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

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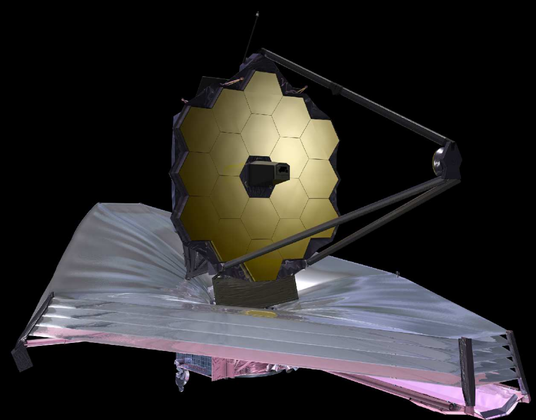
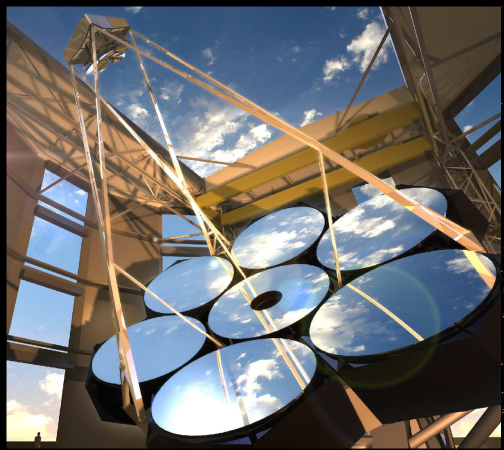
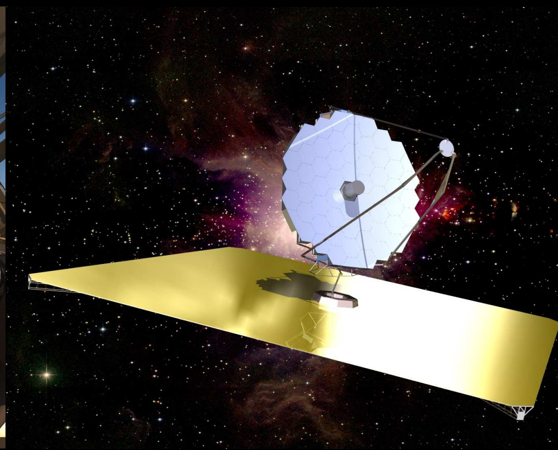






1973∼2020$^+$; 1996∼2031; 2000∼2050$^+$ 2020∼2050$^+$?

Invited Lecture in SES 121 class, ASU Tempe, Arizona (via Zoom)

Monday September 21, 2020. All presented materials are ITAR-cleared.

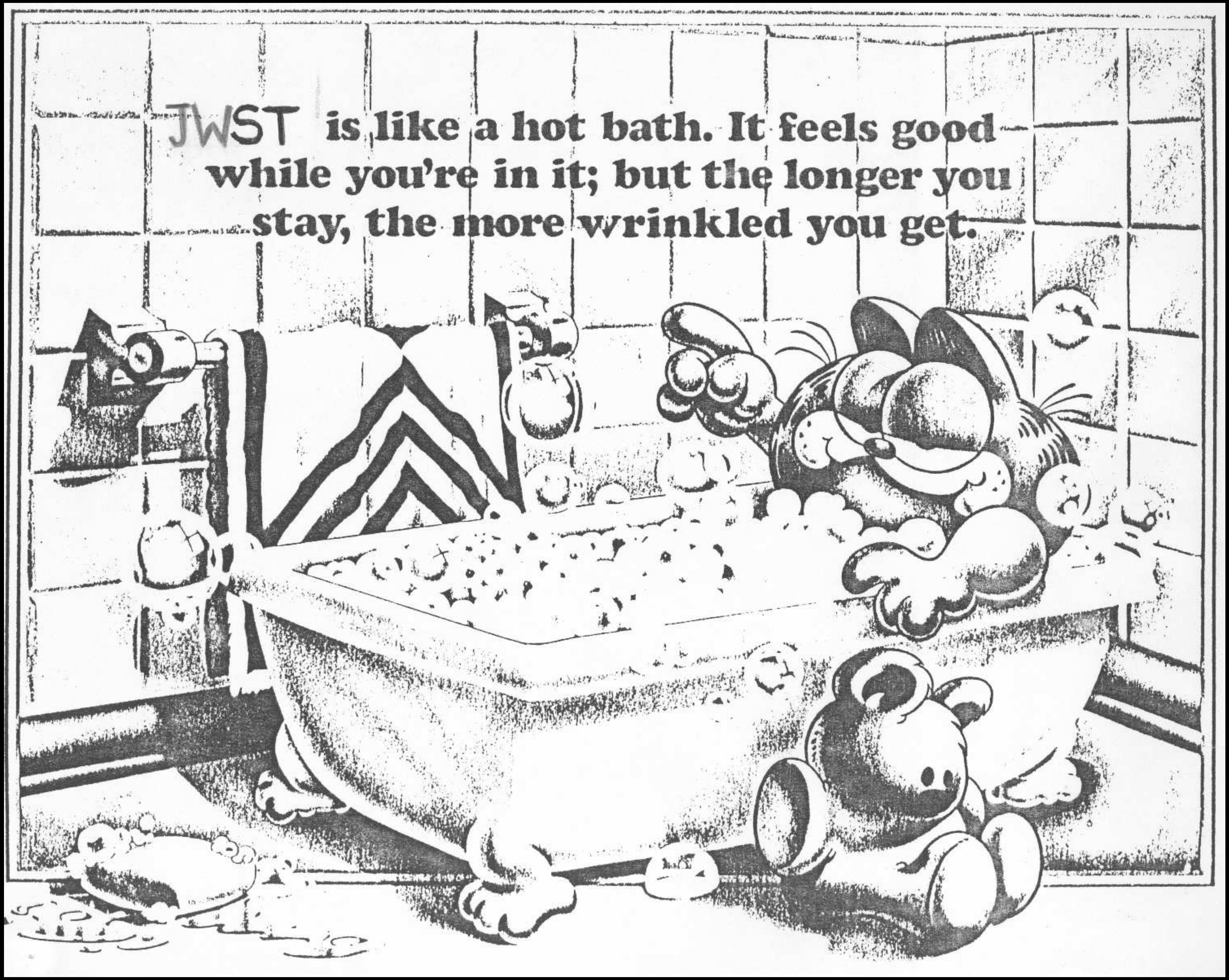
Outline

- (1) Update on the James Webb Space Telescope (JWST), 2020.
- (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 2020.
  - (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

Arizona State University

Talk is on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/asuUGs20SES121_hstjwst.pdf



WARNING: Both Hubble and James Webb are 30–40^{+} year projects:

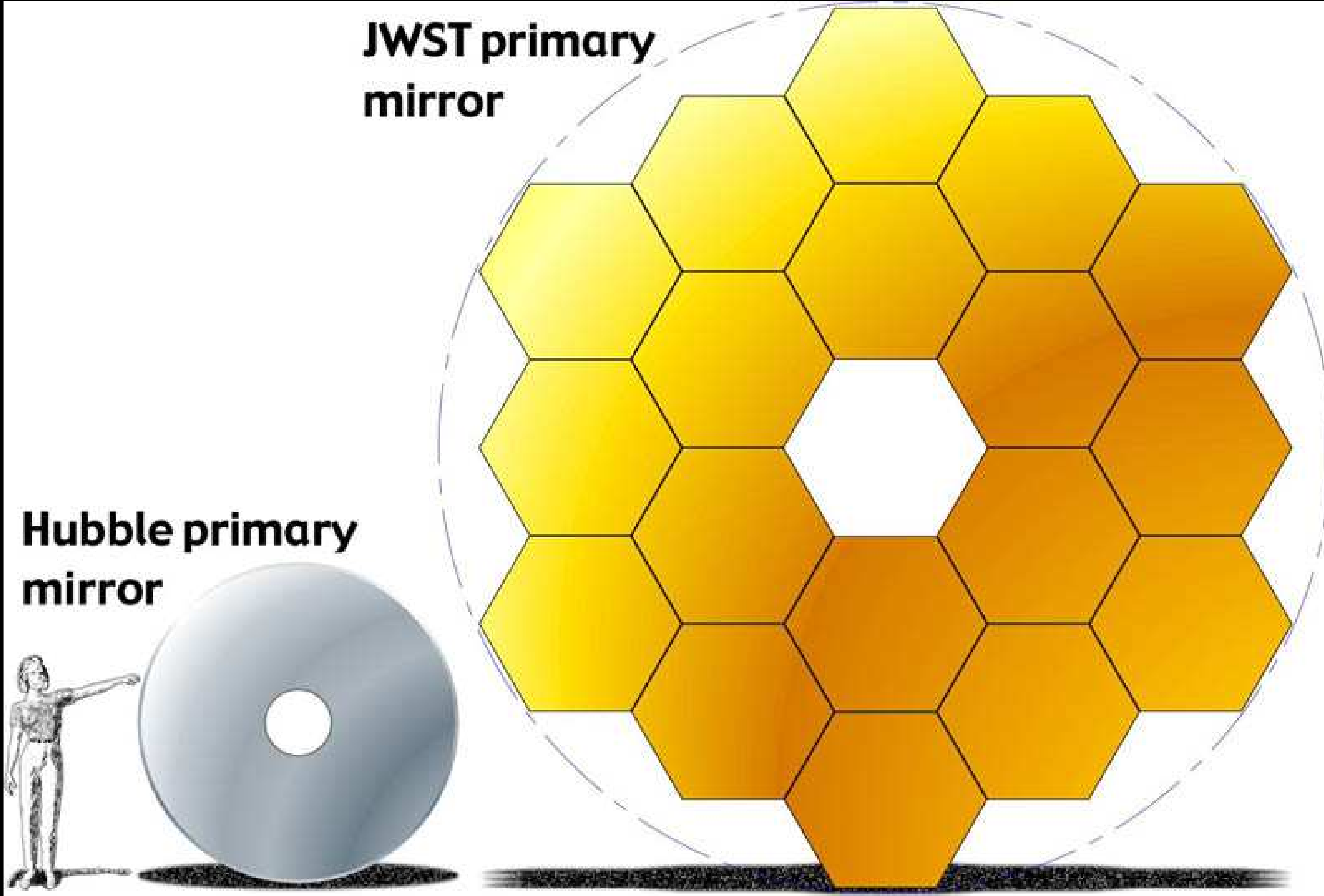
You will feel wrinkled before you know it ... :)

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

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

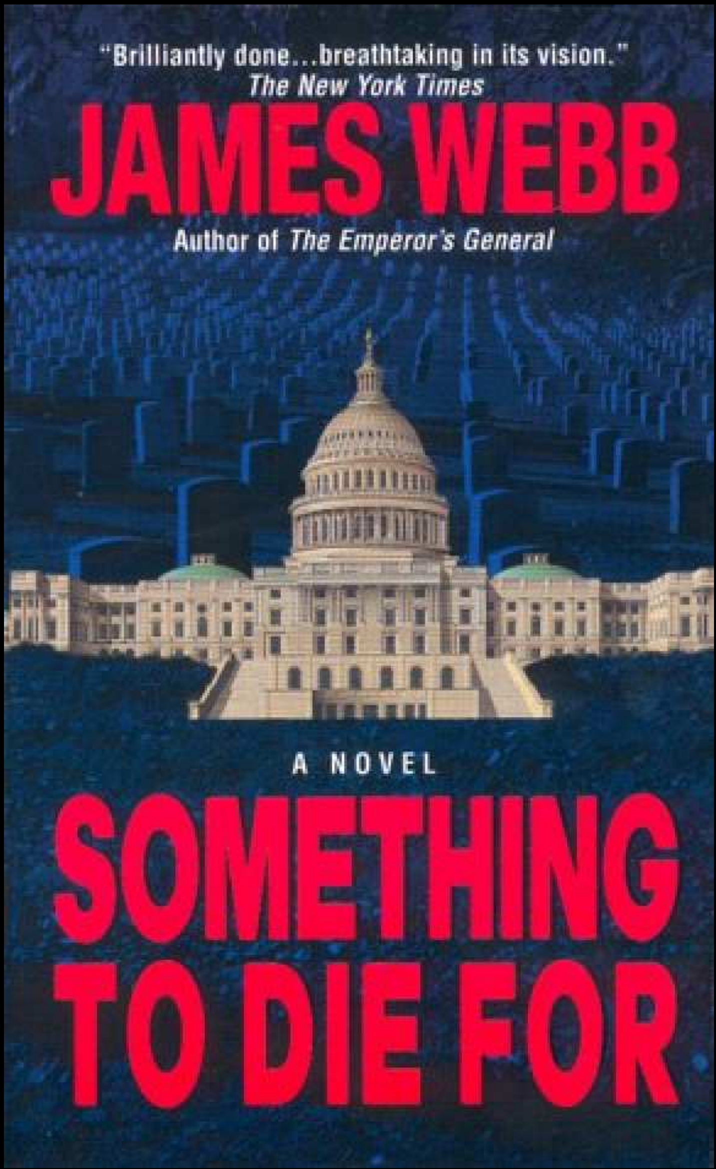
Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2020?.

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



JWST $\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.

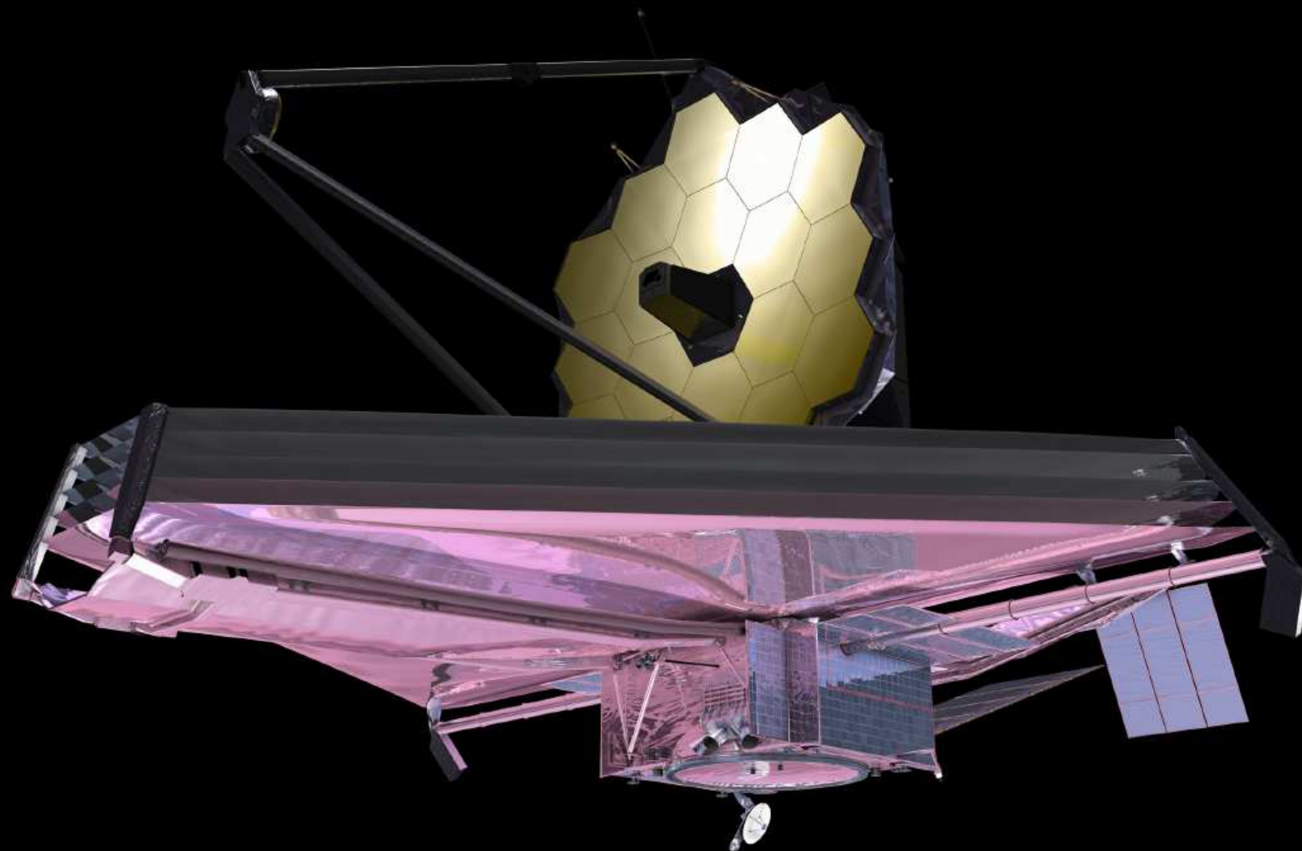
(1) Update of the James Webb Space Telescope (JWST), 2020



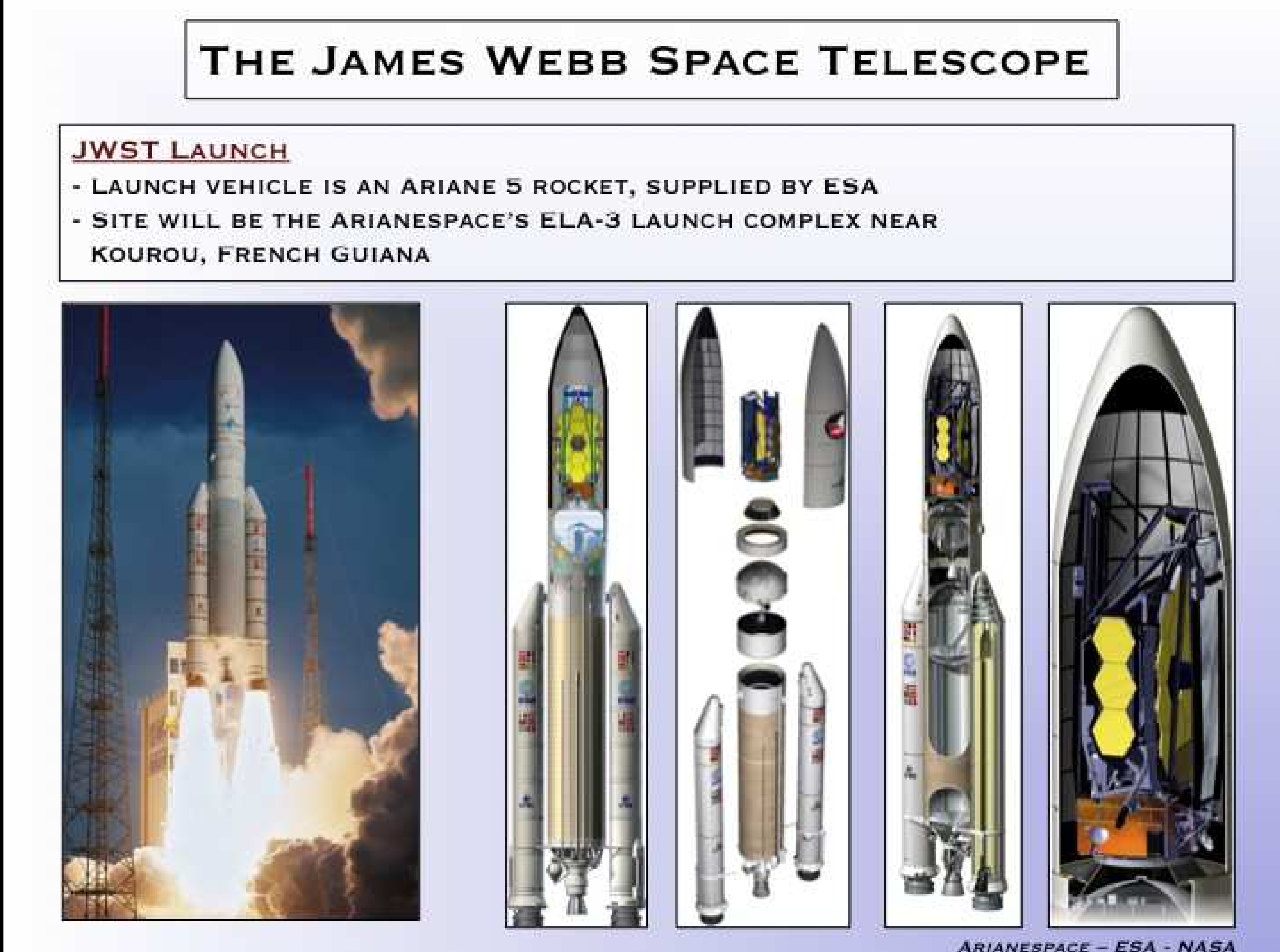
To be used by students & scientists starting 2021 … It'll be worth it.

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

(1) Update of the James Webb Space Telescope as of 2020

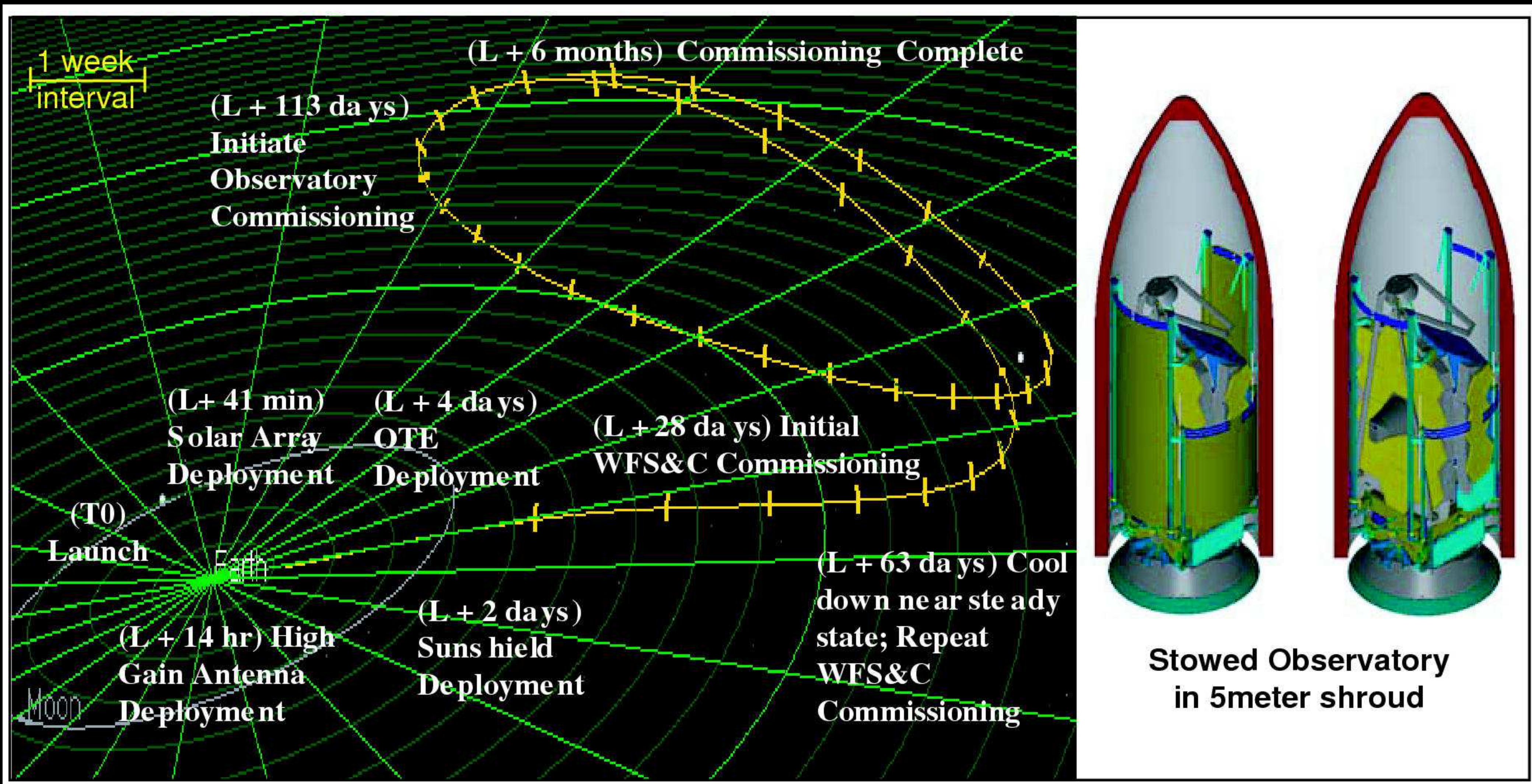


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Oct 2021.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (31.5 mag$\sim$1 FF from Moon), and spectroscopy.



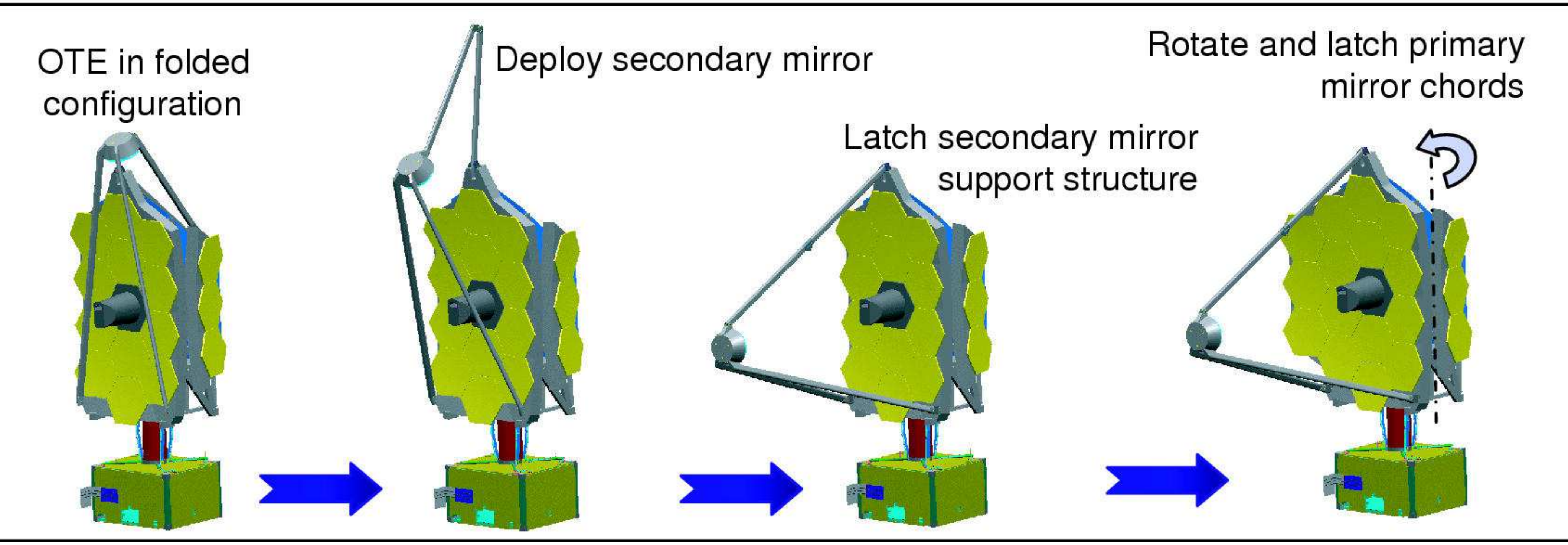
• The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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



- After launch in Oct 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.

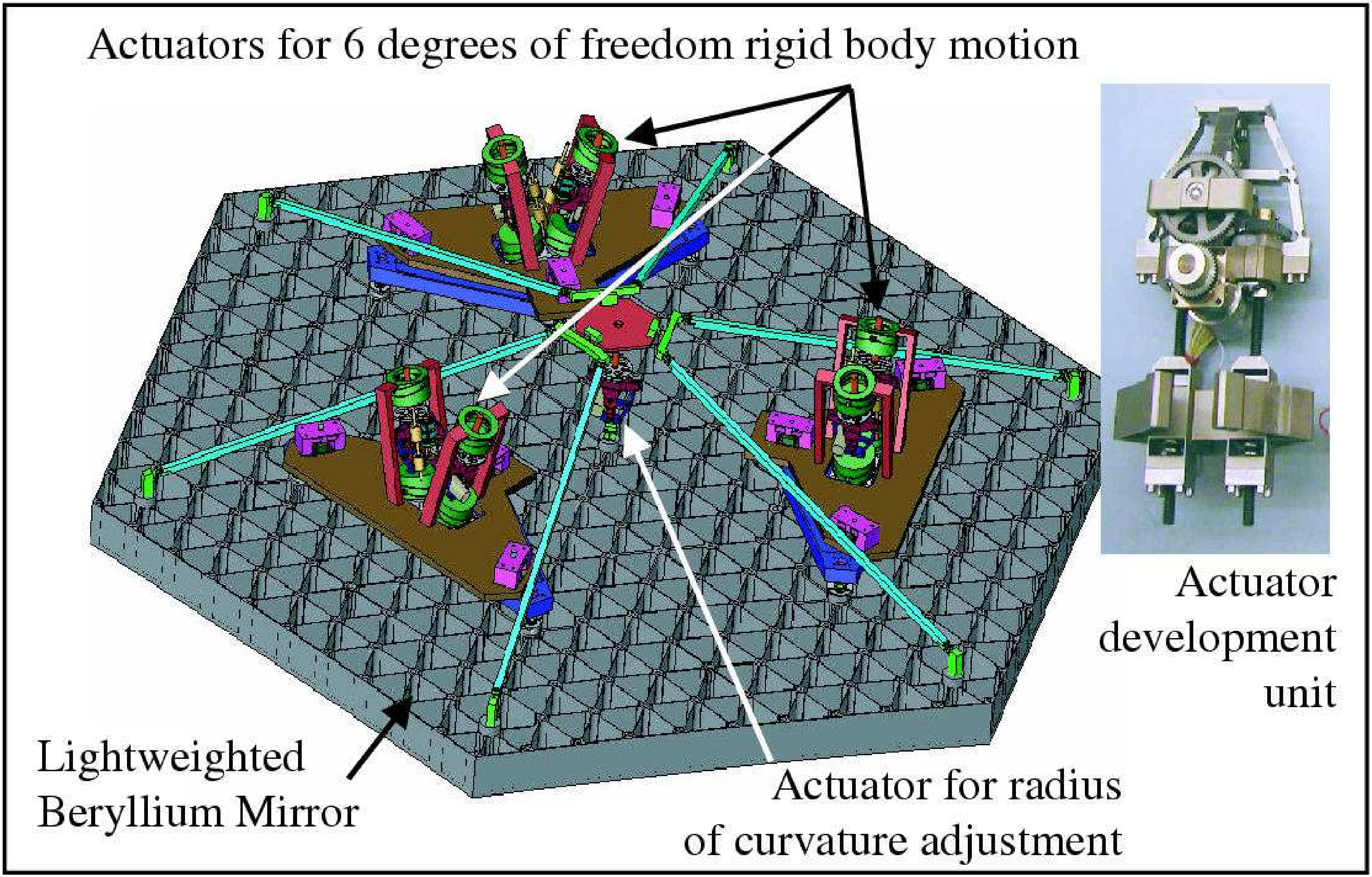
• (1b) How will JWST be automatically deployed?



- 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).

