

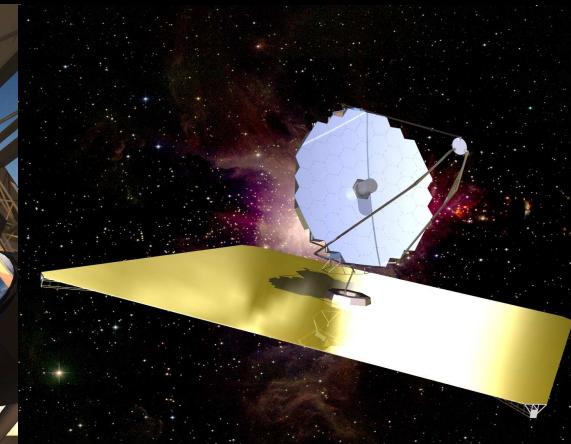
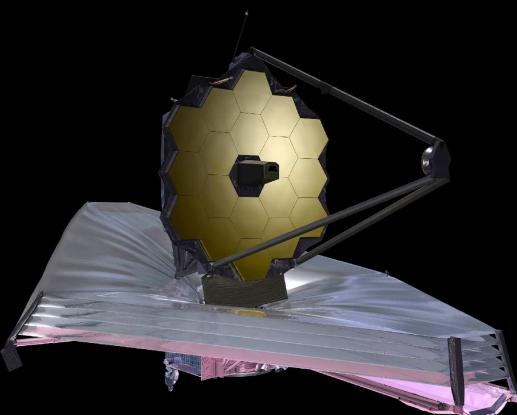
# The Universe Beyond Hubble: The James Webb Space Telescope

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Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

Collaborators: S. Cohen, R. Jansen, L. Nolan, & R. O'Brien (ASU), C. Conselice (UK), S. Driver (OZ), & H. Yan (U-M)

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



1973~2020+;

1996~2031;

2000~2050+

2020~2050+?

*Talk at the ASU Earth and Space Open House, Friday Oct. 22, 2021 (ASU, Tempe, AZ; via Zoom)*

*All presented materials are ITAR-cleared.*

# Outline

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- (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 programmatic as of 2021.
- (8) Where do our students end-up? Possible NASA Careers



Sponsored by NASA/HST & JWST

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



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



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



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

Hubble: Concept in 1970's; Made in 1980's; Operational 1990– $\gtrsim$ 2021?.

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

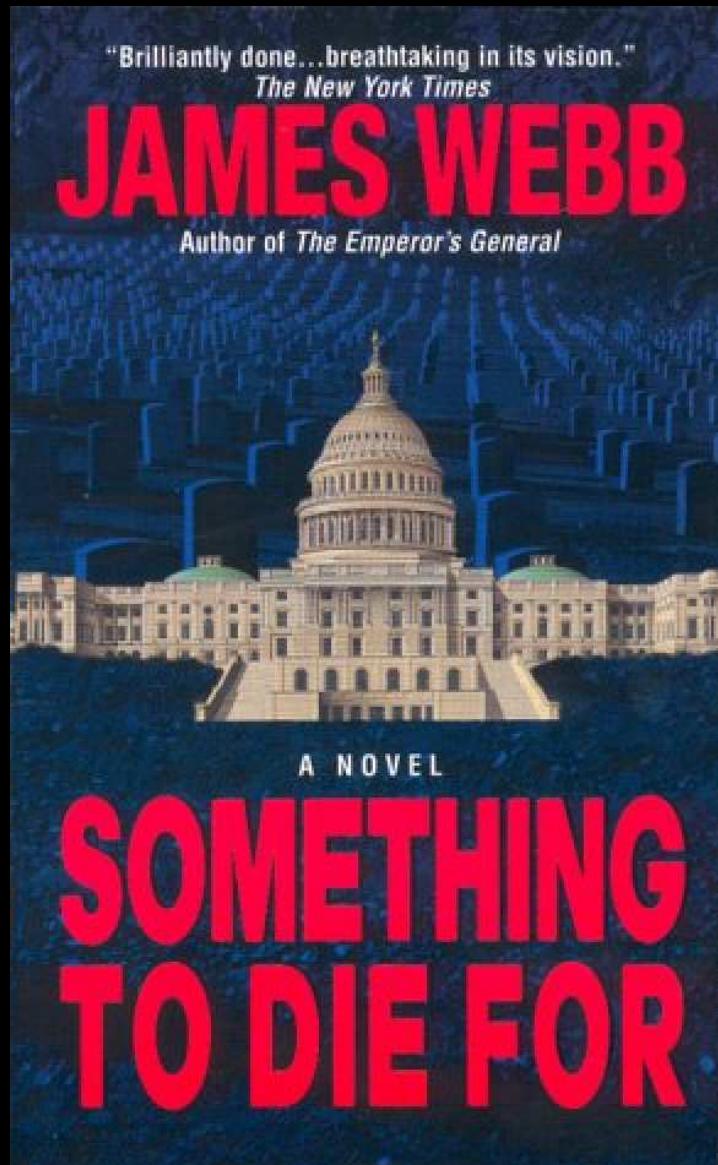
**JWST primary  
mirror**



**Hubble primary  
mirror**

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

# (1) Update of the James Webb Space Telescope (JWST), 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 ( $25 \text{ m}^2$ ) segmented IR telescope for imaging and spectroscopy at  $0.6\text{--}28 \mu\text{m}$  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.

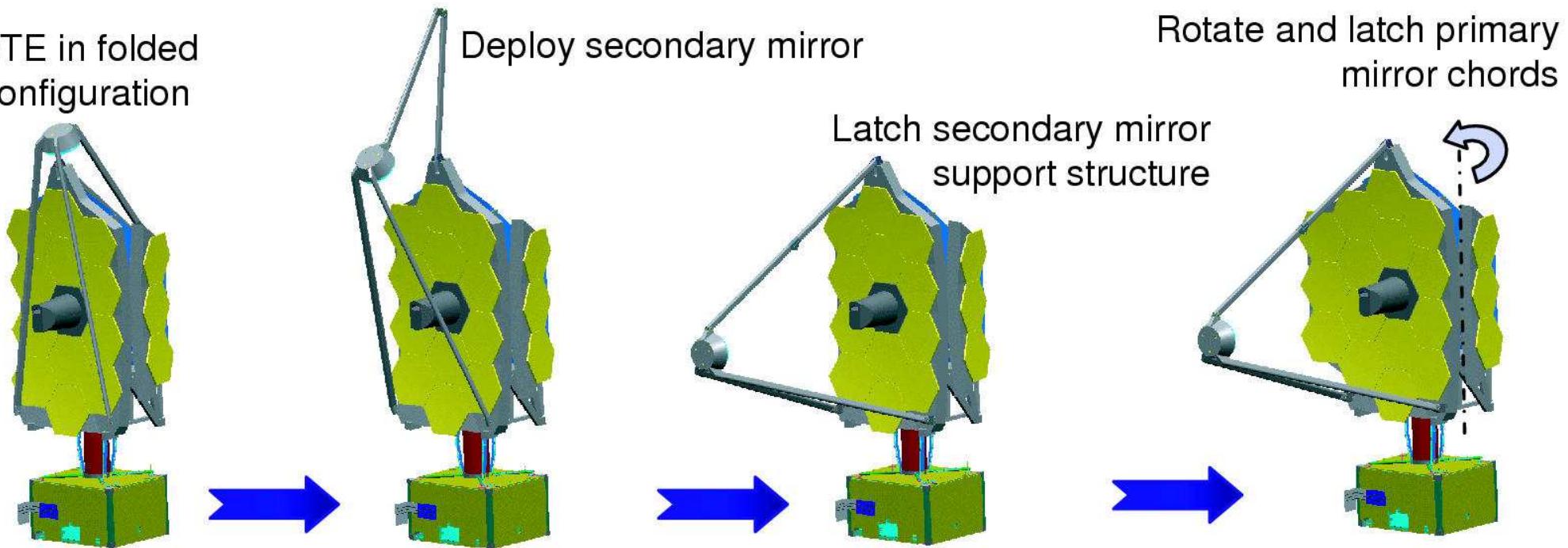
## (1a) How will JWST travel to its L2 orbit?



- 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.

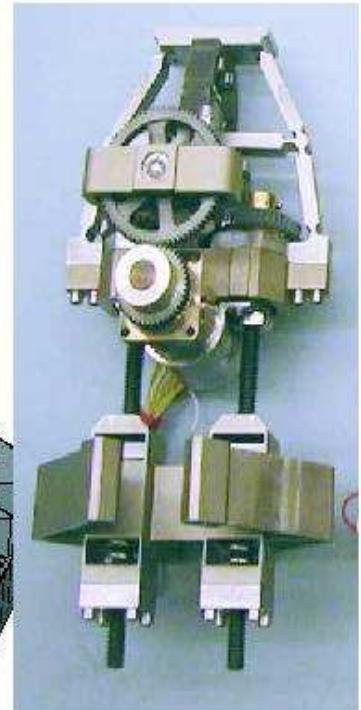
- (1b) How will JWST be automatically deployed?

OTE in folded configuration



- 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.

## Actuators for 6 degrees of freedom rigid body motion



Actuator  
development  
unit

Lightweighted  
Beryllium Mirror

Actuator for radius  
of curvature adjustment

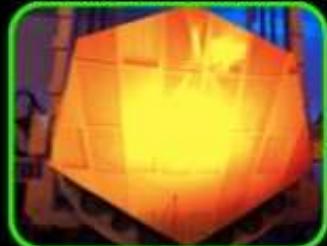
Active mirror segment support through “hexapods”, similar to Keck.

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

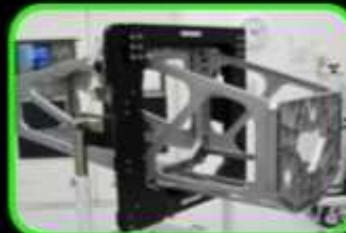


# JWST Hardware Status

Primary Mirror Segment



Aft Optics System



PM Flight Backplane



Tertiary Mirror

Secondary Mirror Pathfinder Strut



Fine Steering Mirror

ISIM Flight Bench



Secondary Mirror Hexapod



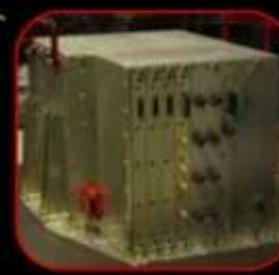
Secondary Mirror



Membrane Mgmt



Pathfinder Membrane



Spacecraft computer Test Unit

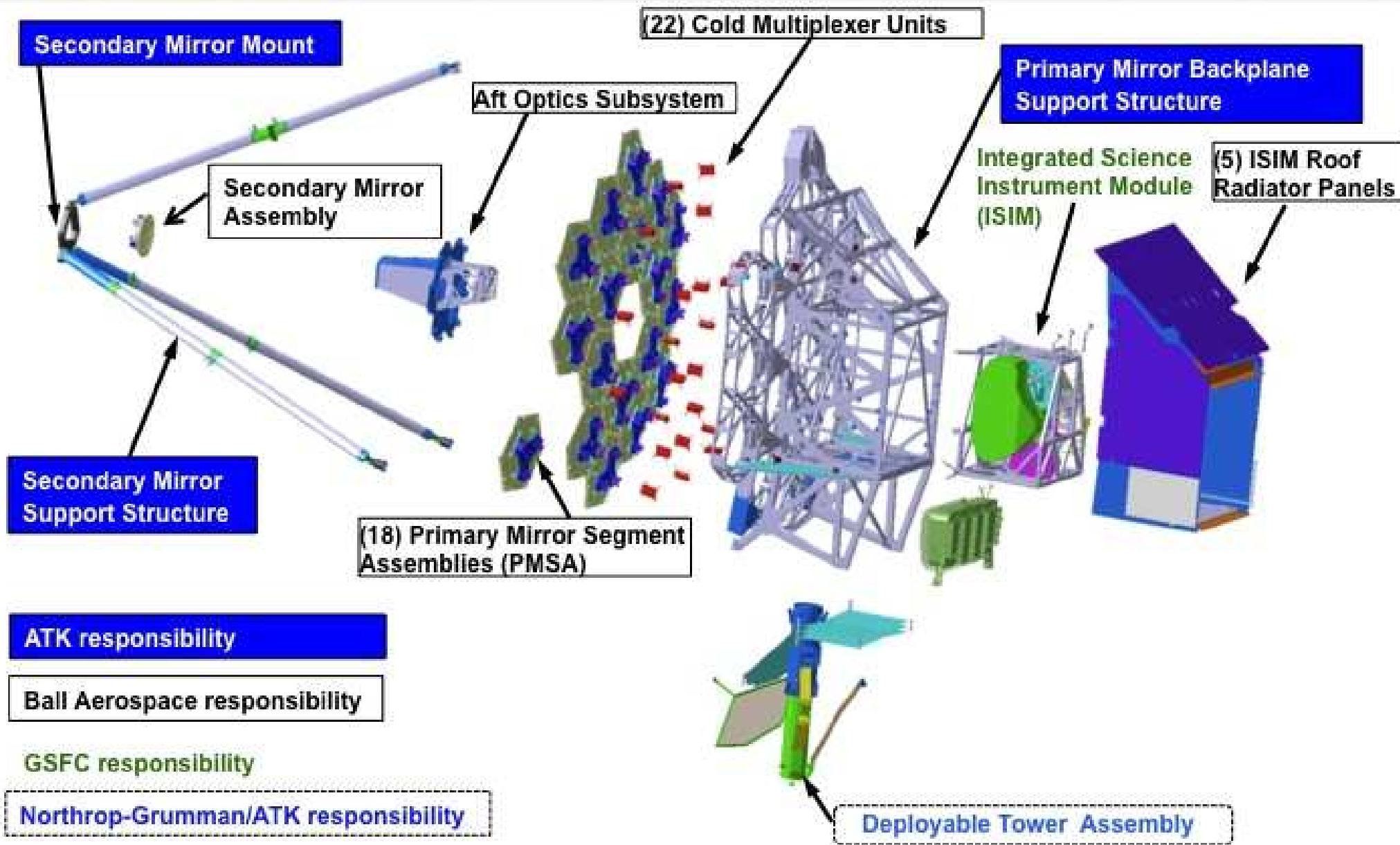


Mid-boom Test

2021: 100% of launch mass designed and built (100% weighed).<sup>3</sup>



# TELESCOPE ARCHITECTURE

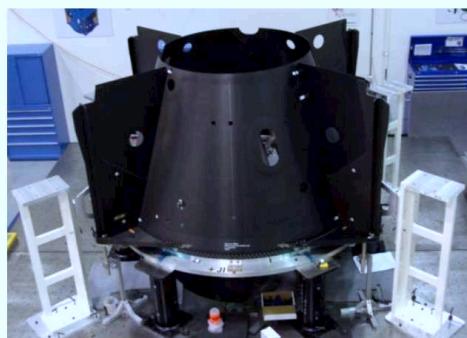
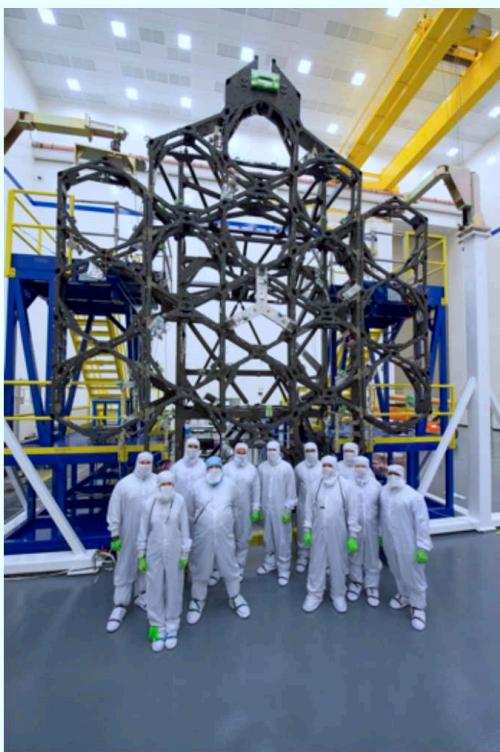


3/31/11

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



# JWST Hardware Progress

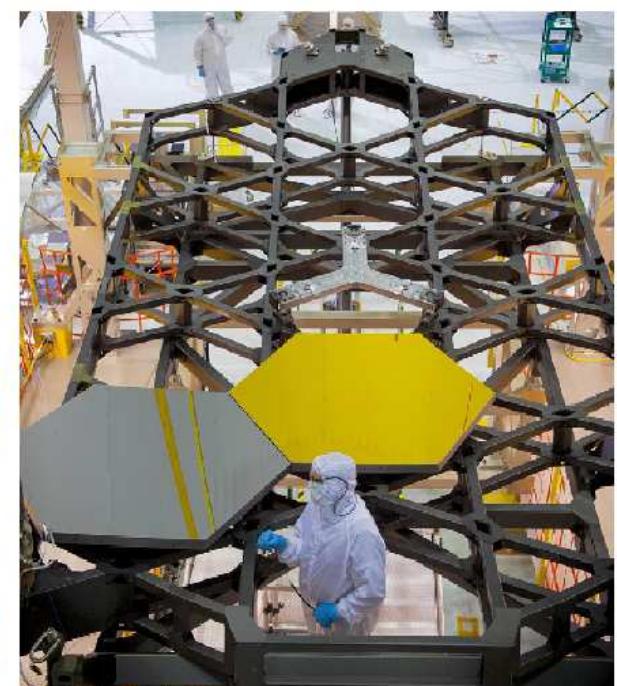
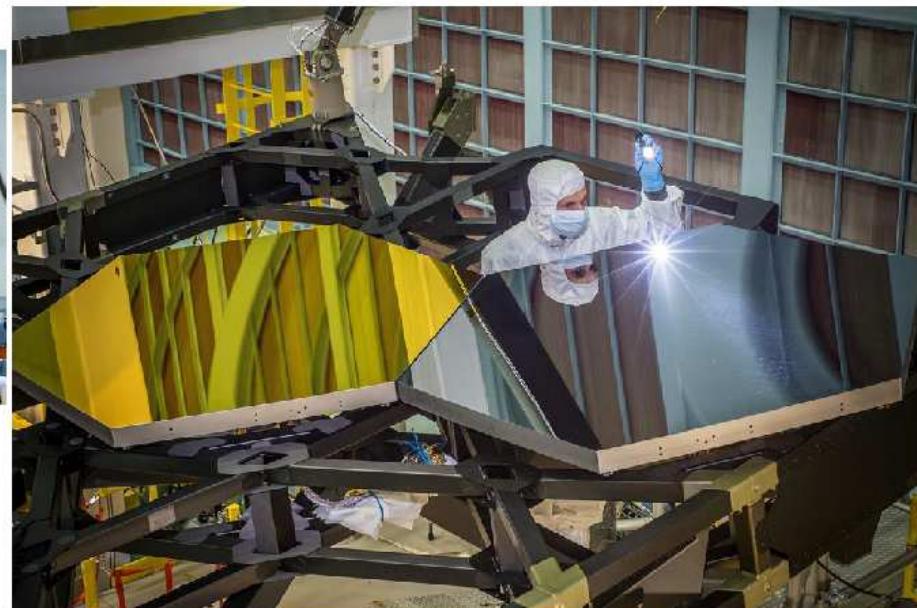
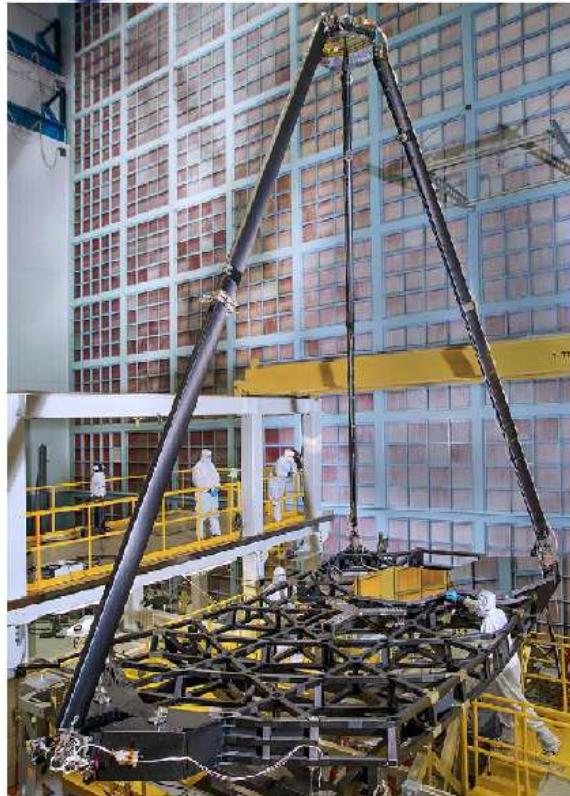


JWST remains on track for an October 2018 launch within its replan budget guidelines  
29

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

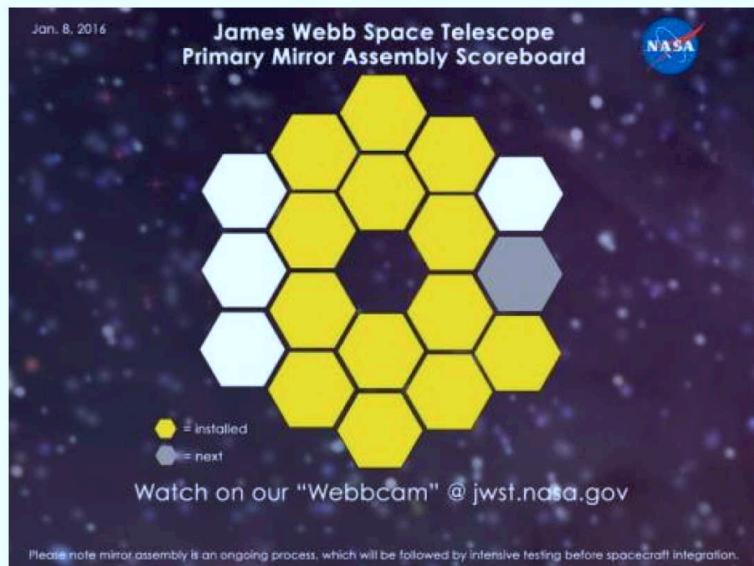


# Telescope Pathfinder – Risk Reduction

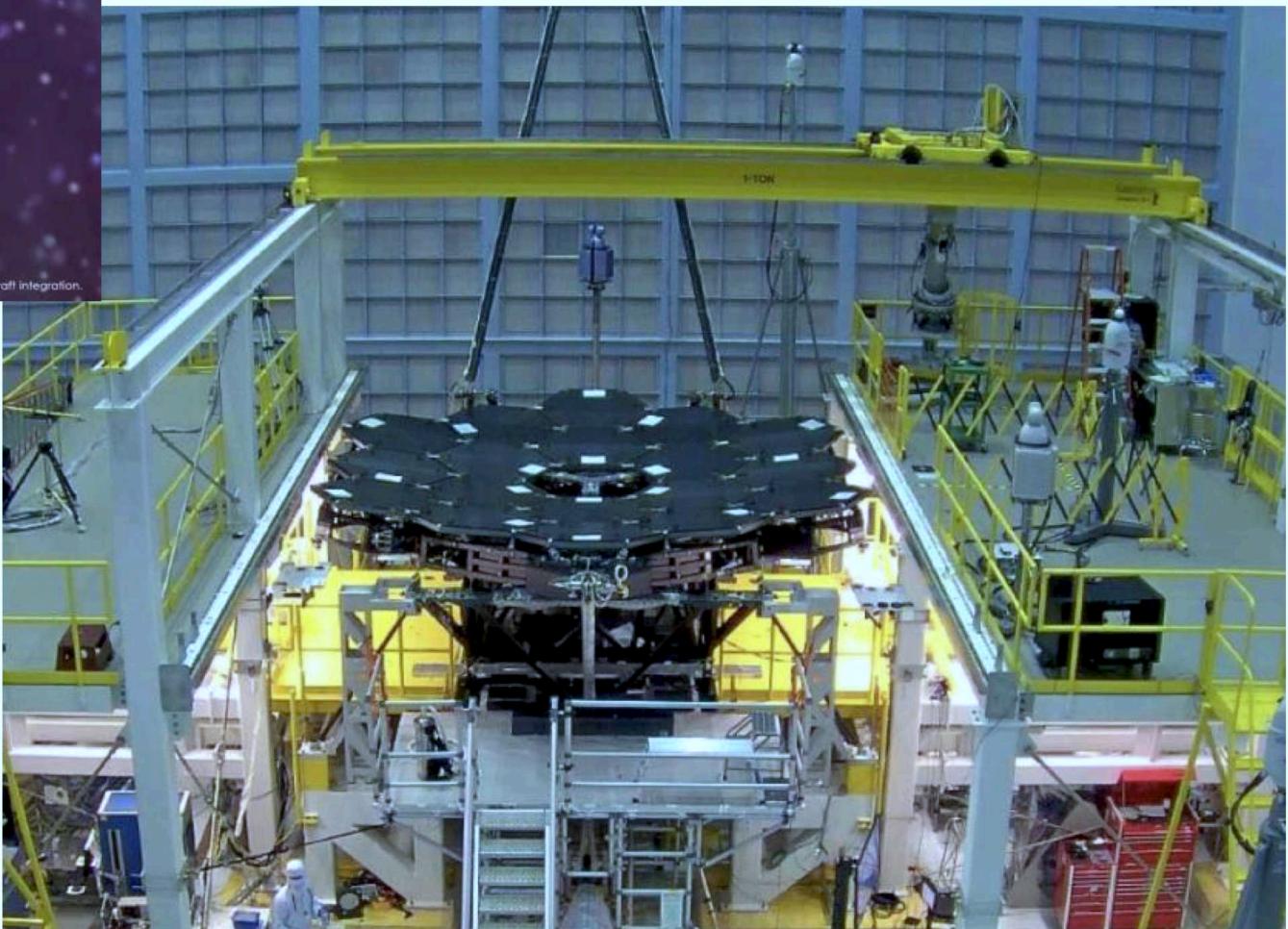


JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

# Much progress has been made in OTE integration



Where we were at last month's call



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



8 February 2016 JWST Monthly Telecon 8

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



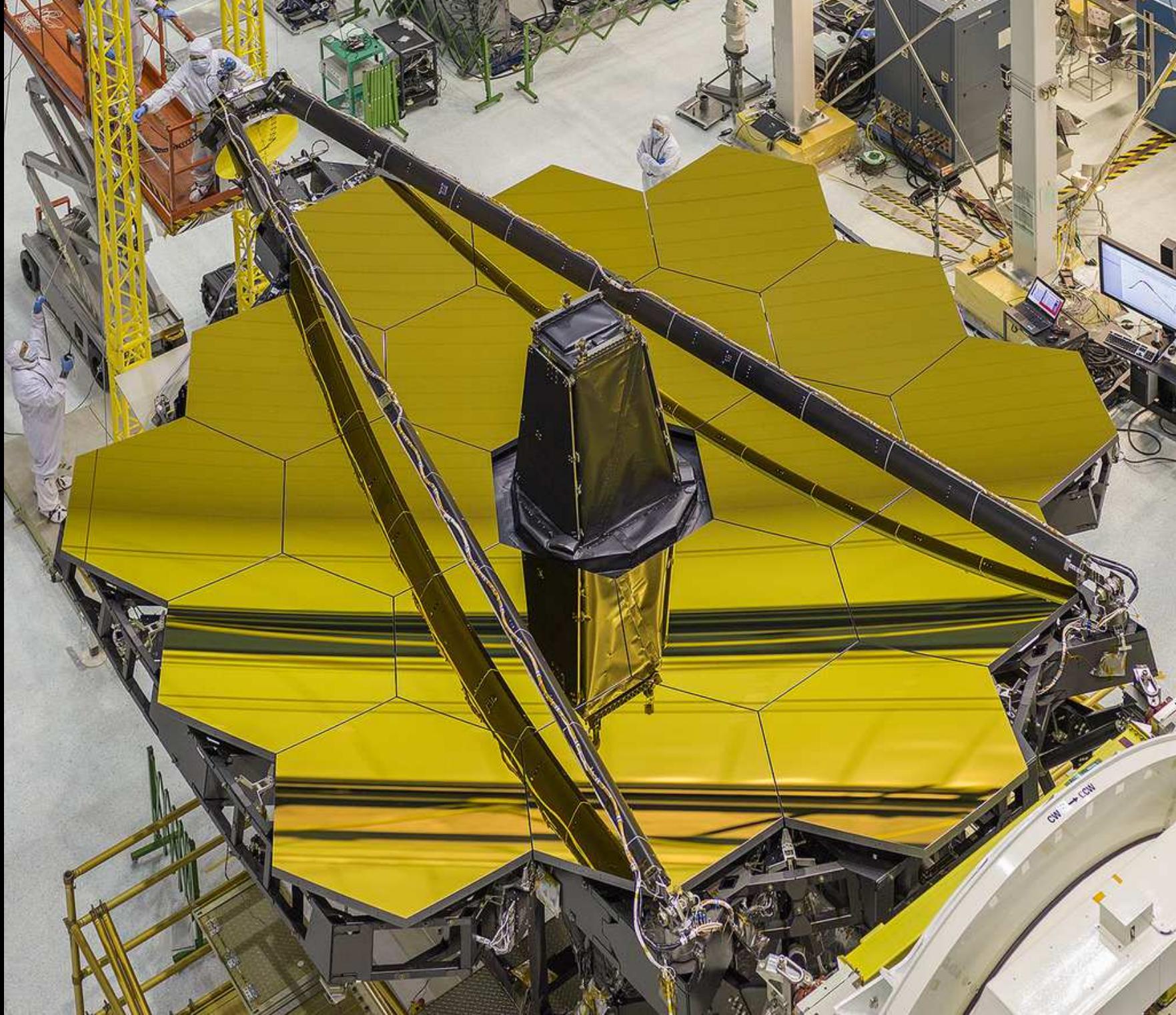
NASA team-work to take JWST mirror covers off!



