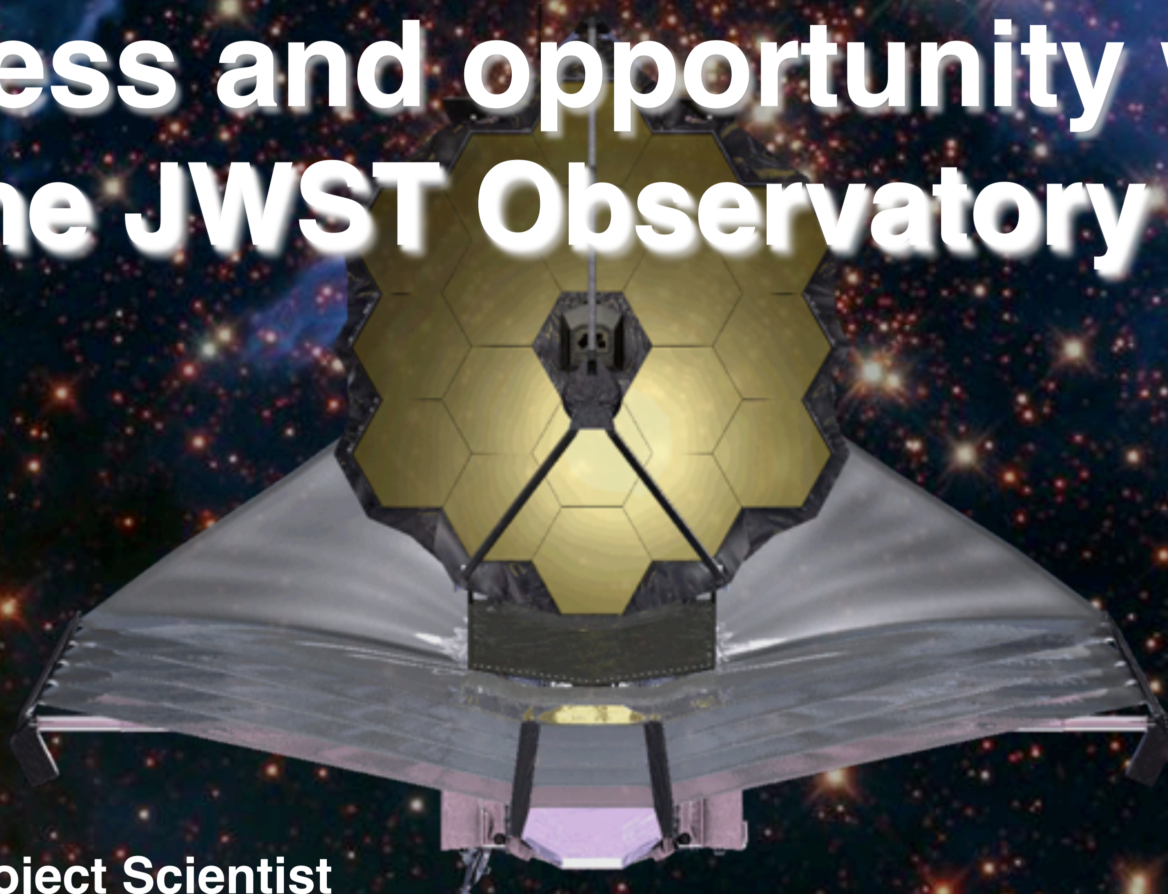
The Beginnings of Everything, from the Big Bang to Planets – progress and opportunity with the JWST Observatory



John Mather
JWST Senior Project Scientist
Goddard Space Flight Center

Jefferson's Implied Question

- How is it, that "the Laws of Nature, and of Nature's God", as he put it, can lead to this: "We hold these truths to be self-evident, that all men are created equal, that they are endowed by their Creator with certain unalienable Rights, that among these are Life, Liberty and the pursuit of Happiness."

The James Webb Space Telescope

James E. Webb (1906 – 1992)

- Second Administrator of NASA (1961 – 1968)
- Oversaw first & Second manned spaceflight programs (Mercury, Gemini)
- Oversaw Mariner and Pioneer planetary exploration programs
- Oversaw Apollo program: On time, On budget! (he asked for enough!)
- Supported space science at NASA and universities

Crab Nebula • M1

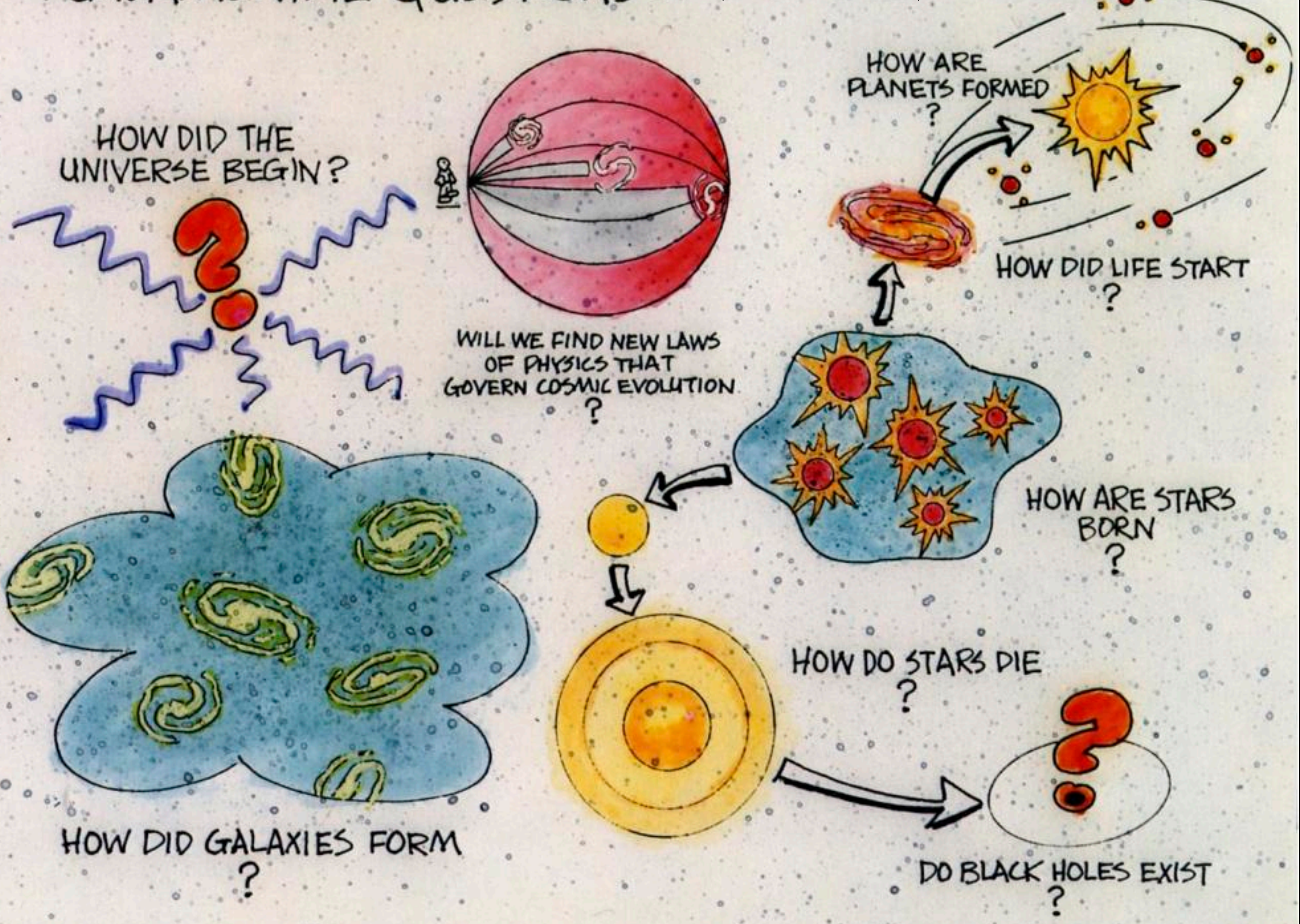
Pillar and Jets HH 901/902

Hubble Space Telescope ▪ WFC3/UVIS

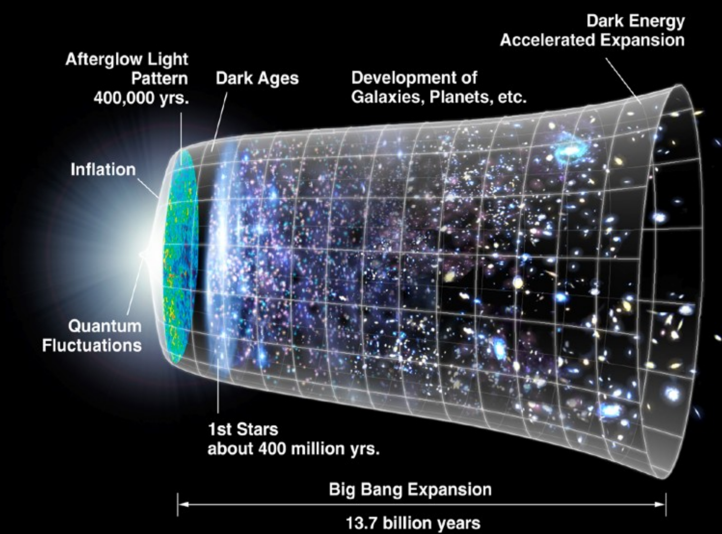
NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

STScI-PRC10-13c

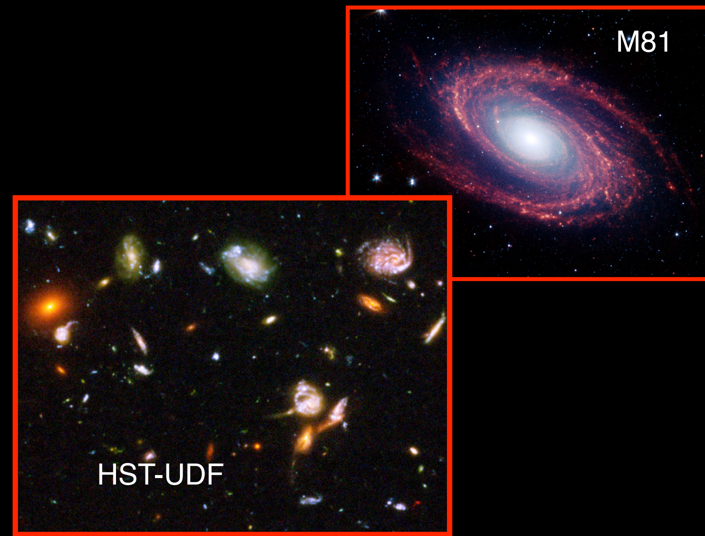
FUNDAMENTAL QUESTIONS: (as of 1985)



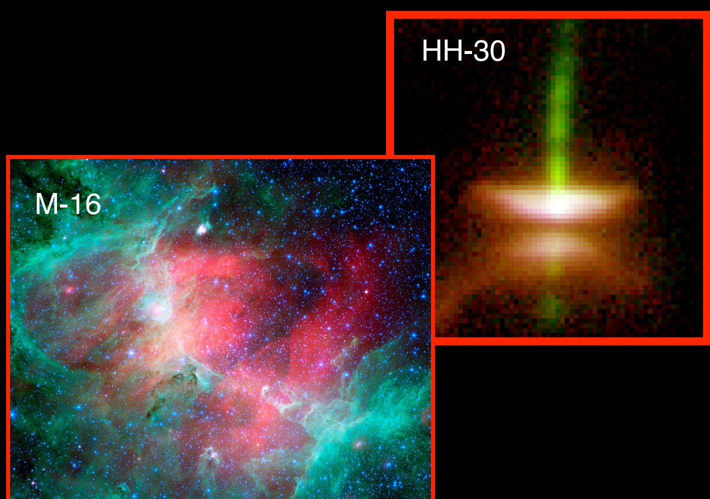
Decadal 2000 & 2010 Science with JWST



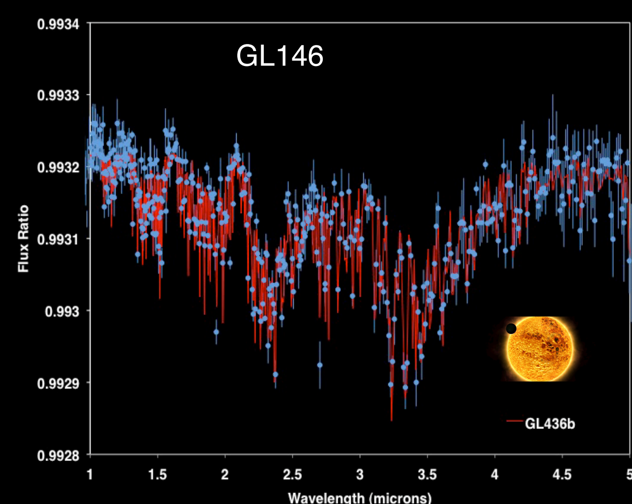
First Light and Re-Ionization



Assembly of Galaxies



Birth of stars and
proto-planetary systems

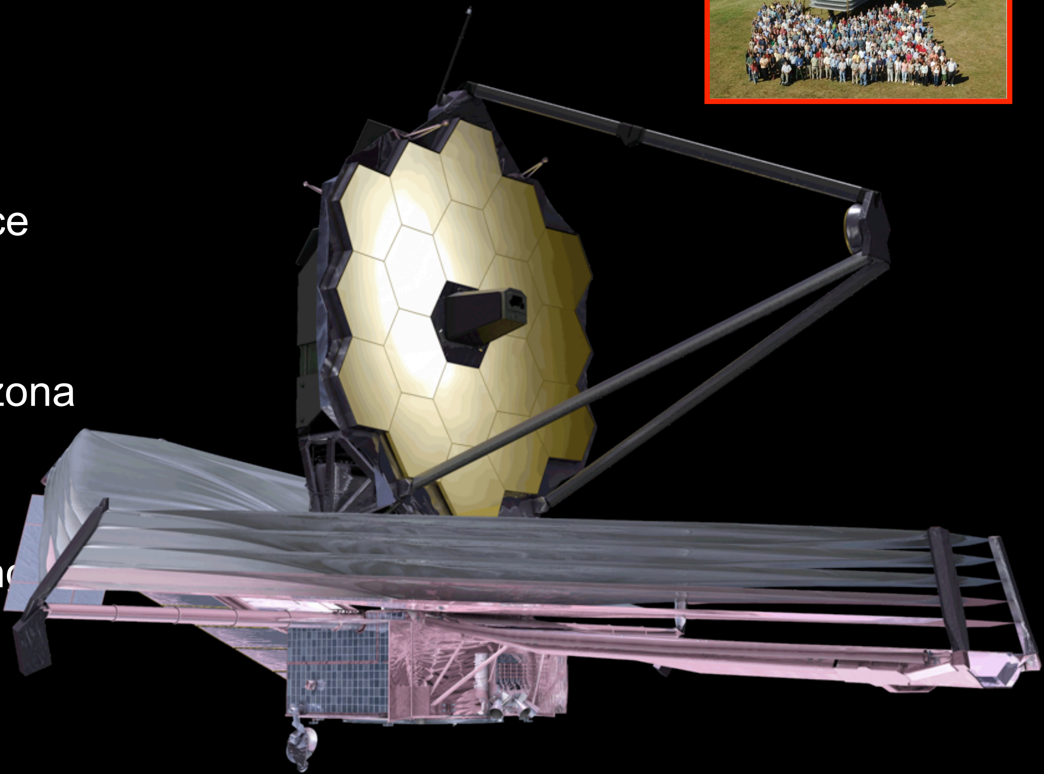


Planetary systems and the
origin of life

James Webb Space Telescope

Organization

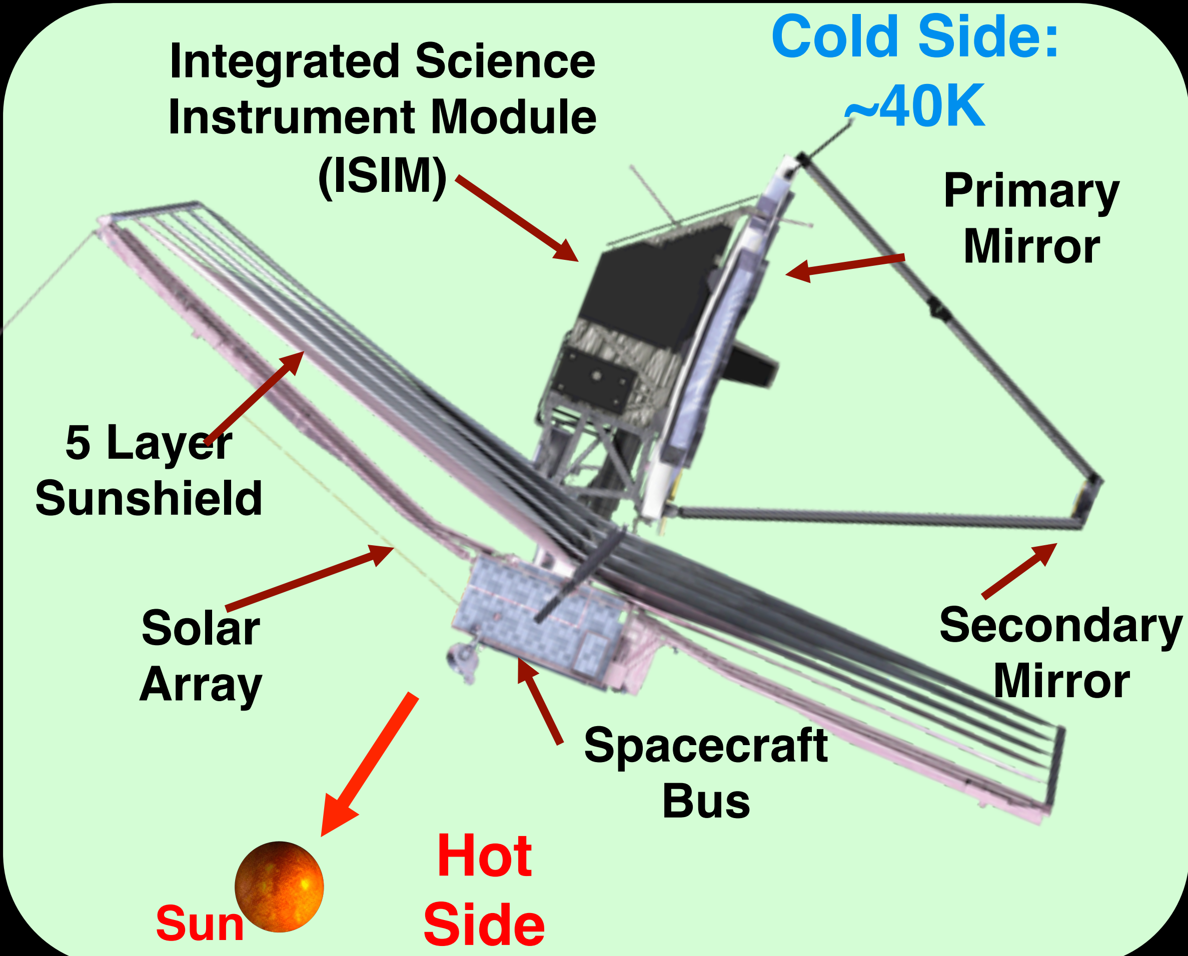
- Mission Lead: Goddard Space Flight Center
- Senior Project Scientist: Dr John Mather
- International collaboration: ESA & CSA
- Prime Contractor: Northrop Grumman Aerospace Systems
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  -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

