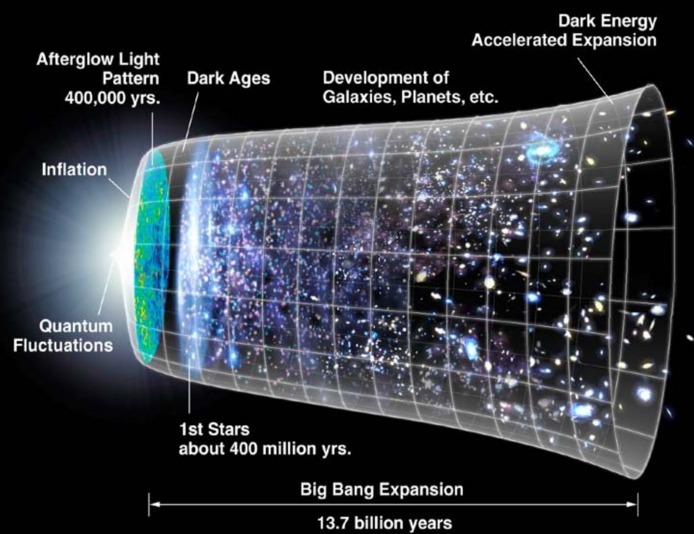
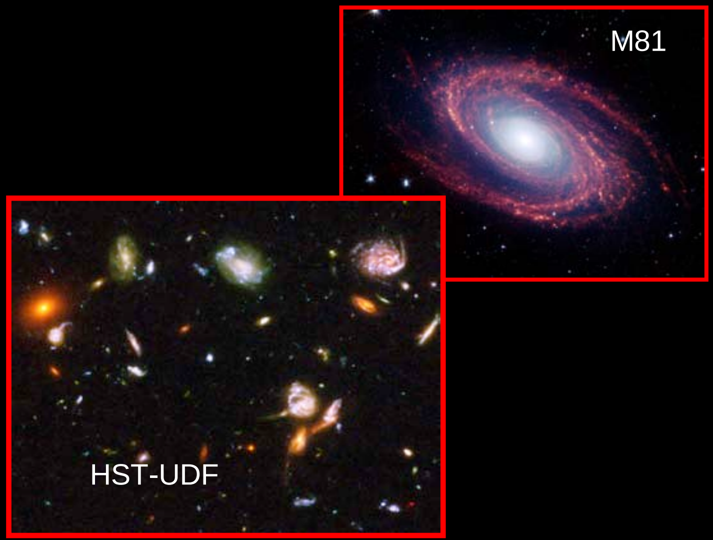
The Beginnings of Everything, from the Big Bang to Planets – progress and opportunity with the JWST Observatory

John Mather
JWST Senior Project Scientist
Goddard Space Flight Center

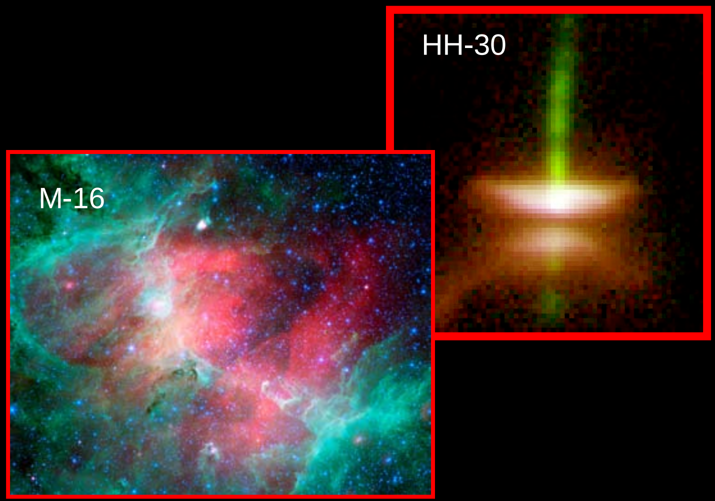
Decadal 2000 & 2010 Science with JWST



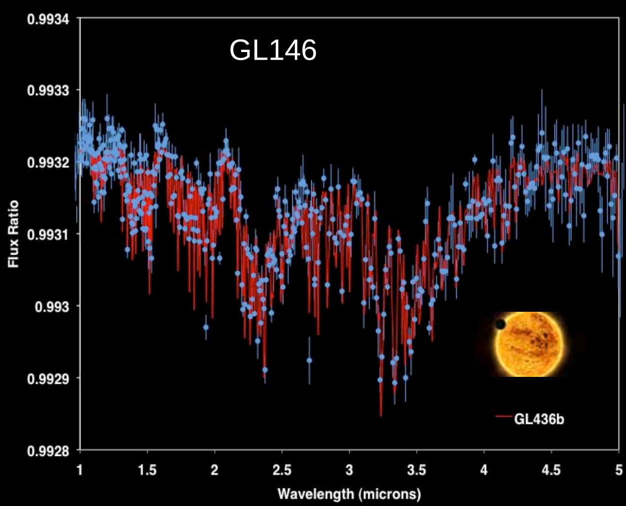
First Light and Re-Ionization



Assembly of Galaxies

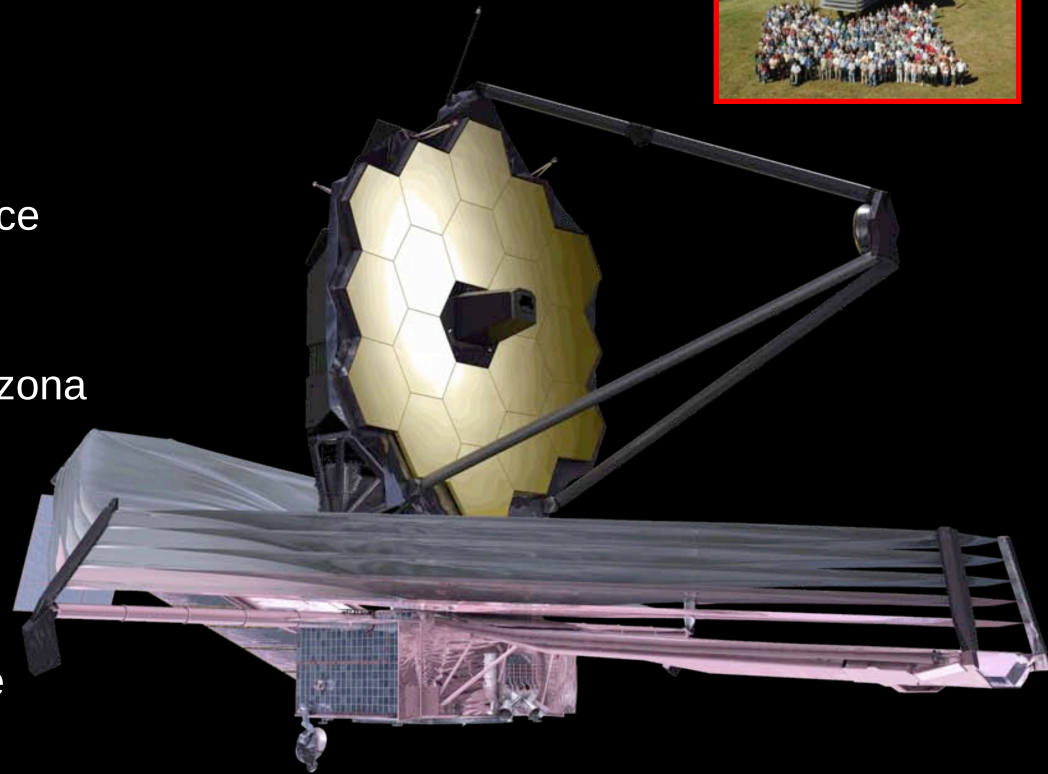


Birth of stars and proto-planetary systems



Planetary systems and the origin of life

James Webb Space Telescope



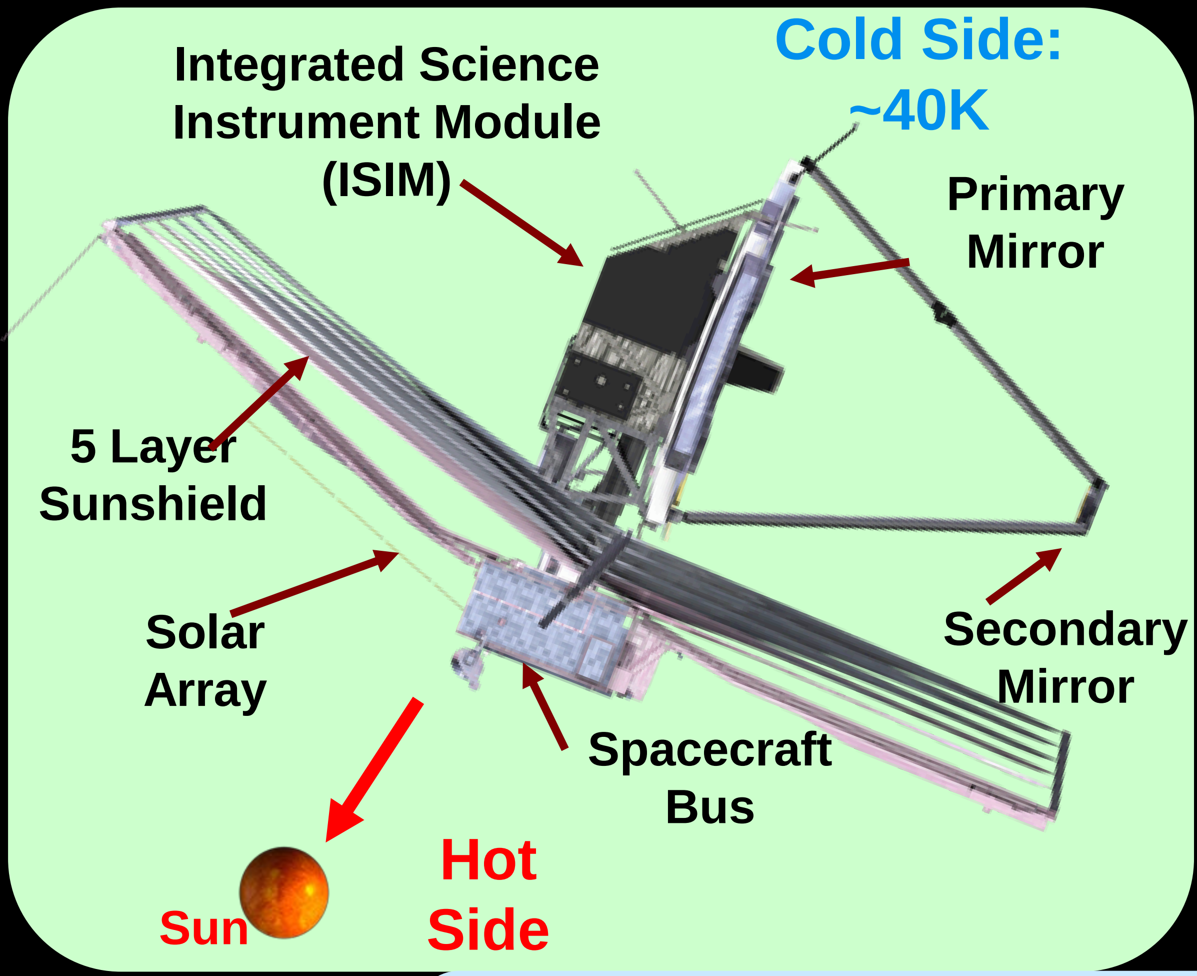
Organization

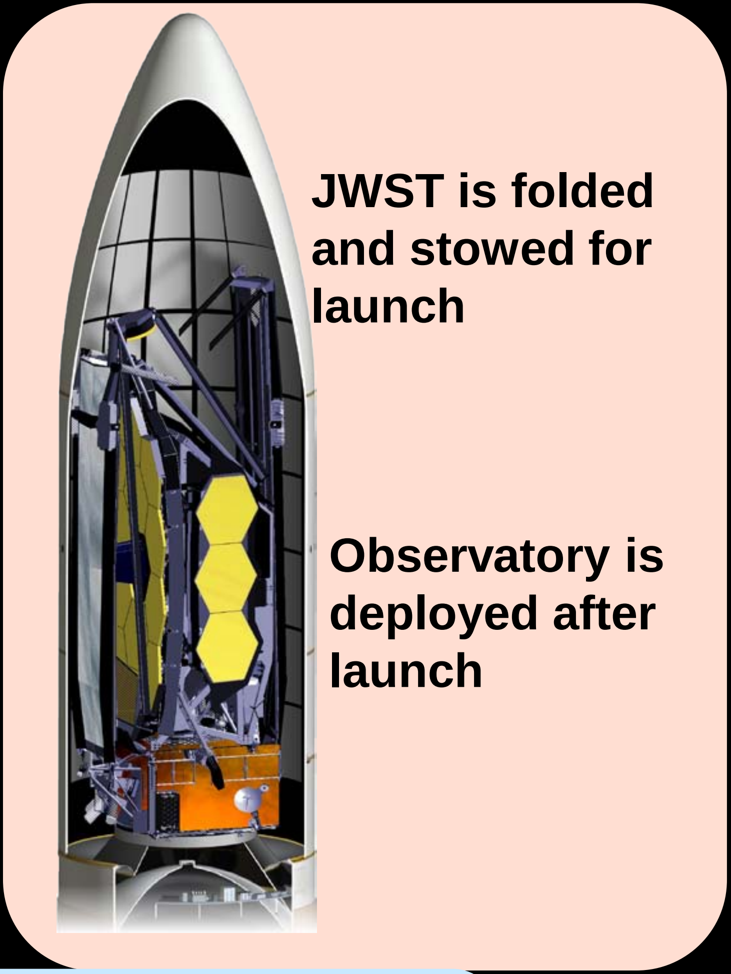
- Mission Lead: Goddard Space Flight Center
- Senior Project Scientist: Dr John Mather
- International collaboration: ESA & CSA
- Prime Contractor: Northrop Grumman Aerospace Systems
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) & Tunable Filter Imager – CSA
- Operations: Space Telescope Science Institute

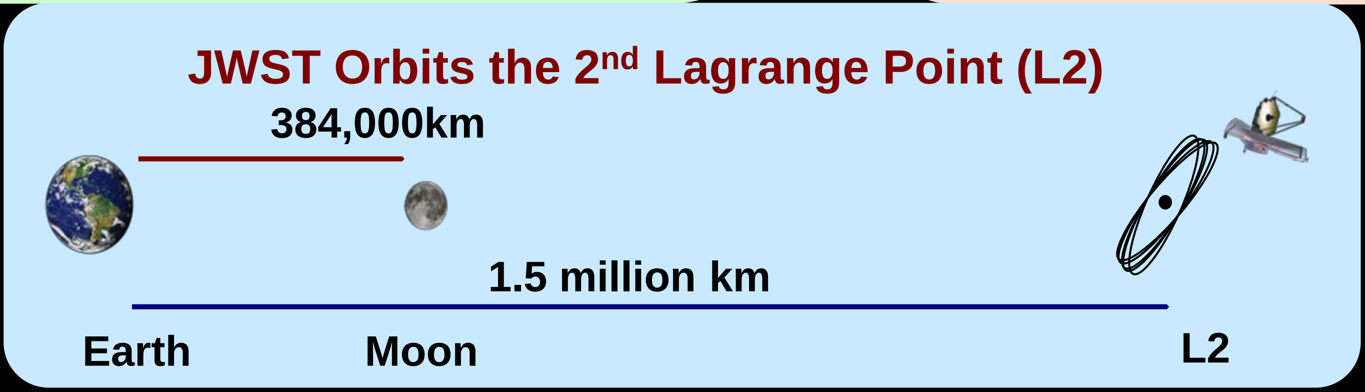
Description

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

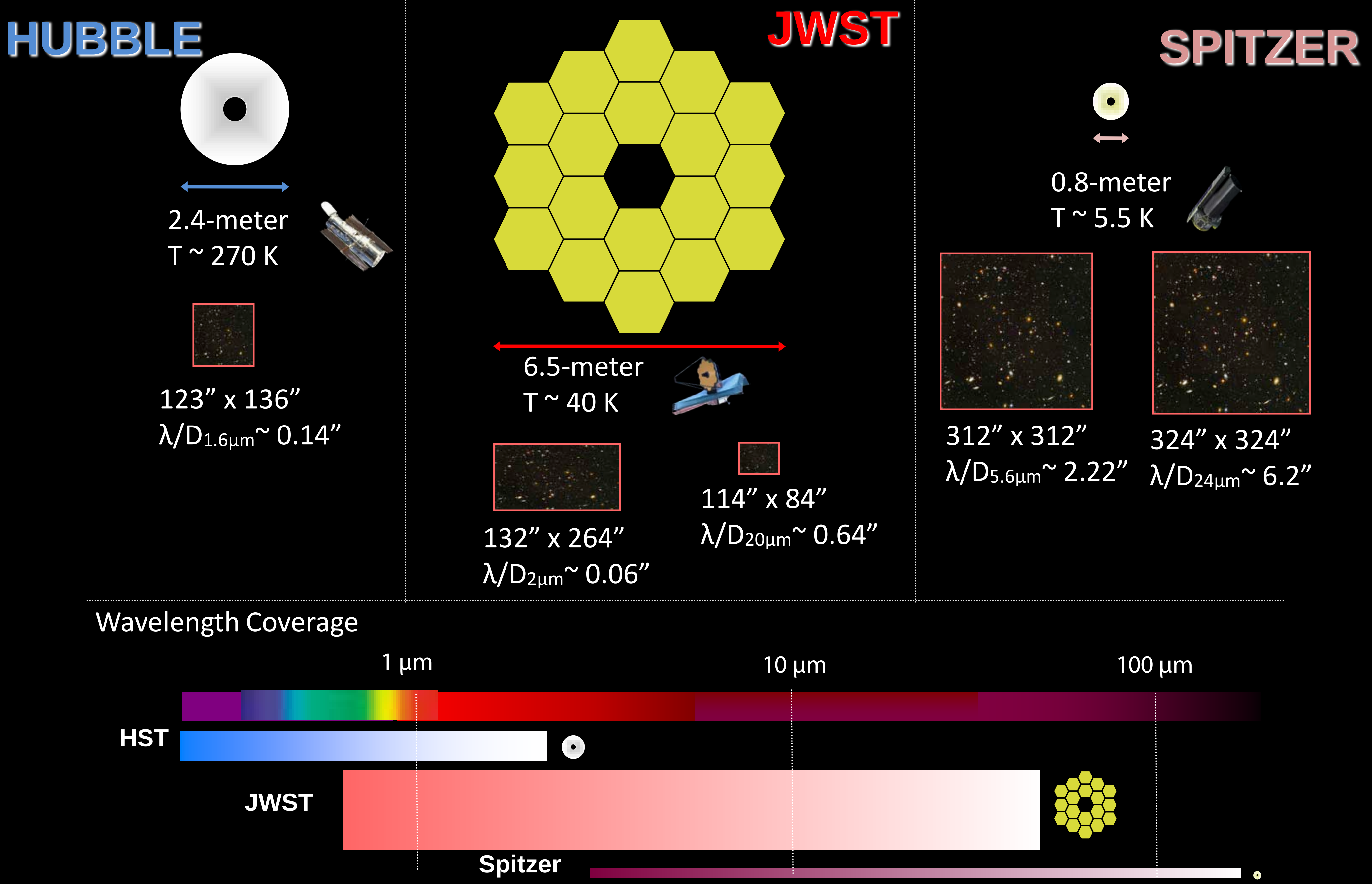
HOW JWST WORKS



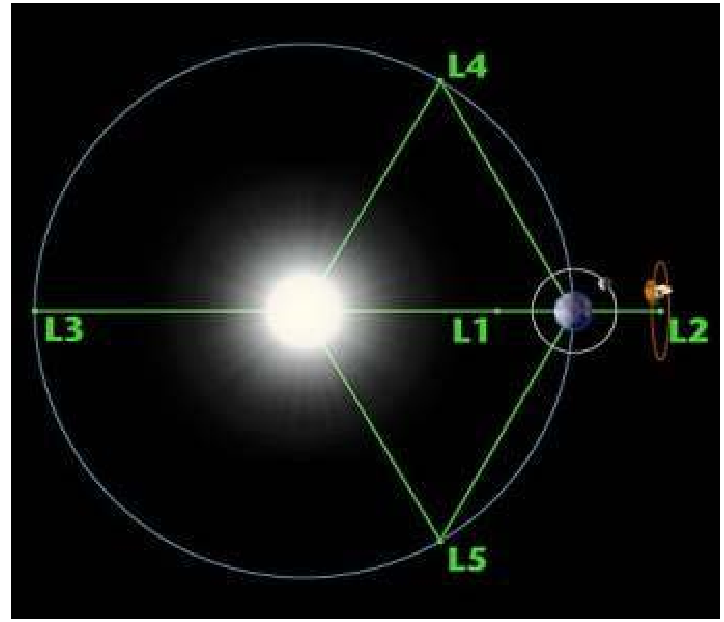




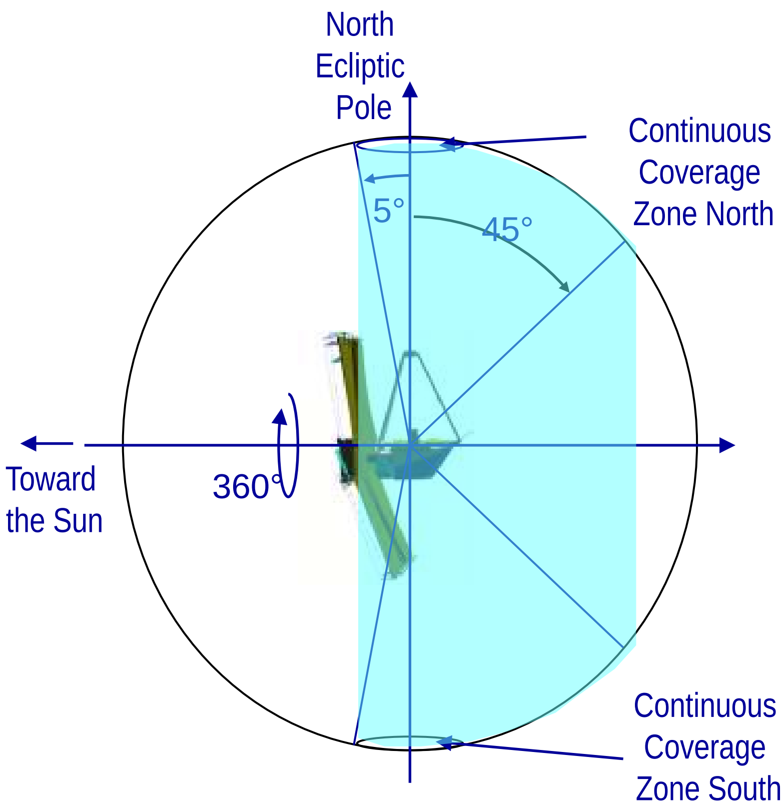
JWST and its Precursors



JWST science objectives require the largest cryogenic telescope ever constructed

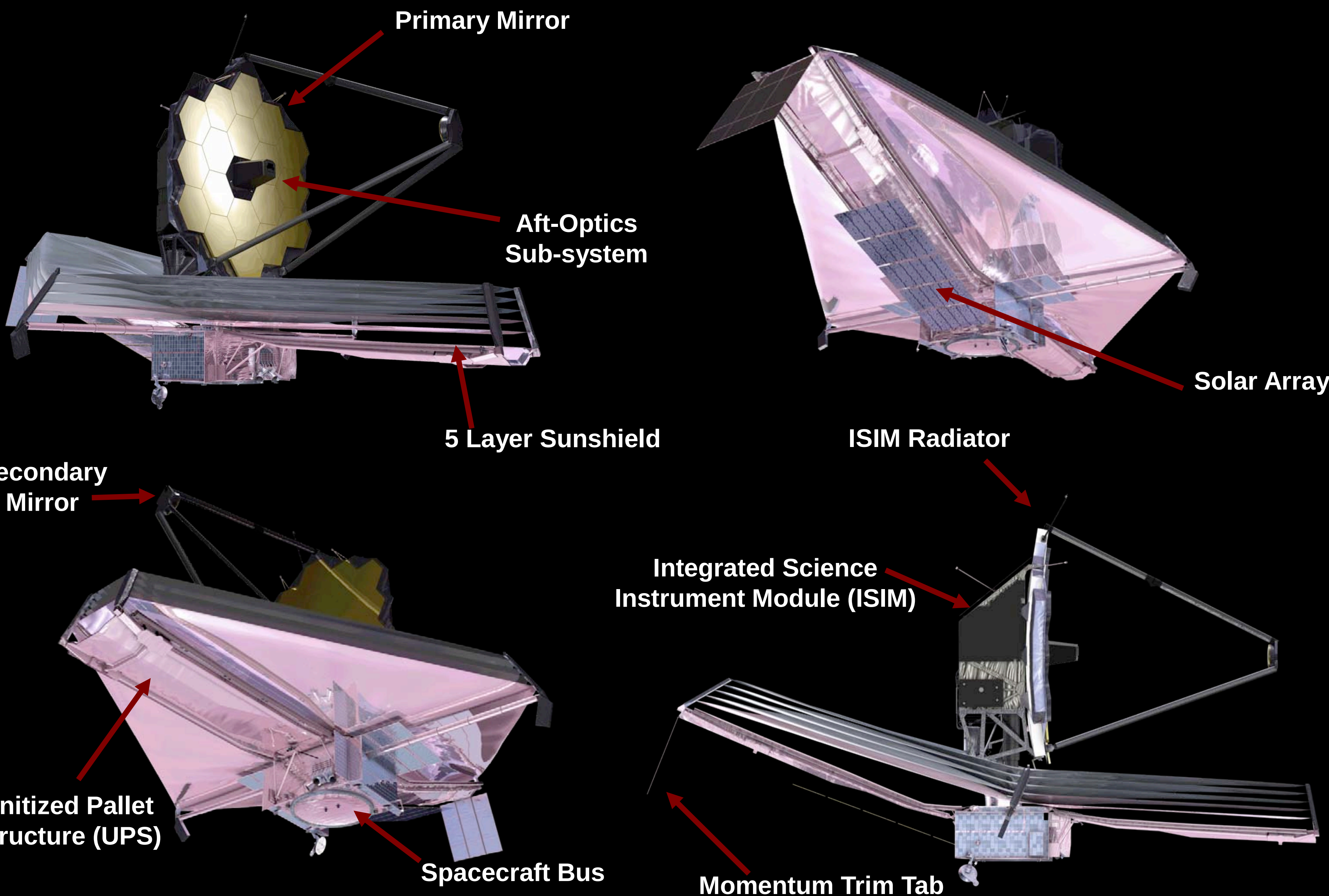


- An L2 point orbit was selected for JWST to enable passive cryogenic cooling
  - Station keeping thrusters fire ~ every 3 weeks to maintain this orbit
  - Propellant sized for 11 years (delta-v ~ 93 m/s)