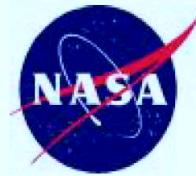
JWST being tilted into the right position



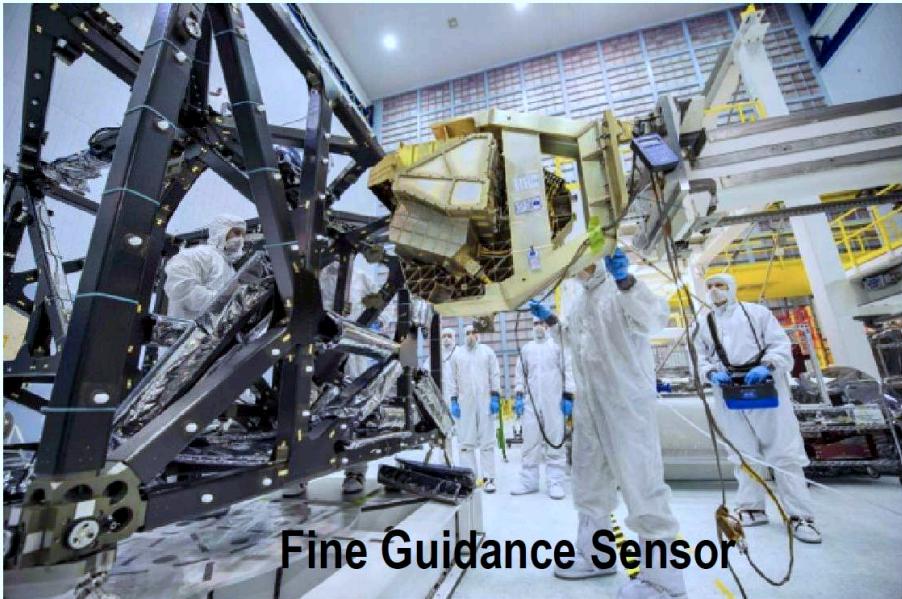
Webb mirrors finally mounted and ready!



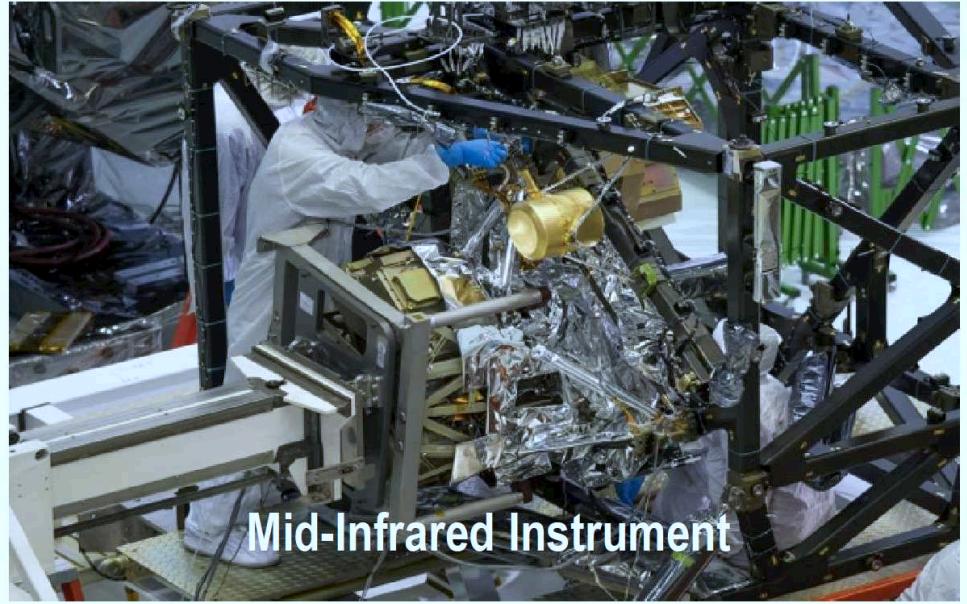
JWST stowed for further instrument mounting



# All Instruments Integrated



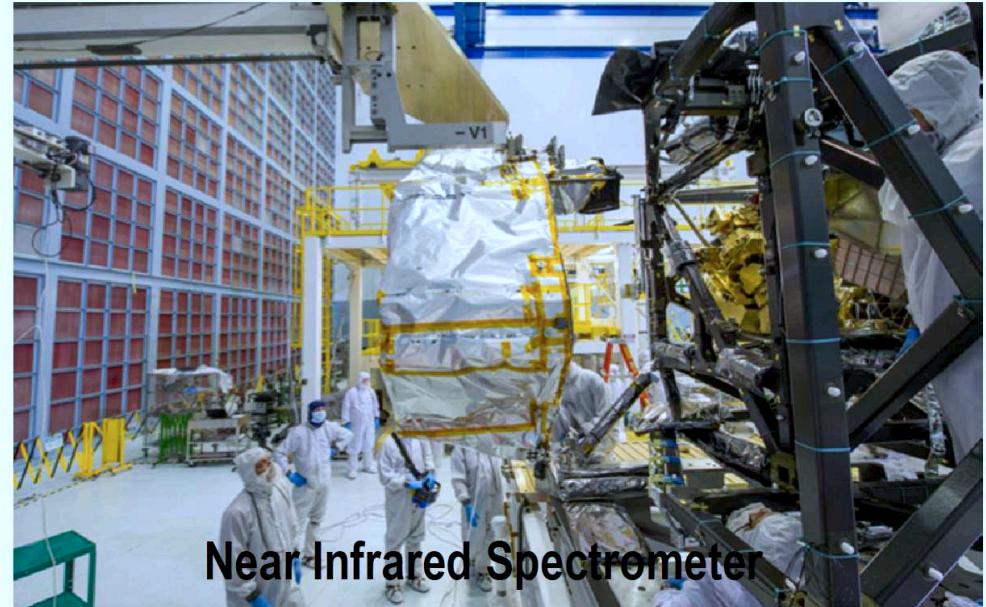
Fine Guidance Sensor



Mid-Infrared Instrument

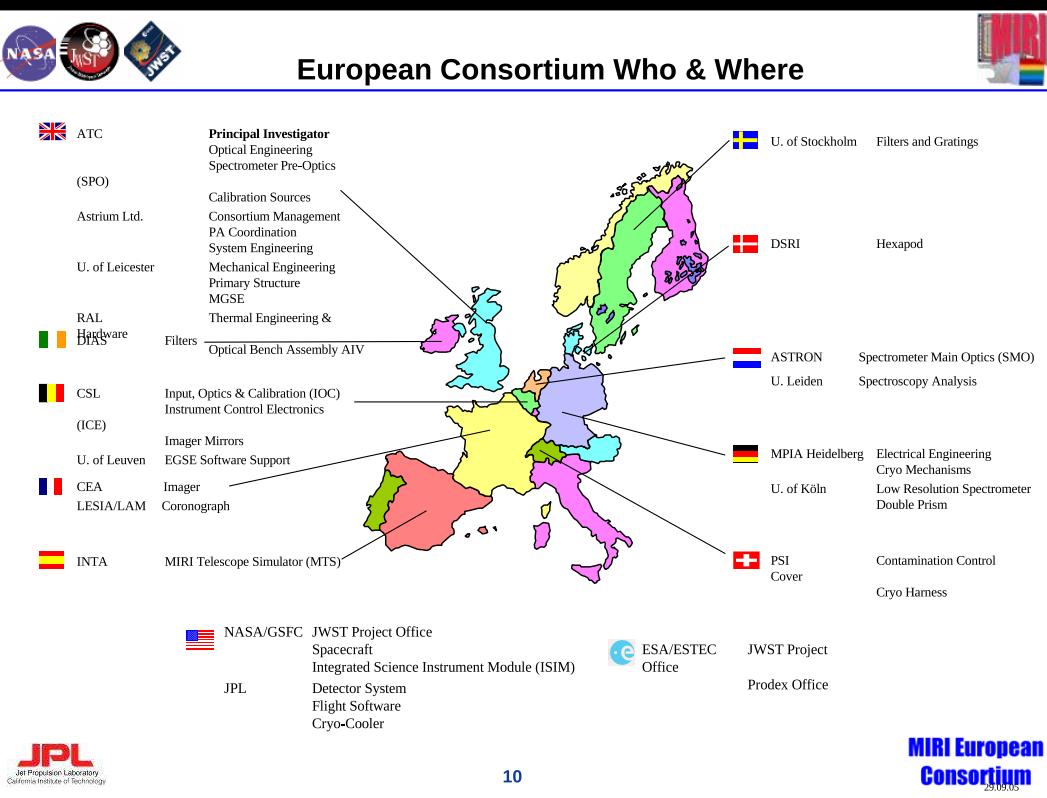
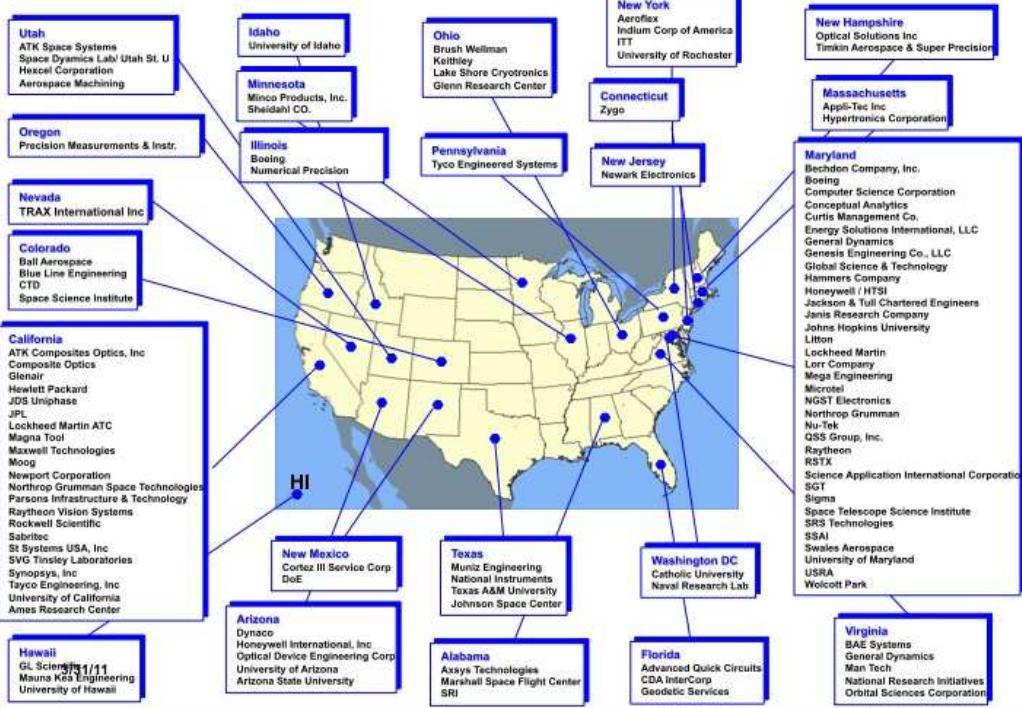


Near Infrared Camera



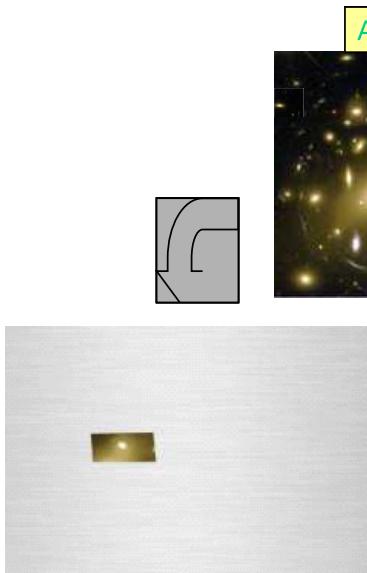
Near Infrared Spectrometer

# JWST: A Product of the Nation

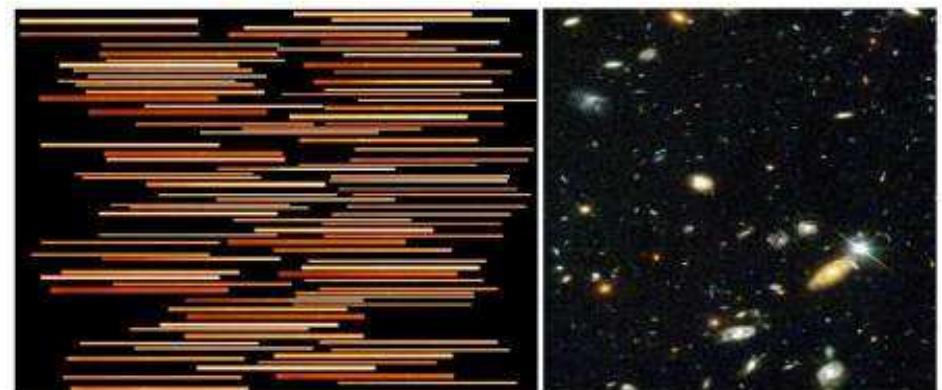
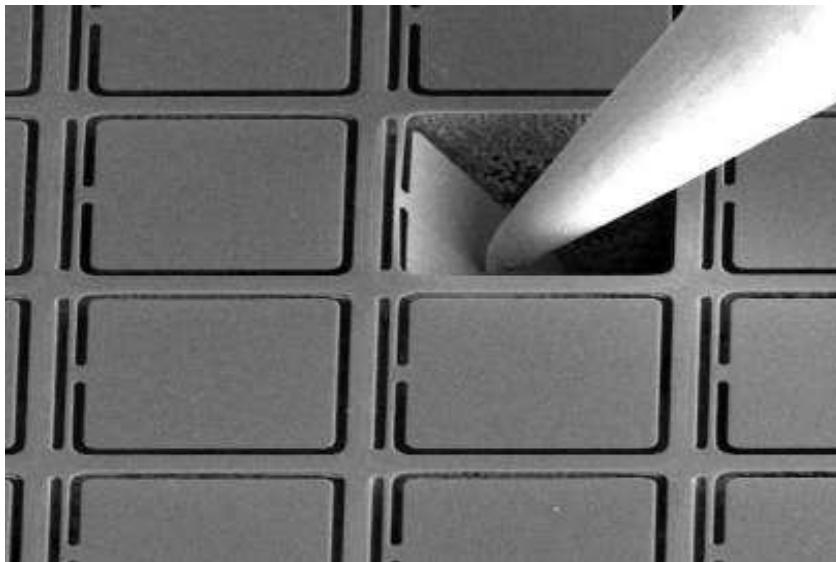
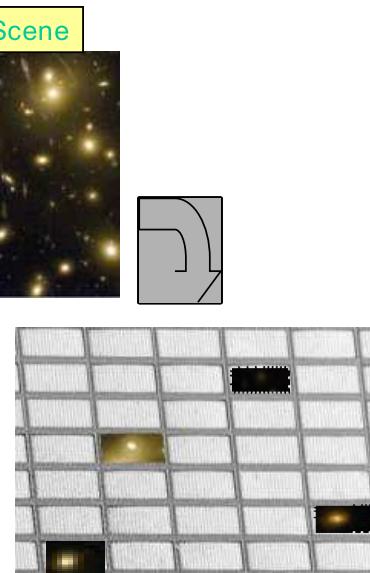


- JWST hardware made in 27 US States: 100% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

# Micro Shutters



Metal Mask/Fixed Slit

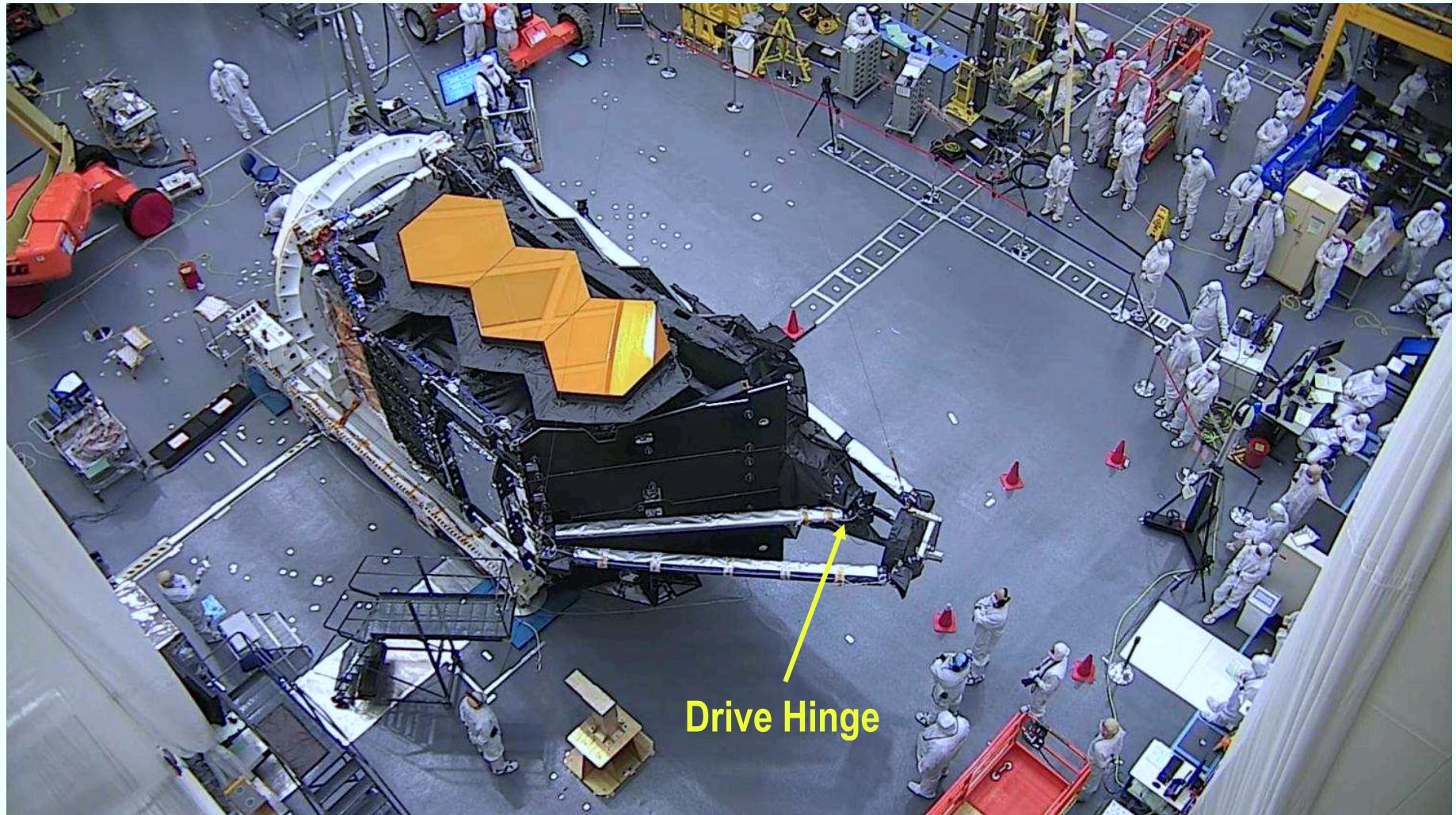




April 2017: Last portrait of JWST at Goddard Space Flight Center (MD).



