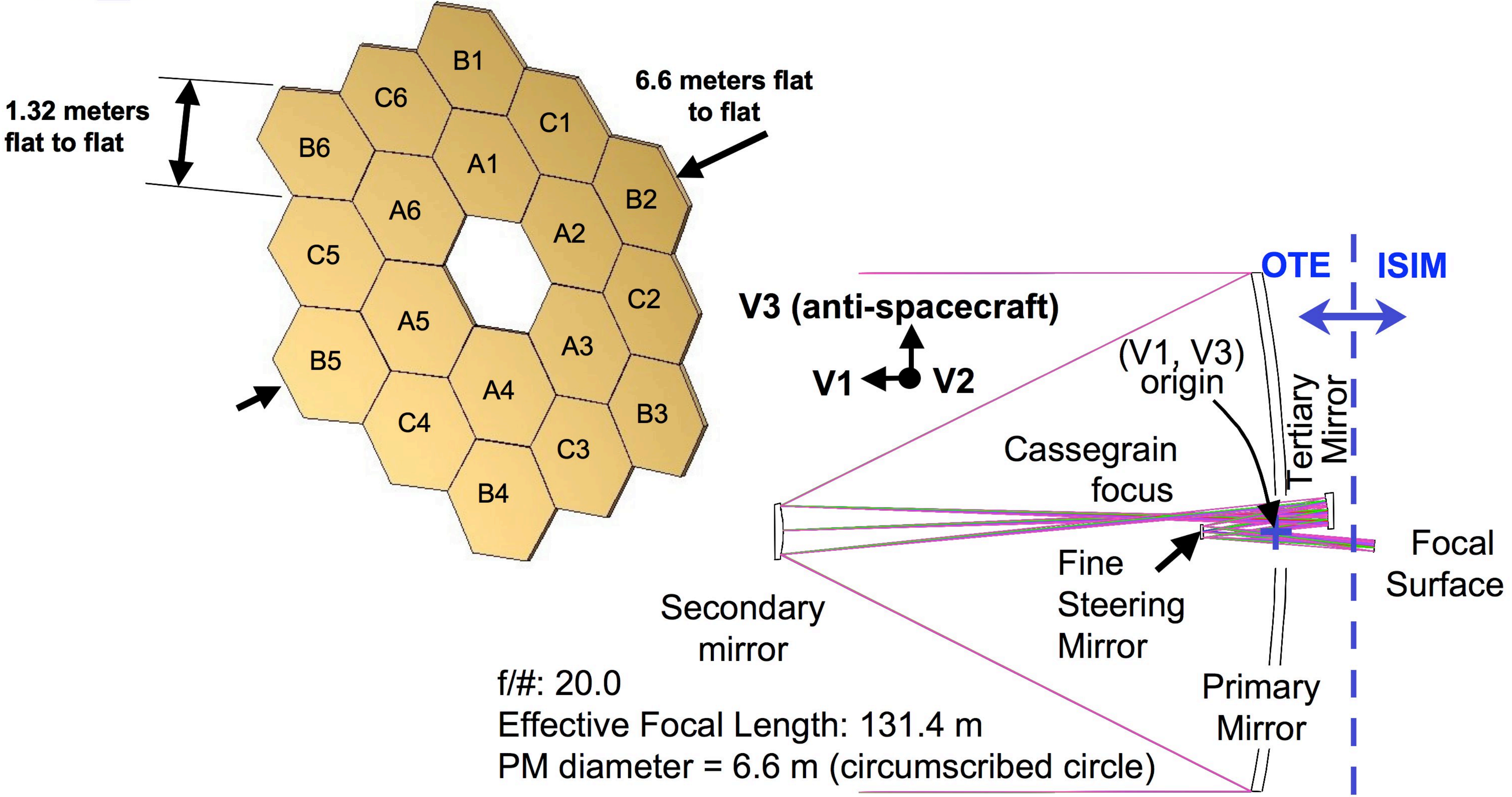
The assembly of galaxies

Birth of stars and proto-planetary systems



Planetary systems and the origin of life

Three Mirror Anastigmat Optical Design Provides a Wide Field-of-View



f/#: 20.0

Effective Focal Length: 131.4 m

PM diameter = 6.6 m (circumscribed circle)

JWST Science Working Group (#4)

- 6 Interdisciplinary Scientists: H. Hammel, S. Lilly, J. Lunine, M. McCaughrean, M. Stiavelli, R. Windhorst
- Instrument Team Lead/ Science Representative: M. Rieke (NIRCam), G. Rieke and G. Wright (MIRI), Rene Doyon (FGS), & rotating scientist member, NIRSpec
- Telescope Scientist: M. Mountain (also STScI Director)
- Ex Officio: J. Mather (Chair), J. Gardner, M. Clampin, M. Greenhouse, P. Stockman (K. Flanagan), G. Sonneborn, P. Jakobsen, J. Hutchings

JWST Science Capabilities

- Space Science Reviews, 123: 485-606 (2006): The James Webb Space Telescope, Jonathan P. Gardner et al.
- Available from SSR (springerlink.com, free PDF!) or astro-ph/0606175

Proposing for JWST time

- Operated by STScI like HST
- 15% time for Europe, 5% for Canada
- Illustrative Design Reference Mission (http://www.stsci.edu/jwst/science/drm) was used to determine payload characteristics, does not control the TACs
- ~ 800 hours allocation of time for each instrument team (NIRCam, NIRSPEC, MIRI), & interdisciplinary scientists (combined)