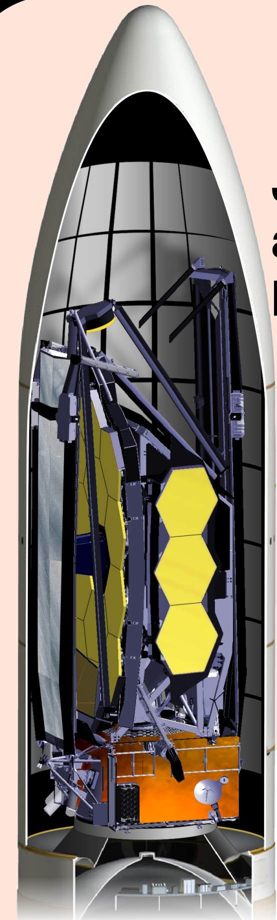


Description

- 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



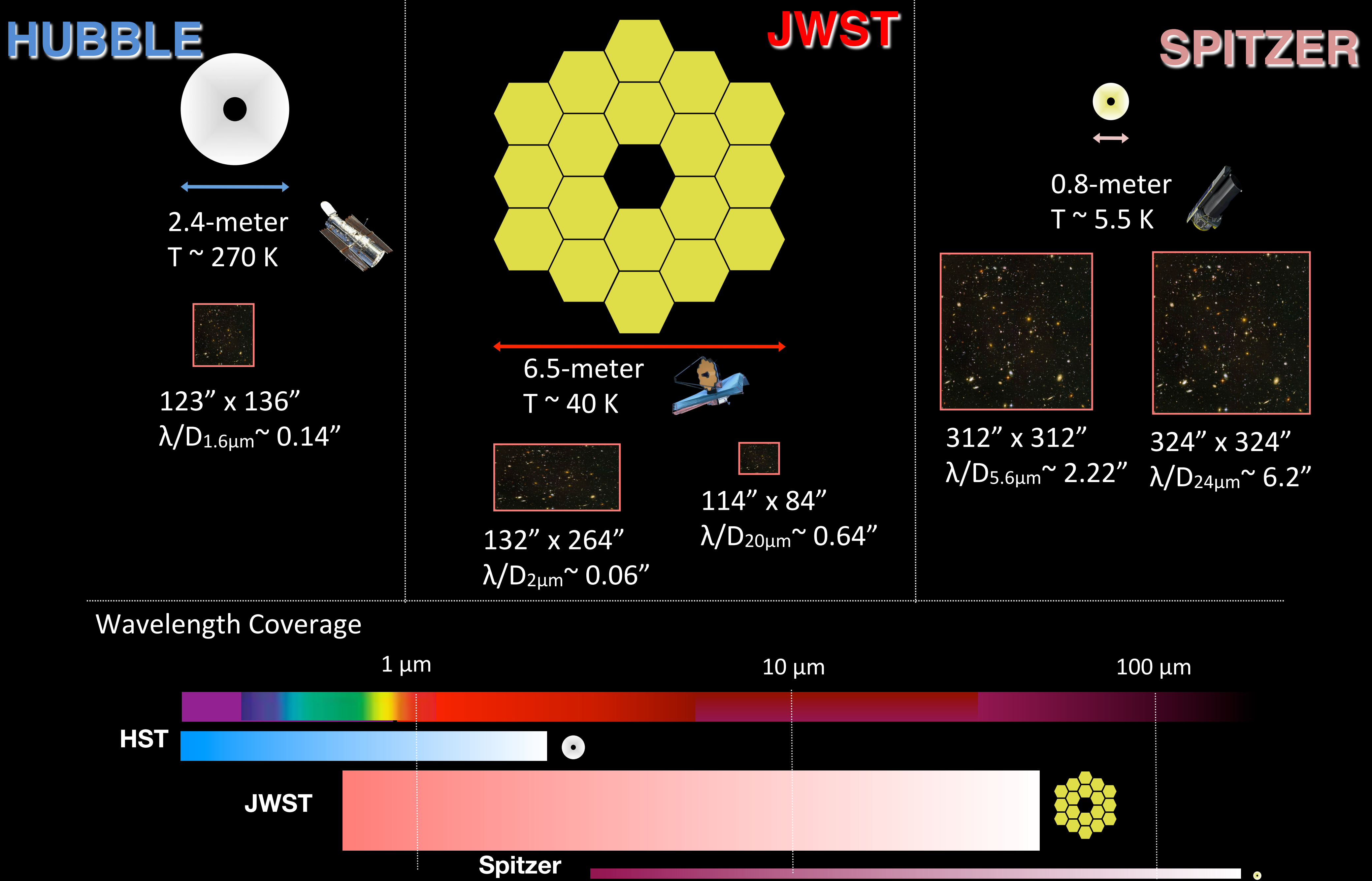


JWST is folded and stowed for launch

Observatory is deployed after launch

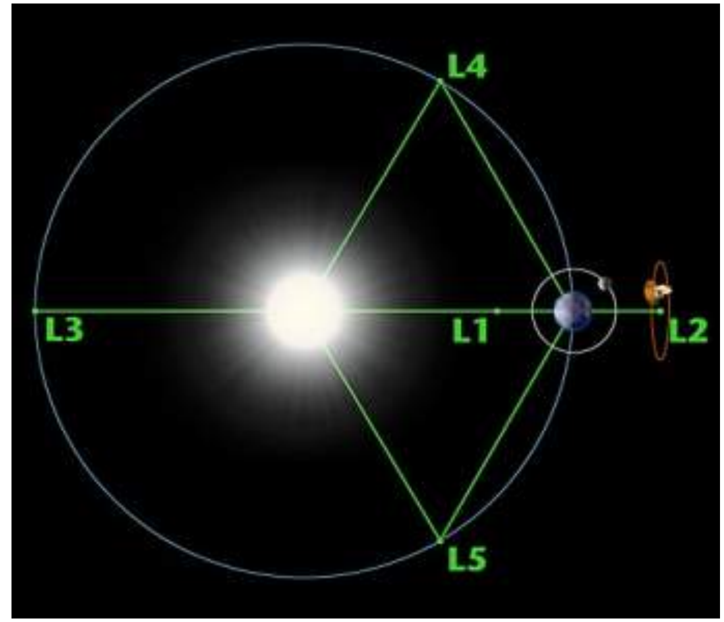
JWST Orbits the 2nd Lagrange Point (L2)

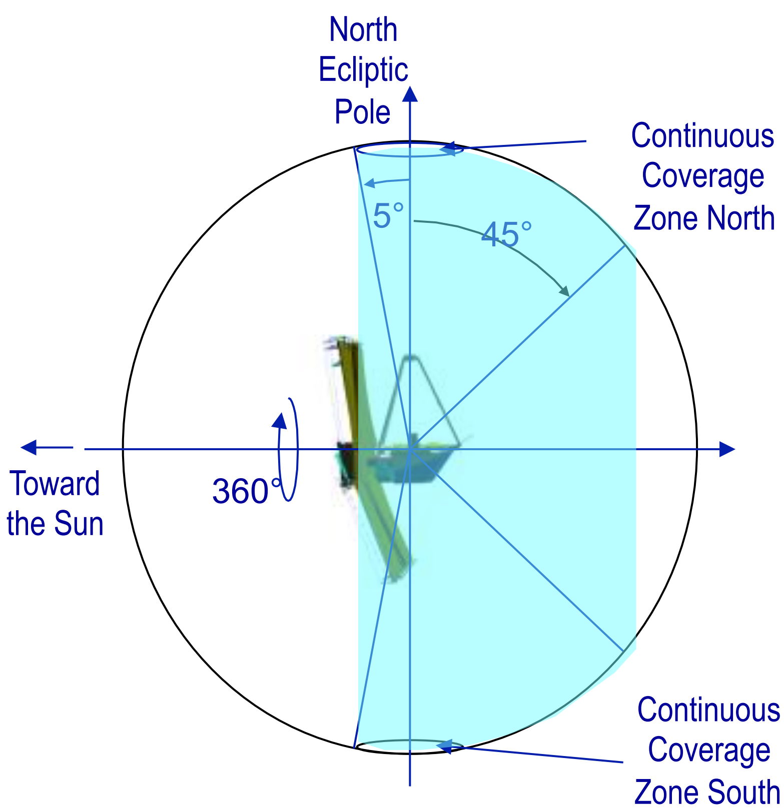
JWST and its Precursors



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)



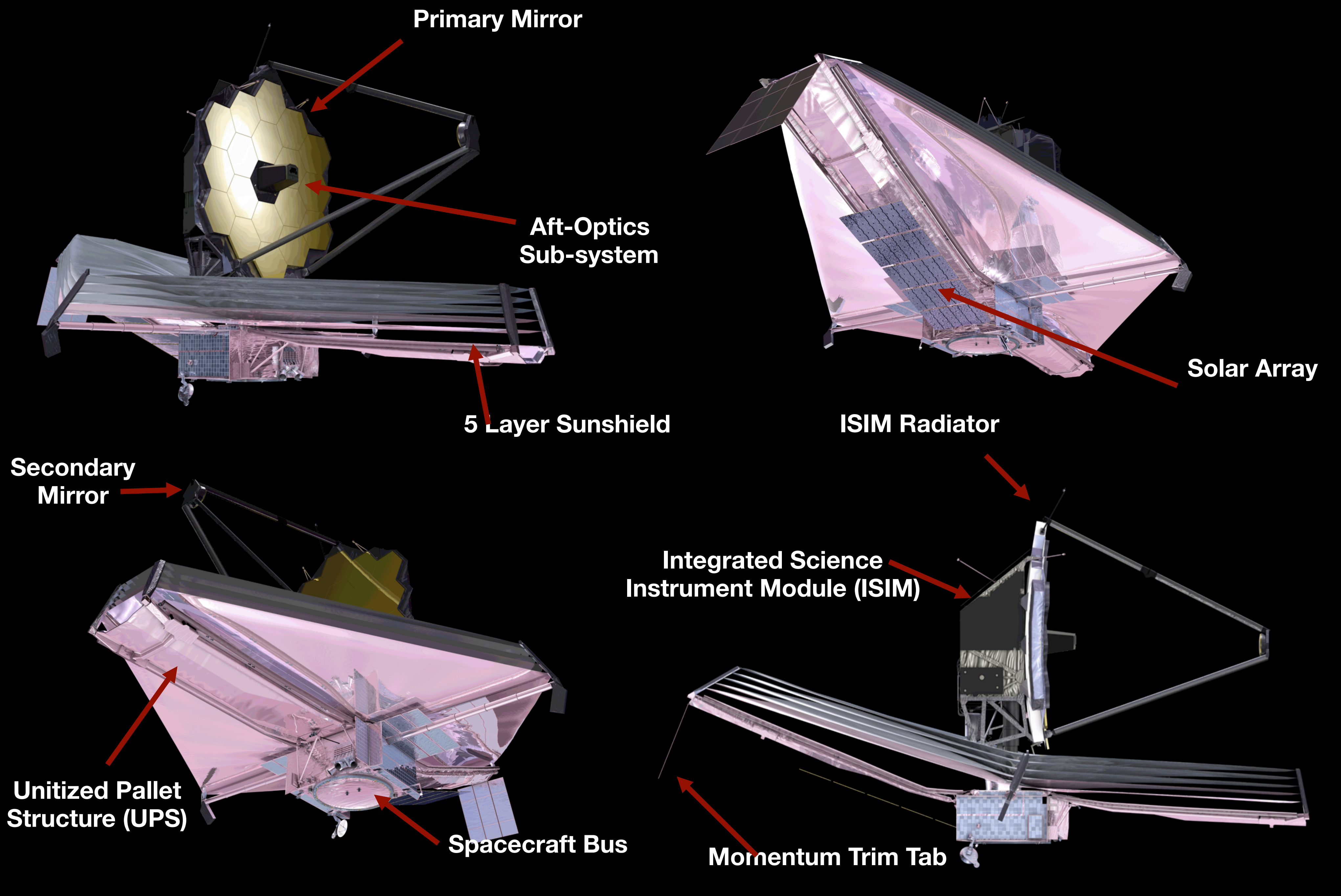


- The JWST can observe the whole sky while remaining continuously in the shadow of its sunshield
  - Field of Regard is an annulus covering 35% of the sky
  - The whole sky is covered each year with small continuous viewing zones at the Ecliptic poles

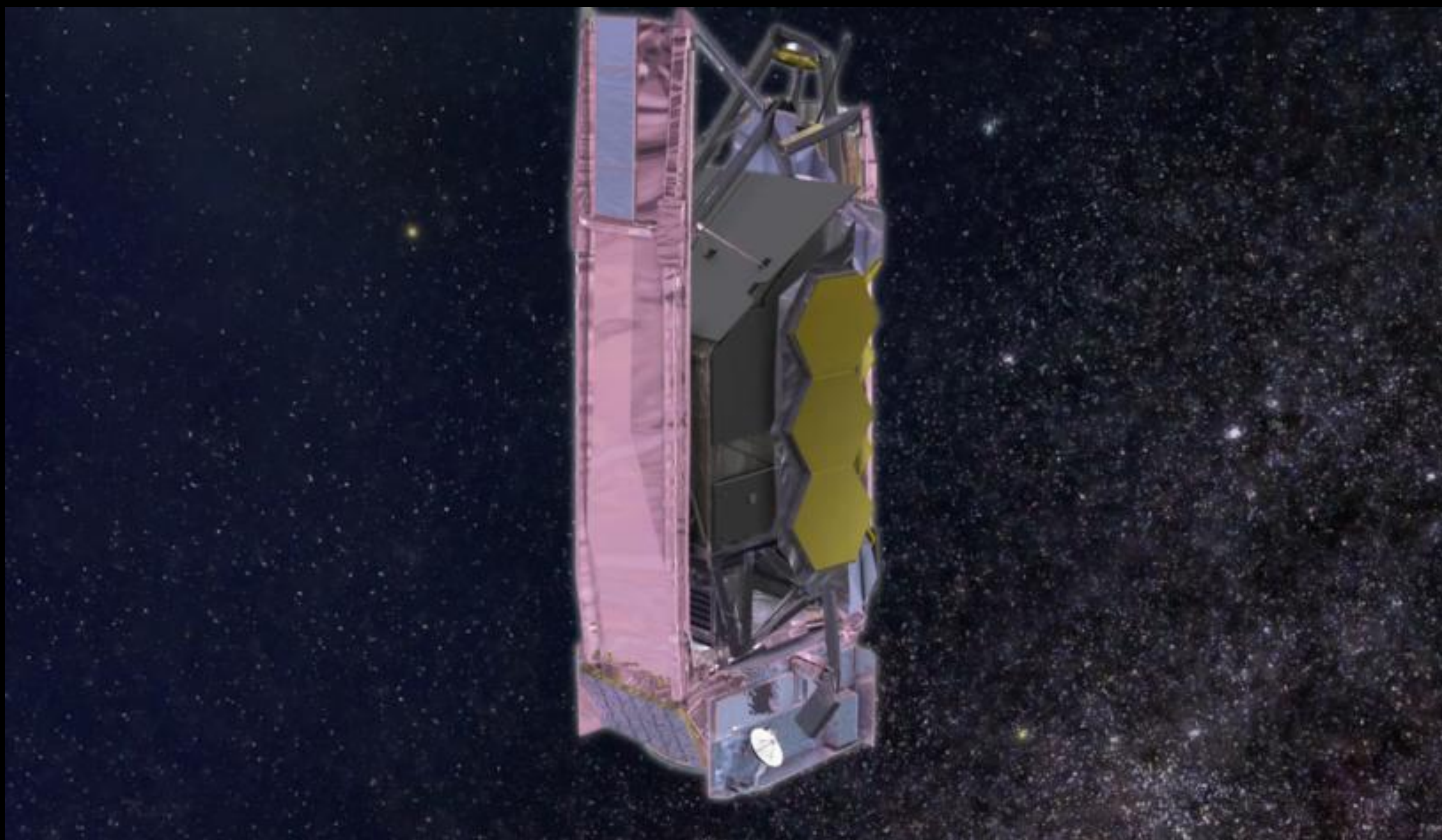
ESA-provided Ariane 5 will launch JWST from Kourou, French Guiana - 2018

Herschel-Planck Launch

JWST Design: Key Features

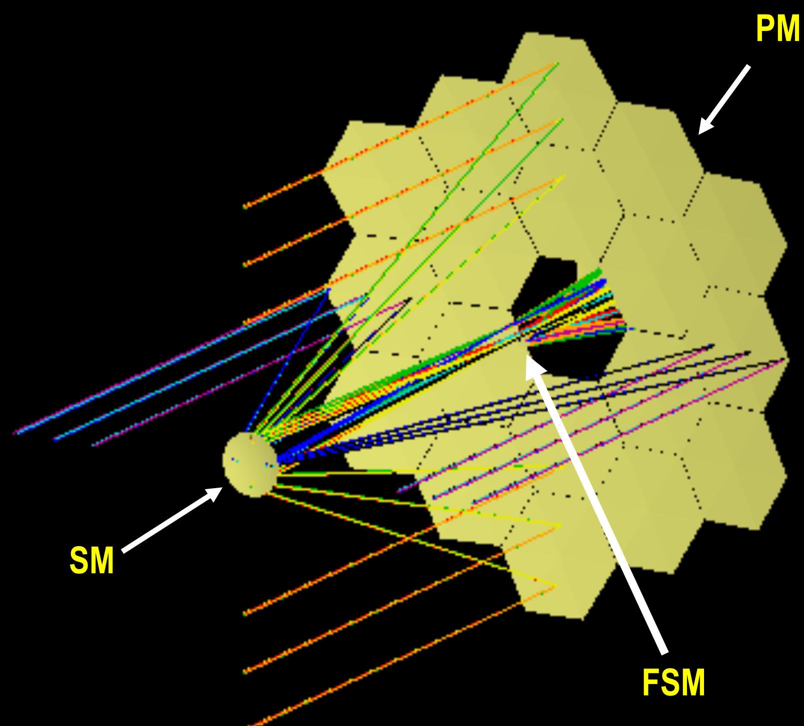


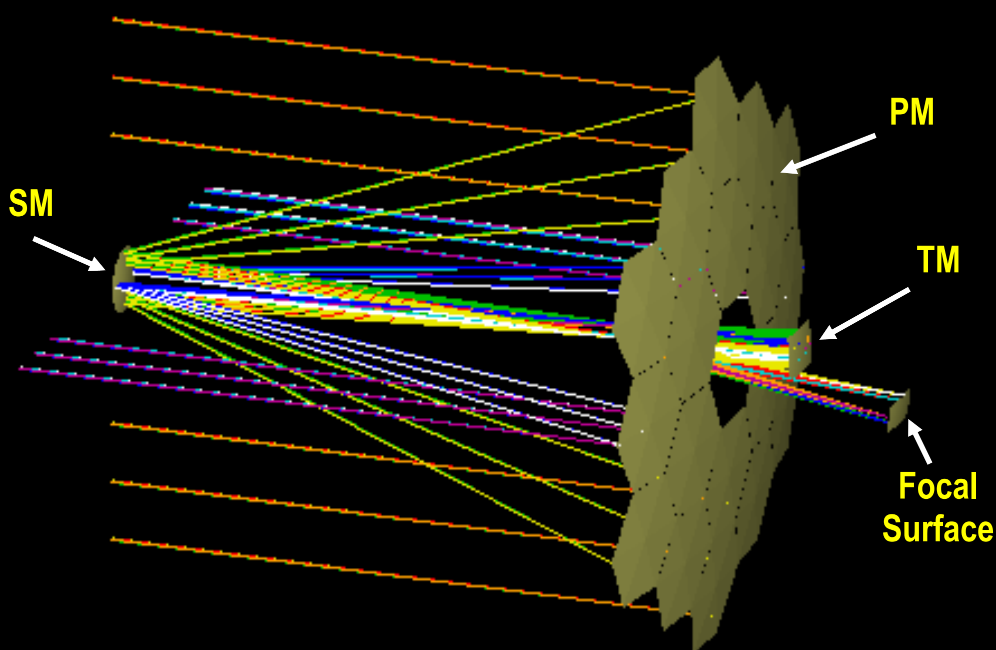
JWST Deployment



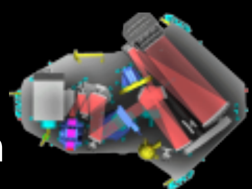
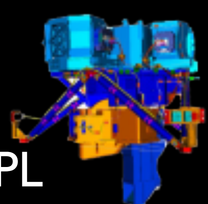
JWST's Optical Design: I