# SMSS Deployment Sequence (1)

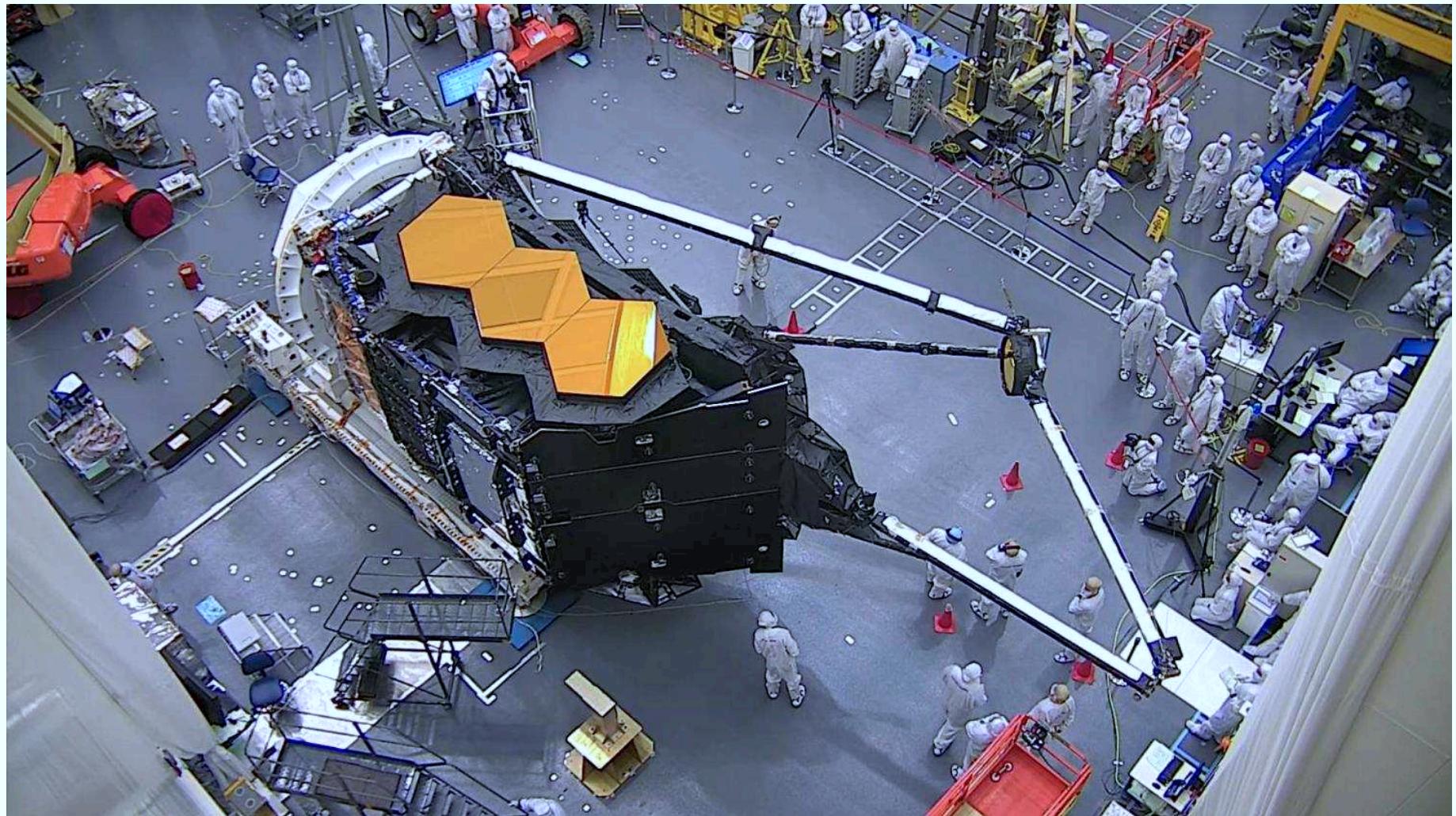


190812 JWST Monthly Telecon 8

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



## SMSS Deployment Sequence (2)

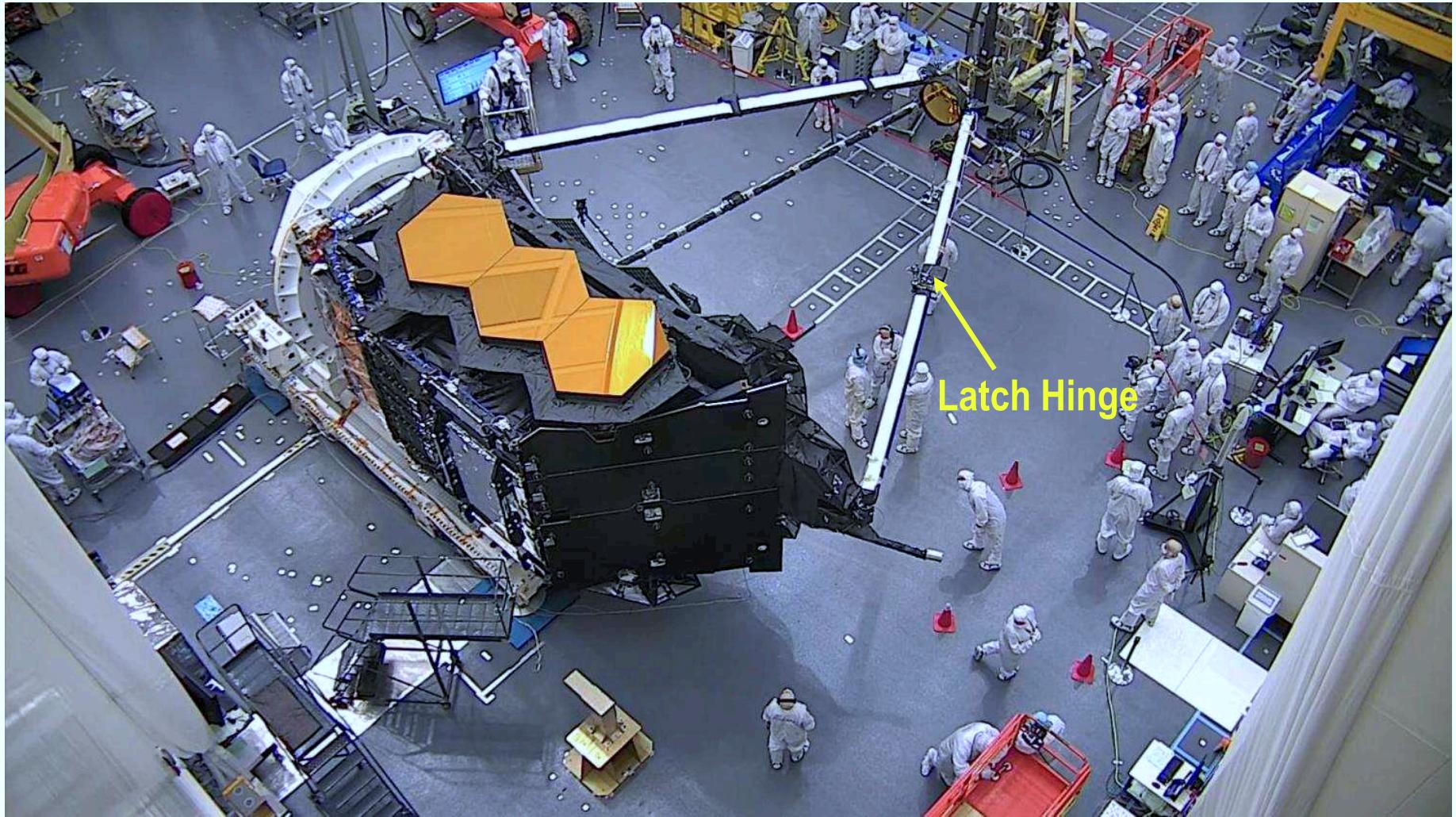


190812 JWST Monthly Telecon 9

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



## SMSS Deployment Sequence (3)



190812 JWST Monthly Telecon 10

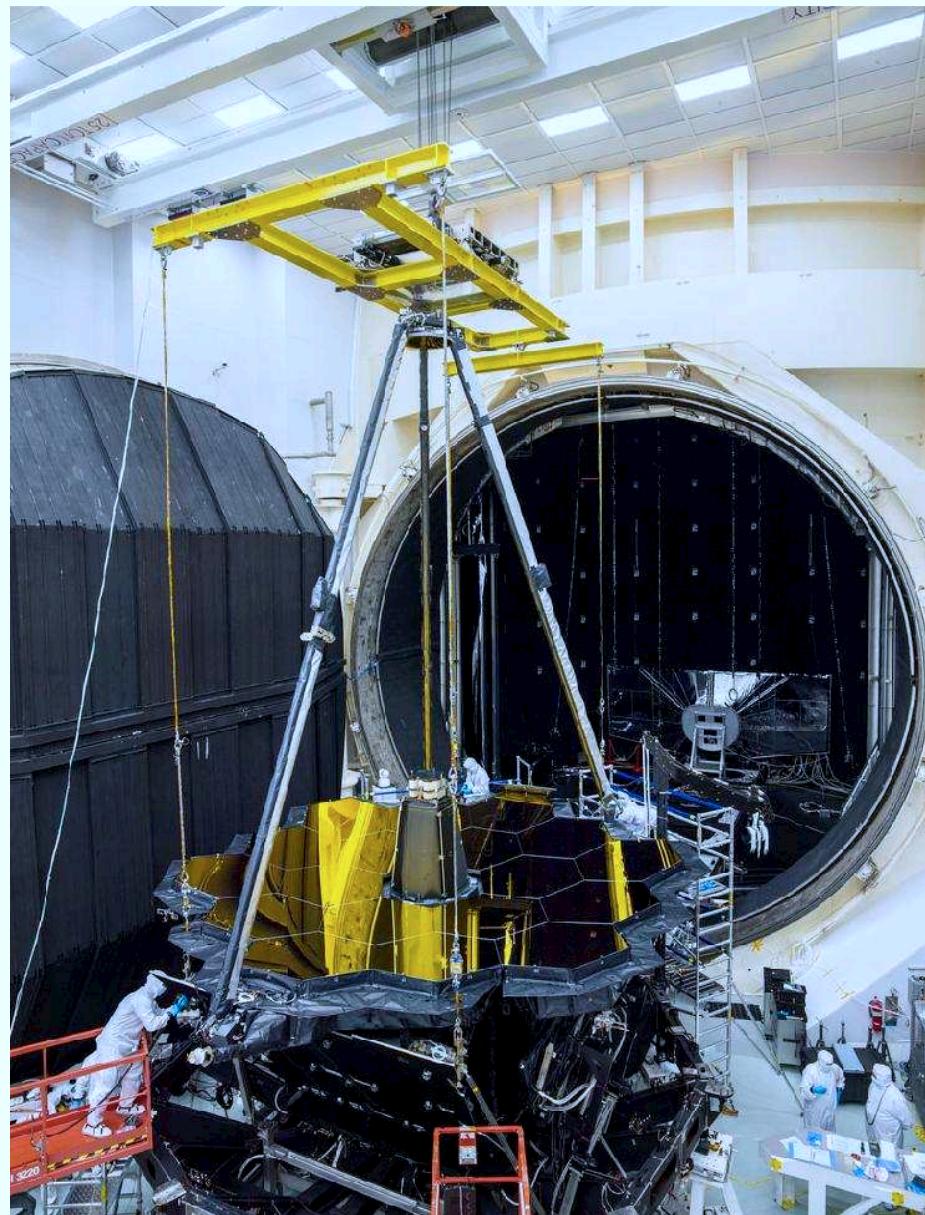
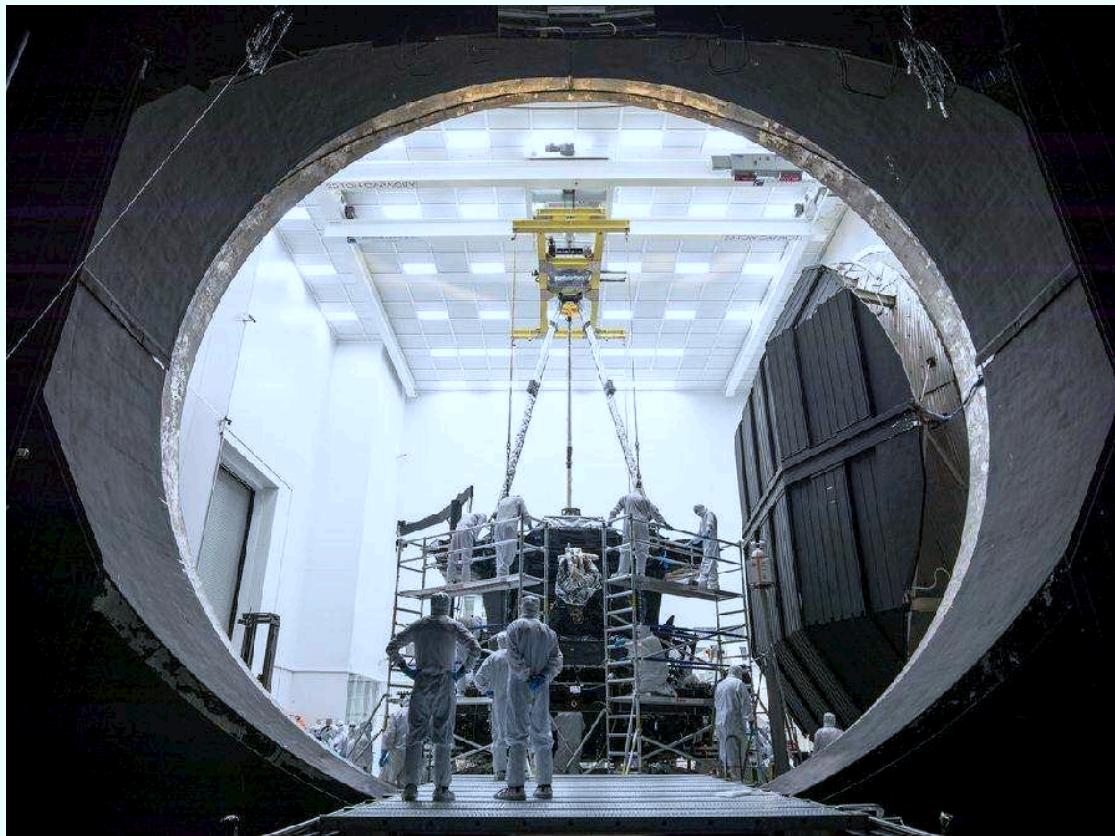
July 2019: Full 1-G deployment of JWST secondary mirror (SM) ...



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

# Program Update: OTIS

NORTHROP GRUMMAN



# Program Updates: Spacecraft and Sunshield

NORTHROP GRUMMAN

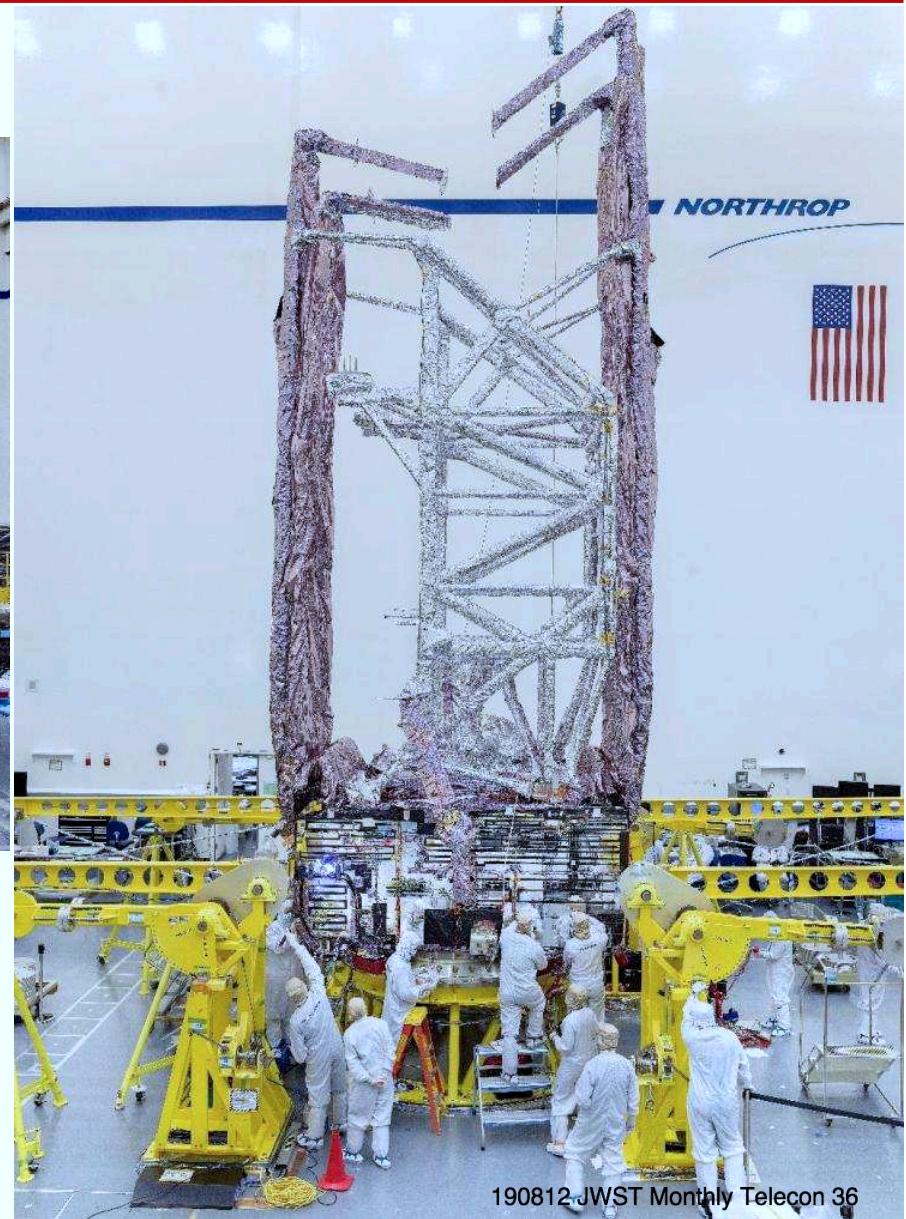


2017–2018: JWST Flight Sunshield assembled and tested at Northrop.



# SCE to Elephant Stand

NORTHROP GRUMMAN



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



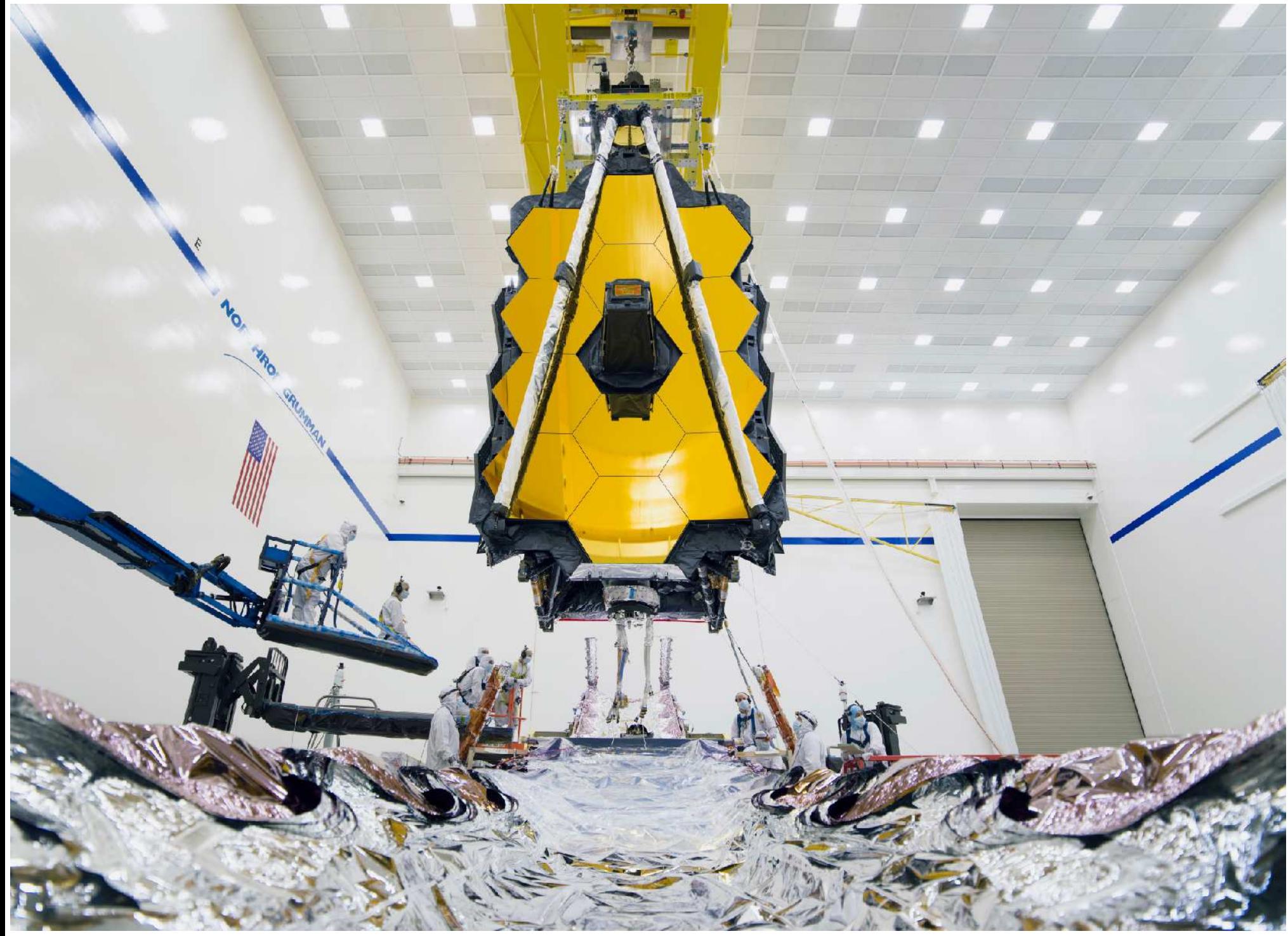
# SMSS Deployment

NORTHROP GRUMMAN



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>

190909-JWST Monday Telecon 11

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



200511 JWST Monthly Telecon 13

May 2020: Solar Array deployment with gravity off-loading



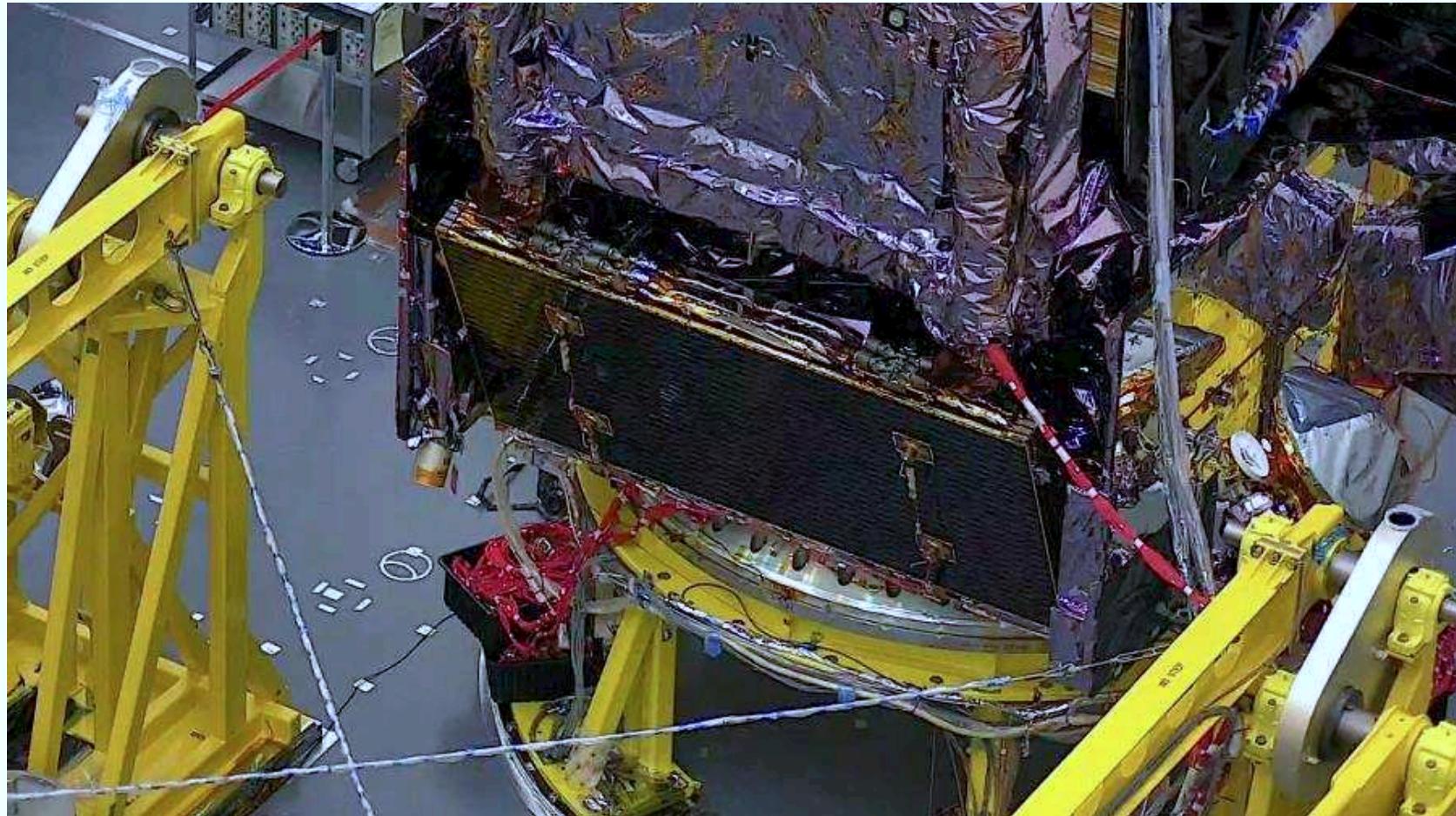
# Solar Array Deployment 3



200511 JWST Monthly Telecon 14

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

## 7/26/20: Solar Array Installed for Environments



5

Approved for Public Release; NG20-1503  
200810 JWST Monthly Telecon Man.

May 2020: Solar Array as installed on JWST Observatory



## 5/28/20: DTA Deployment



Approved for Public Release; NG20-106  
200608 JWST Monthly Telecon 26

June 2020: Deployable Tower Assembly test



## 5/28/20: DTA Deployment



Approved for Public Release; NG20-106  
200608 JWST Monthly Telecon 27

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



## 5/29/20: DTA Deployment



Approved for Public Release; NG20-106  
200608 JWST Monthly Telecon 28

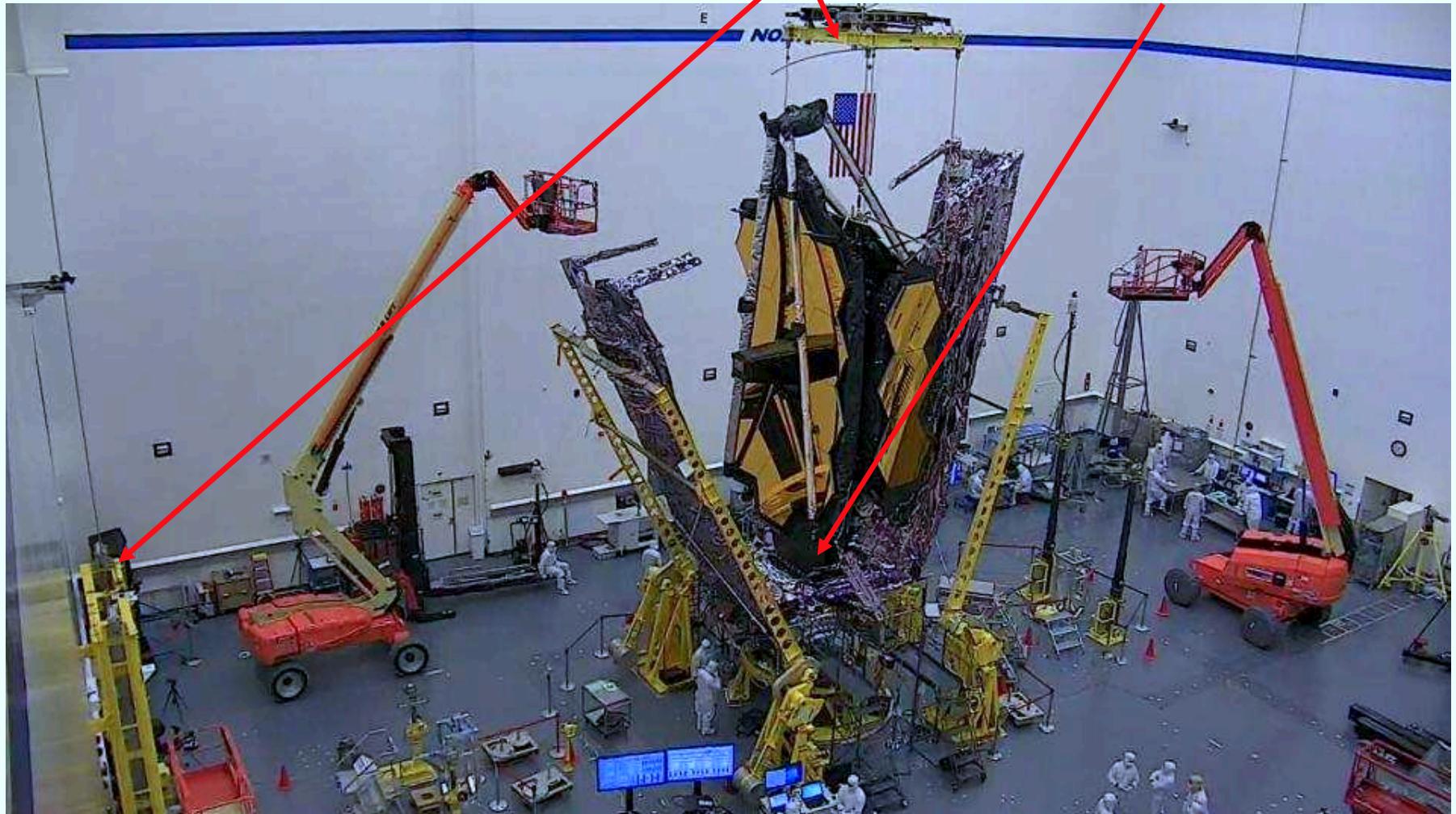
June 2020: Deployable Tower Assembly motor tested in 1G



# DTA Stow 1

Offloading System

Deployable Tower Assembly



200713 JWST Monthly Telecon 9

July 2020: Deployable Tower Assembly stow for launch



# DTA Stow 2

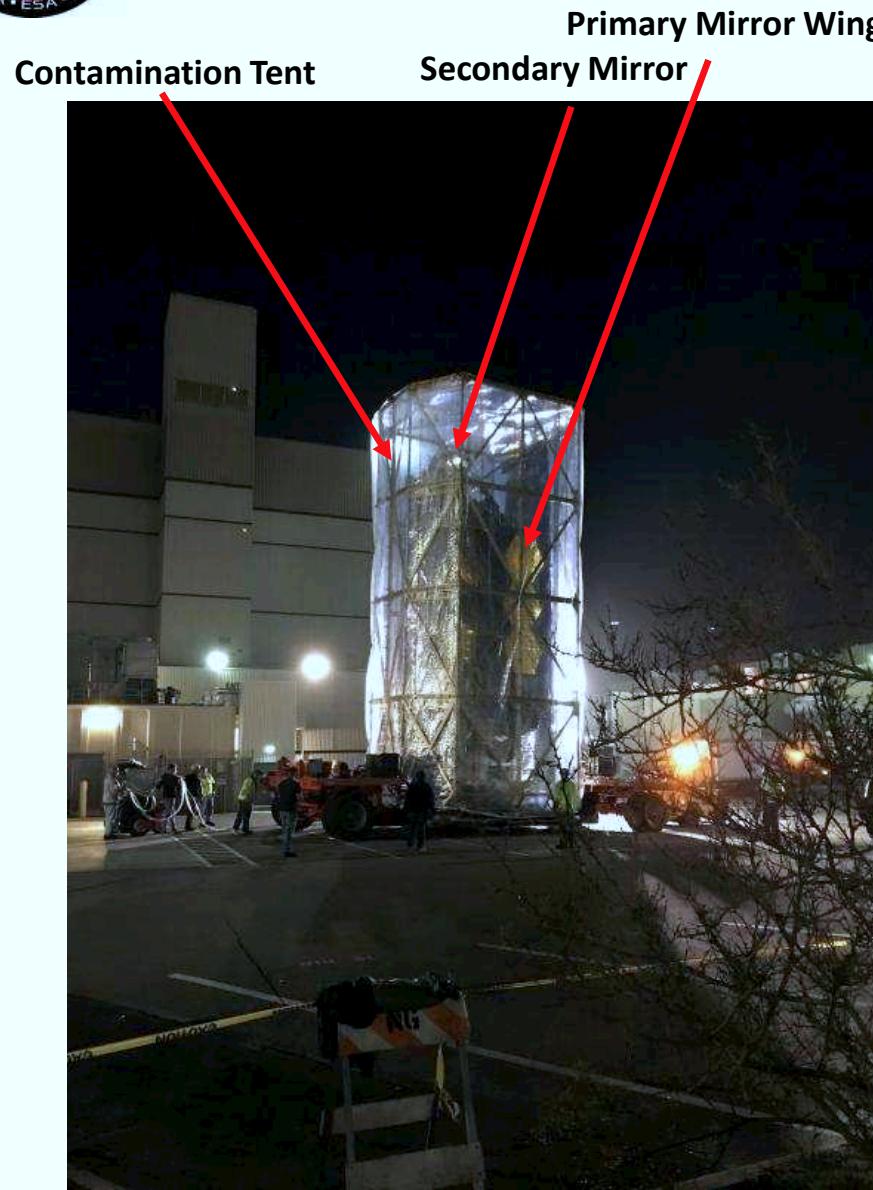


200713 JWST Monthly Telecon 10

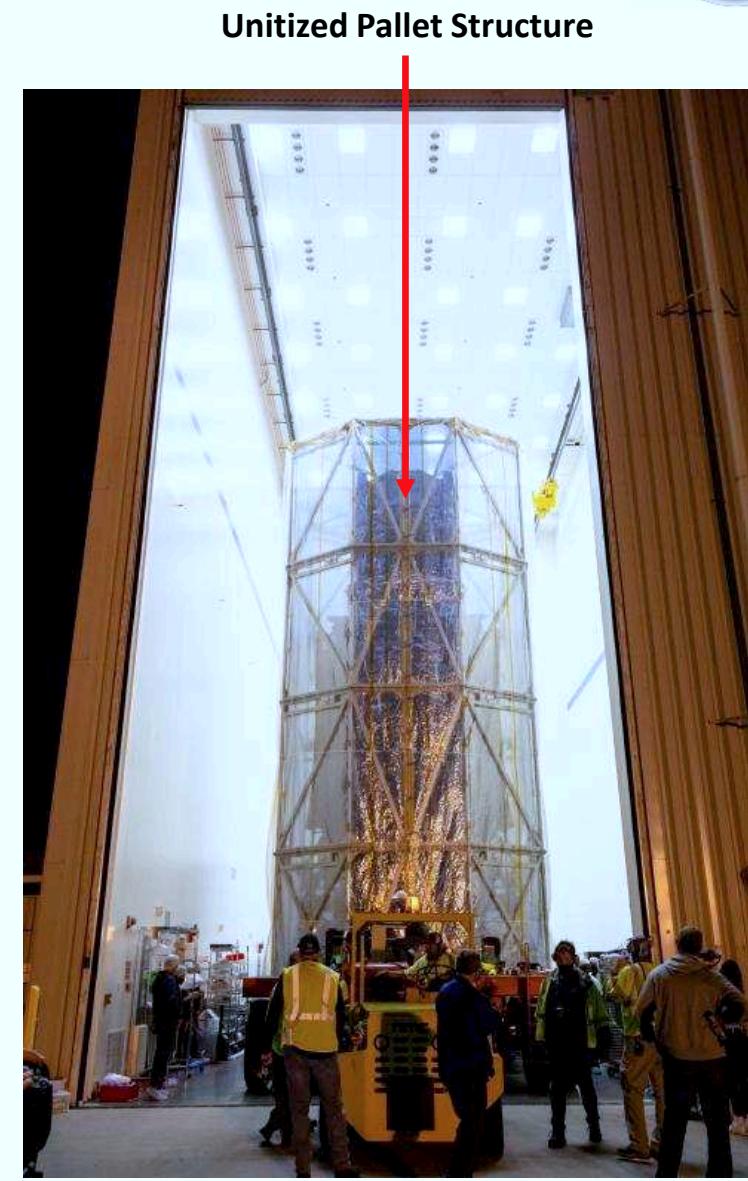
July 2020: Deployable Tower Assembly stowed for launch



