

First Light, Galaxy Assembly, & Supermassive Blackhole Growth: Hubble, Webb and other Future Telescopes

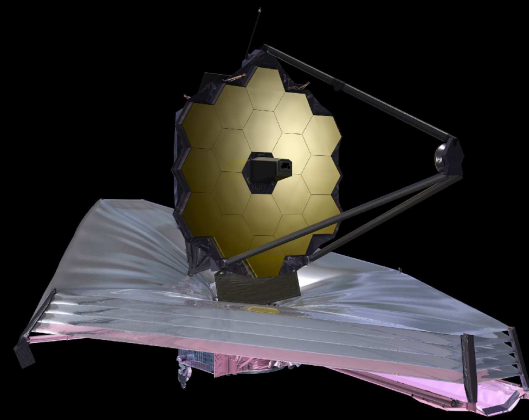
Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

Collaborators: S. Cohen, L. Jiang, R. Jansen (ASU), C. Conselice (UK), S. Driver (OZ), & H. Yan (U-MO)

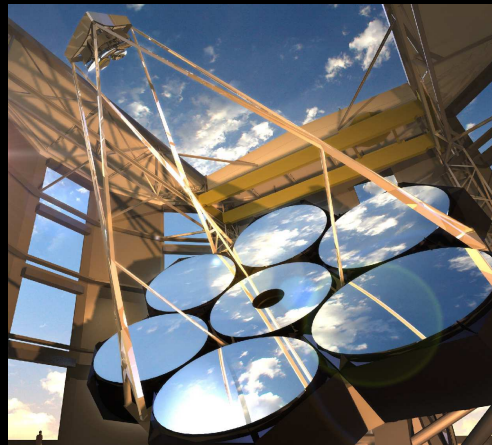
(Ex) ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, B. Smith, & A. Straughn



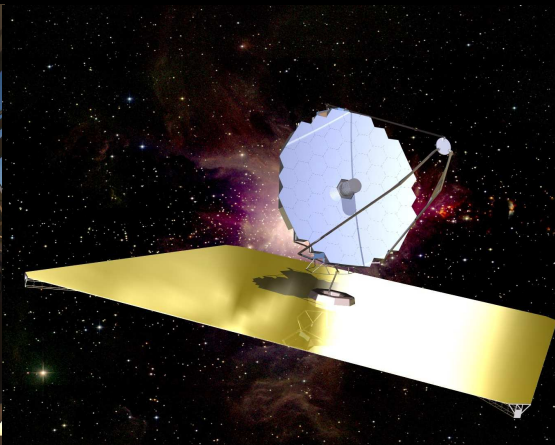
1973~2020⁺;



1996~2031;



2000~2050⁺



2020~2050⁺?

Spirit of the Senses — Salon Talk; Paradise Valley, AZ

Thursday May 30, 2019. All presented materials are ITAR-cleared.

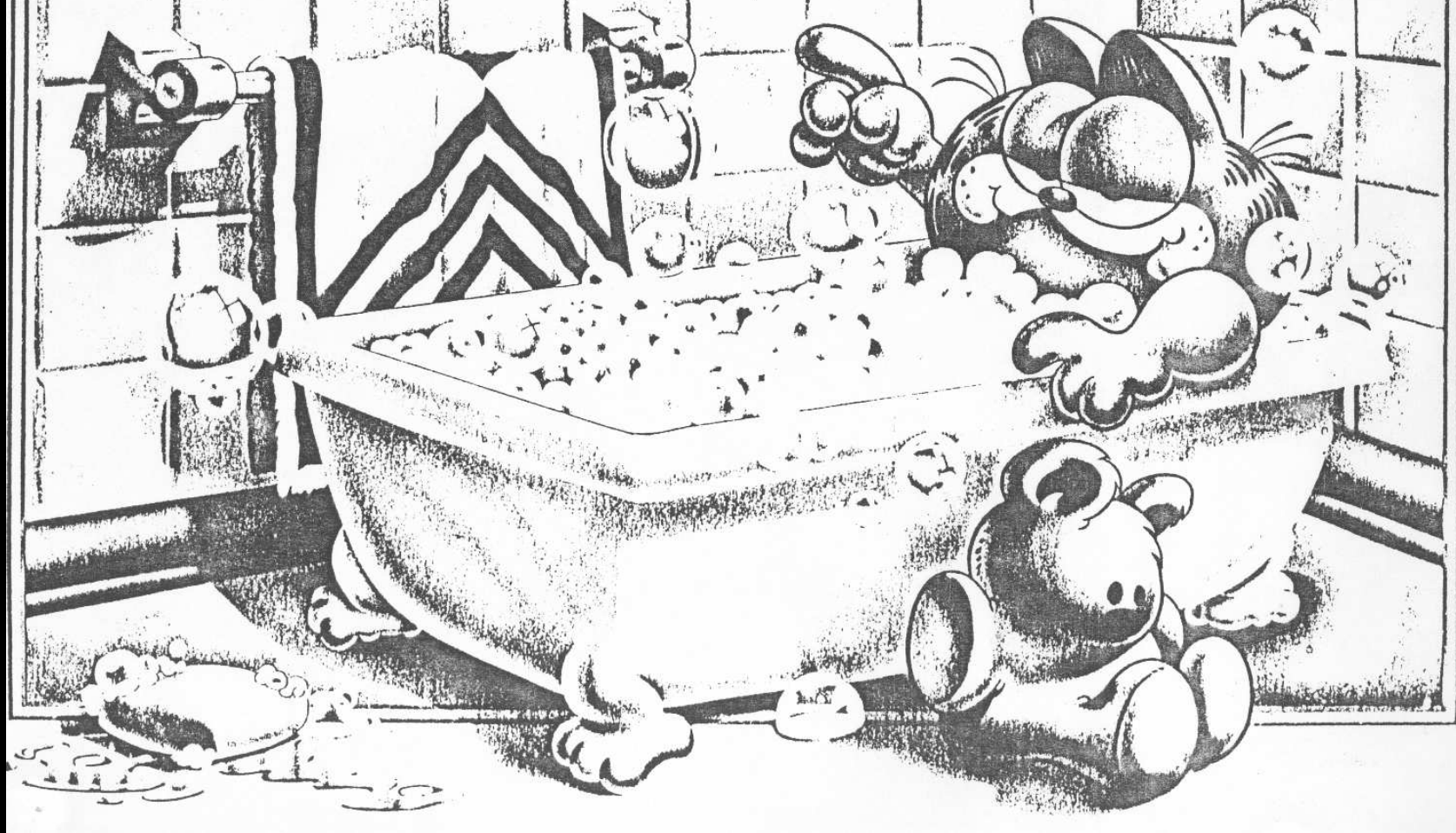
Outline

- (1) Update on the James Webb Space Telescope (JWST), 2019.
- (2) What Hubble has done: Galaxy Assembly & SMBH Growth
- (3) How can JWST measure the Epochs of First Light & Galaxy Assembly, and Supermassive Black-Hole Growth?
- (4) The Future: Next generation 20–40 m telescopes & ATLAST
- (5) Summary and Conclusions
 - (6) Update of JWST programmatics as of 2019.
 - (7) How can JWST measure Star-formation & Earth-like exoplanets?
 - (8) Where do our students end-up? Possible NASA Careers

Sponsored by NASA/HST & JWST



JWST is like a hot bath. It feels good while you're in it; but the longer you stay, the more wrinkled you get.



WARNING: Both Hubble and James Webb are 30–40⁺ year projects:
You will feel wrinkled before you know it ... :)



Edwin P. Hubble (1889–1953) — Carnegie astronomer

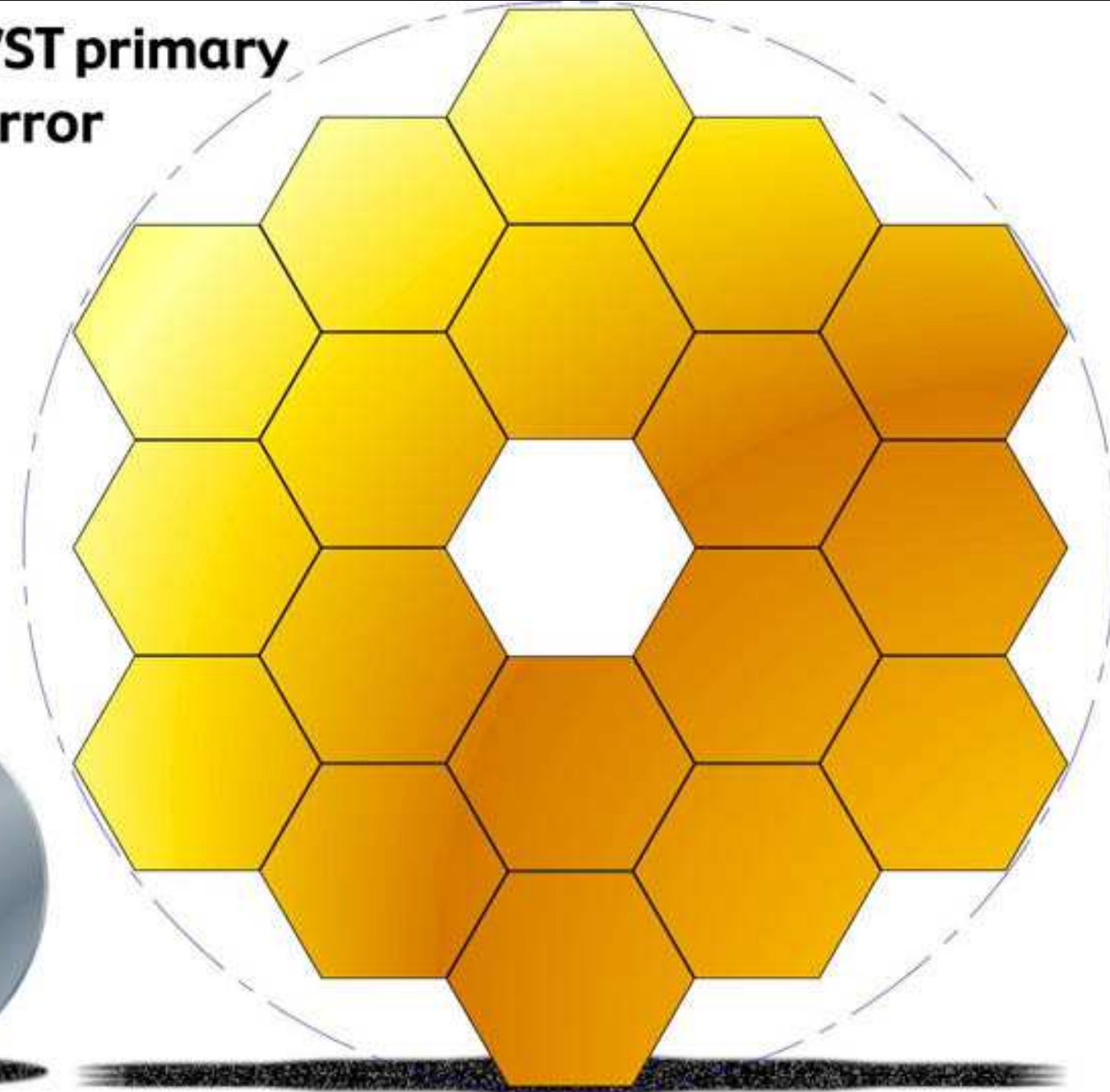


James E. Webb (1906–1992) — Second NASA Administrator

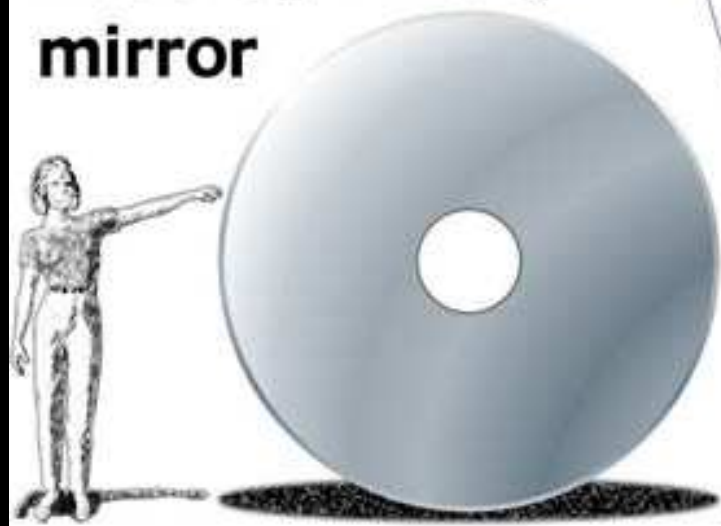
Hubble: Concept in 1970's; Made in 1980's; Operational 1990– \gtrsim 2020?.

JWST: The infrared sequel to Hubble from 2021–2026 (–2031?).

**JWST primary
mirror**

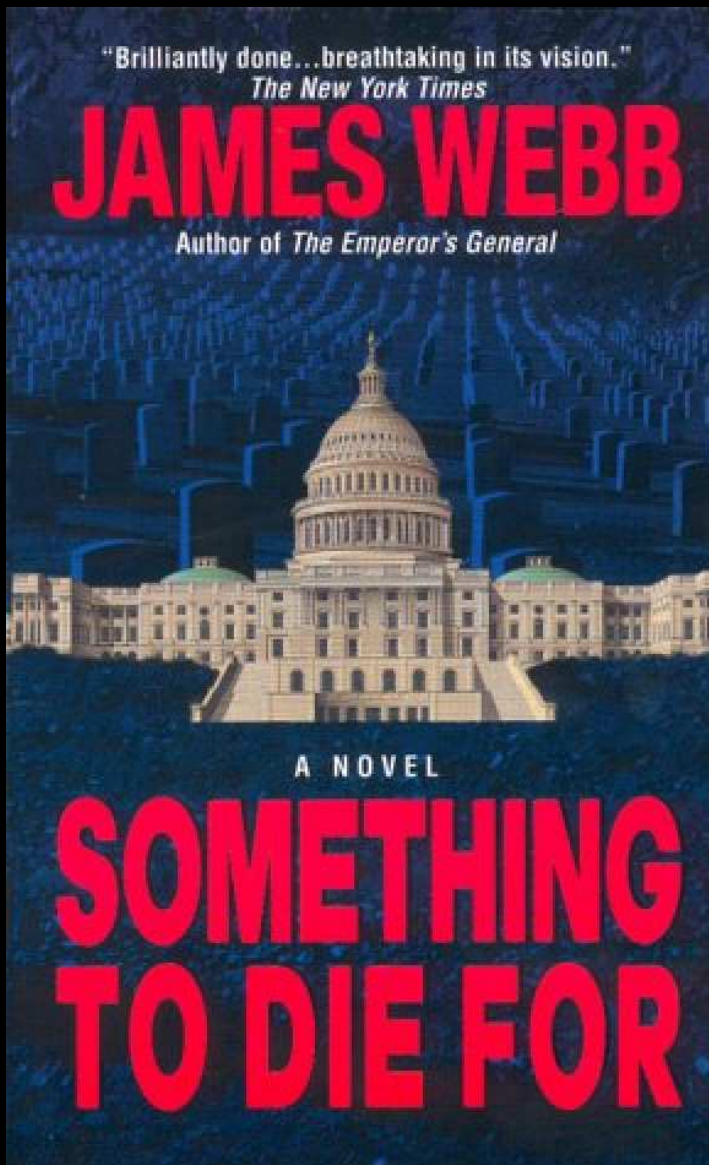


**Hubble primary
mirror**



JWST $\simeq 2.5\times$ larger than Hubble, so at $\sim 2.5\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.

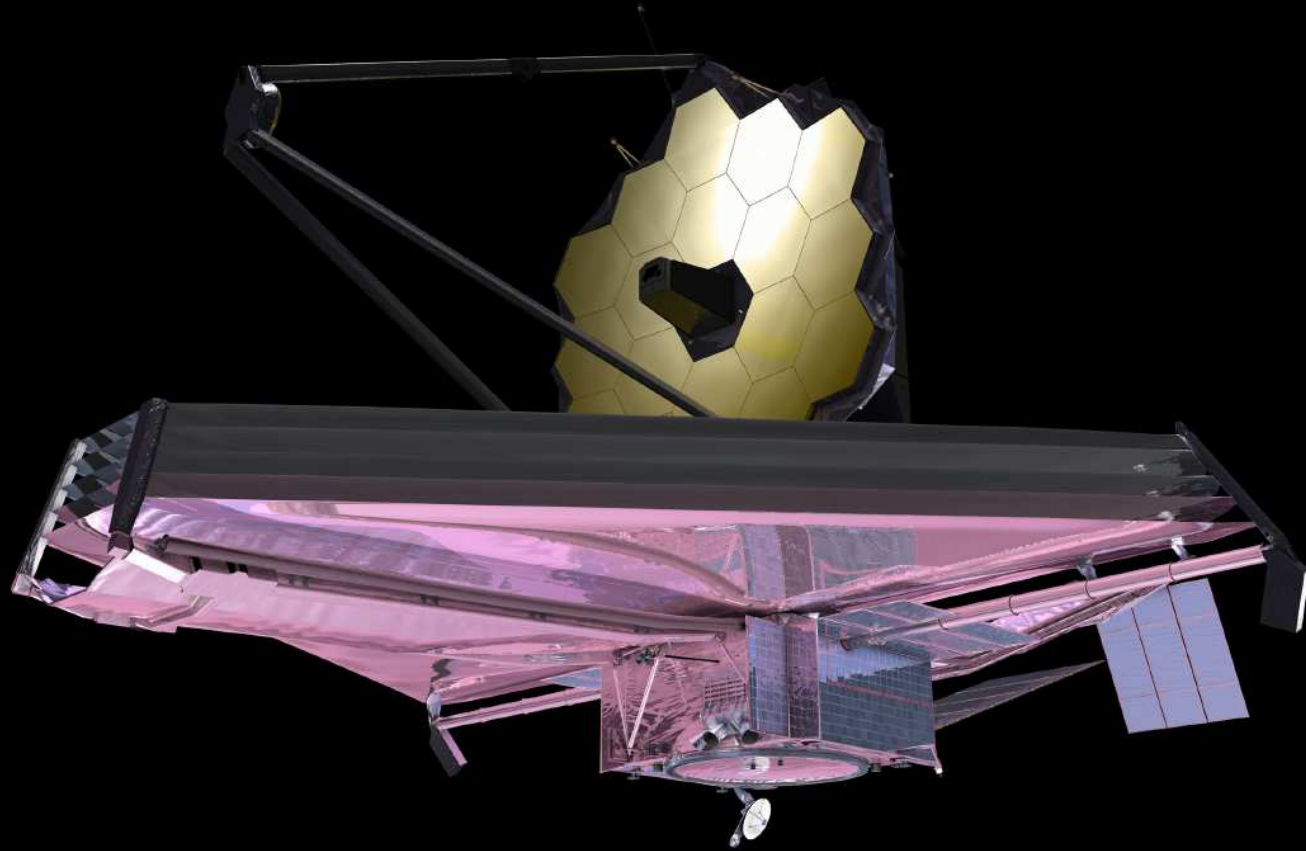
(1) Update of the James Webb Space Telescope (JWST), 2019



To be used by students & scientists starting 2021 ... It'll be worth it.

(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007.

(1) Update of the James Webb Space Telescope as of 2019



- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at $0.6\text{--}28 \mu\text{m}$ wavelength, to be launched in March 2021.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging ($31.5 \text{ mag} \sim 1 \text{ FF}$ from Moon), and spectroscopy.

THE JAMES WEBB SPACE TELESCOPE

JWST LAUNCH

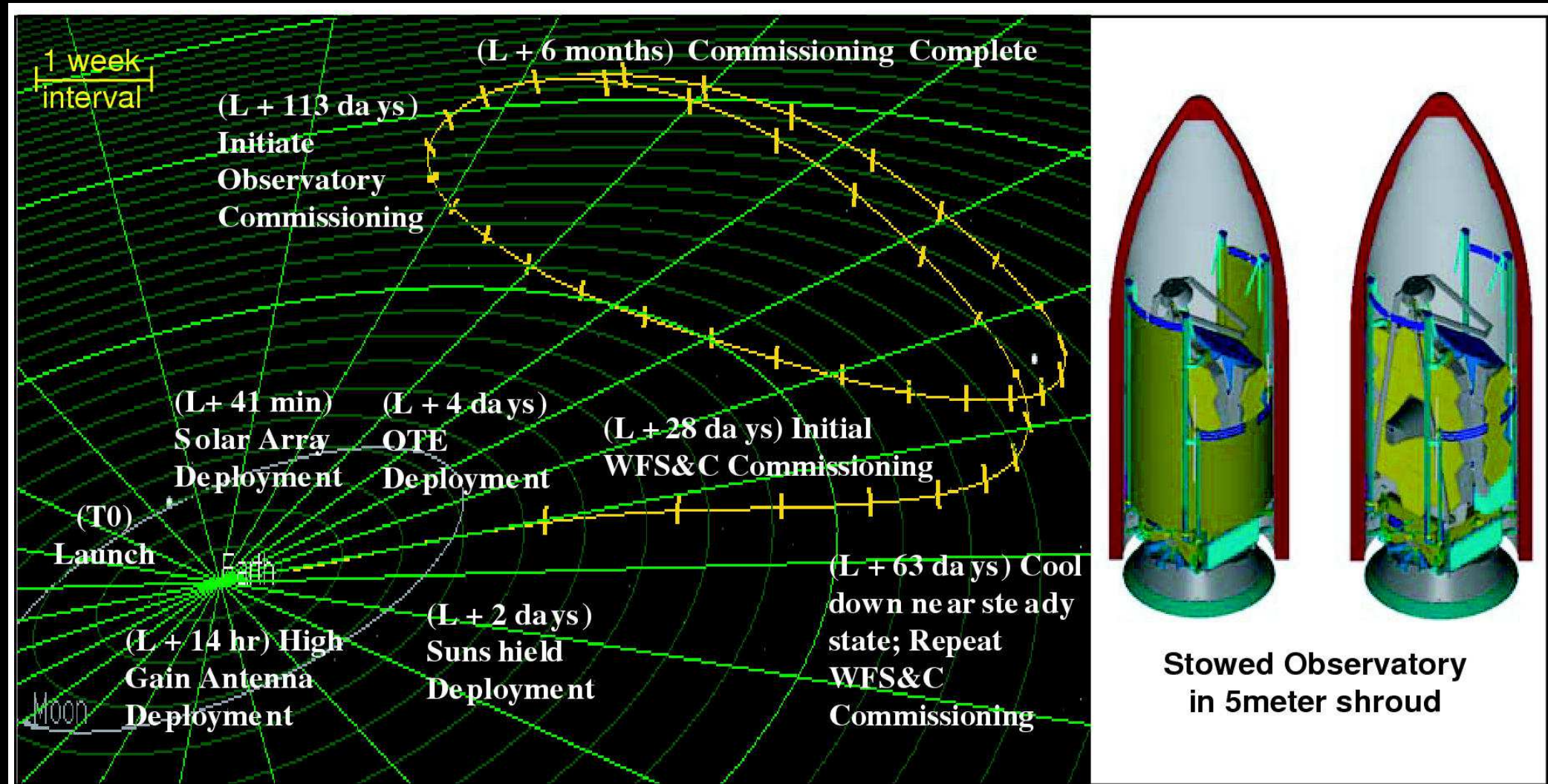
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



ARIANESPACE - ESA - NASA

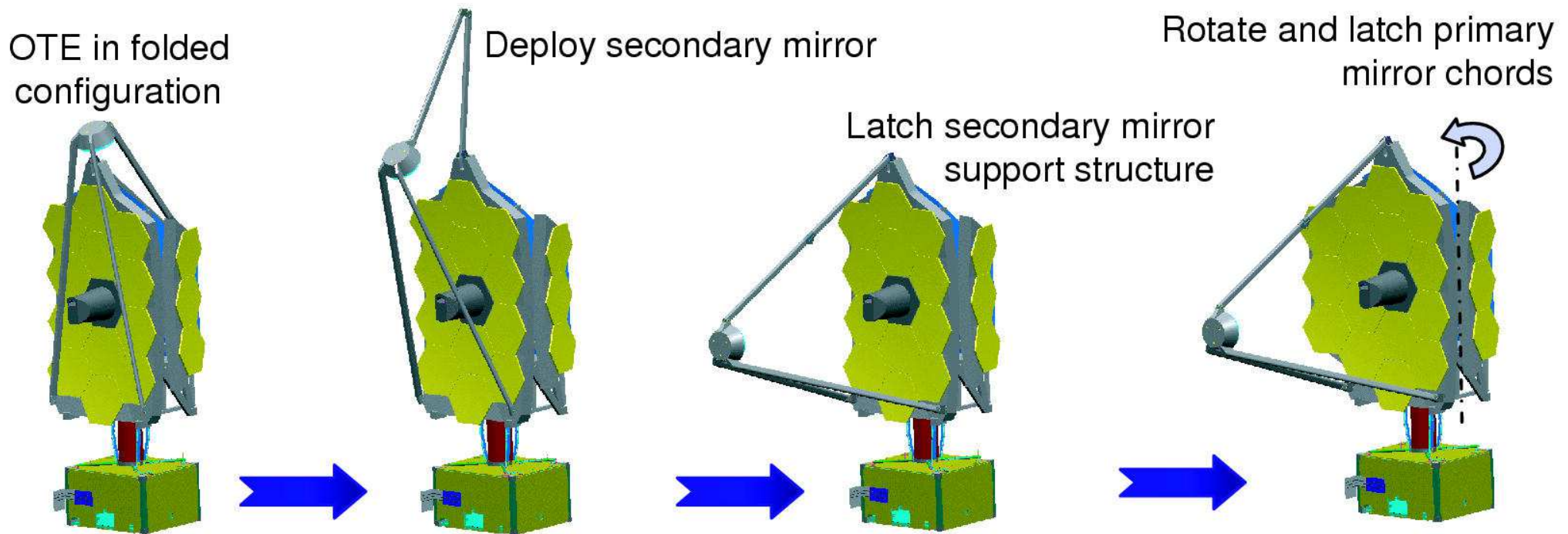
- The JWST launch weight will be $\lesssim 6500$ kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(1a) How will JWST travel to its L2 orbit?



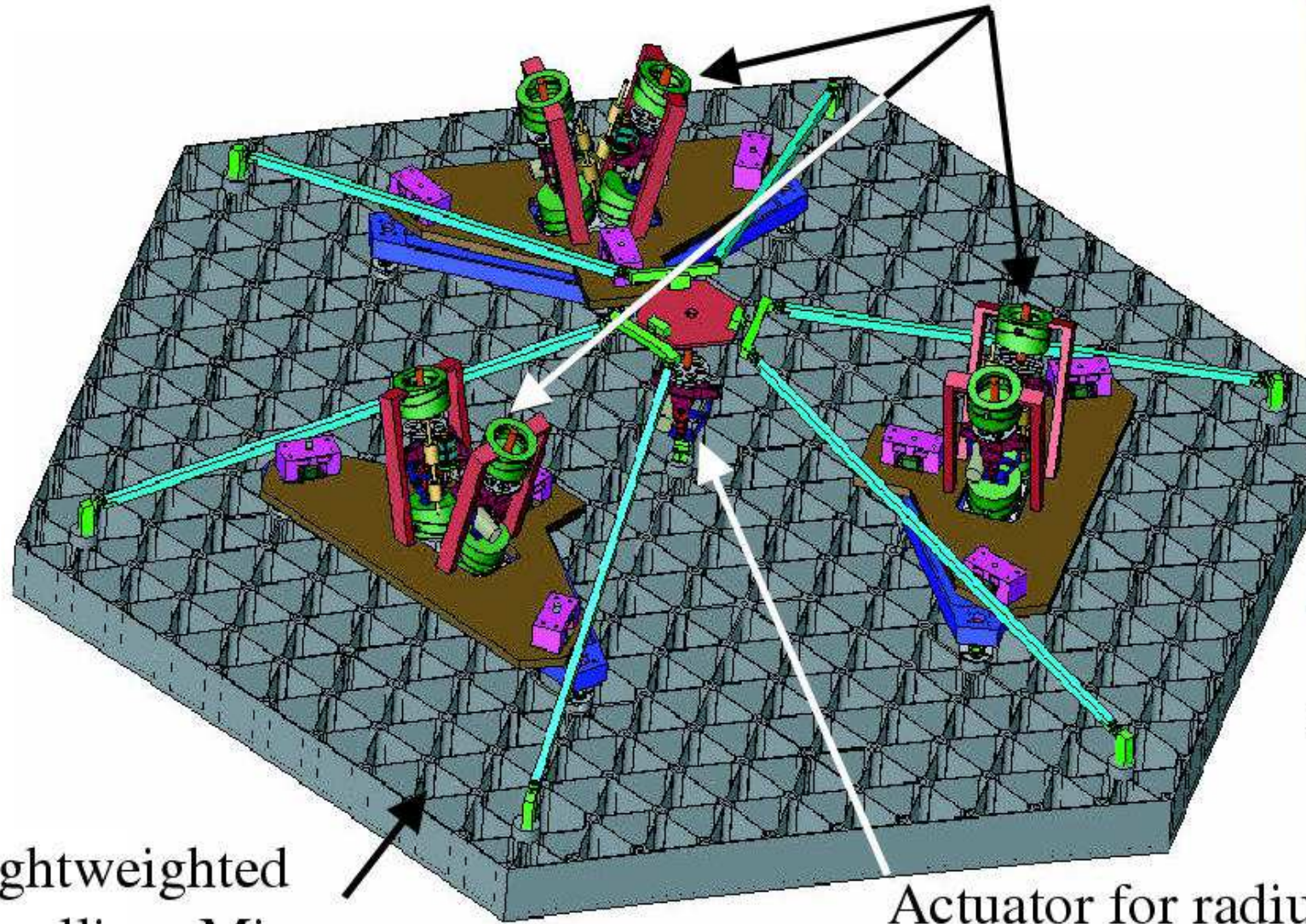
- After launch in March 2021 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim 70\%$ of the time, and send data back to Earth every day.

