How will the Webb Telescope measure Exoplanets, First Light, & Galaxy Assembly: New Frontiers after Hubble

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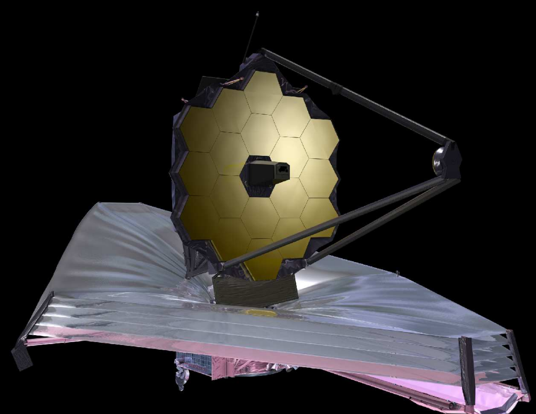
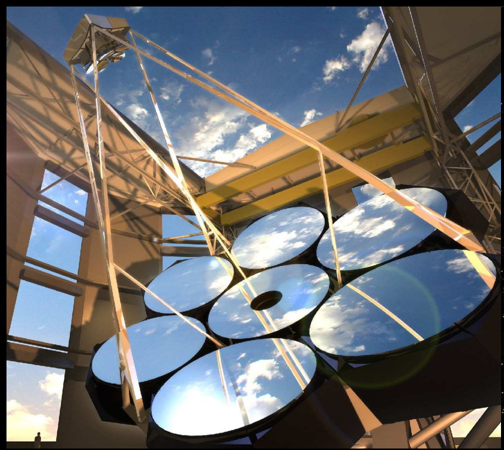
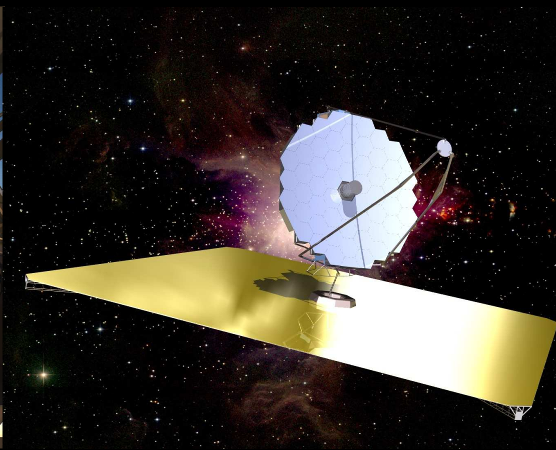
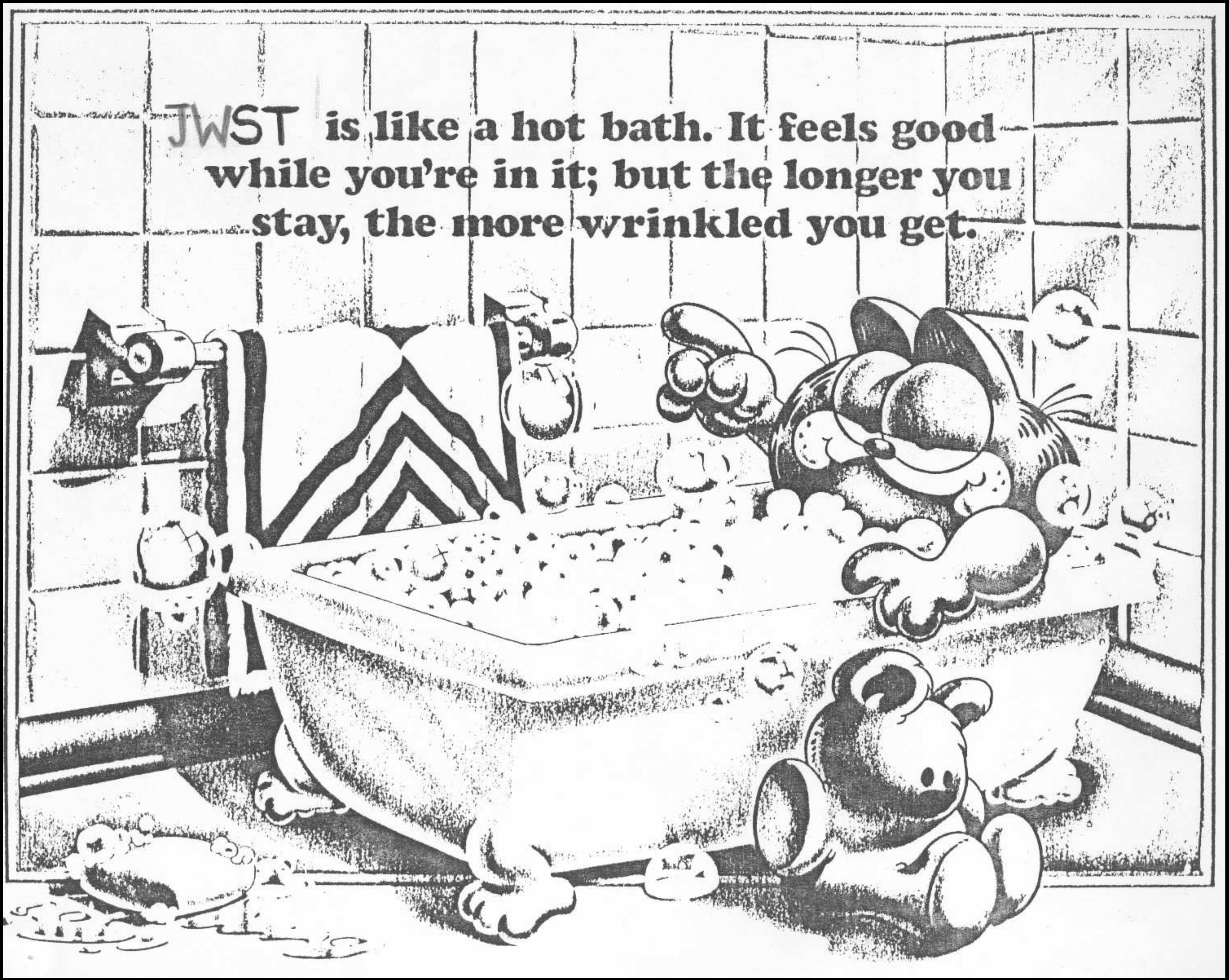




$1973 \sim 2018^{+}$; $1996 \sim 2029$; $2000 \sim 2050^{+}$ $2020 \sim 2050^{+}$?

ASU SESE Undergraduate Student Seminar, Camp SESE, Tontozona, AZ

Saturday Sept. 9, 2017. All presented materials are ITAR-cleared.



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

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

Outline

- (1) Update on the James Webb Space Telescope (JWST), 2017.
- (2) What Hubble has done: Galaxy Assembly & SMBH Growth
- (3) How can JWST measure Star-formation & Earth-like exoplanets?
- (4) How can JWST measure the Epochs of First Light & Galaxy Assembly, and Supermassive Black-Hole Growth?
- (5) The Future: Next generation 20–40 m telescopes & ATLAST
- (6) Where do our students end-up? Possible NASA Careers
- (7) Summary and Conclusions

Sponsored by NASA/HST & JWST

ARIZONA STATE UNIVERSITY

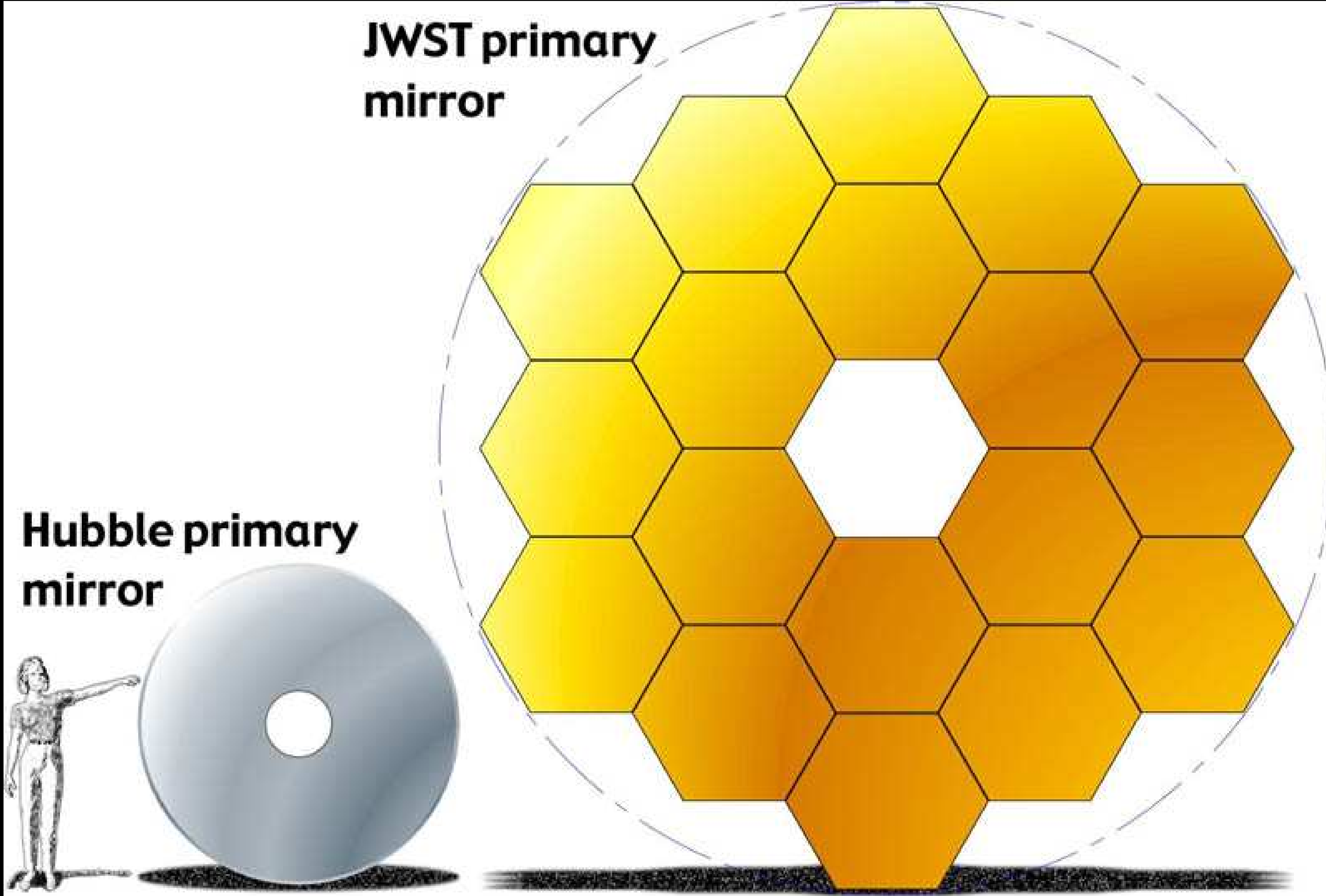
Talk is on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/asu_campSESE17_hstjwst.pdf

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

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

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

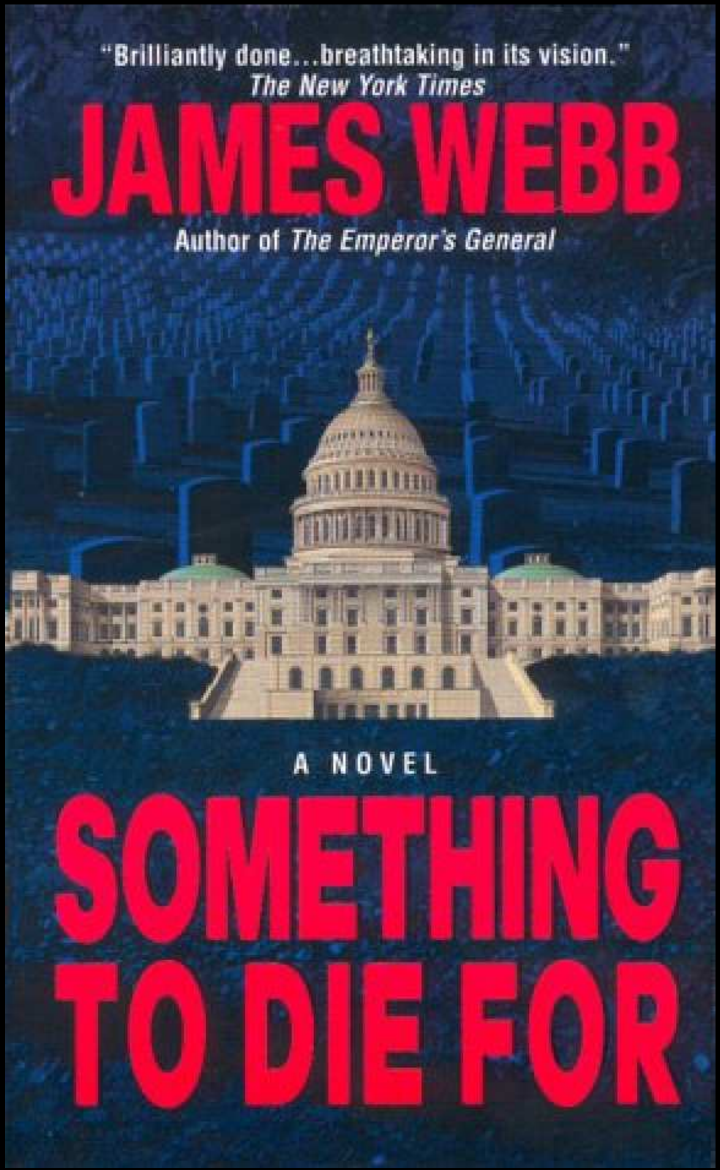
JWST: The infrared sequel to Hubble from 2018–2023 (–2029?).



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.

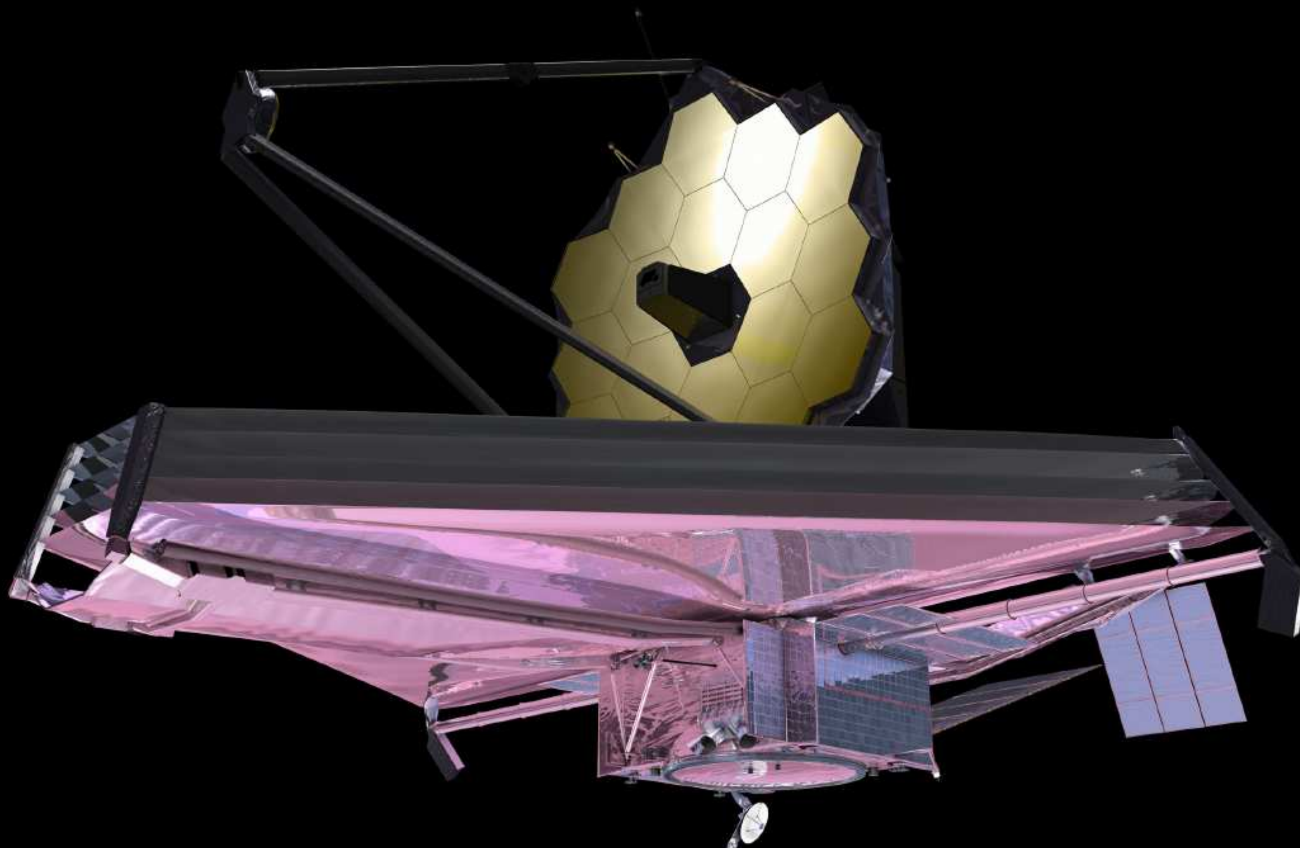
(1) Update of the James Webb Space Telescope (JWST), 2017



To be used by students & scientists after 2018 ... 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 2017



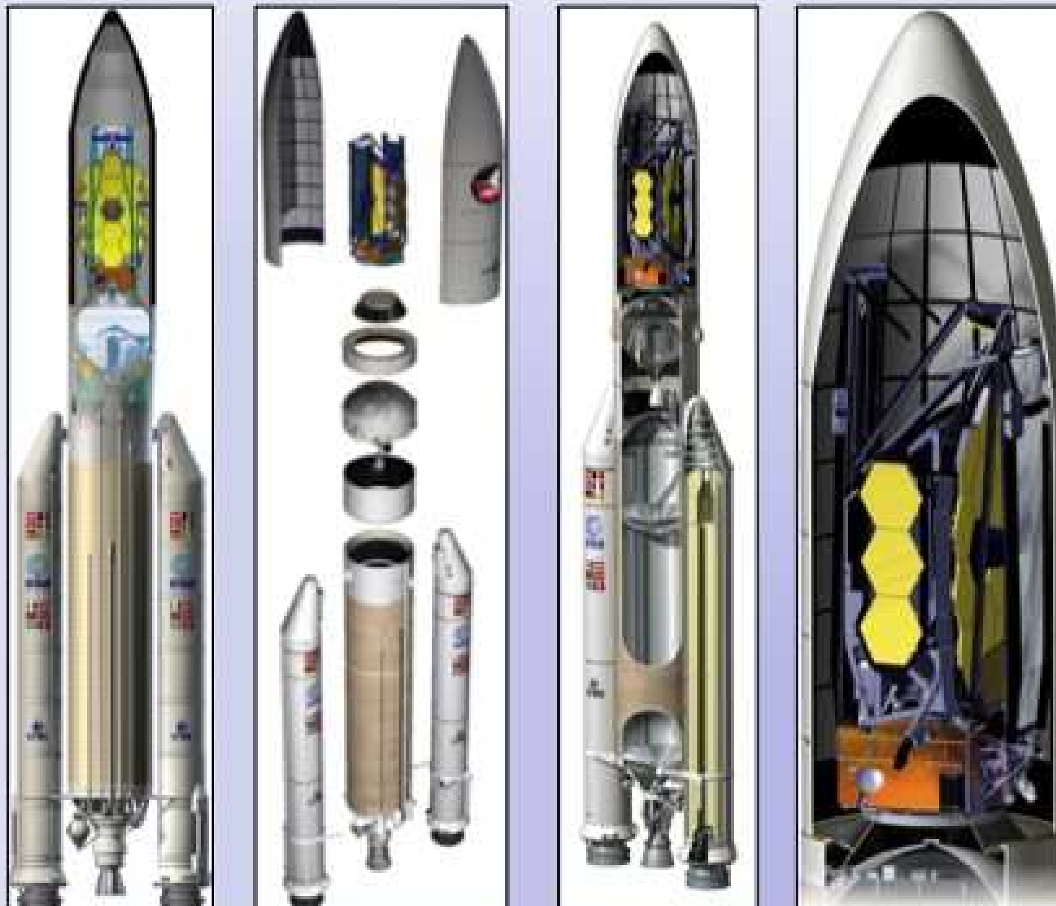
• A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.