- The JWST can observe the whole sky while remaining continuously in the shadow of its sunshield
  - Field of Regard is an annulus covering 35% of the sky
  - The whole sky is covered each year with small continuous viewing zones at the Ecliptic poles

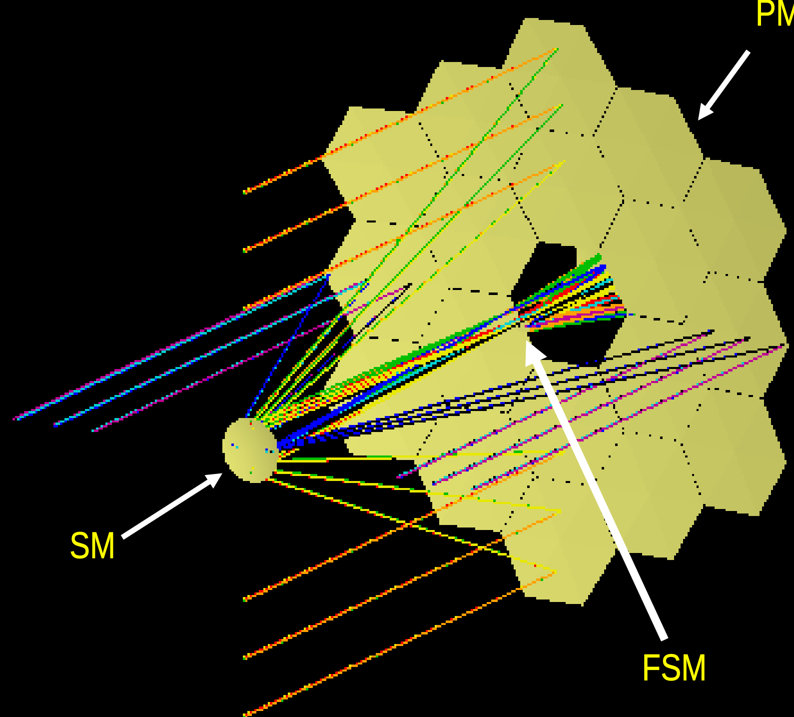
JWST Design: Key Features

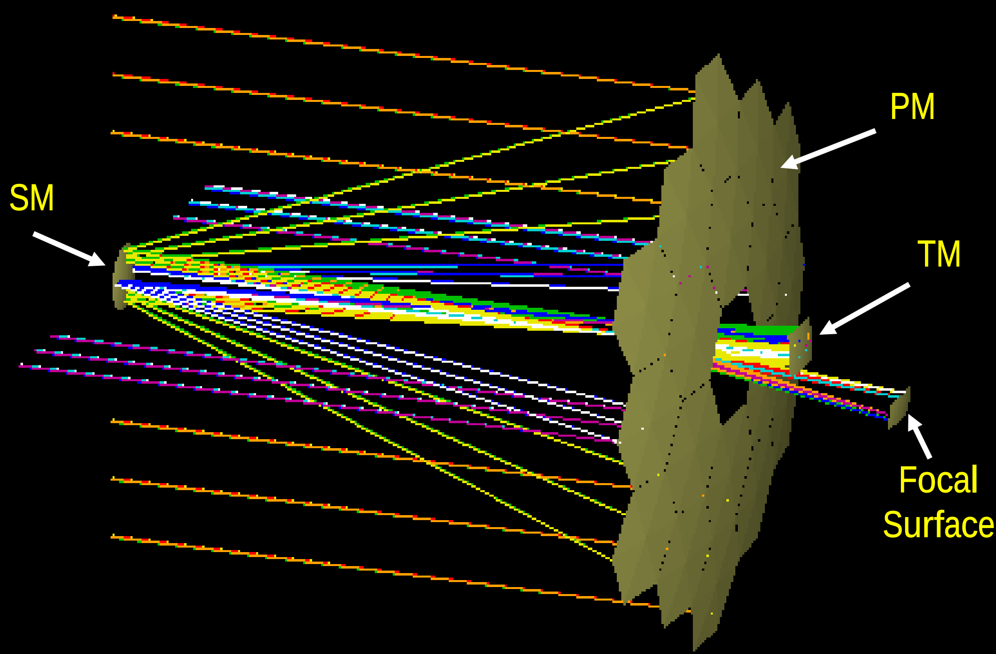


JWST Deployment

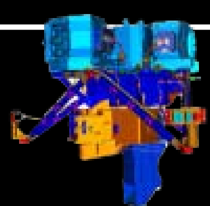
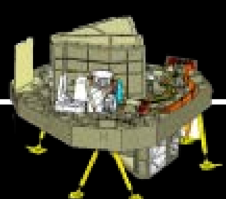
JWST's Optical Design: I

- **JWST's Optical Telescope Element is a Three Mirror Anistigmat (TMA)**
  - **Wide field of view: 18.2 x 9.1 arcmi**
- **Optical design: f/20**
- **Diameter of entrance pupil: 6.6 m**
- **Effective focal length: 131.4 m**
- **Clear aperture area: 25 m^2**

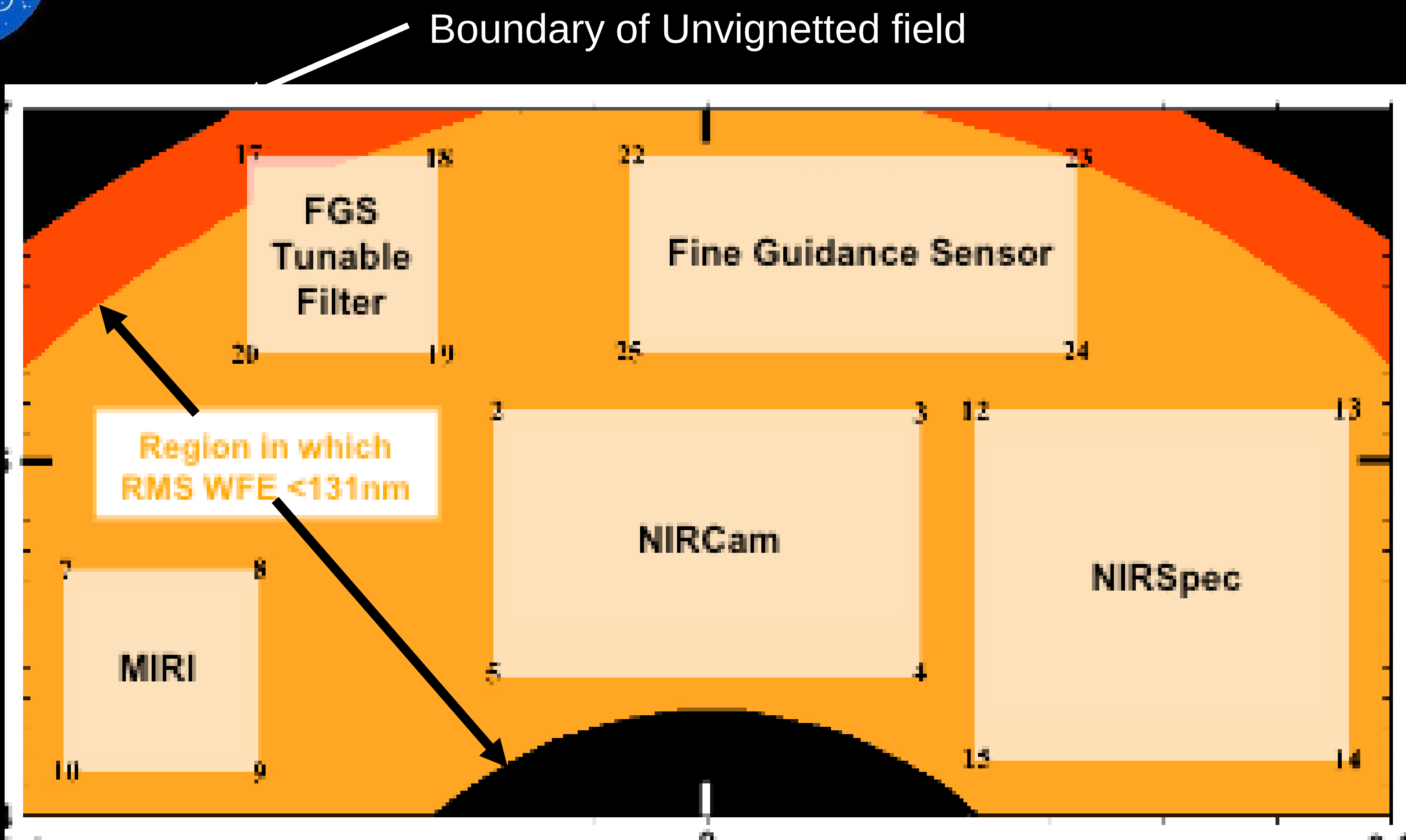




JWST Instrumentation

Instrument	Science Requirement	Capability
NIRCam Univ. Az/LMATC 	Wide field, deep imaging ‣0.6 µm - 2.3 µm (SW) ‣2.4 µm - 5.0 µm (LW)	Two 2.2’ x 2.2’ SW Two 2.2’ x 2.2’ LW Coronagraph
NIRSpec ESA/Astrium 	Multi-object spectroscopy ‣0.6 µm - 5.0 µm	9.7 Sq arcmin Ω + IFU + slits 100 selectable targets: MSA R=100, 1000, 3000
MIRI ESA/UKATC/JPL 	Mid-infrared imaging ‣ 5 µm - 27 µm Mid-infrared spectroscopy ‣ 4.9 µm - 28.8 µm	1.9’ x1.4’ with coronagraph 3.7”x3.7” – 7.1”x7.7” IFU R=3000 - 2250
FGS/TFI CSA 	Fine Guidance Sensor 0.8 µm - 5.0 µm Tunable Filter Imager ‣1.6 µm - 4.9 µm	Two 2.3’ x 2.3’ 2.2’ x 2.2’ R=100 with coronagraph

Field Position of Science Instruments



Instruments and Guidance Sensor Share Telescope Field of View

Sensitivity & Resolution

- Cameras and R ~ 100 spectroscopy background limited at all wavelengths
  - 6.5 m mirror much larger than HST, Spitzer - big gains
  - Background dominated by zodi light, and at > 12 µm from thermal emission from sunshield
  - Other stray light from galaxy, sometimes Earth or Moon
- NIRSpec sensitivity detector limited at R ~ 1000
- Image quality
  - Diffraction limited (λ/14 rms wavefront) at 2 µm (better than ground AO in Strehl and much better Field of View)
  - 0.032 arcsec pixels in NIRCam short band (Nyquist @ 2 µm)
  - 0.065 arcsec in NIRCam long band and .068 in Fine Guider
  - 0.2 x 0.45 arcsec shutters for NIRSpec
  - 0.11 arcsec pixels for MIRI camera
  - 0.19 - 0.28 arcsec pixels for MIRI image slicer integral field unit

Galaxy Evolution Simulation

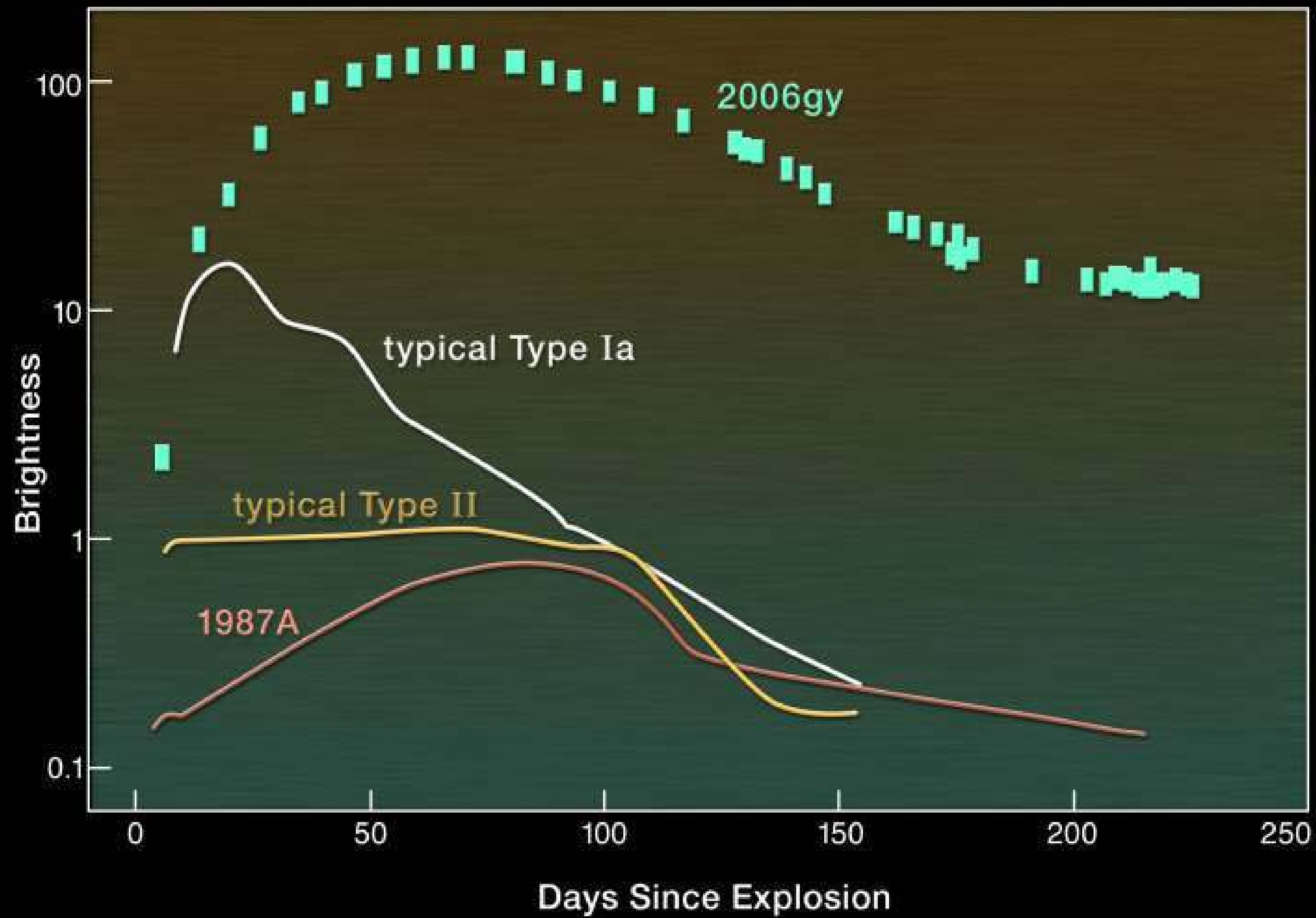
Galaxy collision simulation

End of the dark ages: first light and reionization

… to identify the first luminous sources to form and to determine the ionization history of the early universe.

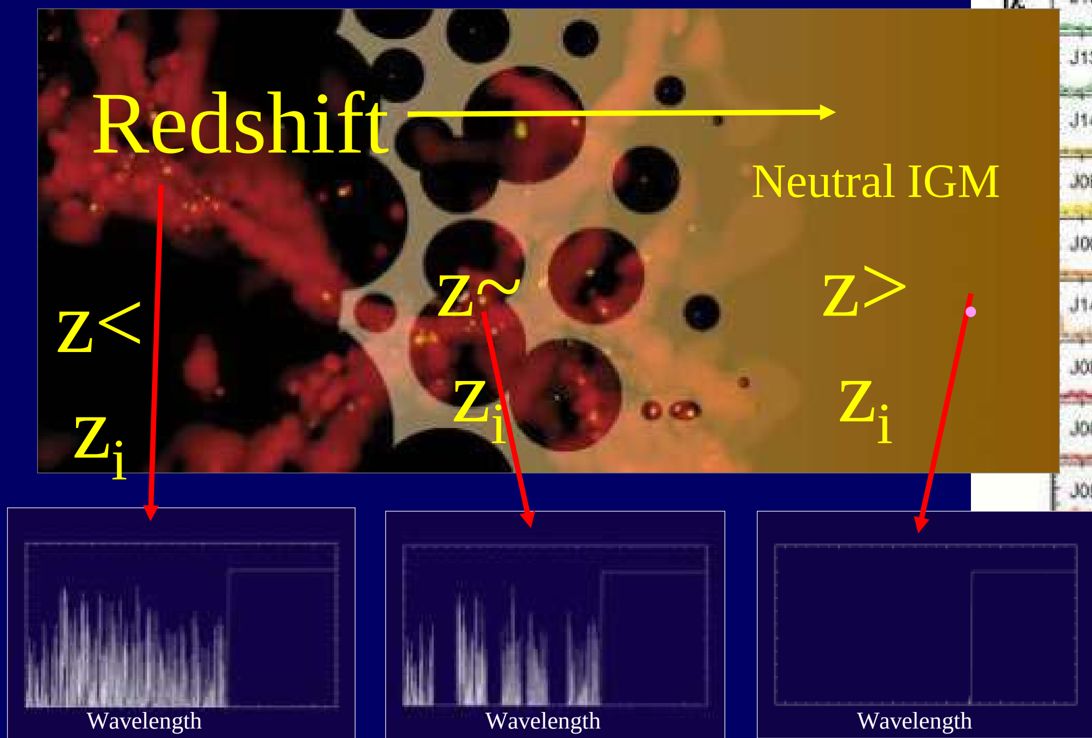
Hubble Ultra Deep Field

SNe as First (individually detectable) Stars



- JWST can easily see these at z = 10-20, but they're rare, and much slower!

When was re-ionization?