# Transport to the Large Acoustic Test Facility



En route through the Space Park, Credit: NGSS



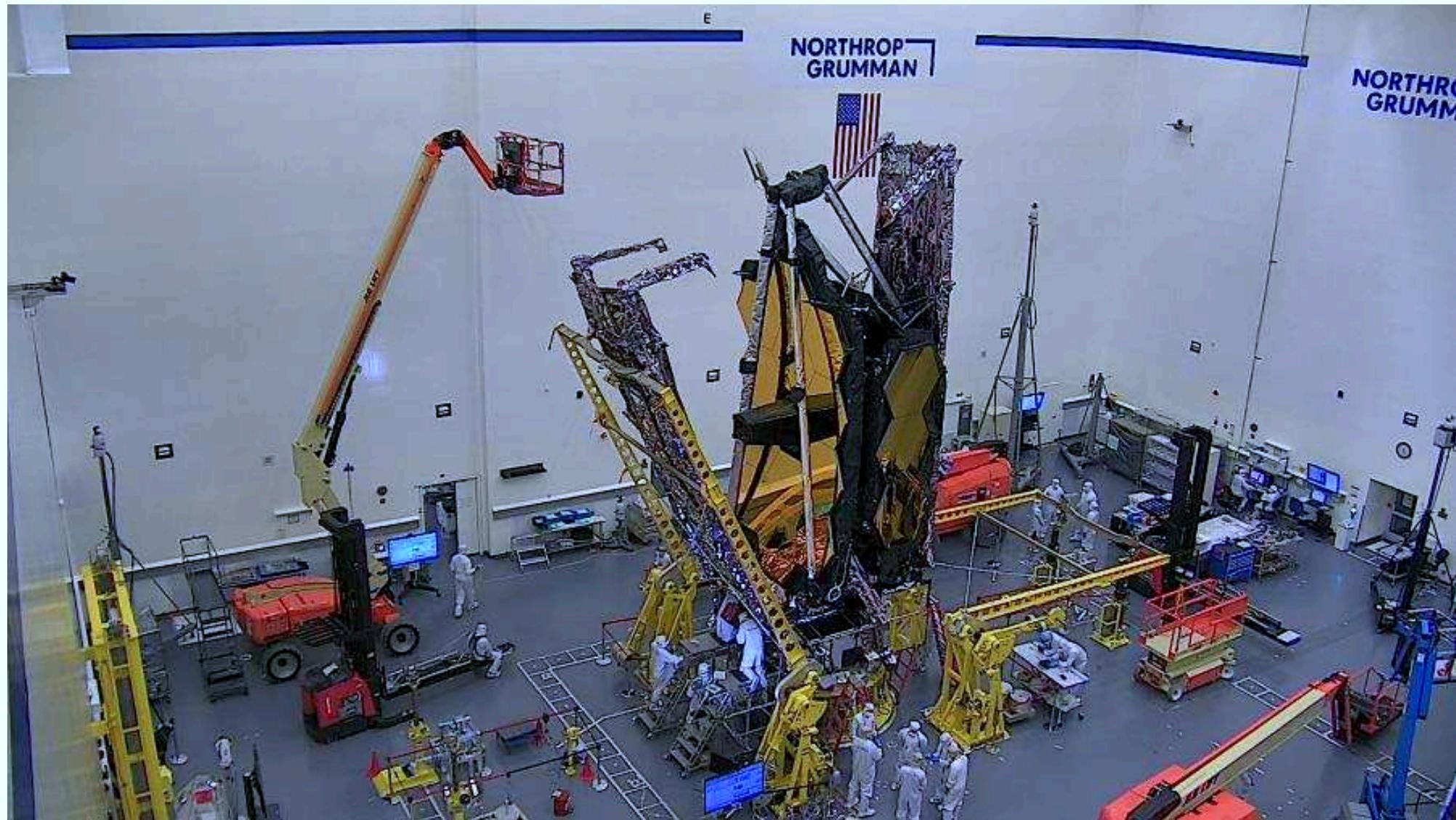
Arriving at the LATF Airlock, Credit: NGSS  
200914 JWST Monthly Telecon 12

Aug 2020: Transport of JWST into Northrop acoustic chamber

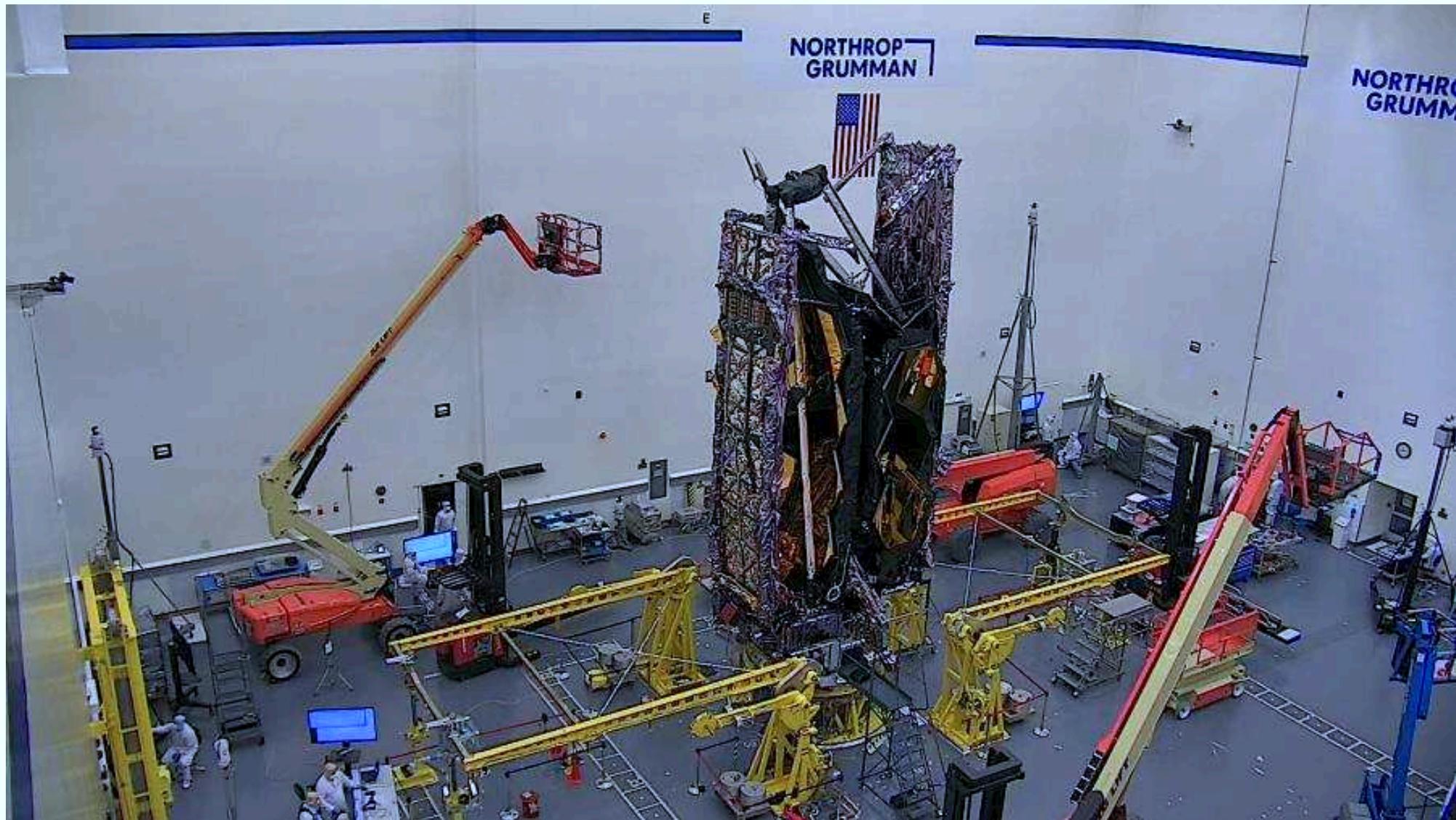
# 7/13/21: AFT UPS Full Stow



# 7/13/21: AFT UPS Full Stow



# 7/14/21: FWD UPS Full Stow



July 2021: Forward UPS stowed for launch



(beautiful)  
**The James Webb  
Space Telescope**

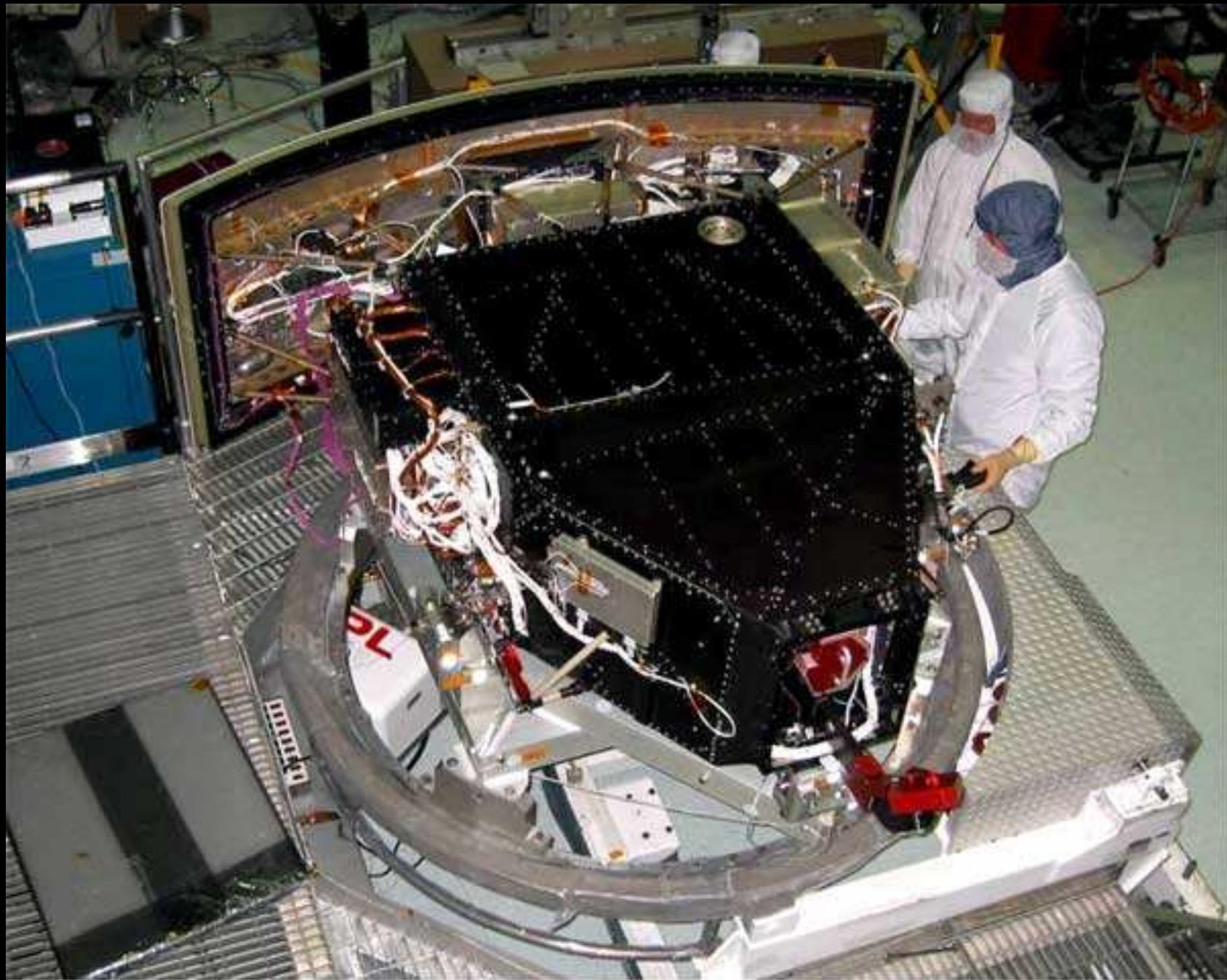
**Stowed for Launch**



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<sup>2</sup> with 0.07–0.15" images from 0.2–1.7μm (UVUBVizYJH). JWST adds 0.05–0.2" FWHM imaging to AB≈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:



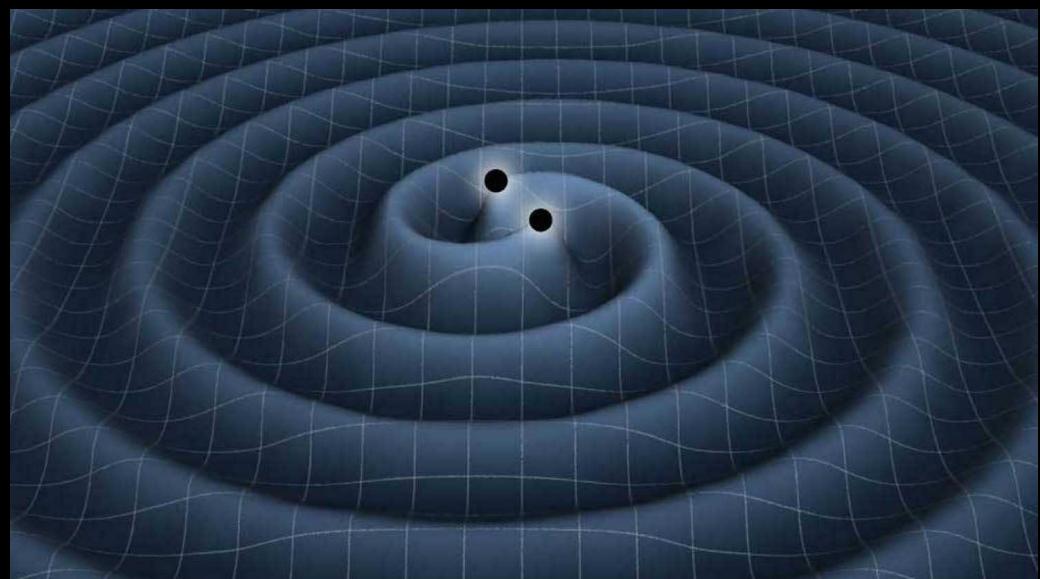
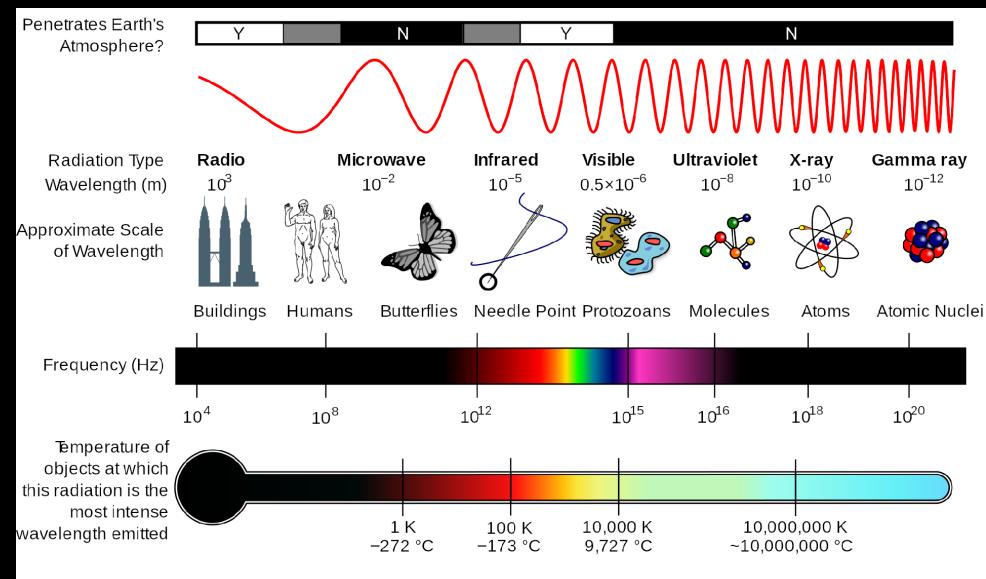
In solids: Earthquakes



In liquids: Surf!



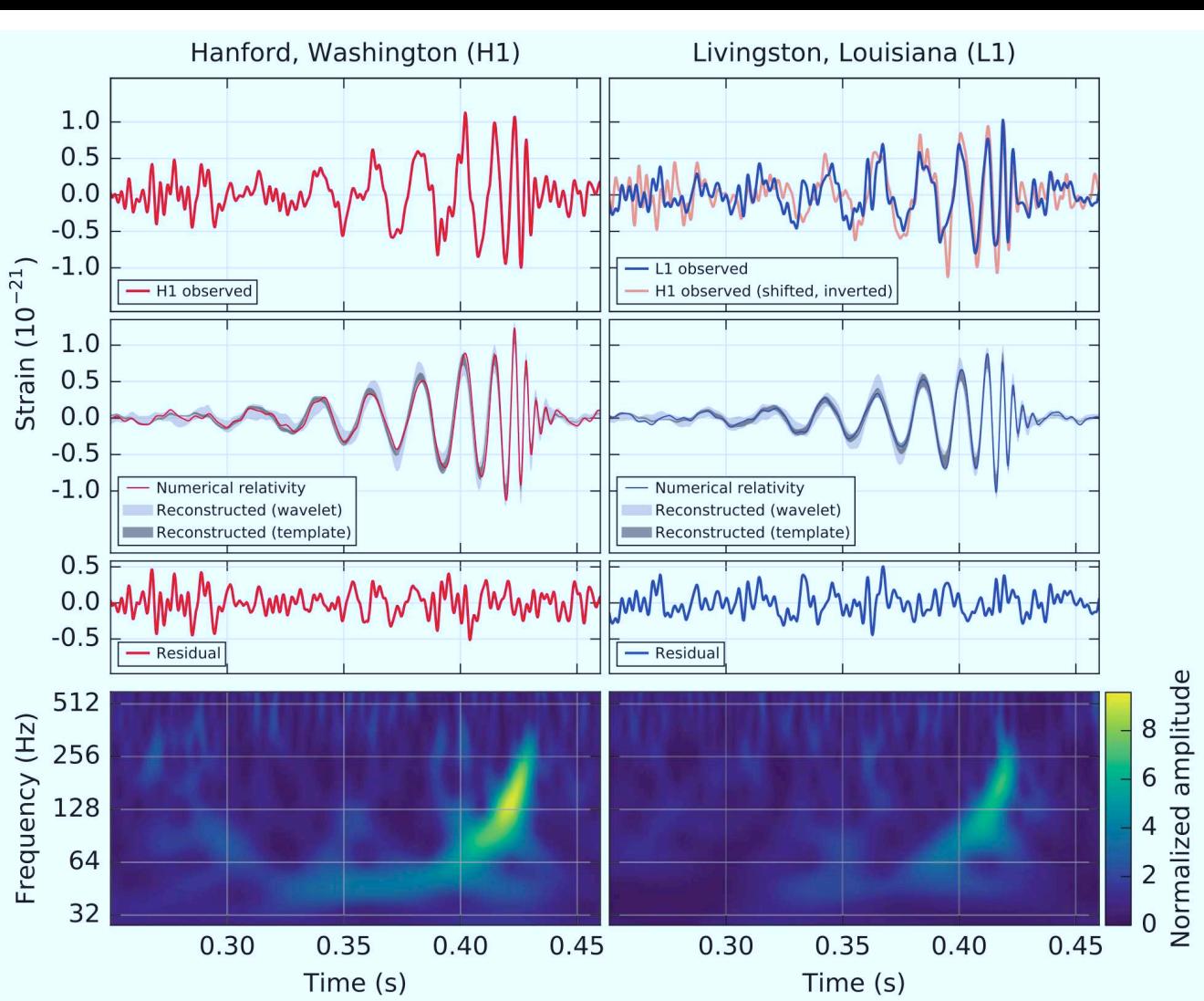
In gasses: Sound



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

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



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

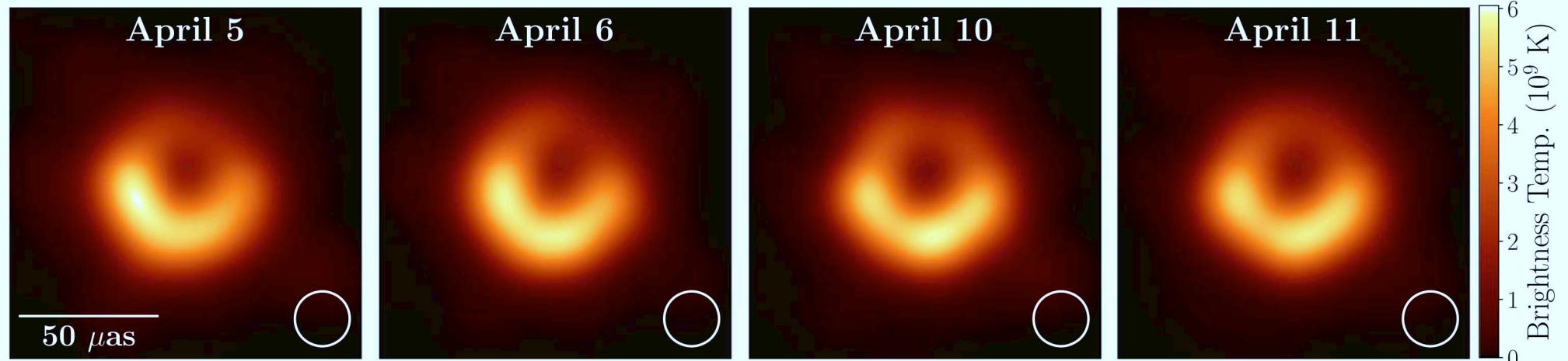
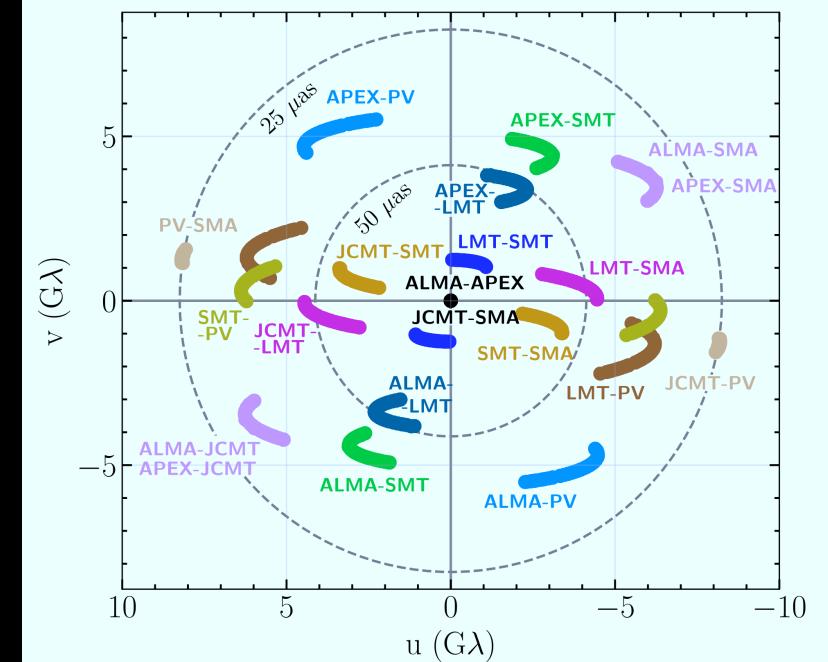
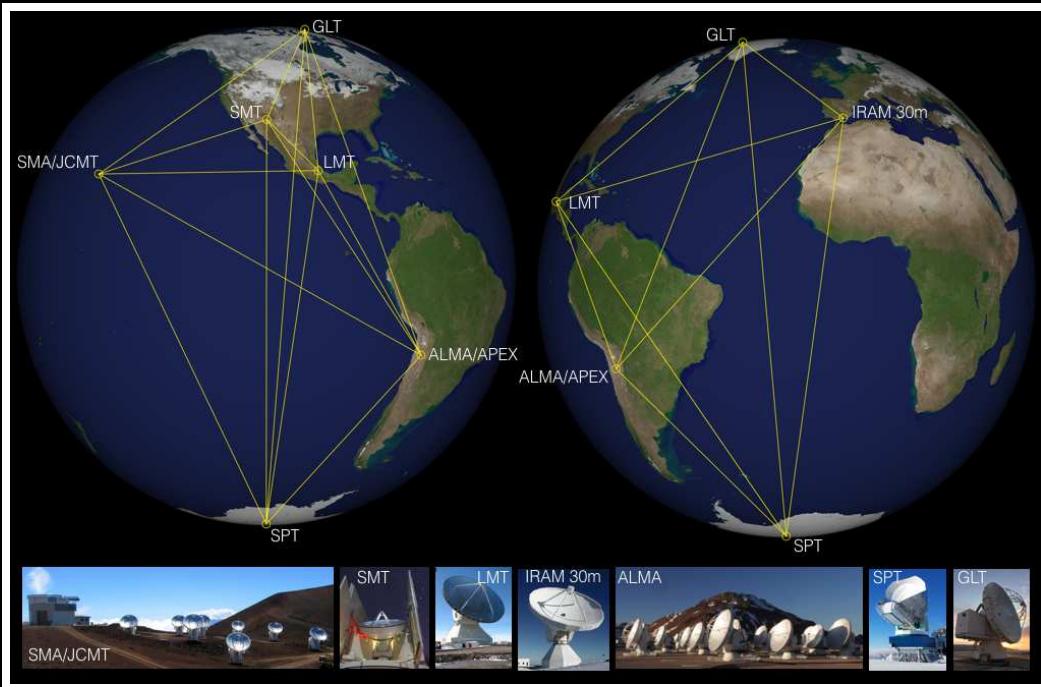
# Elliptical galaxy M87 with Active Galactic Nucleus (AGN) and relativistic jet:



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

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

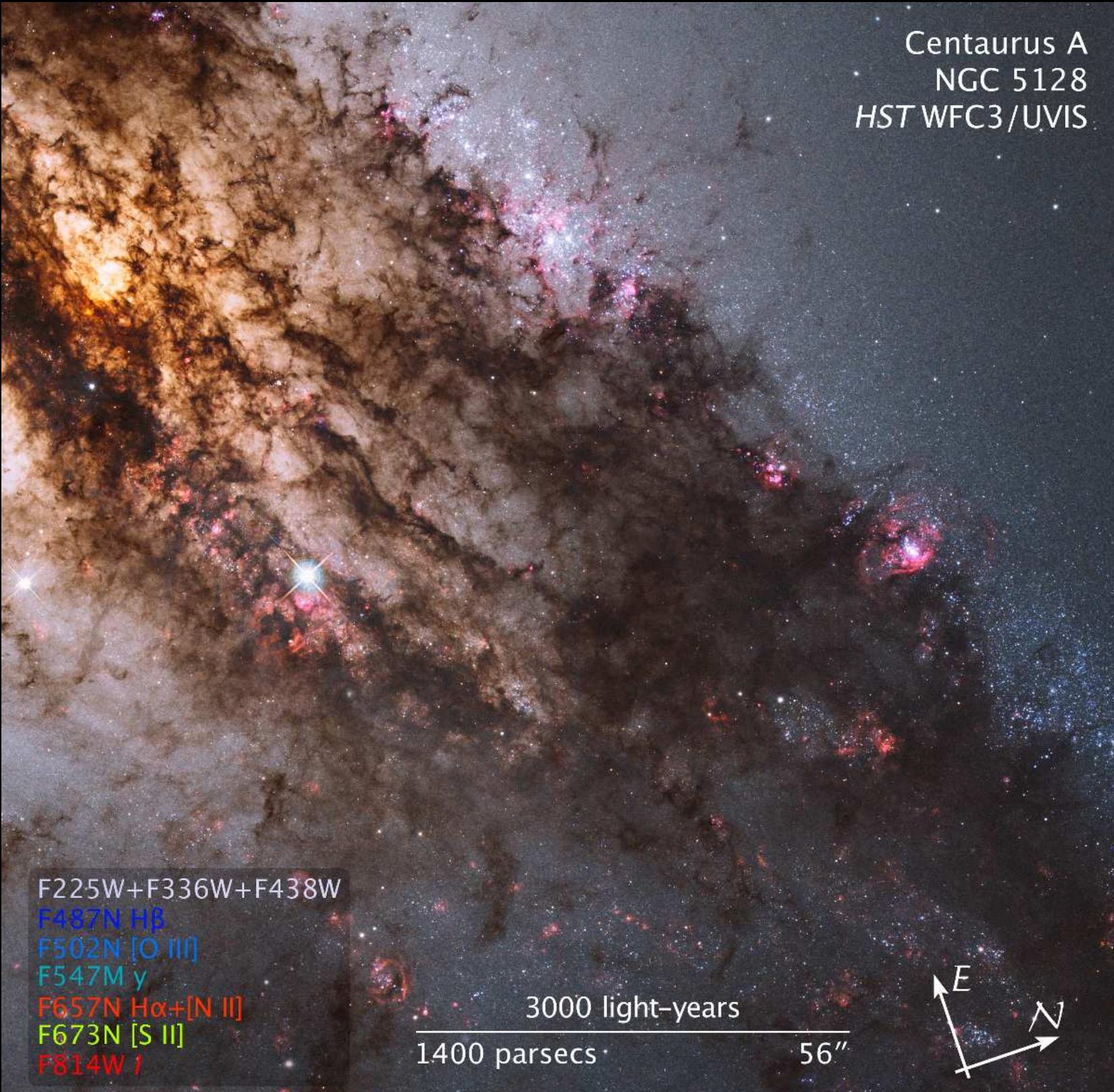
~0.5% of the baryonic mass, but produce most of the photons!