• 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

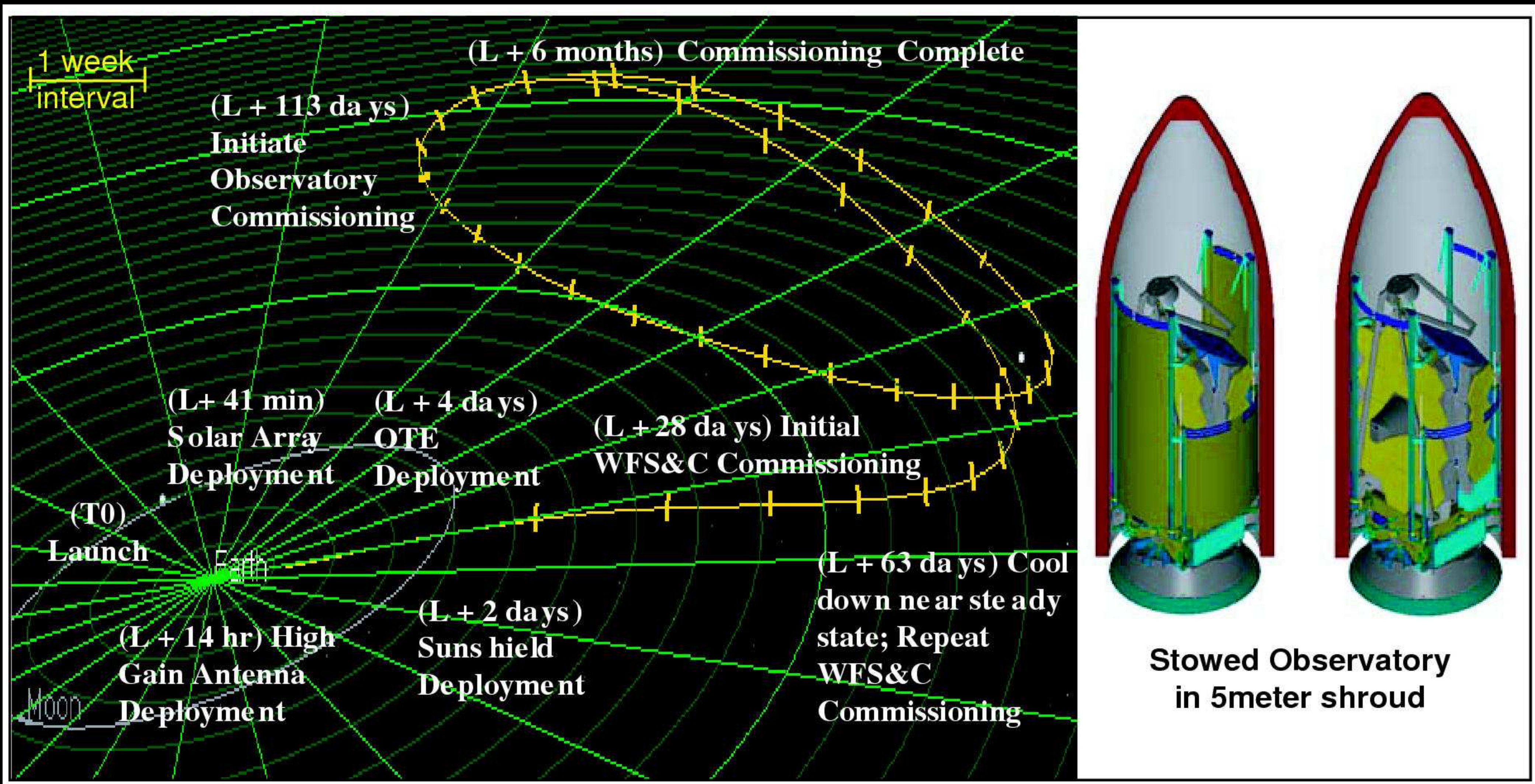
- Launch vehicle is an Ariane 5 rocket, supplied by ESA
- Site will be the Arianespace's ELA-3 launch complex near Kourou, French Guiana



Arianespace – ESA - NASA

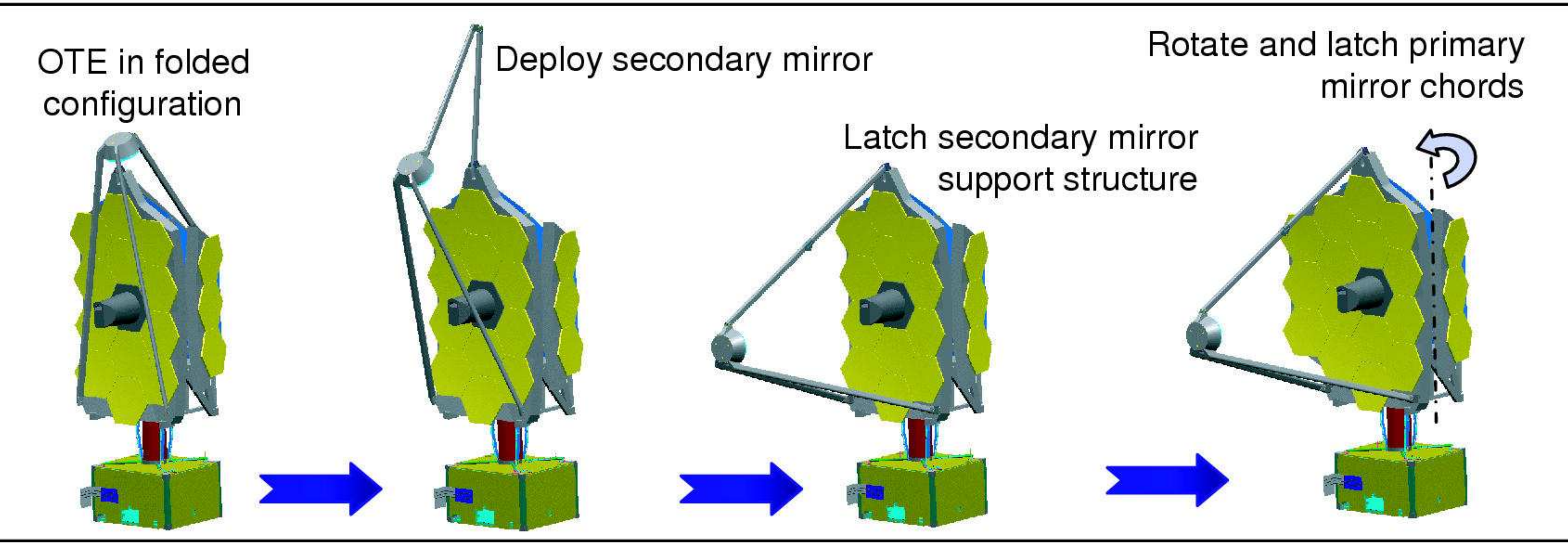
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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



- After launch in (Oct.) 2018 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.

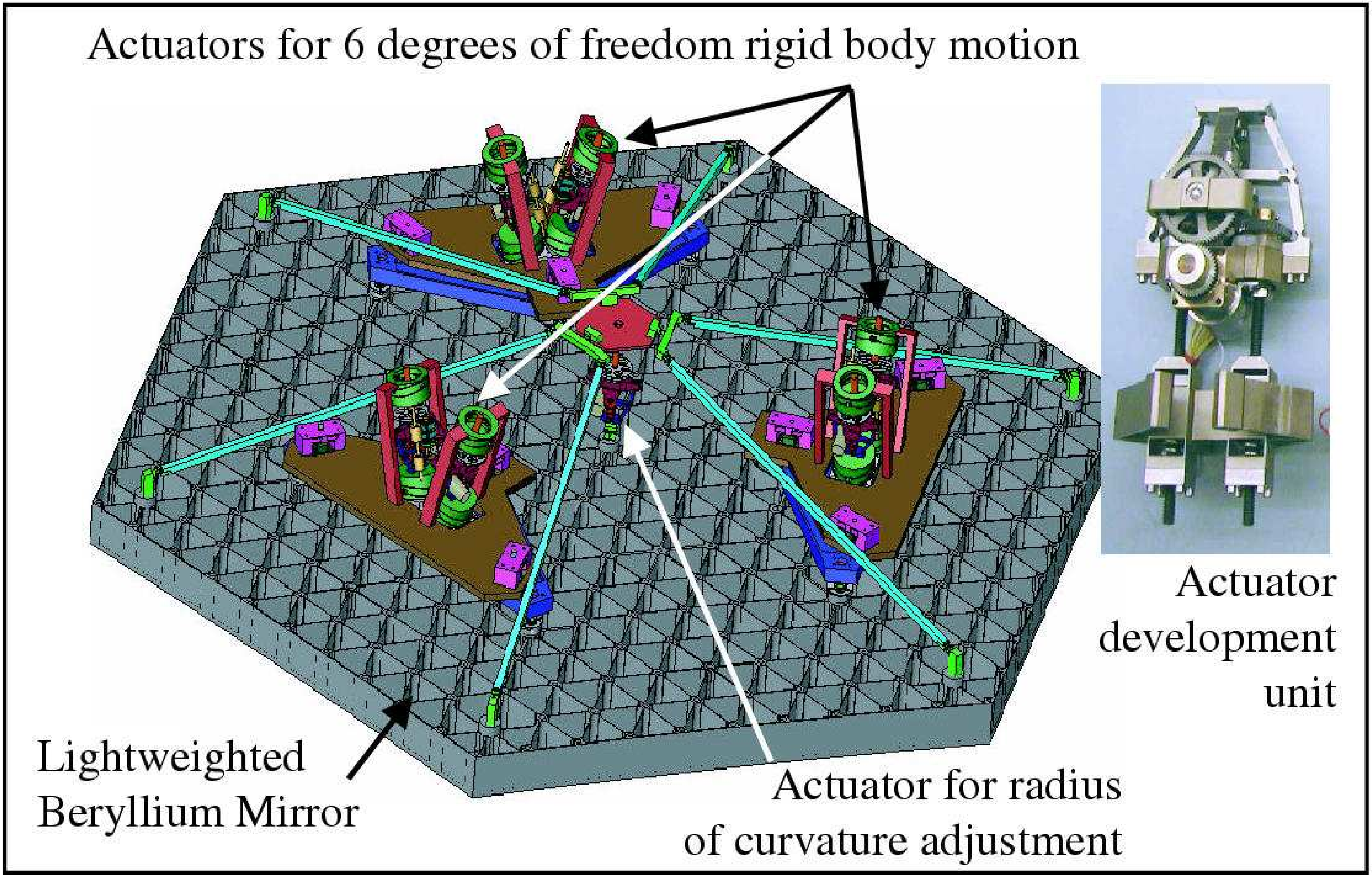
• (1b) How will JWST be automatically deployed?



• 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 2014–2017 at GSFC (MD), Northrop (CA), and JSC (Houston).

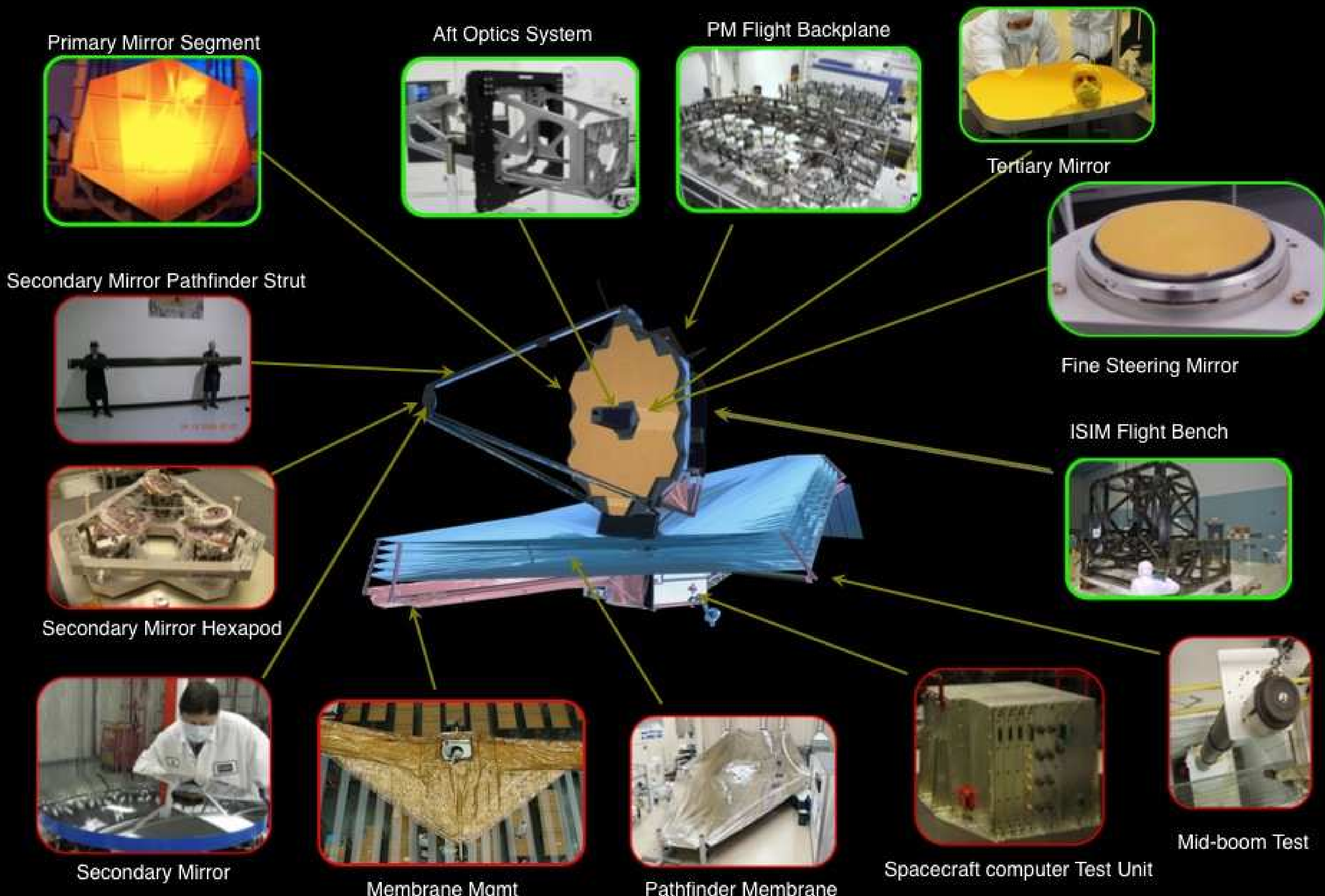
• Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



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

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

JWST Hardware Status



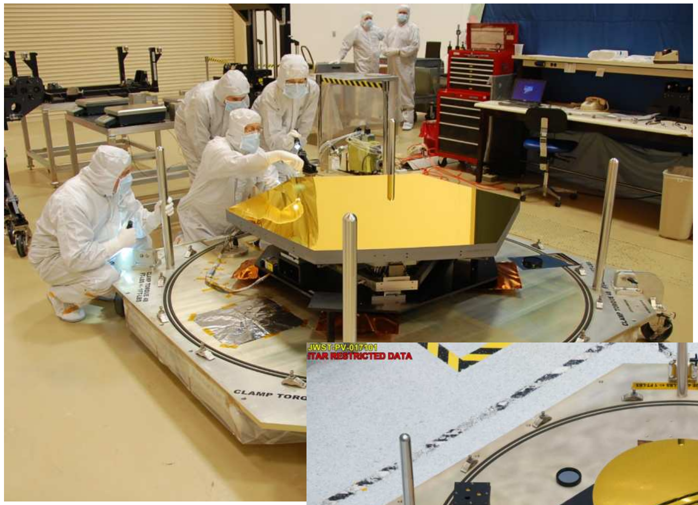
Summer 2017: $\gtrsim$99% of launch mass designed and built ($\gtrsim$99% weighed).