- (1b) How will JWST be automatically deployed?



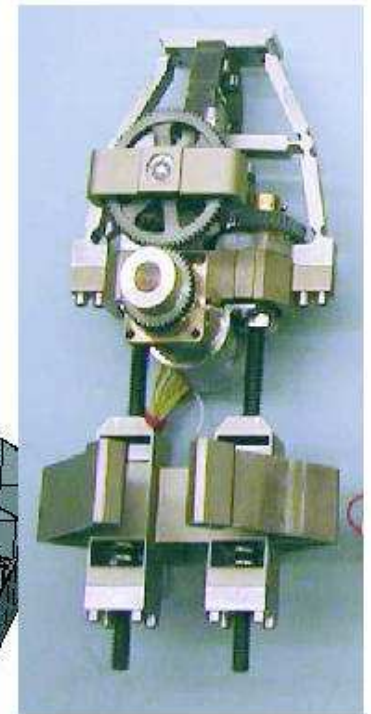
- During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.
- The entire JWST deployment sequence is being tested several times on the ground — but only in 1-G: component and system tests in 2014–2019 at GSFC (MD), Northrop (CA), and JSC (Houston).
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.

Actuators for 6 degrees of freedom rigid body motion



Lightweighted
Beryllium Mirror

Actuator for radius
of curvature adjustment



Actuator
development
unit

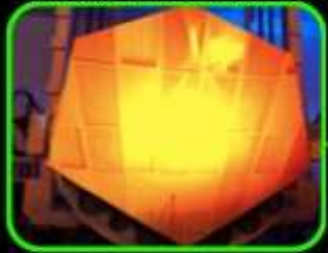
Active mirror segment support through "hexapods", similar to Keck.
Redundant & doubly-redundant mechanisms, quite forgiving against failures.



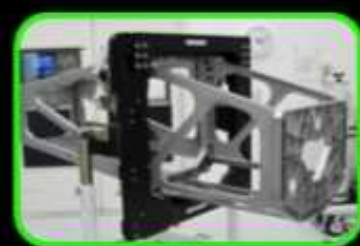
JWST Hardware Status



Primary Mirror Segment



Aft Optics System



PM Flight Backplane



Tertiary Mirror



Fine Steering Mirror

ISIM Flight Bench



Secondary Mirror Pathfinder Strut



Secondary Mirror Hexapod



Secondary Mirror



Membrane Mgmt



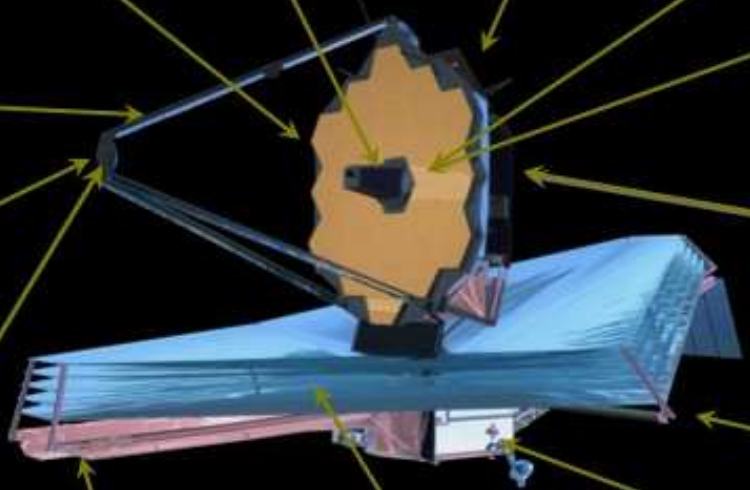
Pathfinder Membrane



Spacecraft computer Test Unit

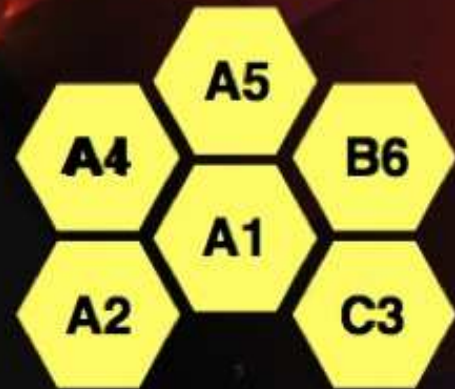


Mid-boom Test



Summer 2018: $\approx 99.5\%$ of launch mass³ designed and built ($\approx 99\%$ weighed).

Mirror Acceptance Testing



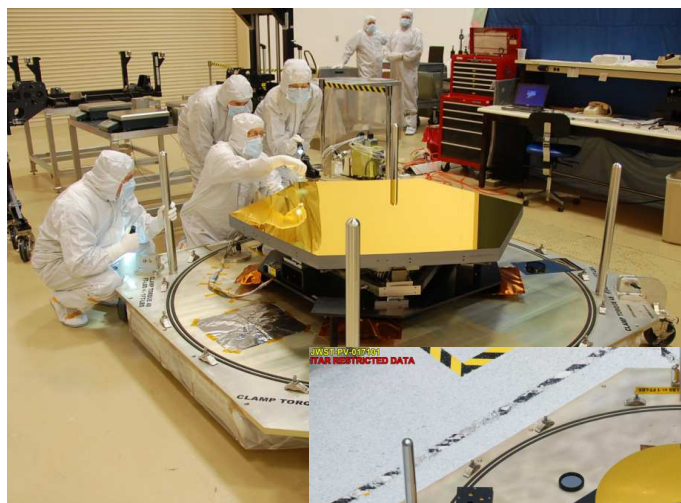




Mirror Status

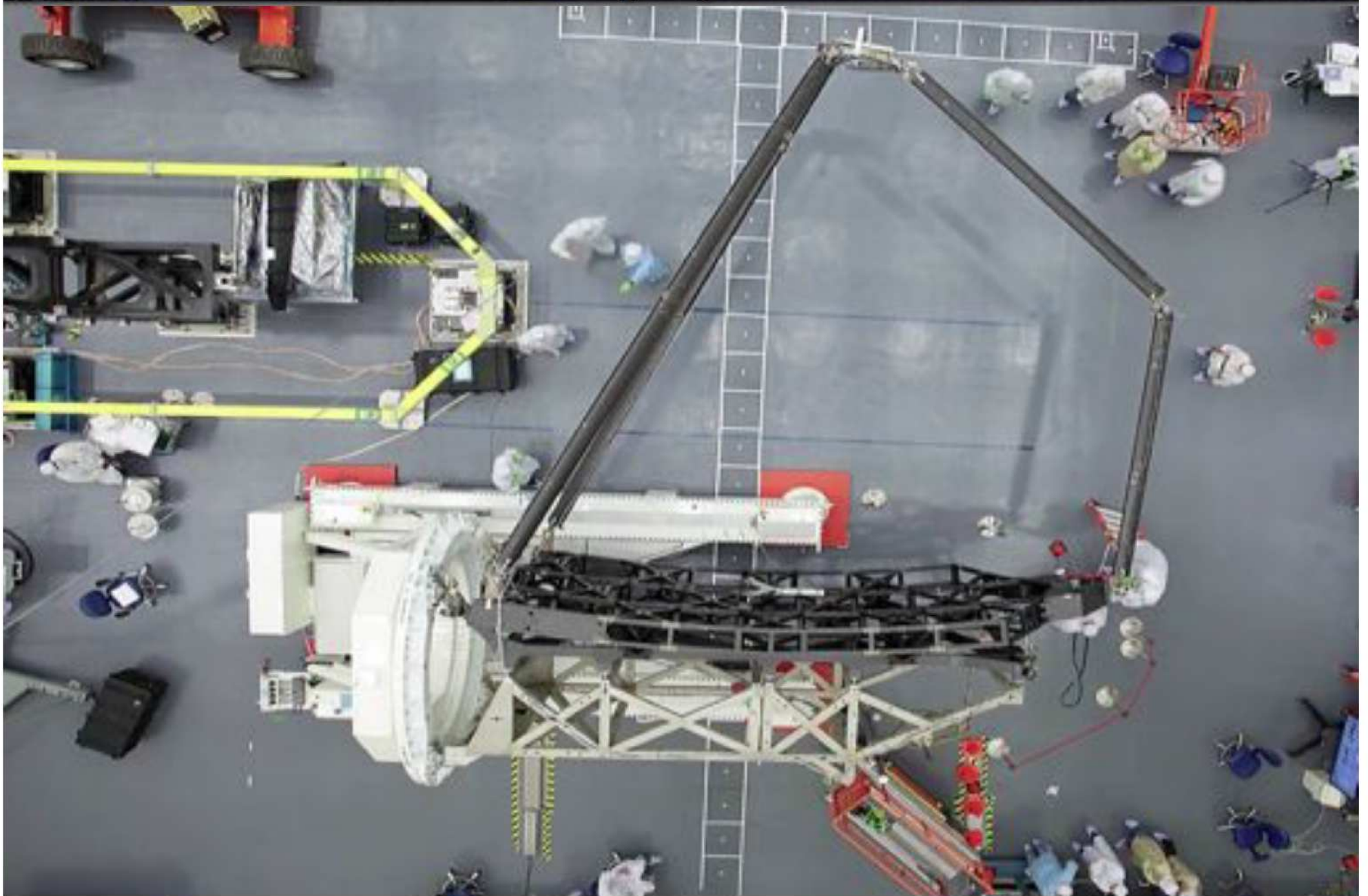


- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
 - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
 - 2 EDU mirrors sent back to Ball for gear motor rework
 - All flight gear motor refurbishment is complete
 - All flight mirrors will be at GSFC by end of year, needed in 2015



Spring 2014: All 18 flight mirrors delivered to NASA GSFC (MD).

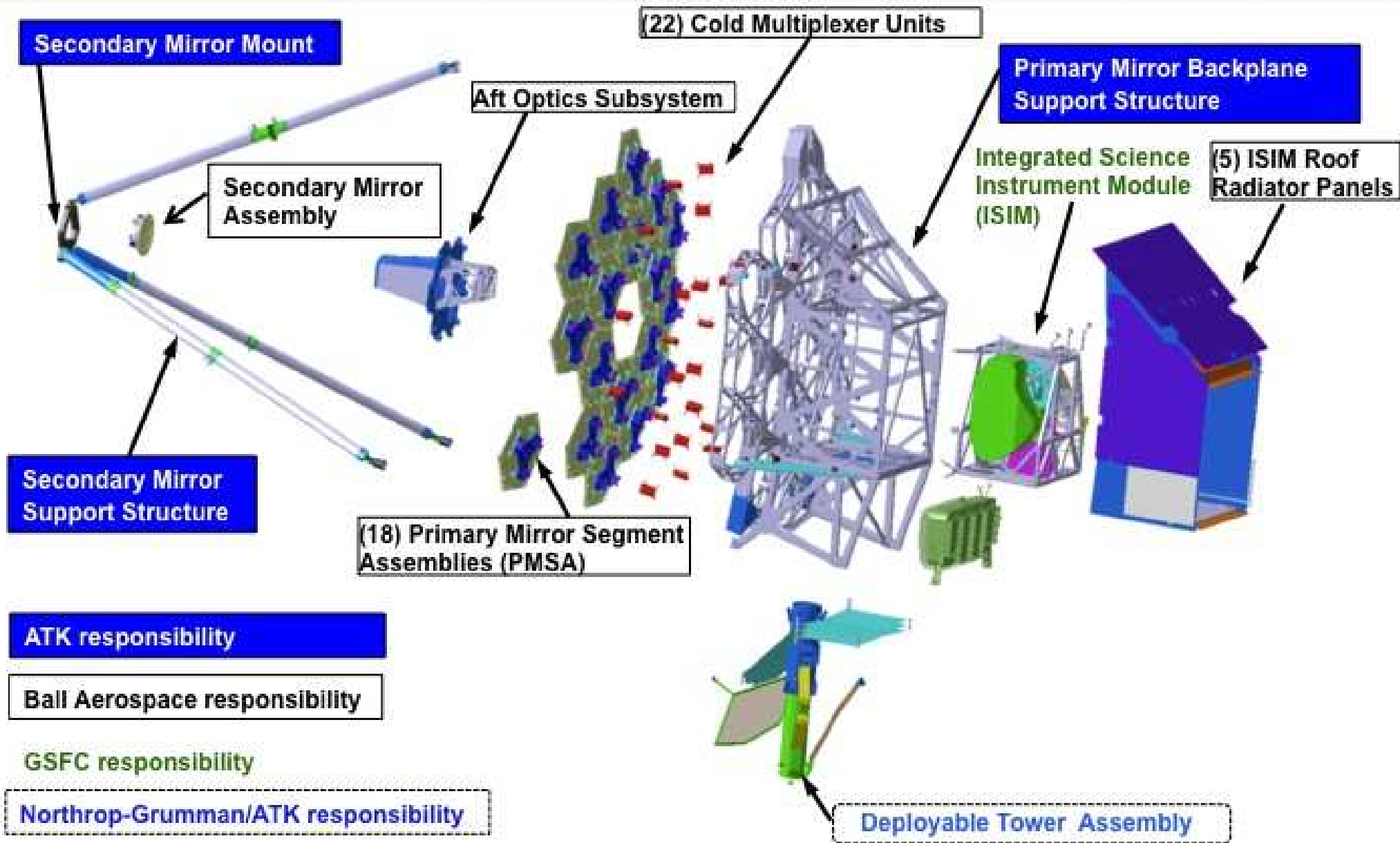
Pathfinder: Powered Deployment of SMSS



July 2014: Secondary Mirror Support deployment successfully tested.



TELESCOPE ARCHITECTURE

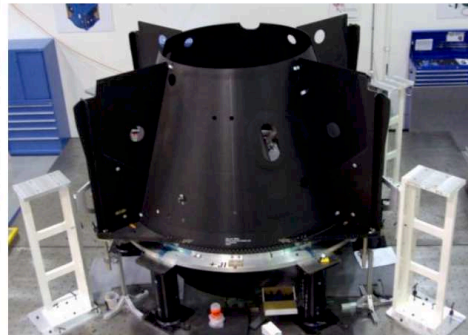


3/31/11

2014–2019: Complete system integration at GSFC and Northrop.



JWST Hardware Progress



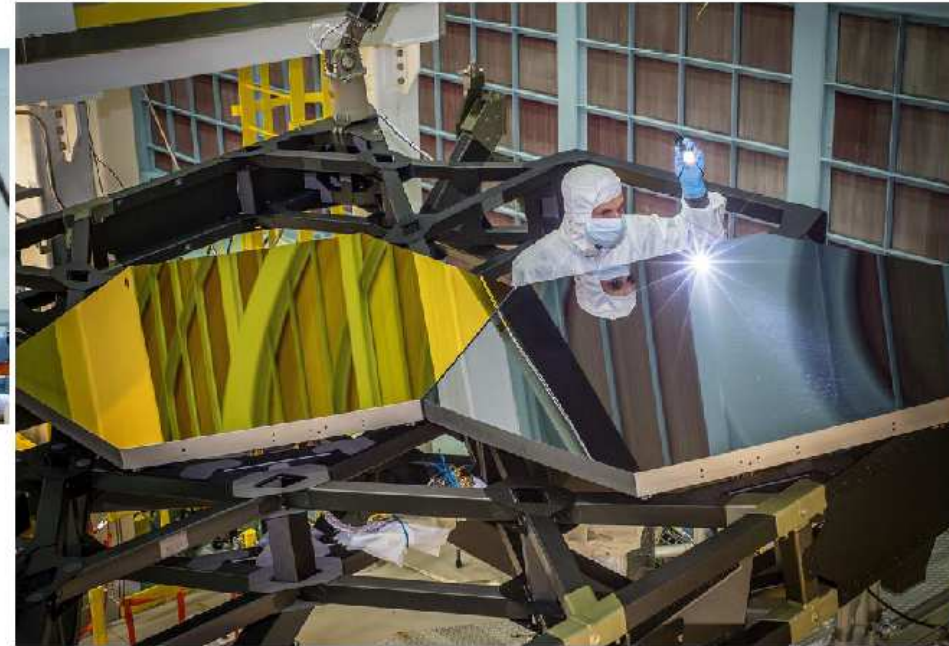
JWST remains on track for an October 2018 launch within its replan budget guidelines

29

July 2014: ● Secondary Mirror Support deployment successfully tested.
2015: ● Engineering sunshield successfully deployed at Northrop (CA).



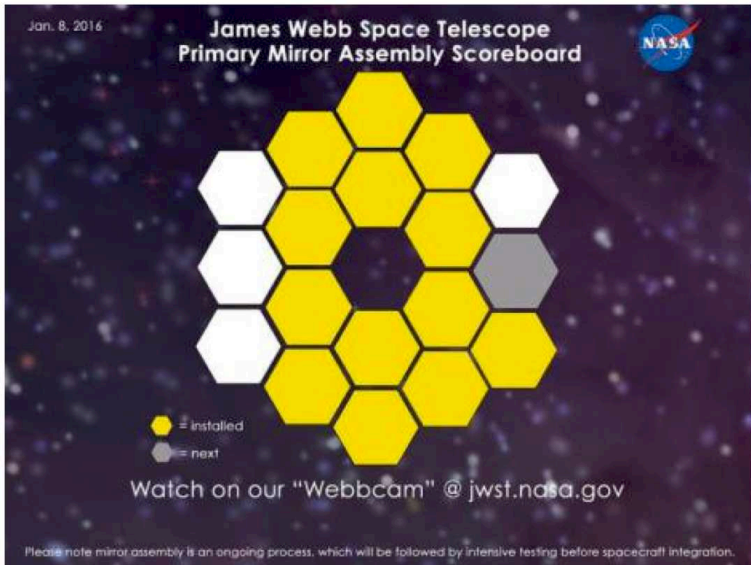
Telescope Pathfinder – Risk Reduction



JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

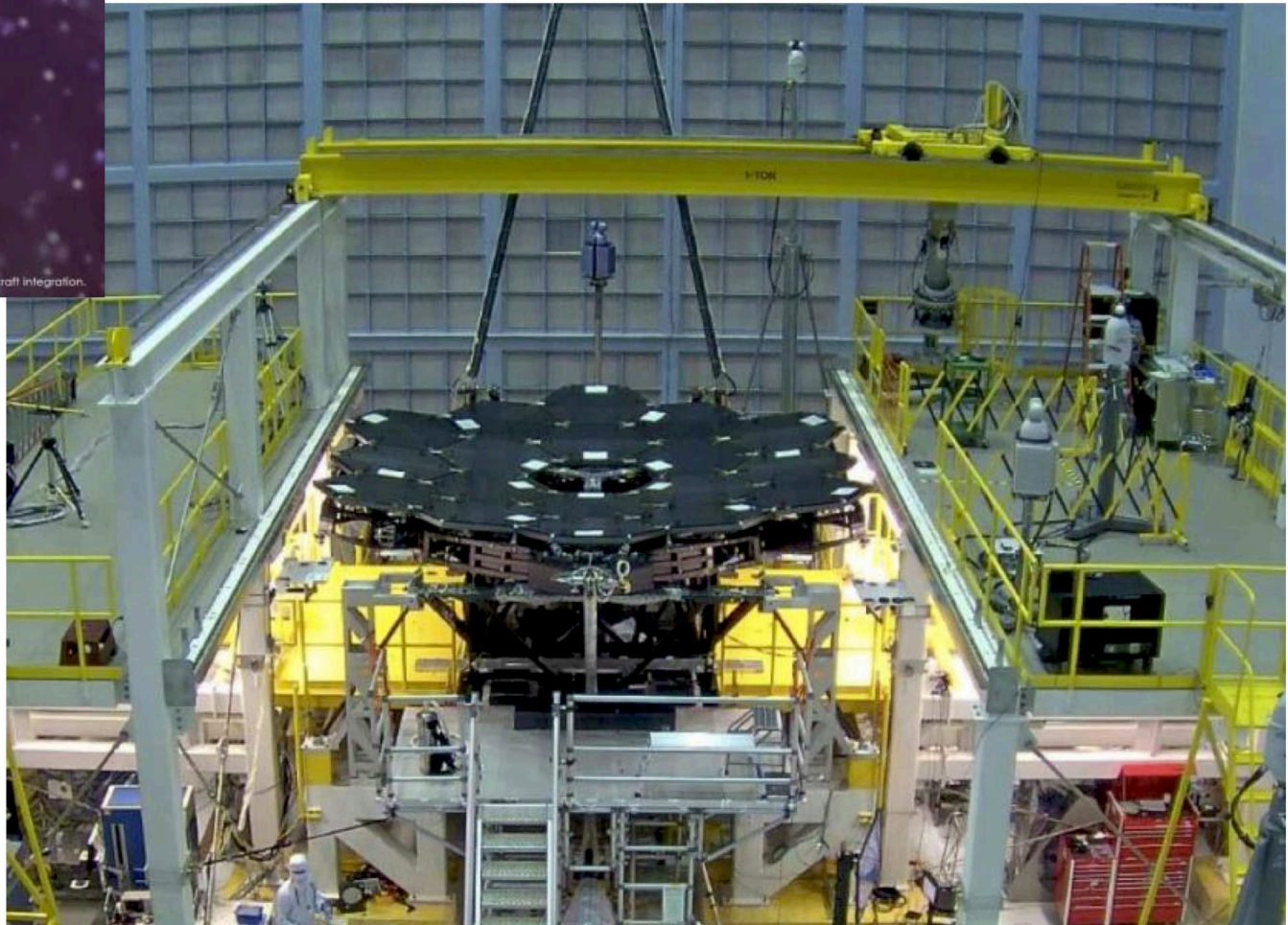


Much progress has been made in OTE integration



← Where we were at last month's call

Current: all 18 PMSAs installed, liquid-shim-cured, & metrologized. Alignments meet specifications, and actuator motions verified
Big milestone!



8 February 2016 JWST Monthly Telecon 8

JWST lifetime: Requirement: 5 yrs; Goal: 10 yrs; Propellant: 14 yrs.



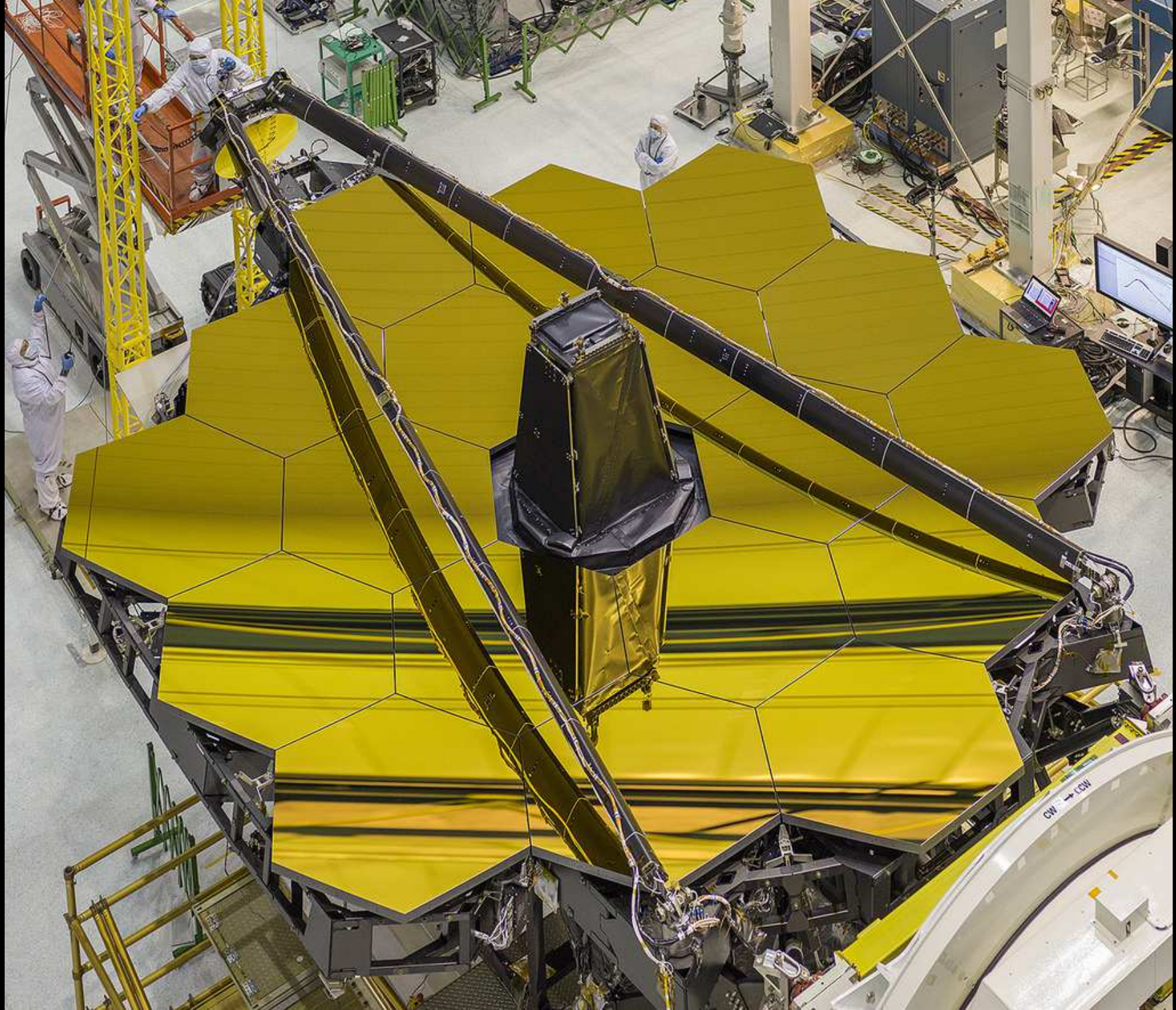
April 2016: NASA team-work to take JWST mirror covers off!



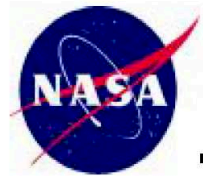
May 2016: JWST being tilted into the right position



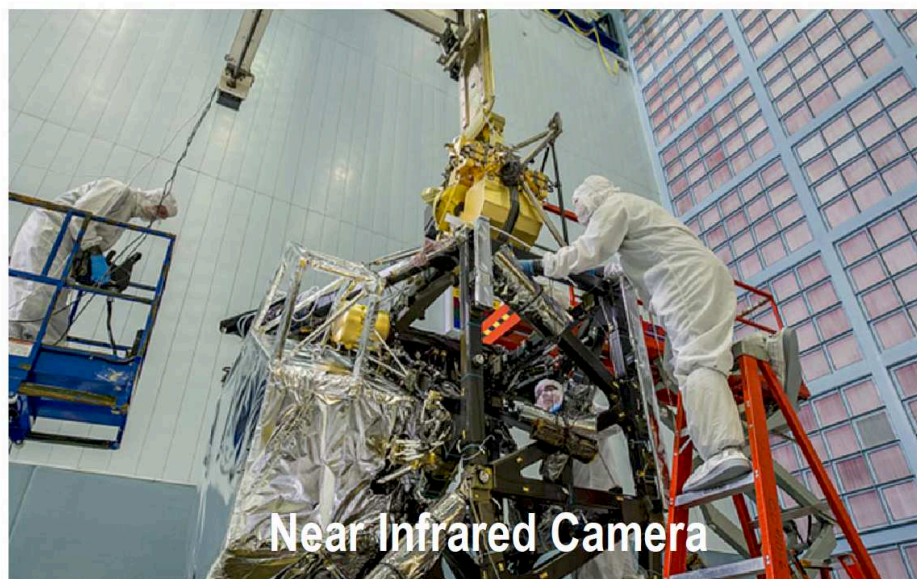
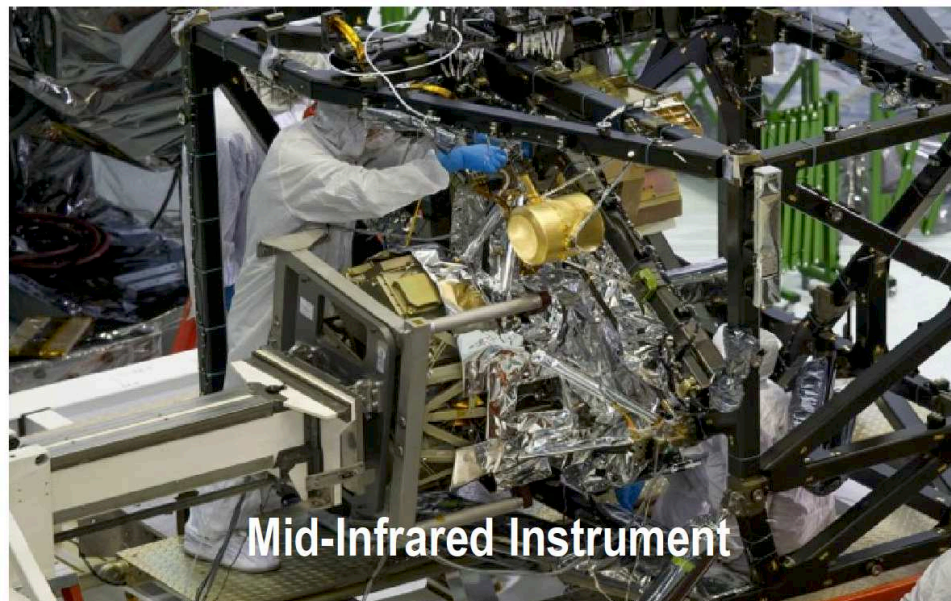
May 2016: Webb mirrors finally mounted and ready!