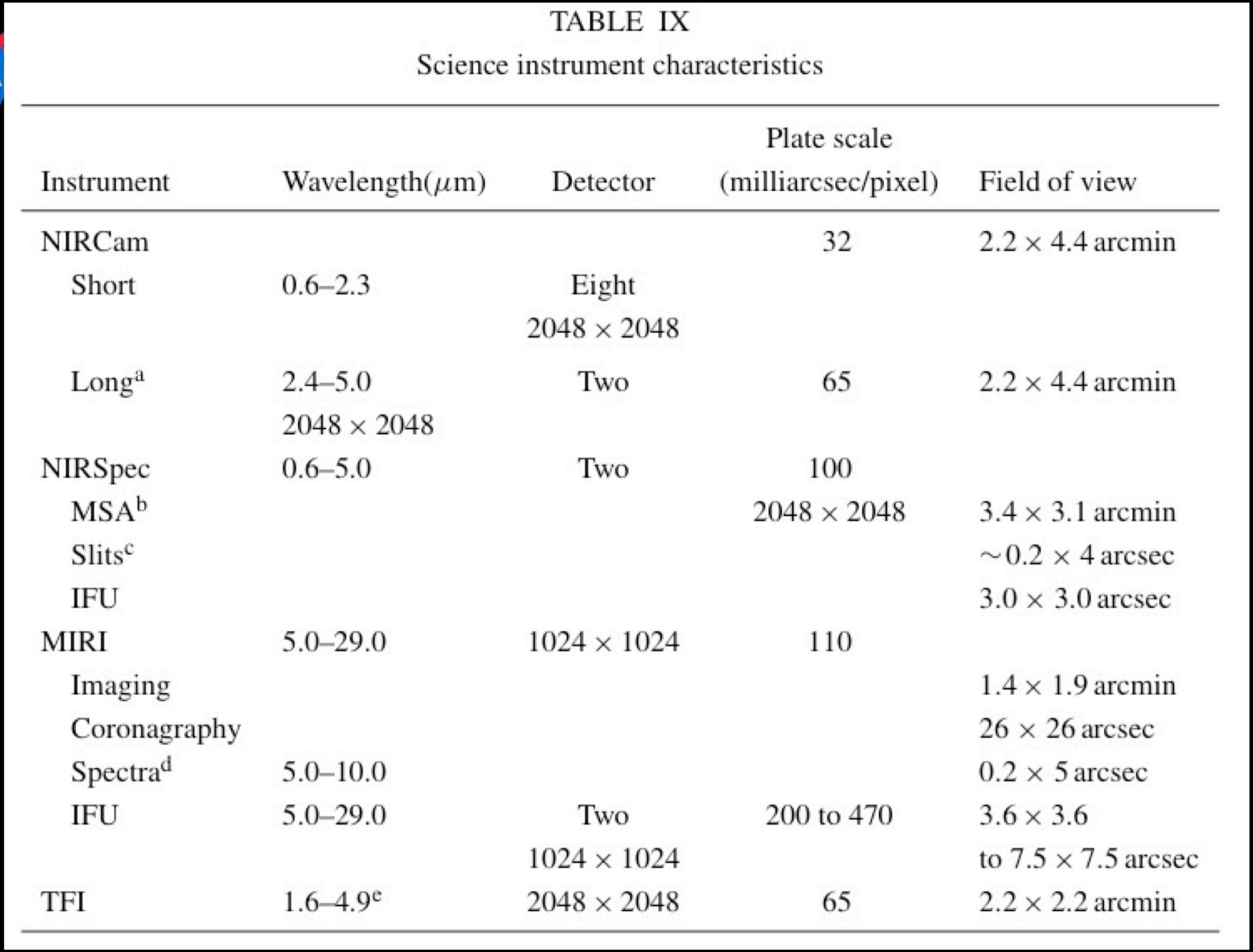
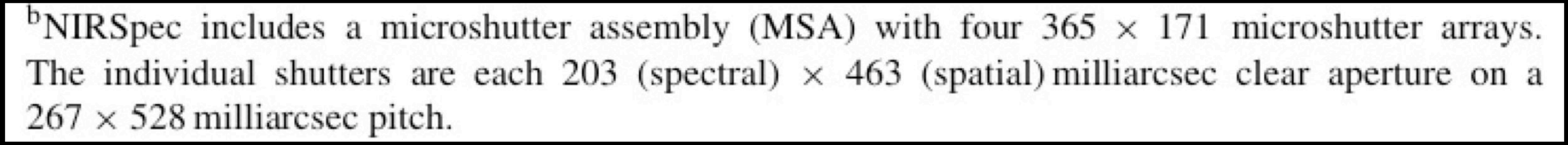


TABLE IX

Science instrument characteristics

Instrument	Wavelength(μm)	Detector	Plate scale (milliarcsec/pixel)	Field of view
NIRCam			32	2.2 × 4.4 arcmin
Short	0.6–2.3	Eight		
		2048 × 2048		
Long[a]	2.4–5.0	Two	65	2.2 × 4.4 arcmin
	2048 × 2048			
NIRSpec	0.6–5.0	Two	100	
MSA[b]			2048 × 2048	3.4 × 3.1 arcmin
Slits[c]				~0.2 × 4 arcsec
IFU				3.0 × 3.0 arcsec
MIRI	5.0–29.0	1024 × 1024	110	
Imaging				1.4 × 1.9 arcmin
Coronagraphy				26 × 26 arcsec
Spectra[d]	5.0–10.0			0.2 × 5 arcsec
IFU	5.0–29.0	Two	200 to 470	3.6 × 3.6
		1024 × 1024		to 7.5 × 7.5 arcsec
TFI	1.6–4.9[e]	2048 × 2048	65	2.2 × 2.2 arcmin



[b] NIRSpec includes a microshutter assembly (MSA) with four 365 × 171 microshutter arrays. The individual shutters are each 203 (spectral) × 463 (spatial) milliarcsec clear aperture on a 267 × 528 milliarcsec pitch.