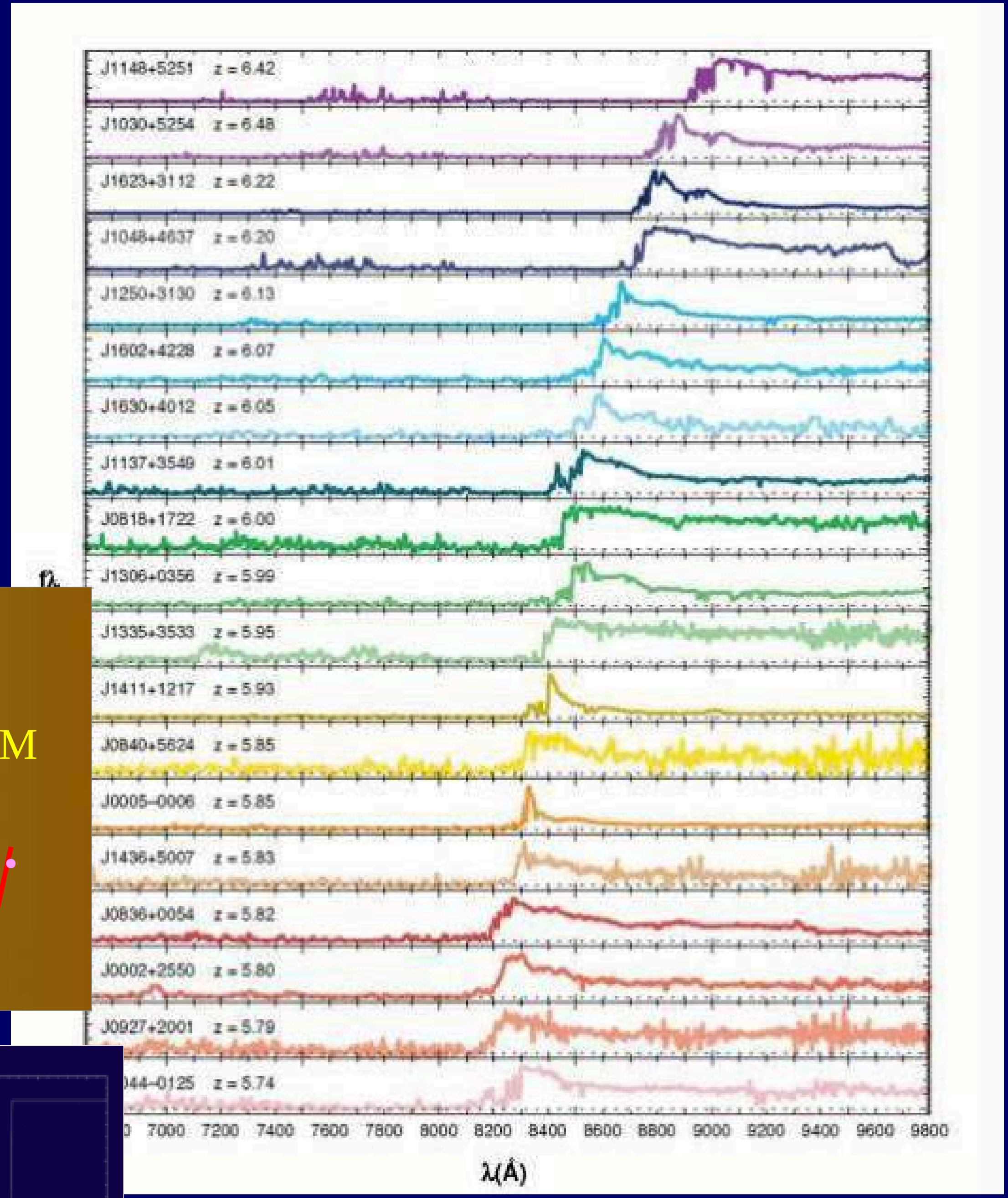
Lyman Forest Absorption

Patchy Absorption

Black Gunn-Peterson trough

6.42

6.00



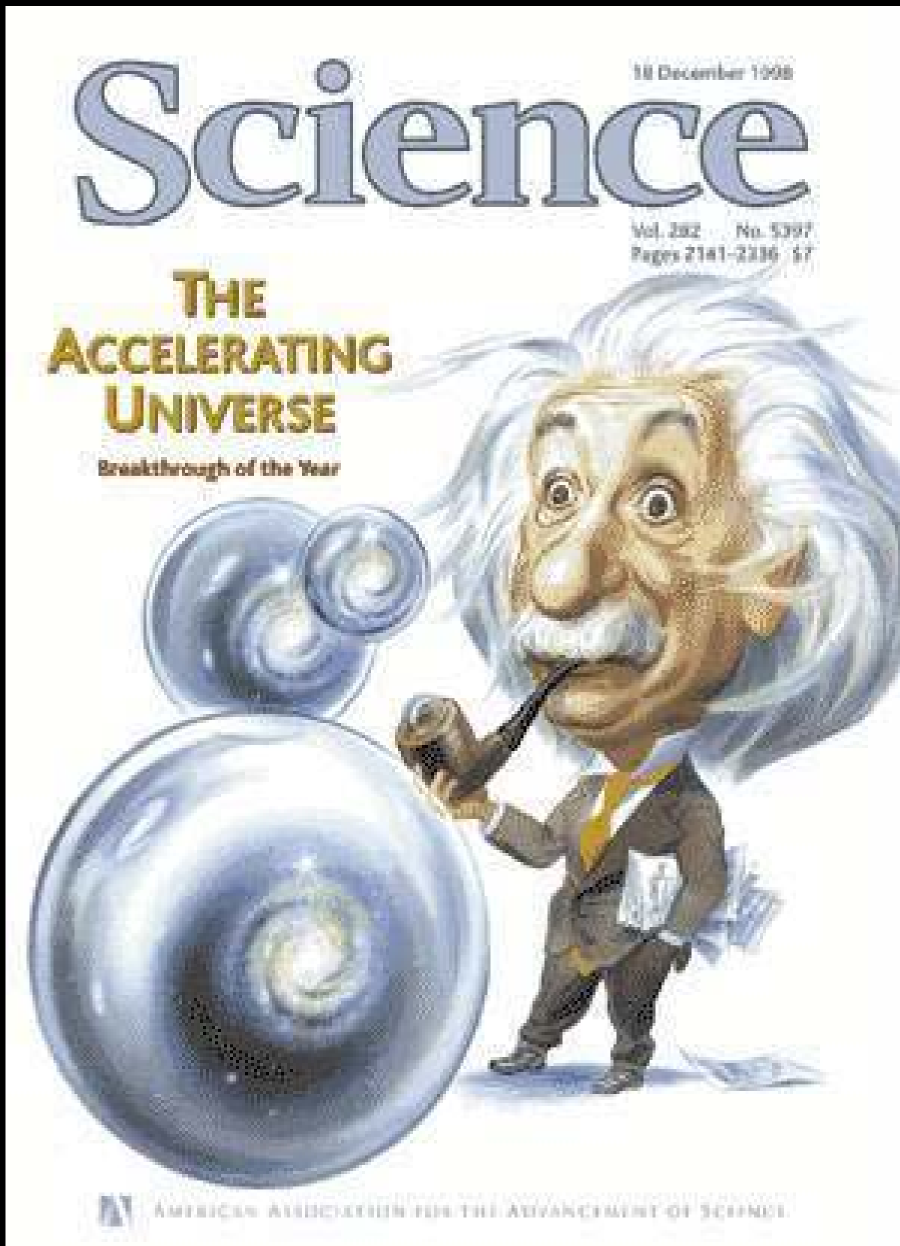
5.74

Mather JWST 2011

Fan, Carilli & Keating 2006, ARAA, 44, 415

Dark Energy!

MacArthur Fellow
2008 - Adam Riess



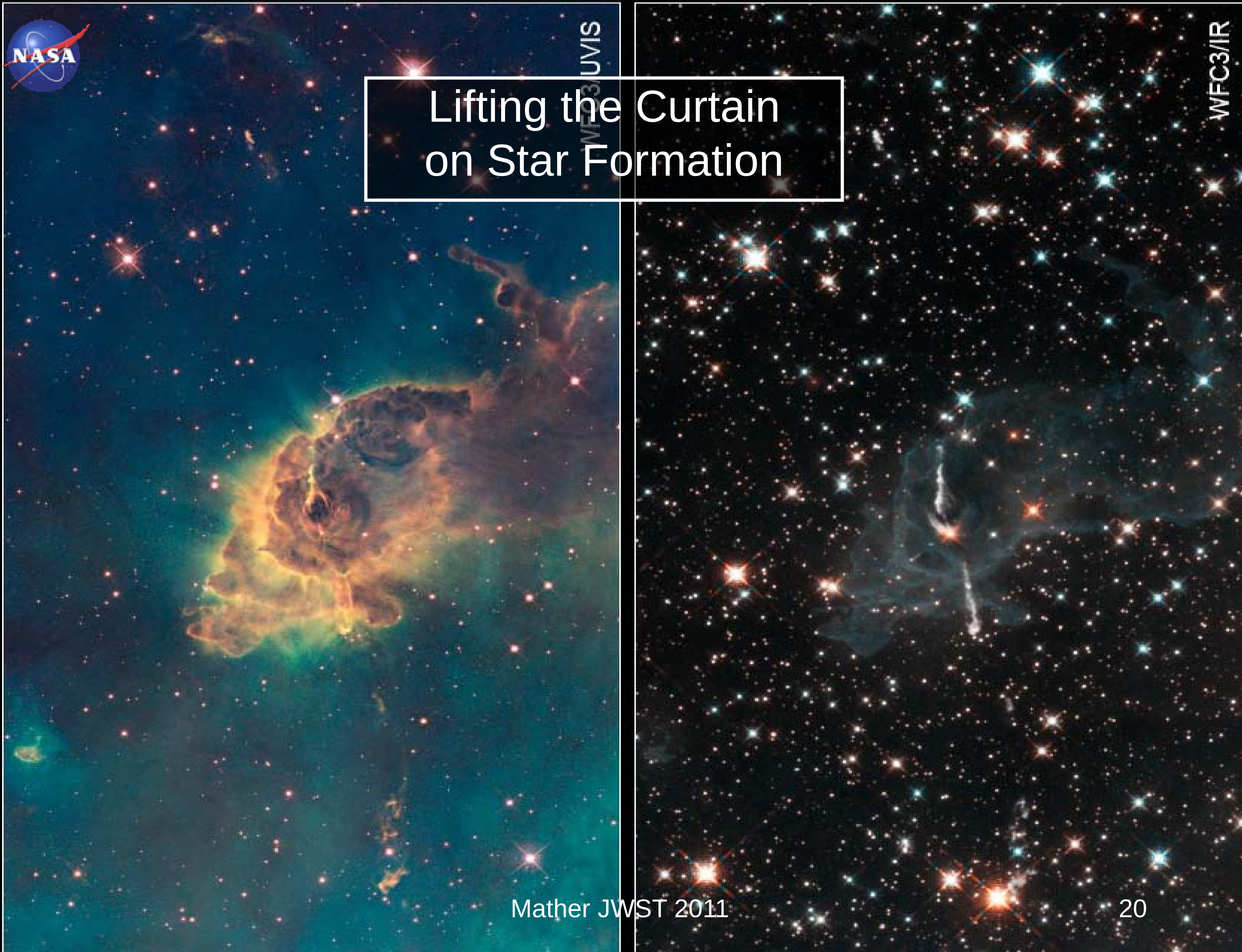
S. Perlmutter, A. Riess, B. Schmidt

How does environment affect star-formation and vice-versa?
What is the sub-stellar initial mass function?

- Massive stars produce winds and radiation
  - Either disrupt star formation, or causes it.
- The boundary between the smallest brown dwarf stars and planets is unknown
  - Different processes? Or continuum?
- Observations:
  - Survey dark clouds, “elephant trunks” and star-forming regions

The Eagle Nebula
as seen in the infrared

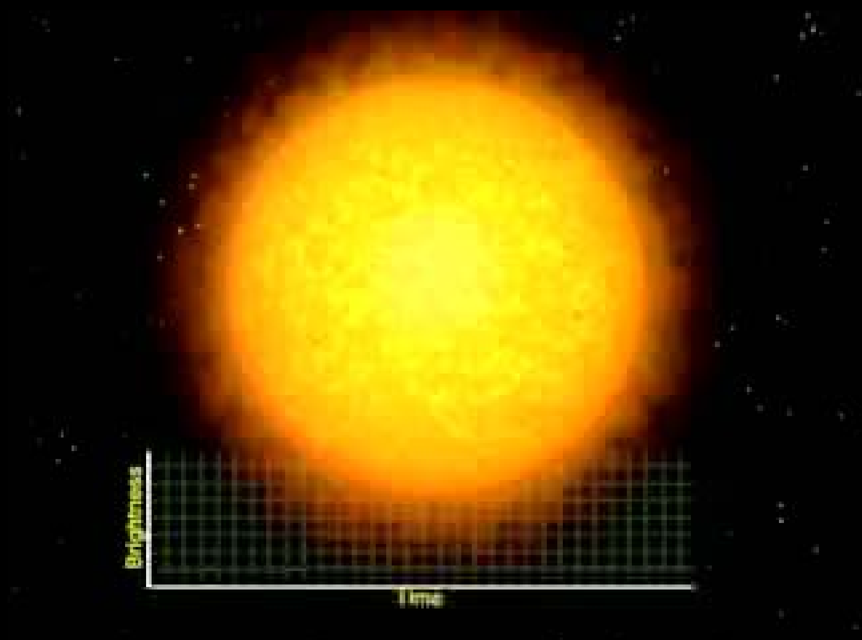
Lifting the Curtain on Star Formation



Exoplanets

- As of May 20, 2011, 551 confirmed planets (exoplanets.eu)
  - Radial velocity: 503 planets, 50 multiple planet systems
  - Transiting: 131 planets, including 10 multiples (most good JWST targets)
  - Microlensing: 12 planets, 1 multiple system
  - Imaging: 24 planets, 1 system (a triple) (all good JWST targets)
  - Timing: 12 planets, 4 multiple planet systems
  - + predictions from dust disk structures
- Kepler launched Mar. 6, 2009, monitors ~ 150,000 stars, to find handful of Earths, thousands of others – 1235 candidates already!
- Microlensing found 10 lonely planets (without stars!)
- JWST Transits Working Group established – M. Clampin

Primary

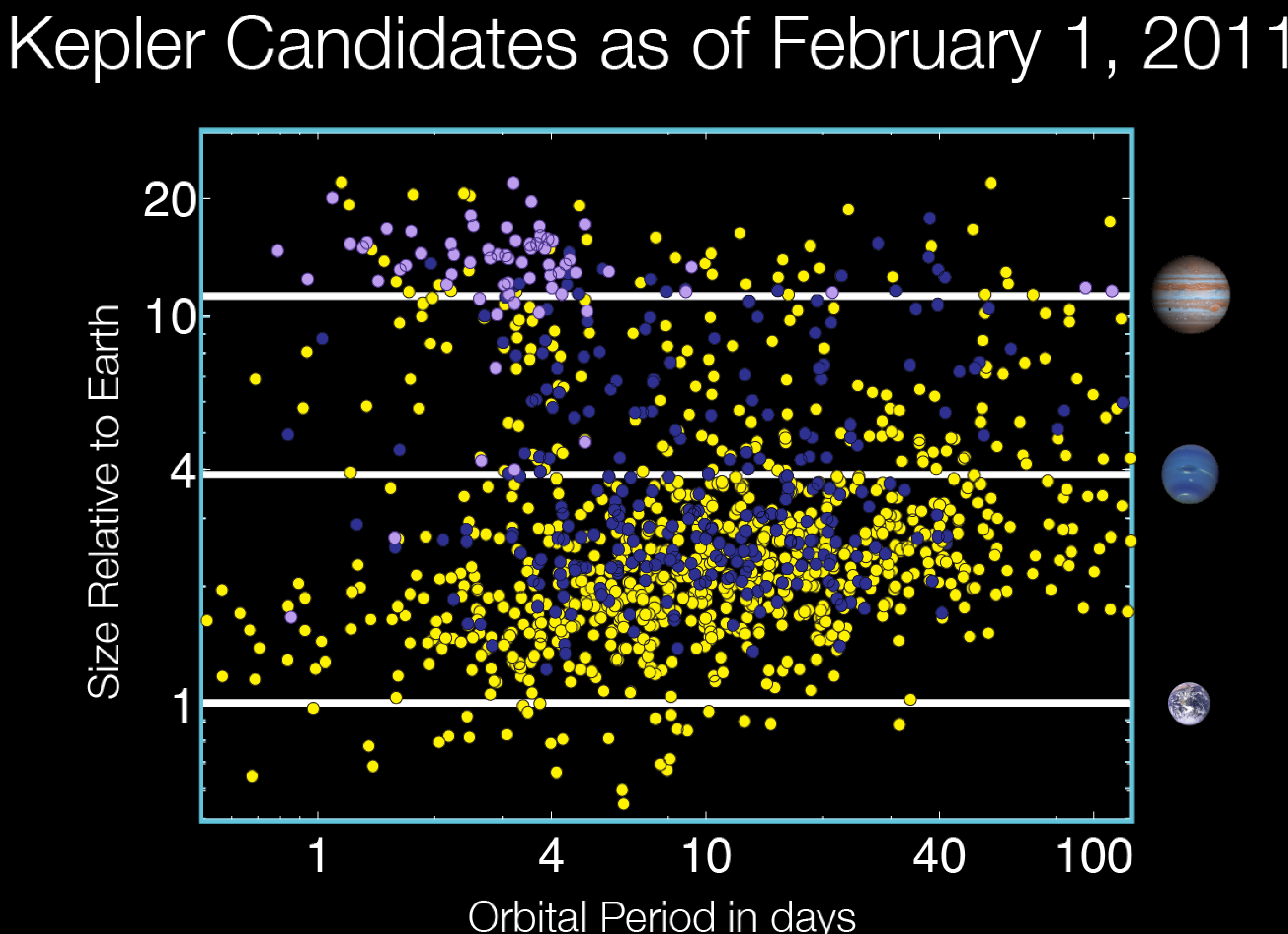


- Planet blocks light from star
- Visible/NIR light (Hubble/JWST)
- Radius of planet/star
- Absorption spectroscopy of planet's atmosphere
- JWST: Look for moons (by timing), constituents of atmosphere, Earth-like planets with water, weather

Secondary

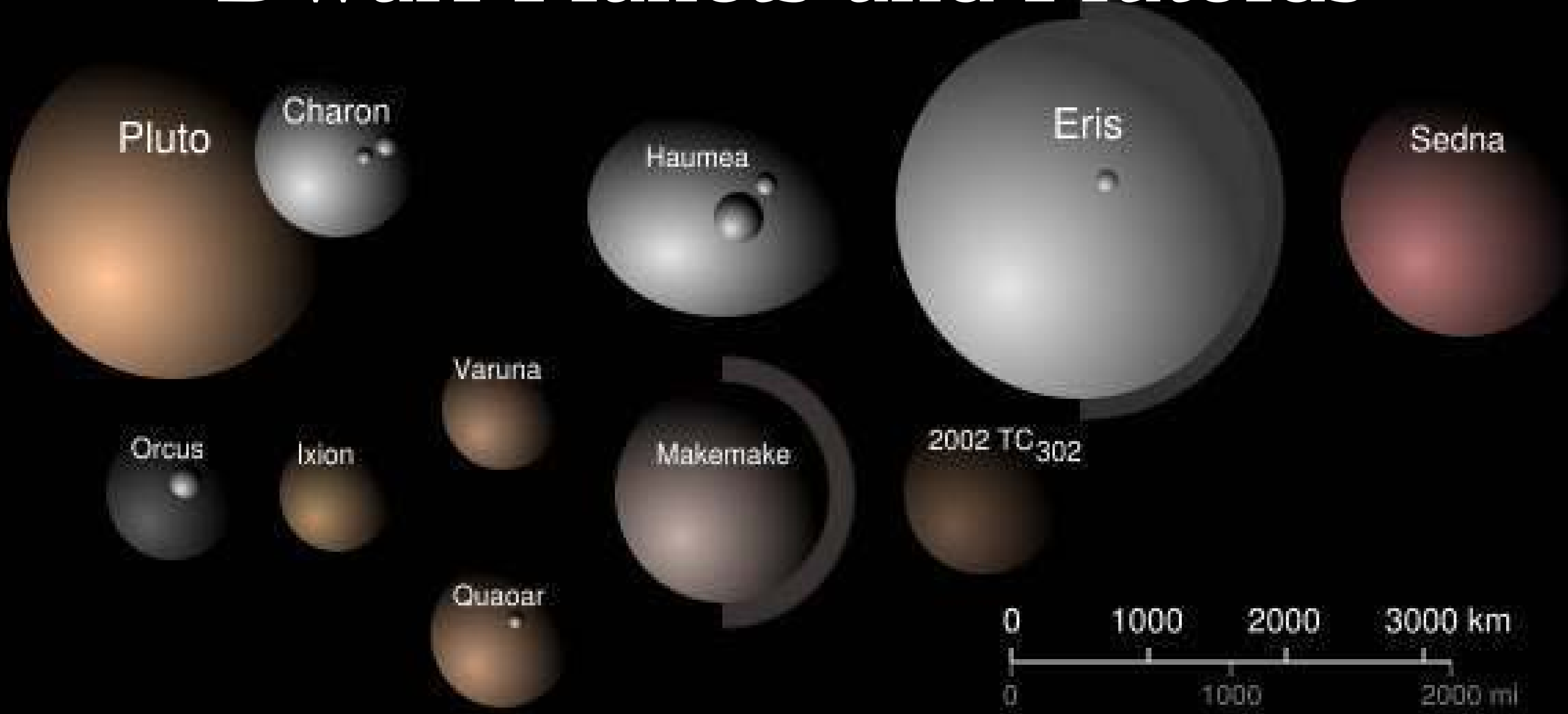
- Star blocks light from planet
- Mid-Infrared light (Spitzer/JWST)
- Direct detection of photons from planet
- Temperature of planet
- Emission from surface
- JWST: Atmospheric characteristics, constituents of atmosphere, map planets

JWST transit spectroscopy candidates:



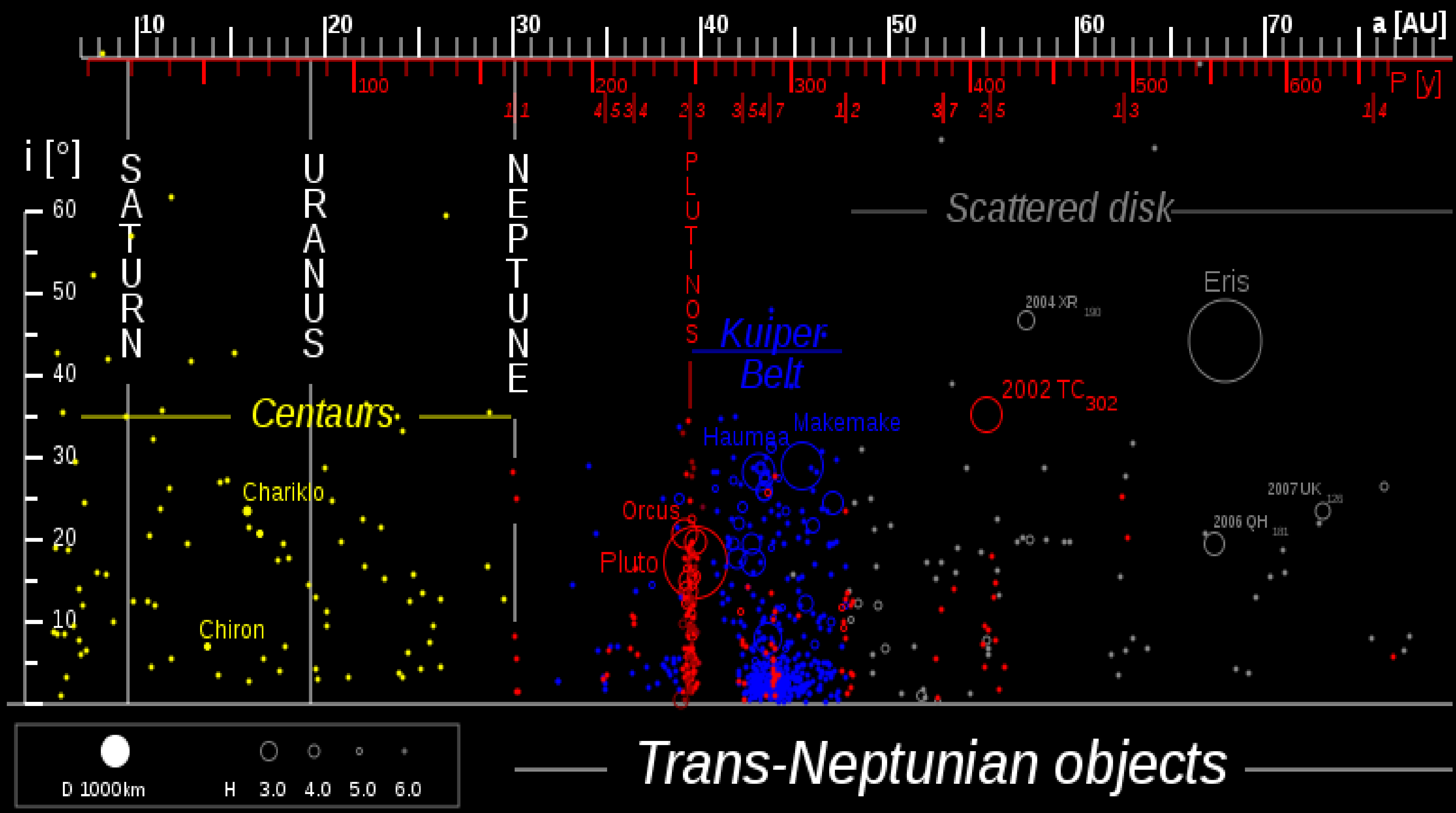
Bill Borucki's Press Conference chart

Dwarf Planets and Plutoids

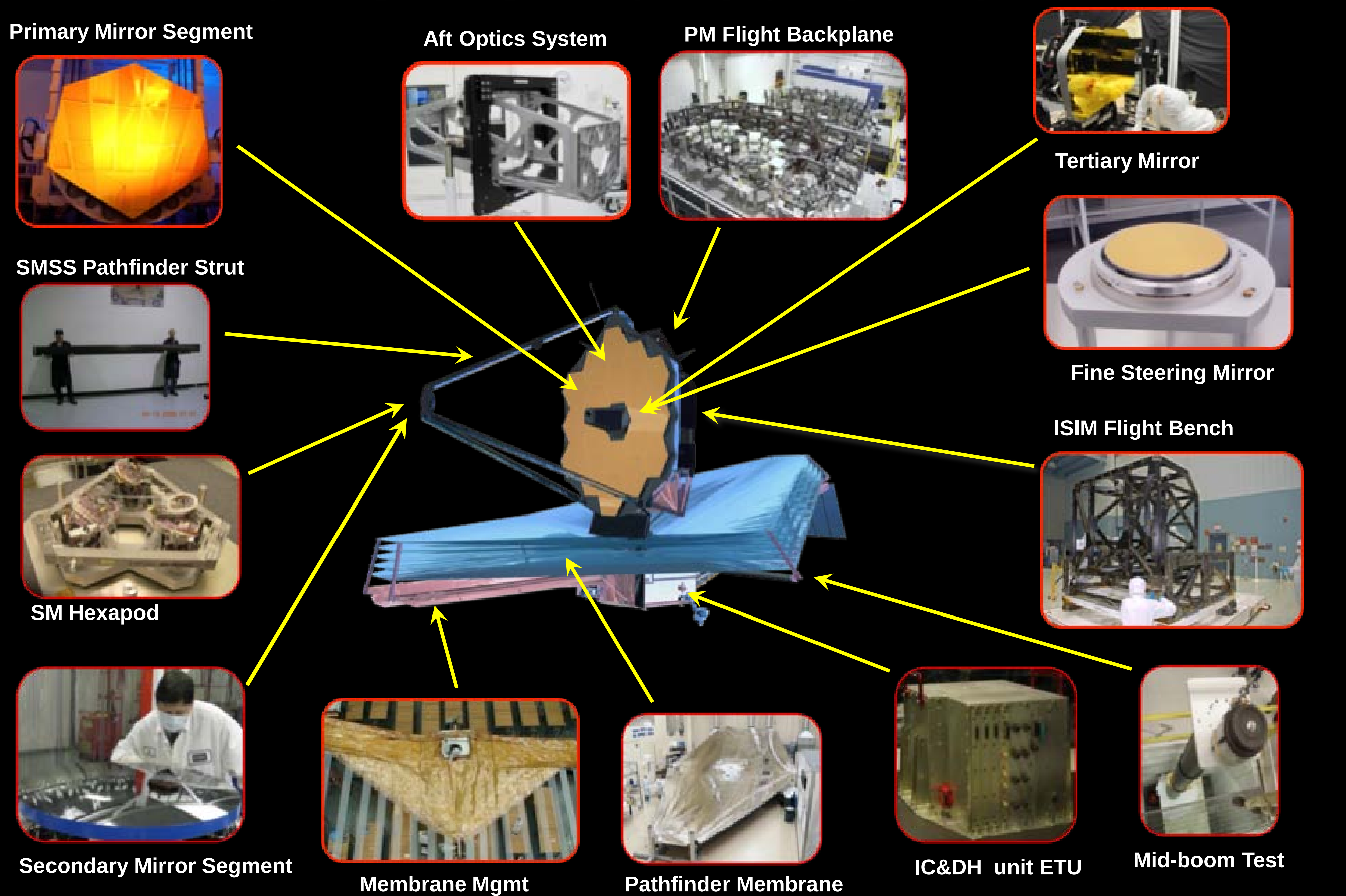


May be 2000 more when whole sky is surveyed
With moving object tracking JWST is perfect tool