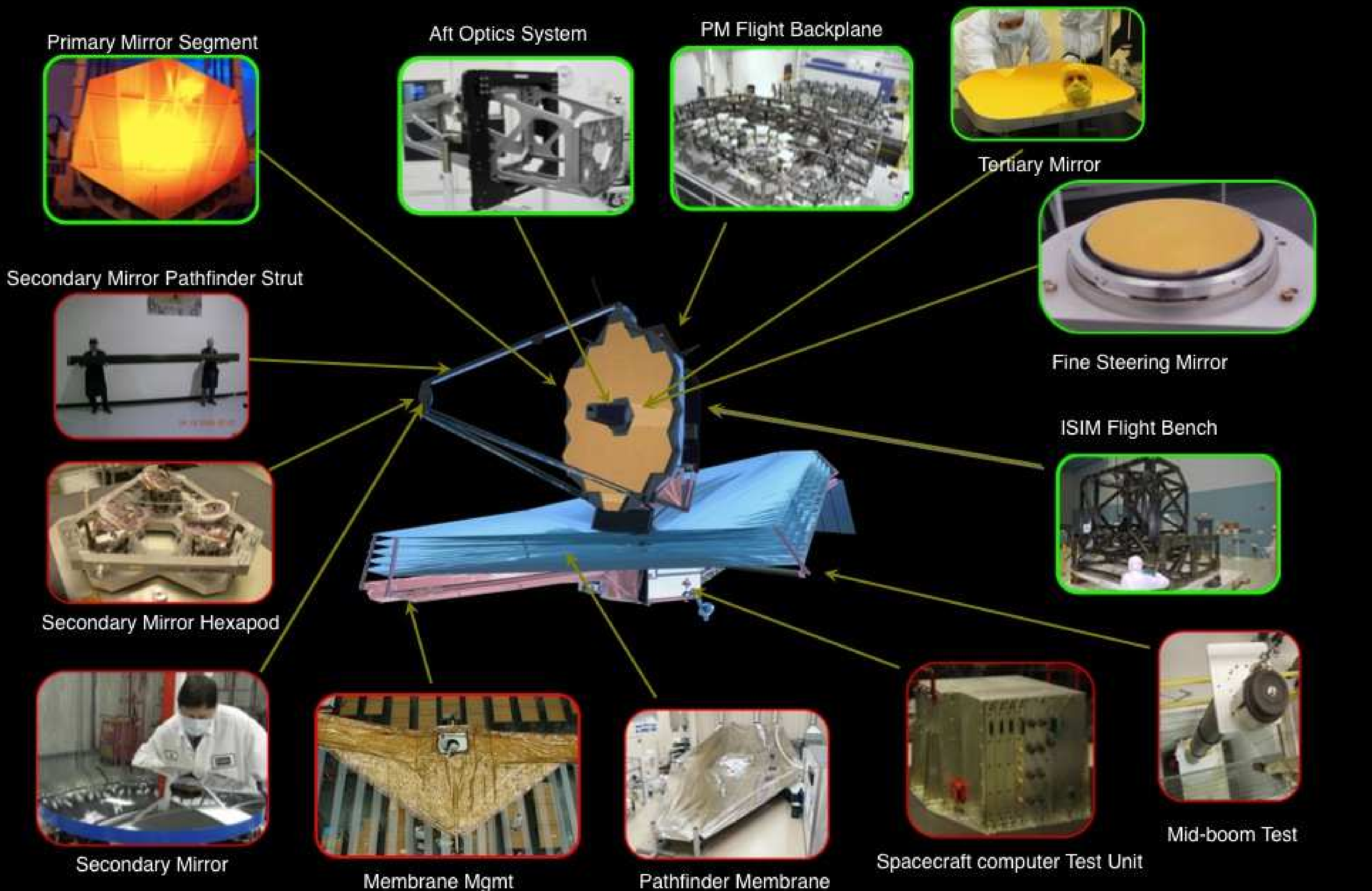
- Component fabrication, testing, & system integration: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



Active mirror segment support through “hexapods”, similar to Keck.

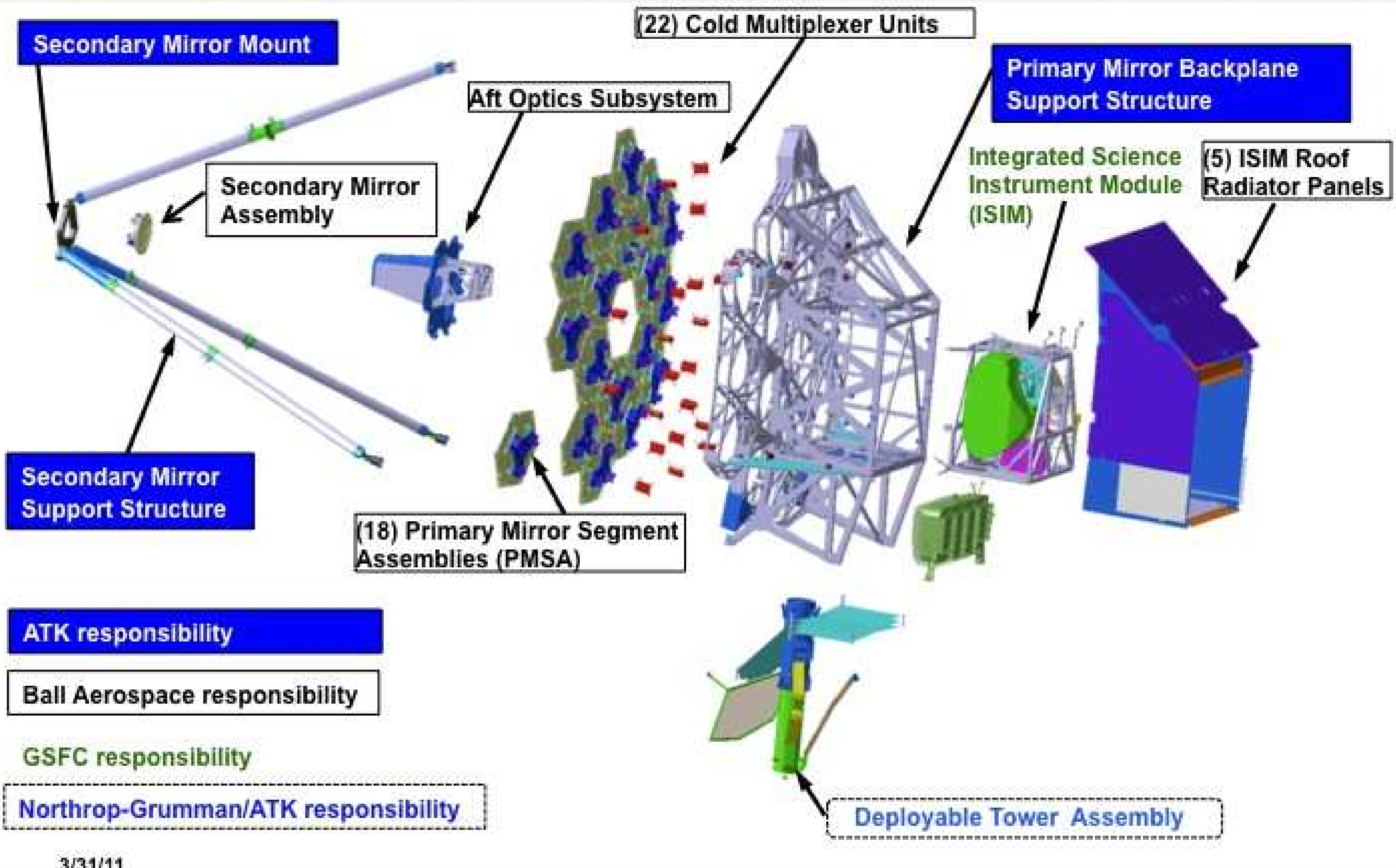
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

JWST Hardware Status



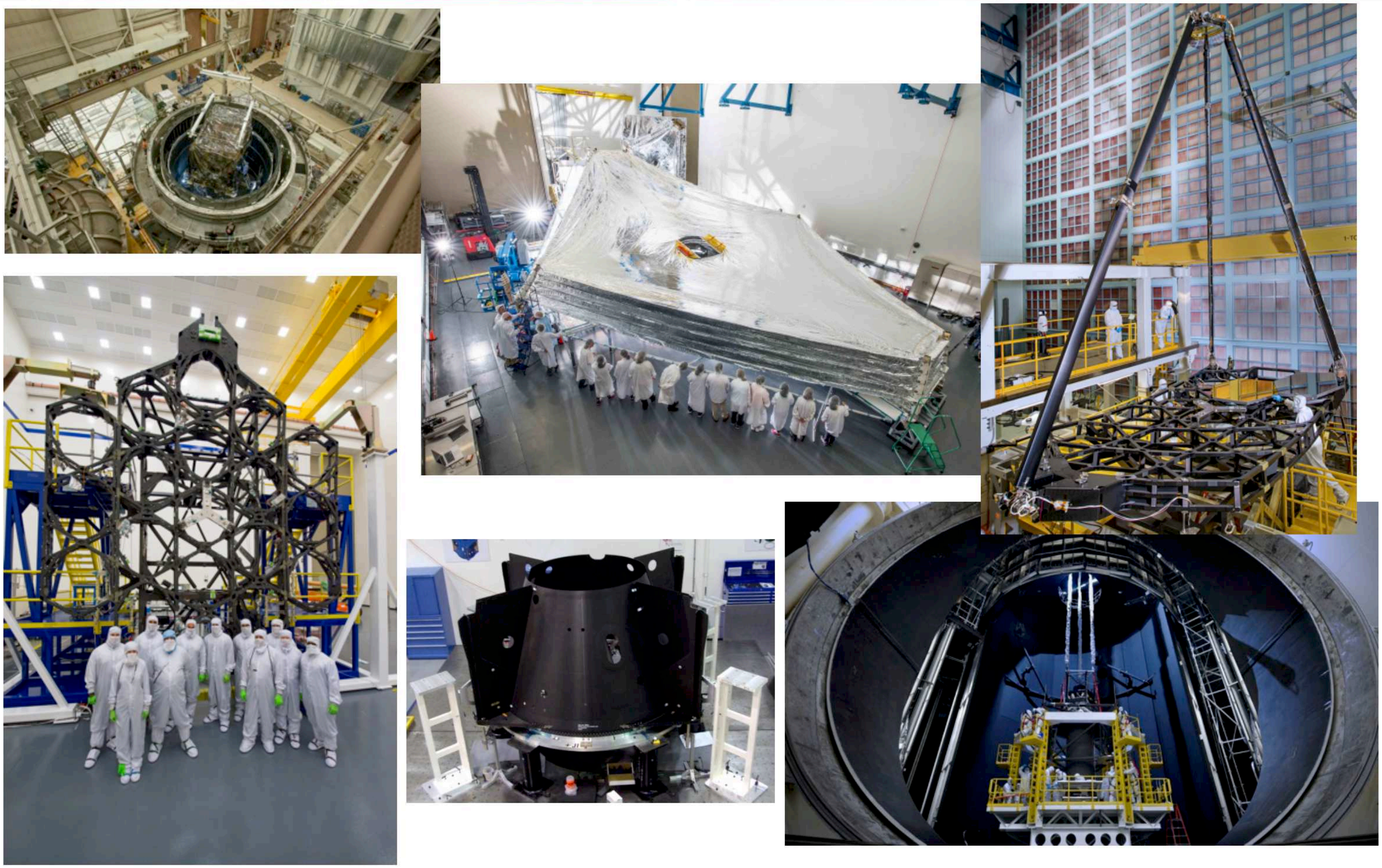
Fall 2020: 100% of launch mass designed and built ($\gtrsim$99% weighed).

TELESCOPE ARCHITECTURE



2014–2020: Complete system integration at GSFC and Northrop.

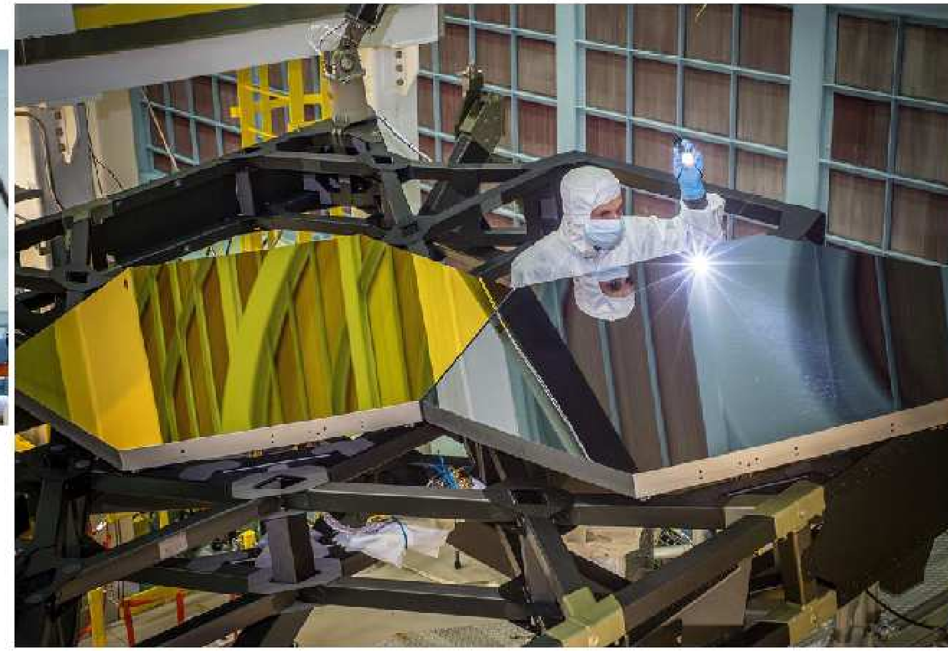
JWST Hardware Progress



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

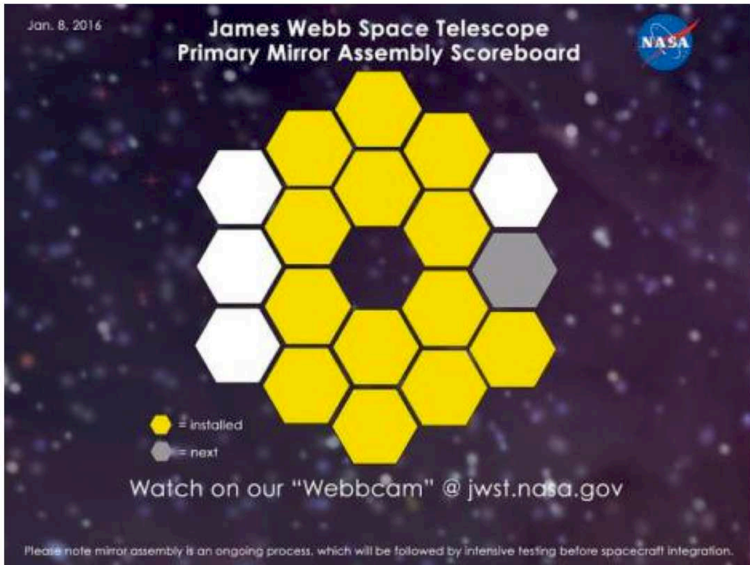
July 2014: • Secondary Mirror Support deployment successfully tested.
2015: • Engineering sunshield successfully deployed at Northrop (CA).

Telescope Pathfinder – Risk Reduction



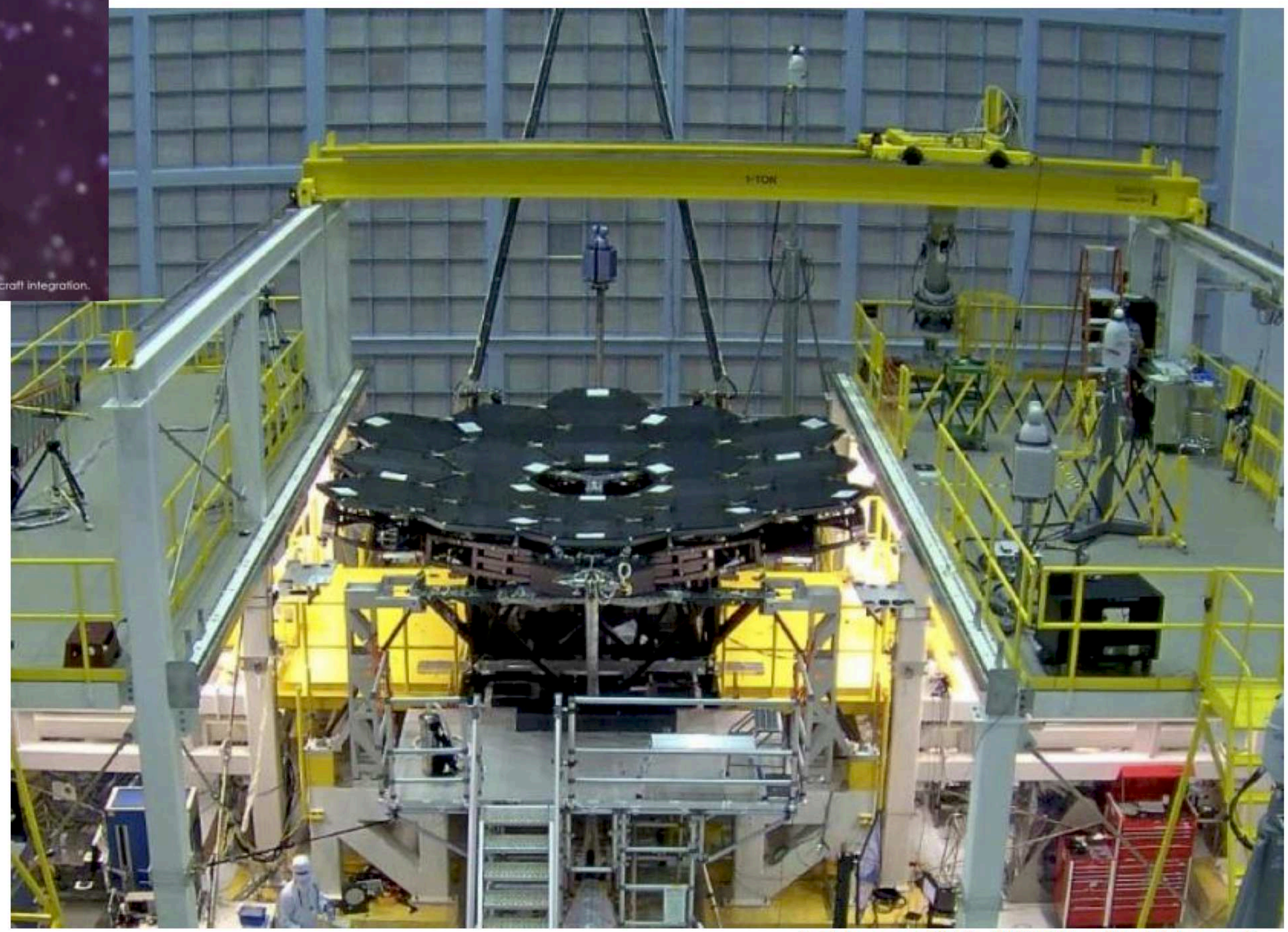
JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

Much progress has been made in OTE integration



← Where we were at last month's call

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

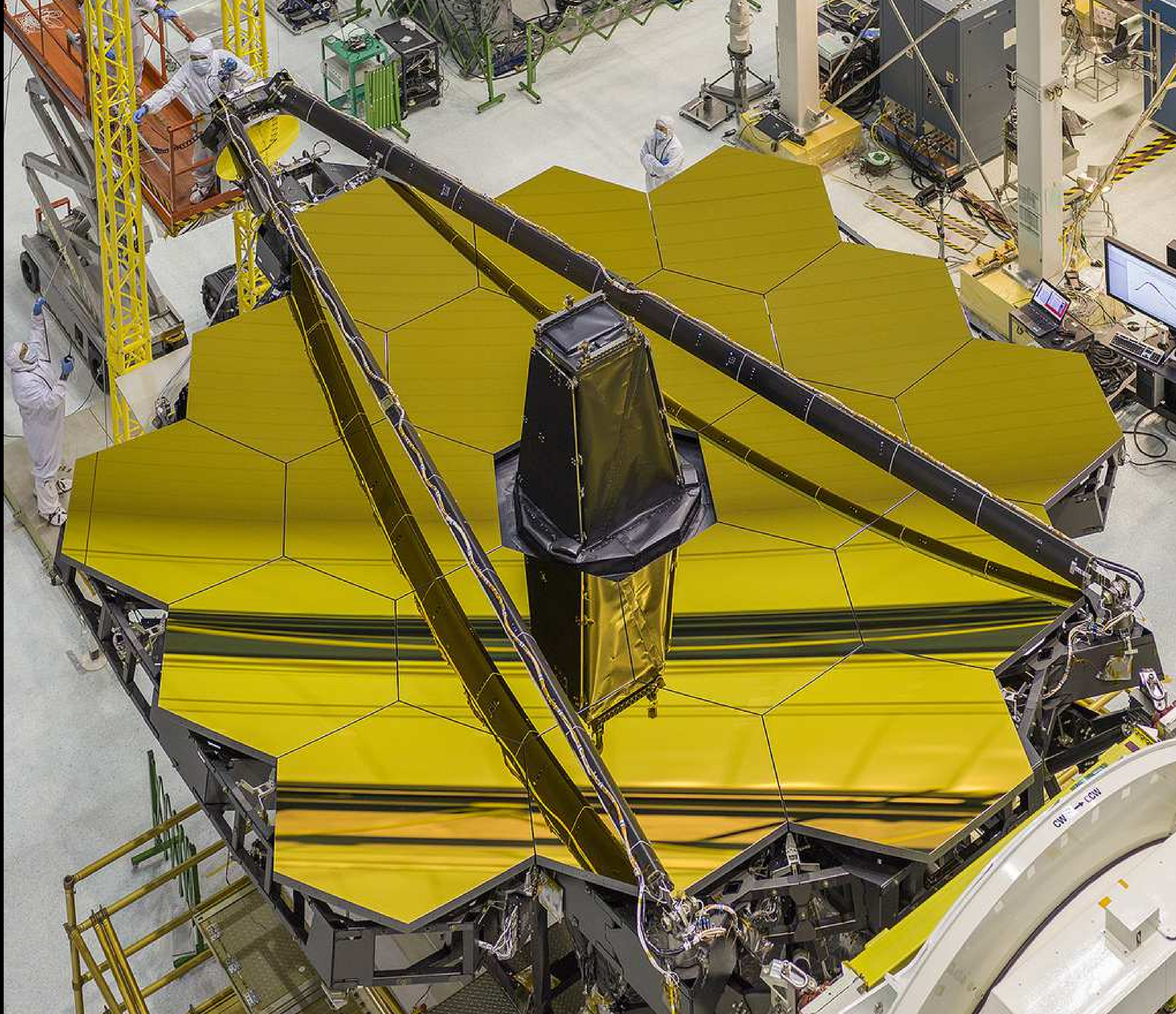


JWST lifetime: Requirement: 5 yrs; Goal: 10 yrs; Propellant: 14 yrs.

NASA team-work to take JWST mirror covers off!

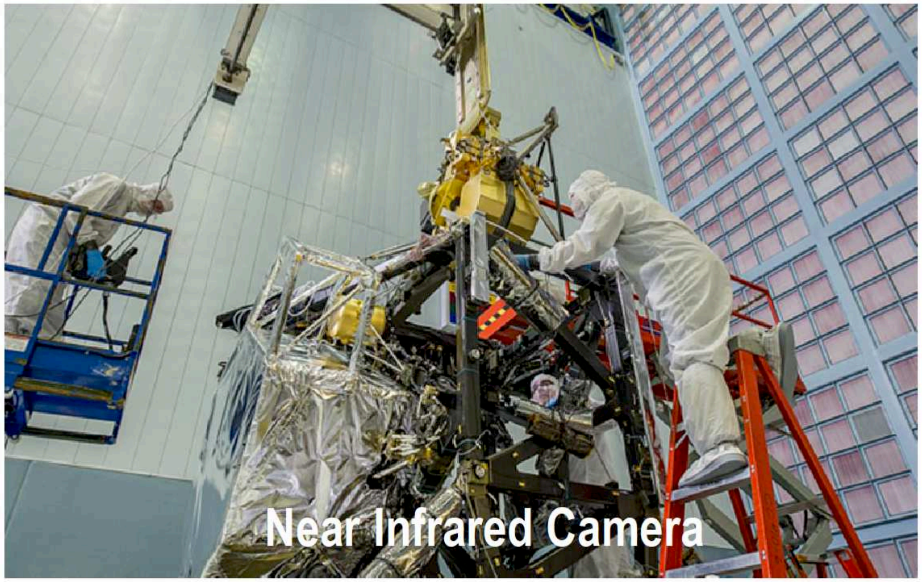
JWST being tilted into the right position

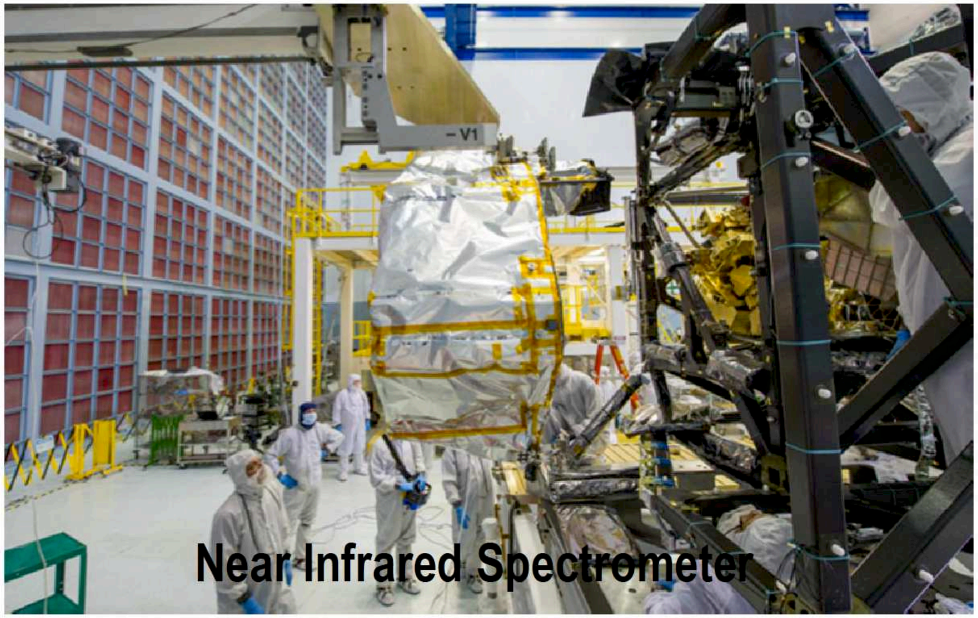
Webb mirrors finally mounted and ready!

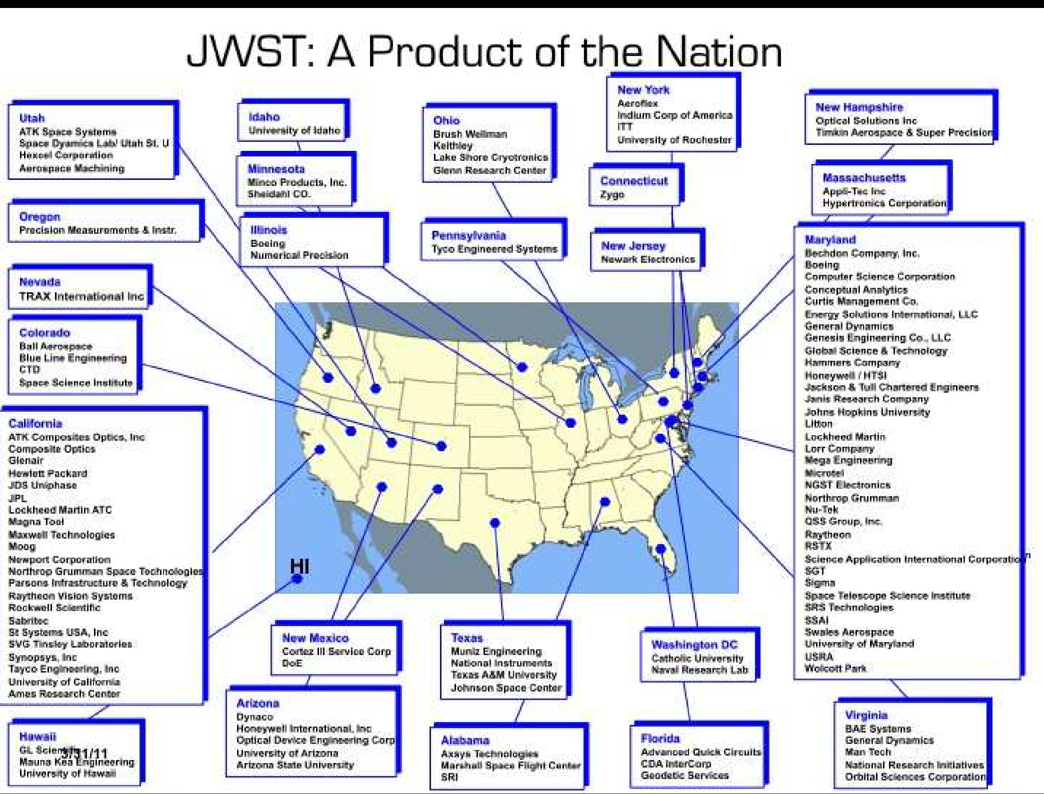


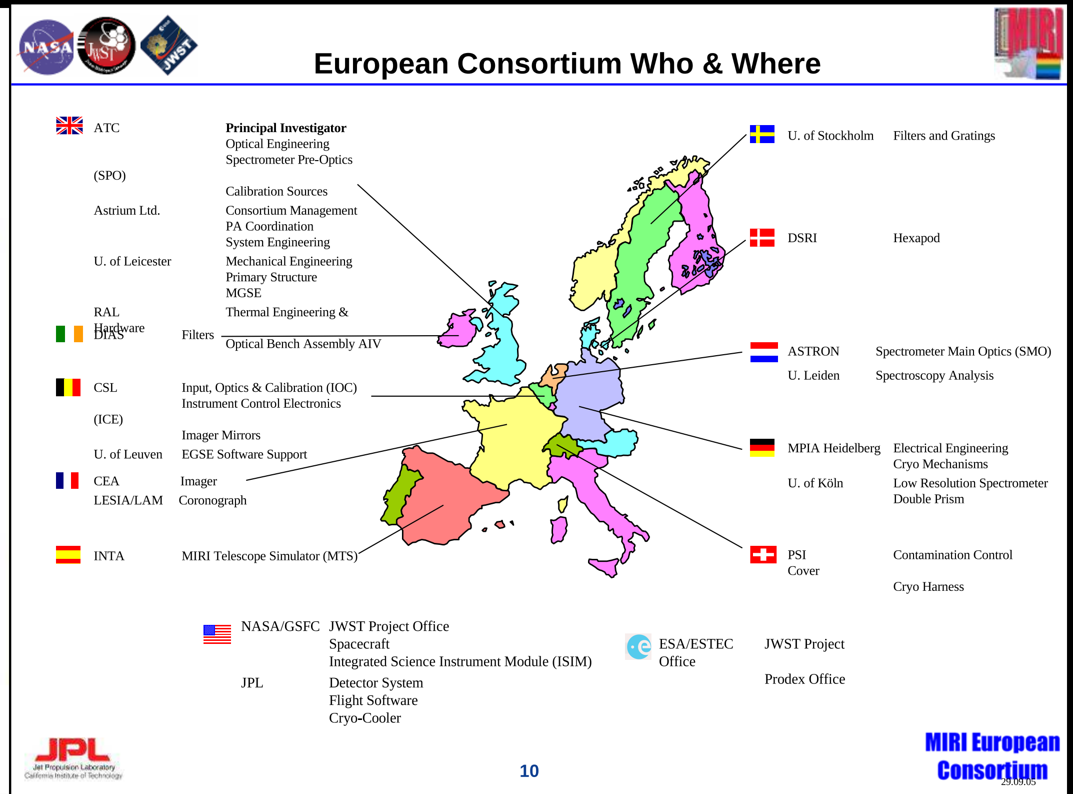
JWST stowed for further instrument mounting

