The Universe Beyond Hubble —
Hubble, Webb and other Future Telescopes

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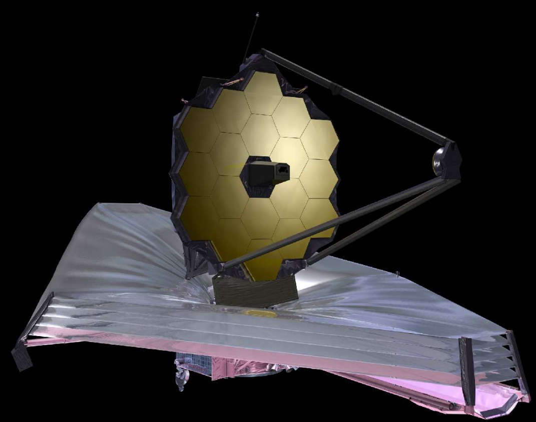
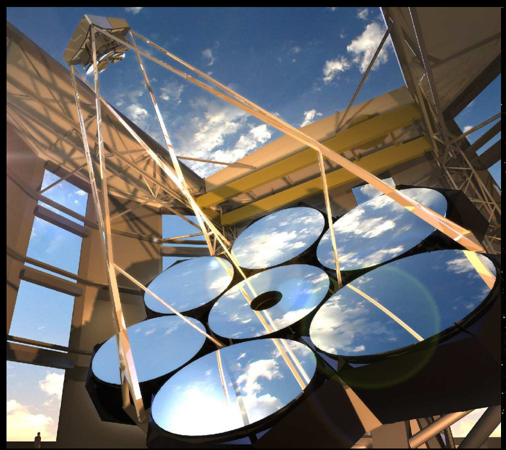
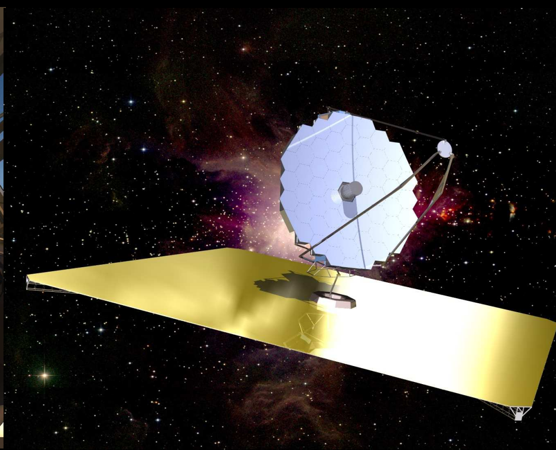
Panel Members: Rolf Jansen, Liam Nolan, & Rosalia O'Brien (ASU)







1973∼2020^{+}; 1996∼2031; 2000∼2050^{+} 2020∼2050^{+}?

ASU Discovery Lecture, Thursday Oct. 7, 2021 (ASU, Tempe, AZ; via Zoom)

All presented materials are ITAR-cleared.

Outline

- (1) Update on the James Webb Space Telescope (JWST), 2021.
- (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) How can JWST measure Star-formation & Earth-like exoplanets?
- (6) Summary and Conclusions
  - (7) Update of JWST programmatics as of 2021.
  - (8) Where do our students end-up? Possible NASA Careers

Sponsored by NASA/HST & JWST

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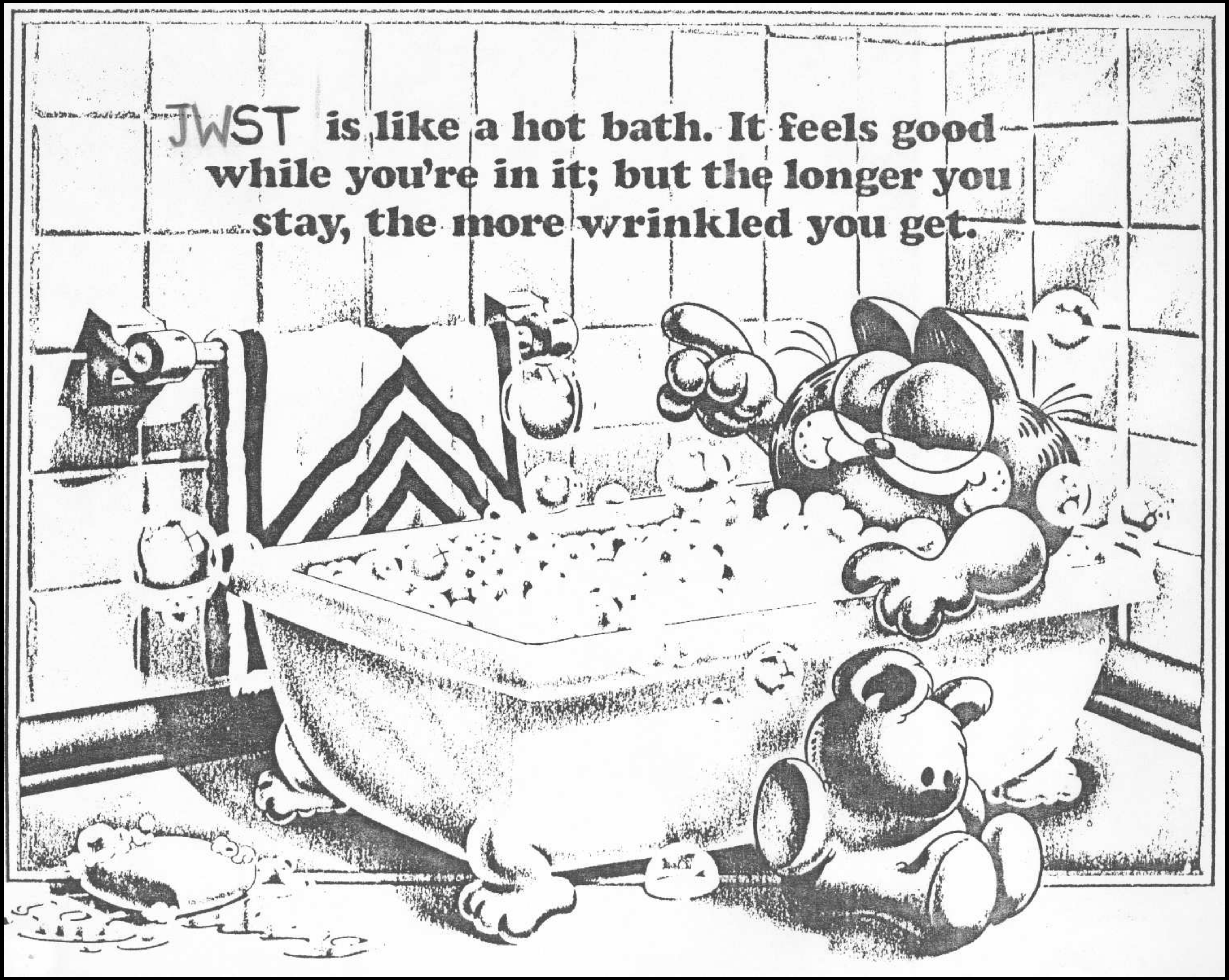
Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/asuDiscoveryLecture_jwst21.pdf`



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

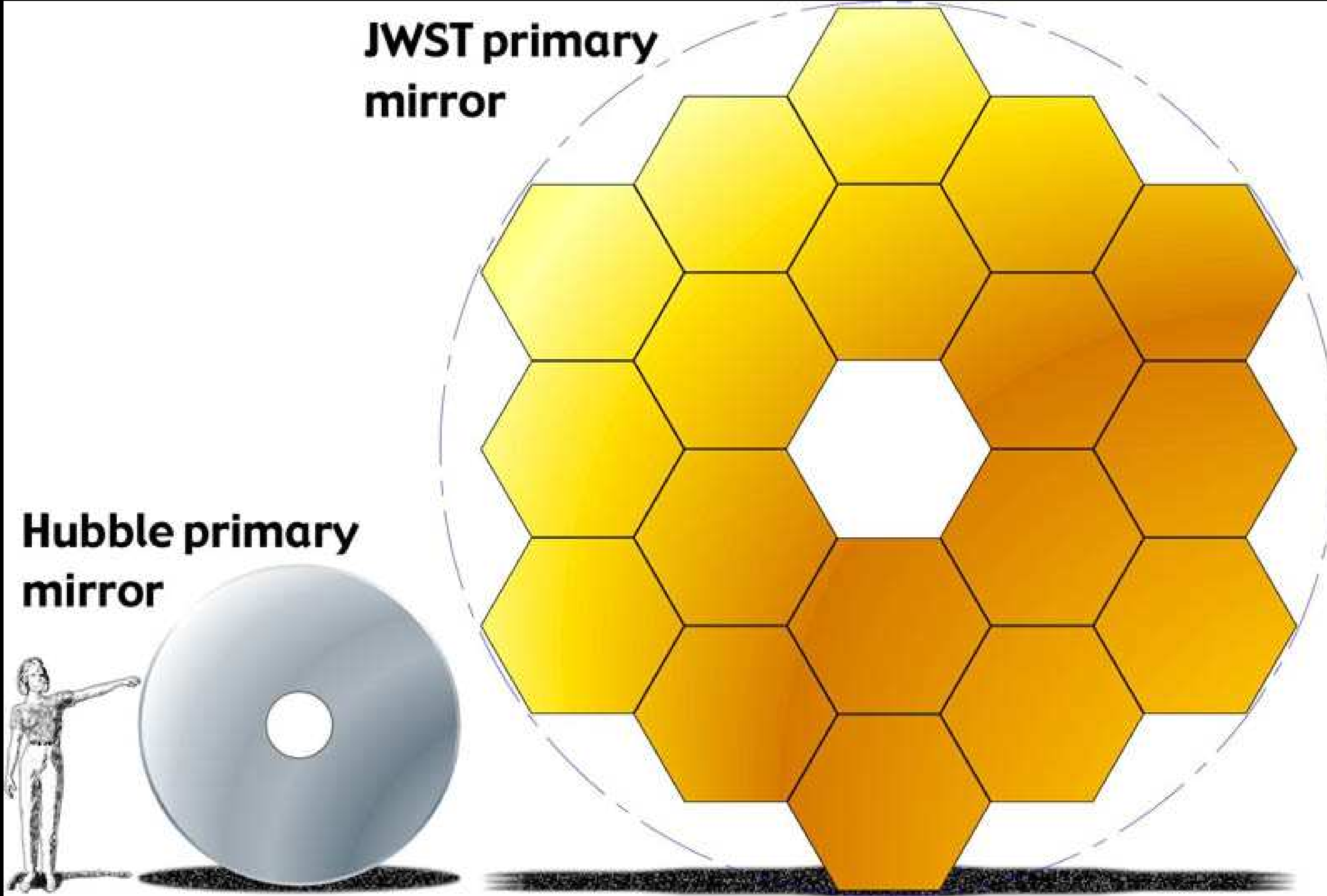
You will feel wrinkled before you know it ... :)

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$2021?.

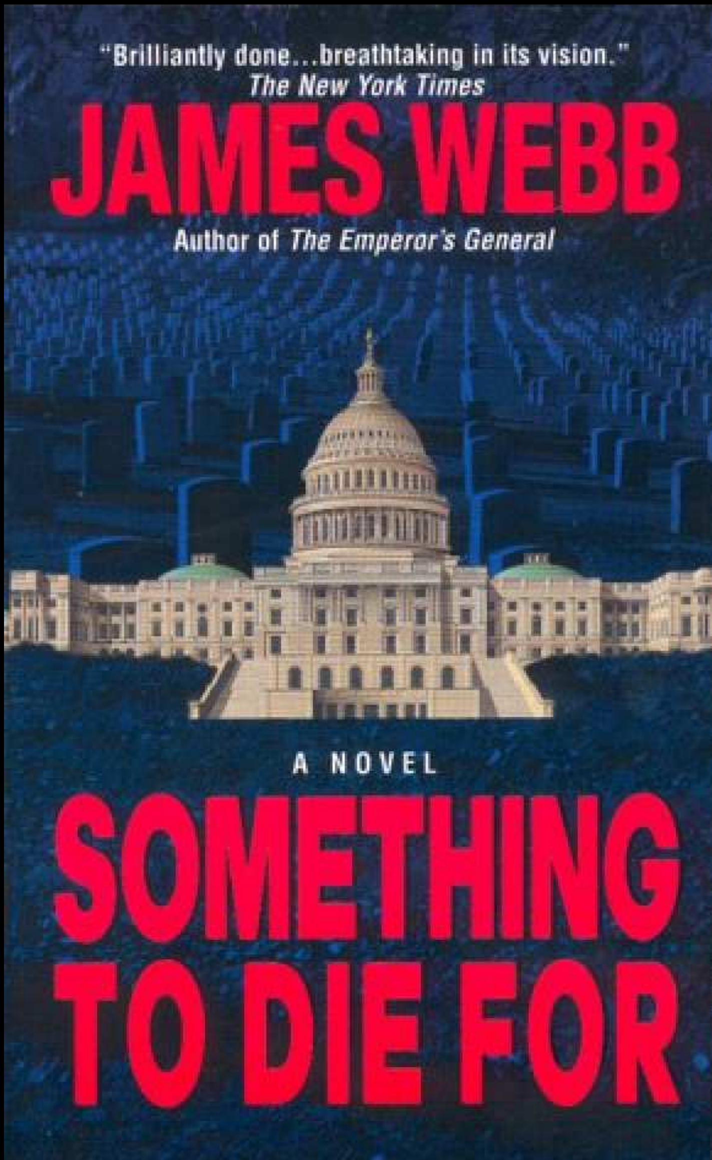
JWST: The infrared sequel to Hubble from 2021–2026 (–2031?).



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.

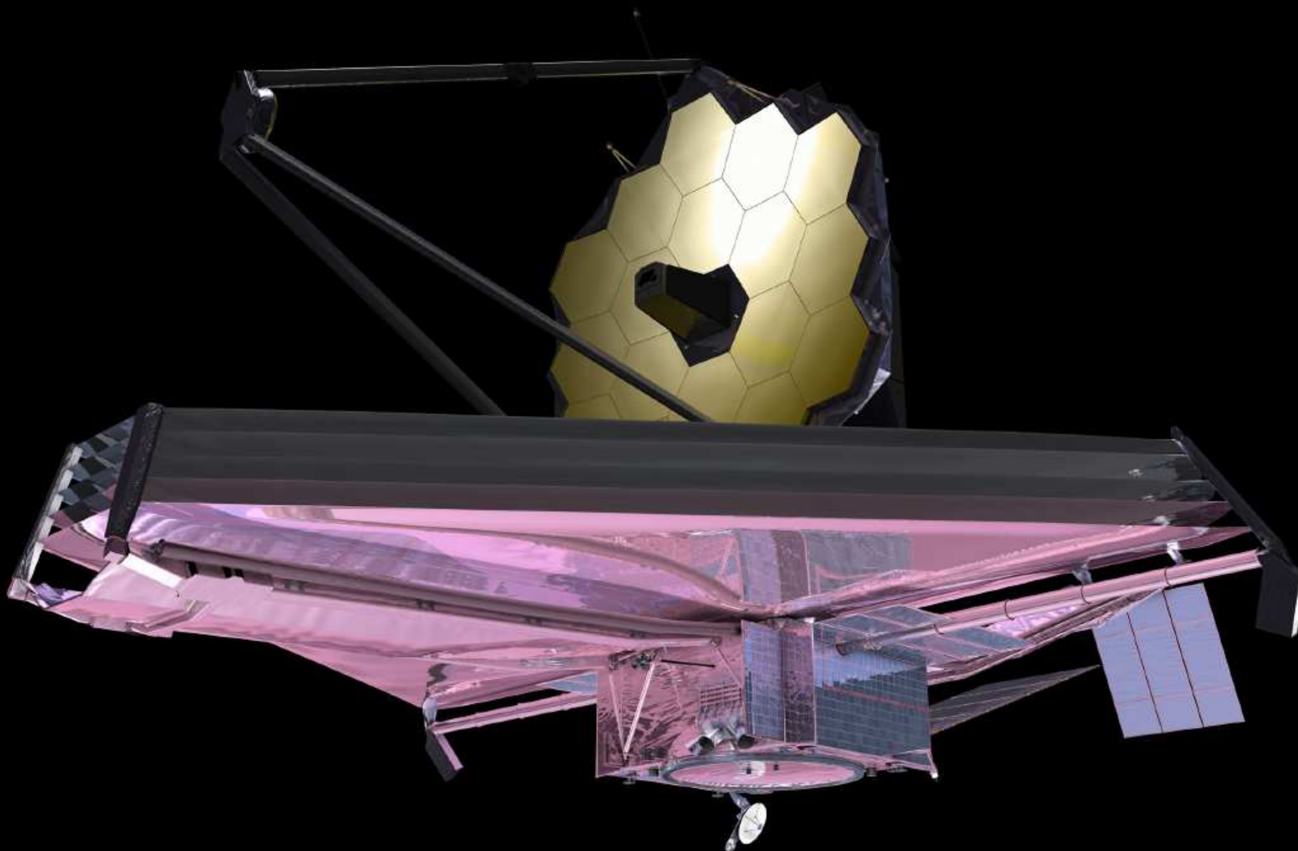
(1) Update of the James Webb Space Telescope (JWST), 2021



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 2021



- 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 Fall 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 James Webb Space Telescope

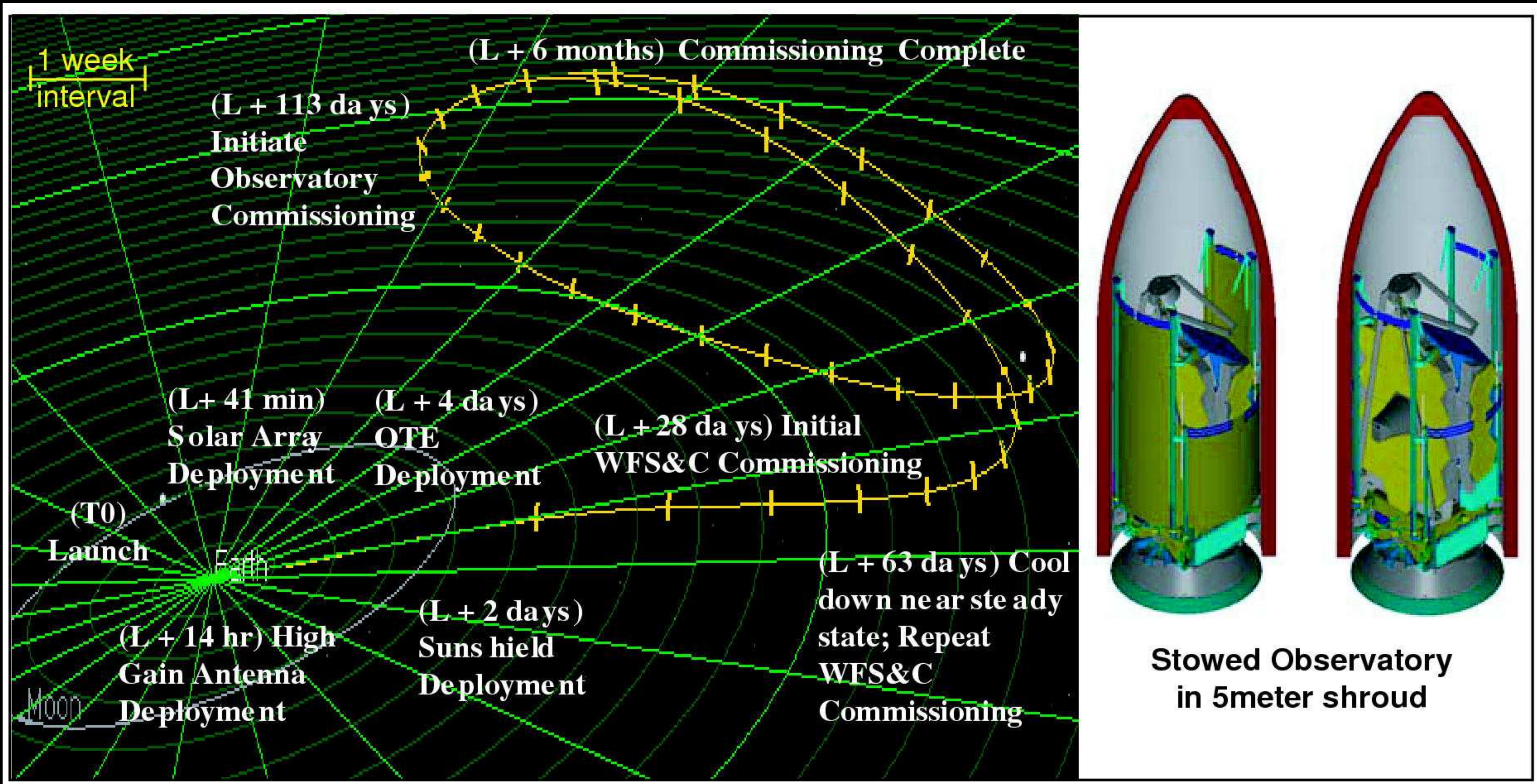
JWST Launch

- 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

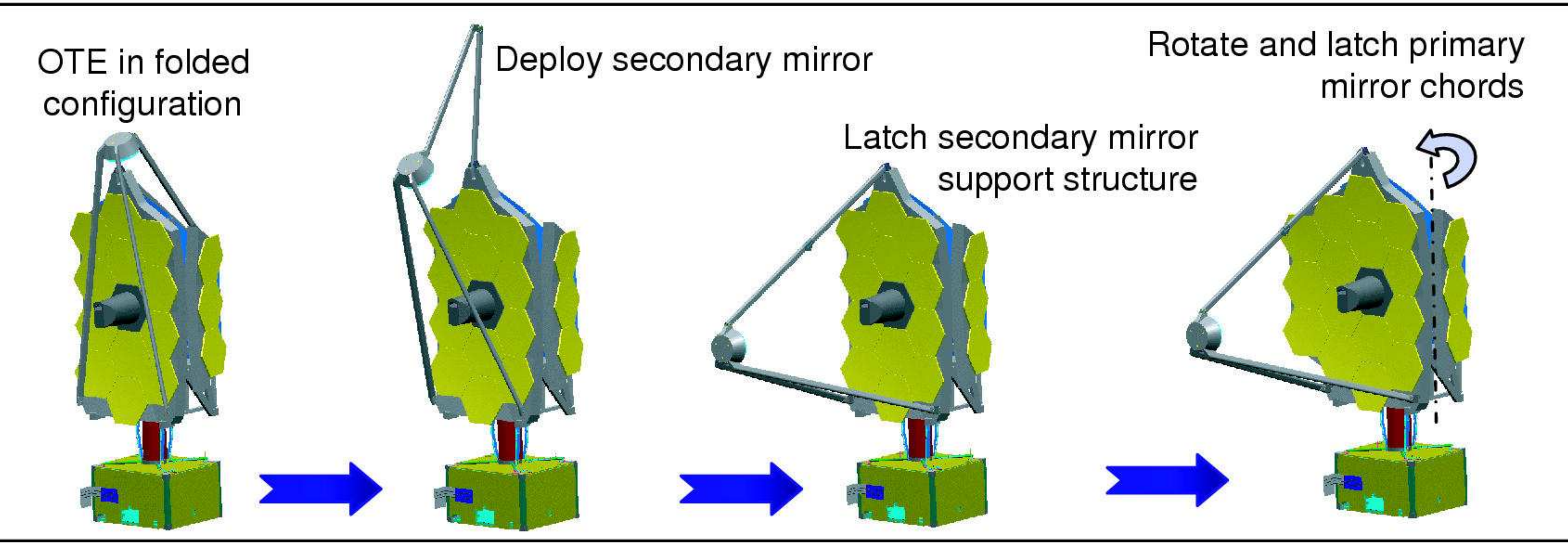
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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



- After launch in Fall 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.

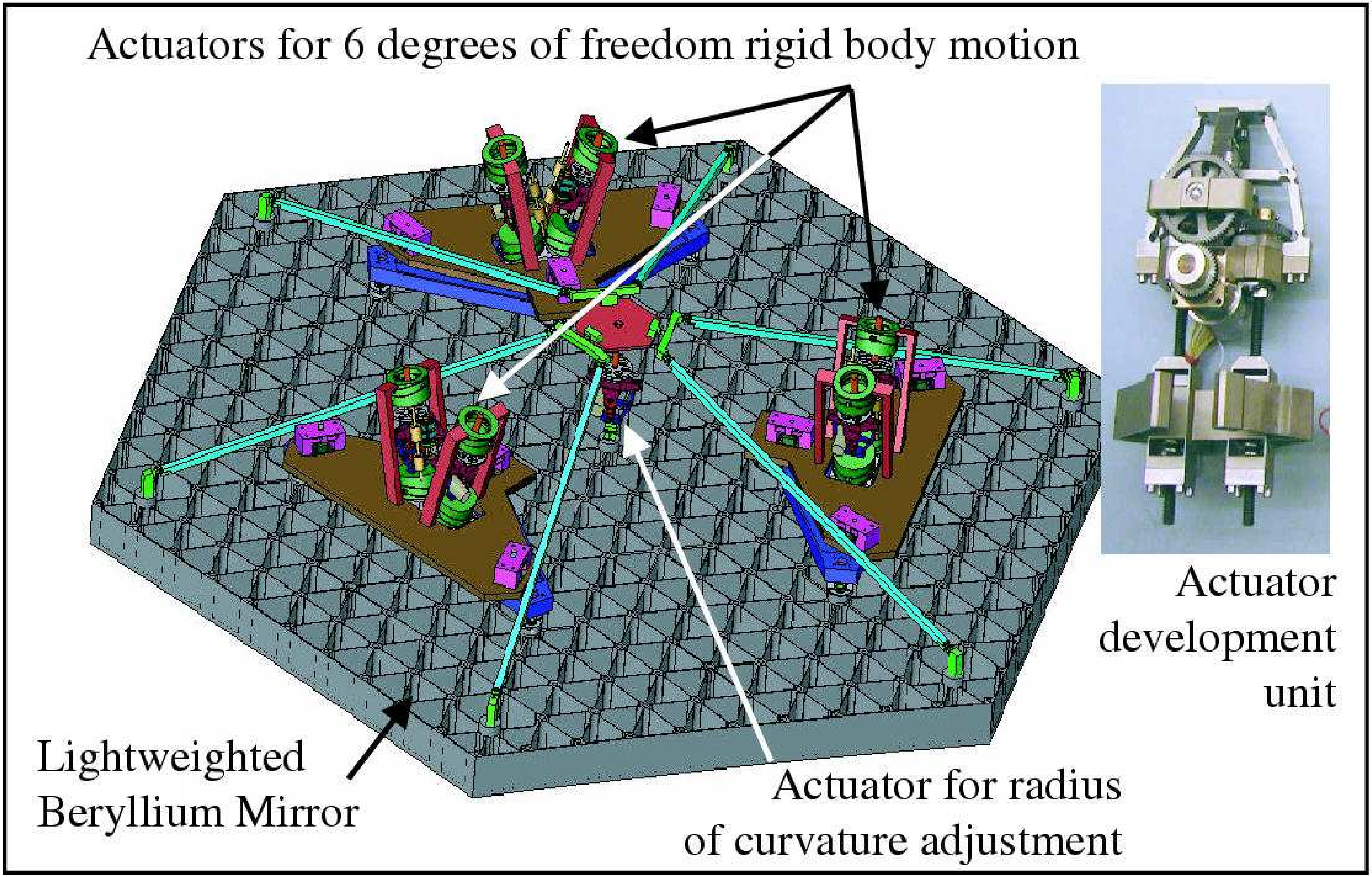
• (1b) How will JWST be automatically deployed?



- 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).

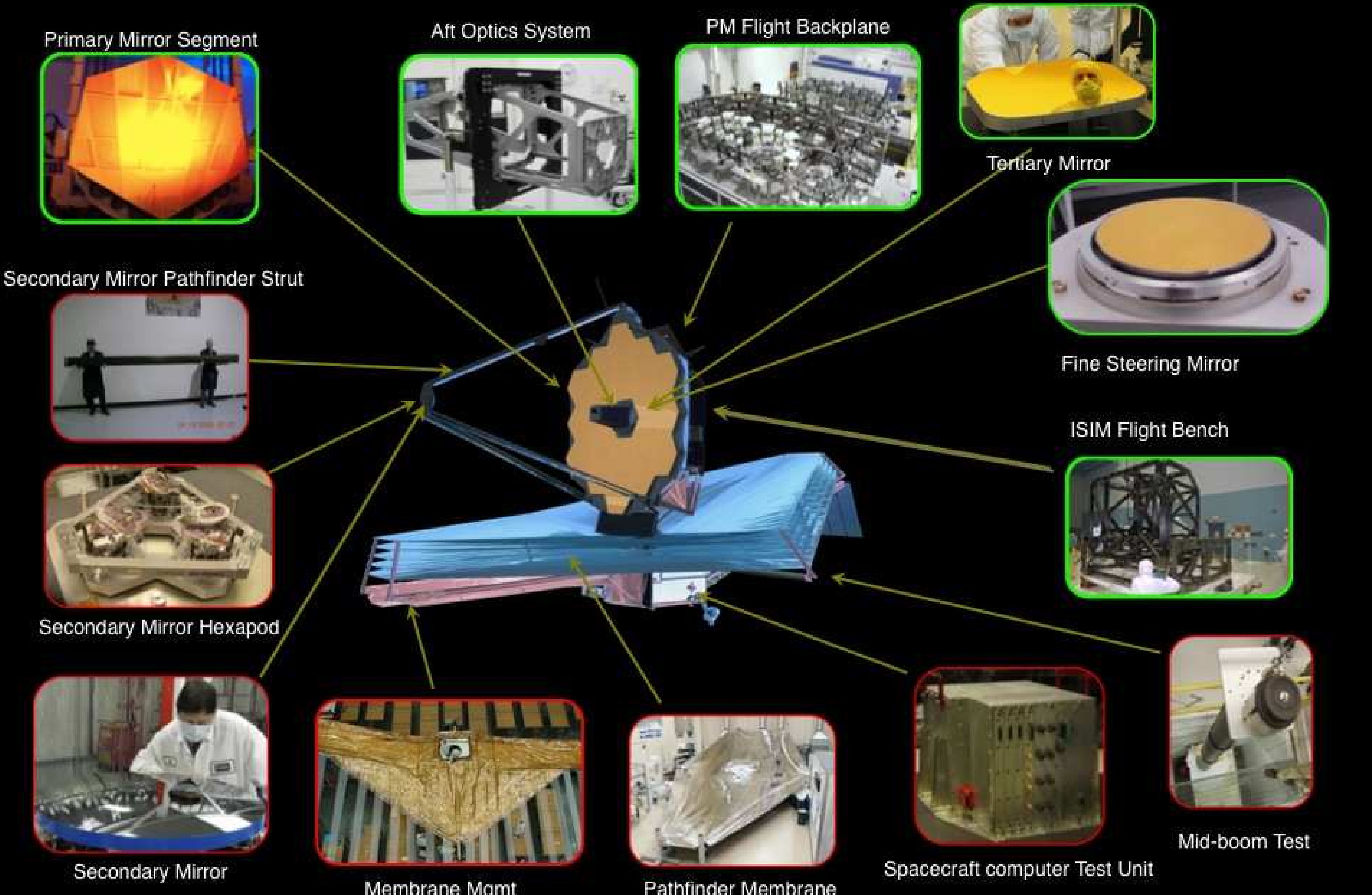
- Component fabrication, testing, & system integration: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



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

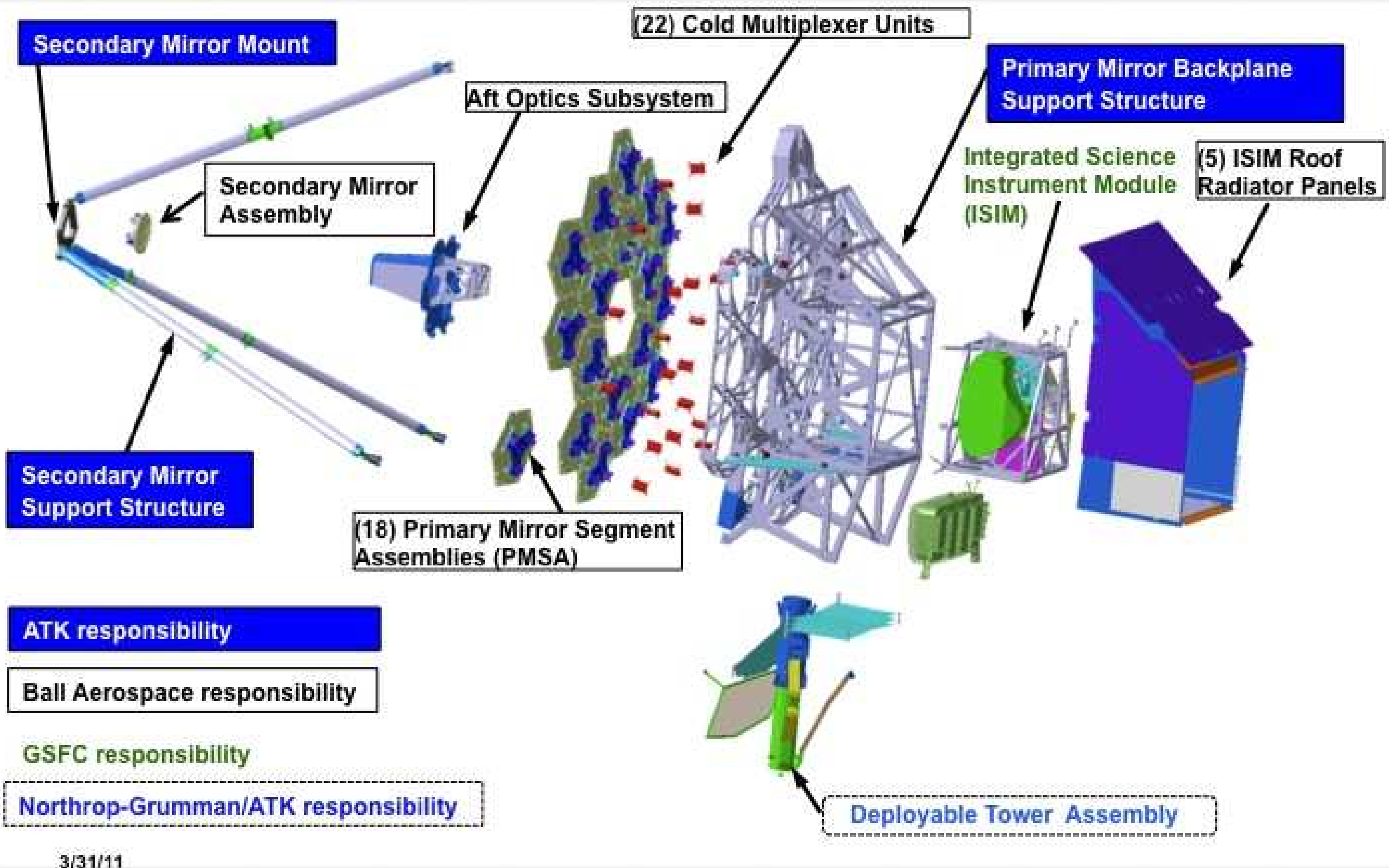
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

JWST Hardware Status



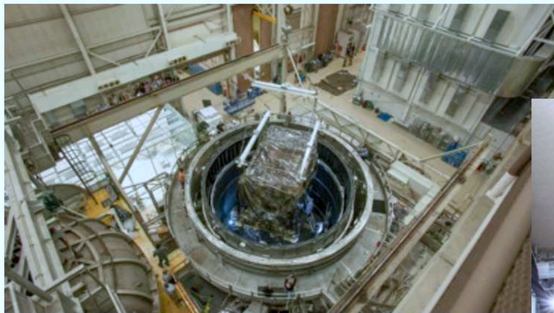
2021: 100% of launch mass designed and built (100% weighed).

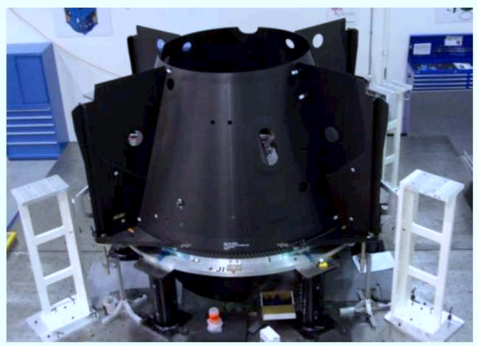
TELESCOPE ARCHITECTURE

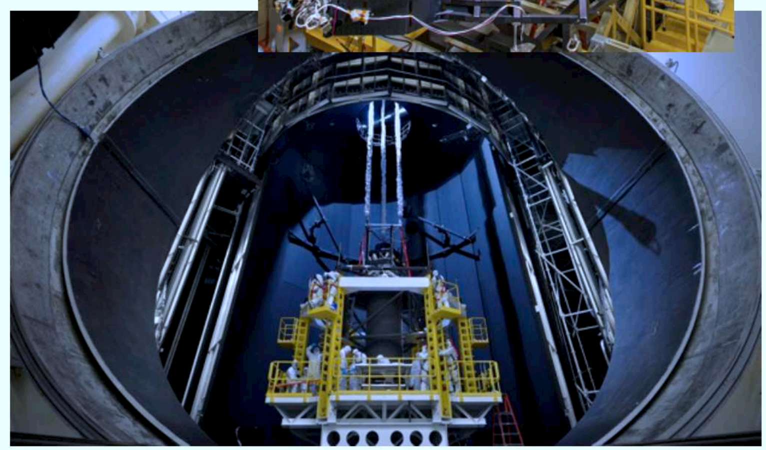


2014–2021: Complete system integration at GSFC and Northrop.

JWST Hardware Progress





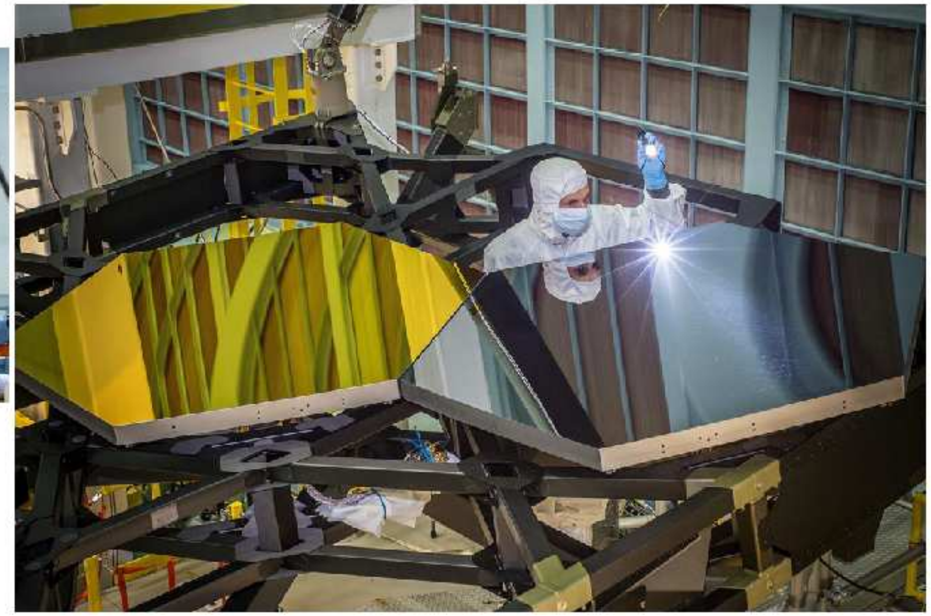


JWST remains on track for an October 2018 launch within its replan budget guidelines

July 2014: • Secondary Mirror Support deployment successfully tested.

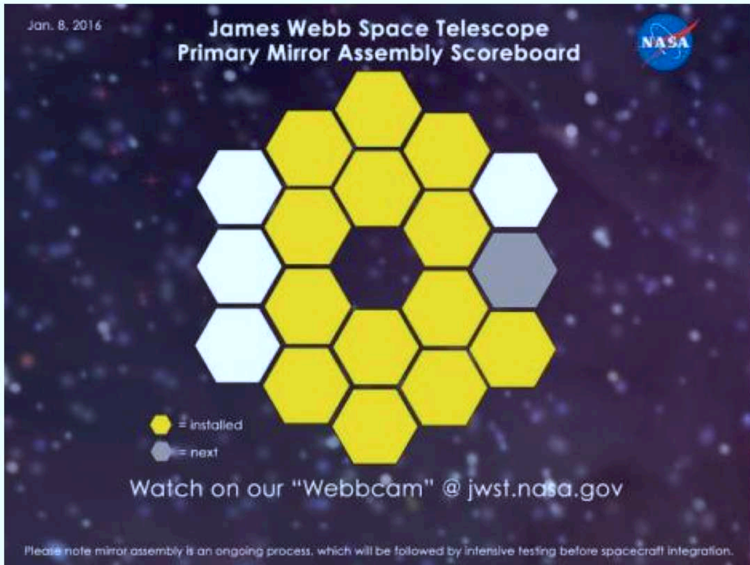
2015: • Engineering sunshield successfully deployed at Northrop (CA).

