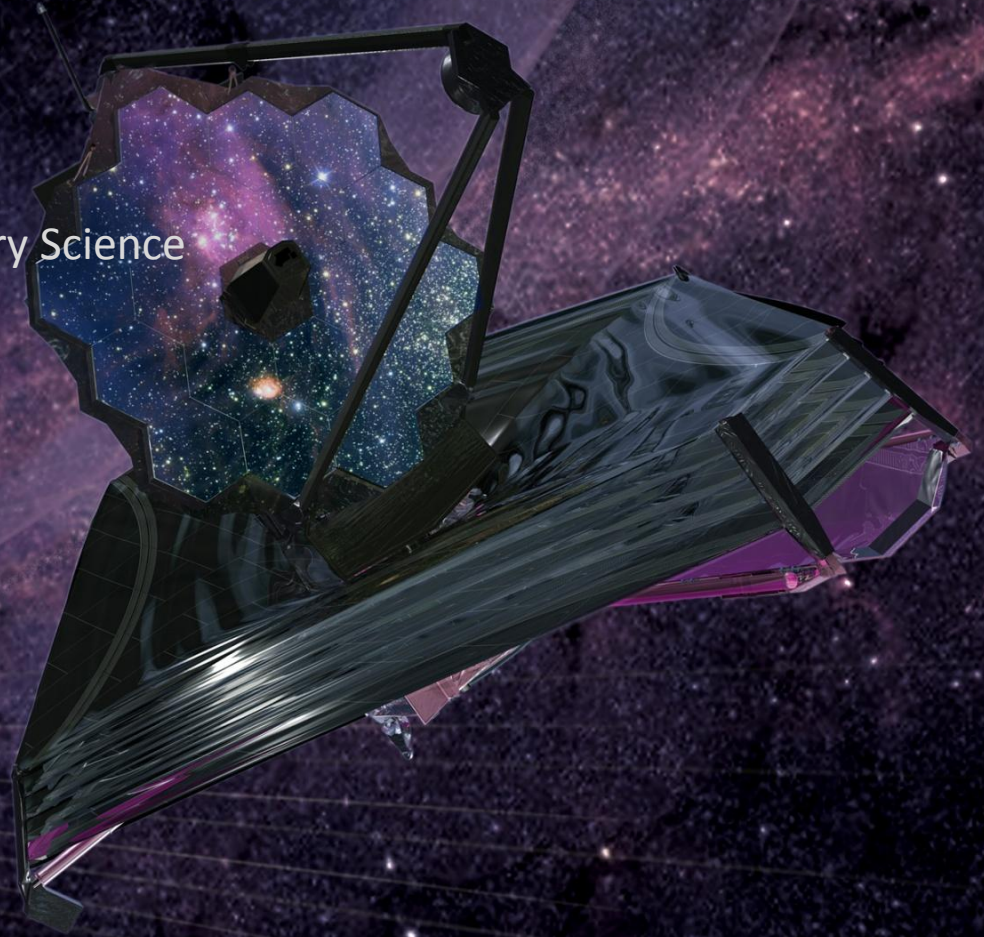
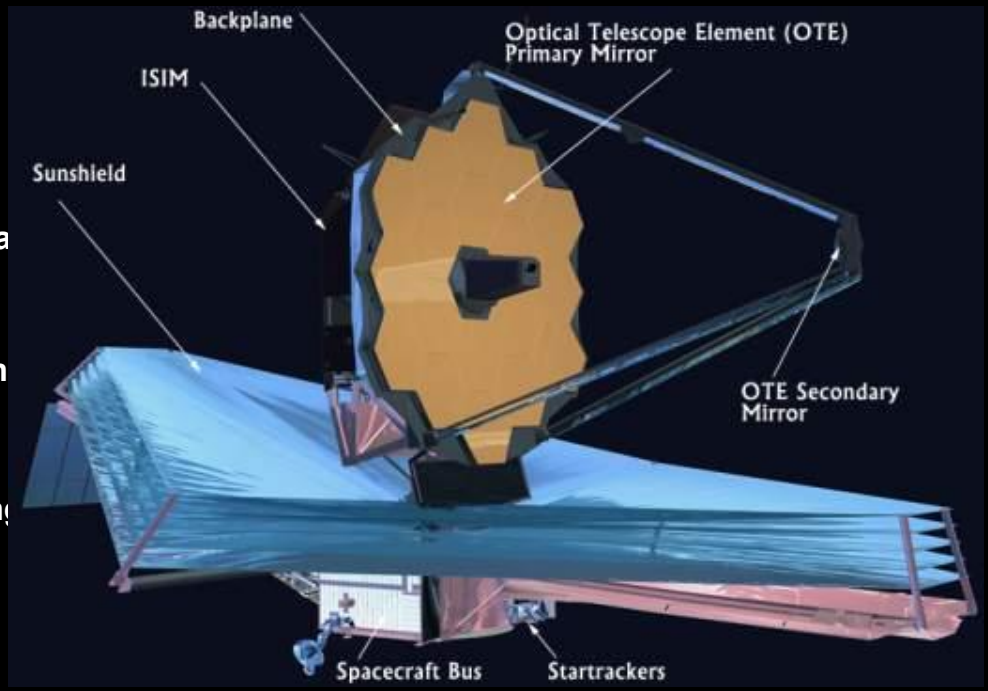
Innovative Solar System Science with the James Webb Space Telescope



Stefanie Milam
JWST Deputy Project Scientist for Planetary Science
NASA Goddard Space Flight Center
19 January 2016

@NASAWebbTelescp
#JWST

James Webb Space Telescope (JWST)



Organization

- Mission Lead: NASA/Goddard Space Flight Center
- International collaboration with ESA & CSA
- Observatory Contractor: Northrop Grumman Aerospa Systems
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizon
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA/EC
  - Fine Guidance Sensor (FGS) and Near IR Imagin 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 – planned October 2018
- 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

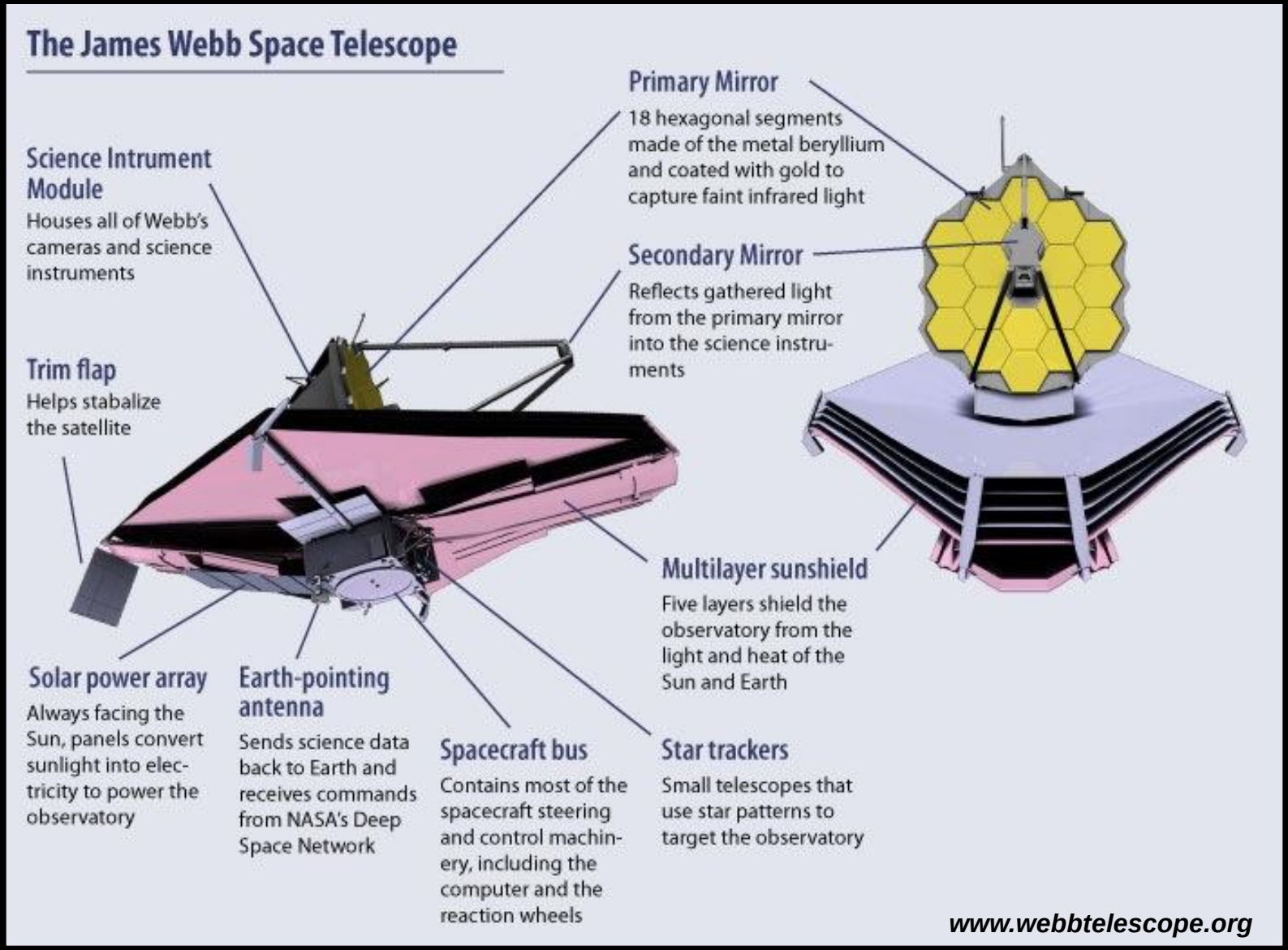
2

The James Webb Space Telescope

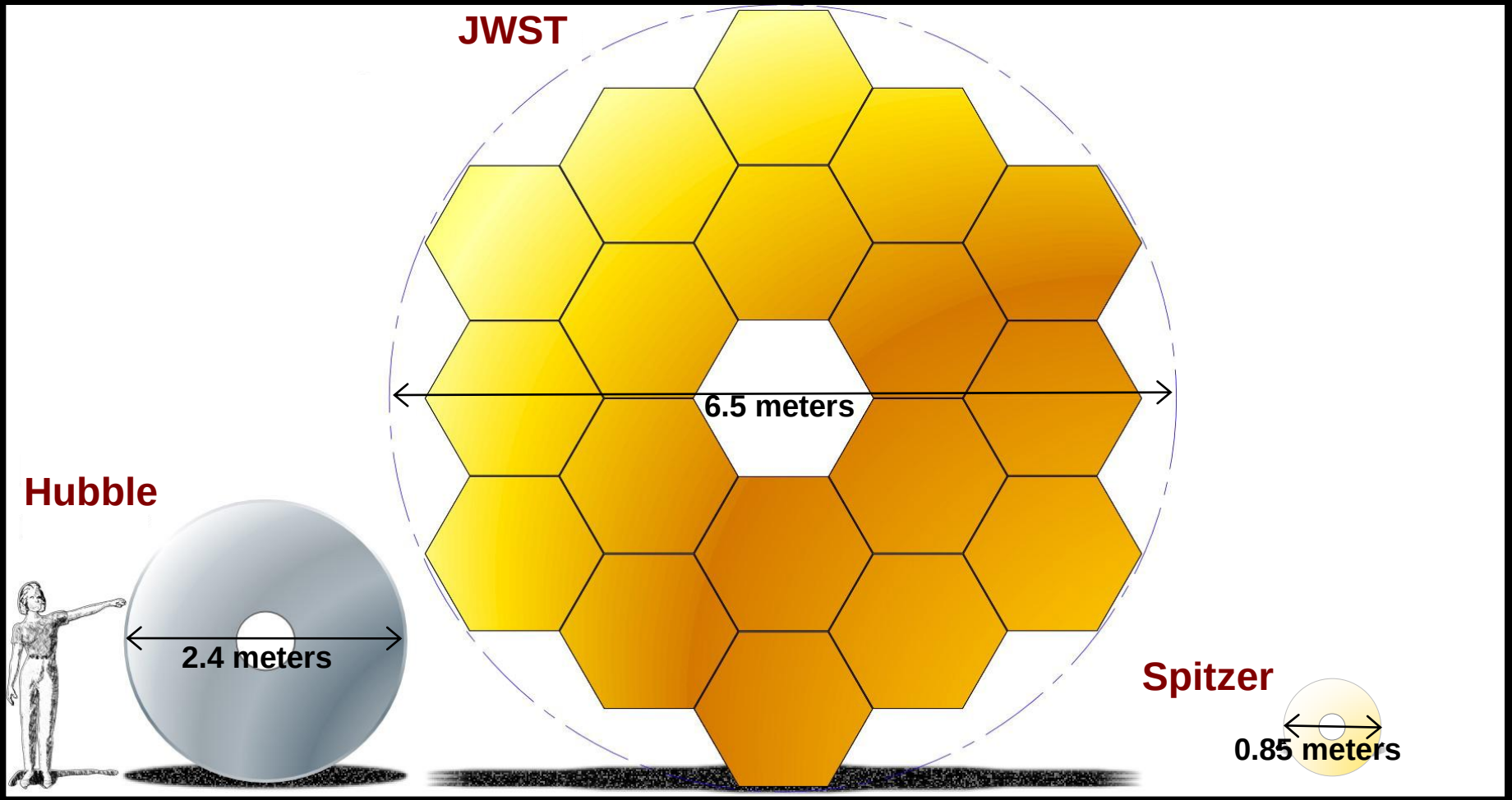
James Webb (1906 – 1992)

- Second Administrator of NASA (1961 – 1968)
- Oversaw first manned spaceflight program (Mercury)
- Oversaw second manned spaceflight program (Gemini)
- Oversaw Mariner and Pioneer planetary exploration programs
- Oversaw Apollo program

The James Webb Space Telescope



The James Webb Space Telescope



Light Gathering Power

JWST = 25 m^2 ; Hubble = 4.5 m^2 ; Spitzer = 0.6 m^2

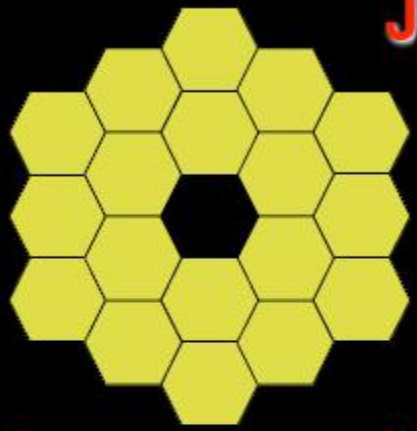
JWST and its Precursors

HUBBLE

2.4-meter
T ~ 270 K

123" x 136"
$\lambda/D_{1.6\mu m}$~ 0.14"

JWST



6.5-meter
T ~ 40 K

132" x 164"
$\lambda/D_{2\mu m}$~ 0.06"

114" x 84"
$\lambda/D_{20\mu m}$~ 0.64"

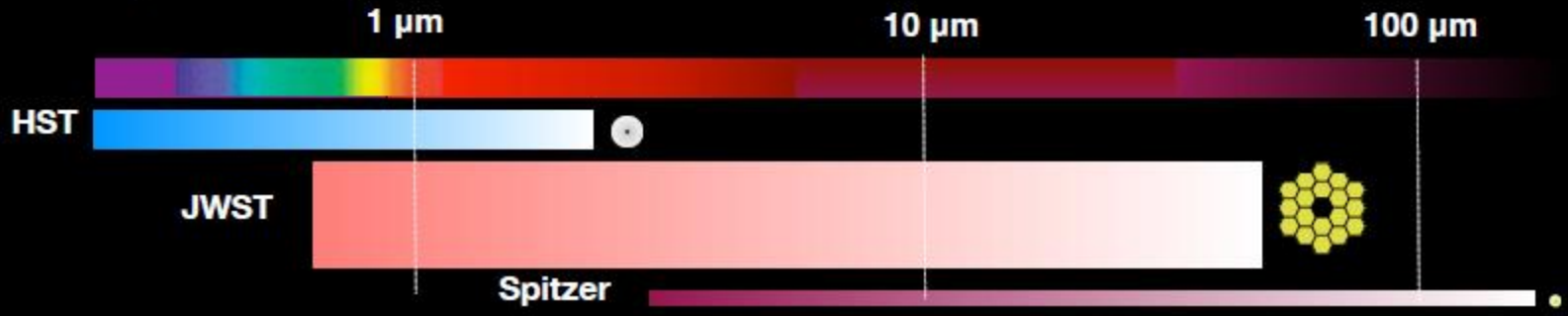
SPITZER

0.8-meter
T ~ 5.5 K

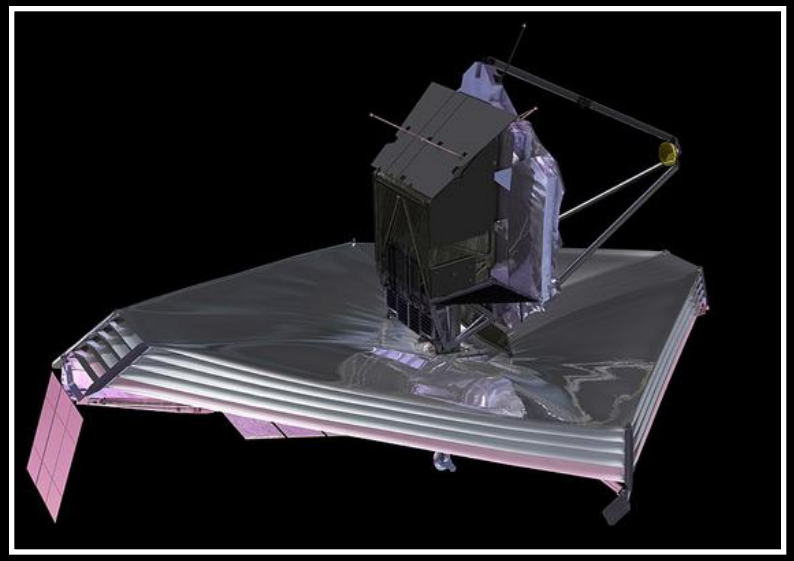
312" x 312"
$\lambda/D_{5.6\mu m}$~ 2.22"