JWST Sensitivities

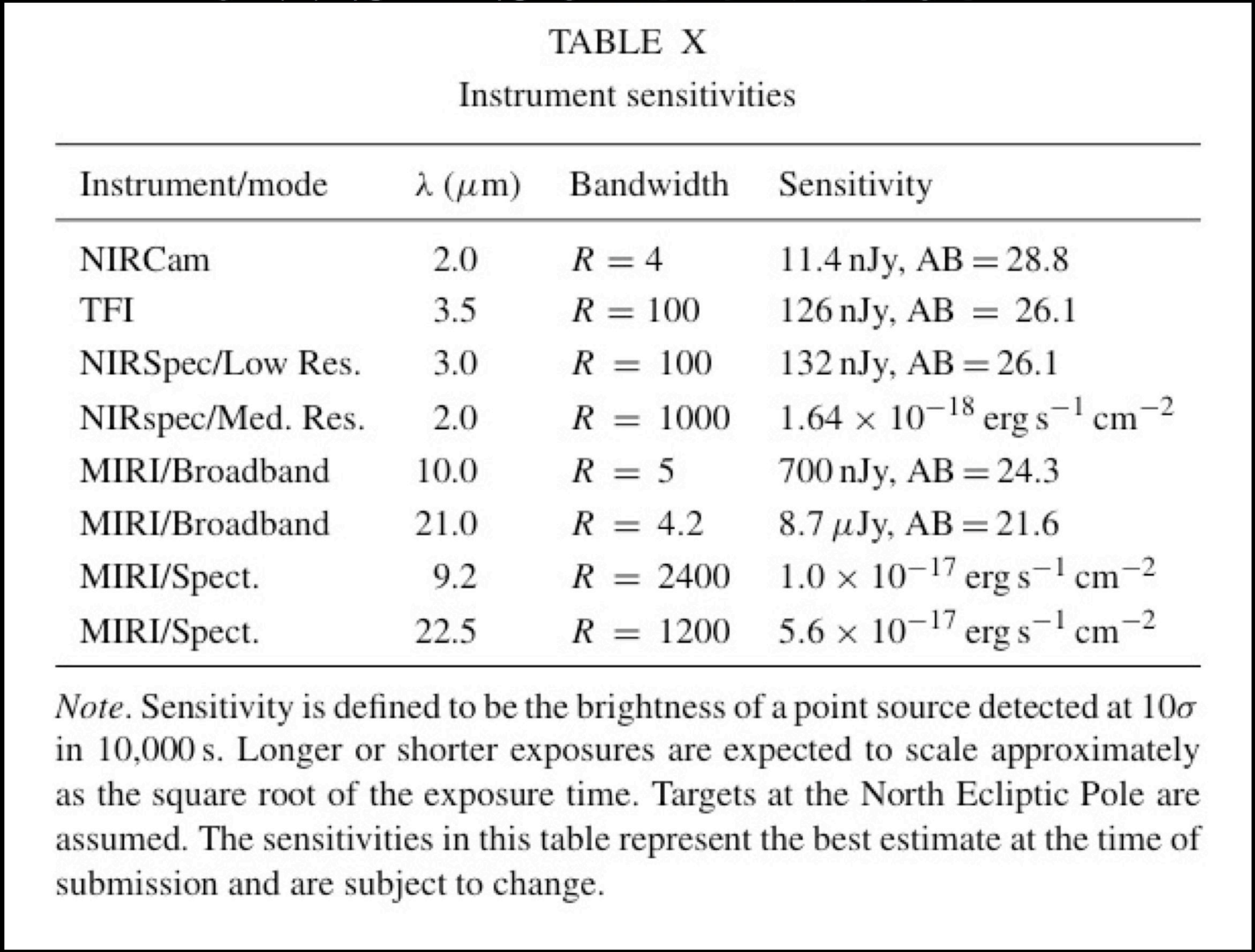


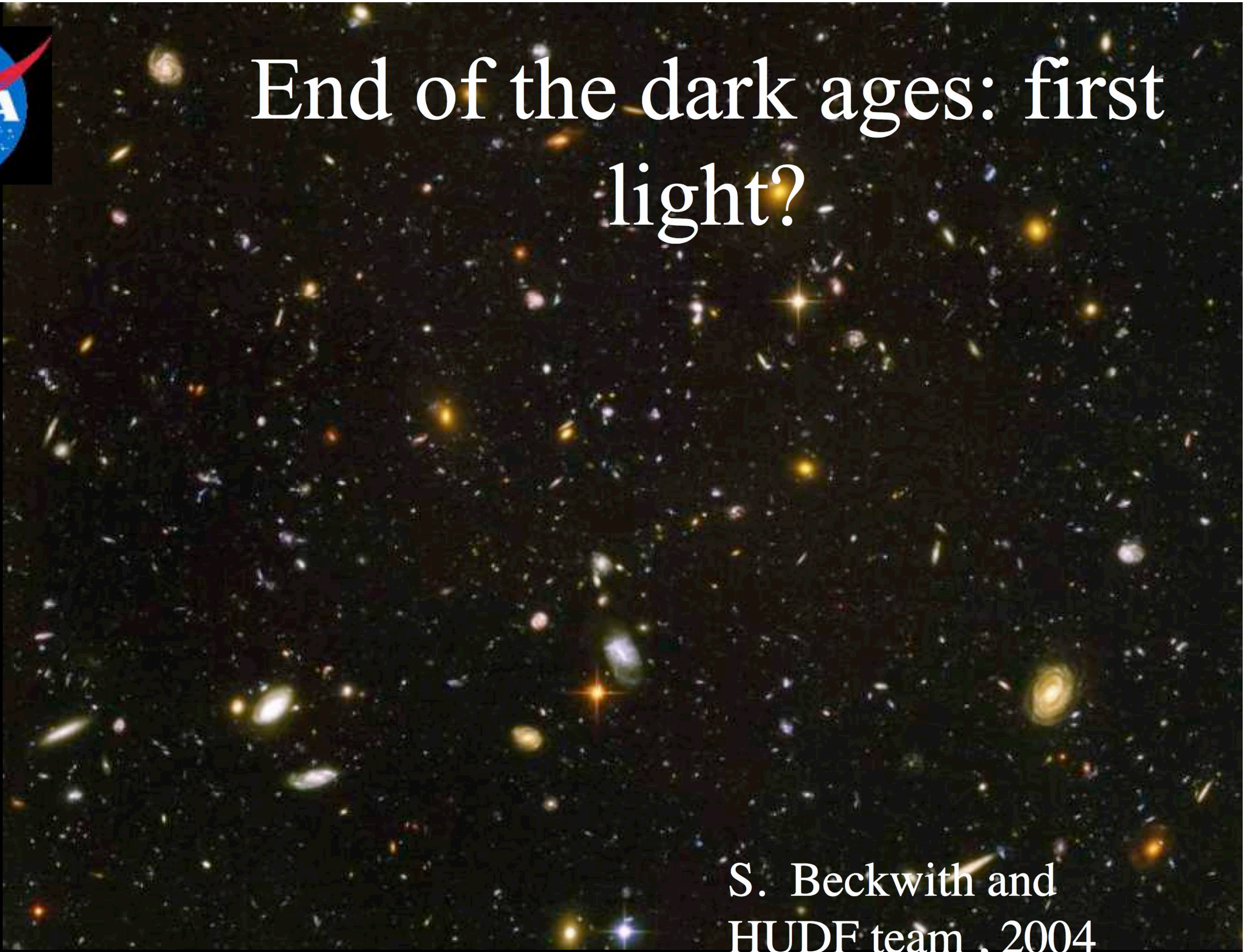
TABLE X

Instrument sensitivities

Instrument/mode	λ (μm)	Bandwidth	Sensitivity
NIRCam	2.0	$R = 4$	11.4 nJy, AB = 28.8
TFI	3.5	$R = 100$	126 nJy, AB = 26.1
NIRSpec/Low Res.	3.0	$R = 100$	132 nJy, AB = 26.1
NIRspec/Med. Res.	2.0	$R = 1000$	1.64×10^{-18} erg s^{-1} cm^{-2}
MIRI/Broadband	10.0	$R = 5$	700 nJy, AB = 24.3
MIRI/Broadband	21.0	$R = 4.2$	8.7 μJy, AB = 21.6
MIRI/Spect.	9.2	$R = 2400$	1.0×10^{-17} erg s^{-1} cm^{-2}
MIRI/Spect.	22.5	$R = 1200$	5.6×10^{-17} erg s^{-1} cm^{-2}

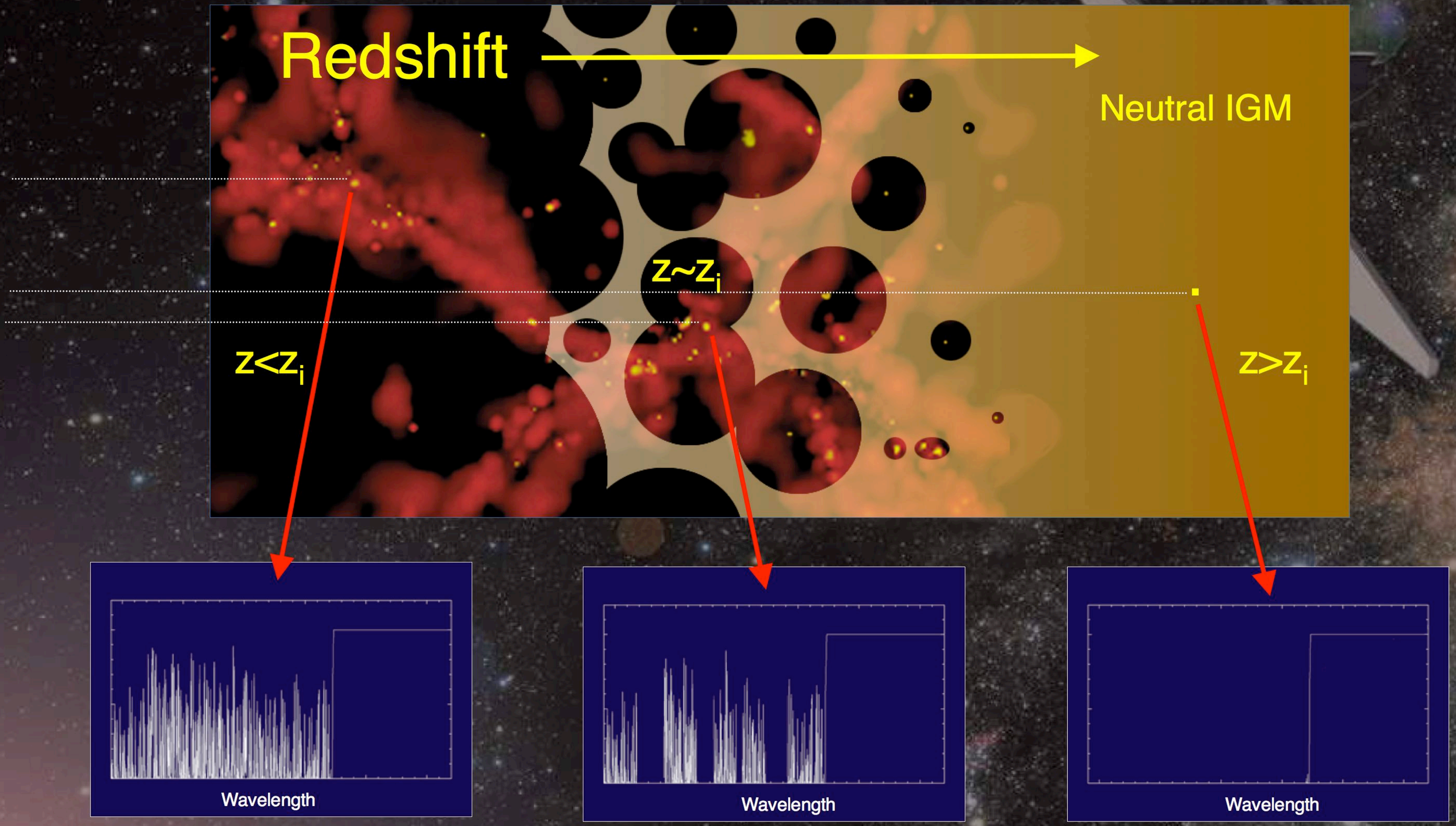
Note. Sensitivity is defined to be the brightness of a point source detected at 10σ in 10,000 s. Longer or shorter exposures are expected to scale approximately as the square root of the exposure time. Targets at the North Ecliptic Pole are assumed. The sensitivities in this table represent the best estimate at the time of submission and are subject to change.