Telescope Pathfinder – Risk Reduction

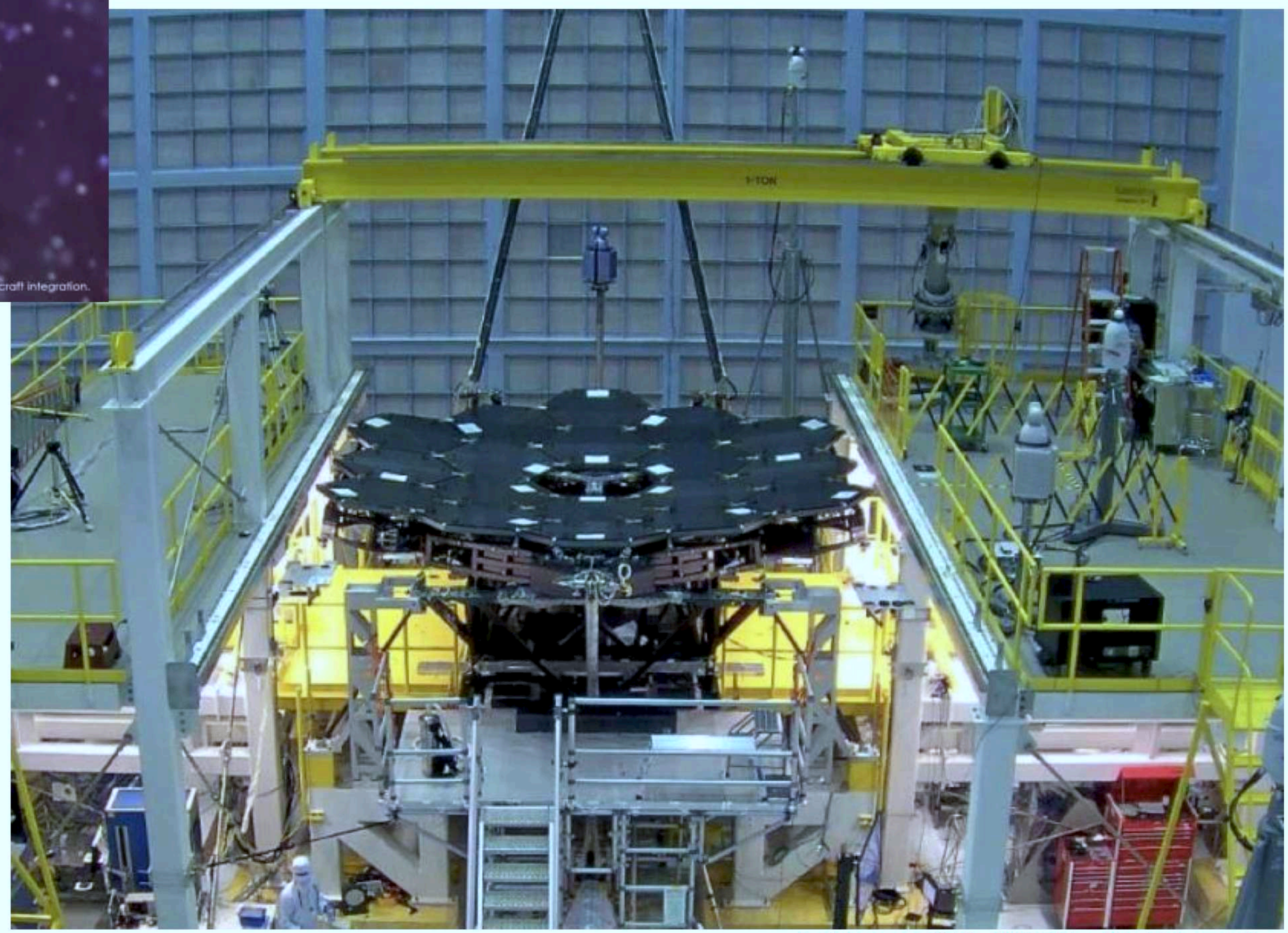


JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

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

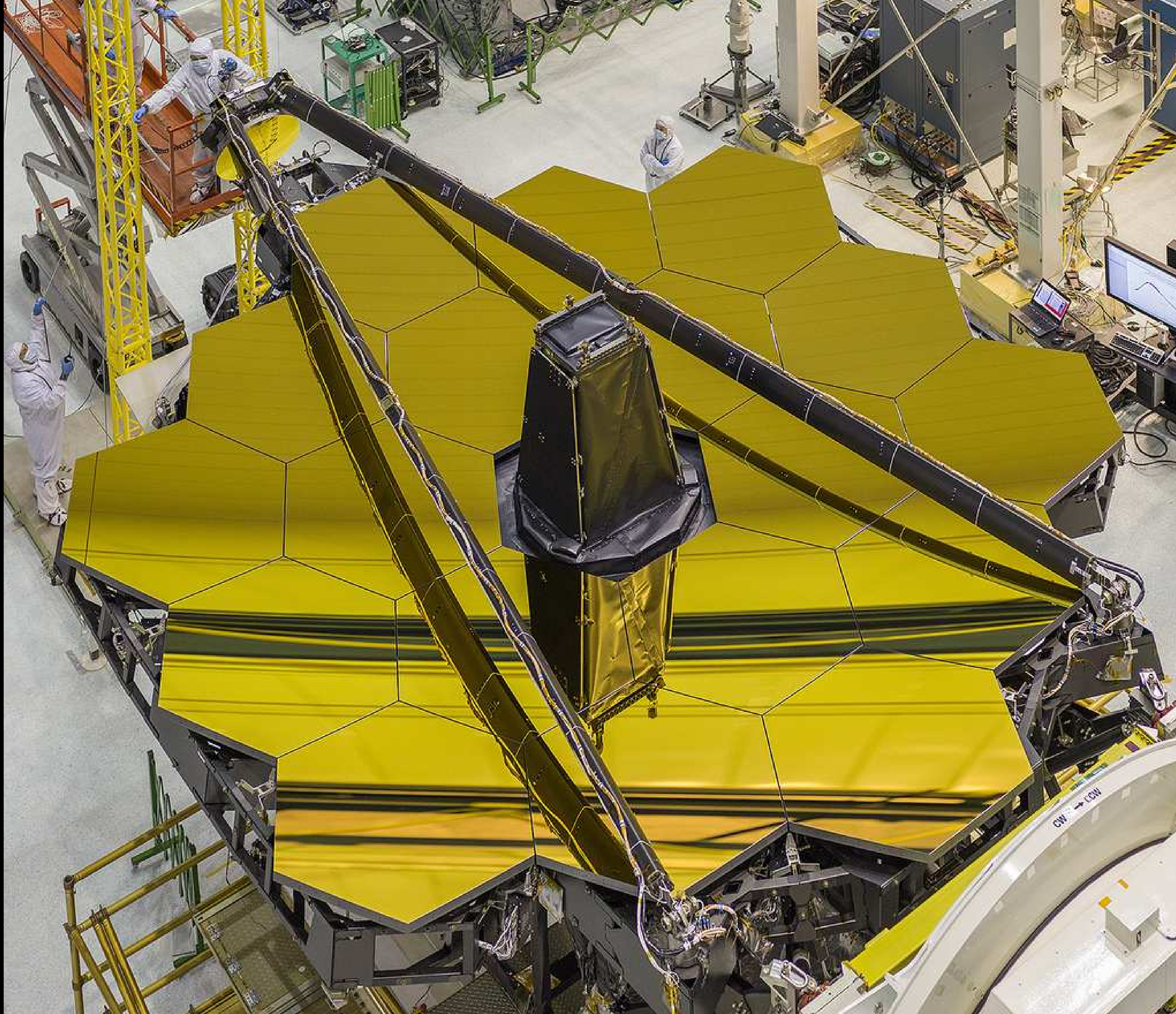
Big milestone!

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

NASA team-work to take JWST mirror covers off!

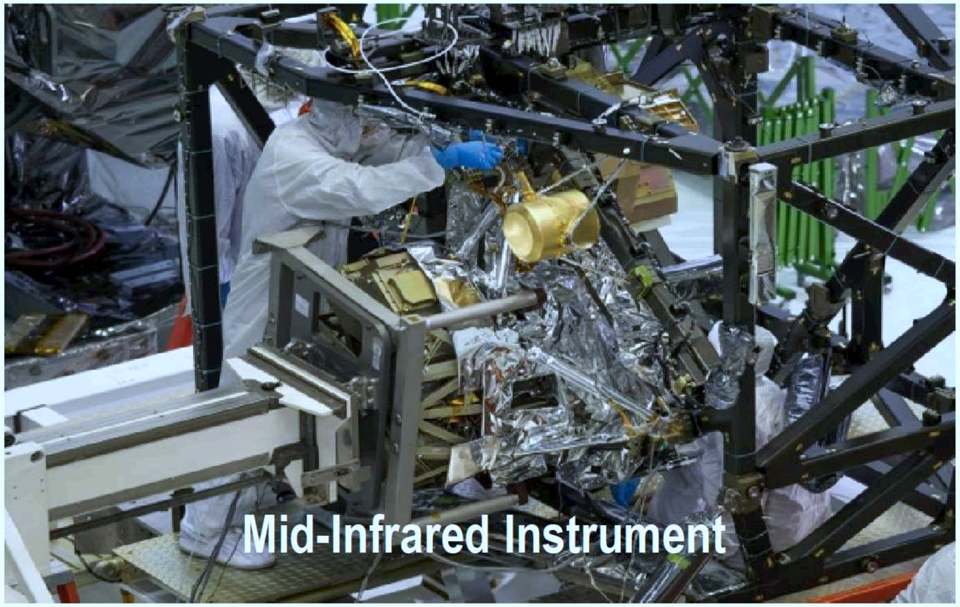
JWST being tilted into the right position

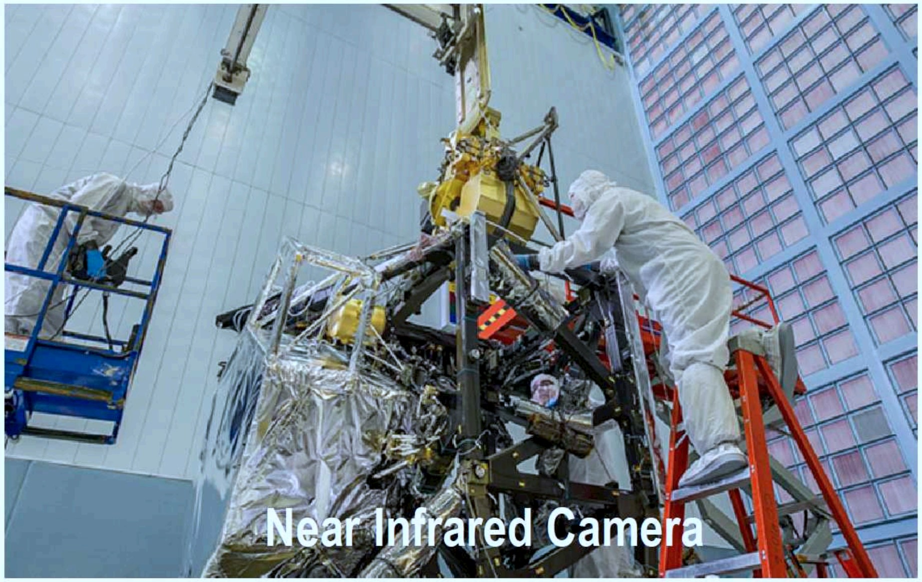
Webb mirrors finally mounted and ready!

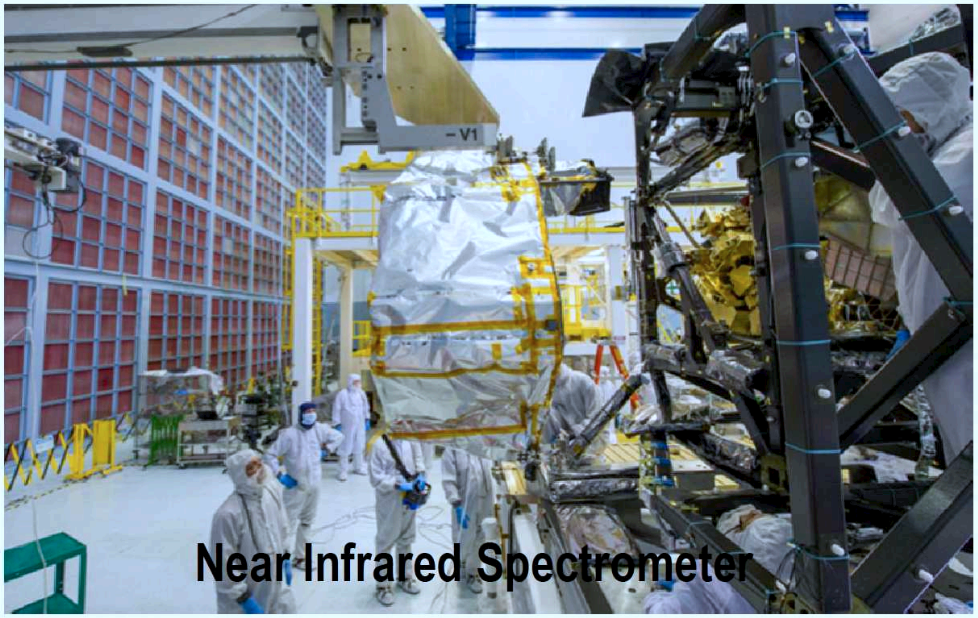


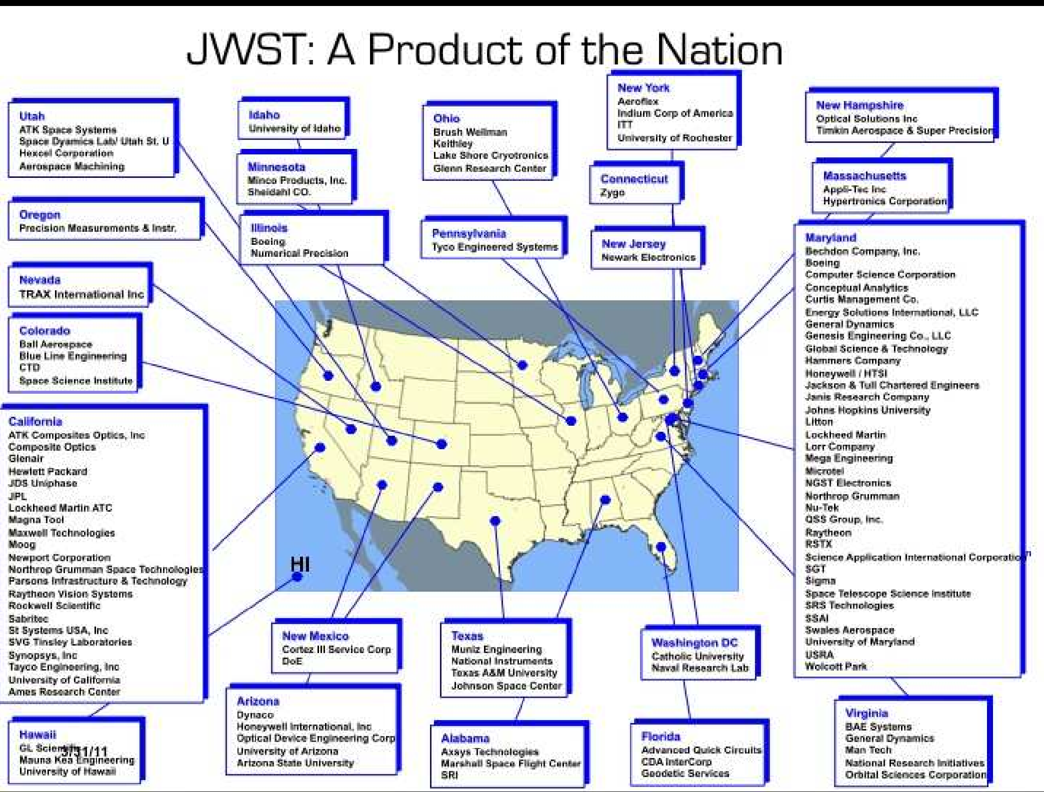
JWST stowed for further instrument mounting

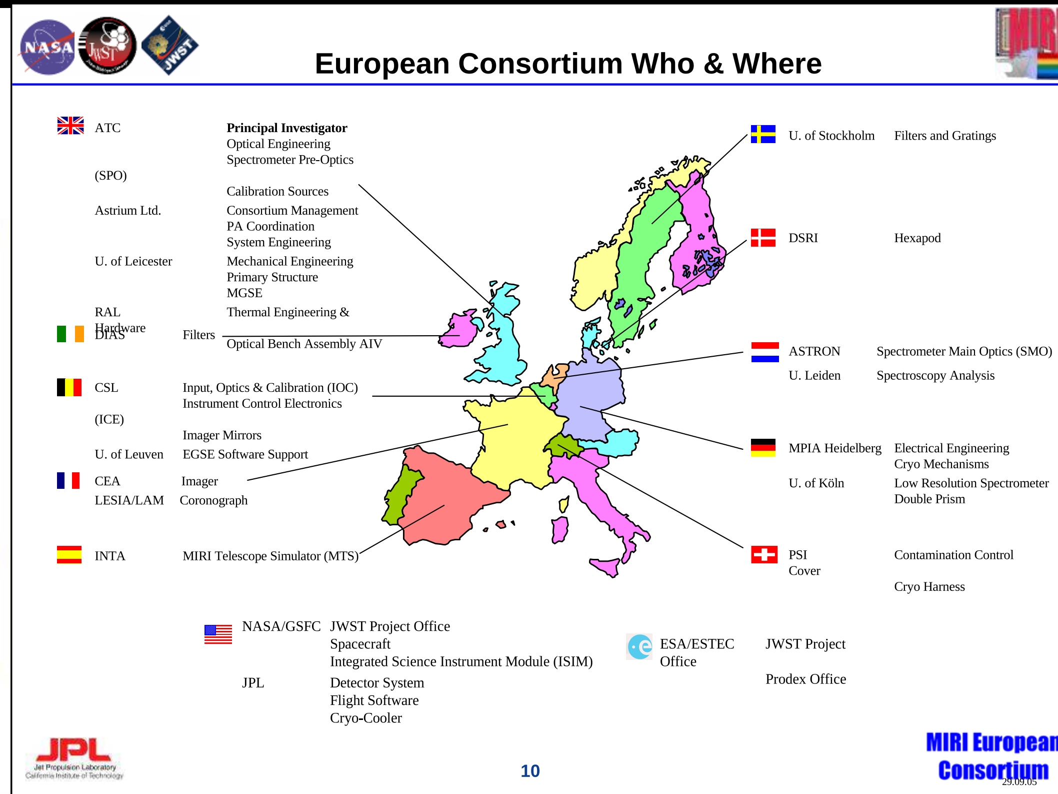
All Instruments Integrated





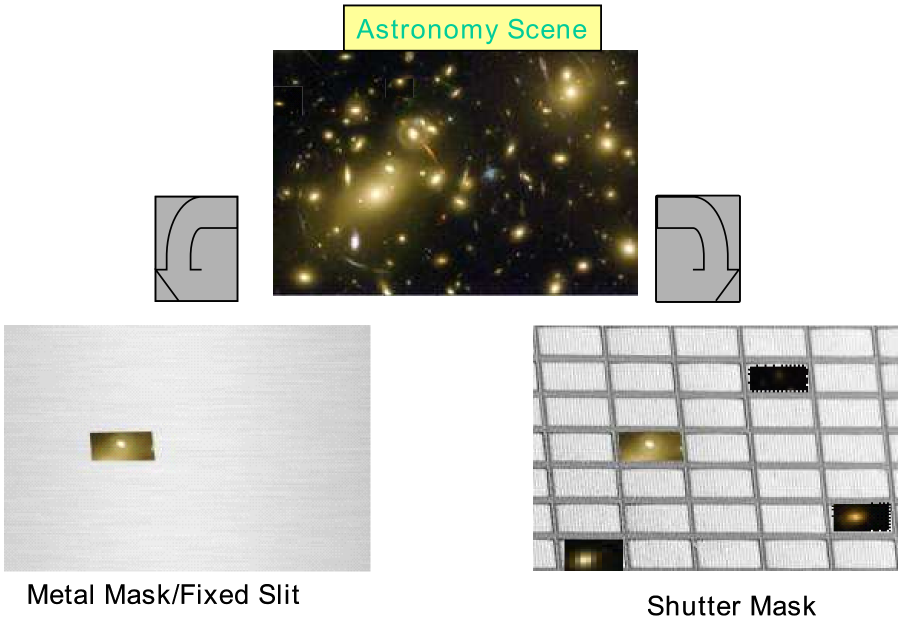


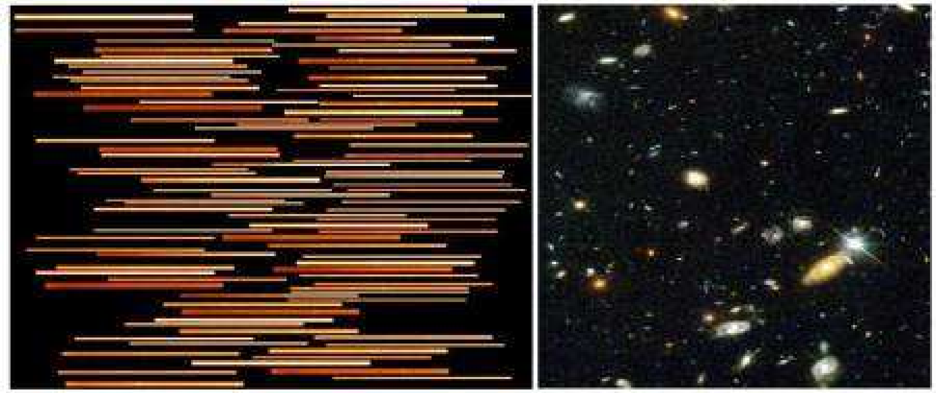


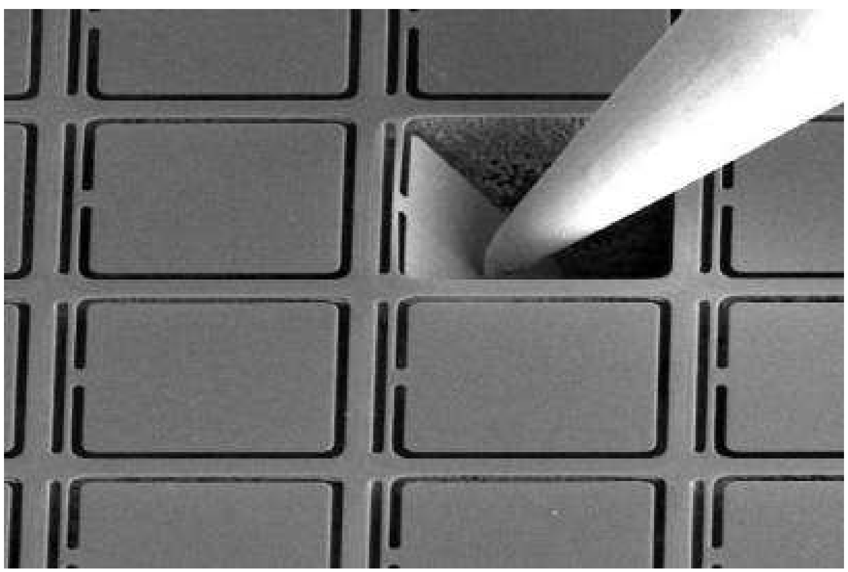


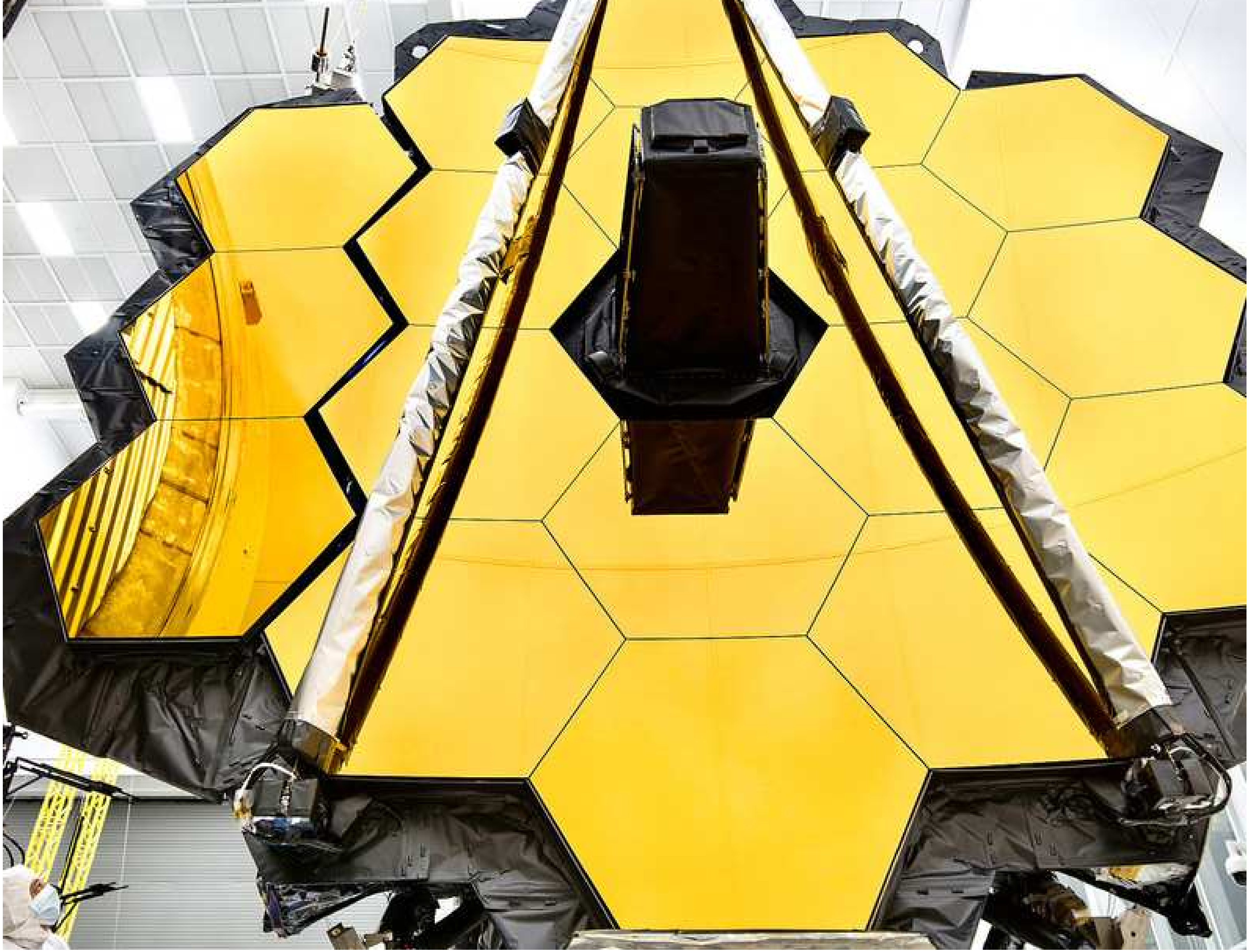
- JWST hardware made in 27 US States: 100% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

Micro Shutters



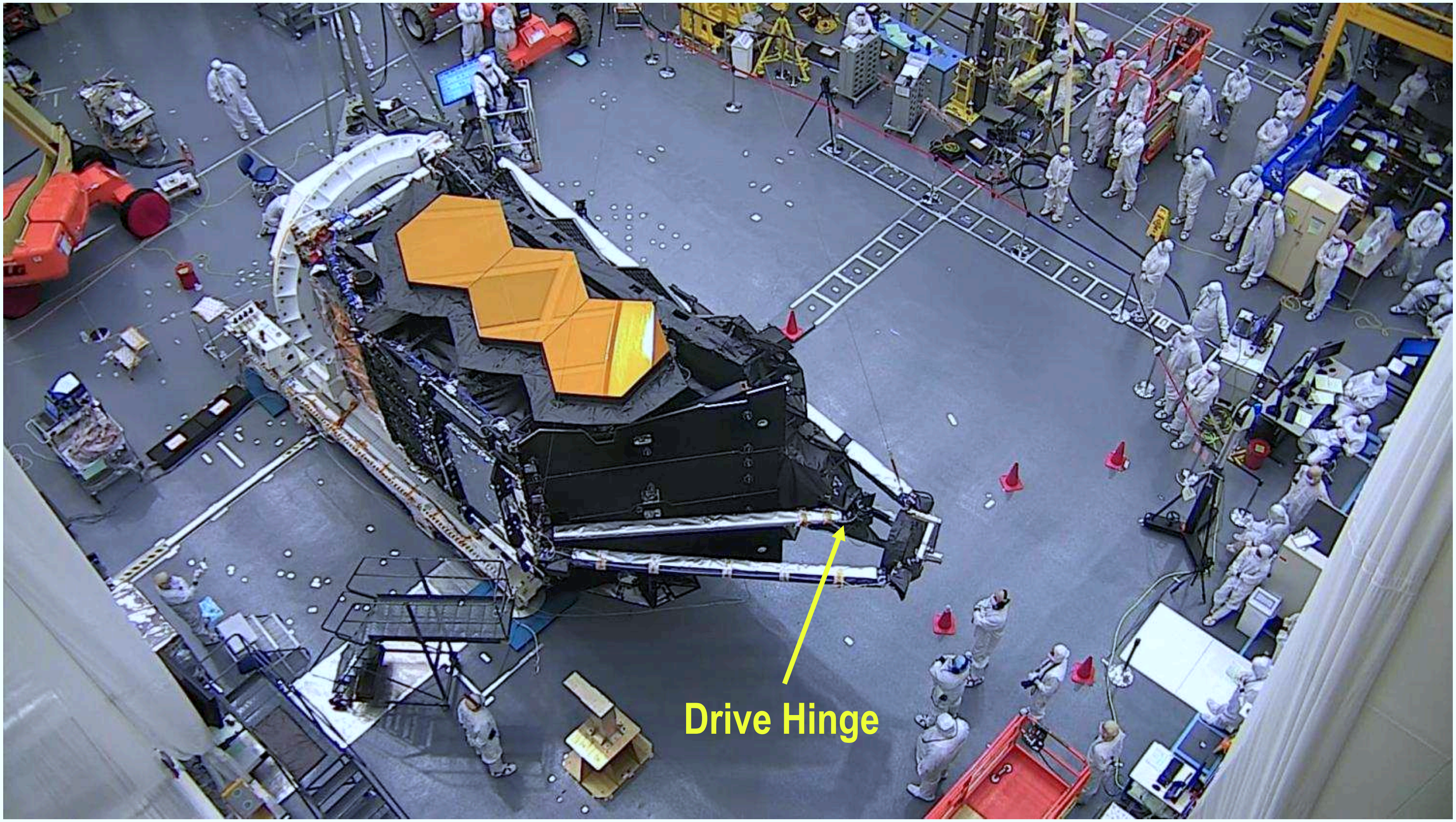






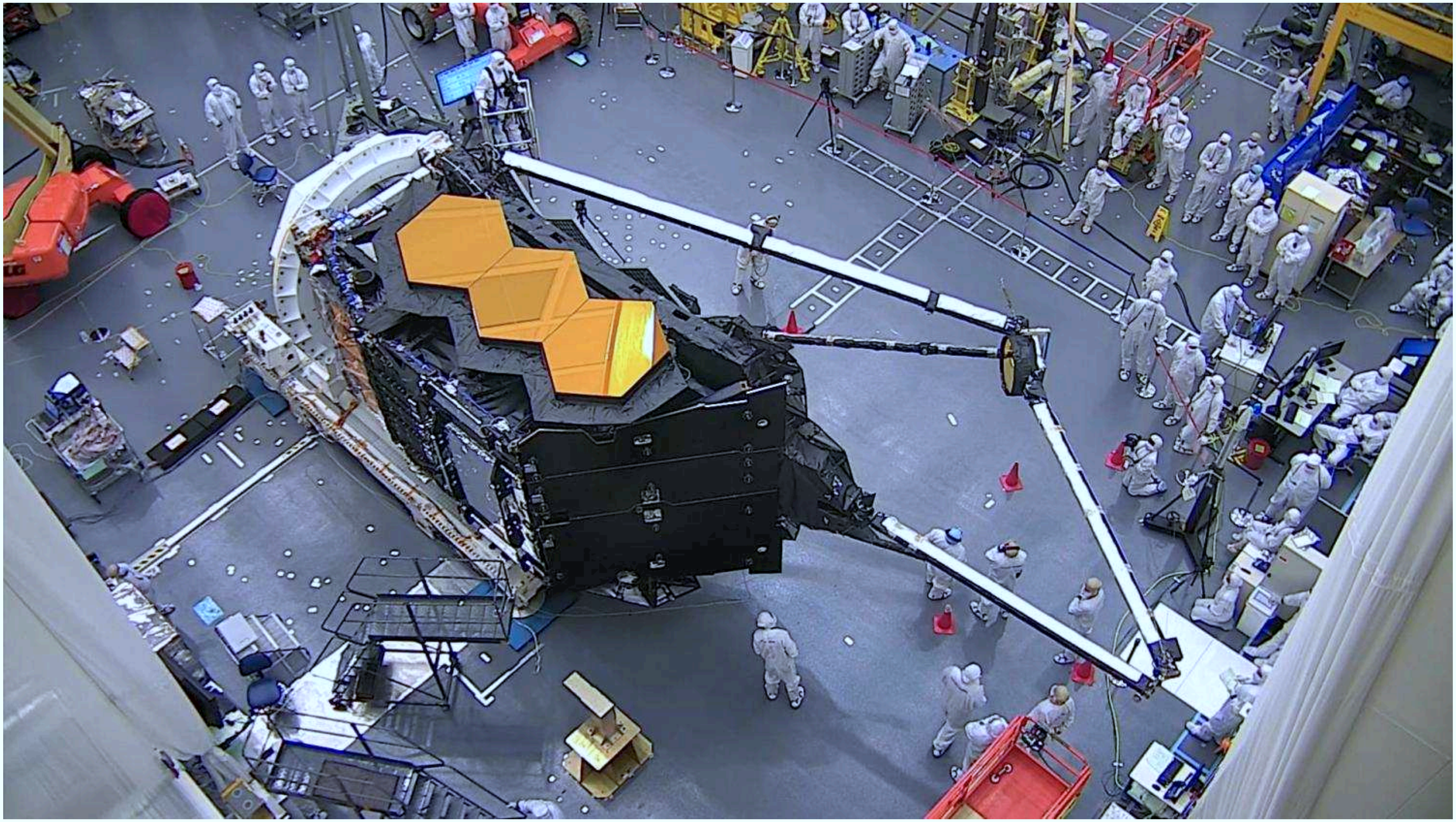
April 2017: Last portrait of JWST at Goddard Space Flight Center (MD).

SMSS Deployment Sequence (1)



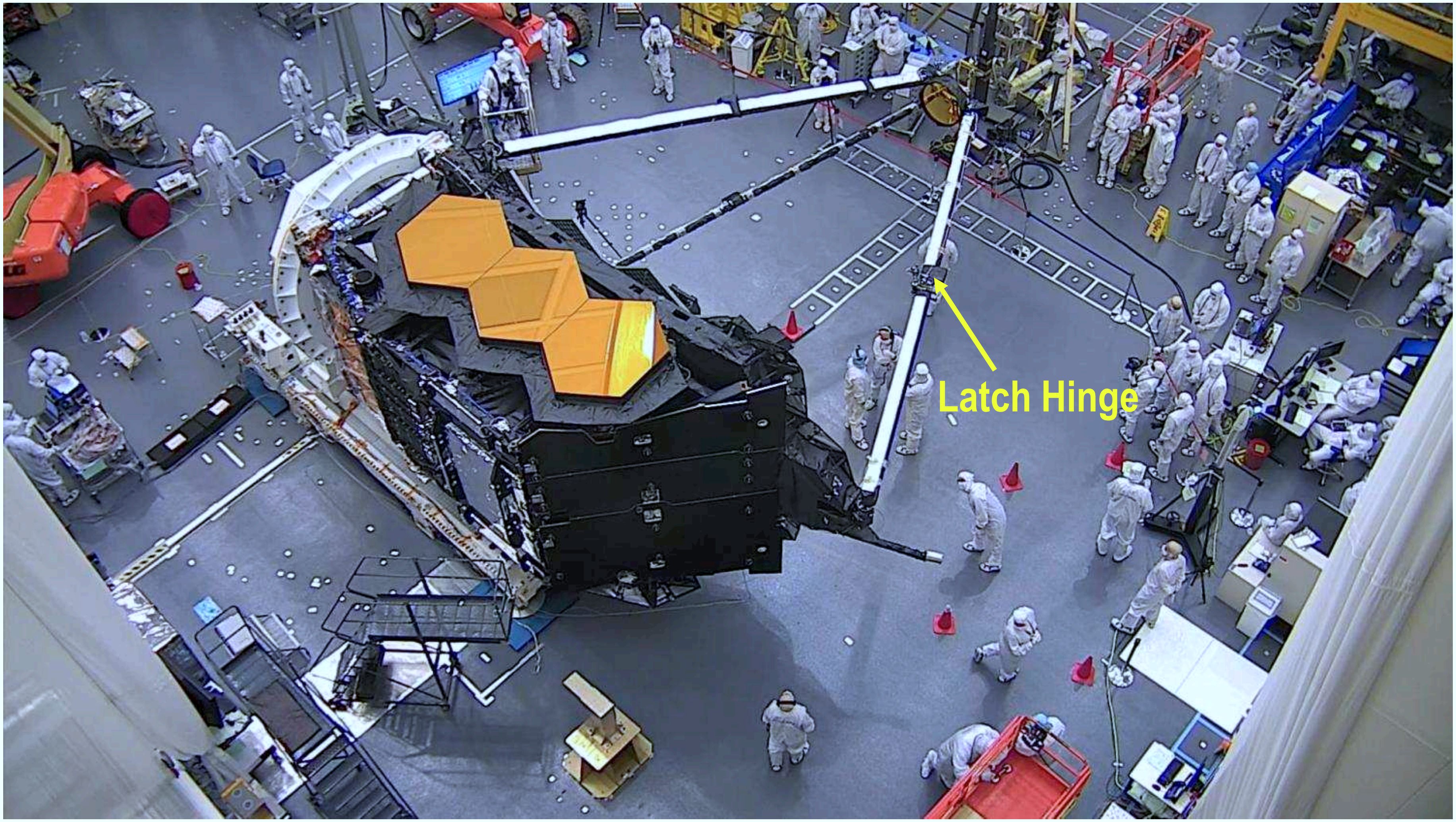
July 2019: Full 1-G deployment of JWST secondary mirror (SM) .