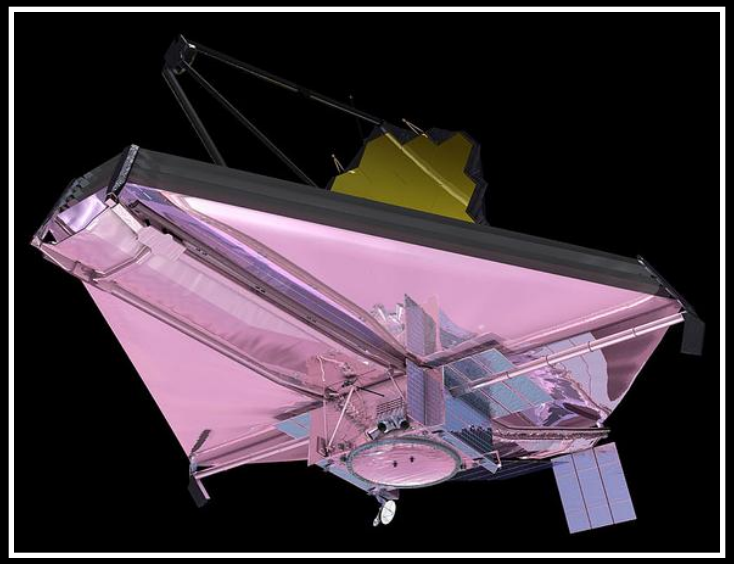
324" x 324"
$\lambda/D_{24\mu m}$~ 6.2"

Wavelength Coverage



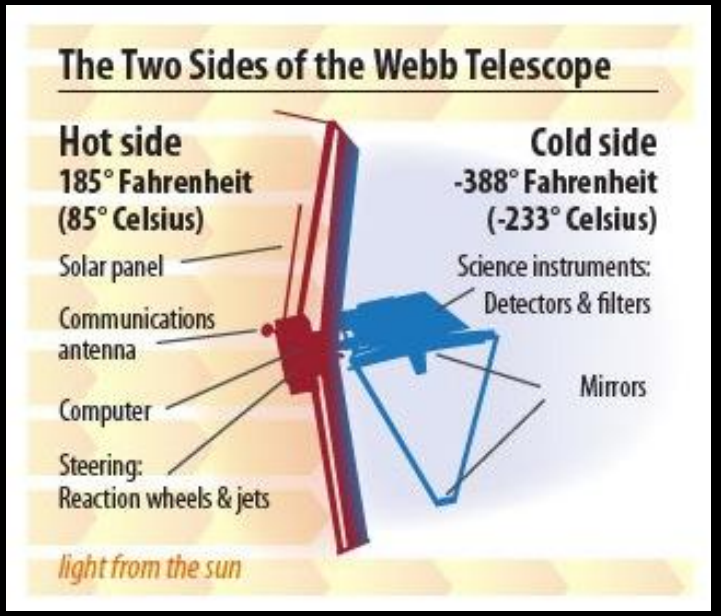
JWST Sunshield



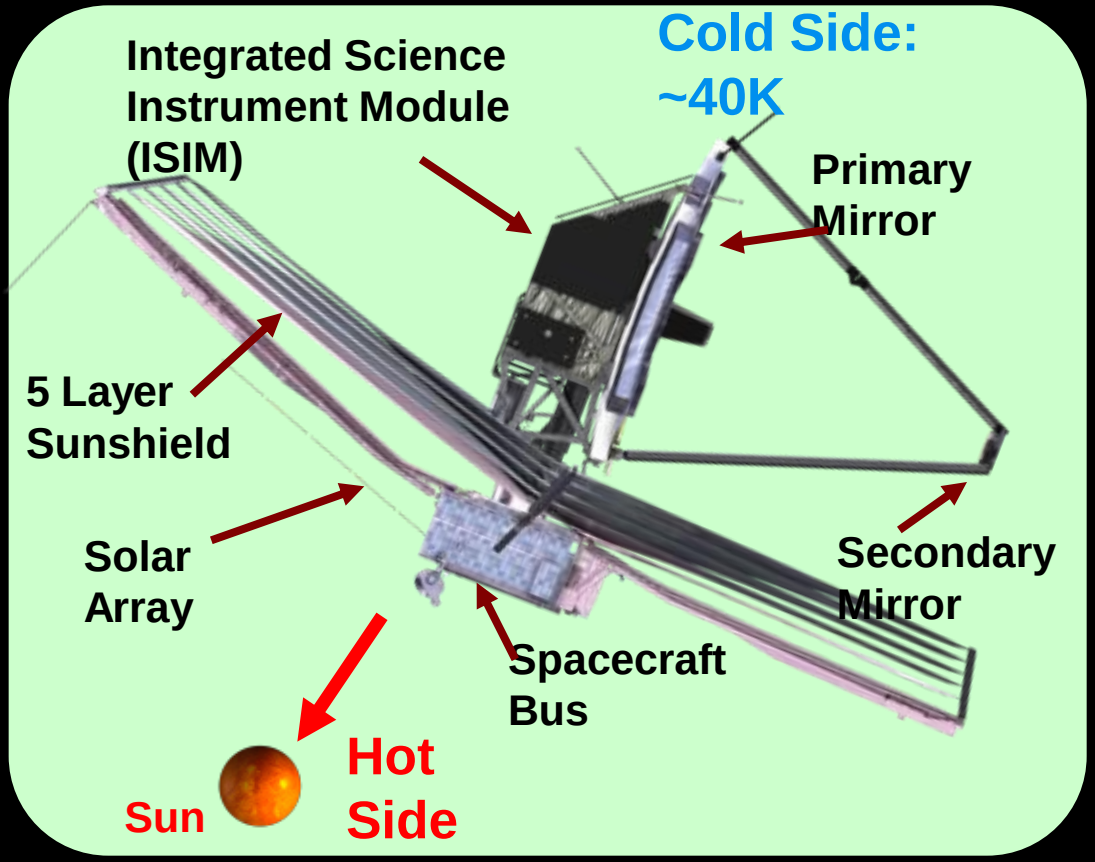


Sunshield Facts

- Measures 73 x 40 feet and has 5 layers
- Contains 400 temperature sensors
- Made of heat-resistant kapton
- Coated with silicon on sun side
- Sun side reaches 358 K (85° C)
- Dark side stays at 40 K (-233° C)



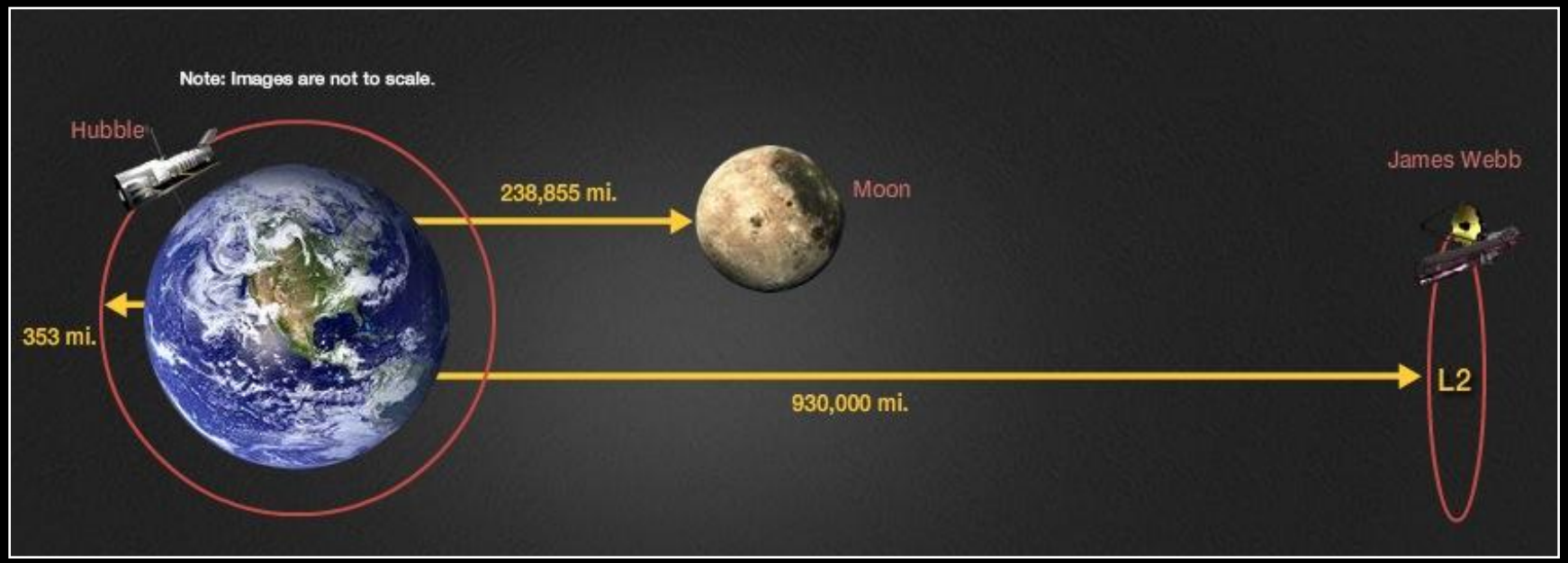
HOW JWST WORKS



JWST is folded and stowed for launch

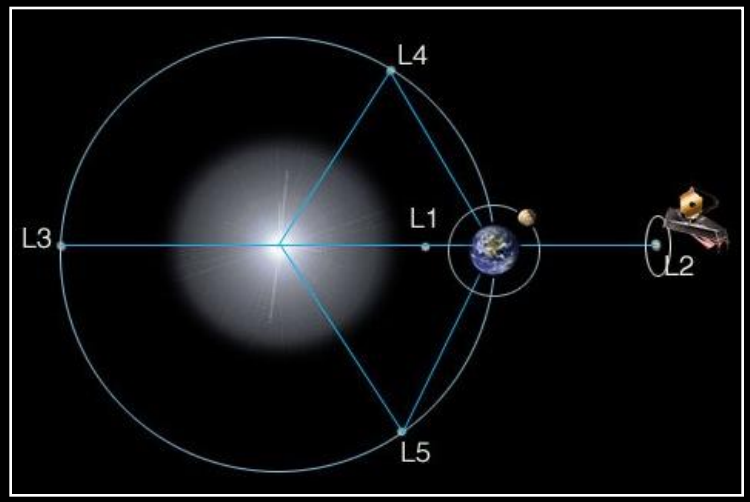
Observatory is deployed after launch

The James Webb Space Telescope

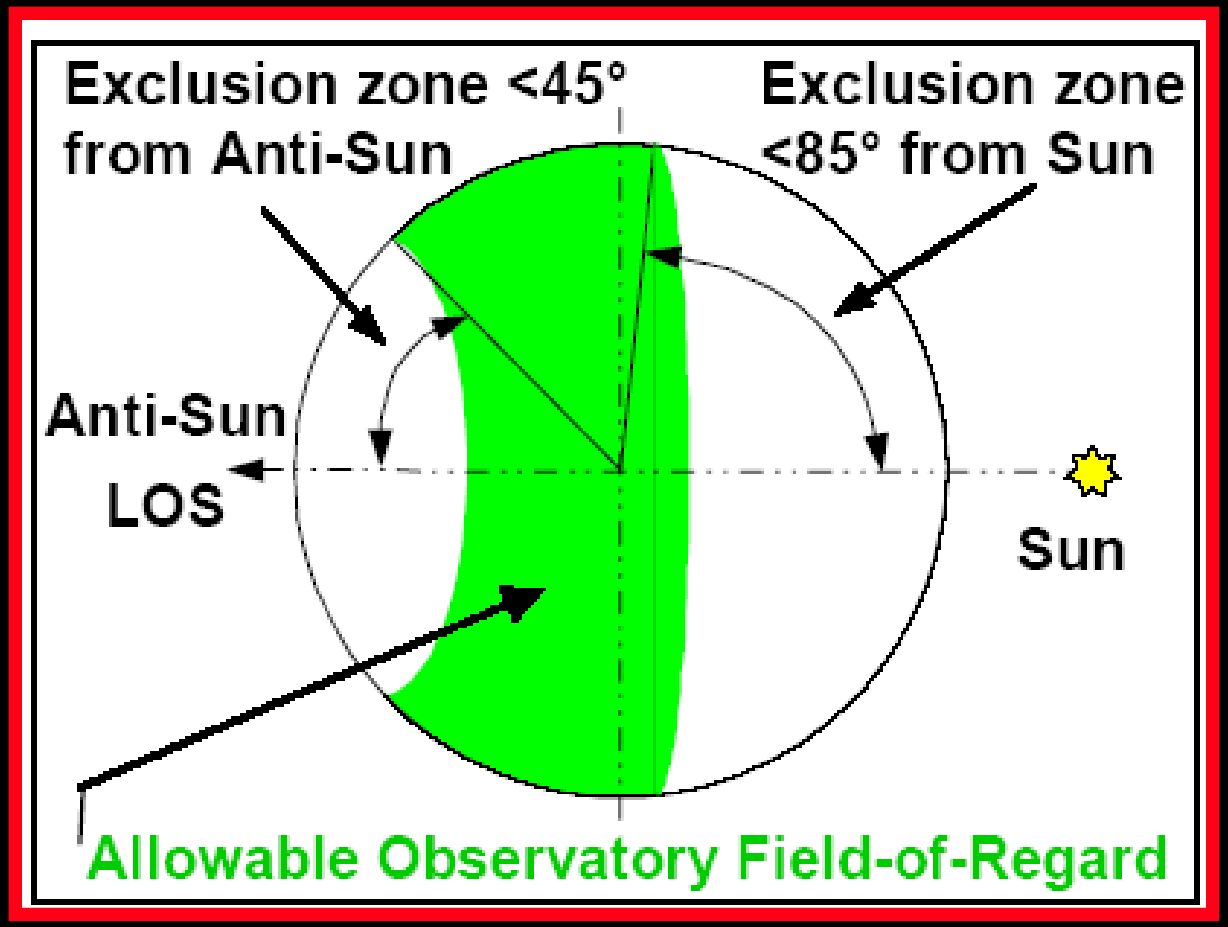


JWST Orbit

- JWST will orbit Sun-Earth L2 Lagrange point, 930,000 miles from Earth



JWST Field of Regard



JWST's optics must always be fully shaded

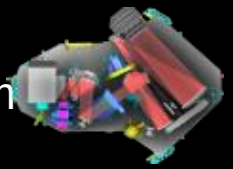
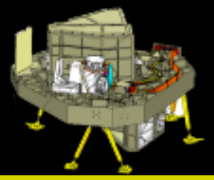
*Solar-system observations will be made near quadrature

Similar to Spitzer and Herschel observatories

JWST Vital Stats

- General Observatory: 5 years required; 10 years goal
- Primary mirror: 21.3 feet (6.5 meters), in 18 segments
- Sunshield: 5 layer, 69.5 feet by 46.5 feet (21.2 meters by 14.2 meters
- Orbit: 930,000 miles (1.5 million kilometers) from Earth around (and avoiding) L2 point
- Operating temperature: Below 50 Kelvin (–370° Fahrenheit)
- Four Science Instruments covering 0.6–28.5 microns (diffraction limited at 2 microns)
  - Filtered Imaging
  - Spectroscopy – Slit, Integral Field, Grism/Prism
  - Coronagraphy – Traditional Lyot + Four Quadrant Phase Masks
  - Aperture Mask Interferometry – Non-Redundant Mask (NRM)

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)	2.2’ x 4.4’ SW at same time as 2.2’ x 4.4’ LW with dichroic 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/Consortium /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”x 3.7” – 7.1”x 7.7” IFU R=3000 - 2250
FGS/NIRISS CSA 	Fine Guidance Sensor 0.8 µm - 5.0 µm Near IR Imaging Slitless Spectrometer	Two 2.3’ x 2.3’ 2.2’ x 2.2’ R= 700 with coronagraph

Sensitivity

- Faint objects, long exposures: can see a bumblebee at distance of the Moon (nano-Jansky levels)

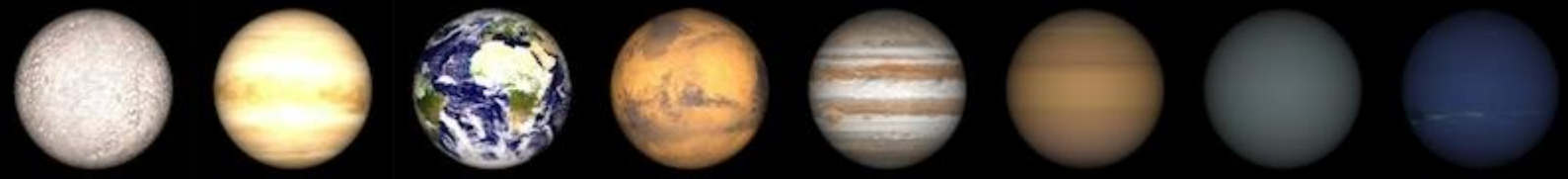
- Bright objects: short exposures, high resolution spectroscopy, special sub-array modes to read detectors faster – can observe all Solar system objects from Mars outwards, can do transit spectroscopy (exoplanets) of all but brightest stars.