Mirror Acceptance Testing

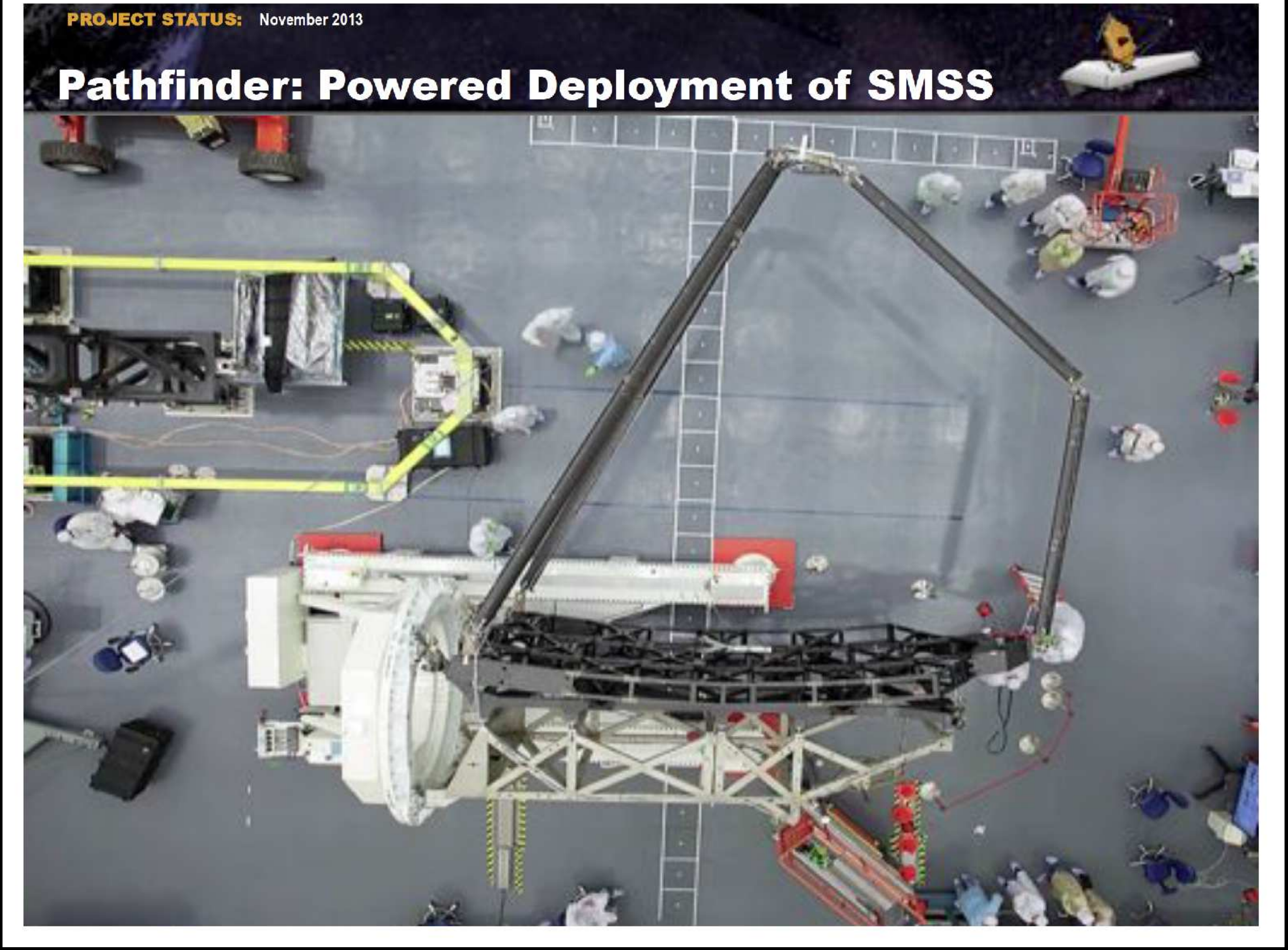

Ball

Mirror Status

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

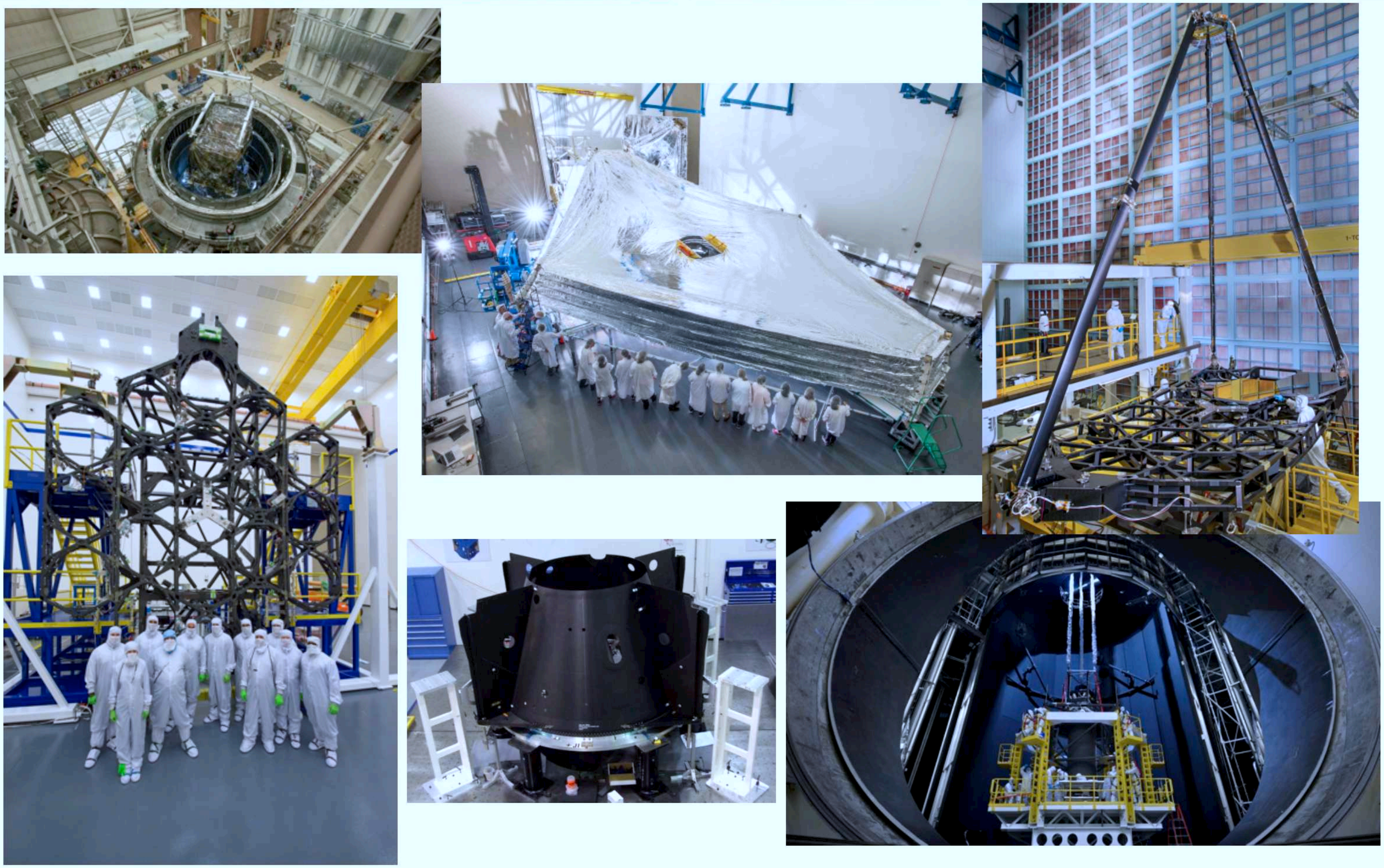


Spring 2014: All 18 flight mirrors delivered to NASA GSFC (MD).



July 2014: Secondary Mirror Support deployment successfully tested.

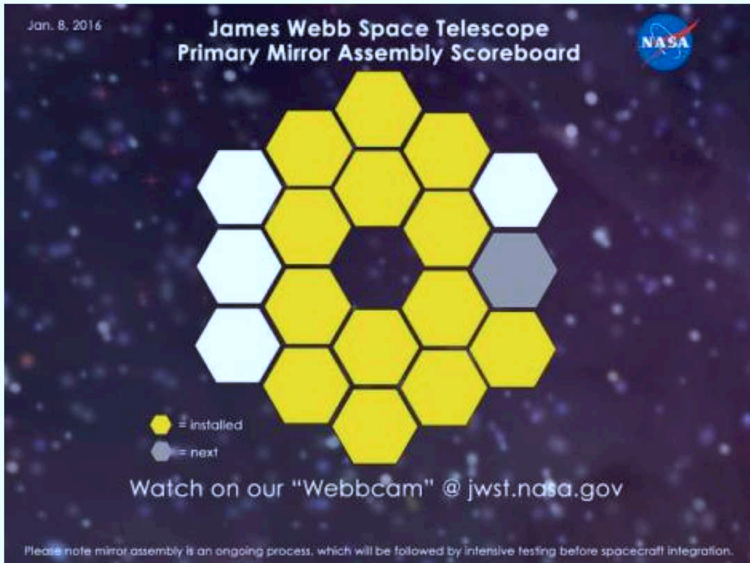
JWST Hardware Progress



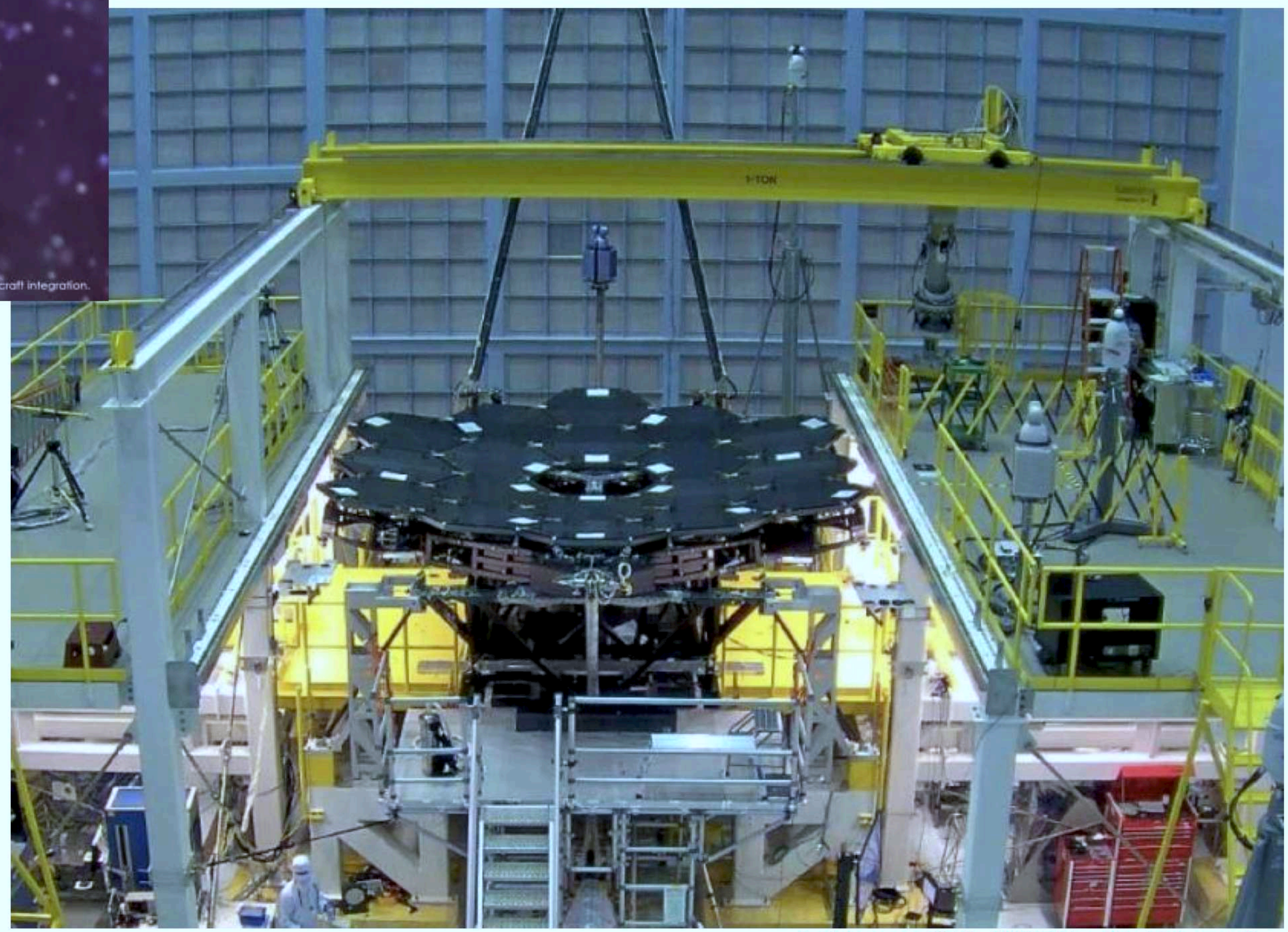
JWST remains on track for an October 2018 launch within its replan budget guidelines

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

Much progress has been made in OTE integration



Where we were at last month's call



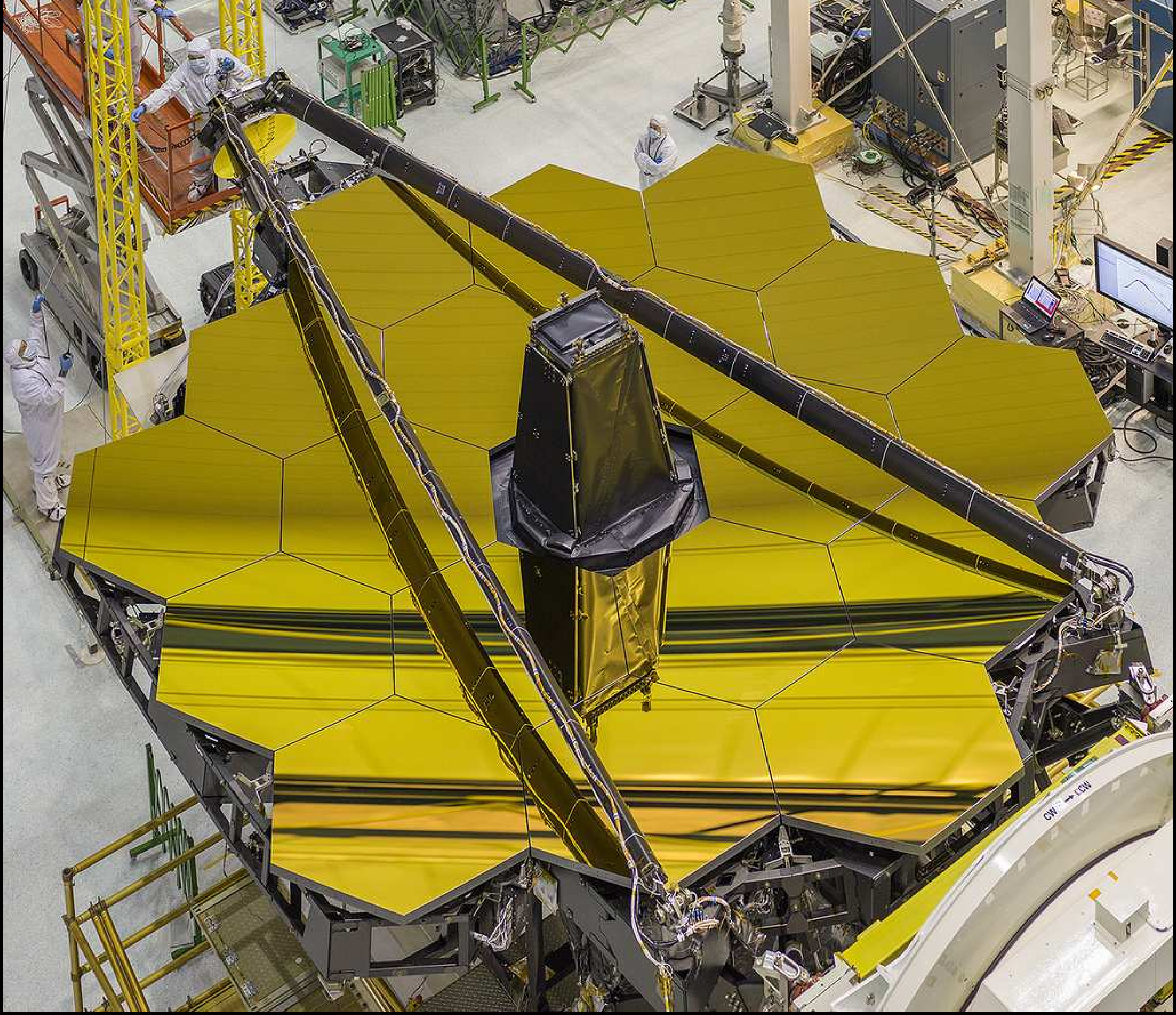
<u>Current</u>: all 18 PMSAs installed, liquid-shim-cured, & metrologized. Alignments meet specifications, and actuator motions verified
Big milestone!

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

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

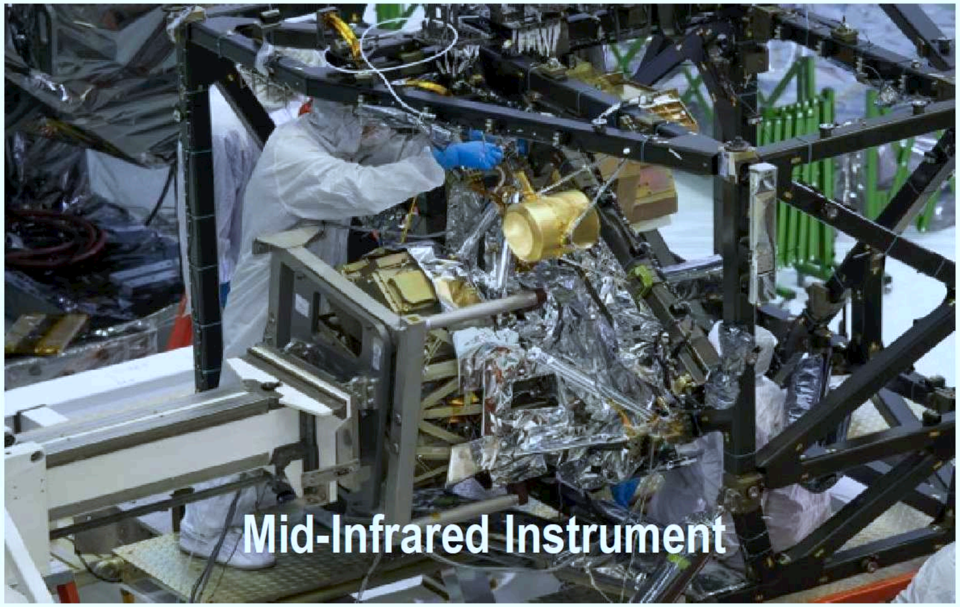
May 2016: JWST being tilted into the right position

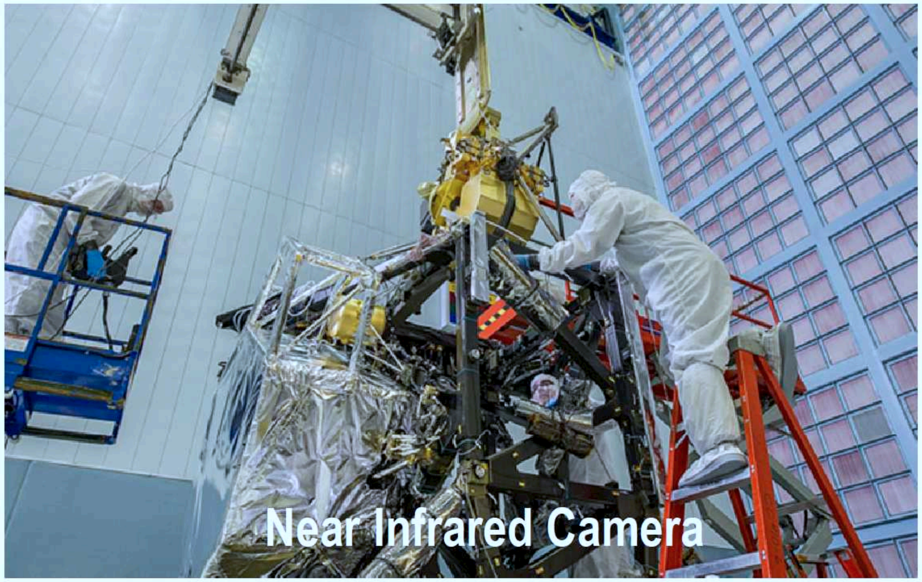
May 2016: Webb mirrors finally mounted and ready!