End of the dark ages: first light?



S. Beckwith and
HUDF team , 2004

The Epoch of Reionization



Lyman Forest Absorption

Patchy Absorption

Black Gunn-Peterson trough

Observing the “First” Light

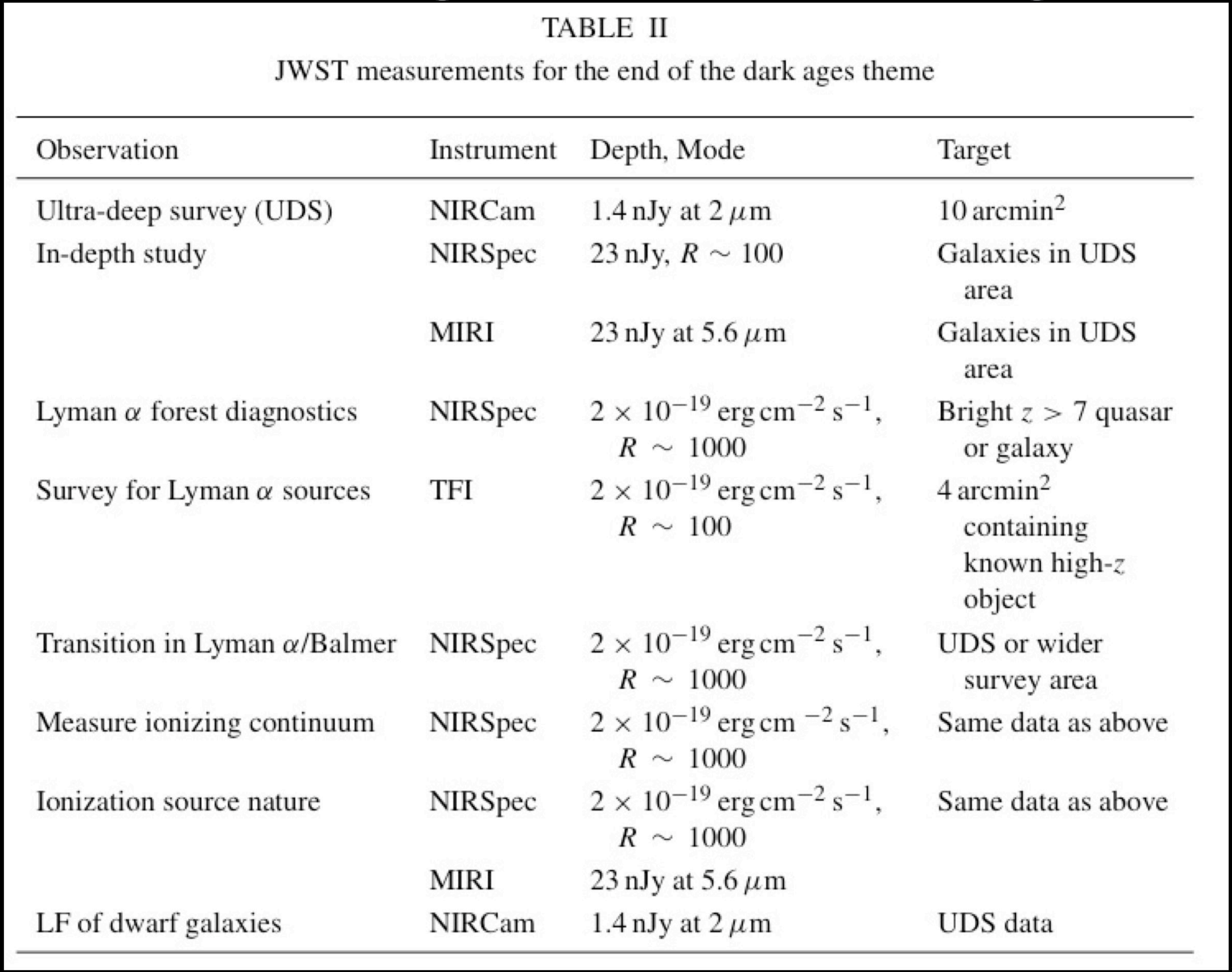


TABLE II

JWST measurements for the end of the dark ages theme

Observation	Instrument	Depth, Mode	Target
Ultra-deep survey (UDS)	NIRCam	1.4 nJy at 2 μm	10 arcmin^2
In-depth study	NIRSpec	23 nJy, $R \sim 100$	Galaxies in UDS area
	MIRI	23 nJy at 5.6 μm	Galaxies in UDS area
Lyman α forest diagnostics	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Bright $z > 7$ quasar or galaxy
Survey for Lyman α sources	TFI	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 100$	4 arcmin^2 containing known high-z object
Transition in Lyman α/Balmer	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	UDS or wider survey area
Measure ionizing continuum	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Same data as above
Ionization source nature	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Same data as above
	MIRI	23 nJy at 5.6 μm	
LF of dwarf galaxies	NIRCam	1.4 nJy at 2 μm	UDS data