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

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

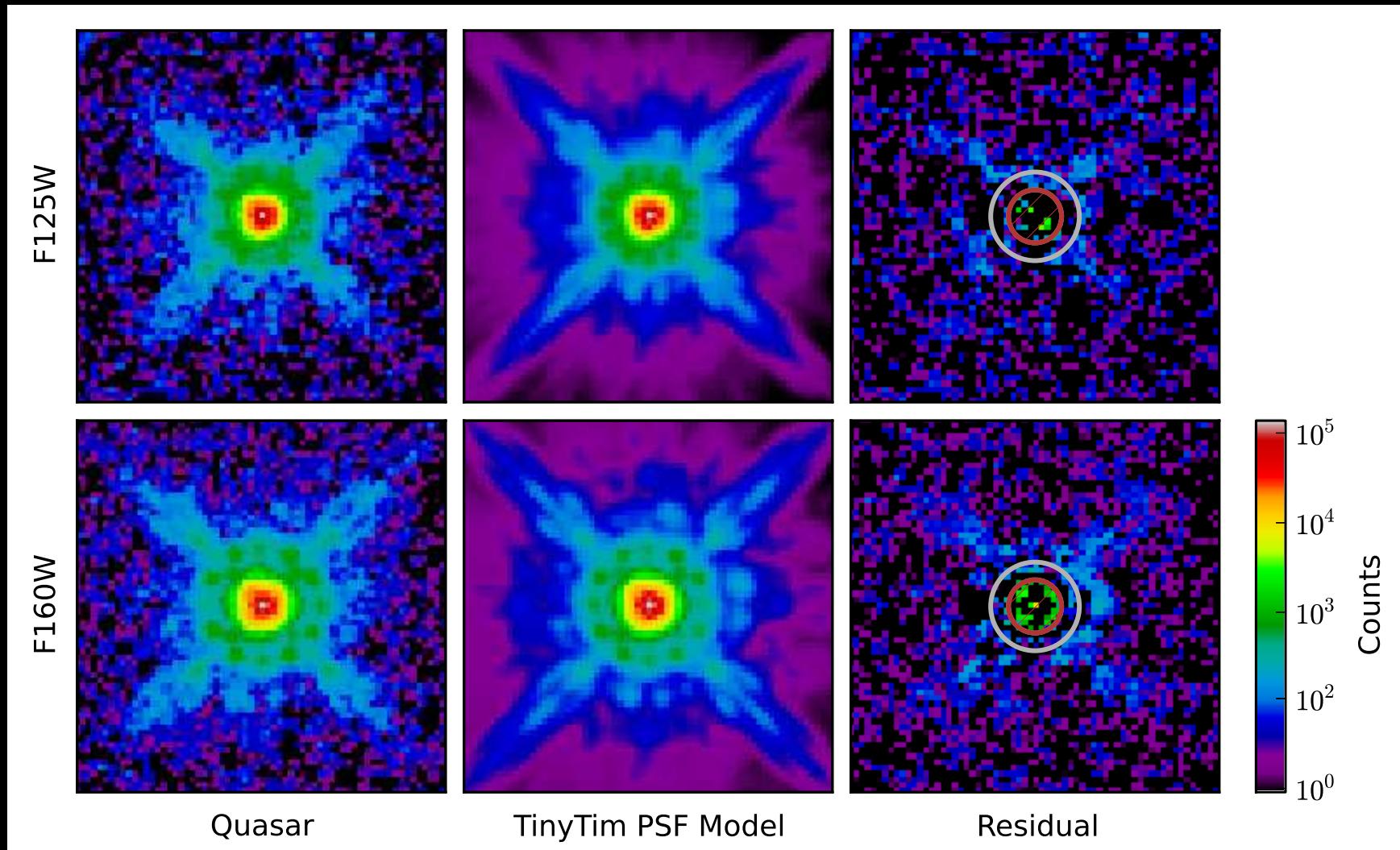
Centaurus A  
NGC 5128  
HST WFC3/UVIS





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

- Quasars: Centers of galaxies with feeding supermassive blackholes:

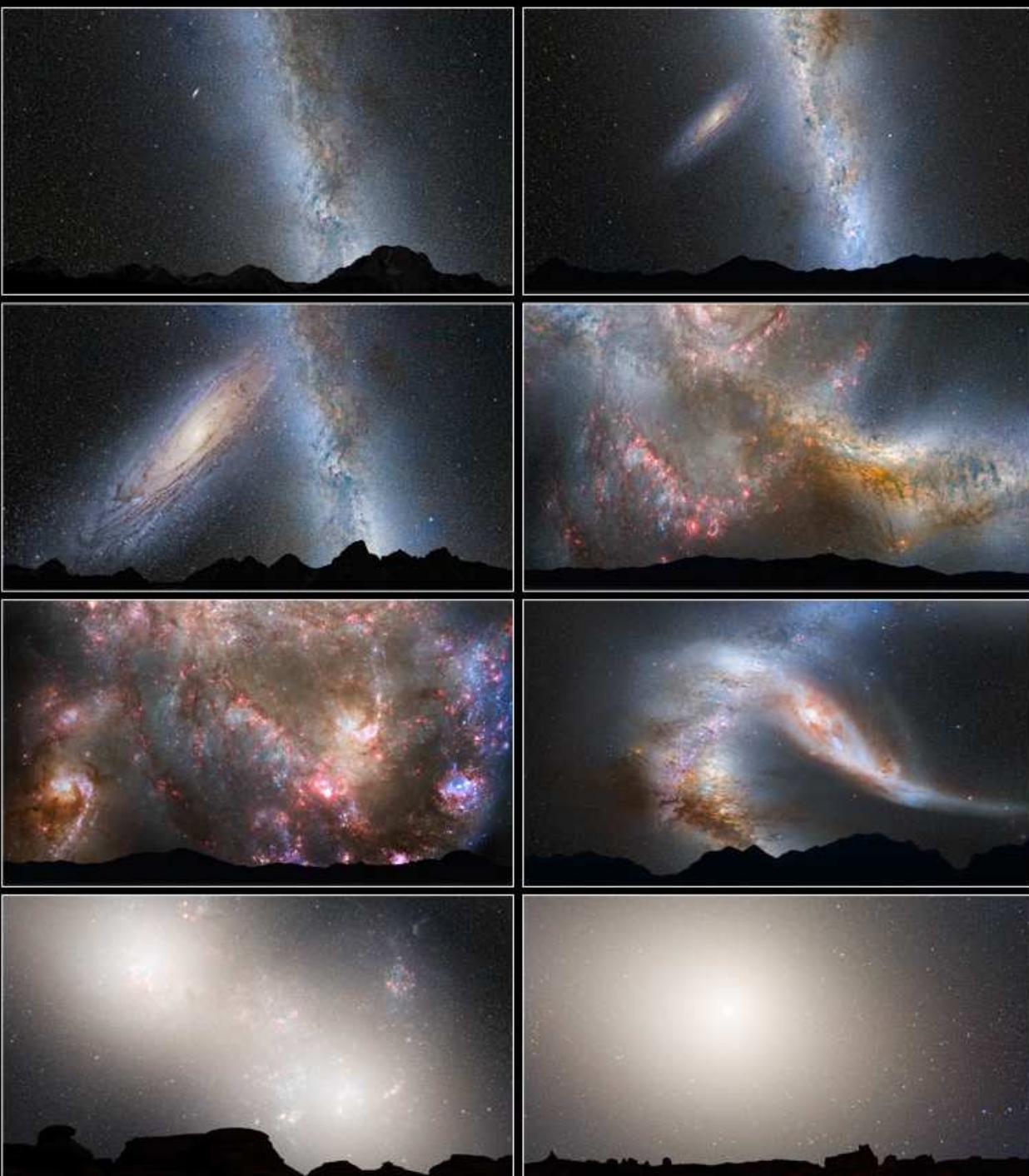


- Hubble IR-images of the most luminous Quasar known in the universe.
- Seen at redshift 6.42 (universe 7.42× smaller than today), 900 Myr old!
- Contains  $10^{14}$  solar luminosities within a region as small as Pluto's orbit!
- A feeding monster blackhole ( $>3 \times 10^9$  solar mass) 900 Myr after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

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



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



Will this ever happen to our own Galaxy?

YES! Hubble showed no lateral motion of Andromeda:  
Approaches at  $-110$  km/s.

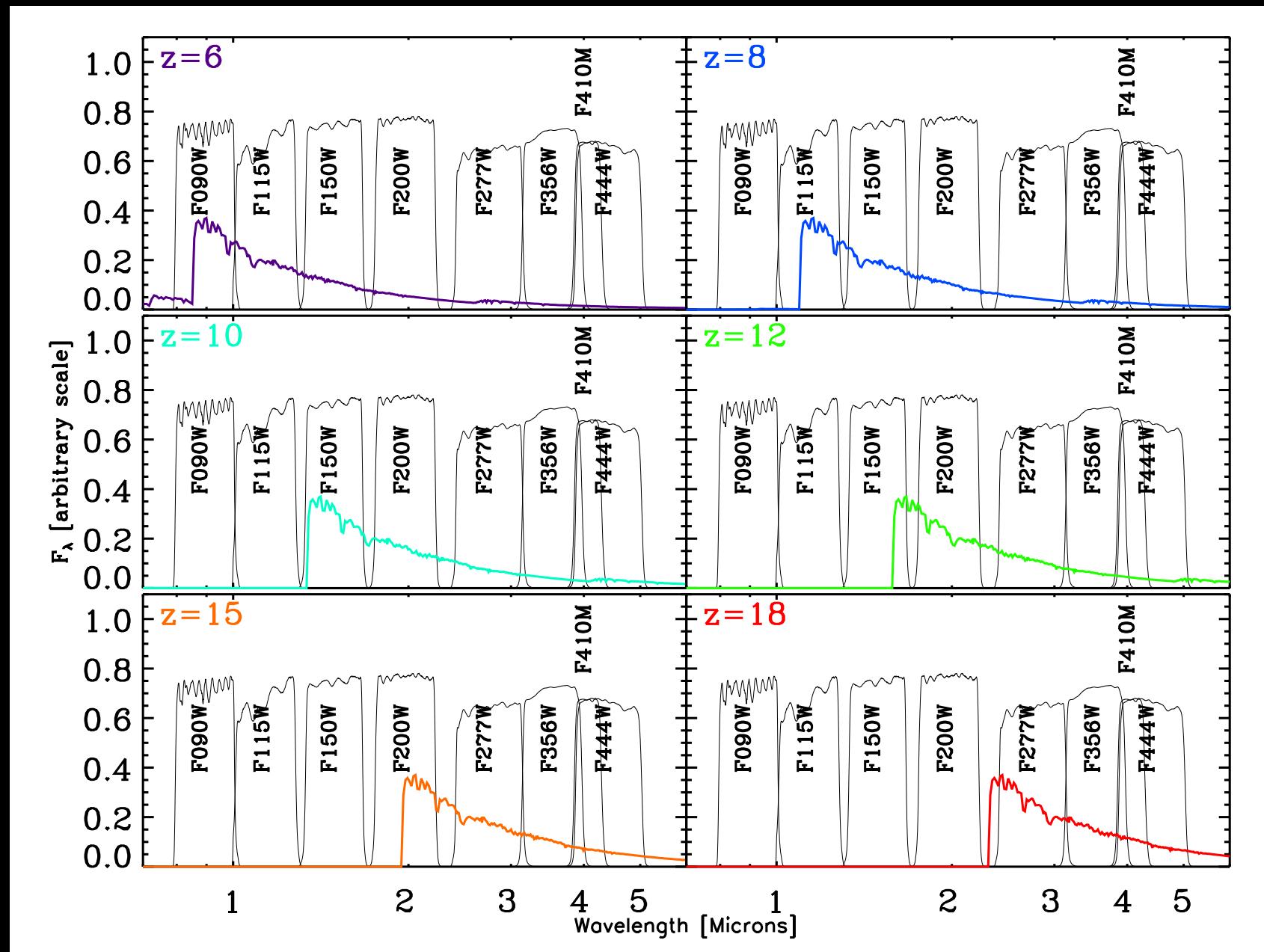
Hence, Andromeda will merge with Milky Way!

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

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

Illustration Sequence of the Milky Way and Andromeda Galaxy Colliding

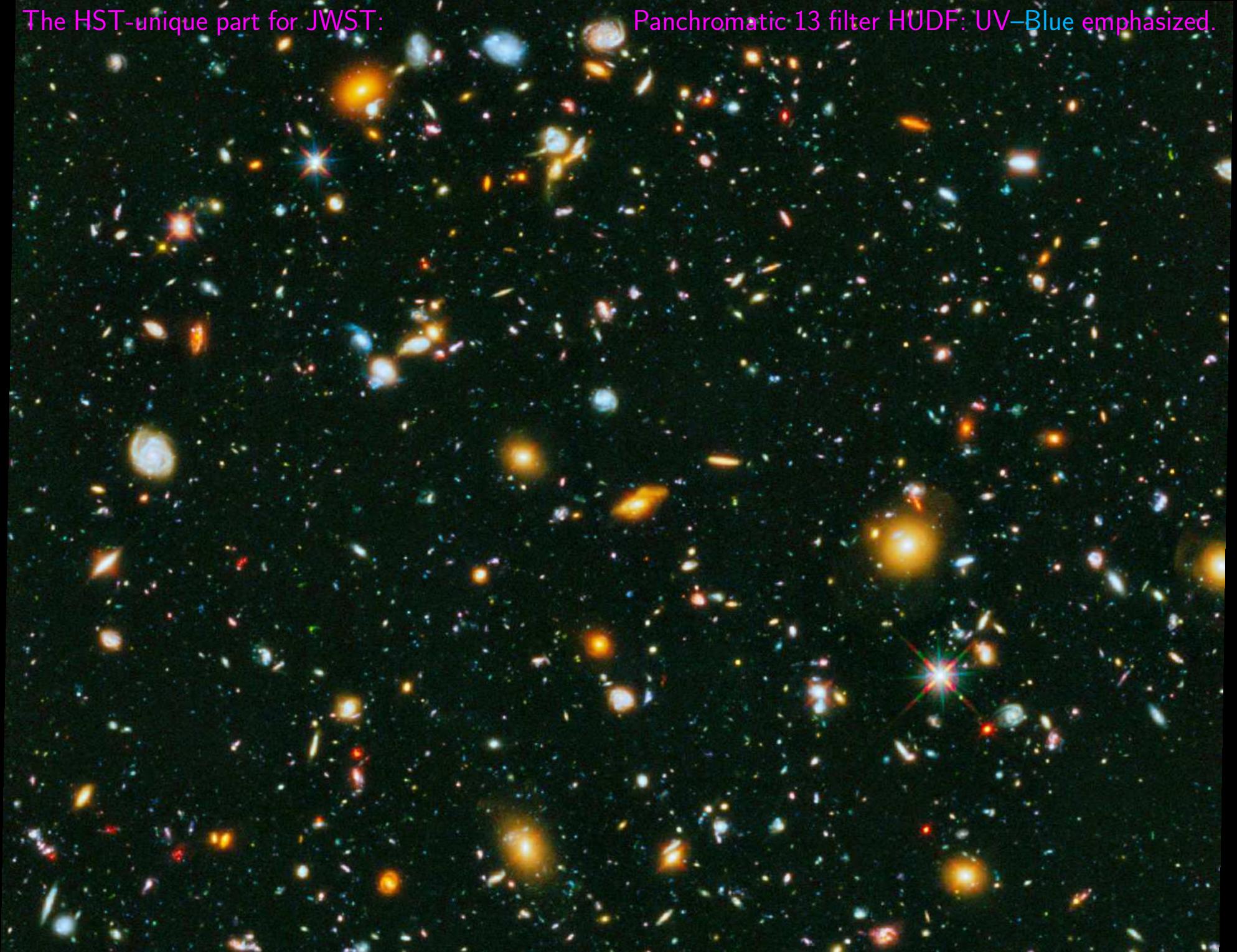
### 3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



- Can't beat redshift: to see First Light, must observe near-mid IR.  
⇒ This is why JWST needs NIRCam at 0.8–5  $\mu\text{m}$  and MIRI at 5–28  $\mu\text{m}$ .

The HST-unique part for JWST:

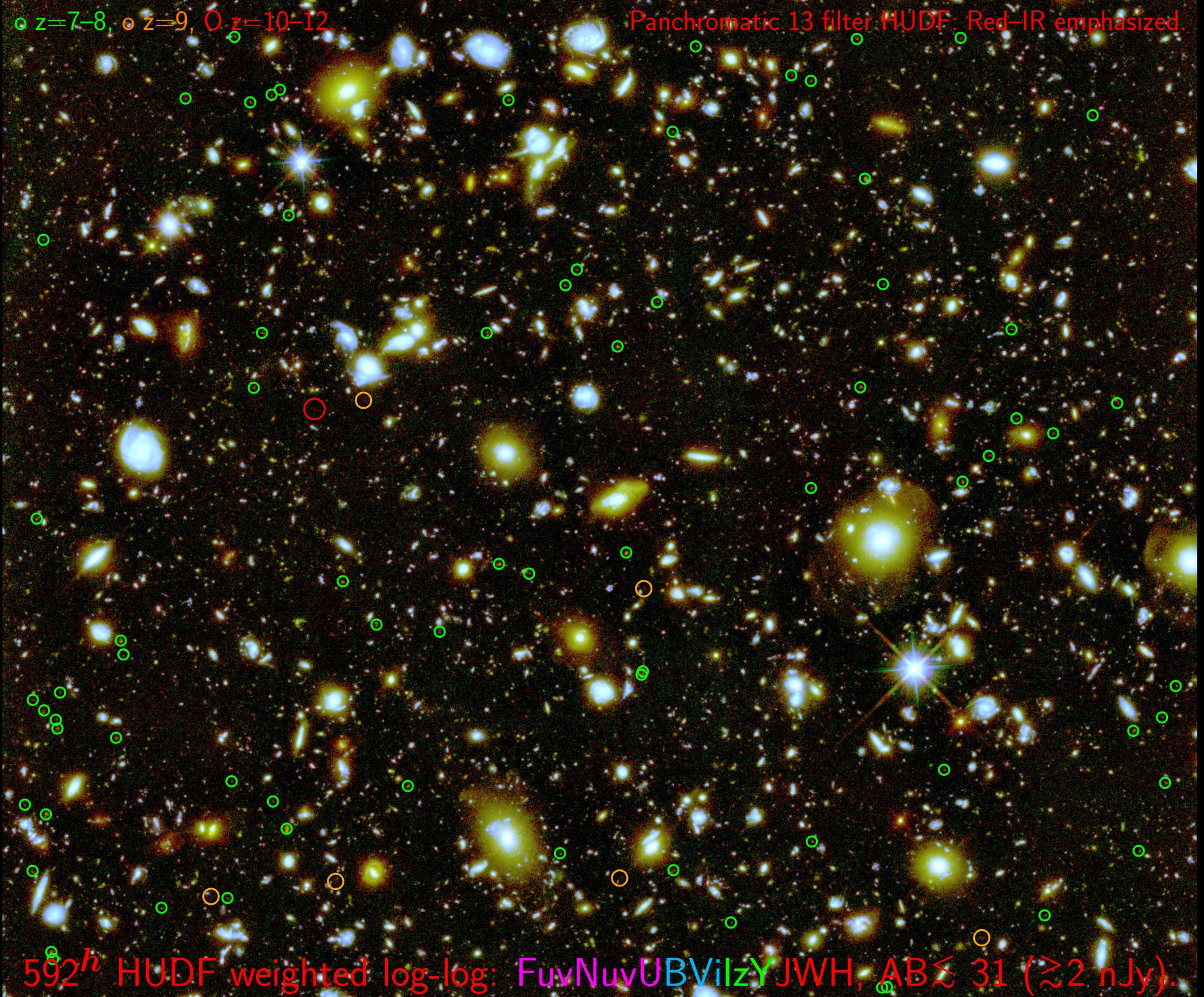
Panchromatic 13 filter HUDF: UV–Blue emphasized.



592<sup>h</sup> HUDF weighted log-log: F<sub>UV</sub>N<sub>UV</sub>U<sub>B</sub>V<sub>I</sub>zYJWH, AB $\lesssim$ 28–31 ( $\gtrsim$ 2 nJy).

○  $z=7-8$ , ○  $z=9$ , ○  $z=10-12$ .

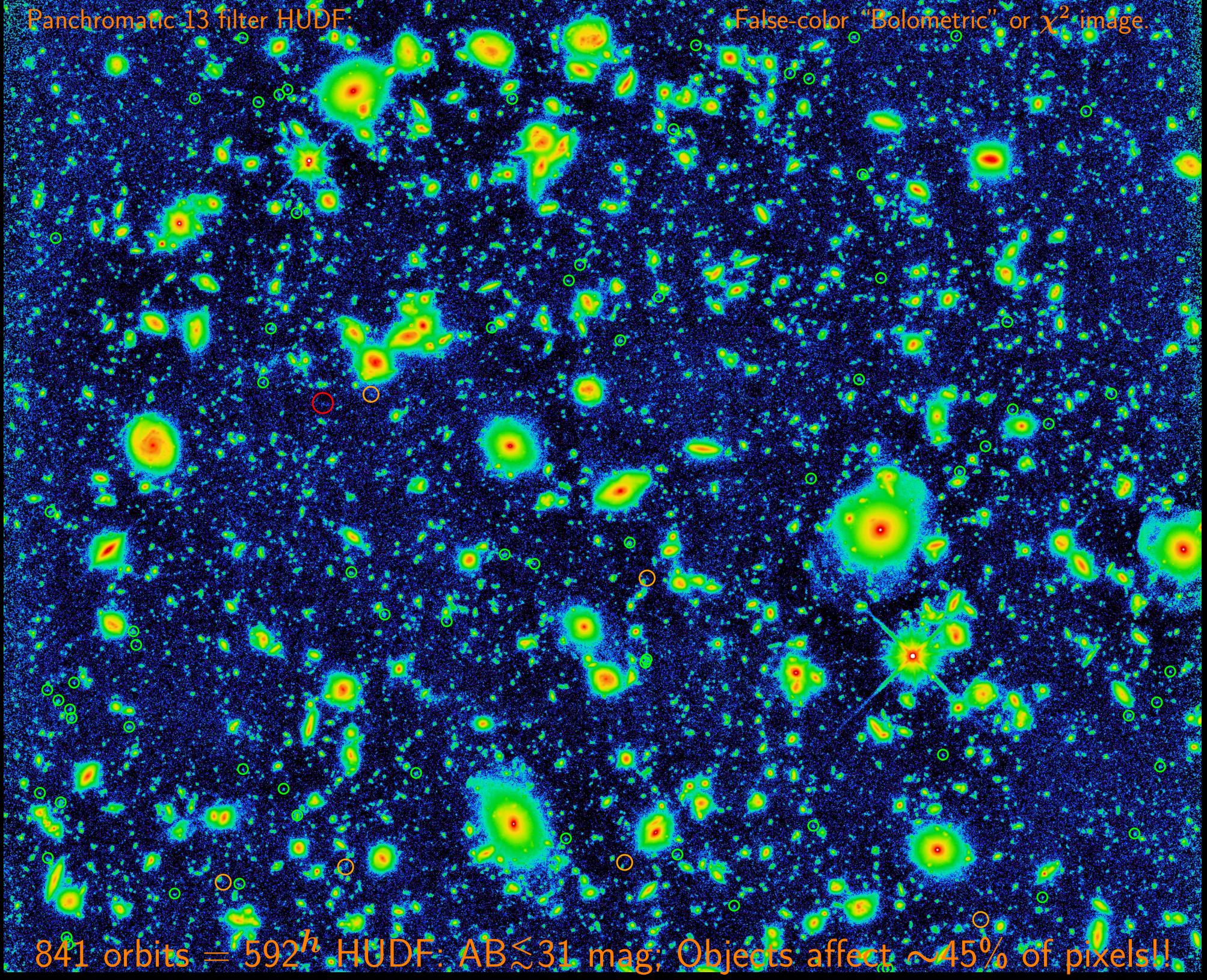
Panchromatic 13 filter HUDF; Red-IR emphasized.



$592^h$  HUDF weighted log-log: F<sub>UV</sub>N<sub>UV</sub>U<sub>BV</sub>I<sub>zYJWH</sub>, AB  $\lesssim 31$  ( $\gtrsim 2$  nJy).

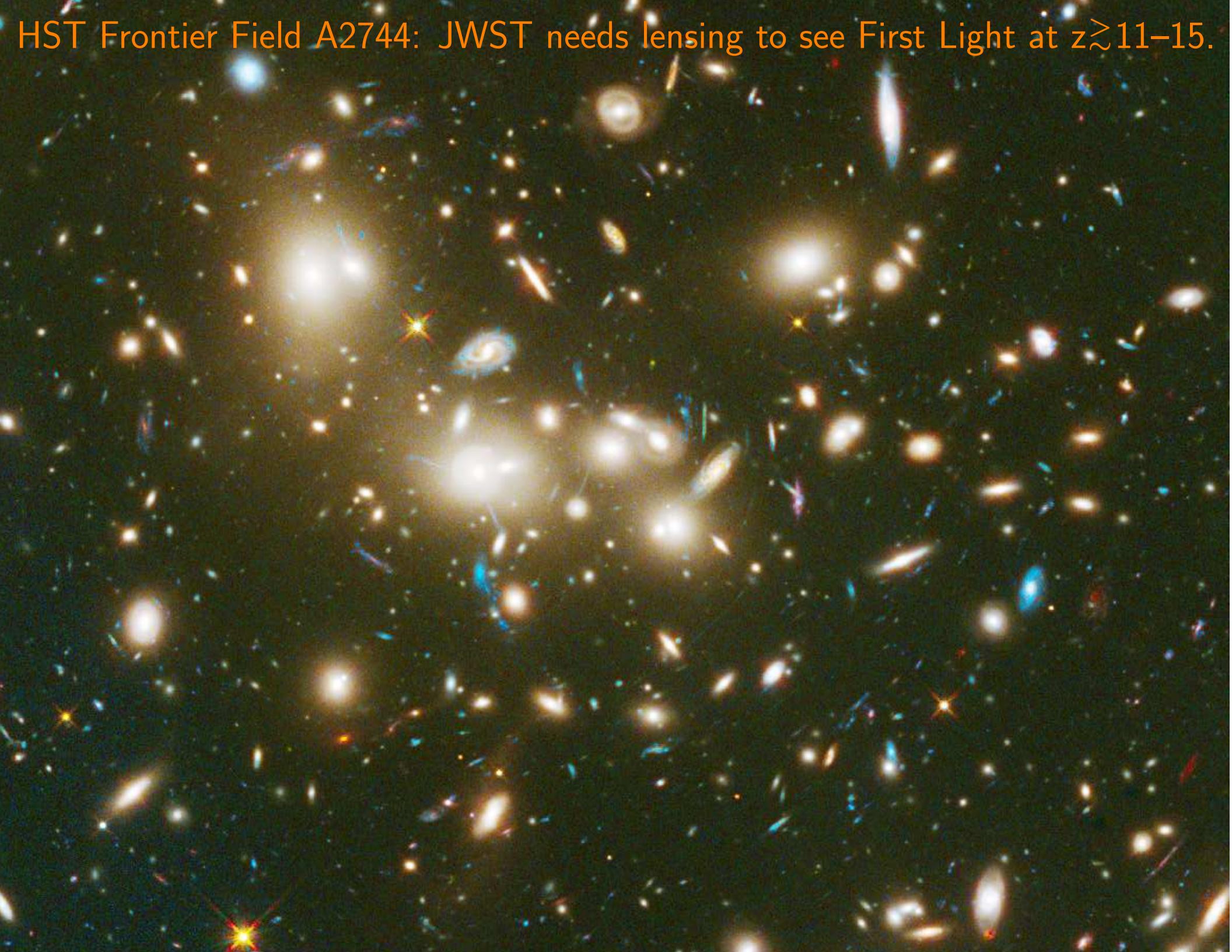
Panchromatic 13 filter HUDF

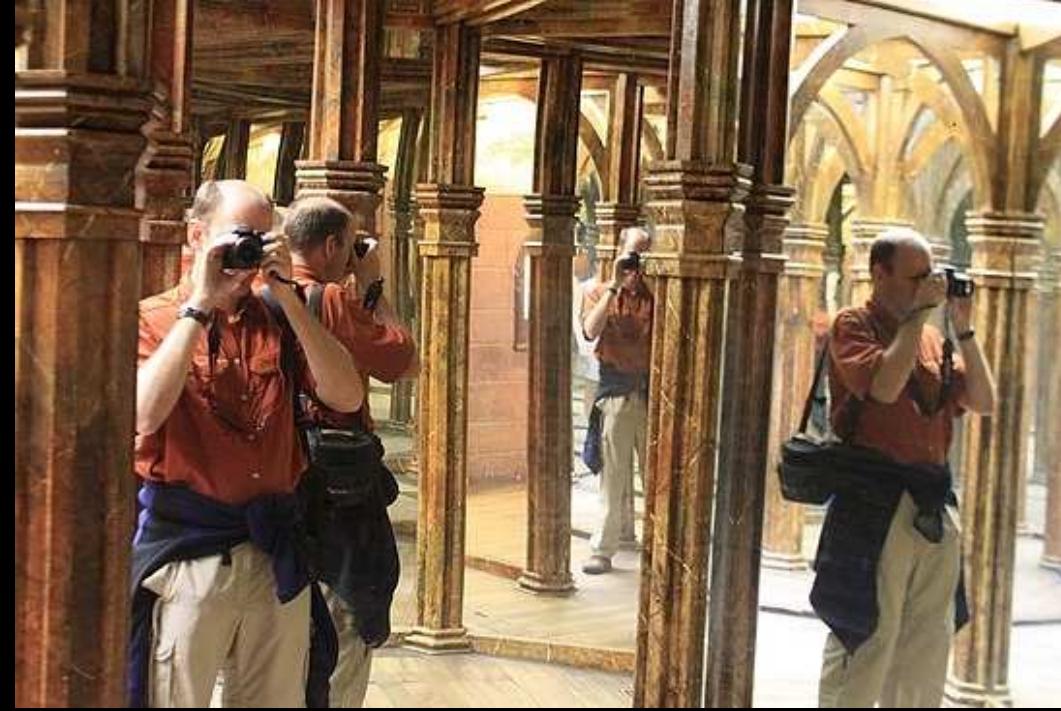
False-color "Bolometric" or  $\chi^2$  image.