Where they are



JWST: Under Construction

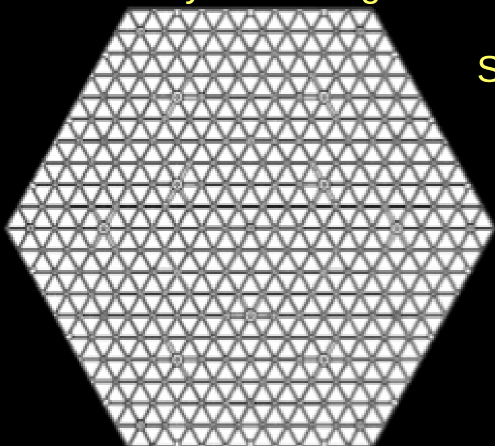


JWST Mirror Fabrication

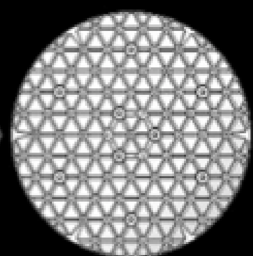
- JWST Mirrors made of beryllium
- Lightweight and stable at 40 K
- Brush-Wellman

Raw Be billet (two mirrors)

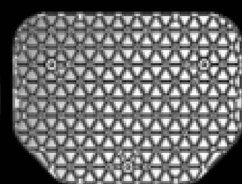
Primary mirror segment



Secondary mirror

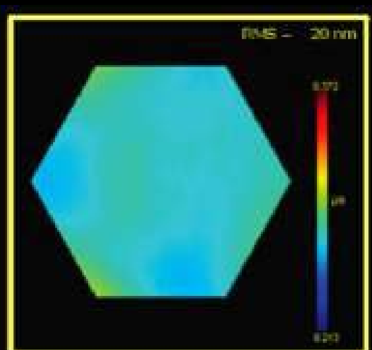


Tertiary mirror

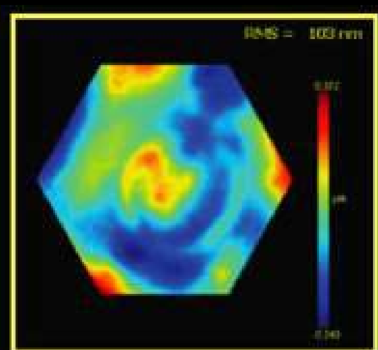


- Machined & lightweighted by Axsys
- 92% material is removed

- Mirrors polished at Tinsley Segment cryo-figure: 20 nm



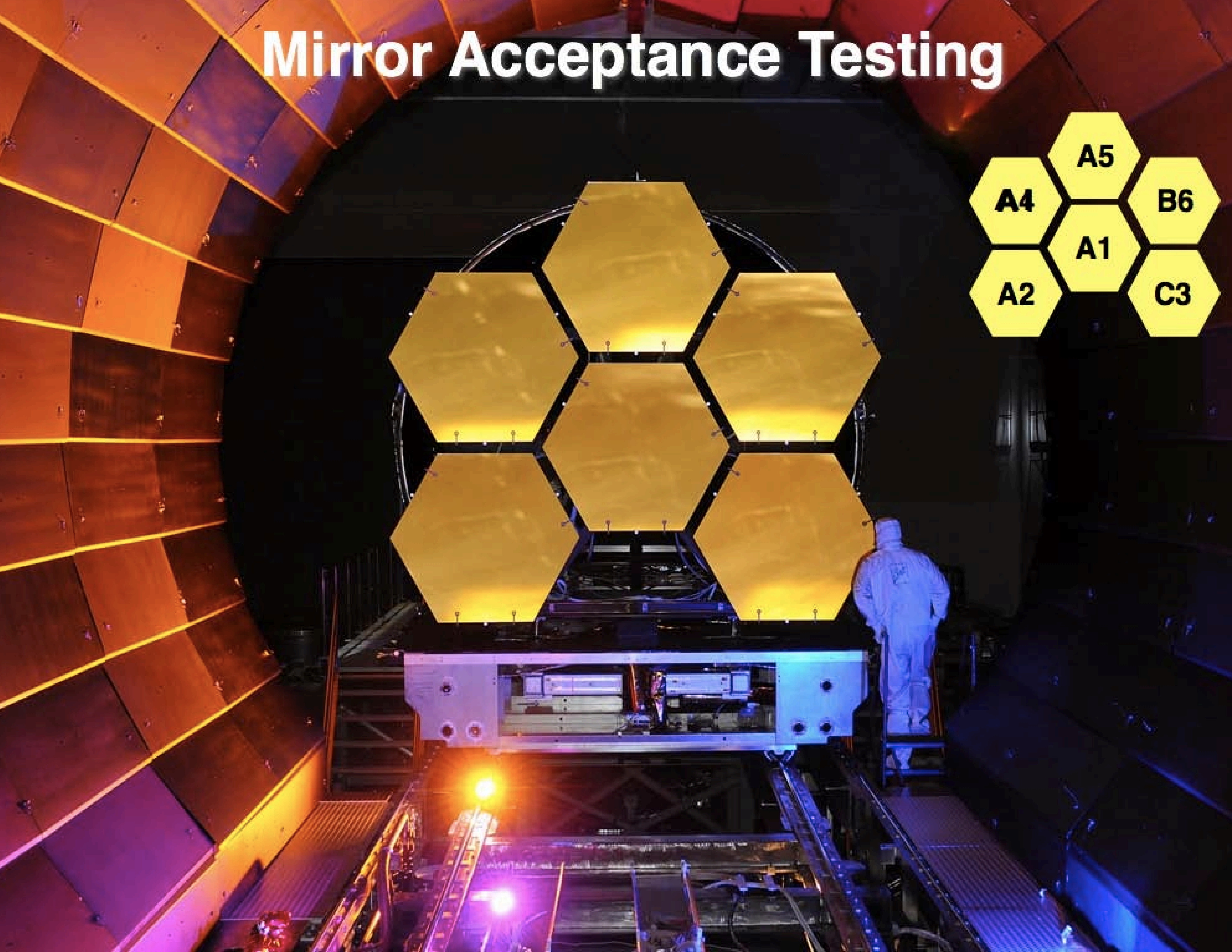
Cryo-surface figure



Ambient

Actuators & Strongback

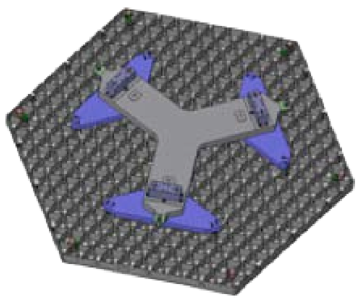
Gold Coating


Mirror Acceptance Testing
A5
A4
B6
A1
A2
C3

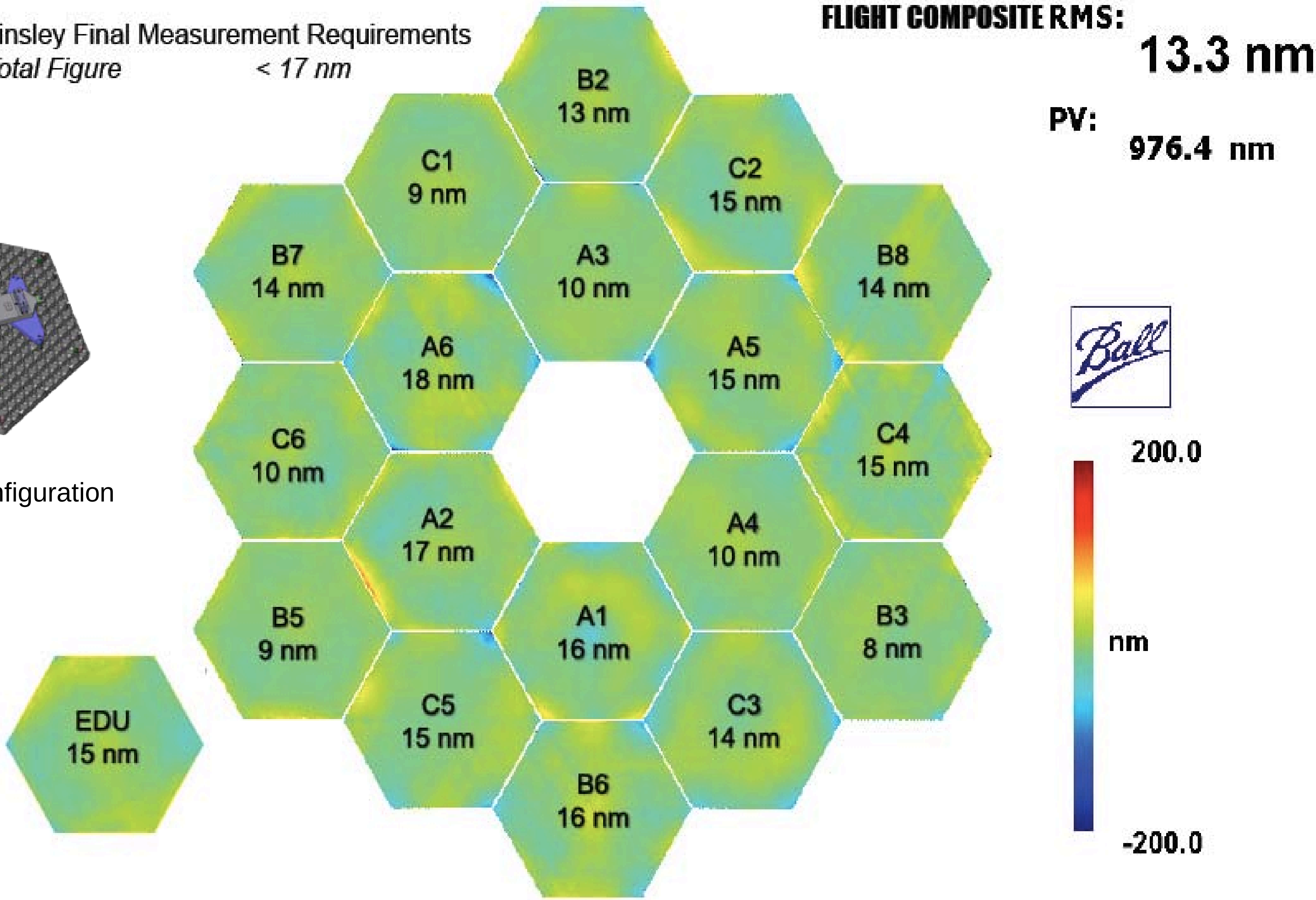
JWST Flight Mirrors Have Completed Polishing

Tinsley Final Measurement Requirements

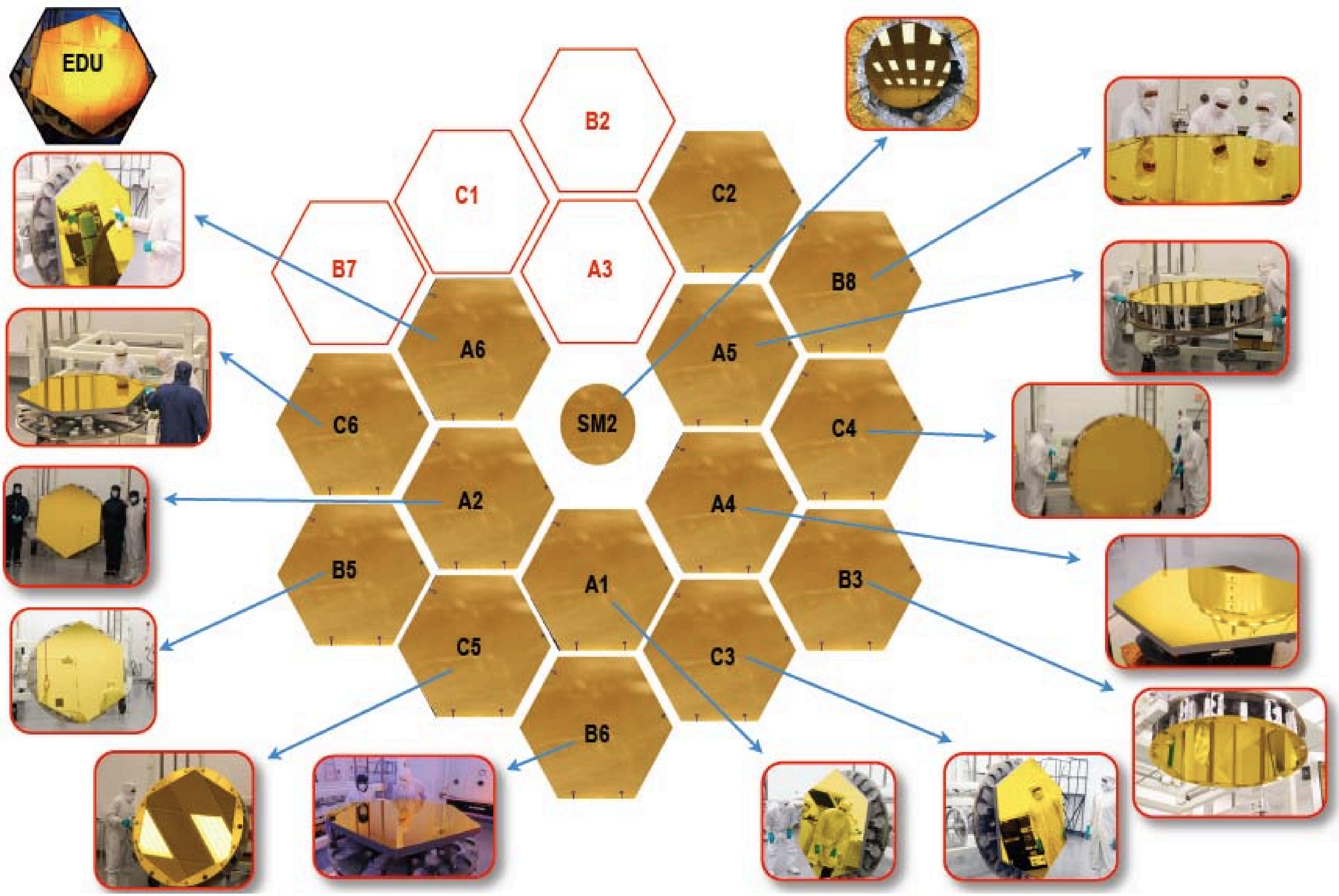
Total Figure *< 17 nm*



Mirror test configuration

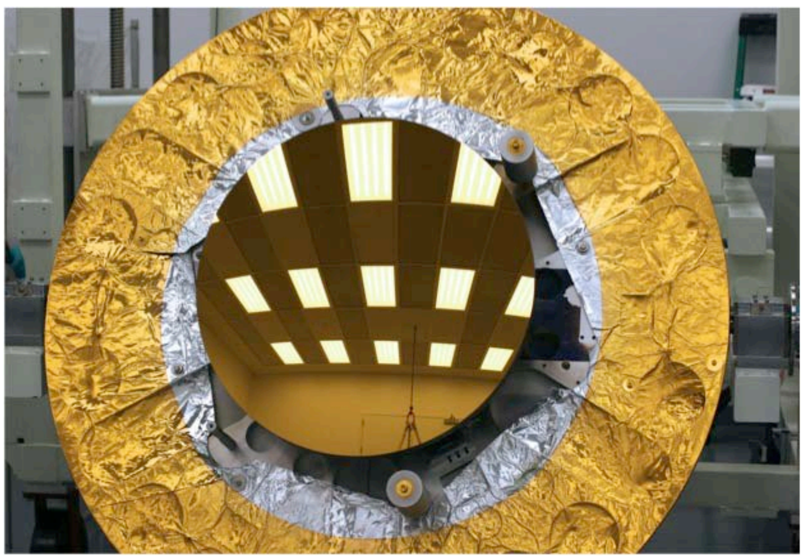


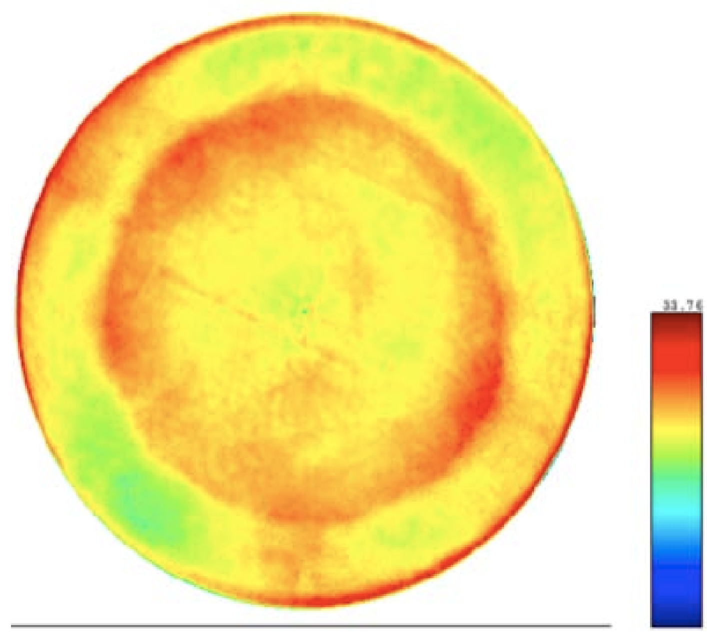
14 Gold-Coated Flight PMSAs



JWST Secondary Mirror

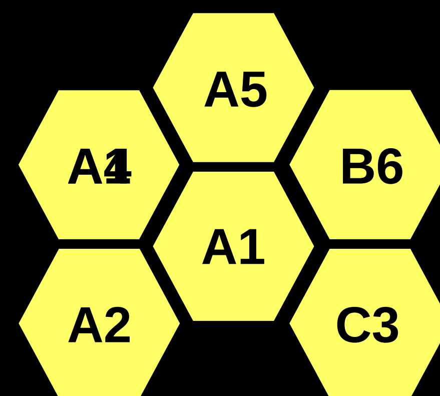
Description	Requirement	Measured
Low Frequency RMS	19 nm RMS	4.5 nm
Mid Frequency RMS	6 nm RMS	3.9 nm
High Frequency RMS	4 nm RMS	2.9 nm





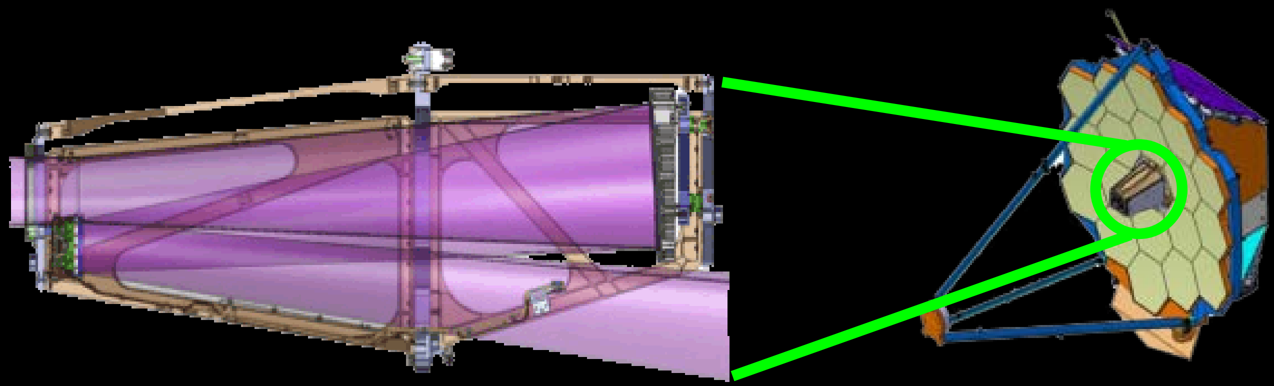
Mirror Acceptance Tests Underway

Flight Mirror A4 in acceptance vibe



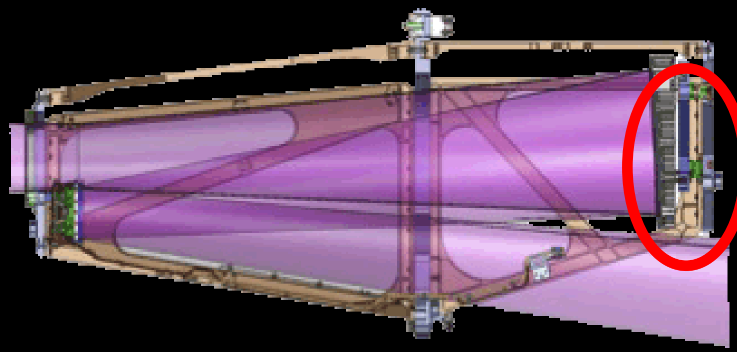
First six flight mirrors in final optical cryo-test