JWST Solar System Observing

- **JWST will fully support Solar System observations**
  - Biggest, Brightest, Fastest objects to observe!!!
  - Planets, satellites & rings (Mars outward)
  - Asteroids, ice-teroids (KBOs) and comets
- **Non-sidereal tracking implemented**
  - Rates up to 30 mas/sec (108 “/hr) – set for Mars
    - Covers everything except fastest NEOs, comets
    - Mars’ average velocity is ~53,691 mph
    - Pluto’s average velocity is ~10,447 mph

Angular Resolution

			# Resolution Elements		
Object	Size (“)	Size (km)	2 μm PSF	NIRSpec IFU	MIRI IFU*
Mars	7	6.8e3	100	70	40
Jupiter	37	1.4e5	530	370	200
Saturn	17	1.2e5	245	170	94
Uranus	3.5	5.1e4	50	34	19
Neptune	2.2	5.0e4	31	22	12
Pluto	0.1	2.4e3	2	1	0.6



Innovative Solar System Science with the James Webb Space Telescope

Stefanie Milam, Special Ed.

http://iopscience.iop.org/1538-3873/128/959.

I. The James Webb Space Telescope's plan for operations and instrument capabilities for observations in the Solar System – S.N. Milam et al.

http://arxiv.org/abs/1510.04567

II. Observing Near-Earth Objects with the James Webb Space Telescope – C.A. Thomas et al.

http://arxiv.org/abs/1510.05637

II. Asteroids and JWST – A. Rivkin et al.

http://arxiv.org/abs/1510.08414

IV. Unique Spectroscopy and Imaging of Mars with JWST – G. Villanueva et al.

http://arxiv.org/abs/1510.04619

V. Giant Planet Observations with the James Webb Space Telescope – J. Norwood et al.

http://arxiv.org/abs/1510.06205

VI. Observing Outer Planet Satellites (except Titan) with JWST: Science Justification and Observational Requirements – L. Keszthelyi et al.

http://arxiv.org/abs/1511.03735

VII. Titan Science with the James Webb Space Telescope (JWST) – C.A. Nixon et al.

http://arxiv.org/abs/1510.08394

VIII. Observing Planetary Rings and Small Satellites with JWST: Science Justification and Observation Requirements – M.S. Tiscareno

http://arxiv.org/abs/1403.6849

IX. Cometary Science with the James Webb Space Telescope – M.S.P. Kelley et al.

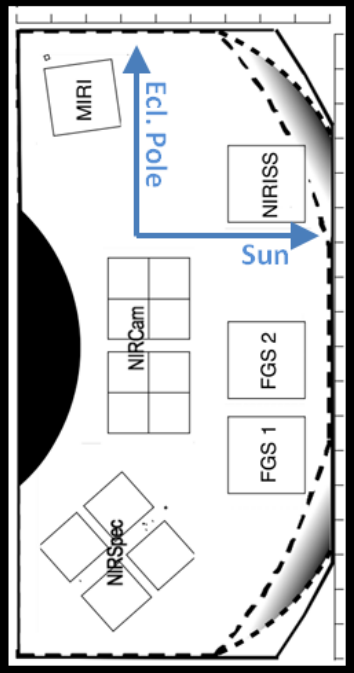
http://arxiv.org/abs/1510.05878

X. Physical Characterization of TNOs with JWST – A. Parker et al.

http://arxiv.org/abs/1511.01112

XI. JWST observations of stellar occultations by solar system bodies and rings – P. Santos-Sanz et al.

http://arxiv.org/abs/1510.06575



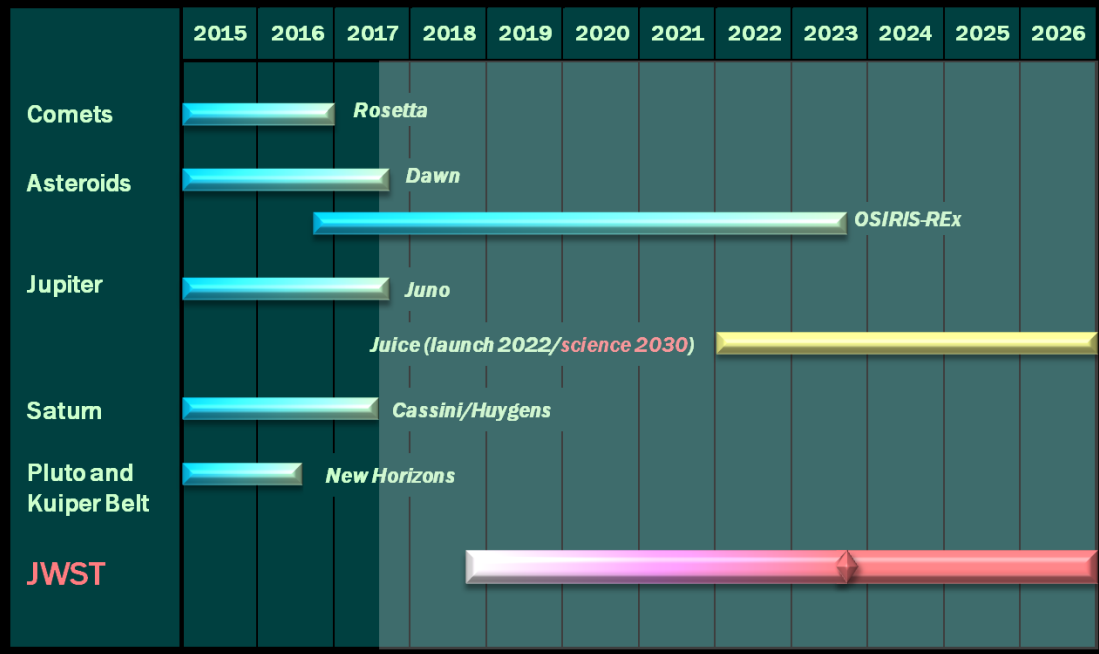
The James Webb Space Telescope's plan for operations and instrument capabilities for observations in the Solar System

S.N. Milam et al.

The four science instruments on JWST cover the wavelength range from 0.6 – ~28μm and offer superb imaging and spectroscopic sensitivity. Subarray readouts will enable non-saturated observations of the giant planets and many bright primitive bodies in a variety of instrument modes.

Science Capability Highlights

- **Important molecular (e.g. H_2O, HDO, CO, CO_2, S_2, CH_4), ice, and mineral spectral features are at wavelengths accessible with JWST but not the ground.**
- **Near-IR spectra or colors (composition), and mid-IR photometry (albedos, sizes), for any Kuiper belt object known today.**
- **Semi-annual monitoring of planetary (and satellite) weather *and seasonal changes*.**
- **Near-simultaneous mapping and spectroscopy of cometary gas and dust from 0.6 – ~*28* μm.**
- **Very sensitive spectral maps at R > 2000 over a 3"x3" field and with 0.1" spatial resolution.**



http://arxiv.org/abs/1510.04567

Motivation

Asteroids have natures ranging from the solar system's earliest solids to the last stages before full planethood. JWST observations will provide a critical link between meteorite samples and rare spacecraft missions.

Composition

Expanded wavelength coverage will further our understanding of asteroid compositions for all populations.

Surface Features

Dozens of main-belt asteroids large enough to be compositionally mapped by NIRCam

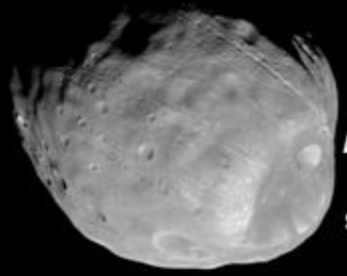
Size/Brightness Limits

NIRSpec can obtain S/N > 10 in 1000 s or less for practically every known main belt asteroid.

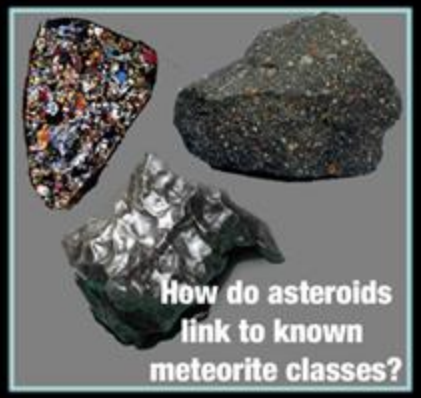
Asteroids and the James Webb Space Telescope:

Rivkin, Marchis, Stansberry, Takir, Thomas et al.

http://arxiv.org/abs/1510.08414

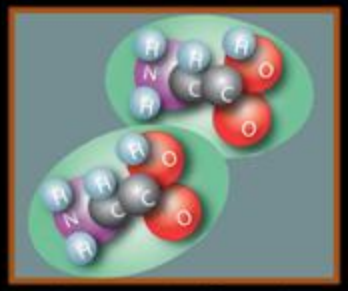


Are the compositions of primaries and secondaries similar?



How do asteroids link to known meteorite classes?

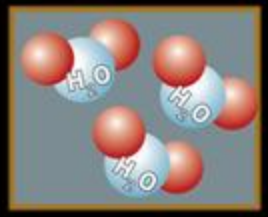
How does Space Weathering affect the surface of asteroids?



Are spectrally red surfaces due to organics?

Which volatile species are present on asteroid surfaces? What amount of volatiles are present?

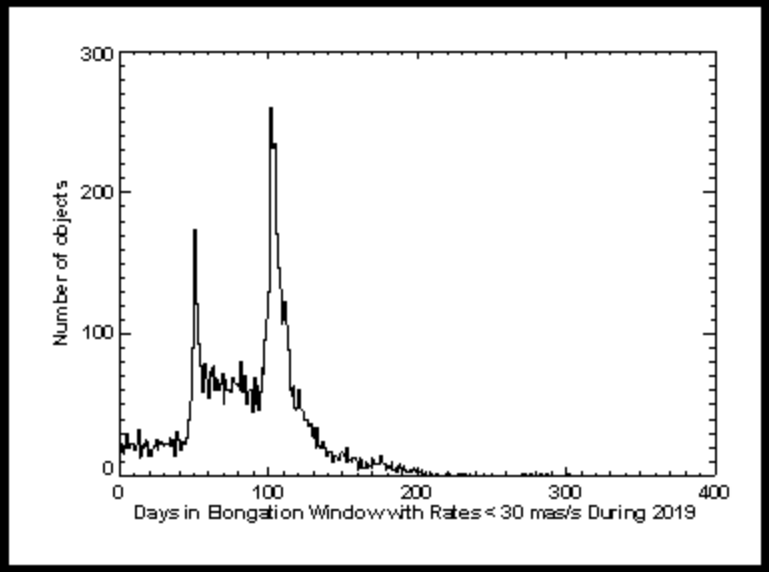
How does hydration vary across the Main Belt?



What are the physical properties of an asteroid's surface?

Observing Near-Earth Objects with the James Webb Space Telescope

C. A. Thomas (GSFC/USRA/PSI), P. Abell (JSC), J. Castillo-Rogez (JPL), N. Moskovitz (Lowell), M. Mueller (SRON), V. Reddy (PSI), A. S. Rivkin (APL), E. Ryan (UMD/GSFC), J. Stansberry (STScI)



Full paper available at:
http://arxiv.org/abs/1510.05637

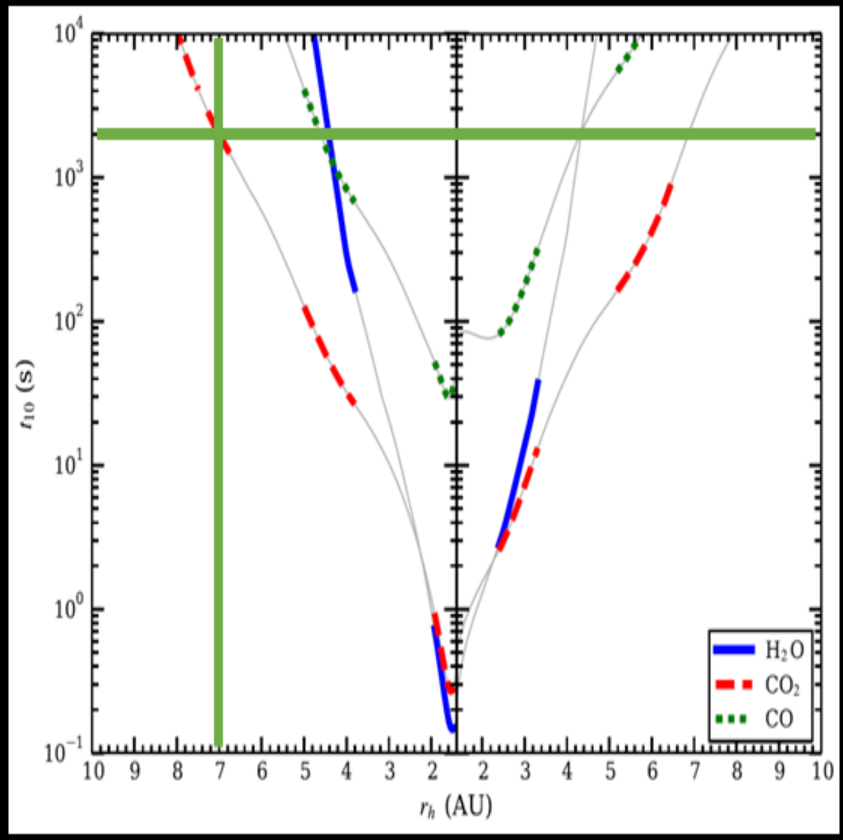
- Observations with JWST will enable a better understanding of the size frequency distribution of small NEOs, study of potential spacecraft targets, and investigations of spectral changes between the Main Belt and near-Earth space.
- Given the nominal observing requirements on elongation angle (85-135°) and non-sidereal rate (<30 mas/s), approximately 75% of NEOs can be observed in a given year.
- JWST can easily execute photometric observations of meter-sized NEOs!

Cometary Science with the James Webb Space Telescope

M. Kelley, C. Woodward, D. Bodewits, T. Farnham, M. Gudipati, D. Harker, D. Hines, M. Knight, L. Kolokolova, A. Li, I. de Pater, S. Protopapa, R. Russell, M. Sitko, D. Wooden

- Water, carbon dioxide, carbon monoxide and coma orbital evolution (NIRSpec, NIRCam, NIRISS)
  - Can measure CO_2 gas out to 7 AU in a moderately bright Oort cloud comet (right).
- Dust and water gas coma heterogeneity (MIRI)
  - Take advantage of high spatial resolution and simultaneous measurements of gas and dust.
- Water ice in comae and on nuclei (NIRSpec)
  - Easily measure coma ice at 4 AU for V=14 mag comet.
  - Potentially measure 3-μm ice absorption feature on large nuclei at 4 AU and beyond.
- Faint comets and main-belt comets (NIRSpec, NIRCam)
  - Direct tests for water gas in main-belt comets.