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



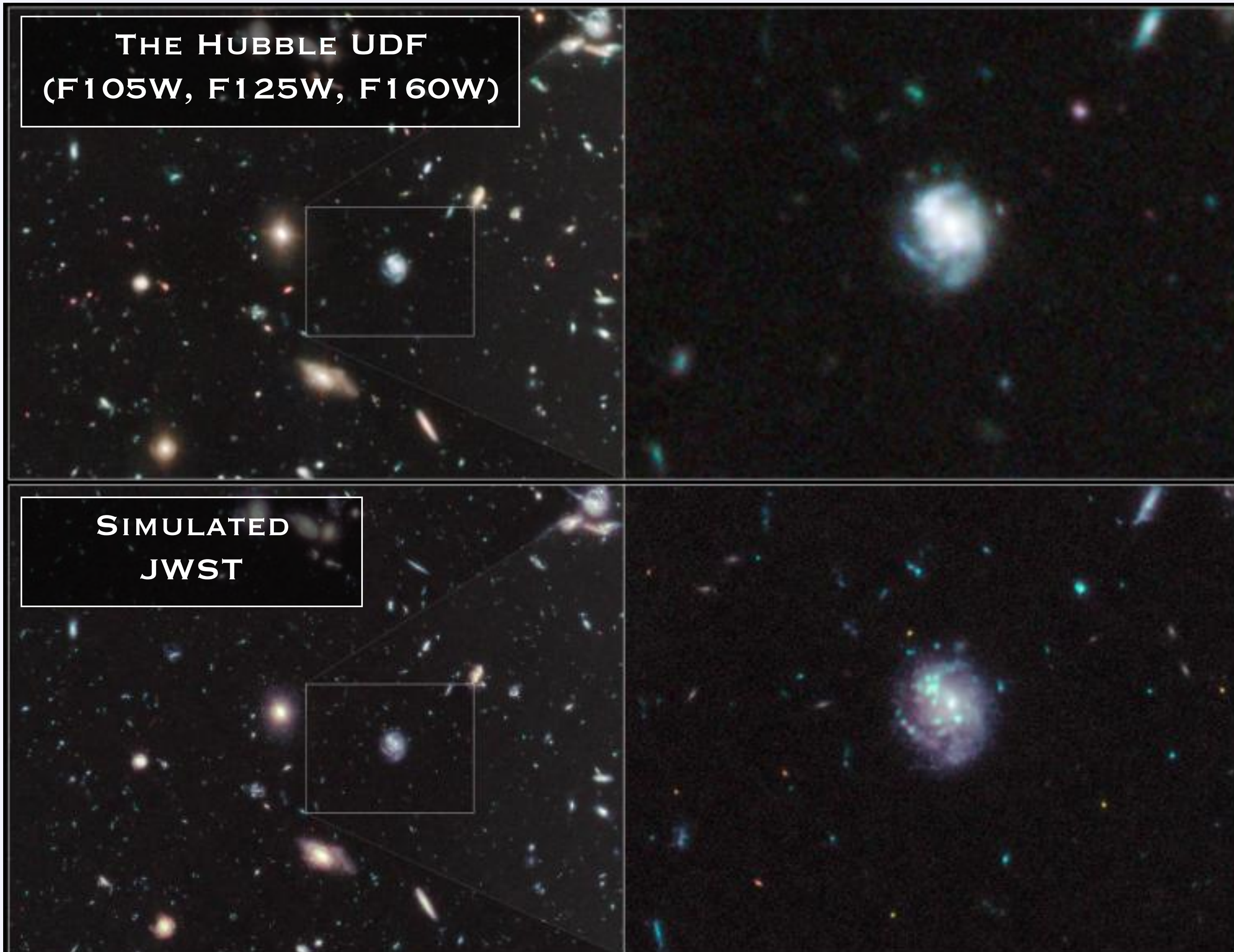


JWST Instrumentation

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/NIRISS CSA 	Fine Guidance Sensor 0.8 µm - 5.0 µm Near IR Imaging Slitless Spectrograph ›1.6 µm - 4.9 µm	Two 2.3’ x 2.3’ 2.2’ x 2.2’ R=150, 700 with coronagraph

The James Webb Space Telescope

JWST Science Themes – The End of the Dark Ages



→ JWST will have higher angular resolution than Hubble for deep fields

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

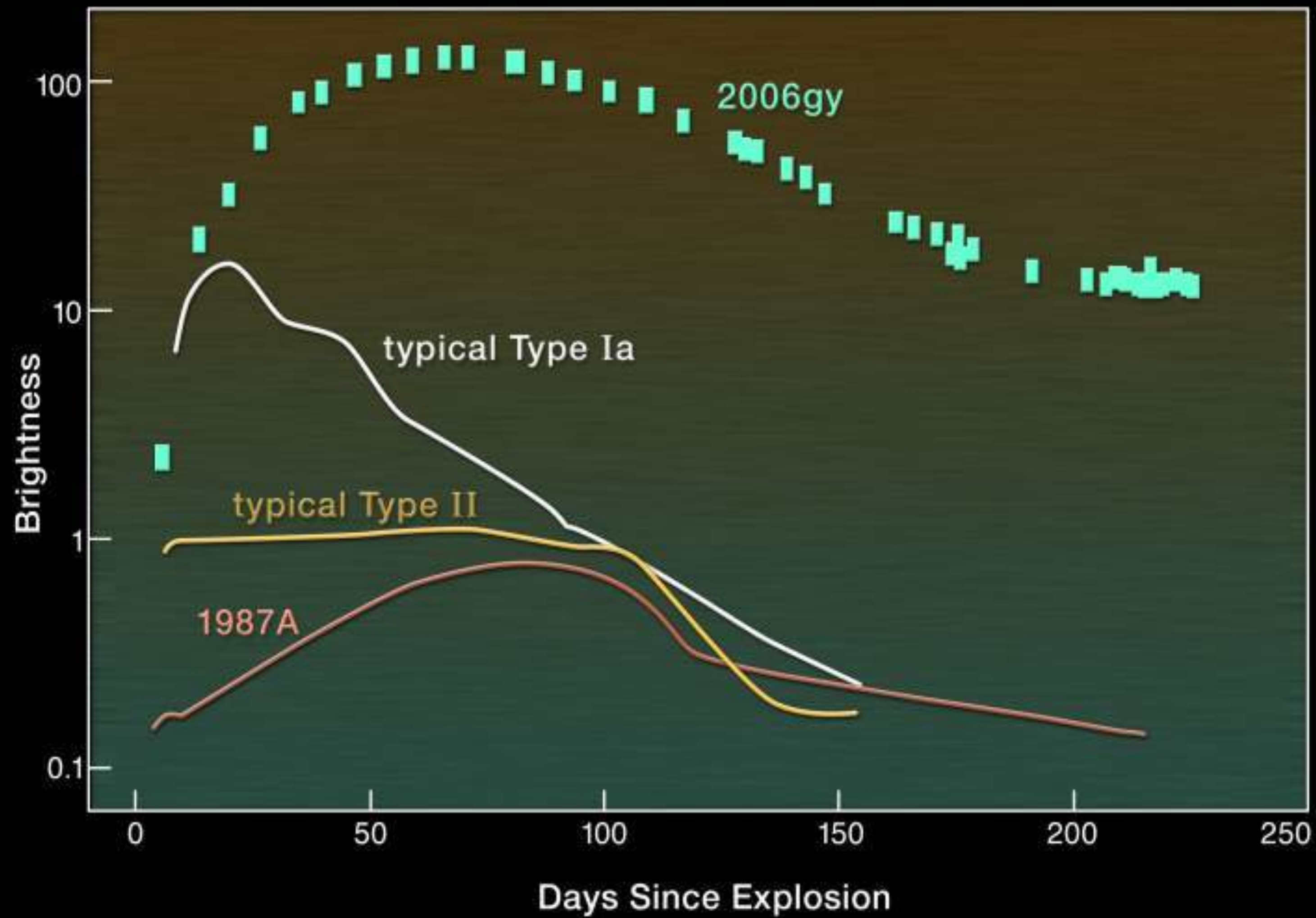
Galaxy collision simulation

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

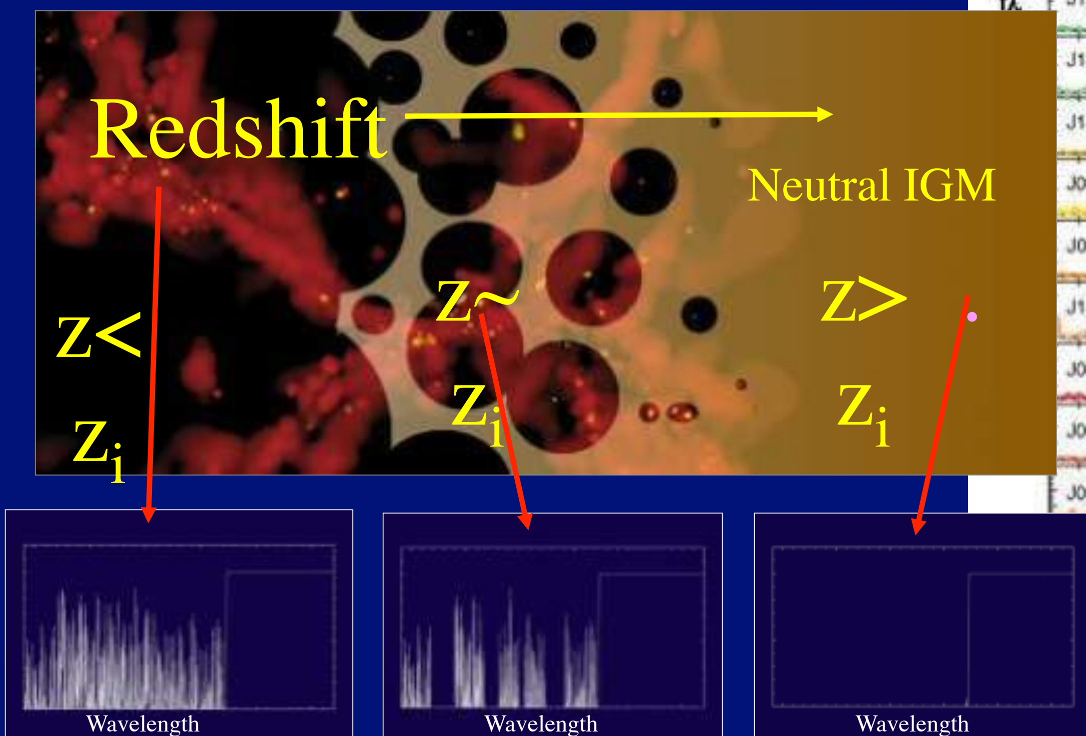


- JWST can easily see these at z = 10-20, but they're rare, and much slower!

6.42

When was re-ionization? And what caused it?

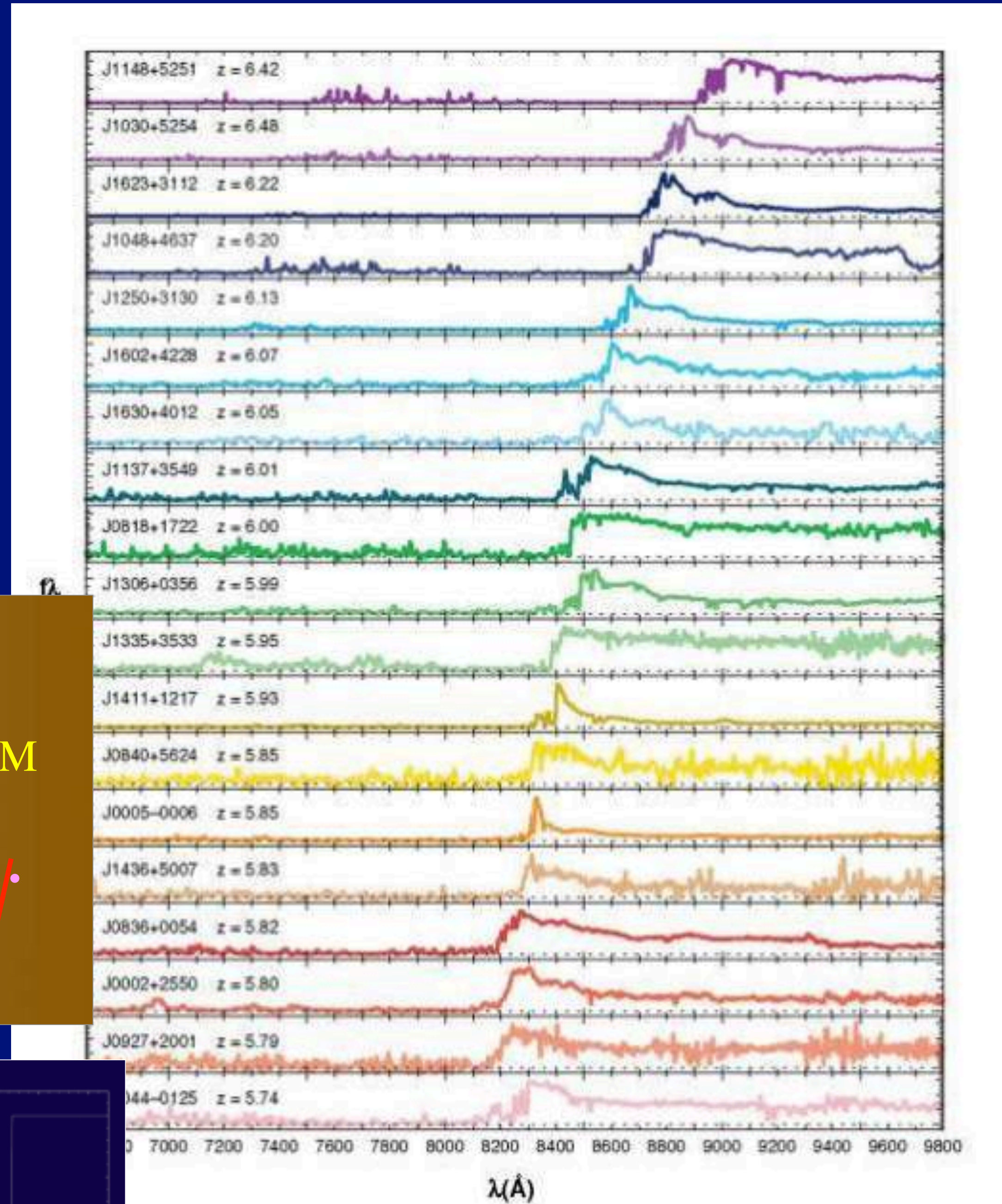
6.00



Lyman Forest Absorption

Patchy Absorption

Black Gunn-Peterson trough

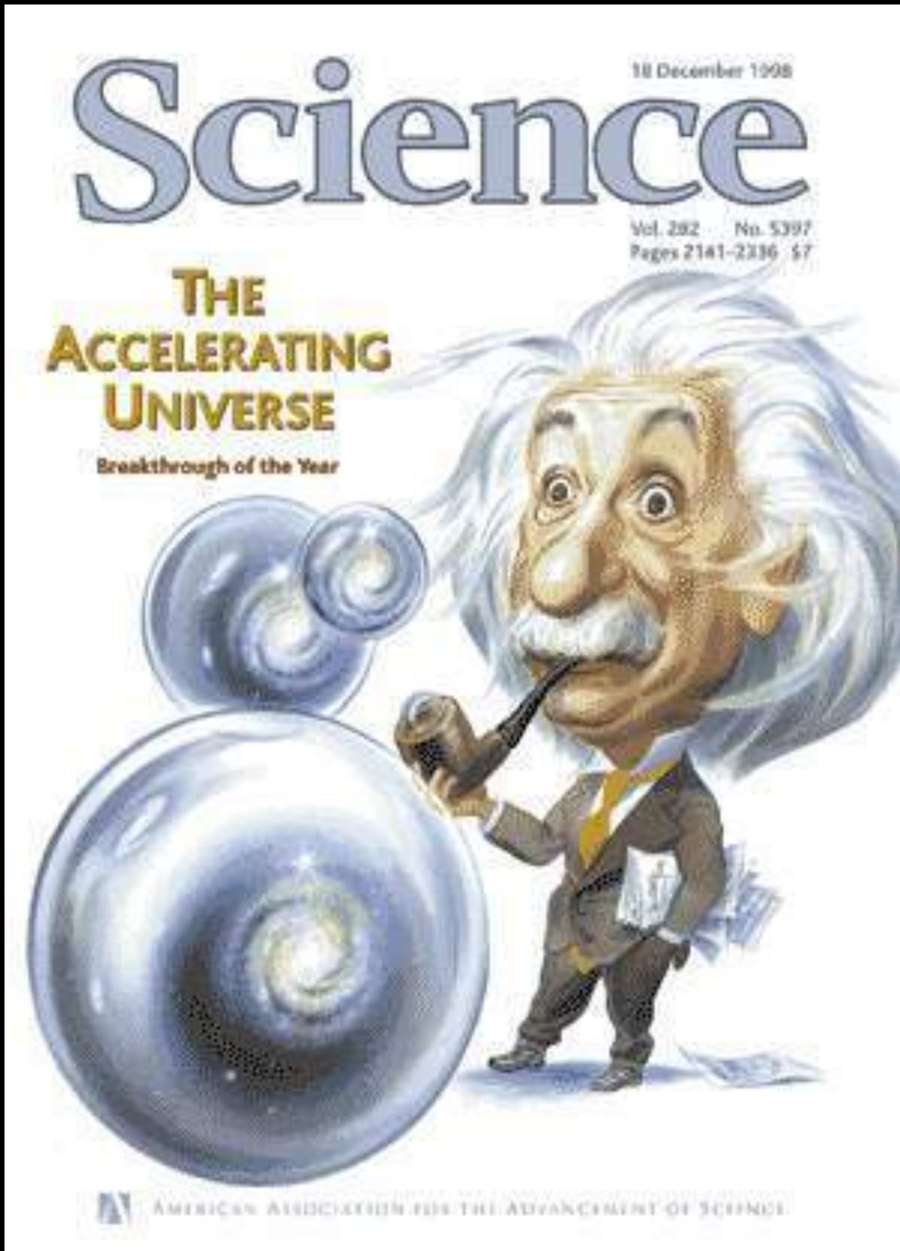


5.74

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

Nobel Prize 2011: Dark Energy!

Brian in 2006!