SMSS Deployment Sequence (2)



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

SMSS Deployment Sequence (3)

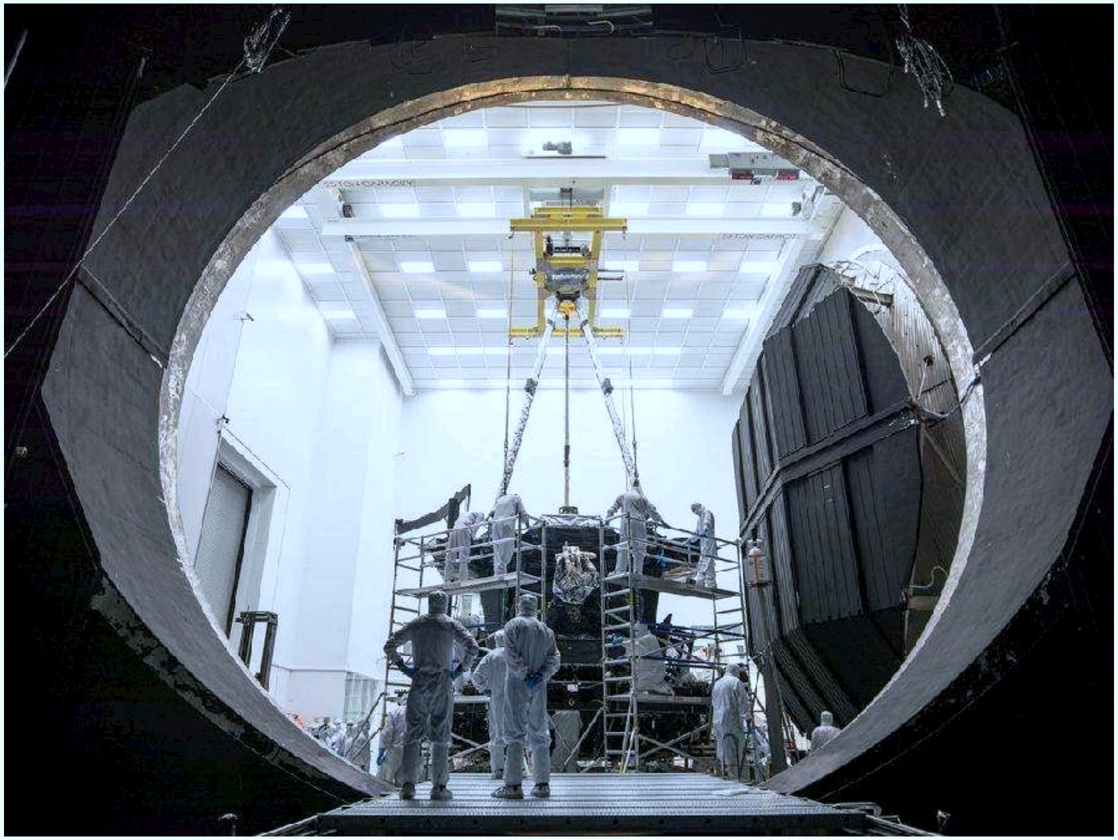


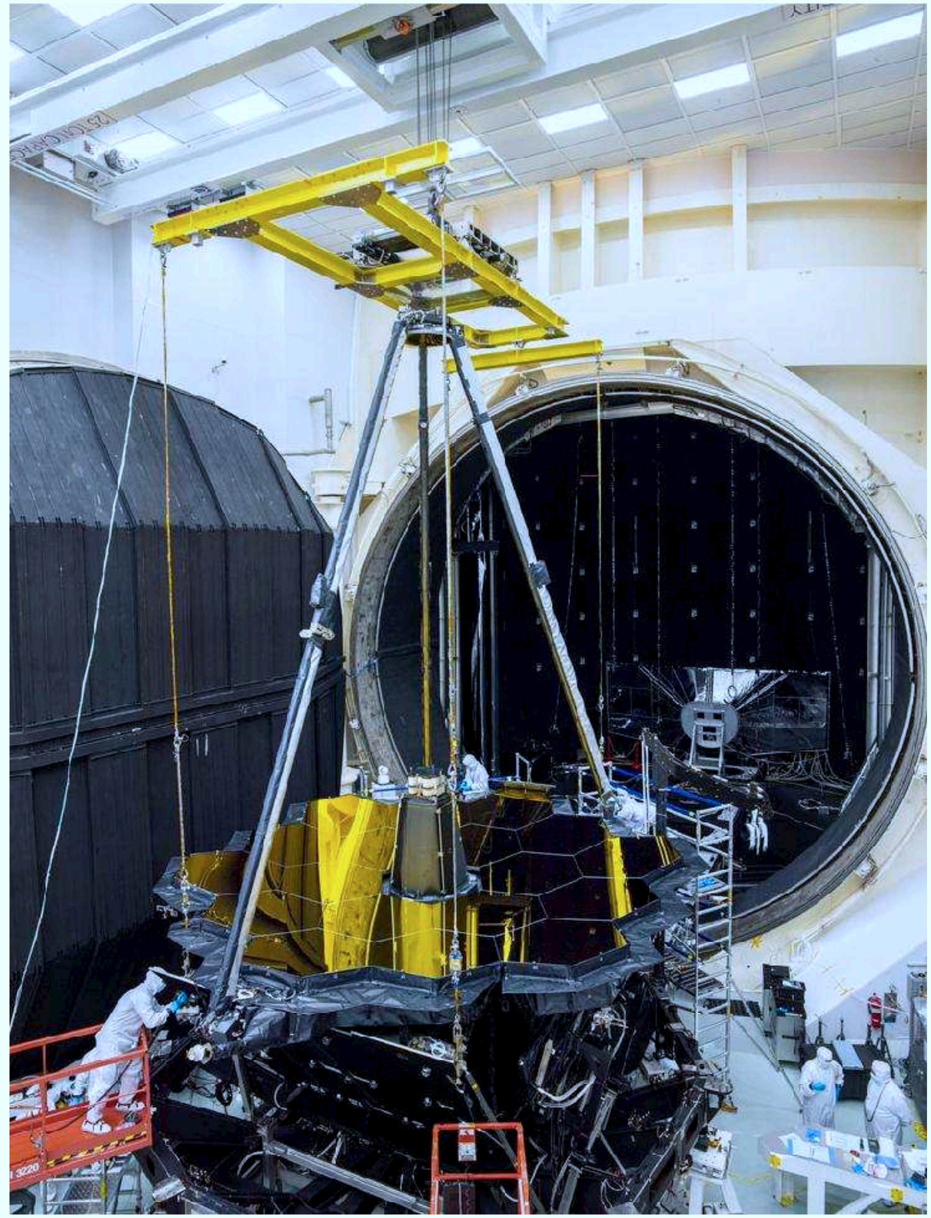
July 2019: Full 1-G deployment of JWST secondary mirror (SM) ...

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

Program Update: OTIS

NORTHROP GRUMMAN

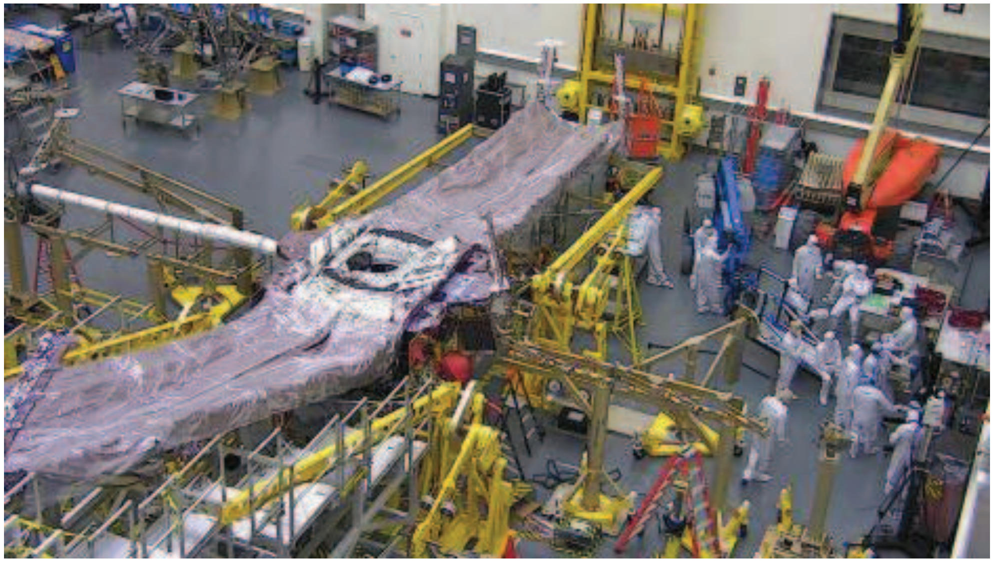


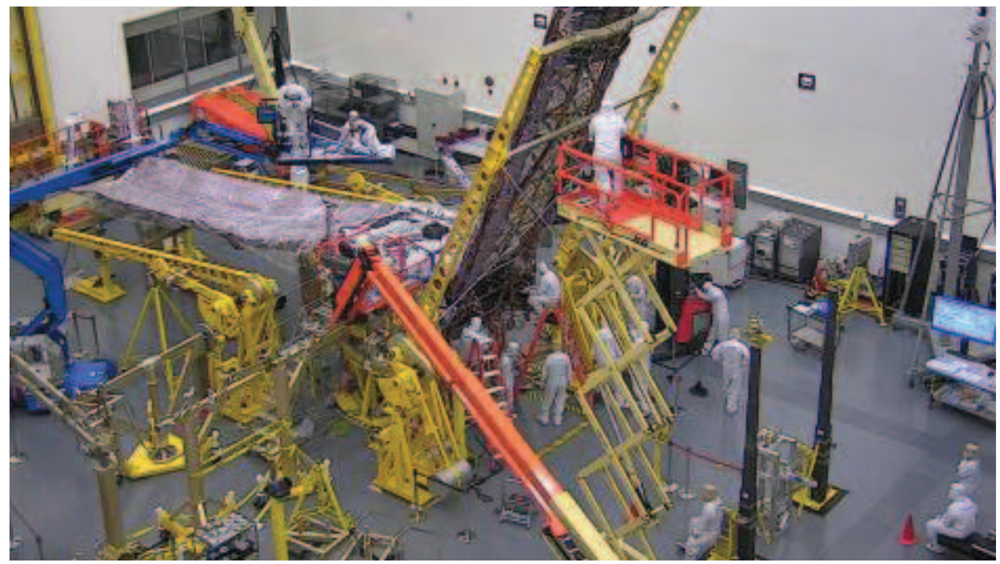


June 2017: JWST going into Chamber A at Johnson Space Center in Houston.

Program Updates: Spacecraft and Sunshield

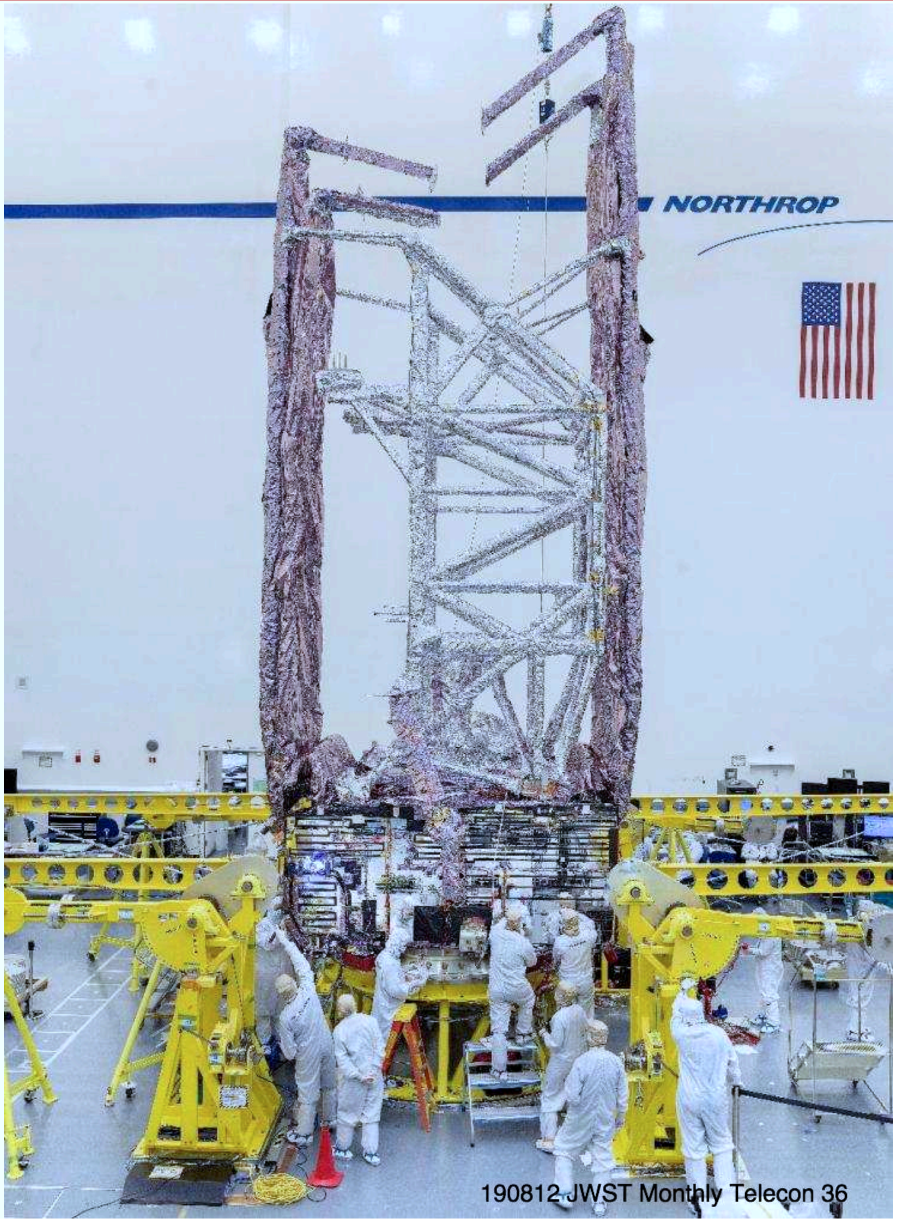
NORTHROP GRUMMAN





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

SCE to Elephant Stand

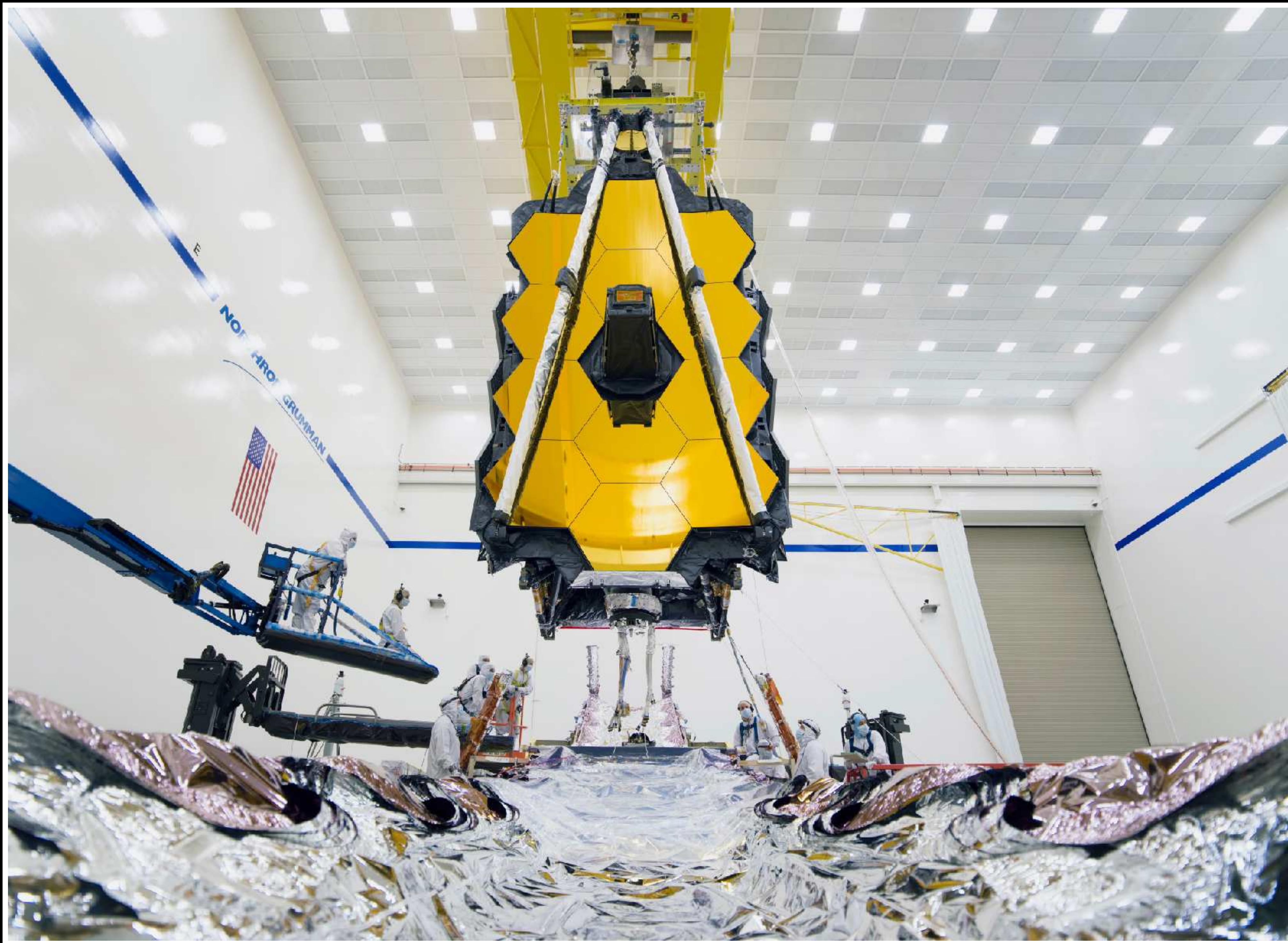


Aug. 2019: Stowed flight sunshield before integration with JWST OTE.

SMSS Deployment

190812 JWST Monthly Telecon 39

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

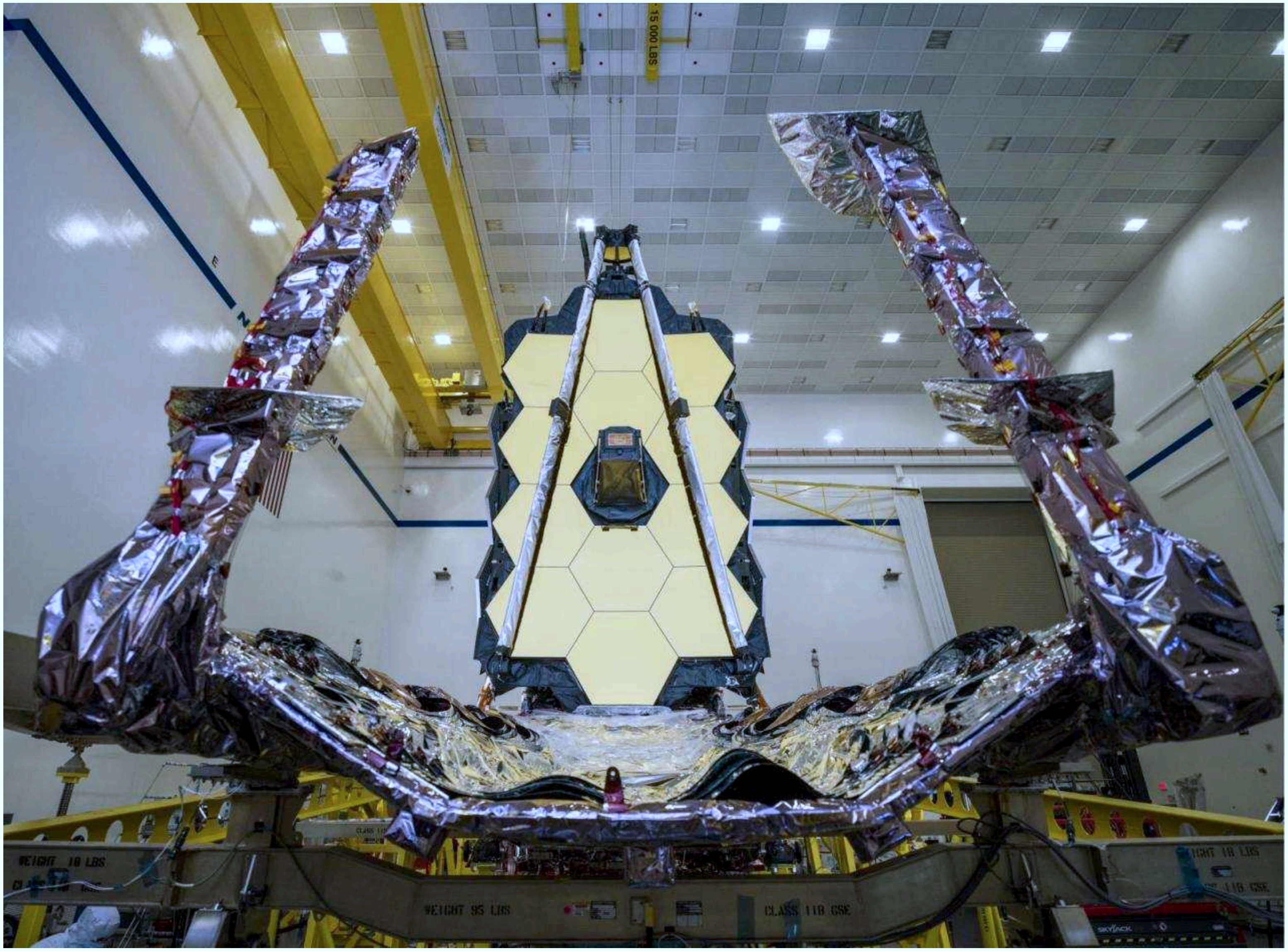


Aug. 2019: JWST OTE+ISIM lowered into Sunshield+Spacecraft

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

200511 JWST Monthly Telecon 12

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

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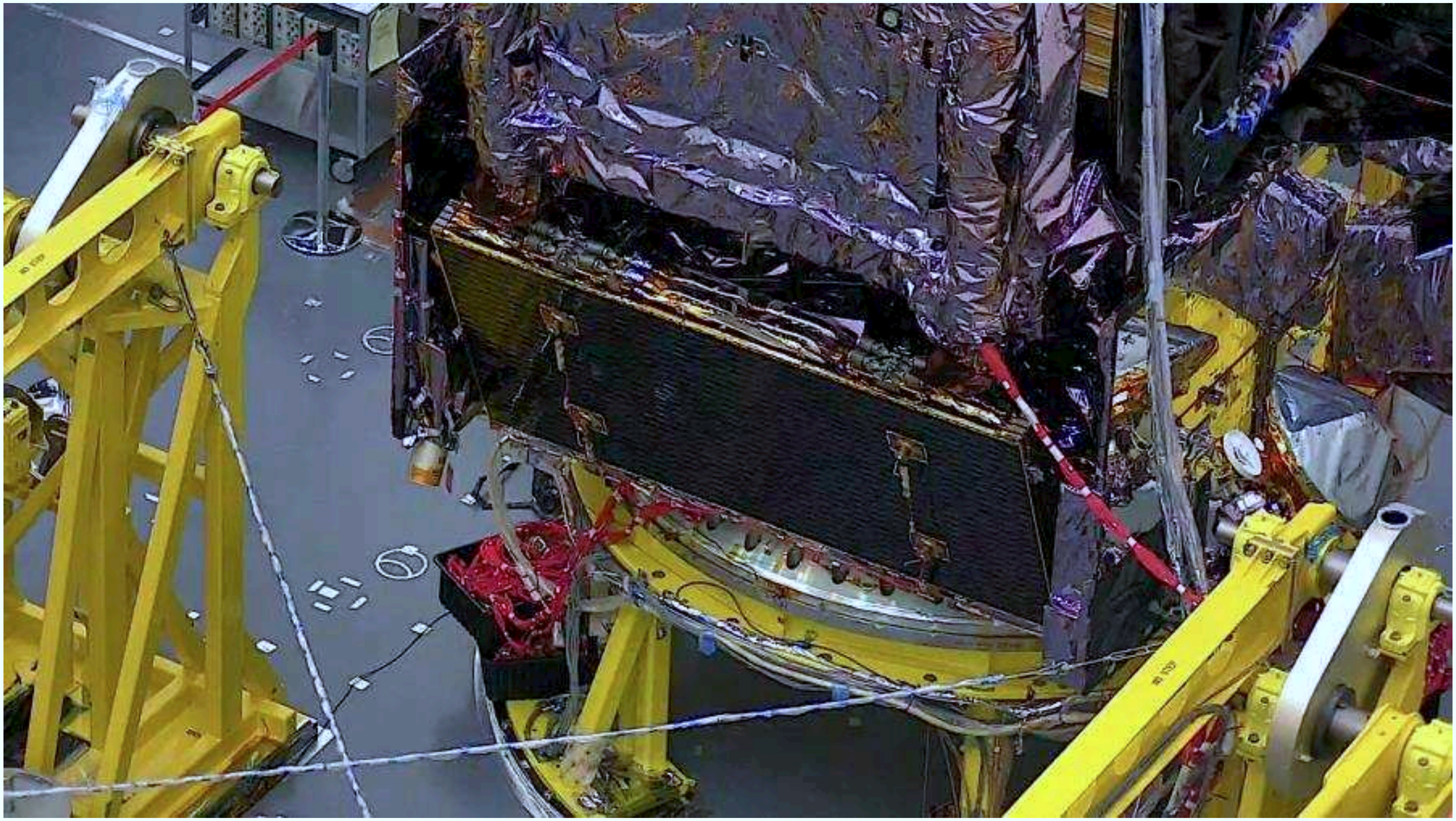
7/26/20: Solar Array Installed for Environments



May 2020: Solar Array as installed on JWST Observatory

5/28/20: DTA Deployment

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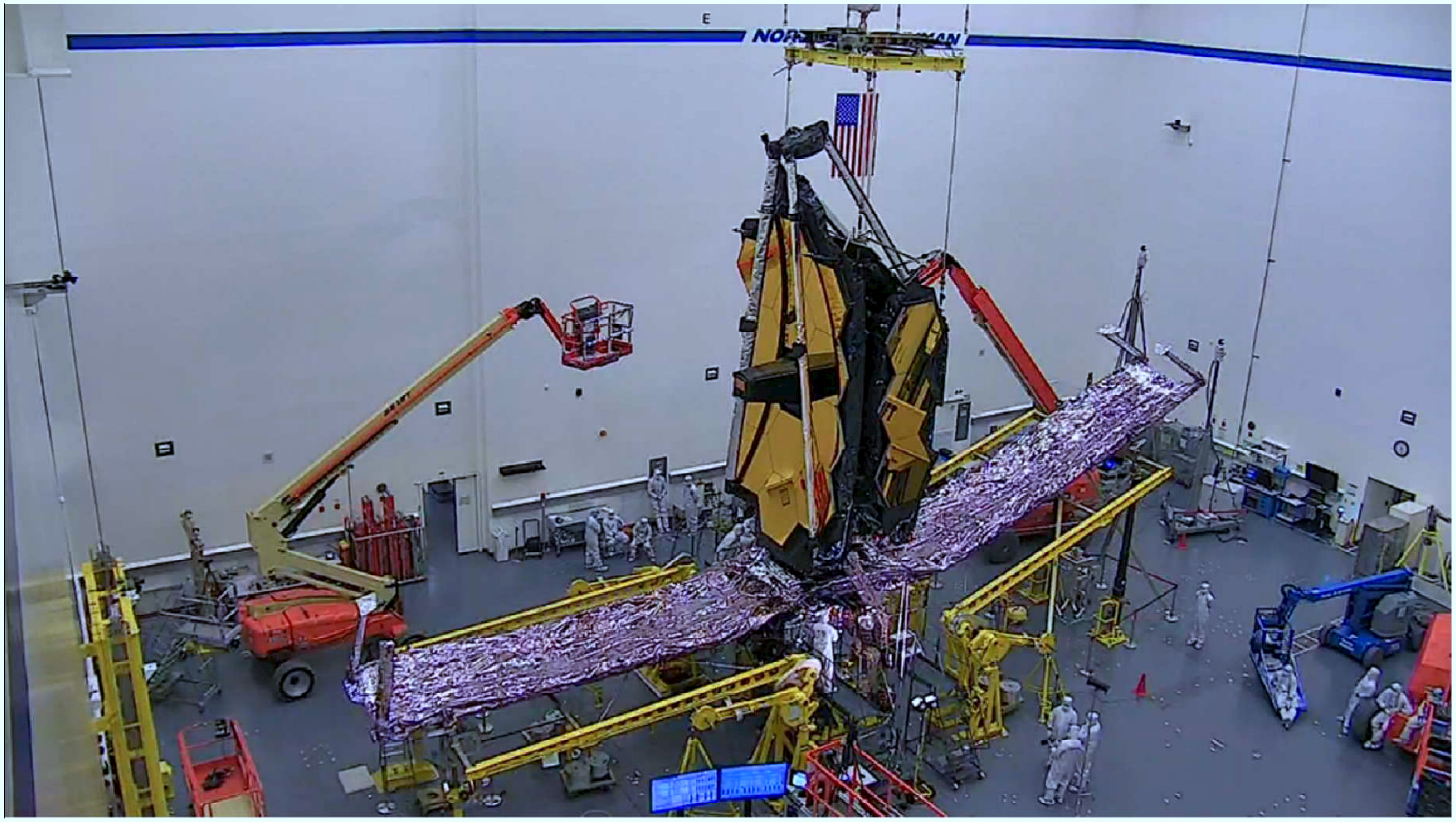
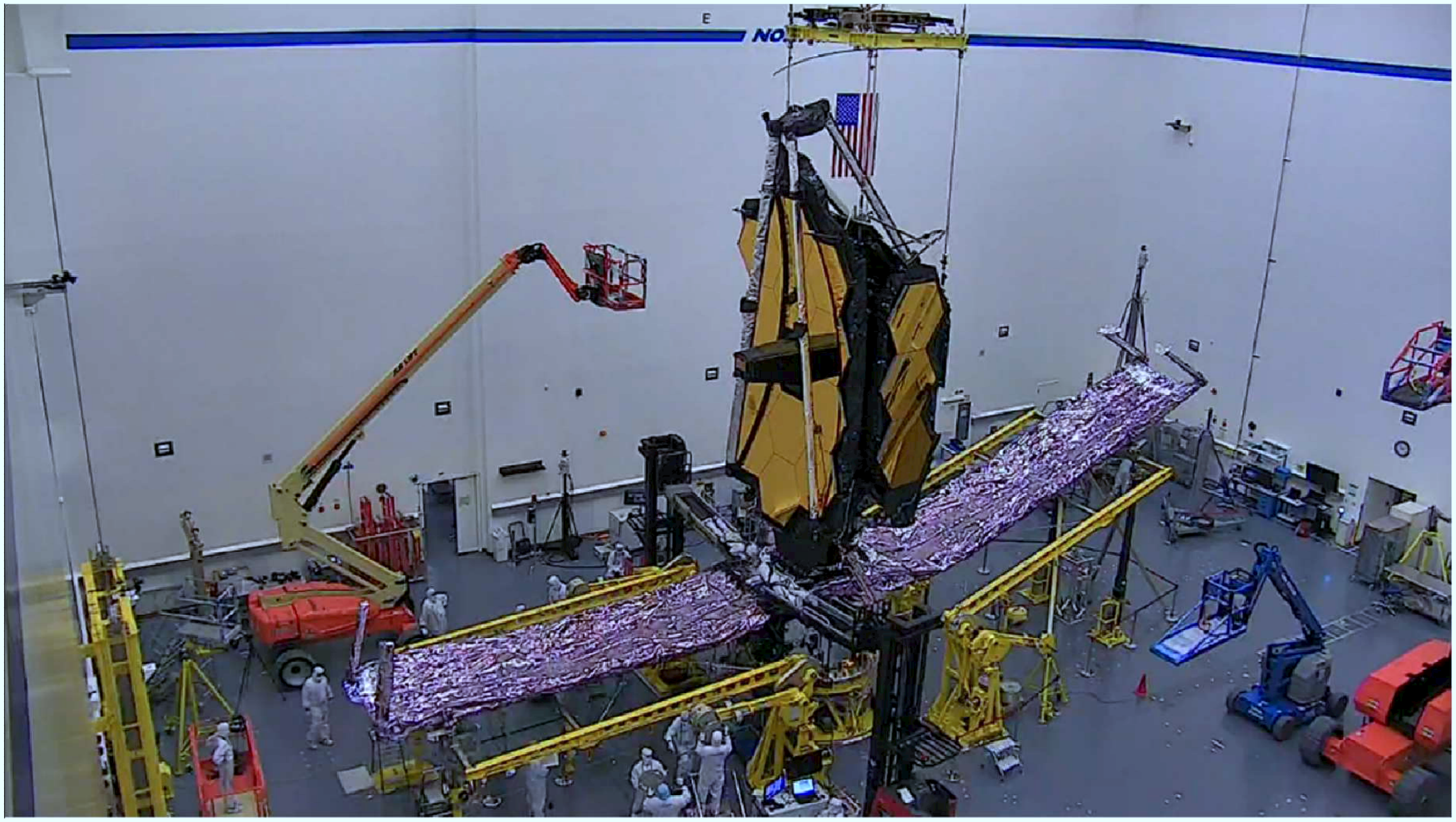
June 2020: Deployable Tower Assembly test

5/28/20: DTA Deployment



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

5/29/20: DTA Deployment

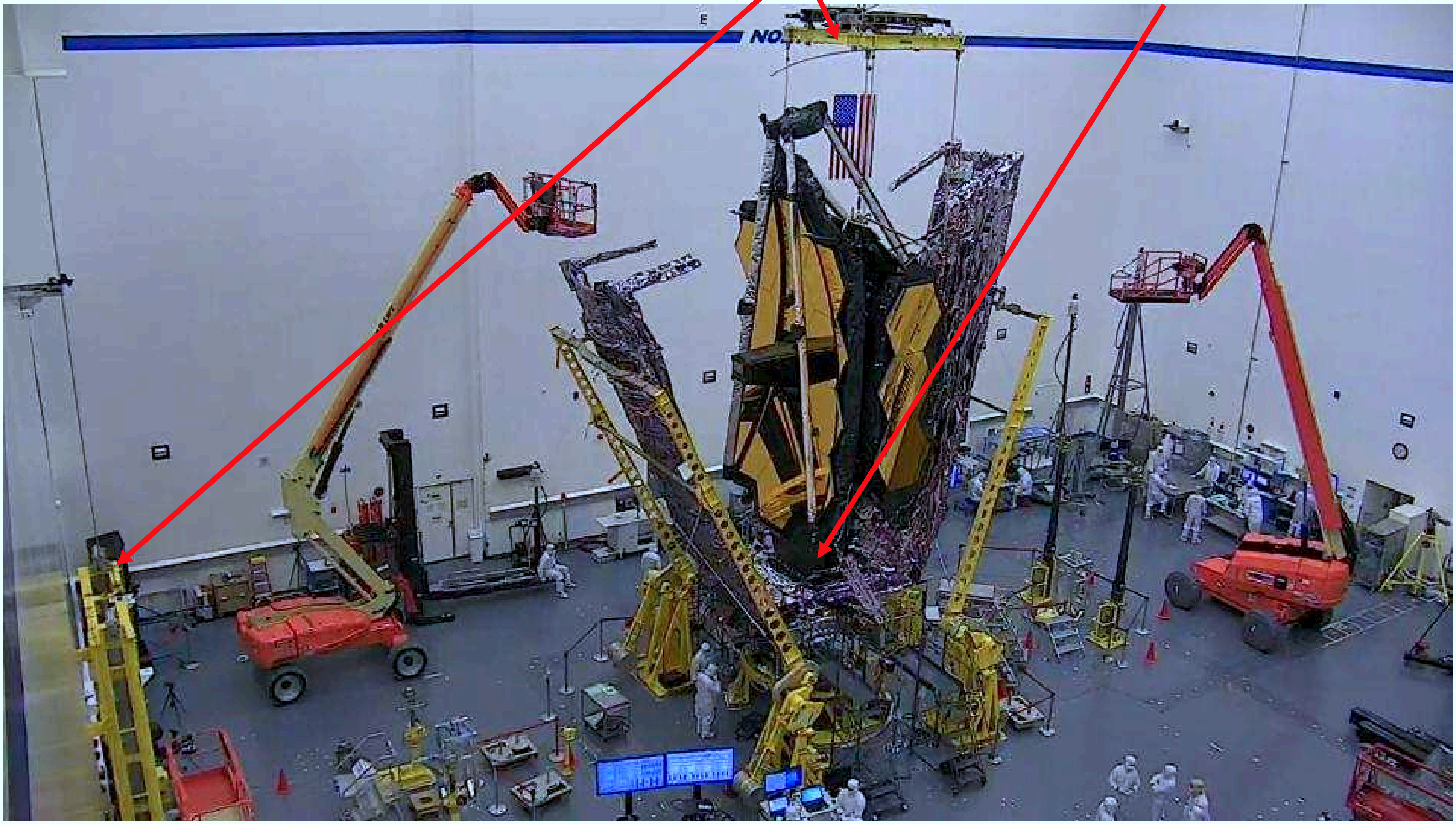


June 2020: Deployable Tower Assembly motor tested in 1G

DTA Stow 1

Offloading System

Deployable Tower Assembly



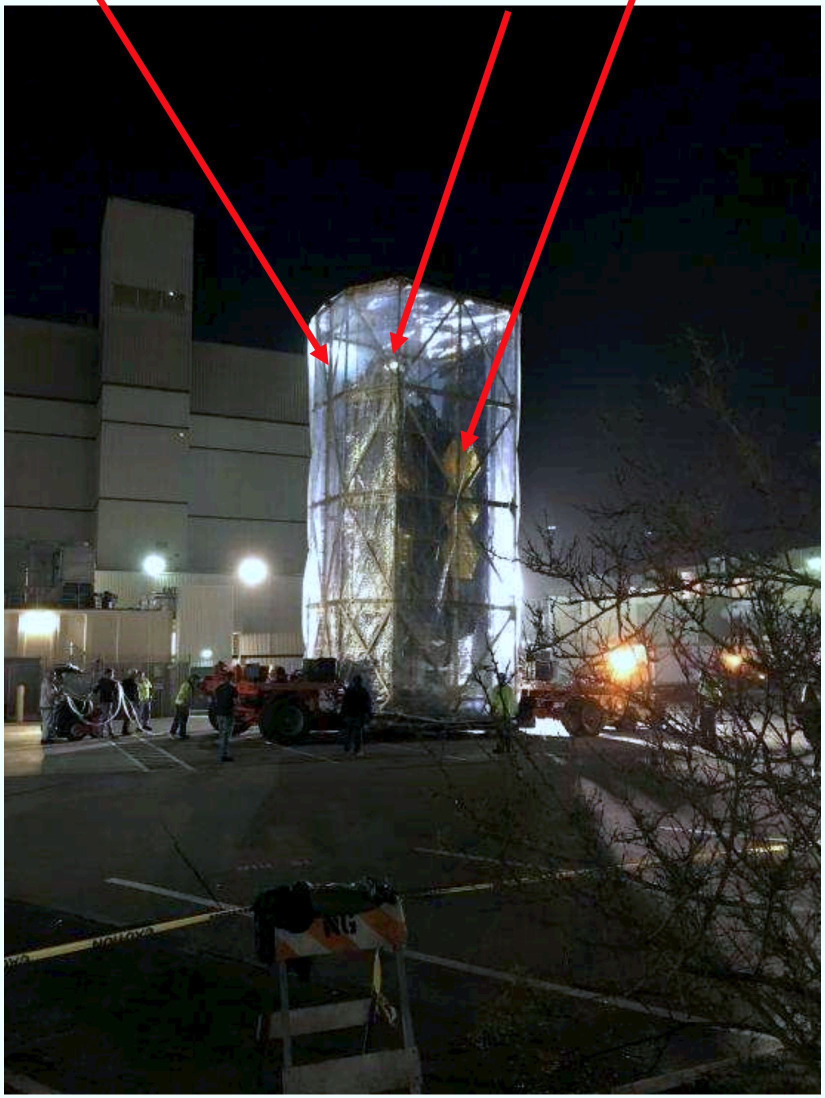
200713 JWST Monthly Telecon 9

July 2020: Deployable Tower Assembly stow for launch

DTA Stow 2

July 2020: Deployable Tower Assembly 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