All Instruments Integrated



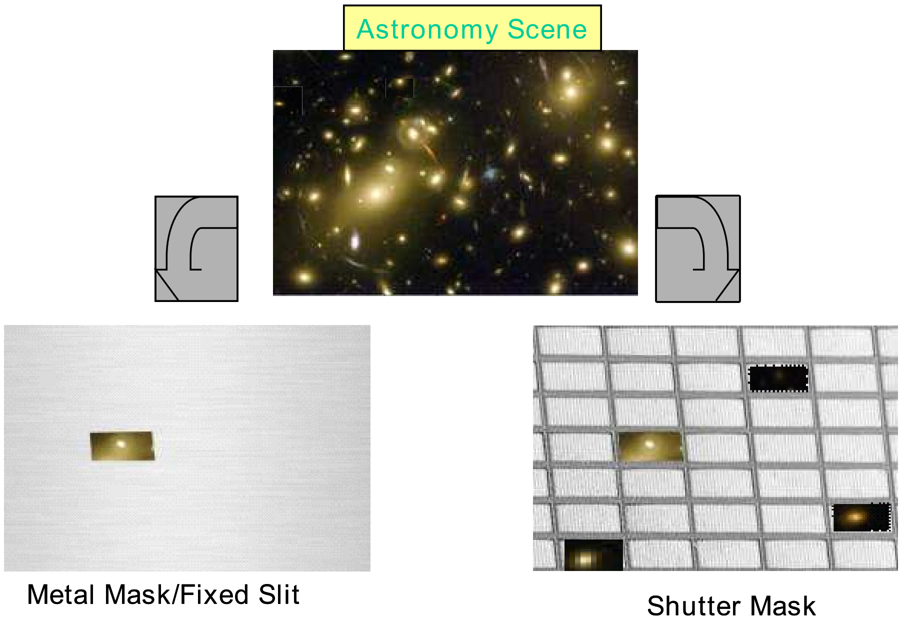


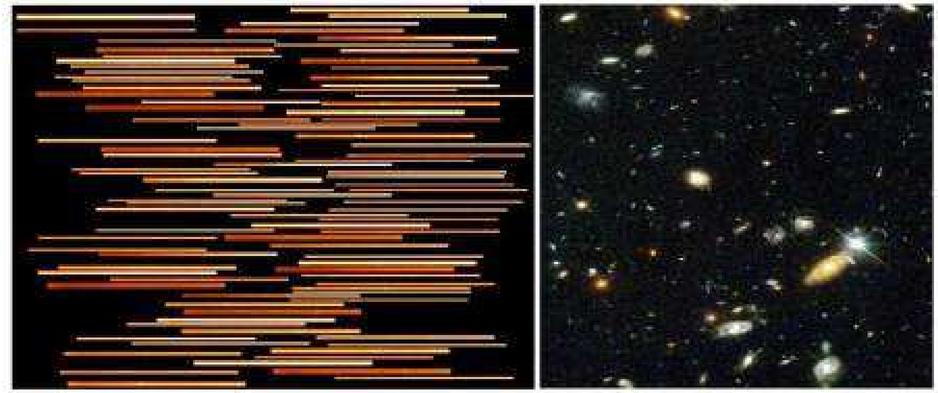


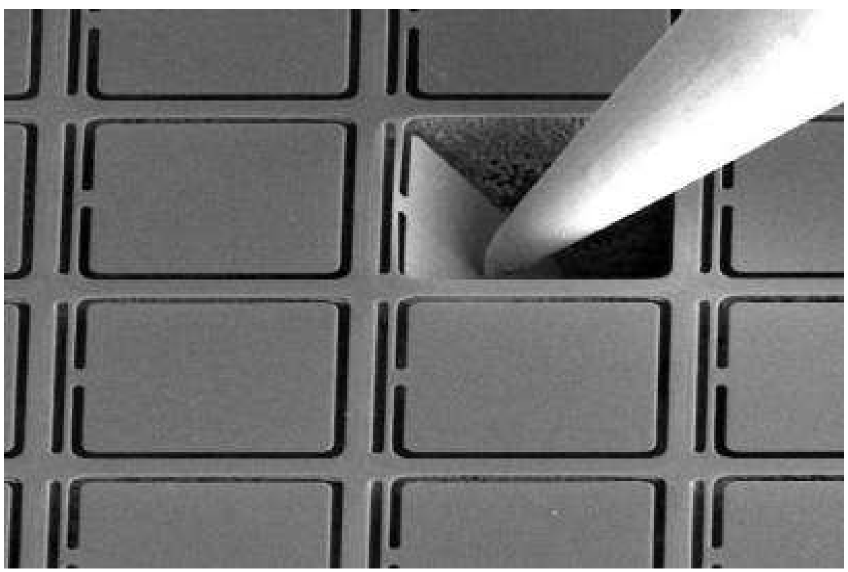


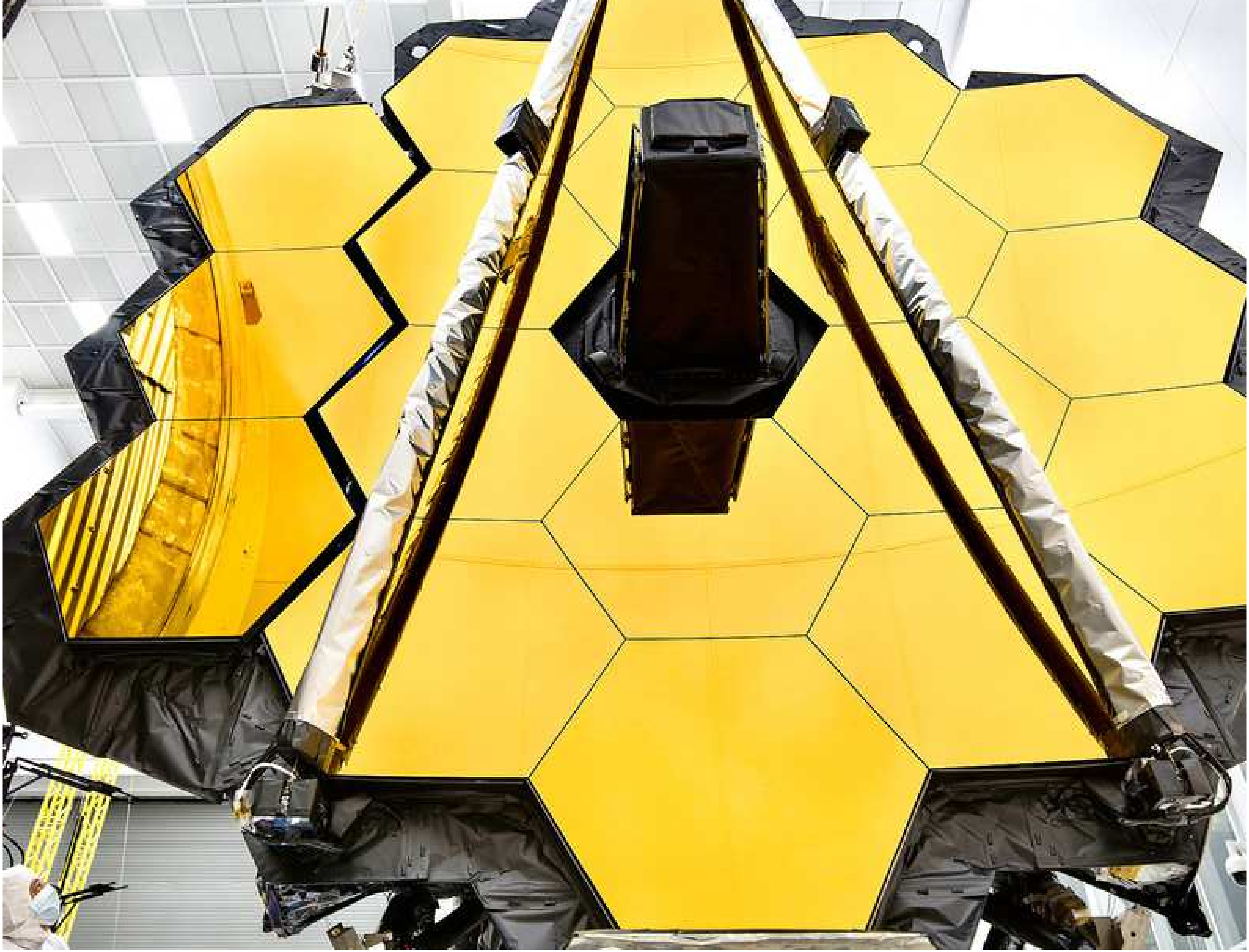
- JWST hardware made in 27 US States: 100% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

Micro Shutters



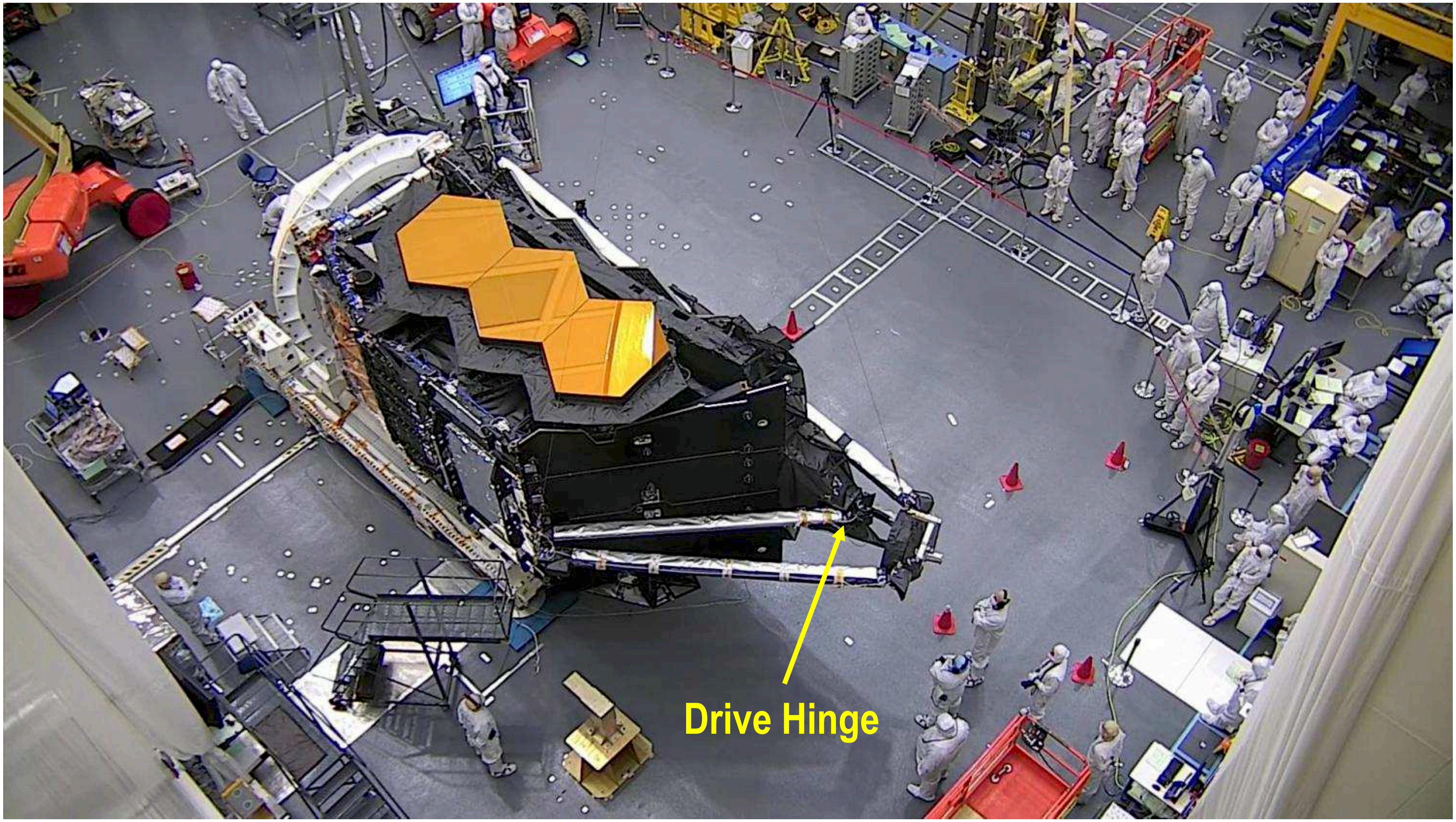






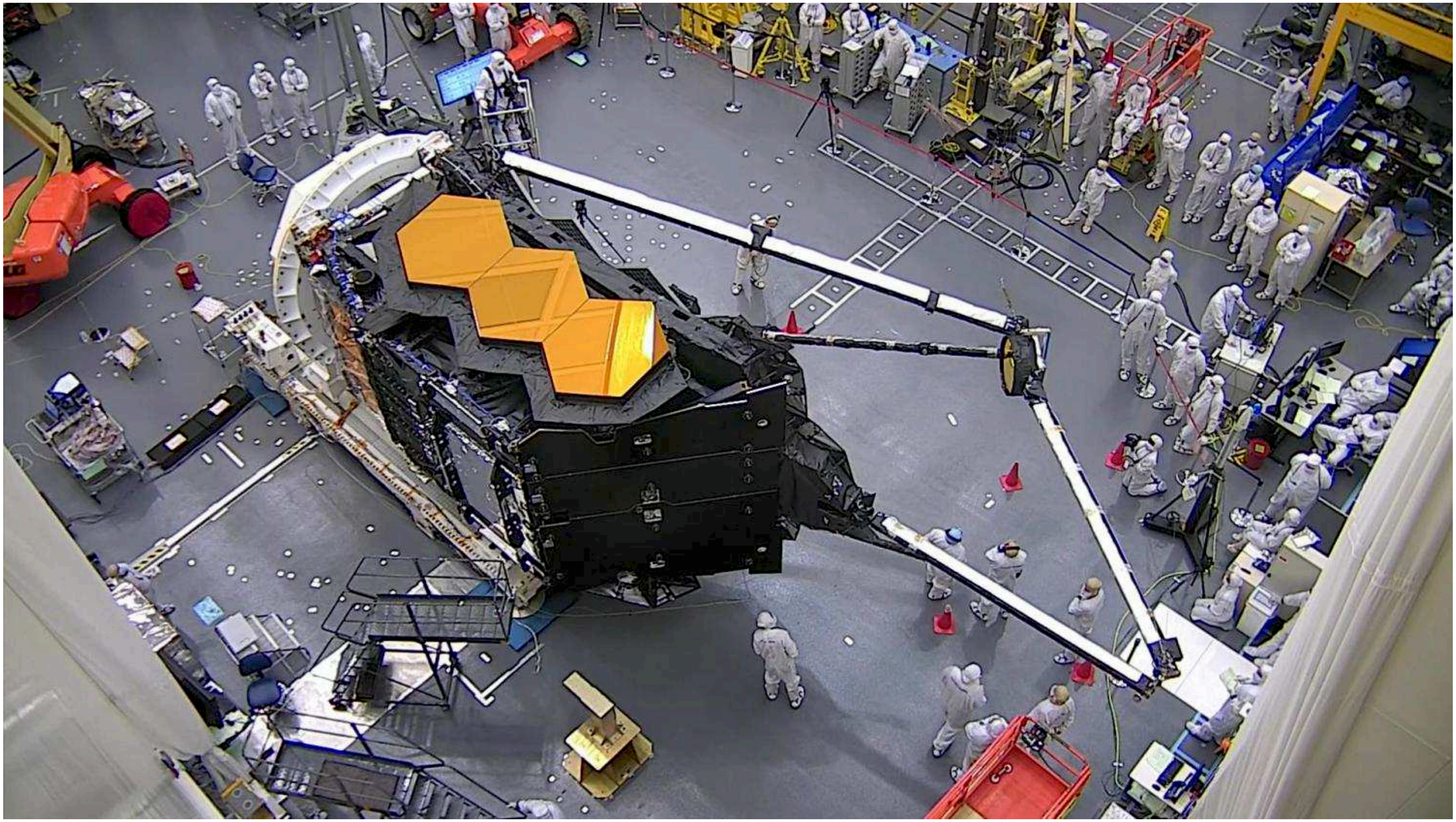
April 2017: Last portrait of JWST at Goddard Space Flight Center (MD).

SMSS Deployment Sequence (1)



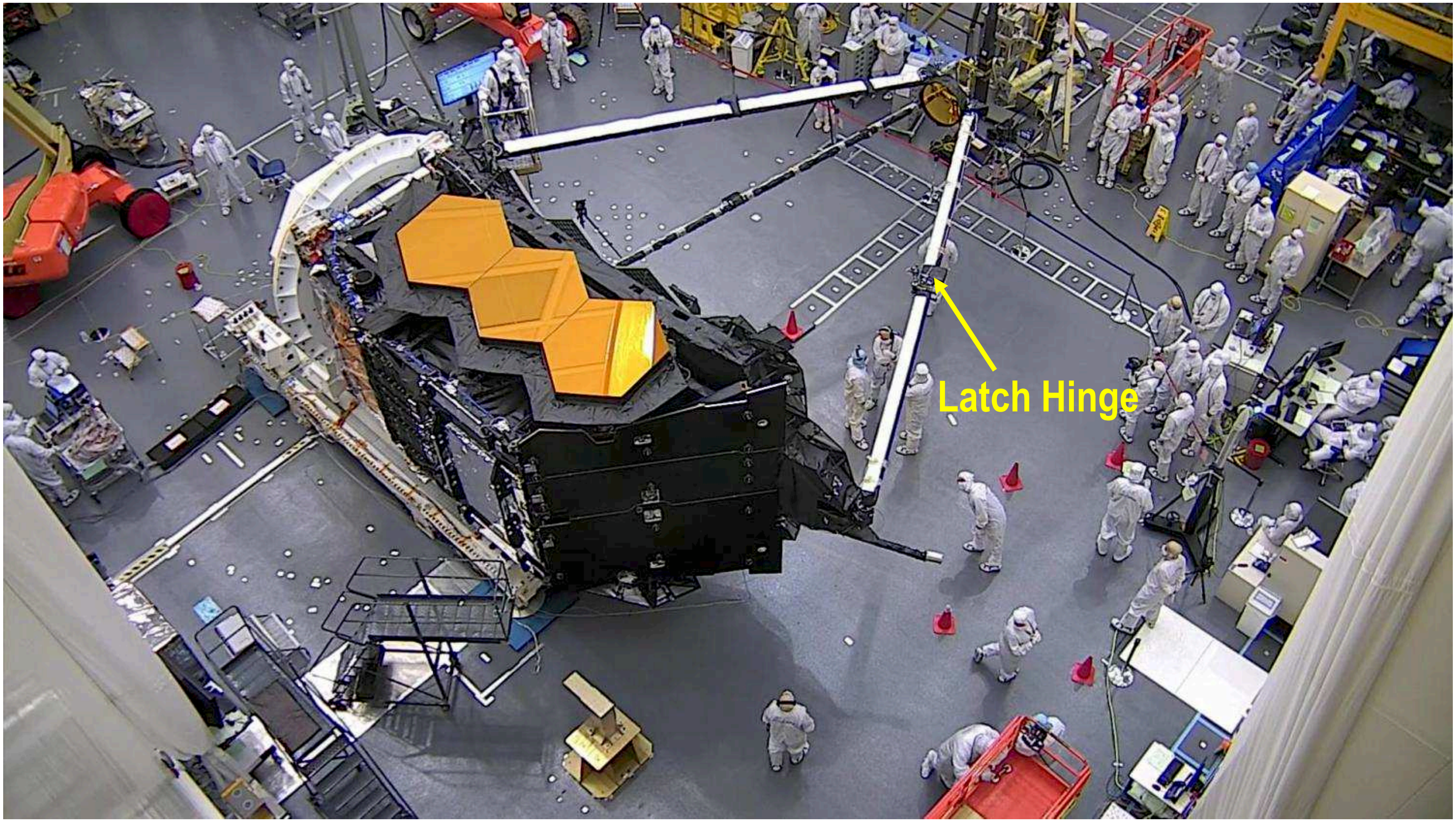
July 2019: Full 1-G deployment of JWST secondary mirror (SM) .

SMSS Deployment Sequence (2)



July 2019: Full 1-G deployment of JWST secondary mirror (SM) ..

SMSS Deployment Sequence (3)



July 2019: Full 1-G deployment of JWST secondary mirror (SM) ...

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

Program Update: OTIS

NORTHROP GRUMMAN

June 2017: JWST going into Chamber A at Johnson Space Center in Houston.

Program Updates: Spacecraft and Sunshield

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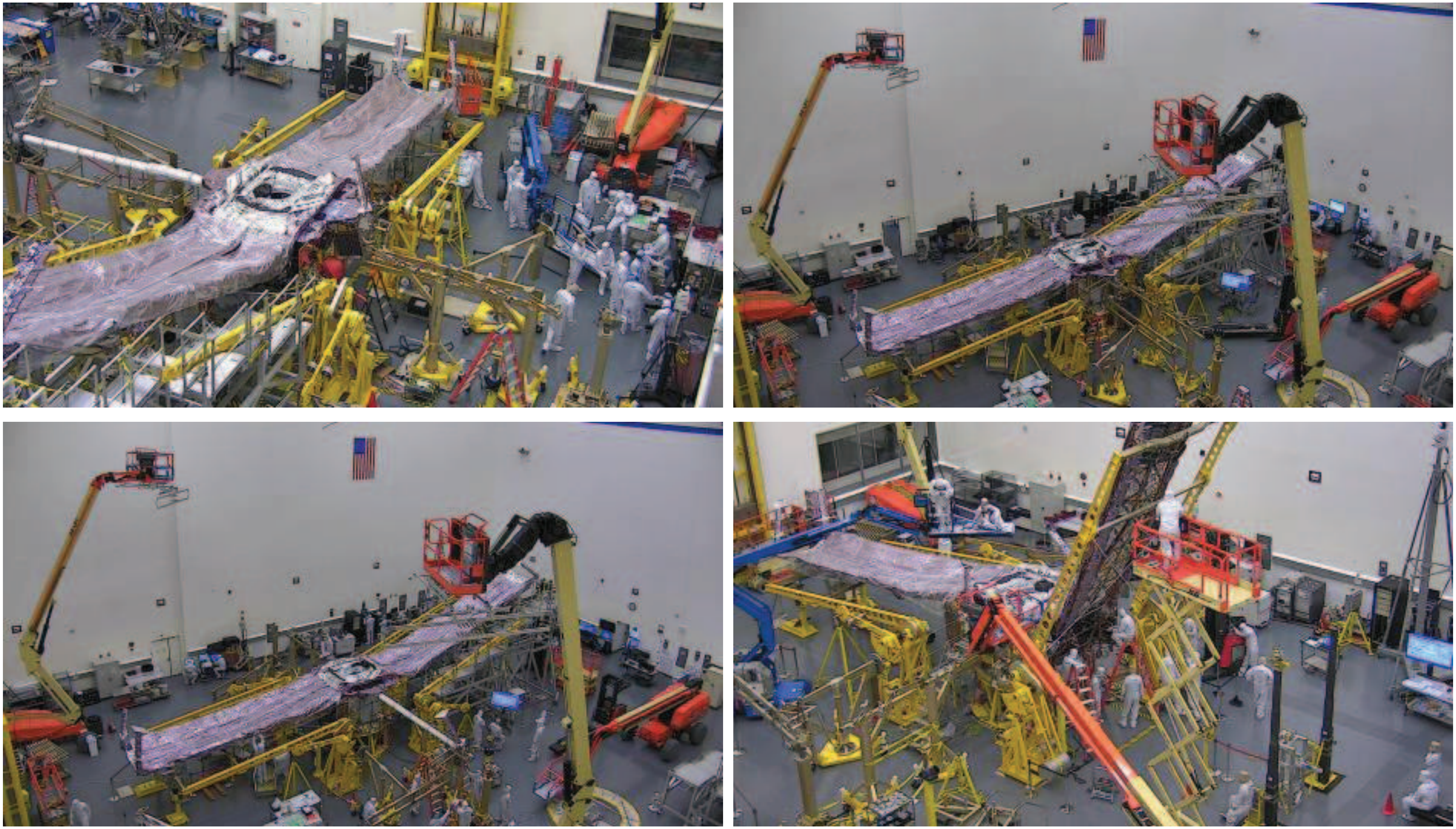
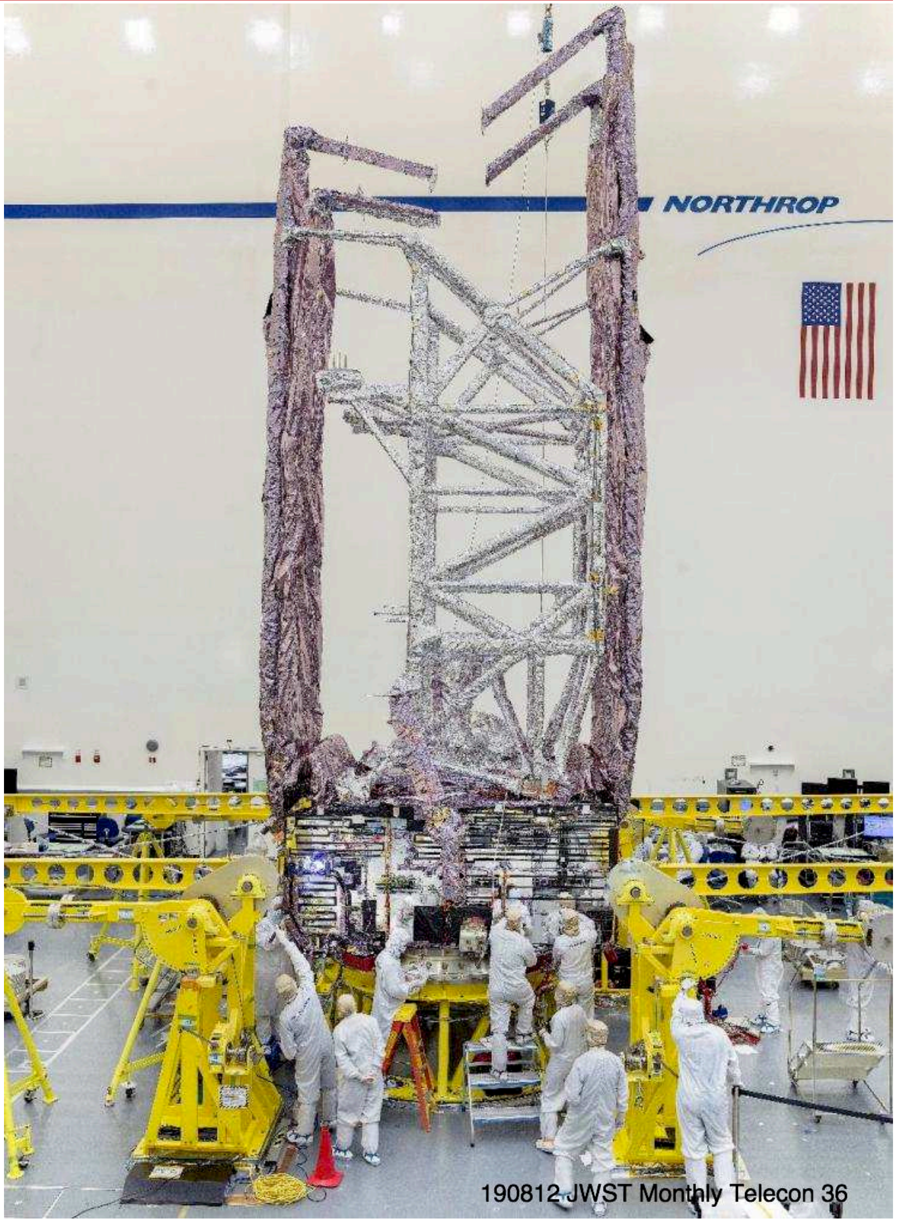


2017–2018: JWST Flight Sunshield assembled and tested at Northrop.

SCE to Elephant Stand



Aug. 2019: Stowed flight sunshield before integration with JWST OTE.

SMSS Deployment

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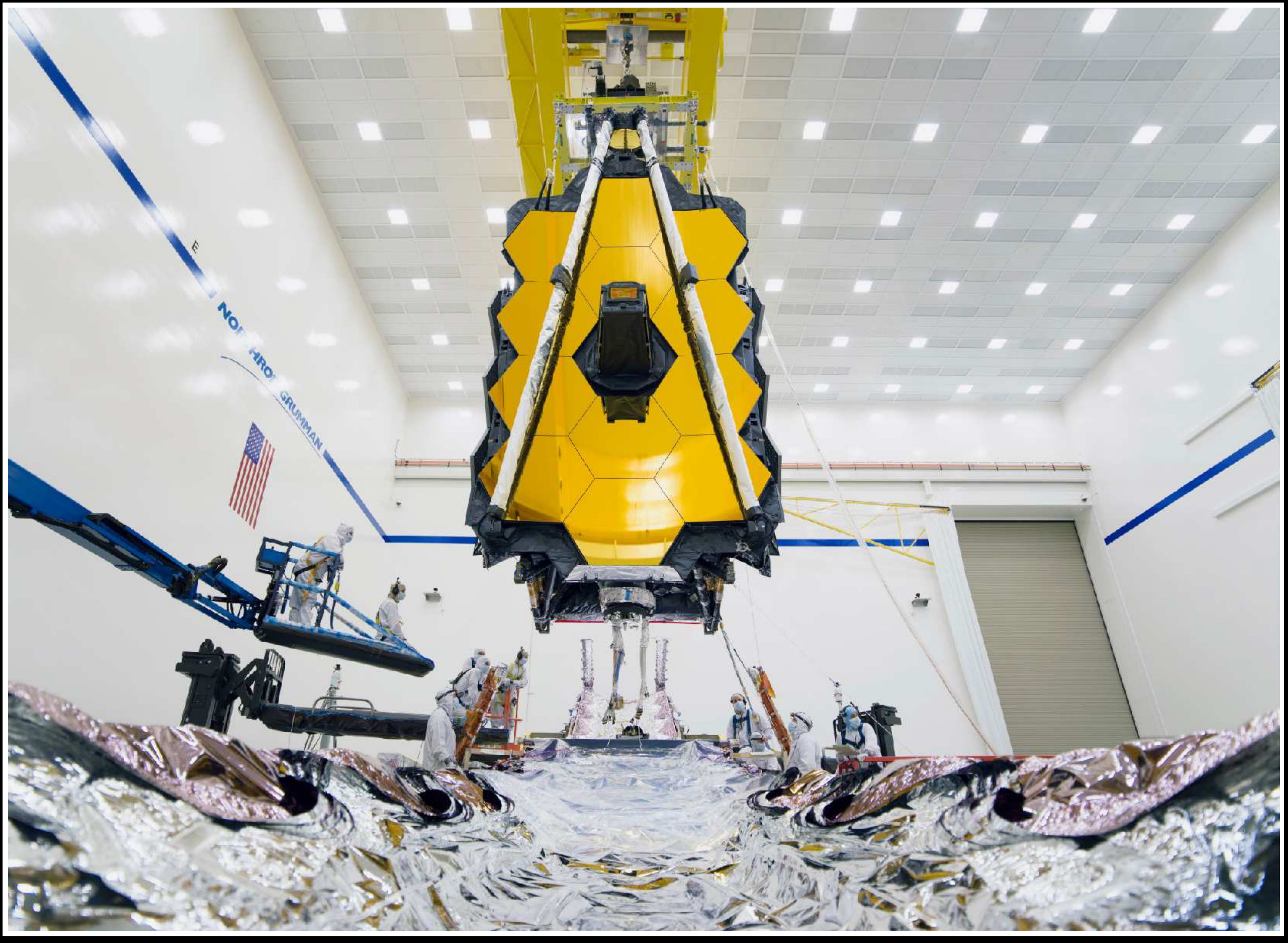
Aug. 2019: OTE before final integration with Sunshield & spacecraft.