2000 s NIRSpec integration on comet C/2013 A1 (Siding Spring) could have detected CO_2 out to 7 AU.



arXiv: 1510.05878

Unique Spectroscopy and Imaging of **Mars** with JWST

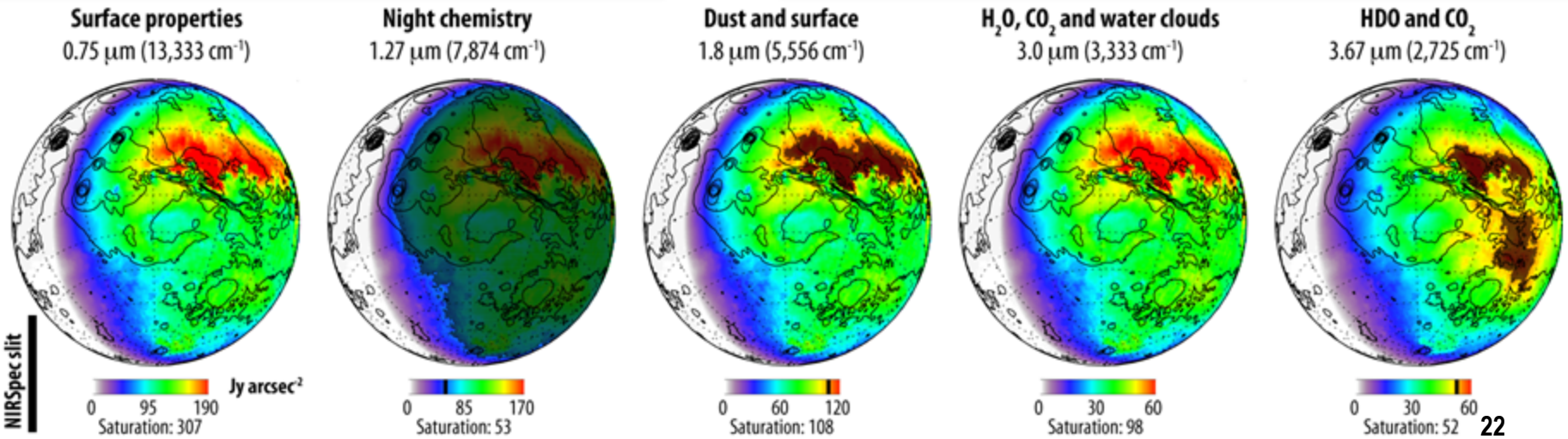
Villanueva (NASA/CUA), Altieri (IAPS/INAF), Clancy (SSI), Encrenaz (LESIA), Fouchet (LEISA), Hartogh (MPS), Lellouch (LEISA) López-Valverde (IAA), Mumma (NASA), Novak (Iona), Smith (NASA), Vandaele (BISA), Wolff (SSI), Ferruit (ESA), Milam (NASA)

The unique value of the JWST L2 orbit

- *Transient and seasonal studies, including the stability of the polar caps.*
- *Diurnal studies and of processes near the day/night terminator.*

New Frontiers with JWST

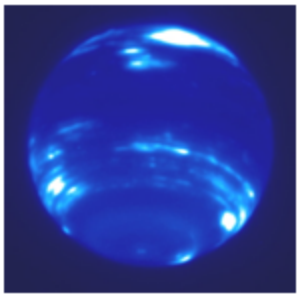
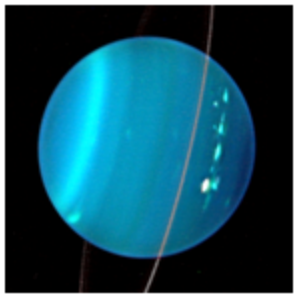
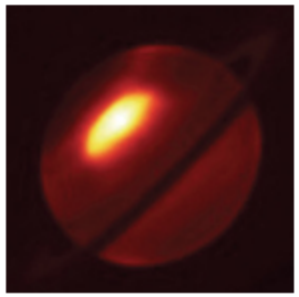
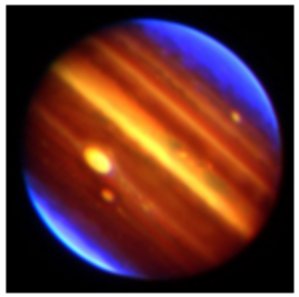
- *Maps of water D/H: How wet was Mars? How much water is currently available?*
- *Photochemical cycles and sensitive searches for organic species (e.g., CH_4).*
- *Formation and evolution of global dust storms and cloud systems over volcanoes.*



http://arxiv.org/abs/1510.

Giant Planet Observations with JWST

J. Norwood, J. Moses, L. Fletcher, G. Orton, P. Irwin, S. Atreya, K. Rages, T. Cavalié, A. Sánchez-Lavega, R. Hueso, N. Chanover

Uranus and Neptune (0.7-28.5 μm):

- Mapping stratospheric hydrocarbon emission (photochemistry, circulation)
- Emission from CO_2, CO, HCN (constrain external sources)
- Cloud structure and varying CH_4 abundance
- Seasonal changes

Jupiter (0.7-10 μm) and Saturn (0.7-17 μm):

- High-res cloud altitudes within storms/vortices
- Abundances and distribution of tropospheric species (NH_3, PH_3, CH_3D, $^{15}NH_3$, …)
- Aftermath of impacts
- Saturn: seasonally variant abundances and temperatures in stratosphere

Image credits: I. de Pater, H. B. Hammel, and W. M. Keck Observatory; L. Sromovsky and W. M. Keck Observatory; L. Fletcher and VLT; P. Irwin and UKIRT.

http://arxiv.org/abs/1510.06205

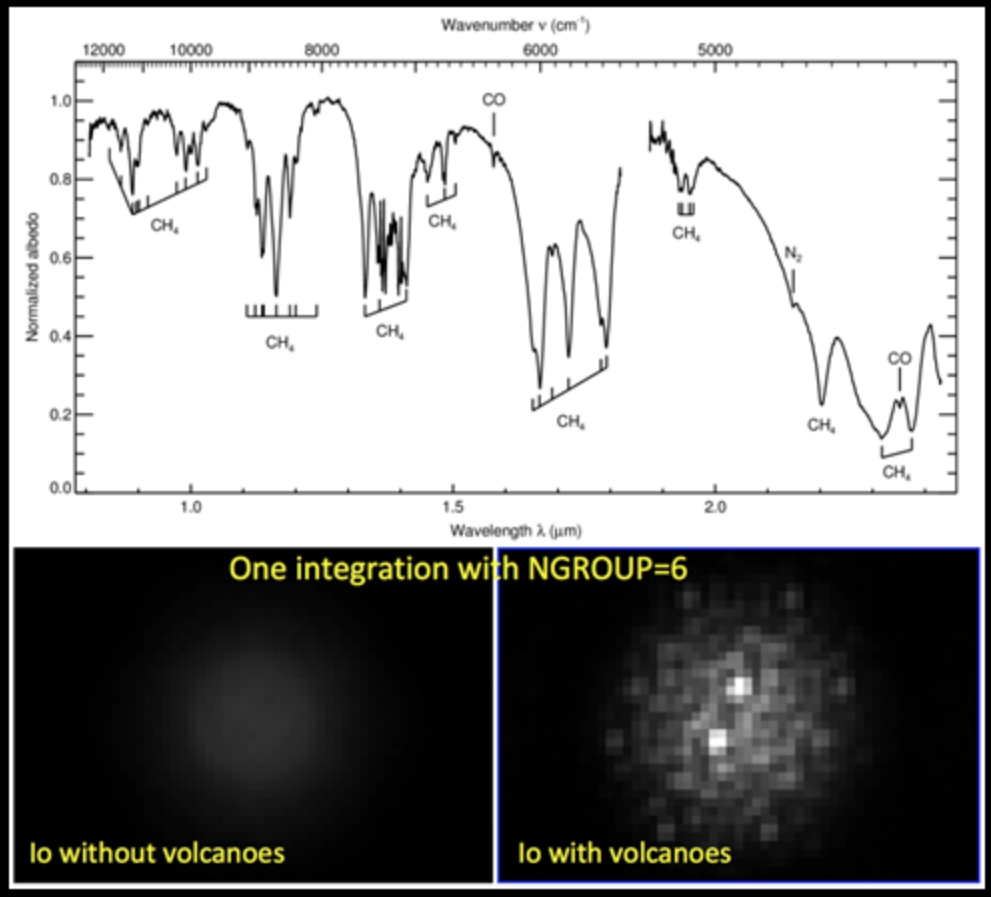
Observing Outer Planet Satellites (Except Titan) with JWST: Science Justification and Observational Requirements

Laszlo Keszthelyi[1], Will Grundy[2], John Stansberry[3], Anand Sivaramakrishnan[3], Deepashri Thatte[3], Murthy Gudipati[4], Constantine Tsang[5], Alexandra Greenbaum[6], Chima McGruder[7]

Two key science areas that JWST has the capacity to excel at:

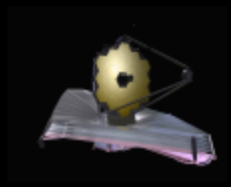
1. Higher spectral resolution infrared observations of icy surfaces to detect additional ice species/phases and organic compounds
2. Twice-a-year observations of geologically active satellites to monitor regional-scale changes.

http://arxiv.org/abs/1511.03735



Titan Science With the James Webb Space Telescope

From 2018, JWST will provide a revolutionary new means to study Saturn's largest moon in the infrared, at 1-28 μm.



The observatory's four spectrometers and cameras will provide insights into Titan's:

- Surface: *composition, rainfall darkening*
- Lower atmosphere clouds: *weather patterns*
- Tropospheric gases: *methane variability*
- Stratospheric gases: *seasonal changes*
- Hazes: *hemispheric reversal of contrast*

Download the paper at http://arxiv.org/abs/1510.08394

Authors: *C. Nixon, R. Achterberg, M. Adamkovics, B. Bezard, G. Bjoraker, T. Cornet, A. Hayes, E. Lellouch, M. Lemmon, M. Lopez-Puertas, S. Rodriguez, C. Sotin, N. Teanby, E. Turtle, R. West*

Observing Rings and Small Satellites with JWST

M.S. Tiscareno[1,2], M.R. Showalter[1], R.G. French[3], J.A. Burns[2], J.N. Cuzzi[4], I. de Pater[5], D.P. Hamilton[6], M.M. Hedman[7], P.D. Nicholson[2], D. Tamayo[8], A.J. Verbiscer[9], S.N. Milam[10], and J.A. Stansberry[11]

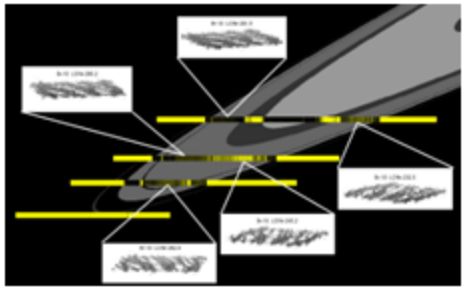
[1]SETI Inst, [2]Cornell U, [3]Wellesley Coll, [4]NASA Ames, [5]U California, [6]U Maryland, [7]U Idaho, [8]CITA, [9]U Virginia, [10]NASA Goddard, [11]STScI

Discovering New Rings and Moons

- JWST will improve upon Hubble with
  - Comparable spatial resolution, but
  - Infrared, so cool objects are brighter
  - Greater sensitivity for deep searches

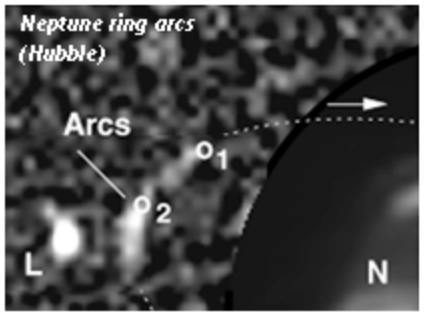
Occultations

- Observing the flickering brightness of a star as it passes behind rings yields high-fidelity structure
- For U and N, can greatly exceed sensitivity of Voyager occs
- Multiple occs can build up a "CAT scan" of ring microstructure



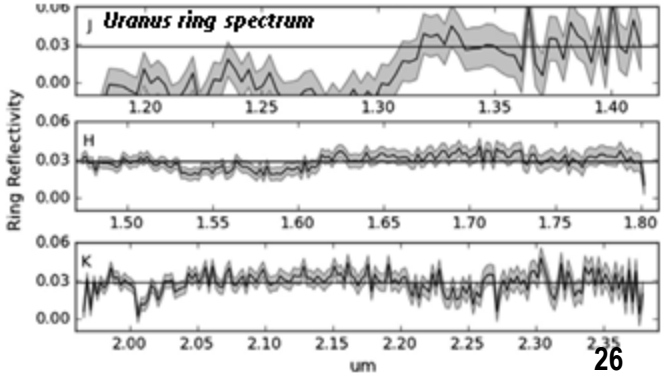
Time-Domain Science

- System evolution yields insights into
  - How and why they operate,
  - System origins,
  - Interactions w/ environment



Unprecedented Spectroscopy

- Compositions of rings and small moons in U and N systems
  - Very little is known from Voyager
  - Must be very different from Saturn
  - May hold clues to system origins
- IR spectra of faint targets is JWST's strong suit!



http://arxiv.org/abs/1403.6849

PHYSICAL CHARACTERIZATION OF TNOs WITH JWST

Alex Parker, Noemi Pinilla-Alonso, Pablo Santos-Sanz, John Stansberry, Alvaro Alvarez-Candal, Michele Bannister, Susan Benecchi, Jason Cook, Wesley Fraser, Will Grundy, Aurelie Guibert, Bill Merline, Arielle Moullet, Michael Mueller, Cathy Olkin, Darin Ragozzine, and Stefanie Milam.

COMPOSITIONS

Spectroscopy

Many molecular ices display fundamental absorption bands between 3 - 5 microns. Will identify currently-undetected volatiles on the surfaces of dwarf planets, verify others.

Spectrophotometry

Capable of distinguishing silicate-, organics-, or water-dominated surfaces, for every known D>100km TNO within the expected time for TNO science

THERMAL

Temperatures, Diameters, Albedos

Thermal peak 50K TNO is beyond JWST coverage. However, slope of TNO thermal emission in the MIRI operating range is sensitive to temperature.

Synergy with other facilities

ALMA offers the possibility of thermal observations contemporaneous with JWST. TNOs with diameters from occultations will provide benchmarks for verifying results

COMMUNITY ACTIONS

Pre-characterization of potential targets

Continue astrometric monitoring
Occultation campaigns
Binary system searches

Support laboratory investigations

Spectral properties of relevant ices in relevant temperature regime lacking for many species over JWST wavelength range.

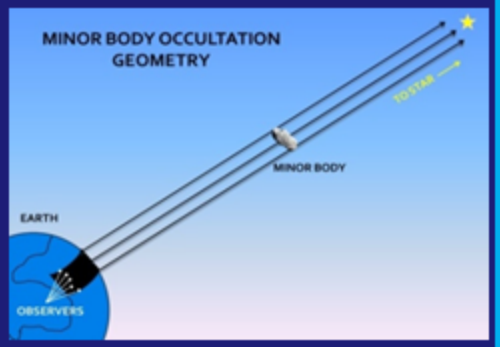
JWST observations of stellar occultations by solar system bodies & rings

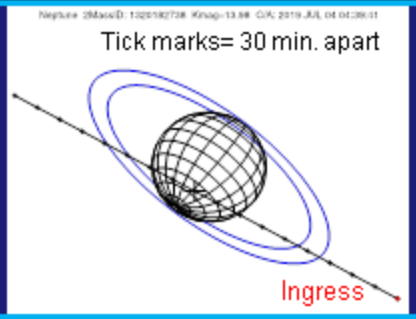
P. Santos-Sanz, R. G. French, N. Pinilla-Alonso, J. Stansberry, Z-Y. Lin, Z-W. Zhang, E. Vilenius, Th. Müller, J.L. Ortiz, F. Braga-Ribas, A. Bosh, R. Duffard, E. Lellouch, G. Tancredi, L. Young, S.N. Milam http://arxiv.org/abs/1510.06575

Stellar occultation: simple method to get high precision sizes/shapes/details/albedos of bodies/rings

Predictable stellar occultations

- Events no more infrequent from JWST than from any other site
- Preferred instrument: NIRCam (high sensitivity & time resolution)
- Most interesting: by distant minor bodies (TNOs, Centaurs)
- From JWST: single-chord→Lower limit for sizes & Discovery/characterization of atmospheres/satellites/rings
- Without accurate JWST orbit knowledge: occultation proposals will be ToO



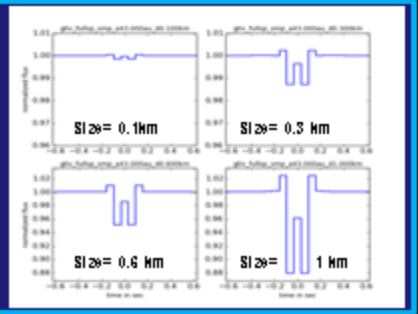


Occultations by rings

- Detailed structure of giant planets rings revealed by occ.(Uranus'/Neptune's discovered by occ.)
- JWST will extend time baseline / exceptionally high-quality profiles
- Occultations by rings visible from JWST identified
- Possibility to discover rings around minor bodies w/ JWST (Chariklo/Chiron)