JWST Telescope Aft Optics

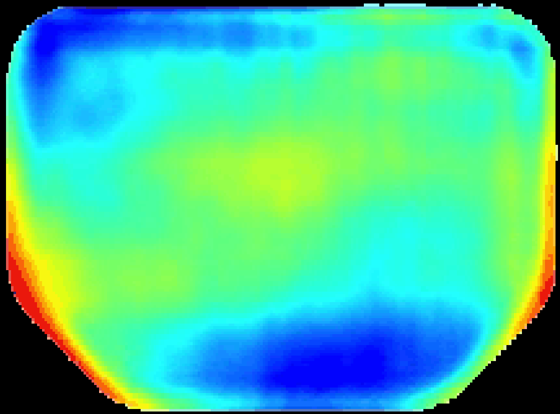


- Aft optics and Aft optics bench complete

JWST Telescope Optics

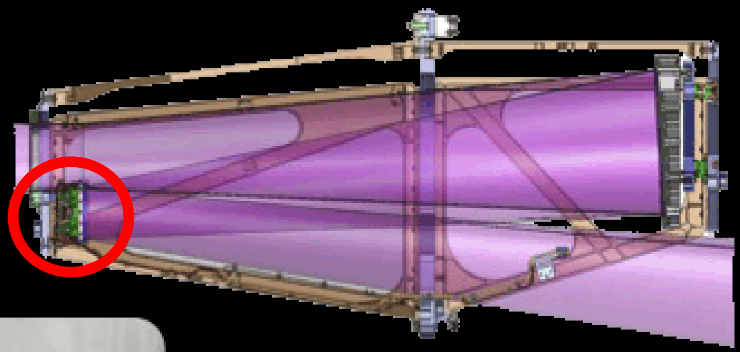


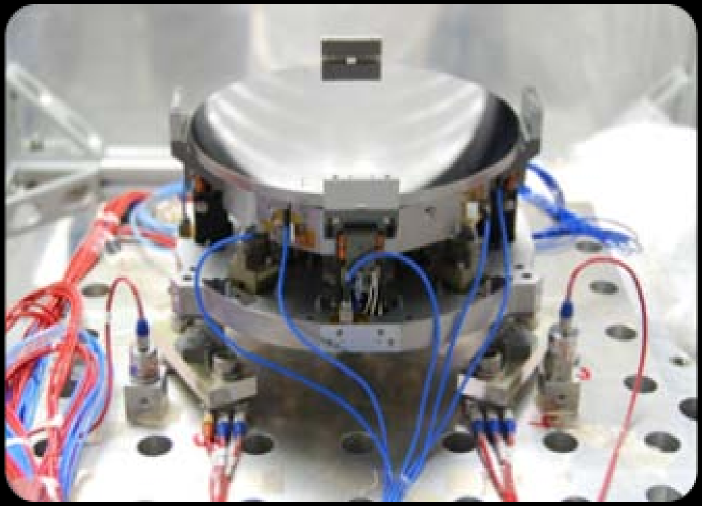
Tertiary Mirror

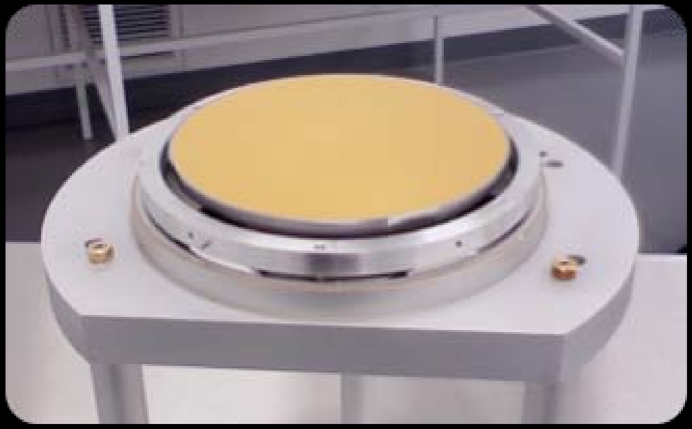


58 nm RMS
(-Tilt, -Power)

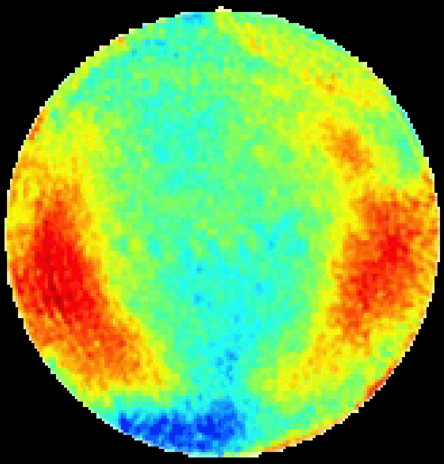
JWST Telescope Optics





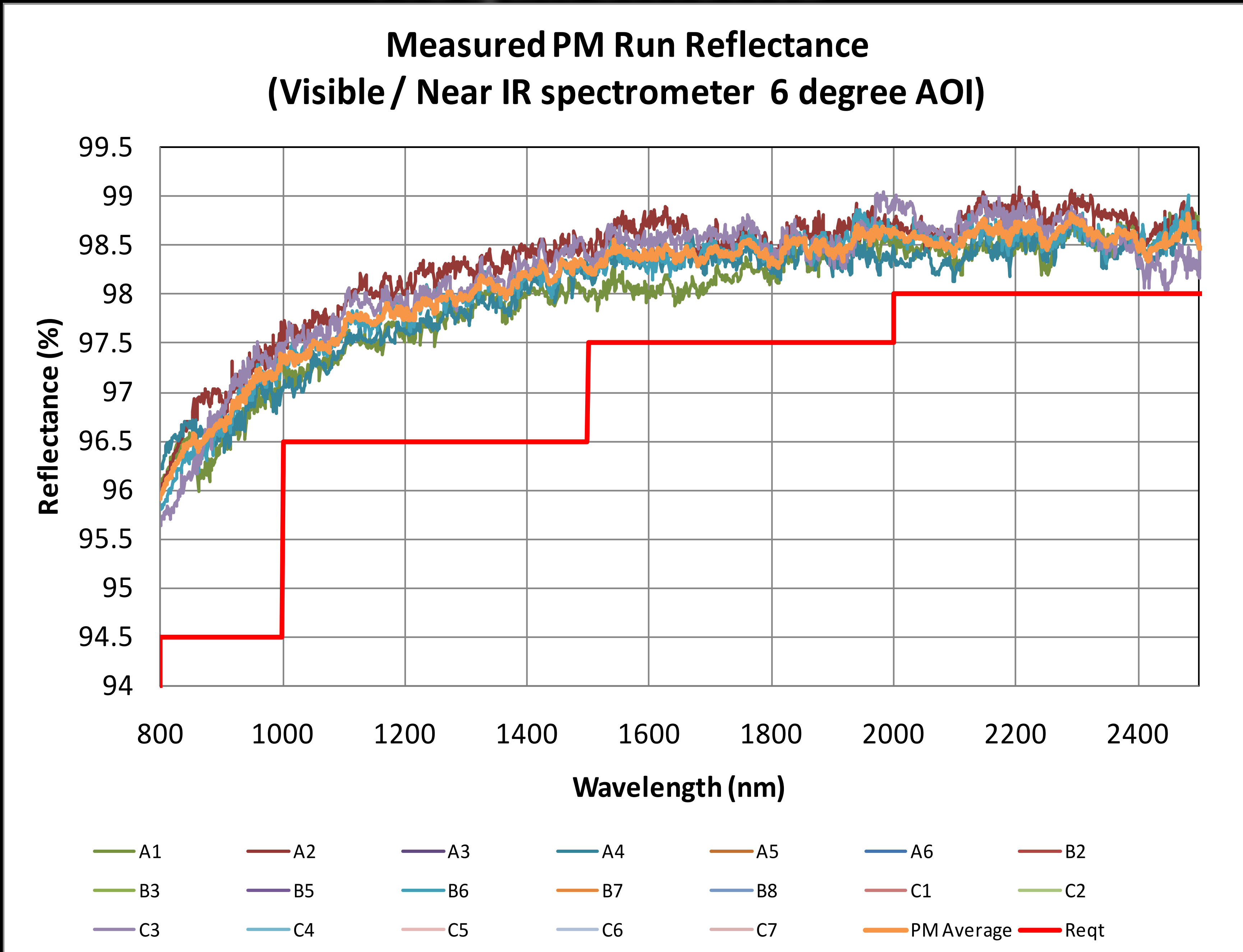


Fine Steering Mirror

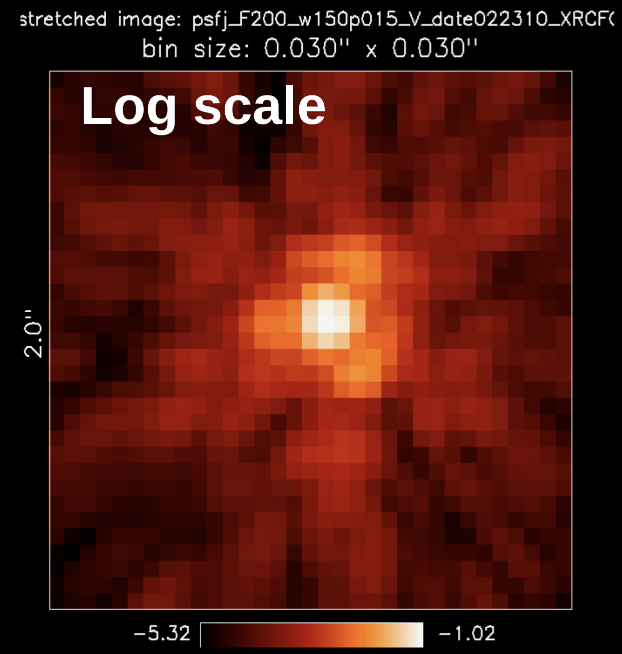


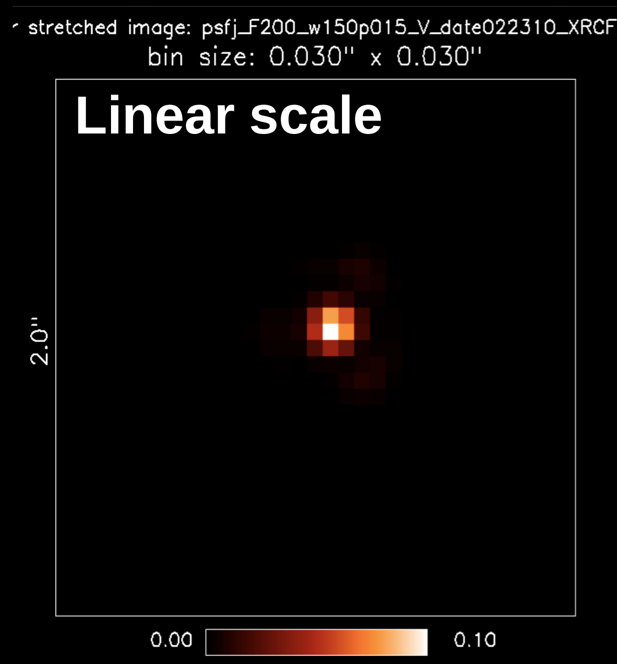
2.3 nm RMS

Gold Coatings Exceed Requirements



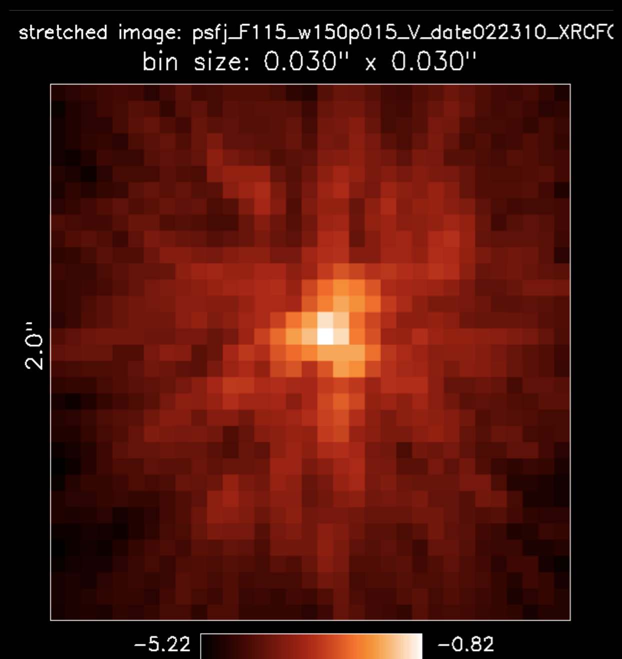
Predicted Image Quality

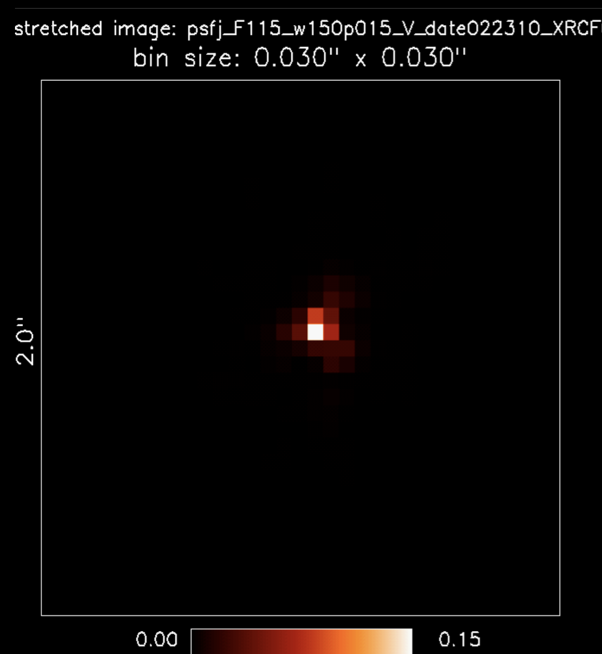




2 µm (diffraction limited, Nyquist sampled by NIRCam)

2.0” x 2.0” box

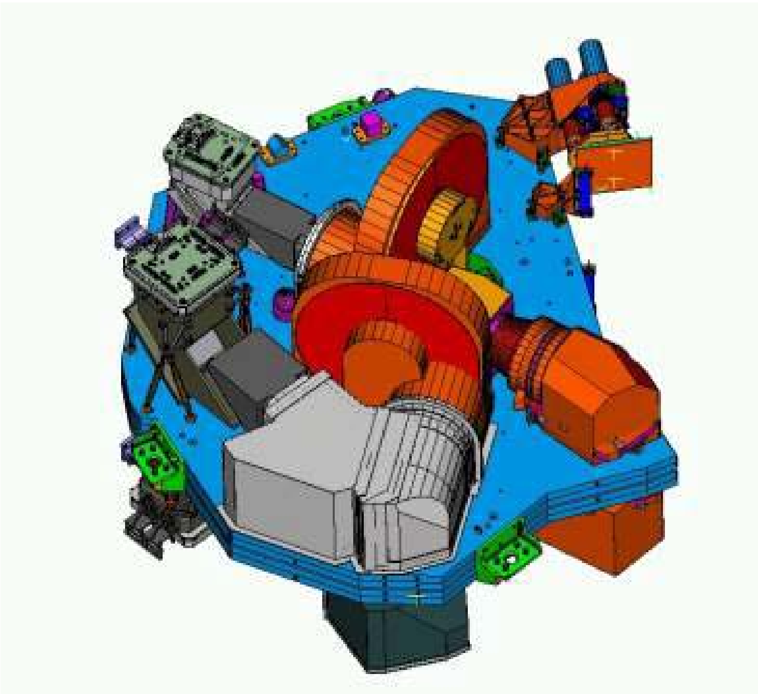


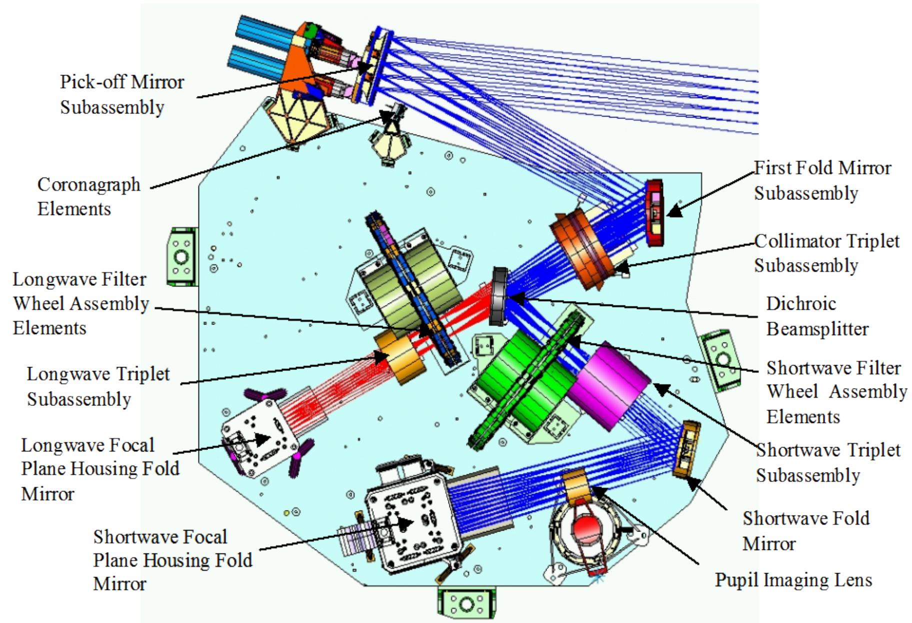


1 µm (Sub-Nyquist sharp core 0.03 arcsec, requires dithering)

2.0” x 2.0” box

The NIRCam instrument will image large portions of the sky identifying primeval galaxy targets for the other instruments

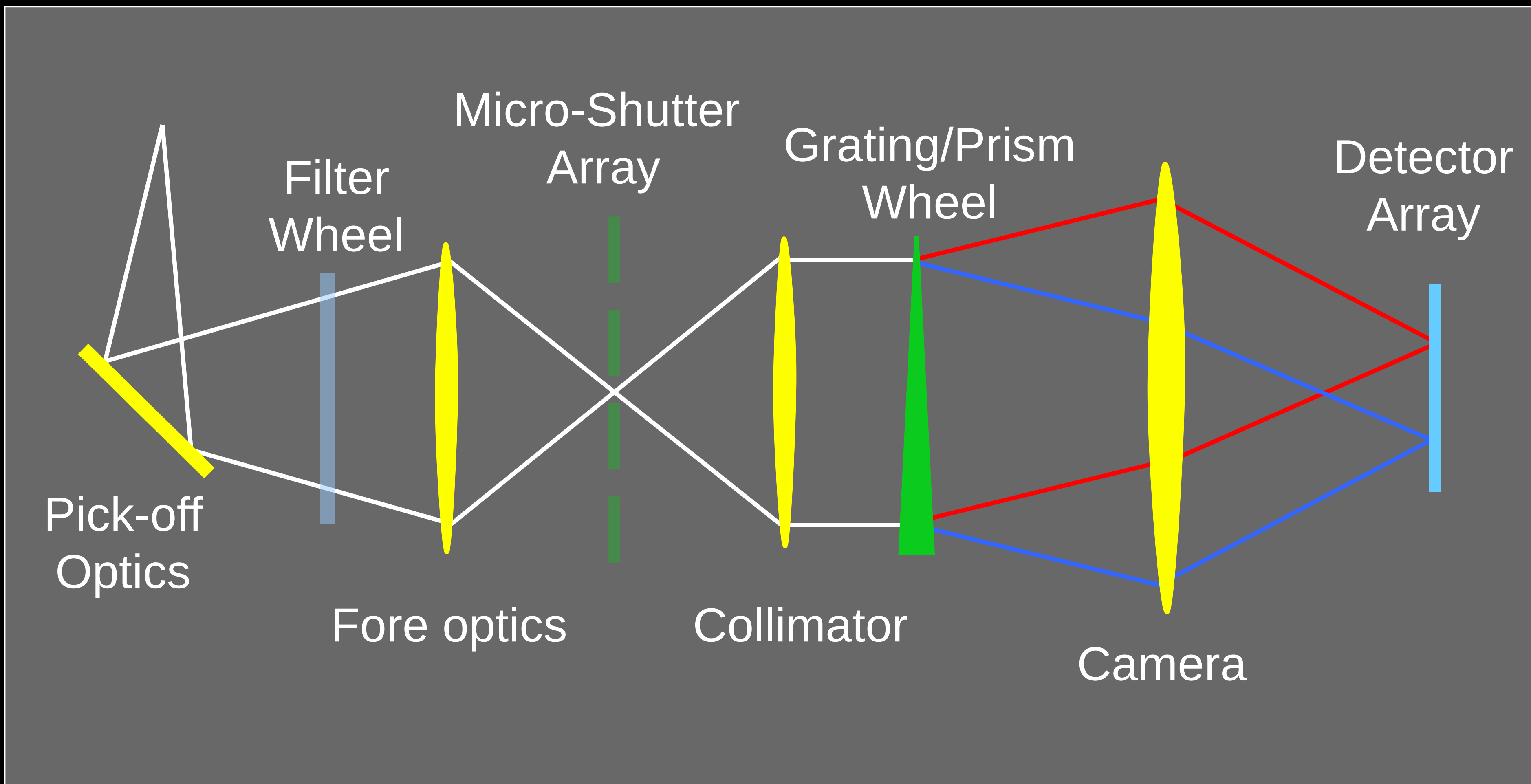




- Developed by the University of Arizona with Lockheed Martin ATC
  - Operating wavelength: 0.6 – 5.0 microns
  - Spectral resolution: 4, 10, 100
  - Field of view: 2.2 x 4.4 arc minutes
  - Angular resolution (1 pixel): 32 mas < 2.3 microns, 65 mas > 2.4 microns
  - Detector type: HgCdTe, 2048 x 2048 pixel format, 10 detectors, 40 K passive cooling
  - Refractive optics, Beryllium structure
  - Simple coronagraph with choice of Lyot masks in wheel
- Supports OTE wavefront sensing

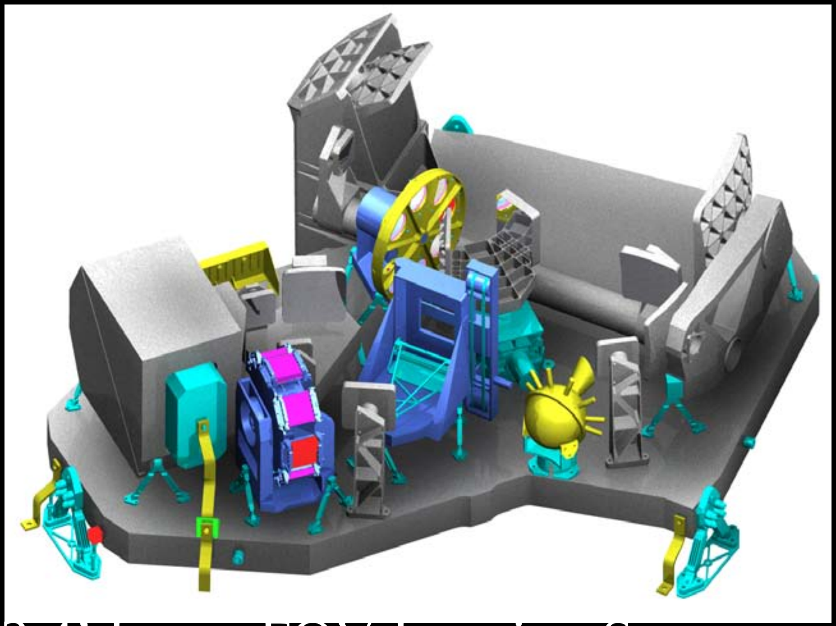
ETU NIRCam

NIRSpec Schematic
0.6-5.0 μm, R = 100, 1000, 3000
Not shown: fixed slits, image slicing IFU