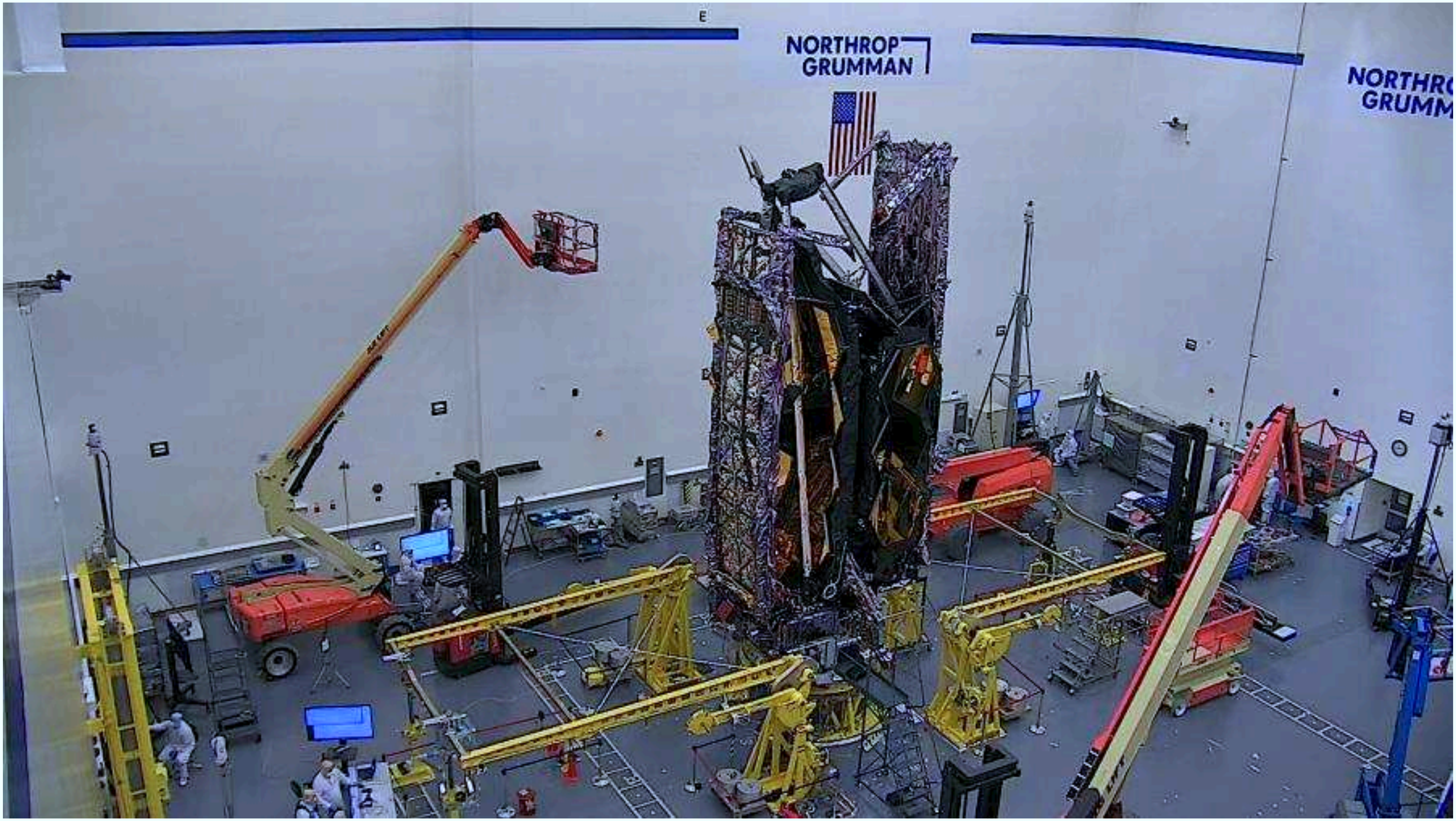
7/13/21: AFT UPS Full Stow

July 2021: Aft UPS stow for launch

7/13/21: AFT UPS Full Stow

July 2021: Aft UPS stowed for launch

7/14/21: FWD UPS Full Stow



July 2021: Forward UPS stowed for launch

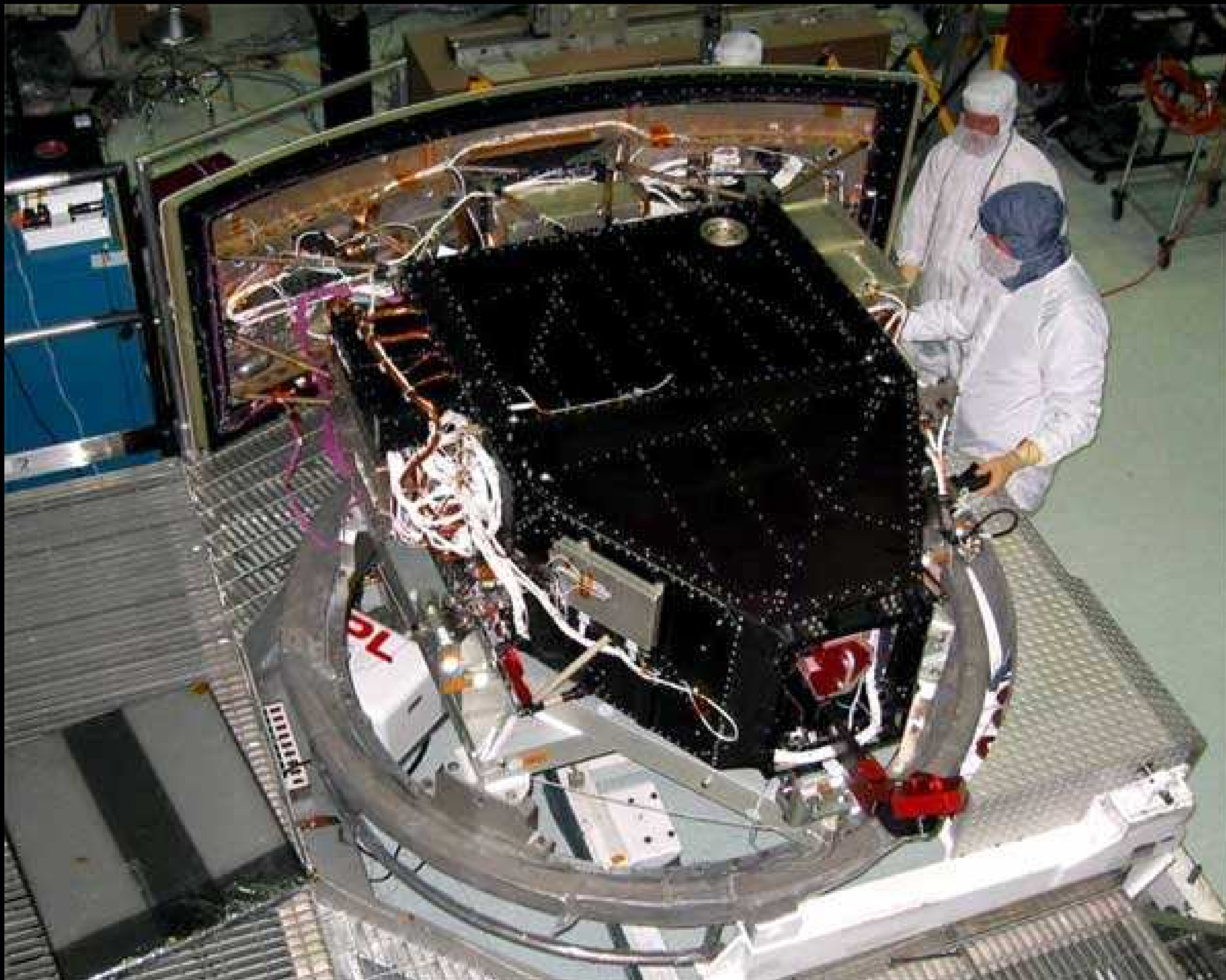
(beautiful)
The ^ James Webb Space Telescope

Stowed for Launch

210913 JWST Monthly Telecon 18

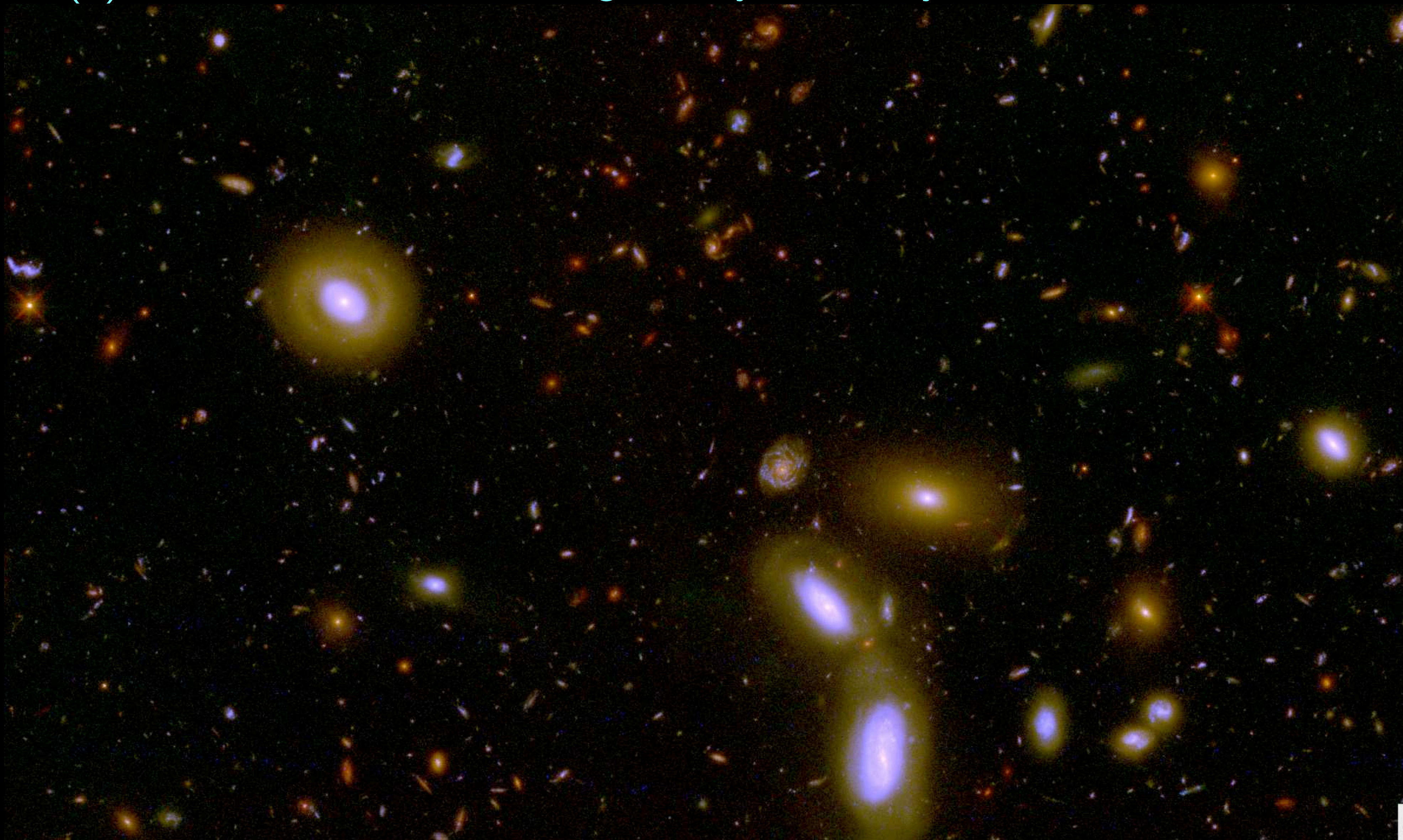
Sept. 2021: JWST ready and stowed for shipping to Kourou

(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).

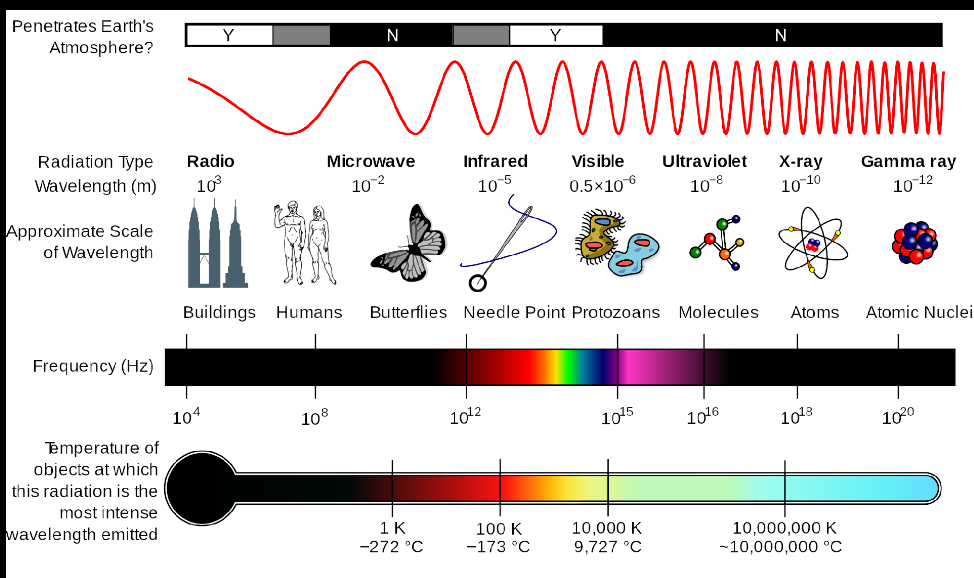
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 FF) at 1–5μm, with 0.2–1.2" images at 5–29μm, tracing young+old stars & dust.

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

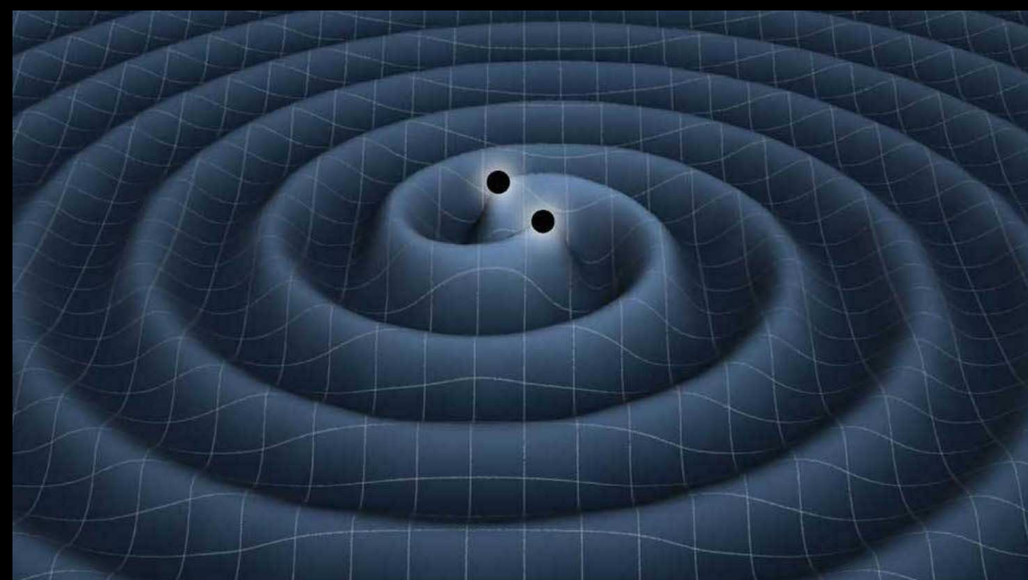
In solids: Earthquakes

In liquids: Surf!

In gasses: Sound

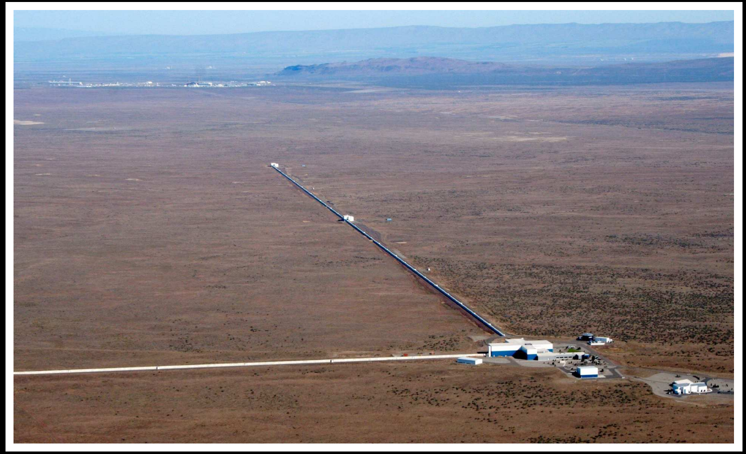


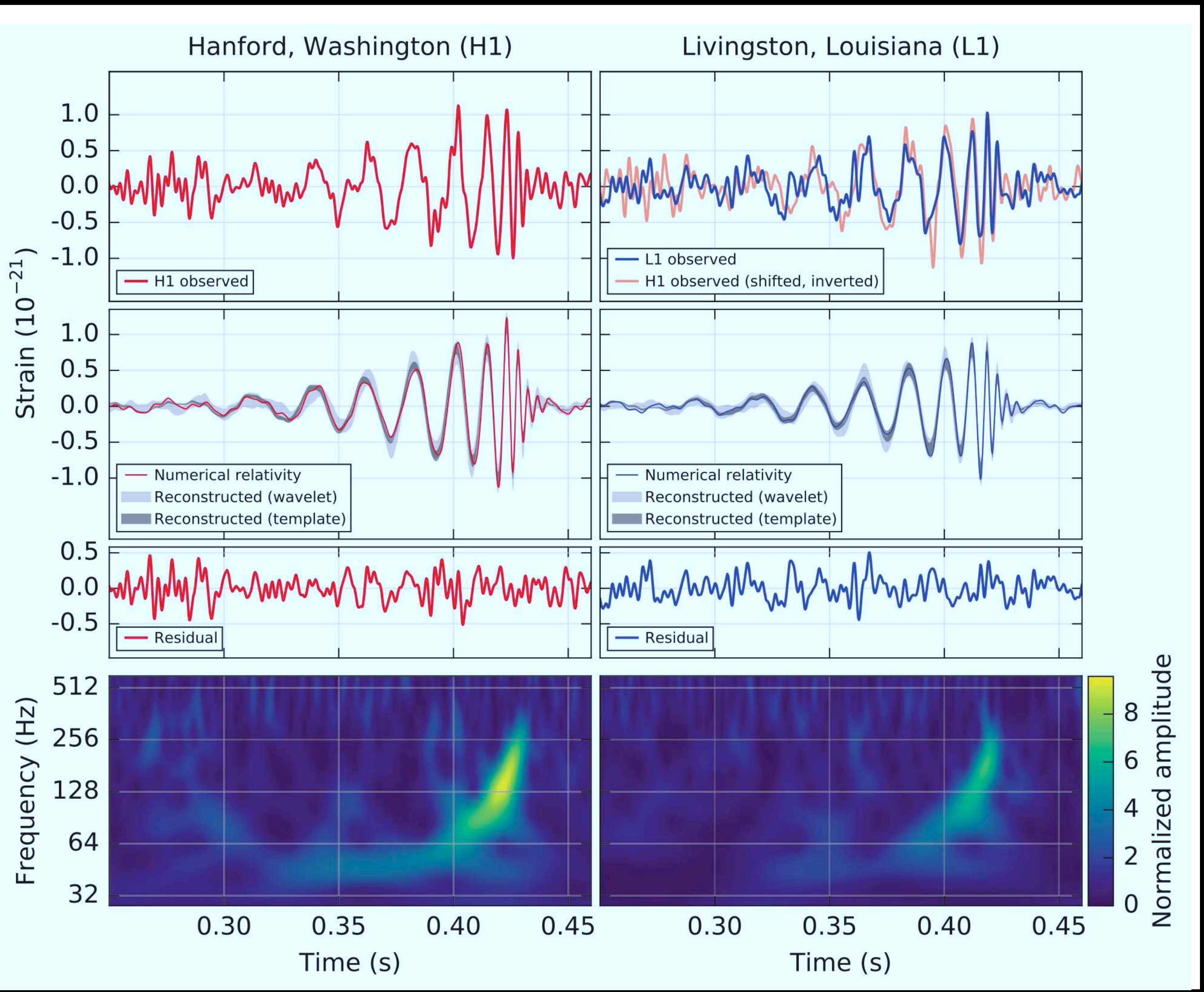
2) Electromagnetic Waves



3) In space-time: Gravity Waves

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

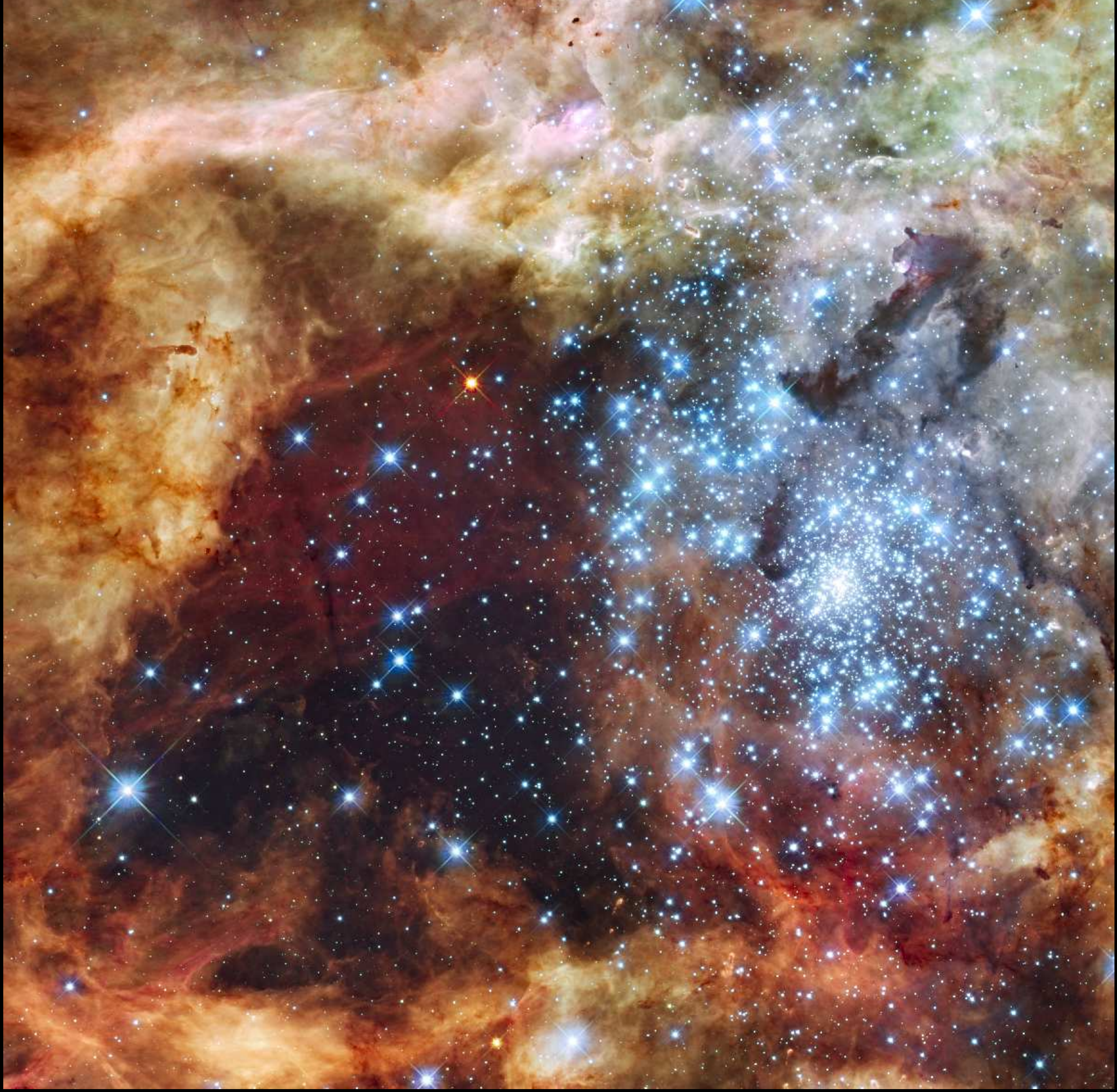




(1) LIGO first observed Gravitational Waves on Sept. 14, 2015.

(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!

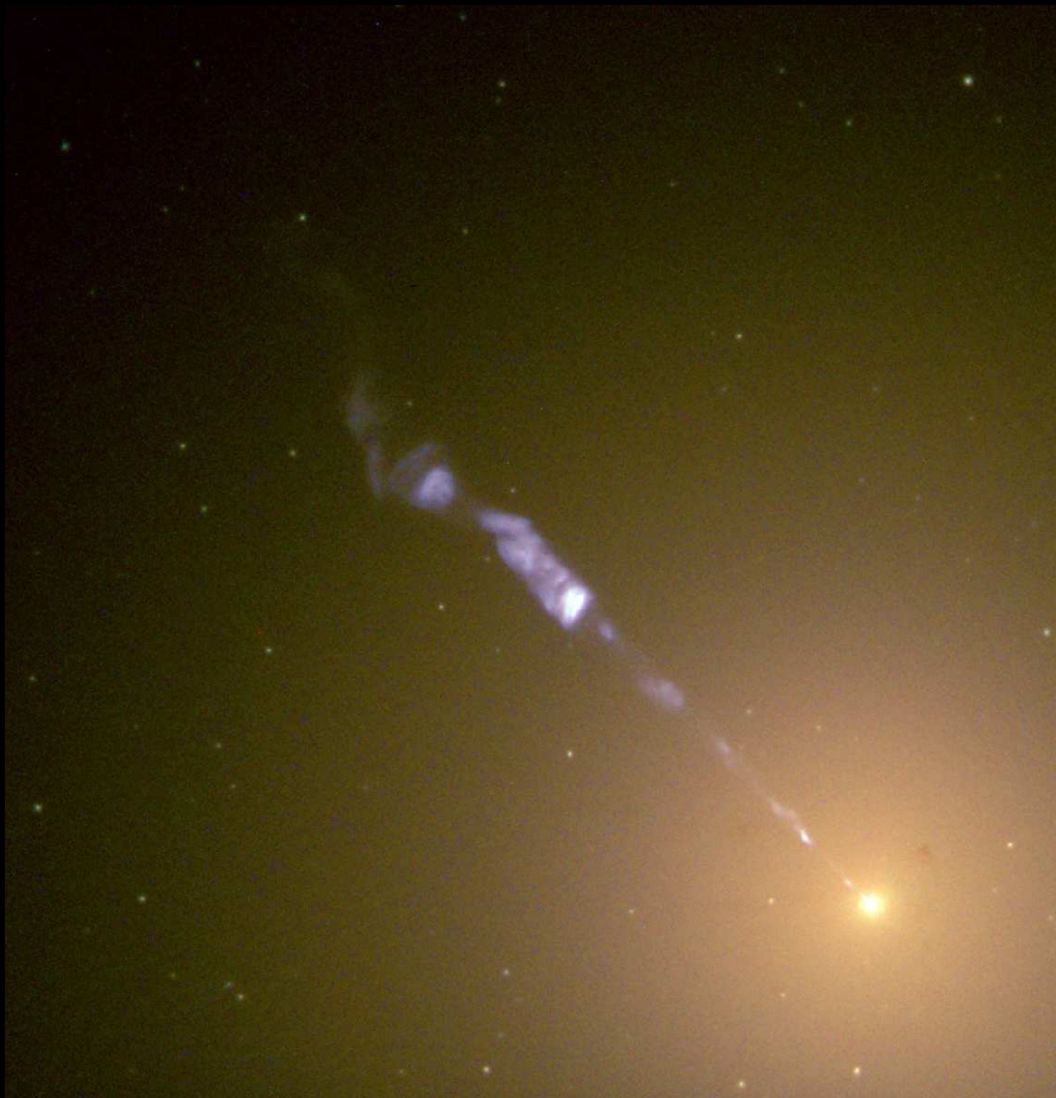


Ordinary massive stars (10–30 $M_{\odot}$) leave modest black holes ($\sim$3–10 $M_{\odot}$).

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:

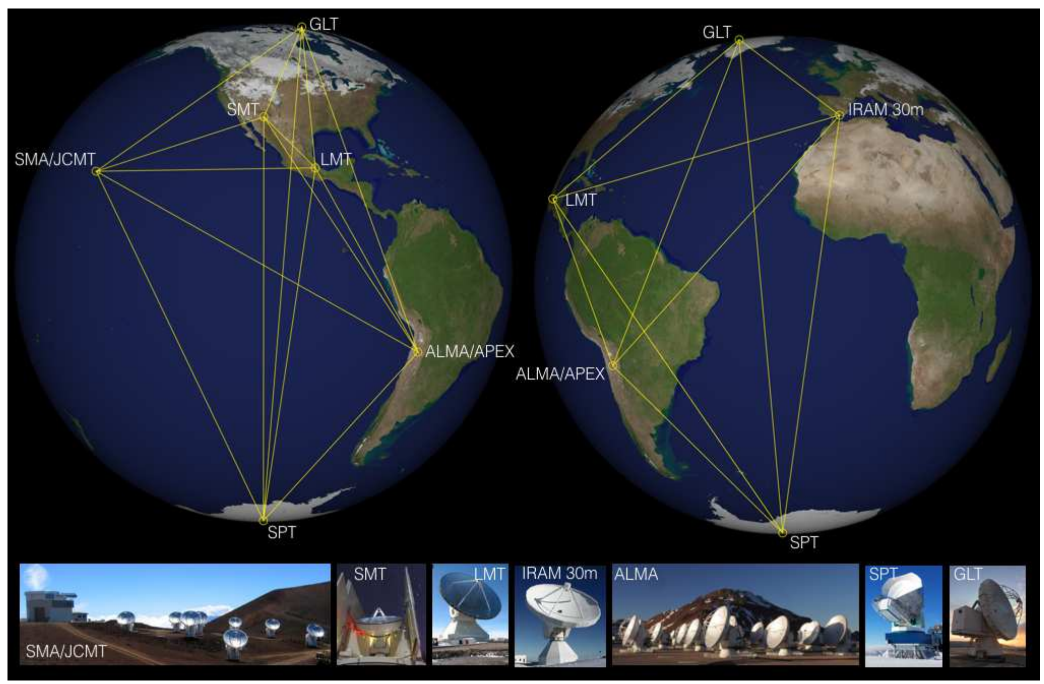


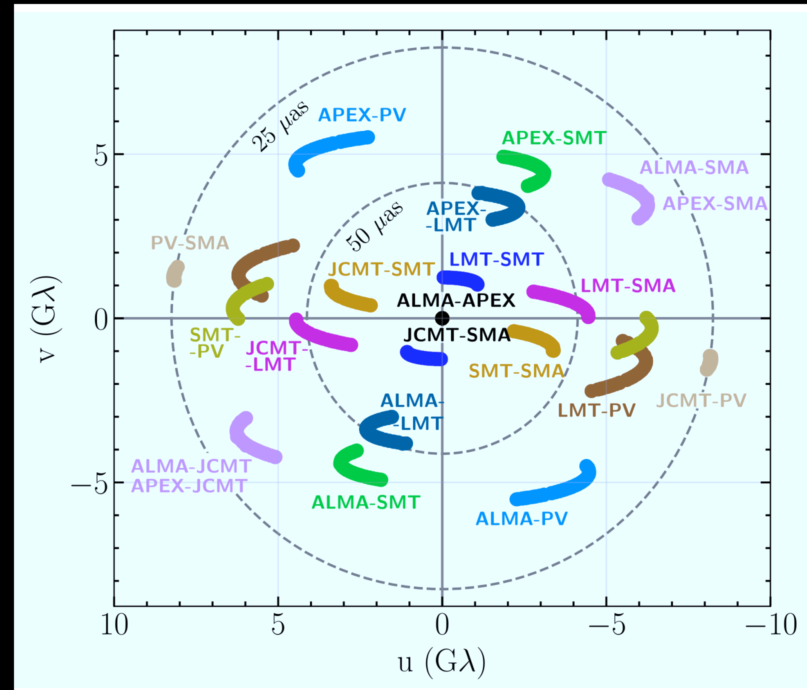
"For God's sake, Edwards. Put the laser pointer away."

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!





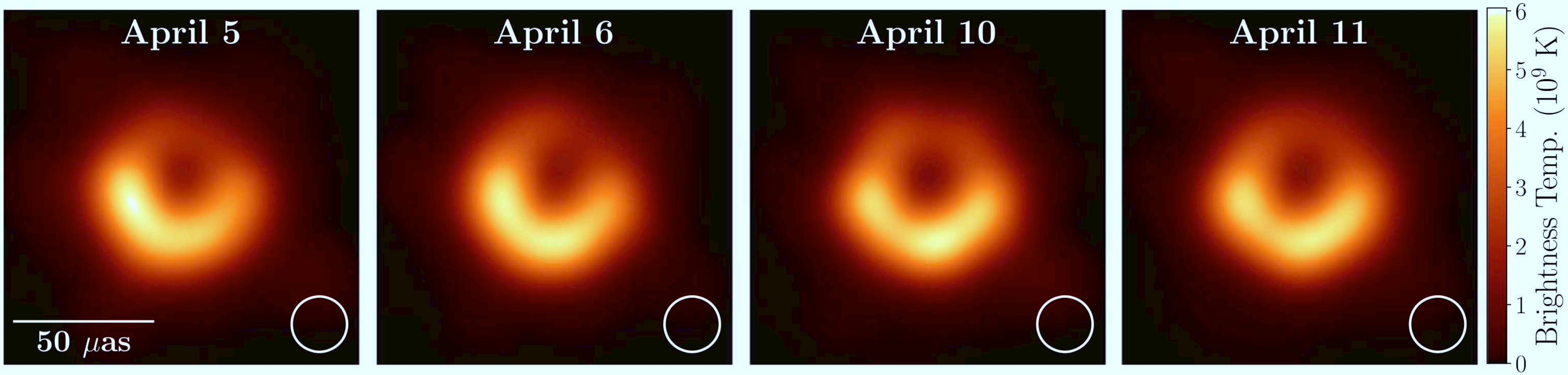
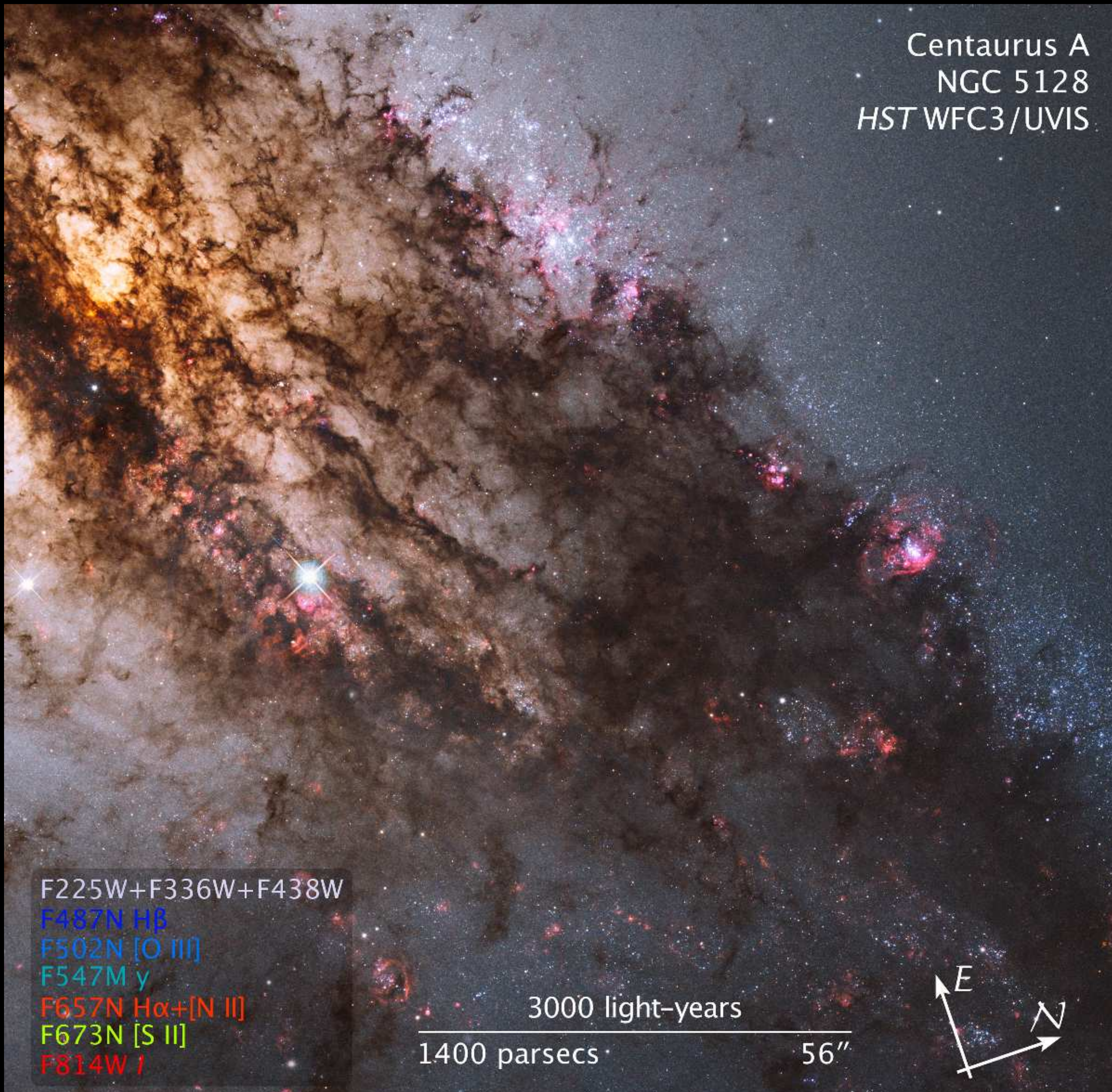
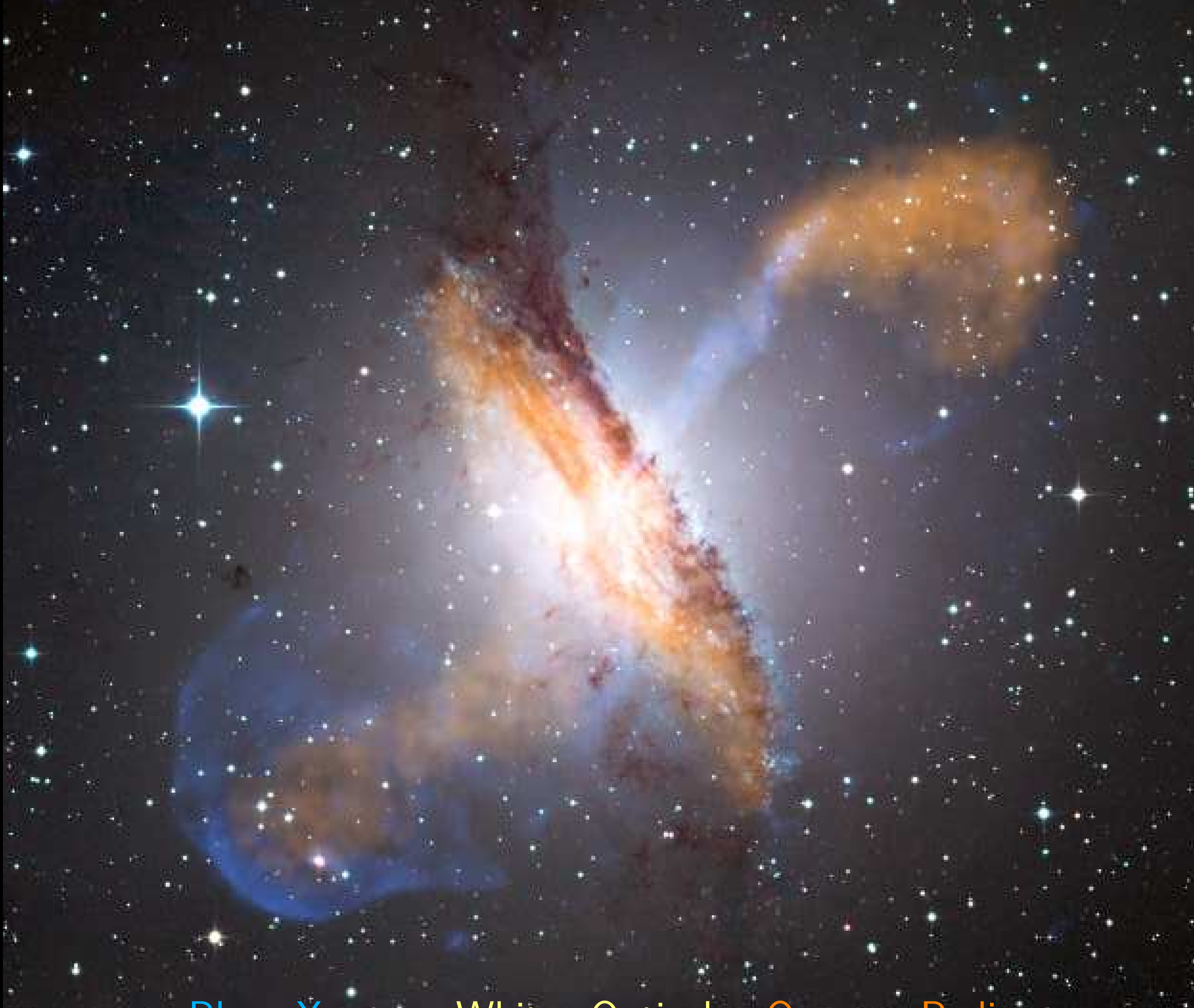


Figure 15. Averages of the three fiducial images of M87 for each of the four observed days after restoring each to an equivalent resolution, as in Figure 14. The indicated beam is 20 μas (i.e., that of `DIFMAP`, which is always the largest of the three individual beams).