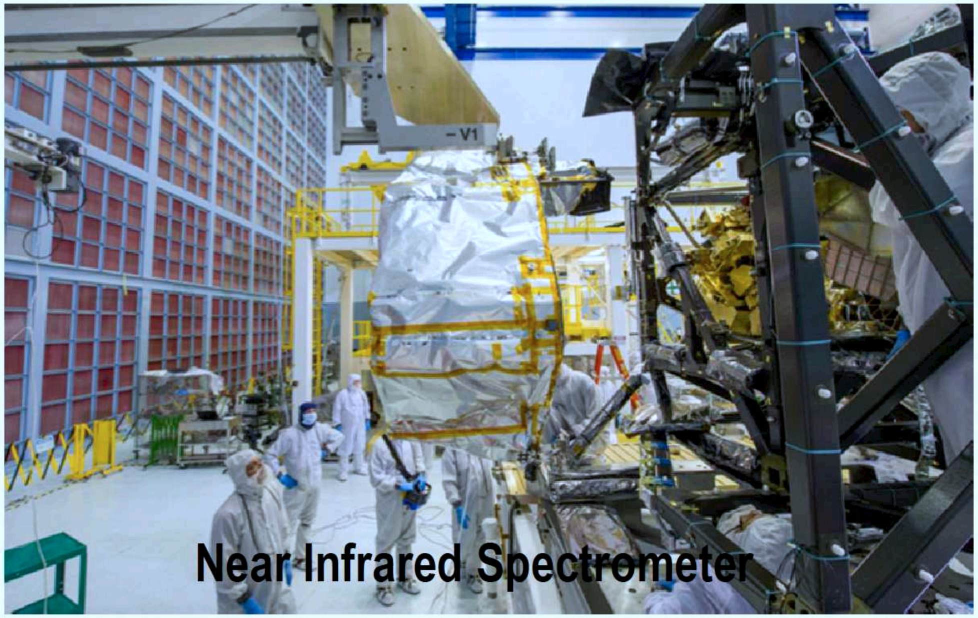


May 2016: JWST stowed for further instrument mounting

All Instruments Integrated







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

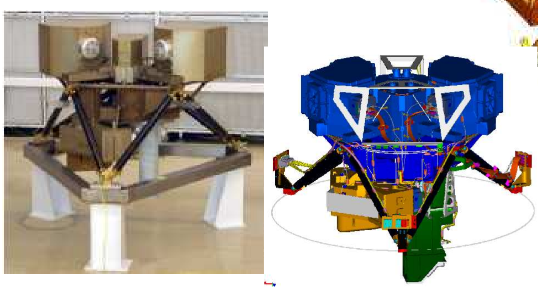
Instrument Overview

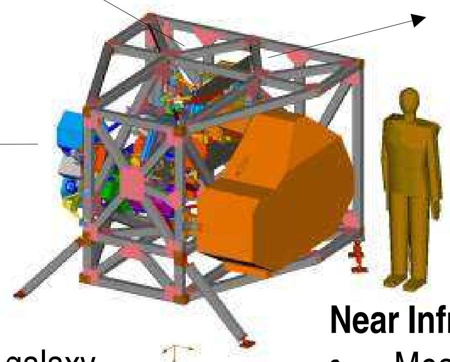
Fine Guidance Sensor (FGS)

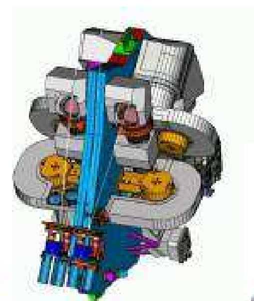
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

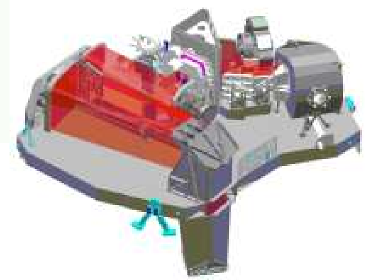
Near Infra-Red Camera (NIRCam)

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









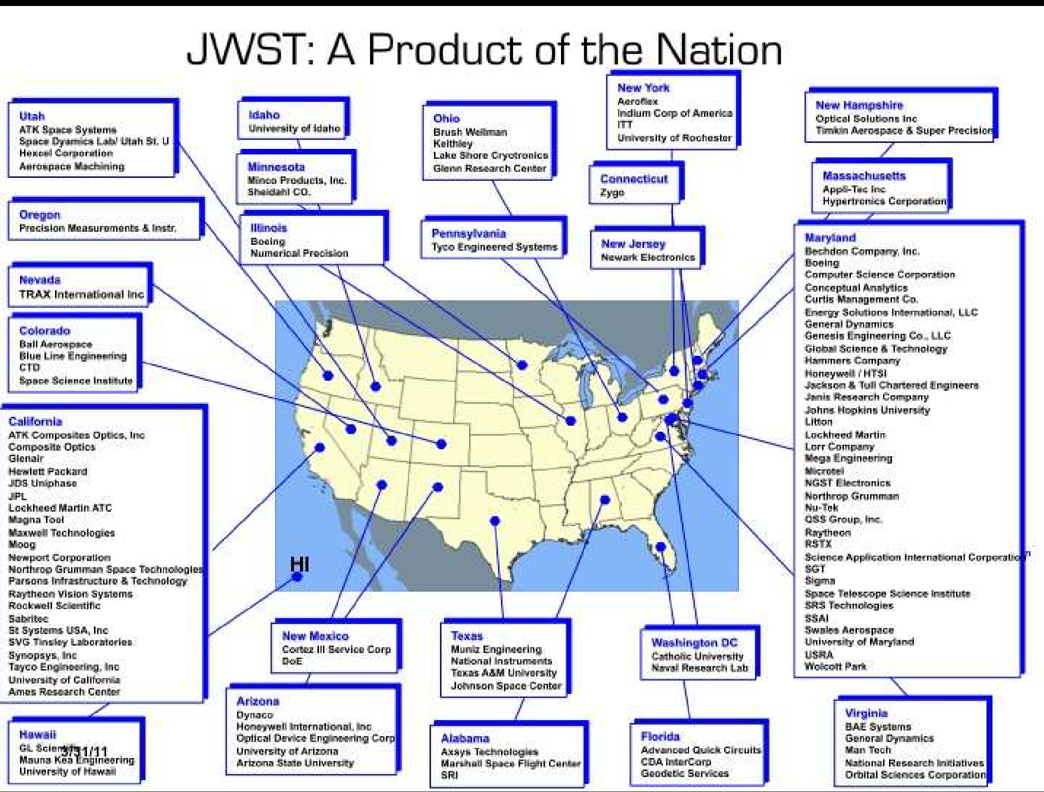
Mid-Infra-Red Instrument (MIRI)

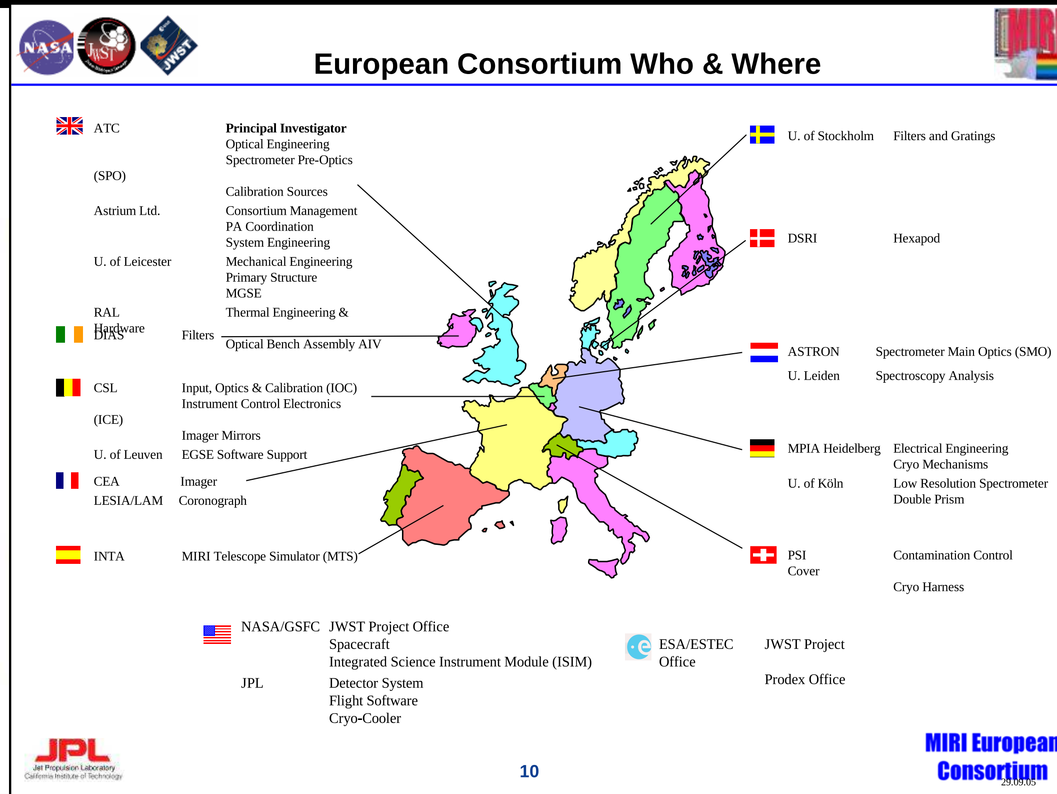
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

Near Infra-Red Spectrograph (NIRSpec)

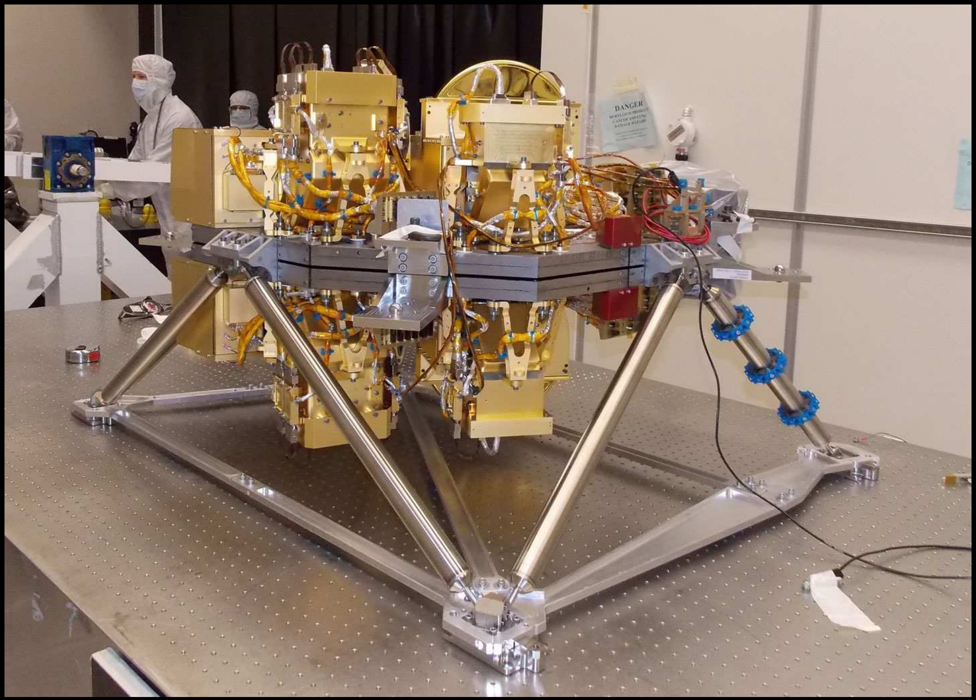
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

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



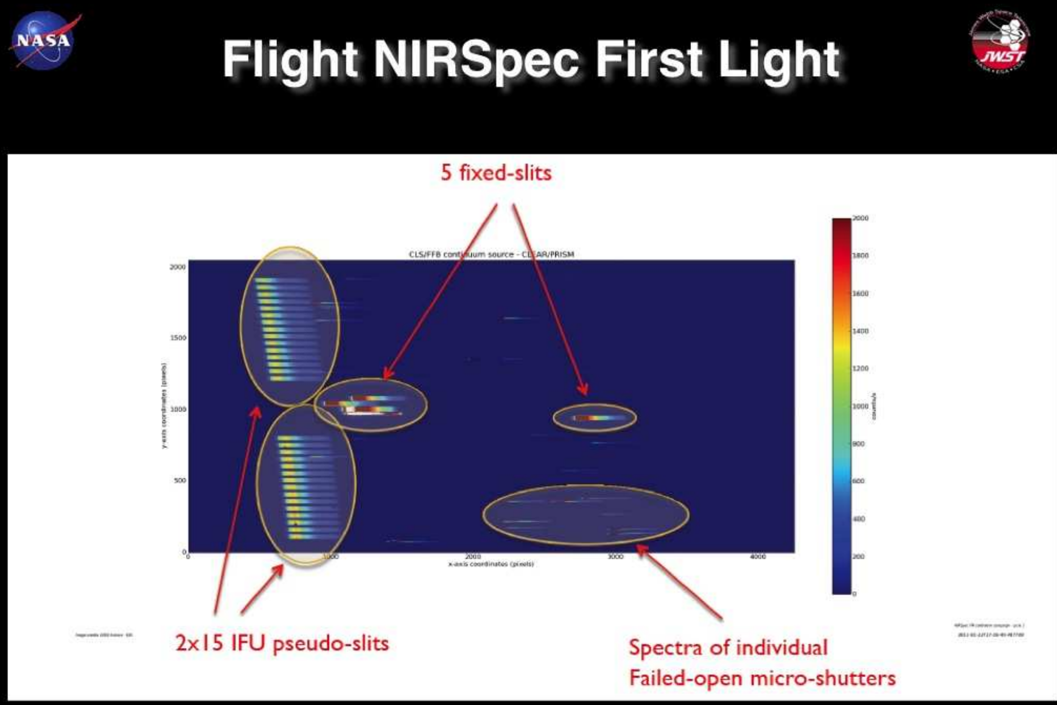


- JWST hardware made in 27 US States: $\gtrsim$99% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.



JWST's short-wavelength (0.6–5.0μm) imagers:

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



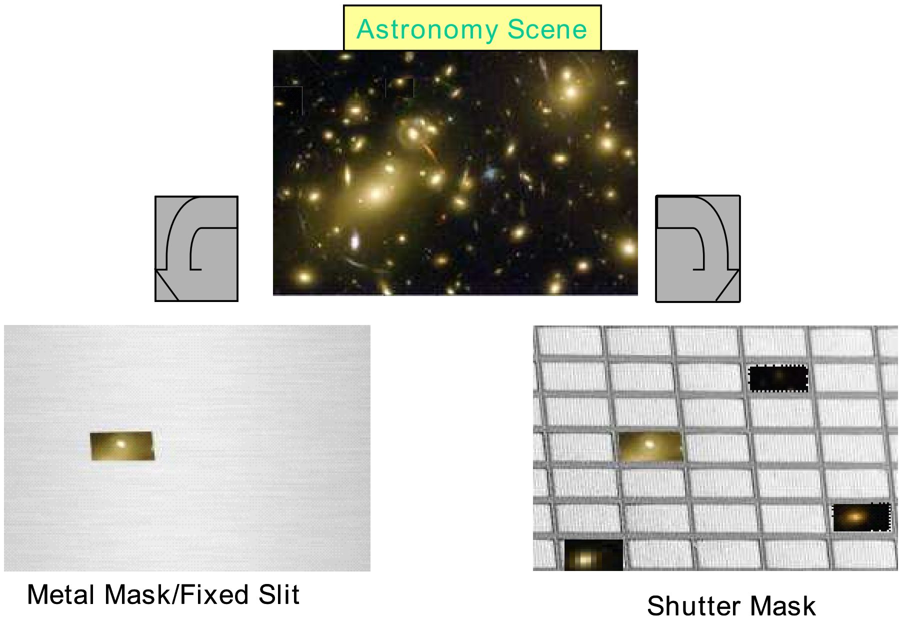
JWST's short-wavelength (0.6–5.0μm) spectrograph:

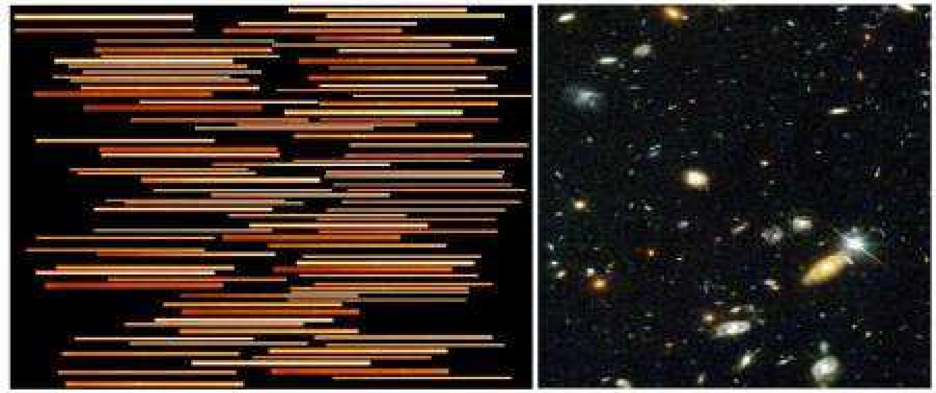
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

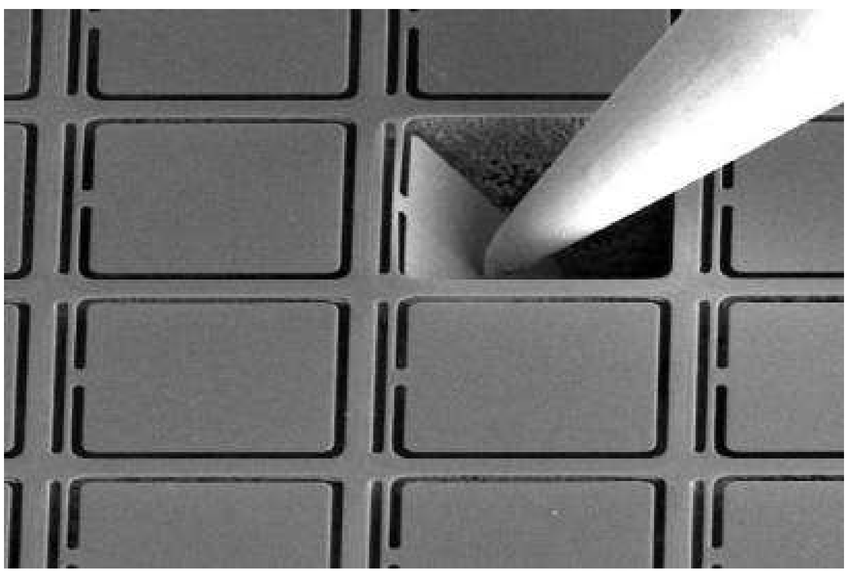
NIRSpec delivered to NASA/GSFC in 09/13.