Serendipitous stellar occultations by TNOs

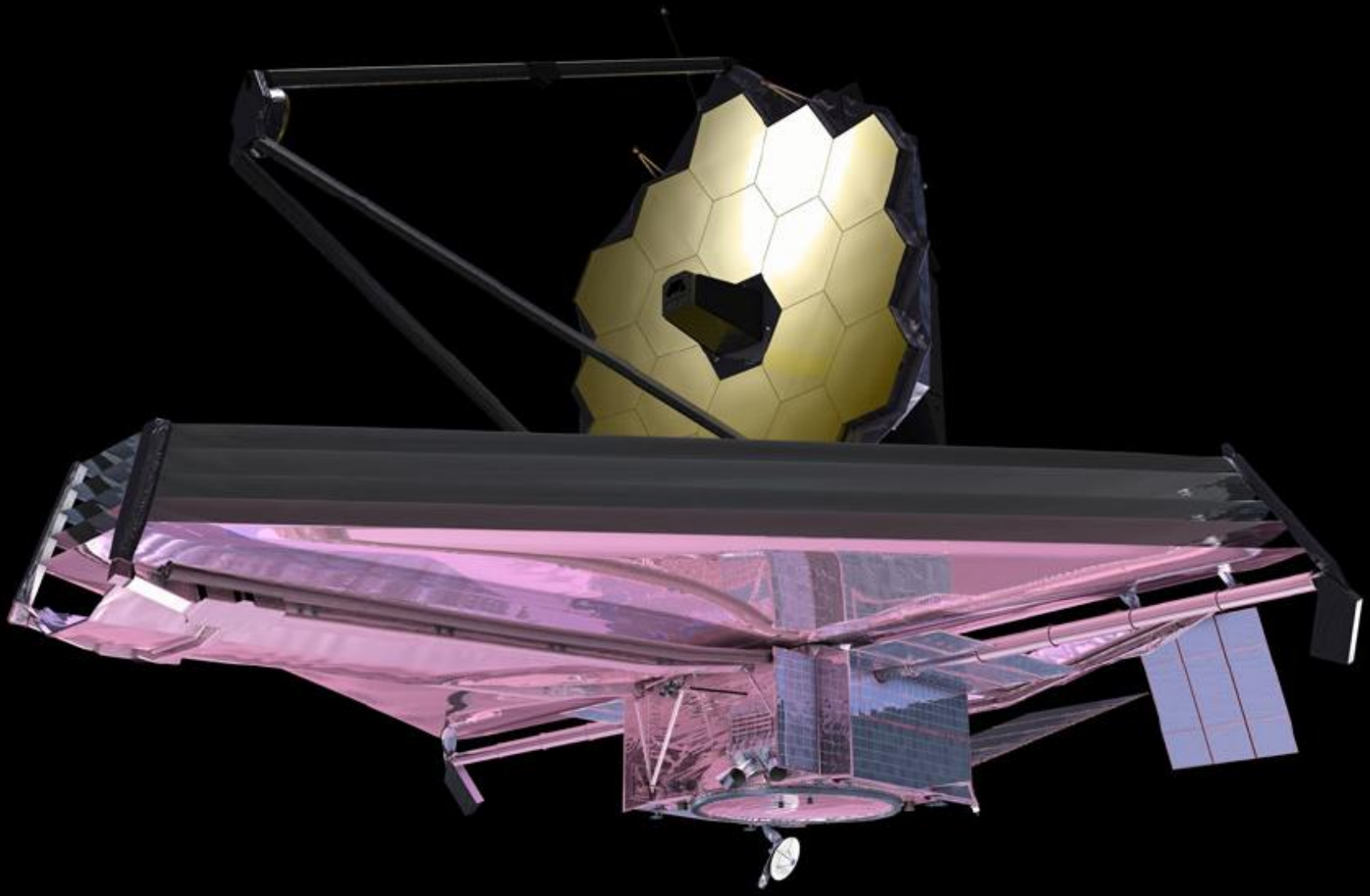
- Detection of diffraction profiles of very small TNOs (< 1 km)
- Preferred instrument: FGS:
  Cadence ~12 Hz + Large amount star/hours + High SNR for guide stars
- JWST more sensitive than HST
- By-product from other projects → valuable information of small TNOs' population



- Predictable occultations require very little telescope time
- Serendipitous occultations by-product of other projects

→ Low observational cost and very important scientific return

JWST Status Report (Jan 2016)



Yearly Themes

2013: Instrument Integration: The Science instruments will be finished and begin their testing as an integrated science payload

2014: Manufacturing the Spacecraft: Construction will commence on the spacecraft that will carry the science instruments and the telescope

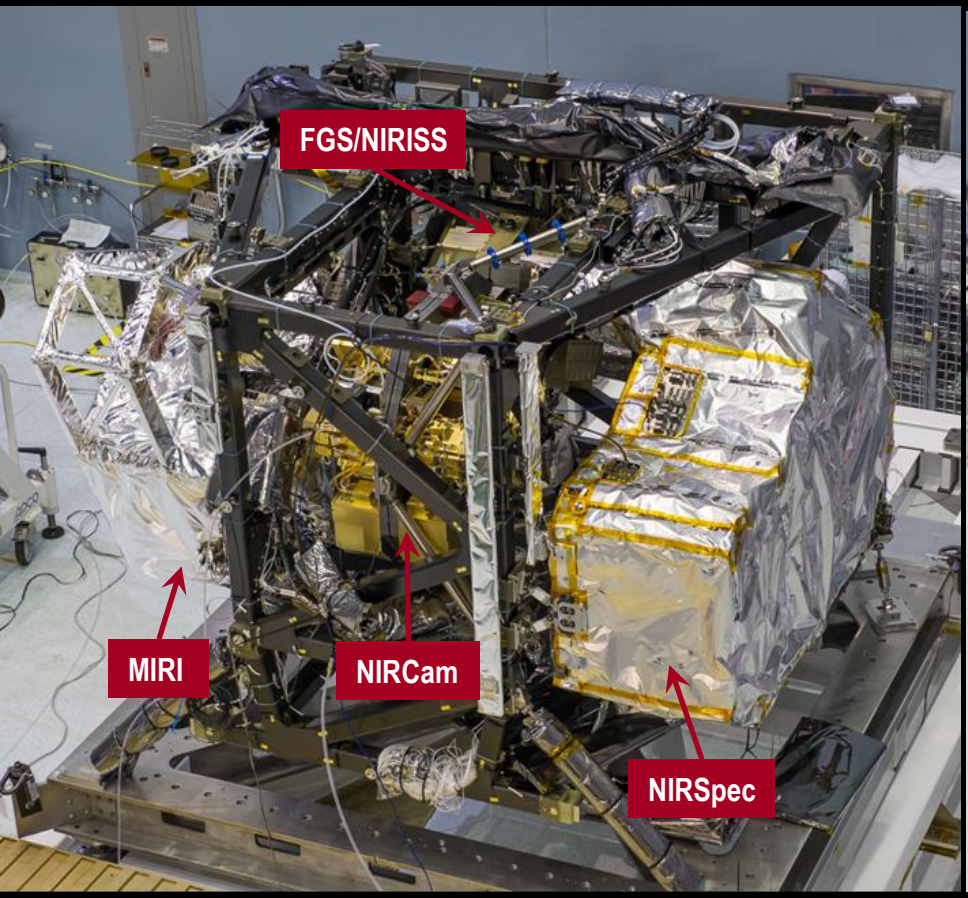
2015: Assembling the Mirror: The mirror segments, secondary mirror and aft optics will all be assembled into the telescope

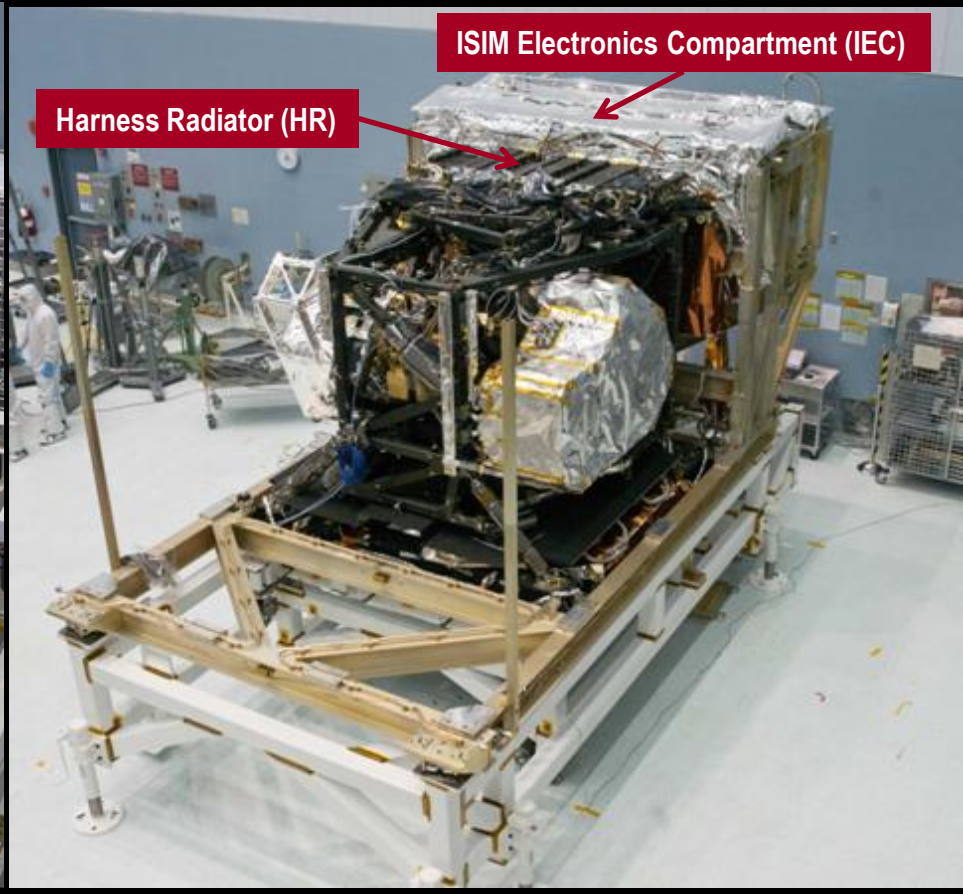
2016: Observatory Assembly: The three main components of the observatory will be completed (instruments, telescope, spacecraft)

2017: Observatory Testing: The three main components of the observatory will be tested and readied for assembly (instruments, telescope, spacecraft) into a single unit

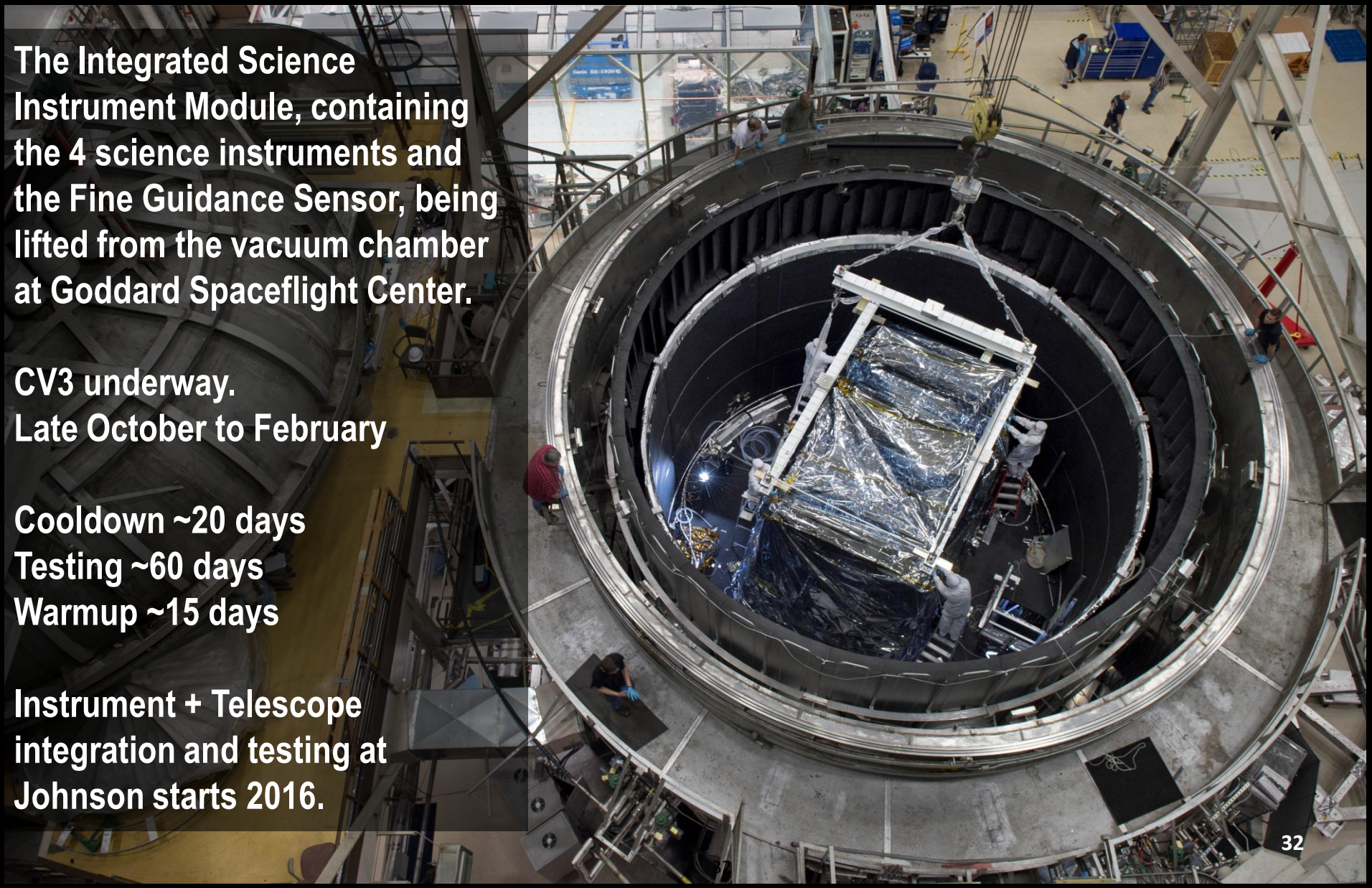
2018: Kourou Countdown: All parts of the observatory will be brought together, tested and readied for launch in Kourou, French Guiana

Flight ISIM test configuration





ISIM Cryo-vac 3 test started



The Integrated Science Instrument Module, containing the 4 science instruments and the Fine Guidance Sensor, being lifted from the vacuum chamber at Goddard Spaceflight Center.

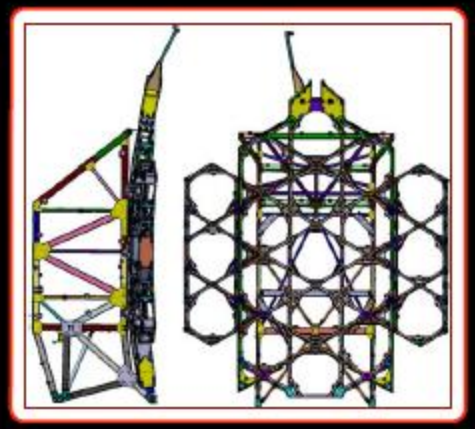
CV3 underway.
Late October to February

Cooldown ~20 days
Testing ~60 days
Warmup ~15 days

Instrument + Telescope integration and testing at Johnson starts 2016.