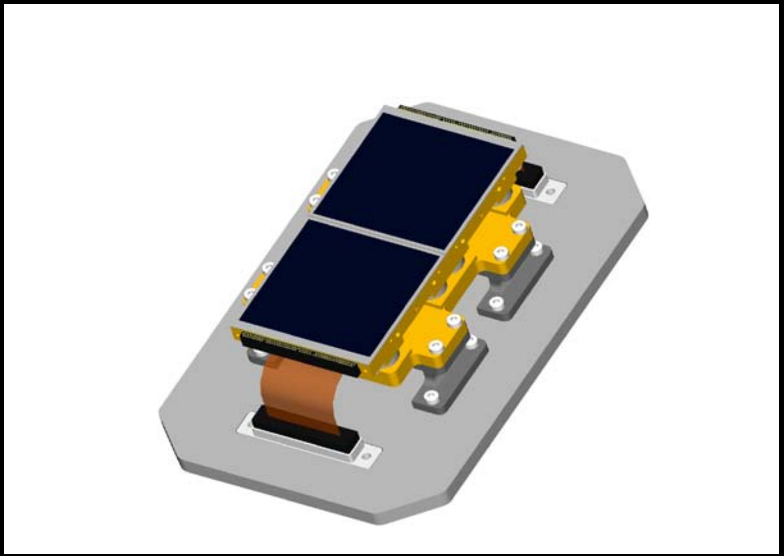
NIRSpec: ESA, Astrium, NASA

- > 100 Objects Simultaneously
- 10 square arcminute FOV



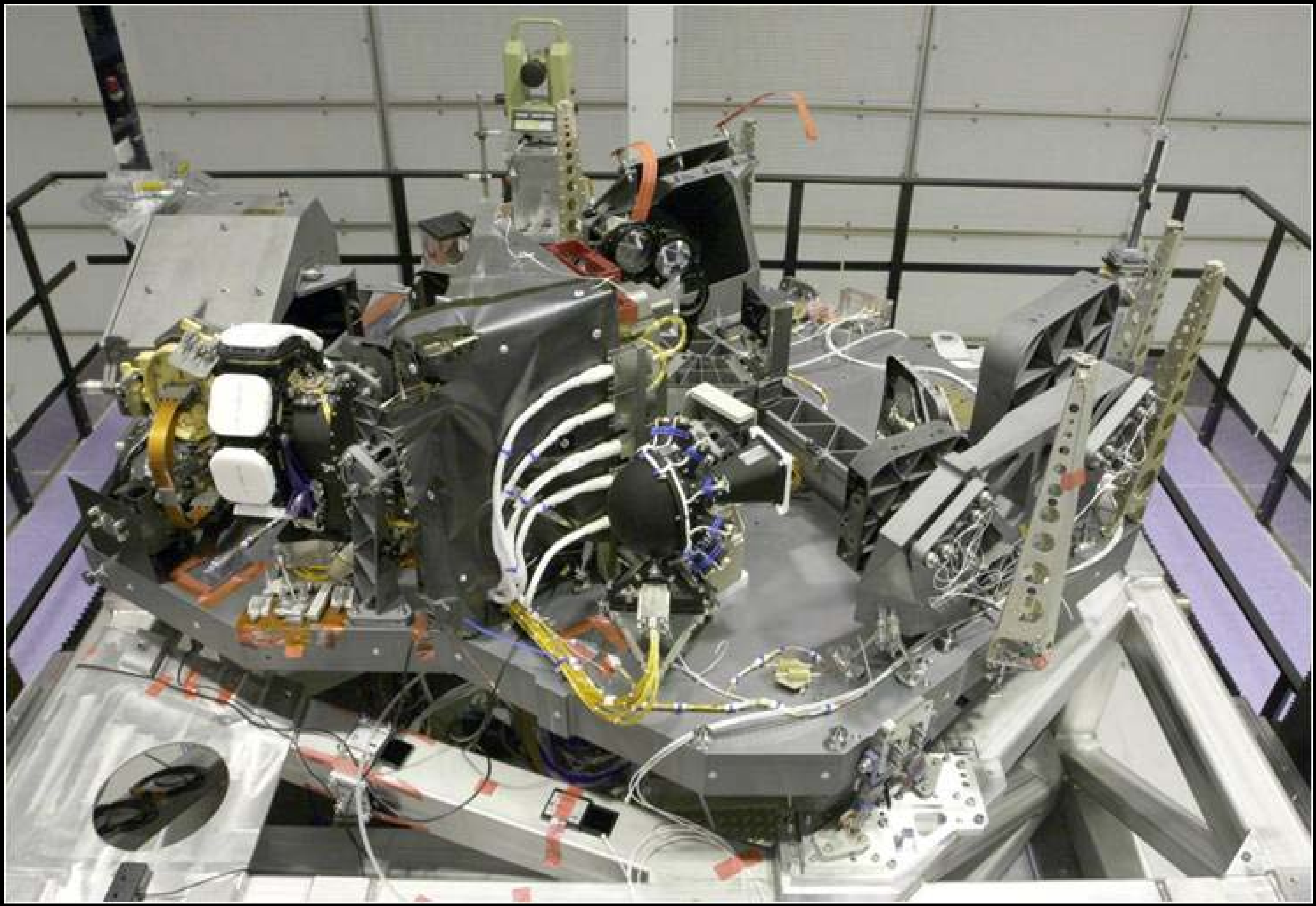
- 3.4’ Large FOV Imaging Spectrograph
- 4 x 175 x 384 element Micro-Shutter Array
  - 250,000 pixels, 203 x 463 mas, pitch 267 x 528
- 2 x 2k x 2k HgCdTe Detector Arrays
- Fixed slits and IFU for backup, contrast
- SiC optical bench & optics

Microshutters make any pattern

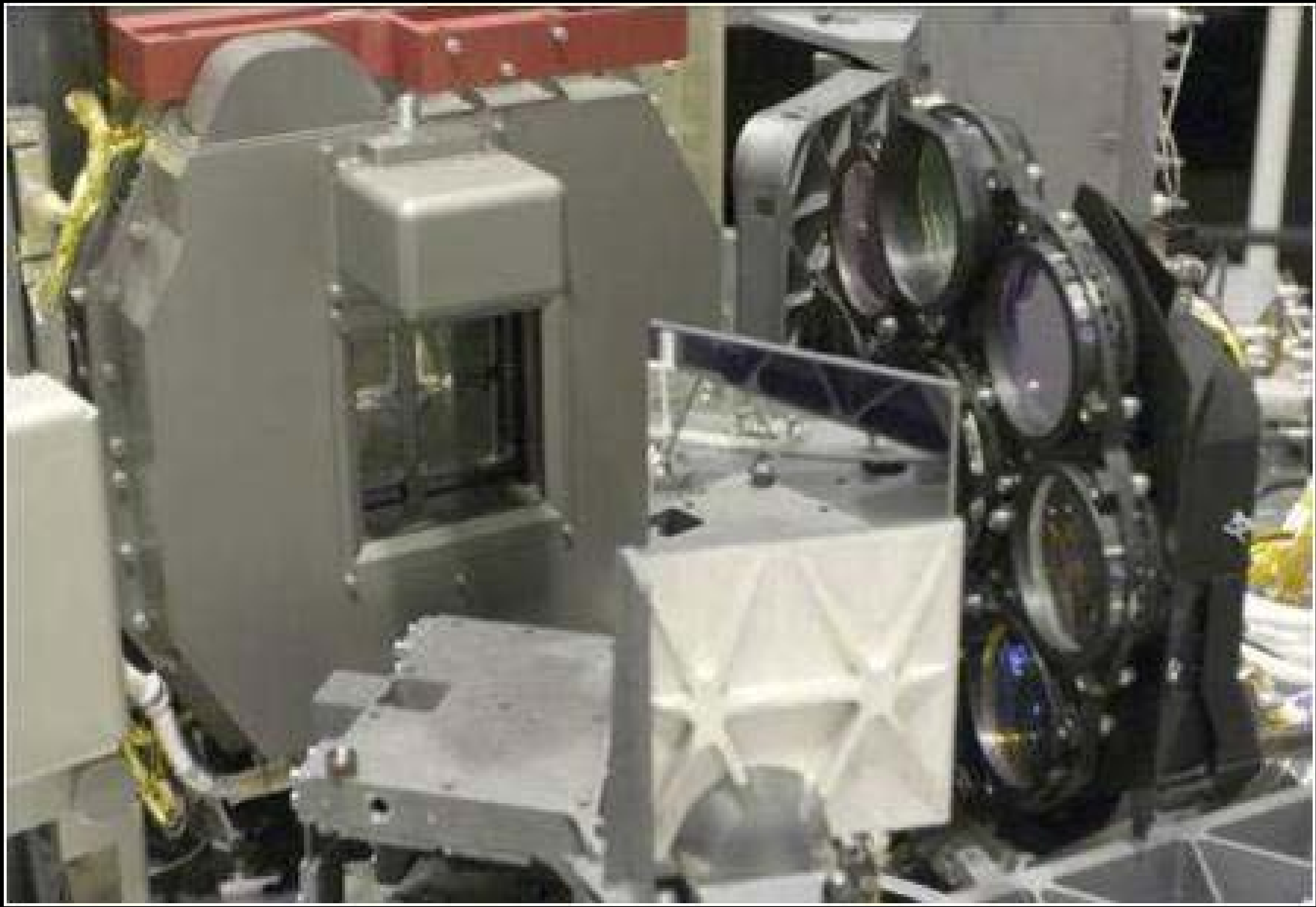


Flight detectors have dark current ~ 10 e/hr

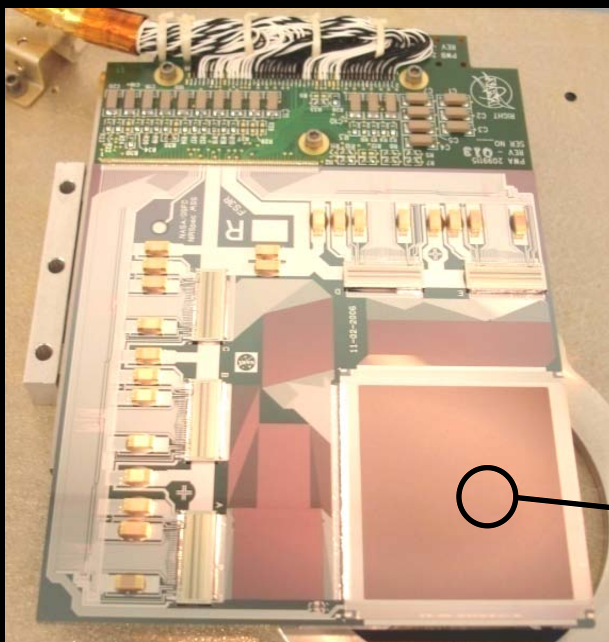
FLIGHT NIRSpec

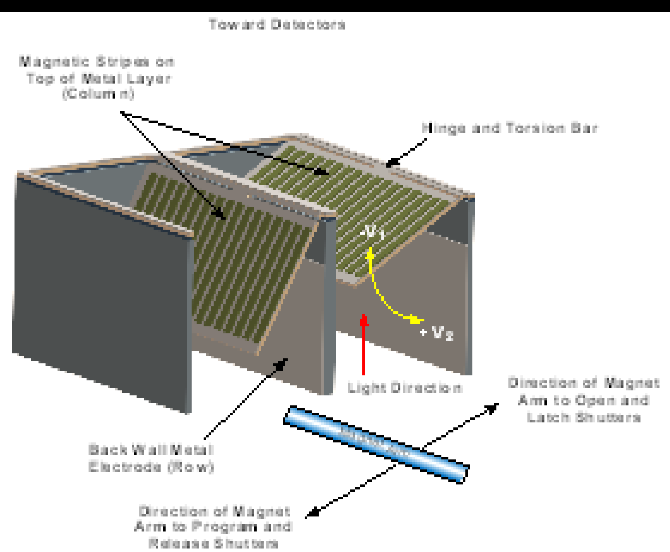


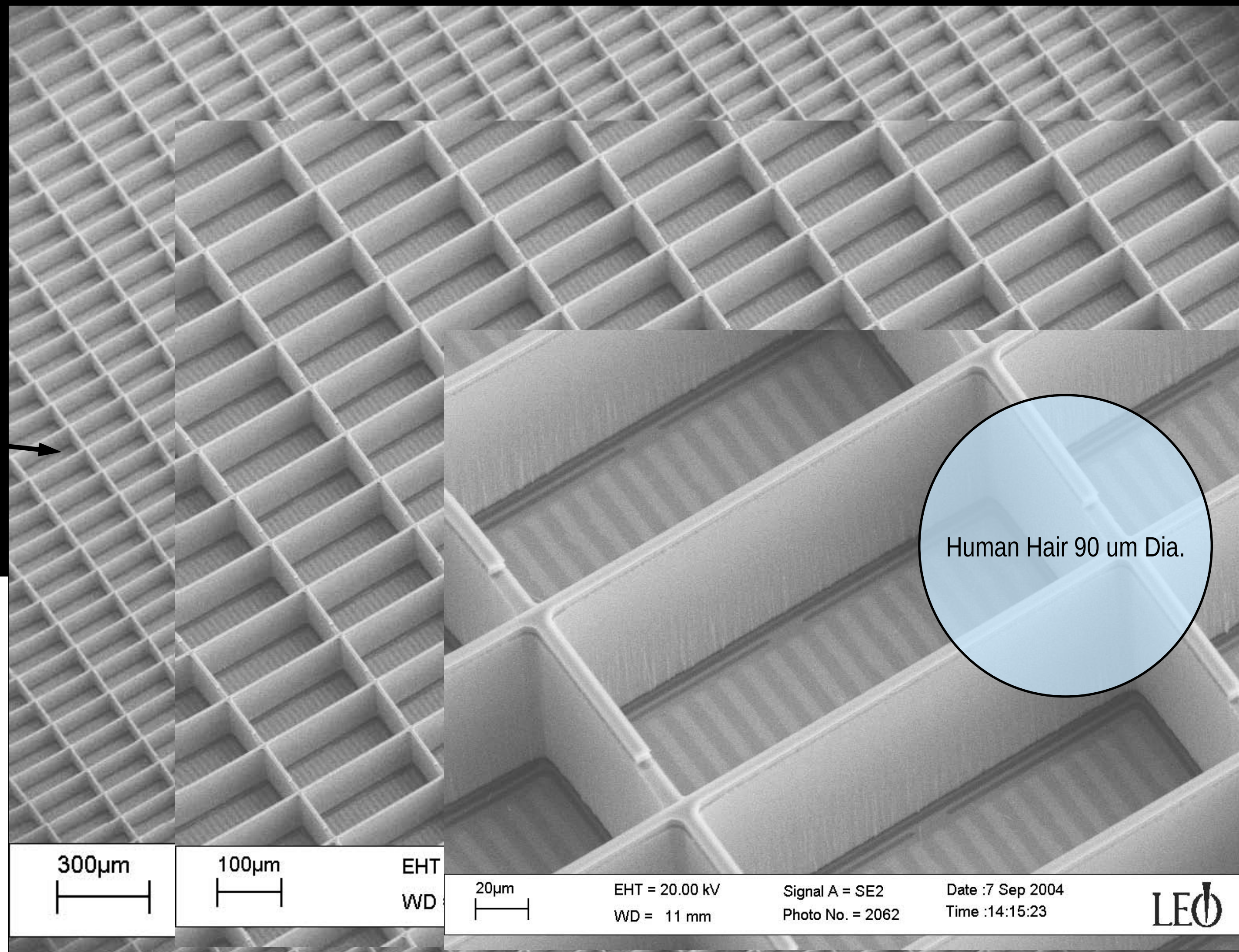
Flight Microshutters Installed



250,000 pixel cryogenic microshutter array system

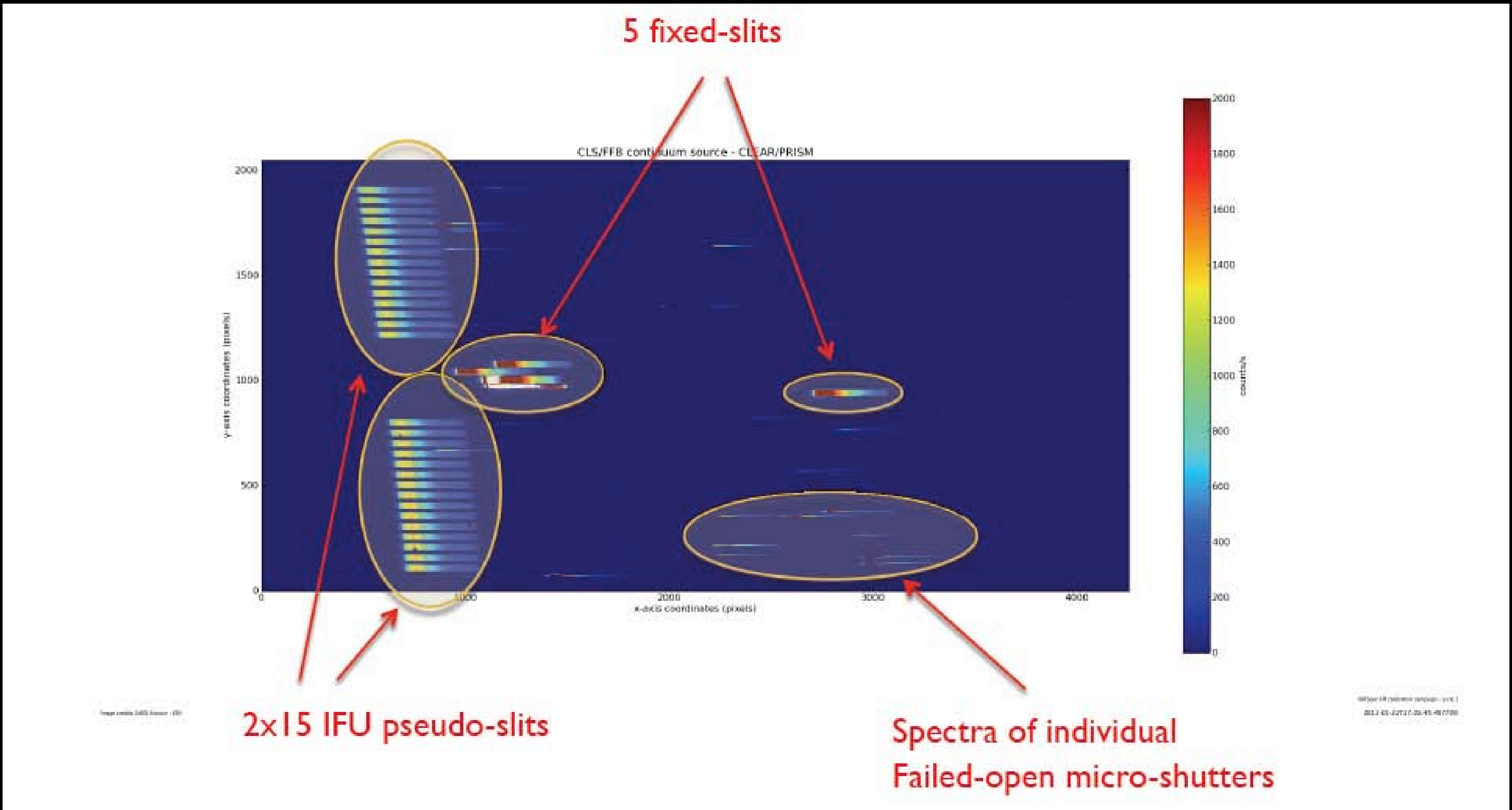






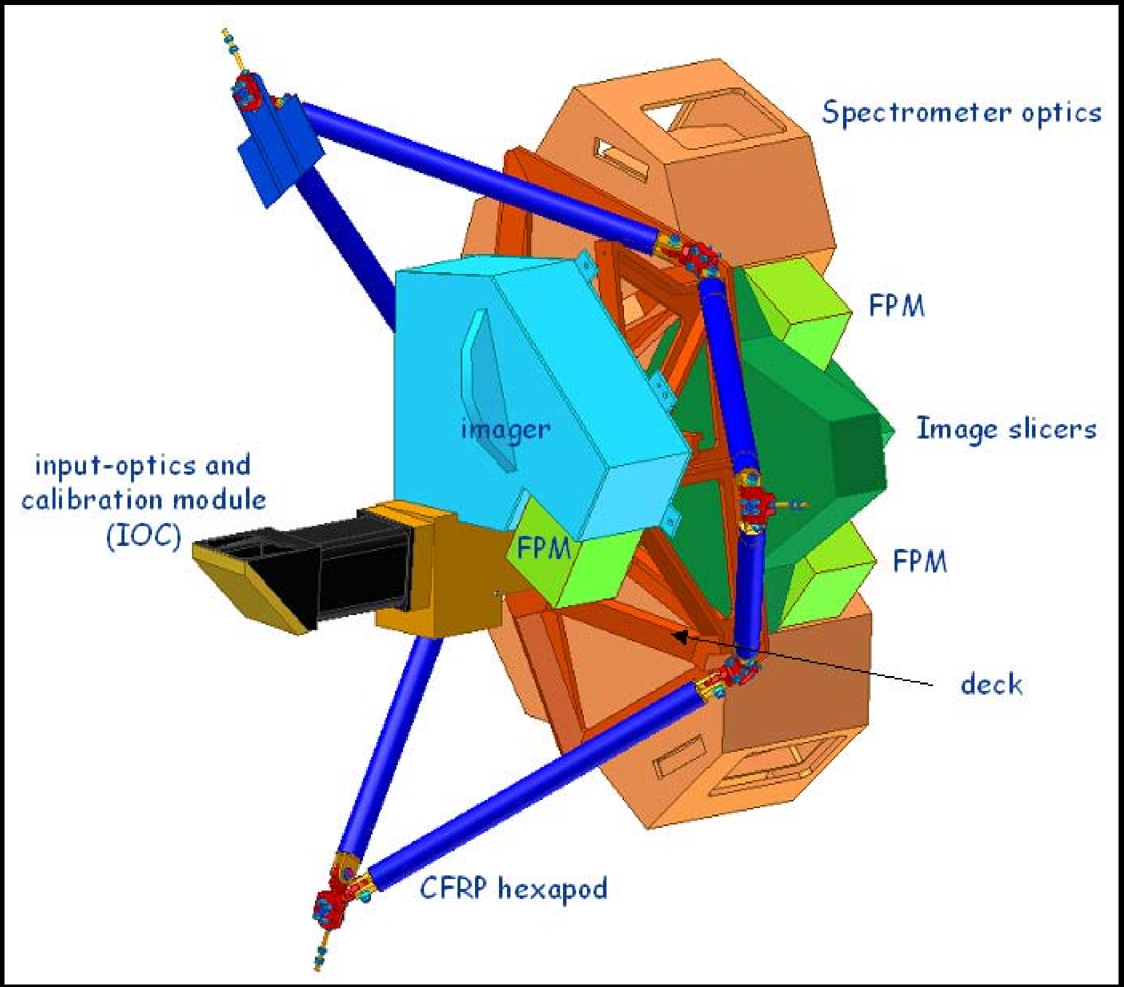
203 x 463 mas shutter pixel clear aperture, 267 x 528 mas pitch,
4 x 171 x 365 array = 249,660 pixels

Flight NIRSpec First Light



Mid-Infrared Instrument (MIRI)