May 2016: JWST stowed for further instrument mounting



All Instruments Integrated



(1c) JWST instrument update: US (UofA, JPL), ESA, & CSA.



Instrument Overview

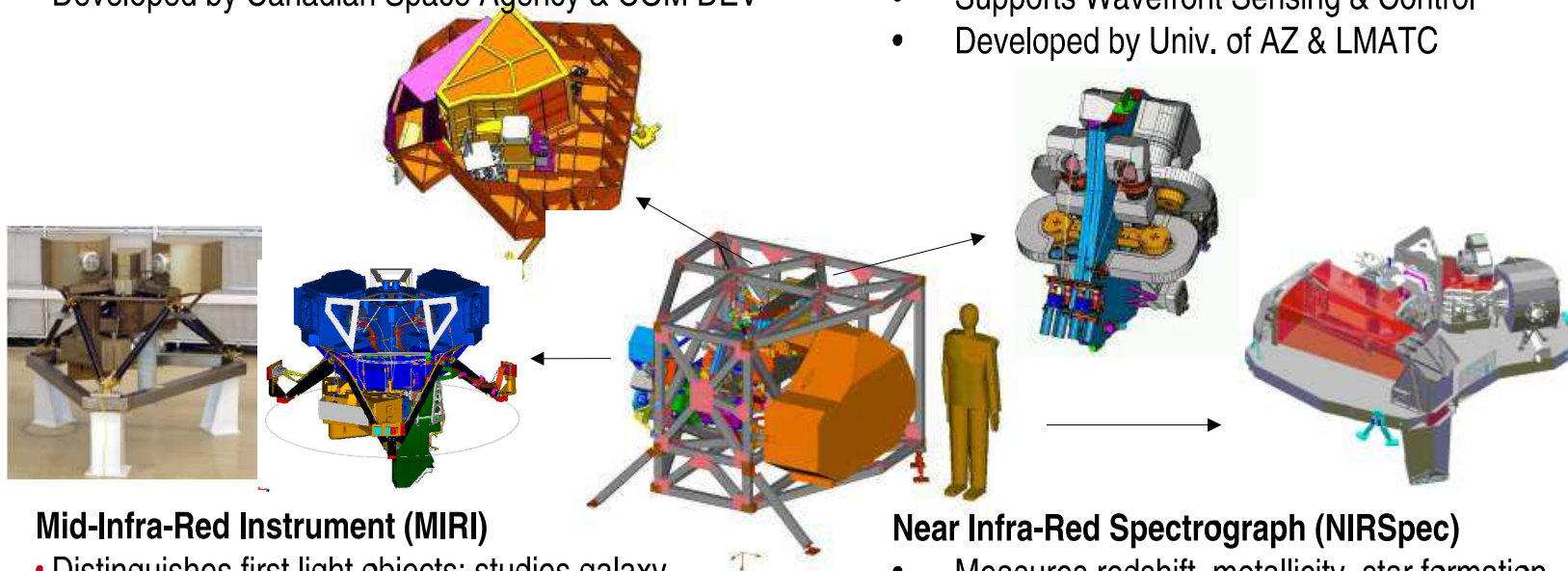


Fine Guidance Sensor (FGS)

- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

Near Infra-Red Camera (NIRCam)

- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC



Mid-Infra-Red Instrument (MIRI)

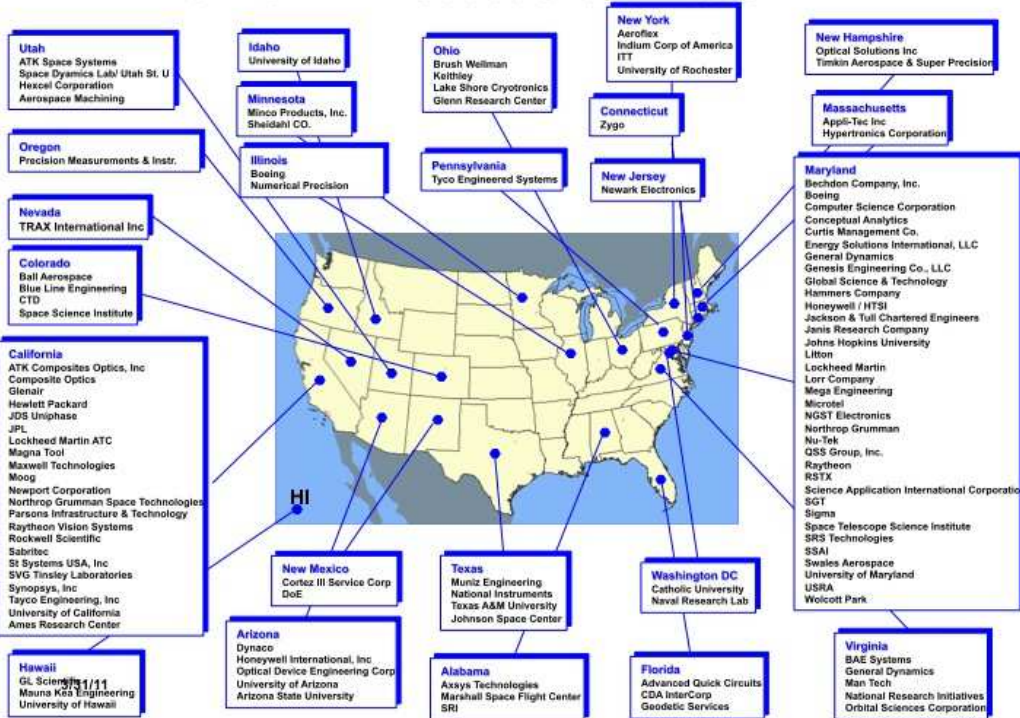
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

Near Infra-Red Spectrograph (NIRSpec)

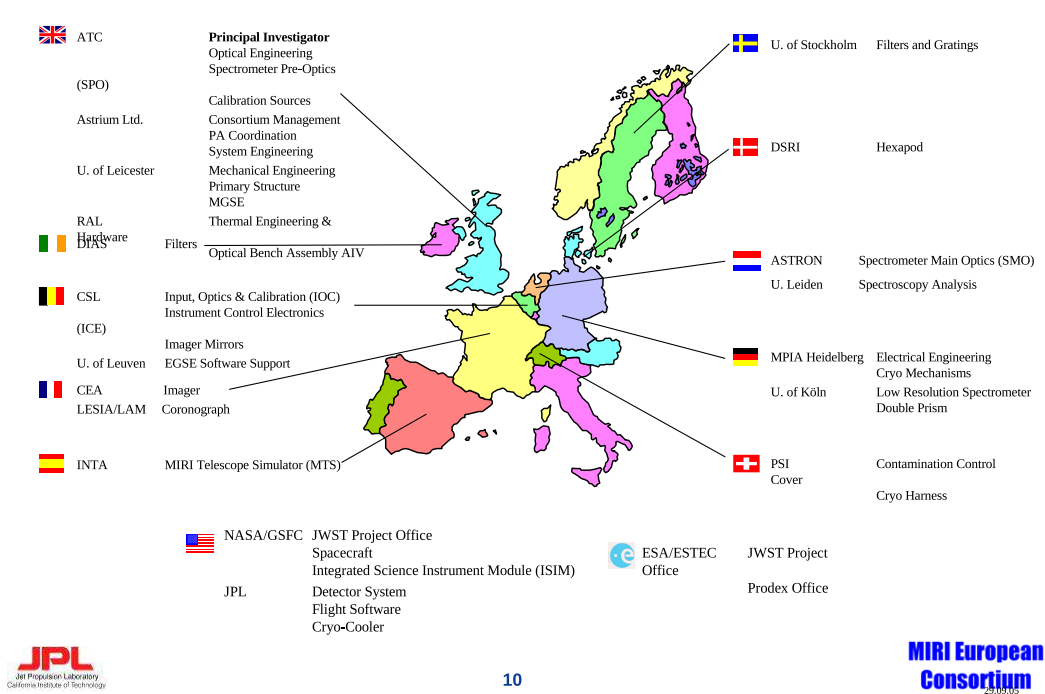
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

All delivered: MIRI 05/12; FGS 07/12; NIRCam 07/13, NIRSpec 9/13.

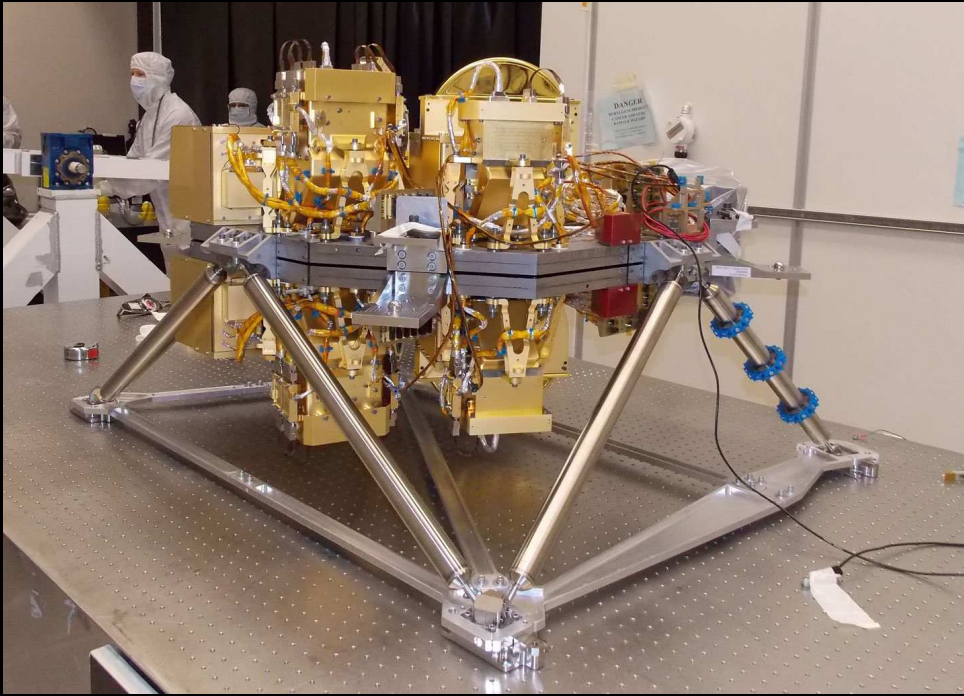
JWST: A Product of the Nation



European Consortium Who & Where



- JWST hardware made in 27 US States: $\approx 99.5\%$ of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCам made by UofA and Lockheed.

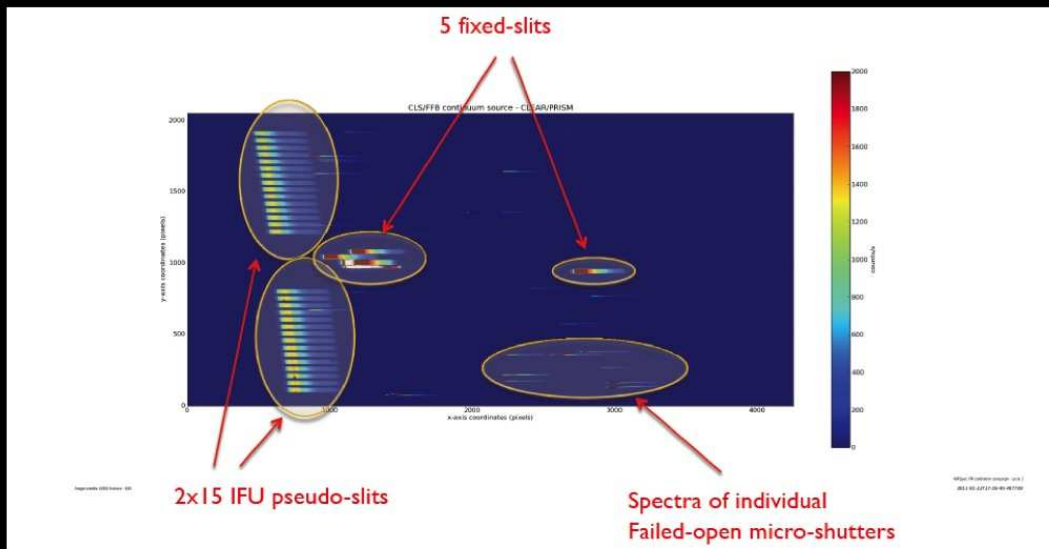


JWST's short-wavelength ($0.6\text{--}5.0\mu\text{m}$) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& $1\text{--}5\mu\text{m}$ grisms) — built by CSA (Montreal).
- FGS includes very powerful low-res Near-IR grism spectrograph (NIRISS).
- FGS delivered to GSFC 07/12; NIRCam delivered 07/13.
- Detectors replaced in 2015 between CryoVacuum tests CV2 and CV3.



Flight NIRSpec First Light



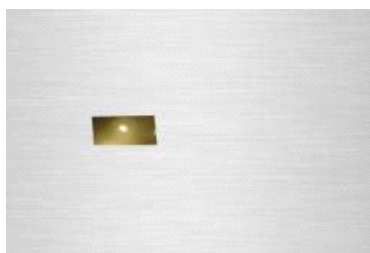
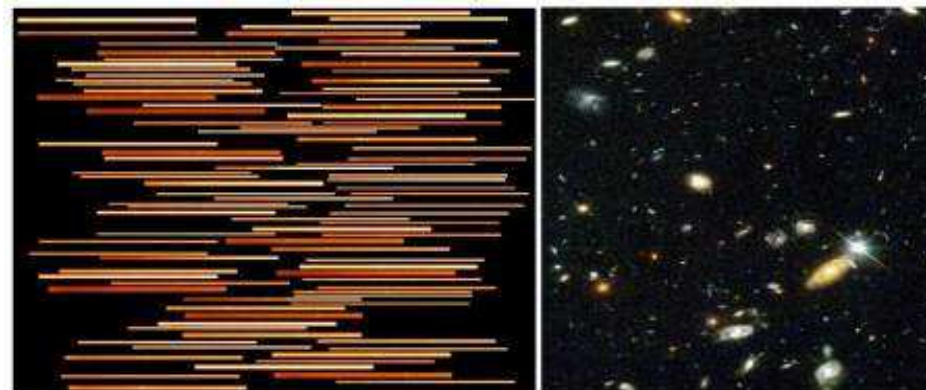
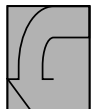
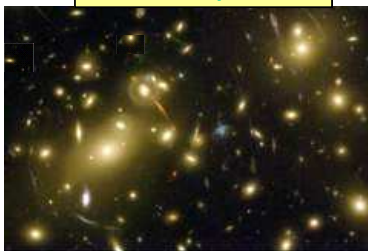
JWST's short-wavelength ($0.6\text{--}5.0\mu\text{m}$) spectrograph:

- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

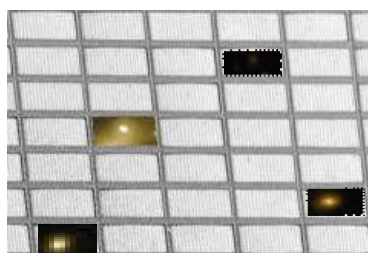
NIRSpec delivered to NASA/GSFC in 09/13.

- Detectors replaced in 2015 between CryoVacuum tests CV2 and CV3.

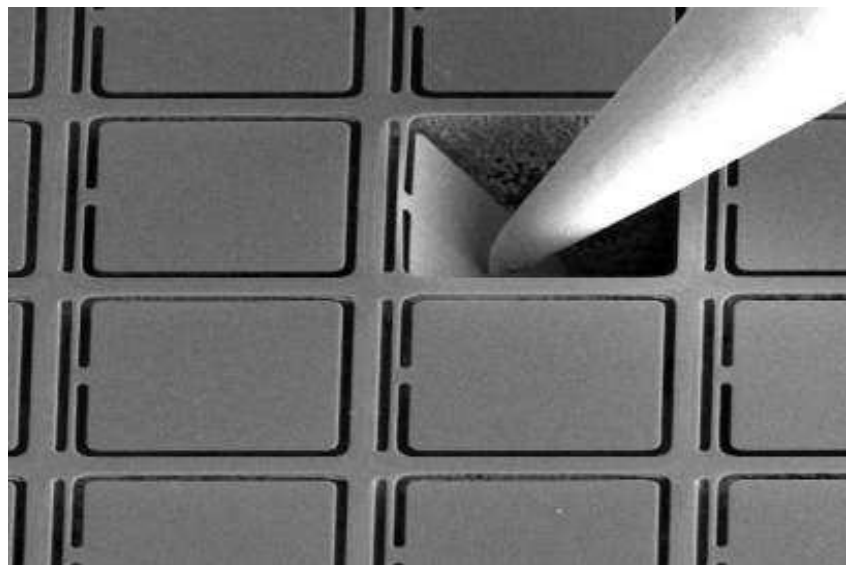
Astronomy Scene



Metal Mask/Fixed Slit



Shutter Mask

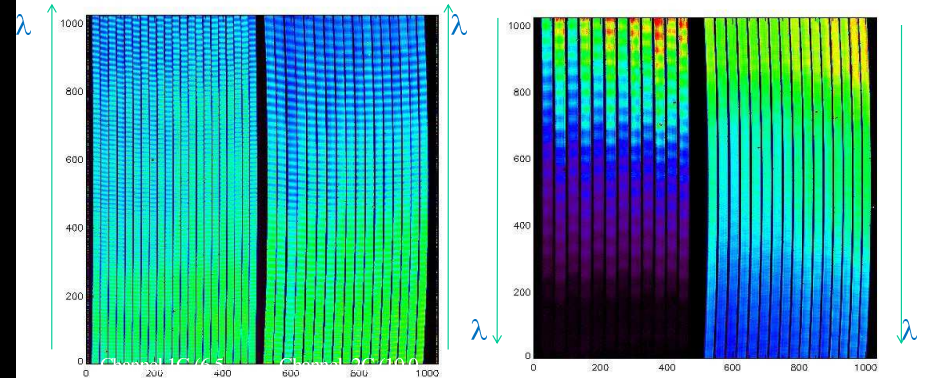




Flight MIRI



Spectrometer First Light – internal calibration source

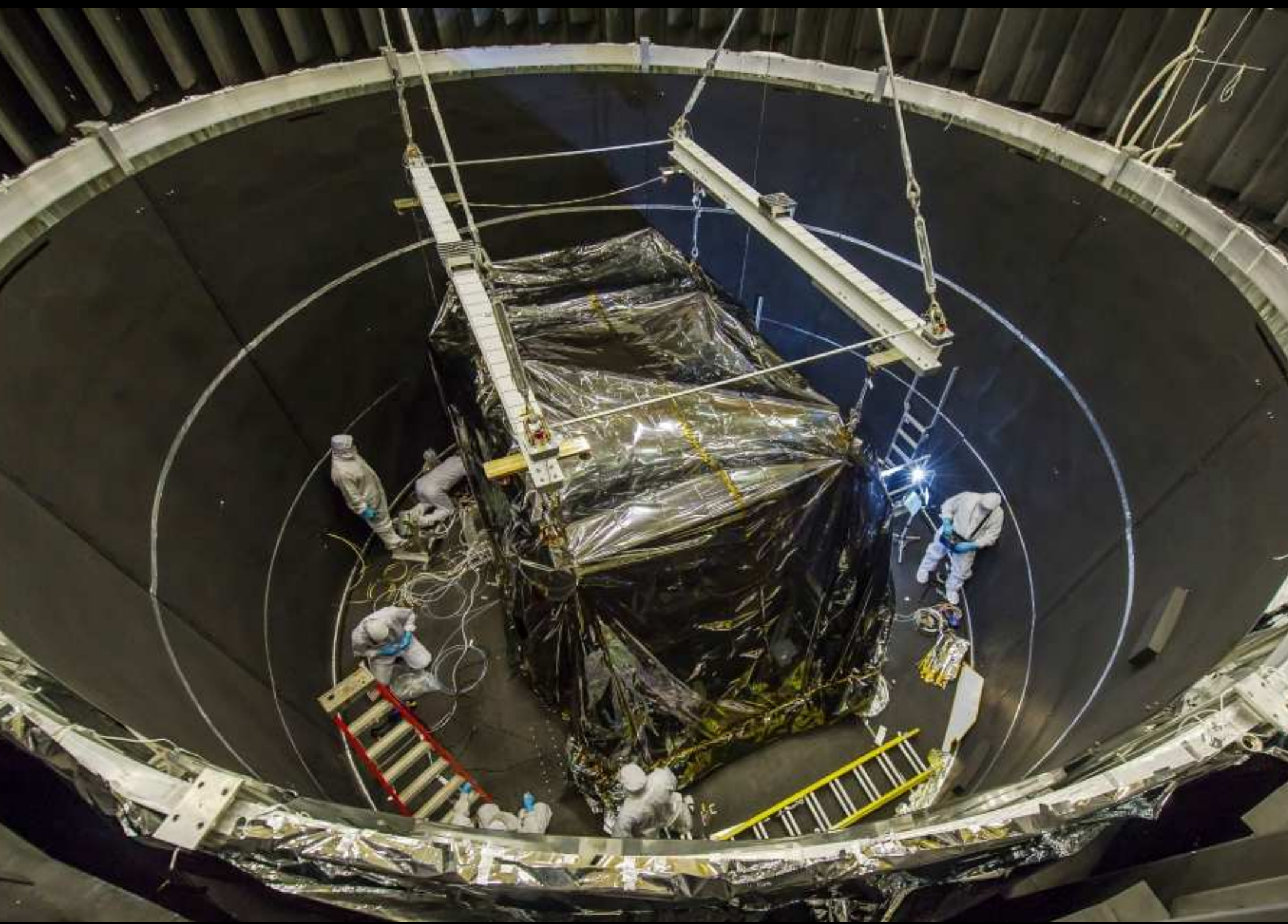


All slices are there and well centred on detectors, fringes look as on VM, the fall off in signal at long wavelengths is expected – temperature of source and relatively short exposure, no “intra-slice” light ☺

JWST's mid-infrared (5–29 μm) camera and spectrograph:

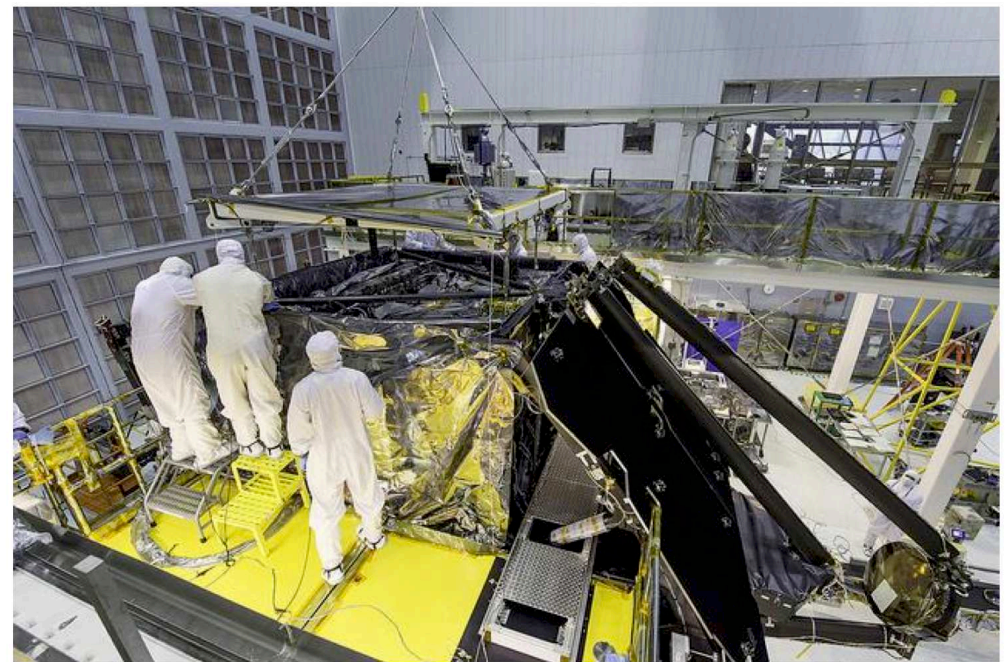
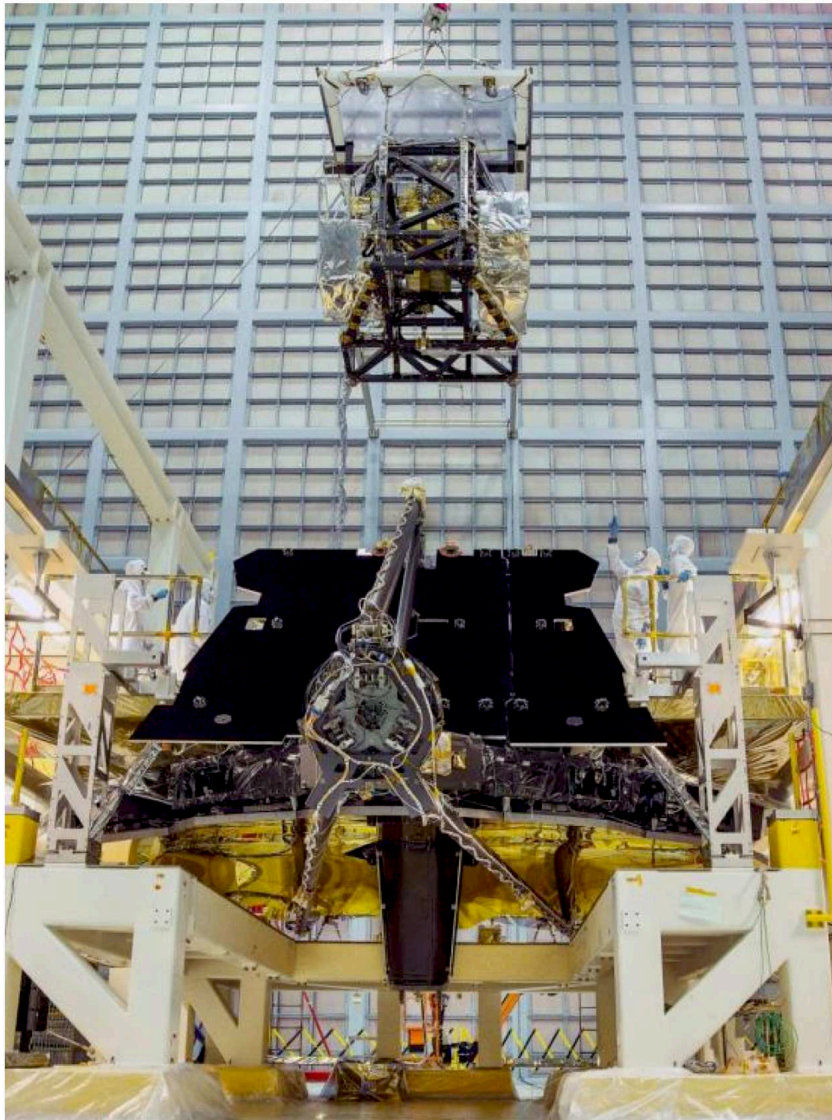
- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012.



2014: Flight ISIM (all 4 instruments) in test; Oct. 15-Feb. 2016: CryoVac3.

Program Update: OTE + ISIM = OTIS



3

160613 JWST Monthly Telecon 28

June 2016: Flight ISIM mated with Optical Telescope Element (OTE).
JWST is now a real working telescope (albeit not yet at 40 K & in 0 G)!



April 2017: Last portrait of JWST at Goddard Space Flight Center (MD).

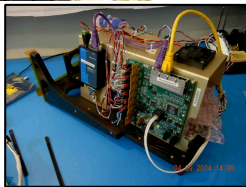
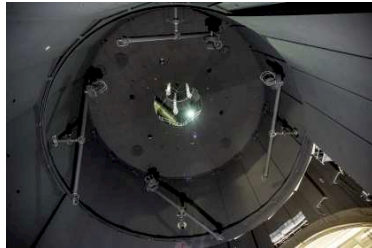


OTIS Test GSE Architecture and Subsystems

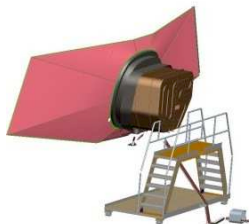


Chamber Isolator Units
Dynamically isolates OTIS Optical Test
- Integration 6 units complete

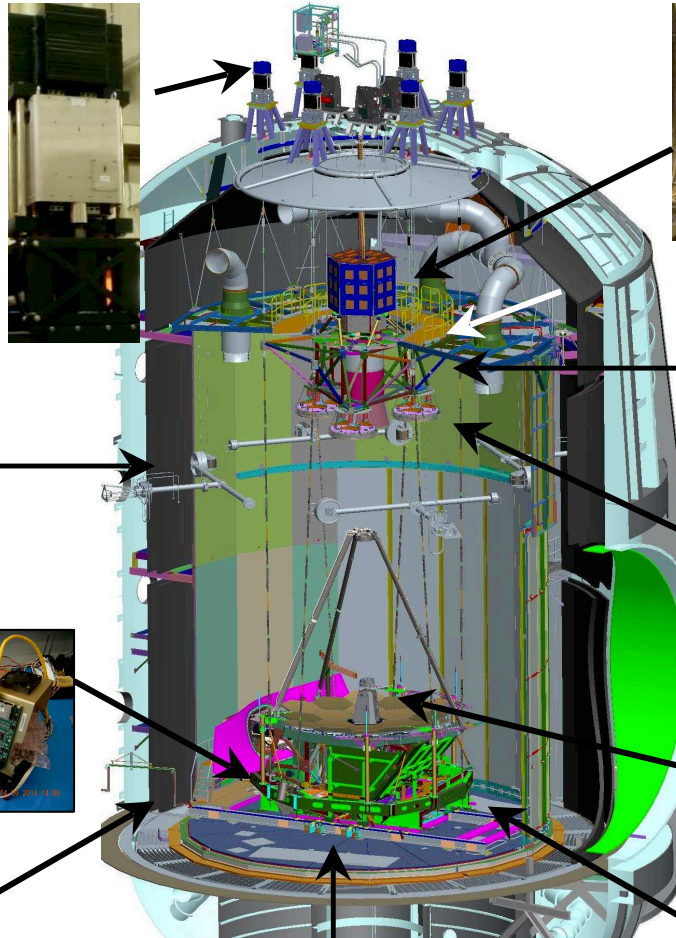
**Cryo Position Metrology (CPM)
Photogrammetry System**
Integration Complete



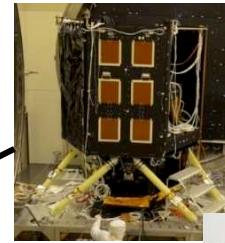
ADM - new Leica
delivered and under test



**Space Vehicle Thermal Simulator (SVTS)
and Sunshield Simulator**
Passed design review and started Procurements and fab subcontracts



HOSS - OTIS support structure
HOSS - will be in the chamber for Bake out in June



Center of Curvature Optical Assembly (COCOA)
• Multiwavelength interferometer (MWIF), null, calibration equipment, coarse/fine PM phasing tools, Displacement Measuring Interferometer - COCOA was exercised at MSFC in December



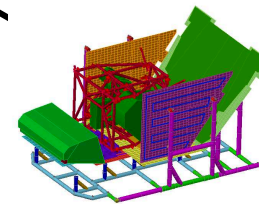
USF Structural Frame - supports Metrology ready for chamber integration and Cryo Load tests



3 Auto collimating Flat Mirrors (ACFs)
1.5 M Plano for Pass and Half Testing
Cryo testing underway, ACF 1 complete, ACF 4 in Cryo test complete, ACF 5 ready for Cryo.