Telescope Structure

Pathfinder Backplane



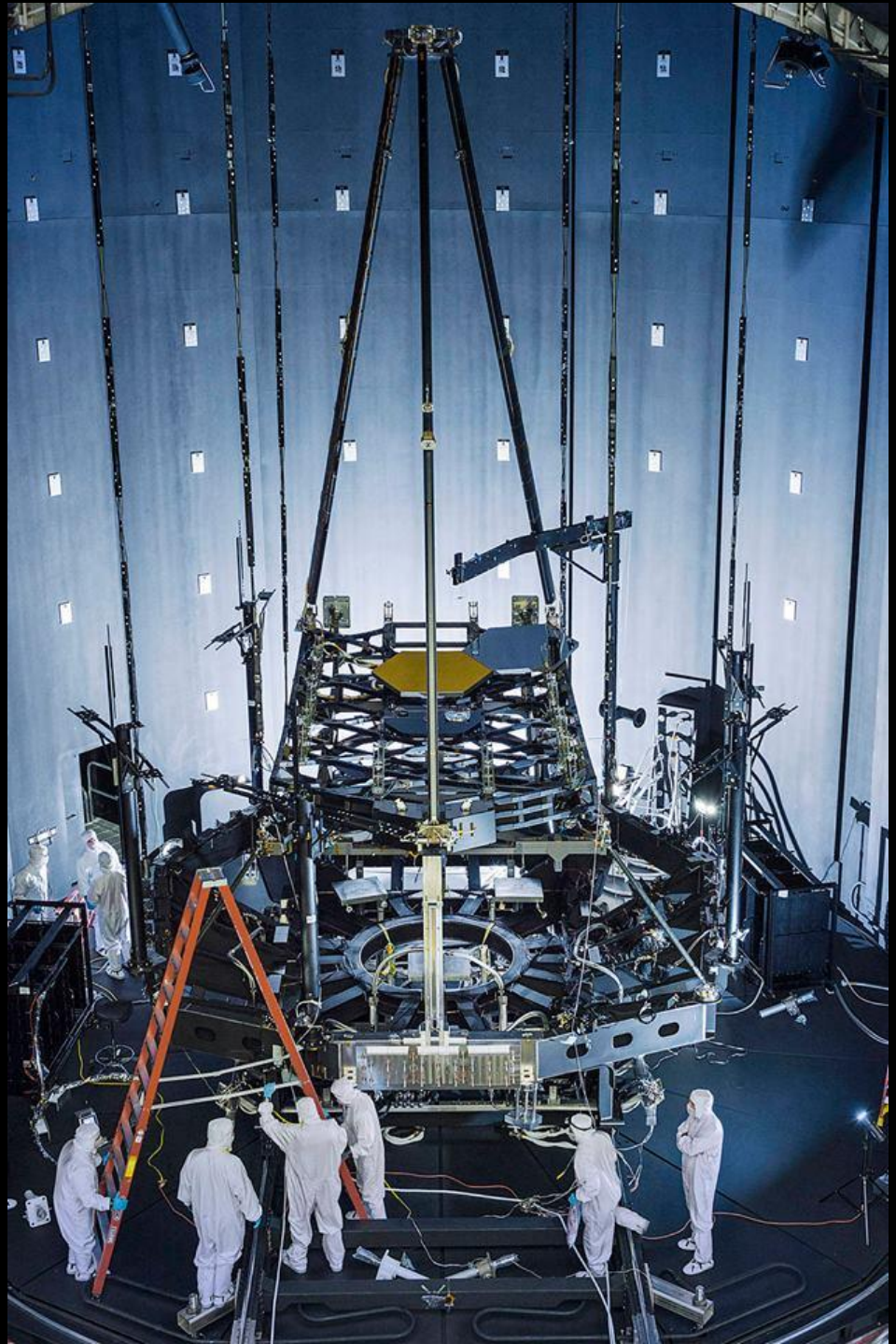
Flight Backplane

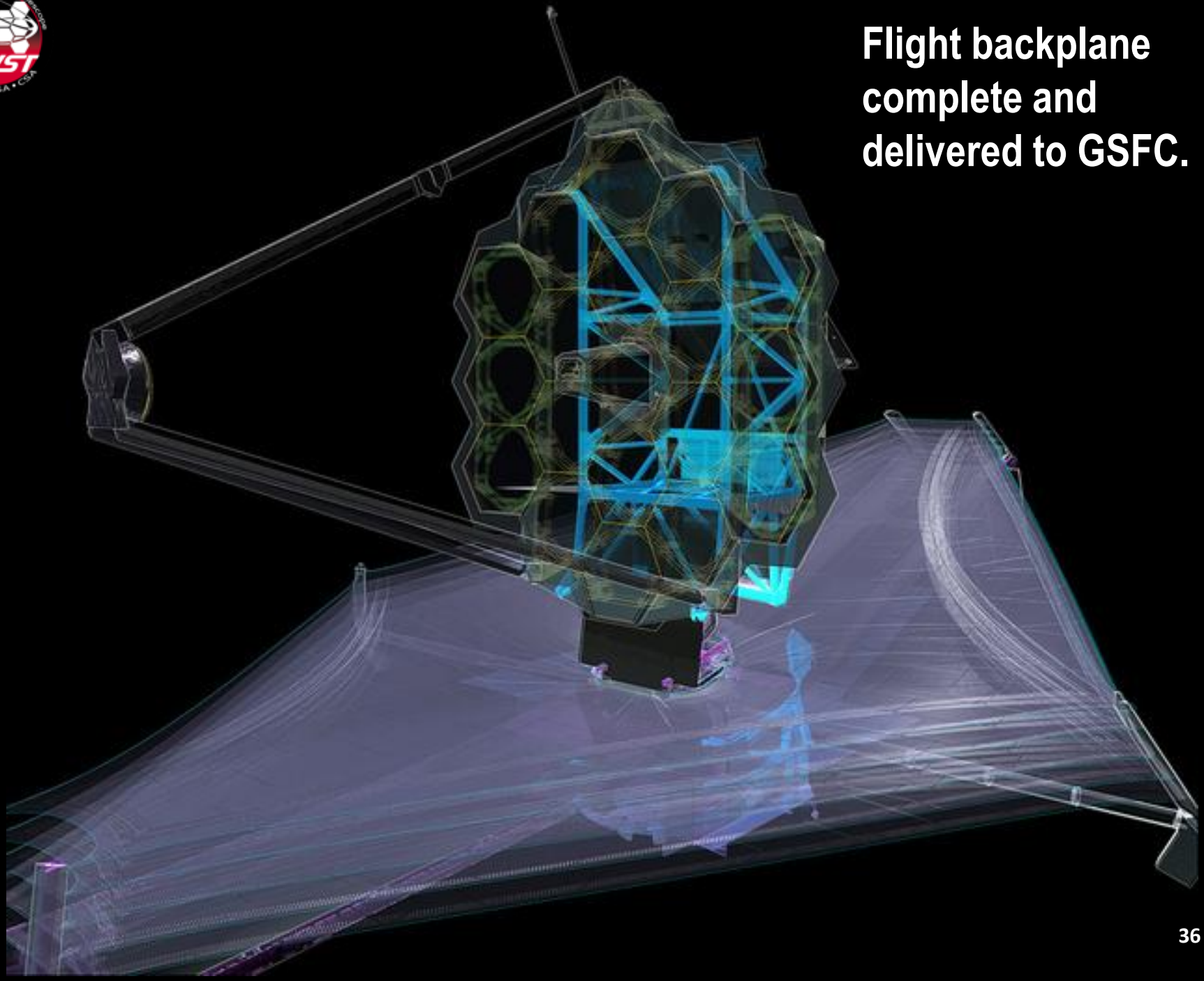
Pathfinder Backplane

- The pathfinder is a backplane section with a secondary mirror support structure (SMSS)
  - ➡ Verify SMSS deployment
- Tests integration of primary mir segment installation with two fli spare mirror segments, plus flight-spare secondary mirror
- Pathfinder conducted cryogenic tests in Chamber-A at JSC to ve the optical test equipment

- Pathfinder JWST primary-mirror central backplane and secondary mirror support structure in JSC Chamber A .

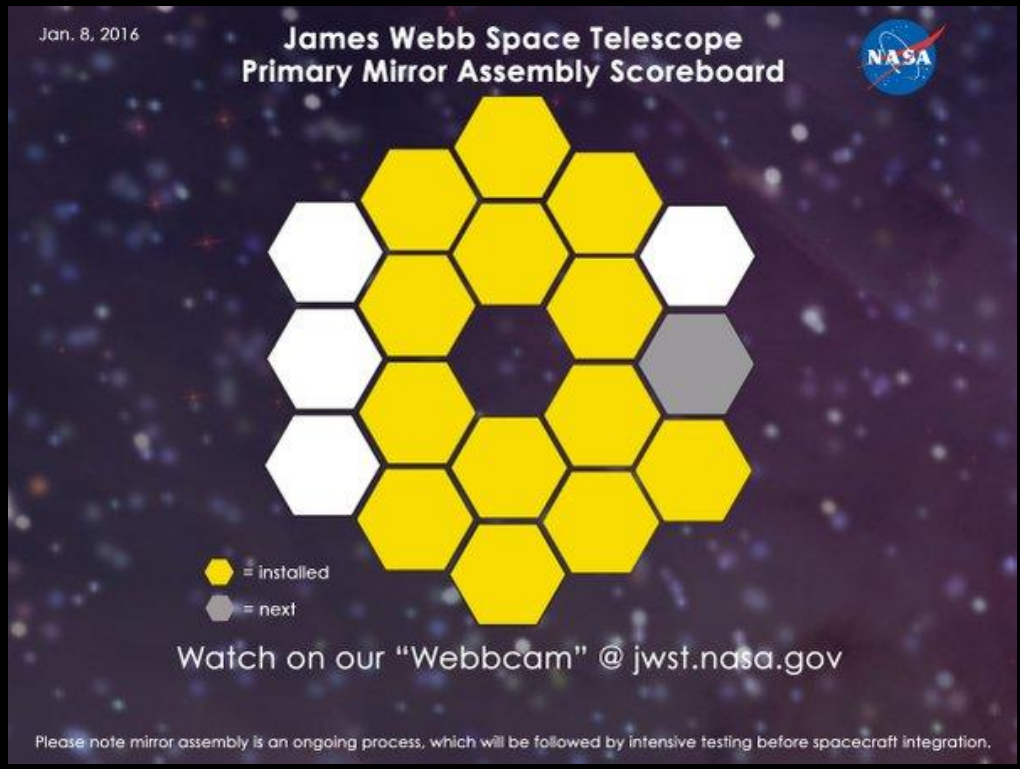
- Optical test equipment delivered and installed. Pathfinder will be used to test alignment of multiple mirrors and the test equipment.





Flight backplane complete and delivered to GSFC.

Mirror Installation #MirrorSeason



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

Sunshield

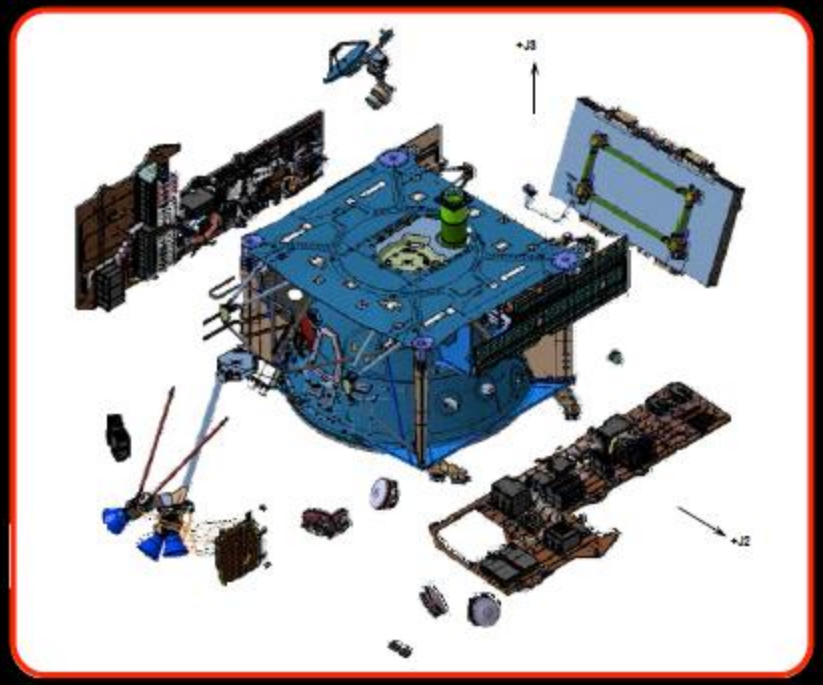
- Five flight-like Template Membrane layers manufactured
  - ➡ Template layers tensioned to flight-like configuration
    - 3-D membrane shapes measured by Lidar
    - Critical for layer-to-layer spacing ➡ thermal performance
    - Edge alignment ➡ thermal performance & stray light
- Flight membranes under construction (#3 completed)

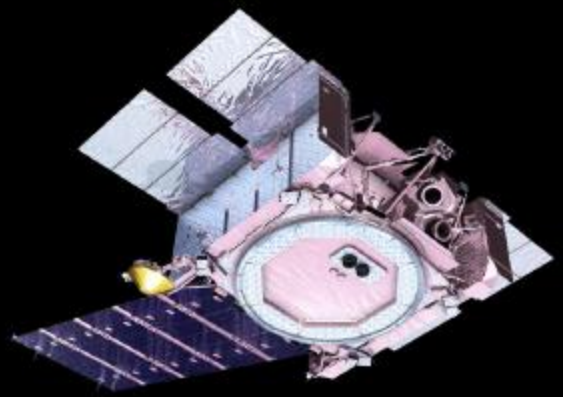
Tensioned to 3x flight tension for shape measurement by Lidar

(3x tension counteracts gravity sag)

Full Deployment Test

Spacecraft Bus - Complete





2016 Highlights

Winter 2016

Complete ISIM cryovacuum testing
Complete Telescope mirror installation
Complete construction of the Mission Operations Center at STScI

Spring 2016

Begin integration of ISIM with Telescope
Start development of Observatory Commissioning Plan