- Science team G. Rieke (lead), G.Wright (co-lead)
- European Consortium sponsored by ESA in partnership with NASA/JPL
- Science Goals include
  - Search for the origins of galaxies
  - Birth of stars and planets
  - Evolution of planetary systems
- Imaging
  - λ=5-29 μm wavelength range
  - Diffraction limited imaging with 0.1” pixels: 3 x 1024^2 Si:As detectors
  - ~1.7’ field of view
  - Able to image sources as bright as 4 mJy at λ=10μm
  - ≥12 bandpass filters
  - Low resolution spectrograph (R~100; λ=5-10 μm) for single, compact sources
  - Simple coronagraph
- Spectroscopy
  - λ=5-29 μm wavelength range, reach λ= 28.3 μm
  - Integral field spectroscopy with 3.5x3.5 and 7x7” field of view
  - R~2000-3700 from λ=5-29 μm

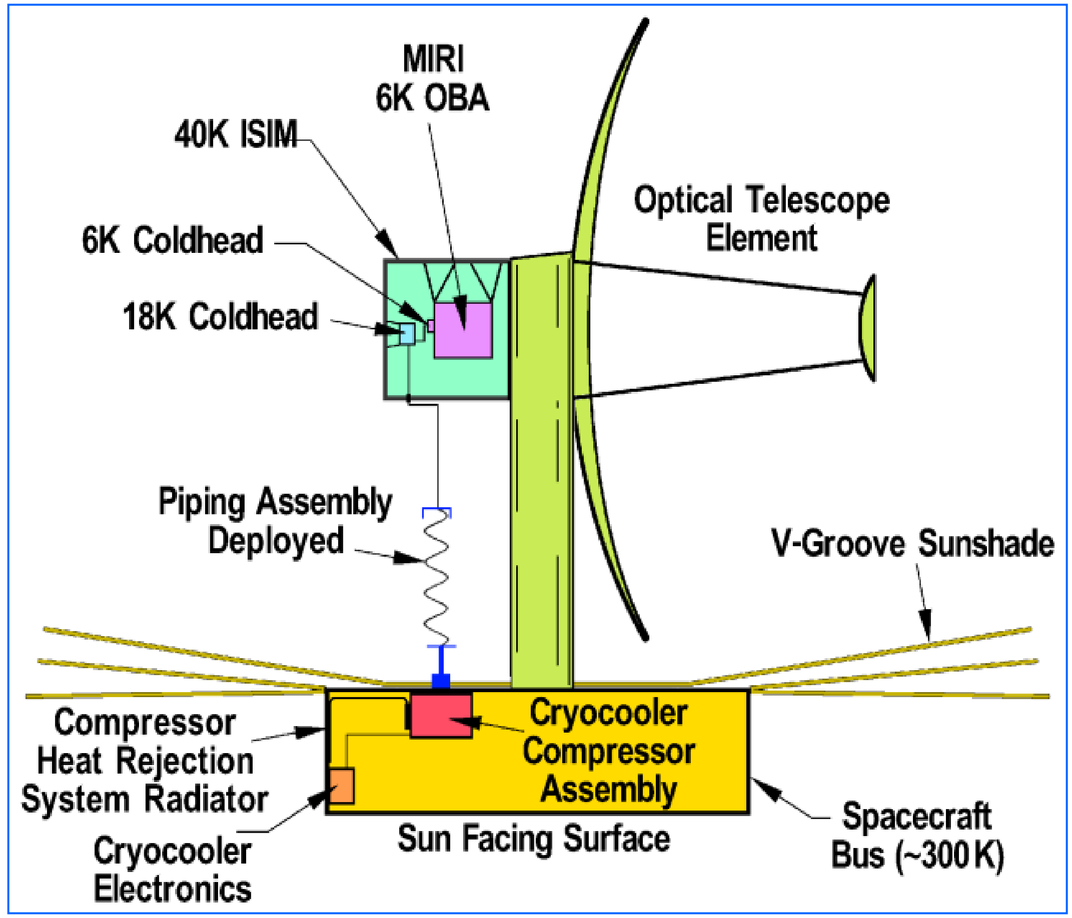


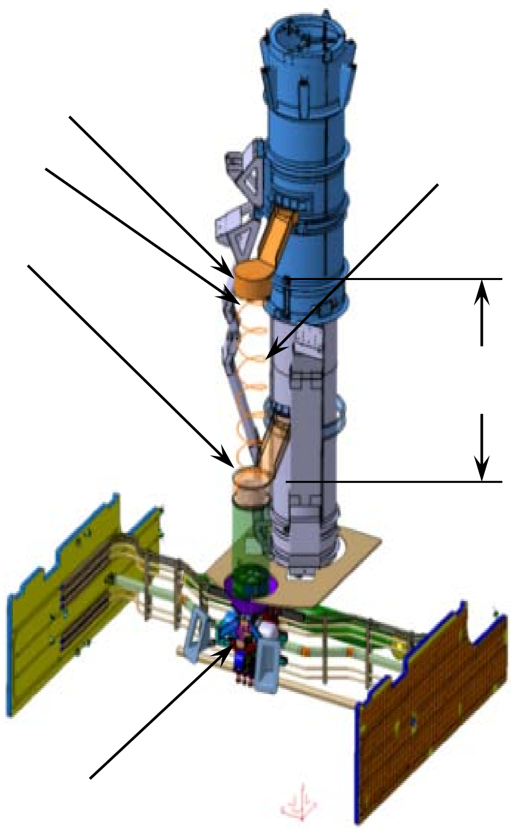
Optics Module concept developed by European Consortium

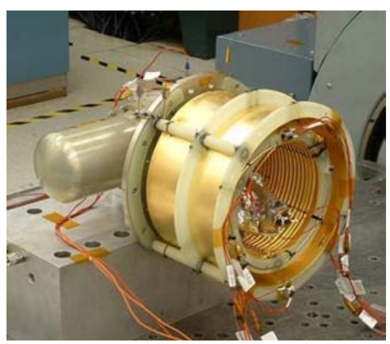
Flight MIRI

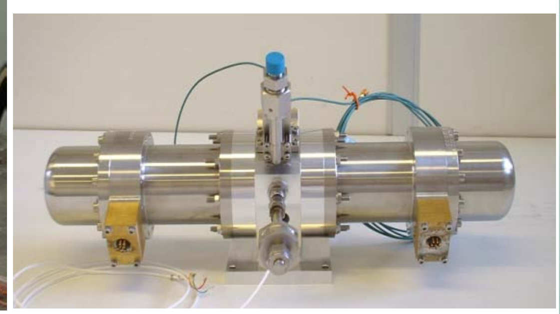
MIRI requires active cooling to 7 K

- A two stage mechanical cooler is used to cool the MIRI below the nominal 40 K ISIM environment that is achieved by passive radiative cooling.
  - The MIRI Cooler will be the first long life, 7K mechanical cooler for space flight
  - Developed by NGAS and JPL

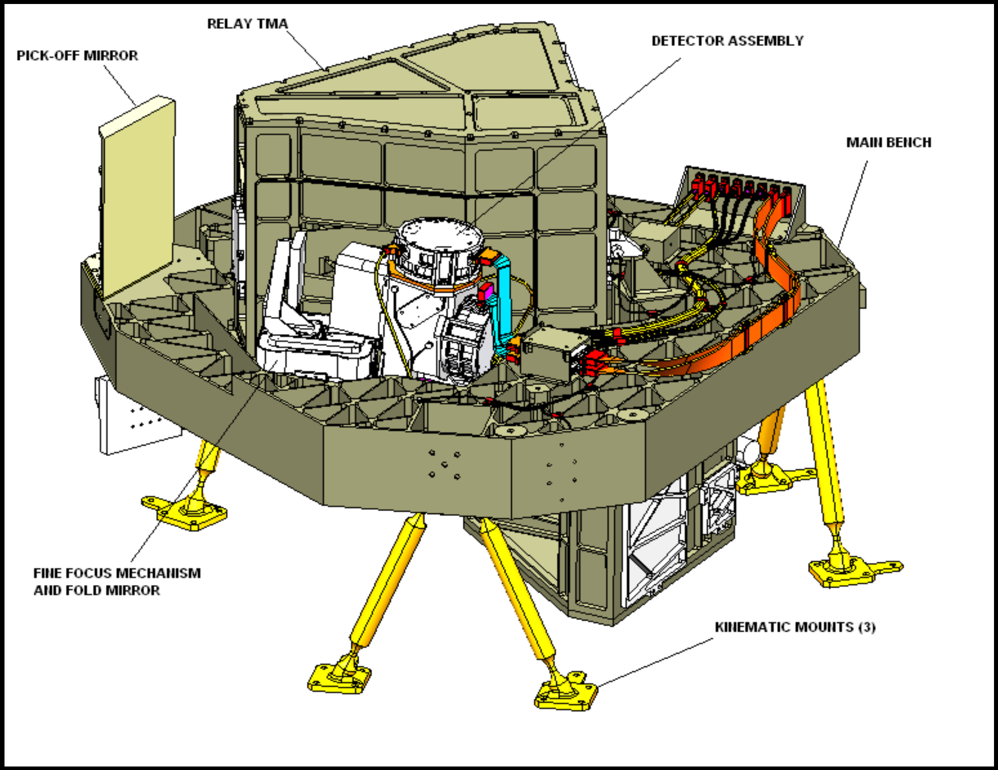


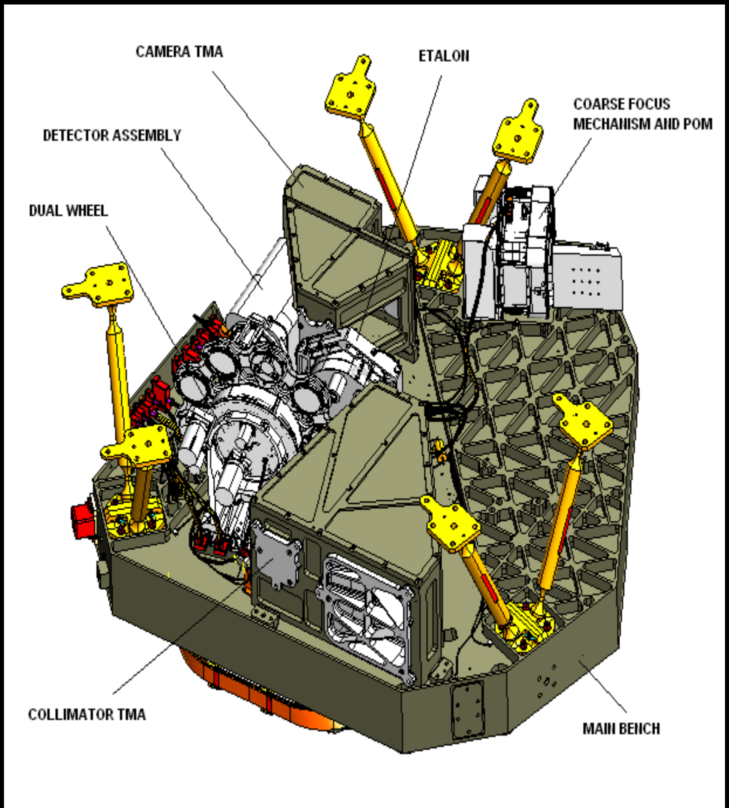






FGS provides pointing control & imaging spectroscopy to reveal primeval galaxies and extra-solar planets





- Developed by the Canadian Space Agency with ComDev
  - Operating wavelength: 0.8 – 4.8 microns
  - Spectral resolution: Broad-band guider and R=100 science imagery
  - Field of view: 2.3 x 2.3 arc minutes
    - R=100 imagery with Fabry-Perot tunable filter and coronagraph
  - Angular resolution (1 pixel): 68 mas
  - Detector type: HgCdTe, 2048 x 2048 pixel format, 3 detectors, 40 K passive cooling
  - Reflective optics, Aluminum structure and optics