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

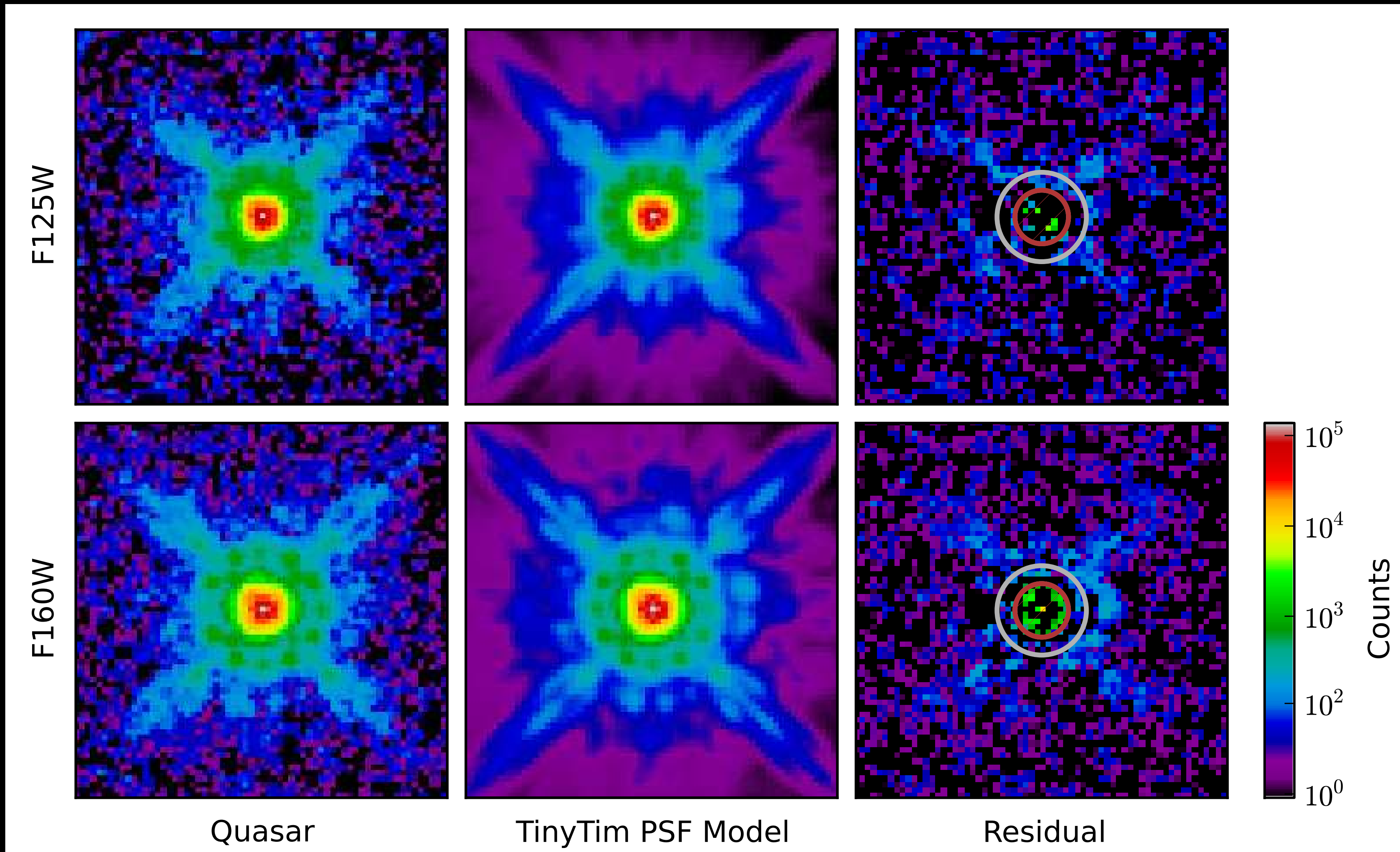


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W I
3000 light-years
1400 parsecs
56″
E
N



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$\times$ smaller than today), 900 Myr old!
- Contains 10^{14} solar luminosities within a region as small as Pluto's orbit!
- A feeding monster blackhole ($>3\times10^9$ 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 $\sim 3\times10^{9}$ 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).

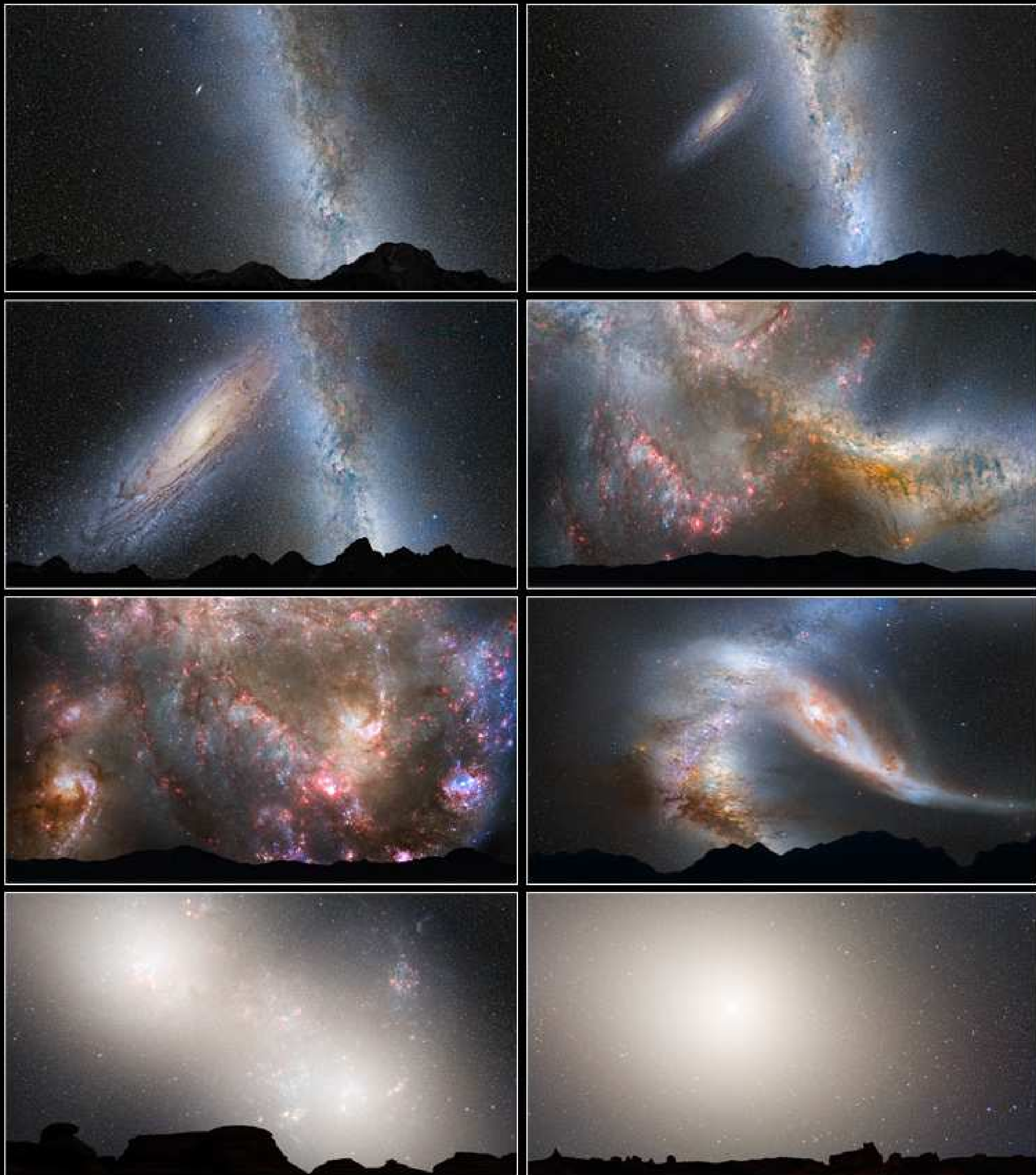


Illustration Sequence of the Milky Way and Andromeda Galaxy Colliding

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:

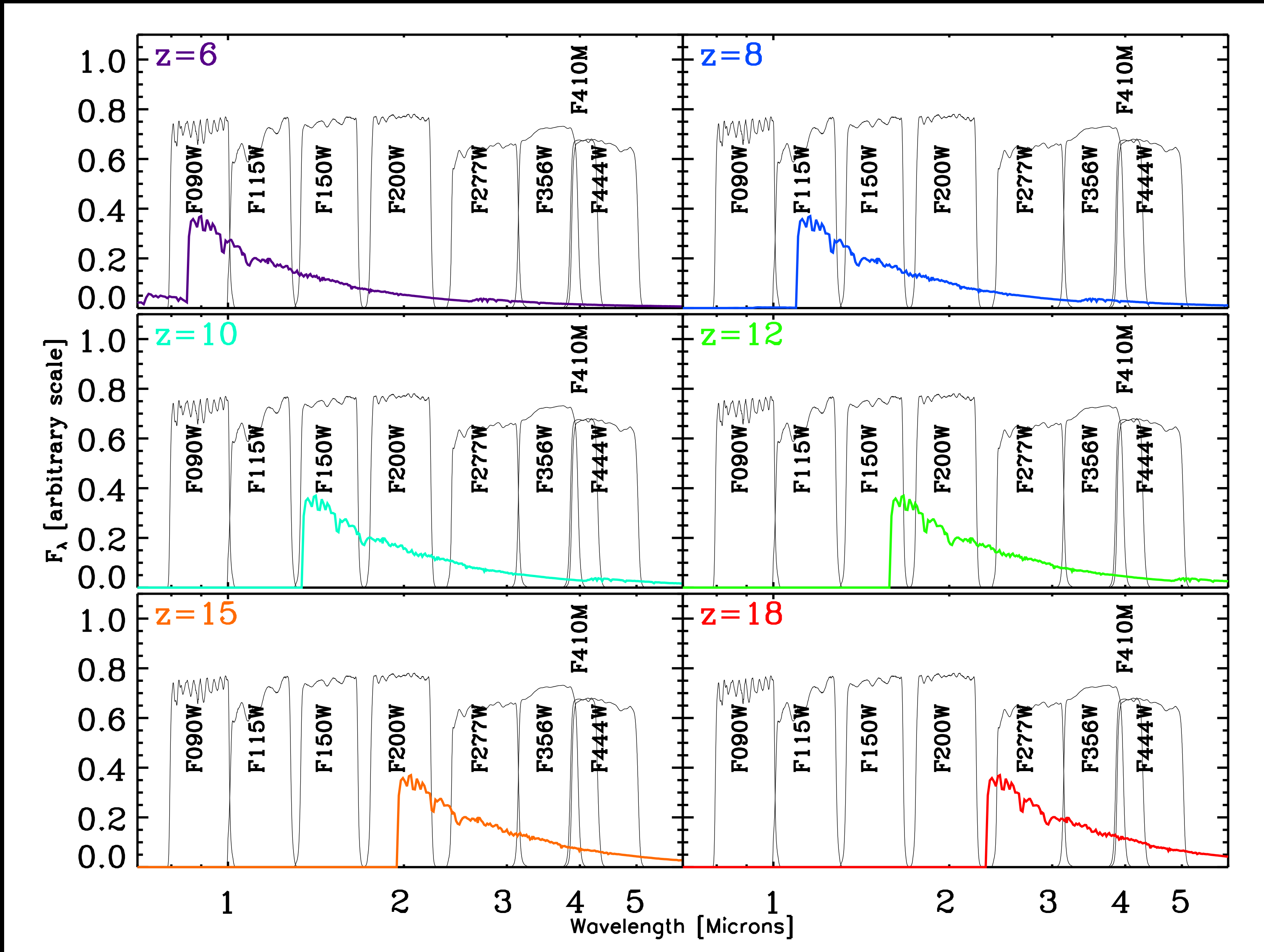
Approaches at –110 km/s.

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!

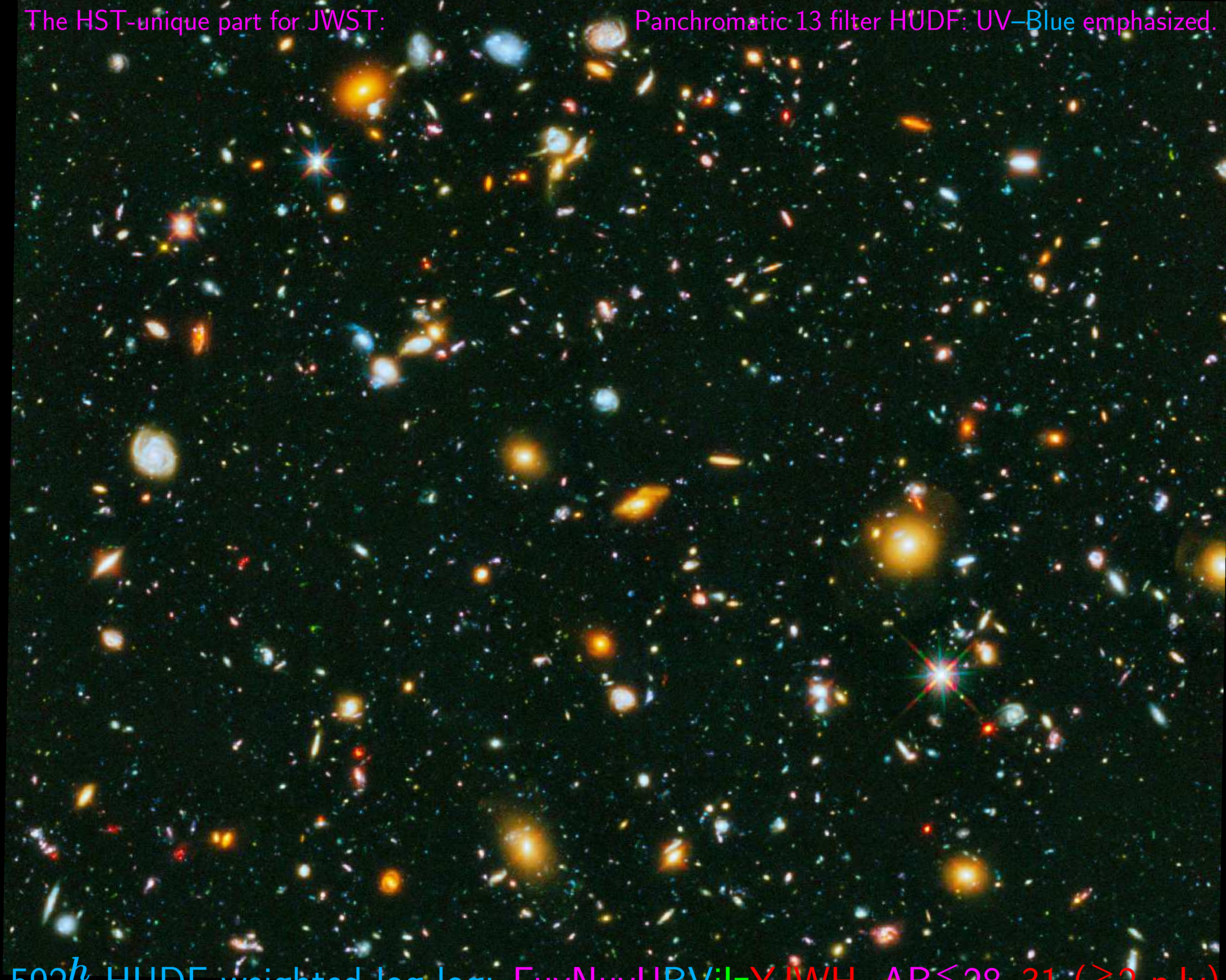
3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



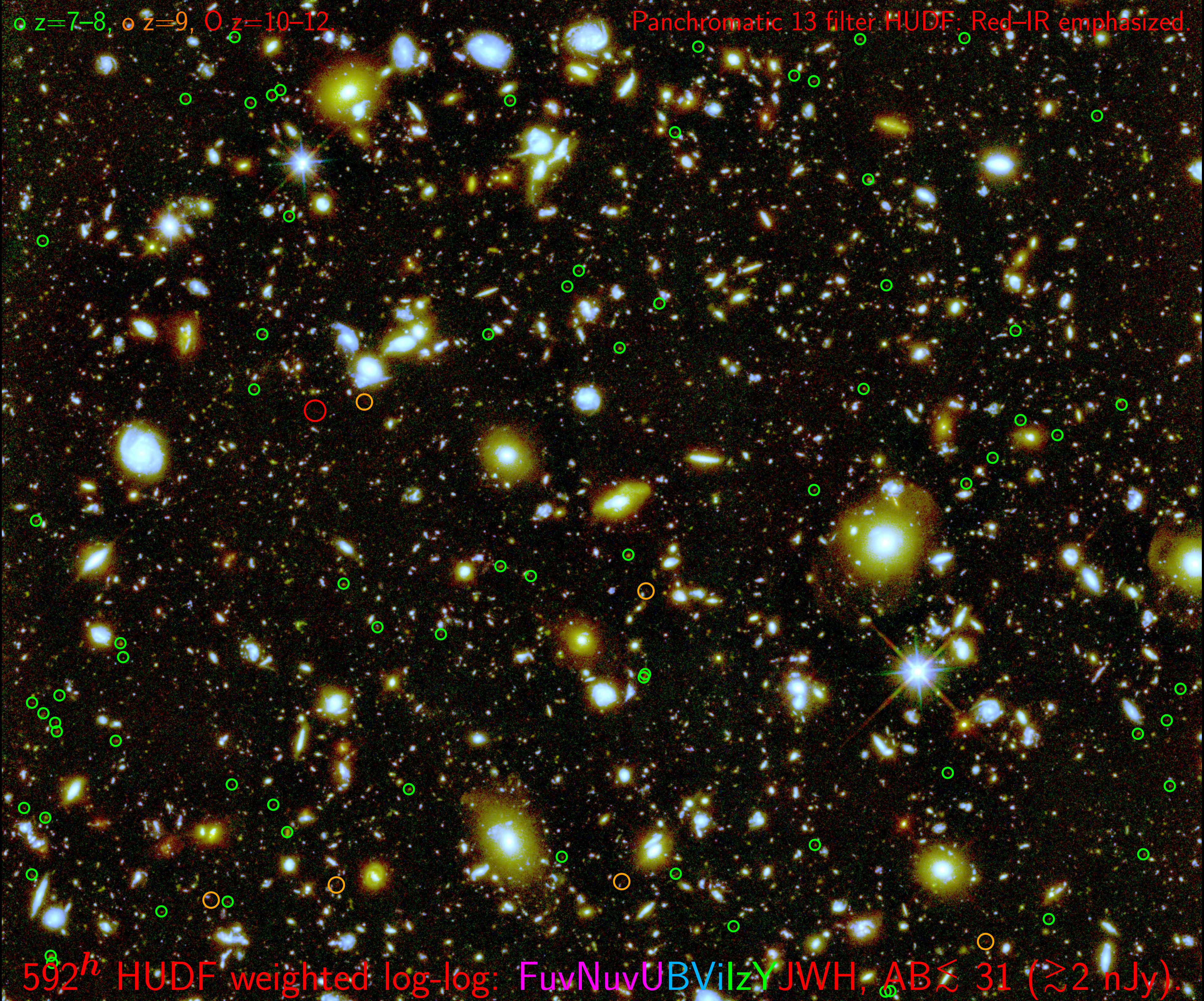
- Can't beat redshift: to see First Light, must observe near–mid IR.

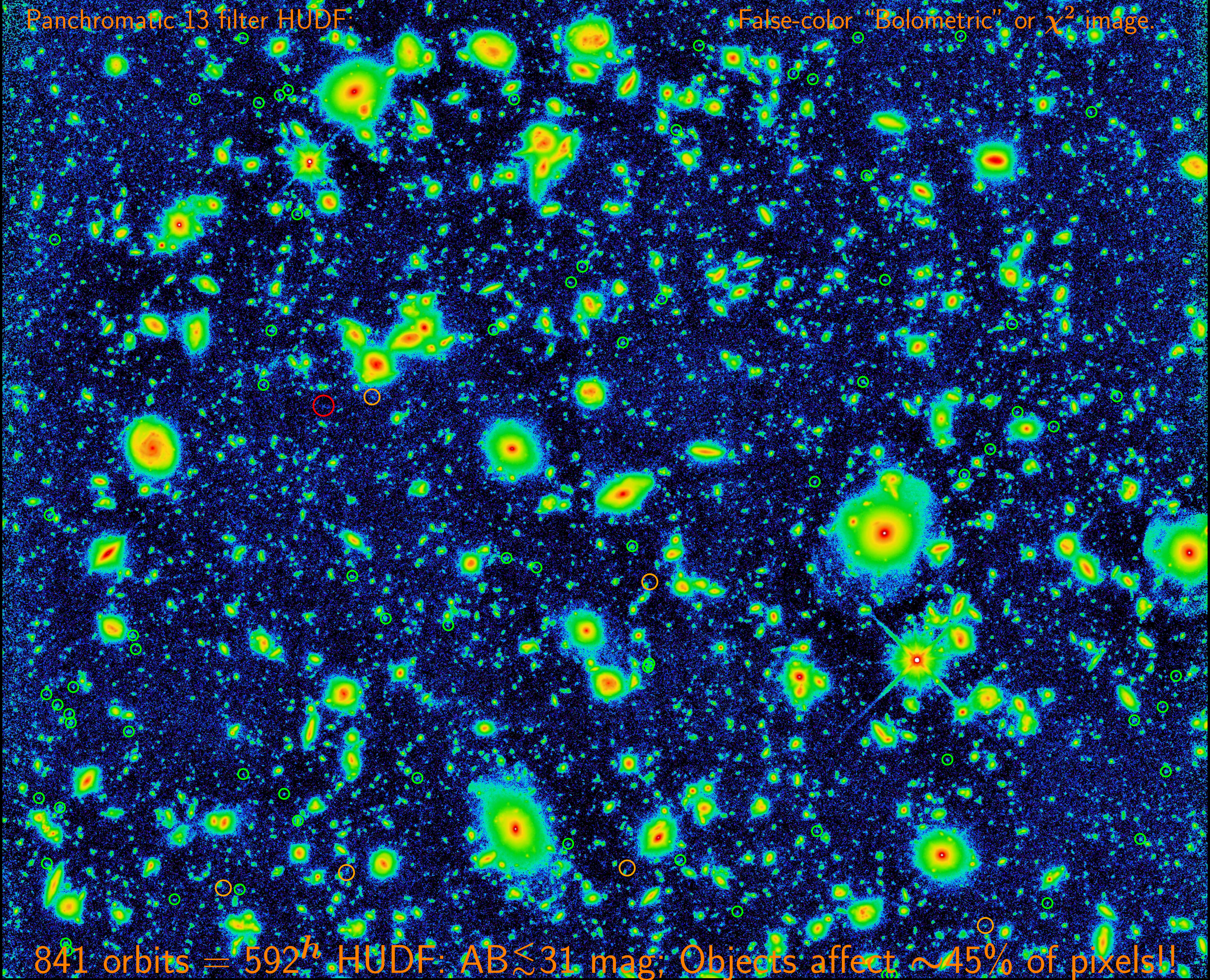
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

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

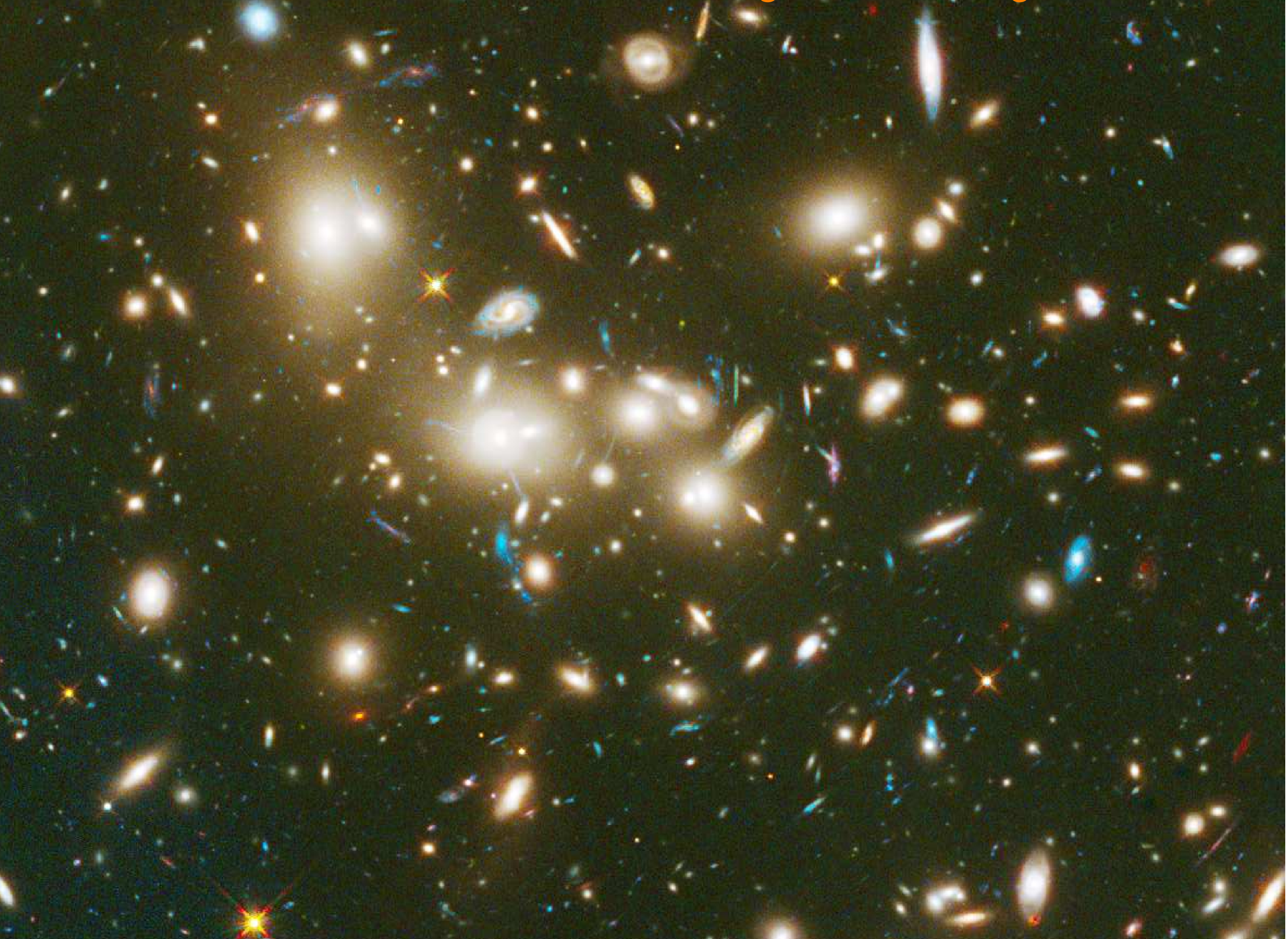


592^{h} HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).


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$\lesssim$ 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).

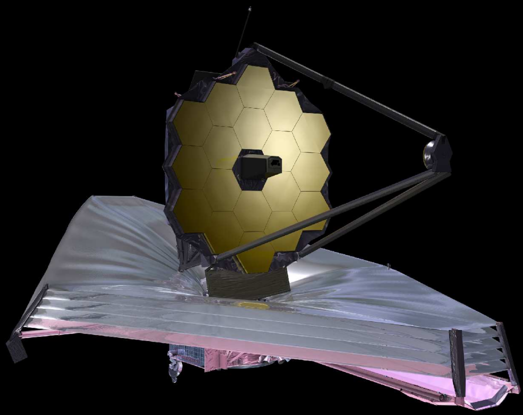
(2) Cannot-see-the-forest-for-the-trees effect ["Natural Confusion" limit]: Background objects blend into foreground because of their own diameter.

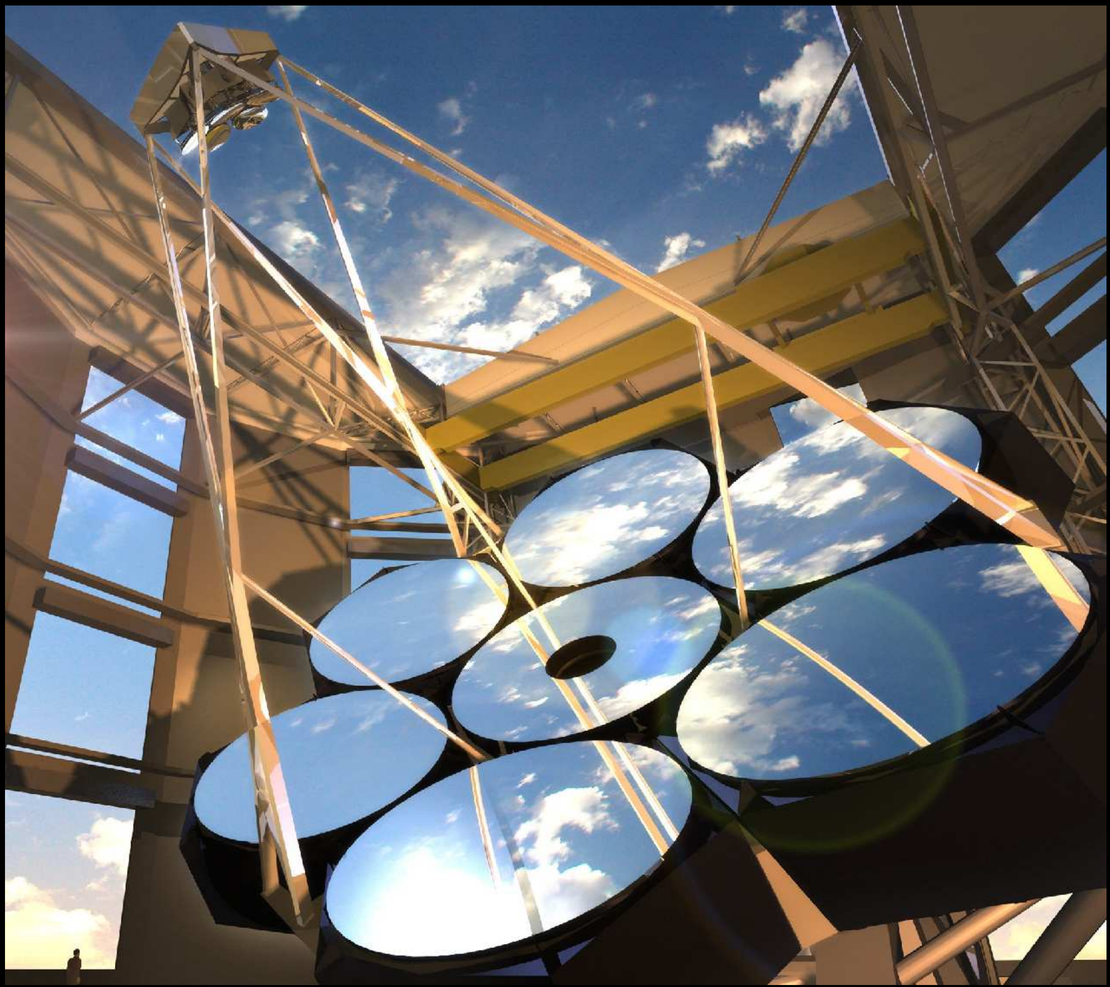
(3) House-of-mirrors effect ["Gravitational Confusion"]:

- 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



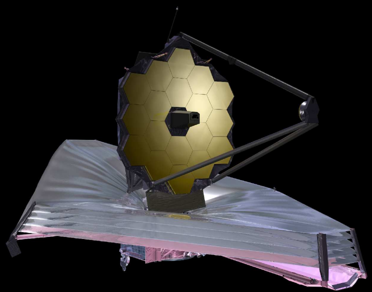


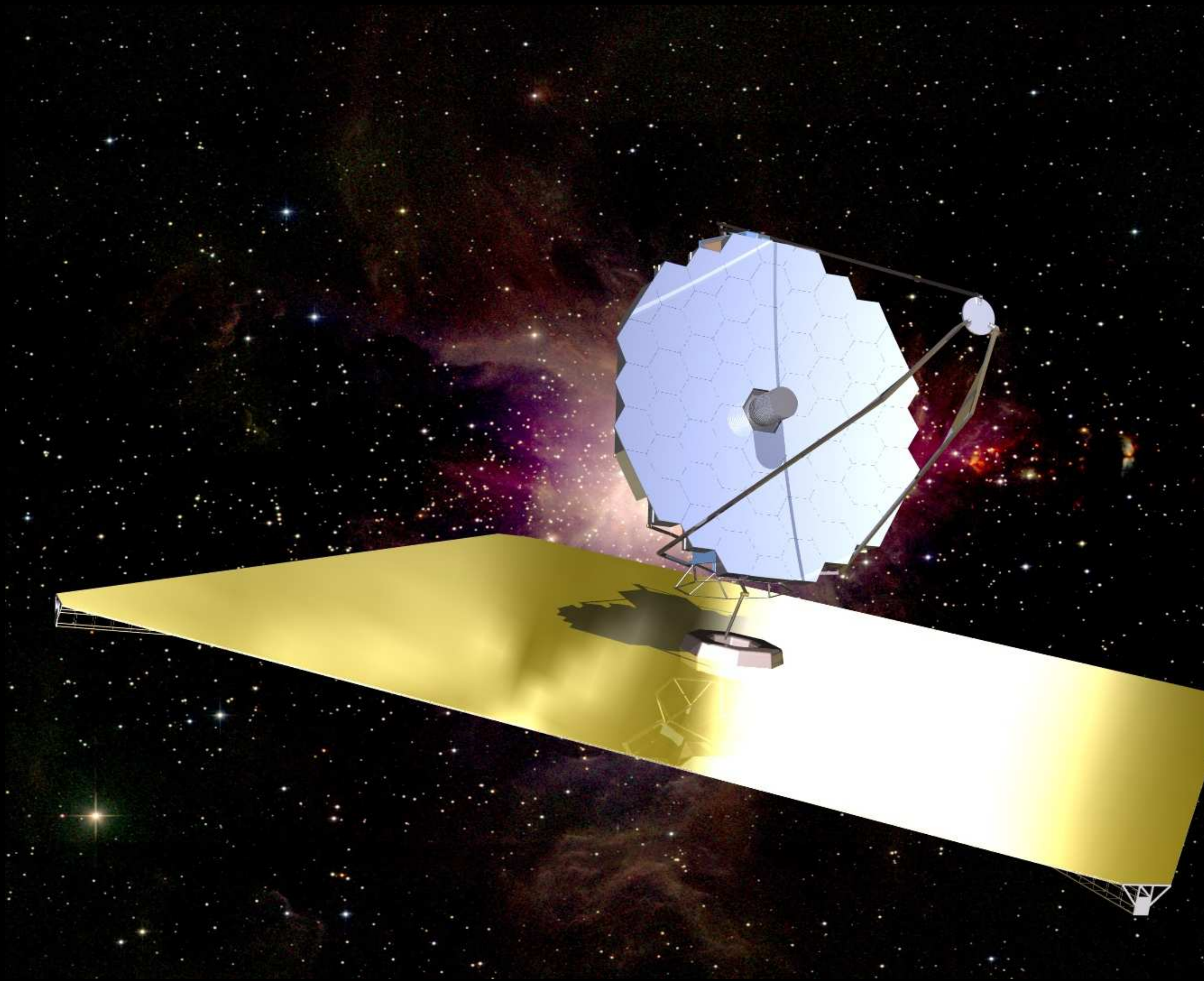
(1973∼2020^{+}); (1996∼2031); (2000∼2050^{+}).

- 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 ...





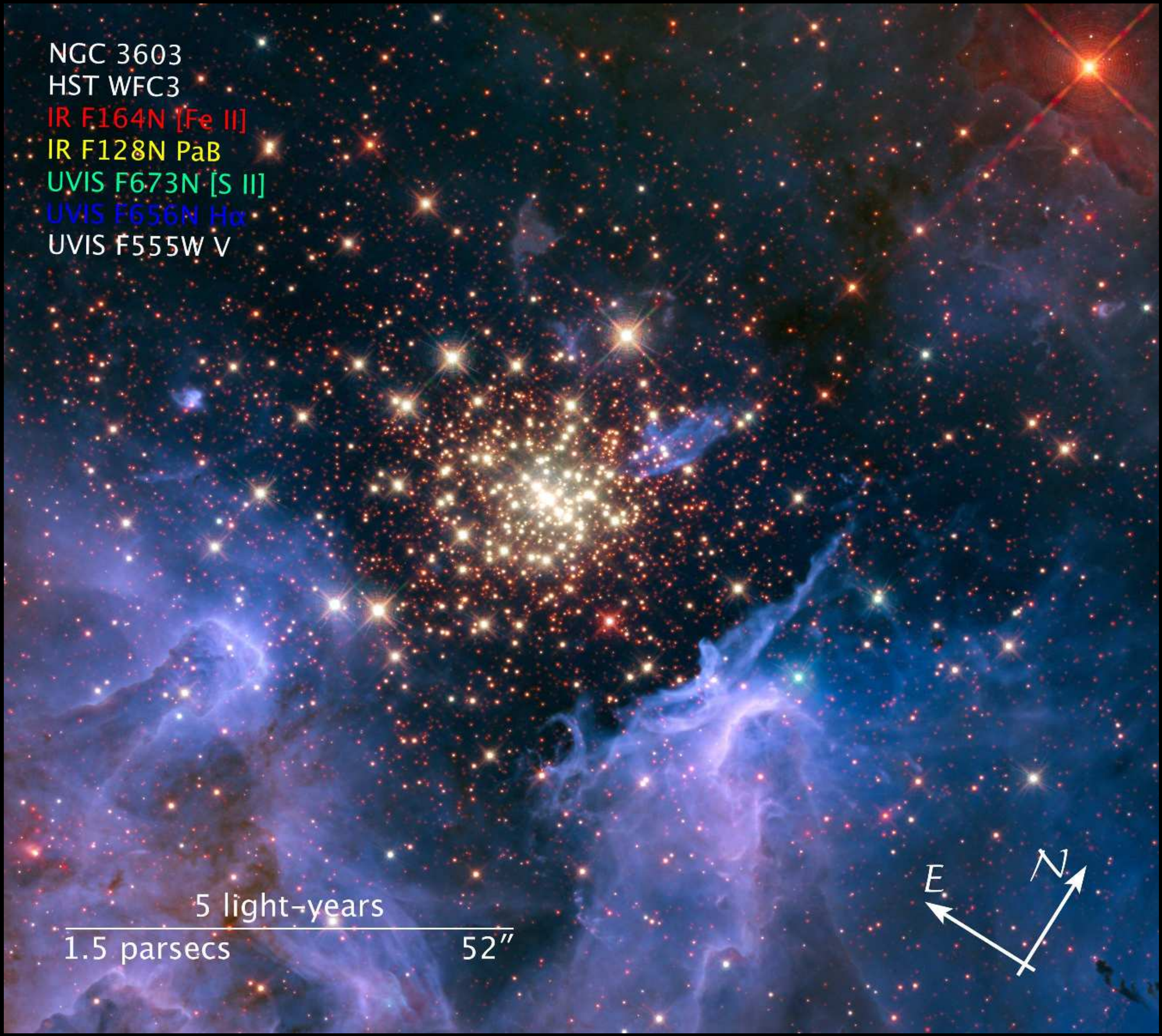
(1973∼2020$^+$); (1996∼2031); (2020∼2050$^+$?).

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

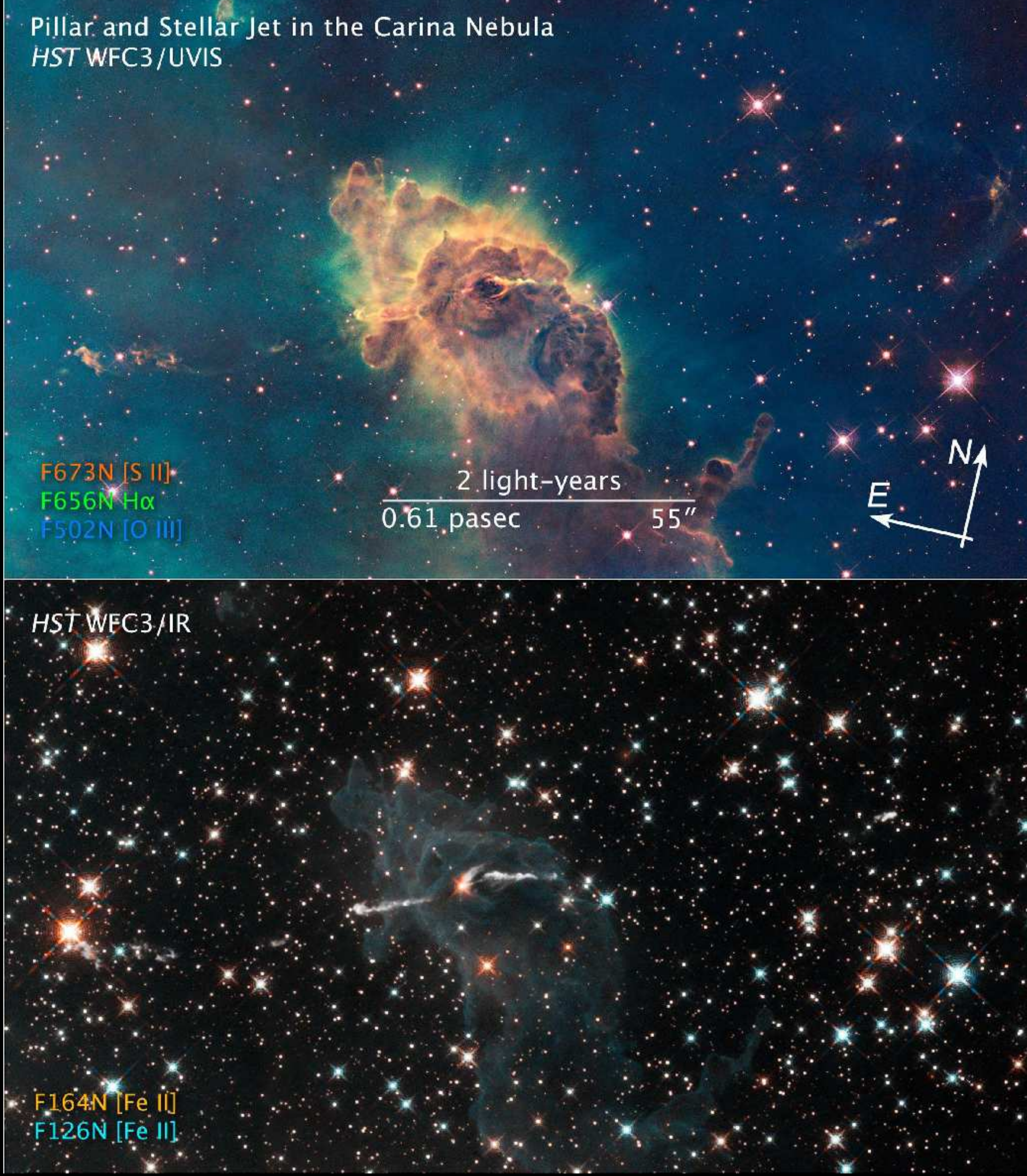
Each of GMT and ATLAST facility nearly fills the whole Yankee ballpark ...