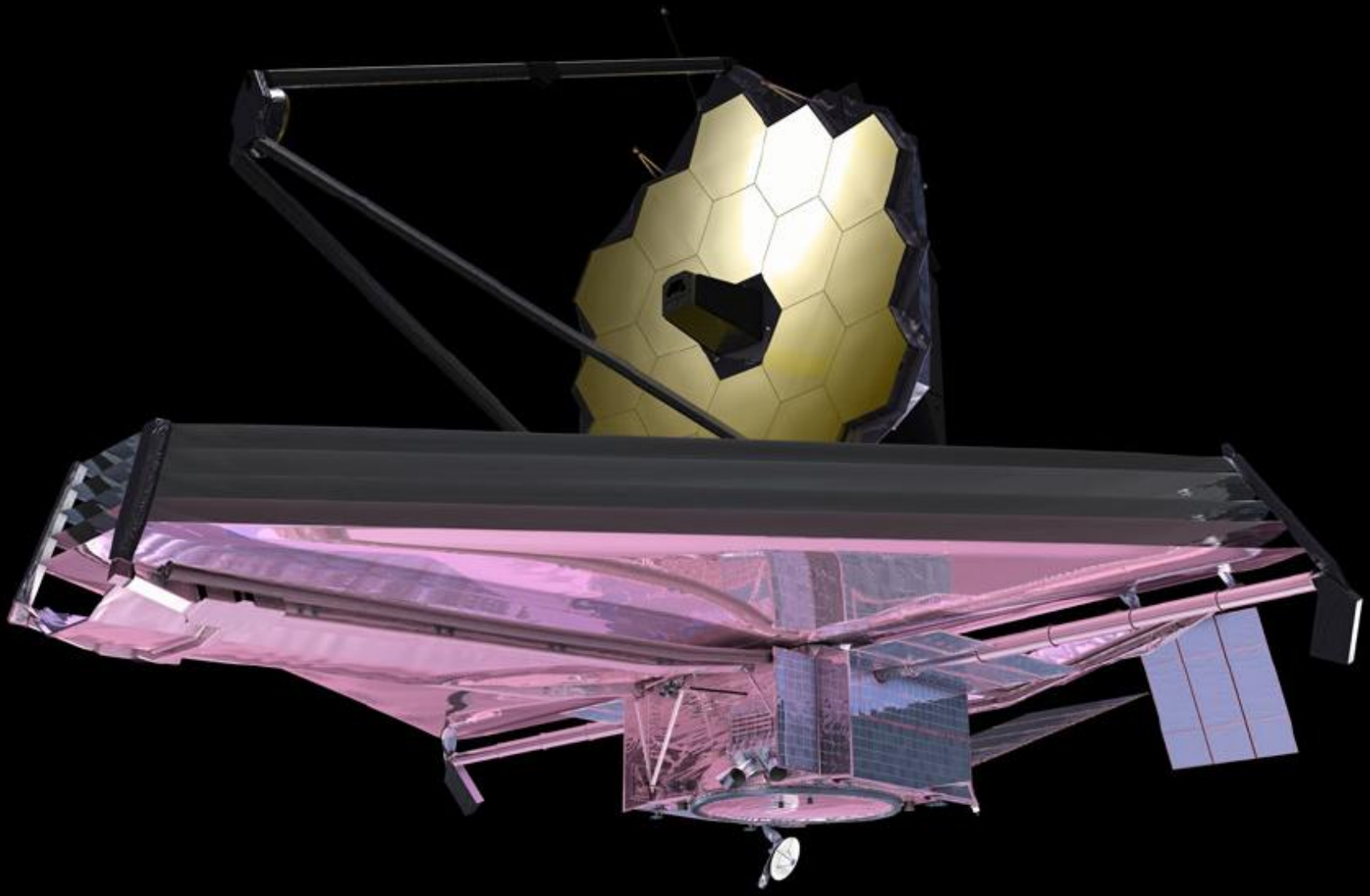
Summer 2016

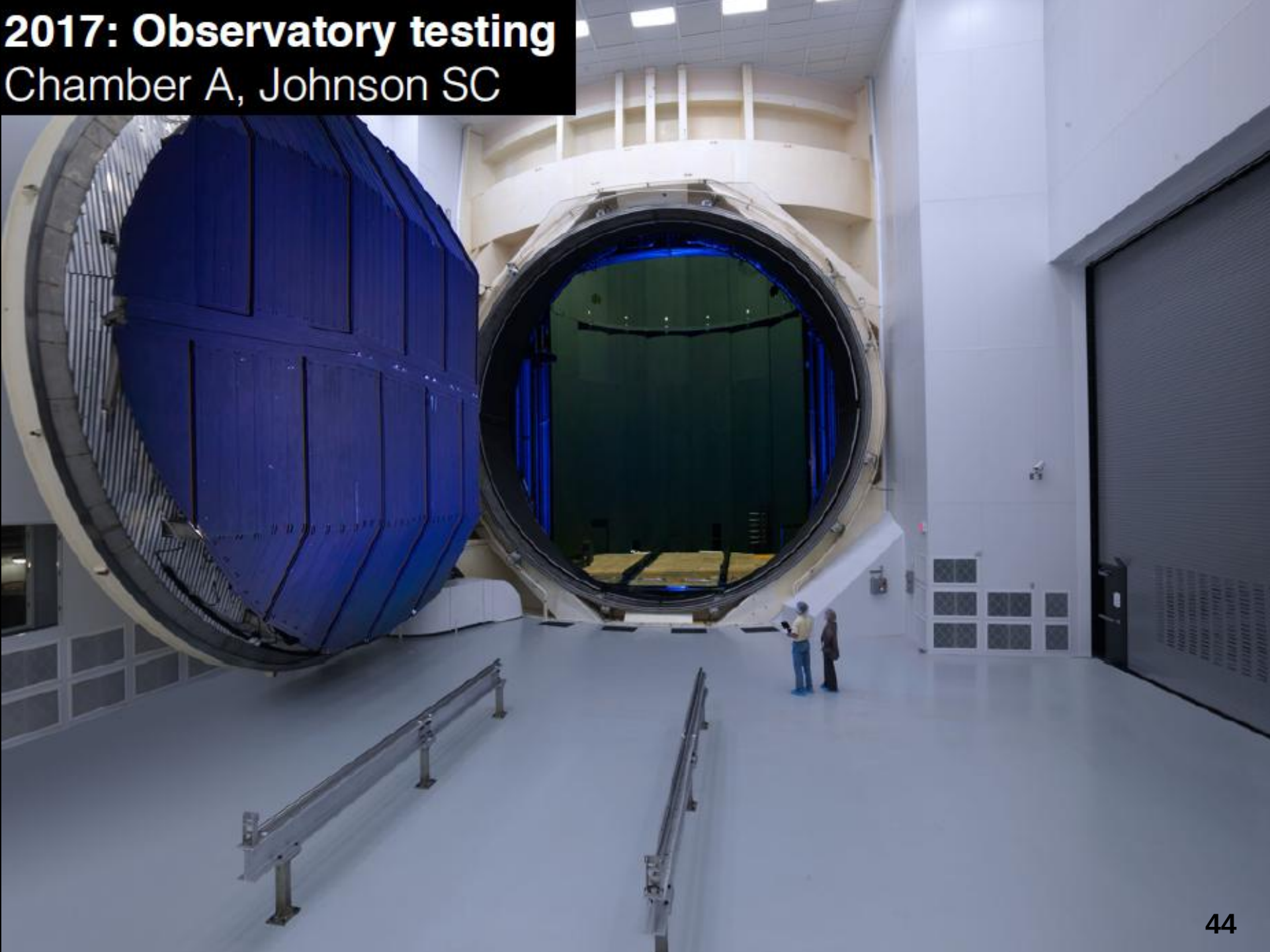
Complete MIRI cryocooler testing and deliver to spacecraft I&T
Complete spacecraft panels avionics box integration

Fall 2016

Combined Telescope and Instrument environmental testing
Complete sunshield membrane manufacturing
Complete Thermal Pathfinder testing at JSC

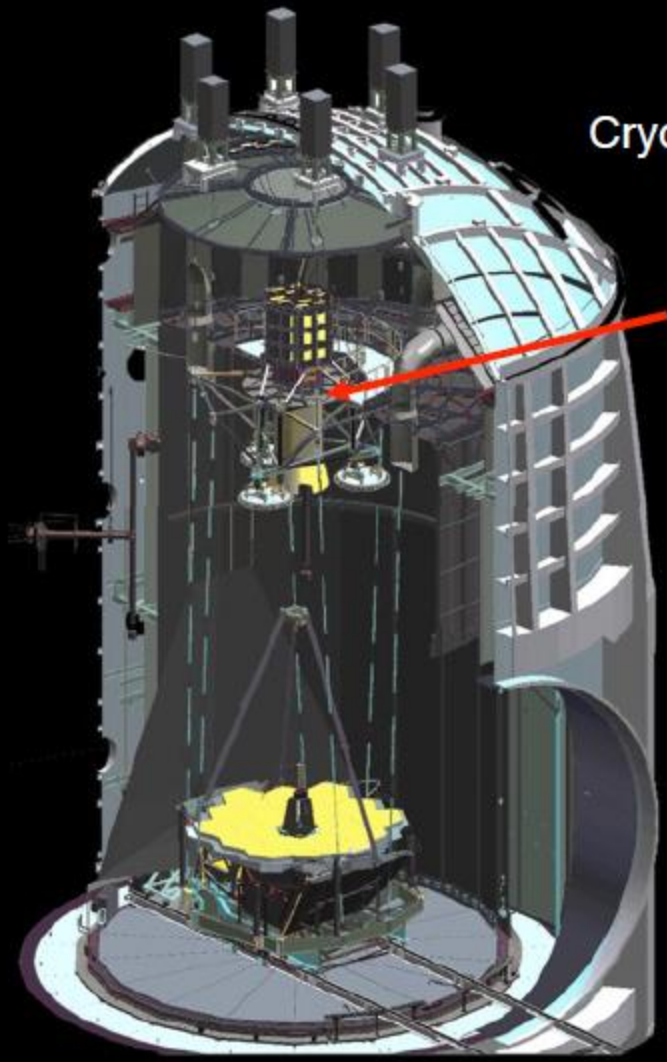
2017: Observatory Testing




2017: Observatory testing
Chamber A, Johnson SC

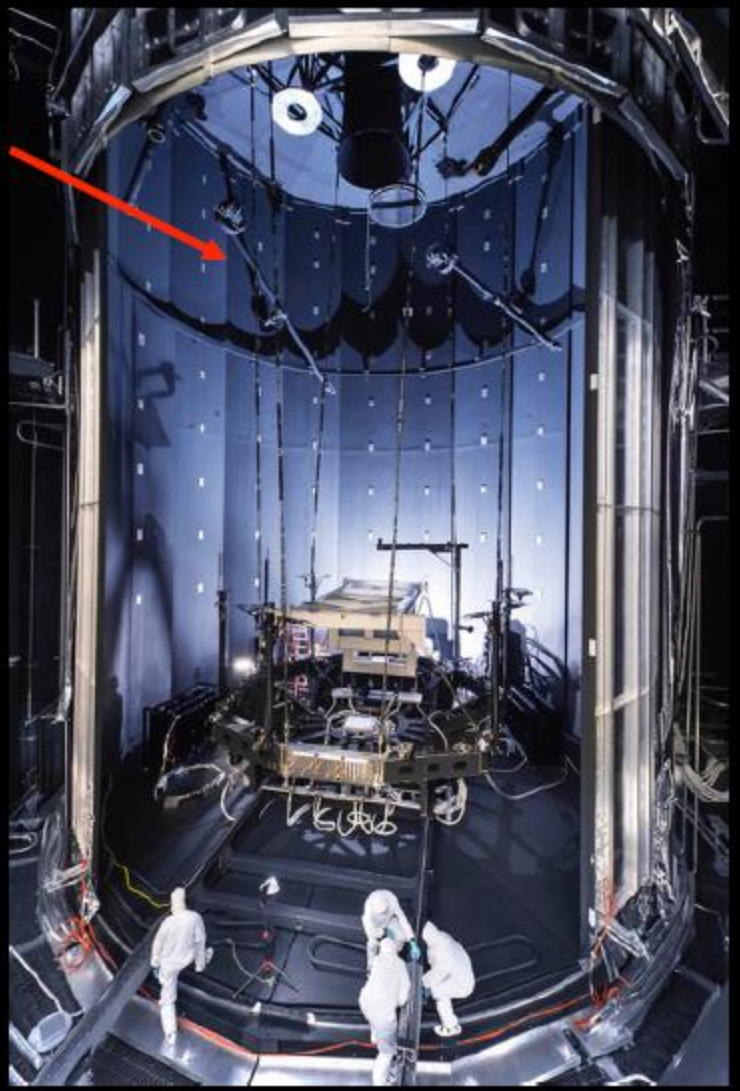
Test Preparations Underway

Chamber Isolator Units



Cryo Position Metrology

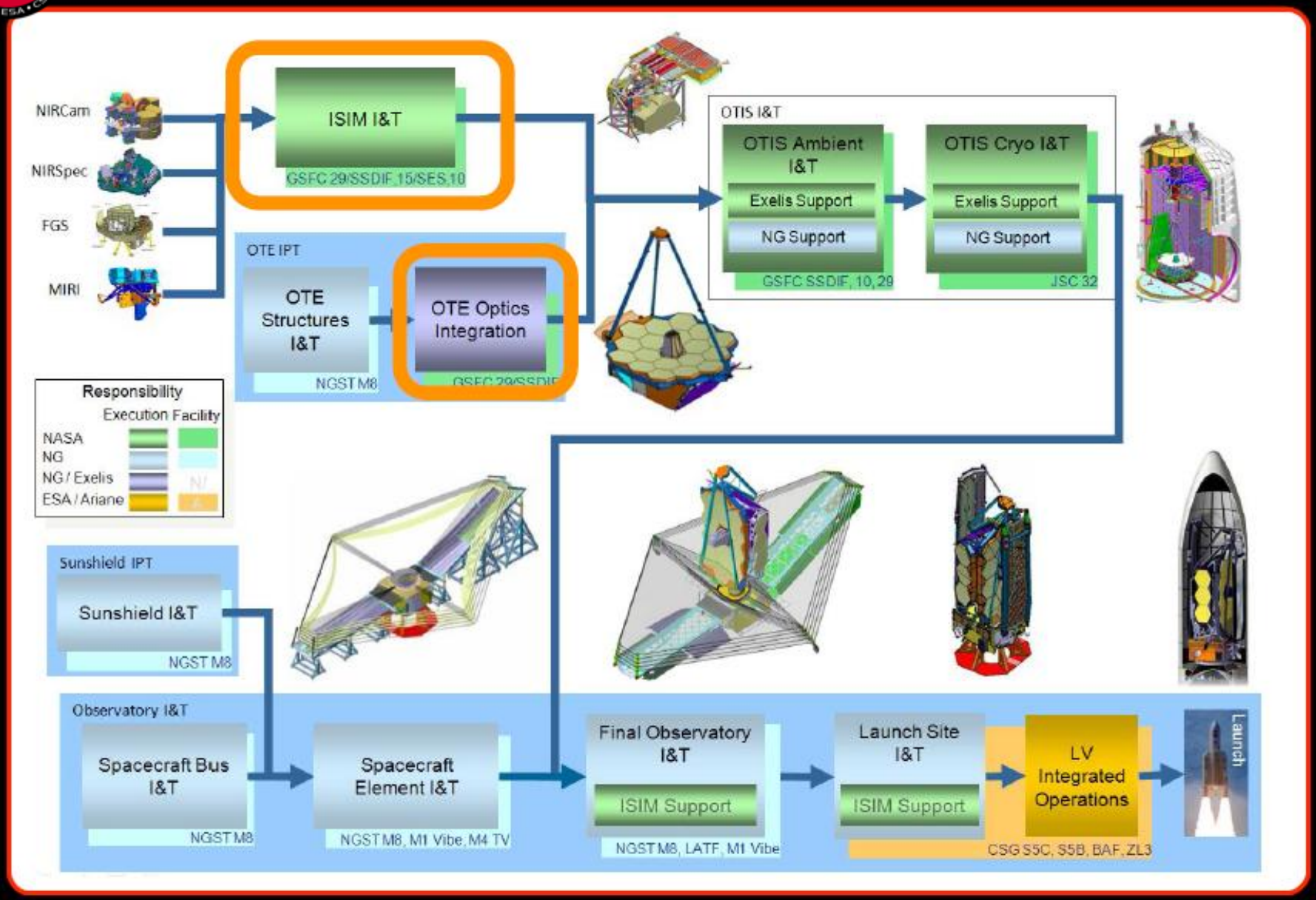
Center of Curvature
Optical Assembly



2018: Observatory integration and launch

sunshield + spacecraft + observatory

JWST Integration

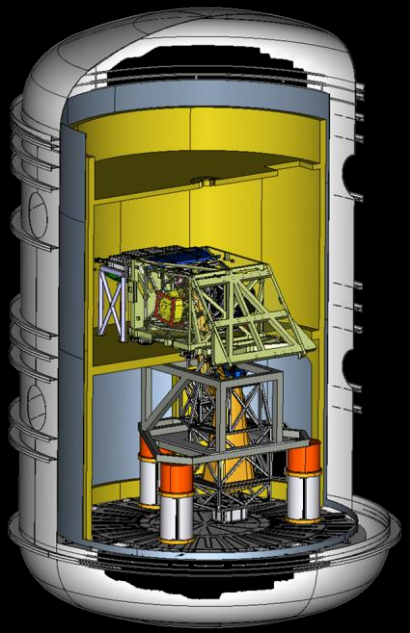


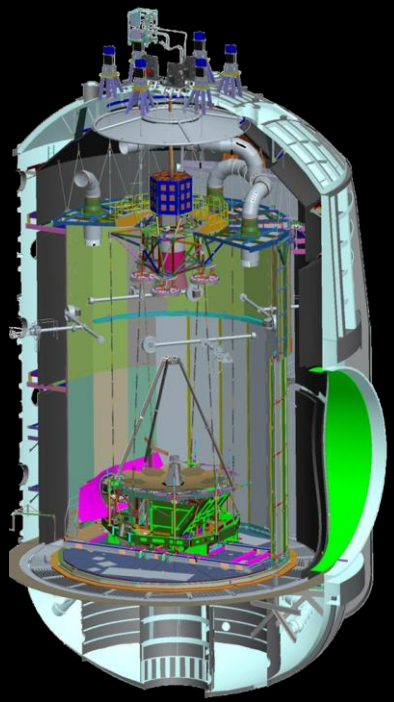
In Summary …

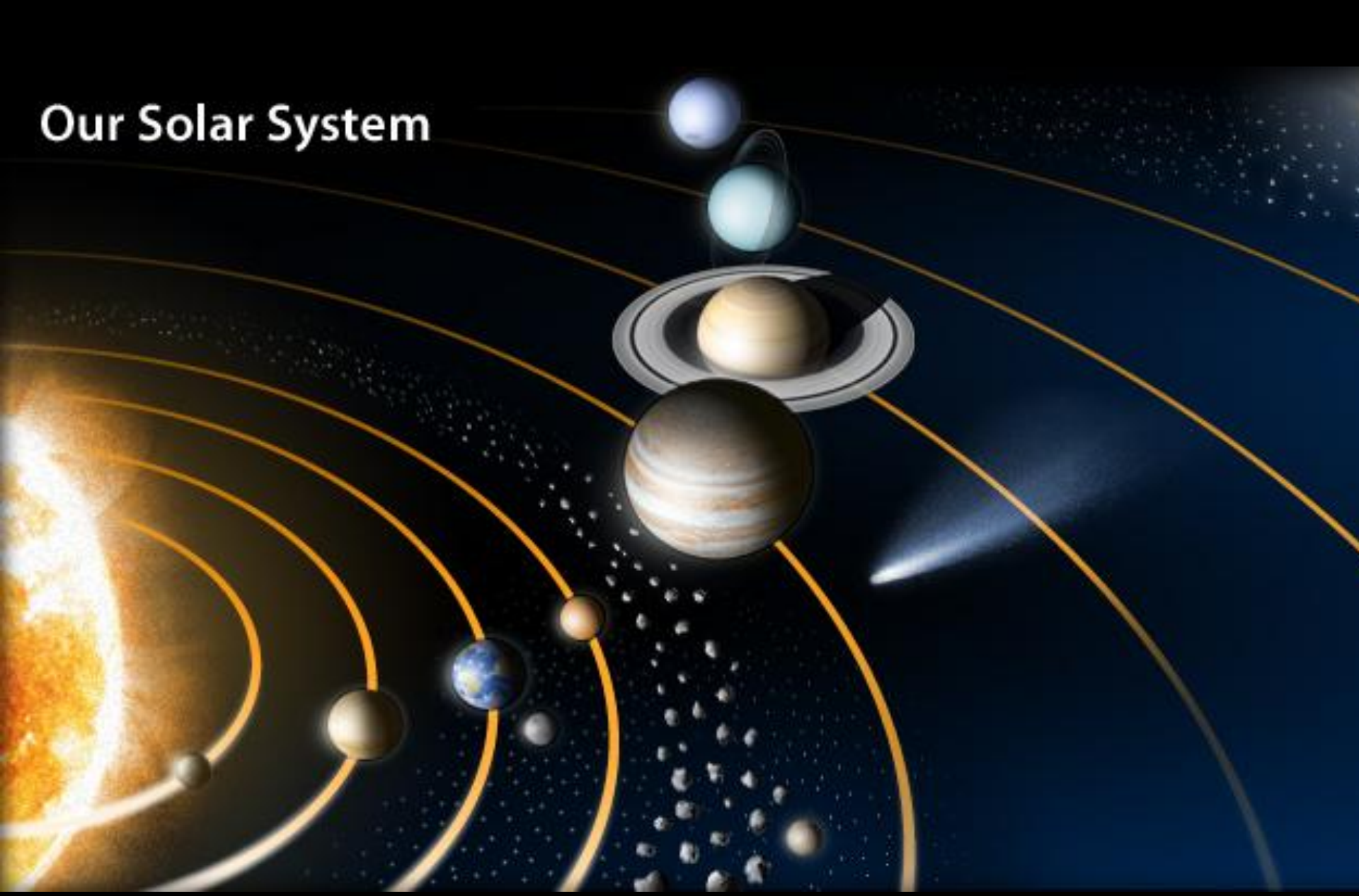
Last element-level ISIM test begins during October 2015 in GSFC SES chamber