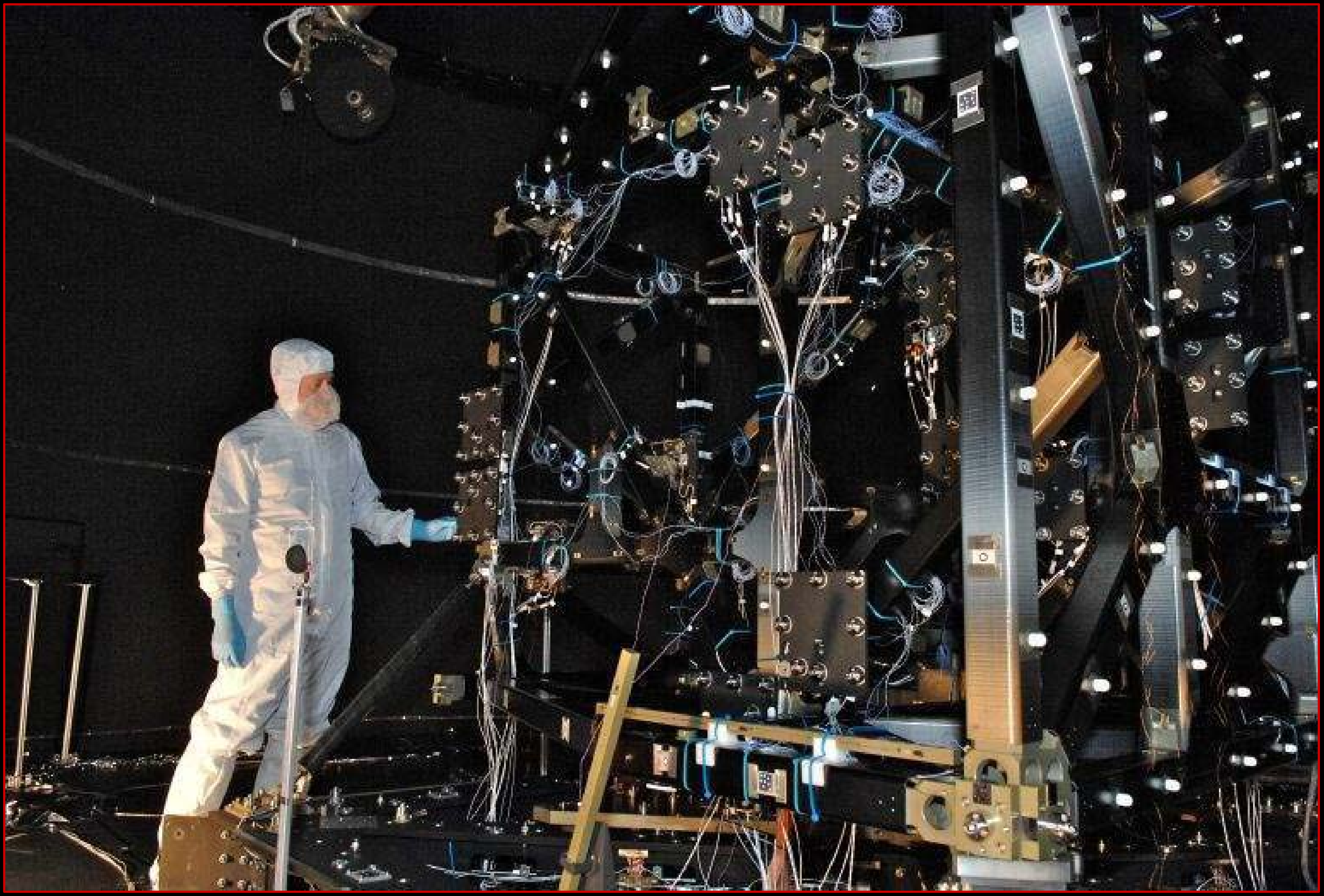
Flight Fine Guidance Sensor

Engineering Test Units Instruments at GSFC

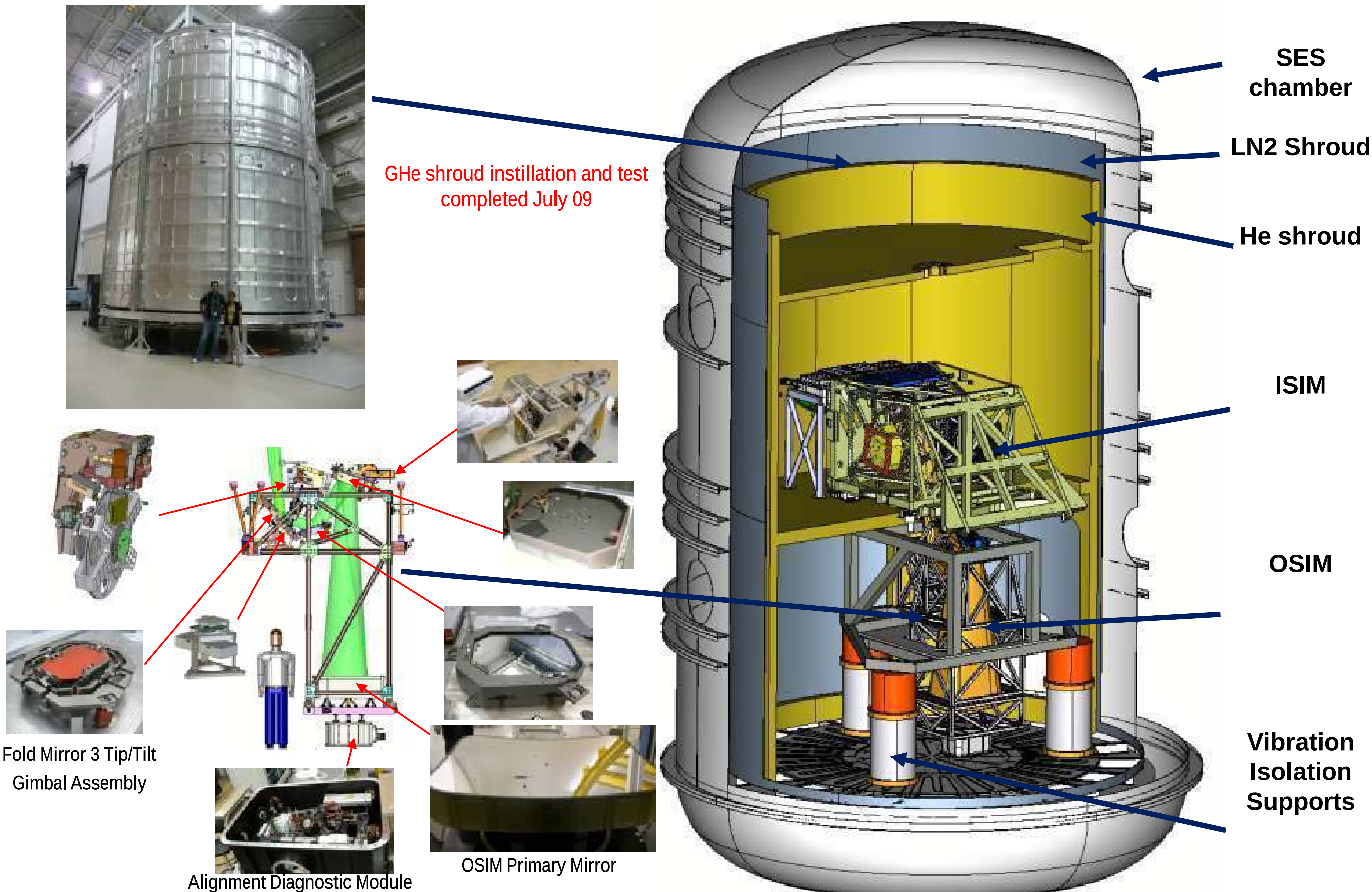
OSIM

http://www.jwst.nasa.gov/webcam.html

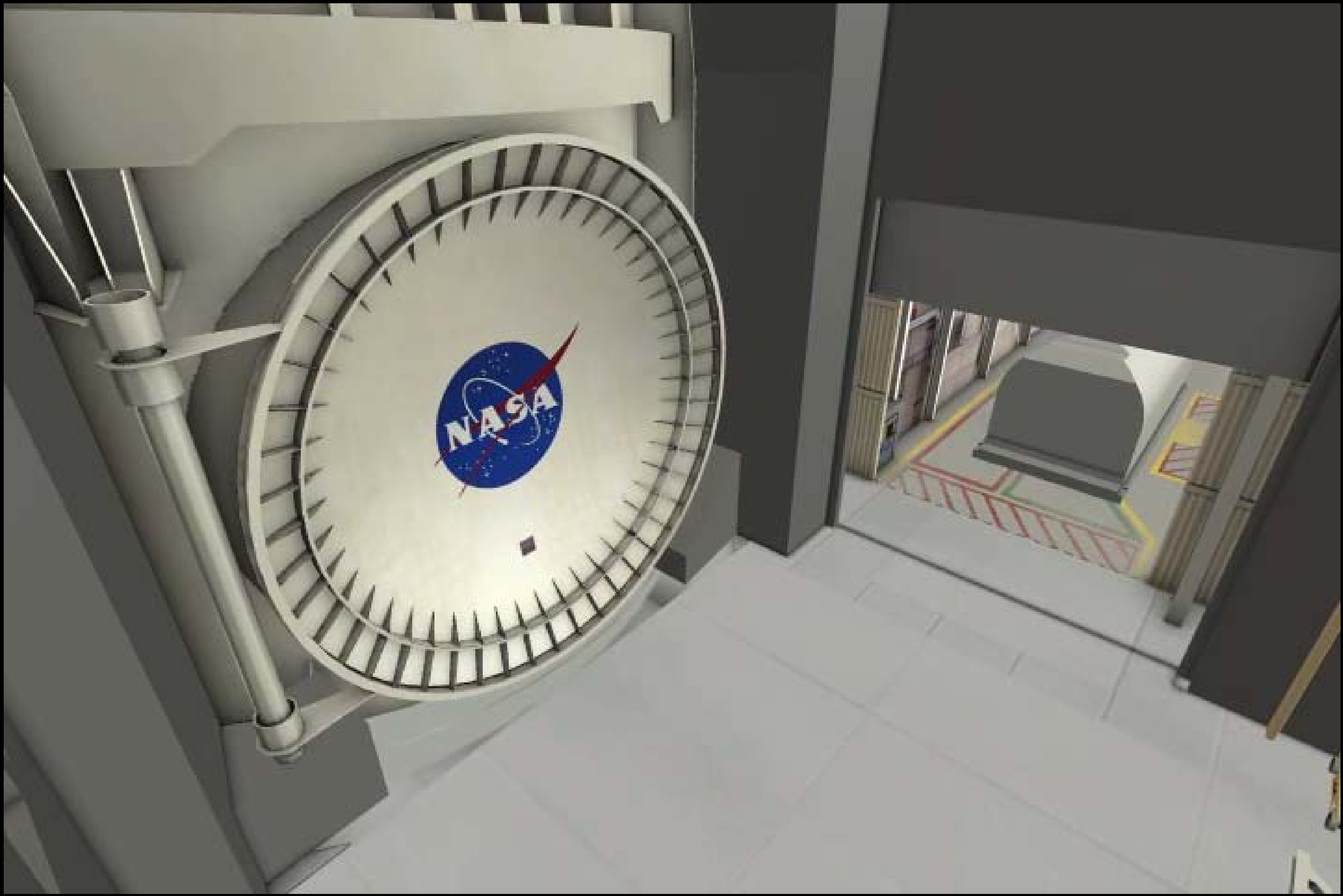
ISIM Structure Cryoset Test



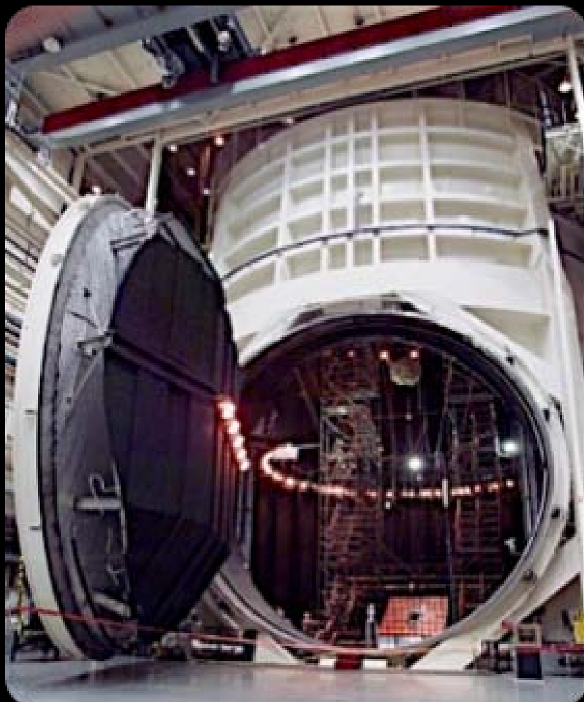
ISIM Test Configuration



Getting JWST into the JSC chamber



Optical End-to-End Test @ JSC

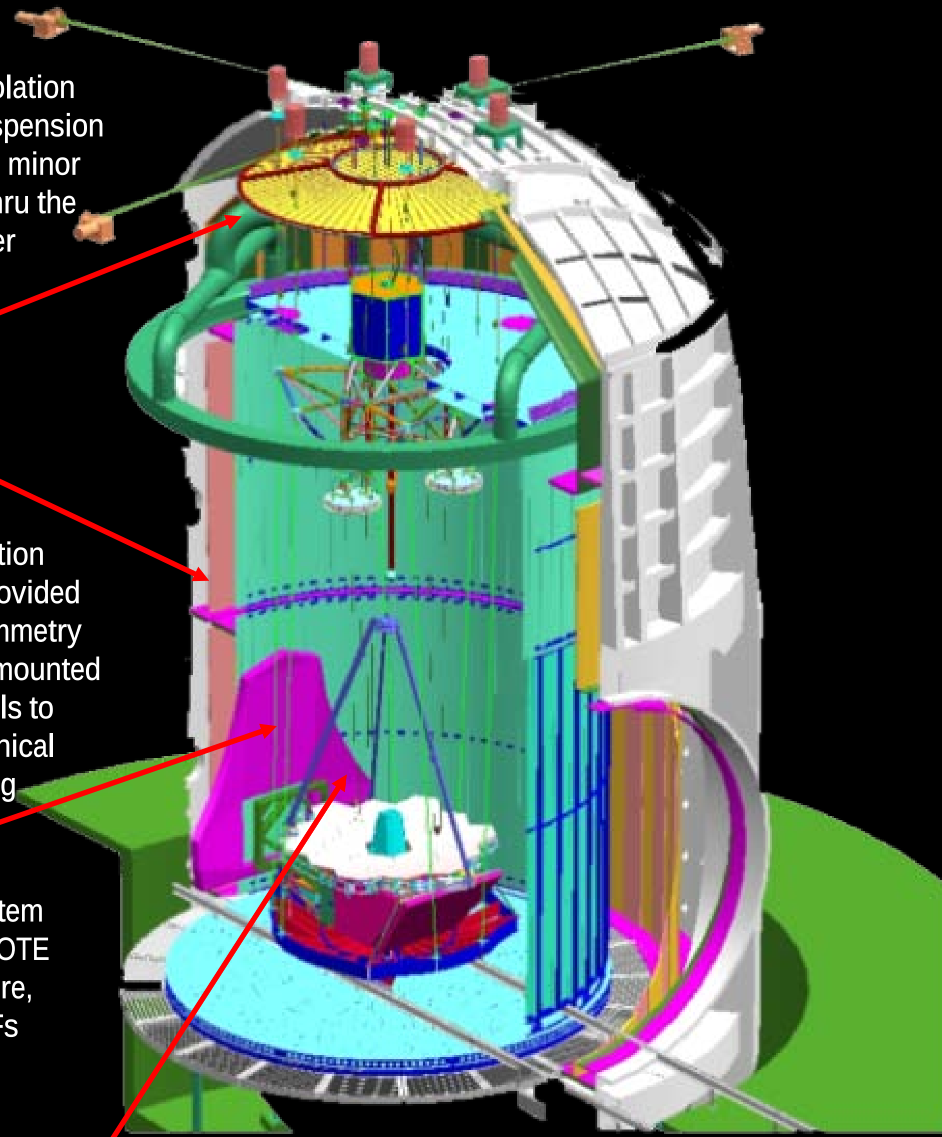


- Chamber 65’ dia x 120’ high
- Goals of Test
  - Verify Optical alignment
  - Verify workmanship
  - Thermal balance

Vibration isolation system for suspension system. Six minor intrusions thru the chamber

Cryo-Position Metrology provided by photogrammetry with cameras mounted on windmills to provide conical scanning

Suspension system which holds the OTE support structure, CoCI, and ACFs

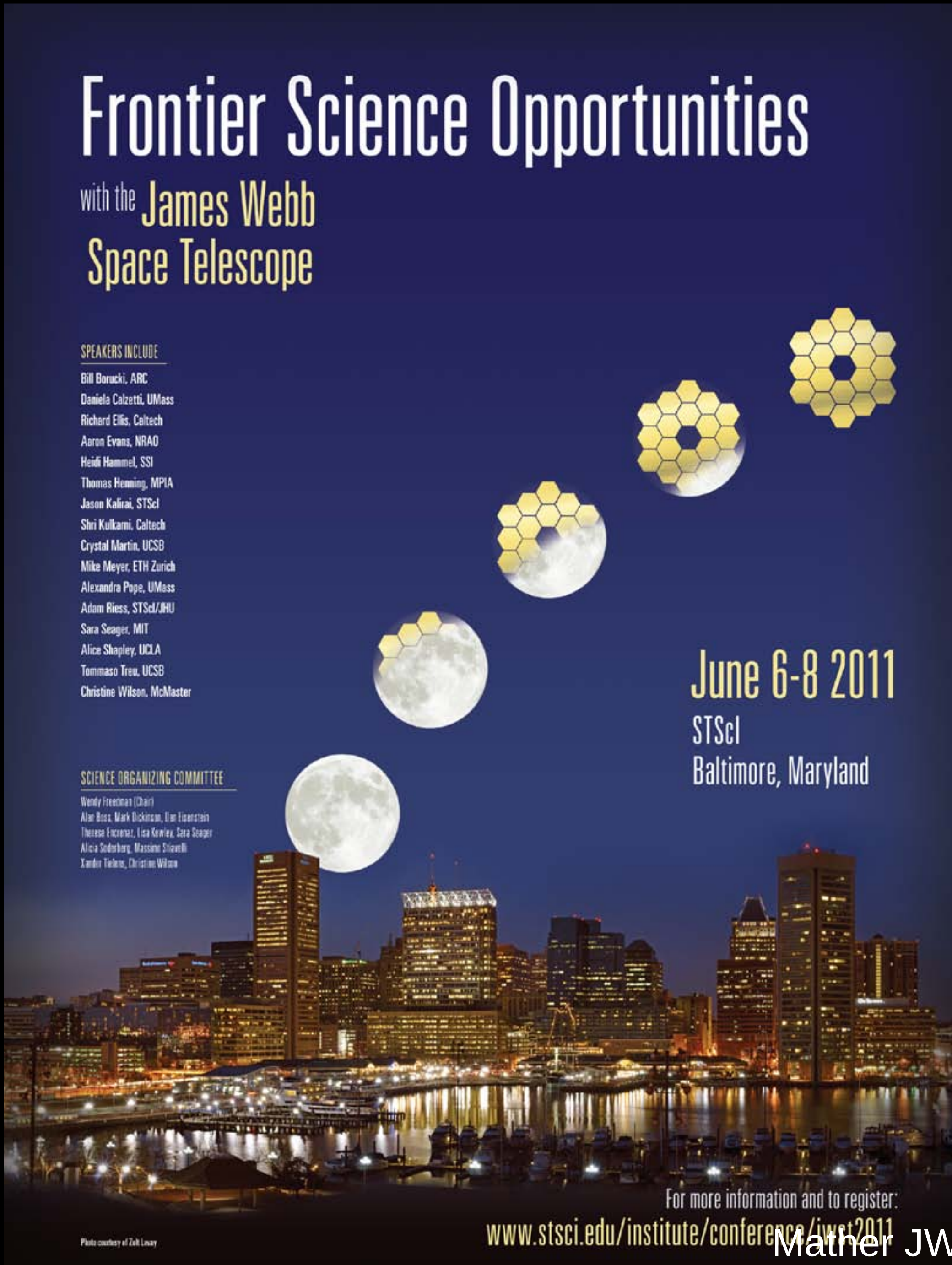


Test sources mounted on the AOS entrance. Inward sources sample the Tertiary Mirror. Outward sources make a pass and a half thru the OTE optics.

Sunshield Deployment

- NGAS models validate deployment approach, membrane folding and deployment boom performance

Science with JWST



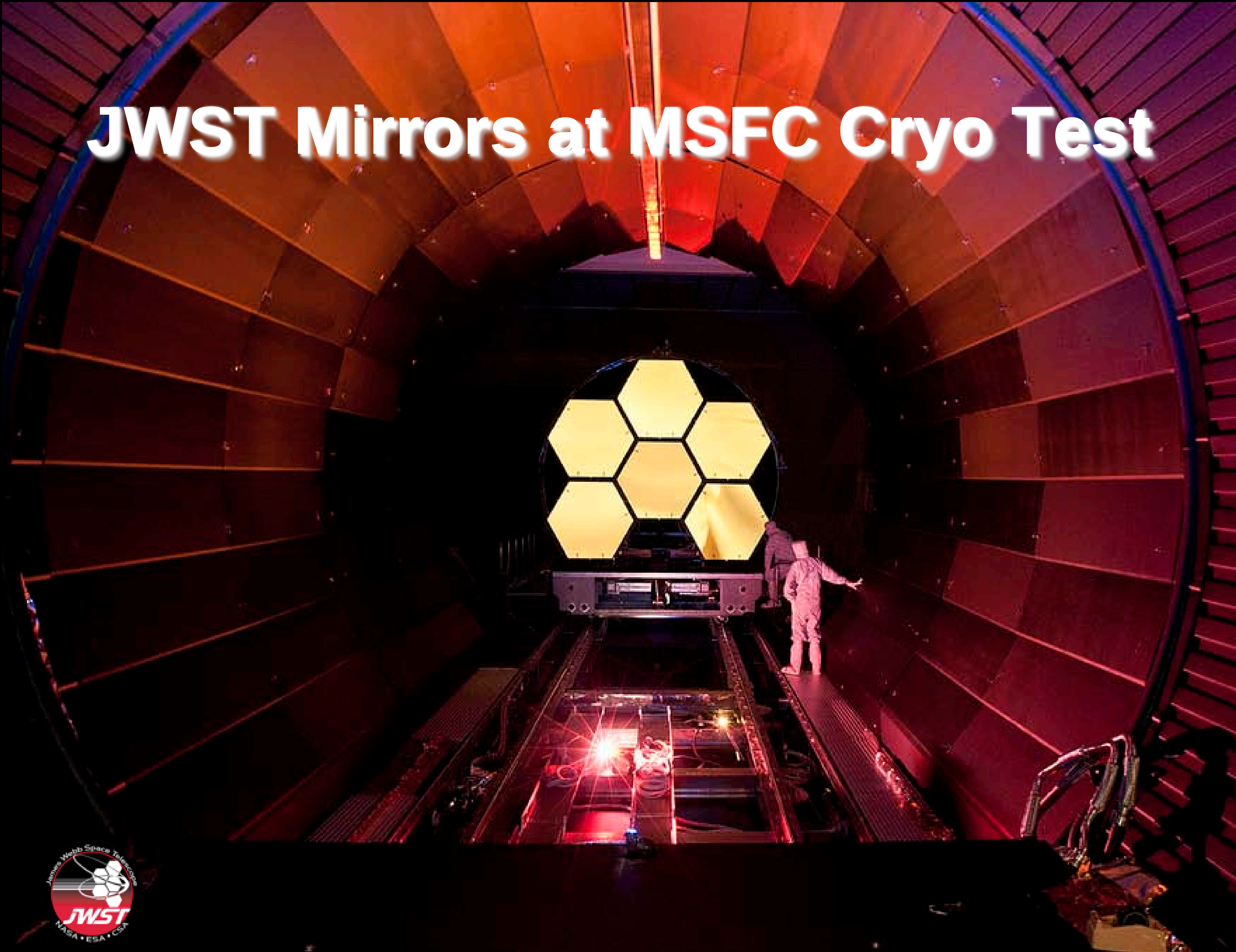
Frontier Science Opportunities

STScI released JWST Exposure Time Calculators, simulated images, and data challenges in connection with this meeting.

Talks are online.

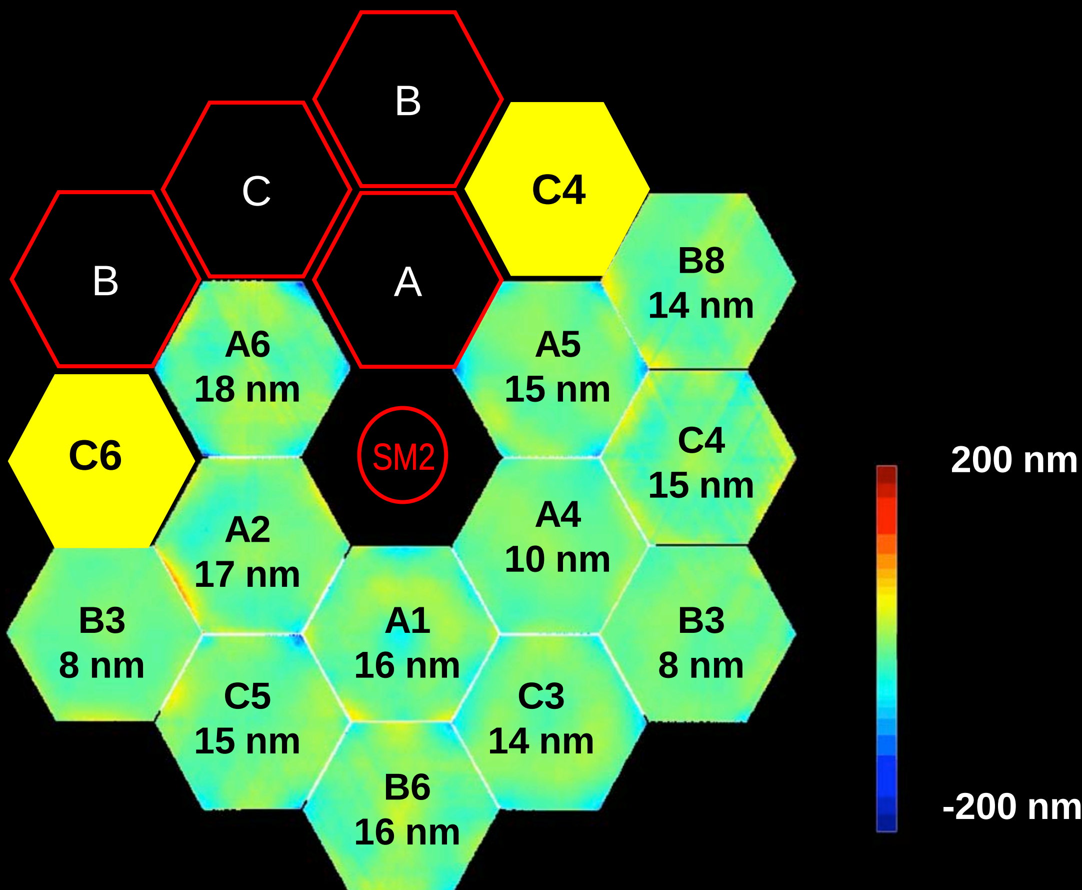
The End and the Beginning

JWST Mirrors at MSFC Cryo Test

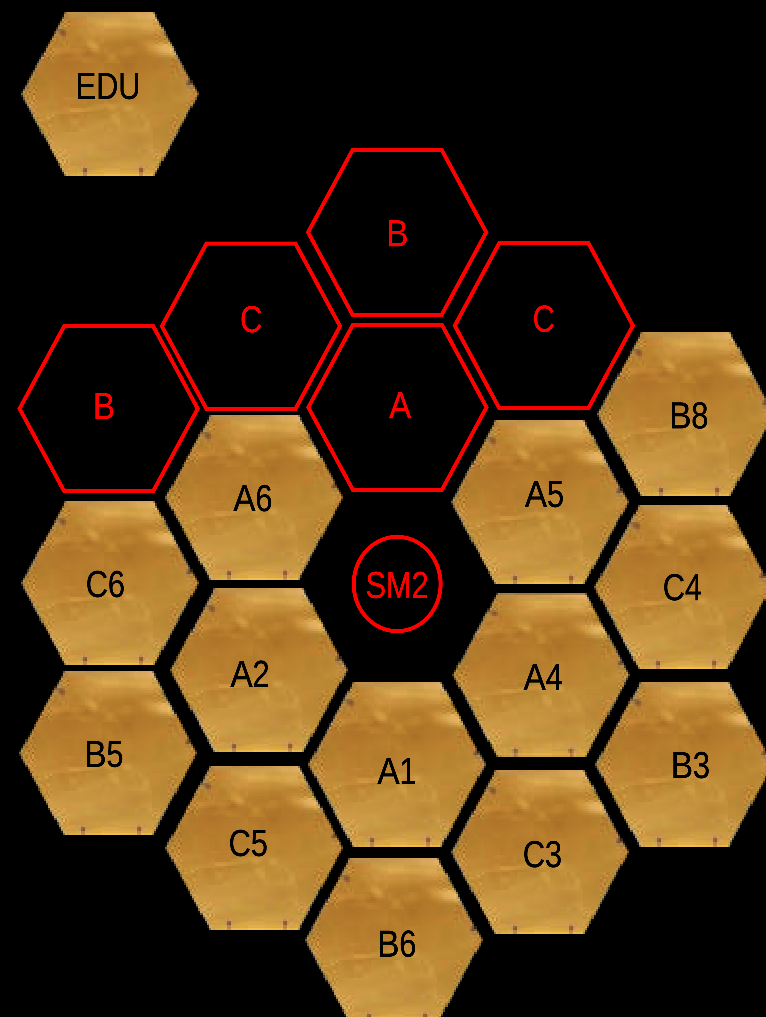


Flight Mirrors Meet Specification

- **Flight mirrors delivered by Tinsley at completion of polishing**
  - **Flight composite wavefront error 14 nm (requirement 17 nm)**



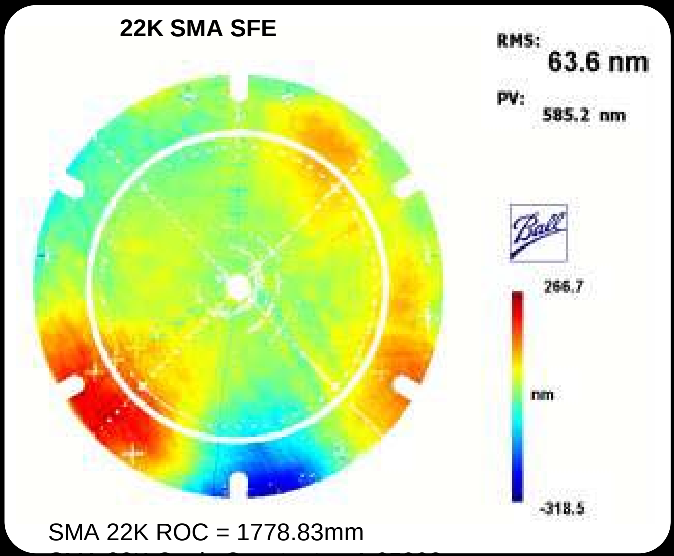
Completed polishing

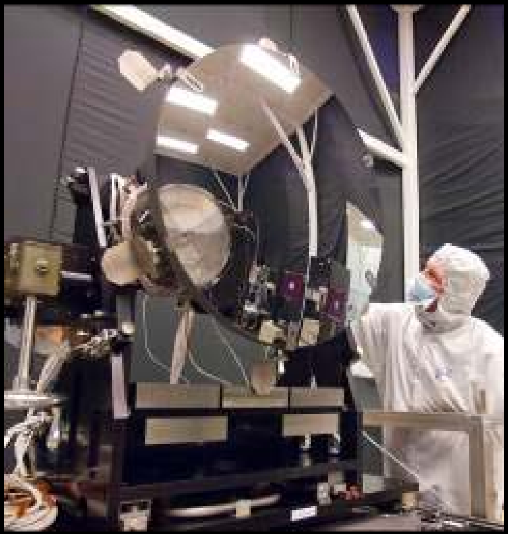


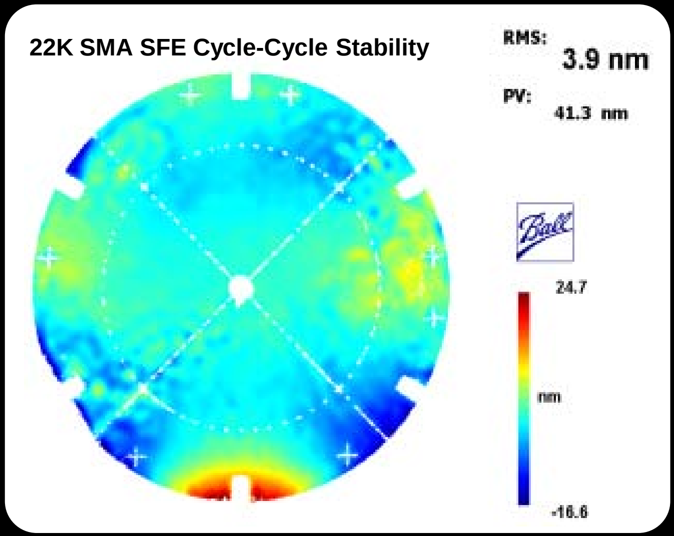
Gold Coated

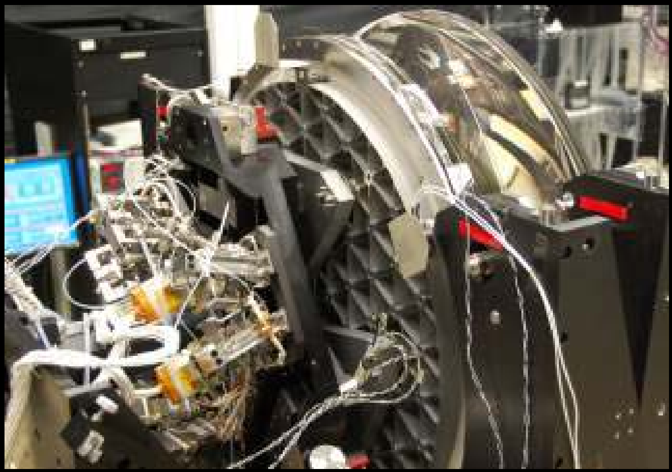
Secondary Mirror

- **SM flight spare meets requirements**









Programmatic Events

- **Independent Comprehensive Review Panel (ICRP) Report (released 11/10/10)**

> "The problems causing cost growth and schedule delays on the JWST Project are associated with budgeting and program management, not technical performance. The technical performance on the Project has been commendable and often excellent."
>
> *Executive Summary, p. 3*

- Based upon ICRP recommendations NASA has taken steps to implement:
  - Reorganized program and project management and reporting structures at GSFC and Headquarters,
  - Elevated Program visibility, reporting, performance assessment and cost control at GSFC, HQ, contractors and subcontractors
- **Other Reviews:**
  - Successful Technical portion of Mission Critical Design Review (MCDR) 4/2010
  - Currently in Implementation (Phase C-D)
  - Programmatic portion of MCDR not completed (overtaken by ICRP, other reviews)
  - Technical problems and challenges have been addressed but with increased cost and schedule delay
  - Science Instruments, Telescope & Sunshield have all successfully completed CDR's
  - 72% of the JWST dry mass is past CDR and in fabrication