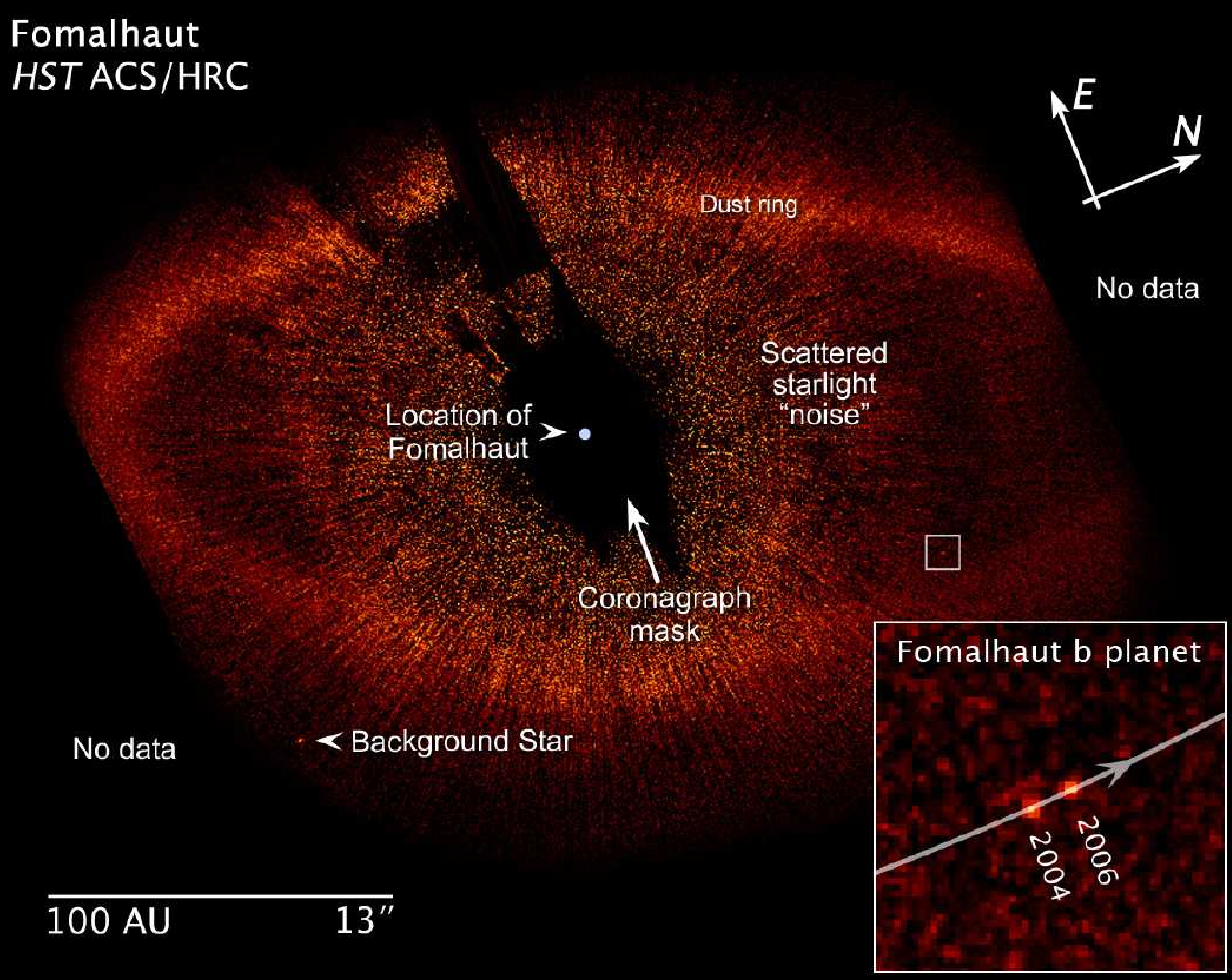
- New paradigm: They are too large for an individual university to take on.
  - Universities need to collaborate nation-wide to make this happen.

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



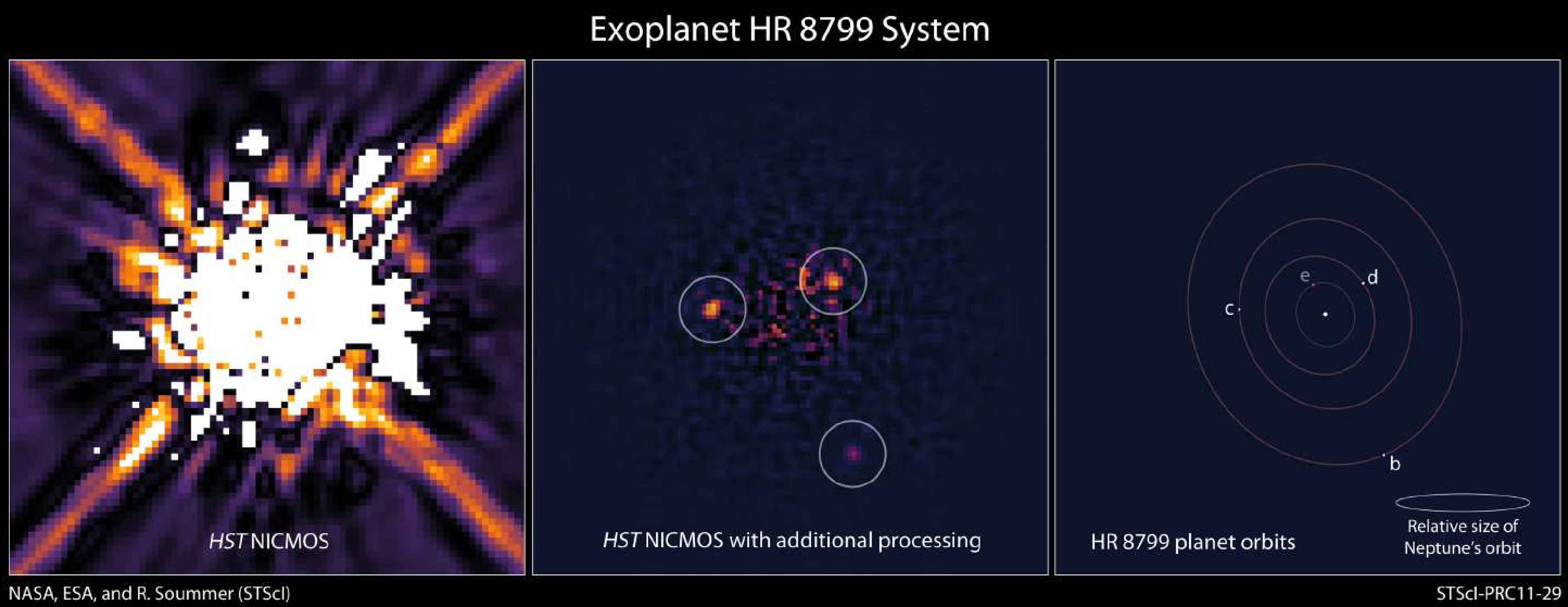
NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"


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!

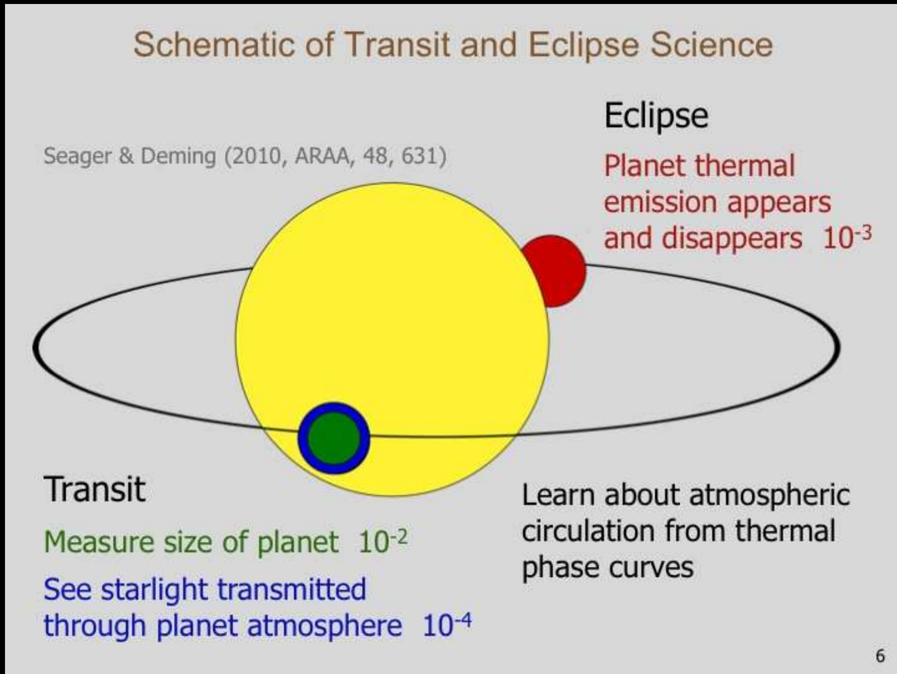
JWST can find such planets much closer in for much farther stars.

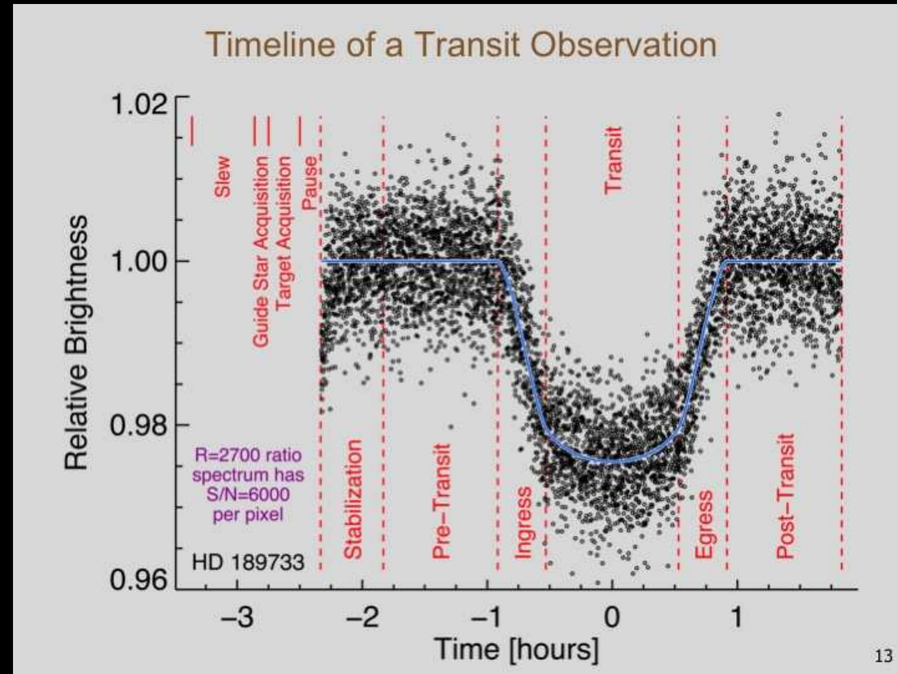


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

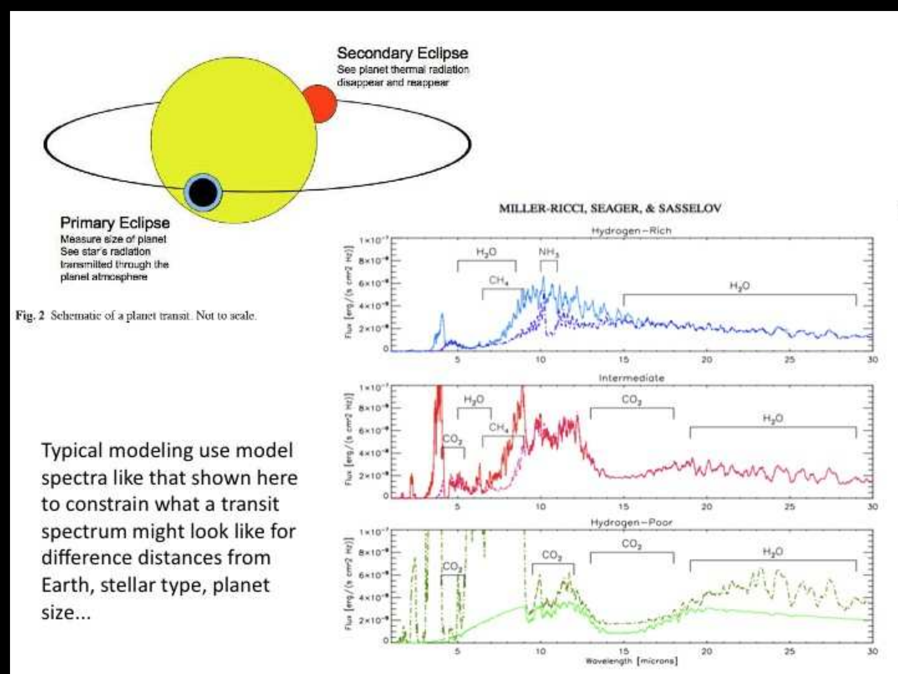
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



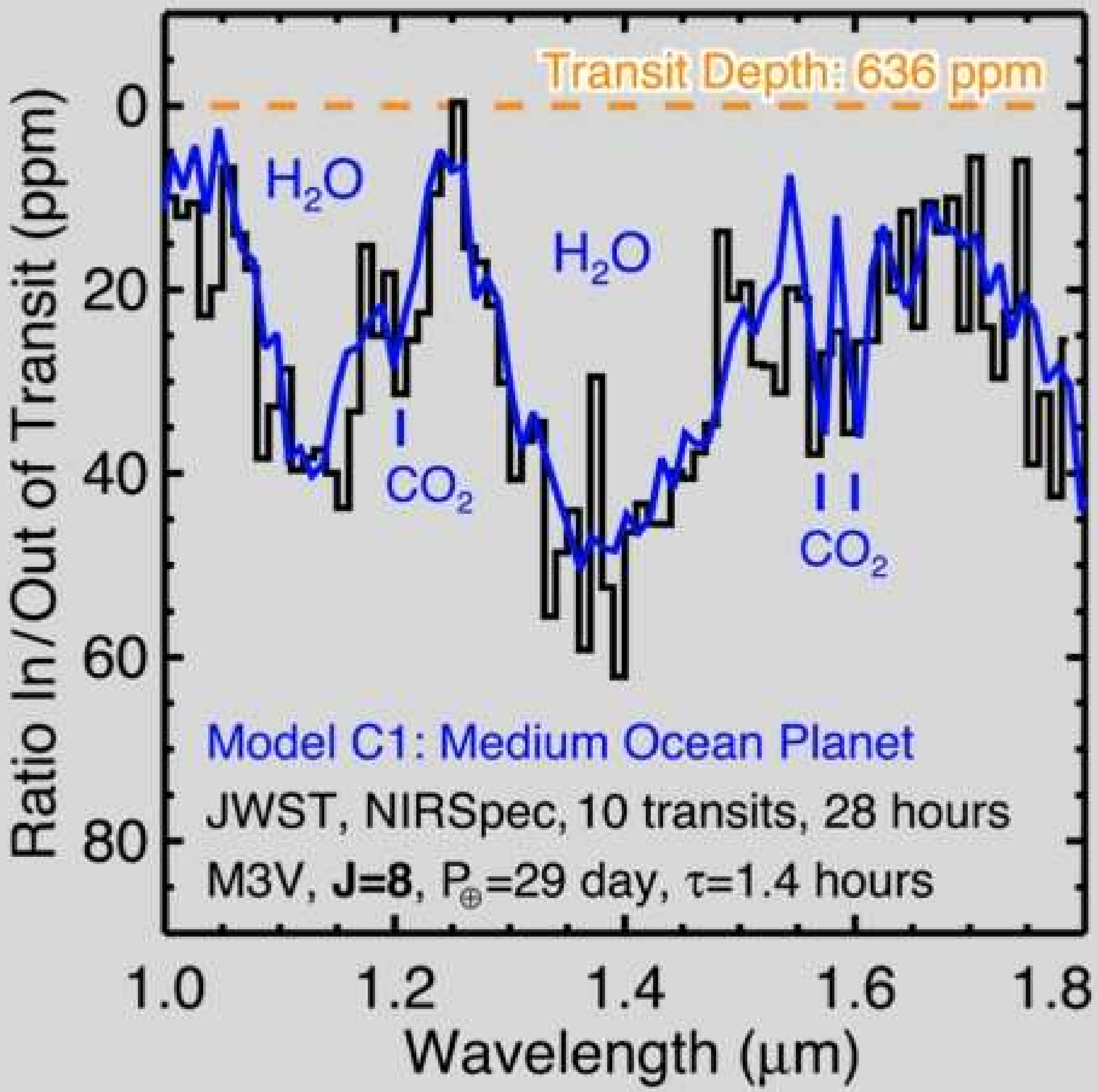


JWST can do very precise photometry of transiting Earth-like exoplanets.

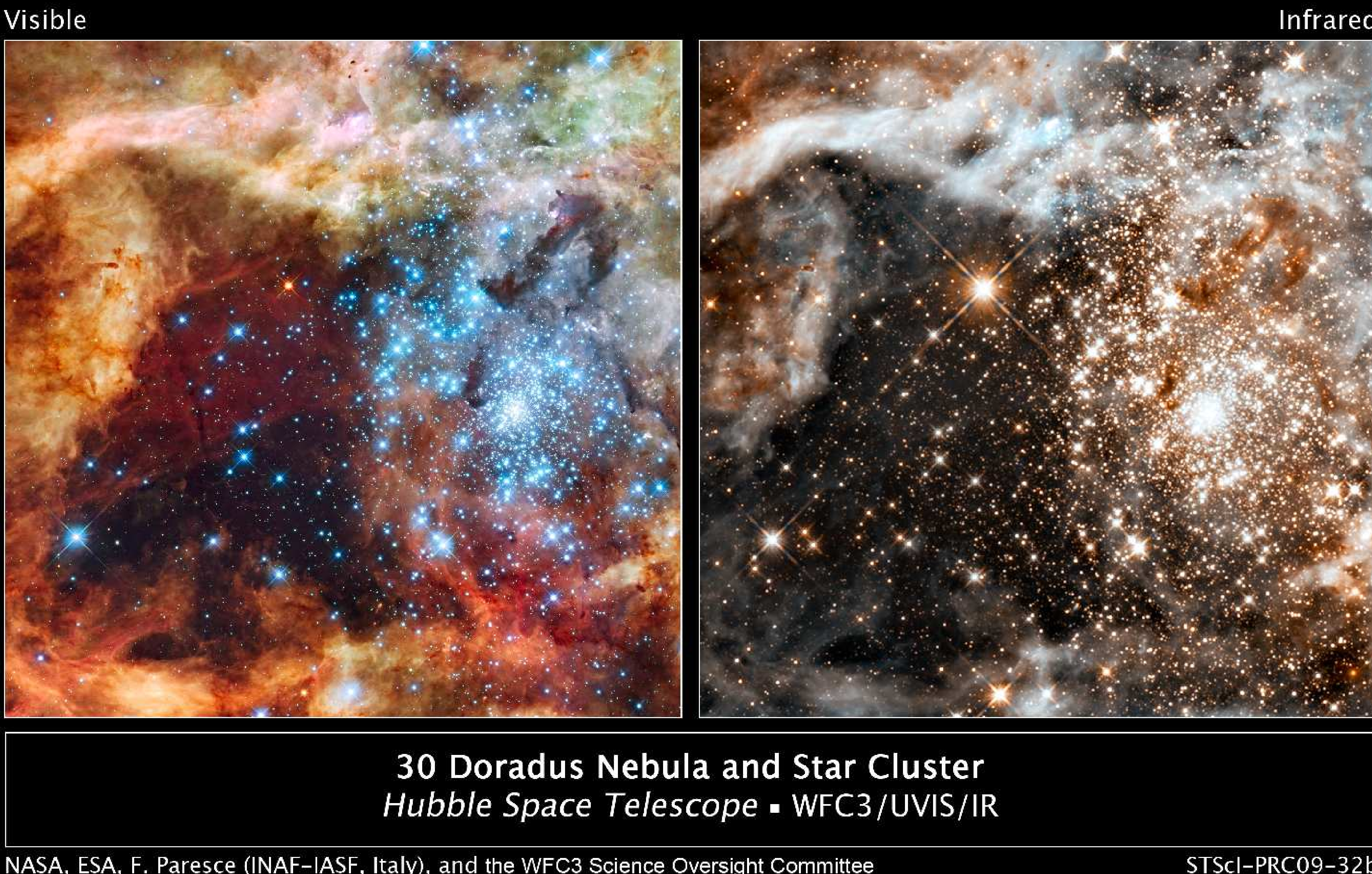


JWST IR spectra can find water and CO_2 in (super-)Earth-like exoplanets.

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).

(6) 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

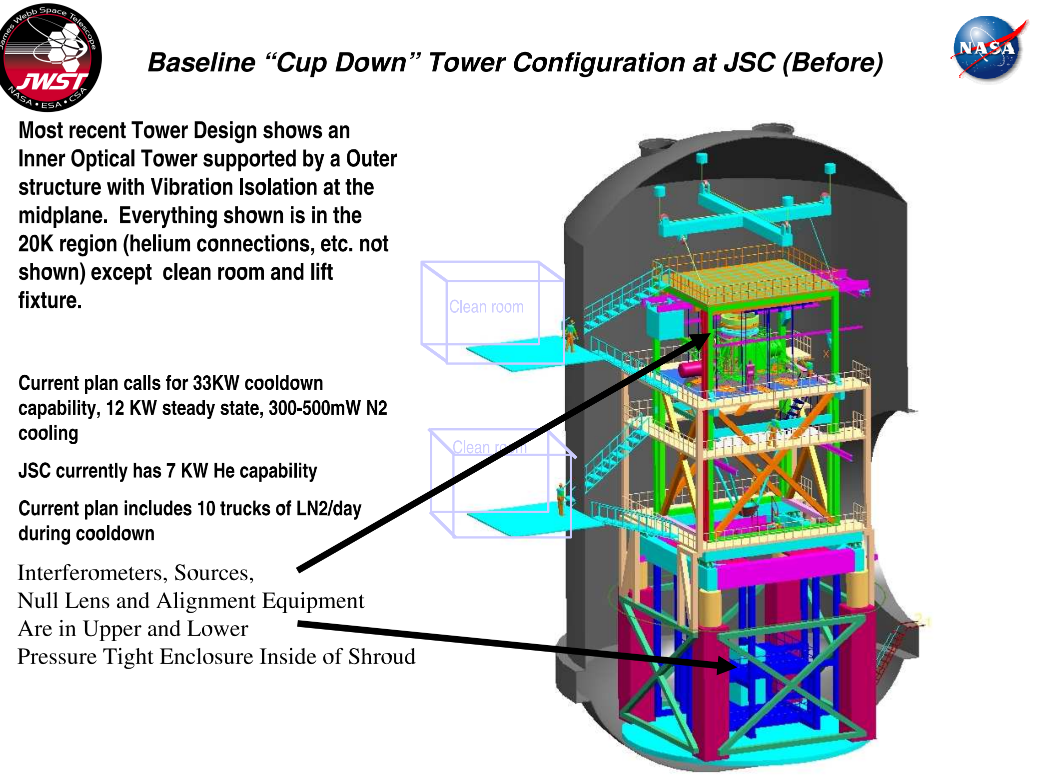
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

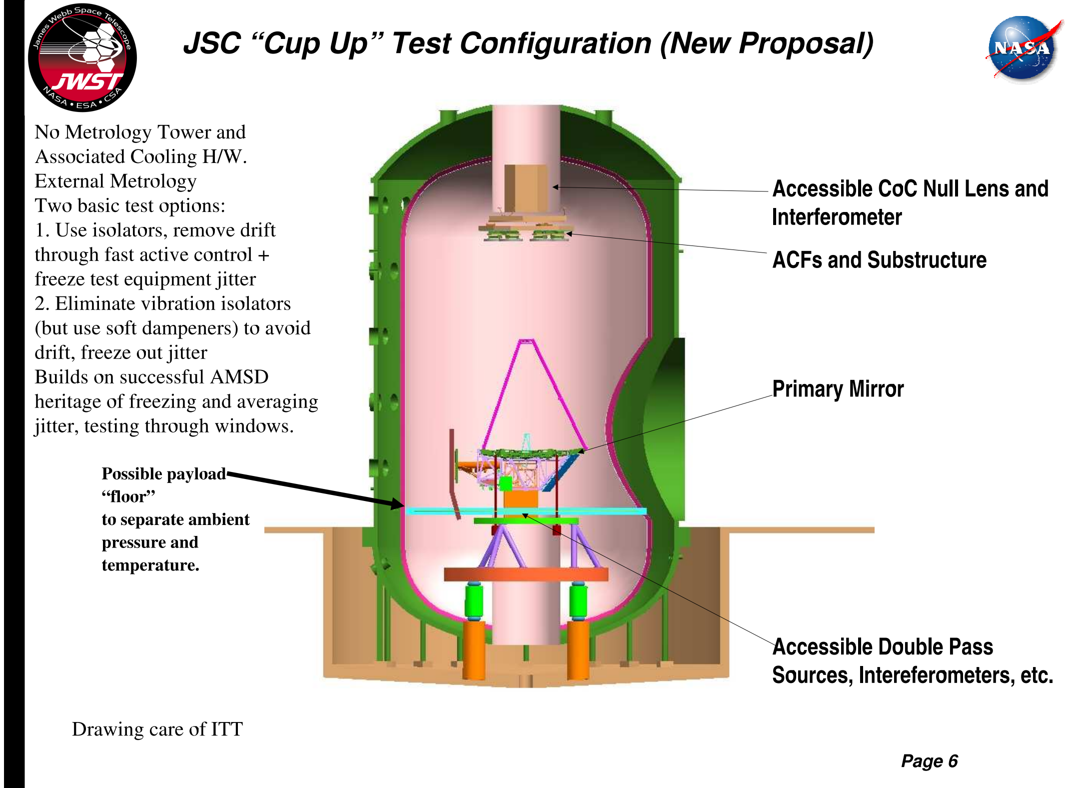
Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

• (7) Update of JWST programmatics as of 2021

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

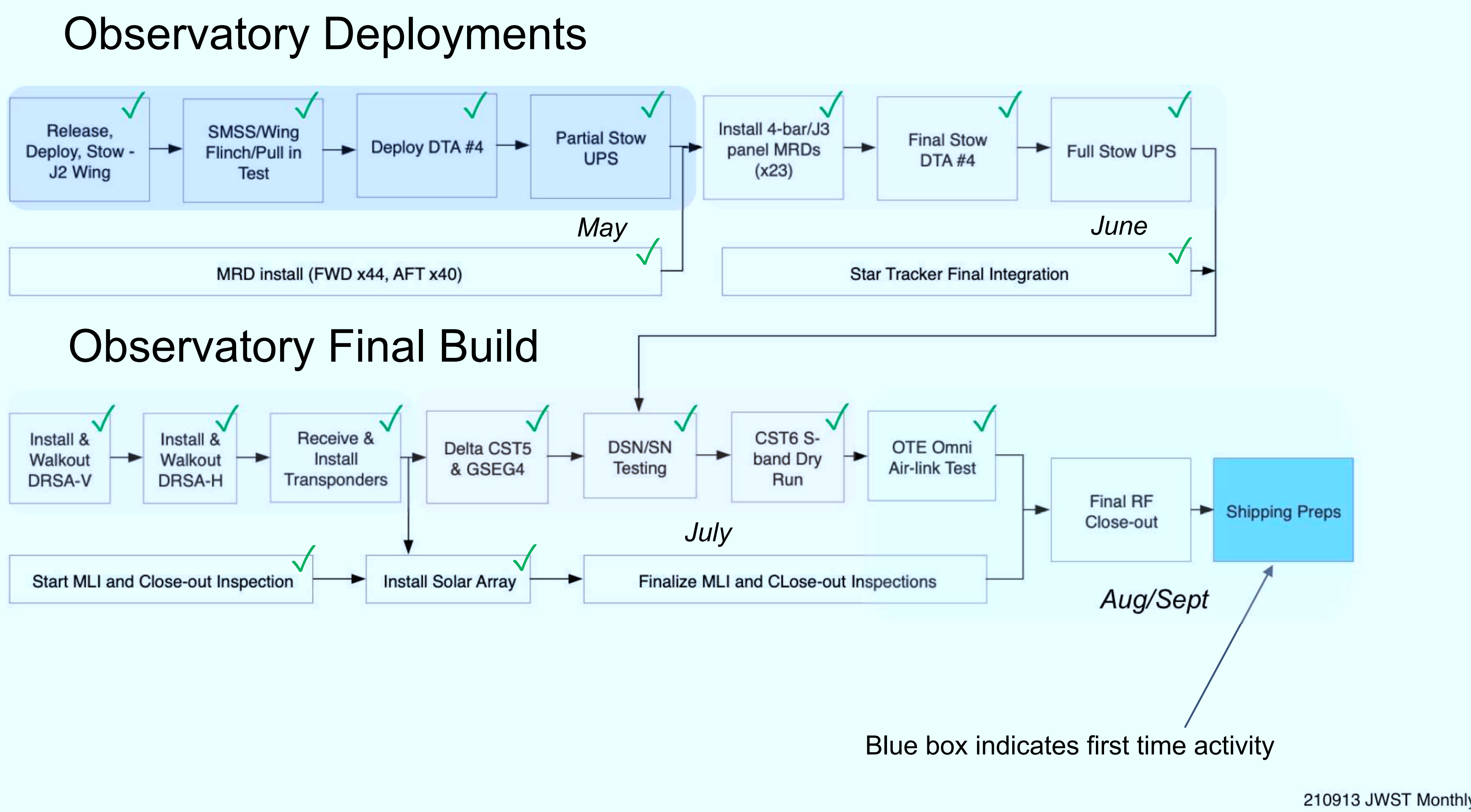




JWST underwent several significant replans and risk-reduction schemes:

- $\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 $\Rightarrow$ Fall 2021 launch.

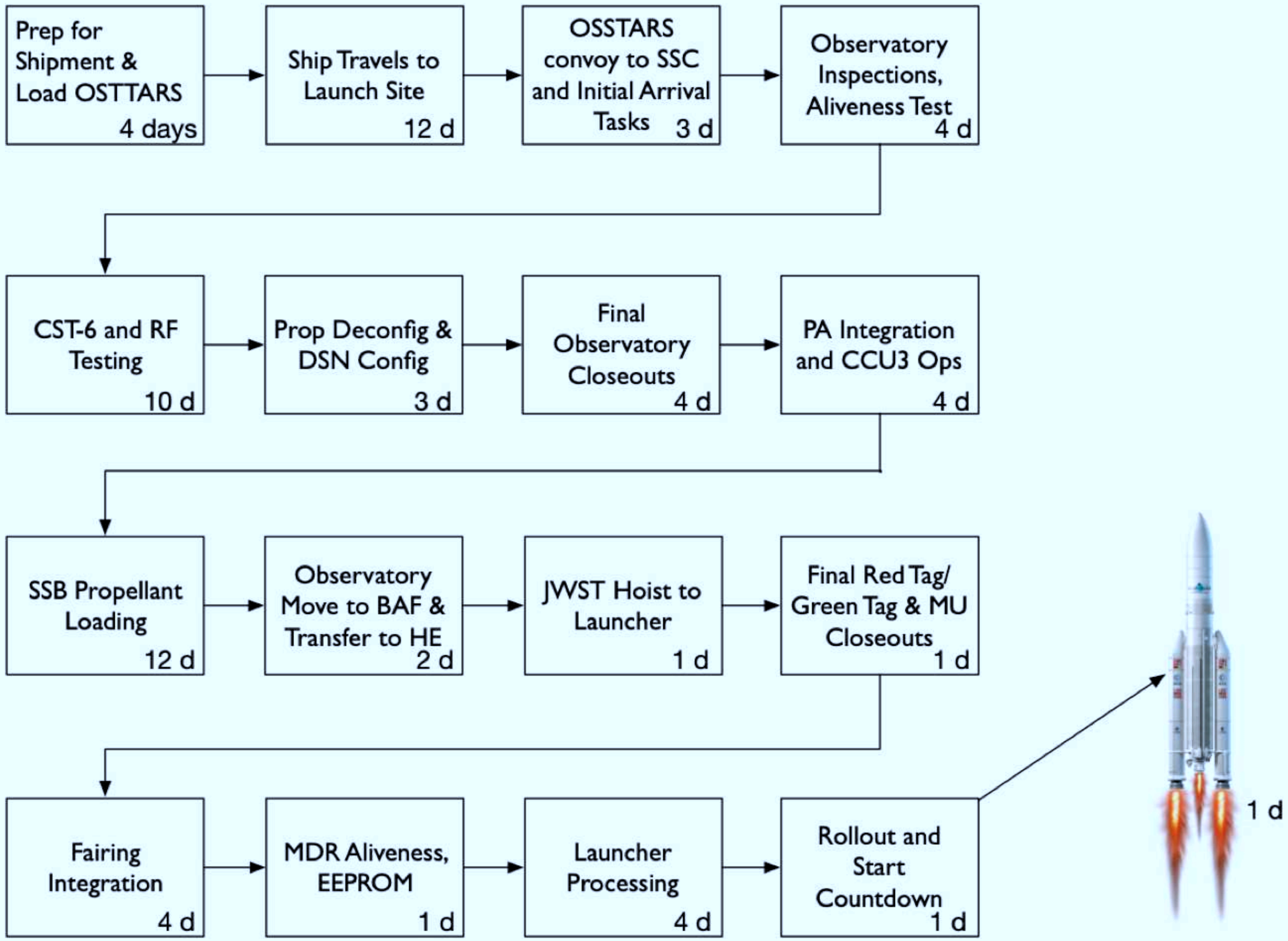
Remaining I&T Steps



Flowchart of Project tasks for FY21.

Blue = First-time operation (all others done before at sub-system level).

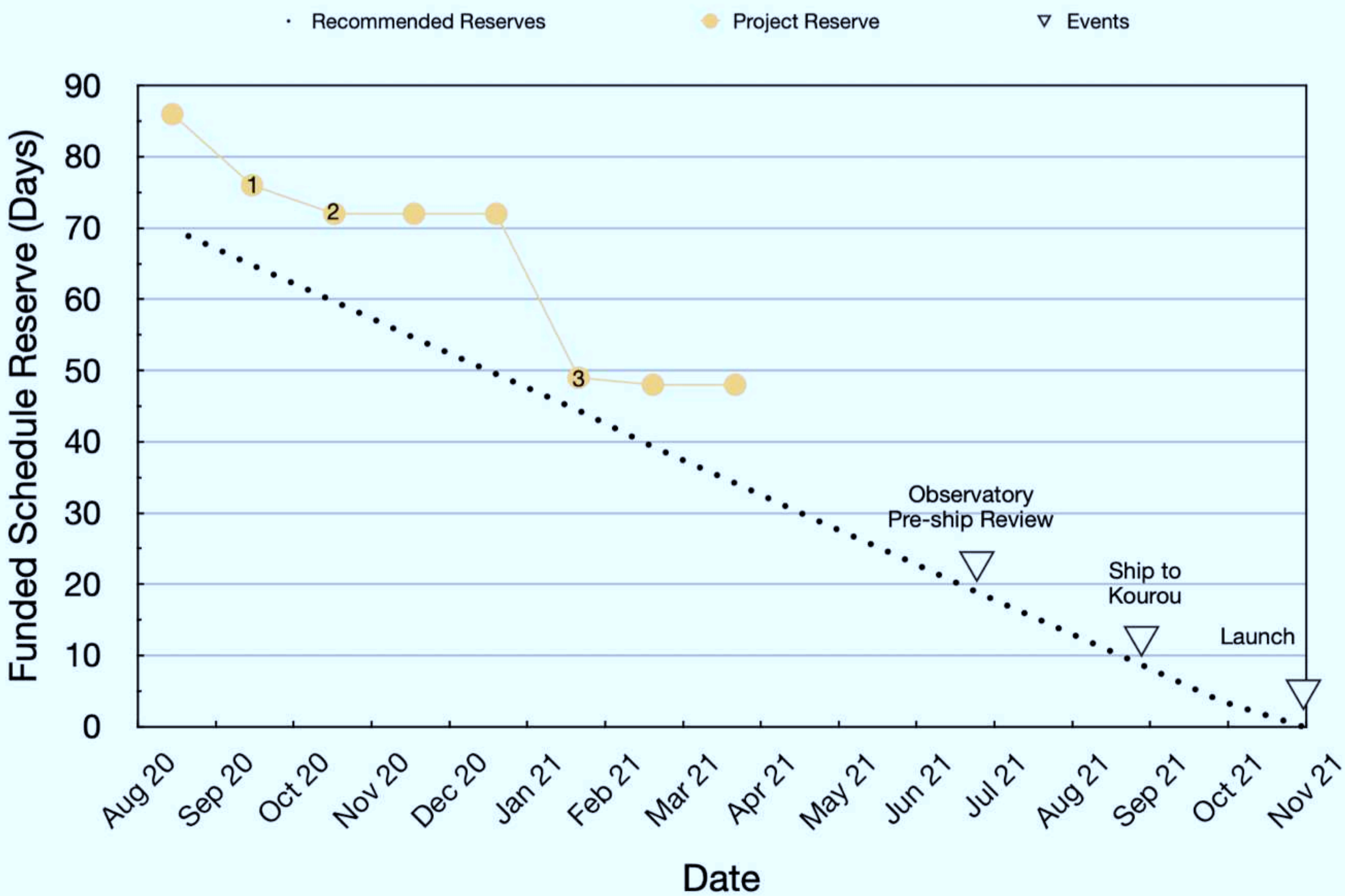
Kourou Activities



2108

Flowchart of ESA and Project tasks at Kourou (French Guyana).

Current Funded Schedule Reserve



Reserve uses: (1) Bldg M4 issues, additional Z-axis vibe run, (2) Ka-band measurements, APCO adapter (3) Planned sunshield repairs and patching

Project reserves in Spring 2021 for launch in Fall 2021.

Fiscal Year 2021 JWST HQ Milestones

Month		Milestone	Comment
Oct-20	1	Complete Observatory Envronmental Testing	Completed 10/2/20
Nov-20			
Dec-20	2	Complete Post Environmental Testing Spacecraft Bus Deployments	Completed 11/12/20
Jan-21	3	Complete Post Environmental Testing Sunshield Deployments	Completed 12/16/20
Feb-21	4	Complete Comprehensive System Test #5	Completed 2/13/21
Mar-21	5	Complete Cycle 1 Geneal Observer Proposal Reviews	Completed 3/30/21
	6	Sunshield Fold Complete	Completed 4/6/21
	7	Launch Readiness Exercise #2	Completed 3/8/21
Apr-21			
May-21	8	Final Deployable Tower deployment	Completed 6/8/21
Jun-21			
Jul-21	9	Final Observatory Stow Complete	Completed 7/15/21
	10	Observatory Pre-Ship Review	Completed 7/29/21
	11	Launch Readiness Exercise #4	Completed 6/22/21
Aug-21	12	Operational Readiness Review	
	13	Ship Observatory to Launch Site	
Sep-21			

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

Milestones left to go as of Summer 2021.

Operational Readiness Review passed in Aug. 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 mo due to Oct 2013 Government shutdown.

FY15: Most "Lates" not on critical path.