Assembly of Galaxies

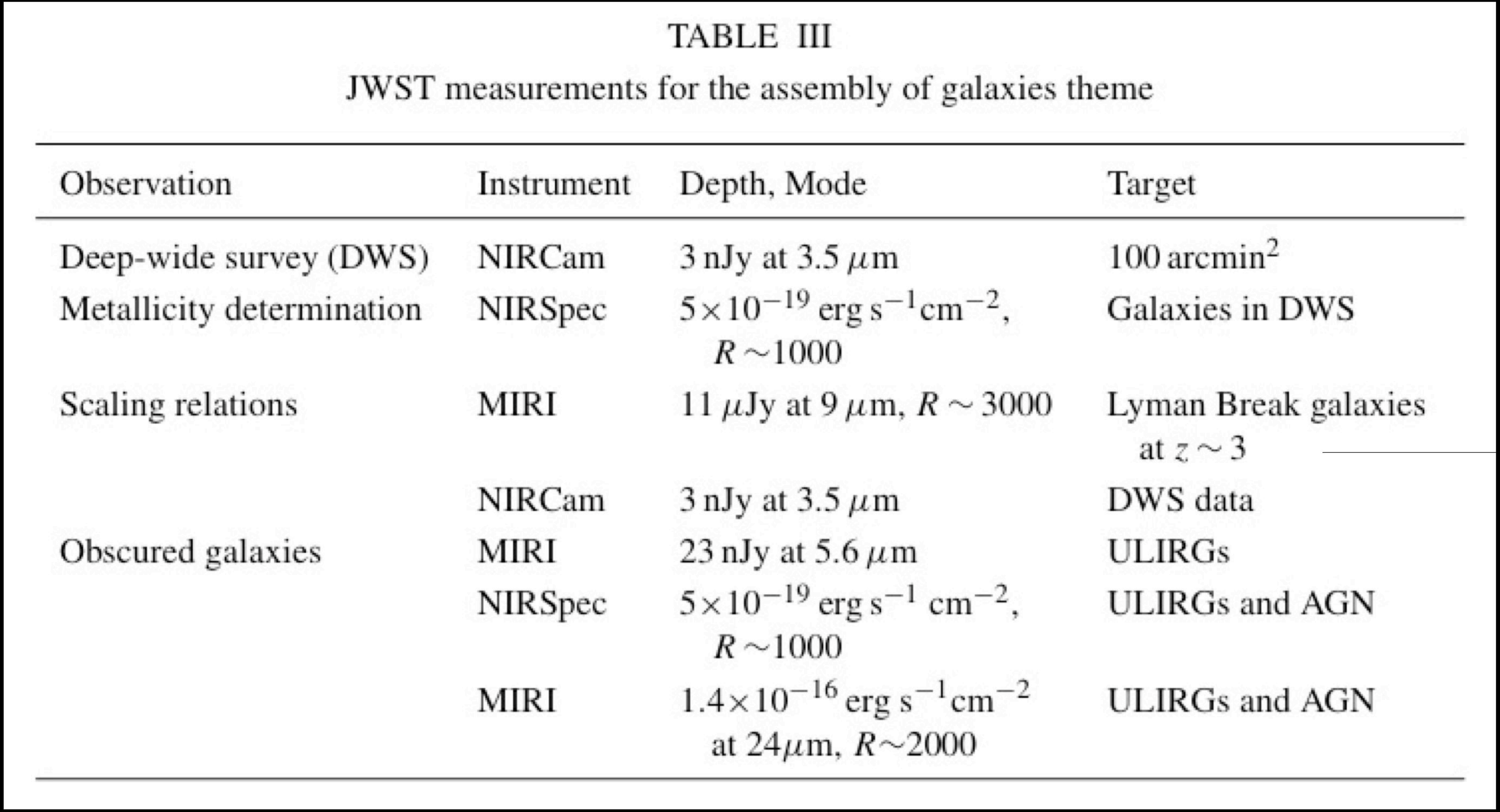


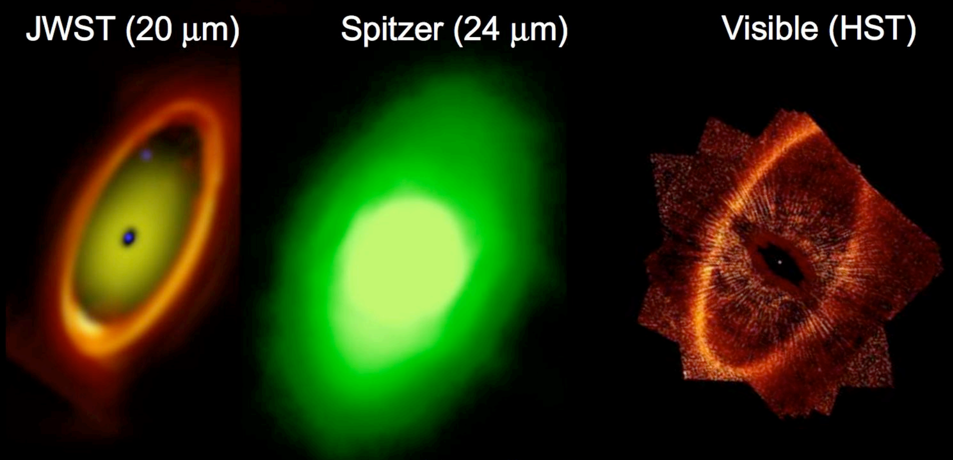
TABLE III

JWST measurements for the assembly of galaxies theme

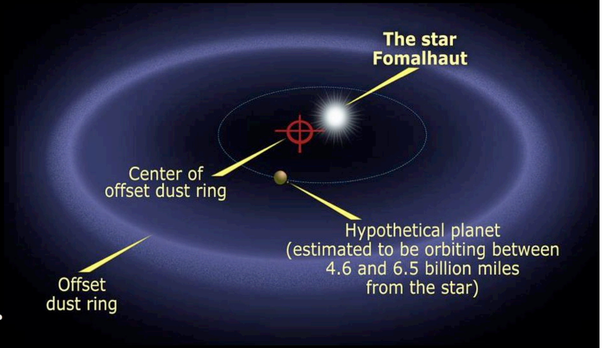
Observation	Instrument	Depth, Mode	Target
Deep-wide survey (DWS)	NIRCam	3 nJy at 3.5 μm	100 arcmin^2
Metallicity determination	NIRSpec	5×10^{-19} erg s^{-1}cm^{-2}, $R\sim1000$	Galaxies in DWS
Scaling relations	MIRI	11 μJy at 9 μm, $R\sim3000$	Lyman Break galaxies at $z\sim3$
	NIRCam	3 nJy at 3.5 μm	DWS data
Obscured galaxies	MIRI	23 nJy at 5.6 μm	ULIRGs
	NIRSpec	5×10^{-19} erg s^{-1} cm^{-2}, $R\sim1000$	ULIRGs and AGN
	MIRI	1.4×10^{-16} erg s^{-1}cm^{-2} at 24μm, $R\sim2000$	ULIRGs and AGN

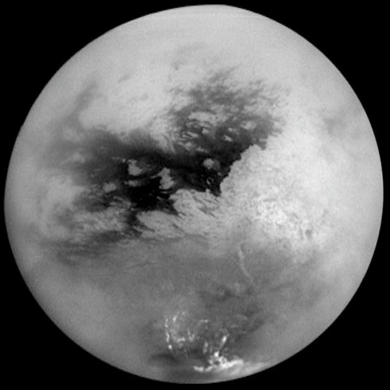
Planetary systems and the origins of life

- How do planets form?
- Are exosolar systems like our own?
- How are habitable zones established?
- Detection of planets via debris disks
  - Directly image very young planets
  - Indirectly detect planets via their footprints in debris disks