AOS Source Plate
Sources for Pass and Half Test
72 optical fiber support cont.



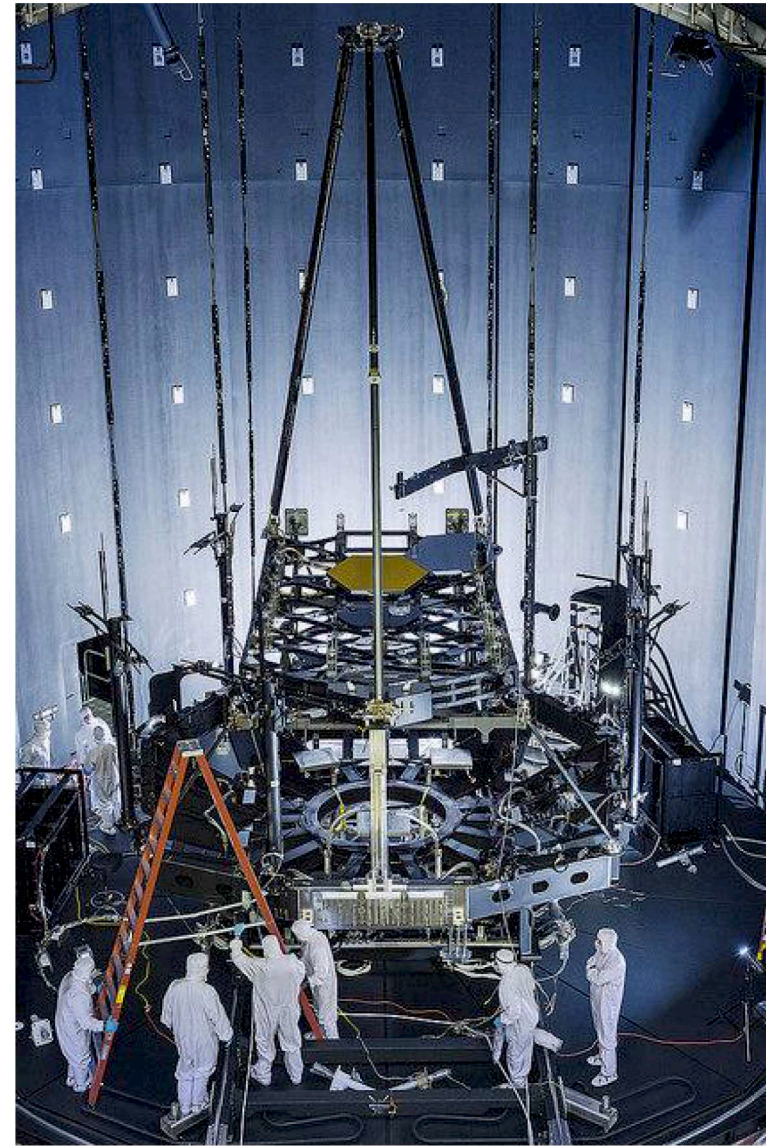
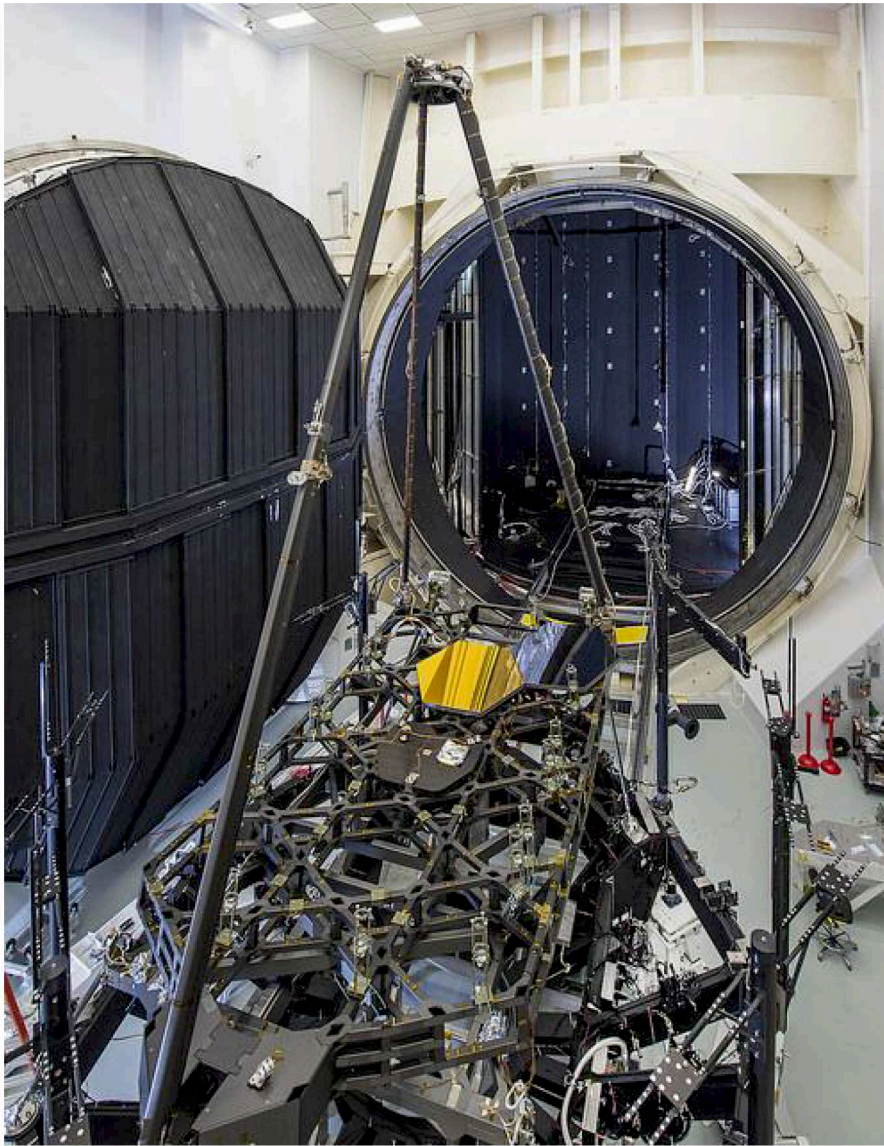
Deep Space Edge Radiation Sink (DSERS)
Thermal modeling of payload and DSERS started



Mag Damper Cryo Test Article
Fabrication started

World's largest TV chamber OTIS: testing JWST June-Oct. 2017.

Pathfinder & JSC Chamber A: getting ready for OGSE1 (and eventually OGSE2 & Thermal Pathfinder)

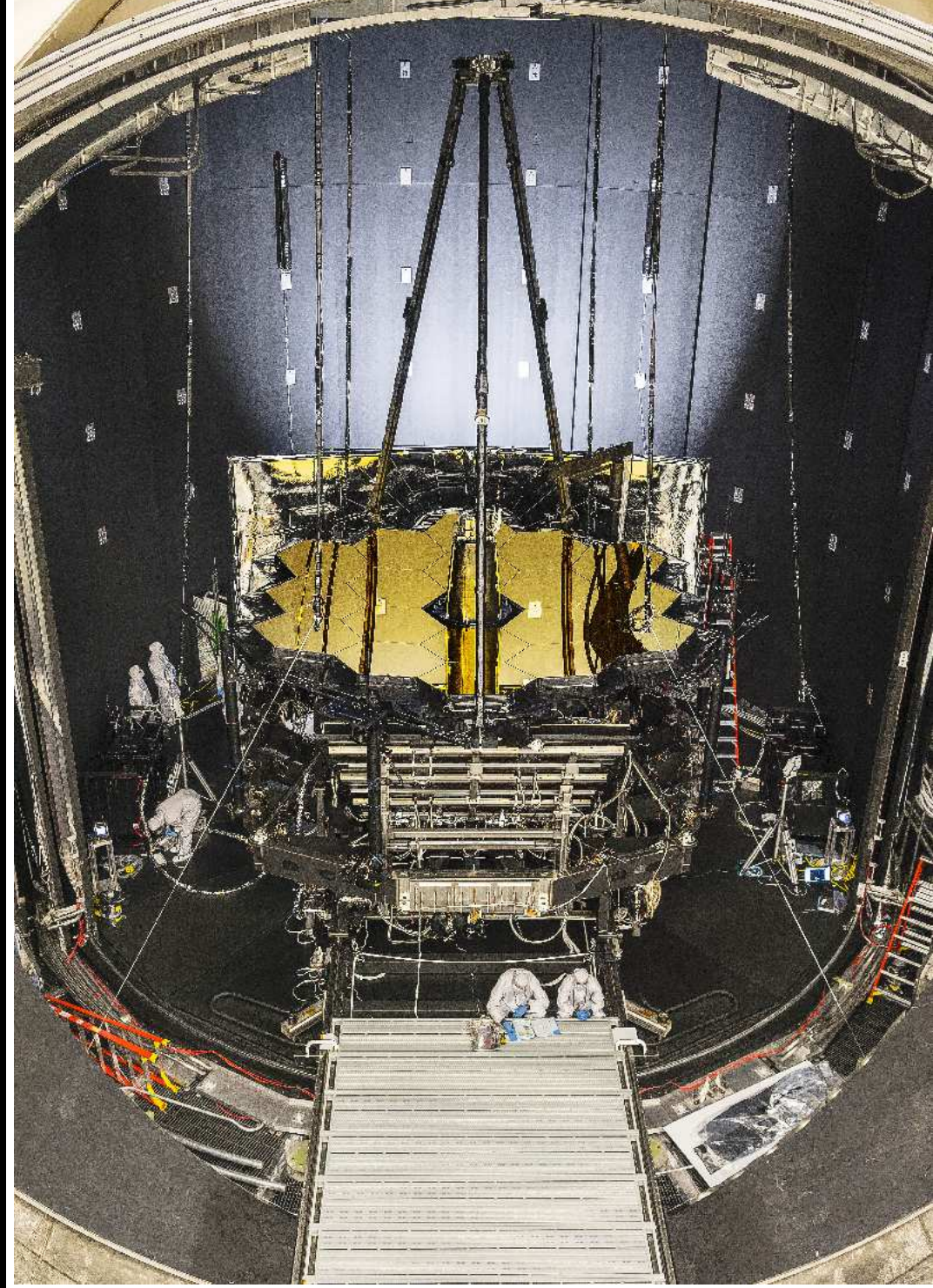


2015–2016: Testing OTIS chamber with the JWST Engineering model.



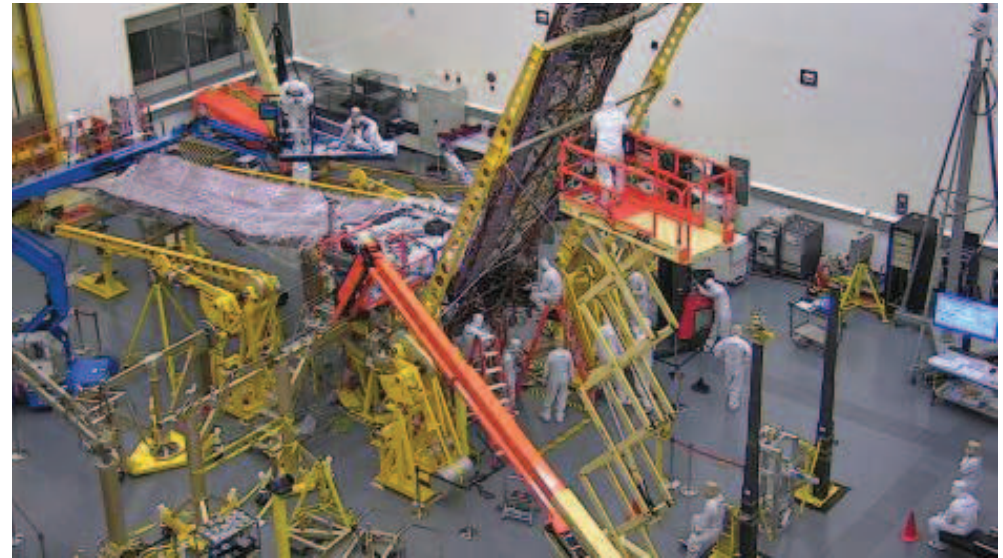
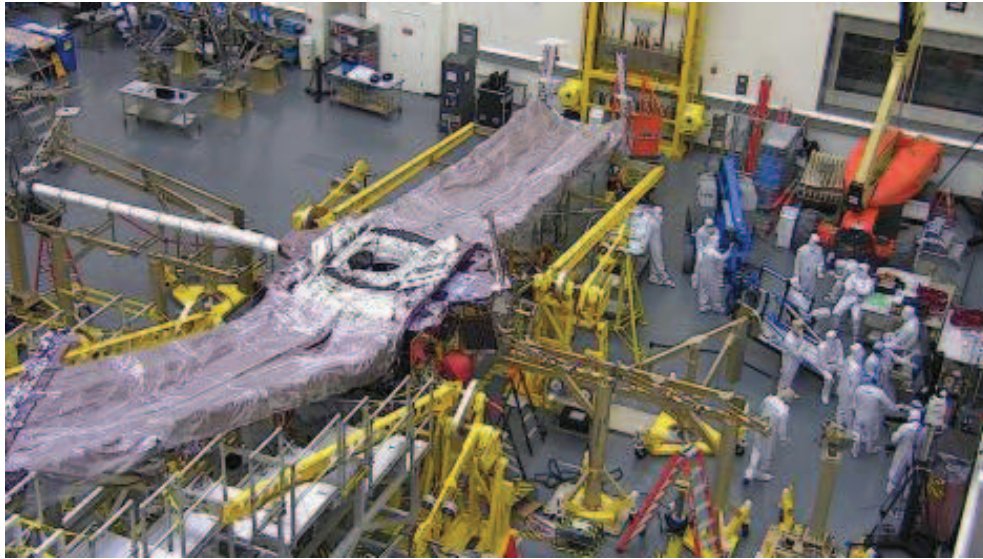
May 2017: JWST in enclosure at Johnson Space Center in Houston.





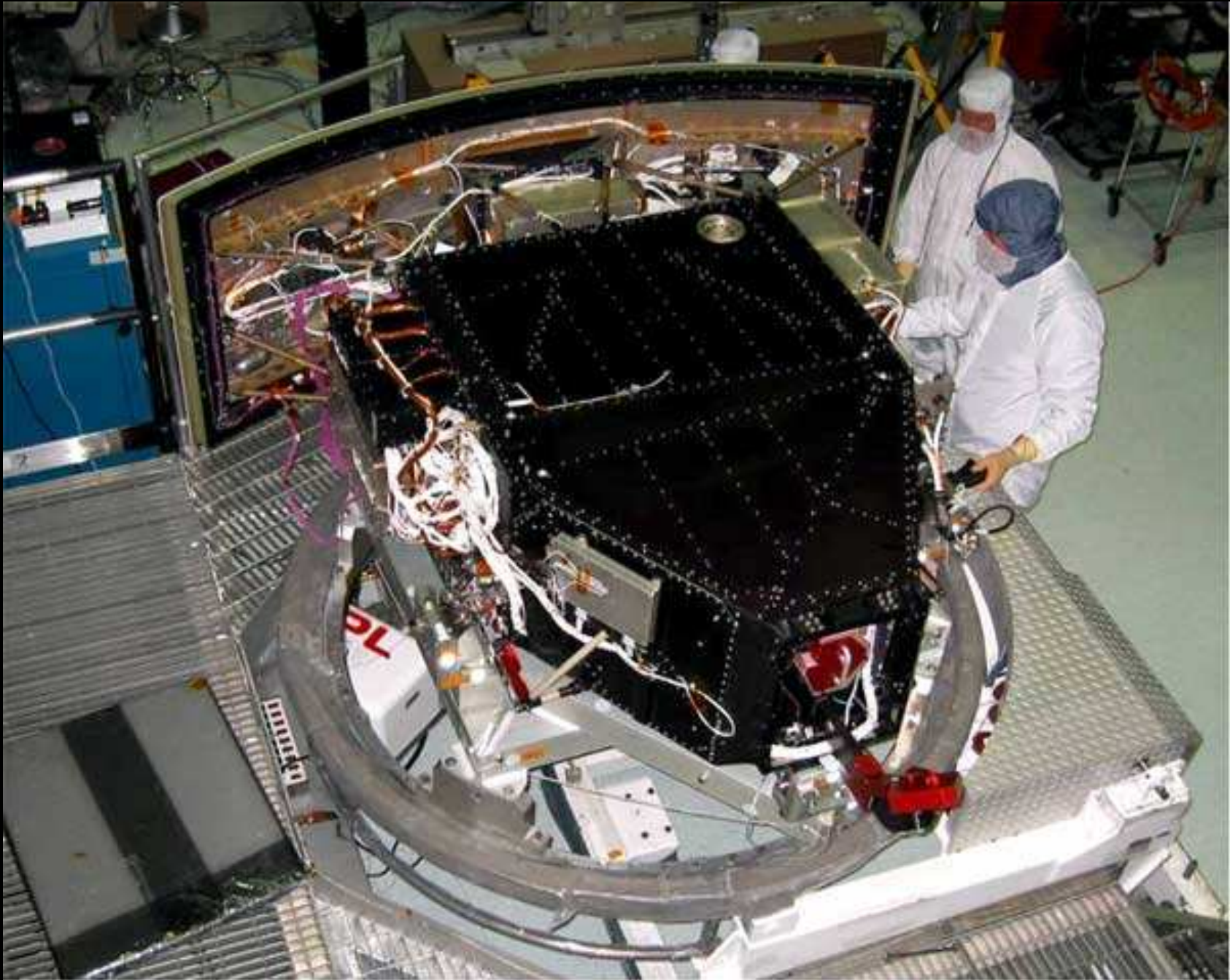
Sep. 2017: JWST now in Chamber A at Johnson Space Center in Houston!

Program Updates: Spacecraft and Sunshield



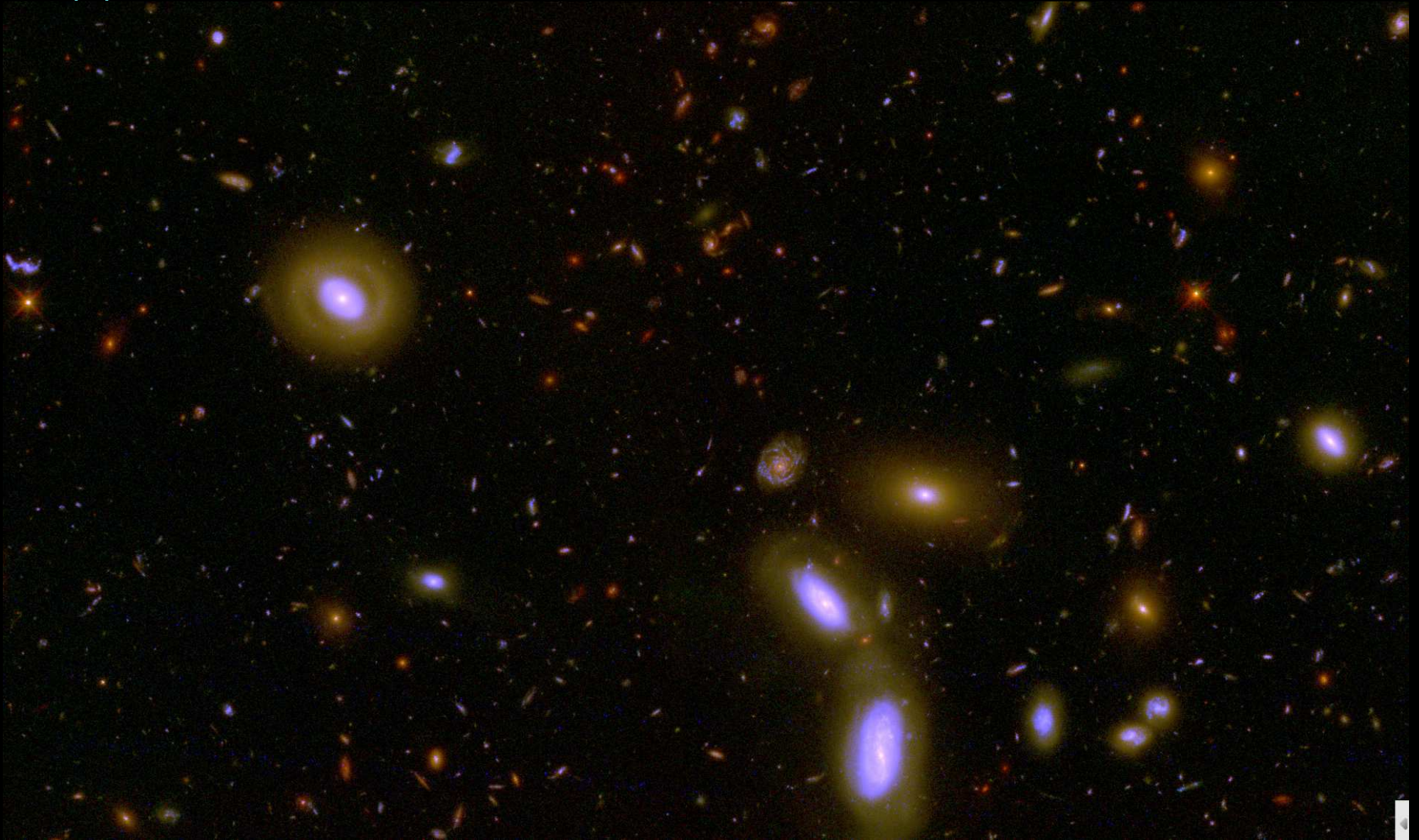
Spring–Fall 2017: JWST Flight Sunshield assembled and tested at Northrop.

(2) WFC3: Hubble's new Panchromatic High-Throughput Camera



HST WFC3 and its **IR channel**: a critical pathfinder for JWST science.

(2) Hubble WFC3: Measuring Galaxy Assembly and SMBH Growth?



10 filters with Hubble WFC3 & ACS reaching $AB=26.5-27.0$ mag over 40 arcmin² with $0.07-0.15''$ images from $0.2-1.7\mu\text{m}$ (UVUBVizYJH).

JWST adds $0.05-0.2''$ FWHM imaging to $AB \simeq 31.5$ mag (1 FF) at $1-5\mu\text{m}$, with $0.2-1.2''$ images at $5-29\mu\text{m}$, tracing young+old stars & dust.

Black Hole growth — Waves that happen in Nature: 1) Sounds Waves:



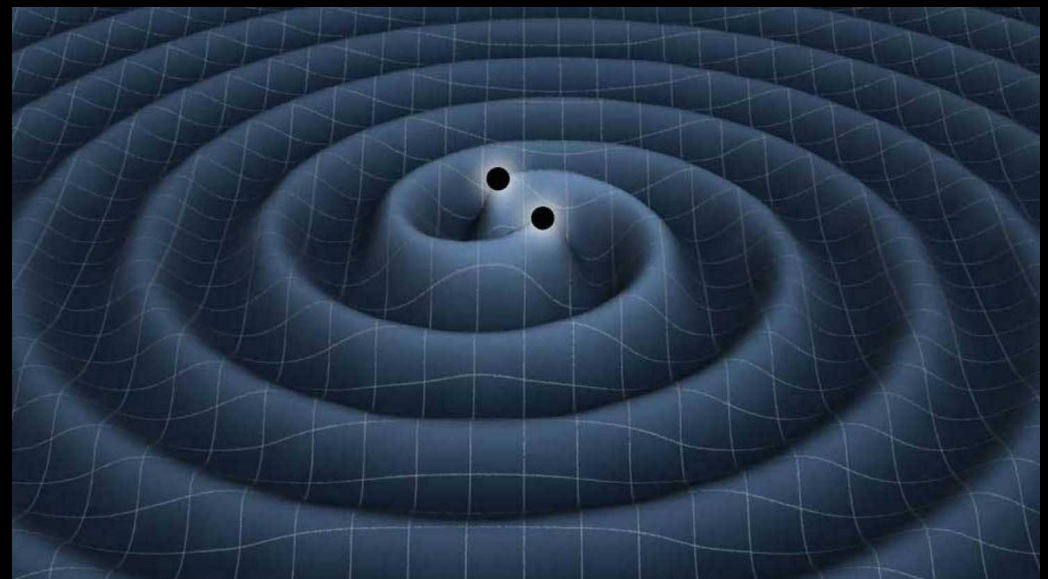
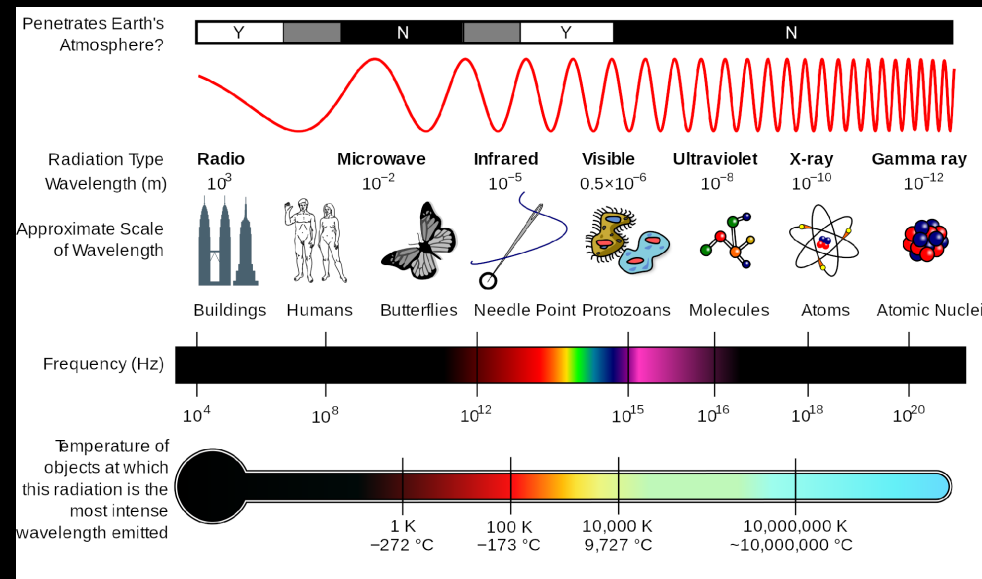
In solids: Earthquakes



In liquids: Surf!