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

Commissioning At A Glance

Commissioning begins at launch and is ~180 days long, including the following key events:

1. Launch and Ascent – power positive, safe attitude, and communications established
2. Mid Course Correction – MCC1 (a and b) corrects launcher dispersions for proper L2 trajectory
3. Deployments
4. Cool-Down/Cryo-Cooler Activation
5. Mirror segment deploy and wave-front control
6. Science Instrument calibrations and checkout

Items 1–3: Launch and Deploy Phase

Items 4–6: Cool-Down/OTIS Phase

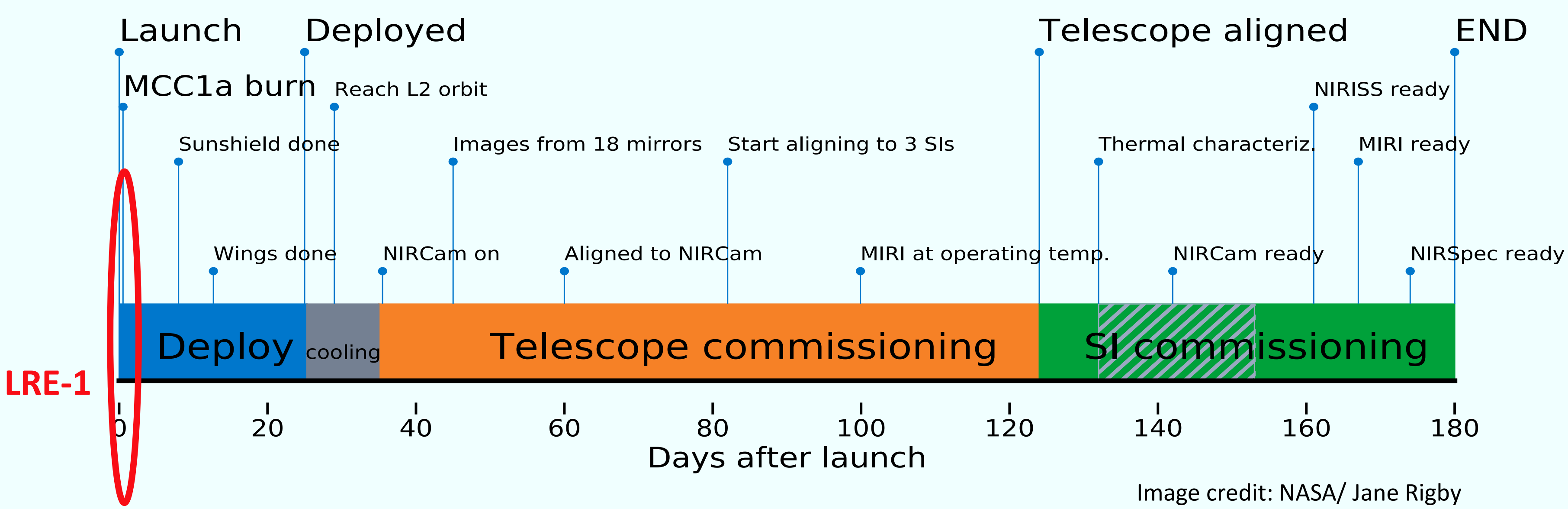
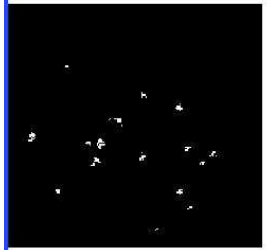
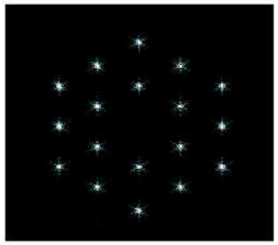
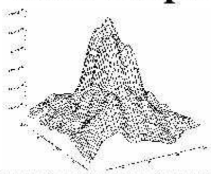
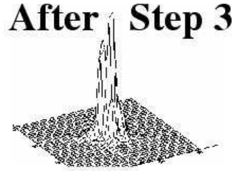
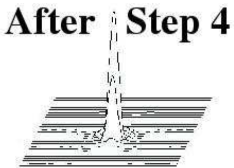


Image credit: NASA/ Jane Rigby

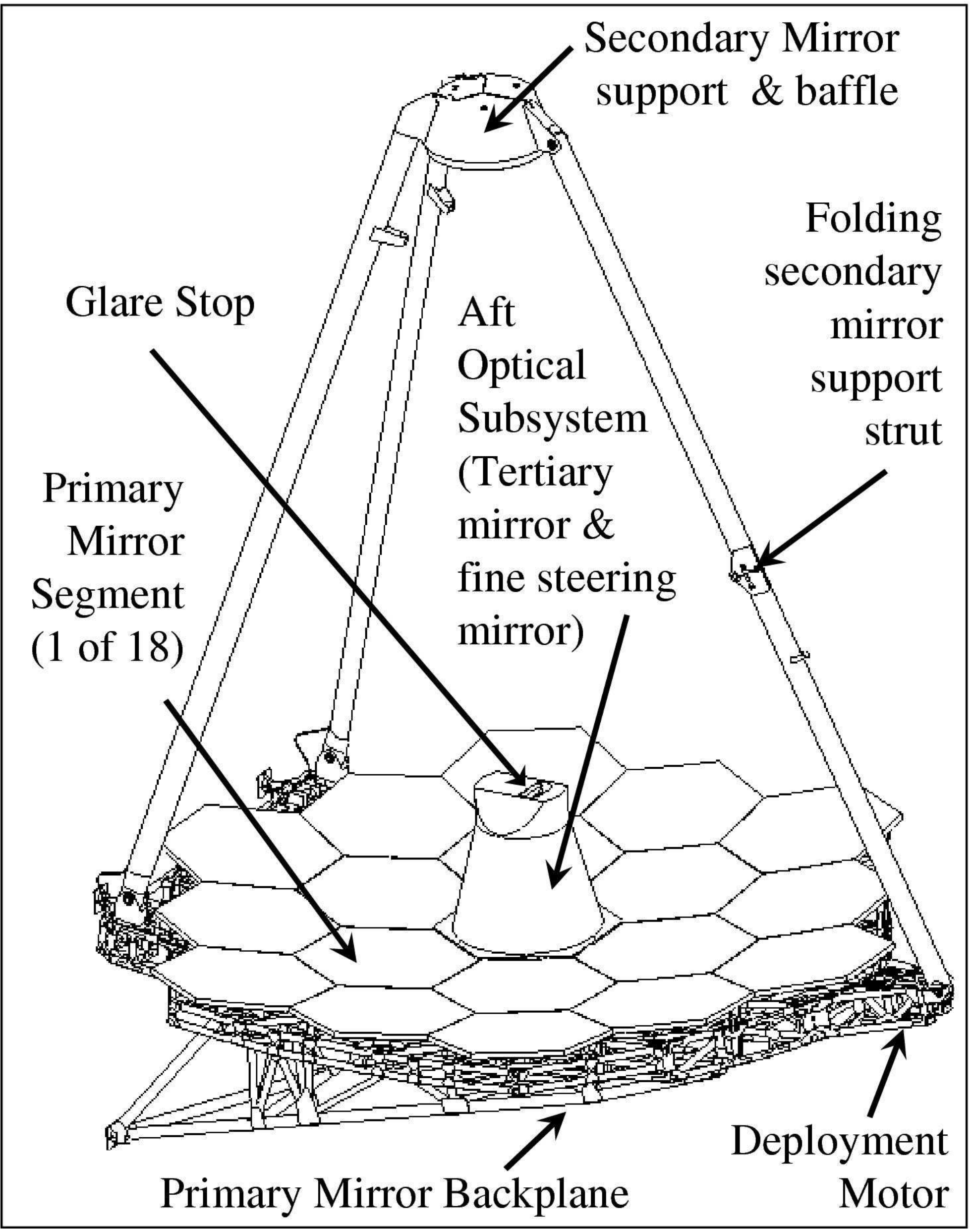
201109 JWST Monthly

JWST Commissioning Plan after launch from Kourou in Fall 2021.

		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)

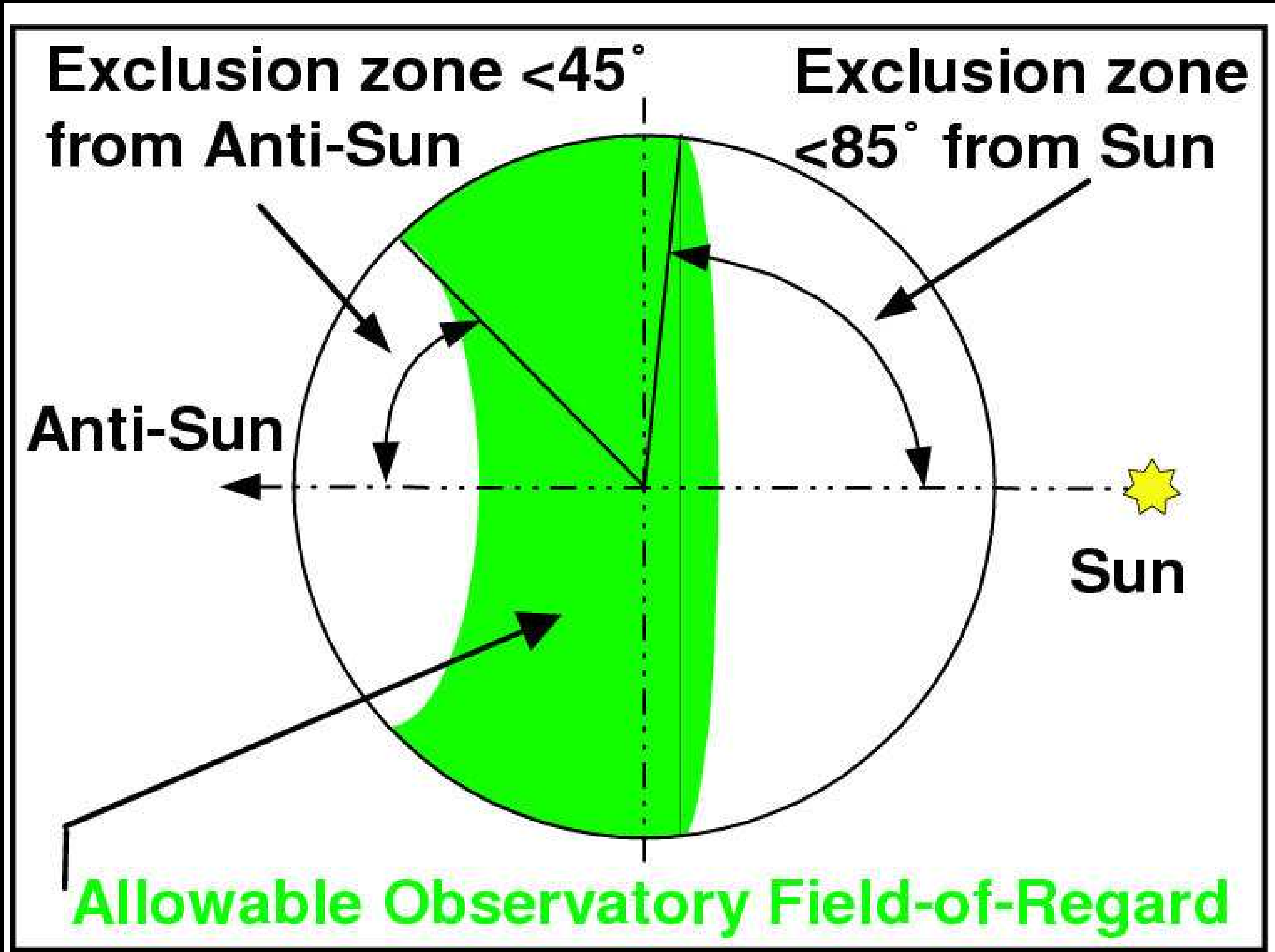
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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.

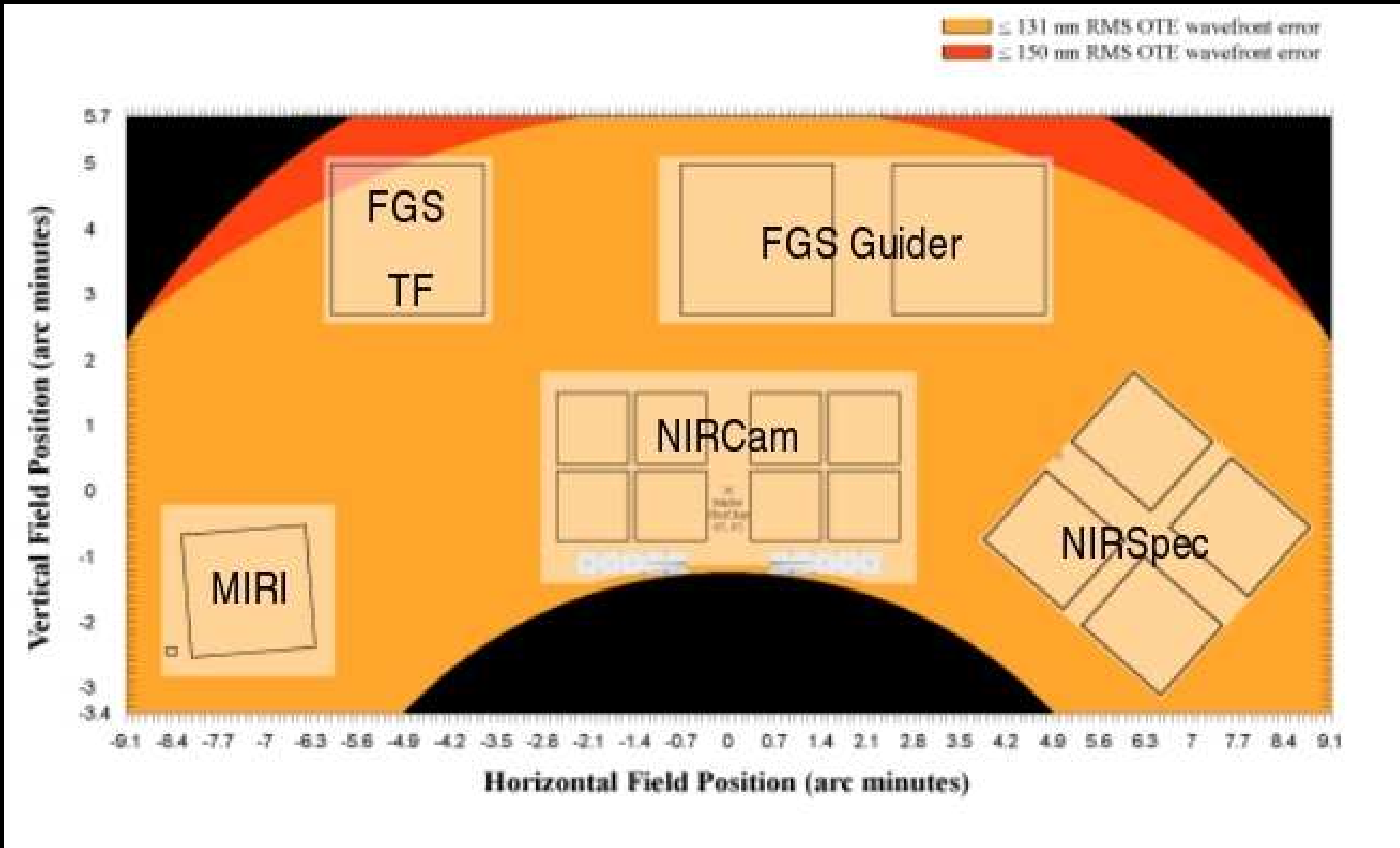
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.



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.*

(8) What do our Astrophysics College Graduates do? Future Careers at NASA:

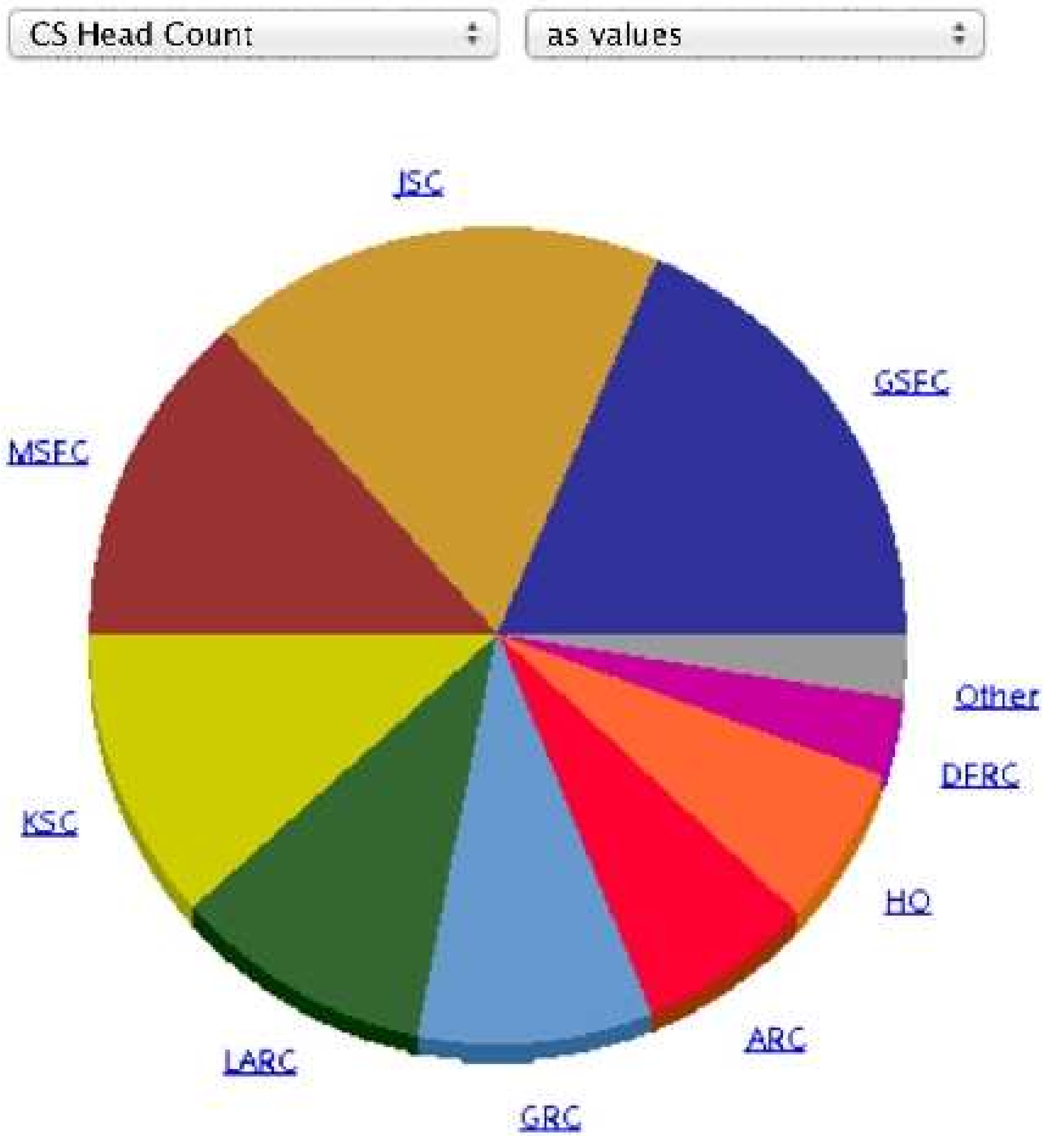
- Over the last 25 years, (ASU) Astrophysics College Graduates typically:
- (0) Have very low unemployment ($\lesssim$few %).
- (1) About 30% are faculty at Universities or 4-year colleges.
- (2) About 30% are researchers at NASA or other government centers.
- (3) About 20% work in Aerospace or related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

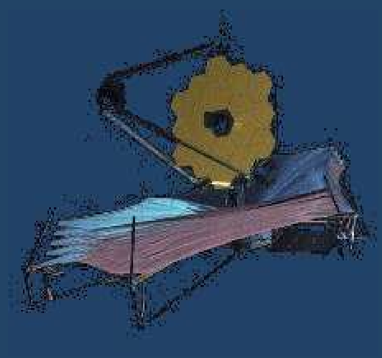
Nation-wide NASA contractors (Northrop, Lockheed, Boeing, etc): 150,000.

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.



JWST as a Time-Domain Science Facility

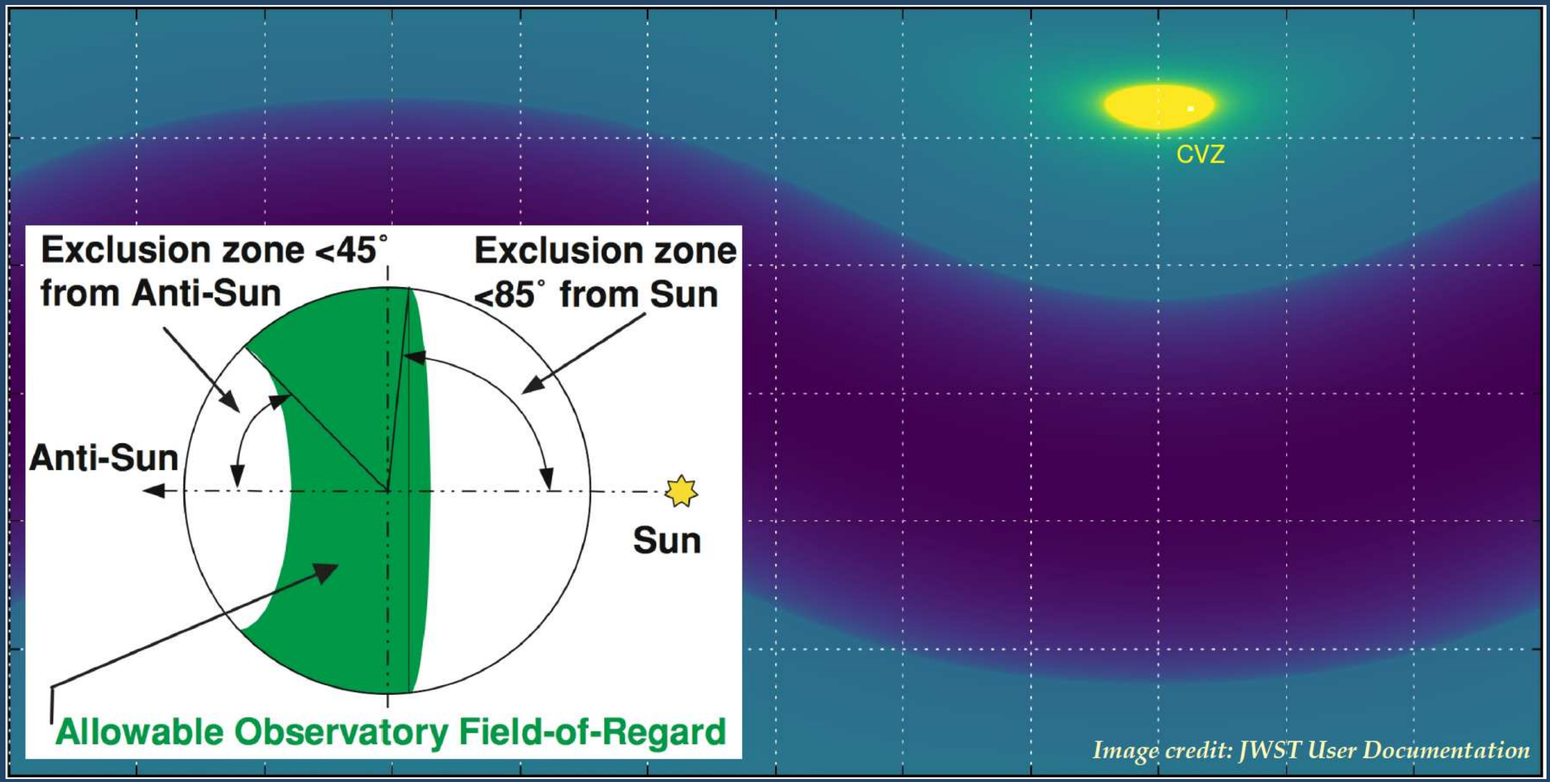
- **Advent of the era of deep, large area (survey) time-domain science (relatively faint objects with, e.g., PanSTARRS, *Rubin*/LSST, *Roman*)**
  - **Solar System**
  - **Galactic neighborhood (and beyond)**
  - **Objects at cosmological distances / large look-back times**

- **Question: can *JWST* do time-domain survey science? What would it add?**
  - ***Rubin* / LSST: $m_{\rm AB} \lesssim$ 23.8 mag (10σ per 2×15 s visit; ∼15 min – 1 hr time-scales over large fraction of the sky)**
  - ***JWST*/NIRCam: $m_{\rm AB} \sim$ 26.8–28.3 mag (10σ per epoch; ∼15 min – 1 hr time-scales in a suitable survey field):**

▷ **Unexplored magnitude regime for variability studies: $m_{\rm AB} \gtrsim$ 24 mag**
  - **Supernovae (Type Ia SNe to $z \sim 5$, Core Collapse SNe to $z \sim 1.5$, Pair Instability SNe to the Epoch of Reionization); AGN; brown dwarf atmospheres**

▷ **Unexplored regime for proper motion detections: $m_{\rm AB} \gtrsim$ 24 mag, $p \gtrsim$ 0.5 mas/yr**
  - **Extreme outer Solar System objects; interstellar asteroids and comets (such as 1I/'Oumuamua or 2I/Borisov); nearby Galactic brown dwarfs and low-mass stars, and ultra-cool white dwarfs.**

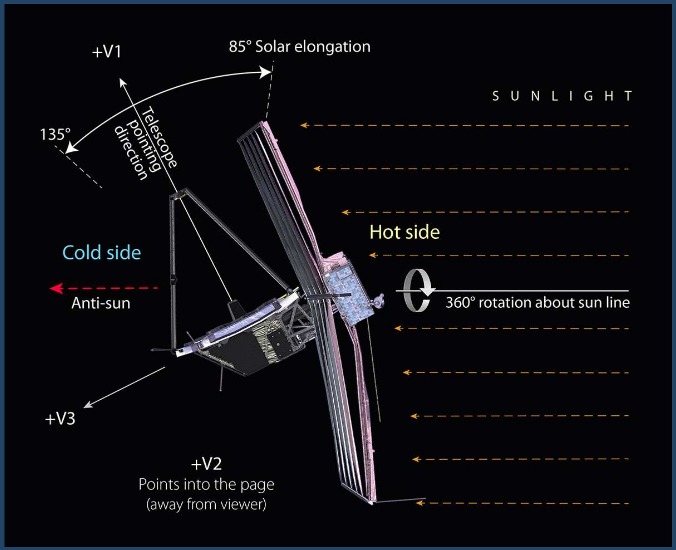
JWST Operational Restrictions = Orientation Restrictions

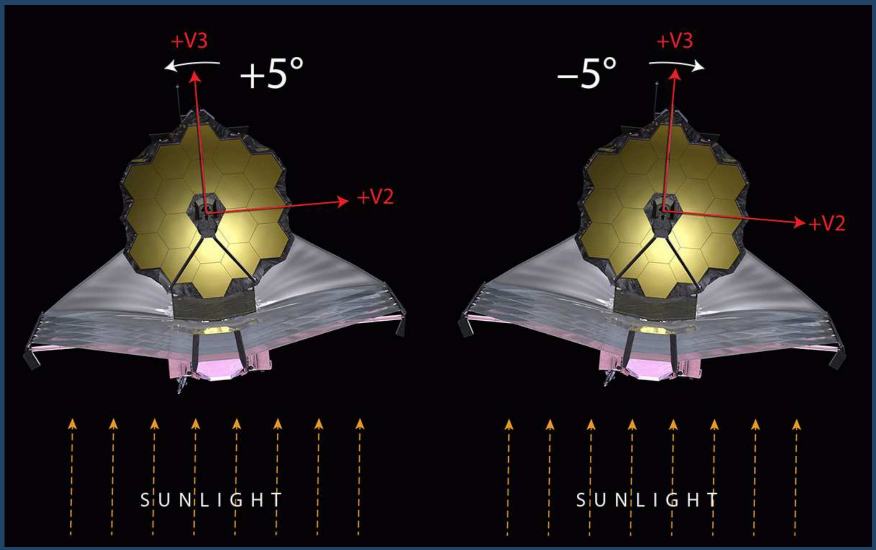


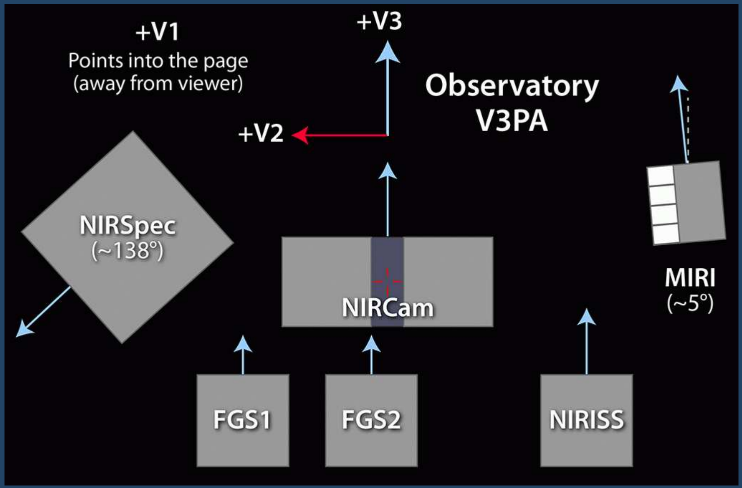
- **Sun avoidance, power generation, and shielding requirements of the cryogenic telescope restricts object visibility to two time intervals per year**

▷ **Except for objects within two small ($r < 5°$) continuous viewing zones (CVZs) centered on the North Ecliptic Pole (NEP) and the South Ecliptic Pole (SEP).**

JWST Operational Restrictions = Orientation Restrictions



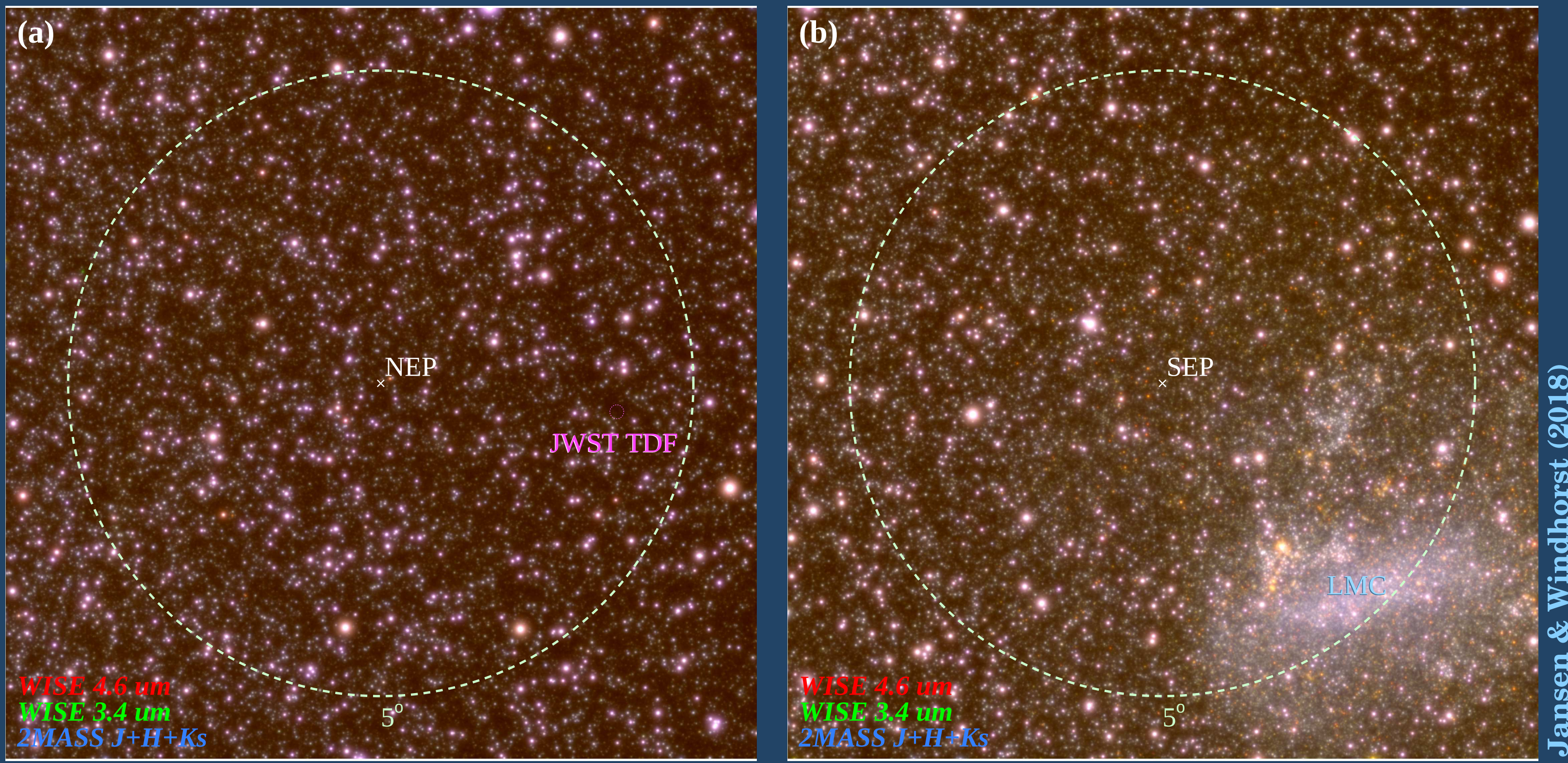




- **The date of observation dictates the orientation of the instrument foot-prints on the sky, limiting the range of possible orientations for a given object.**
  - **Except for objects located within *JWST*'s CVZs.**

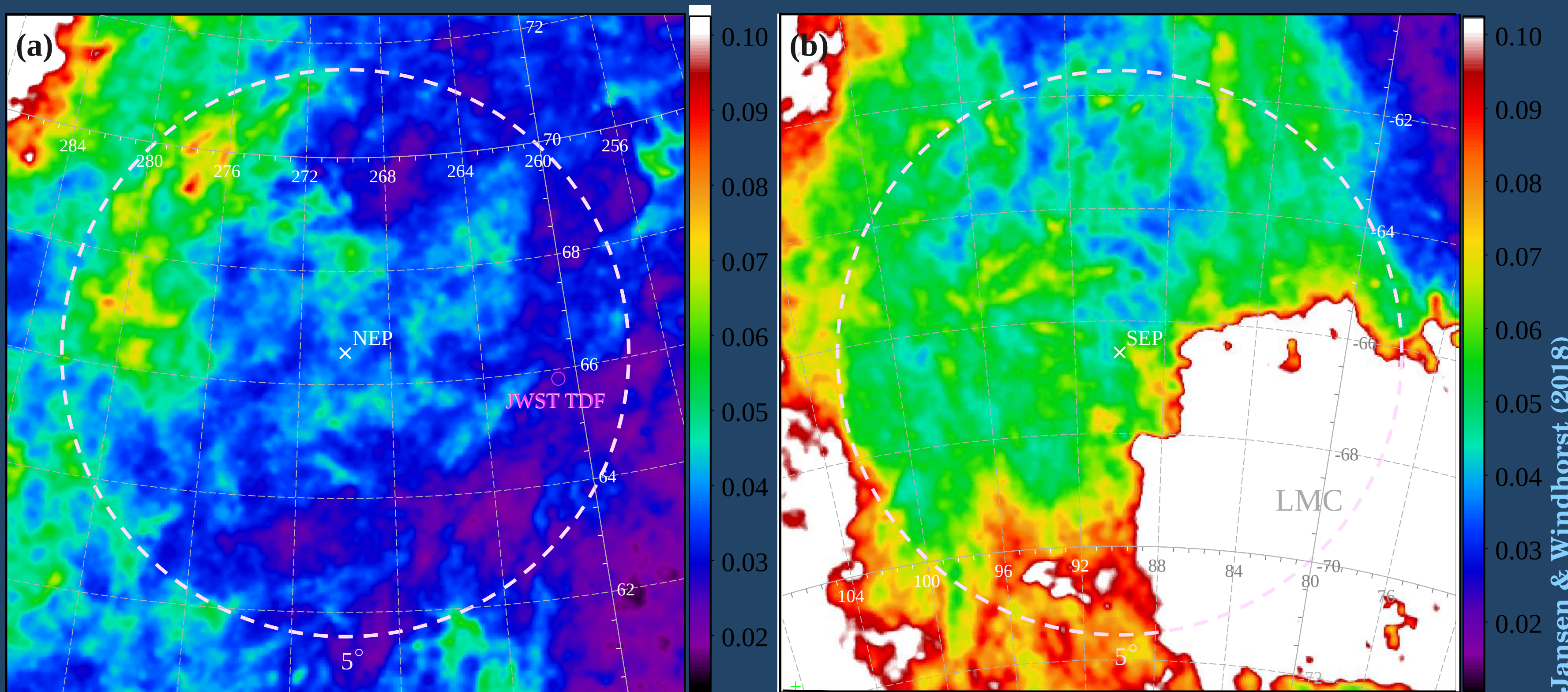
NASA / JWST User Documentation

JWST's Northern and Southern CVZs



- ***JWST*** **Time-Domain Science on time-scales of minutes to years implies a survey field that *must* be located within *JWST*'s CVZs.**
  - ▷ **Existing, well-established, fields (e.g., from *HST*, *Chandra*, *XMM*, VLA) won't do.**
  - ▷ **Northern CVZ emptier sky than Southern CVZ (LMC and Galactic structures)**

JWST's Northern and Southern CVZs



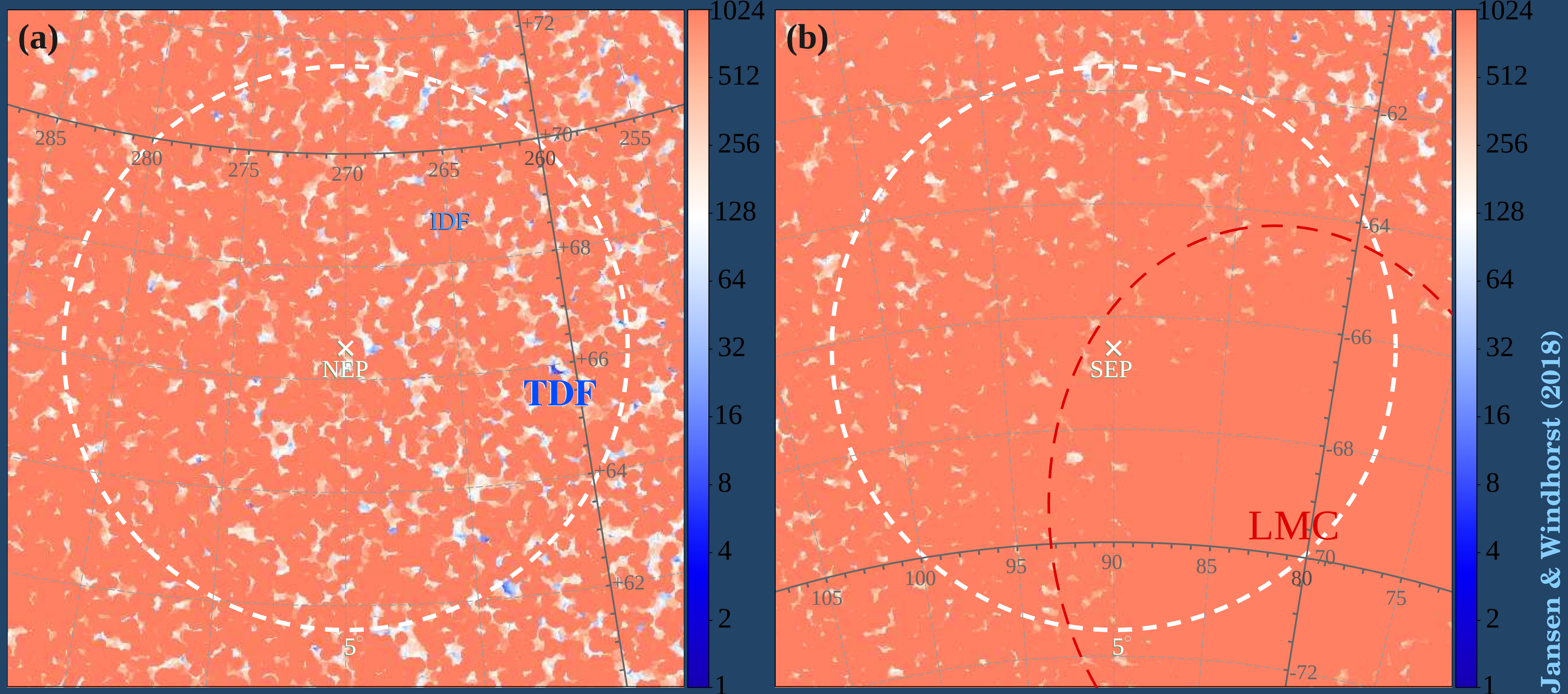
- Maps of $E(B-V)$ values (Schlegel et al. 1998; Schlafly & Finkbeiner 2011) in the $12^\circ \times 12^\circ$ area around (a) the NEP, and (b) the SEP.
  - ▷ Northern CVZ has less foreground extinction by dust than Southern CVZ (LMC and Galactic structures)

Selection of a new *JWST* field for Time-Domain Surveys

- **Field size and shape: $\sim 14'$ diameter, circular**
  - **accommodates the imaging instruments (NIRCam, NIRISS, and MIRI) in *JWST*'s focal plane *at any orientation*, and allows contiguous survey coverage for various dithering strategies**

- **Bright Object concerns: no 2–4 μm-bright stars ($m_{\rm AB} \lesssim 15.5$ mag) within field of view**
  - **Persistence acts as localized reductions in sensitivity and increases in image noise**
  - **Persistence forms a record of observations that may have taken place hours earlier $\longrightarrow$ source of sample contamination**
  - **Persistence no longer modelable and correctable for $m_{\rm AB} \lesssim$ 15.5,mag.**

Selection of a new *JWST* field for Time-Domain Surveys



- $12^\circ \times 12^\circ$ maps of $\sim$4 μm source penalties for (a) the NEP, and (b) the SEP. There are *very* few regions 14′ diameter or larger devoid of sources brighter than $m_{\rm AB} = 15.5$ mag in *JWST*'s Northern CVZ (appearing in dark blue hues; the biggest one marked "TDF") and *none* within the Southern CVZ.