Fomalhaut



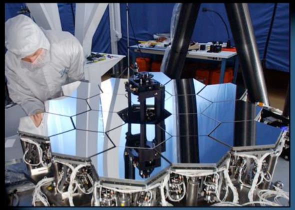


Titan

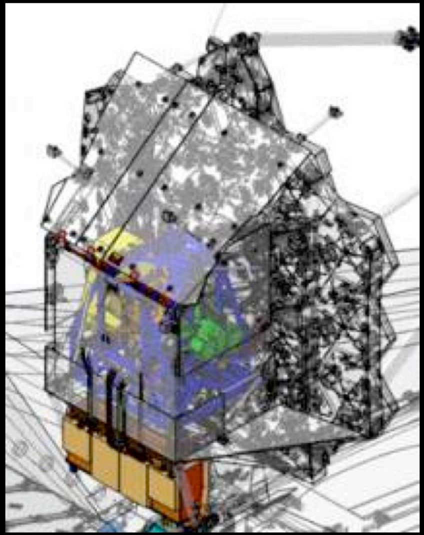
- Exosolar giant planets
  - direct imaging by blocking star’s light
- Spectra of organic molecules in disks, comets and Kuiper belt objects in outer solar system
- Atmospheric composition of exosolar planets
  - Observe transits of planets