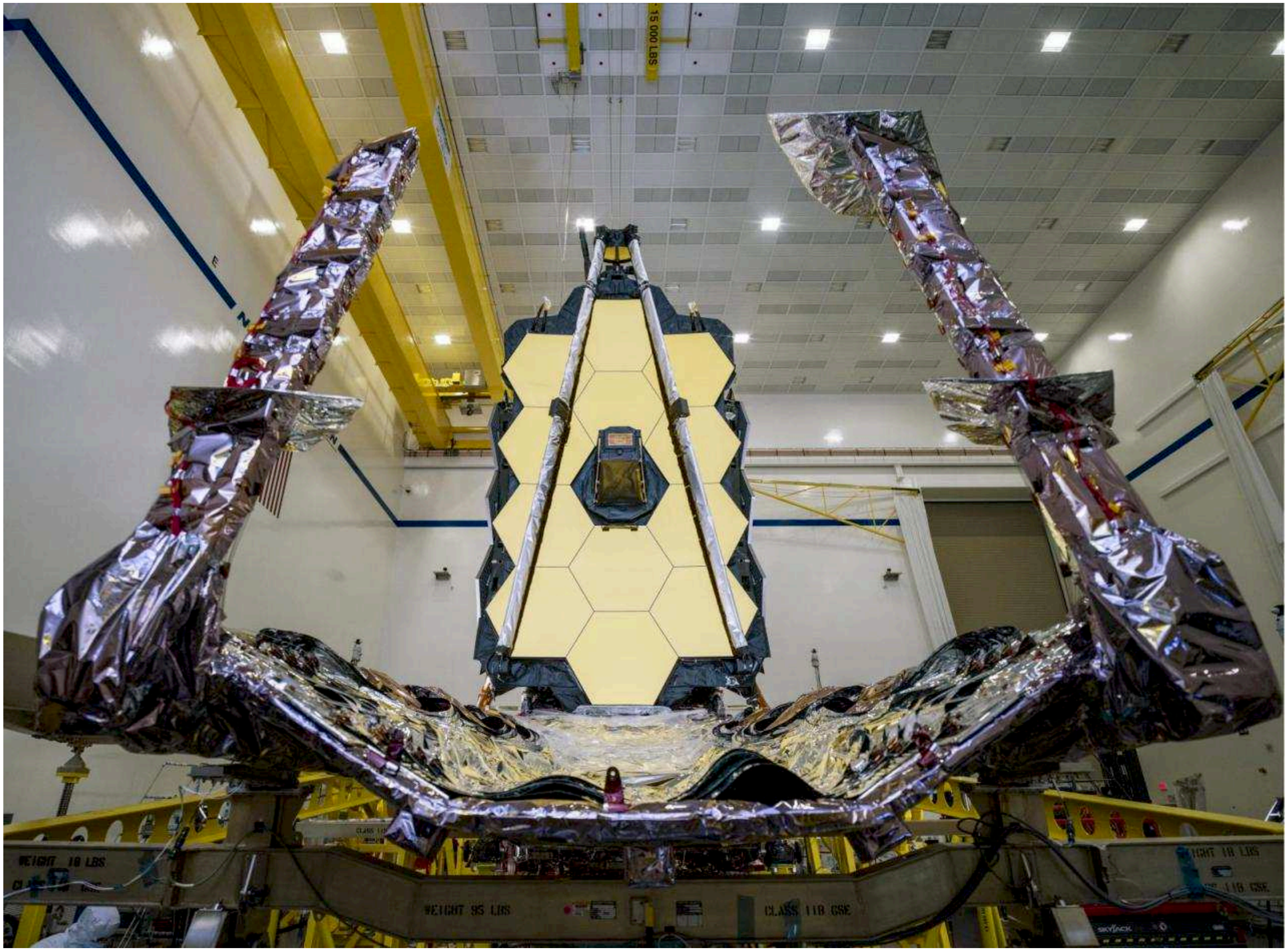


Aug. 2019: JWST OTE+ISIM lowered into Sunshield+Spacecraft

August 2019: JWST OTE+ISIM integrated with Sunshield+Spacecraft!

August 2019: JWST OTE+ISIM integrated with Sunshield and Spacecraft!

Meet the JWST Observatory 1



See NASA Press Release here:
https://www.nasa.gov/feature/goddard/2019/nasa-s-james-webb-space-telescope-has-been-assembled-for-the-first-time

August 2019: JWST OTE+ISIM integrated with Sunshield and Spacecraft!

Solar Array Deployment 1

Five Panel Sunshield
Stowed

Offloading System

May 2020: Ready for Solar Array deployment test

Solar Array Deployment 2

May 2020: Solar Array deployment with gravity off-loading

Solar Array Deployment 3

May 2020: Solar Array fully deployed and motor tested in 1G

7/26/20: Solar Array Installed for Environments

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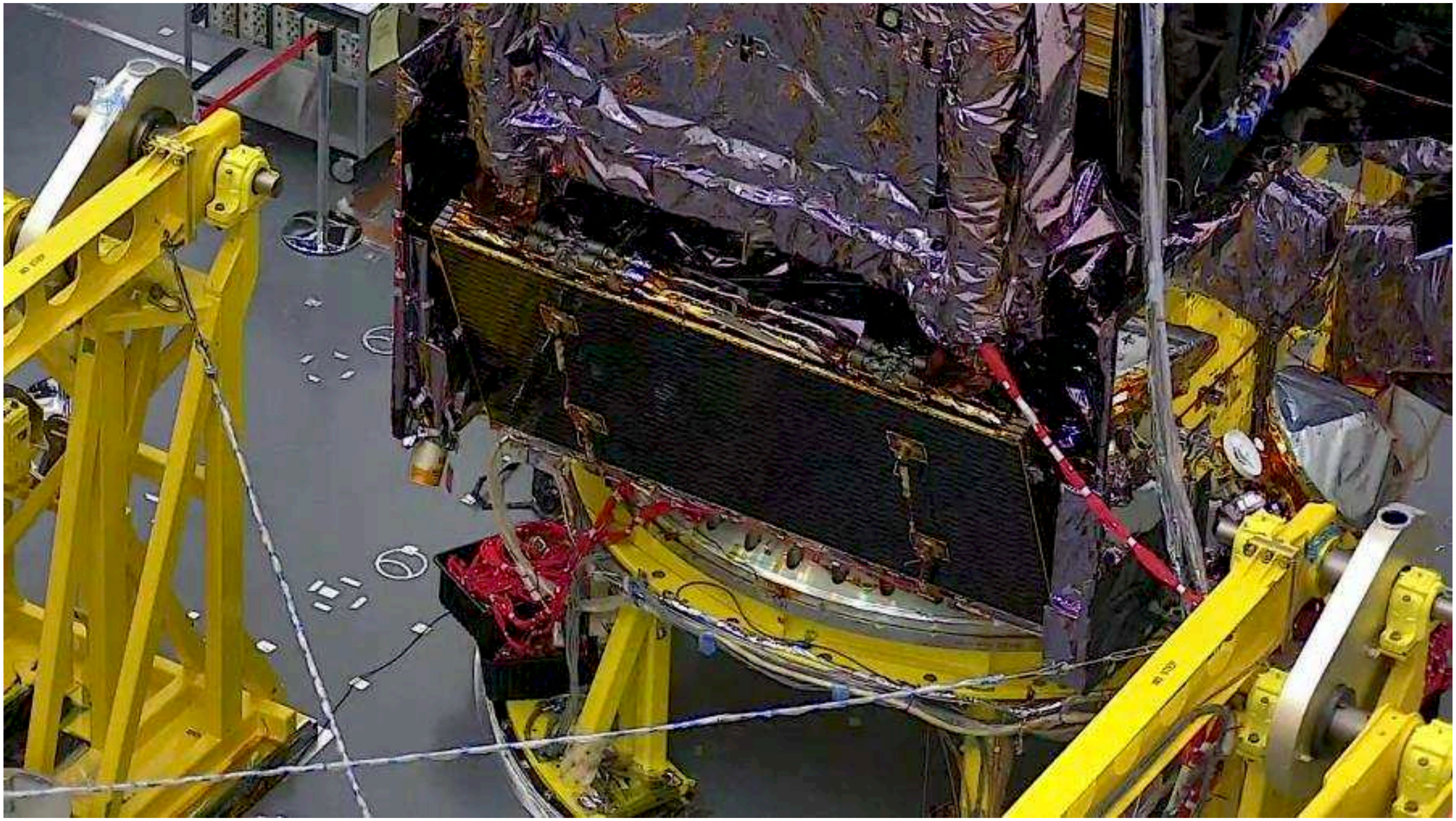

Approved for Public Release; NG20-1503
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May 2020: Solar Array as installed on JWST Observatory

5/28/20: DTA Deployment

Approved for Public Release; NG20-106

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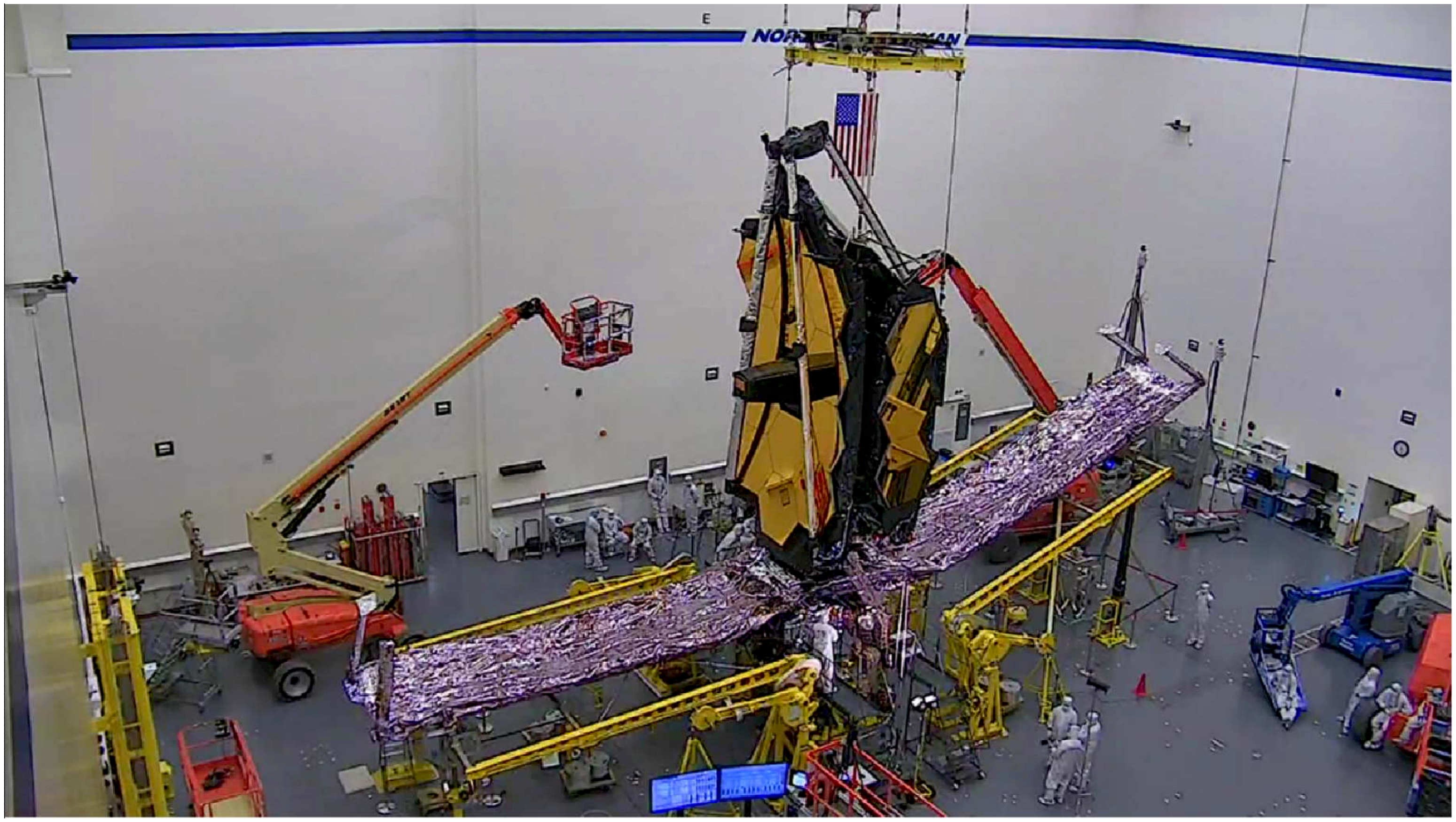
June 2020: Deployable Tower Assembly test

5/28/20: DTA Deployment



Approved for Public Release; NG20-106

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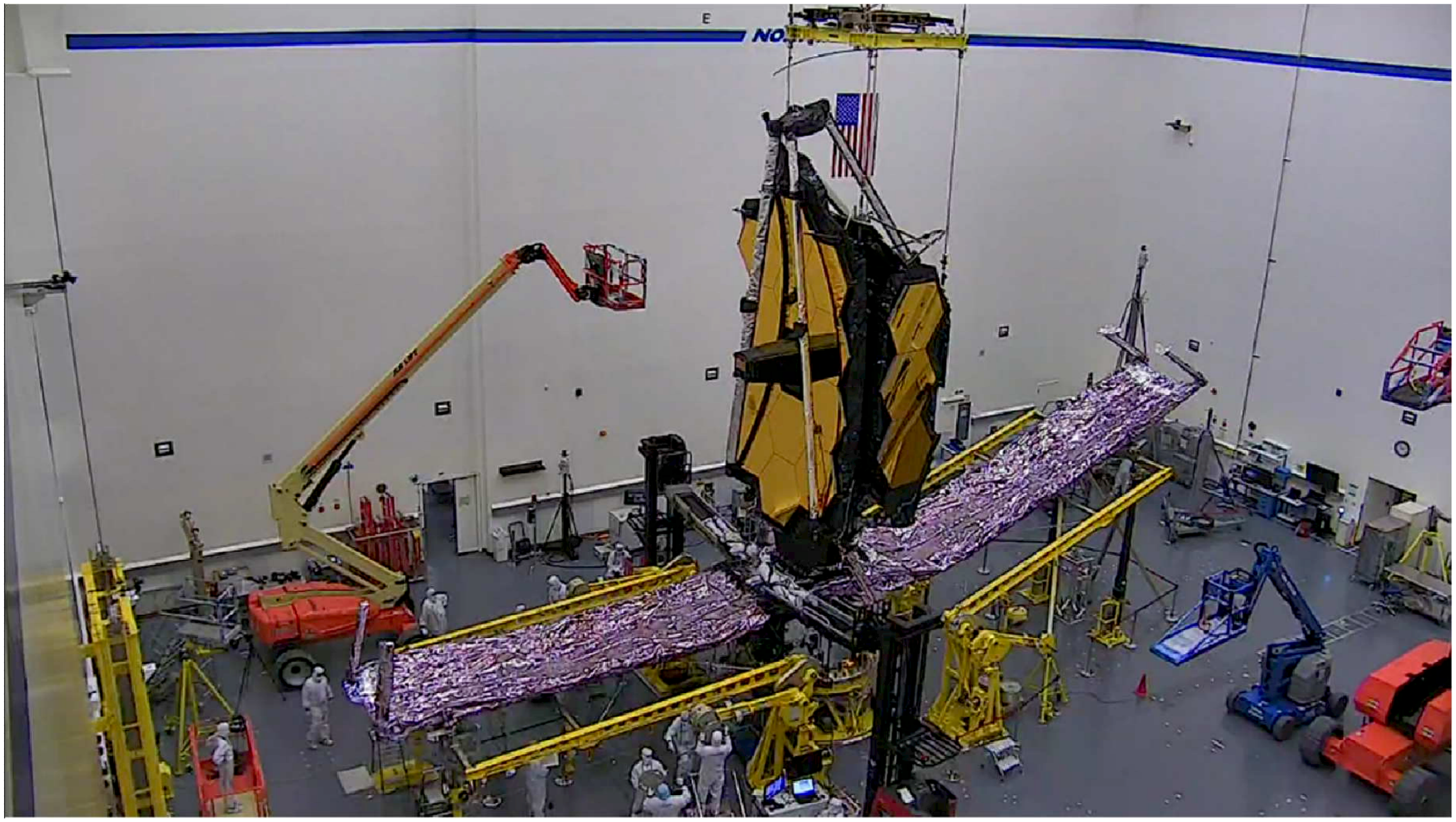
June 2020: Deployable Tower Assembly test with gravity off-loading.

5/29/20: DTA Deployment



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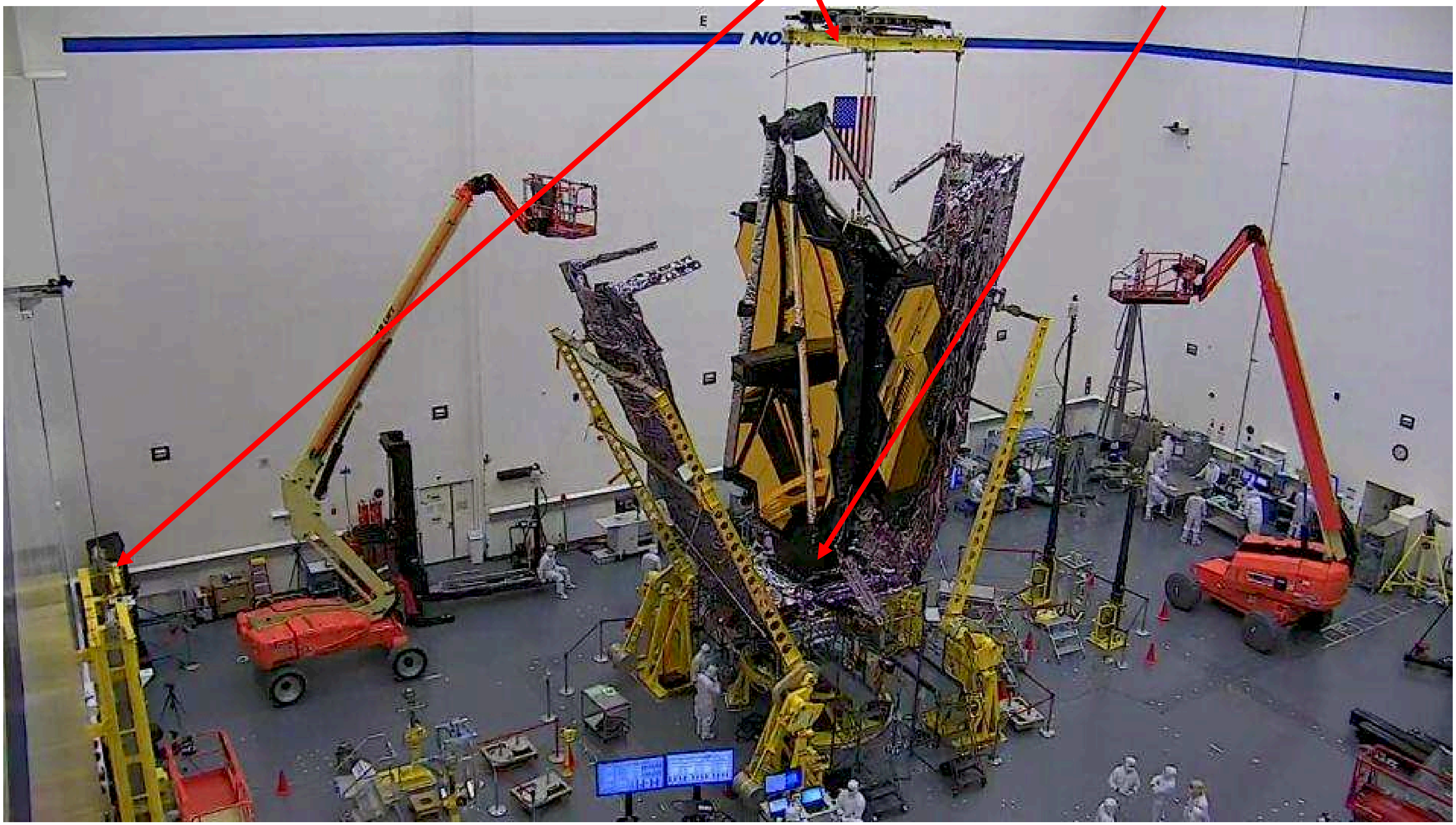
June 2020: Deployable Tower Assembly motor tested in 1G

DTA Stow 1



200713 JWST Monthly Telecon 9

July 2020: Deployable Tower Assembly stow for launch

DTA Stow 2

200713 JWST Monthly Telecon 10

July 2020: Deployable Tower Assembly stowed for launch

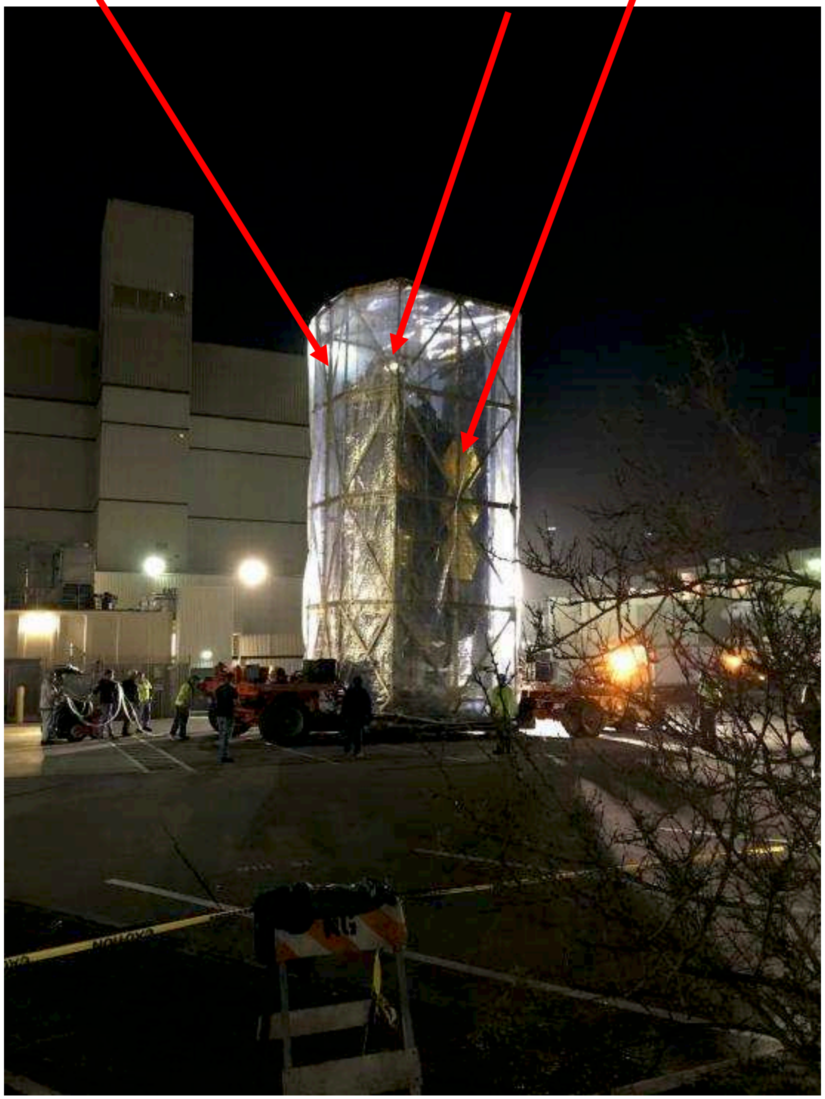
Aft UPS Stow 1

July 2020: Aft UPS stow for launch

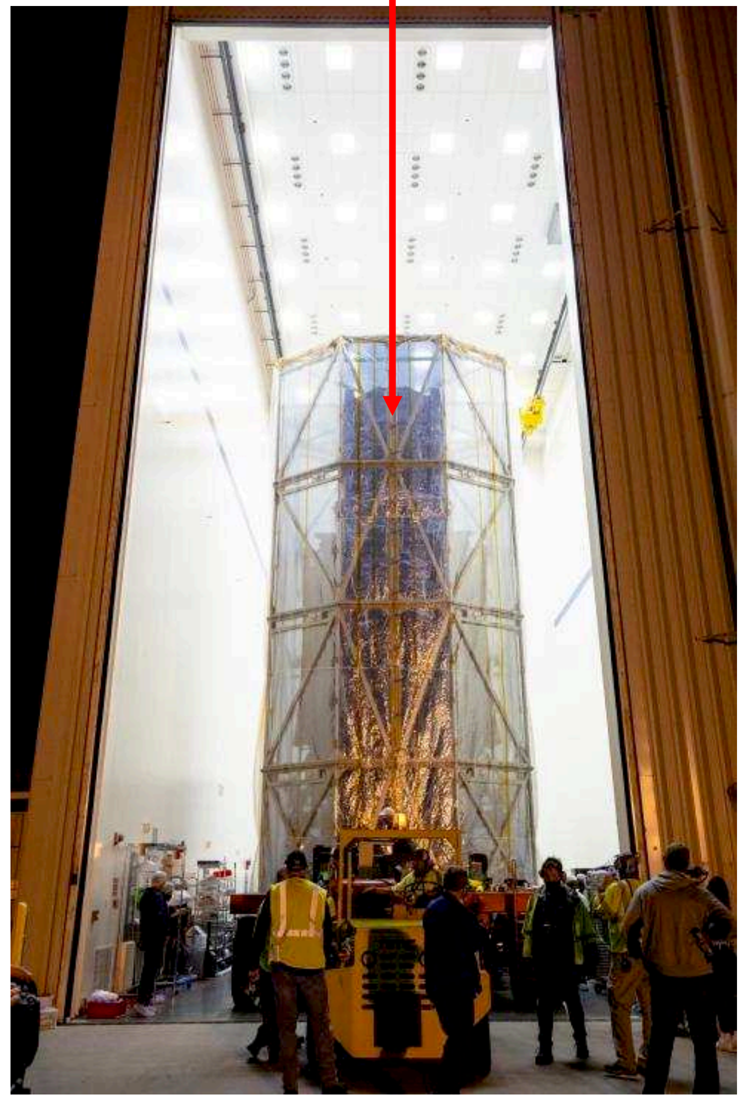
Aft UPS Stow 2

Fall 2020: Aft UPS stowed for launch

Transport to the Large Acoustic Test Facility



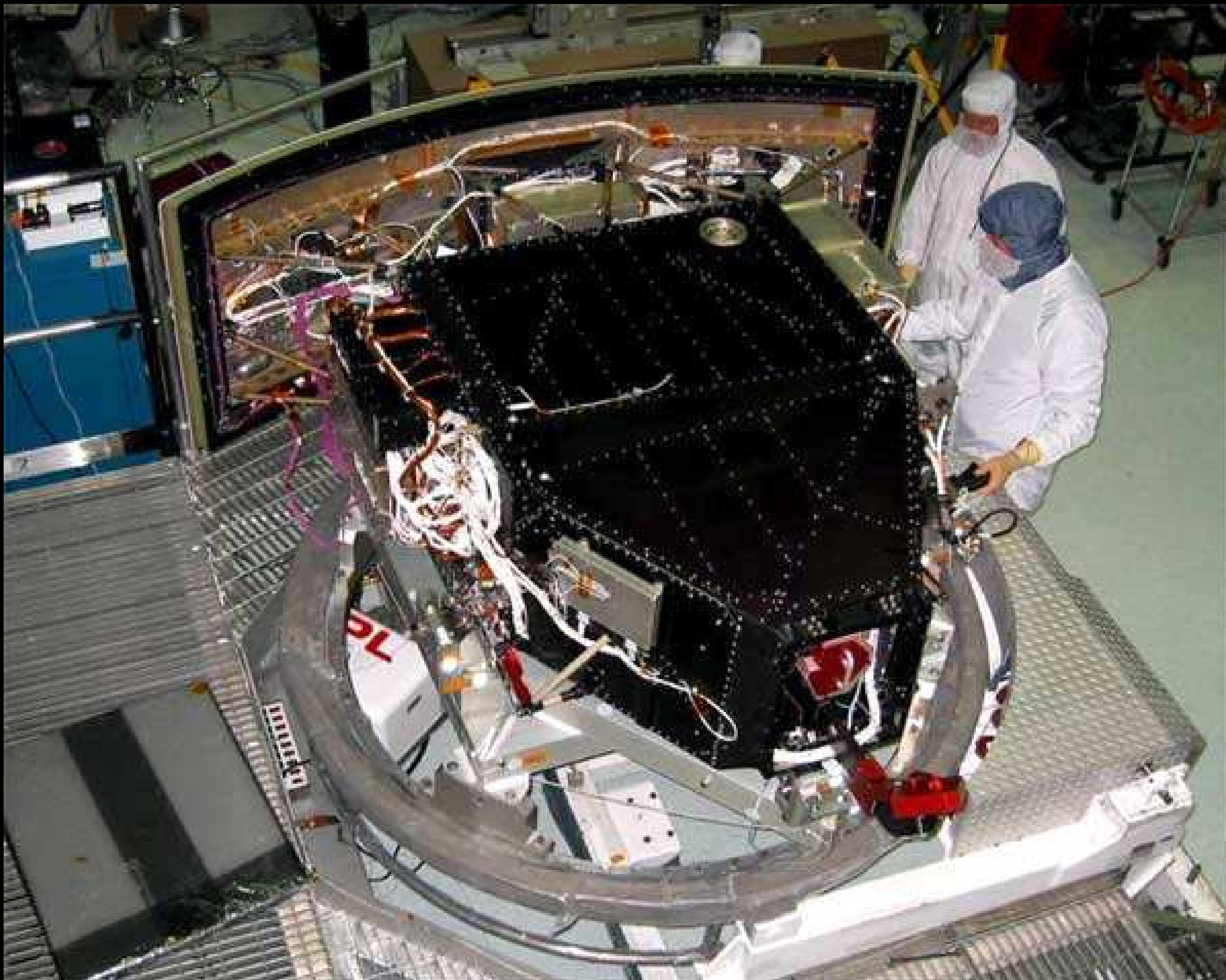
En route through the Space Park, Credit: NGSS



Arriving at the LATF Airlock, Credit: NGSS

Aug 2020: Transport of JWST into Northrop acoustic chamber

(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 arcmin^{2} with 0.07–0.15" images from 0.2–1.7μm (UVUBVizYJH).