Selection of a new *JWST* field for Time-Domain Surveys

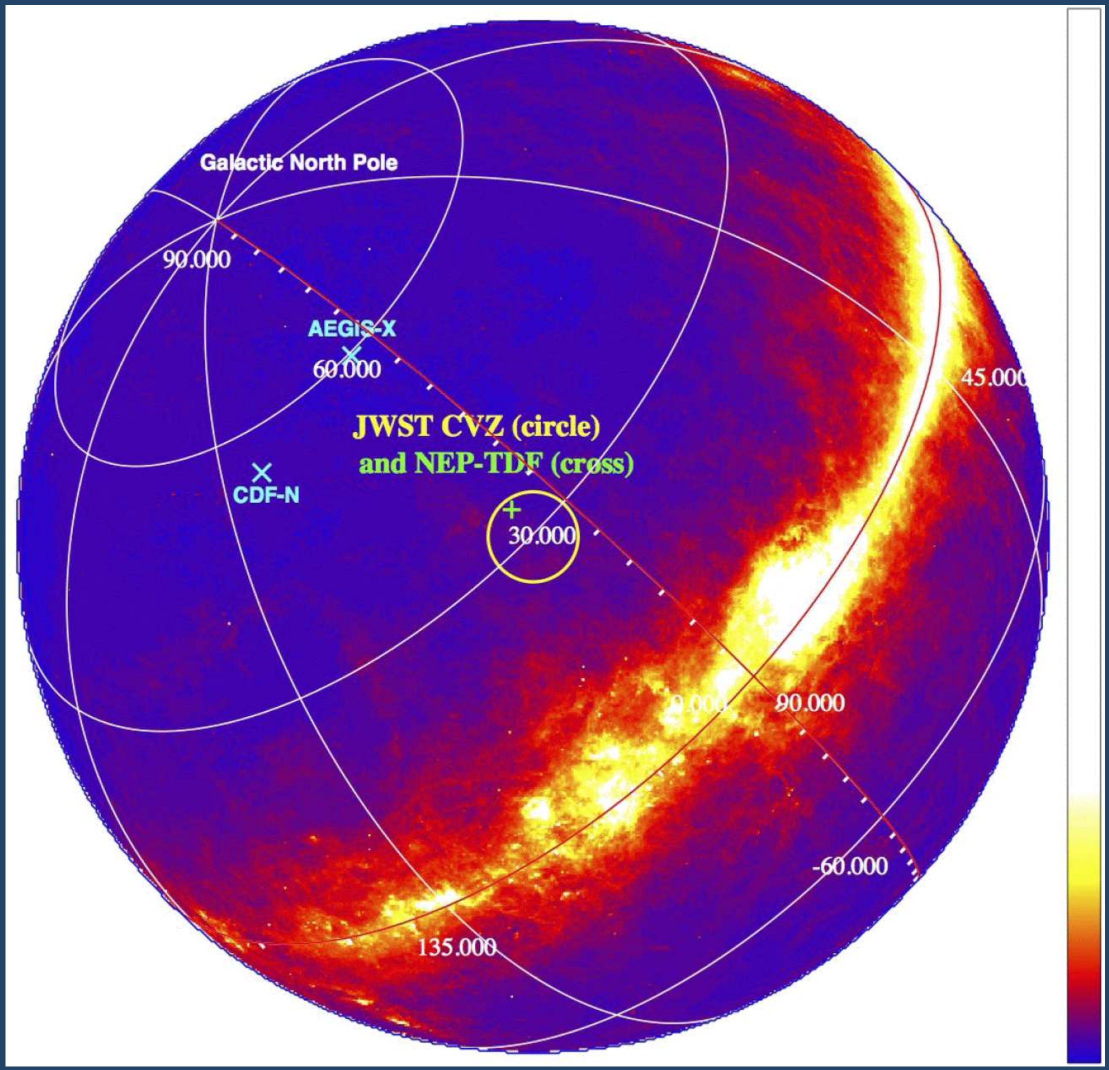
▷ No solutions found in the SEP CVZ

- The very best region also has guide star solutions for *Hubble*, a bright quasar that can serve as a phase calibrator for radio interferometric observations, and has low Galaxy foreground extinction $E(B-V) \lesssim 0.03$ for extragalactic surveys.

▷ *JWST NEP Time-Domain Field* centered at (RA, Dec)$_{\mathrm{J2000}}$ = (17:22:47.896, +65:49:21.54)

- Low Zodiacal foreground emission: NEP and SEP always have lowest foreground

Selection of a new *JWST* field for Time-Domain Surveys



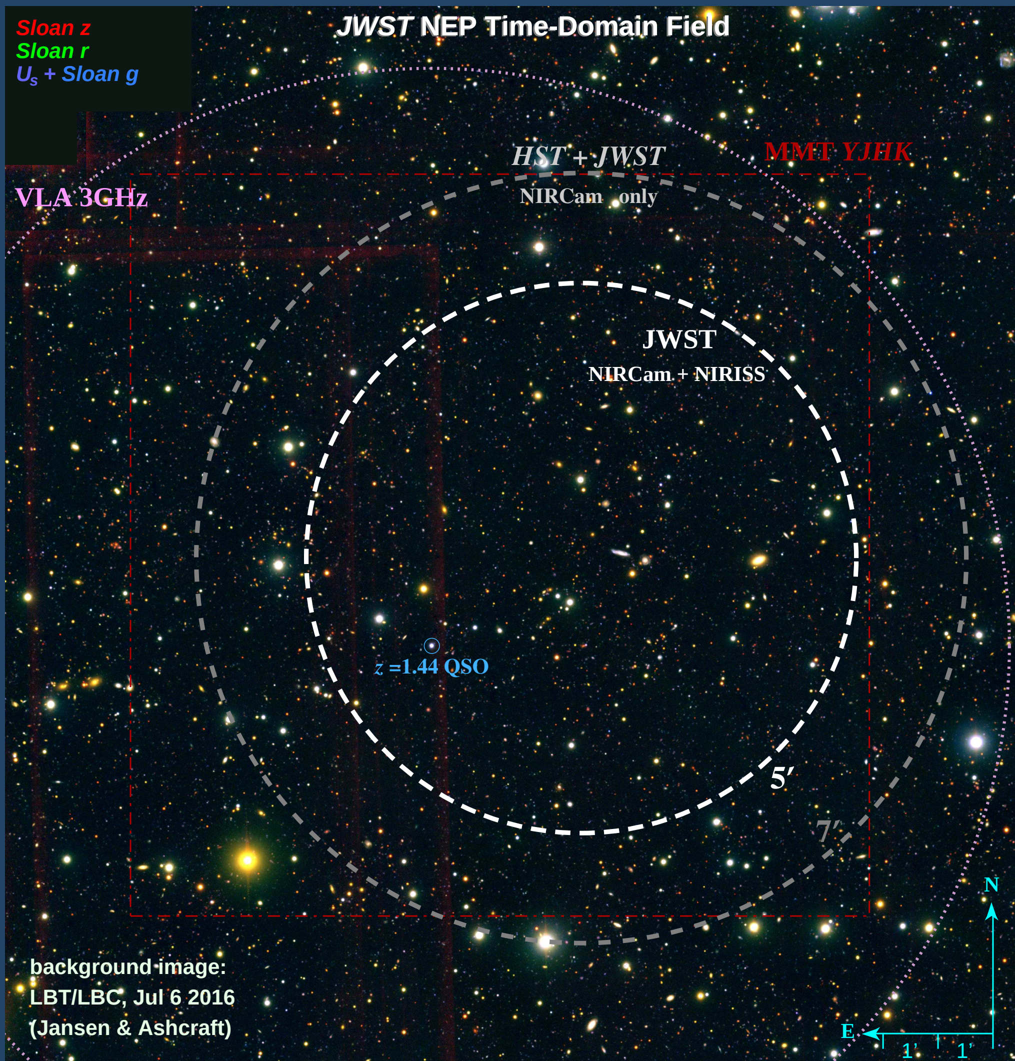
Maksym et al. (2019)

- **Relatively long but clear sight-line through our Galaxy**

$$(l^{\mathrm{II}}, b^{\mathrm{II}}) \simeq (96°, +33°)$$

▷ **also good for Galactic time-domain science!**

Verification of the *JWST* NEP Time-Domain Field

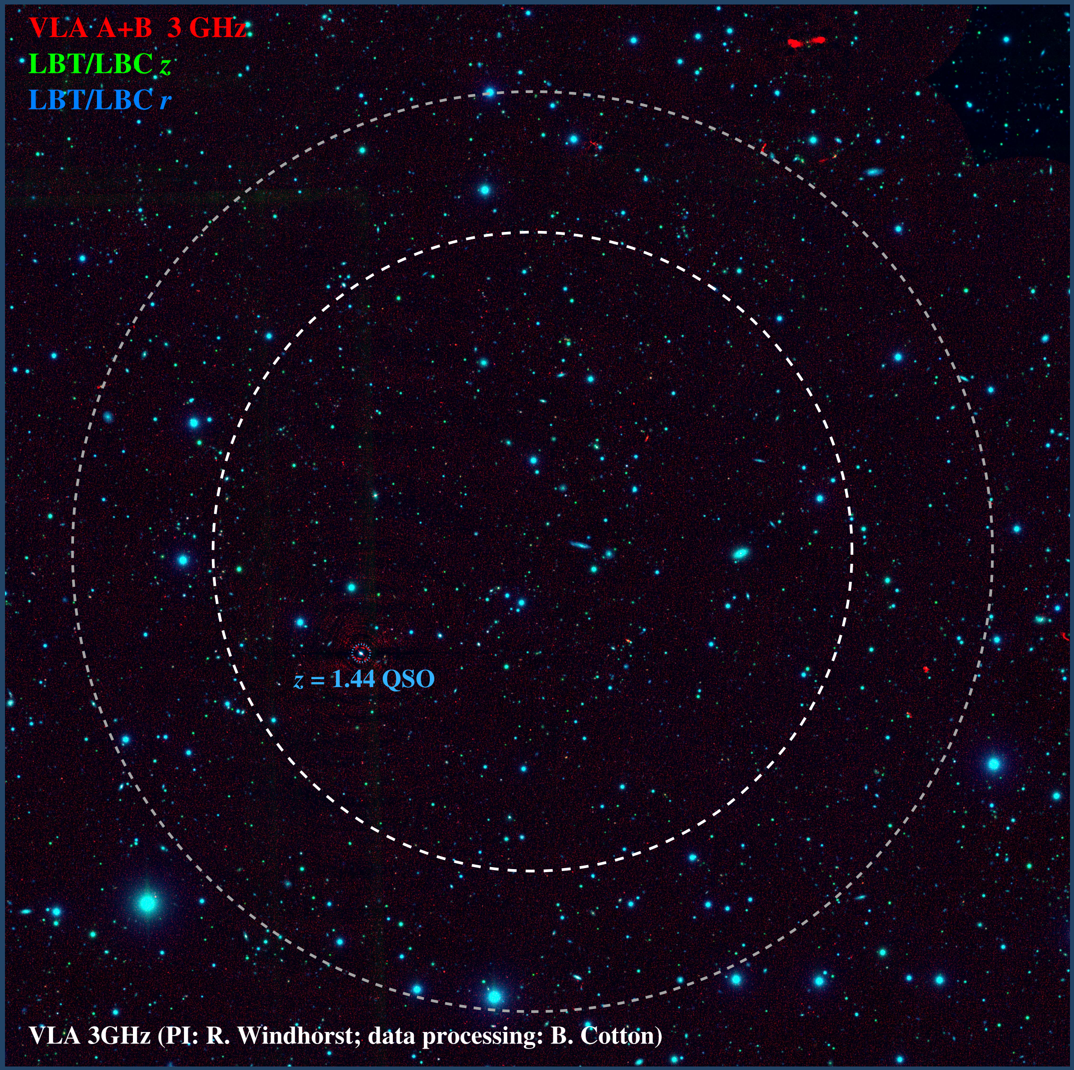


Jansen & Windhorst (2018)

- Verified using 2×8.4 m Large Binocular Telescope / LBC *Ugriz* imaging to $m_{\rm AB} \sim 26.5$ mag at $\sim 0''.95$ FWHM
  (PI: R. Jansen)
- Verified using 6.5 m MMT/-MMIRS *YJHK* imaging to $m_{\rm AB} \sim 24$–22 mag
  (PI: C. Willmer)

▷ Best region selected is indeed devoid of bright *red* stars & excellent for deep extragalactic science

Verification of the *JWST* NEP Time-Domain Field



- **Verified using VLA A+B configuration 3 GHz ($\lambda \sim 10$ cm) observations to 0.9 μJy (PI: R. Windhorst)**
  - ▷ **Most of the faint radio sources detected have faint visible–near-IR counterparts.**
  - ▷ **Nature of these μJy radio sources is being studied: most appear powered by *star formation* rather than by AGN.**

Development as a *JWST Community Field*: Ancillary X-ray through Radio Observations in the *JWST* NEP TDF

- **Field selection & Verification:**
  - **Field selection (Jansen & Windhorst 2018)**
  - **Large Binocular Telescope/LBC *Ugriz* (Jansen)**
  - **MMT/MMIRS *YJHK* & spectroscopy (Willmer), and**
  - **VLA 3 GHz observations (Windhorst)**

- **Imaging with *Hubble* at wavelengths inaccessible to *Webb*:**
  - ***HST* Cycle 25 + Cycle 28+29 UV–Visible imaging ($m_{\mathrm{AB}} \sim$ 27.3–29 mag) of central $r \lesssim 5'$ area (completed), and of the annulus to $r \lesssim 7.5'$ (in progress) (PI: R. Jansen; PI: R. Jansen & N. Grogin)**

- **IDS GTO *JWST*/NIRCam imaging ($m_{\mathrm{AB}} \lesssim 29$ mag) + NIRISS slitless grism spectroscopy ($m_{\mathrm{AB}} \lesssim 28$ mag) (PI: R. Windhorst)**
  - **After the Dec 18 2021 launch & 6-month on-orbit verification, we expect the first observations of the field with *Webb* in June 2022!**

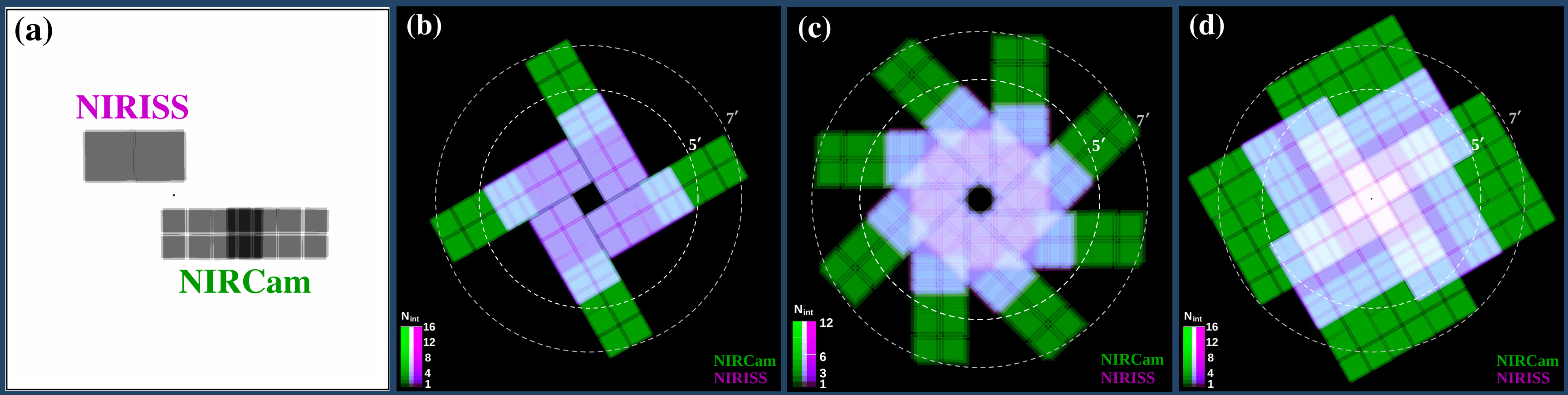
- **Coverage across the electromagnetic spectrum secured by the community:**

Development as a *JWST Community Field*: Ancillary X-ray through Radio Observations in the *JWST* NEP TDF

- ***JWST* NEP Time-Domain Field multiwavelength community investment**

Telescope	PI	Status	Depth
NuSTAR 3–24 keV	F. Civano	extant (33 sources) / in progress	687 ks / 780 ks; $>$50 cts
Chandra/ACIS-I 0.2–10 keV	W.P. Maksym	extant; 238 sources	540 ks; $\sim 1\times 10^{-16}$ cgs
″	″	in progress	1260 ks; ″
XMM-Newton 0.5–2.0 keV	F. Civano/M. Ward/N. Cappelluti	approved / proposed	40 ks / 800 ks; 3×10^{-16} cgs
HST/WFC3+ACS	R.A. Jansen	extant / in progress	60 / 32 CVZ orbits; $r \lesssim 7'.5$
F275W,F435W,F606W		GO 15278, GO 16252, GO 16793	$m \sim$ 27.3, 28.2, 29 mag
LBT/LBC U_{sp}*griz*	R.A. Jansen	extant; wide-field (2 epochs)	11 hrs; $m \sim$ 26.8–26.0 mag
Subaru/HSC *giz*,nb816,nb921	G. Hasinger / E. Hu	extant; wide-field	5 hrs; $m \sim$ 25.5–25.1 mag
GTC/HiPERCAM *ugriz*	V. Dhillon	extant; $r < 5'$	16$\times$1 hr; $m \sim$ 27 mag
TESS (0.6–1.0μm bandpass)	G. Berriman & B. Holwerda	in progress; ultra wide-field	357 days; low-SB xtd
MMT/MMIRS *YJHK*$_s$	C.N.A. Willmer	extant	68 hrs; $m \sim$ 24.5–23.5 mag
JWST/NIRCam+NIRISS	R.A. Windhorst / H.B. Hammel	*guaranteed time*	$\sim$49 hrs; 54.7 arcmin^2
0.8–5 μm + 1.75–2.23 μm		GTO #1176, #1255	$m <$ 29–28.5 mag
JCMT/SCUBA-2 850μm	I. Smail / M. Im	extant; 113 sources (82 at $>4\sigma$)	43.4 hrs; rms $\sim$ 0.8 mJy
″	″	approved	20.0 hrs; rms $\sim$ 0.7 mJy
SMA 0.87 mm	G. Fazio	in progress (5 sources)	30 hrs; rms $\sim$ 0.9 mJy/beam
IRAM/Nika2 1.2, 2 mm	S.H. Cohen	in progress	30 hrs; rms $\sim$ 2 mJy
VLA 3(2–4) GHz	R.A. Windhorst / W. Cotton	extant; $\sim$2500 sources	47 hrs; rms $\sim$ 0.9 μJy
VLBA 4.7 GHz	W. Brisken	extant; $\sim$128 targets	147 hrs; rms $\sim$ 3 μJy
LOFAR 150 MHz	R. van Weeren	extant; ultra-wide field	72 hrs; rms $\sim$ 0.12 mJy
J-PAS (56 narrow-bands)	S. Bonoli / R. Dupke	extant; ultra-wide field	48 hrs; $m \sim$ 21.5–22.5 mag
MMT/Binospec (mos)	C.N.A. Willmer	extant; 1378 spectra/799 redshifts	26 hrs; $m \sim$ 22.5–24 mag
MMT/MMIRS (mos)	C.N.A. Willmer	approved	$m <$ 22, $z >$ 0.4

JWST IDS GTO and Possible GO implementations

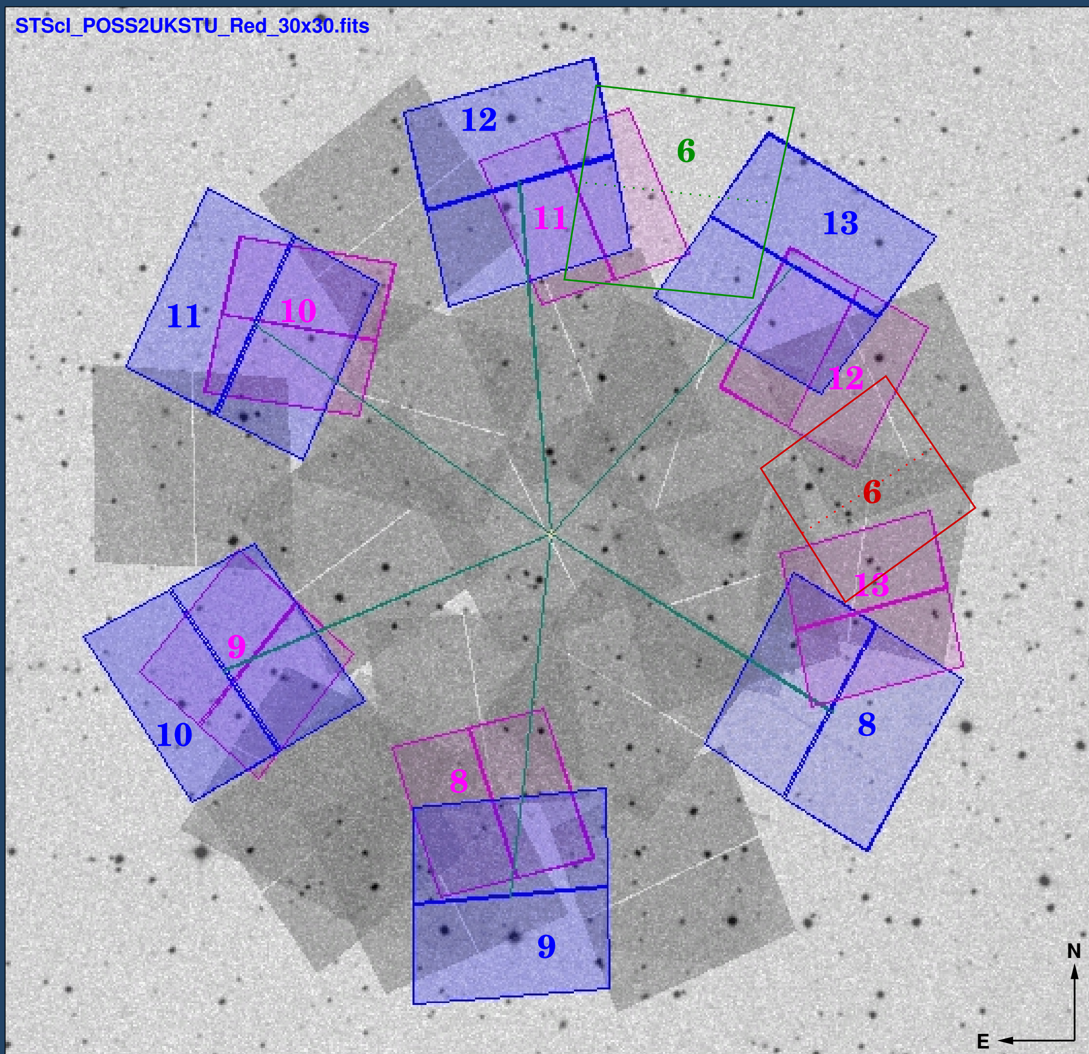


Jansen & Windhorst (2018)

- [*a*] Footprint on the sky of a 2×1 mosaic of pointings with *JWST*/NIRCam (8-filter 0.8–5.0 μm imaging), and NIRISS 1.75–2.23 μm slitless spectroscopy taken in parallel. Upon 180° rotation, the footprints of NIRCam will almost fully overlap NIRISS coverage. [*b*] the 4-spoke design adopted in the Windhorst GTO program. [*c*] and [*d*] possible strategies to fully map the *JWST* NEP Time-Domain Field by replicating this 4-spoke pattern at either different orientations or different offset pointings.

- The actual orientation of these patterns on the sky will depend on the *JWST* launch date.

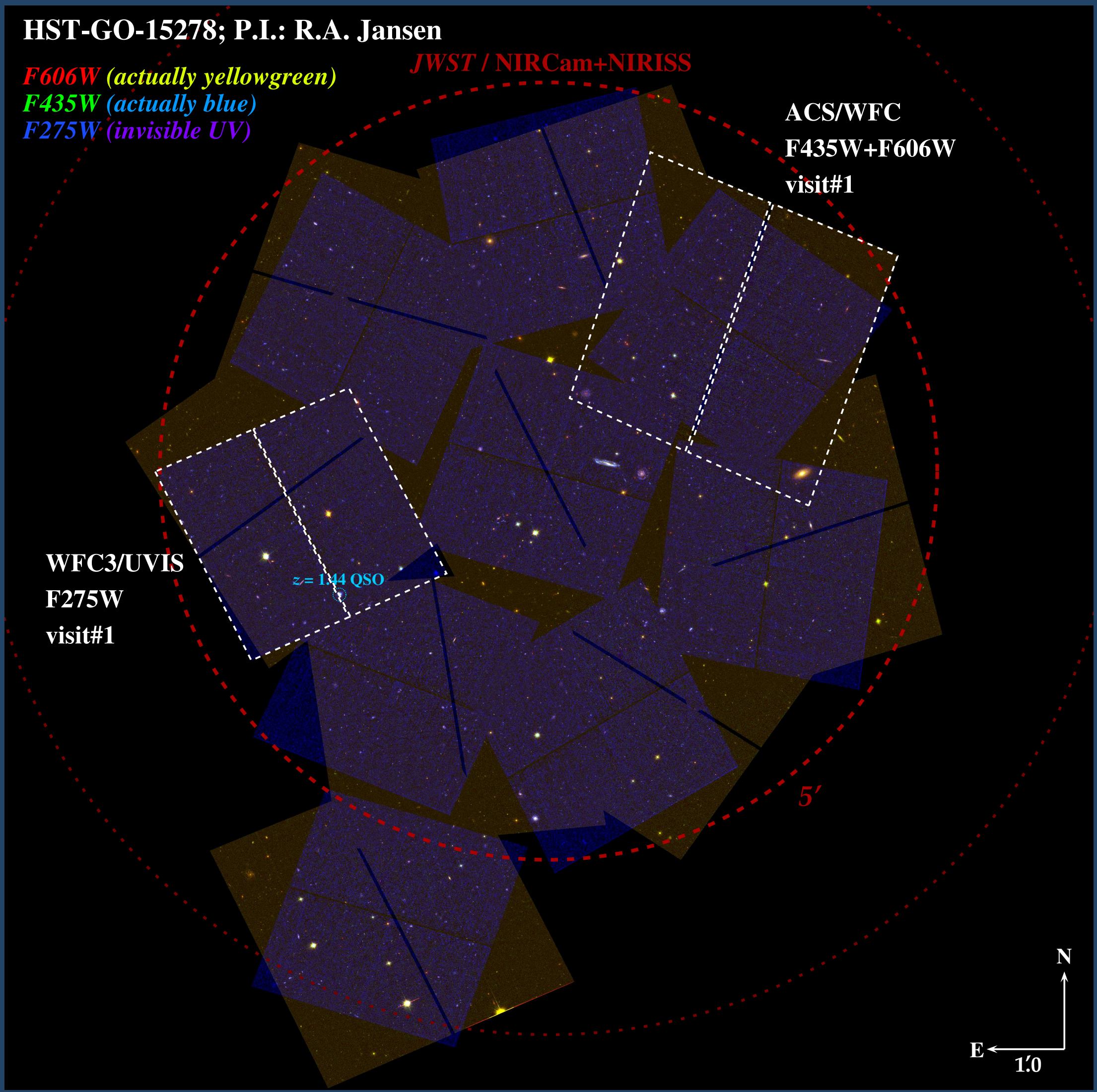
Ancillary Observations in the *JWST* NEP TDF: *Hubble*



- **UV–Visible survey of the *JWST* NEP Time-Domain Field in 3 filters (WFC3/UVIS F275W [*UV*], ACS/WFC F435W [*blue*] and F606W [*yellowgreen light*]). The rosette of grey footprints indicates the extant coverage; colored ones are targeted in Cycle 29. The Cycle 25 (PI: Jansen) and Cycle 28+29 (PI: Jansen & Grogin) programs were awarded a total of 88 CVZ orbits, nominally spread over 22 separate visits.**

R.A. Jansen

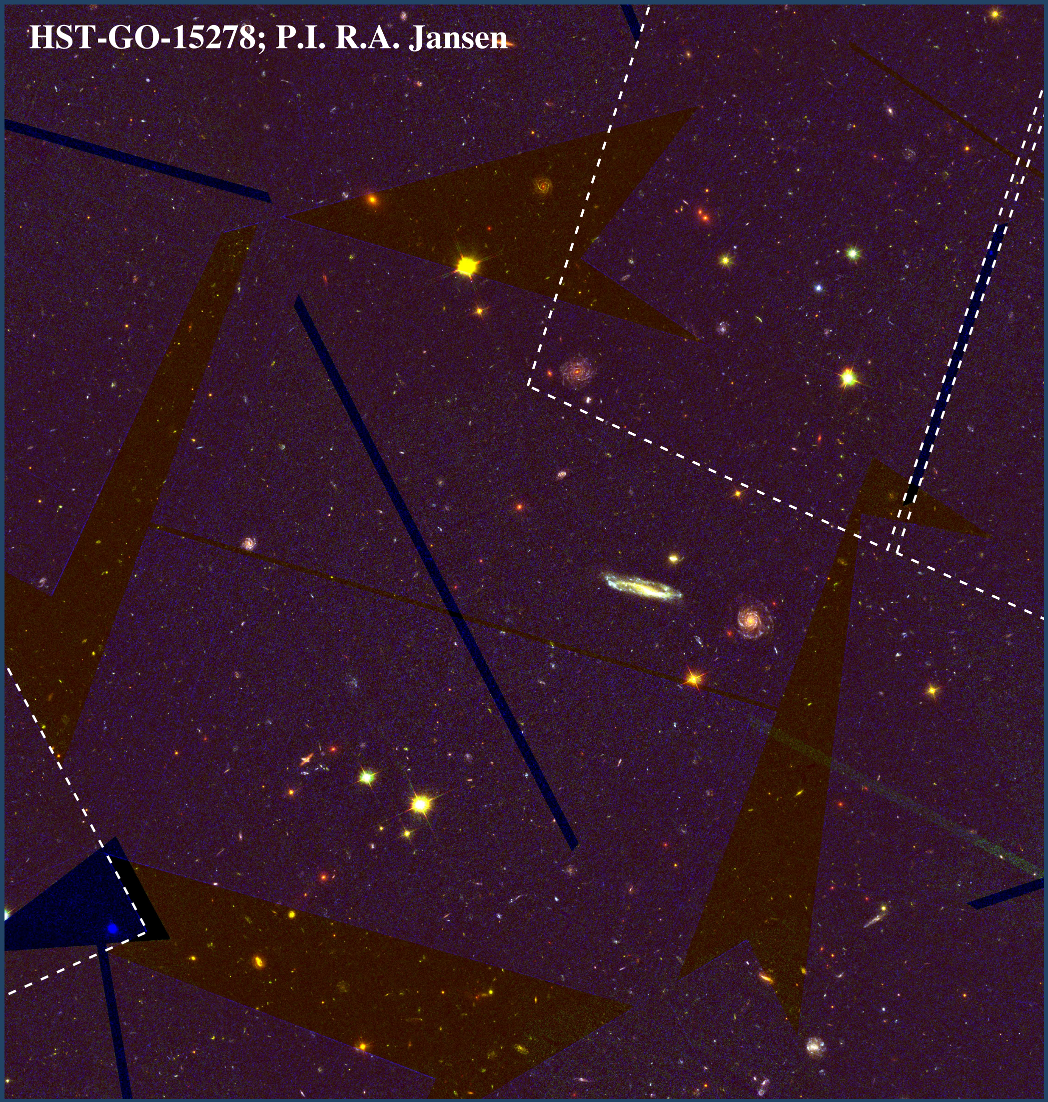
Ancillary Observations in the *JWST* NEP TDF: *Hubble*



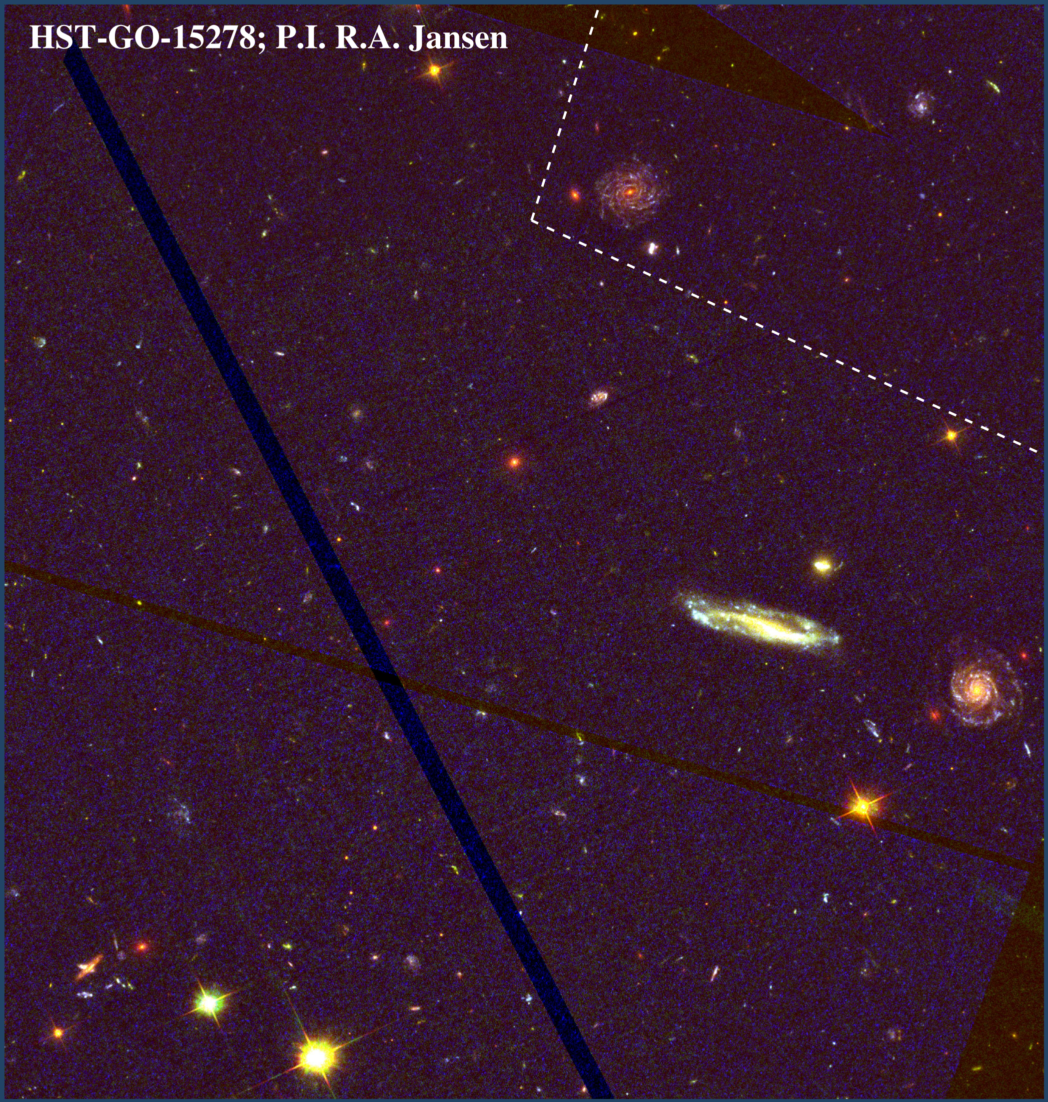
- Mosaic of the *Hubble* observations of Cycle 25. The dark red circle (radius = 5′) indicates where NIRCam and NIRISS GTO observations will overlap.
- Preliminary analyses resulted in Senior Theses by C. White (2019), V. Jones (2019), and S. Bechel (2020), and in ASU/NASA Space Grant presentations by T. Tyburczy (2019) and L. Nolan (2020, 2021).
- Detailed analysis by ASU graduate student R. O'Brien is in progress.

R.A. Jansen

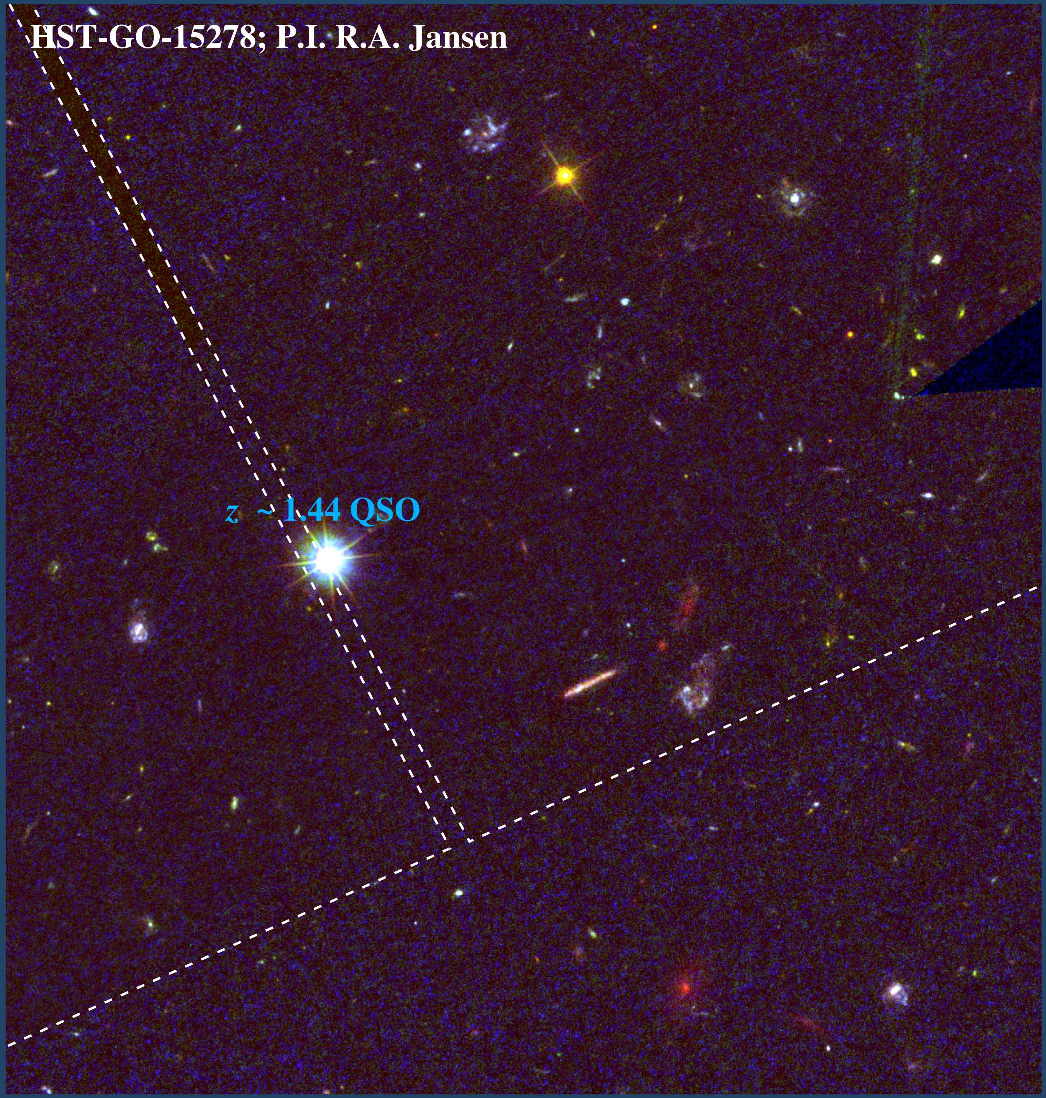
Ancillary Observations in the *JWST* NEP TDF: *Hubble*



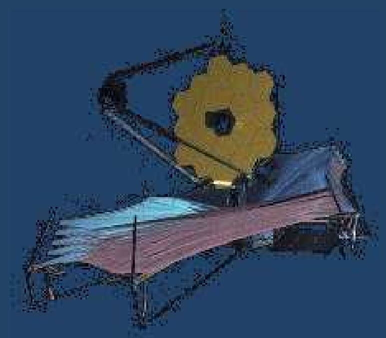
Ancillary Observations in the *JWST* NEP TDF: *Hubble*



Ancillary Observations in the *JWST* NEP TDF: *Hubble*



Take-home Message



- **Can *Webb* do ultra-deep time-domain survey science?**

  Yes... but only in a few very special locations in the sky.

- **The best field to do so is the *JWST* NEP Time-Domain Field**
  - ▷ **new *community field*, centered at: (RA, Dec)$_{J2000}$ = (17:22:47.896, +65:47:21.54)**
  - ▷ **field size: ∼14 arcmin diameter, or an area of 154 arcmin^2**
  - ▷ **ancillary data from radio through X-ray**
  - ▷ **first *Webb* observations at 4 orientations provided by IDS R. Windhorst in Year 1**

Are you moved by moving objects?
or are celestial beacons that vary in brightness more your style?

The JWST NEP Time-Domain Field is for you!