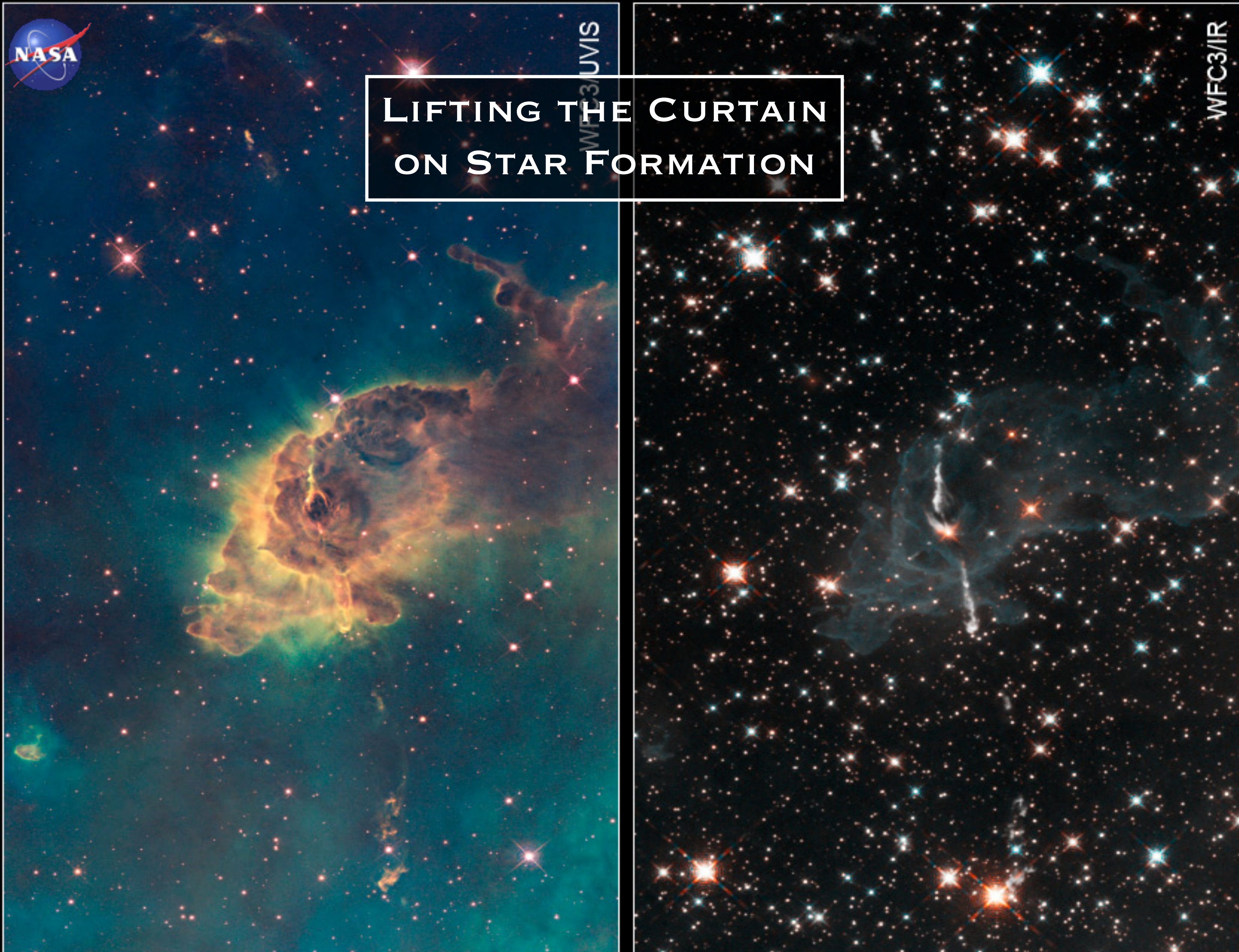
S. Perlmutter, A. Riess, B. Schmidt receiving the Shaw Prize

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

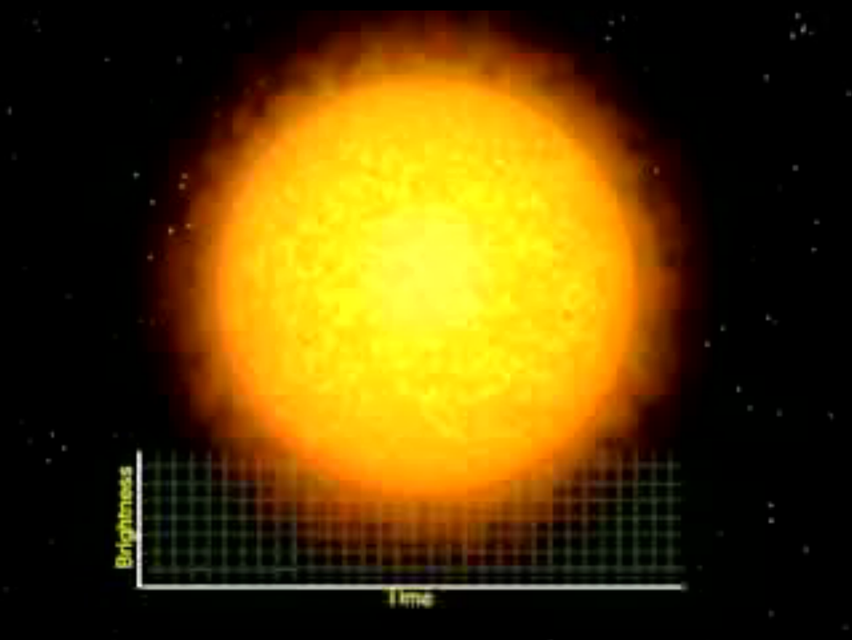
Lifting the Curtain on Star Formation



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 – 1790 host stars, 2321 candidates already!
- Microlensing found 10 lonely planets (without stars!)
- JWST Transits Working Group established – M. Clampin

Primary

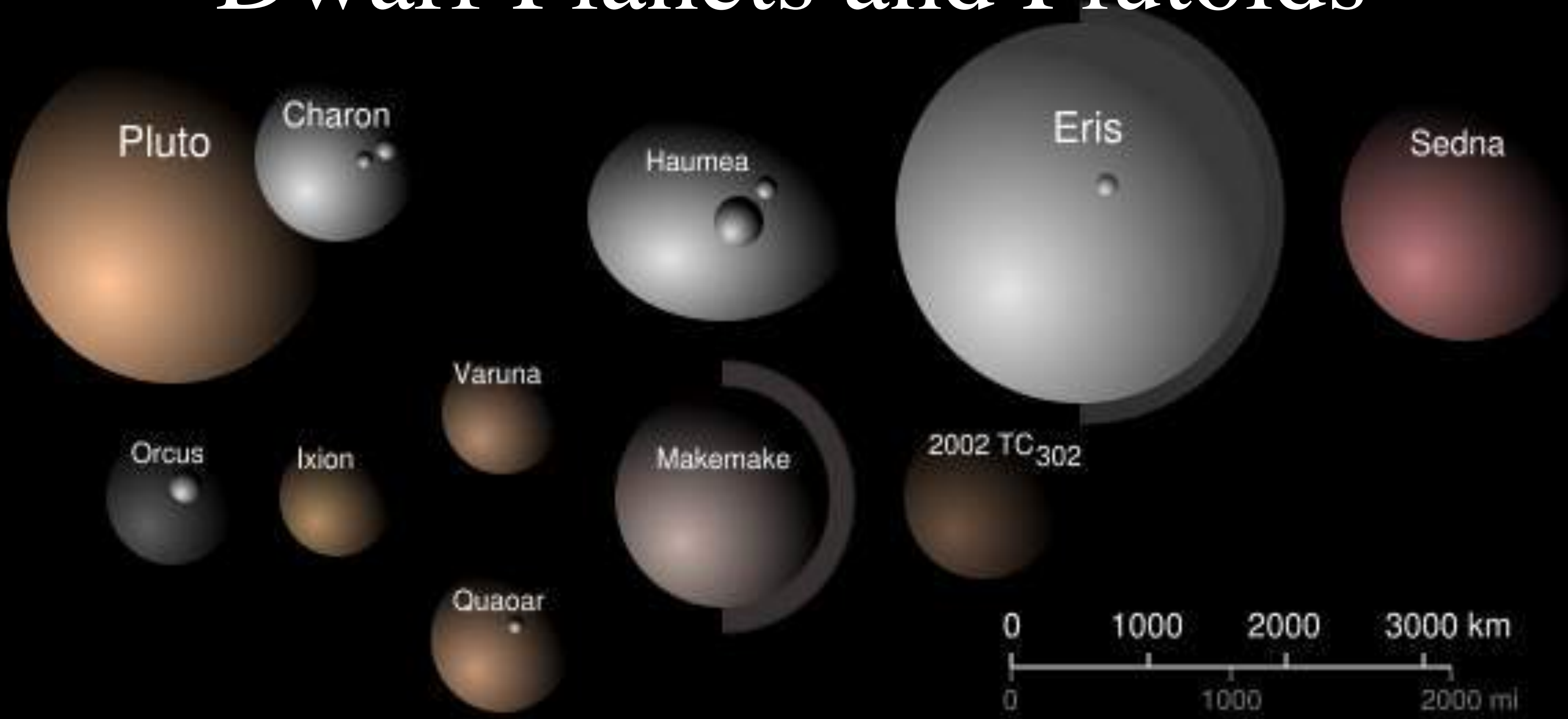


- Planet blocks light from star
- Visible/NIR light (Hubble/JWST)
- Radius of planet/star
- Absorption spectroscopy of planet's atmosphere
- JWST: Look for moons (by timing), constituents of atmosphere, Earth-like planets with water, weather

Secondary

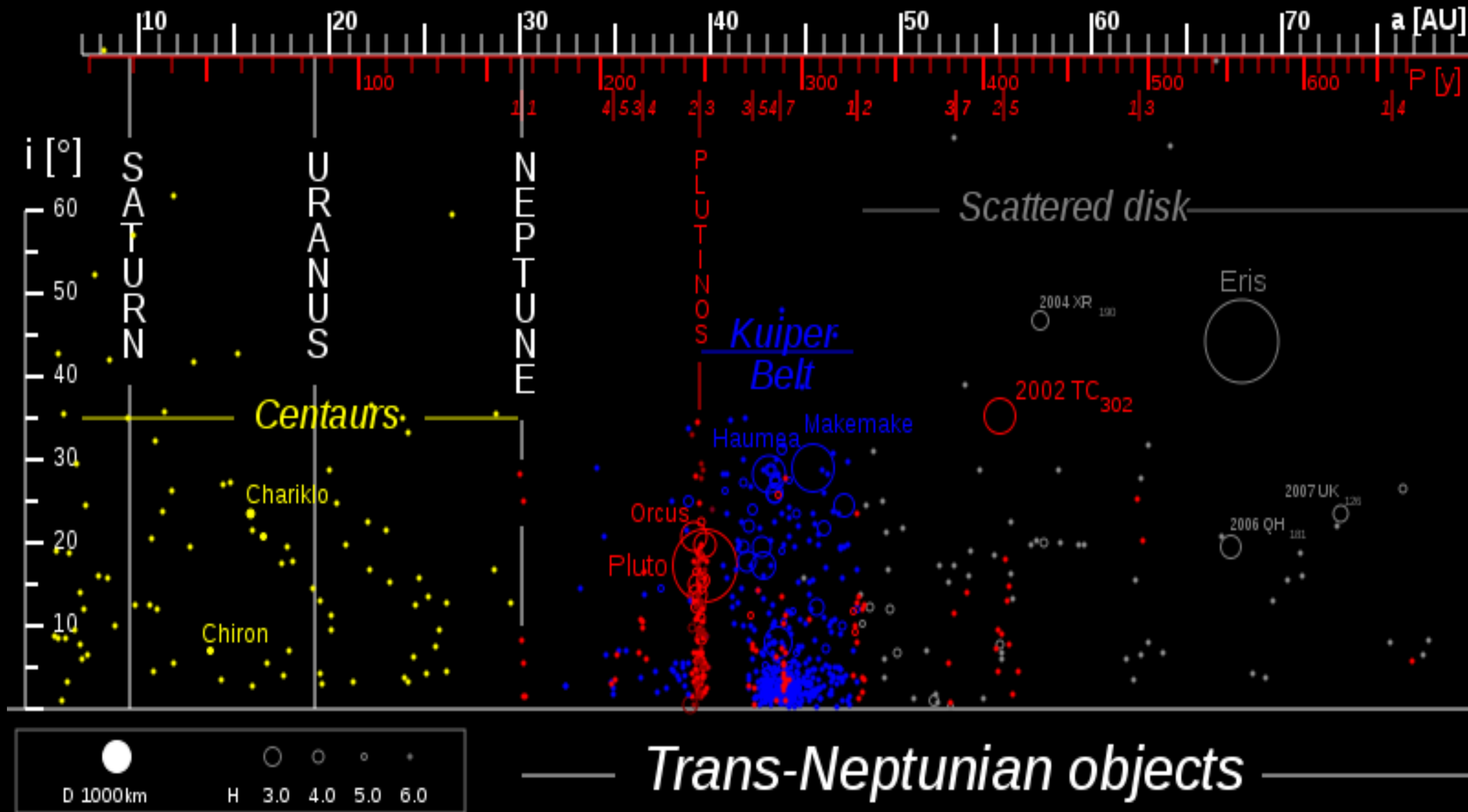
- Star blocks light from planet
- Mid-Infrared light (Spitzer/JWST)
- Direct detection of photons from planet
- Temperature of planet
- Emission from surface
- JWST: Atmospheric characteristics, constituents of atmosphere, map planets

Dwarf Planets and Plutoids

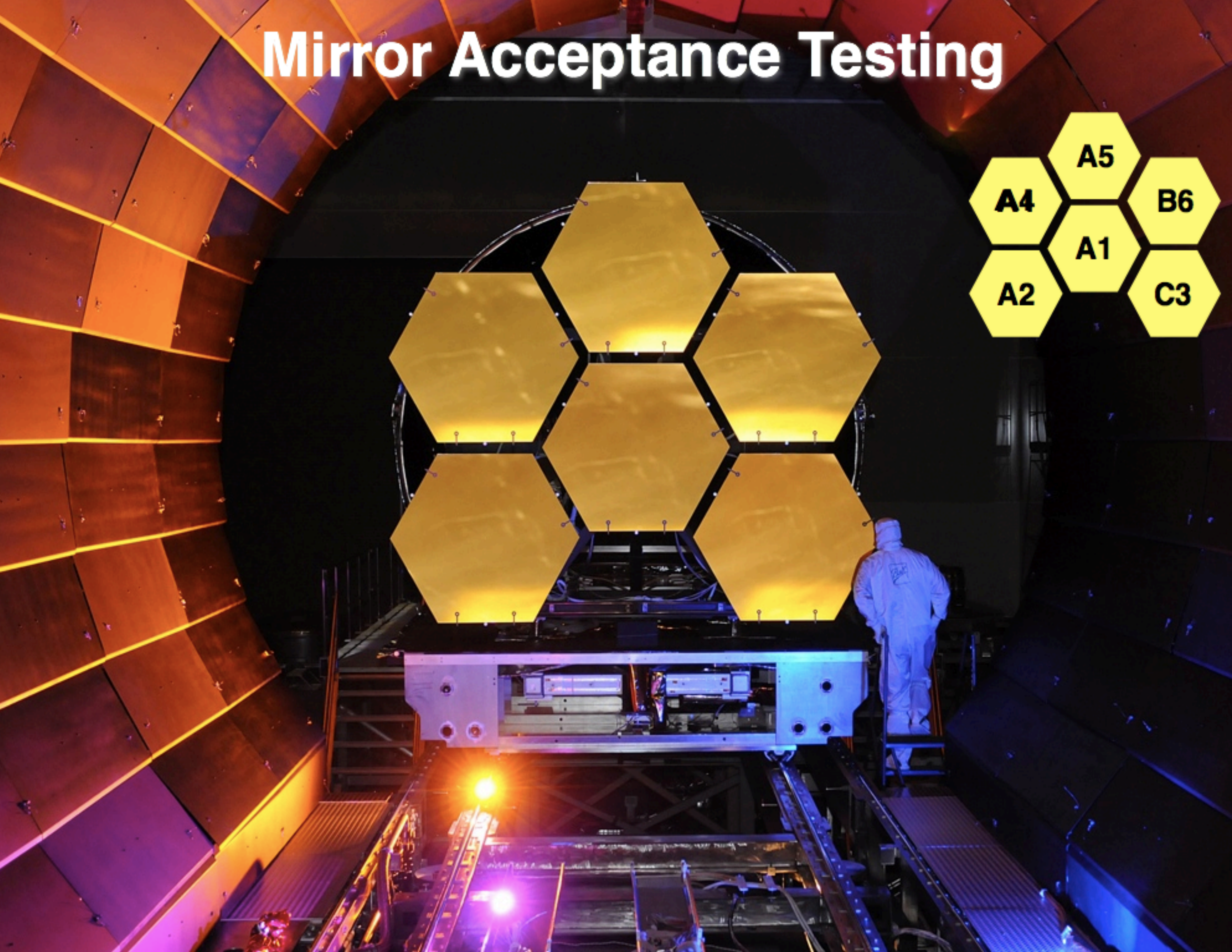


May be 2000 more when whole sky is surveyed
With moving object tracking JWST is perfect tool