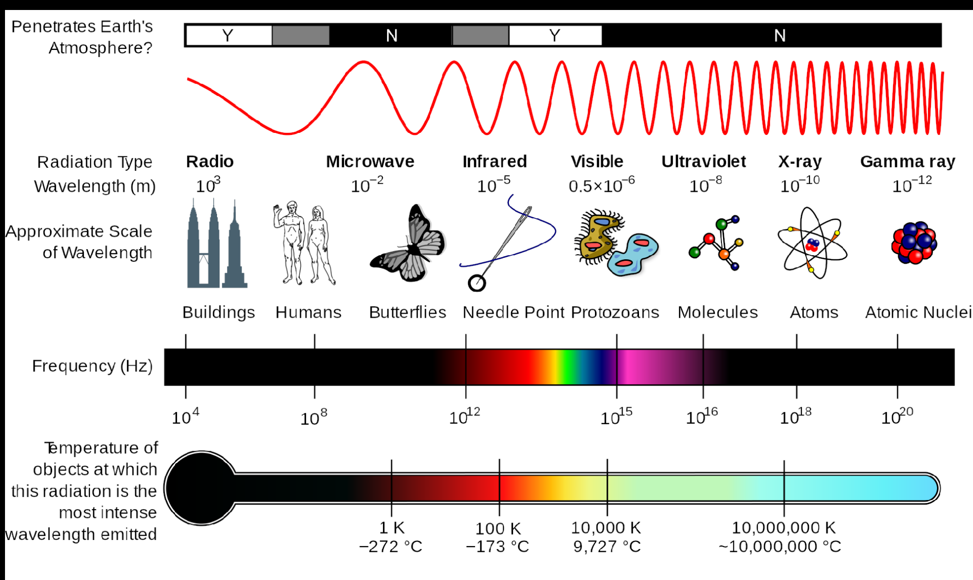
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 FF) at 1–5μm, with 0.2–1.2" images at 5–29μm, tracing young+old stars & dust.

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

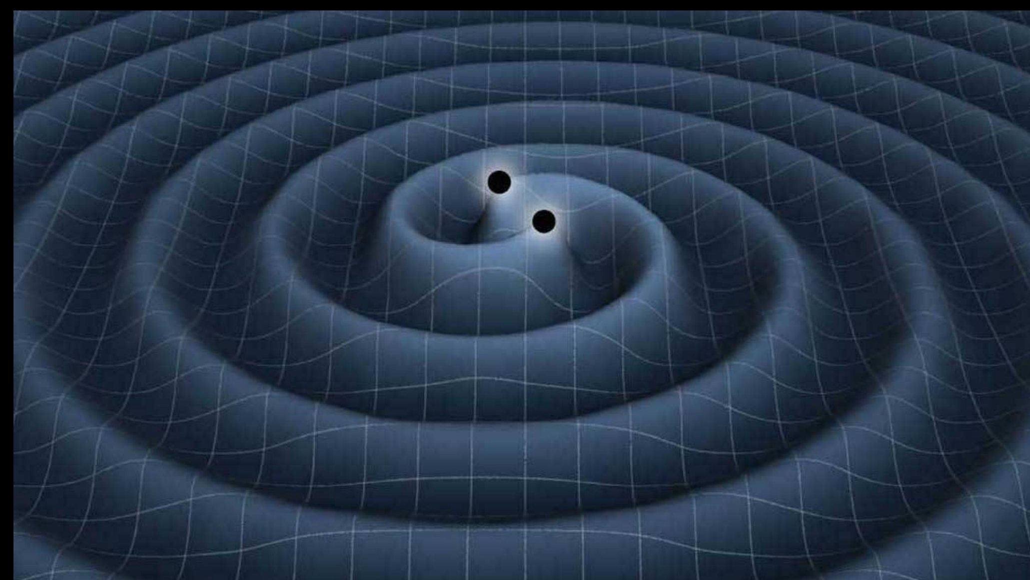
In solids: Earthquakes

In liquids: Surf!

In gasses: Sound

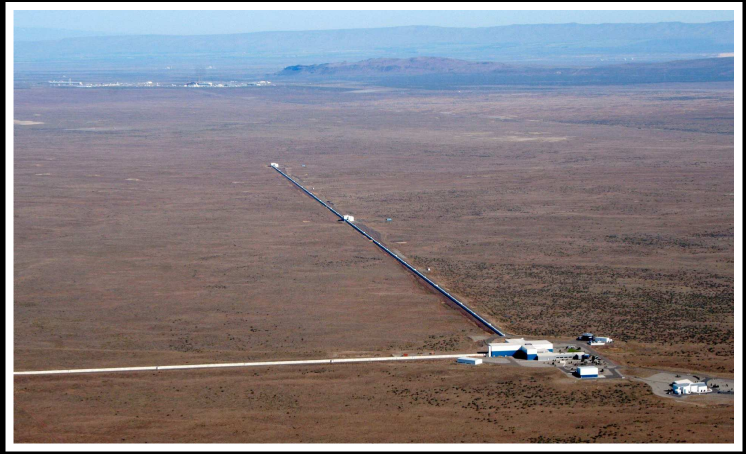


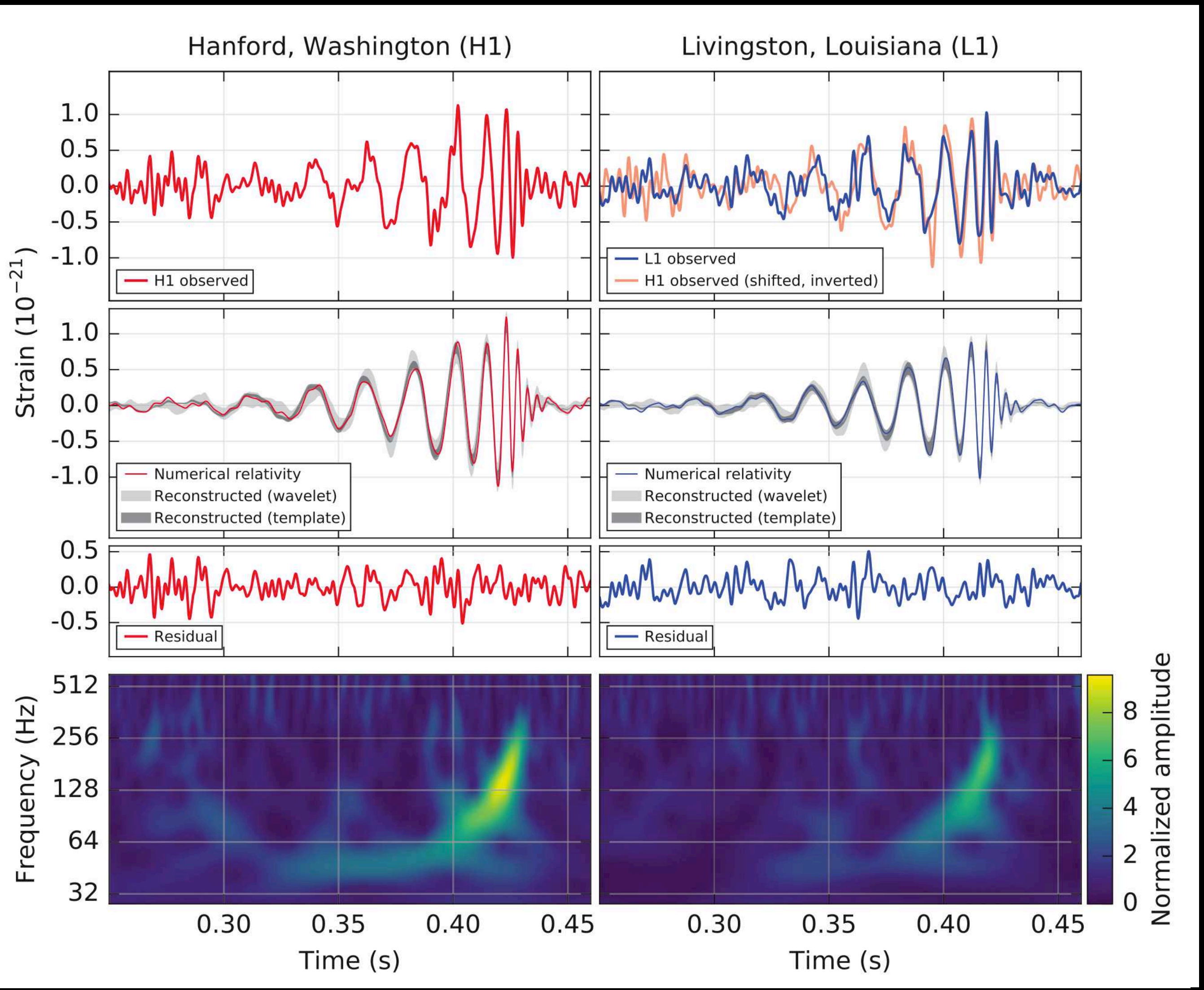
2) Electromagnetic Waves



3) In space-time: Gravity Waves

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

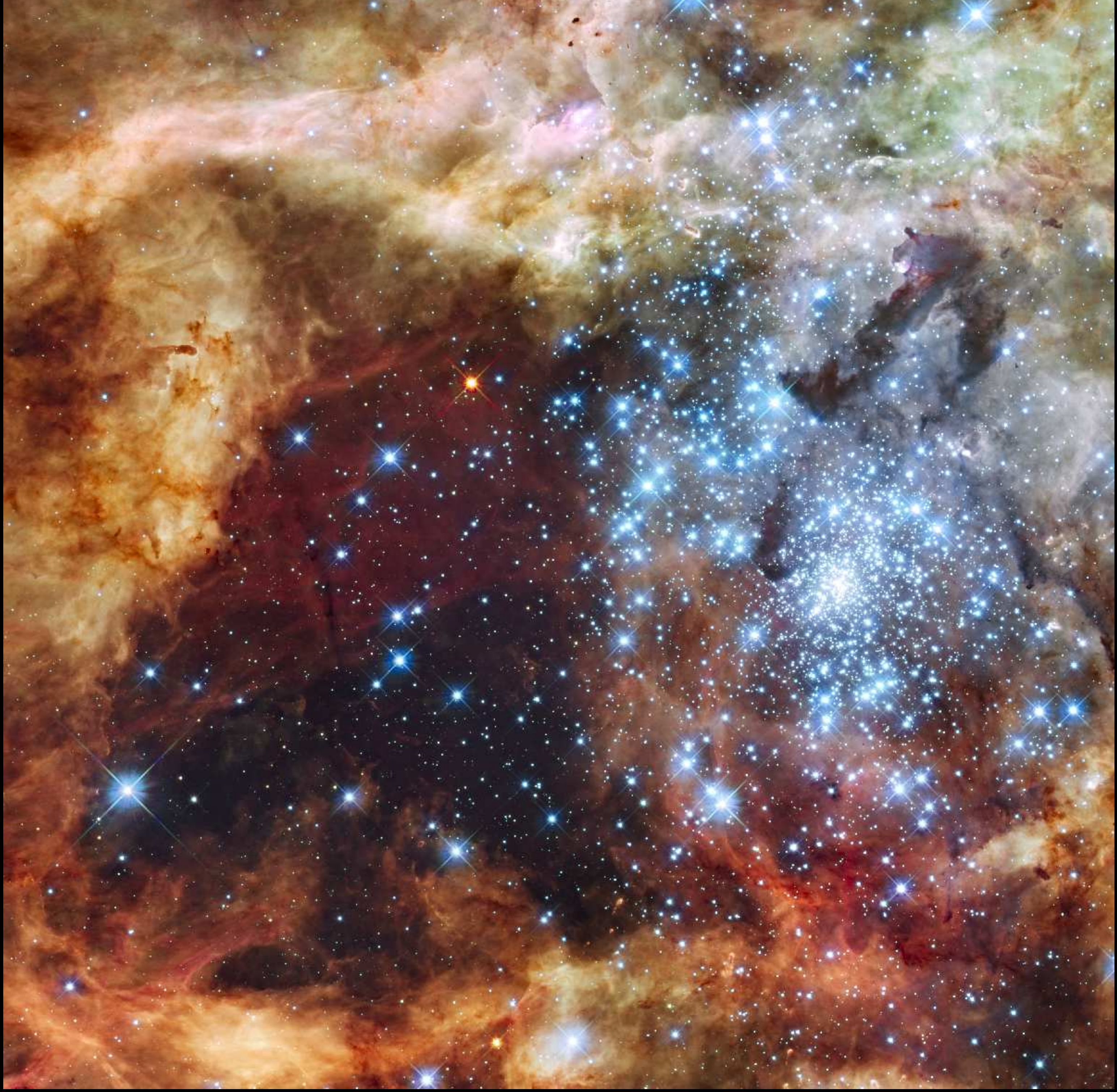




(1) LIGO first observed Gravitational Waves on Sept. 14, 2015.

(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!

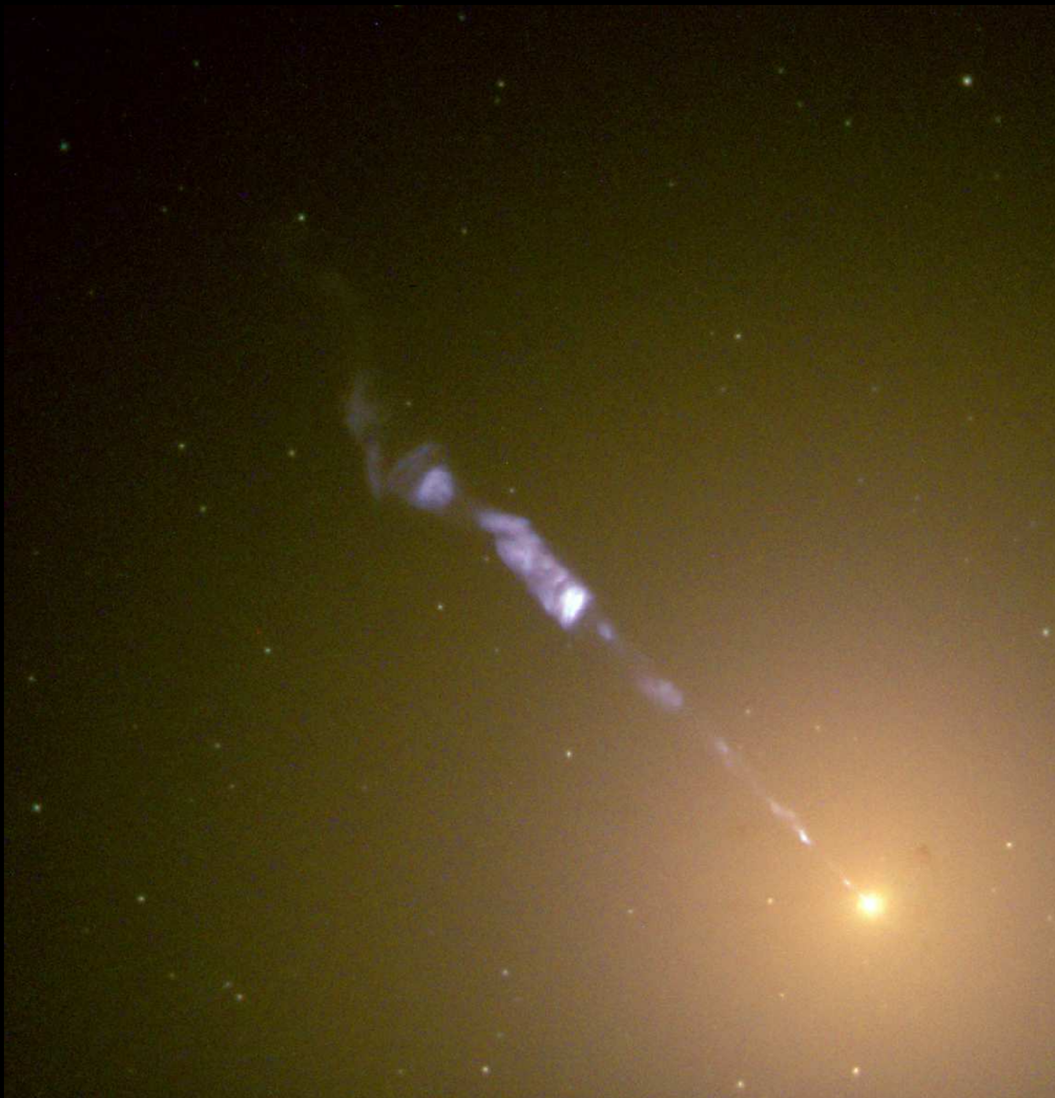


Ordinary massive stars (10–30 $M_{\odot}$) leave modest black holes ($\sim$3–10 $M_{\odot}$).

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:

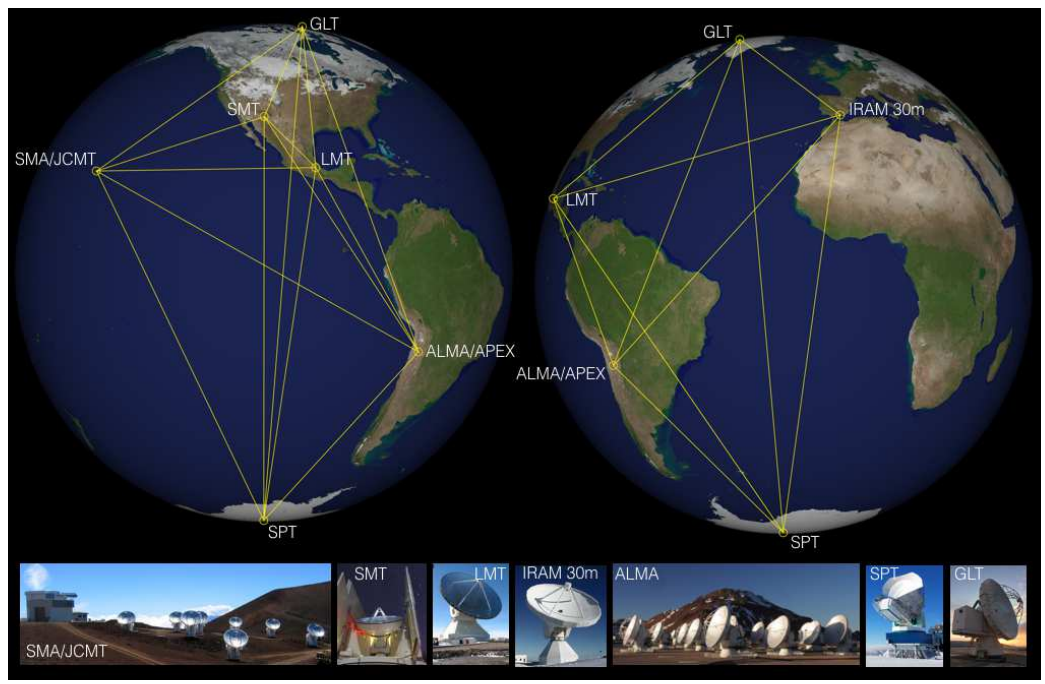


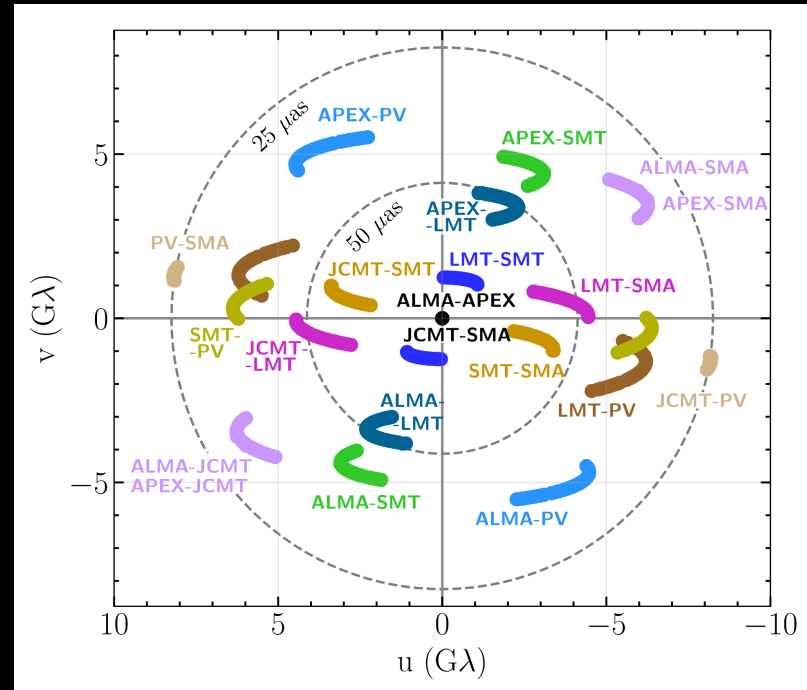
“For God’s sake, Edwards. Put the laser pointer away.”

The danger of having Quasar-like devices too close to home ...

They are EXTREMELY bright sources if viewed “down-the-pipe”.

$\sim$0.5% of the baryonic mass, but produce most of the photons!





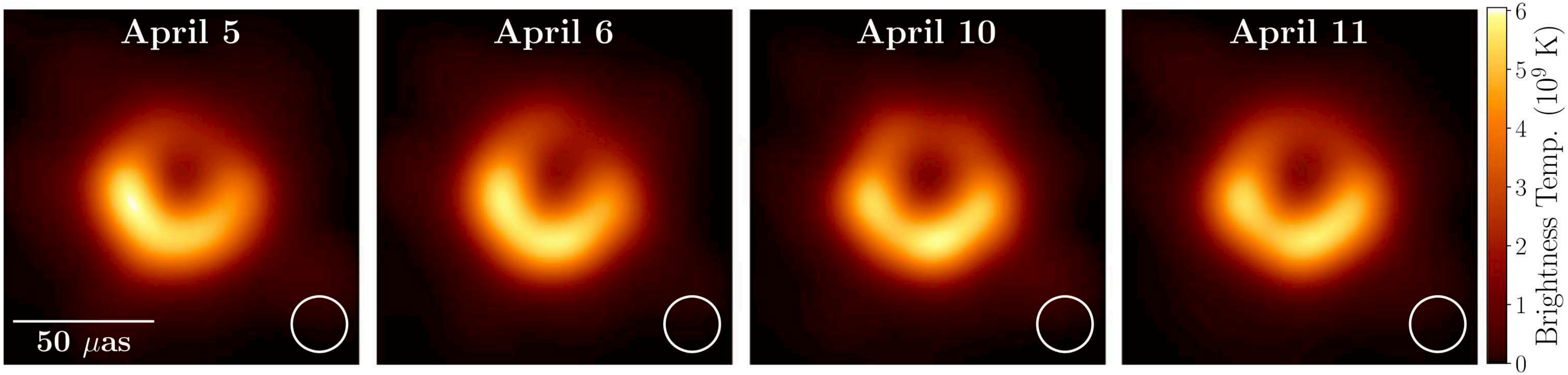
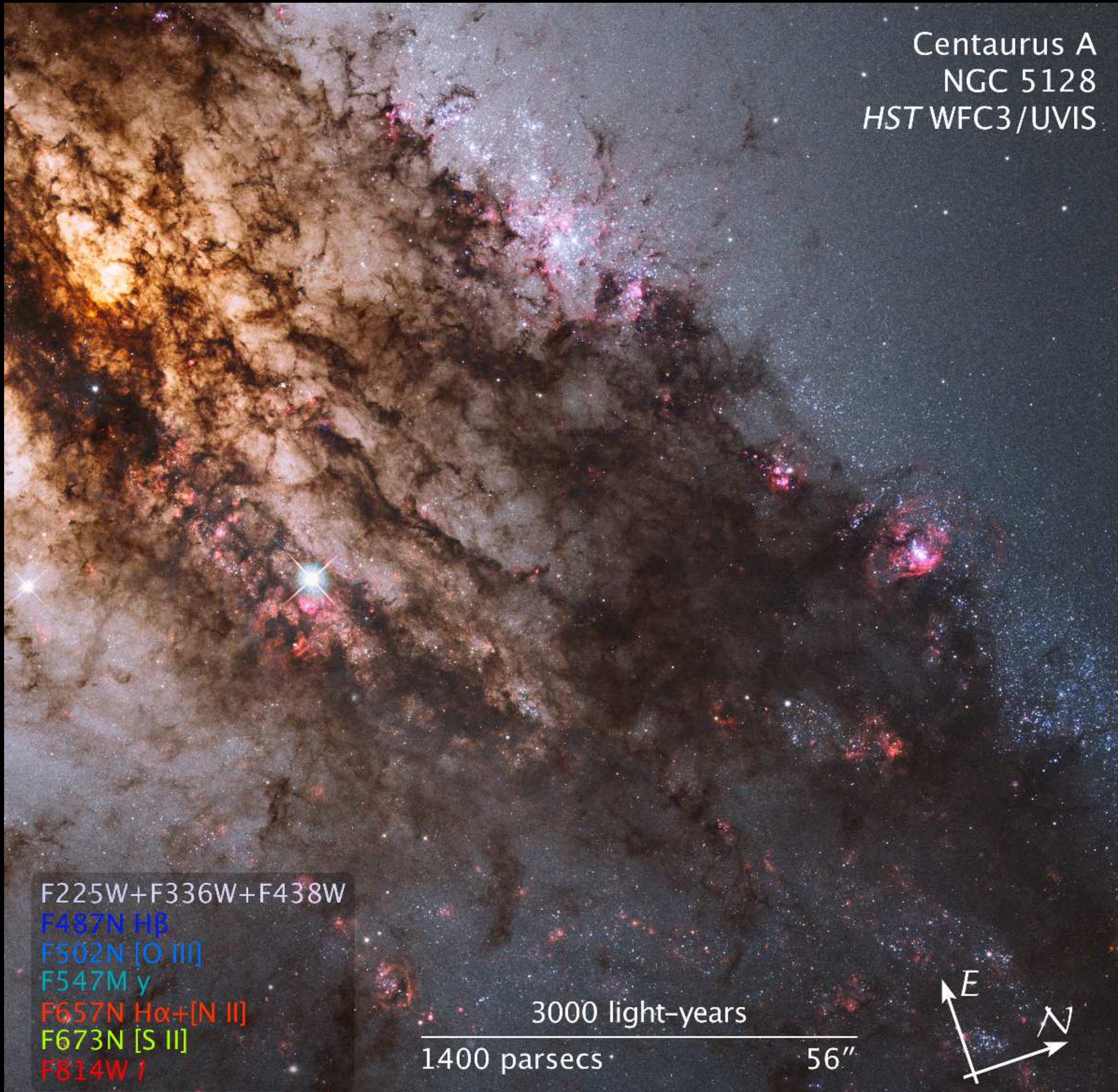
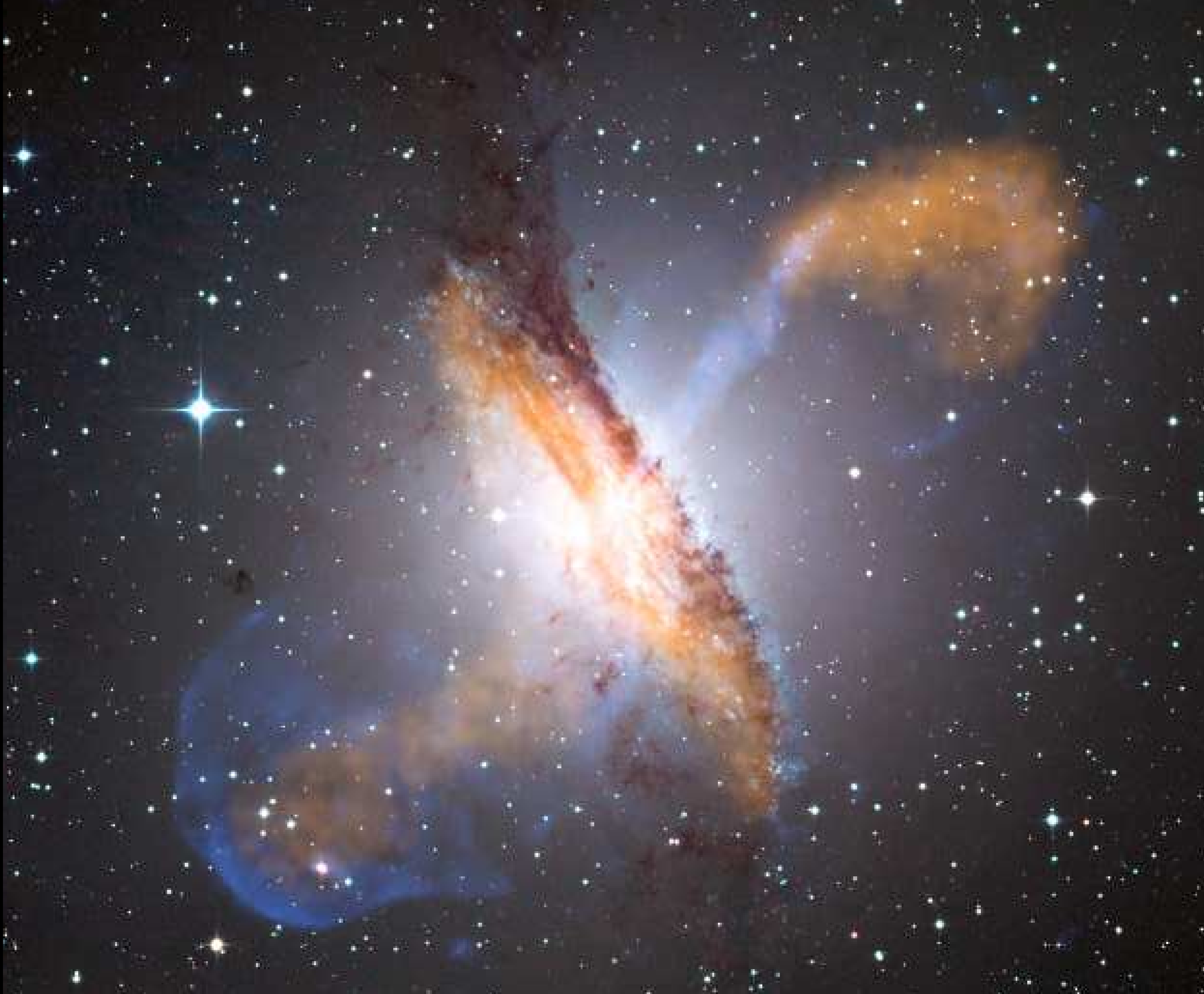


Figure 15. Averages of the three fiducial images of M87 for each of the four observed days after restoring each to an equivalent resolution, as in Figure 14. The indicated beam is 20 μas (i.e., that of `DIFMAP`, which is always the largest of the three individual beams).