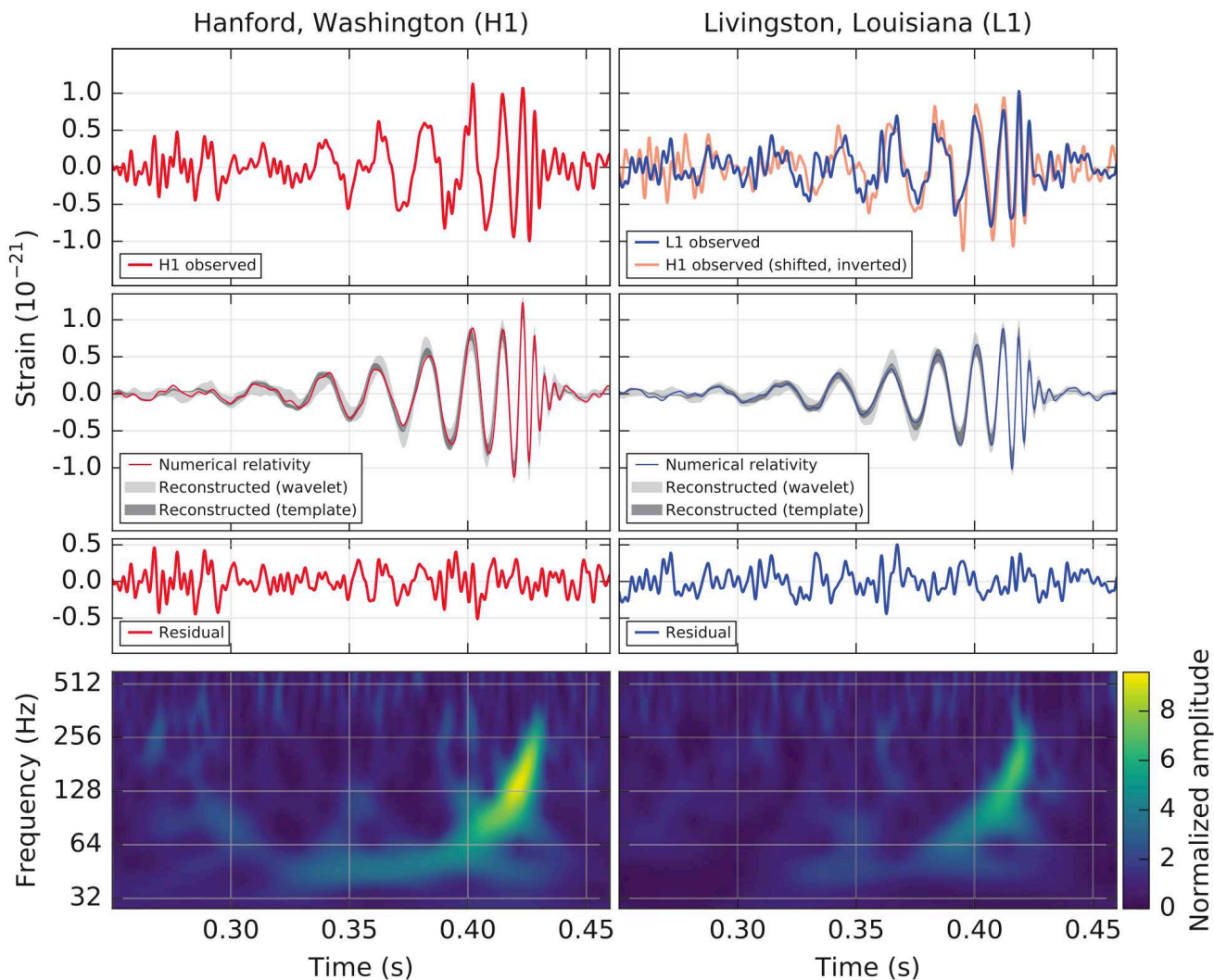
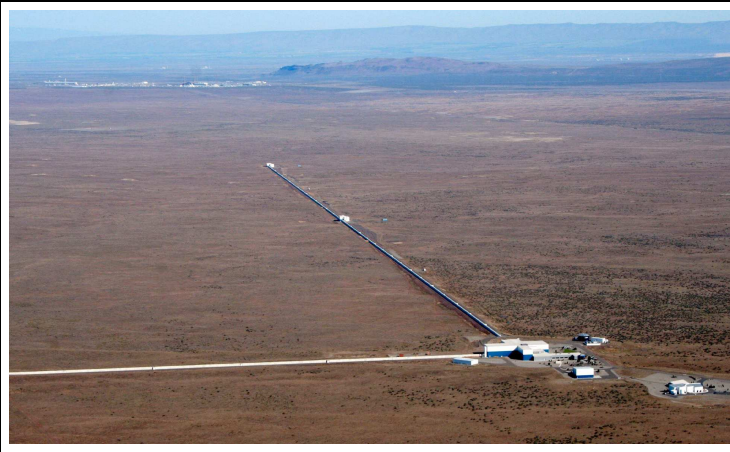
In gasses: Sound



2) Electromagnetic Waves

3) In space-time: Gravity Waves

Sept. 2015: LIGO added Gravity Waves as a new way to observe Nature!



(1) LIGO first observed Gravitational Waves on Sept. 14, 2015.

(2) These were caused by two merging ($29+36 M_{\odot}$) black holes about 1 Gyr ago!

● $E=Mc^2$: $3 M_{\odot}$ was converted to energy in a fraction of a second!



Ordinary massive stars ($10\text{--}30 M_{\odot}$) leave modest black holes ($\sim 3\text{--}10 M_{\odot}$).

Conclusion 1: Most low-mass black holes today are small, slow eaters:



- 29–36 M_{\odot} blackholes may be leftover from First Stars (first 500 Myr).
- Likely too massive to be leftover from ordinary Supernova explosions, ...
- How come only now seen merging by LIGO (12.5 Byr after BB)?
- They were likely not fast & efficient eaters, but slow and messy ...

Elliptical galaxy M87 with Active Galactic Nucleus (AGN) and relativistic jet:



The danger of having Quasar-like devices too close to home ...
They are EXTREMELY bright sources if viewed "down-the-pipe".
~0.5% of the baryonic mass, but produce most of the photons!

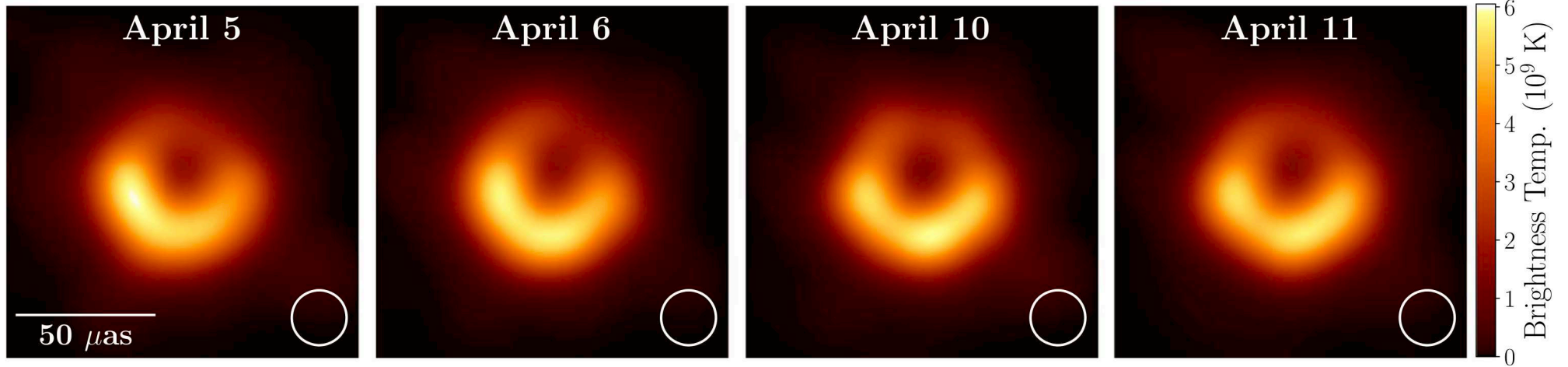
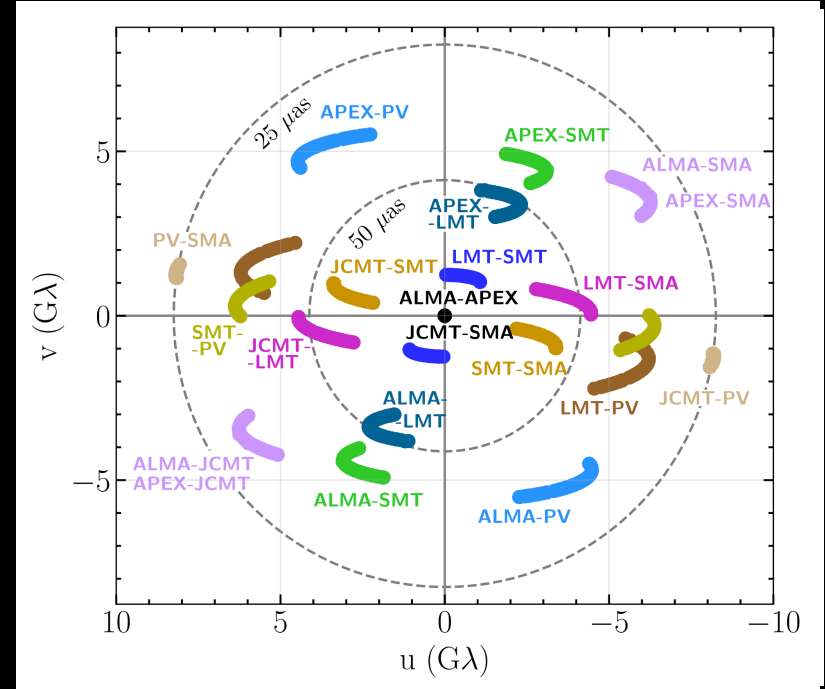
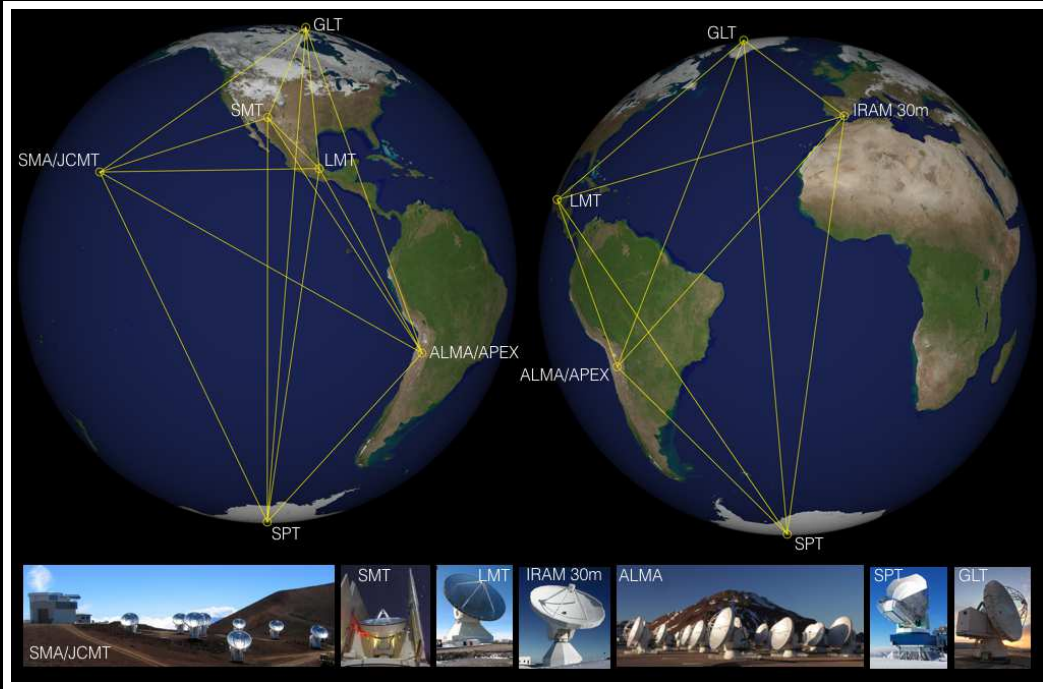


Figure 15. Averages of the three fiducial images of M87 for each of the four observed days after restoring each to an equivalent resolution, as in Figure 14. The indicated beam is $20 \mu\text{as}$ (i.e., that of DIFMAP, which is always the largest of the three individual beams).

2019 discovery of Black Hole Shadow in M87 by Event Horizon Telescope:
M87 at 55 Mlyr distance has a black hole mass of $\sim 6.5 \times 10^9 M_{\odot}$!

Centaurus A
NGC 5128
HST WFC3/UVIS

F225W+F336W+F438W
F487N H β
F502N [O III]
F547M y
F657N H α + [N II]
F673N [S II]
F814W I

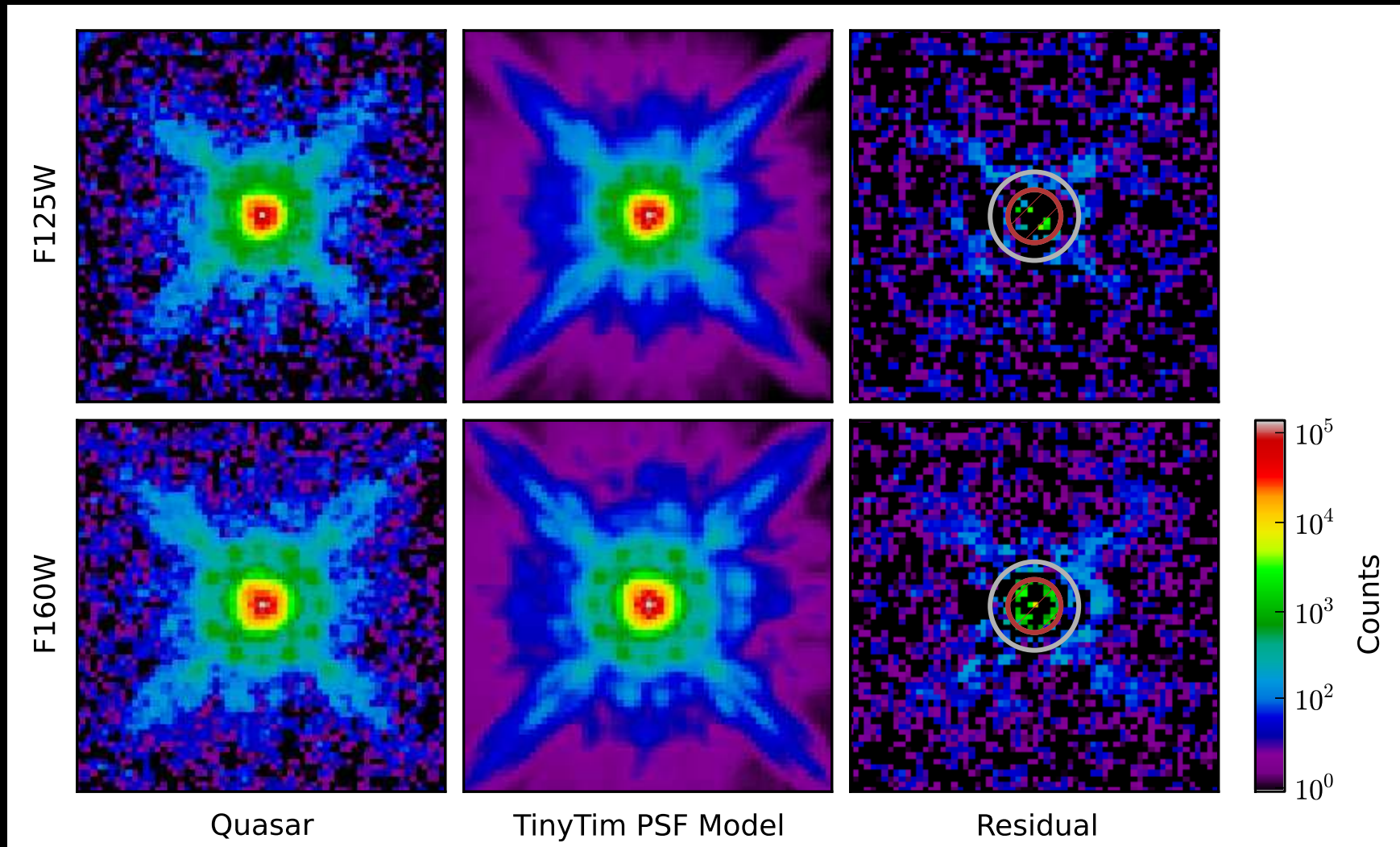
3000 light-years
1400 parsecs
56''





Blue=X-rays; White=Optical; Orange=Radio

- Quasars: Centers of galaxies with feeding supermassive blackholes:



- Hubble IR-images of the most luminous Quasar known in the universe.
- Seen at redshift 6.42 (universe $7.42\times$ smaller than today), 900 Myr old!
- Contains 10^{14} solar luminosities within a region as small as Pluto's orbit!
- A feeding monster blackhole ($>3\times 10^9$ solar mass) 900 Myr after BB!

Conclusion 2: Supermassive black holes started early & were very rapid eaters:



- Massive galaxies today contain a super-massive blackhole, no exceptions!
- Masses $\sim 3 \times 10^9$ solar, leftover from the First Stars (first 500 Myr)?
- Must have fed enormously rapidly in the first 1 Byr after the Big Bang.
- Were eating *cat*-astrophically (and secretly) until they ran out of food ...
- JWST can image the First Quasars to $z \gtrsim 10$ (*if* we can find them).



Will this ever happen to our own Galaxy?

YES! Hubble showed no lateral motion of Andromeda:

Approaches at -110 km/s.

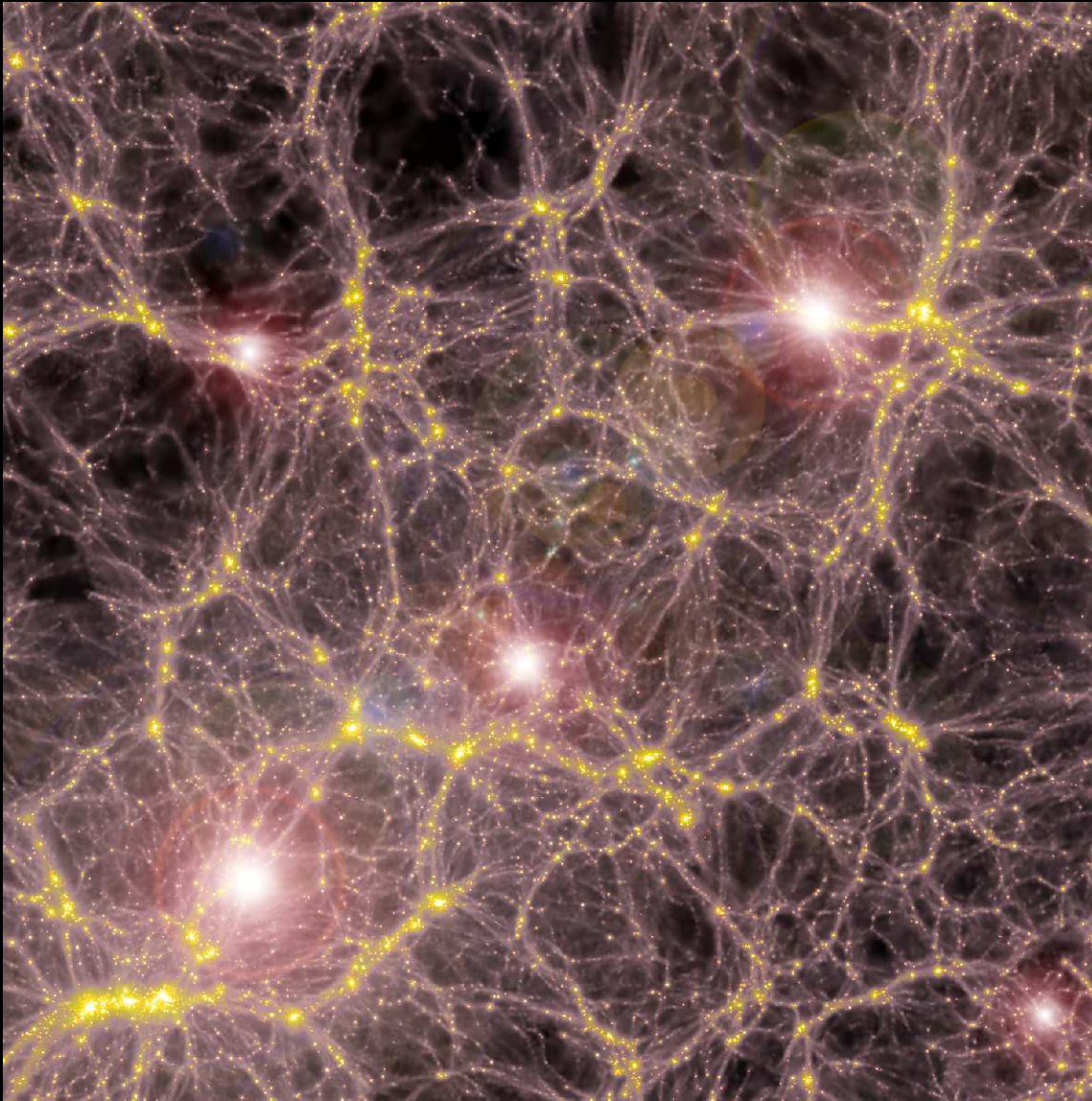
Hence, Andromeda will merge with Milky Way!

The two blackholes (10^6 – 10^7 suns) will also merge!

Not to worry: only 4–5 Byr from today!

Illustration Sequence of the Milky Way
and Andromeda Galaxy Colliding

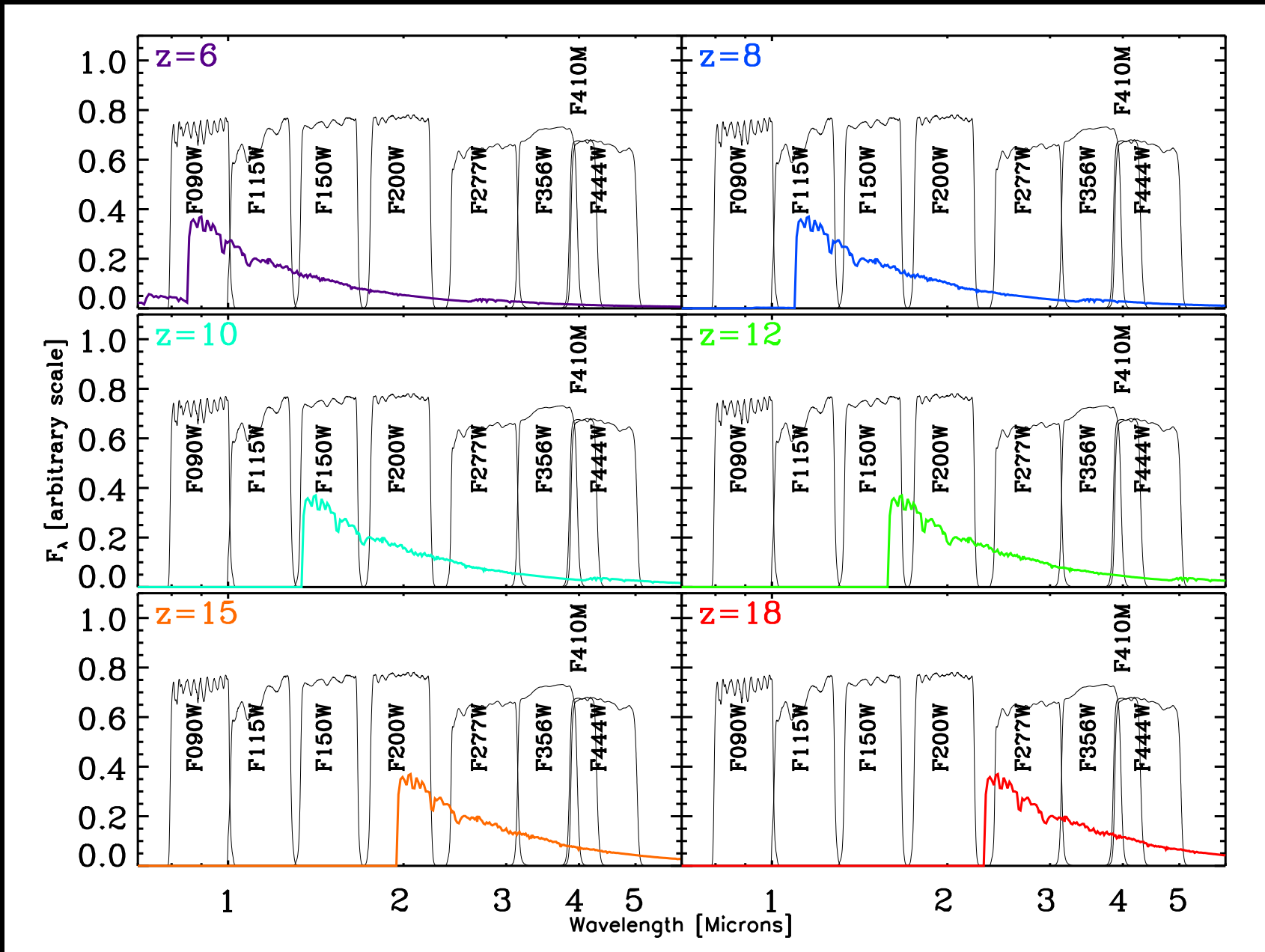
(3) How will JWST Observe First Light and Reionization?



- Detailed cosmological models (V. Bromm) suggest that massive “Pop III” stars ($\gtrsim 100 M_{sun}$) started to reionize the universe at $z \lesssim 10-30$ (0.1–0.5 Gyr; “First Light”).
- This should be visible to JWST as the first Pop III stars or surrounding (Pop II.5) star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \rightarrow 30$.

We must make sure that we theoretically understand the likely Pop III mass-range, their IMF, their duplicity and clustering properties, their SN-rates, etc., before JWST flies, so we know what to look for.

3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?

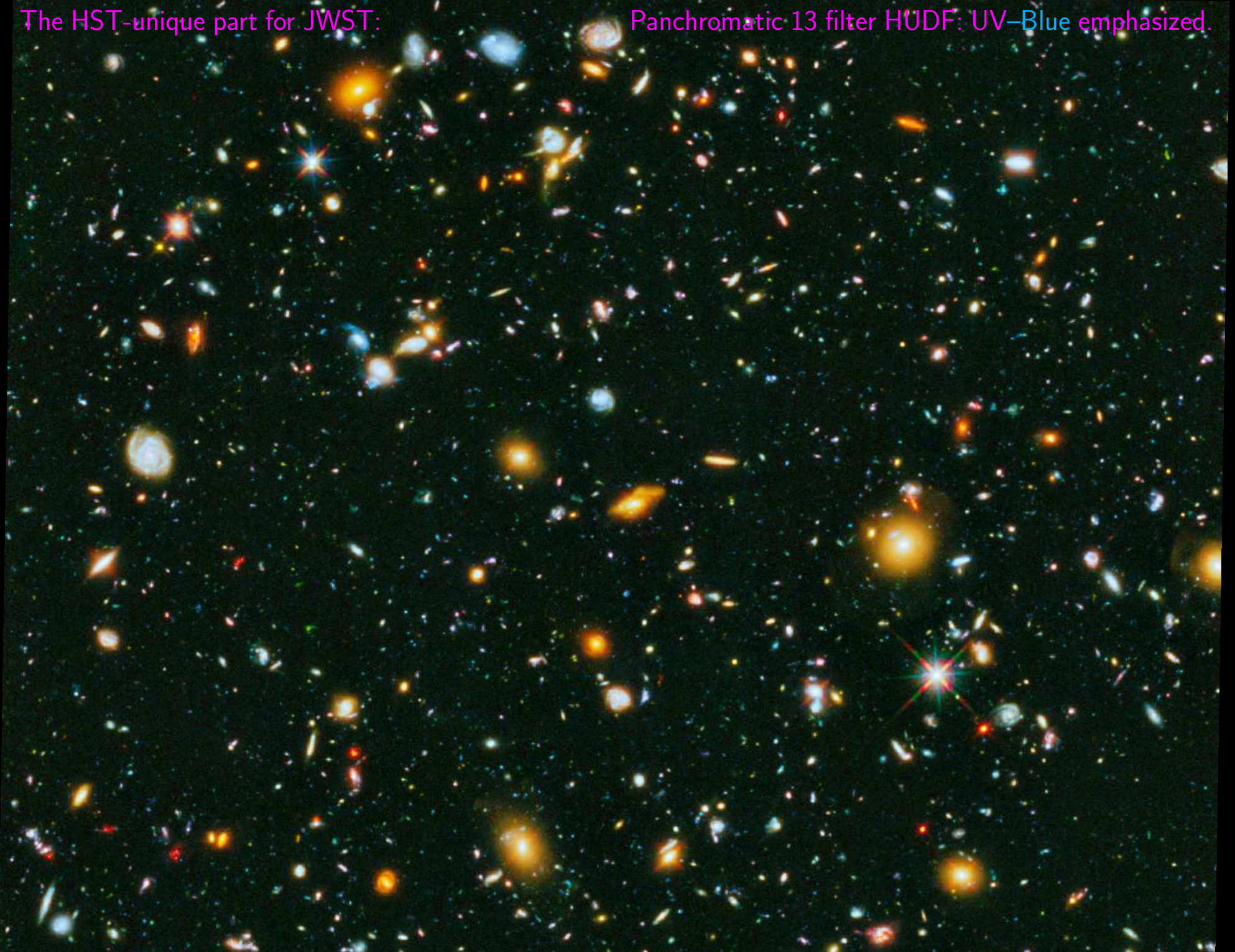


● Can't beat redshift: to see First Light, must observe near-mid IR.

⇒ This is why JWST needs NIRCам at 0.8–5 μm and MIRI at 5–28 μm .