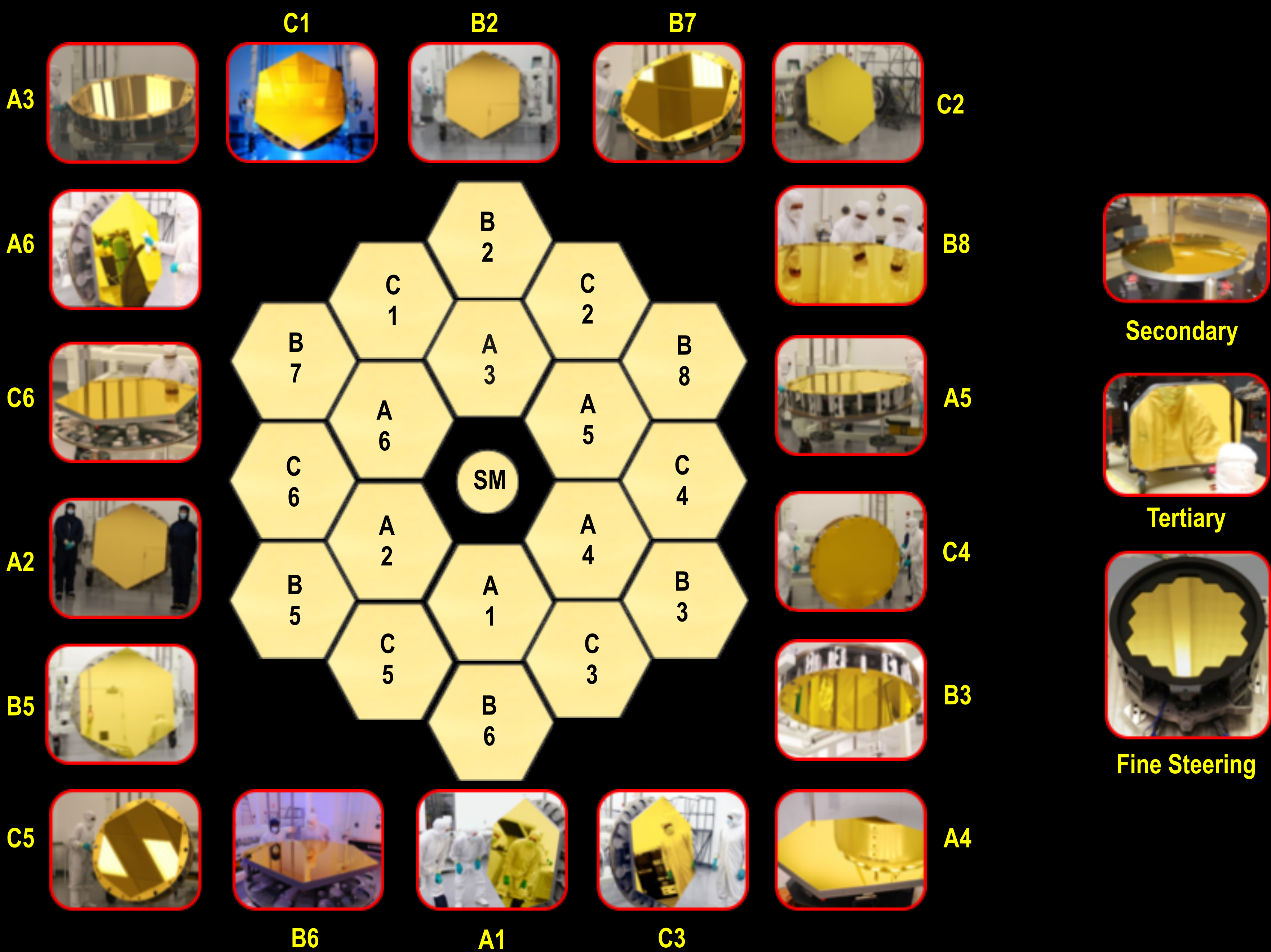
Where they are



Mirror Acceptance Testing

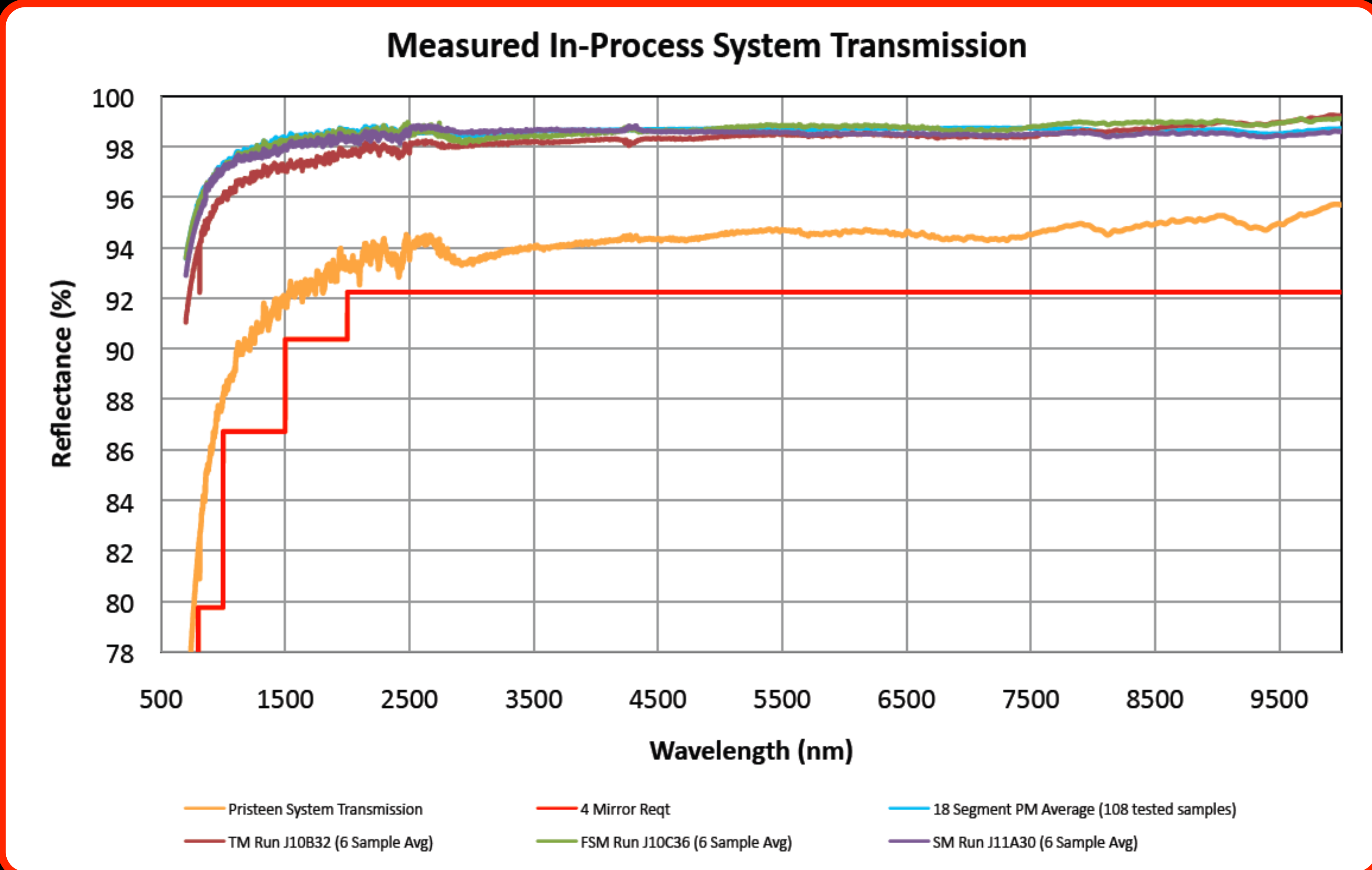


Telescope Mirrors Gold Coated



Mirror Reflectivity

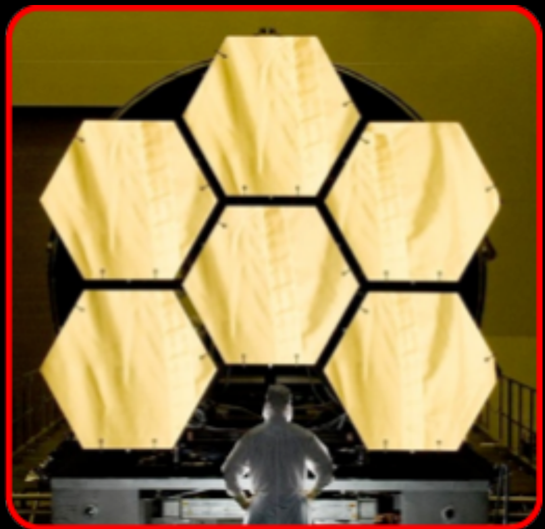
- Measured reflectivity of newly coated mirrors (i.e. pristine)



Flight Mirrors: Cryo-Performance

- Preliminary Surface Figure Error (SFE) for OTE optical elements
  - ➡ Preliminary as-built cryo-measured surface figure error (SFE)

Mirror	Measured (nm RMS SFE)	Uncertainty (nm RMS SFE)	Total (nm RMS SFE)	Requirement (nm RMS SFE)	Margin (nm RMS SFE)
18 Primary Mirrors (composite)	23.7	8.1	25.0	25.8	6.4
Secondary	14.5	14.9	20.8	23.5	10.9
Tertiary	17.5	9.4	19.9	23.3	11.9
Fine Steering	14.7	8.7	17.1	17.5	3.7



Primary Mirror

Flight Mirrors: Cryo-Performance

- Preliminary Surface Figure Error (SFE) for OTE optical elements
  - ➡ Preliminary as-built cryo-measured surface figure error (SFE)

Mirror	Measured (nm RMS SFE)	Uncertainty (nm RMS SFE)	Total (nm RMS SFE)	Requirement (nm RMS SFE)	Margin (nm RMS SFE)
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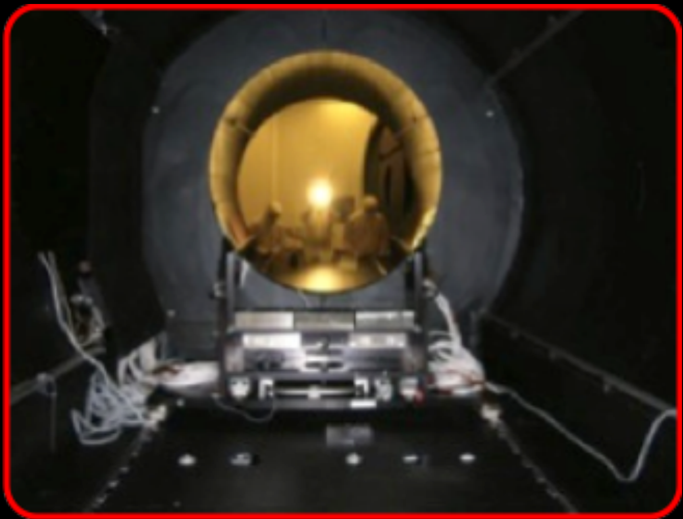
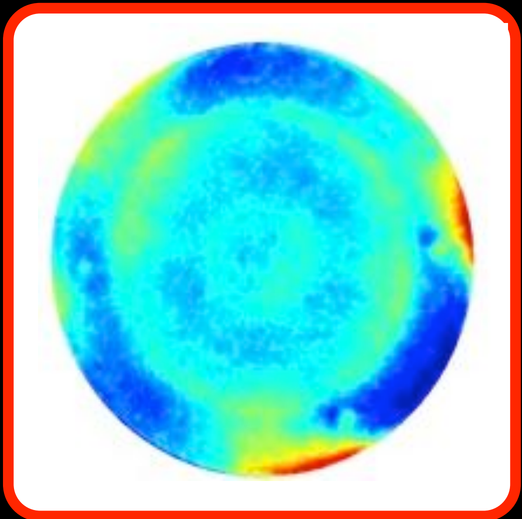
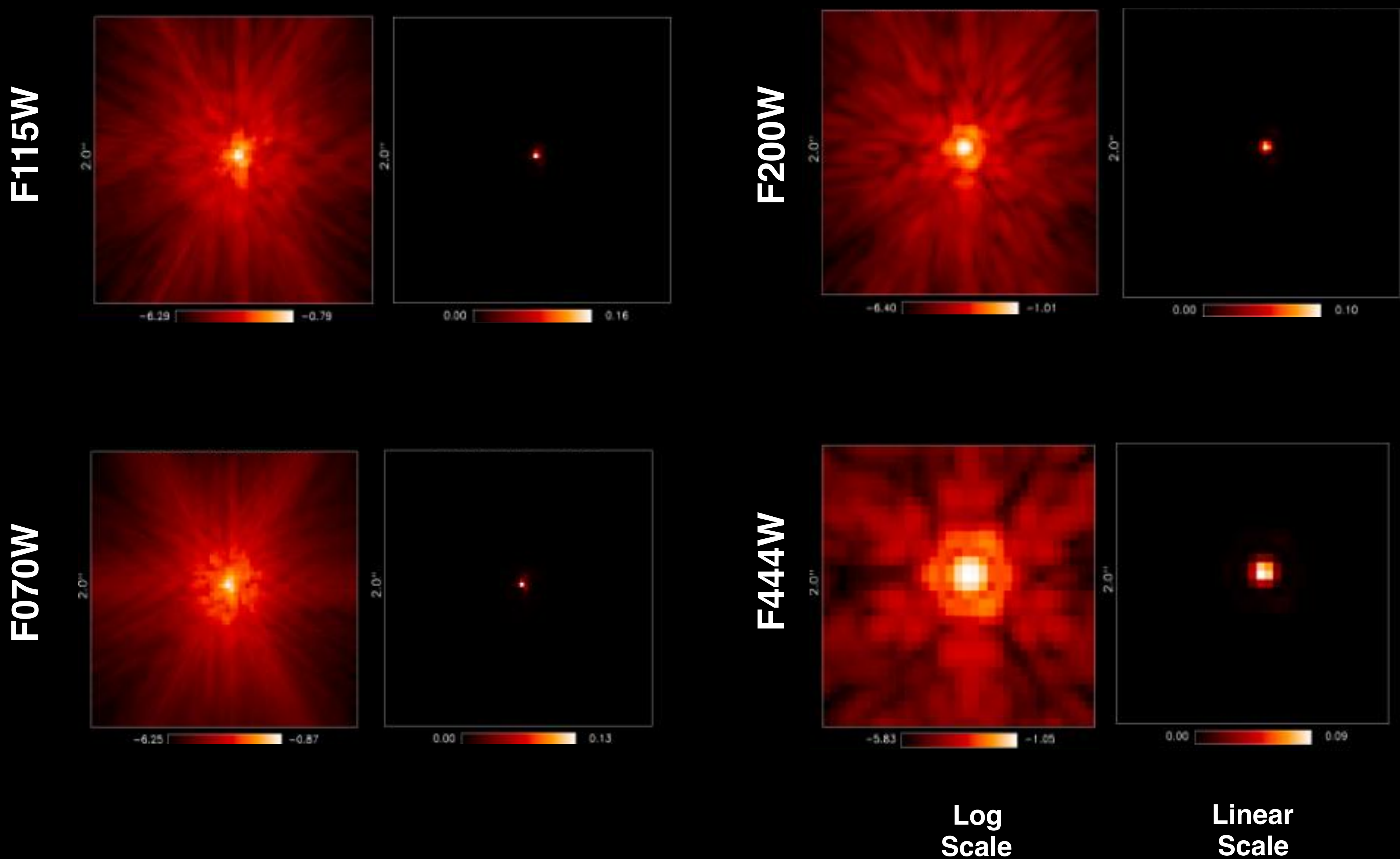




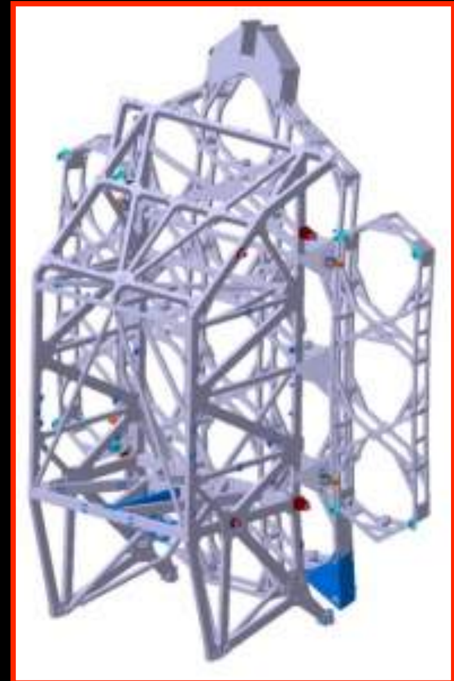
Secondary Mirror

Predicted Image Quality



Primary Mirror Backplane

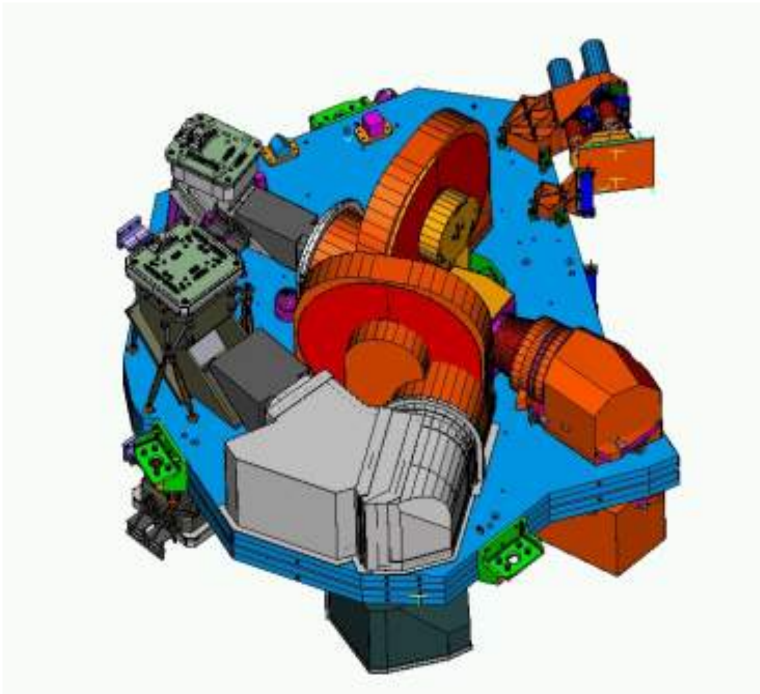
- Pathfinder backplane (central section) is complete
  - ➡ Primary use is verification of test procedures at JSC
- Flight Backplane side sections under construction

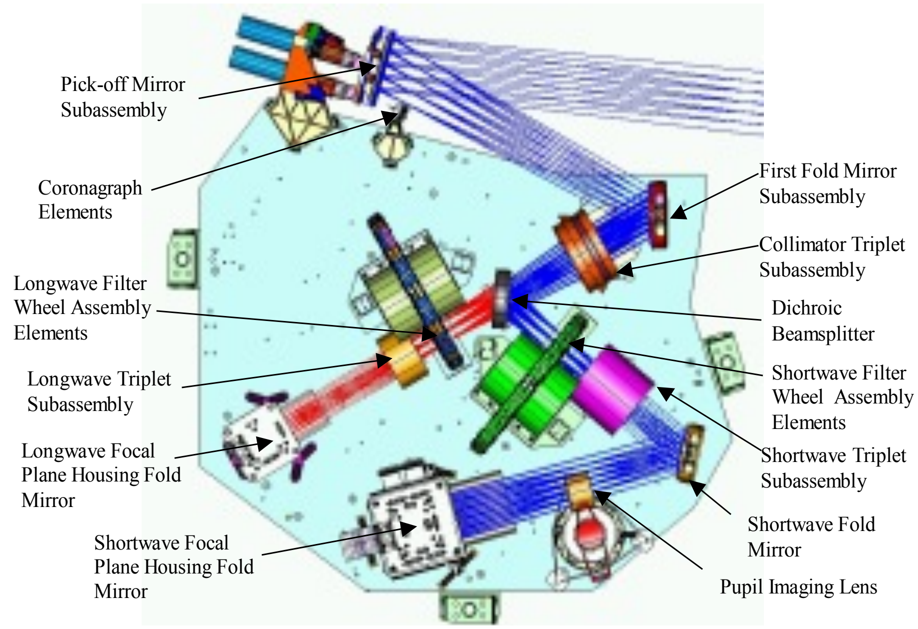


Flight backplane center section complete

Pathfinder

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



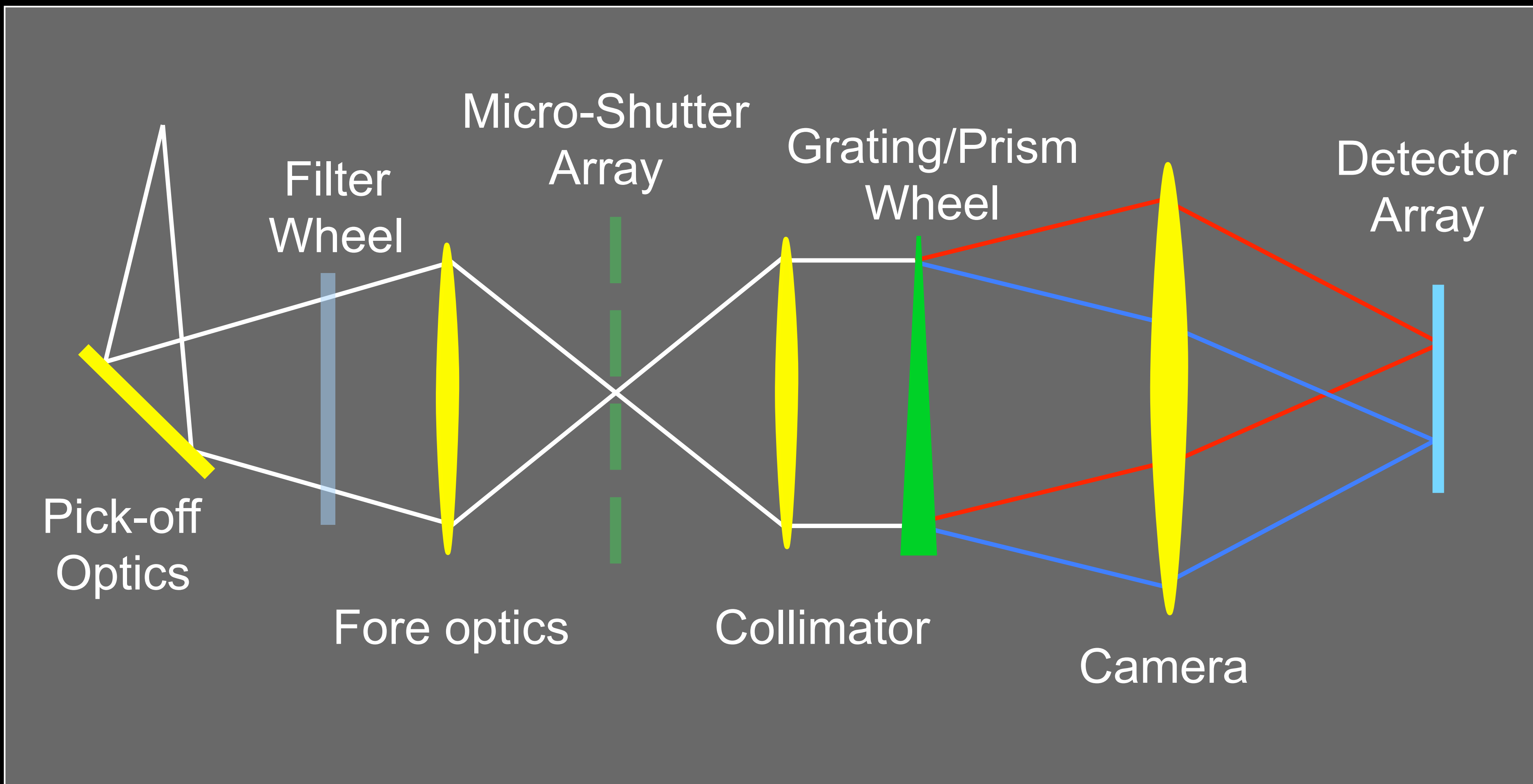


- Developed by the University of Arizona with Lockheed Martin ATC
  - Operating wavelength: 0.6 – 5.0 microns
  - Spectral resolution: 4, 10, 100
  - Field of view: 2.2 x 4.4 arc minutes
  - Angular resolution (1 pixel): 32 mas < 2.3 microns, 65 mas > 2.4 microns
  - Detector type: HgCdTe, 2048 x 2048 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

NIRCam ***Environmental Testing to Begin***

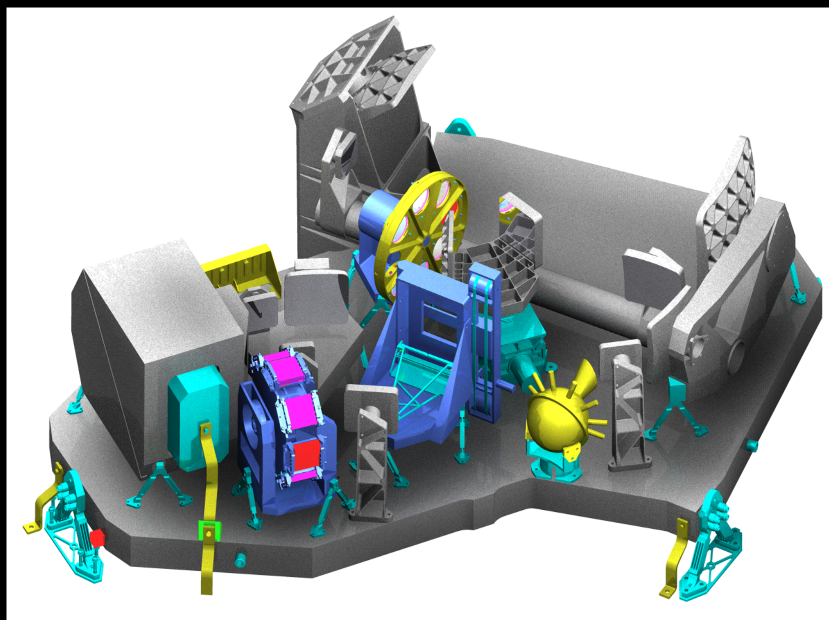
- **Palo, Alto, CALIF., April 16, 2012** – Lockheed Martin [NYSE: LMT], under a contract from the University of Arizona (U of A), has completed assembly of the Near Infrared Camera (NIRCam) Instrument Modules. NIRCam is the prime near-infrared imaging instrument for NASA's James Webb Space Telescope (JWST). The work was done at the Lockheed Martin Space Systems Advanced Technology Center (ATC) in Palo Alto, where environmental testing is about to begin. U of A and Lockheed Martin are responsible for the NIRCam instrument design (Optical, Mechanical, Structural, Thermal, Electronic, Precision Mechanisms and Control Software), the instrument control and focal plane electronics and software. Delivery of the NIRCam instrument to the NASA Goddard Space Flight Center is expected to occur in late summer 2012.