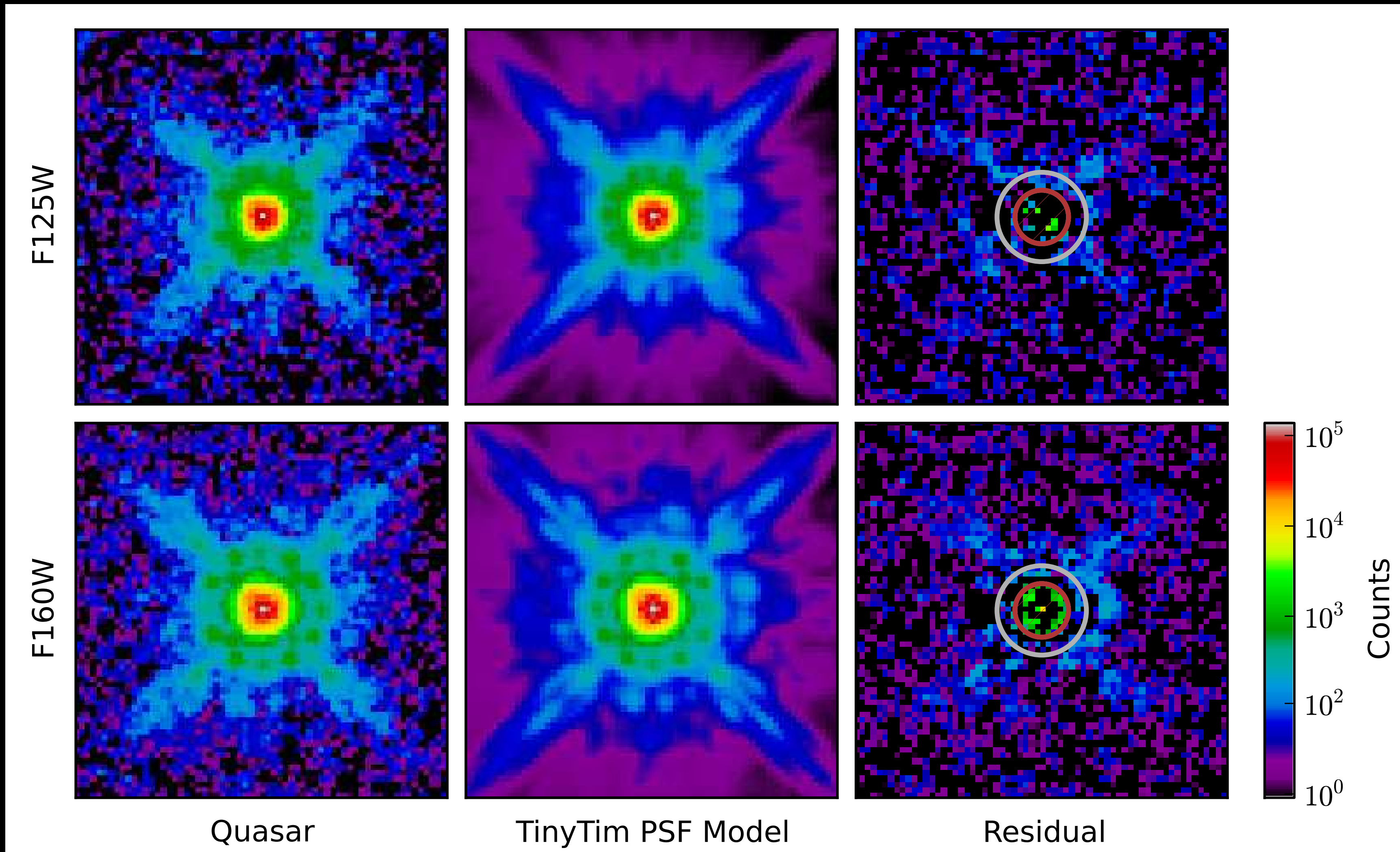
2019 discovery of Black Hole Shadow in M87 by Event Horizon Telescope: M87 at 55 Mlyr distance has a black hole mass of $\sim 6.5 \times 10^9 \; M_\odot$!


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W I
3000 light-years
1400 parsecs
56″
E
N



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× smaller than today), 900 Myr old!

• Contains 10^{14} solar luminosities within a region as small as Pluto's orbit!

• A feeding monster blackhole ($>3\times10^9$ 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).

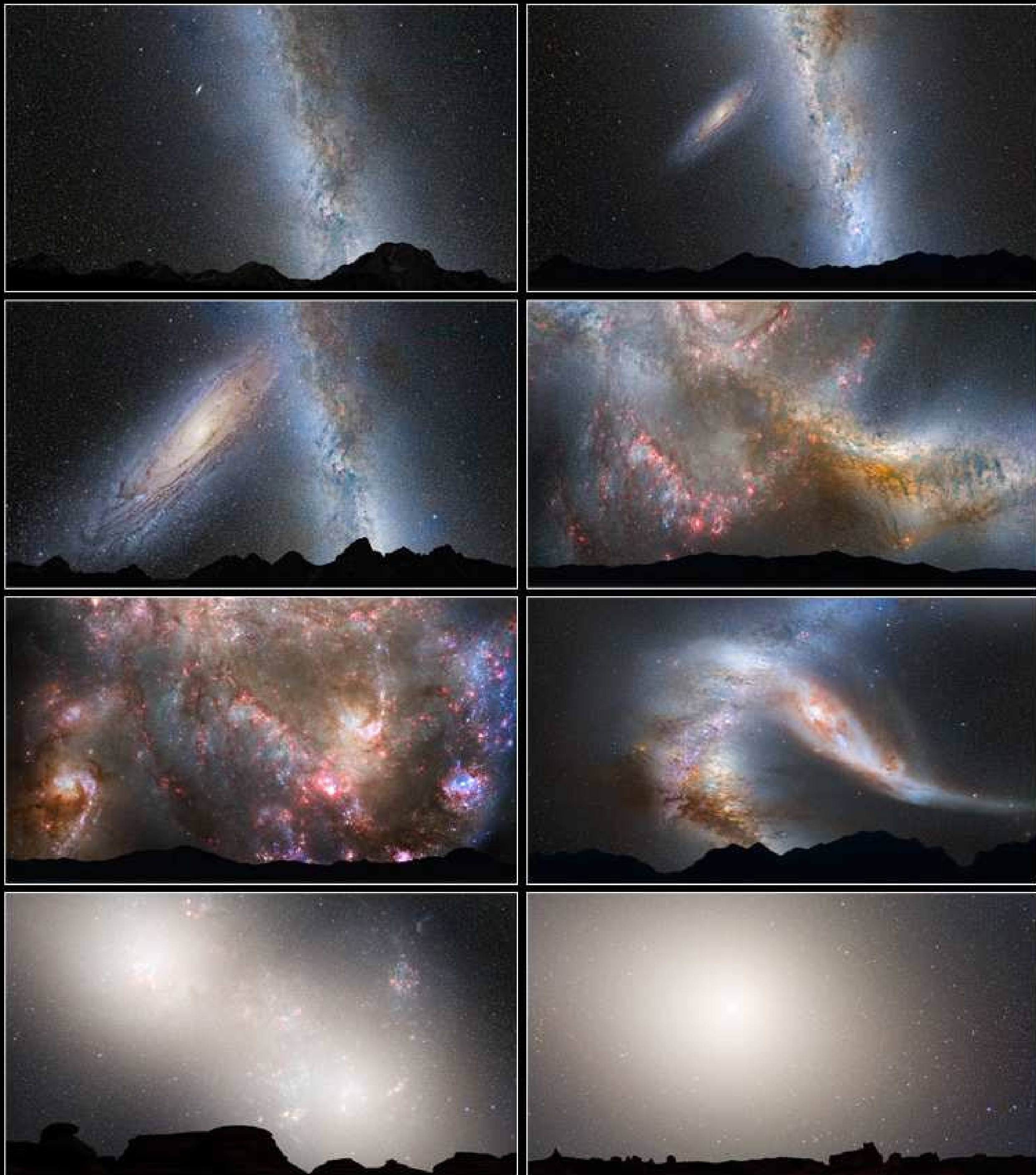


Illustration Sequence of the Milky Way and Andromeda Galaxy Colliding

NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger ▪ STScI-PRC12-20b

Will this ever happen to our own Galaxy?

YES! Hubble showed no lateral motion of Andromeda:

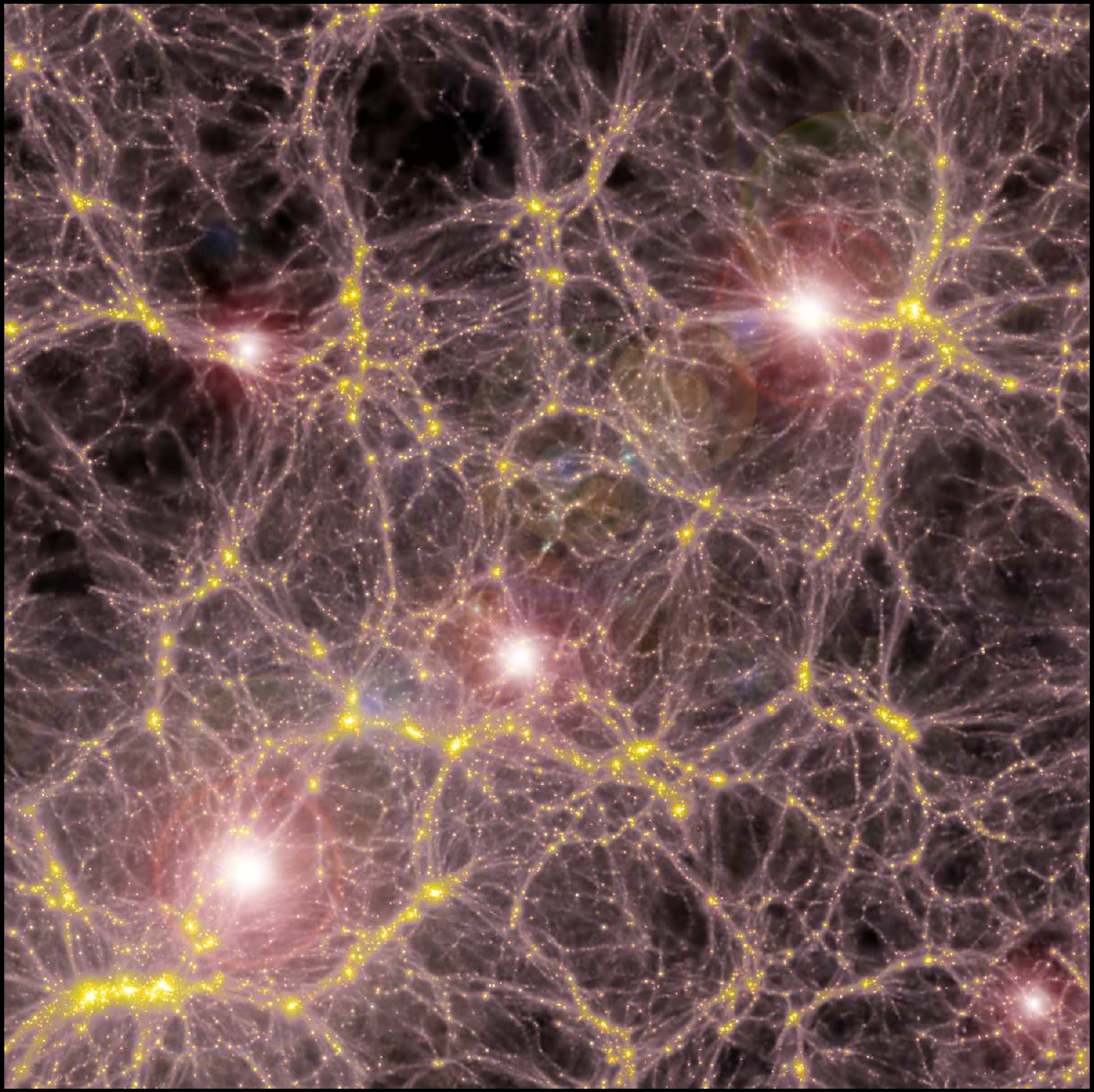
Approaches at –110 km/s.

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!

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

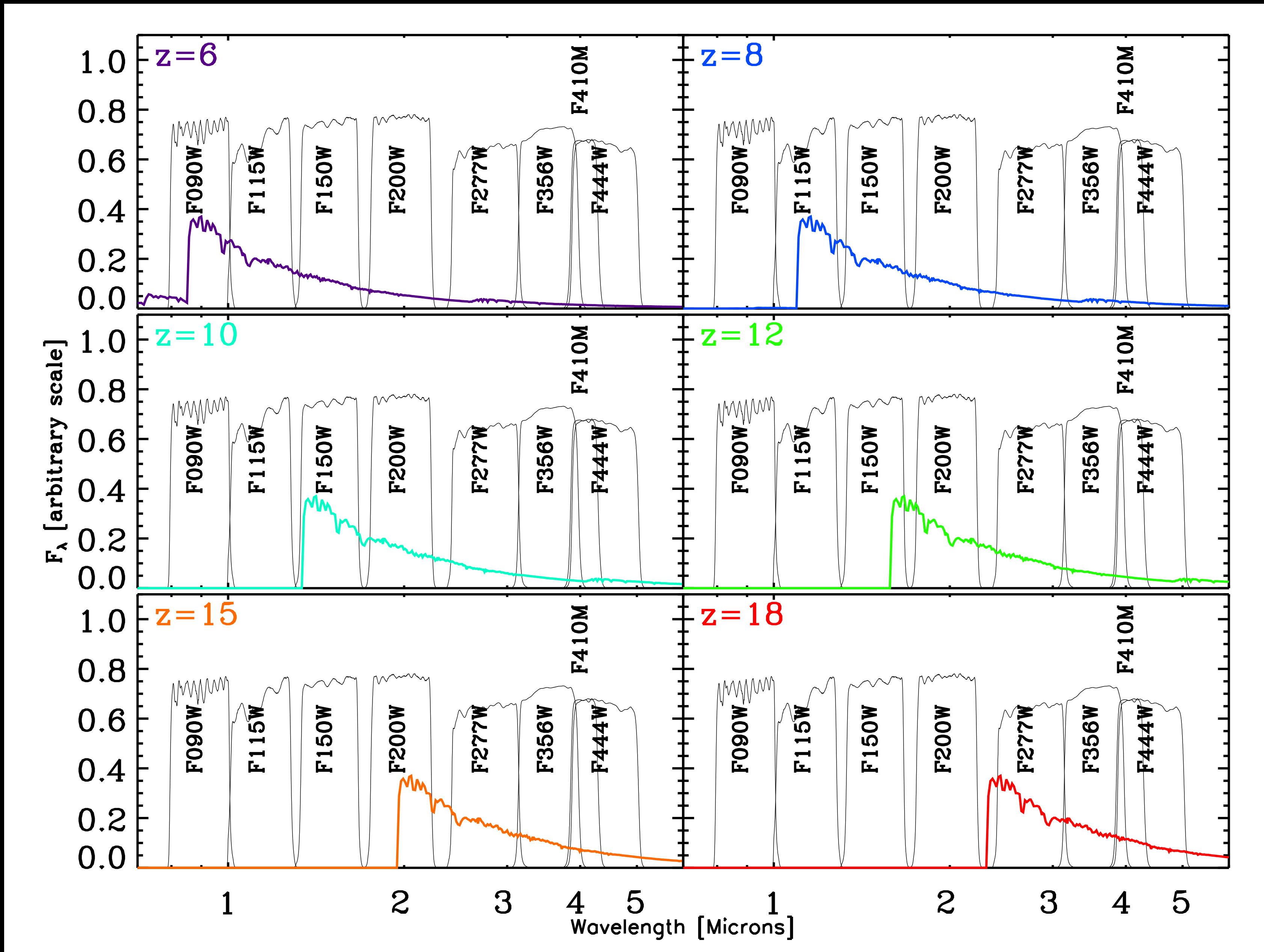


- Detailed cosmological models (V. Bromm) suggest that massive "Pop III" stars ($\gtrsim$100 M_{sun}) started to reionize the universe at z$\lesssim$10–30 (0.1–0.5 Gyr; "First Light").

- 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$10$\longrightarrow$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.

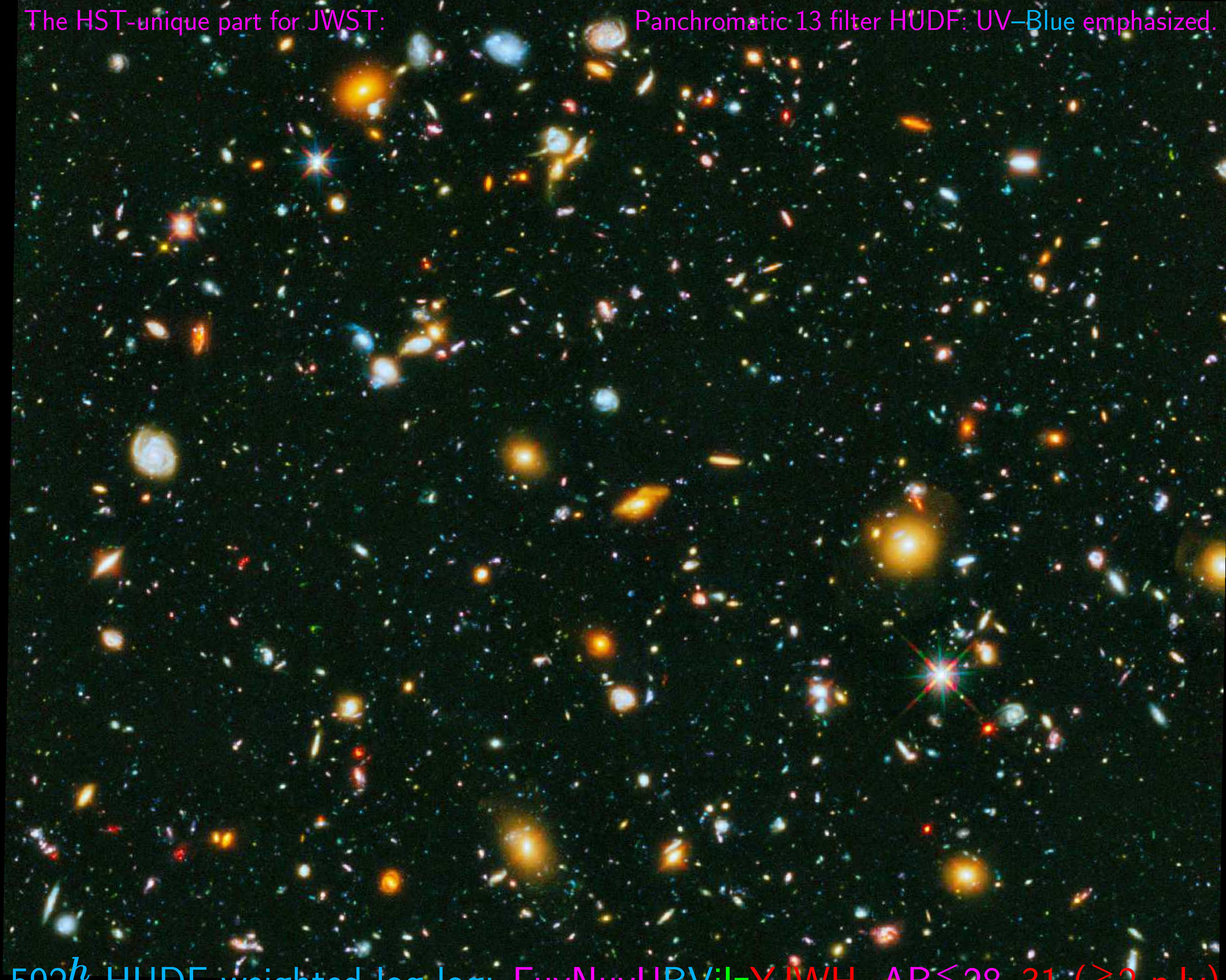
3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



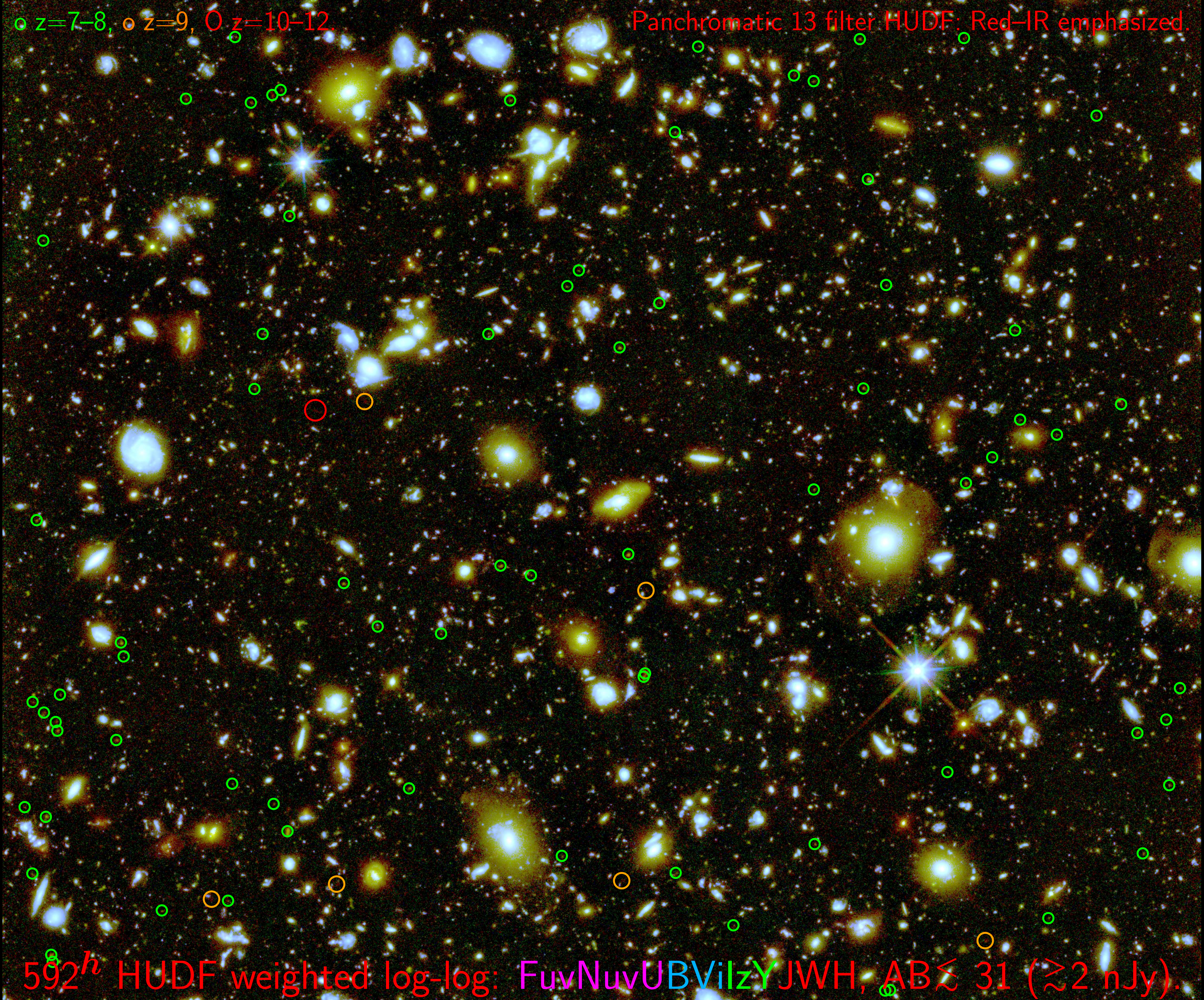
- Can't beat redshift: to see First Light, must observe near–mid IR.

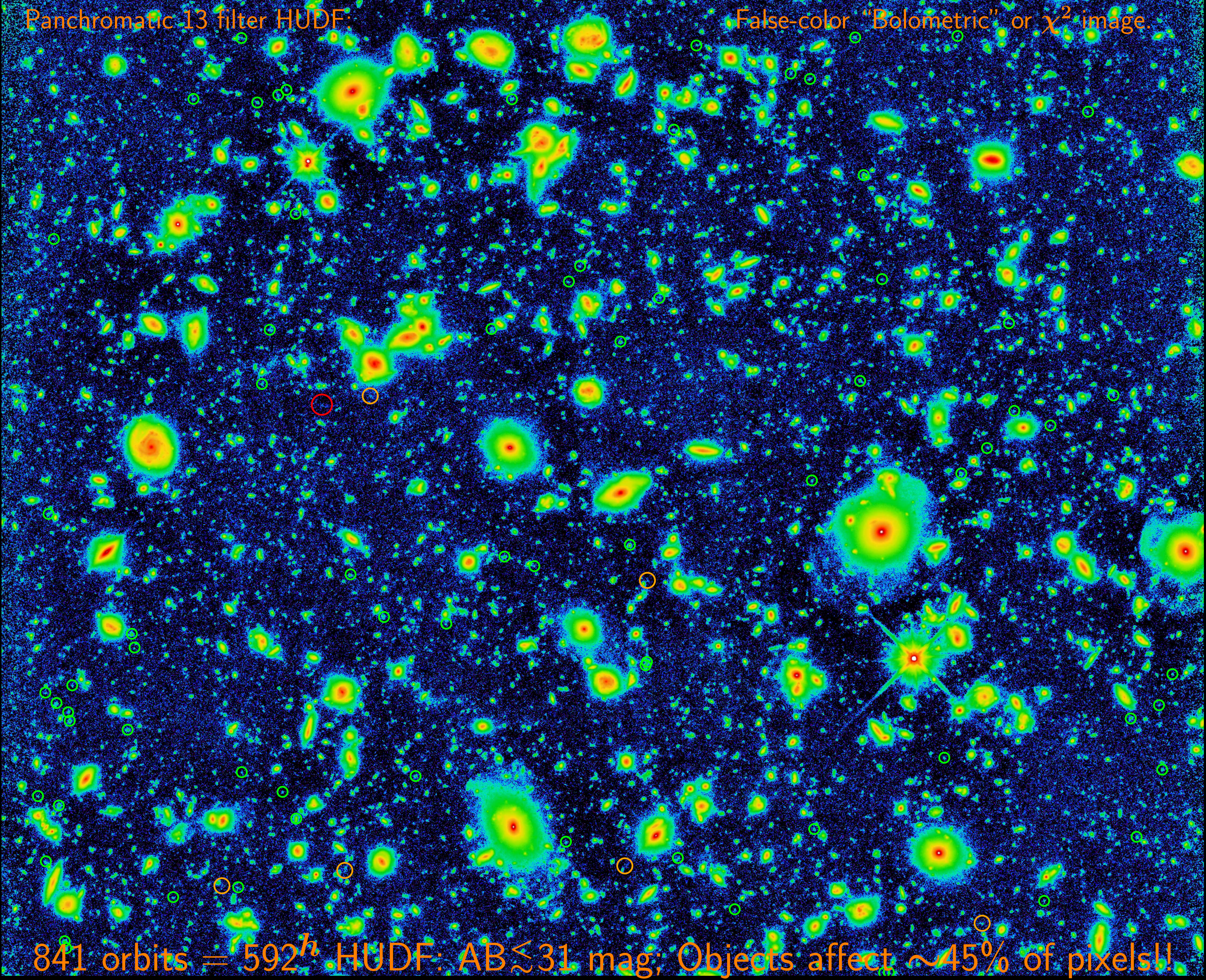
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.

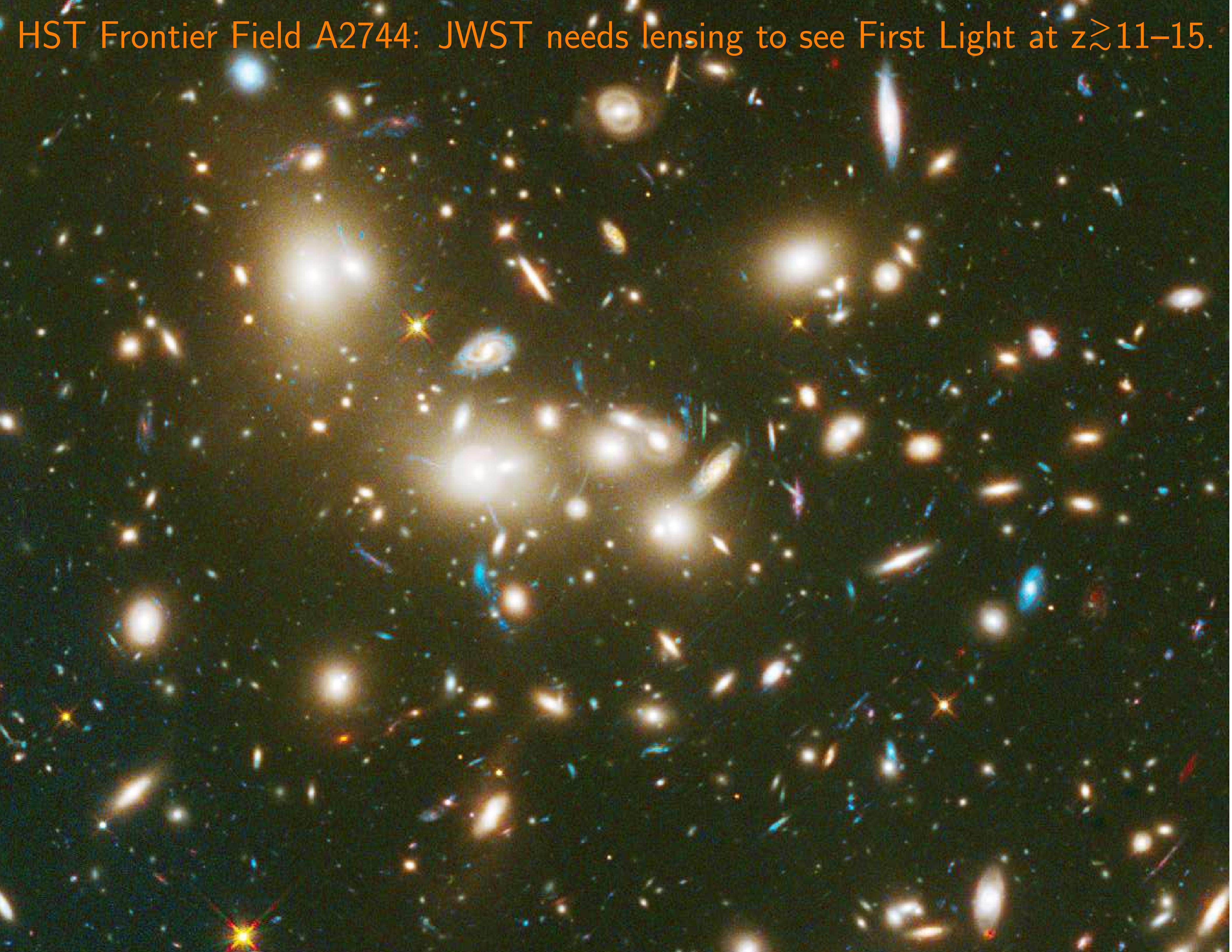


592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).


o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB≲ 31 (≳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).

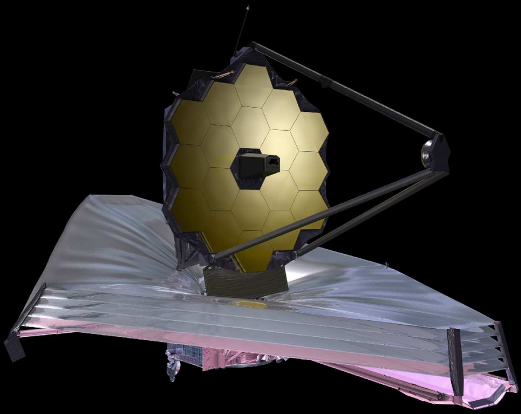
(2) Cannot-see-the-forest-for-the-trees effect ["Natural Confusion" limit]:
Background objects blend into foreground because of their own diameter.