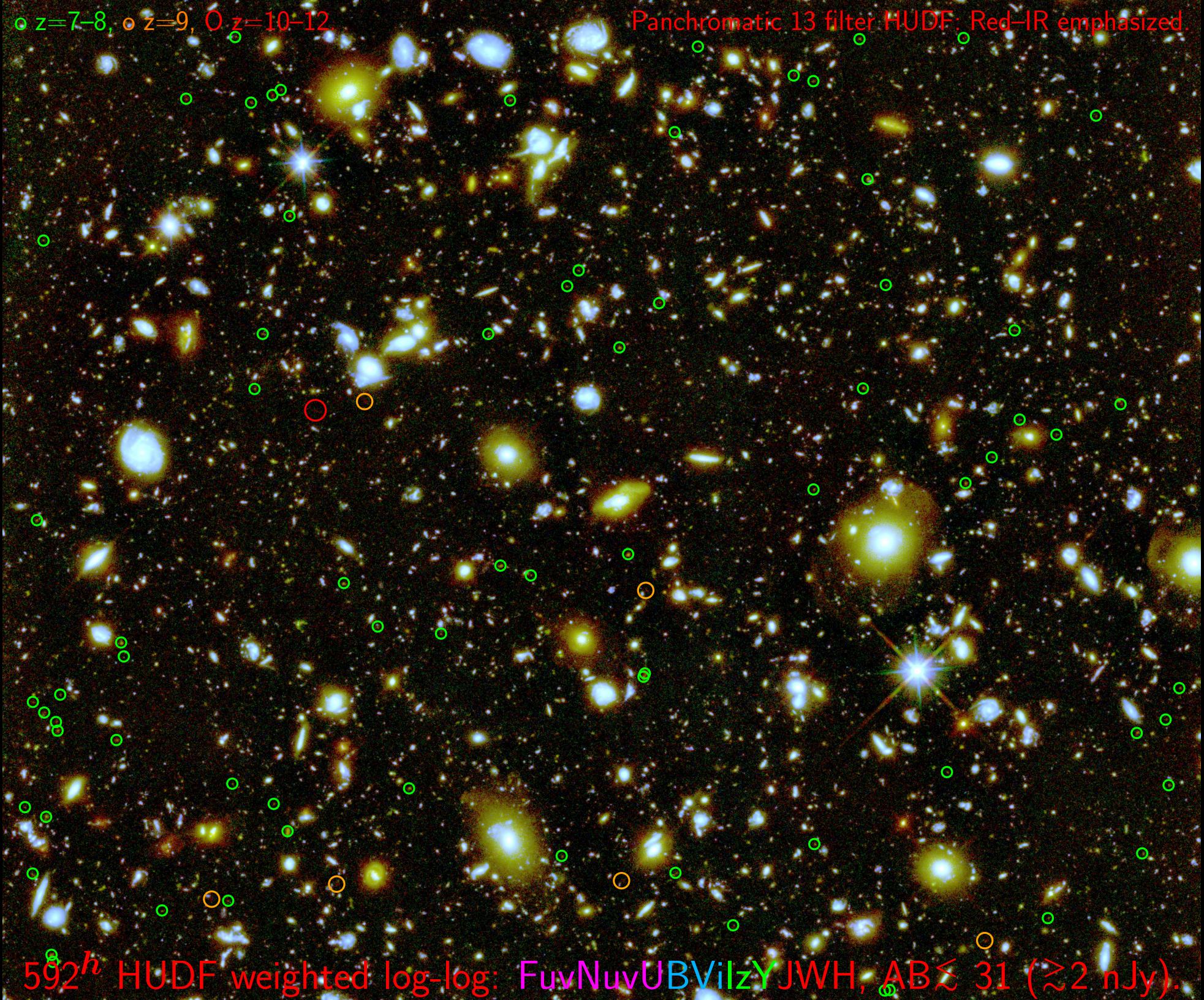
The HST-unique part for JWST:

Panchromatic 13 filter HUDF: UV-Blue emphasized.



592^h HUDF weighted log-log: FuvNuvUBVilzYJWH, AB $\lesssim 28-31$ ($\gtrsim 2$ nJy).

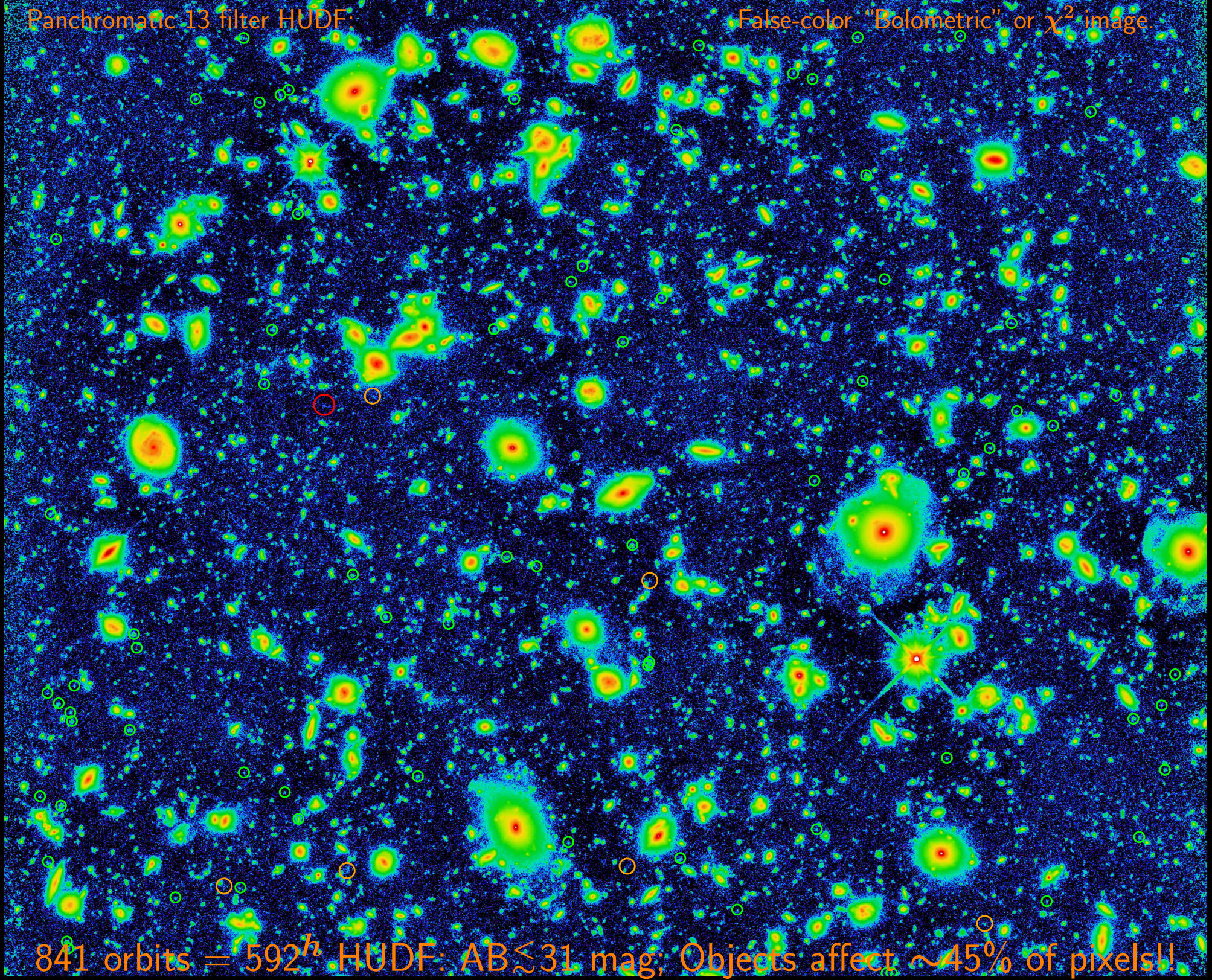
○ $z=7-8$, ○ $z=9$, ○ $z=10-12$. Panchromatic 13 filter HUDF: Red-IR emphasized.



592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB $\lesssim 31$ ($\gtrsim 2$ nJy).

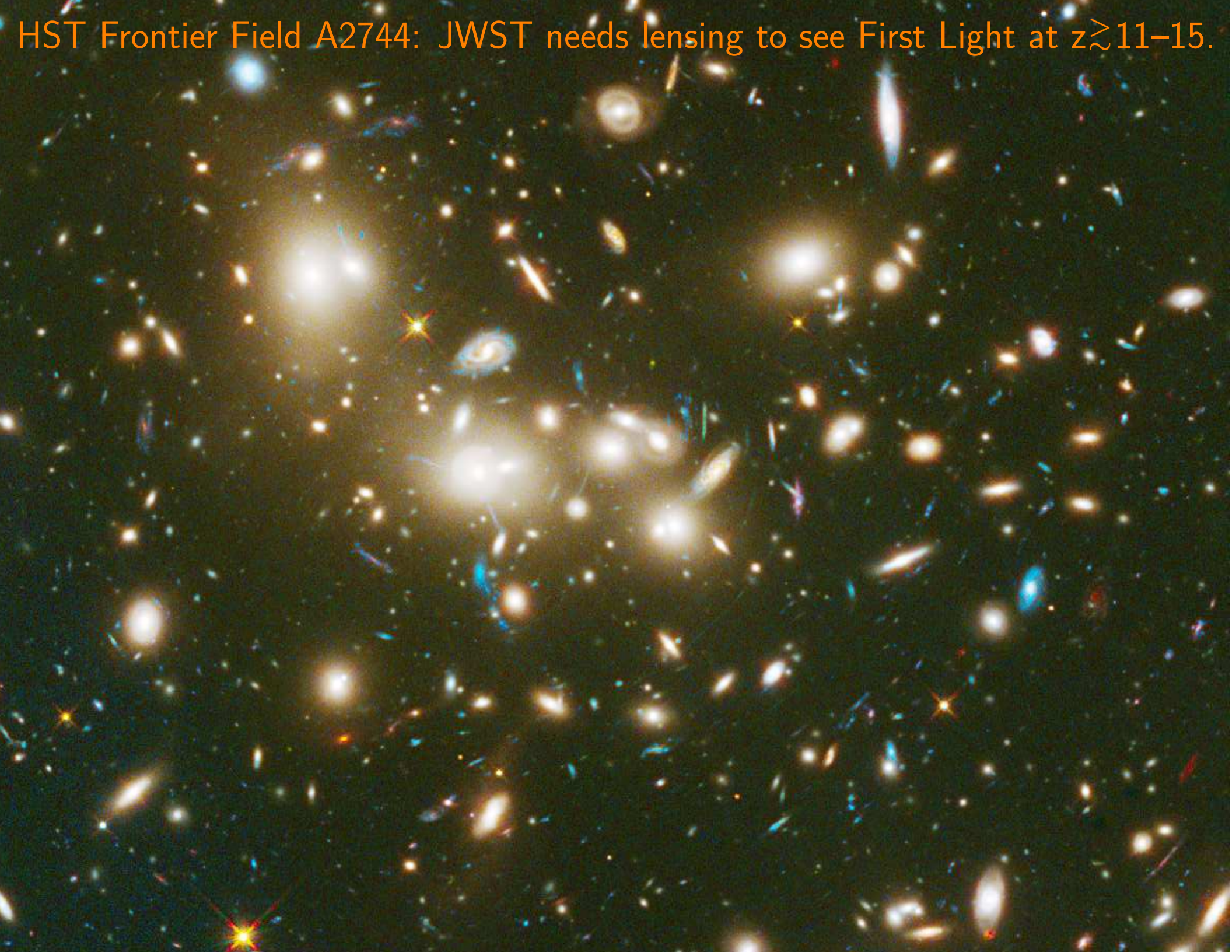
Panchromatic 13 filter HUDF:

False-color "Bolometric" or χ^2 image.



841 orbits = 592^h HUDF: AB \lesssim 31 mag; Objects affect \sim 45% of pixels!!

HST Frontier Field A2744: JWST needs lensing to see First Light at $z \gtrsim 11-15$.





Conclusion: JWST First Light strategy must consider three aspects:

(1) The catastrophic drop in the object density at $z \gtrsim 8$ ($\lesssim 0.5$ Gyr).

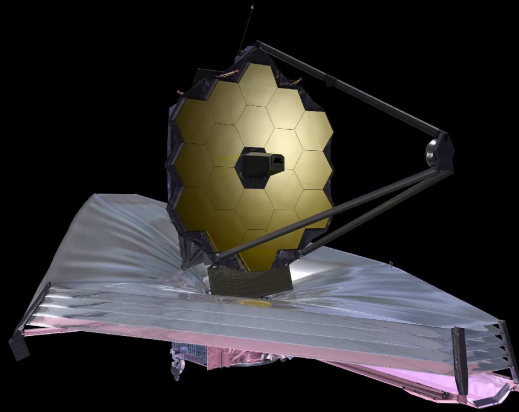
(2) Cannot-see-the-forest-for-the-trees effect [“Natural Confusion” limit]:
Background objects blend into foreground because of their own diameter.

(3) House-of-mirrors effect [“Gravitational Confusion”]:

- JWST needs to find most First Light objects at $z \gtrsim 10$ –15 through the best cosmic lenses (this will make the images even more crowded):
- Lensing is needed to see what Einstein thought was impossible to observe!

(4) Future: Next generation 20–40 m ground-based telescopes and ATLAST

True relative size: Hubble, James Webb, & Giant Magellan Telescope

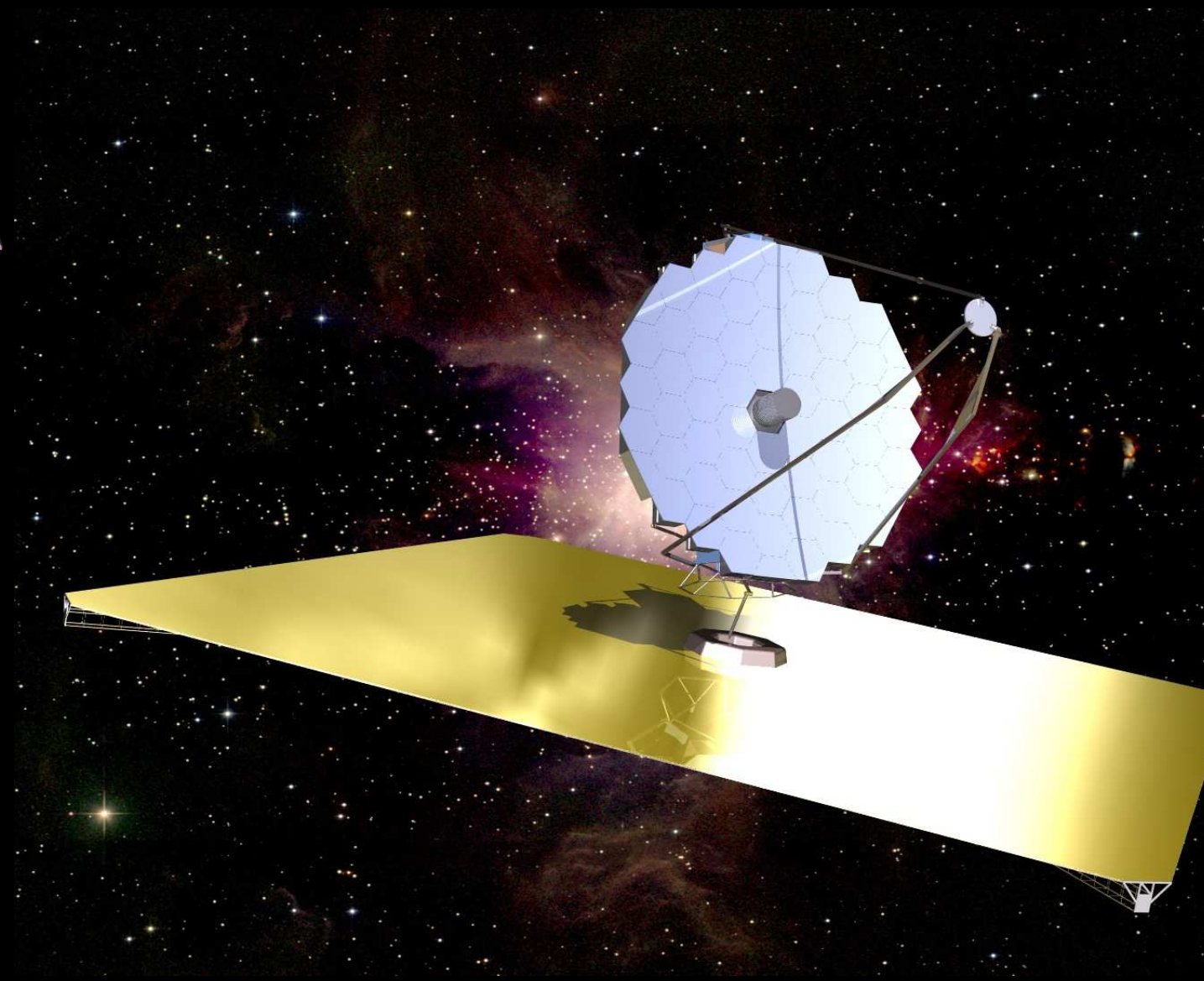
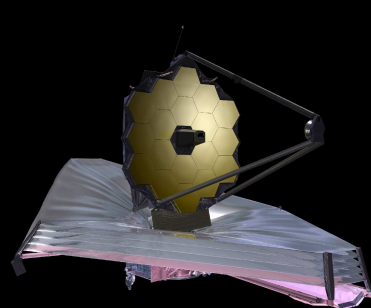


(1973~2020+); (1996~2031);

(2000~2050⁺).

- JWST has superbly dark L2-sky & SB-sensitivity, and stable PSF.
- GMT has 4× higher Res (AO), high-Res spectra, long-term time-domain.

(4) Future: Next generation 20–40 m ground-based telescopes and ATLAST
True relative size: Hubble, James Webb, and ATLAST ...



(1973~2020+);

(1996~2031);

(2020~2050+?).

(4) Future: How can we knock it out of the ball-park in the next 30 years?



Each of GMT and ATLAST facility nearly fills the whole Yankee ballpark ...

- New paradigm: They are too large for an individual university to take on.
- Universities need to collaborate nation-wide to make this happen.

(5) Summary and Conclusions

(1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.

(2) JWST passed Preliminary & Critical Design Reviews in 2008 & 2010.

Management replan in 2010-2011. No technical showstoppers thus far:

- More than 99% of JWST H/W built or in fab, & meets/exceeds specs.

(3) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail. JWST will determine:

- Formation and evolution of the first star-clusters after 0.2 Gyr.

- How dwarf galaxies formed and reionized the Universe after 1 Gyr.

(4) JWST will have a major impact on astrophysics this decade:

- IR sequel to HST starting 2021: Training next generation researchers.

- JWST will define the next frontier to explore: the Dark Ages at $z \gtrsim 20$.

SPARE CHARTS

- References and other sources of material shown:

<http://www.asu.edu/clas/hst/www/jwst/> [Talk, Movie, Java-tool]

<http://www.asu.edu/clas/hst/www/ahah/> [Hubble at Hyperspeed Java-tool]

<http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/> [Clickable HUDF map]

<http://www.jwst.nasa.gov/> & <http://www.stsci.edu/jwst/>

<http://ircamera.as.arizona.edu/nircam/>

<http://ircamera.as.arizona.edu/MIRI/>

<http://www.stsci.edu/jwst/instruments/nirspec/>

<http://www.stsci.edu/jwst/instruments/fgs>

Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

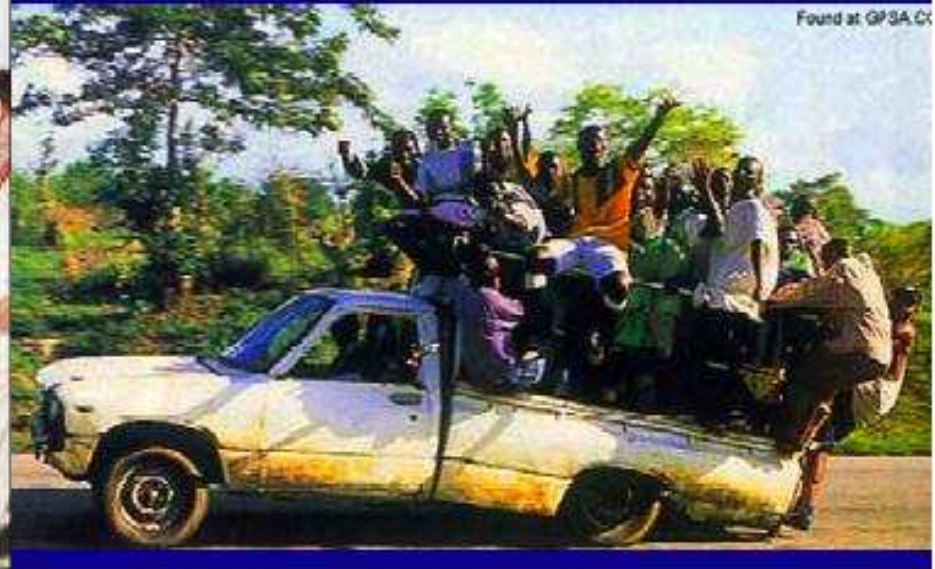
What the Scientists See:



What the Project Manager Sees:



The Happy Balance



Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

- (6) Update of JWST programmatic as of 2019

Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements





Baseline "Cup Down" Tower Configuration at JSC (Before)



JSC "Cup Up" Test Configuration (New Proposal)



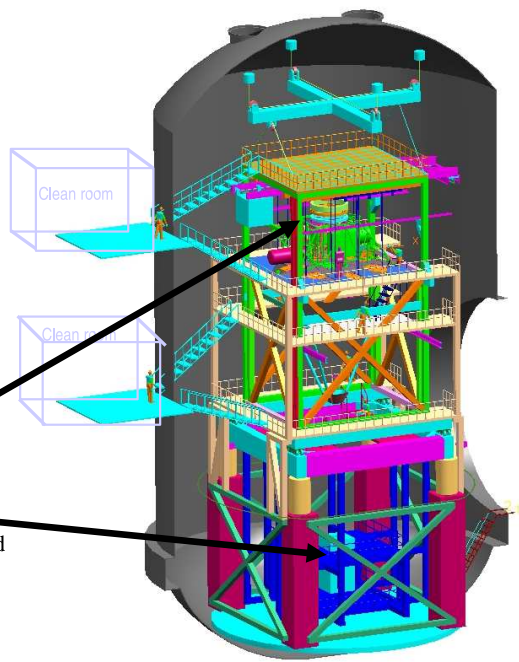
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling

JSC currently has 7 KW He capability

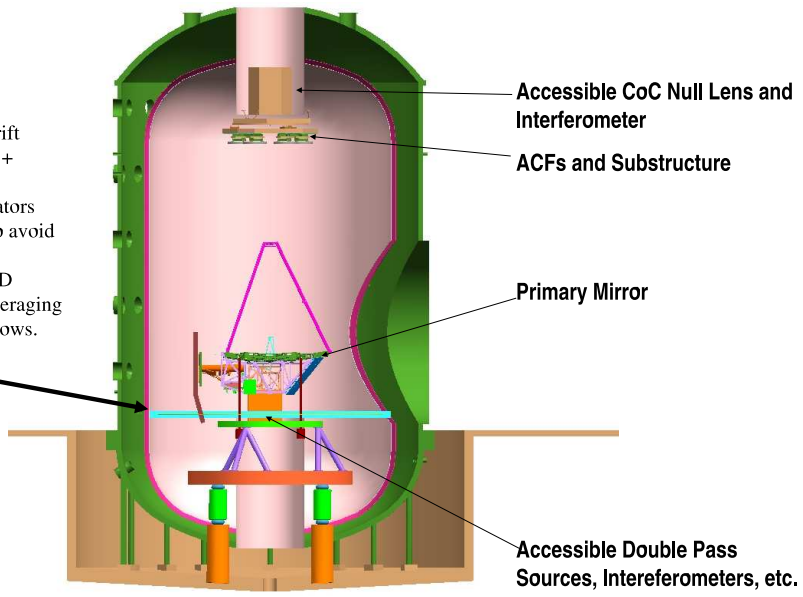
Current plan includes 10 trucks of LN2/day during cooldown

Interferometers, Sources, Null Lens and Alignment Equipment Are in Upper and Lower Pressure Tight Enclosure Inside of Shroud



No Metrology Tower and Associated Cooling H/W. External Metrology
Two basic test options:
1. Use isolators, remove drift through fast active control + freeze test equipment jitter
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter
Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

Possible payload "floor" to separate ambient pressure and temperature.



Drawing care of ITT

JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim 2003$: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.

Fiscal Year 2017 JWST HQ Milestones

Month	Milestone	FY2016 Deferral	Comment
Oct-16	1 Complete portable clean room for Telescope and Science Instruments (OTIS)		<u>Completed 10/13/16</u>
	2 Complete final checkout of new shaker tables at Goddard Space Flight Center		• <u>Completed 10/13/16</u>
	3 Begin making electrical connections between spacecraft panels		<u>Completed 10/7/16</u>
	4 Complete Sunshield Mid-Boom Assembly #2 functional test		• <u>Completed 12/5/16</u>
Nov-16	5 Start optical measurements of OTIS prior to vibration and acoustic tests		<u>Completed 10/24/16</u>
	6 Deliver Science and Operations Center release 1		<u>Completed 9/30/16</u>
	7 Perform Cryocooler installation into the spacecraft bus and begin functional testing		<u>Completed 10/29/16</u>
	8 Complete Aft Unitized Pallet Structure assembly		• <u>Completed 10/29/16</u>
	9 Deliver Aft Unitized Pallet Structure to Observatory I&T		• <u>Completed 3/14/17</u>
Dec-16	10 Deliver Forward Sunshield Pallet Structure to Observatory Integration and Test (I&T)		• <u>Completed 3/28/17</u>
	11 Start OTIS vibration and acoustic testing program		<u>Completed 11/19/16</u>
	12 Complete final test of engineering model of telescope center section at Johnson Space Center (JSC)		<u>Completed 10/31/16</u>
	13 Deliver sunshield flight membranes to Observatory I&T		<u>Completed 12/15/16</u>
Jan-17	14 Complete OTIS vibration and acoustics testing		<u>Completed 3/2/17</u>
	15 Deliver observing proposal and planning subsystem software build that supports launch		<u>Completed 1/12/17</u>
	16 Complete electrical testing of the spacecraft at Northrop-Grumman		<u>Completed 3/7/17</u>
Feb-17	17 Complete OTIS optical measurements after vibration and acoustic tests		<u>Completed 3/31/17</u>
	18 Deliver wavefront and control software that supports launch (controls telescope mirror shape)		<u>Completed 1/20/17</u>
	19 Deliver horizontal deployable radiators to Observatory I&T		<u>Delayed June for release testing</u>
Mar-17	20 Deliver OTIS to the Johnson Space Center		<u>Completed 5/7/17</u>
	21 Deliver the pre-launch Flight Operations System software build		<u>Completed 2/17/17</u>
	22 Delivery of sunshield extension boom #2 membrane attachment assembly to Observatory I&T		<u>Completed 4/13/17</u>
Blue font(<u>underline</u>) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late. "*" denotes 2016 milestones carried forward.			

170612 JWST Monthly Telecon 2

Milestones: How the Project reports its progress monthly to Congress.

Summer–Early Fall 2017: Lates started to outnumber the Early's.

Milestone Performance

- Since the September 2011 replan JWST reports high-level milestones monthly to numerous stakeholders

	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year	Deferred more than one quarter
FY2011	21	21	6	3	0	0
FY2012	37	34	16	2	3	3
FY2013	41	38	20	5	3	2
FY2014❖	36	23	10	8	11	10
FY2015	48	44	22	12	4	3
FY2016	45	39	25	7	6	2
FY2017	38	32	12	13	8	5
FY2018	31	18	7	2	13	13
FY2019	25	10	6	1	0	0

❖ Milestone accounting in FY2014 was complicated by the government shutdown and multicomponent milestones

5

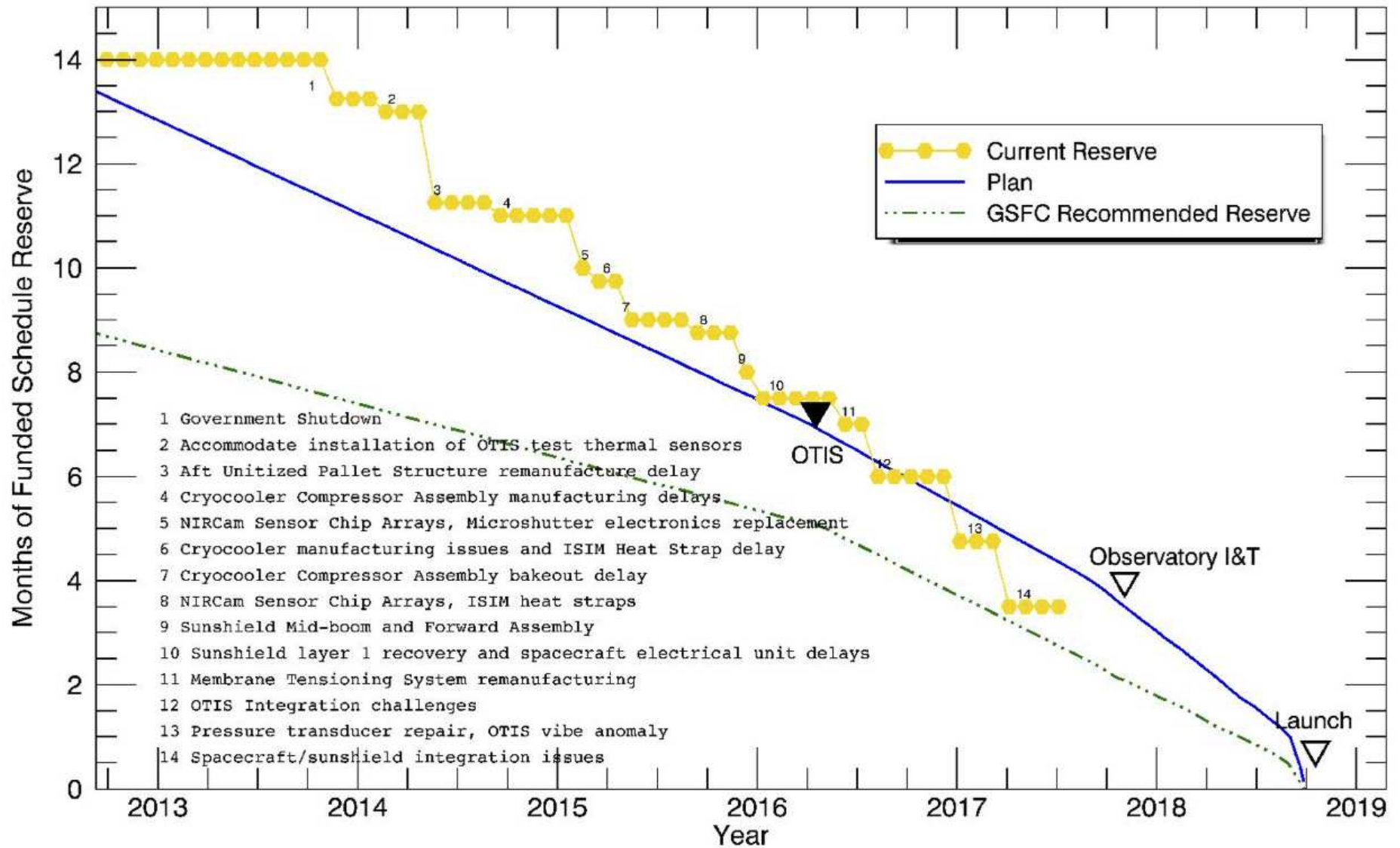
190408 JWST Monthly Telecon 6

FY14: 8 milestones late by 1 month due to Oct 13 Government shutdown.