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

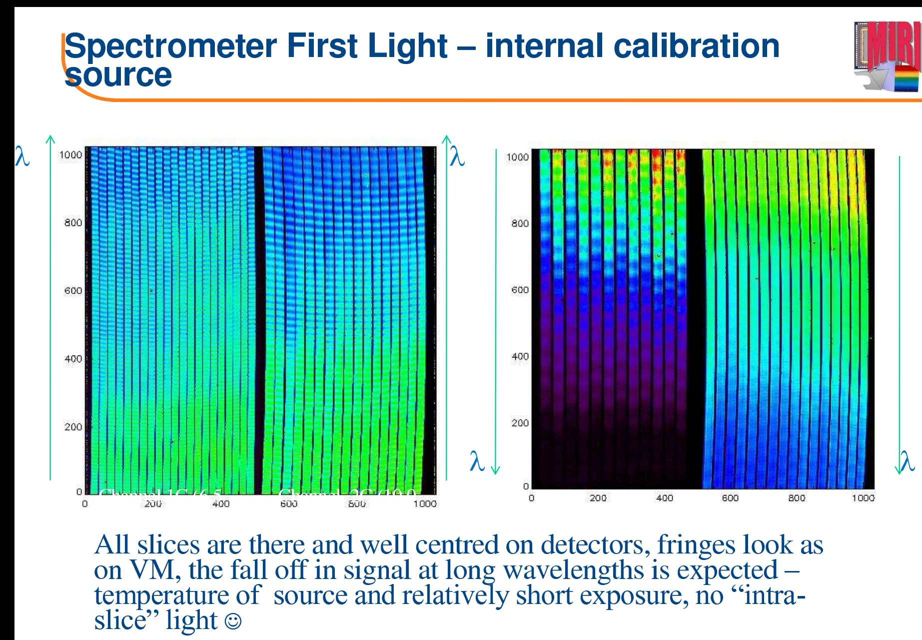
Micro Shutters







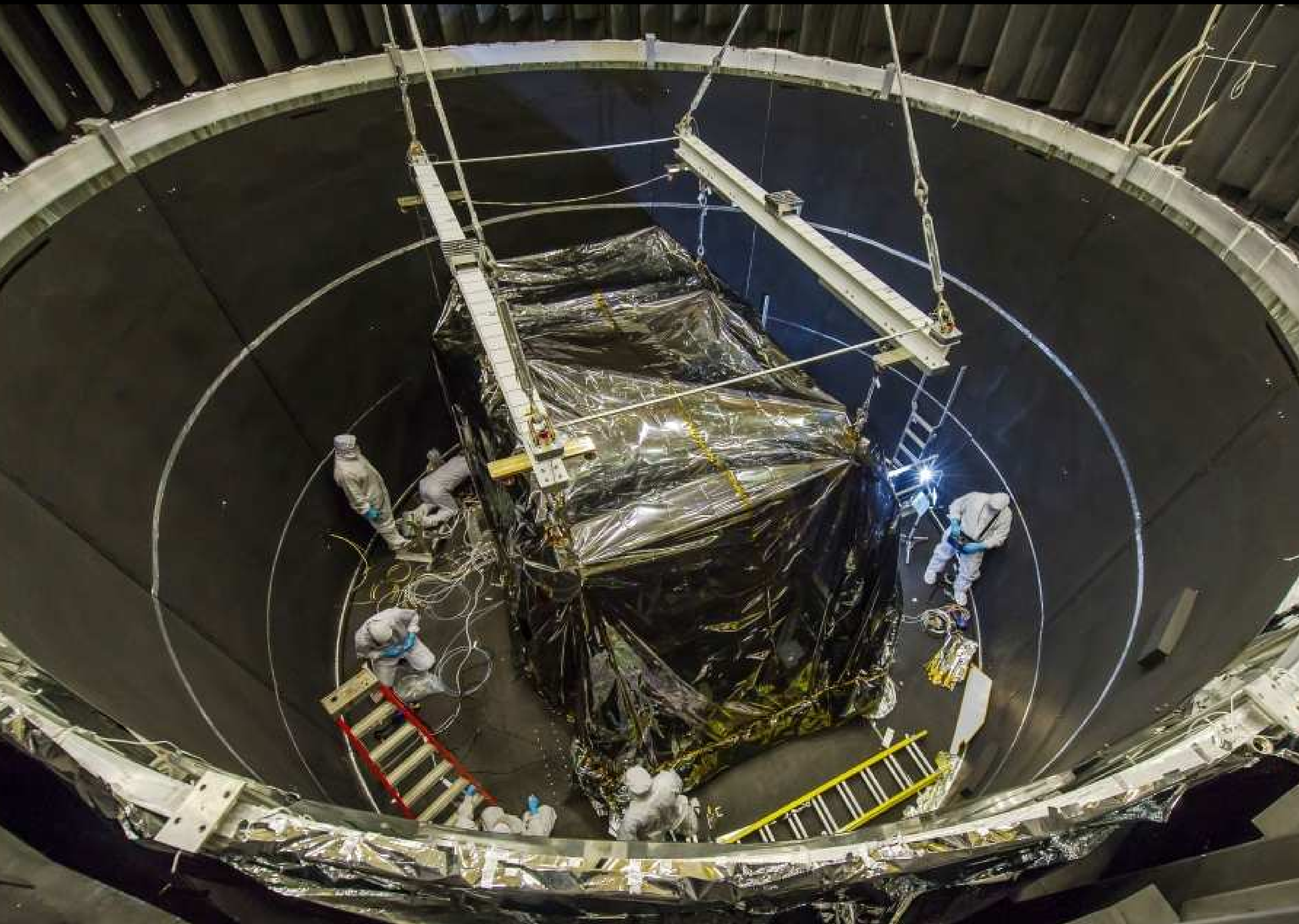
Flight MIRI



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

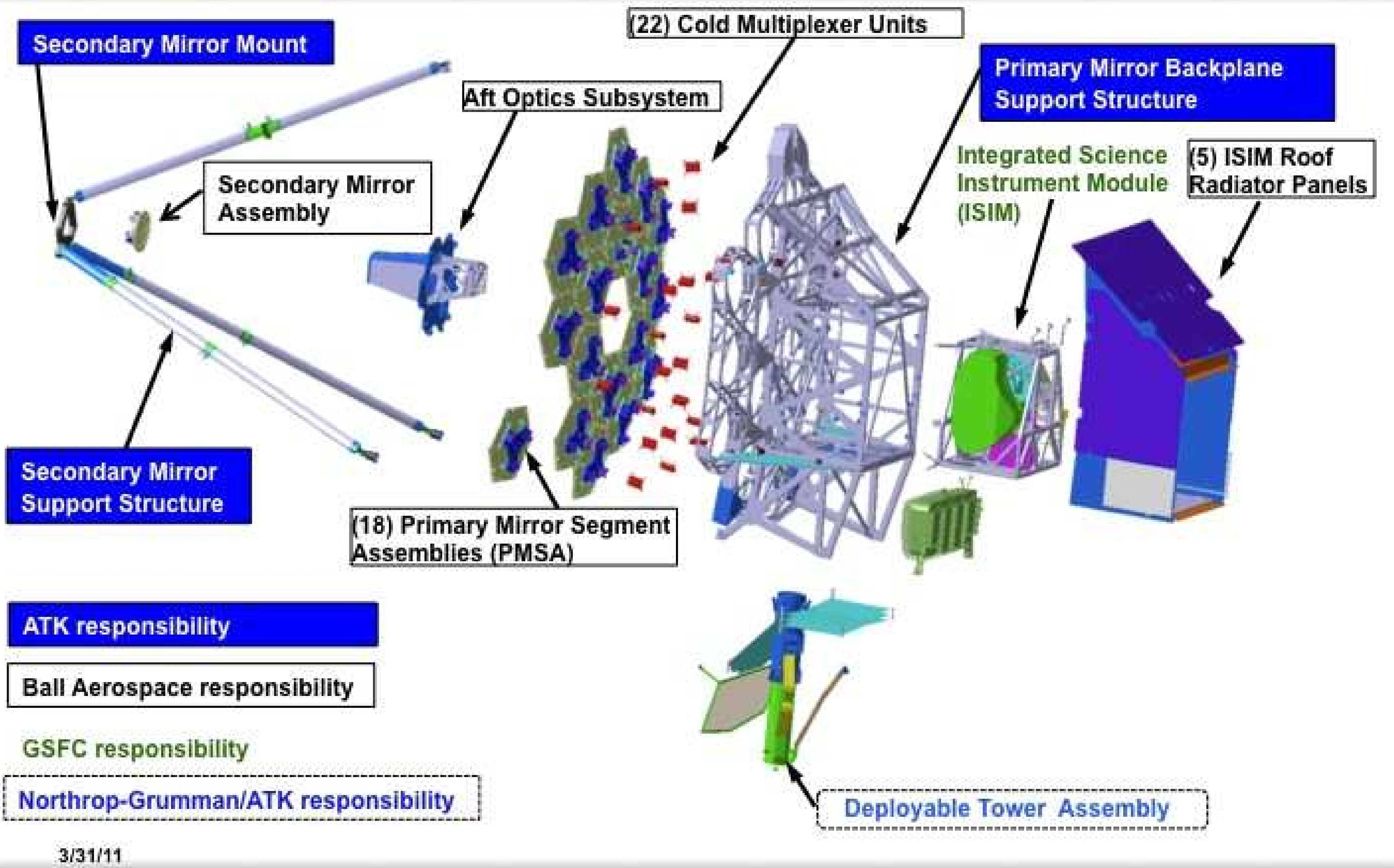
- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012.



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

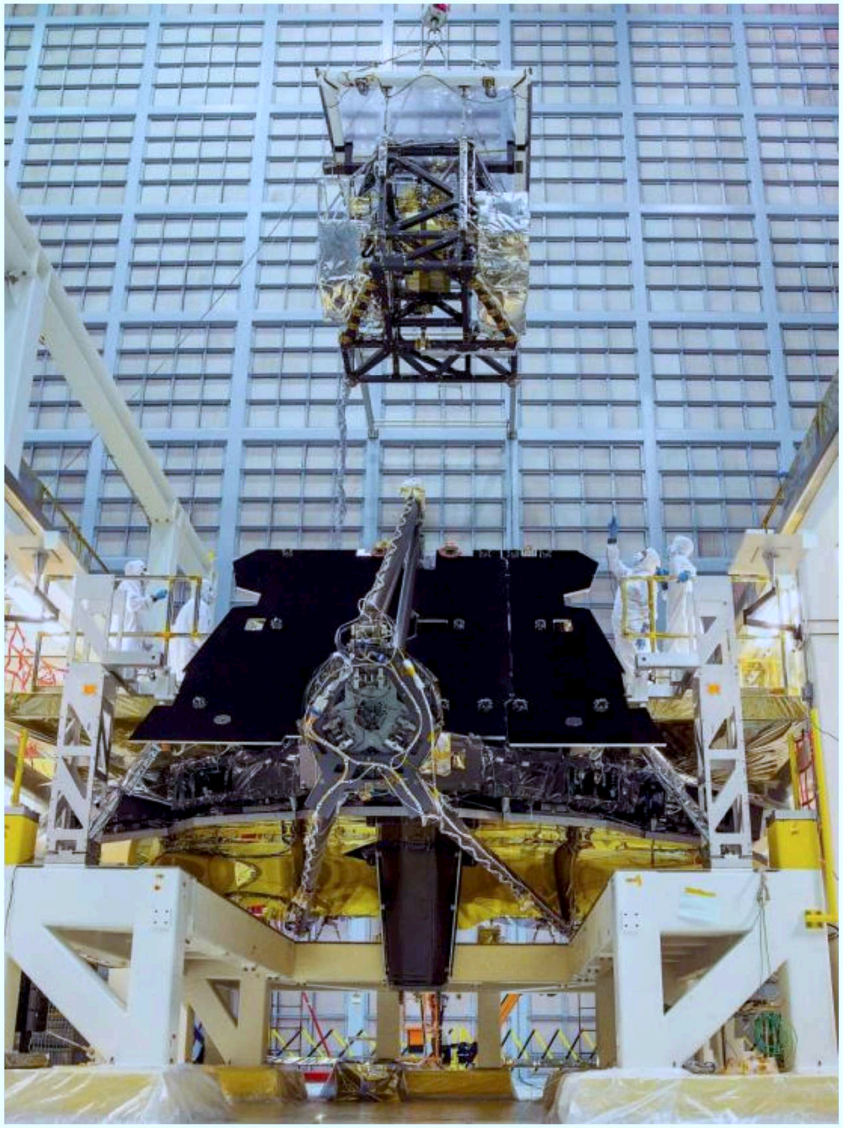
TELESCOPE ARCHITECTURE

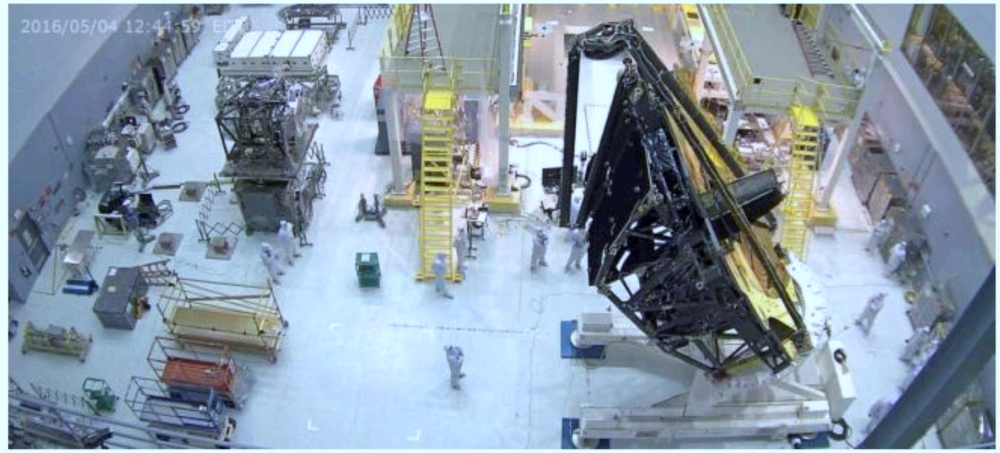


2014–2017: Complete system integration at GSFC and Northrop.