(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

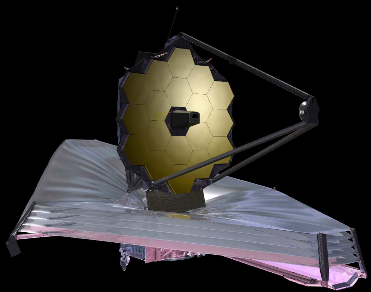


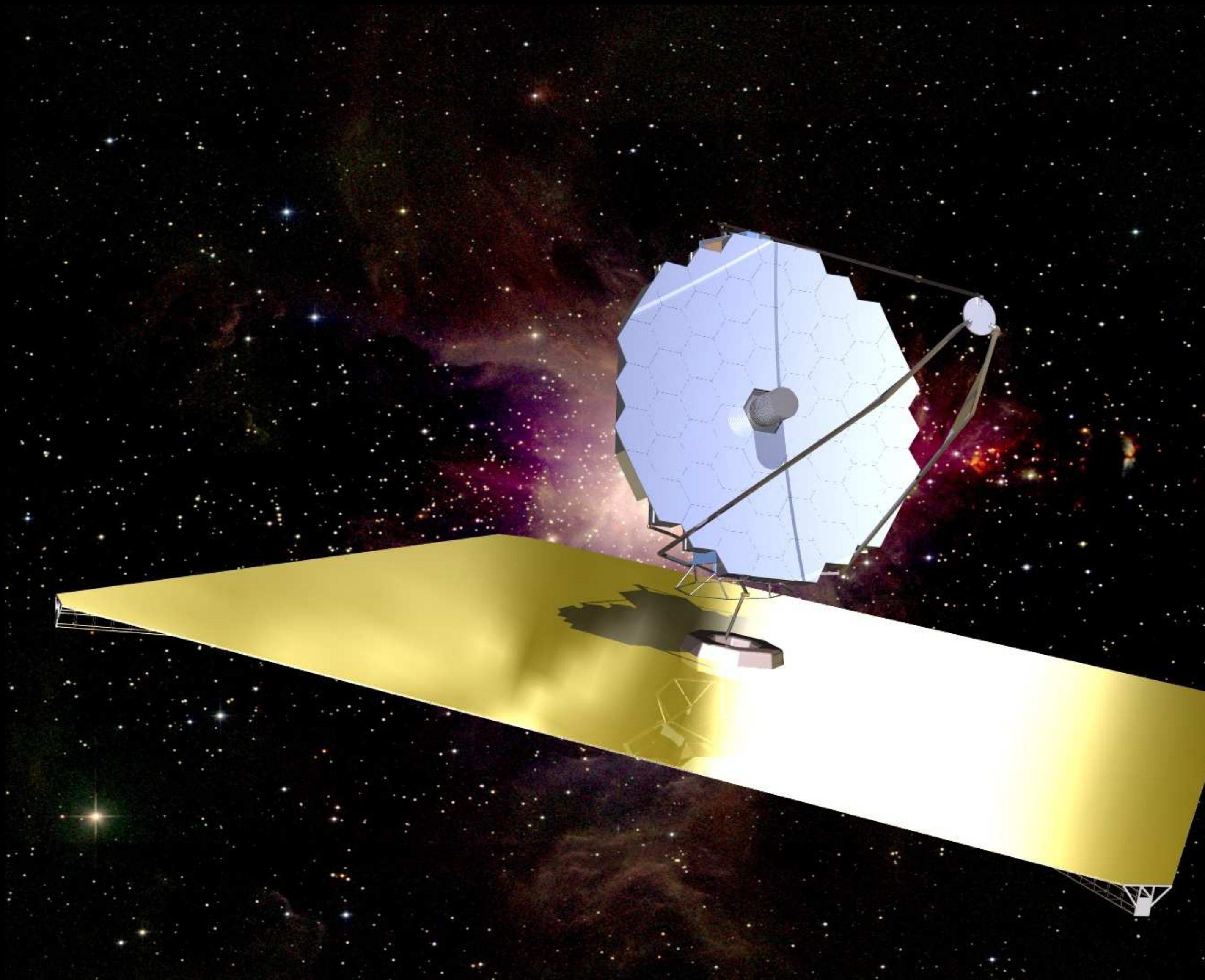
(1973∼2020$^+$); (1996∼2031); (2000∼2050$^+$).

- 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:

- 100% of JWST H/W built, & meets/exceeds specs. Final I&T.

(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).

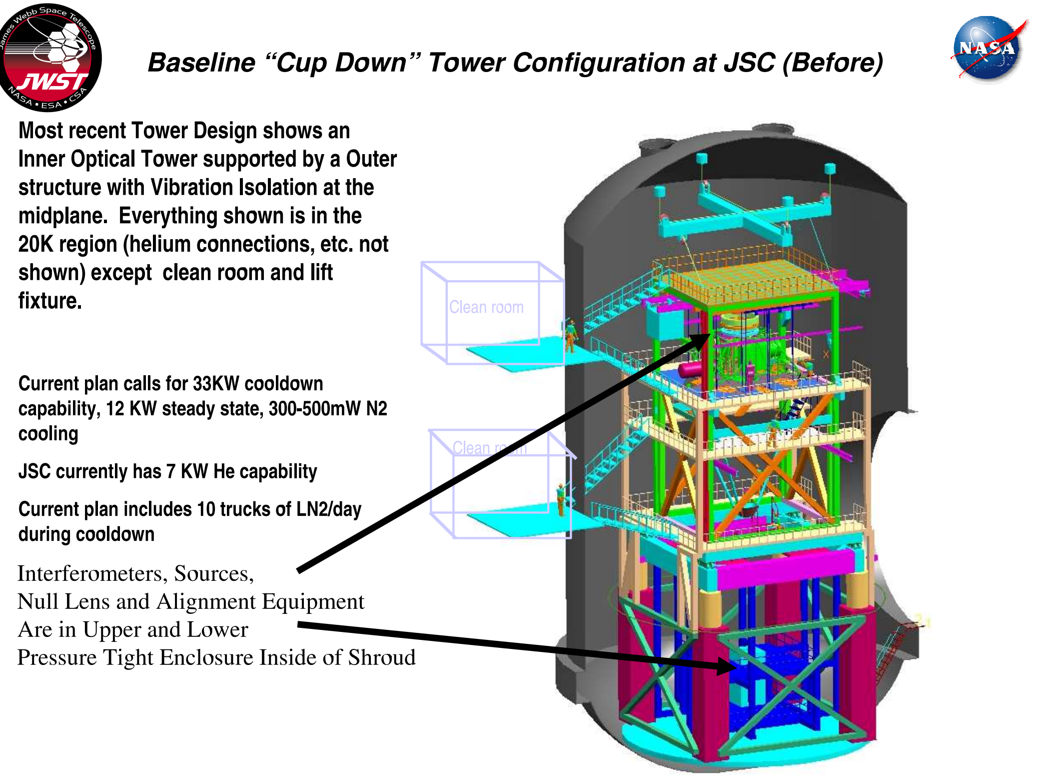
Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

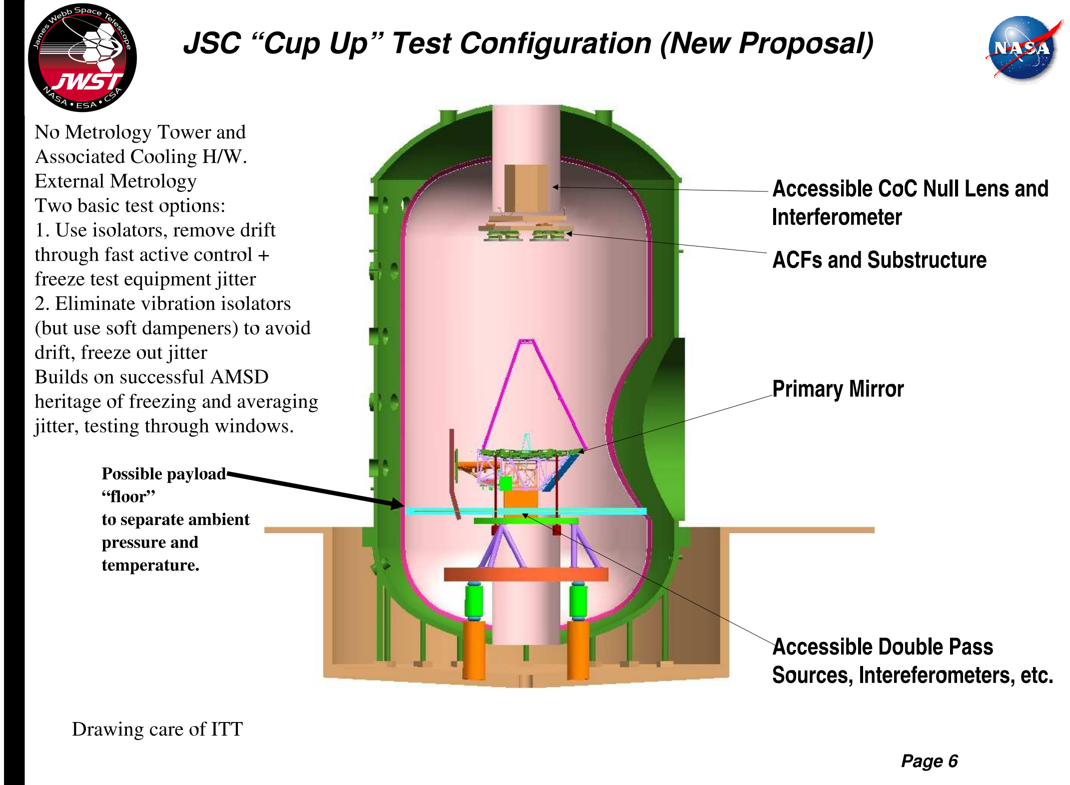
• (6) Update of JWST programmatics as of 2020

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







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).
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.
- 2017–2018: Replan final Integration & Testing $\Rightarrow$ Oct 2021 launch.

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	Complete 4/5/2019
	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	Completed 4/7/19
	13	Deliver the flight version of launch vehicle coupled loads analysis #2 Observatory model	Completed 5/6/19
Apr-19	14	Open thermal vacuum chamber door following testing	Completed 5/19/19
	15	Conduct Wavefront Sensing rehearsal #3 at the MOC	Completed 4/12/19
May-19	-	NONE	
Jun-19	16	Complete Spacecraft Element post-launch environmental testing deployment	replanned to follow science payload installation (FY20)
	17	Complete the secondary mirror structure deployment driven by the Spacecraft Element	Completed 7/13/19
Jul-19	18	Received updated Cycle 1 proposals from the Guaranteed Time Observers	Completed 6/25/19
	19	Conduct Science Operations rehearsal #5 at the MOC	Completed 7/12/19
Aug-19	20	Complete Spacecraft Element post-launch environments and thermal vacuum testing folding	replanned to follow science payload installation (FY20)
	21	Observatory System Integration Review (SIR)	Completed 7/25/2019 (Part 1), 10/19 (Part 2)
Sep-19	22	Install science payload onto the Spacecraft Element	Completed 8/23/19
	23	Deliver the flight version of launch vehicle coupled loads analysis #2 results and detailed assessment	replanned to follow science payload installation (FY20)
	24	Spacecraft Element Integration complete	Completed 6/29/19
	25	Conduct Contingency Planning rehearsal #3 at the MOC	Completed 9/27/19

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

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

Milestone Performance

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

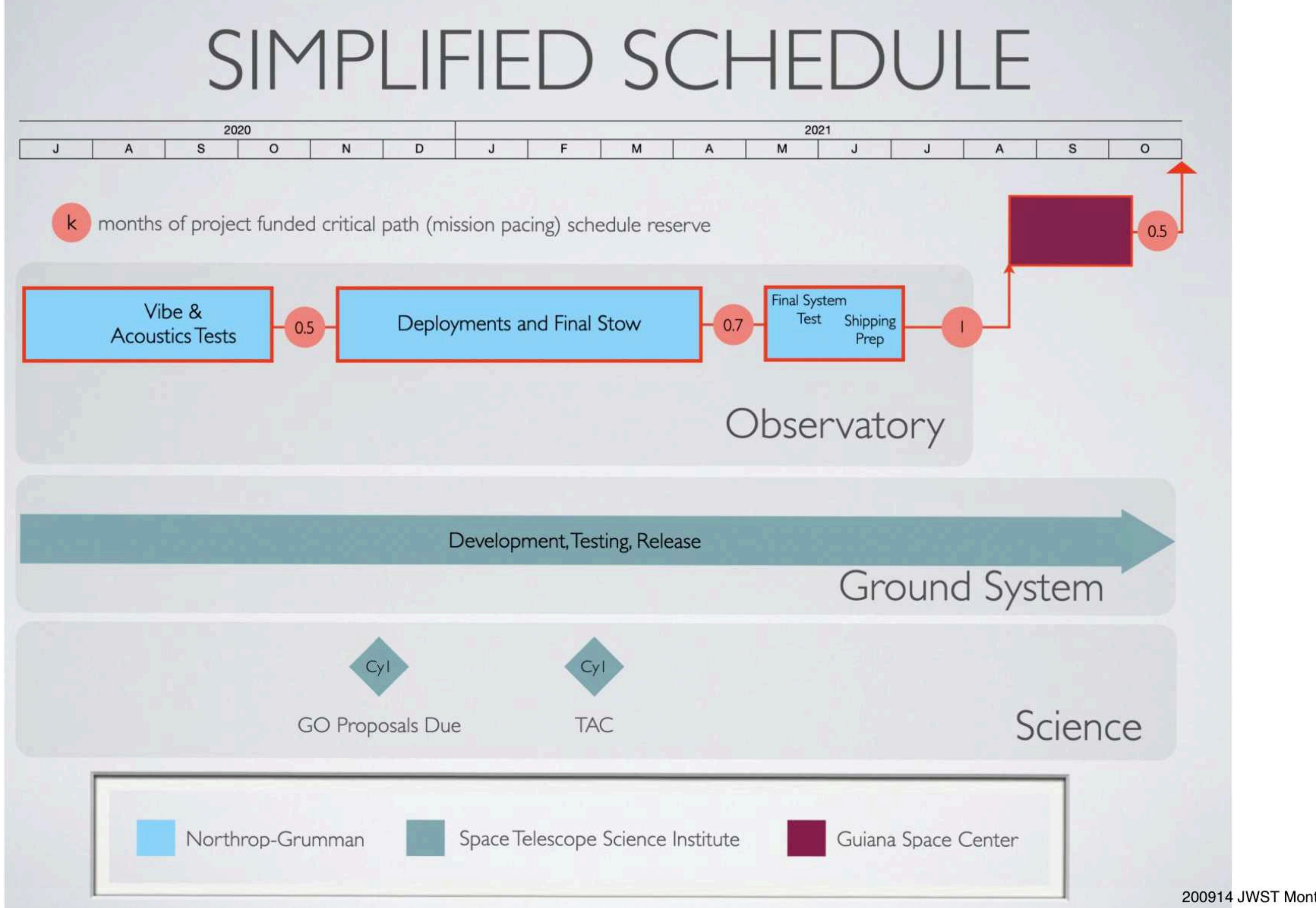
	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year	Deferred more than one quarter
FY2011	21	21	6	3	0	0
FY2012	37	34	16	2	3	3
FY2013	41	38	20	5	3	2
FY2014❖	36	23	10	8	11	10
FY2015	48	44	22	12	4	3
FY2016	45	39	25	7	6	2
FY2017	38	32	12	13	8	5
FY2018	31	18	7	2	13	13
FY2019	25	19	8	9	2	1

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

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

FY15: Most “Lates” not on critical path.

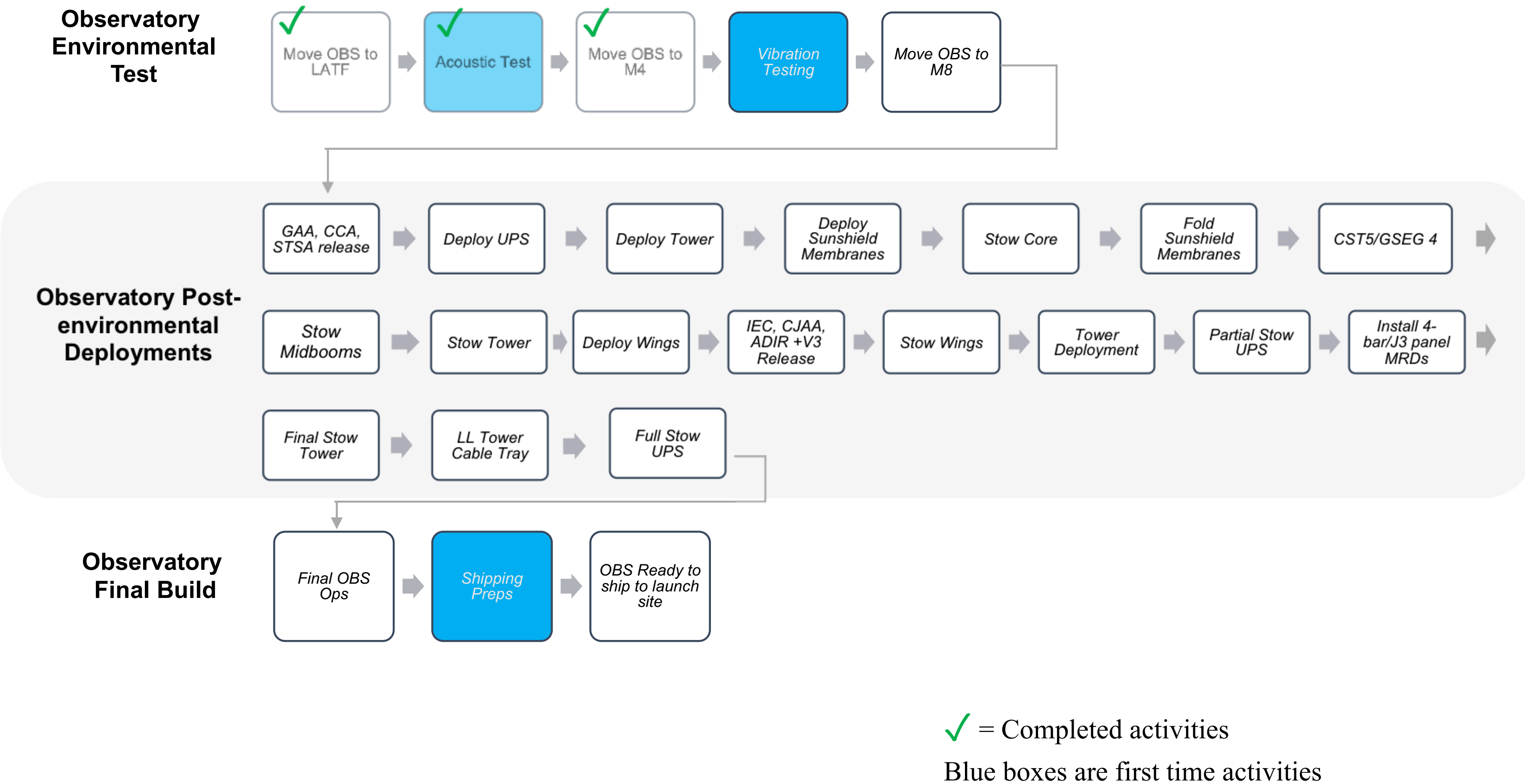
FY17: Lates started to outnumber Early’s $\Rightarrow$ Replan Integration & Testing.



Path forward to Launch (NOW: Oct 2021): $\lesssim$2.7 mos schedule reserve.

- Final testing done in Fall 2020/Spring 2021 (at Northrop).

Remaining I&T Activities

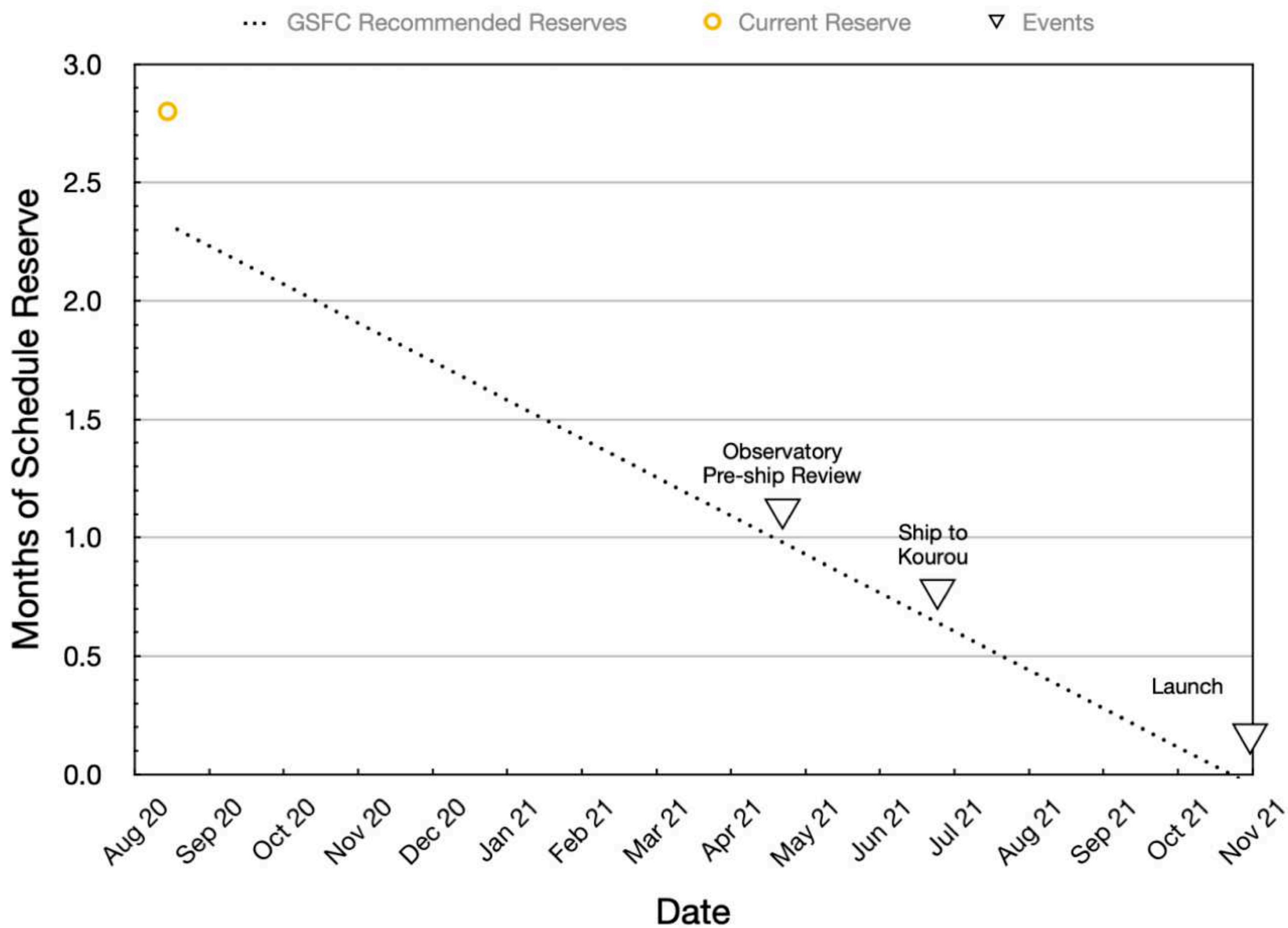


200914 JWST Monthly Teleco

Flowchart of future Project tasks for FY21.

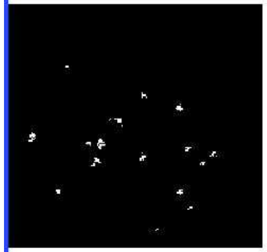
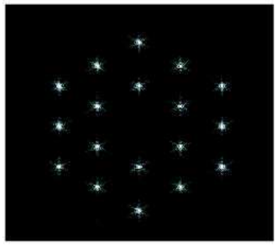
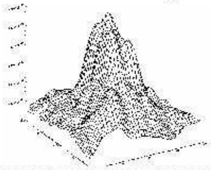
Blue = First-time System test (but done before at the sub-system level).

Current Funded Schedule Reserve



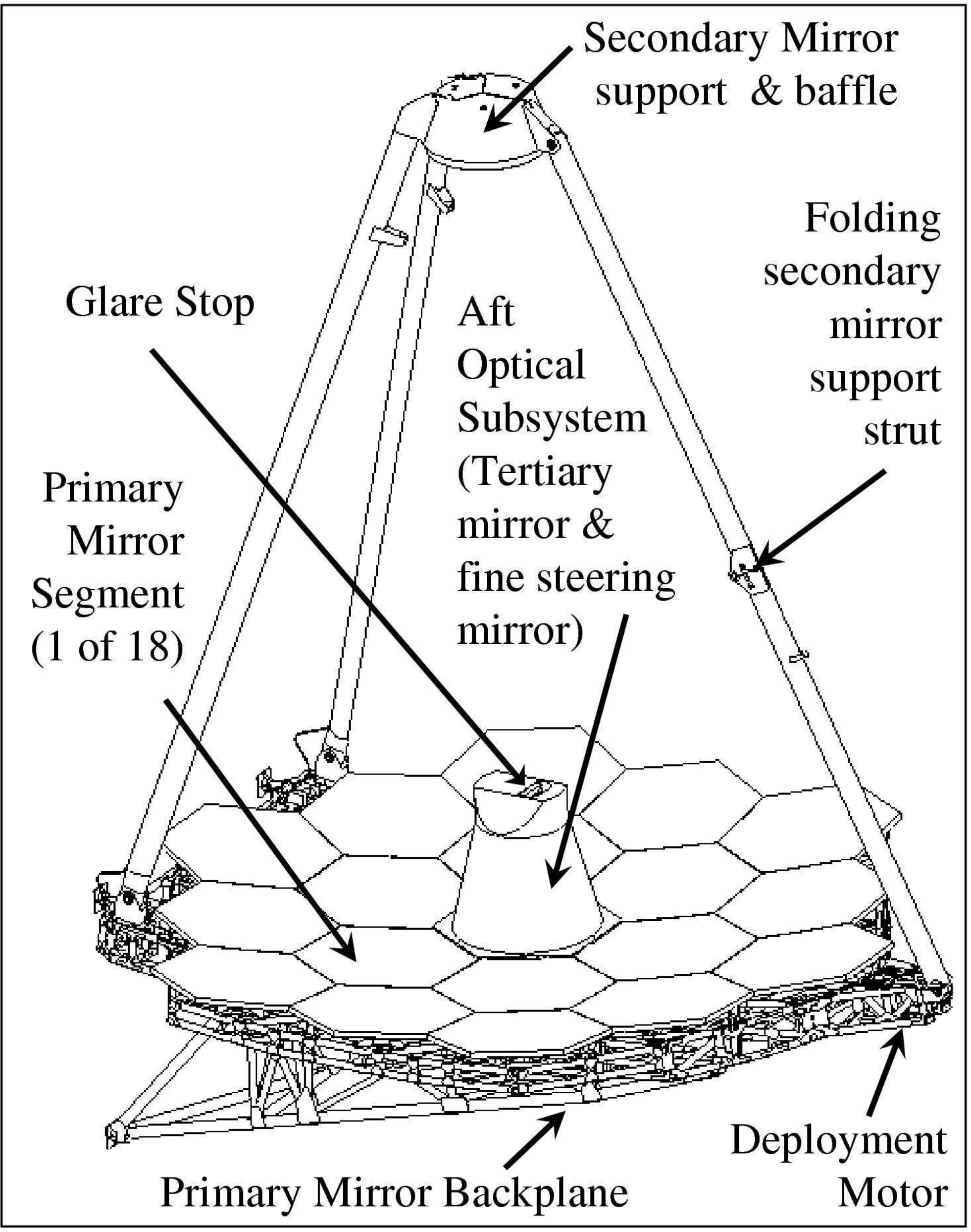
2009

Project reserves in Fall 2020 for launch in Oct 2021.

Step		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	After Step 1 	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)

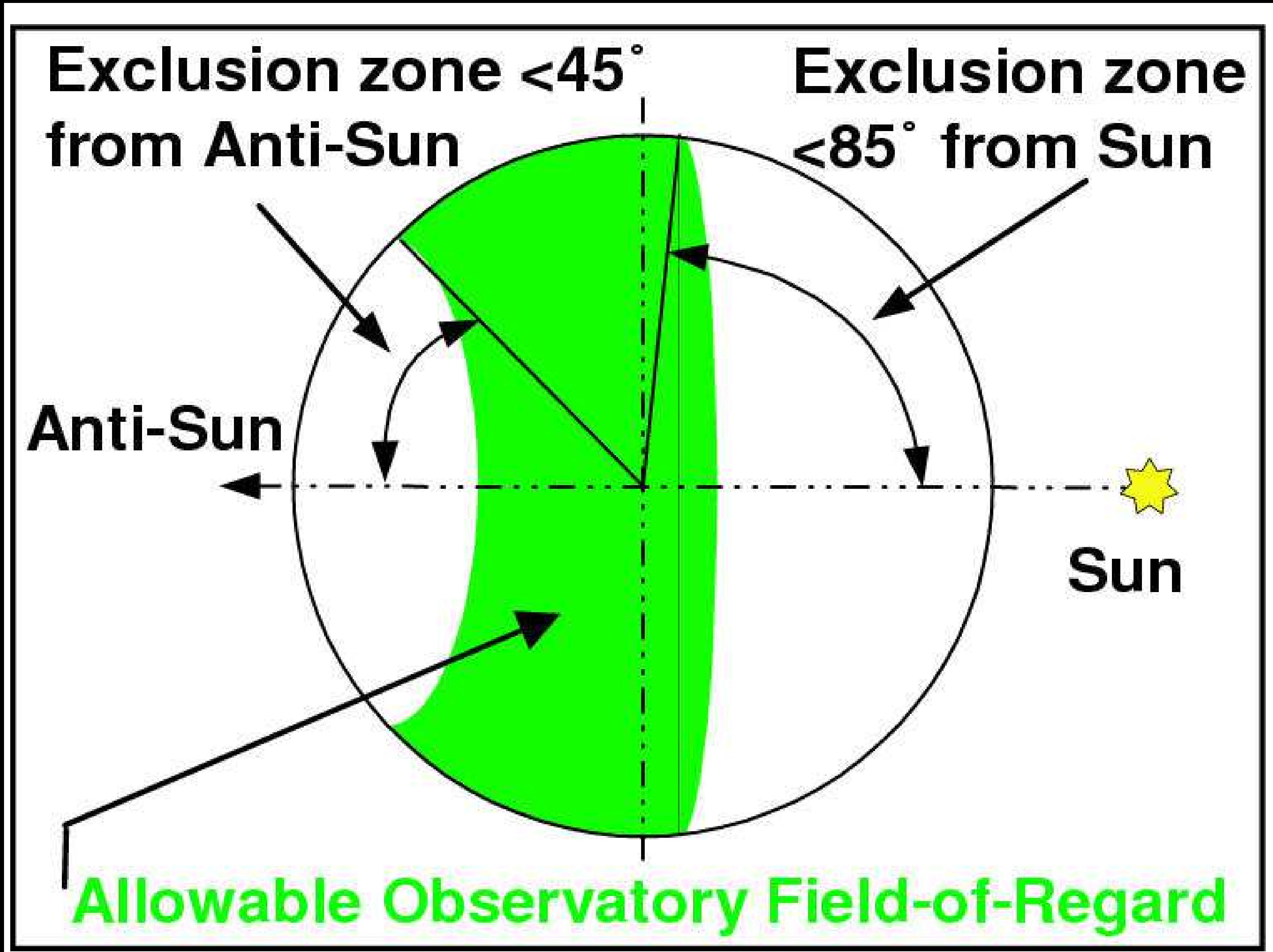
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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.