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



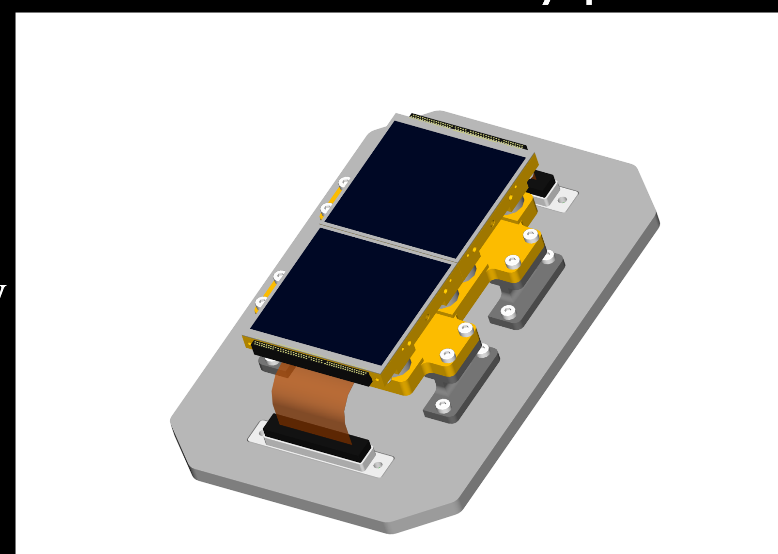
NIRSpec: ESA, Astrium, NASA

- > 100 Objects Simultaneously
- 10 square arcminute FOV



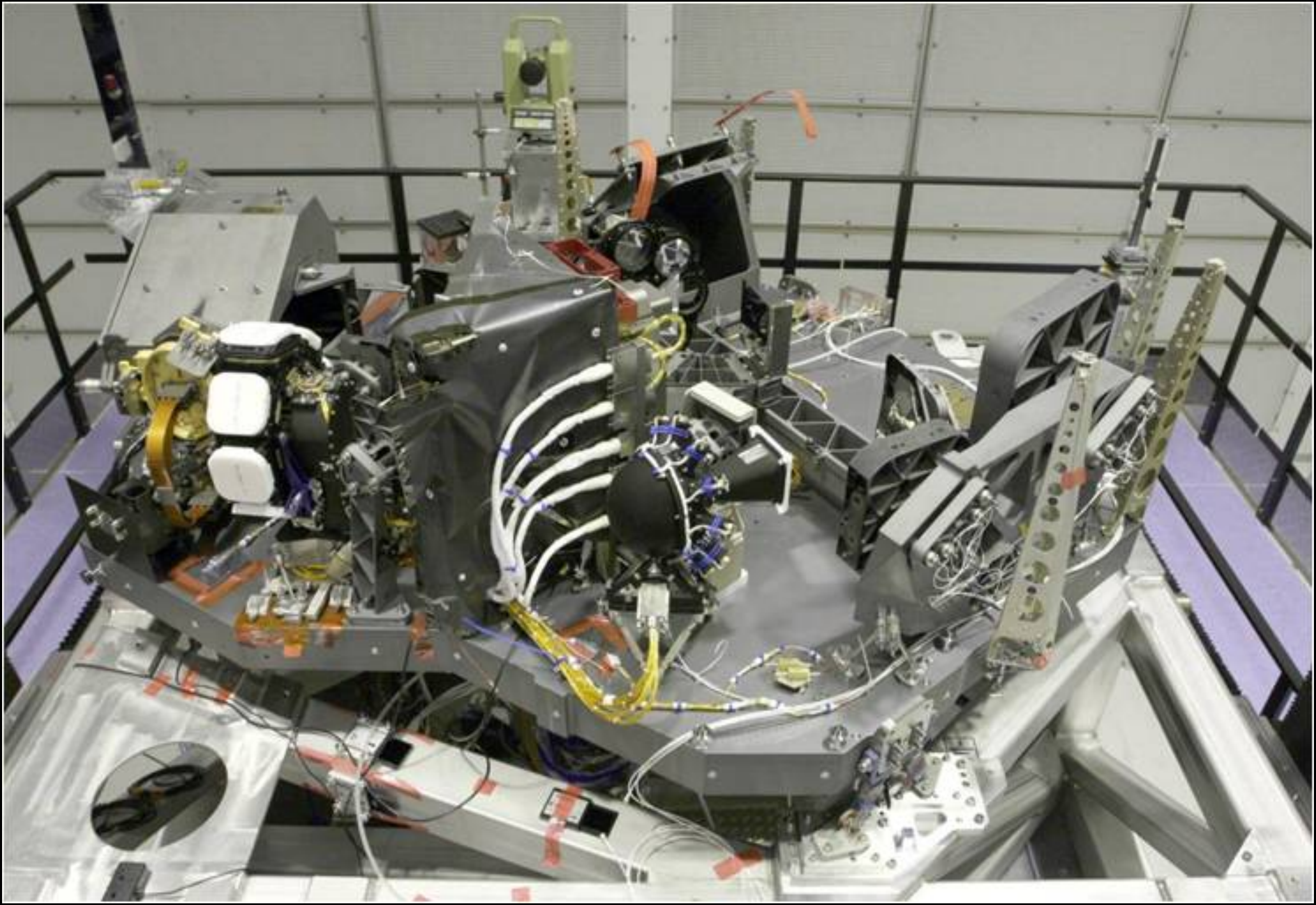
- 3.4’ Large FOV Imaging Spectrograph
- 4 x 175 x 384 element Micro-Shutter Array
  - 250,000 pixels, 203 x 463 mas, pitch 267 x 528
- 2 x 2k x 2k HgCdTe Detector Arrays
- Fixed slits and IFU for backup, contrast
- SiC optical bench & optics

Microshutters make any pattern

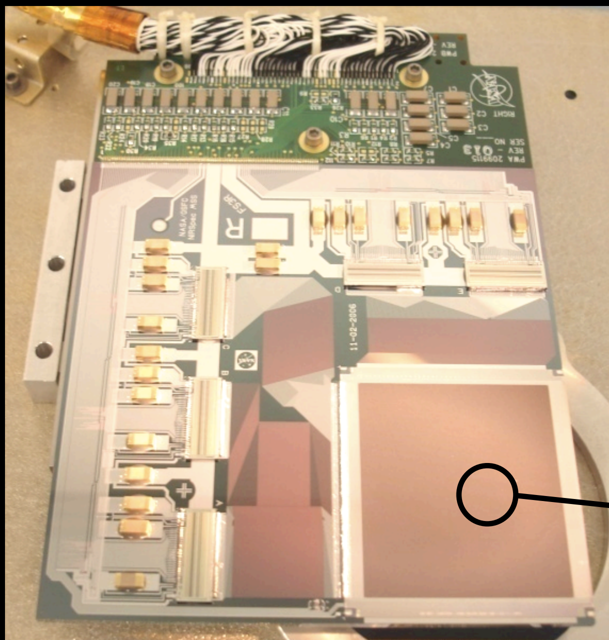


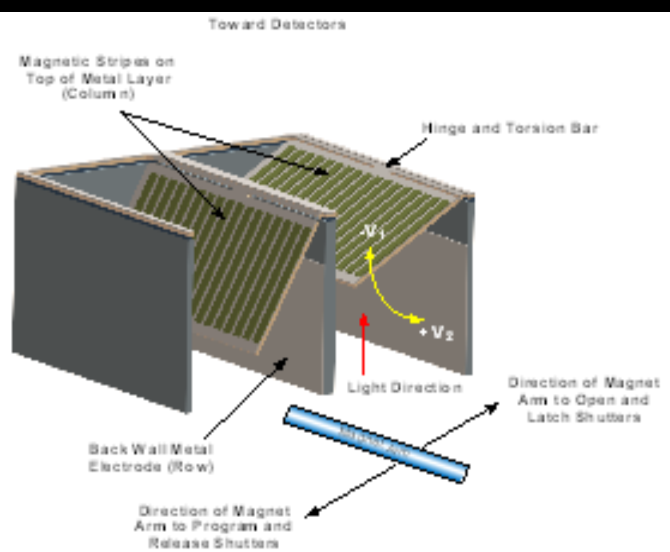
Flight detectors have dark current ~ 10 e/hr

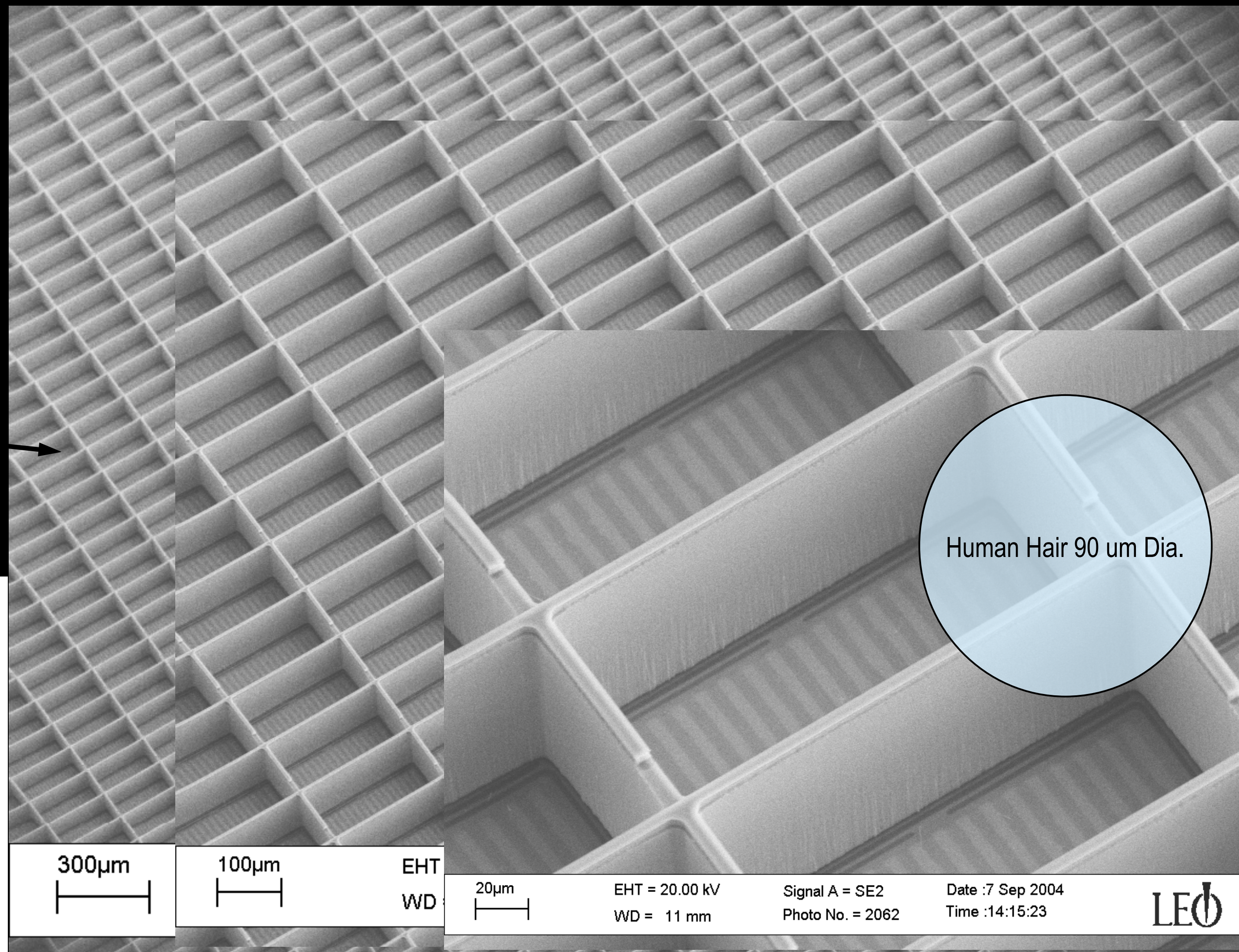
FLIGHT NIRSpec



250,000 pixel cryogenic microshutter array system

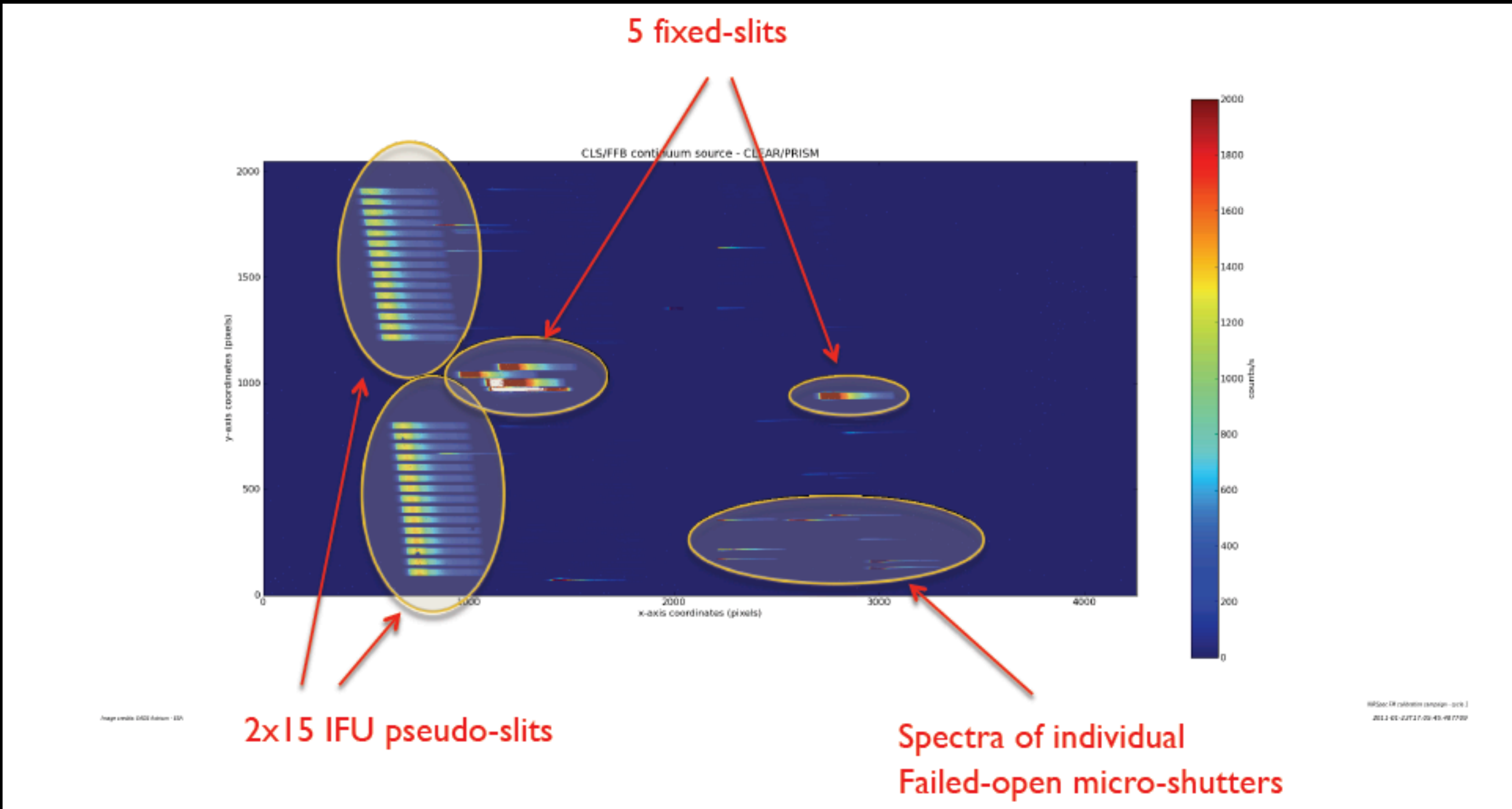






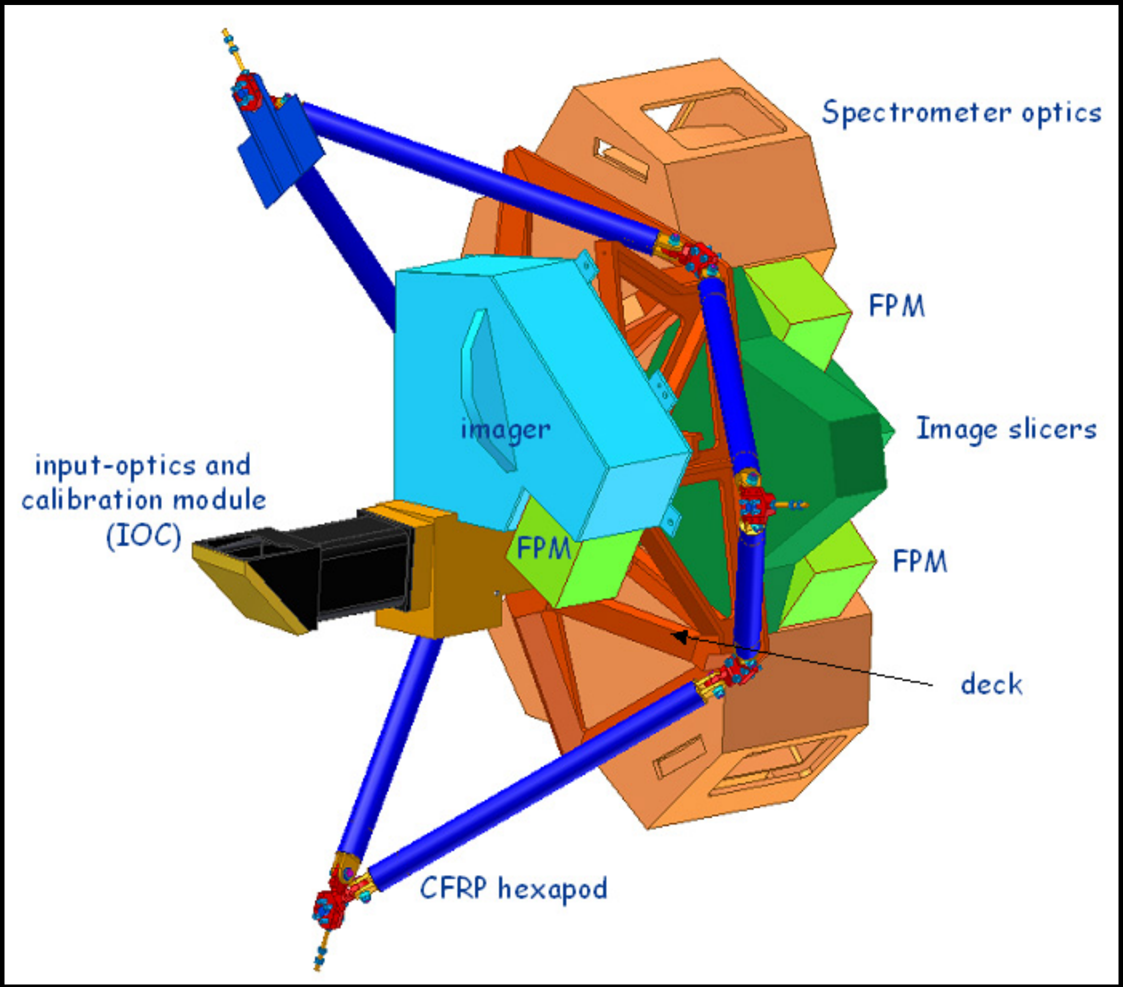
203 x 463 mas shutter pixel clear aperture, 267 x 528 mas pitch,
4 x 171 x 365 array = 249,660 pixels