841 orbits = 592<sup>h</sup> HUDF: AB  $\lesssim$  31 mag; Objects affect  $\sim$  45% of pixels!!

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



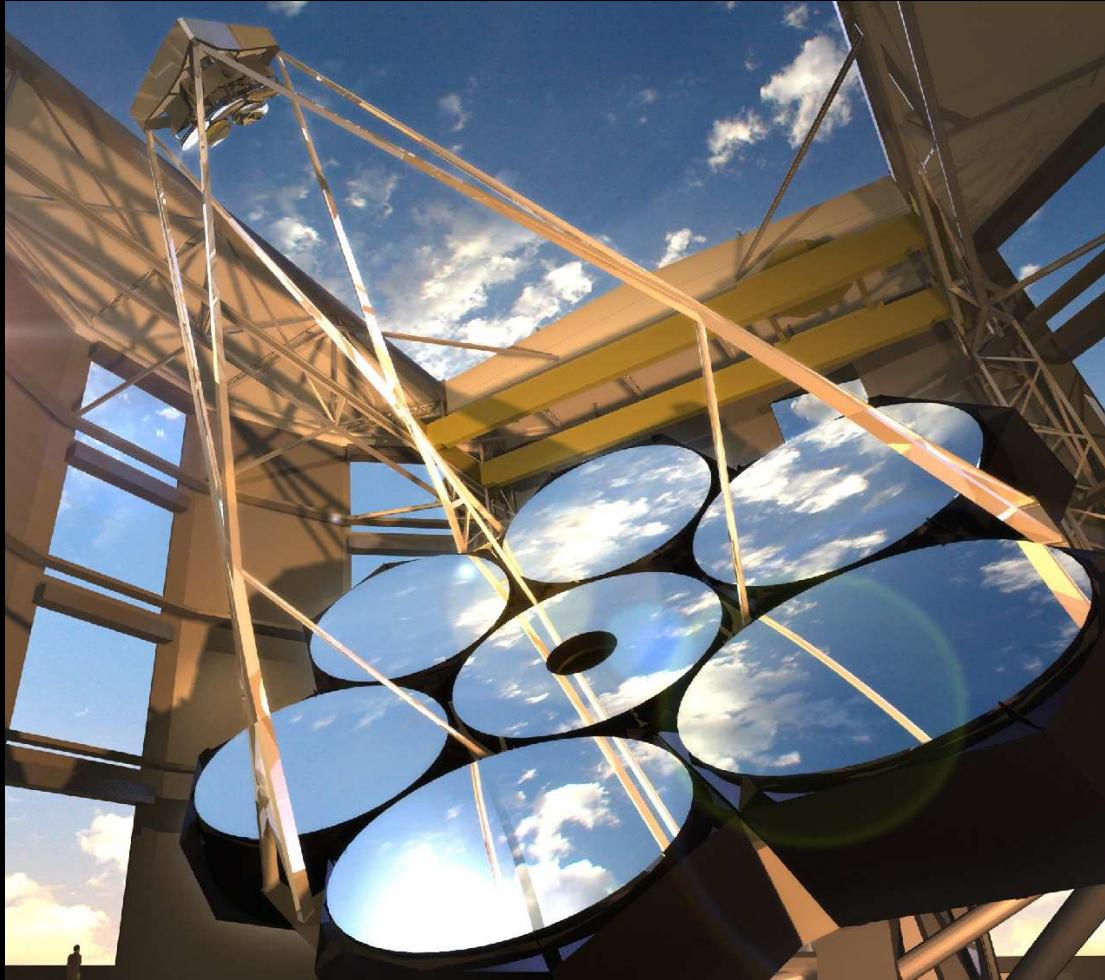
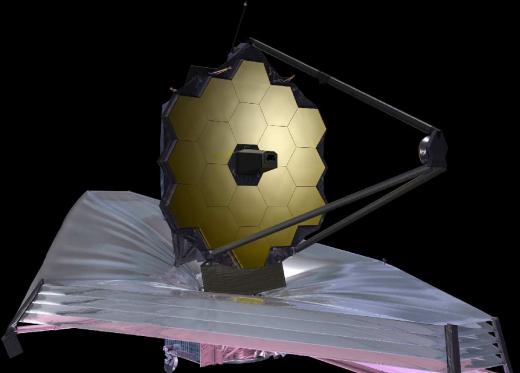


Conclusion: JWST First Light strategy must consider three aspects:

- (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



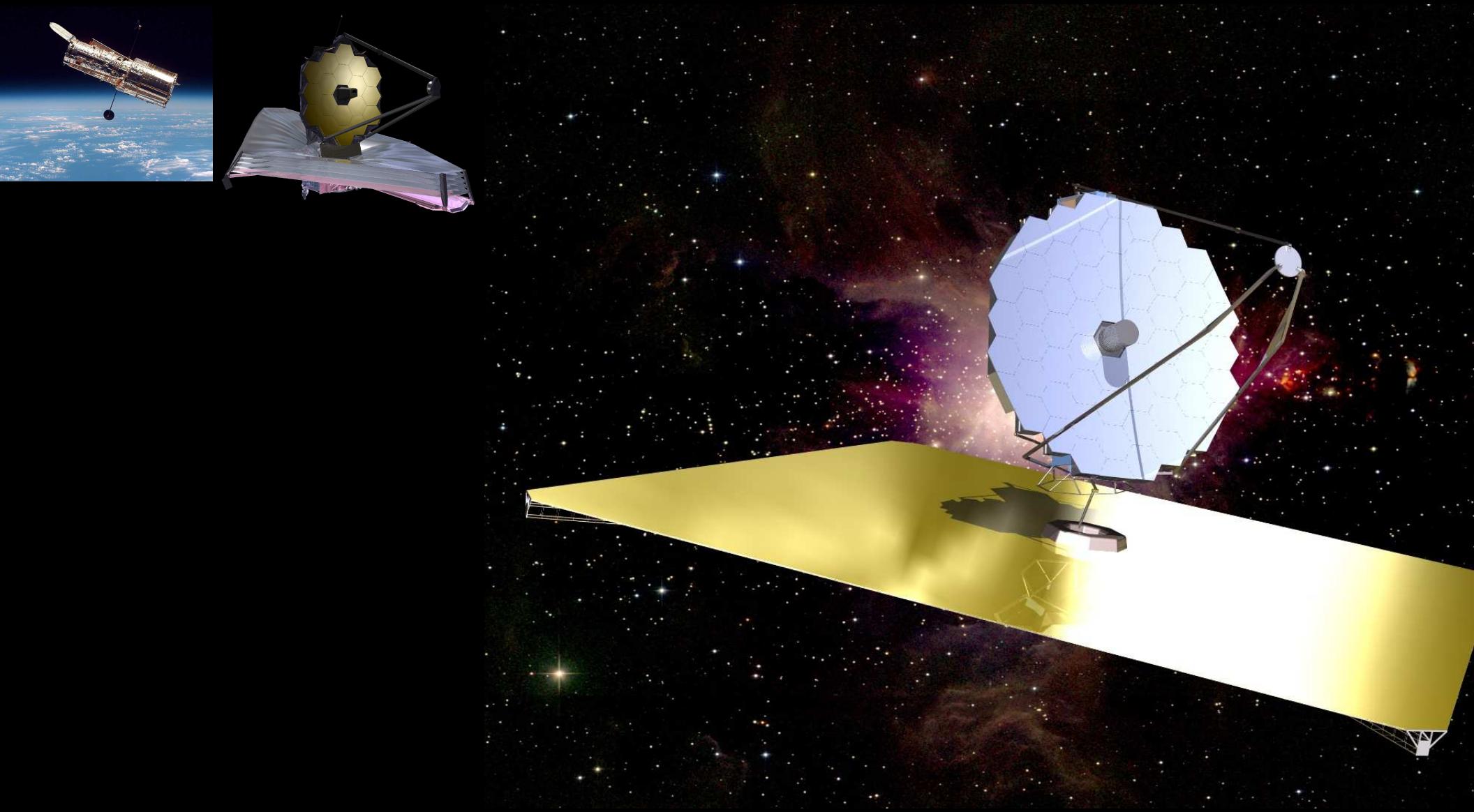
(1973~2020<sup>+</sup>); (1996~2031);

(2000~2050<sup>+</sup>).

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

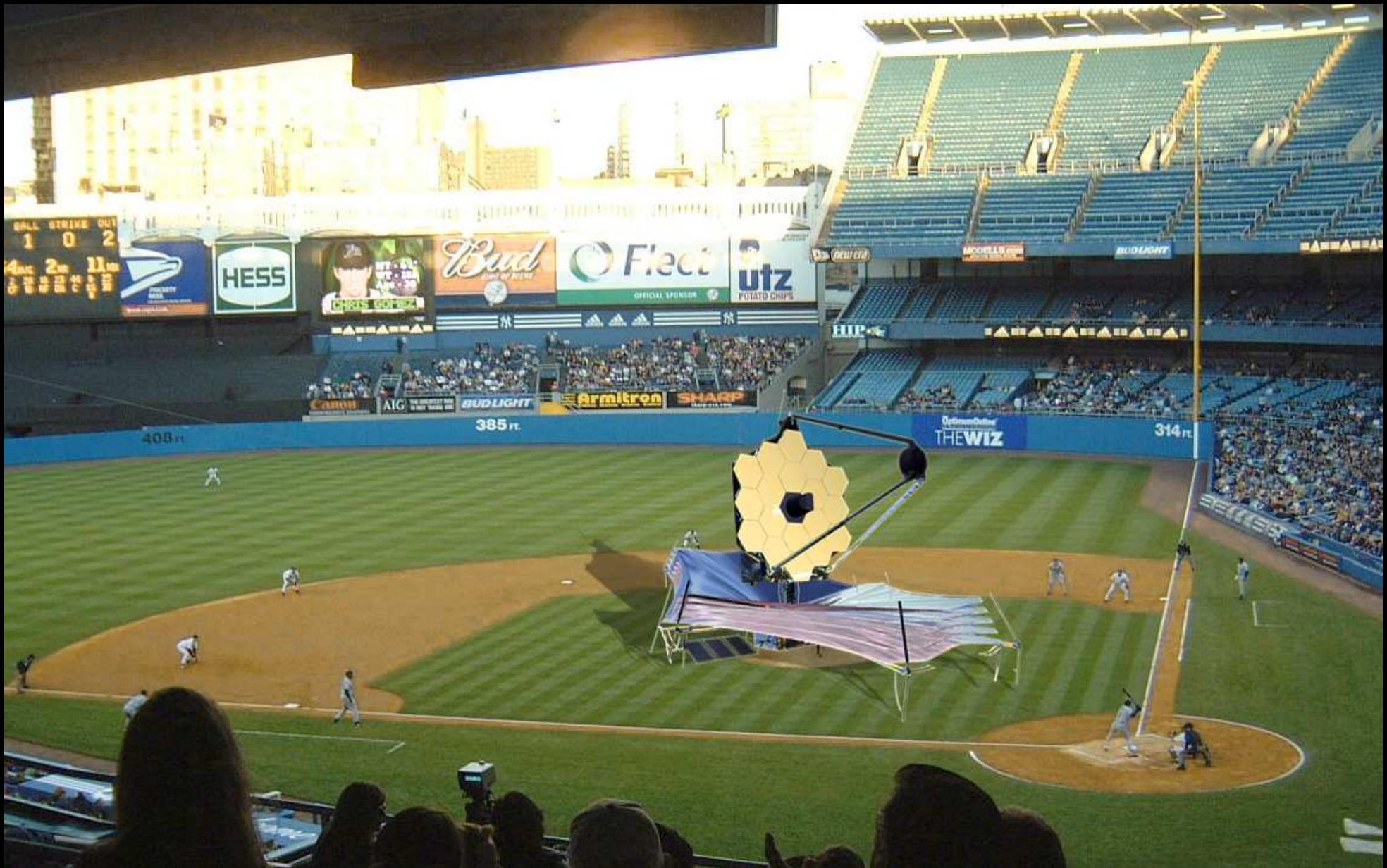
(4) Future: Next generation 20–40 m ground-based telescopes and ATLAST

True relative size: Hubble, James Webb, and ATLAST ...



(1973~2020<sup>+</sup>); (1996~2031); (2020~2050<sup>+</sup>?).

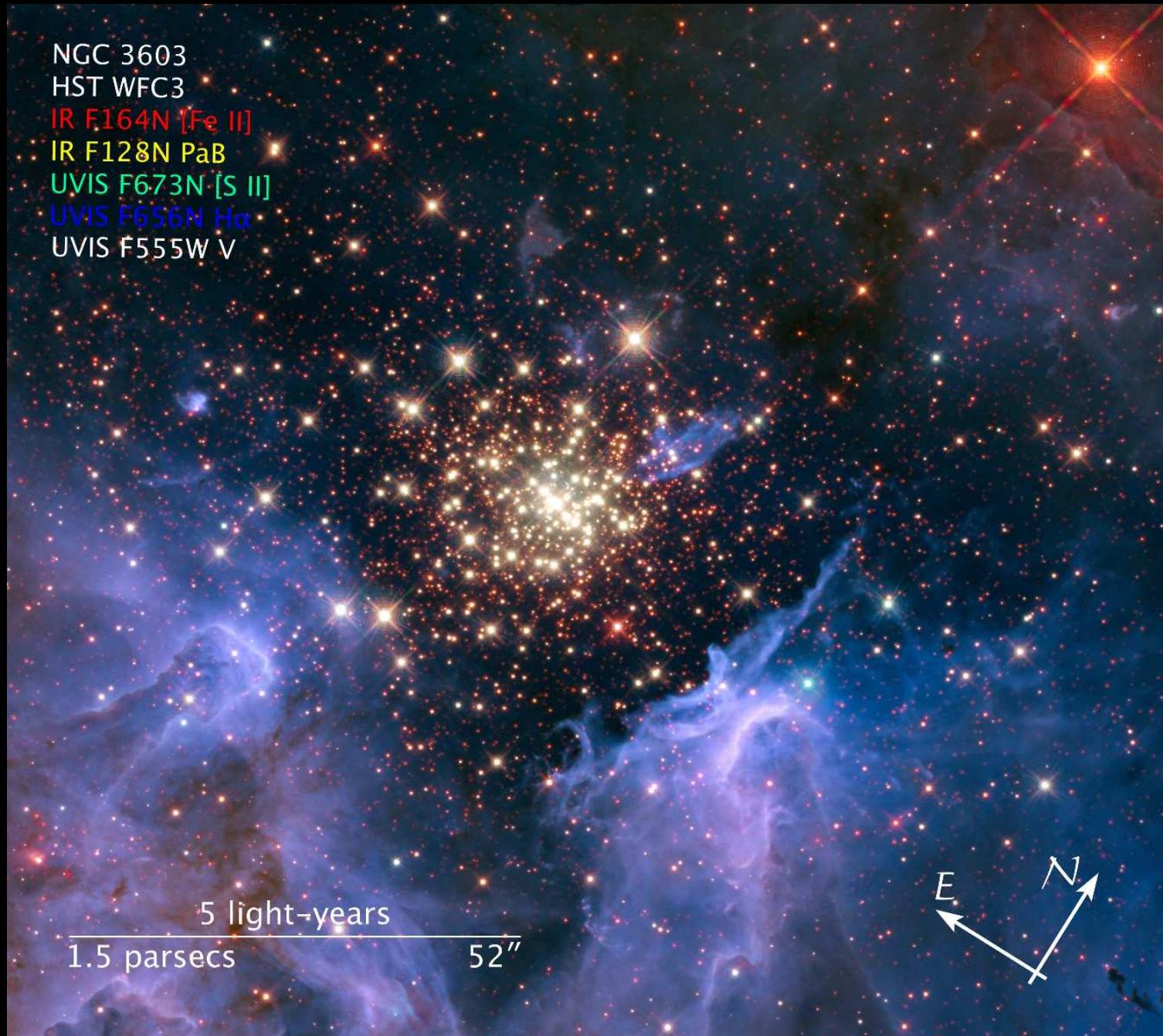
#### (4) Future: How can we knock it out of the ball-park in the next 30 years?



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

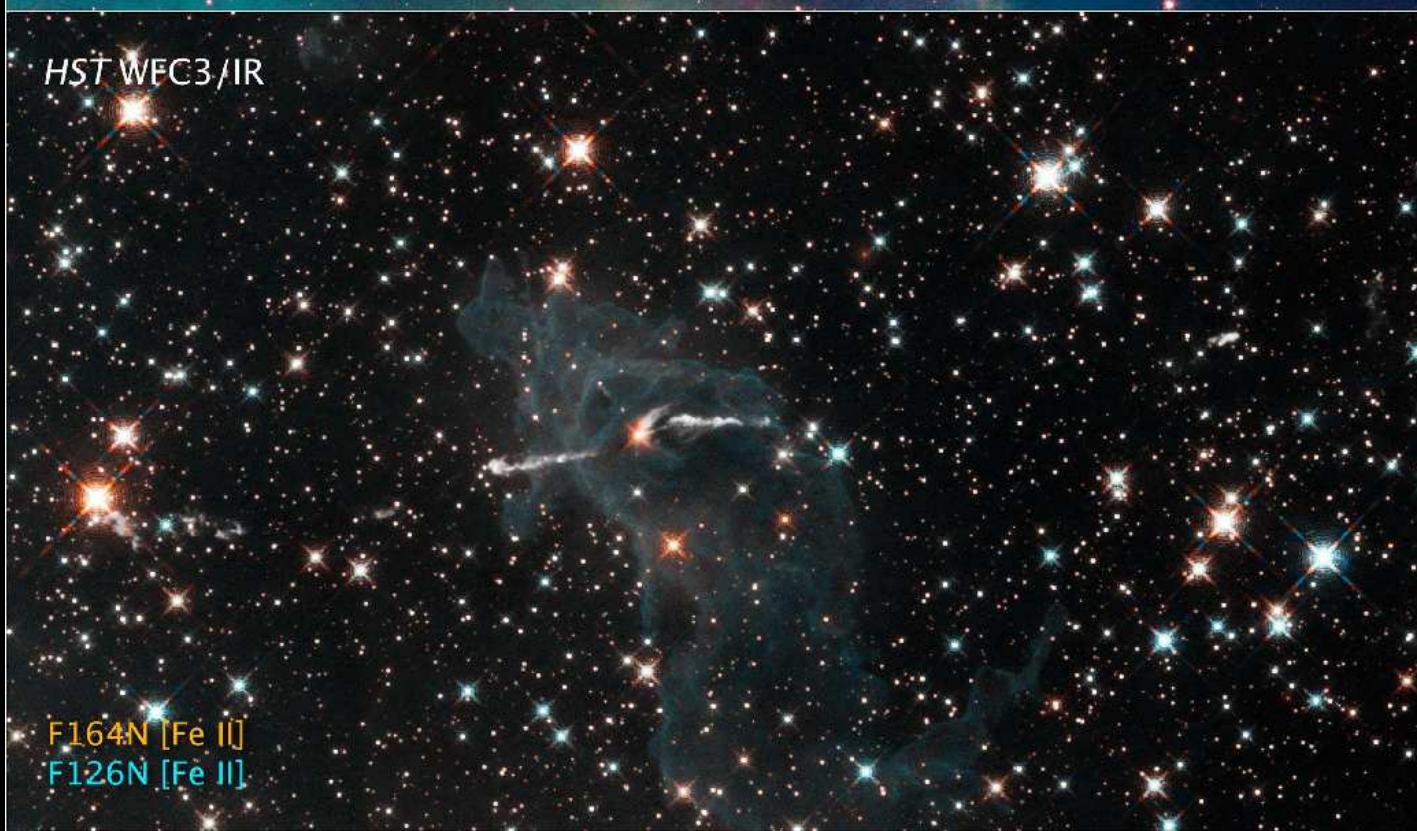
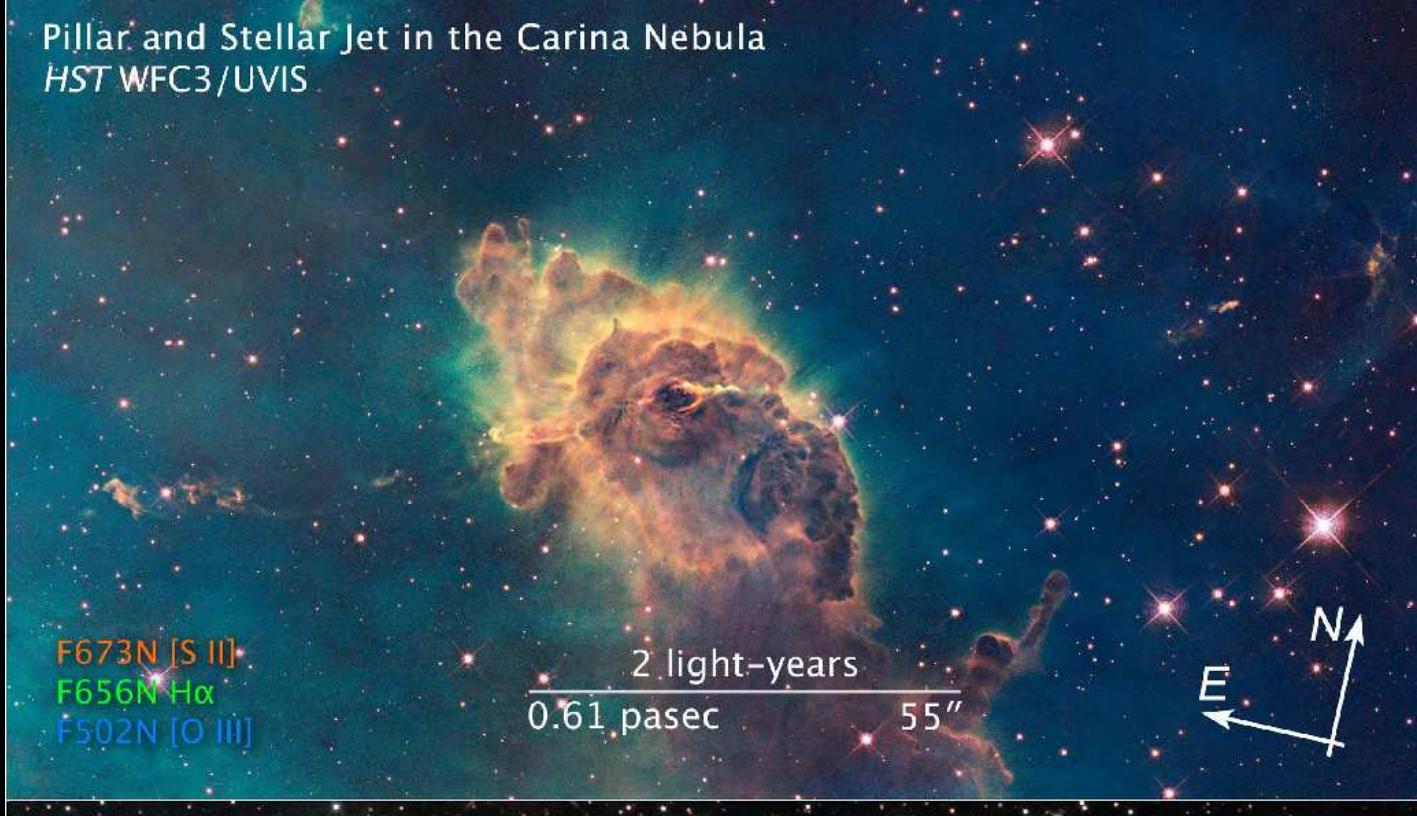
- New paradigm: They are too large for an individual university to take on.
- Universities need to collaborate nation-wide to make this happen.

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

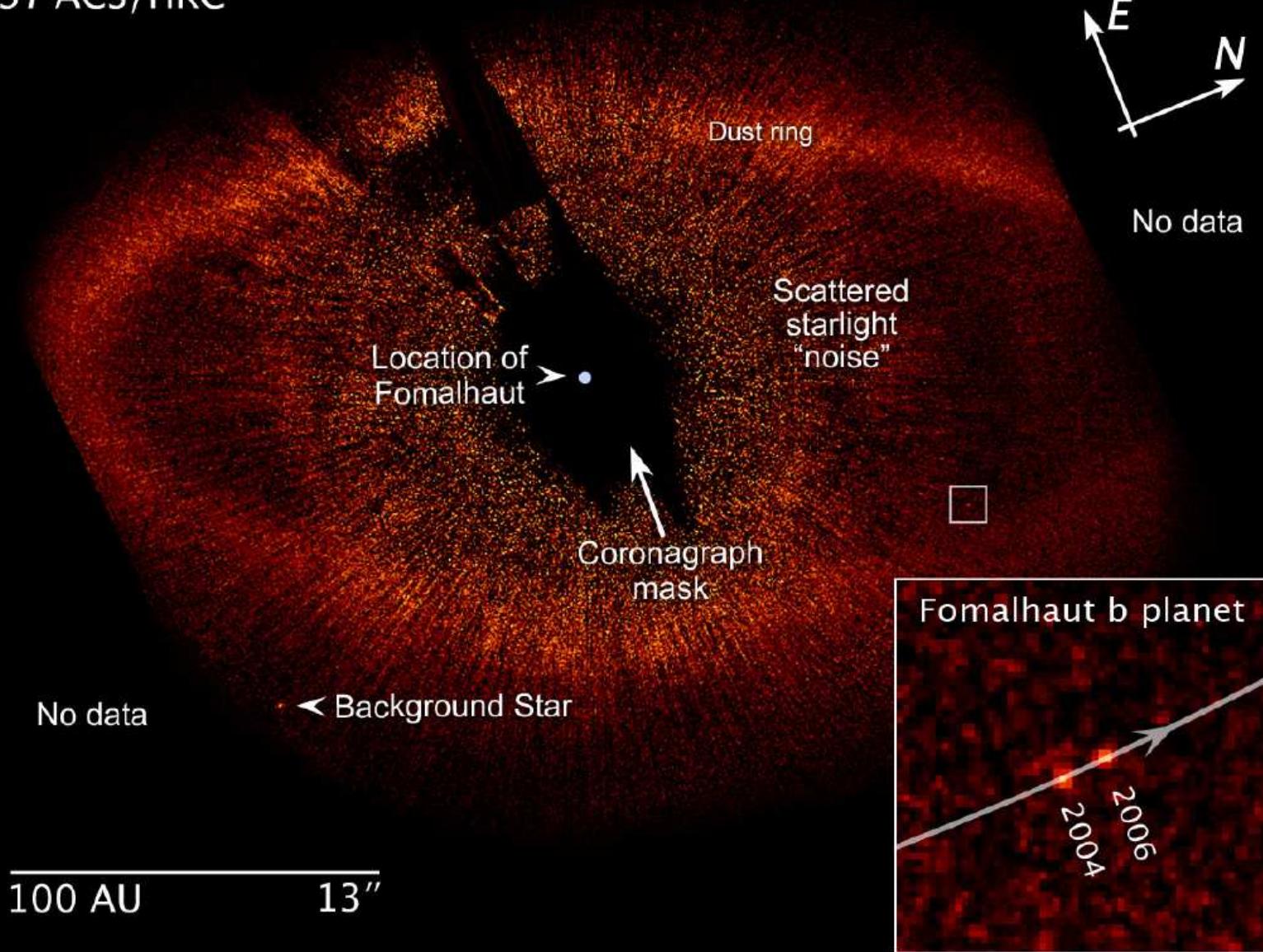


NGC 3603: Young star-cluster triggering star-birth in “Pillars of Creation”

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

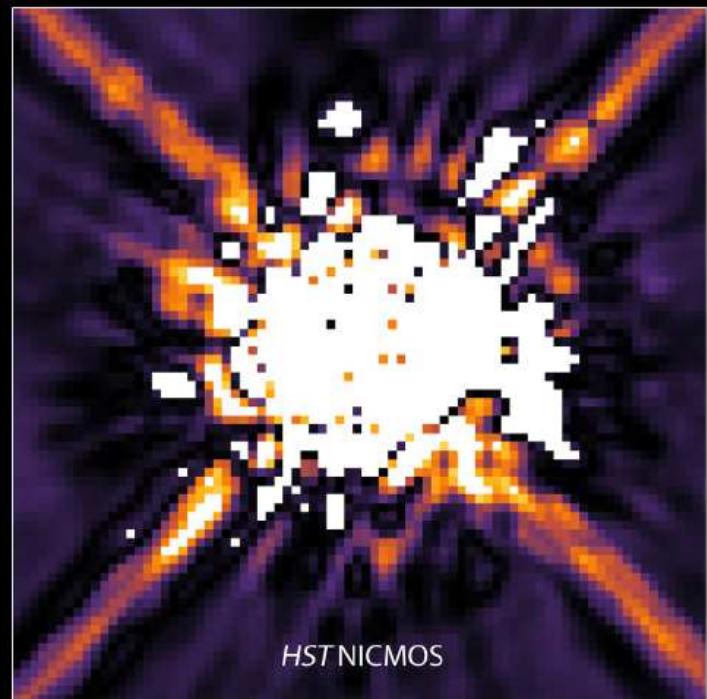


Fomalhaut  
HST ACS/HRC

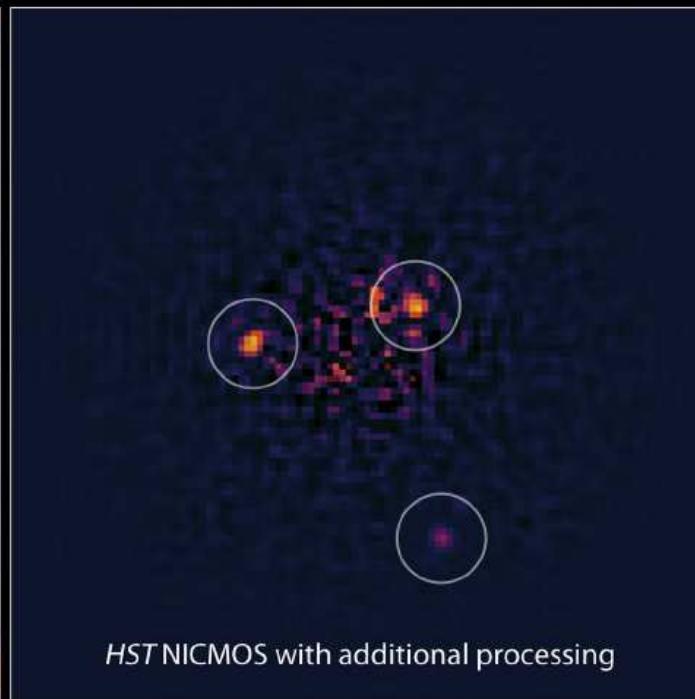


HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut:  
First direct imaging of a moving planet forming around a nearby star!  
JWST can find such planets much closer in for much farther stars.