JWST Technology

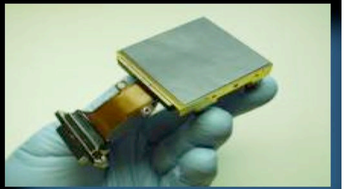
Mirror Phasing Algorithms



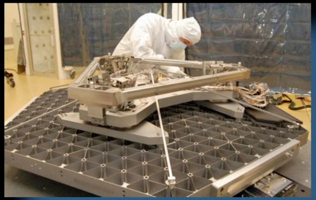
Backplane

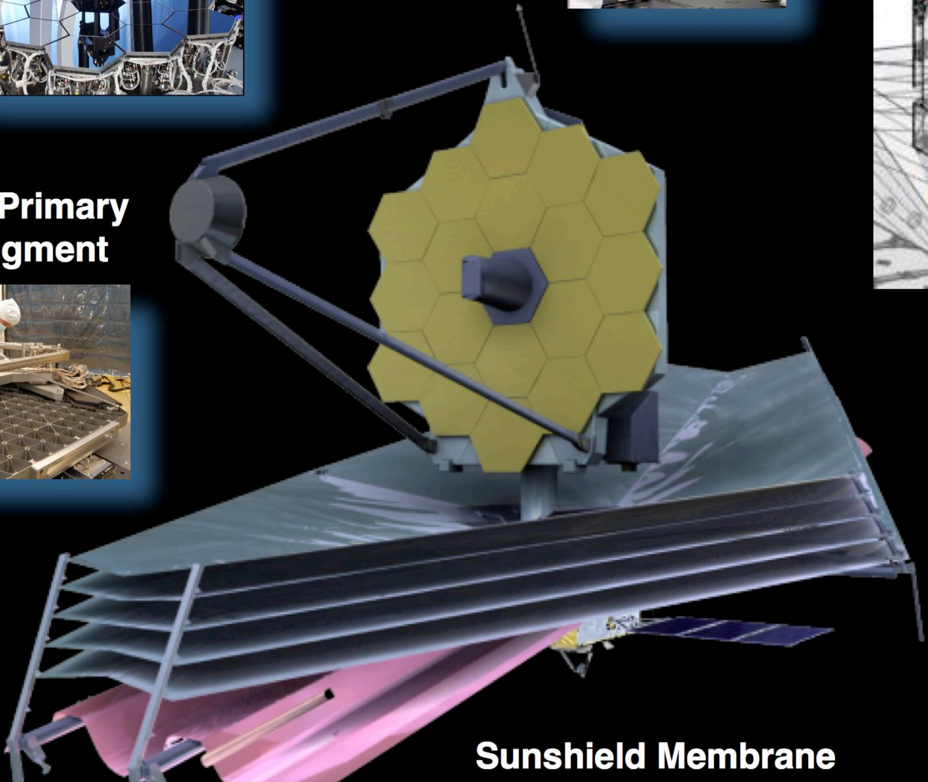


Near-Infrared Detecto

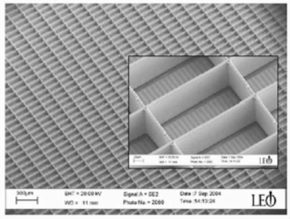


Beryllium Primary Mirror Segment

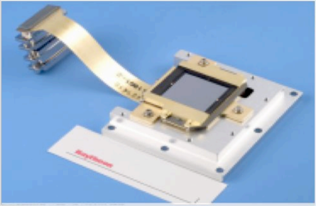




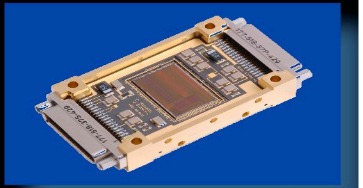
μShutters



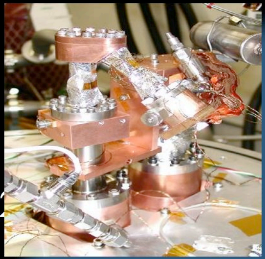
Mid-Infrared Detecto



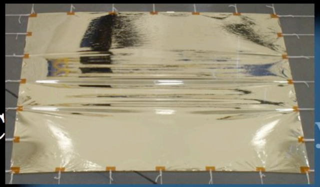
Cryogenic ASICs



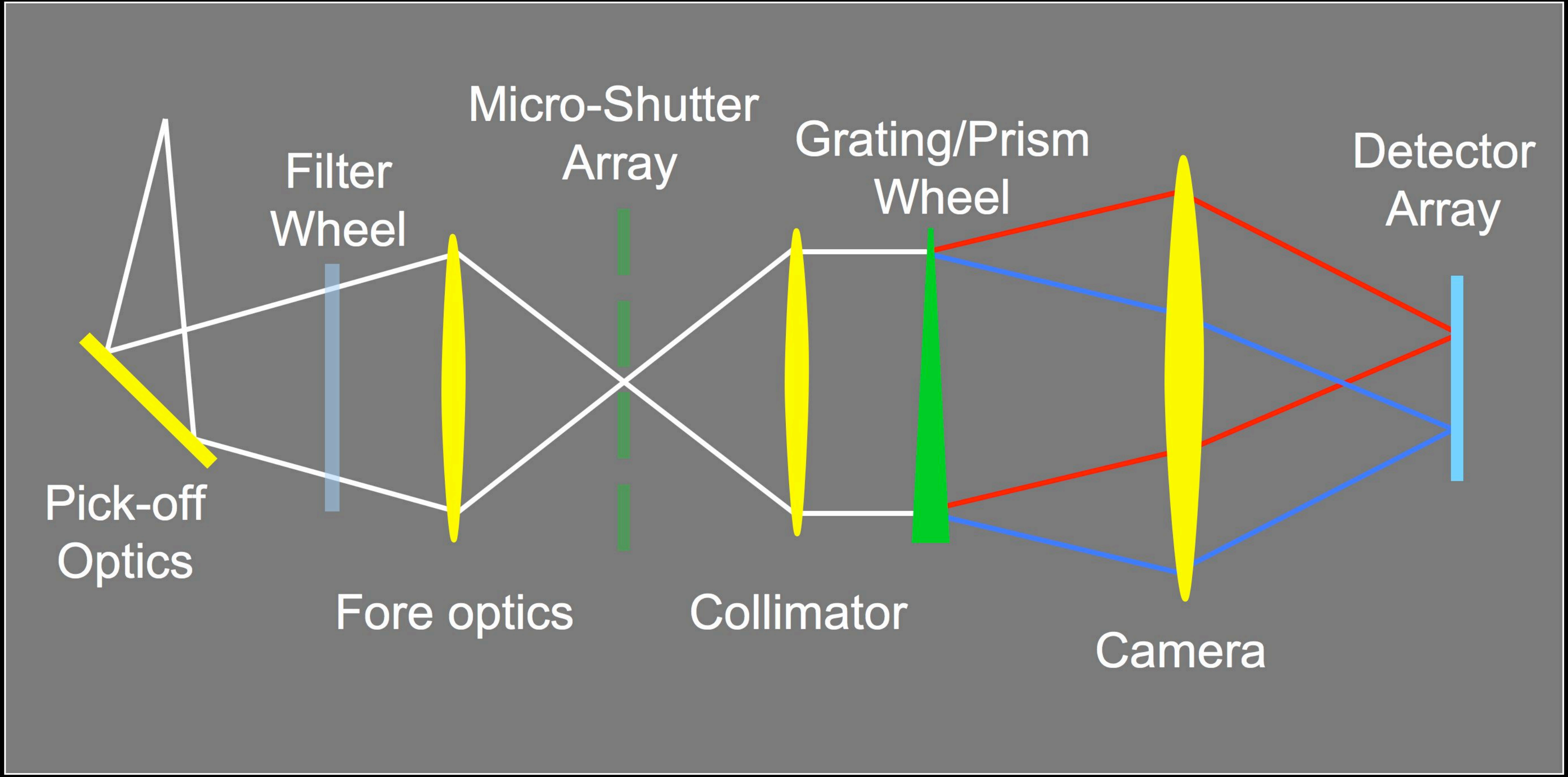
Cryocooler



Sunshield Membrane

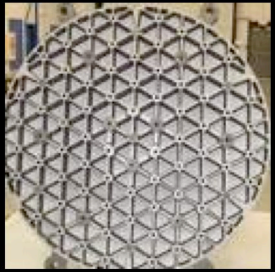


NIRSpec Schematic

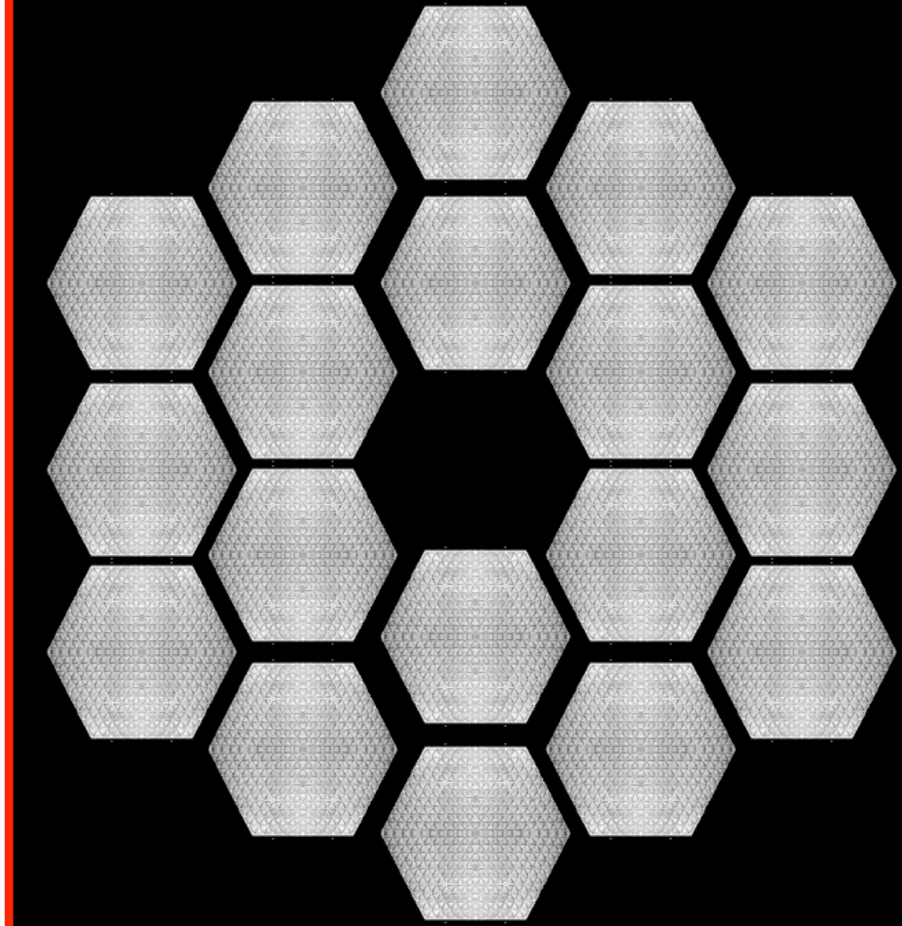


Flight Mirror Lightweighting Complete

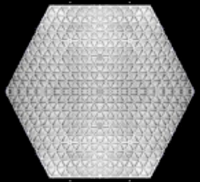
- **Lightweighting**
- **Axsys**



Secondary Mirror



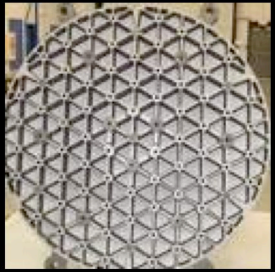
Primary Mirror Segments



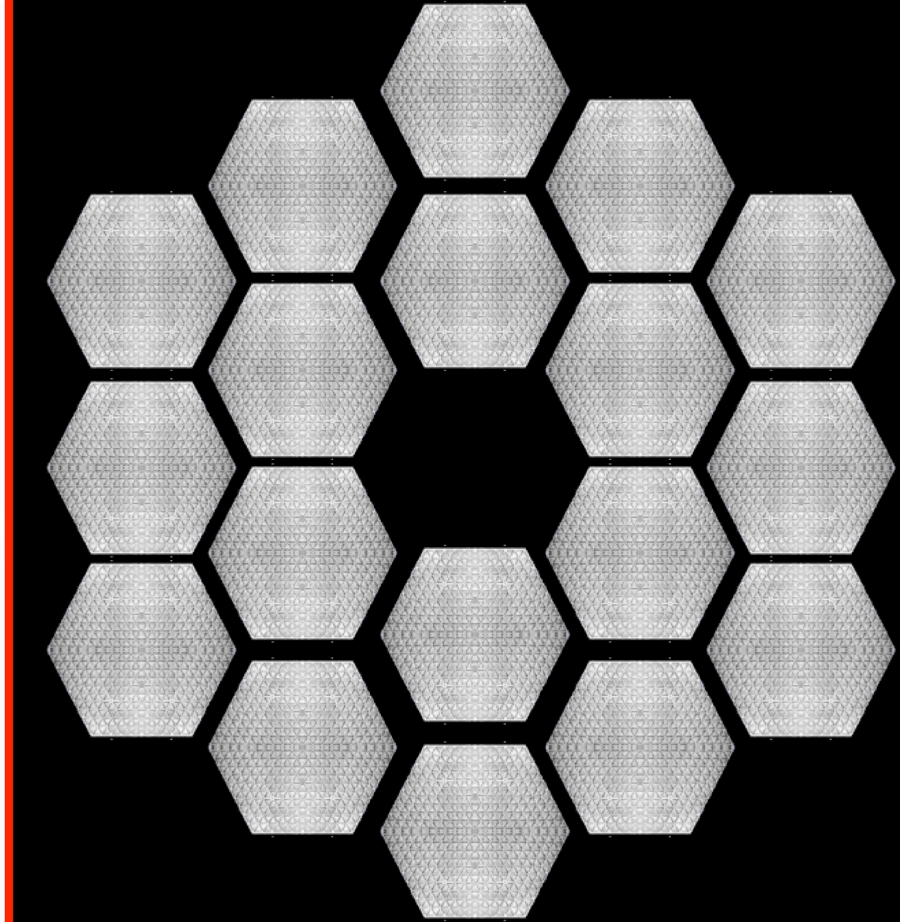
Pathfinder Mirror

Flight Mirror Lightweighting Complete

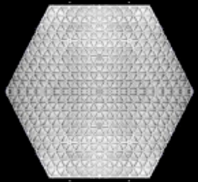