FY15: Most “Lates” not on critical path.

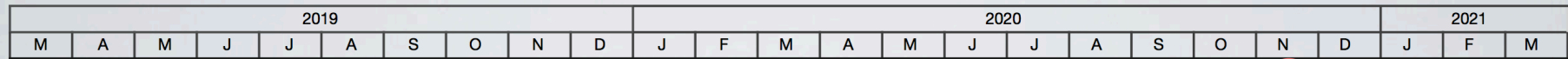
FY17: Lates started to outnumber the Early’s.

Funded Schedule Reserve

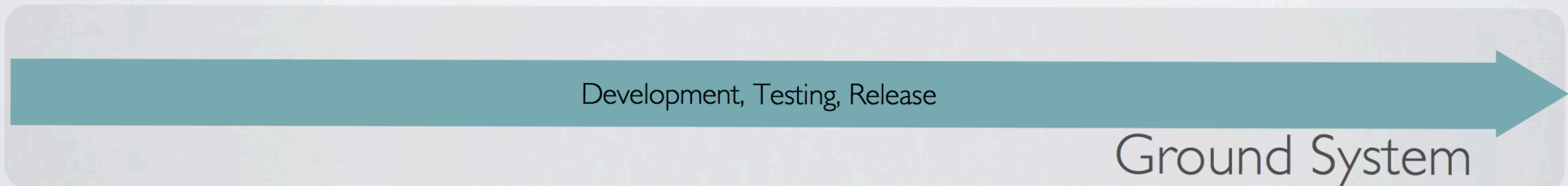
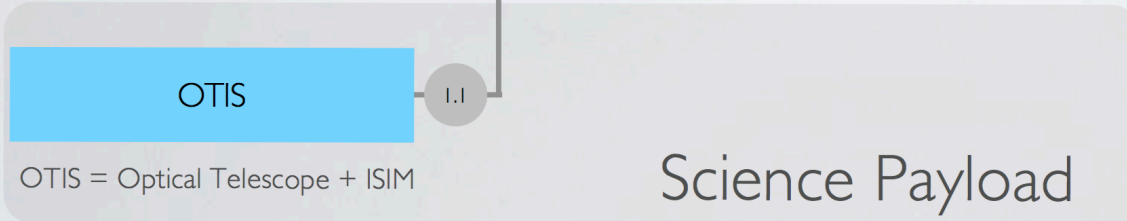
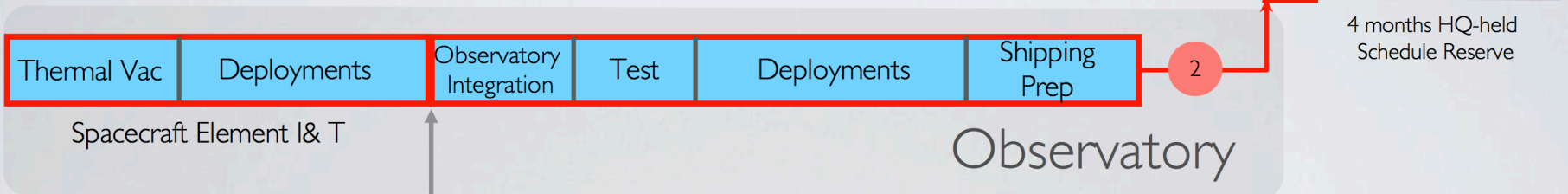


To stay on schedule, need: 1) Sufficient Project contingency ($\gtrsim 25\%$ of total).
 2) Replanned and newly managed Project (in 2011 and 2017/2018).

SIMPLIFIED SCHEDULE



k months of project funded critical path (mission pacing) schedule reserve



- Path forward to Launch (NOW: March 2021): $\lesssim 5$ mos schedule reserve.
- Spacecraft and Sunshield are now on critical path (at Northrop).

Fiscal Year 2019 JWST HQ Milestones

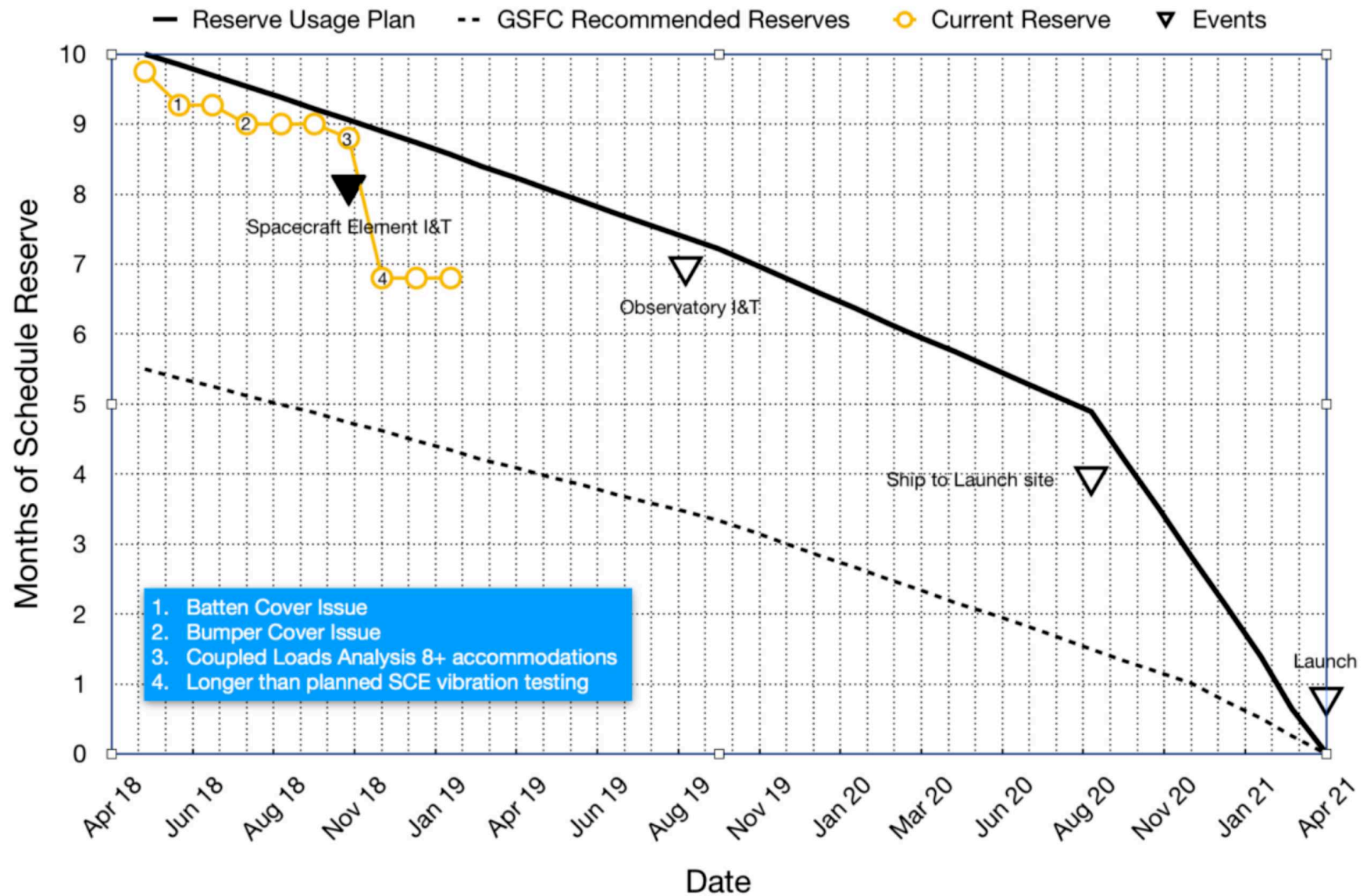
Month	Milestone	Comment
Oct-18	1 Conduct Wavefront Sensing rehearsal #2 at the Missions Operations Center (MOC)	Completed 10/6/18
	2 Stow the sunshield into launch position following repairs of the membrane covers	Completed 9/28/18
	3 Spacecraft Element (SCE) ready for resumption of environmental testing following MCA repairs	Completed 10/19/18
Nov-18	4 Complete Spacecraft Element Acoustic Test	Completed 10/28/18
	5 Deliver Observatory Science and Operations software build	Completed 10/19/18
Dec-18	6 Conduct Science Operations rehearsal #4 at the MOC	Completed 12/21/18
	7 Begin Spacecraft Element vibration testing	Completed 11/15/18
	8 Complete the validation of science payload software	Completed 10/27/18
Jan-19	9 Conduct a SCE Comprehensive System Test in preparation for thermal vacuum testing	Completed 9/26/18
Feb-19	10 Deliver final results for SCE environmental testing	
	11 Conduct Early Commissioning Exercise #2 at the MOC	Completed 3/6/2019 (Government shutdown delay)
Mar-19	12 Begin Spacecraft Element thermal vacuum test	
	13 Deliver the flight version of launch vehicle coupled loads analysis #2 Observatory model	
Apr-19	14 Open thermal vacuum chamber door following testing	
	15 Conduct Wavefront Sensing rehearsal #3 at the MOC	
May-19	- NONE	
Jun-19	16 Complete Spacecraft Element post-launch environmental testing deployment	
	17 Complete the secondary mirror structure deployment driven by the Spacecraft Element	
Jul-19	18 Received updated Cycle 1 proposals from the Guaranteed Time Observers	
	19 Conduct Science Operations rehearsal #5 at the MOC	
Aug-19	20 Complete Spacecraft Element post-launch environments and thermal vacuum testing folding	
	21 Observatory System Integration Review (SIR)	
Sep-19	22 Install science payload onto the Spacecraft Element	
	23 Deliver the flight version of launch vehicle coupled loads analysis #2 results and detailed assessment	
	24 Spacecraft Element Integration complete	
	25 Conduct Contingency Planning rehearsal #3 at the MOC	

Blue font(underline) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late.

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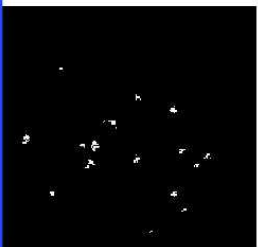
Project now back on track in Fall 2018/early 2019 to launch in March 2021.

Funded Schedule Reserve

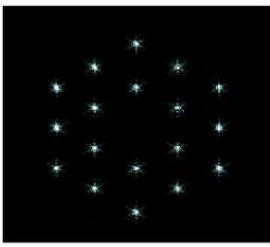


Project now back on track in Fall 2018/early 2019 to launch in March 2021.

**First light
NIRCam**



1. Segment Image Capture



After Step 1

Initial Capture

Final Condition

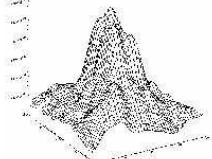
18 individual 1.6-m diameter aberrated sub-telescope images
 PM segments: < 1 mm, < 2 arcmin tilt
 SM: < 3 mm, < 5 arcmin tilt

PM segments:
 < 100 μm,
 < 2 arcsec tilt
 SM: < 3 mm,
 < 5 arcmin tilt

2. Coarse Alignment

Secondary mirror aligned
 Primary RoC adjusted

After Step 2



Primary Mirror segments:
 < 1 mm, < 10 arcsec tilt
 Secondary Mirror :
 < 3 mm, < 5 arcmin tilt

WFE < 200 μm (rms)

3. Coarse Phasing - Fine Guiding (PMSA piston)

After Step 3

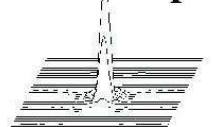


WFE: < 250 μm rms

WFE < 1 μm (rms)

4. Fine Phasing

After Step 4

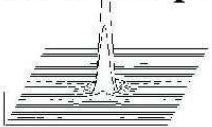


WFE: < 5 μm (rms)

WFE < 110 nm (rms)

5. Image-Based Wavefront Monitoring

After Step 5

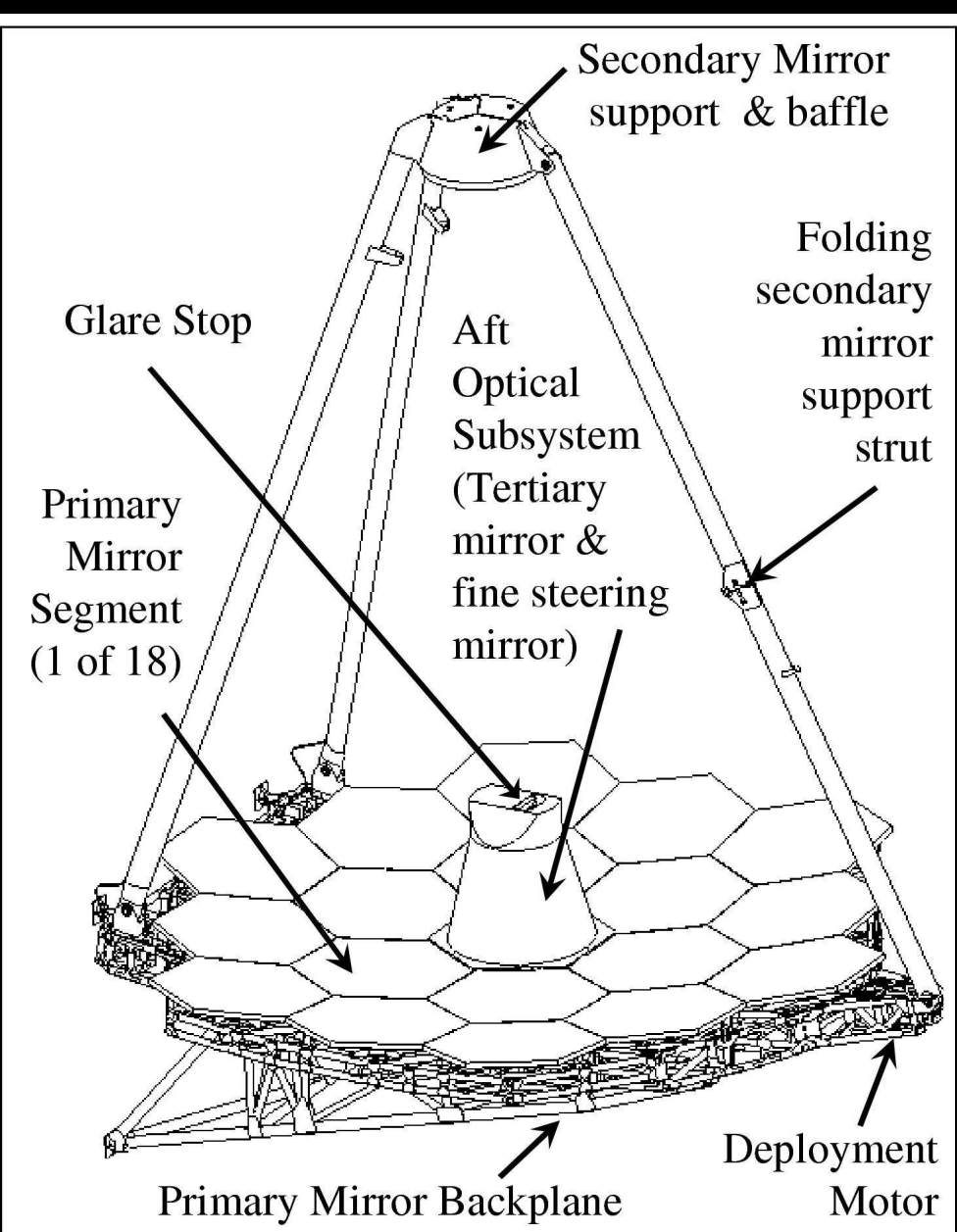


WFE: < 150 nm (rms)

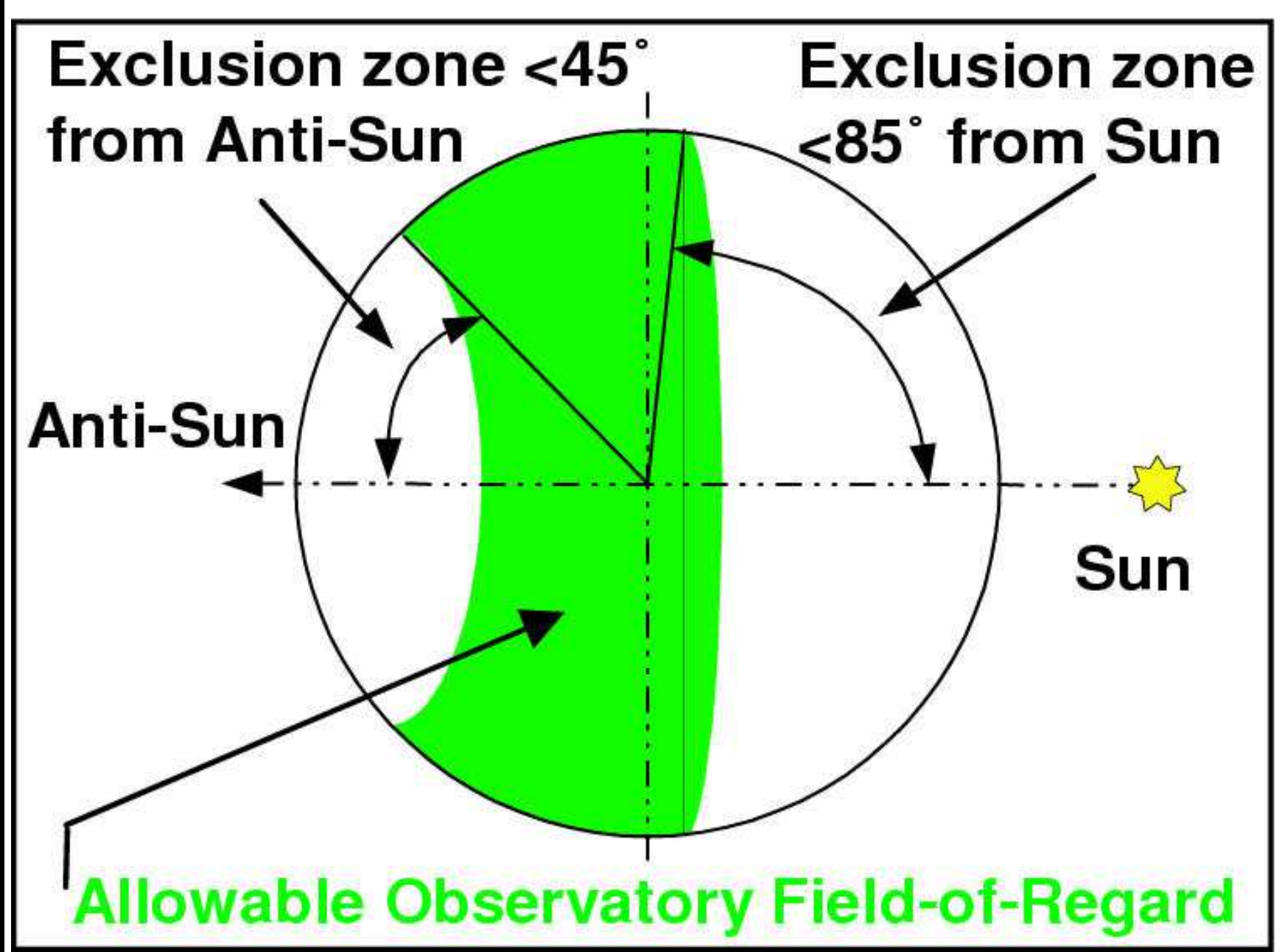
WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to the Keck telescope.

In L2, need WFS updates every 10 days depending on scheduling/illumination.



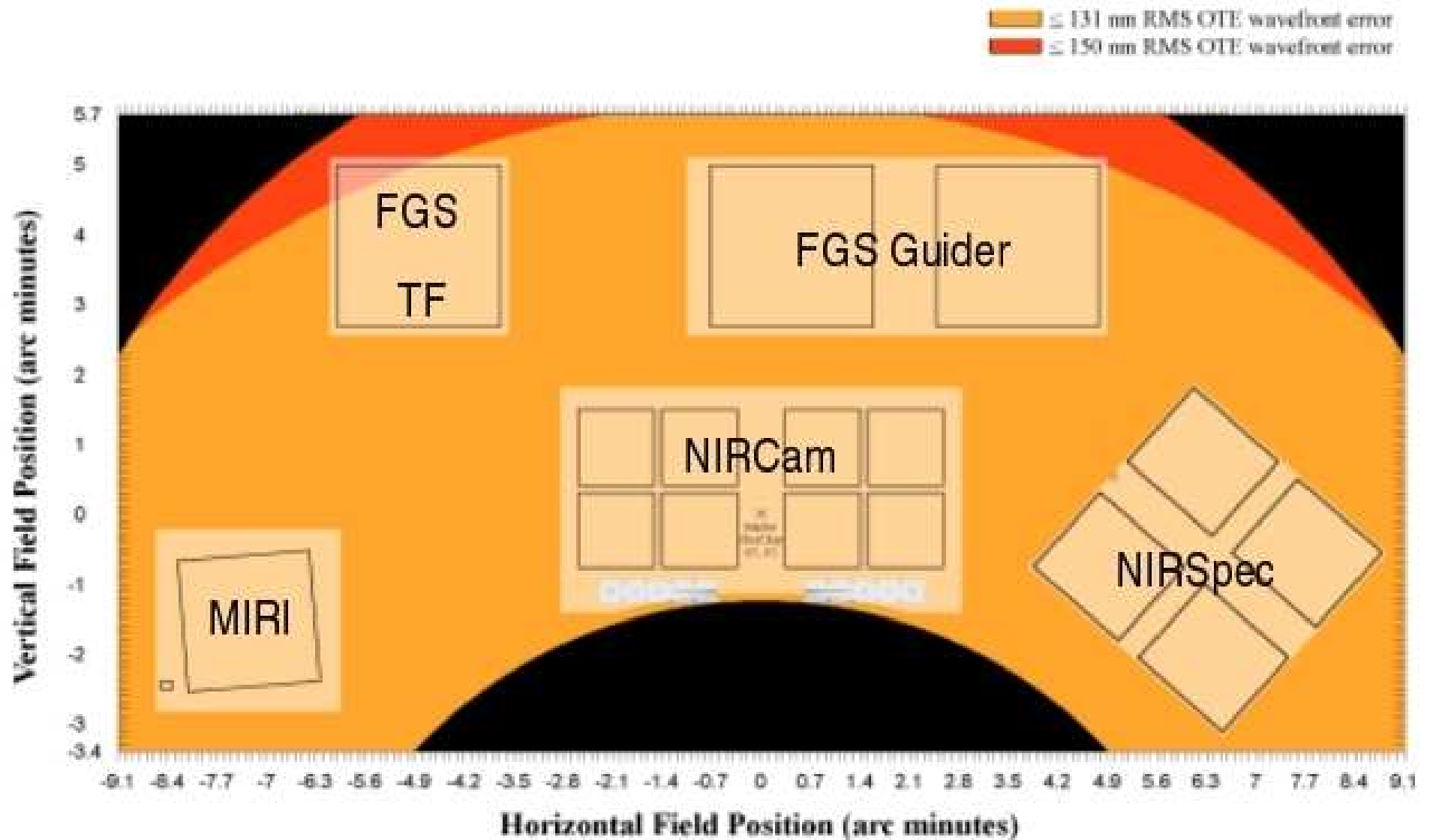
Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015–2017.
Ball 1/6 scale-model for WFS: produces diffraction-limited $2.0 \mu\text{m}$ images.



JWST can observe North/South Ecliptic pole targets continuously:

- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- JWST gets the very best reaction wheels (Rockwell Collins; Heidelberg).

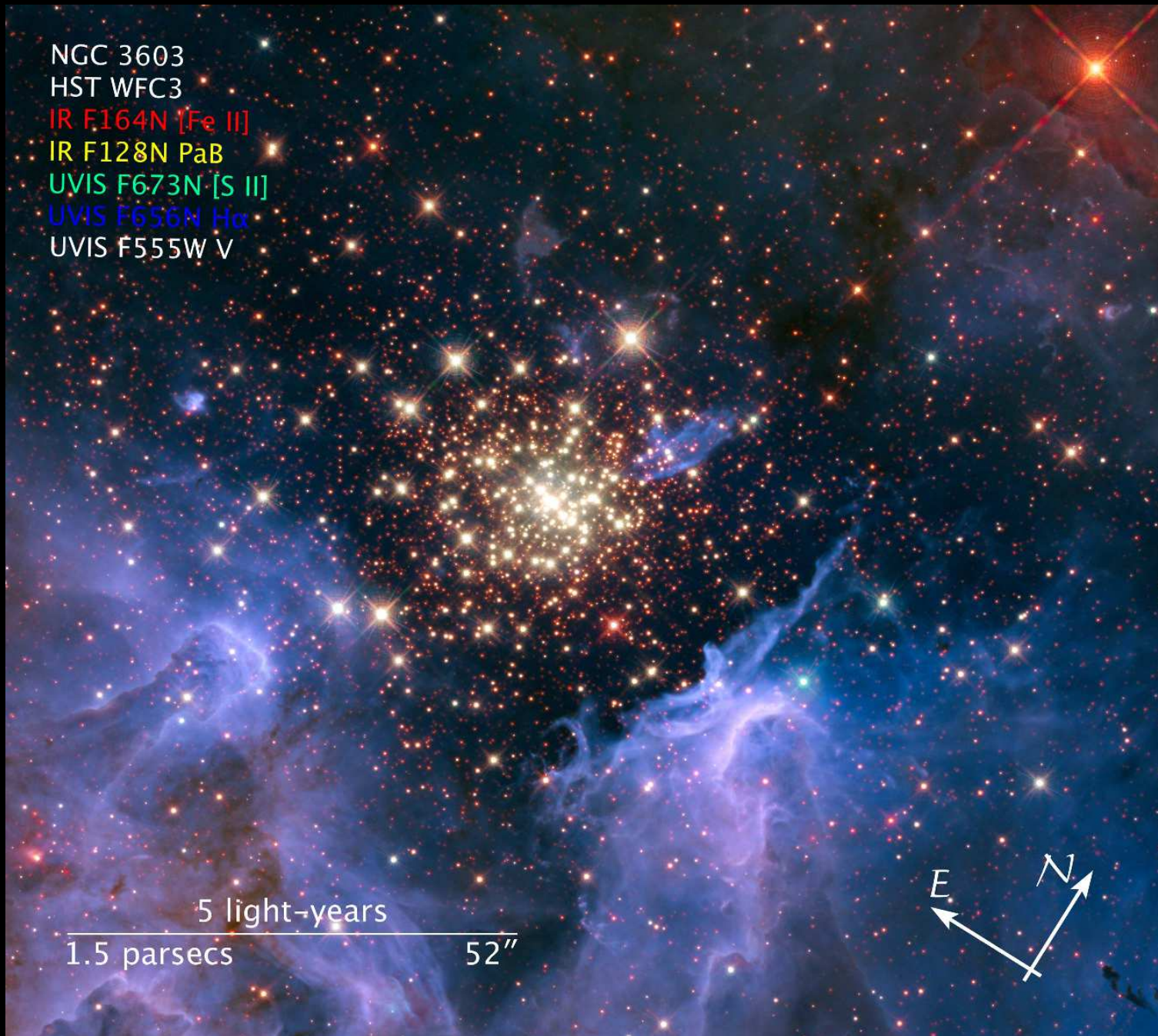
- What instruments will JWST have?