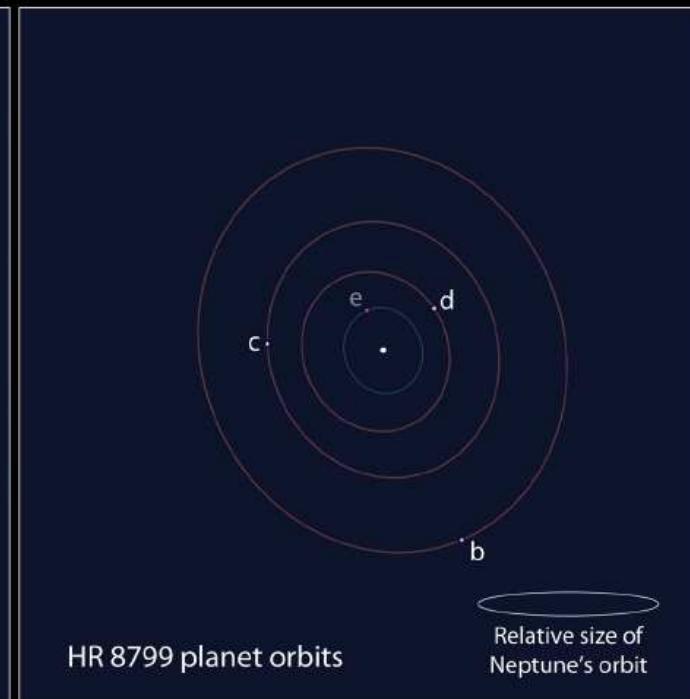
## Exoplanet HR 8799 System



NASA, ESA, and R. Soummer (STScI)



HST NICMOS with additional processing



HR 8799 planet orbits

Relative size of  
Neptune's orbit

STScI-PRC11-29

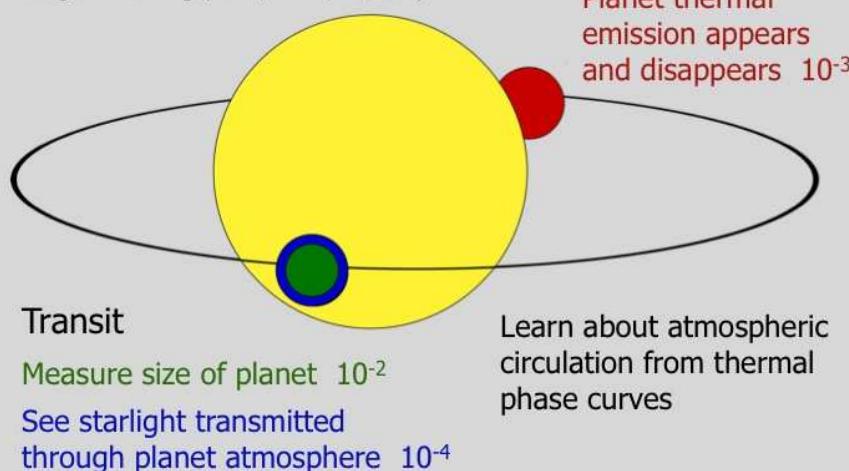
HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

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

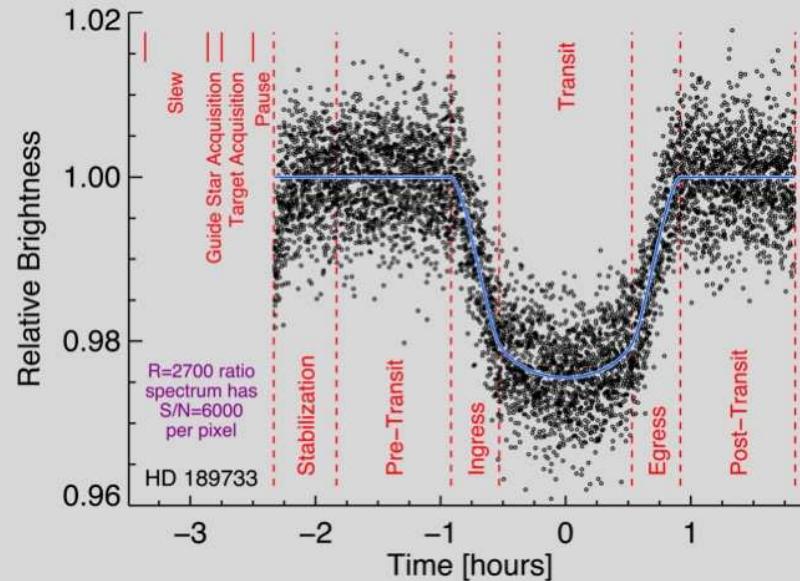
JWST can find such planets much closer in for much farther-away stars.

## Schematic of Transit and Eclipse Science

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



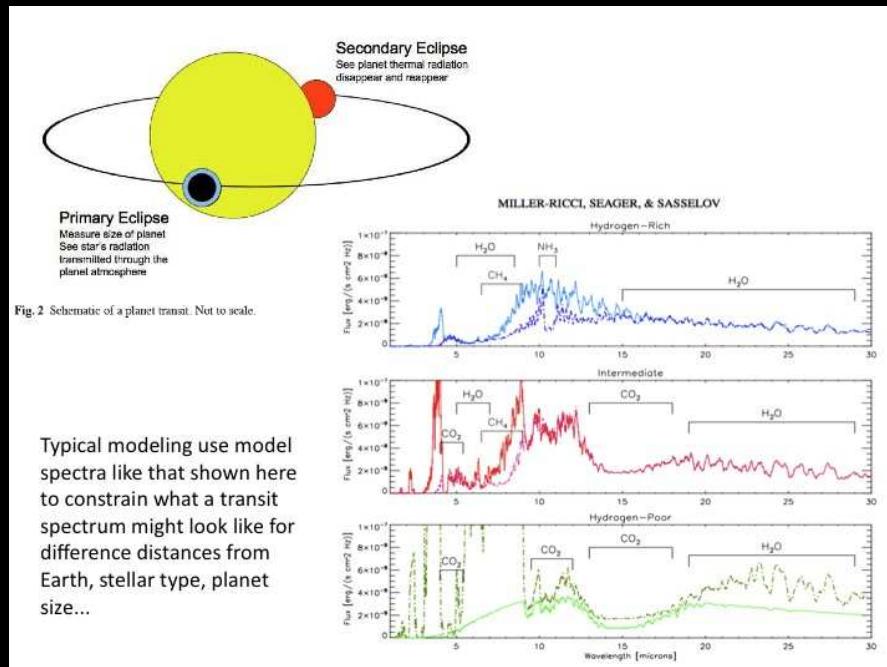
## Timeline of a Transit Observation



6

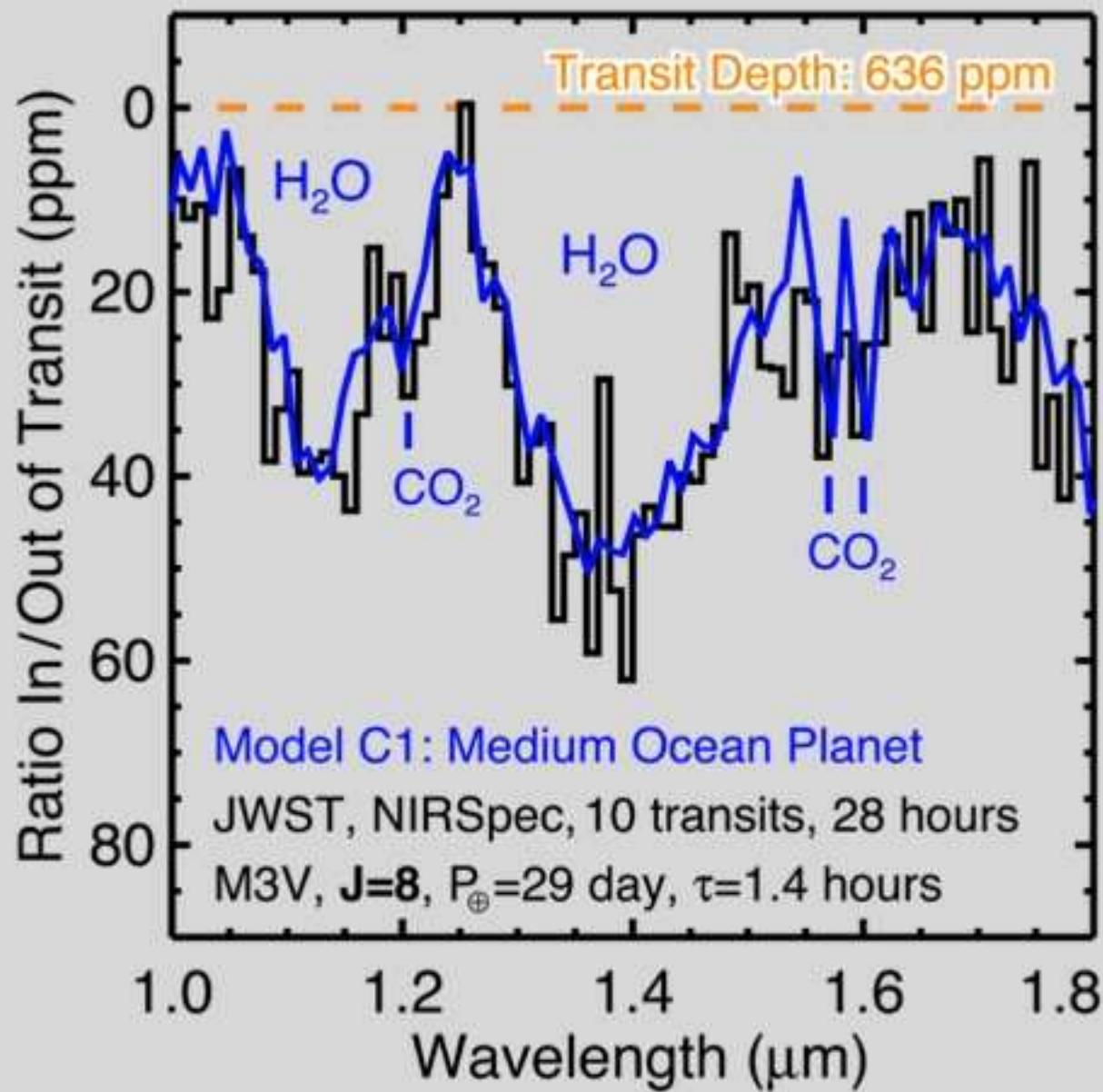
13

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



JWST IR spectra can find water and  $\text{CO}_2$  in (super-)Earth-like exoplanets.

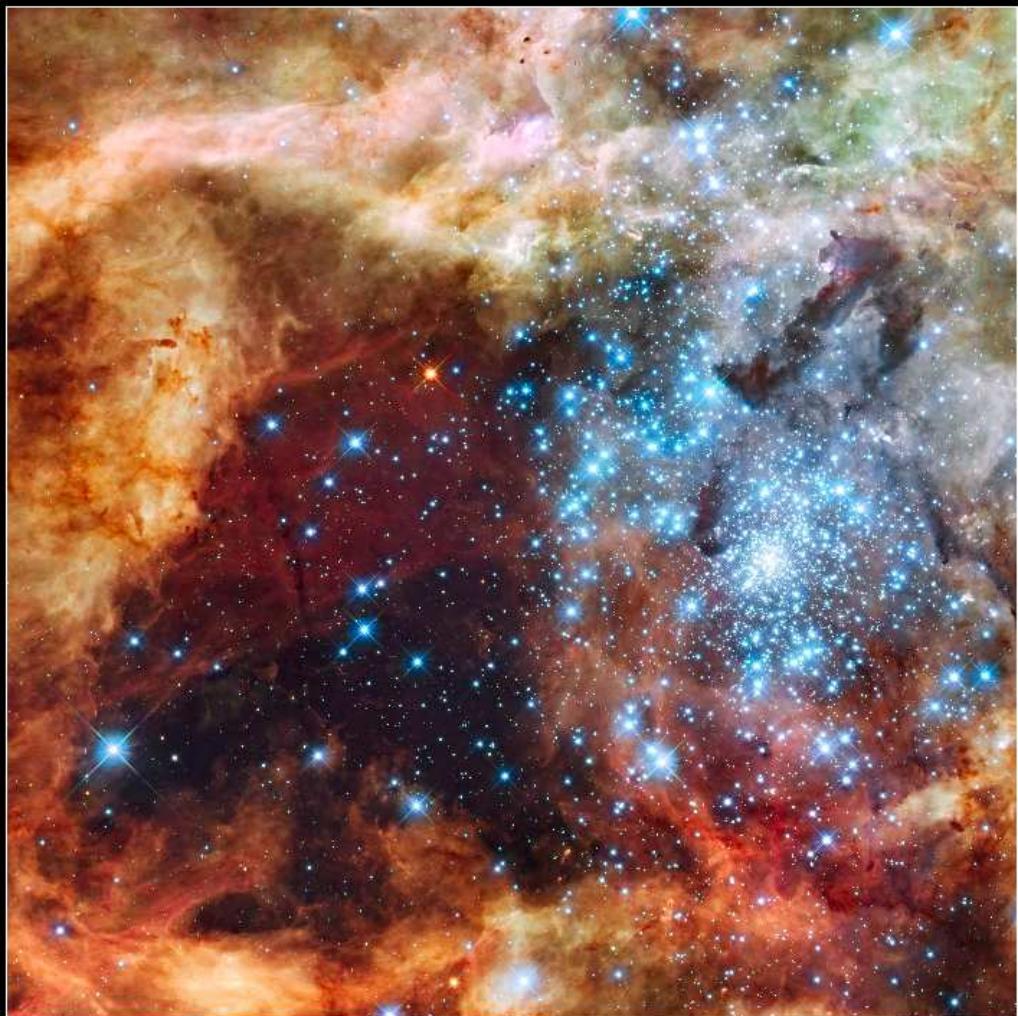
# Transit Spectrum of Habitable “Ocean Planet”



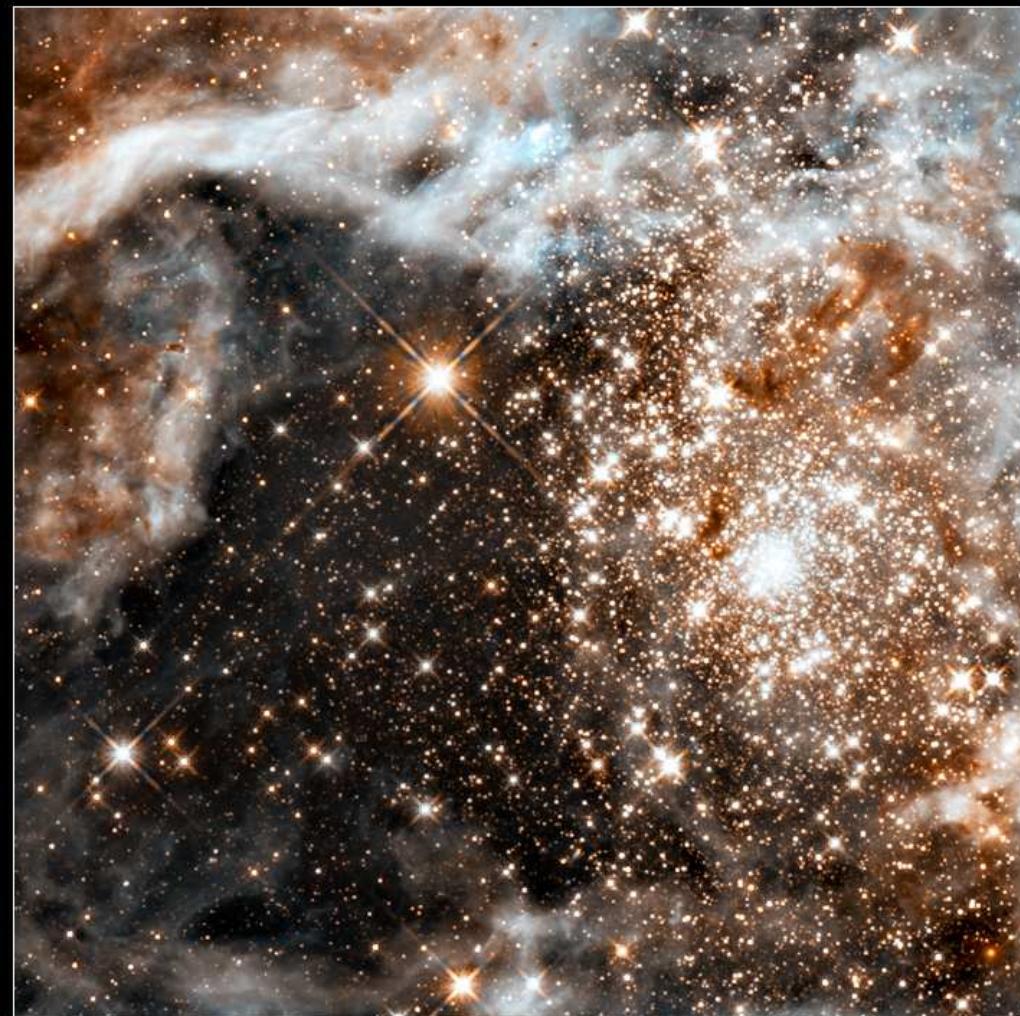
17

JWST IR spectra can find water and  $\text{CO}_2$  in transiting Earth-like exoplanets.

Visible



Infrared



## 30 Doradus Nebula and Star Cluster

*Hubble Space Telescope • WFC3/UVIS/IR*

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

STScI-PRC09-32b

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





## (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

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- References and other sources of material shown:

<http://ahah.asu.edu/> [Appreciating Hubble at Hyperspeed]

<http://ahah.asu.edu/download.html> [Download Java–tool]

<http://ahah.asu.edu/clickonHDF/index.html> [Clickable map]

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

<https://blogs.nasa.gov/webb/>

<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

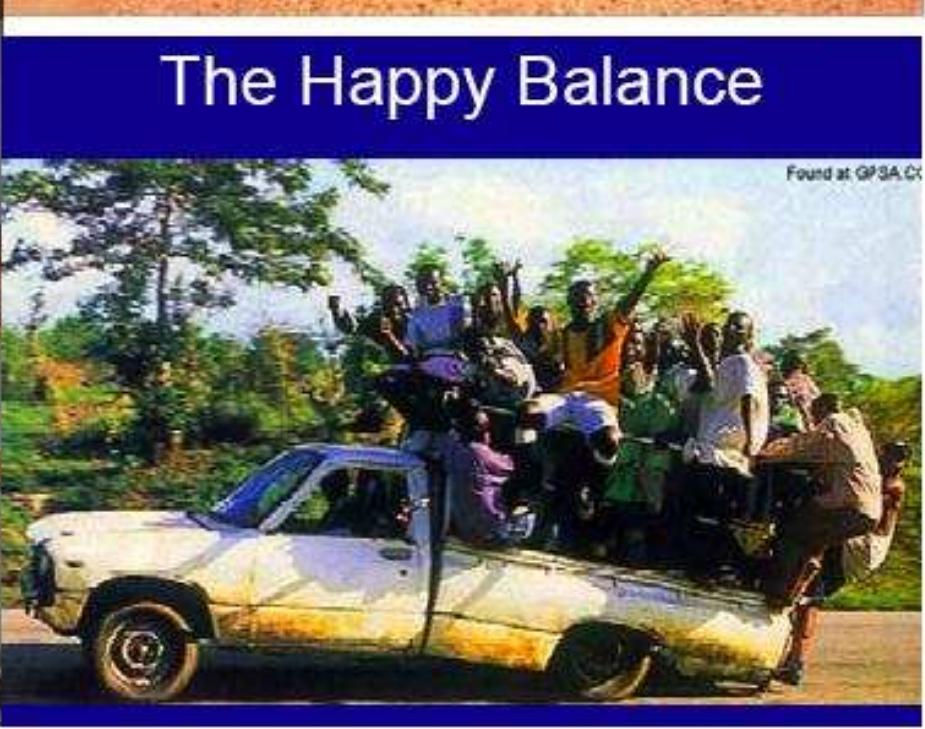
Mather, J., & Stockman, H. 2000, *Proc. SPIE Vol. 4013*, 2

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

Windhorst, R., et al., 2011, *ApJS*, 193, 27 ([astro-ph/1005.2776](http://arxiv.org/abs/1005.2776)).

What the Scientists See:

What the Project Manager Sees:



The Happy Balance

Found at GP3A.CX

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 programmaticas 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



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



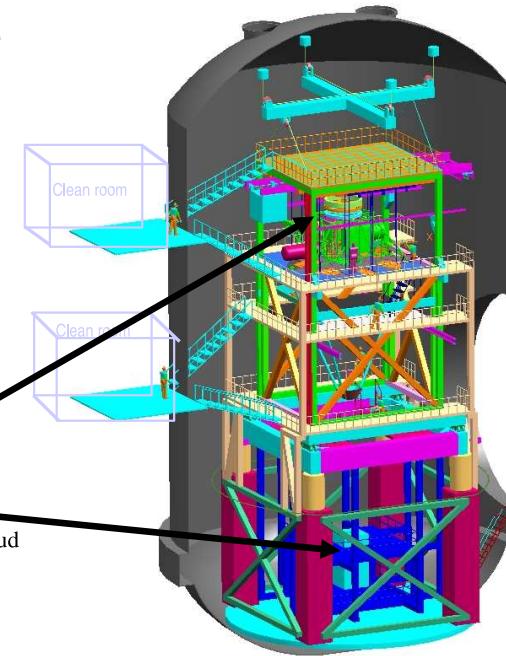
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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

JSC currently has 7 KW He capability

Current plan includes 10 trucks of LN2/day during cooldown

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



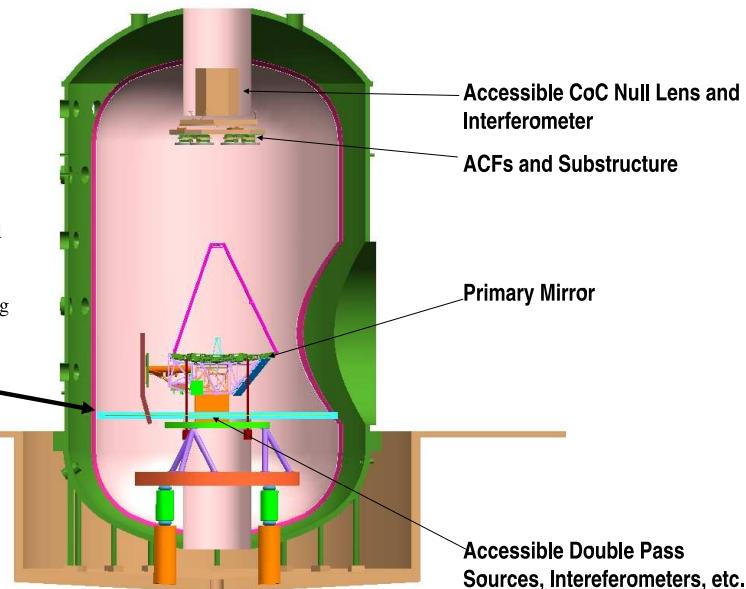
## JSC "Cup Up" Test Configuration (New Proposal)



No Metrology Tower and Associated Cooling H/W. External Metrology

Two basic test options:

1. Use isolators, remove drift through fast active control + freeze test equipment jitter
  2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter
- Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.