- **Lightweighting**
- **Axsys**



Secondary Mirror

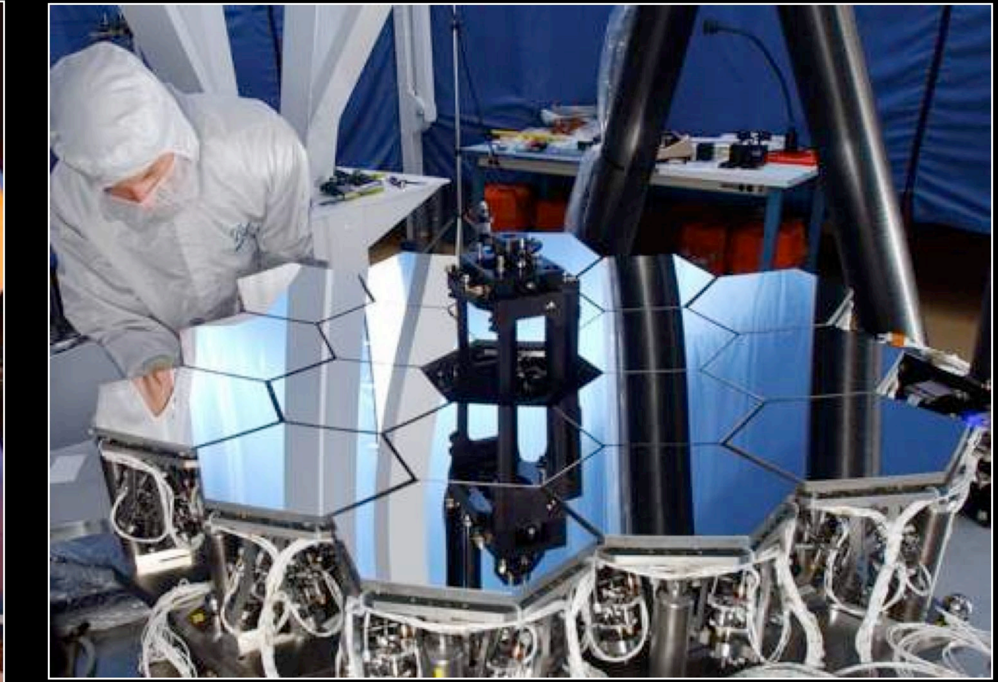


Primary Mirror Segments



Pathfinder Mirror

Wavefront Sensing and Control – Testbed

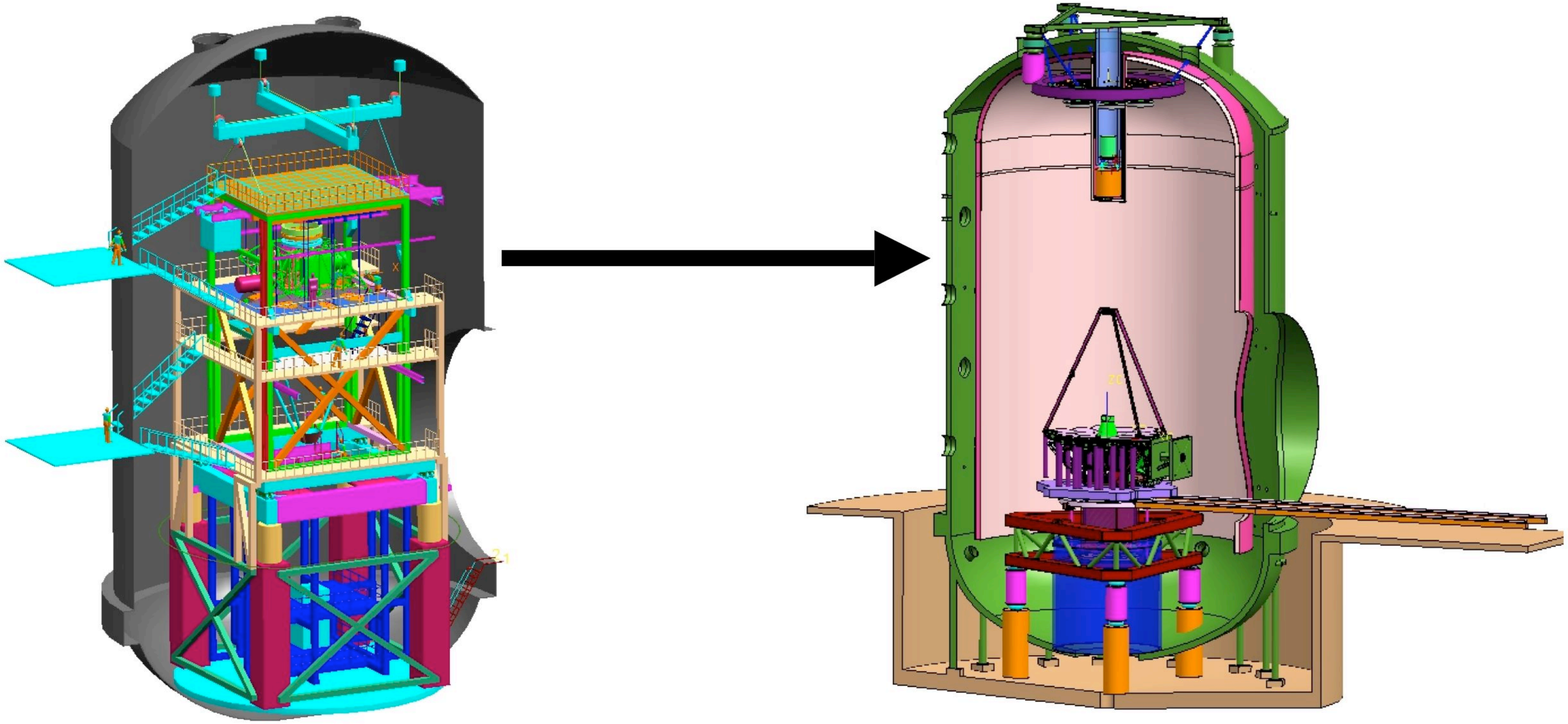


- WFSC Testbed Telescope is a 1/6th scale, fully functional model of the JWST telescope with performance traceable to JWST
- Testbed provides functionally accurate simulation platform for developing deliverable WFSC algorithms and software
- Algorithms have had initial check outs on the testbed
- Remaining WFSC TRL task is to demonstrate end-to-end wavefront sensing and control through final alignment

Simplified Test Configuration at JSC

Old "Cup Down" Configuration
Included Large Metrology Tower
And Test Equipment Inside Shrouds

New "Cup Up" Configuration Eliminates Tower
And Allows for Accessibility to Test Equipment
From Top and Bottom of Chamber during testing



JSC Size, Accessibility, and Large Side Door Access
Make it Well Suited for This Configuration

The End