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

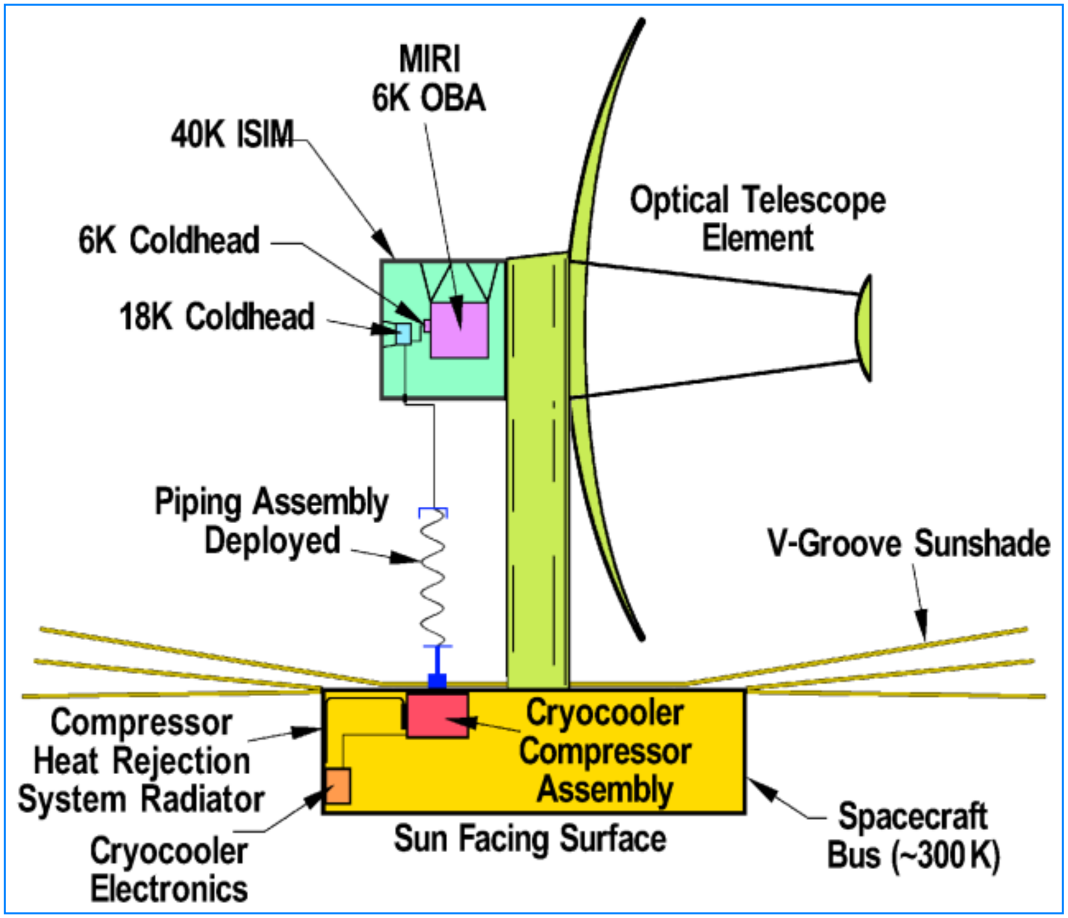


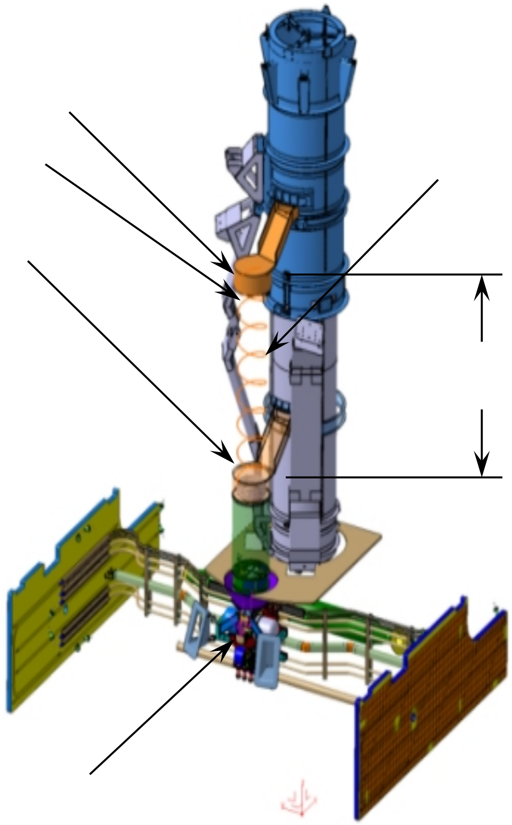
Optics Module concept developed by European Consortium

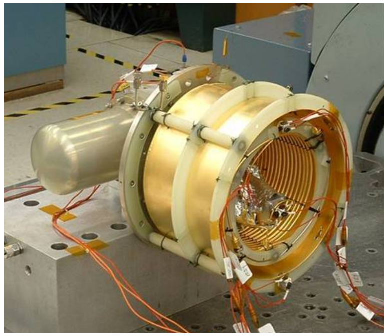
Flight MIRI

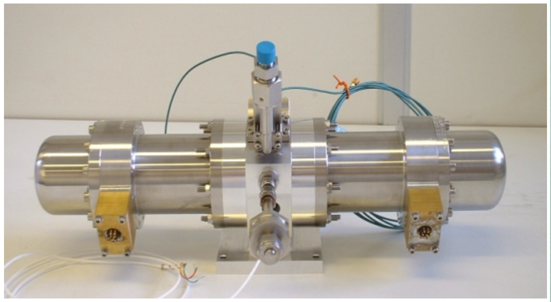
MIRI requires active cooling to 7 K

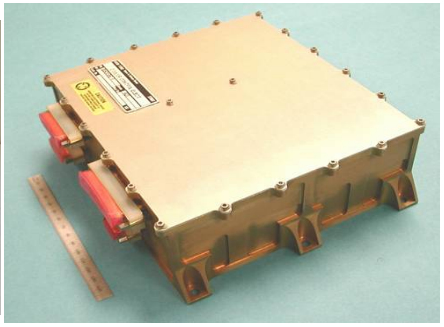
- **A two stage mechanical cooler is used to cool the MIRI below the nominal 40 K ISIM environment that is achieved by passive radiative cooling.**
  - The MIRI Cooler will be the first long life, 7K mechanical cooler for space flight
  - Developed by NGAS and JPL





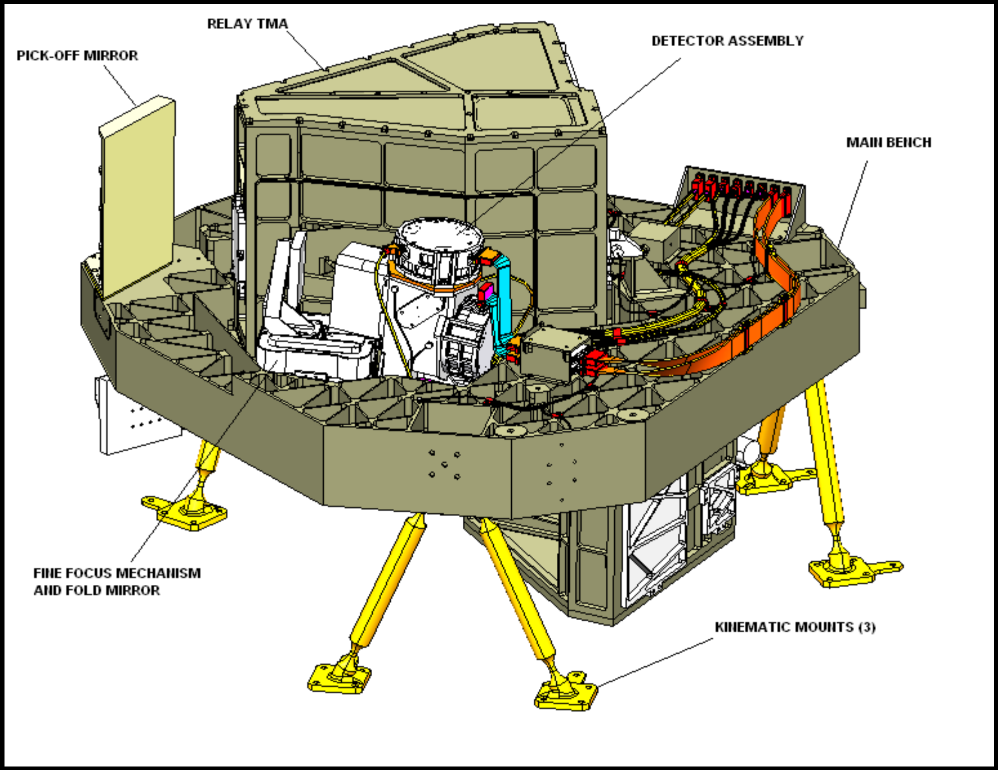


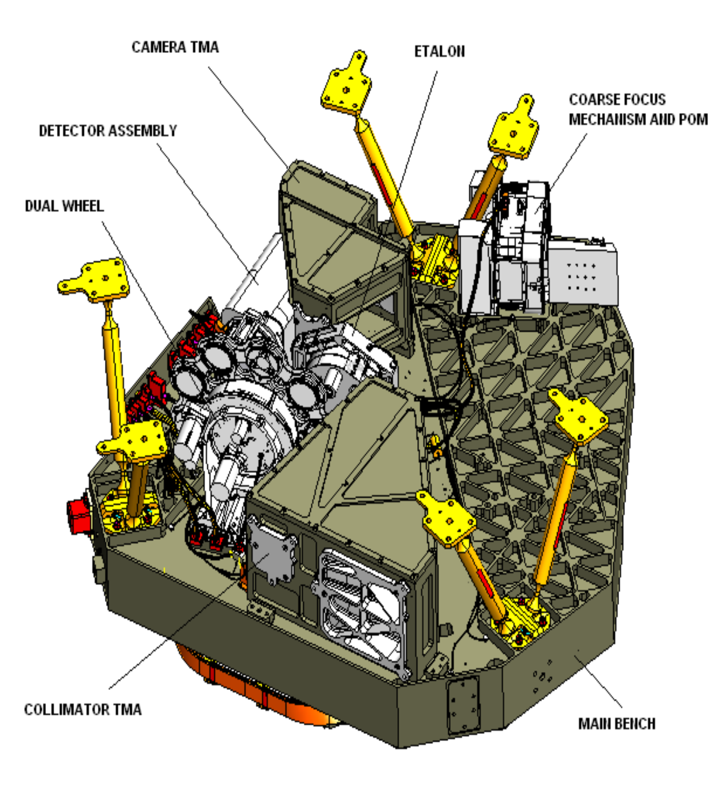




MIRI flies British Airways to USA

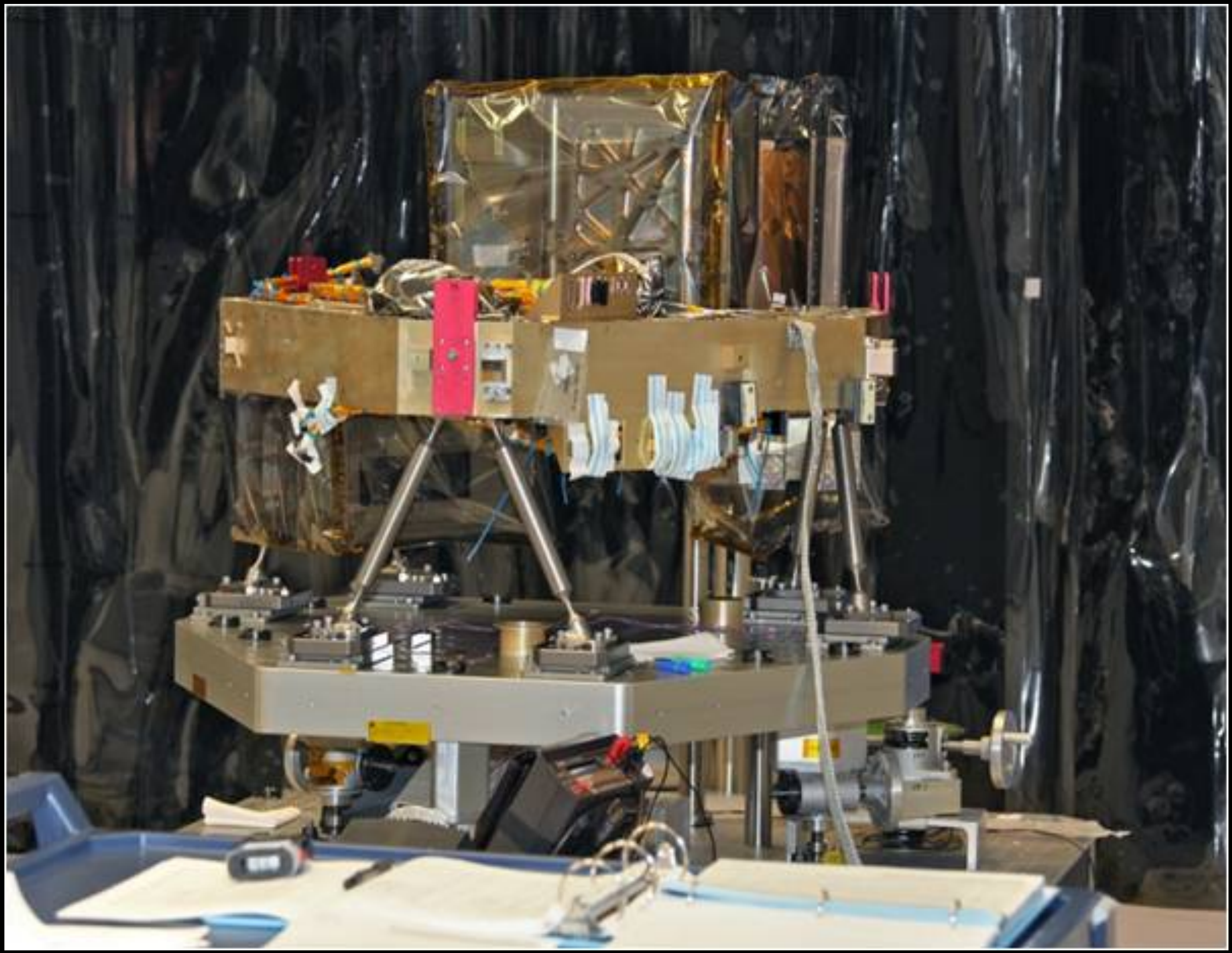
FGS provides pointing control & imaging spectroscopy to reveal primeval galaxies and extra-solar planets





- 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

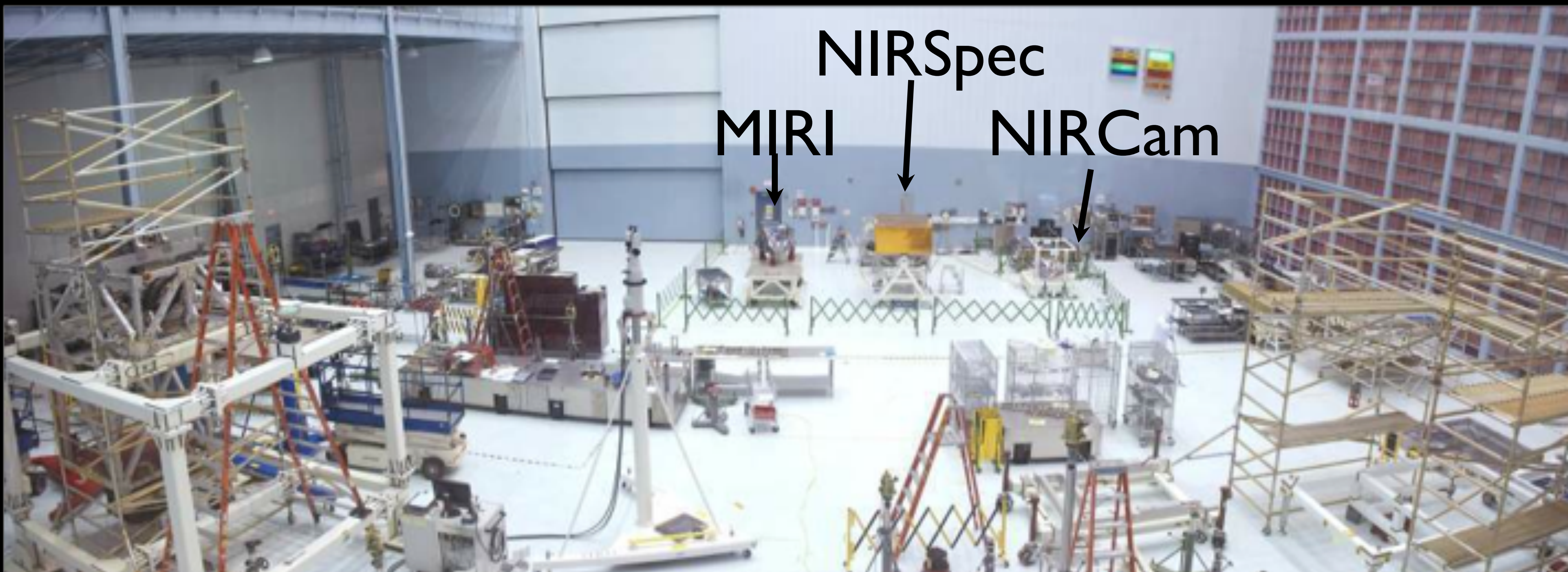
Flight Fine Guidance Sensor



Minister Paradis Unveils the Made-in-Canada Technology That Will Direct the World's Most Powerful Space Telescope

Longueuil, Quebec, July 25, 2012 — Today, the Honourable Christian Paradis, Minister of Industry and Minister responsible for the Canadian Space Agency (CSA), unveiled Canada's contribution to the James Webb Space Telescope, successor to the Hubble Space Telescope. The CSA is contributing a two-in-one instrument that will direct the telescope precisely, allowing it to study stars and planets forming in other stellar systems. The highly advanced, made-in-Canada technology will be delivered to NASA for integration into the Webb telescope on July 30.