Program Update: OTE + ISIM = OTIS

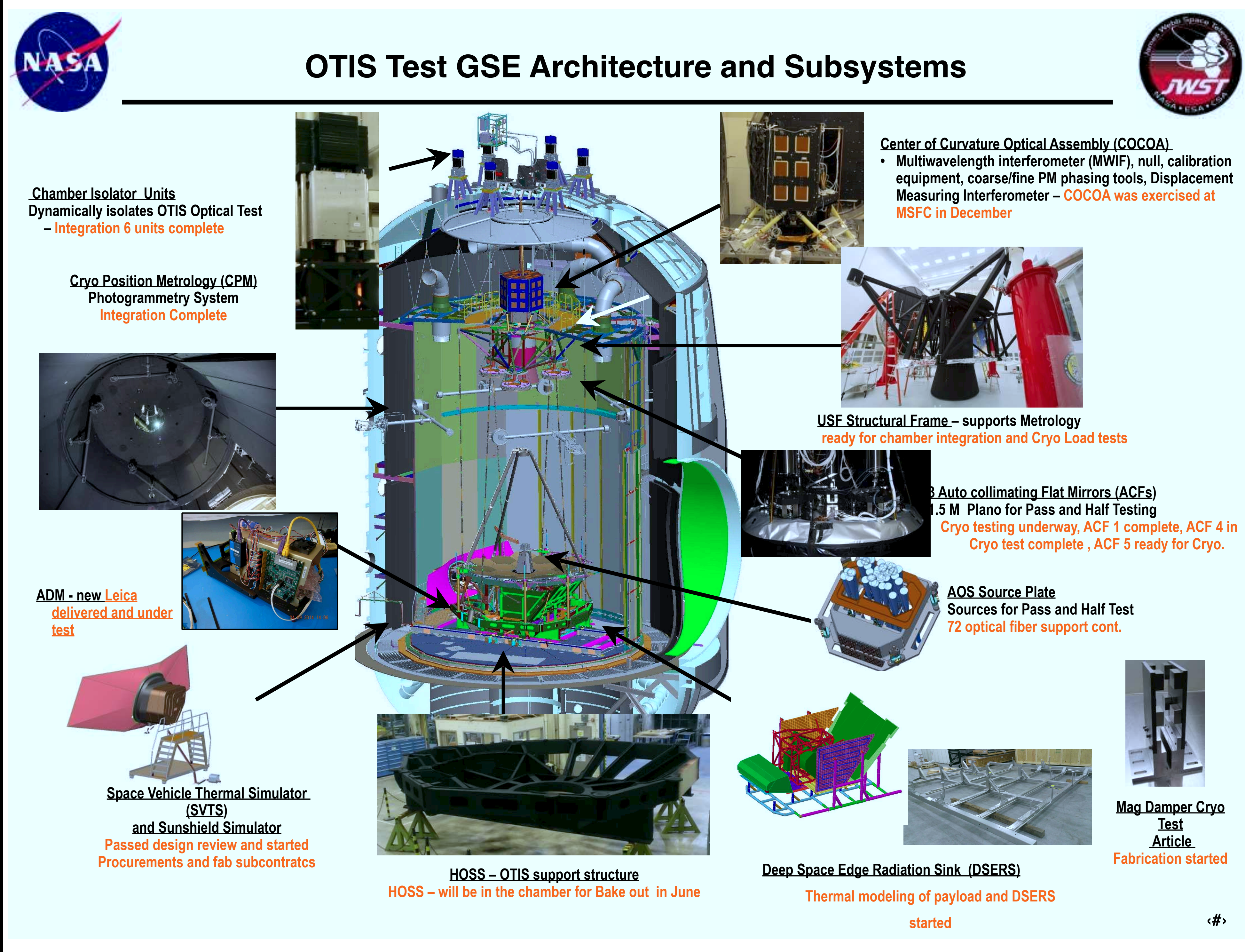
NORTHROP GRUMMAN





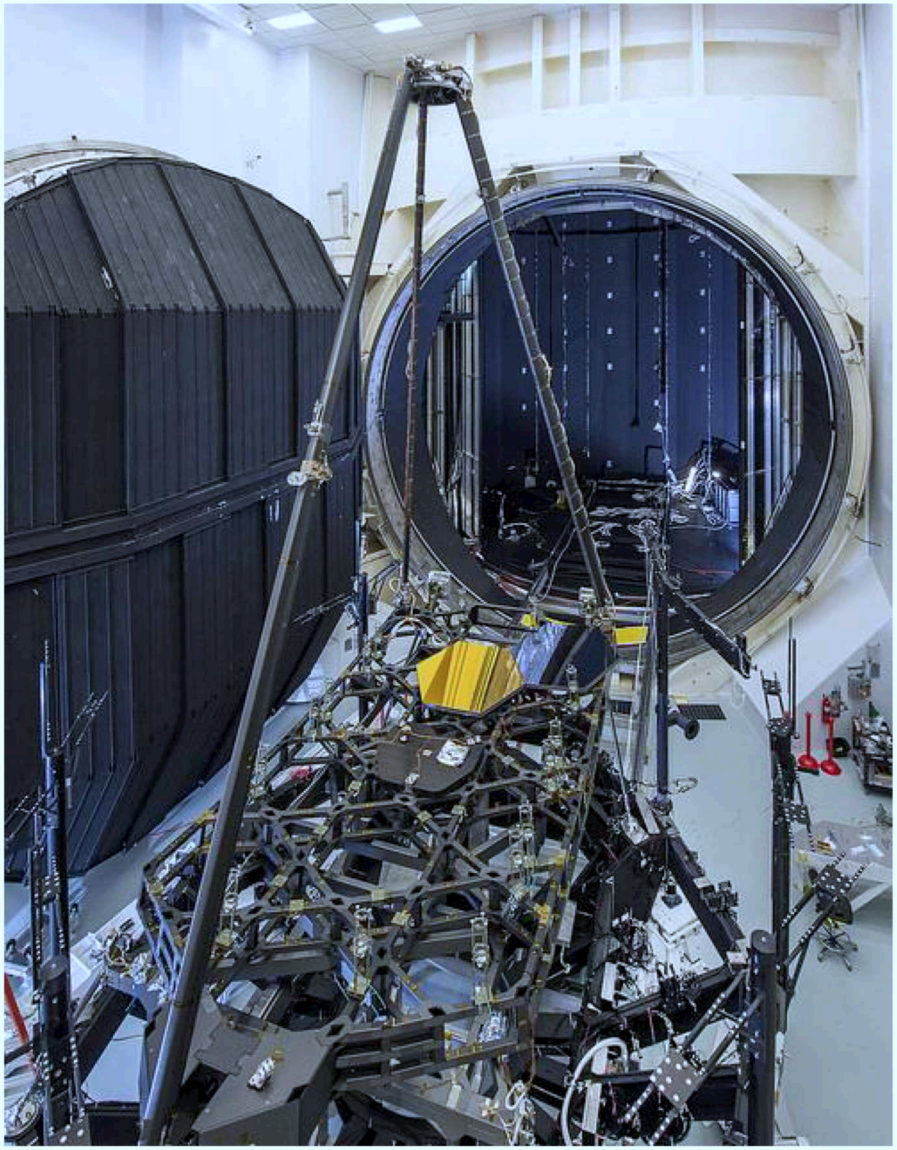
June 2016: Flight ISIM mated with Optical Telescope Element (OTE).
JWST is now a real working telescope (albeit not yet at 40 K & in 0 G)!

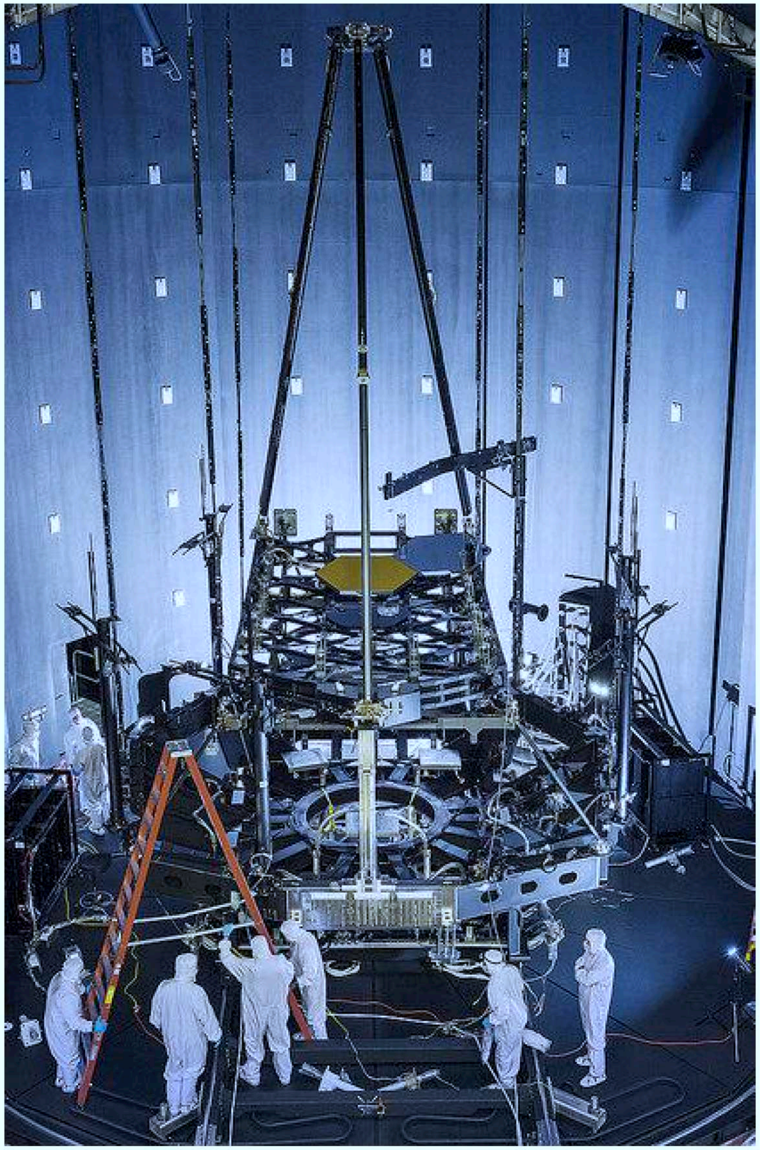
April 2017: Last portrait of JWST at Goddard Space Flight Center (MD).



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

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



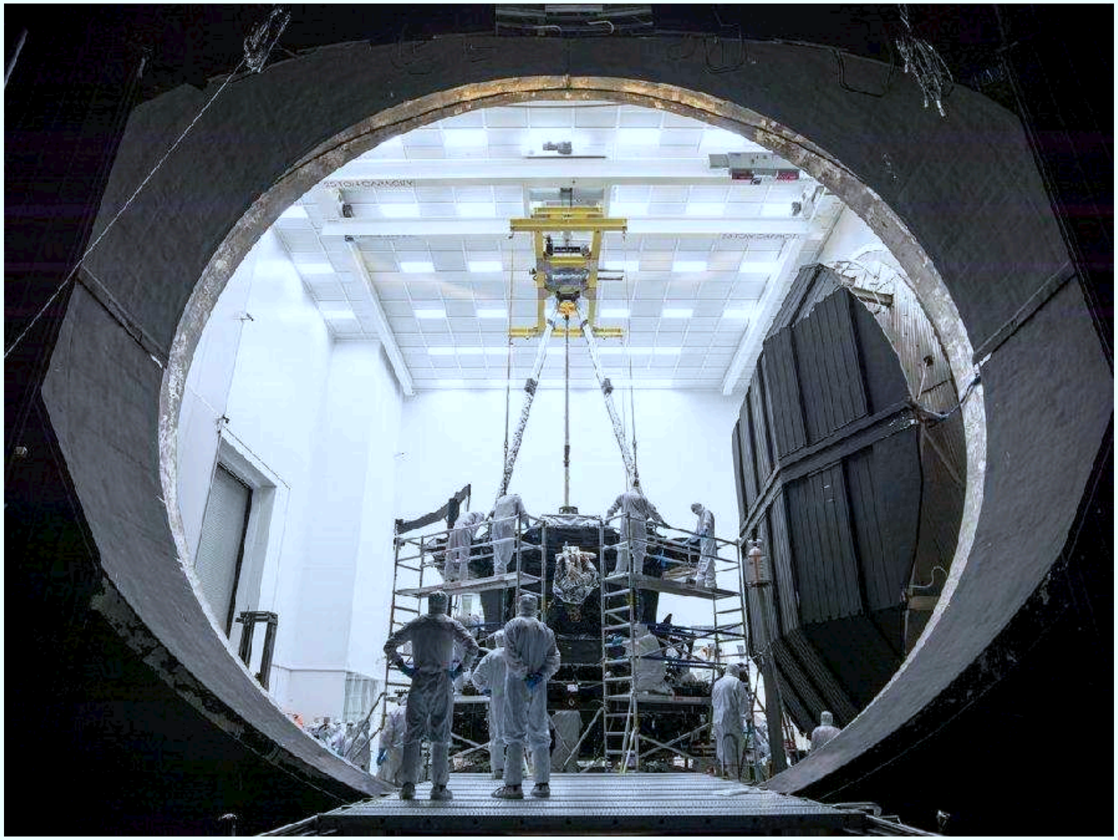


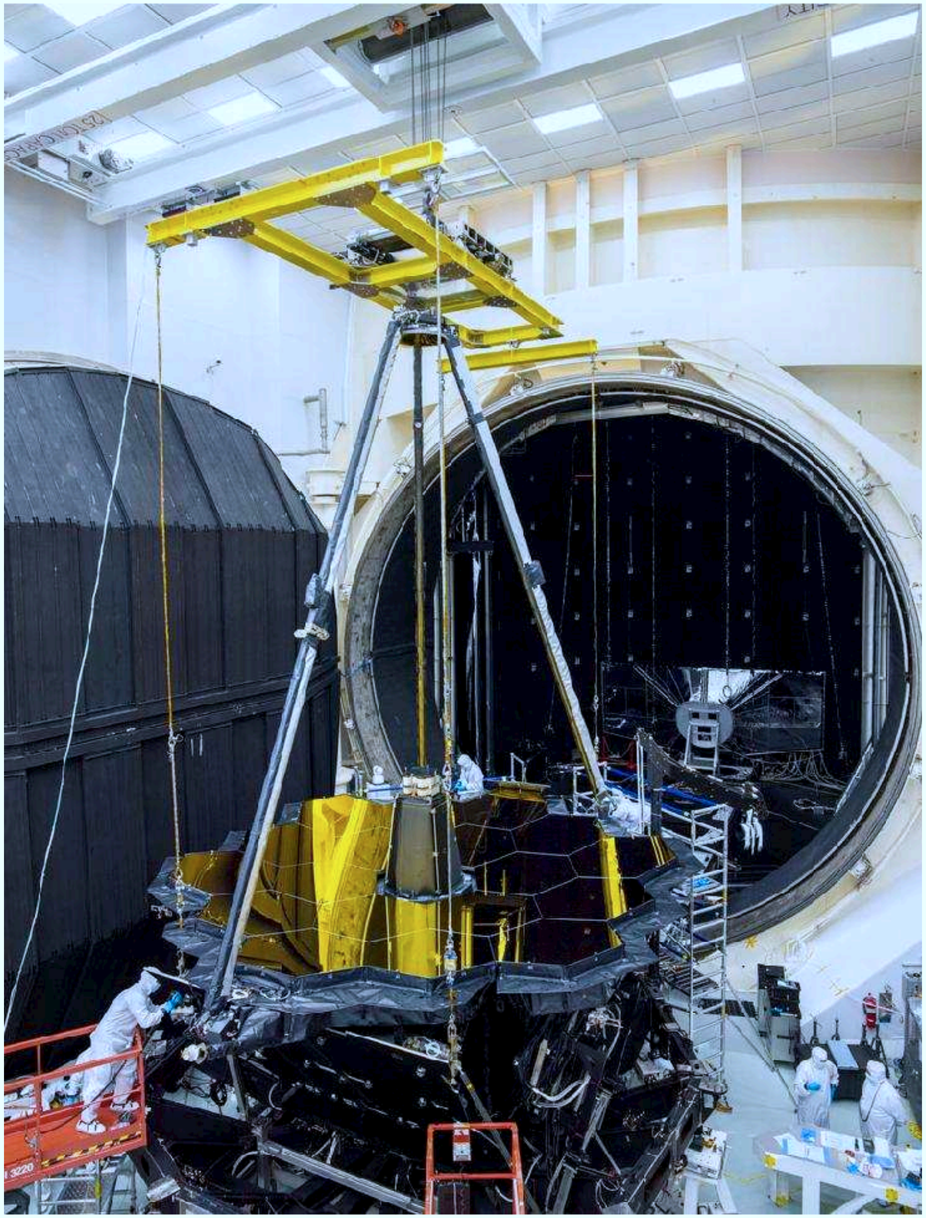
2015–2016: Testing OTIS chamber with the JWST Engineering model.

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

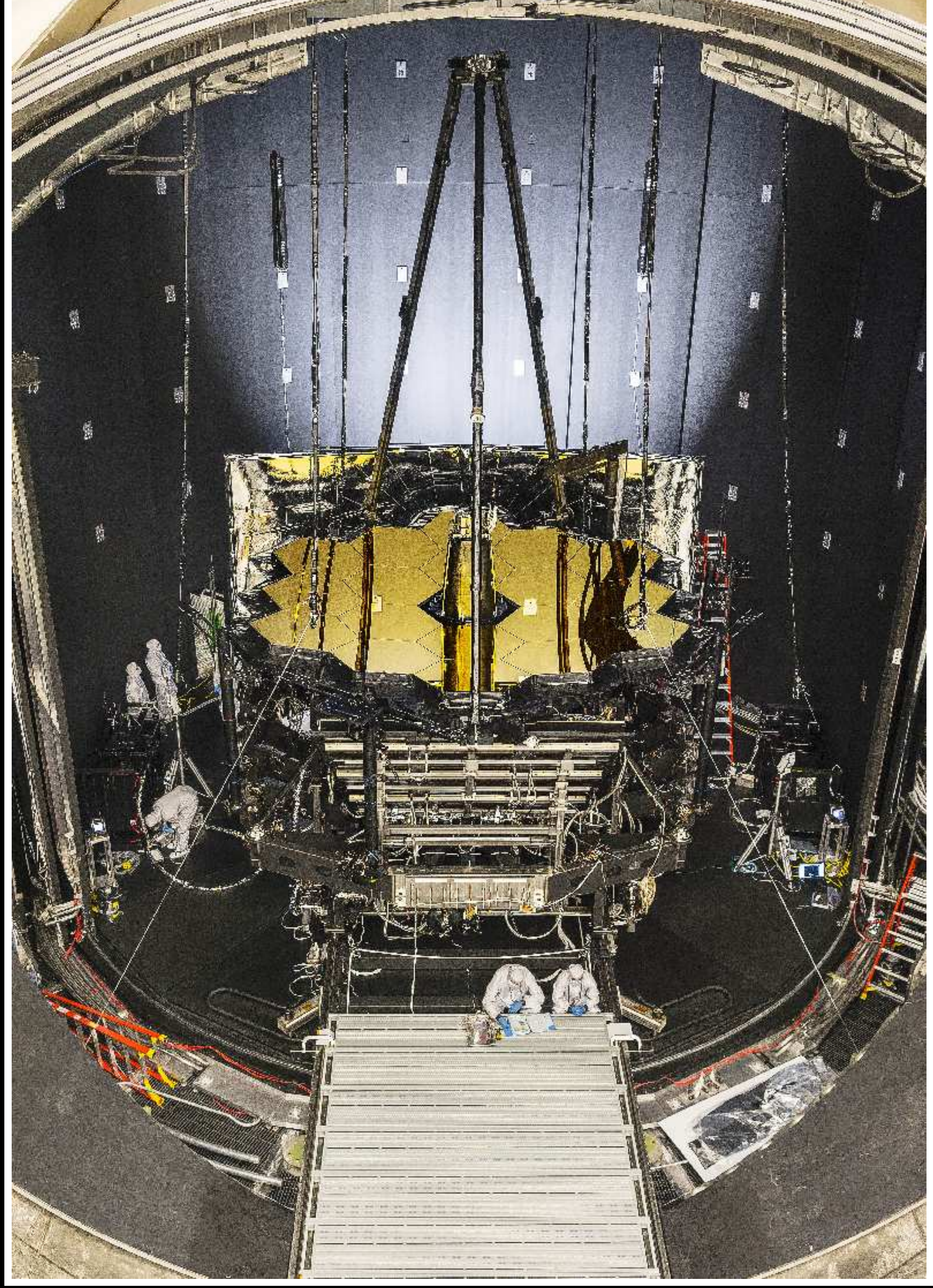
Program Update: OTIS

NORTHROP GRUMMAN



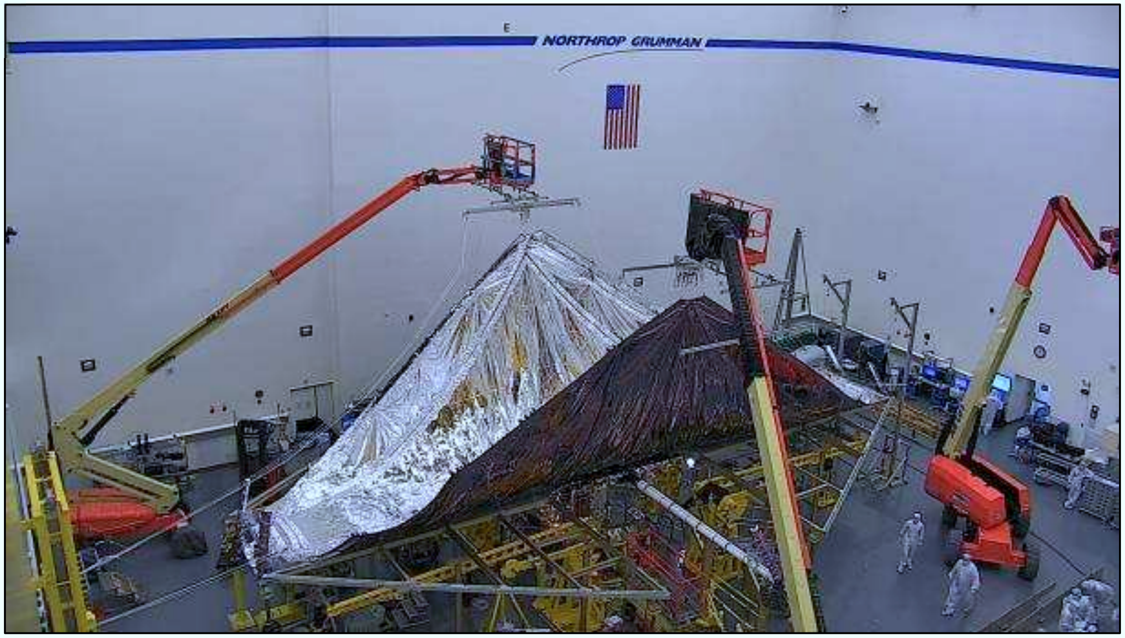


June 2017: JWST going into Chamber A at Johnson Space Center in Houston.