Observatory end-to-end optical test begins during December 2016 in JSC Chamber-A

Launch 2018 from Kourou Launch Center (French Guiana)






Our Solar System

JWST Deployment video

https://www.youtube.com/watch?v=bTxLAGchWnA&index=1&list=PL691BF261E32A4420

Where to Learn More…

Visit JWST at:

- The Space Telescope Science Institute (STScI): http://www.stsci.edu/jwst
- NASA Goddard Space Flight Center (GSFC): http://www.jwst.nasa.gov
- European Space Agency (ESA): http://sci.esa.int/science-e/www/area/index.cfm?fareaid=29
- Canadian Space Agency (CSA): http://www.asc-csa.gc.ca/eng/satellites/jwst/default.asp
- Northrop Grumman: http://www.as.northropgrumman.com/products/jwst/index.html
- flickr: http://www.flickr.com/photos/nasawebbtelescope

- JWST Public Facebook: http://www.facebook.com/webbtelescope
- Twitter: @NASAWebbTelescp
- Youtube: http://www.youtube.com/user/NASAWebbTelescope
- JWST Webb-cam: http://www.jwst.nasa.gov/webcam.html

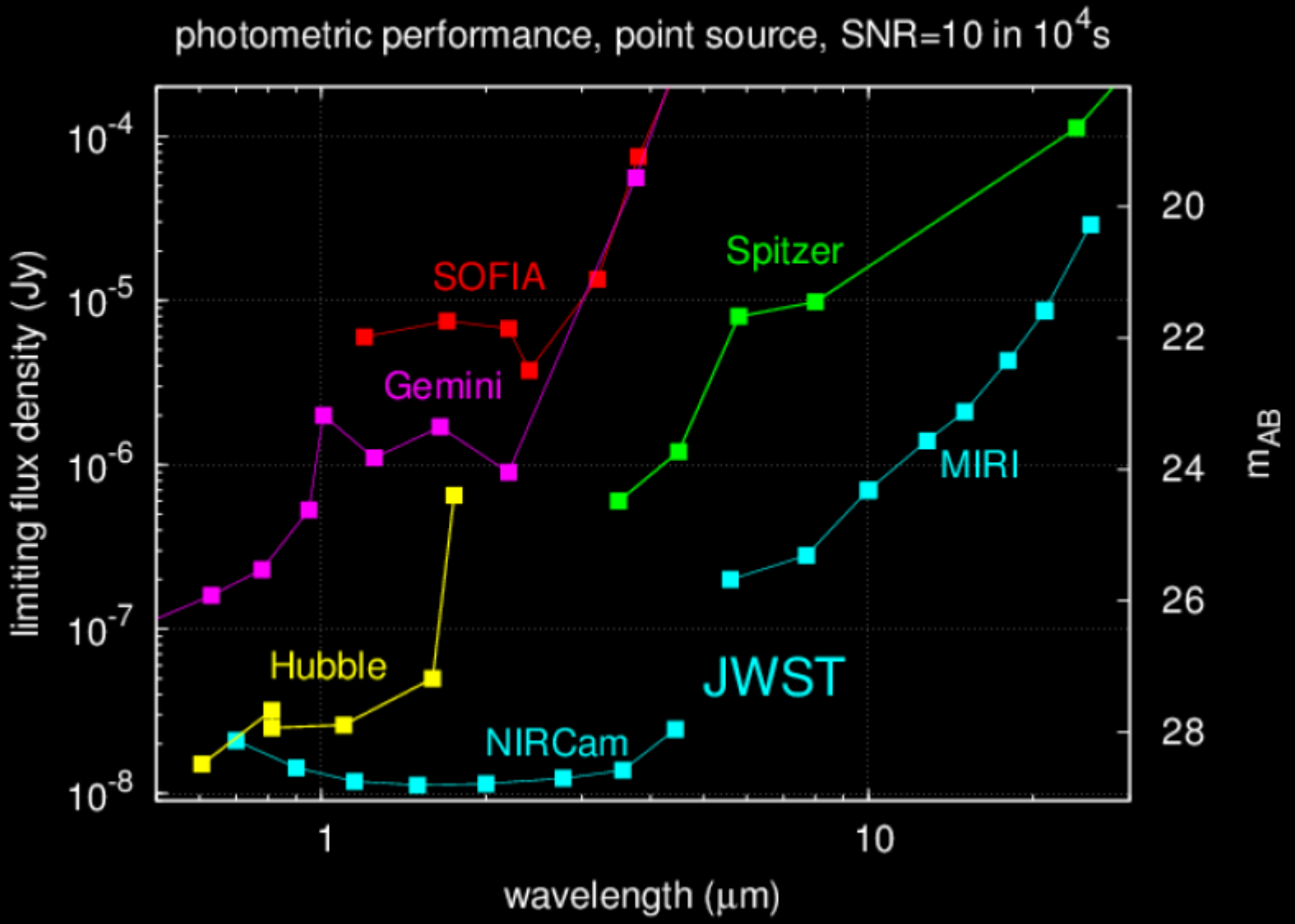
- Newsletter at STScI: https://blogs.stsci.edu/newsletter/
- Newsletter at GSFC: http://www.jwst.nasa.gov/newsletters.html

- Solar System Science with JWST: http://www.stsci.edu/jwst/science/solar-system

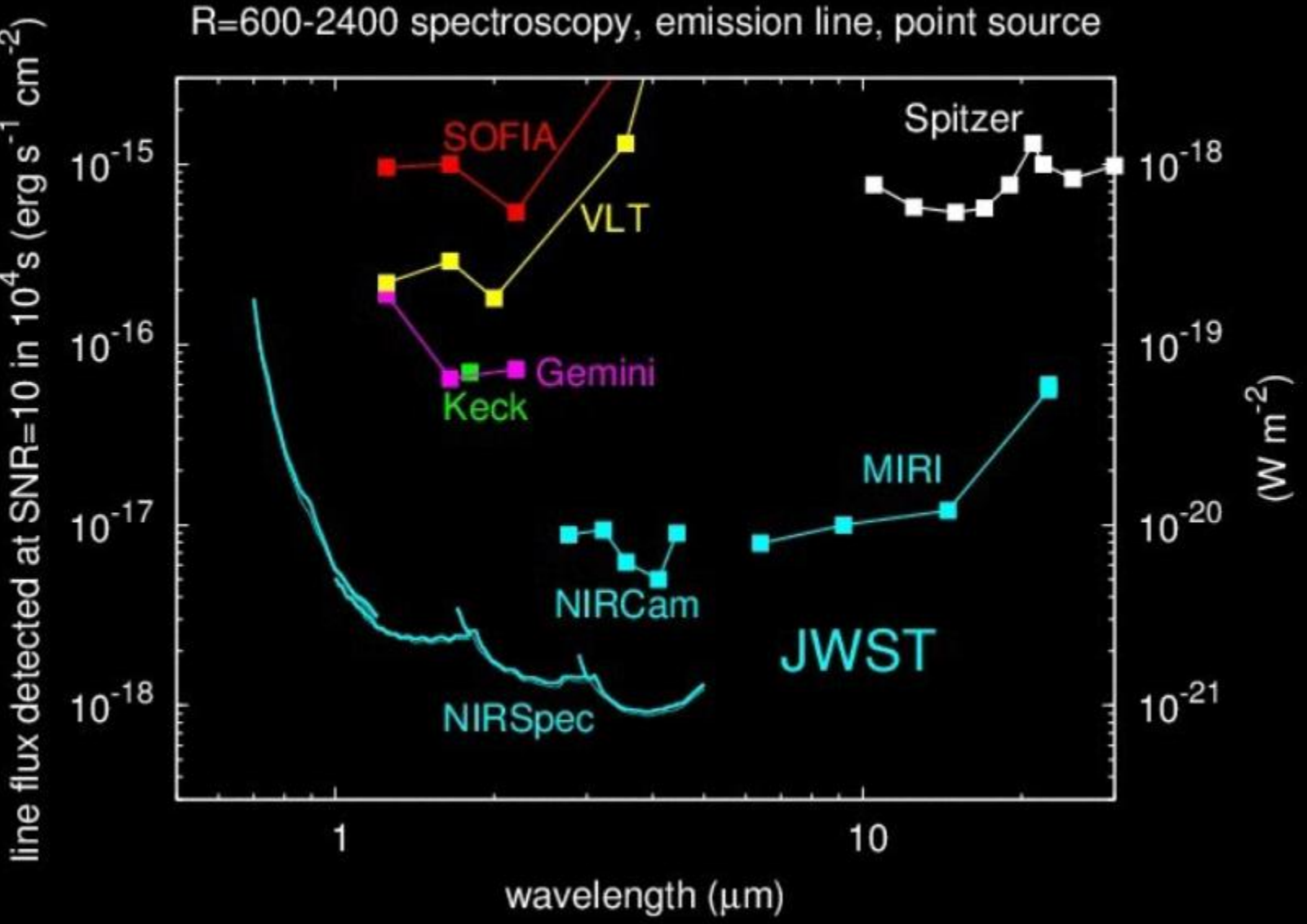
Stefanie Milam, stefanie.n.milam@nasa.gov

Extra Slides

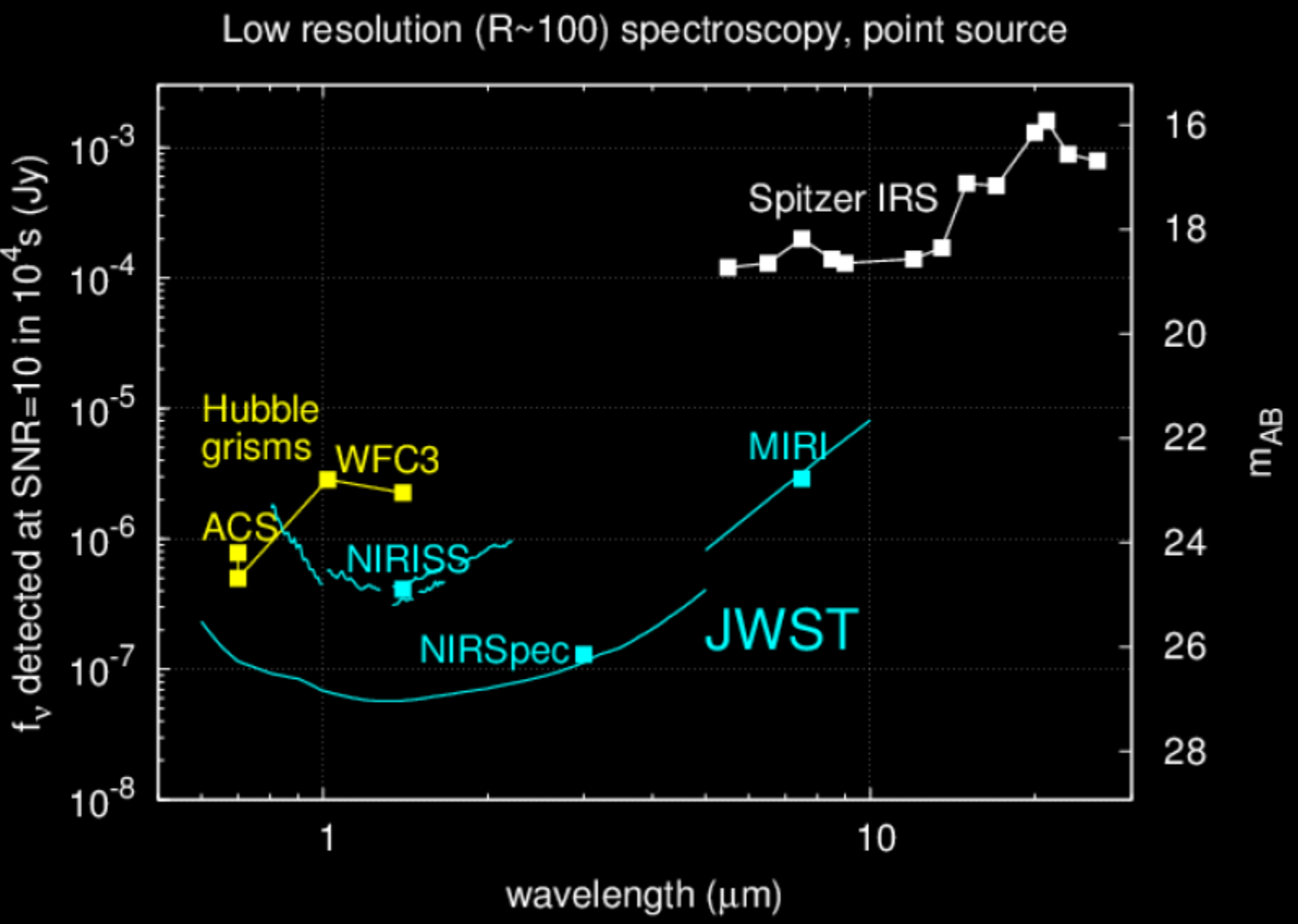
Sensitivity



Sensitivity



Sensitivity



JWST Imaging Modes

Mode	Instrument	Wavelength (microns)	Pixel Scale (arcsec)	Full-Array* Field of View
Imaging	NIRCam*	0.6 – 2.3	0.032	2.2 x 2.2′
	NIRCam*	2.4 – 5.0	0.065	2.2 x 2.2′
	NIRISS	0.9 – 5.0	0.065	2.2 x 2.2′
	MIRI*	5.0 – 28	0.11	1.23 x 1.88′
Aperture Mask Interferometry	NIRISS	3.8 – 4.8	0.065	------
Coronography	NIRCam	0.6 – 2.3	0.032	20 x 20″
	NIRCam	2.4 – 5.0	0.065	20 x 20″
	MIRI	10.65	0.11	24 x 24″
	MIRI	11.4	0.11	24 x 24″
	MIRI	15.5	0.11	24 x 24″
	MIRI	23	0.11	30 x 30″

JWST Spectroscopy Modes

Mode	Instrument	Wavelength (microns)	Resolving Power ($\lambda/\Delta\lambda$)	Field of View
Slitless Spectroscopy	NIRISS	1.0 – 2.5	150	2.2′ x 2.2′
	NIRISS	0.6 – 2.5	700	single object
	NIRCam	2.4 – 5.0	2000	2.2′ x 2.2′
Multi-Object Spectroscopy	NIRSpec	0.6 – 5.0	100, 1000, 2700	3.4′ x 3.4′ with 250k 0.2 x 0.5″ microshutters
Single Slit Spectroscopy	NIRSpec	0.6 – 5.0	100, 1000, 2700	slit widths 0.4″ x 3.8″ 0.2″ x 3.3″ 1.6″ x 1.6″
	MIRI	5.0 – ~14.0	~100 at 7.5 microns	0.6″ x 5.5″ slit
Integral Field Spectroscopy	NIRSpec	0.6 – 5.0	100, 1000, 2700	3.0″ x 3.0″
	MIRI	5.0 – 7.7	3500	3.0″ x 3.9″
	MIRI	7.7 – 11.9	2800	3.5″ x 4.4″
	MIRI	11.9 – 18.3	2700	5.2″ x 6.2″
	MIRI	18.3 – 28.8	2200	6.7″ x 7.7″