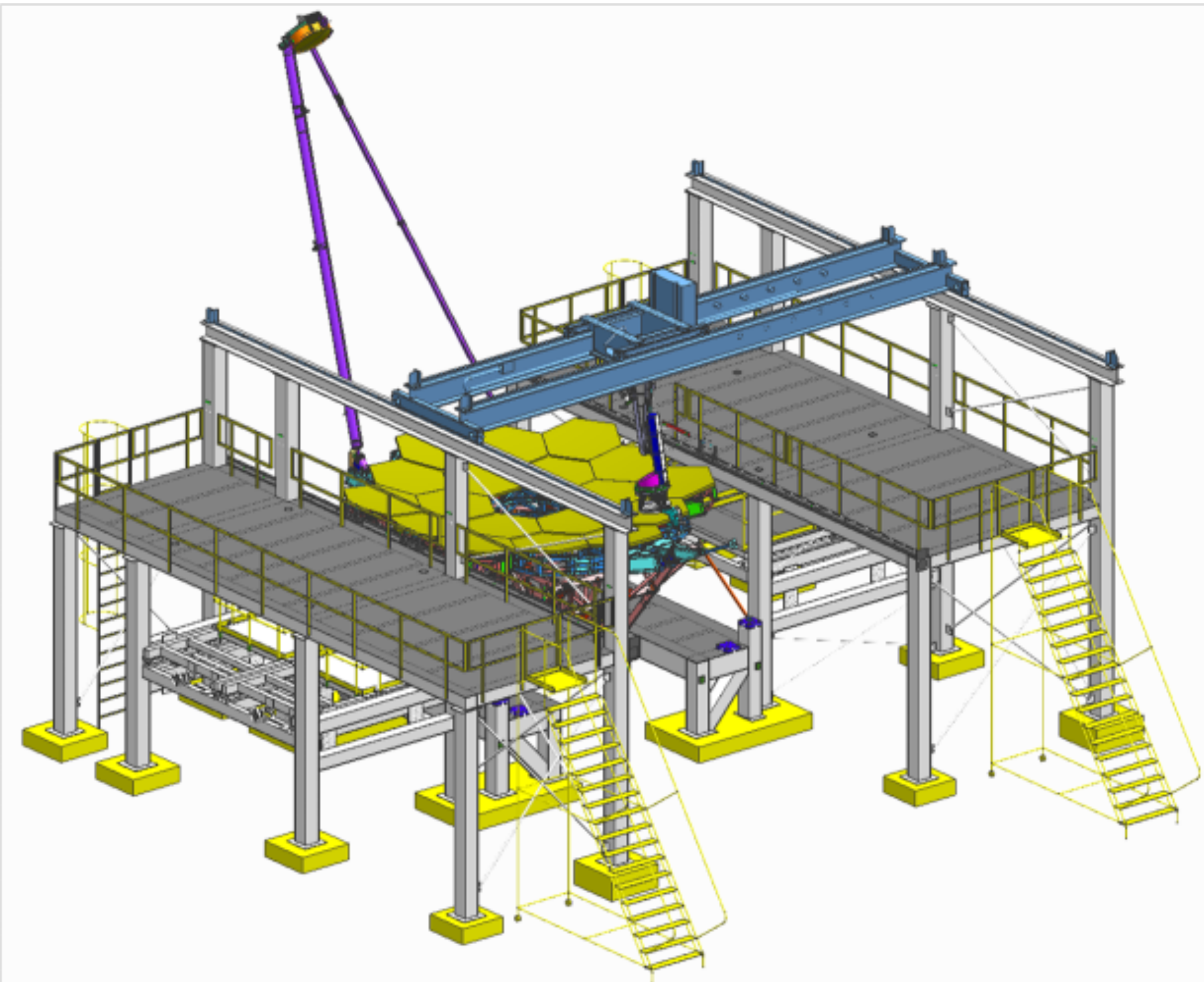
Engineering Test Units Instruments at GSFC



OSIM

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

Optical Telescope Element will be integrated on this alignment stand using the machine at right for primary mirror segment installation

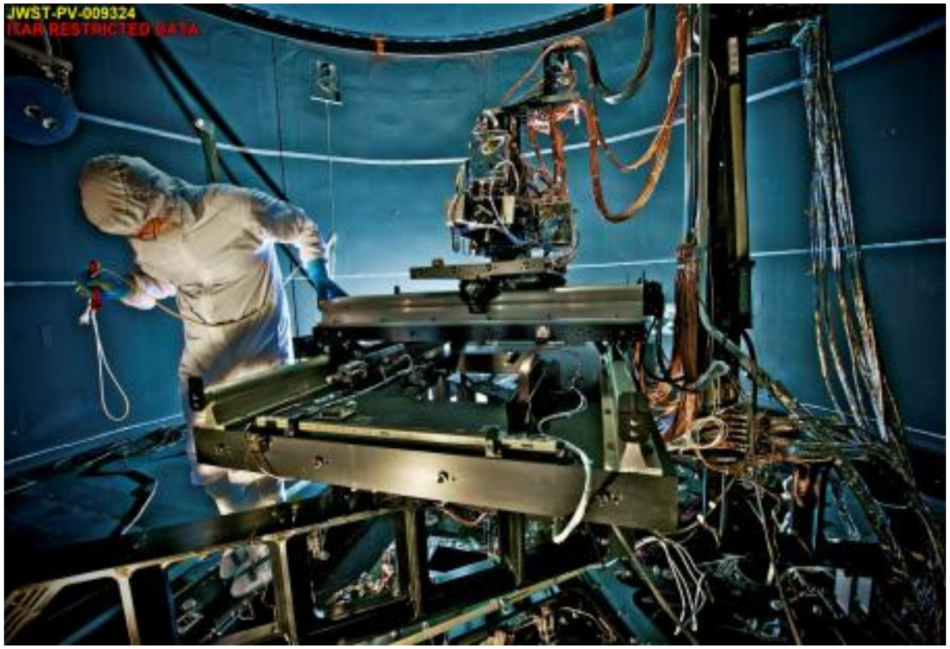


followed by attachment of the ISIM to make OTIS – scheduled for 2016

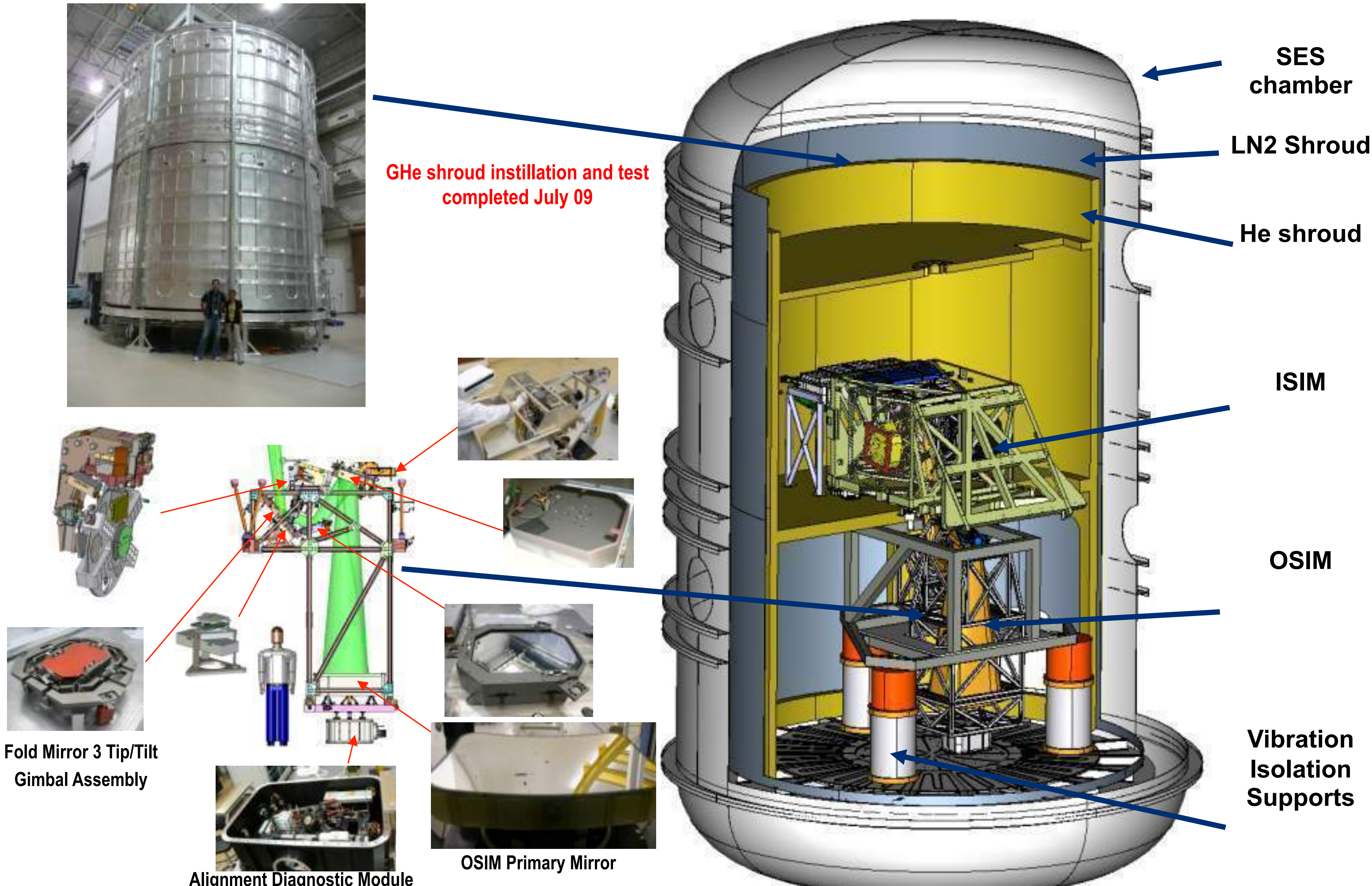
ISIM Structure Cryoset Test

ISIM Integration GSE

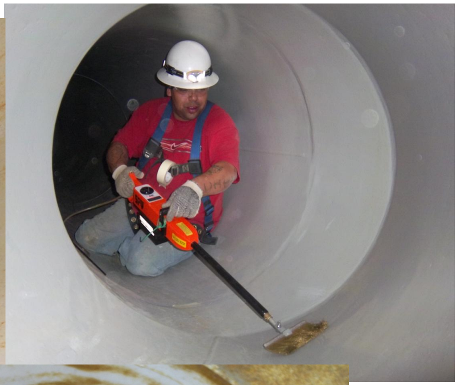
- **Optical Telescope Element (OTE) Simulator (OSIM)**
  - Simulates Optical Telescope Element (OTE) with high fidelity
  - First phase of cryo performance testing has completed, transition to ambient is in progress
    - Another test run prior to ISIM CV1 has been baselined for final measurements



ISIM Test Configuration



Chamber A Mods

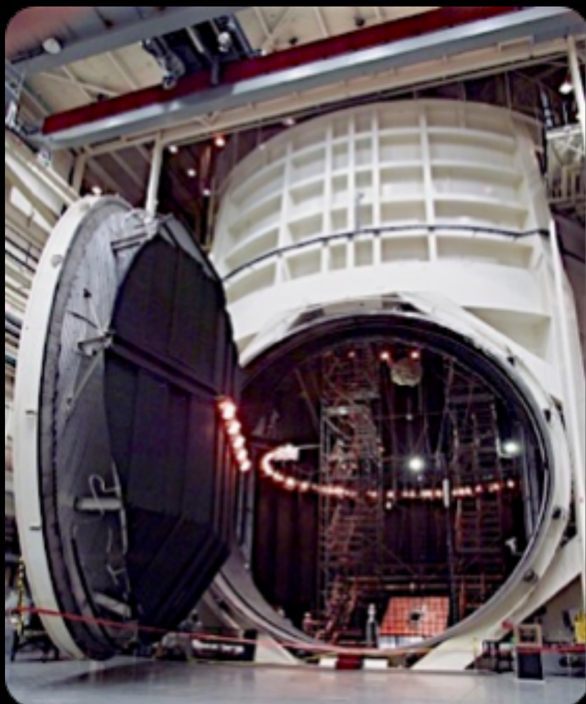


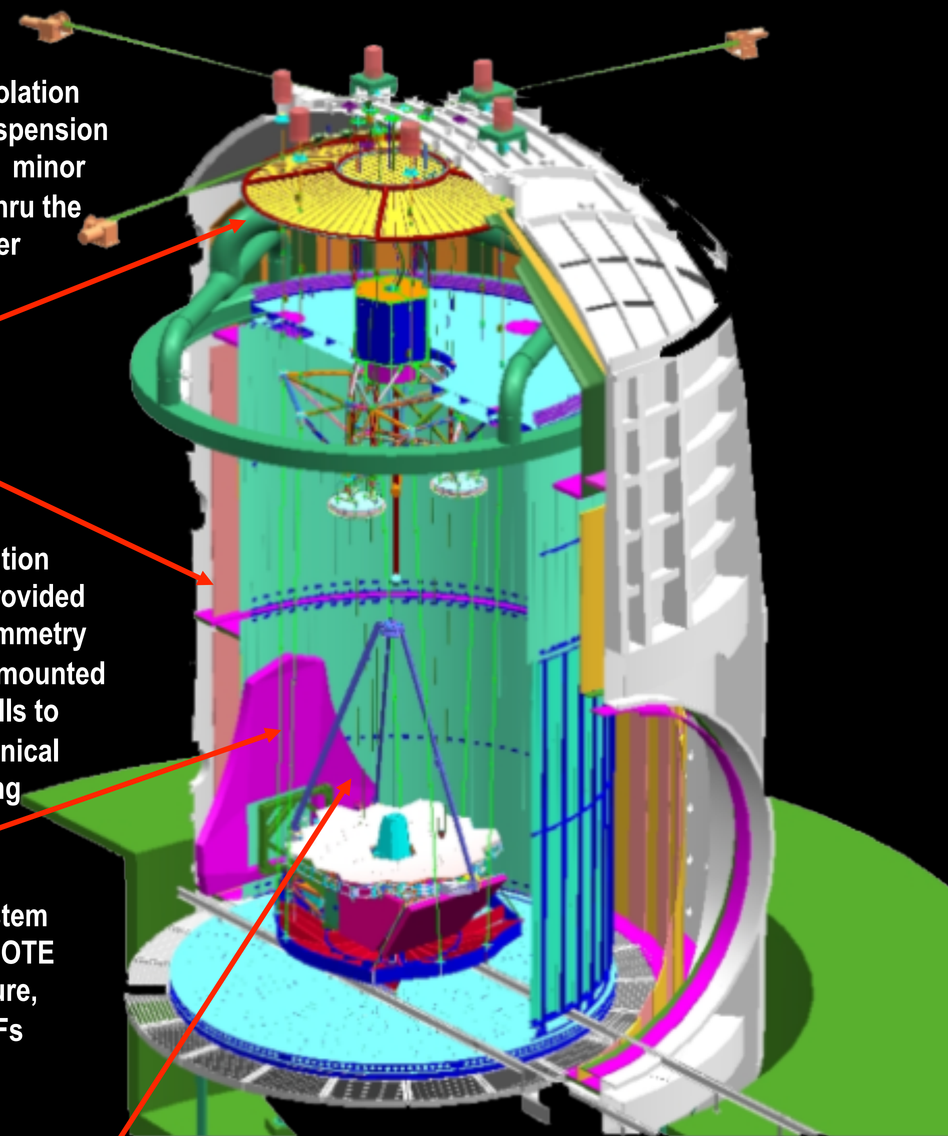
Before

After

Air Flow Management System: Large Bore Pipe Cleaning

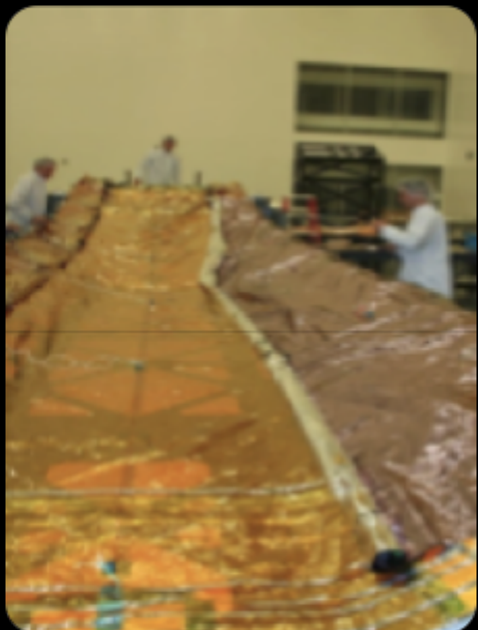
Optical End-to-End Test @ JSC





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

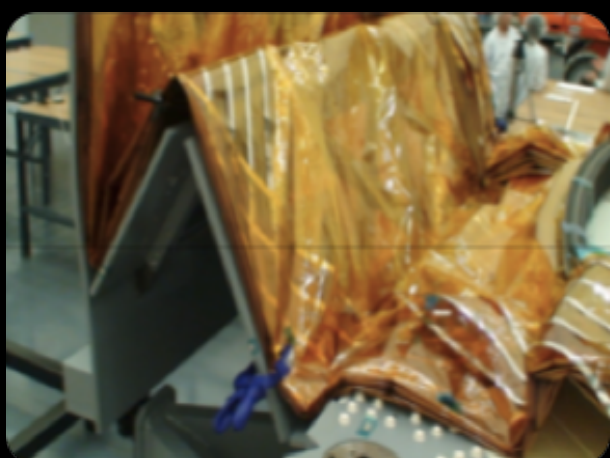
Sunshield Deployment



Sunshield cover test

1/3rd scale thermal test

UPS Deployment/clearance tests



Membrane fold tests

Sunshield alignment

Sunshield deployment tests

3D Shape Measurement: Layer 3

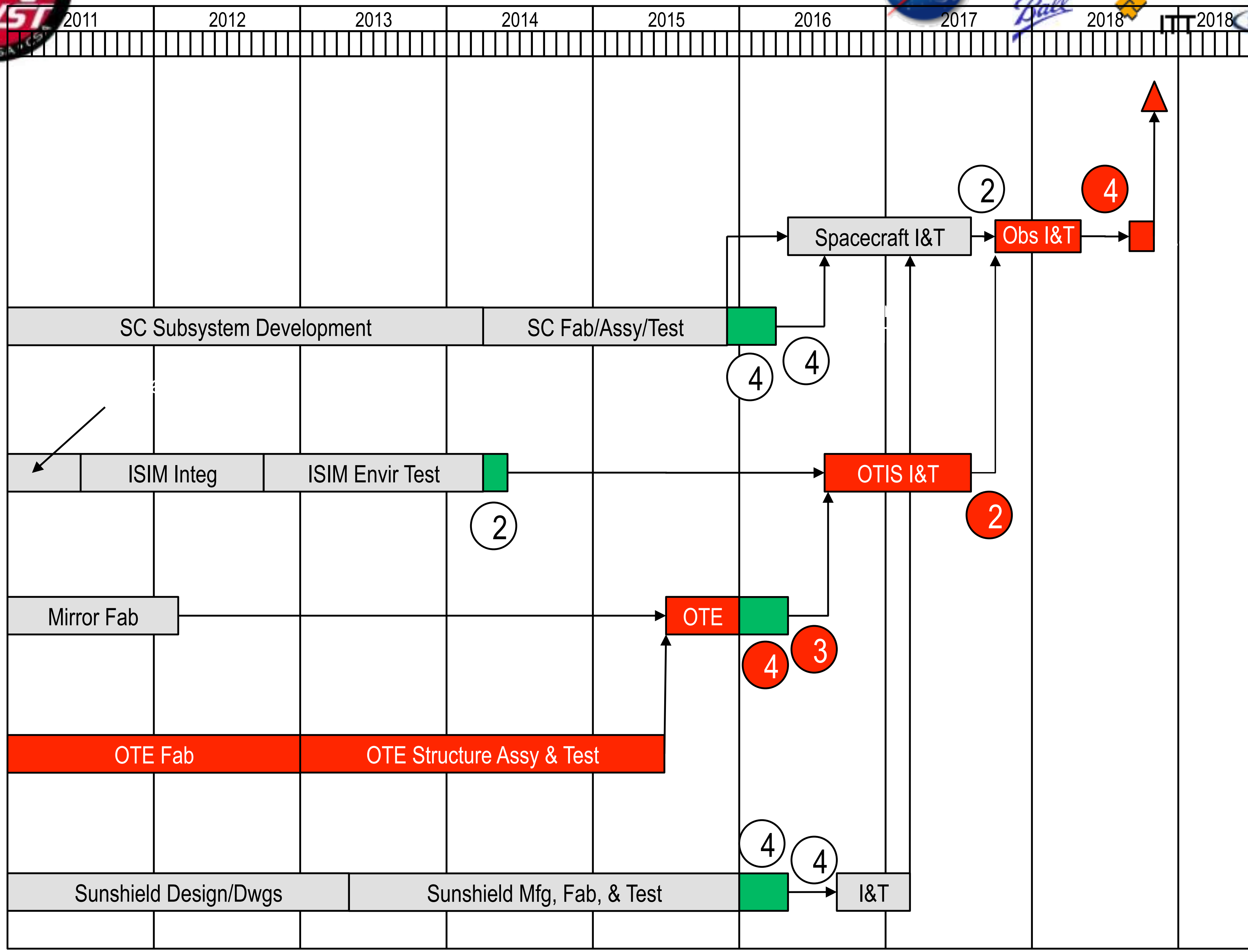
- Layer 3 template membrane is being used to verify 3D shape and alignment tolerances: Layers, 5, 4, 2, and 1 will be tested next year
- Next step is hole-punching. Designed to verify release pin hole alignments on five folded membranes

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.


2011
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Spacecraft I&T
Obs I&T
SC Subsystem Development
SC Fab/Assy/Test
ISIM Integ
ISIM Envir Test
OTIS I&T
Mirror Fab
OTE
OTE Fab
OTE Structure Assy & Test
Sunshield Design/Dwgs
Sunshield Mfg, Fab, & Test
I&T
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The End and the Beginning