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

Spacecraft Element Sunshield Folding

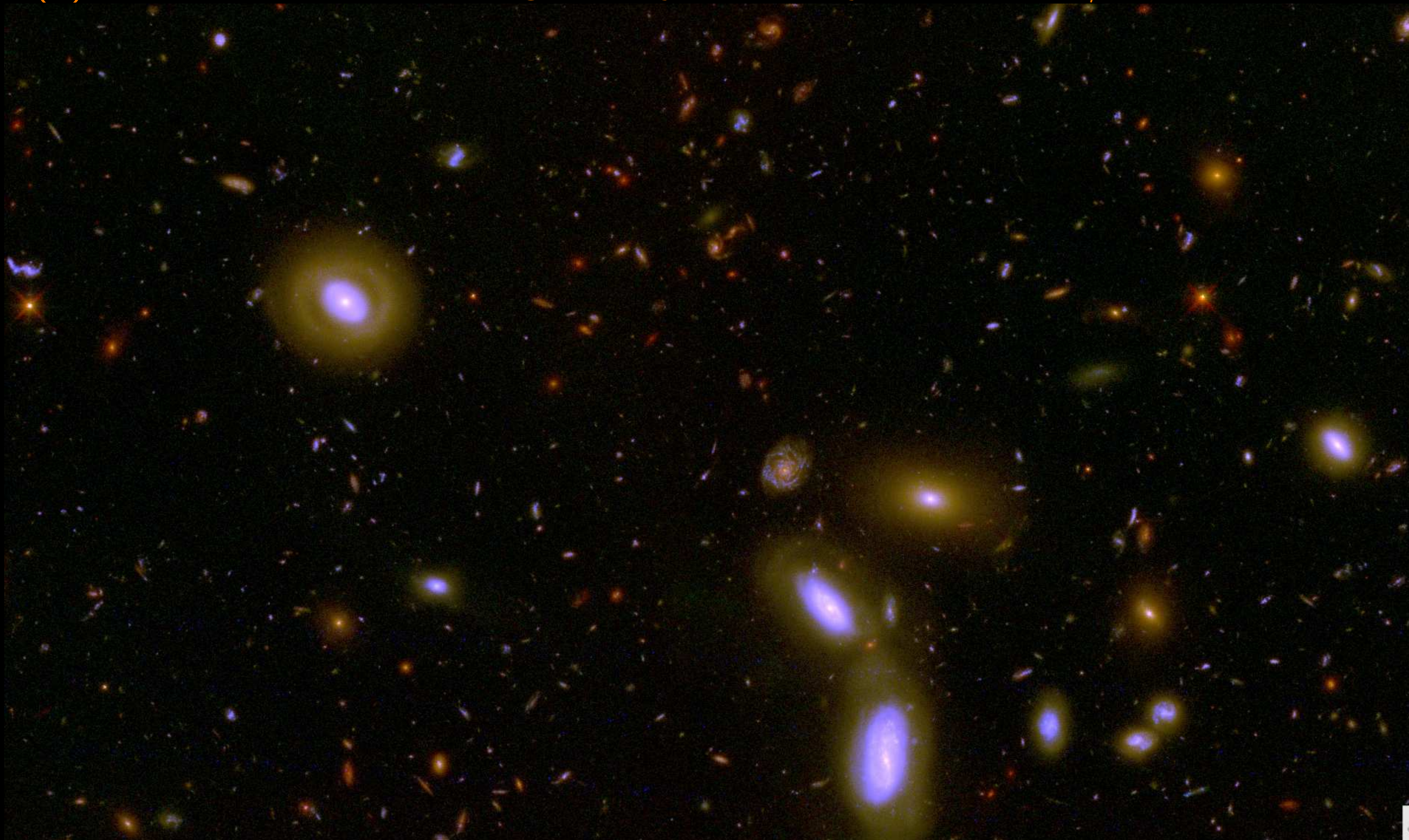


5 layer sunshield positioned to begin folding with supporting mechanical equipment

5 layer sunshield folded onto the UPS

Sept. 2017: JWST Flight Sunshield assembled and tested at Northrop (CA).

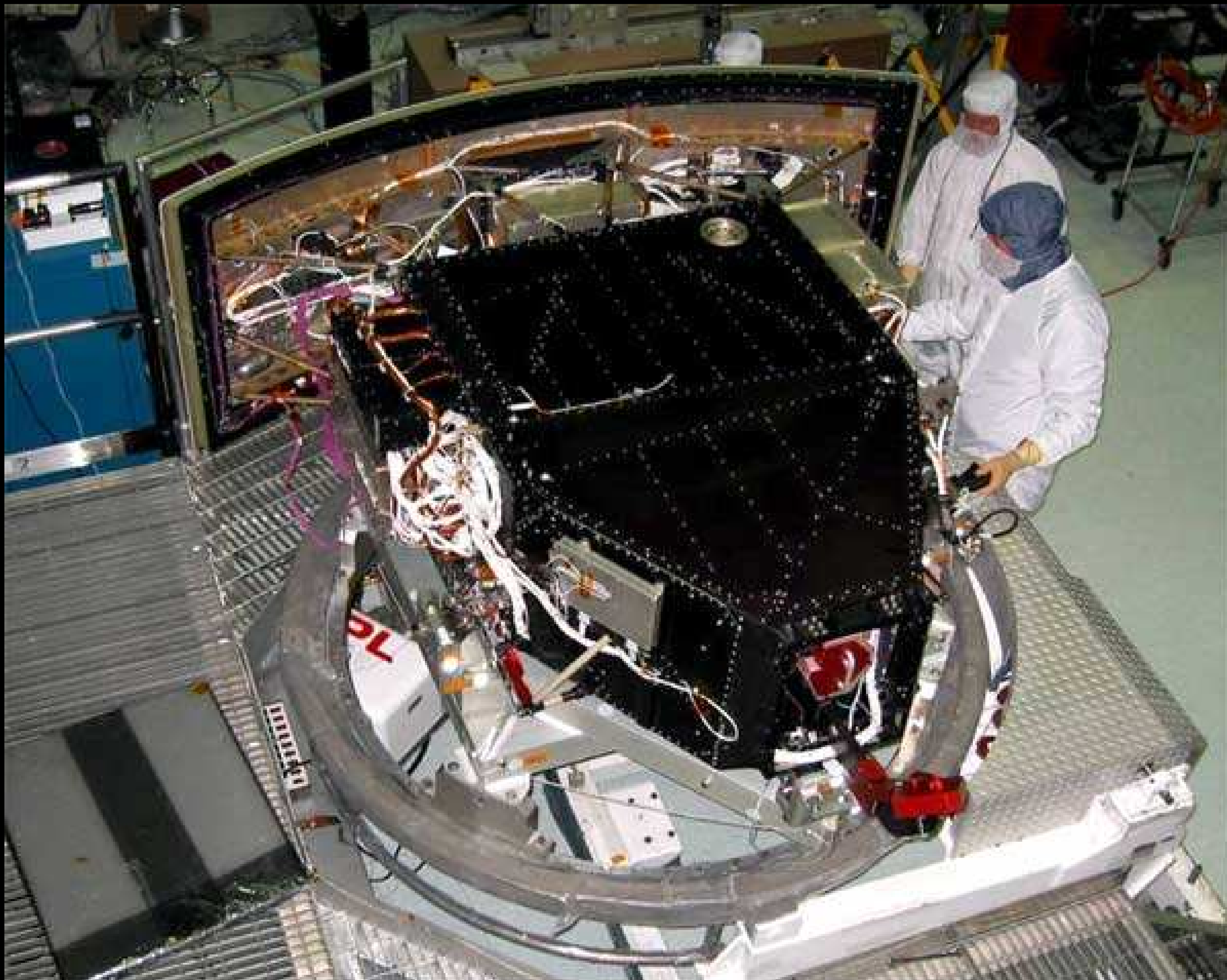
(2) HST WFC3: Measuring Galaxy Assembly and SMBH/AGN Growth?



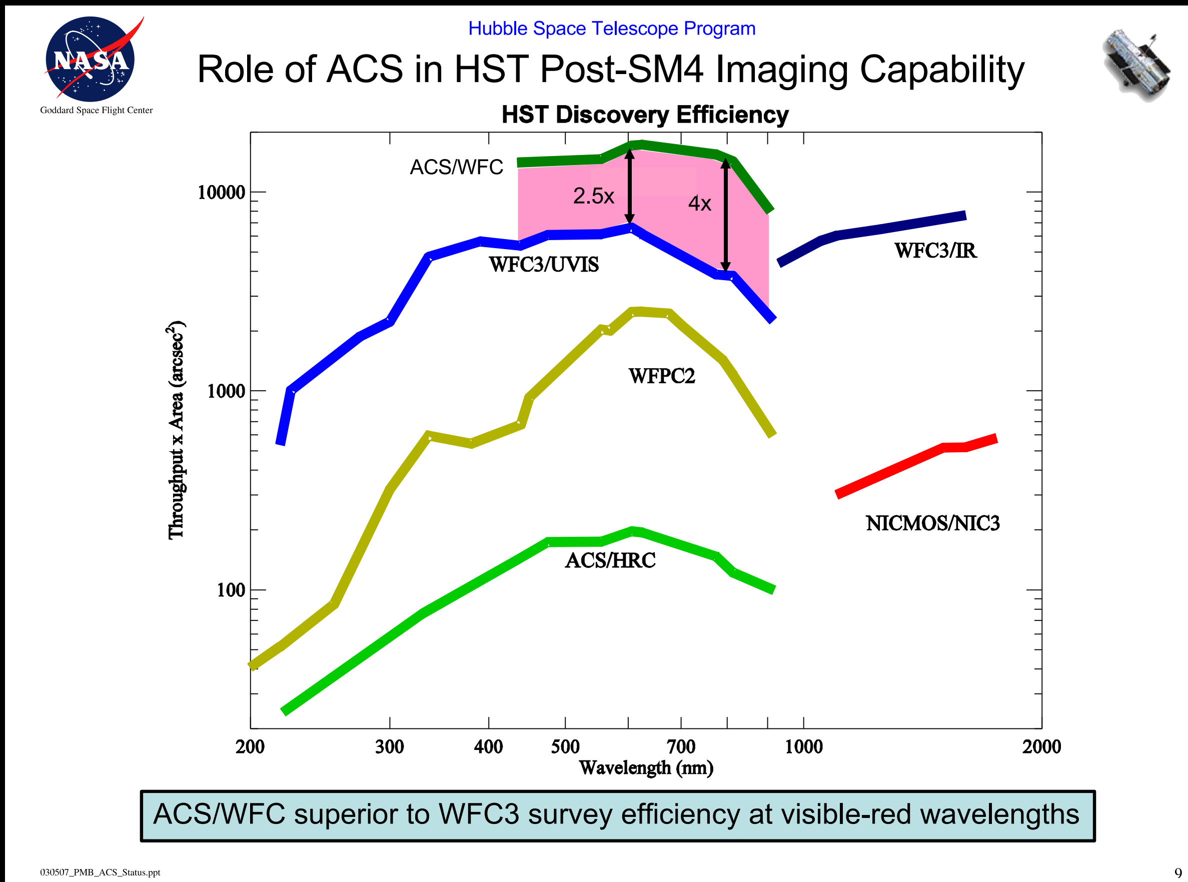
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

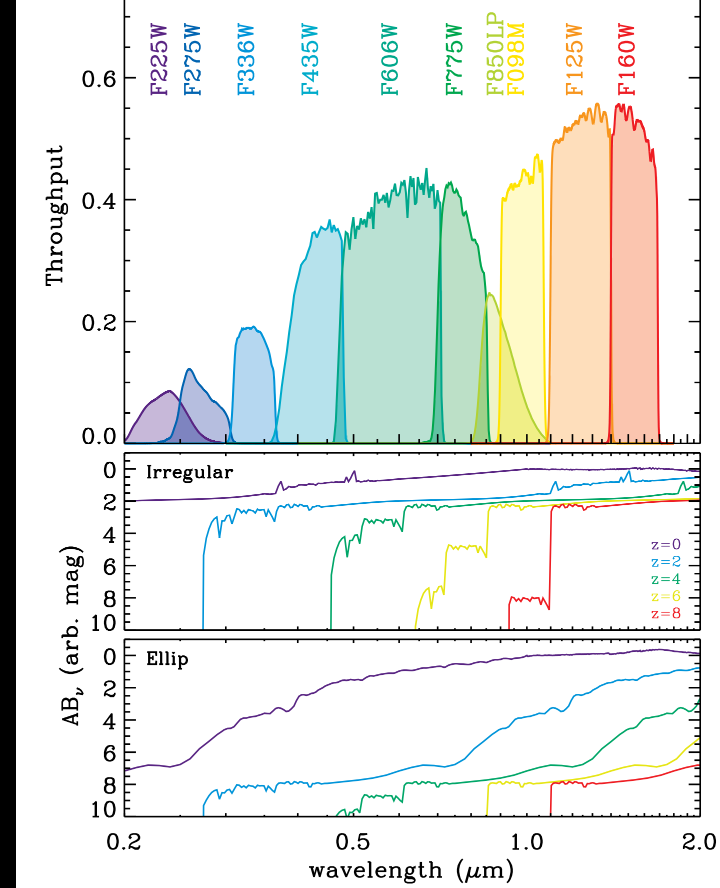
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

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



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





WFC3/UVIS channel unprecedented UV–blue throughput & areal coverage:

- QE$\gtrsim$70%, 4k$\times$4k array of 0$''$.04 pixel, FOV $\simeq$ 2$'$.67 $\times$ 2$'$.67.

WFC3/IR channel unprecedented near–IR throughput & areal coverage:

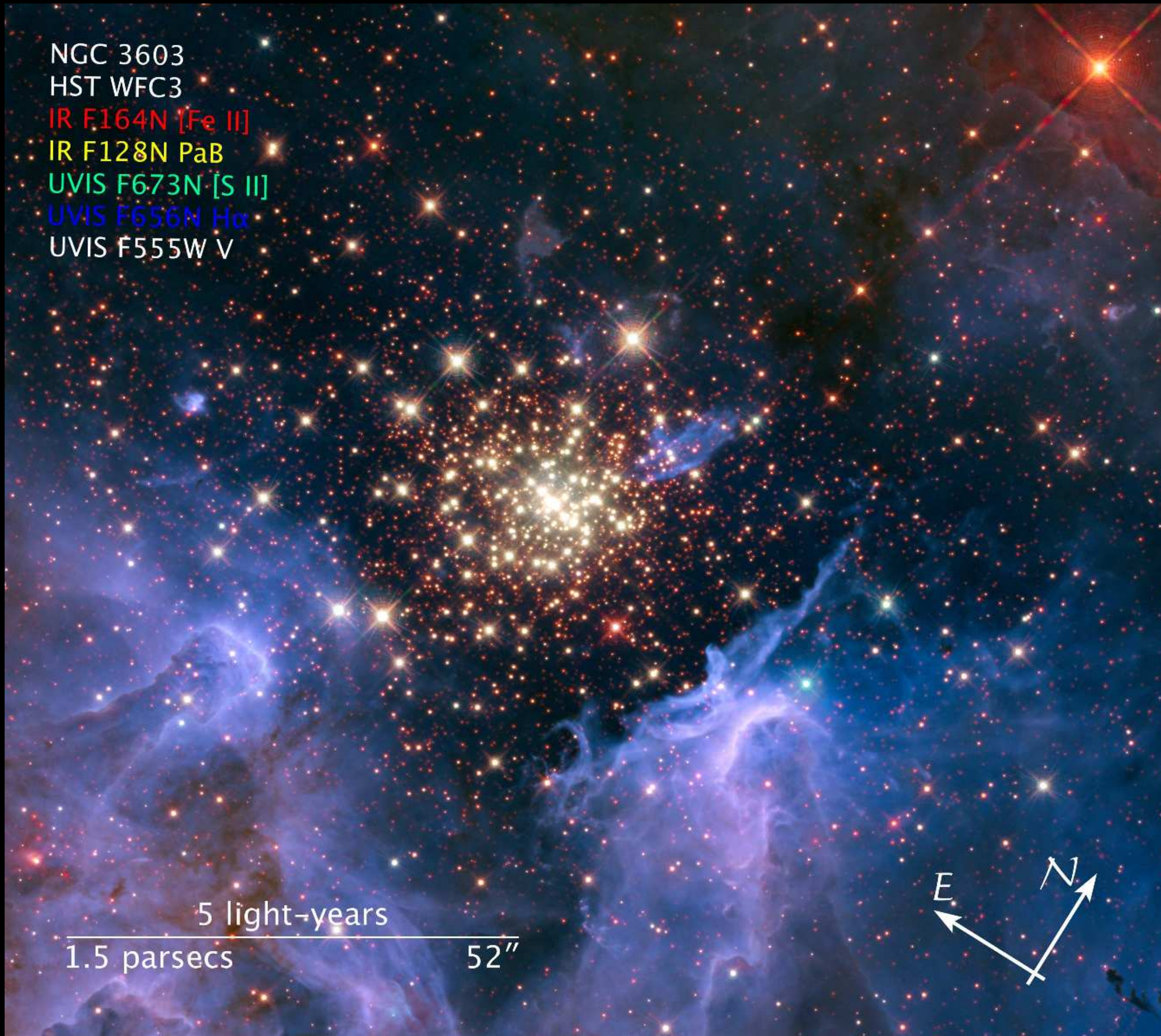
- QE$\gtrsim$70%, 1k$\times$1k array of 0$''$.13 pixel, FOV $\simeq$ 2$'$.25 $\times$2$'$.25.