All JWST instruments can in principle be used in parallel observing mode:

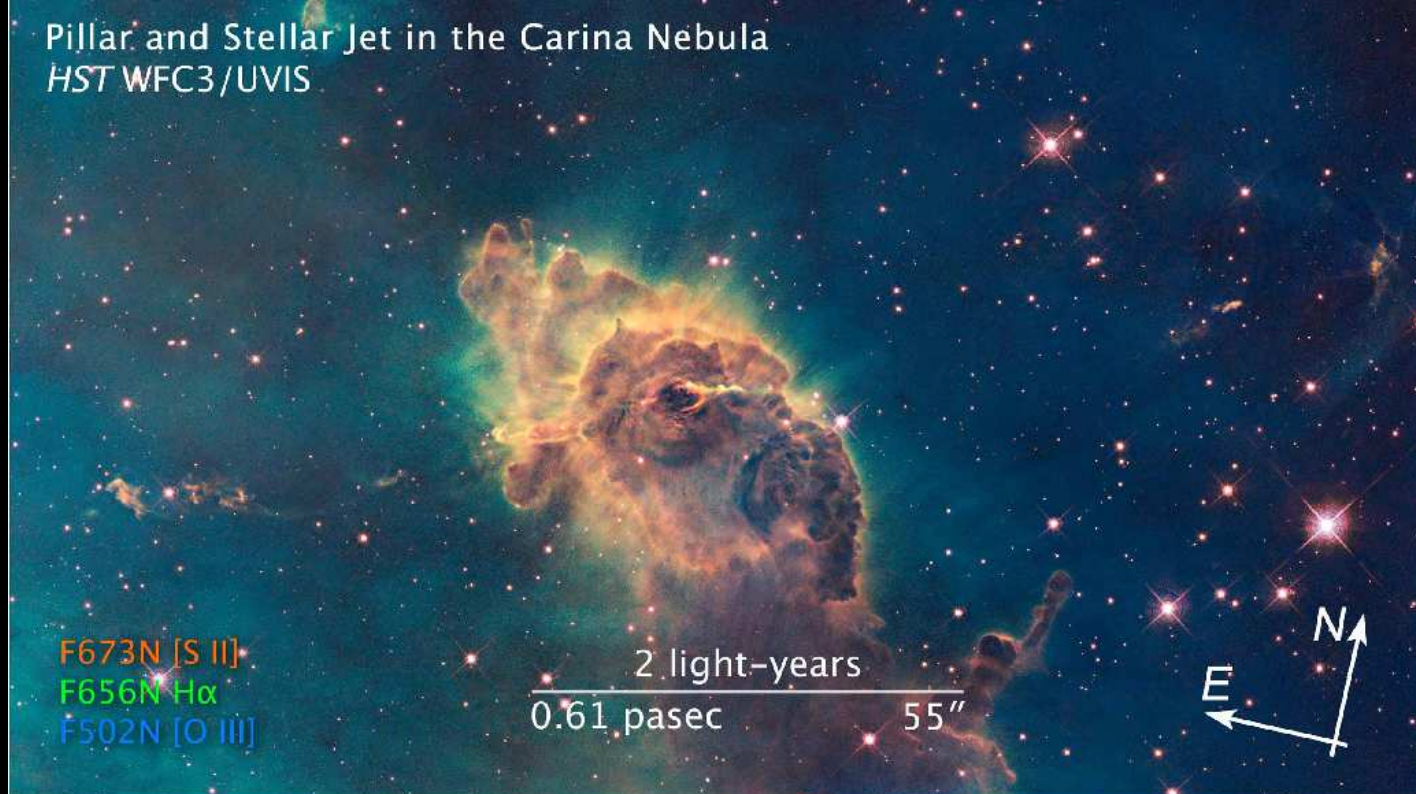
- Currently only being implemented for parallel *calibrations*.

(7) How can JWST measure Star-Formation and Earth-like exoplanets?



NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"

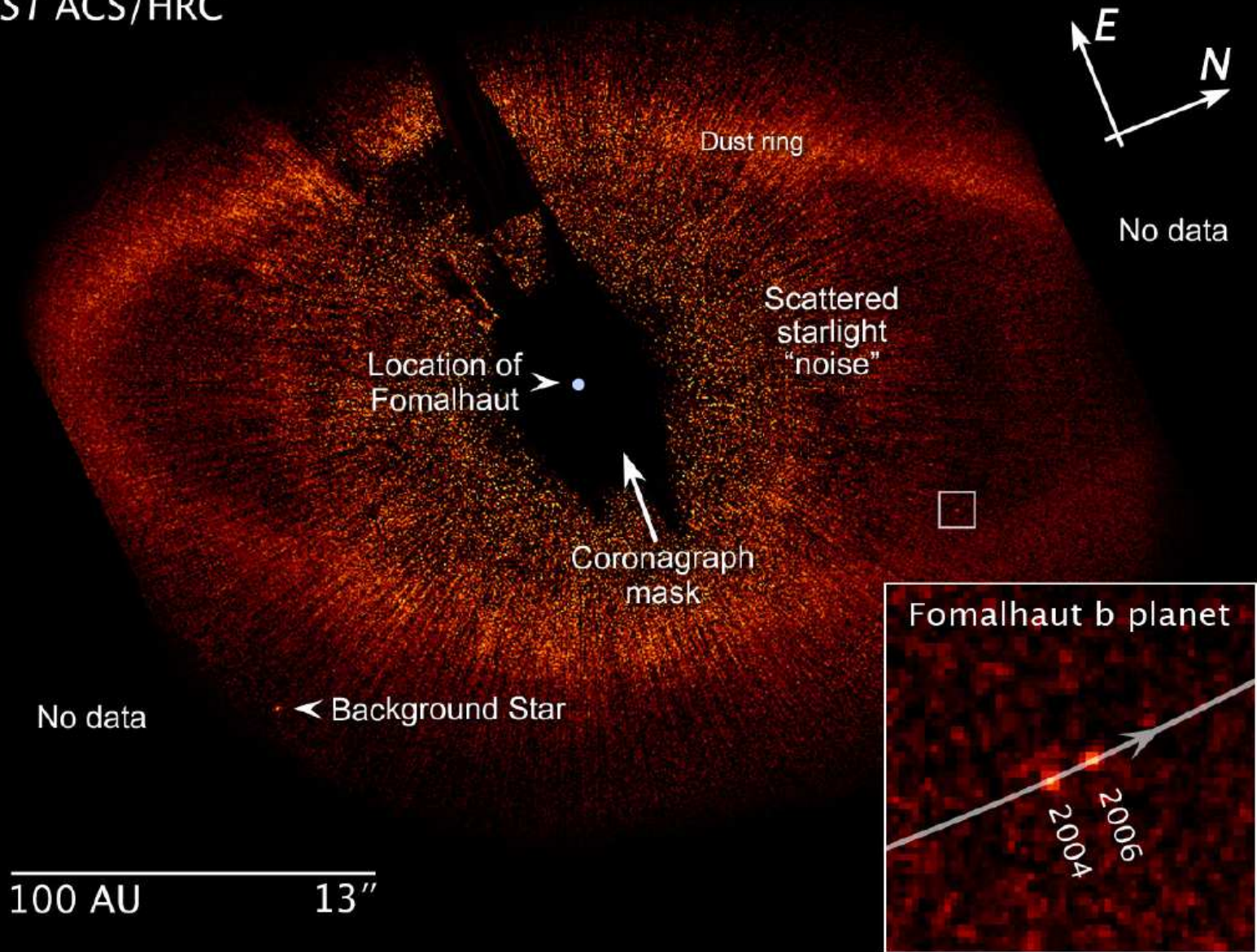
Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS



HST WFC3/IR



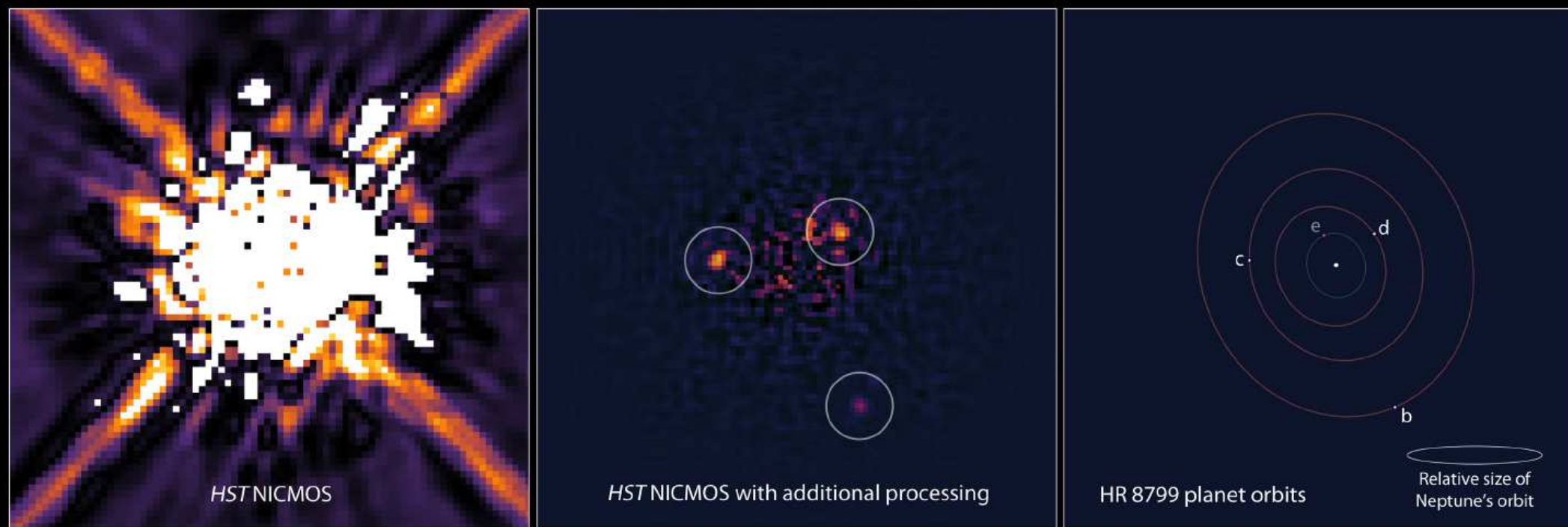
Fomalhaut
HST ACS/HRC



HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut:
First direct imaging of a moving planet forming around a nearby star!

JWST can find such planets much closer in for much farther stars.

Exoplanet HR 8799 System



HST/NICMOS

HST/NICMOS with additional processing

HR 8799 planet orbits

Relative size of
Neptune's orbit

NASA, ESA, and R. Soummer (STScI)

STScI-PRC11-29

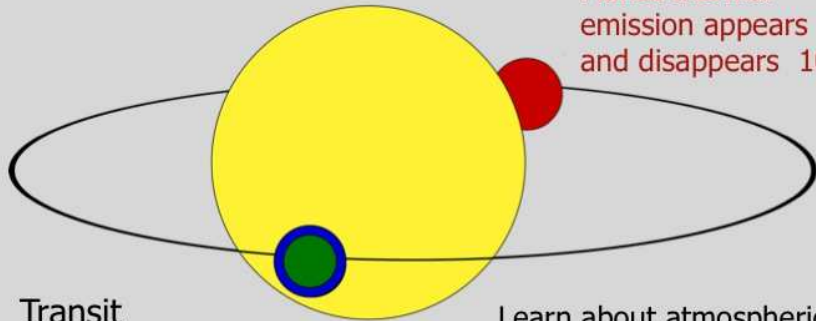
HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

Press release: <http://hubblesite.org/newscenter/archive/releases/2011/29/>

JWST can find such planets much closer in for much farther-away stars.

Schematic of Transit and Eclipse Science

Seager & Deming (2010, ARAA, 48, 631)



Transit

Measure size of planet 10^{-2}

See starlight transmitted through planet atmosphere 10^{-4}

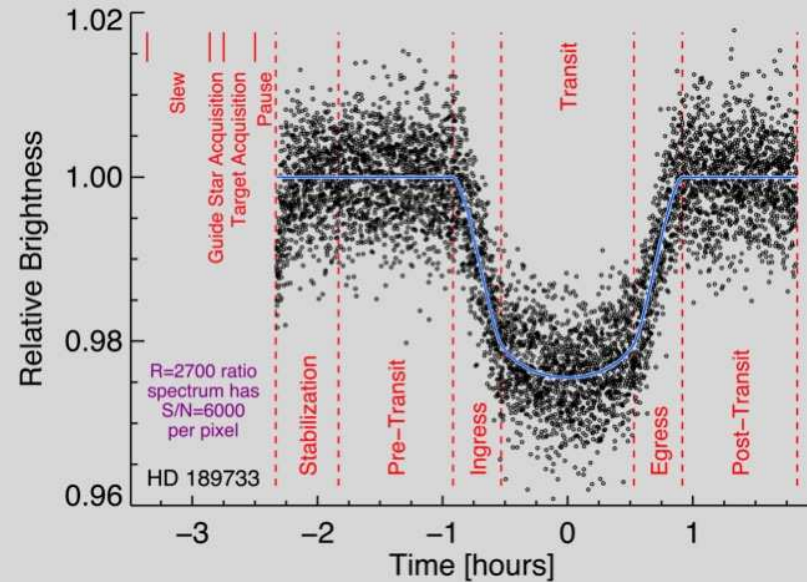
Eclipse

Planet thermal emission appears and disappears 10^{-3}

Learn about atmospheric circulation from thermal phase curves

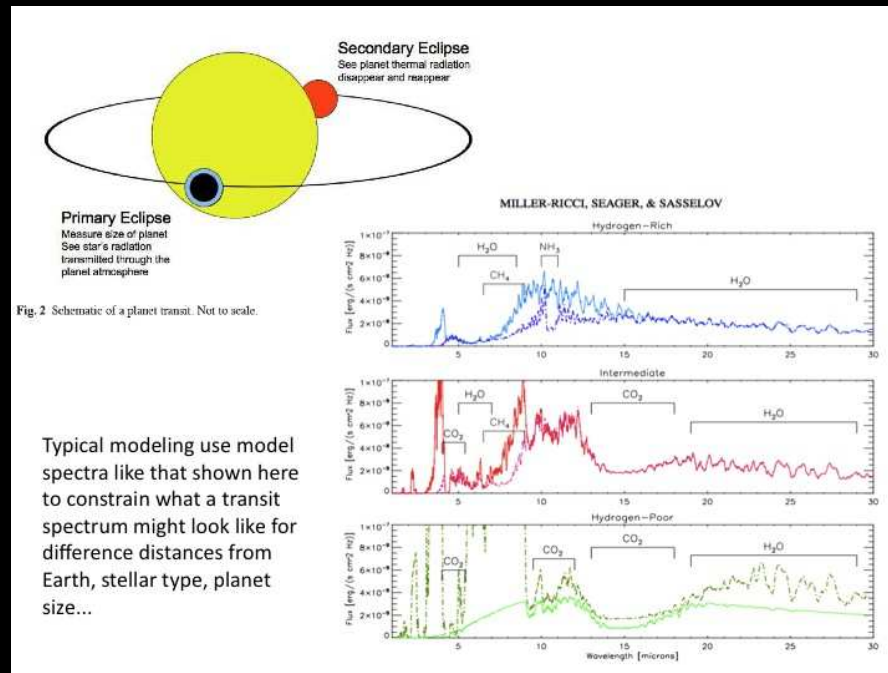
6

Timeline of a Transit Observation



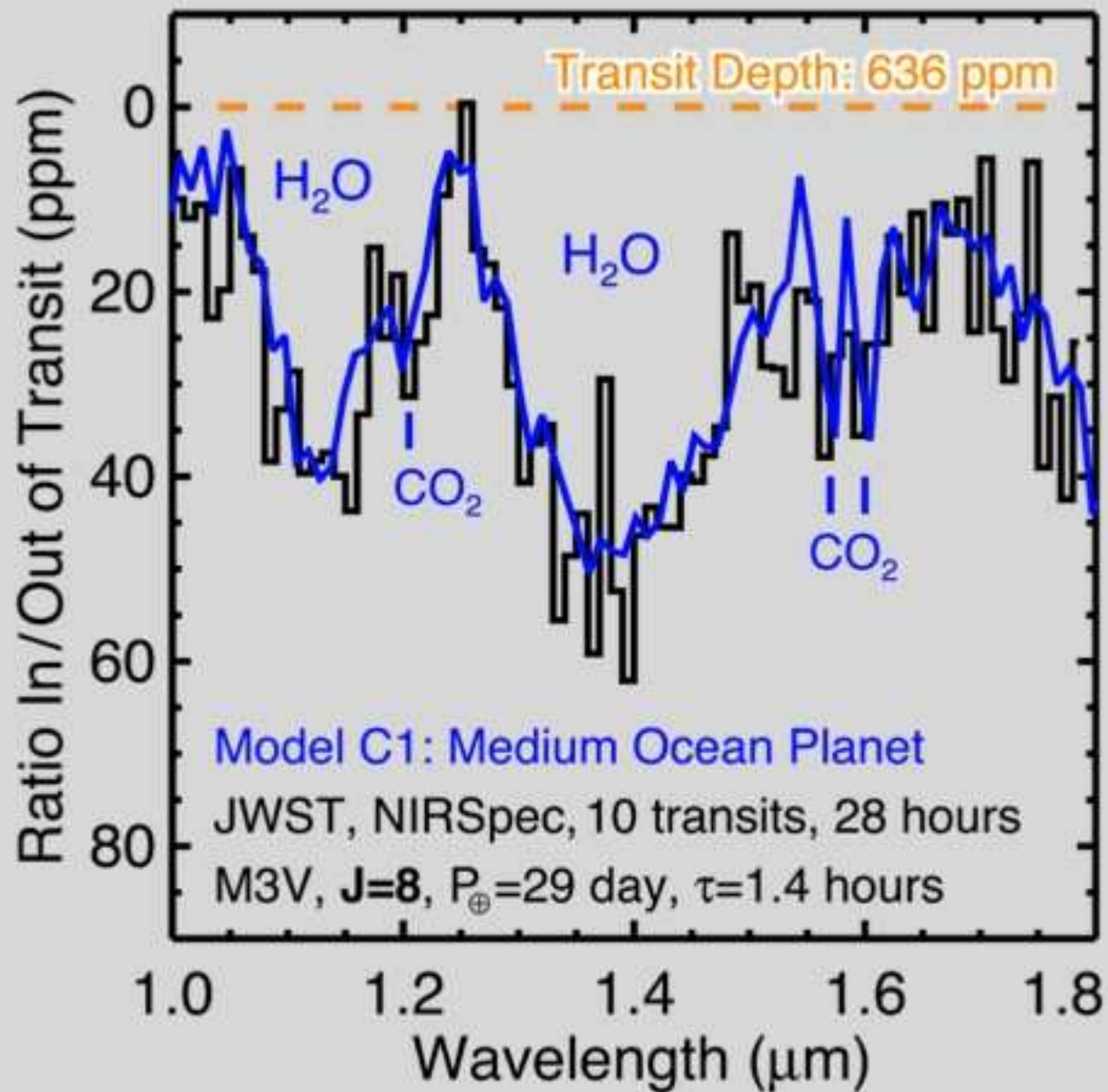
13

JWST can do very precise photometry of transiting Earth-like exoplanets.



JWST IR spectra can find water and CO₂ in (super-)Earth-like exoplanets.

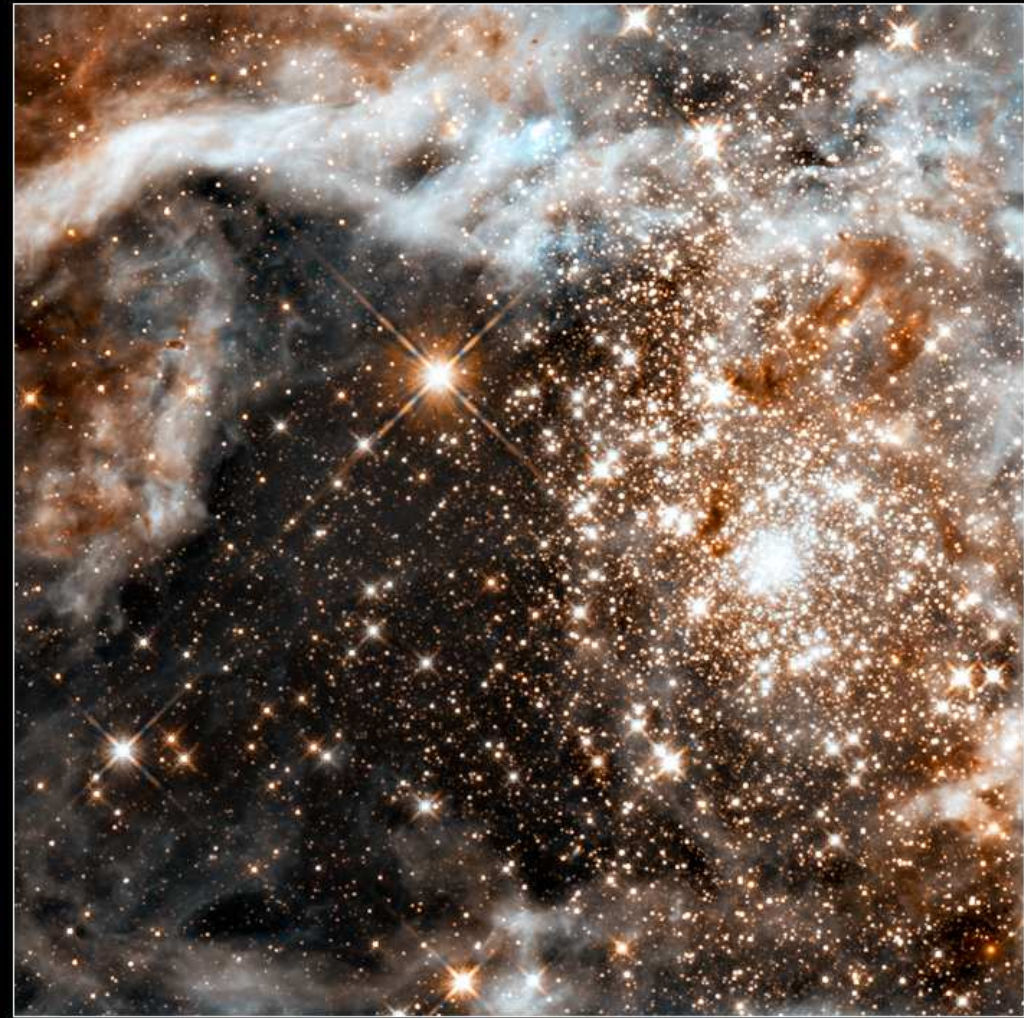
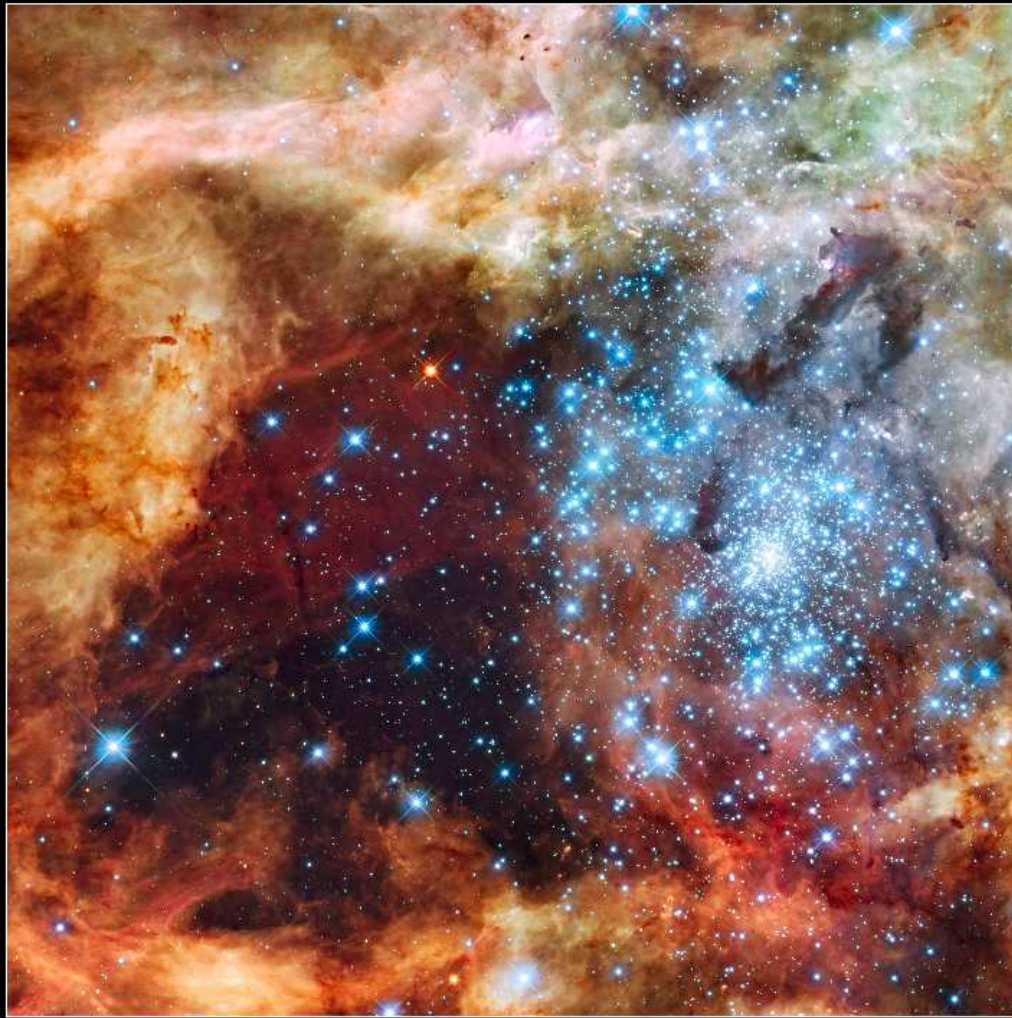
Transit Spectrum of Habitable "Ocean Planet"



JWST IR spectra can find water and CO₂ in transiting Earth-like exoplanets.

Visible

Infrared



30 Doradus Nebula and Star Cluster
Hubble Space Telescope ■ WFC3/UVIS/IR

NASA, ESA, F. Paresce (INAF-IASF, Italy), and the WFC3 Science Oversight Committee

STScI-PRC09-32b

30 Doradus: Giant young star-cluster in Large Magellanic Cloud (150,000 ly), triggering birth of Sun-like stars (and surrounding debris disks).





(8) What do our Astrophysics College Graduates do?

Future Careers at NASA:

- Over the last 25 years, (ASU) Astrophysics College Graduates typically:
- (0) Have very low unemployment (\lesssim few %).
- (1) About 30% are faculty at Universities or 4-year colleges.
- (2) About 30% are researchers at NASA or other government centers.
- (3) About 20% work in Aerospace or related industries.
- (4) About 20% are faculty at Community Colleges or Highschools.

See also: <http://aas.org/learn/careers-astronomy>

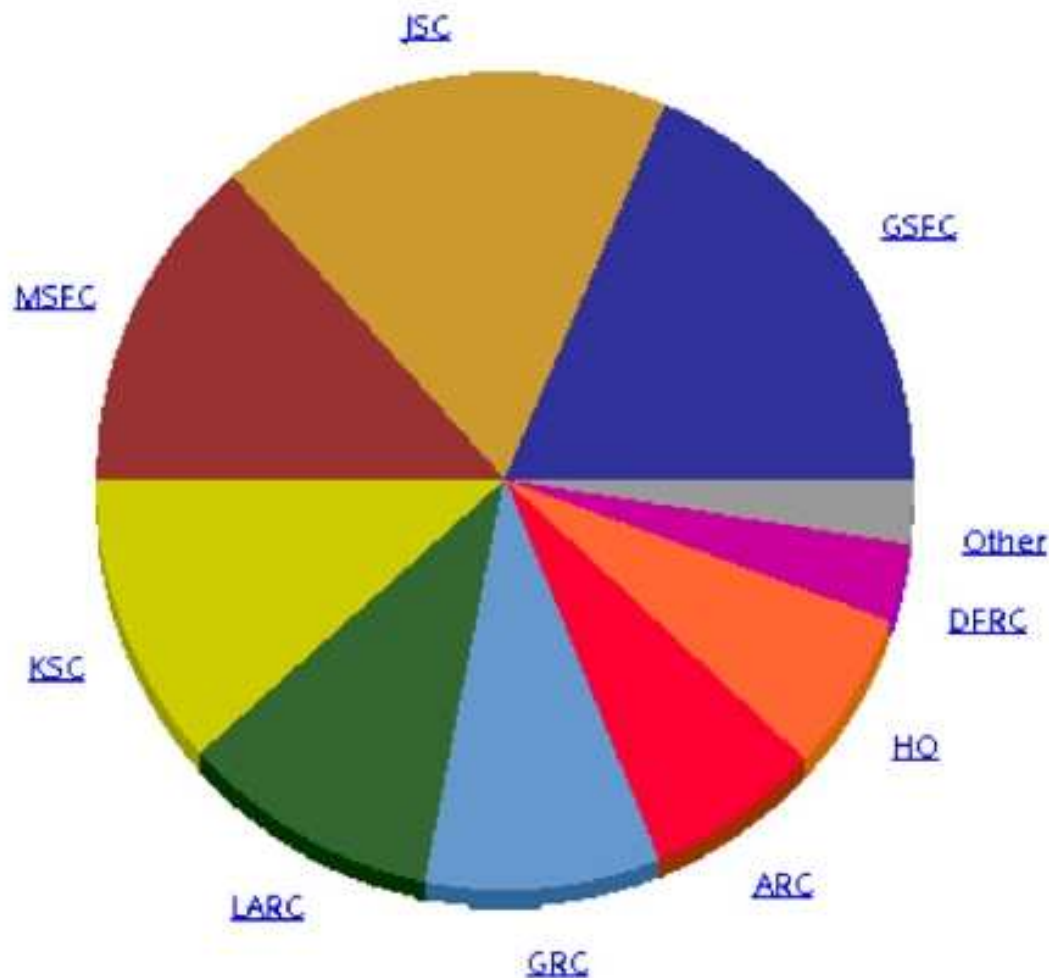
<http://www.aip.org/statistics/astronomy/>

<https://webapp4.asu.edu/programs/t5/careerdetails/19-2011.00?init=false&nopassive=true>

<http://scitation.aip.org/content/aip/magazine/physicstoday/article/68/6/10.1063/PT.3.2815>

CS Head Count

as values



Centers & NSSC	CS Head Count
<u>GSFC</u>	3,354
<u>JSC</u>	3,203
<u>MSFC</u>	2,432
<u>KSC</u>	2,055
<u>LARC</u>	1,881
<u>GRC</u>	1,640
<u>ARC</u>	1,215
<u>HQ</u>	1,152
<u>DERC</u>	558
Other	454

NASA workforce as pie-chart and in numbers — 2013 total: about 18,000).
Nation-wide NASA contractors (Northrop, Lockheed, Boeing, etc): 150,000.

See also: <https://wicn.nssc.nasa.gov/generic.html>

Some of our ASU grad students do important outreach events:



Annual Girl Scout Stargazing at the White House South lawn (July 2015).

Our own Amber Straughn (right; now at NASA GSFC working for Nobel Laureate Dr. John Mather) informs the Obama's about NASA.