Drawing care of ITT

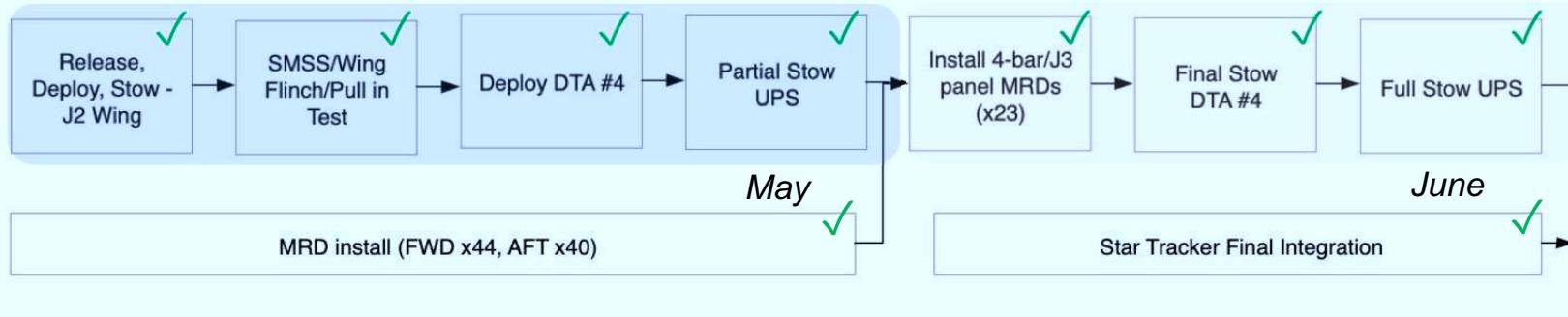
Page 6

JWST underwent several significant replans and risk-reduction schemes:

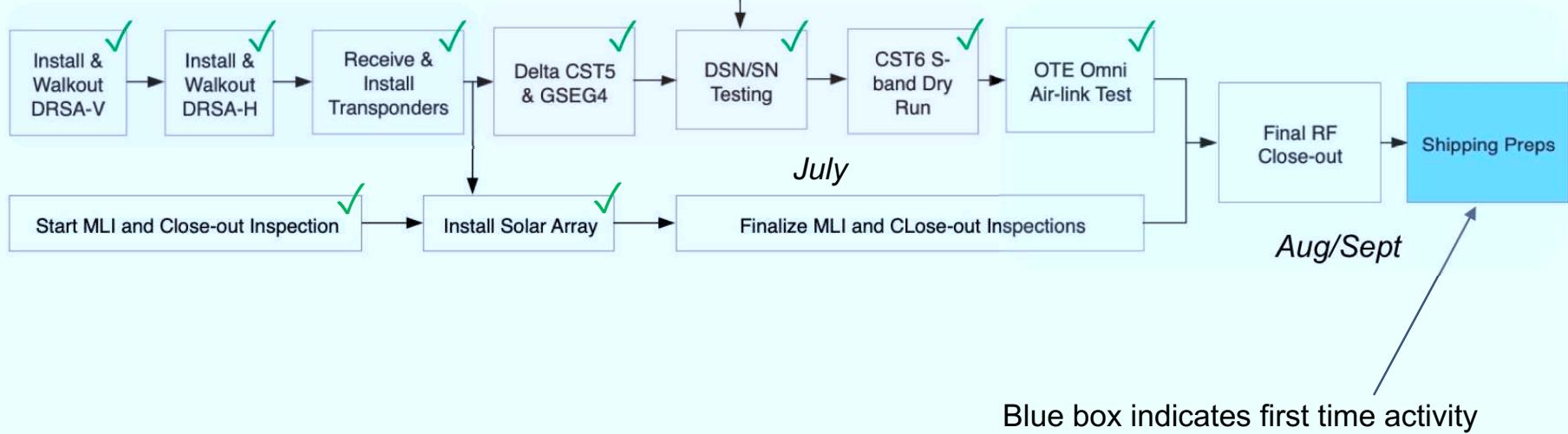
- ≈2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (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

## Observatory Deployments



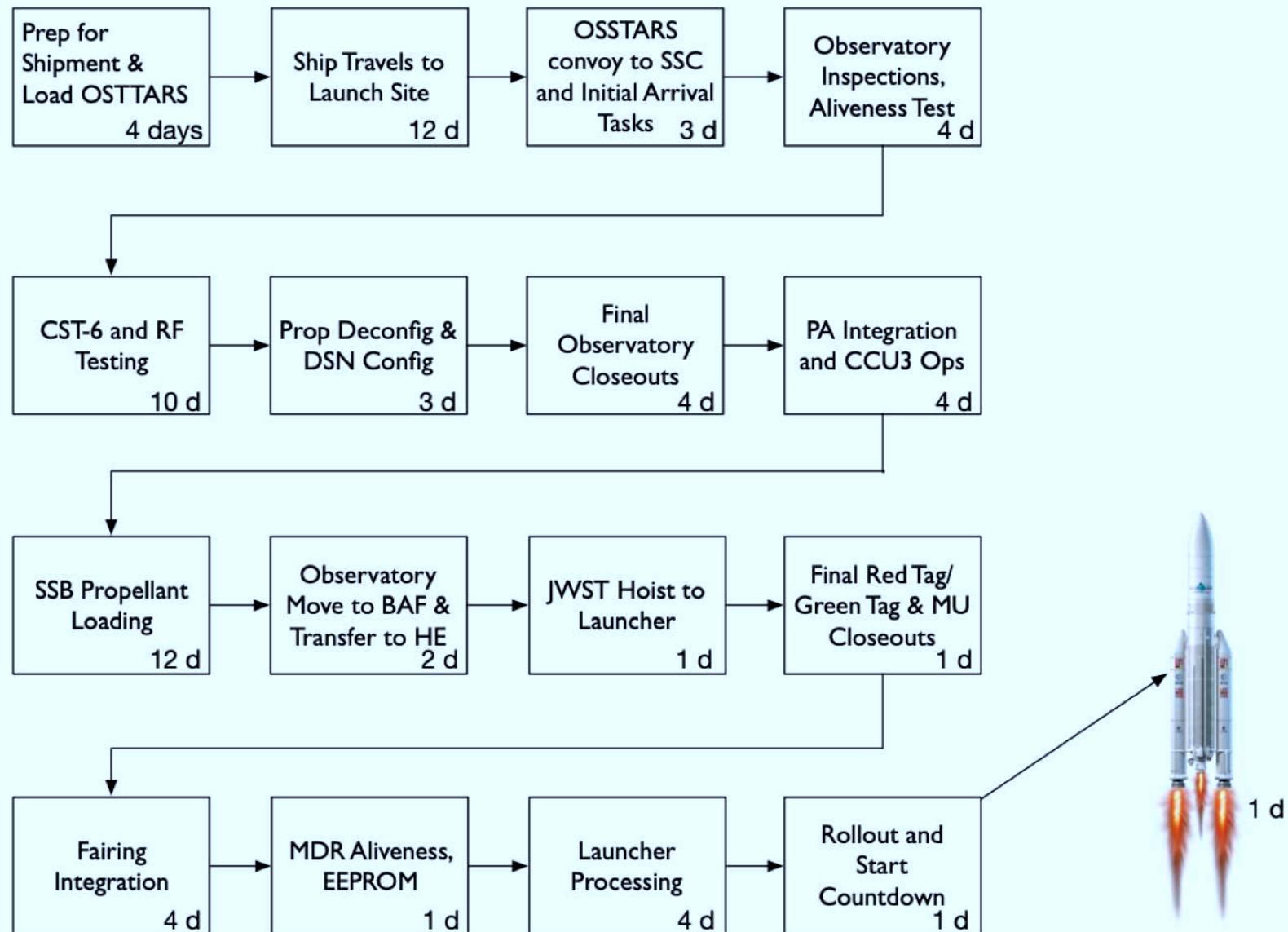
## Observatory Final Build



Flowchart of Project tasks for FY21.

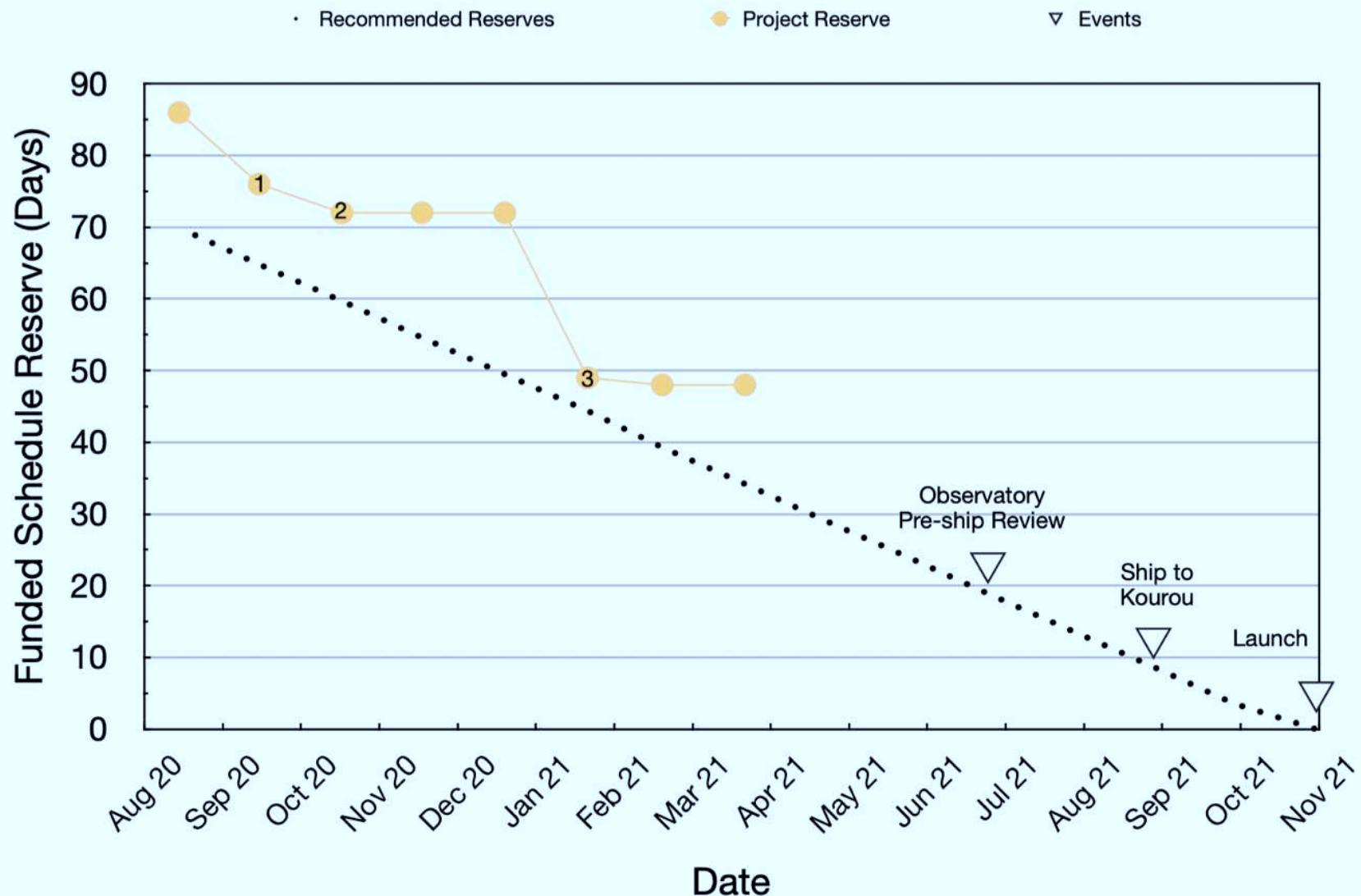
Blue = First-time operation (all others done before at sub-system level).

# Kourou Activities



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 Environmental Testing	Completed 10/2/20
Nov-20		
Dec-20	2 Complete Post Environmental Testing Spacecraft Bus Deployments	<u>Completed 11/12/20</u>
Jan-21	3 Complete Post Environmental Testing Sunshield Deployments	<u>Completed 12/16/20</u>
Feb-21	4 Complete Comprehensive System Test #5	Completed 2/13/21
Mar-21	5 Complete Cycle 1 General Observer Proposal Reviews	<u>Completed 3/30/21</u>
	6 Sunshield Fold Complete	<u>Completed 4/6/21</u>
	7 Launch Readiness Exercise #2	Completed 3/8/21
Apr-21		
May-21	8 Final Deployable Tower deployment	<u>Completed 6/8/21</u>
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	<u>Completed 6/22/21</u>
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.

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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

4

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FY14: 8 milestones late by 1 mo due to Oct 2013 Government shutdown.

FY15: Most “Lates” not on critical path.

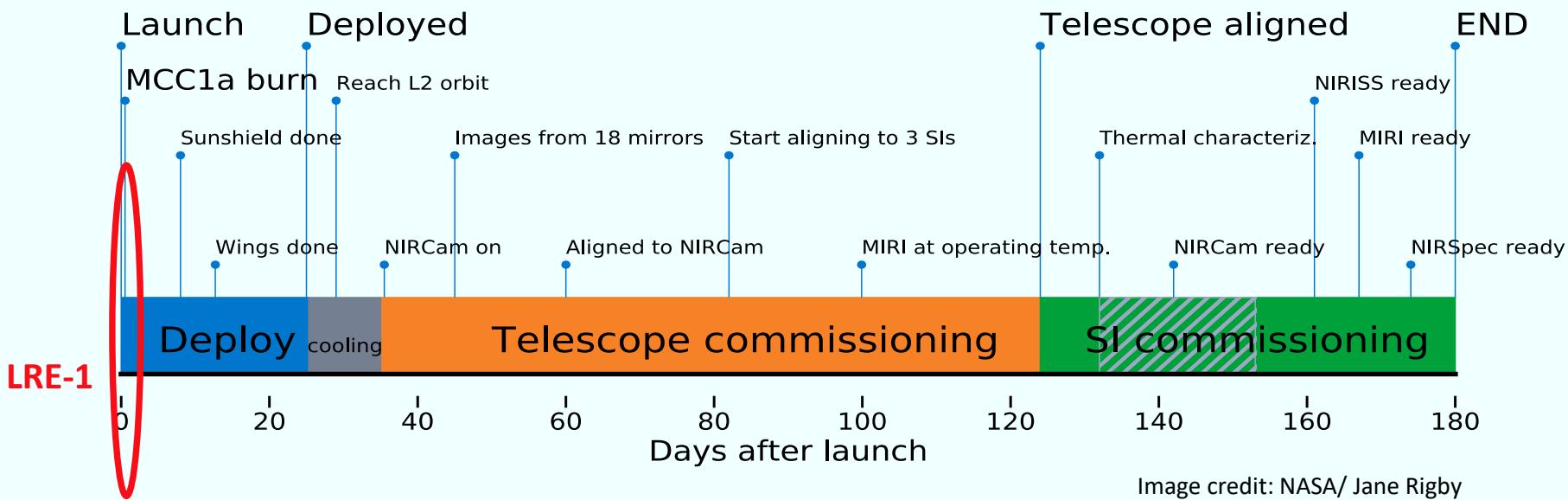
FY17: Lates started to outnumber Early's ⇒ Replan Integration & Testing.

# Commissioning At A Glance

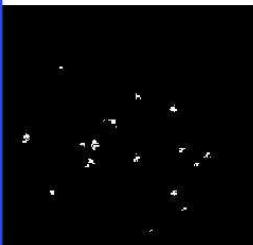
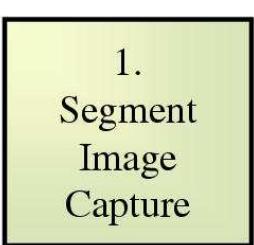
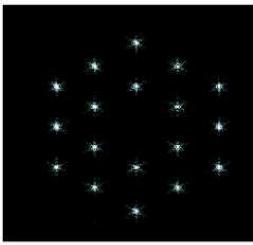
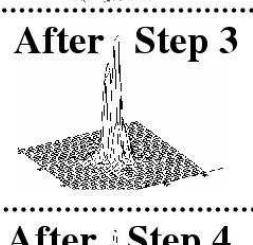
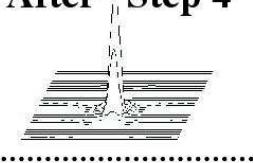
Commissioning begins at launch and is ~180 days long, including the following key events:

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
- Launch and Deploy Phase

Cool-Down/OTIS Phase

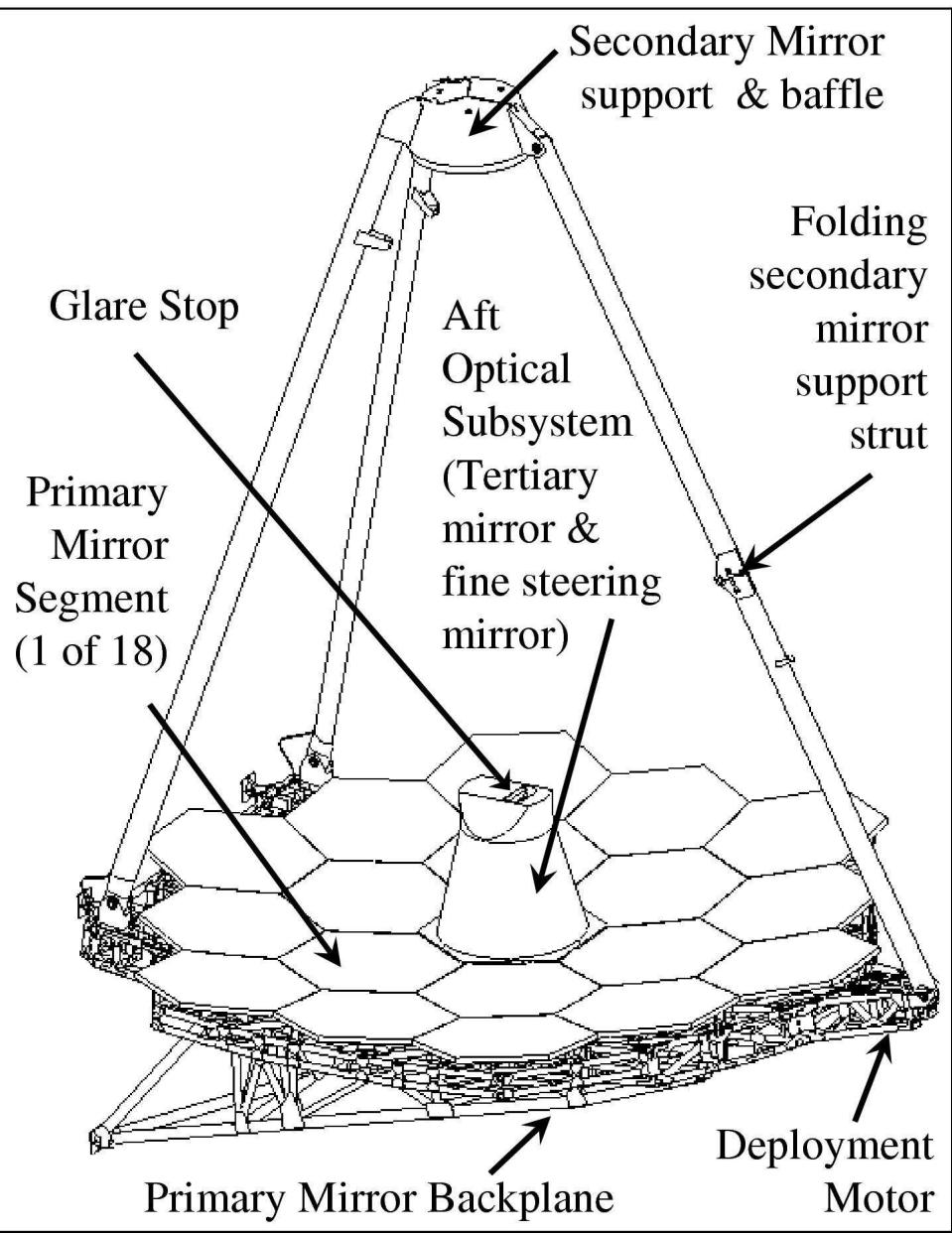


JWST Commissioning Plan after launch from Kourou in Fall 2021.

<i>First light NIRCam</i>	<i>After Step 1</i>	<i>Initial Capture</i>	<i>Final Condition</i>
		<p>18 individual 1.6-m diameter aberrated sub-telescope images</p> <p>PM segments: &lt; 1 mm, &lt; 2 arcmin tilt</p> <p>SM: &lt; 3 mm, &lt; 5 arcmin tilt</p>	<p>PM segments:            &lt; 100 <math>\mu\text{m}</math>,            &lt; 2 arcsec tilt</p> <p>SM: &lt; 3 mm,            &lt; 5 arcmin tilt</p>
<b>2. Coarse Alignment</b> Secondary mirror aligned Primary RoC adjusted		<p>Primary Mirror segments:            &lt; 1 mm, &lt; 10 arcsec tilt</p> <p>Secondary Mirror :            &lt; 3 mm, &lt; 5 arcmin tilt</p>	WFE < 200 $\mu\text{m}$ (rms)
<b>3. Coarse Phasing - Fine Guiding (PMSA piston)</b>		WFE: < 250 $\mu\text{m}$ rms	WFE < 1 $\mu\text{m}$ (rms)
<b>4. Fine Phasing</b>		WFE: < 5 $\mu\text{m}$ (rms)	WFE < 110 nm (rms)
<b>5. Image-Based Wavefront Monitoring</b>		WFE: < 150 nm (rms)	WFE < 110 nm (rms)

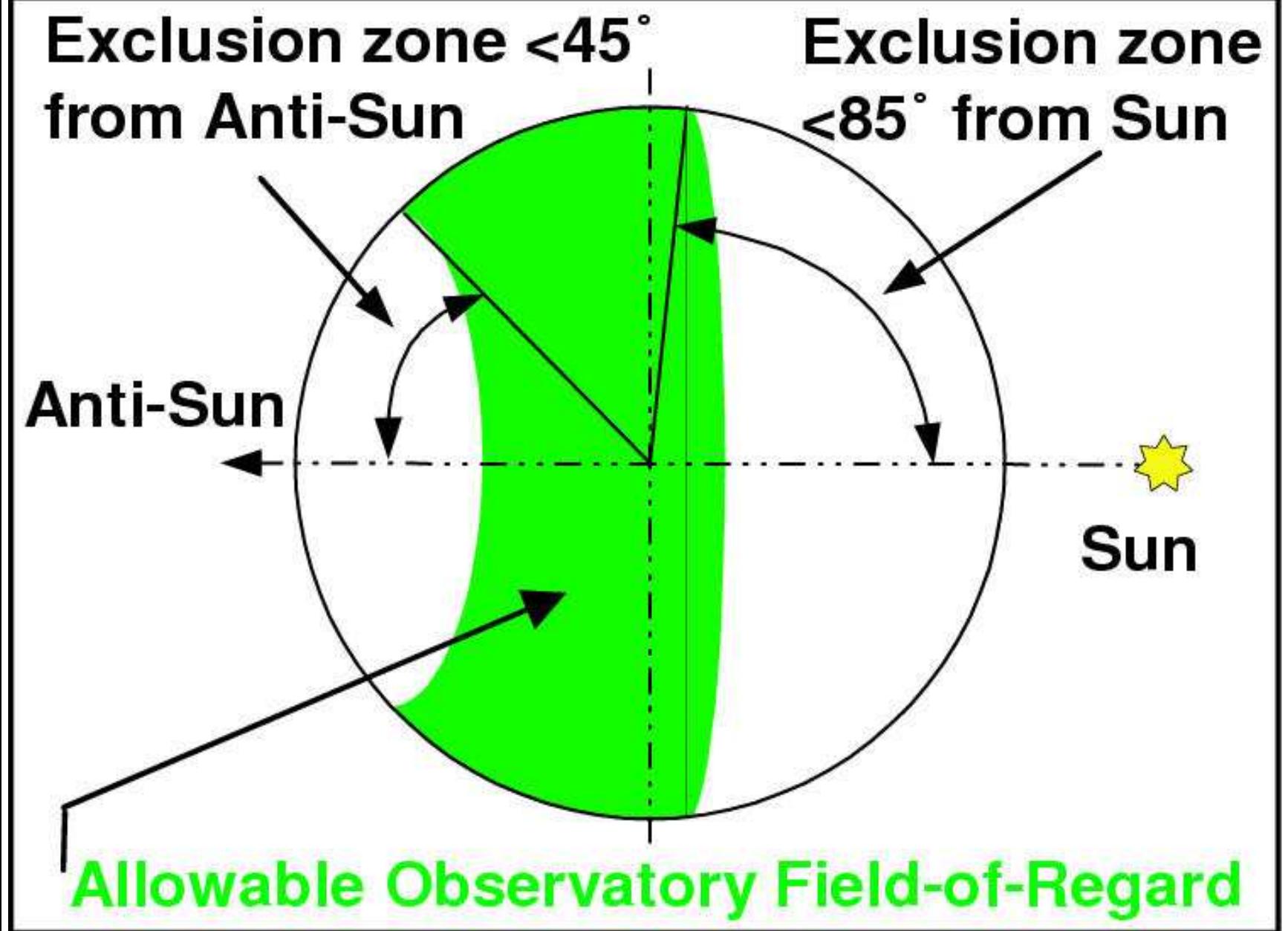
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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



Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015–2017.

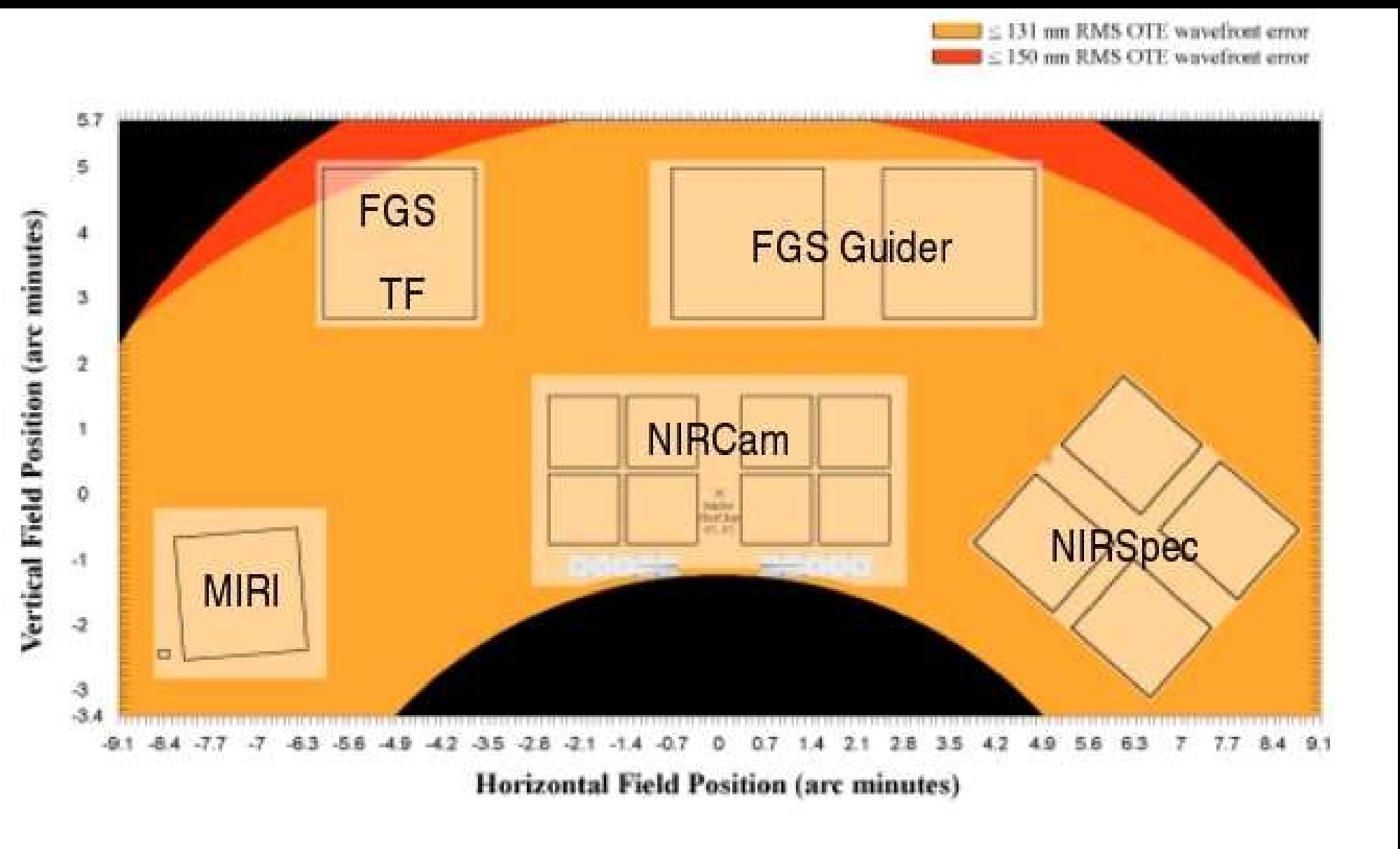
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0  $\mu\text{m}$  images.



JWST can observe North/South Ecliptic pole targets continuously:

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

- What instruments will JWST have?



- All JWST instruments can in principle be used in parallel observing mode:
- Currently only being implemented for parallel *calibrations*.

## (8) What do our Astrophysics College Graduates do?

### Future Careers at NASA:

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

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

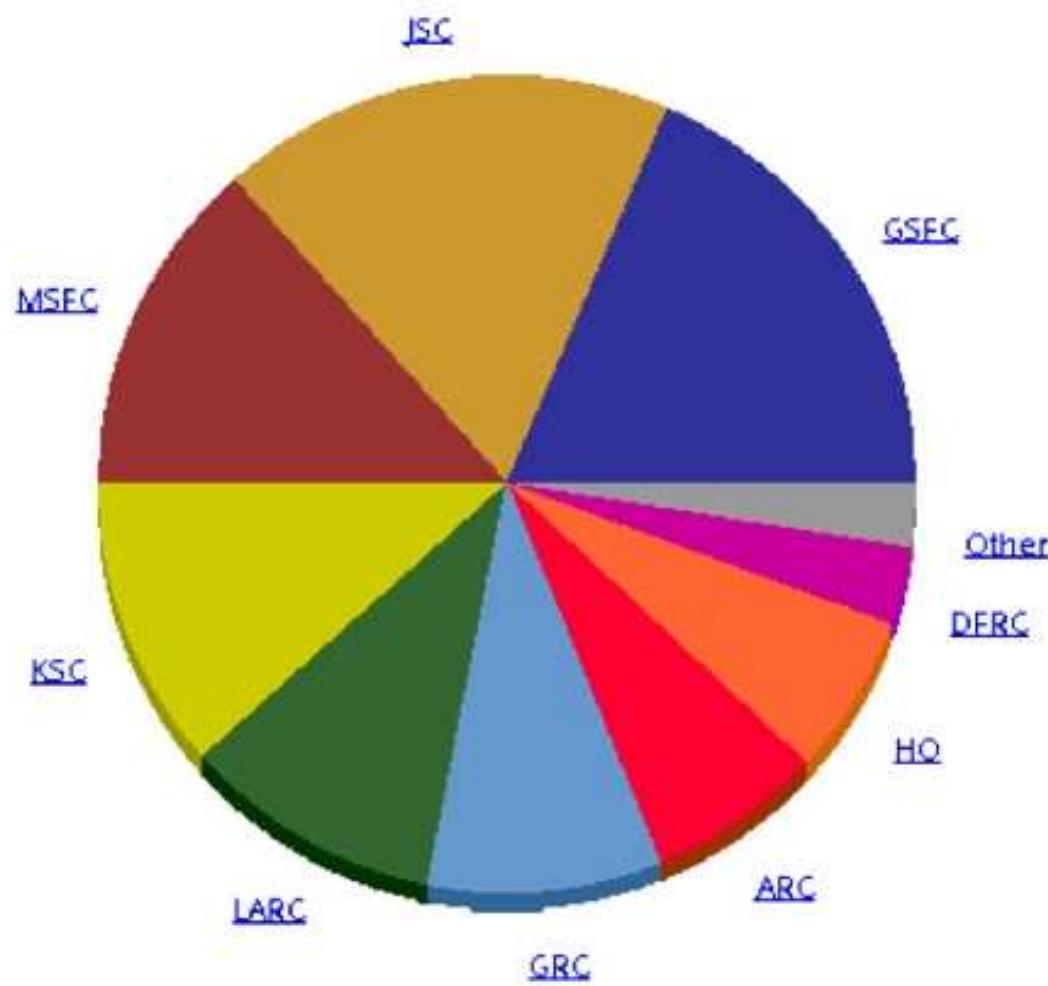
<http://www.aip.org/statistics/astronomy/>

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

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

CS Head Count

as values



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.