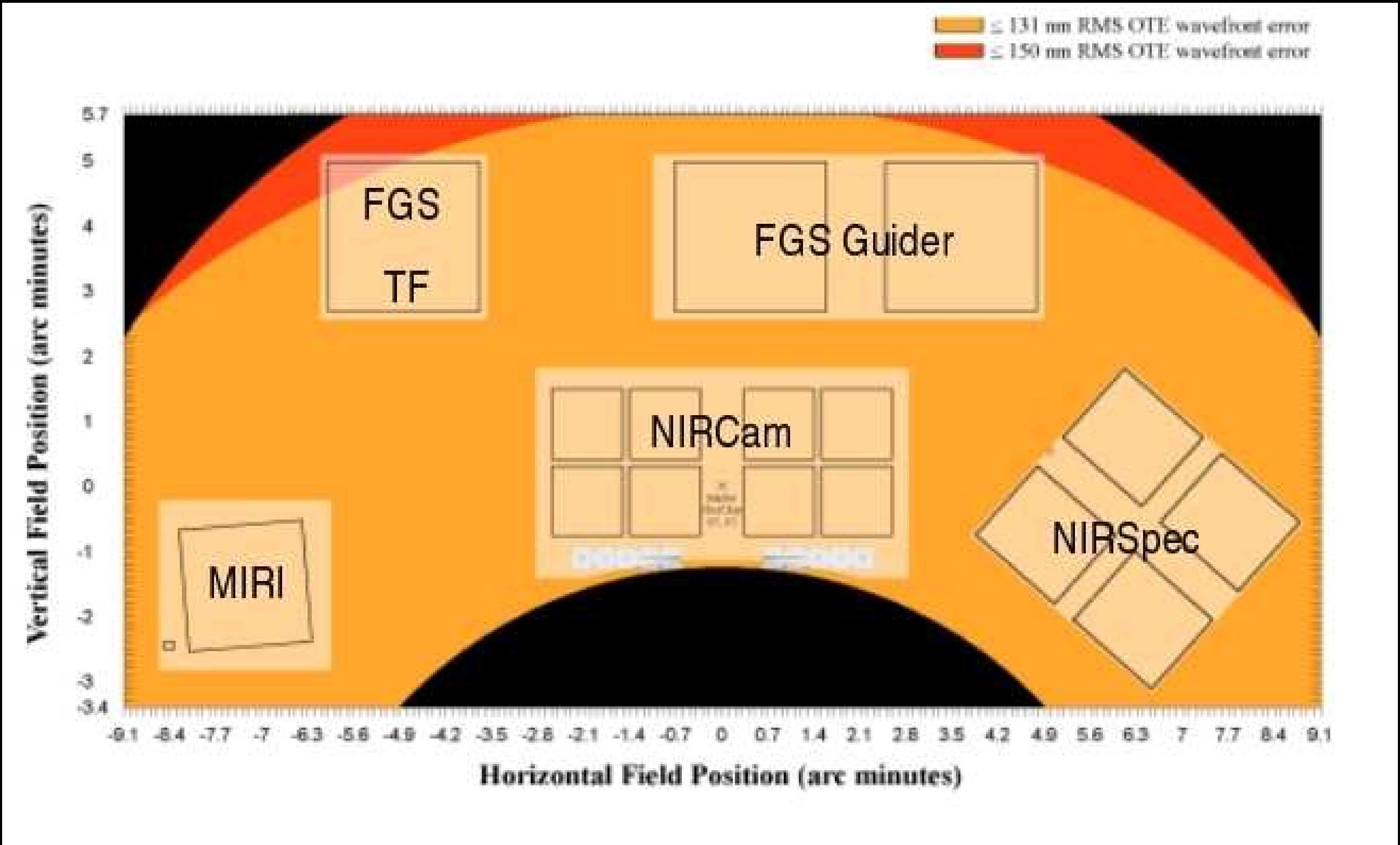
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.



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).

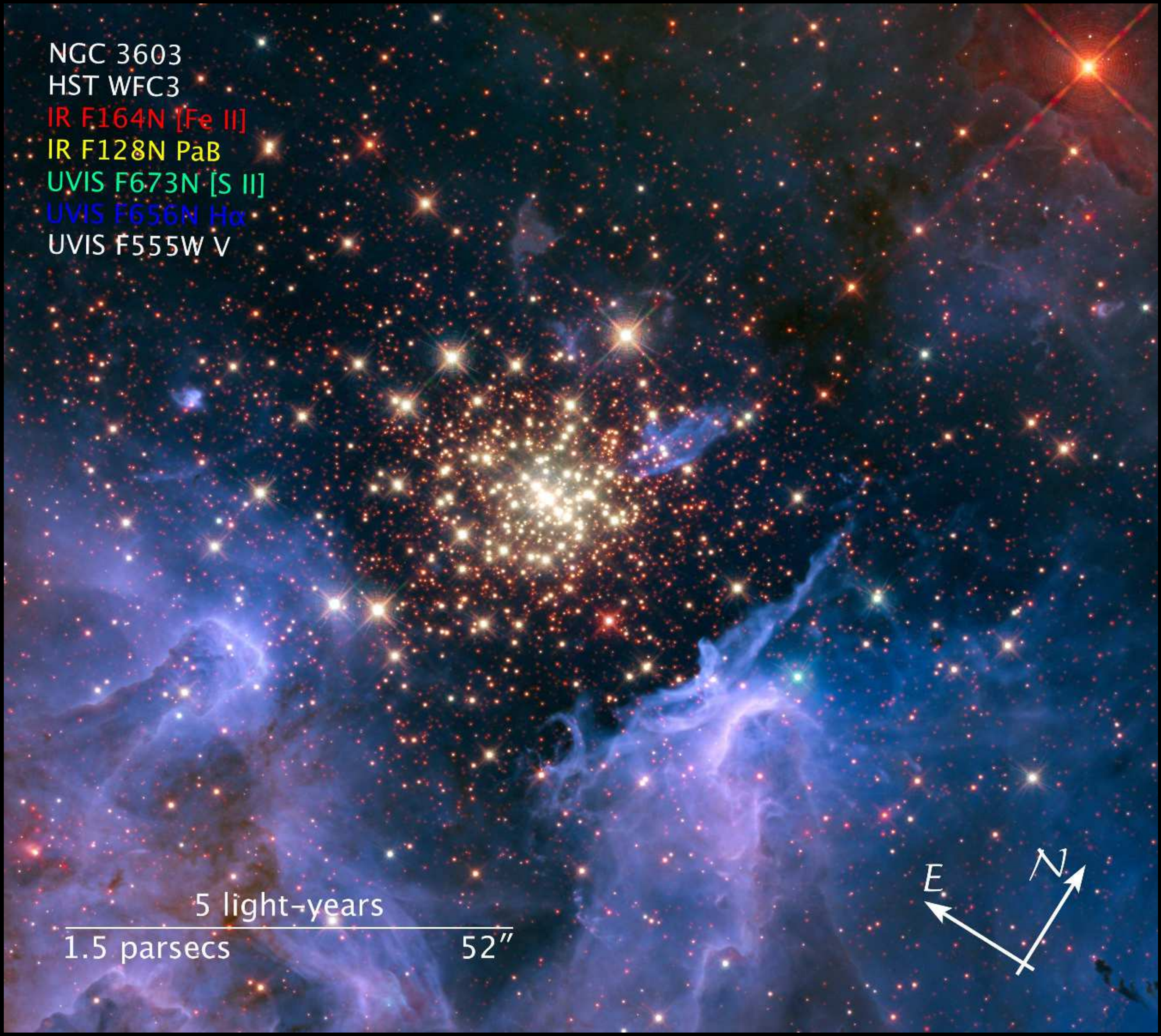
• What instruments will JWST have?



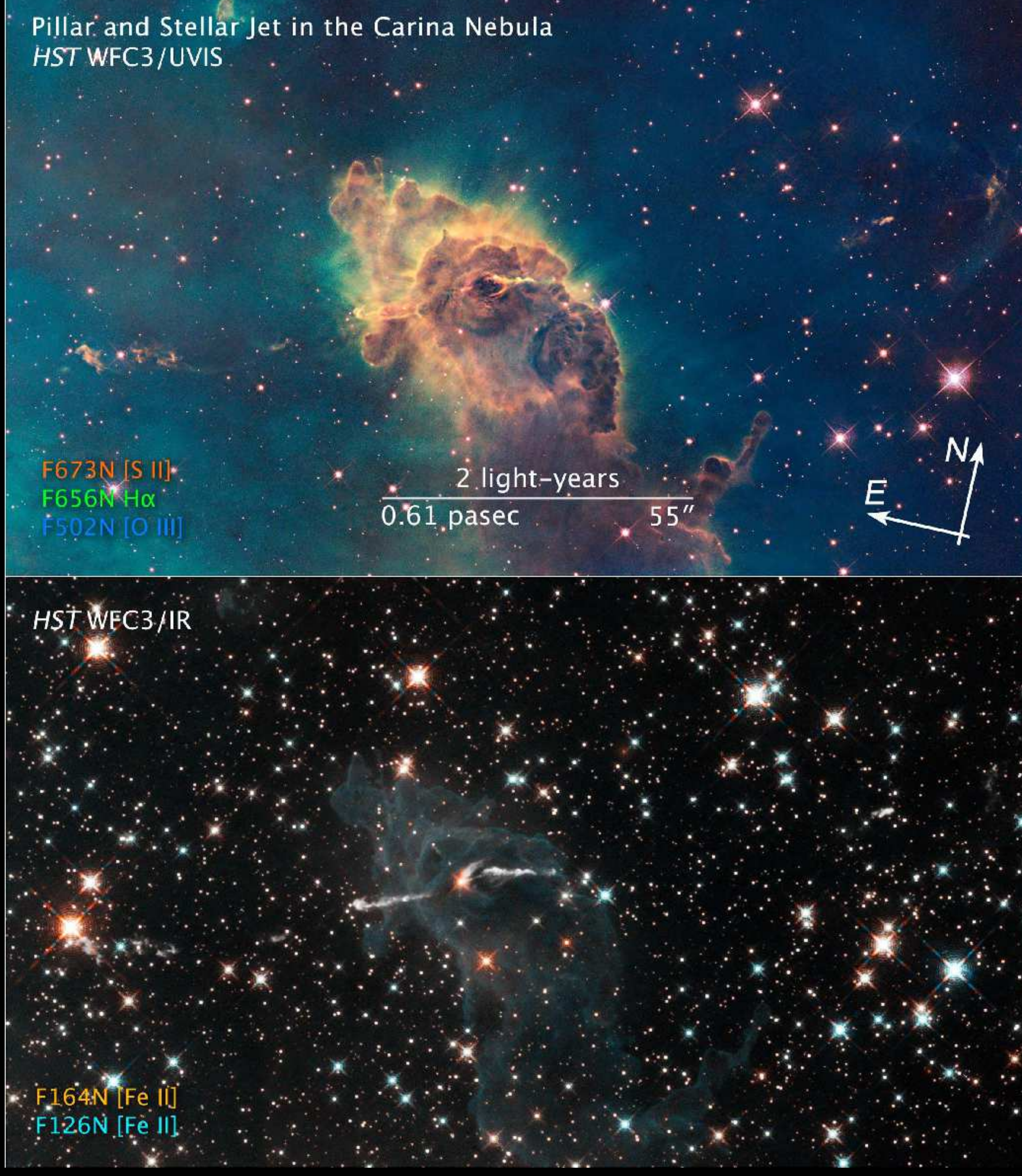
All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations.*

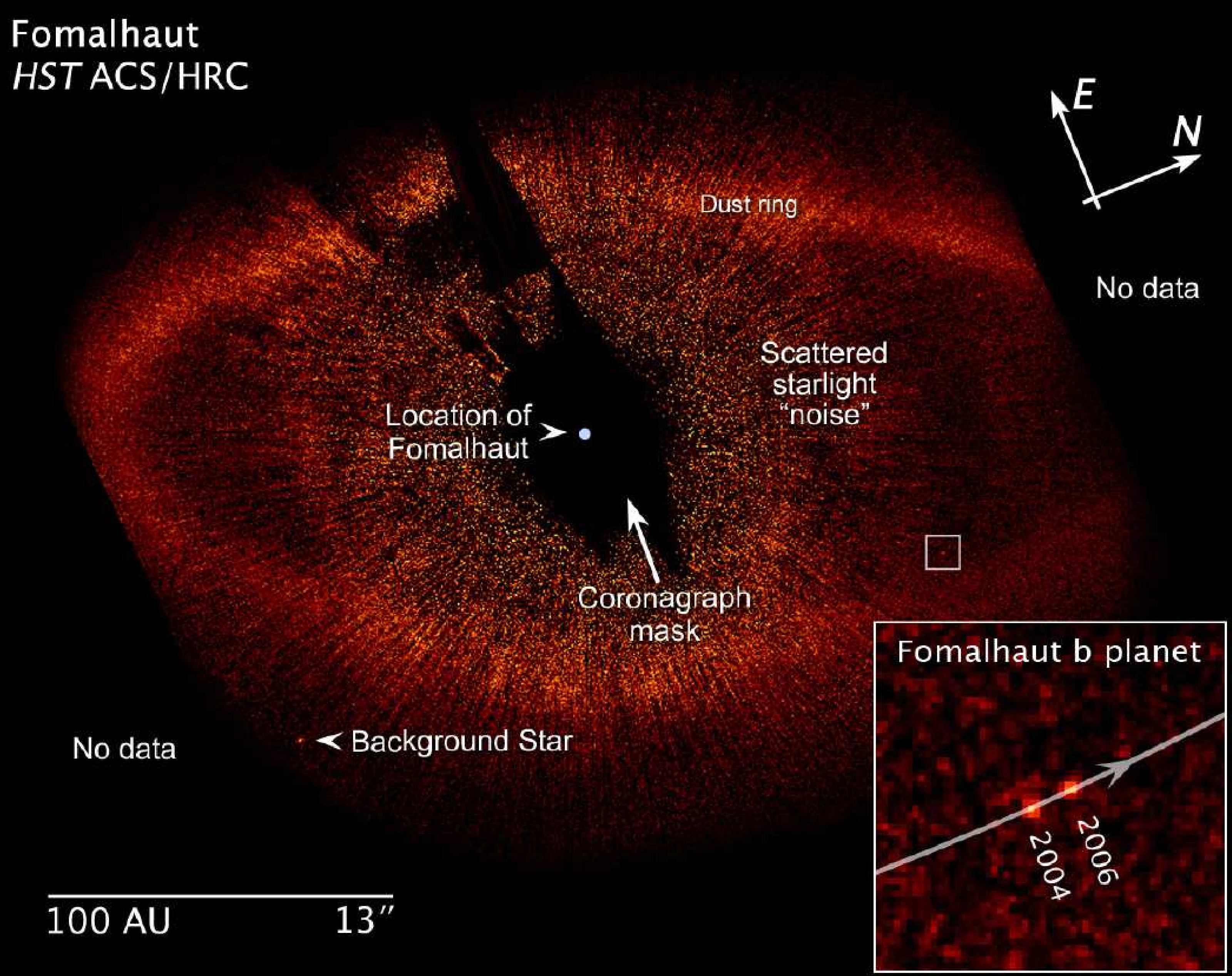
(7) How can JWST measure Star-Formation and Earth-like exoplanets?



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

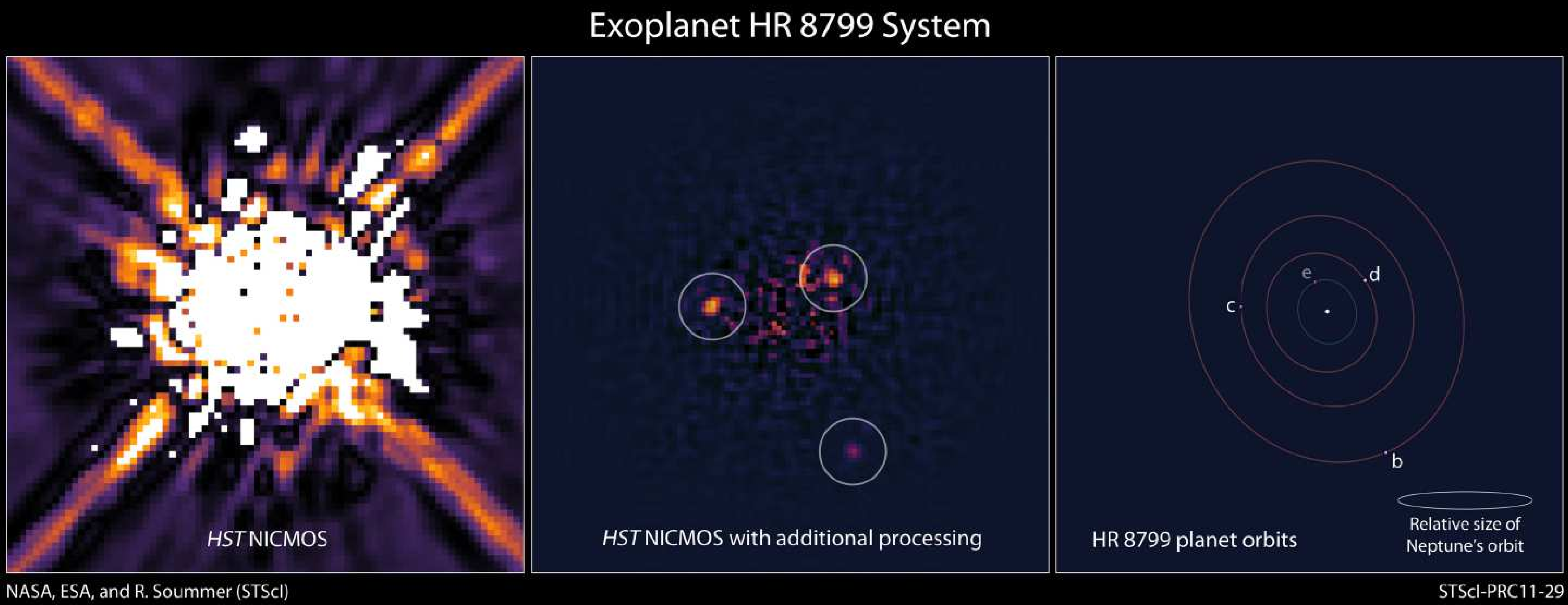


Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS
F673N [S II]
F656N Hα
F502N [O III]
2 light-years
0.61 pasec
55″
N
E
HST WFC3/IR
F164N [Fe II]
F126N [Fe II]



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

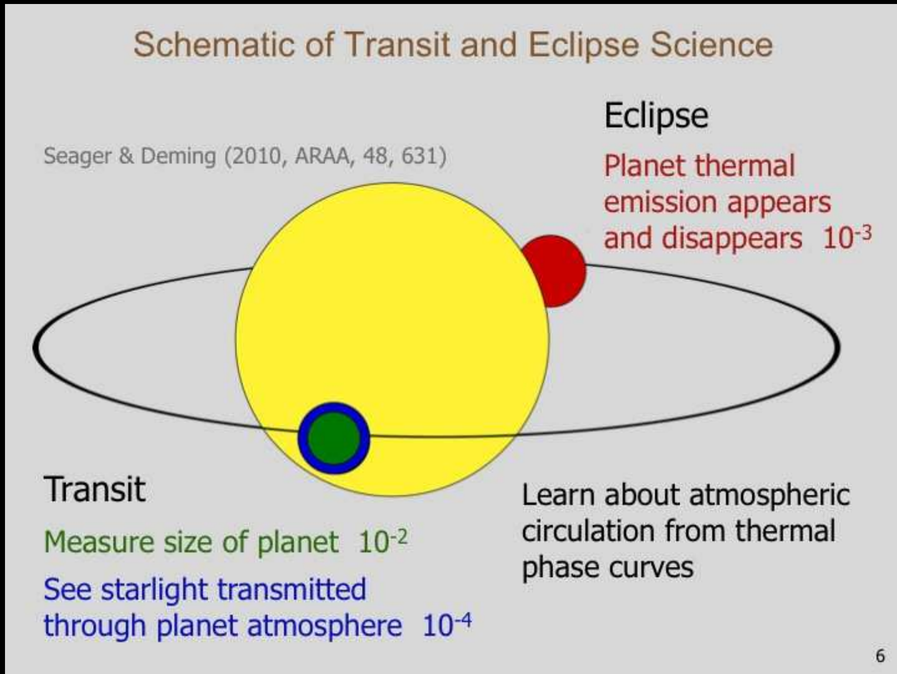
JWST can find such planets much closer in for much farther stars.

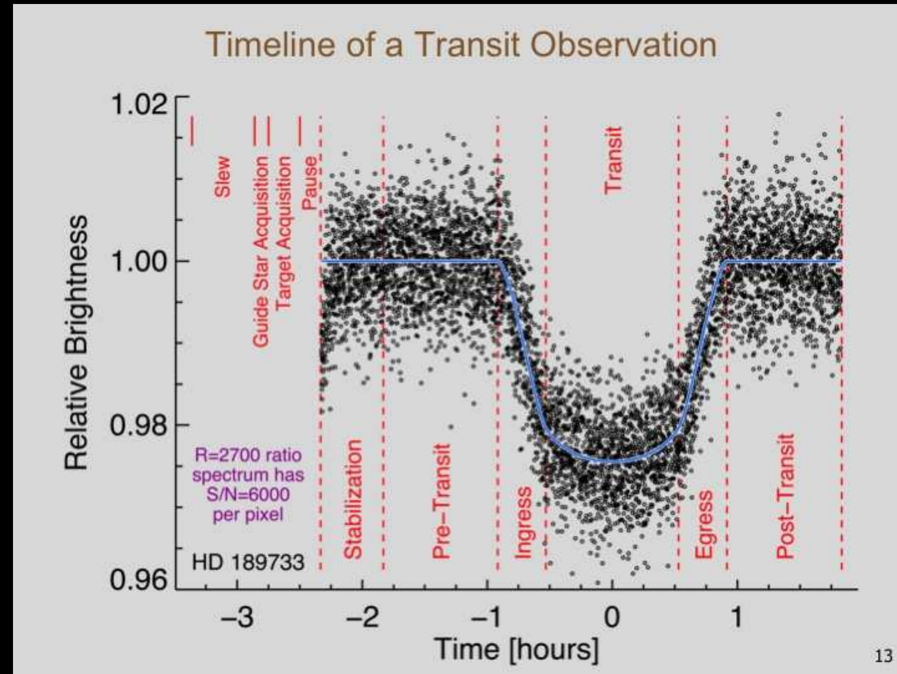


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

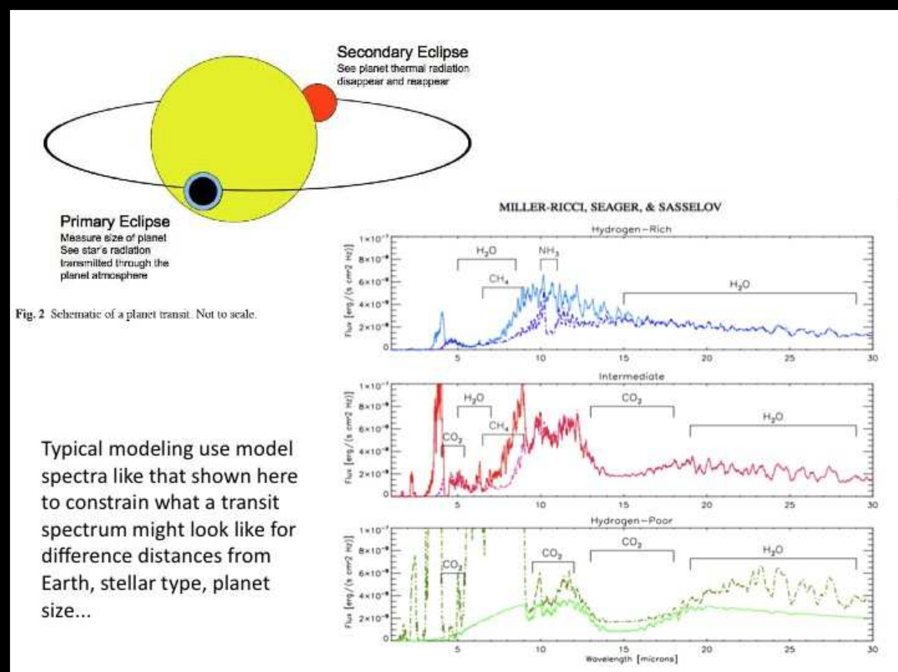
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



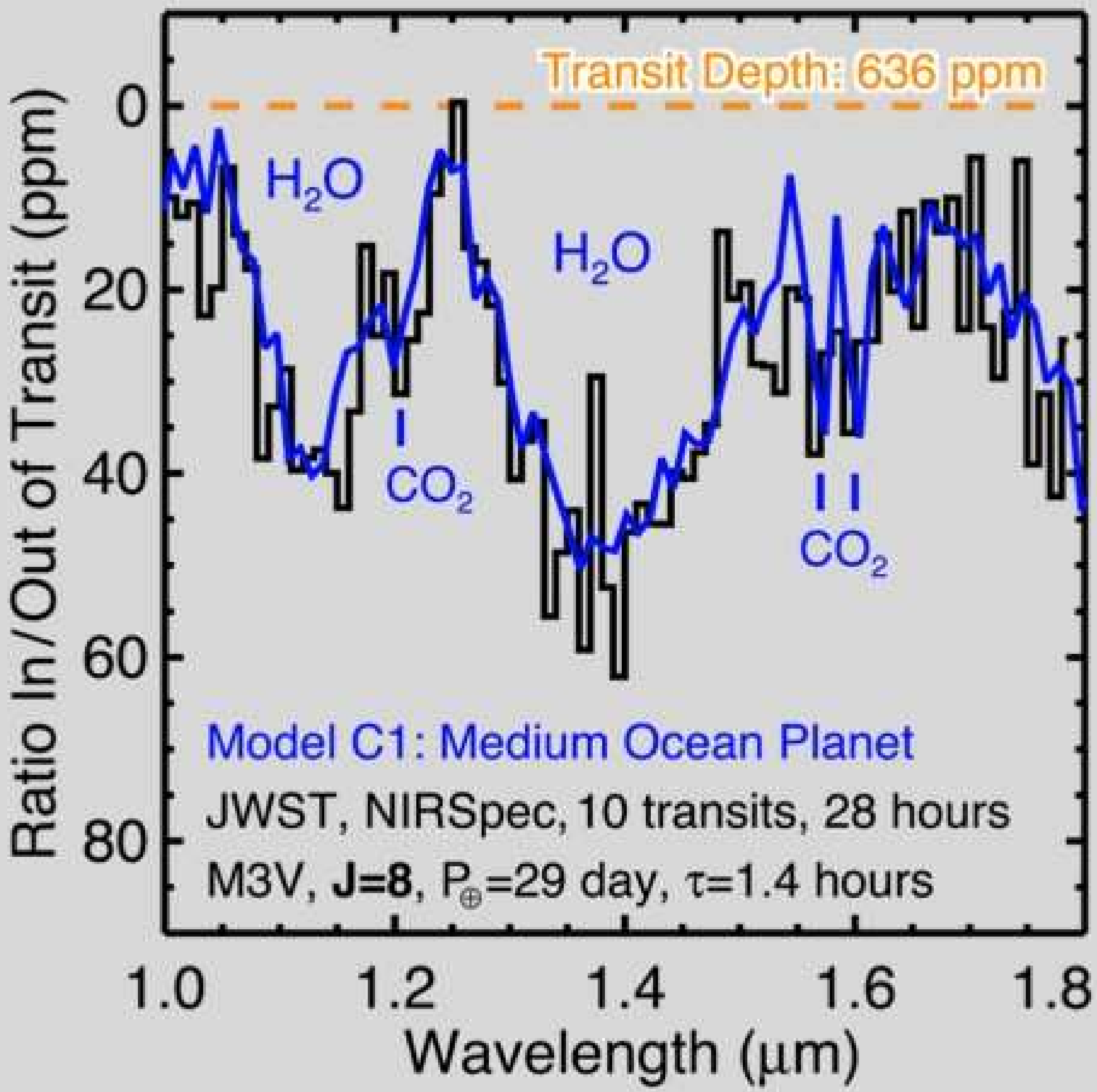


JWST can do very precise photometry of transiting Earth-like exoplanets.



JWST IR spectra can find water and CO_2 in (super-)Earth-like exoplanets.

Transit Spectrum of Habitable "Ocean Planet"



JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.

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:

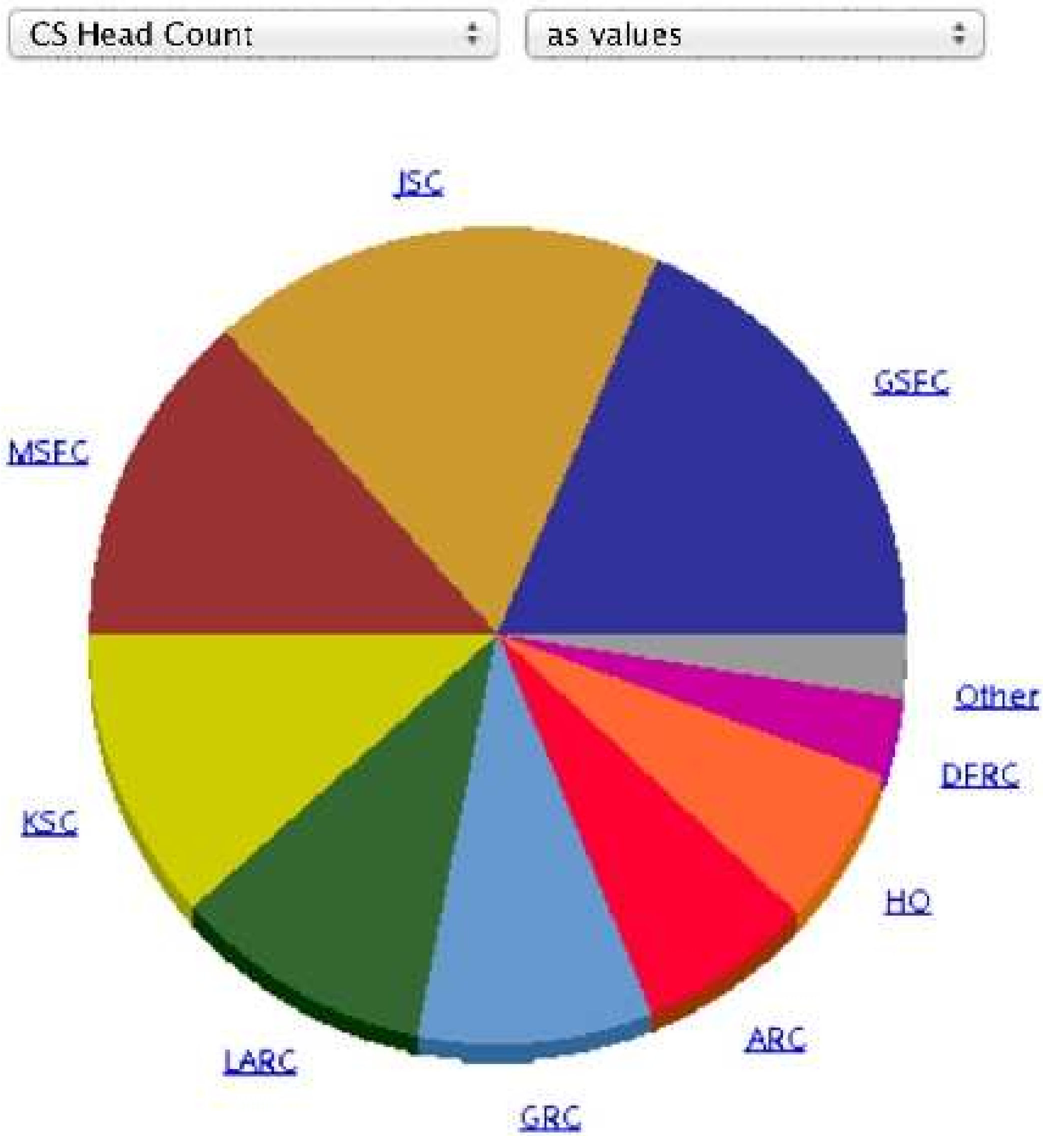
- Over the last 25 years, (ASU) Astrophysics College Graduates typically:
- (0) Have very low unemployment ($\lesssim$few %).
- (1) About 30% are faculty at Universities or 4-year colleges.
- (2) About 30% are researchers at NASA or other government centers.
- (3) About 20% work in Aerospace or related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



	Centers & NSSC	CS Head Count
	GSFC	3,354
	JSC	3,203
	MSFC	2,432
	KSC	2,055
	LARC	1,881
	GRC	1,640
	ARC	1,215
	HQ	1,152
	DFRC	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.