$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:

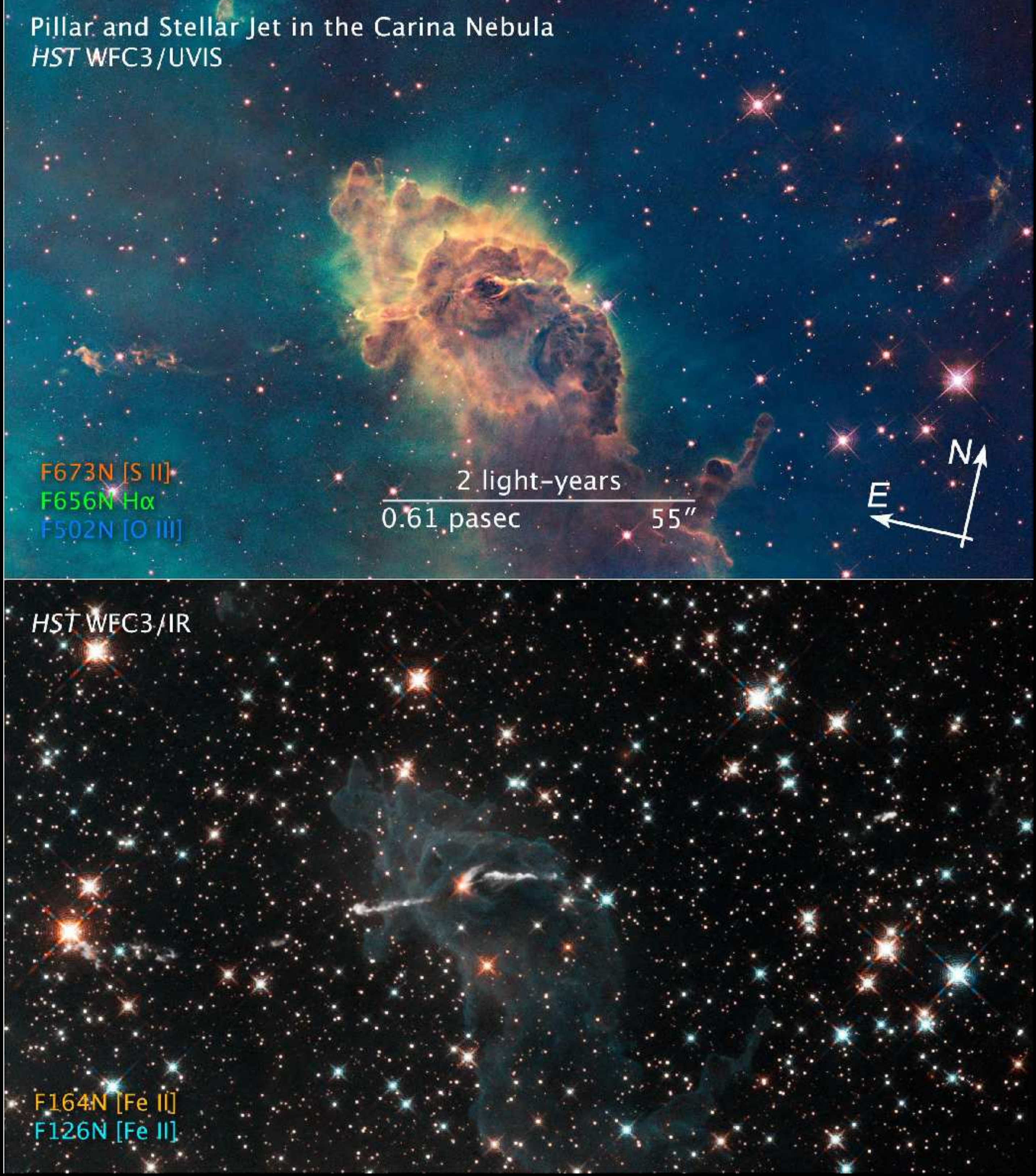
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

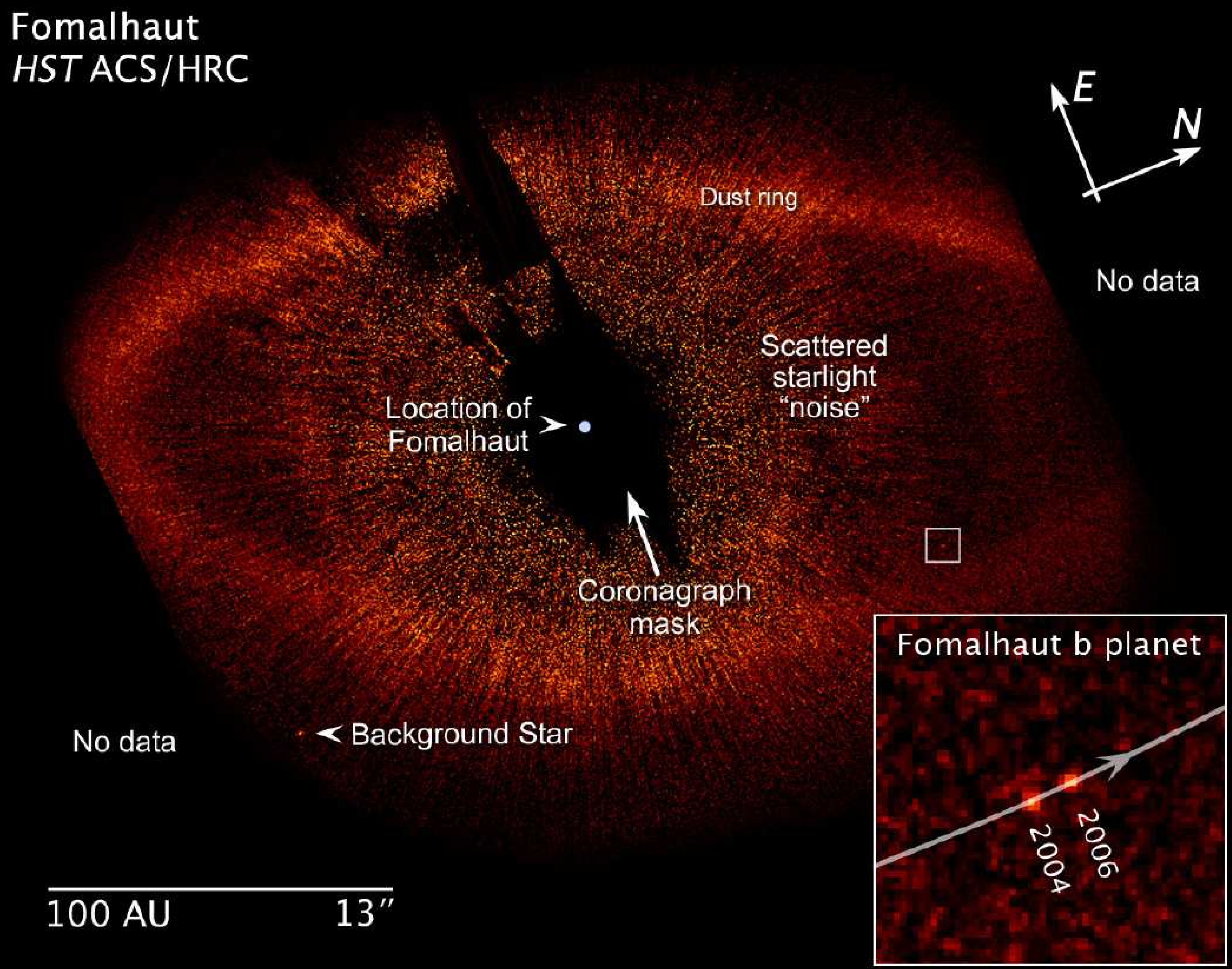
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

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



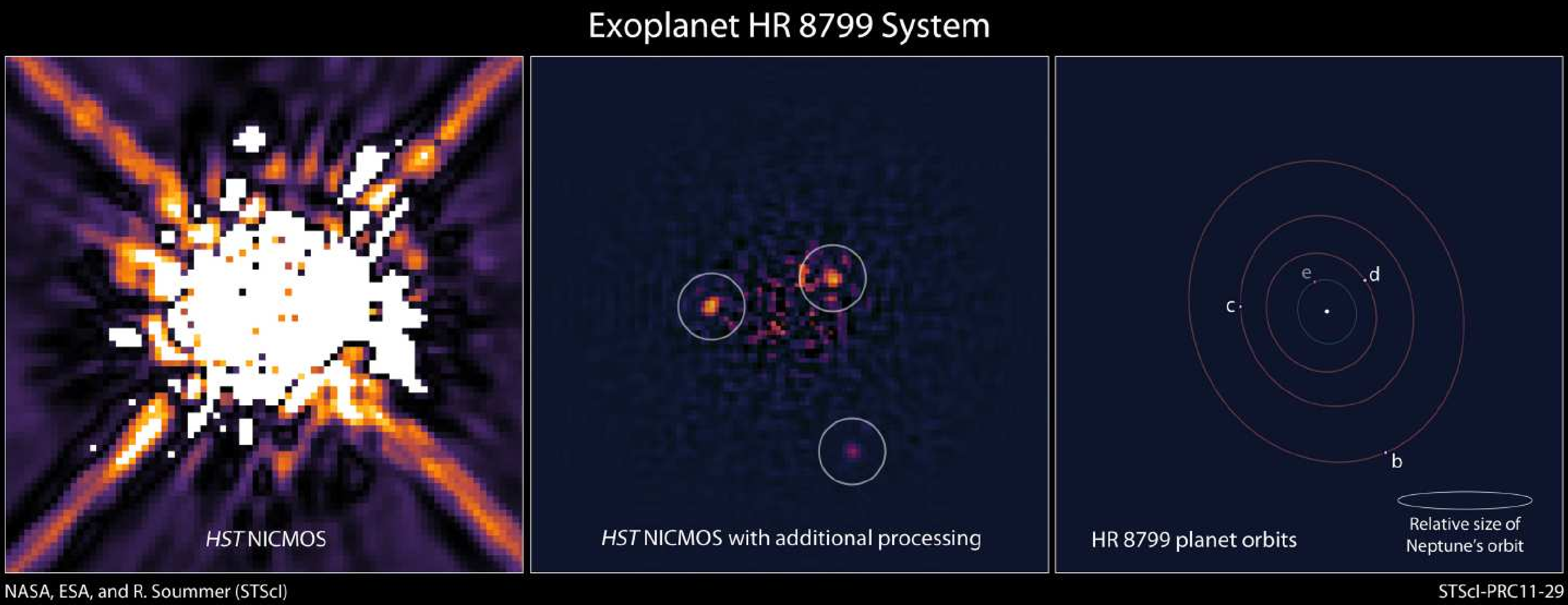
NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"


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!

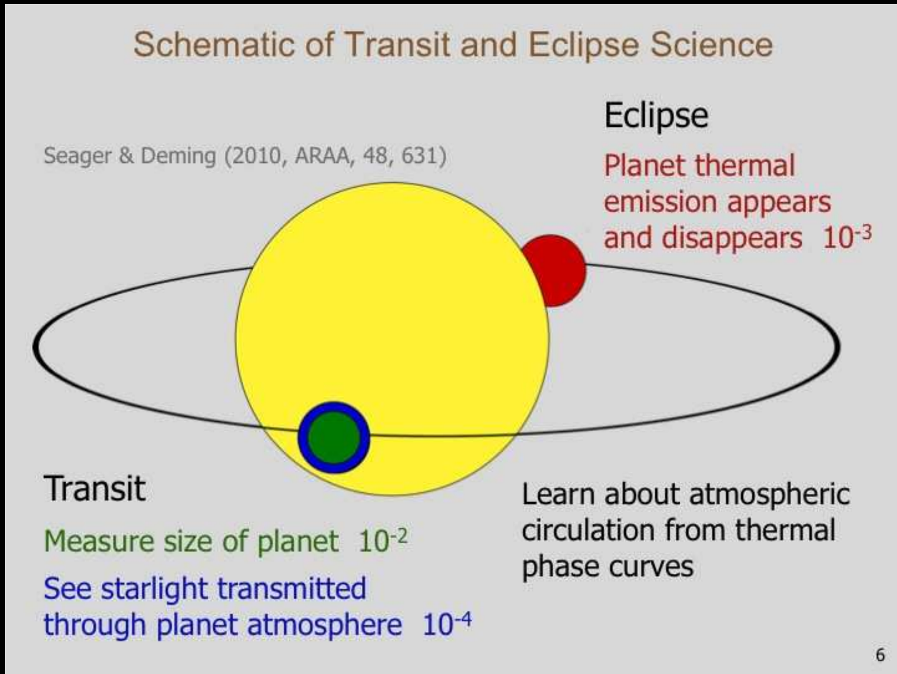
JWST can find such planets much closer in for much farther stars.

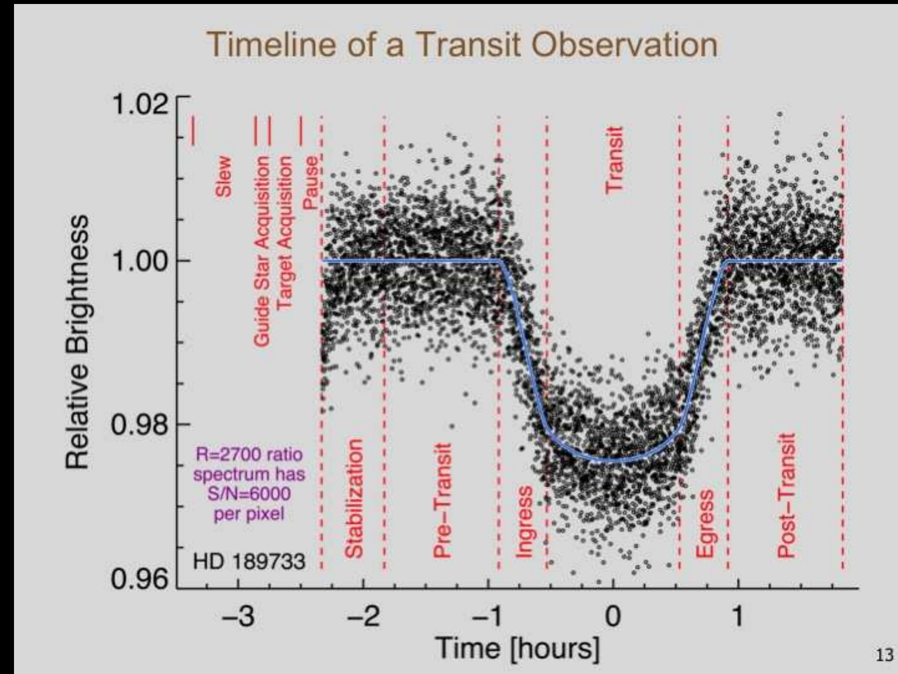


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

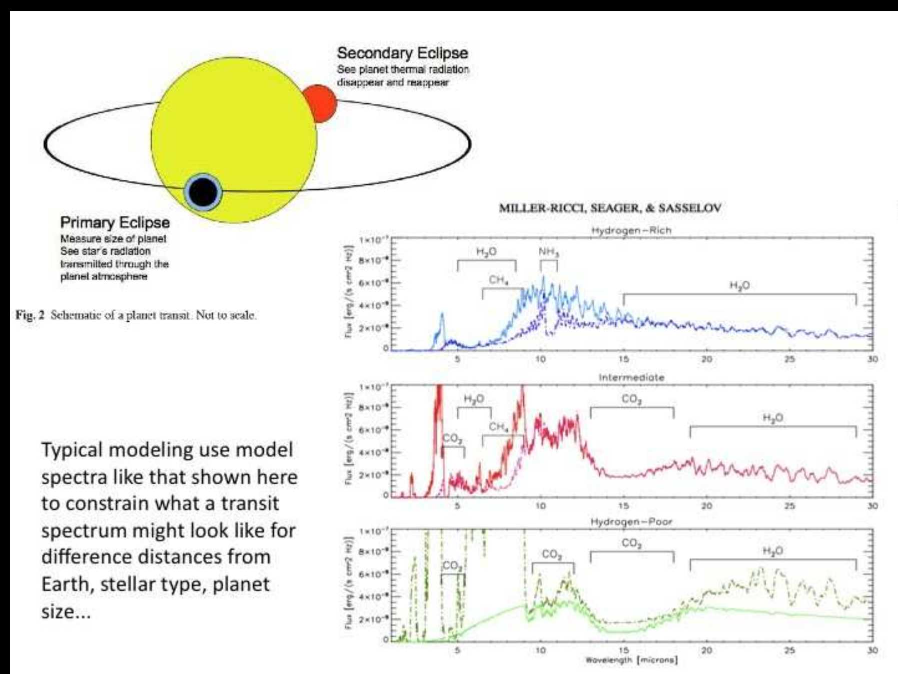
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



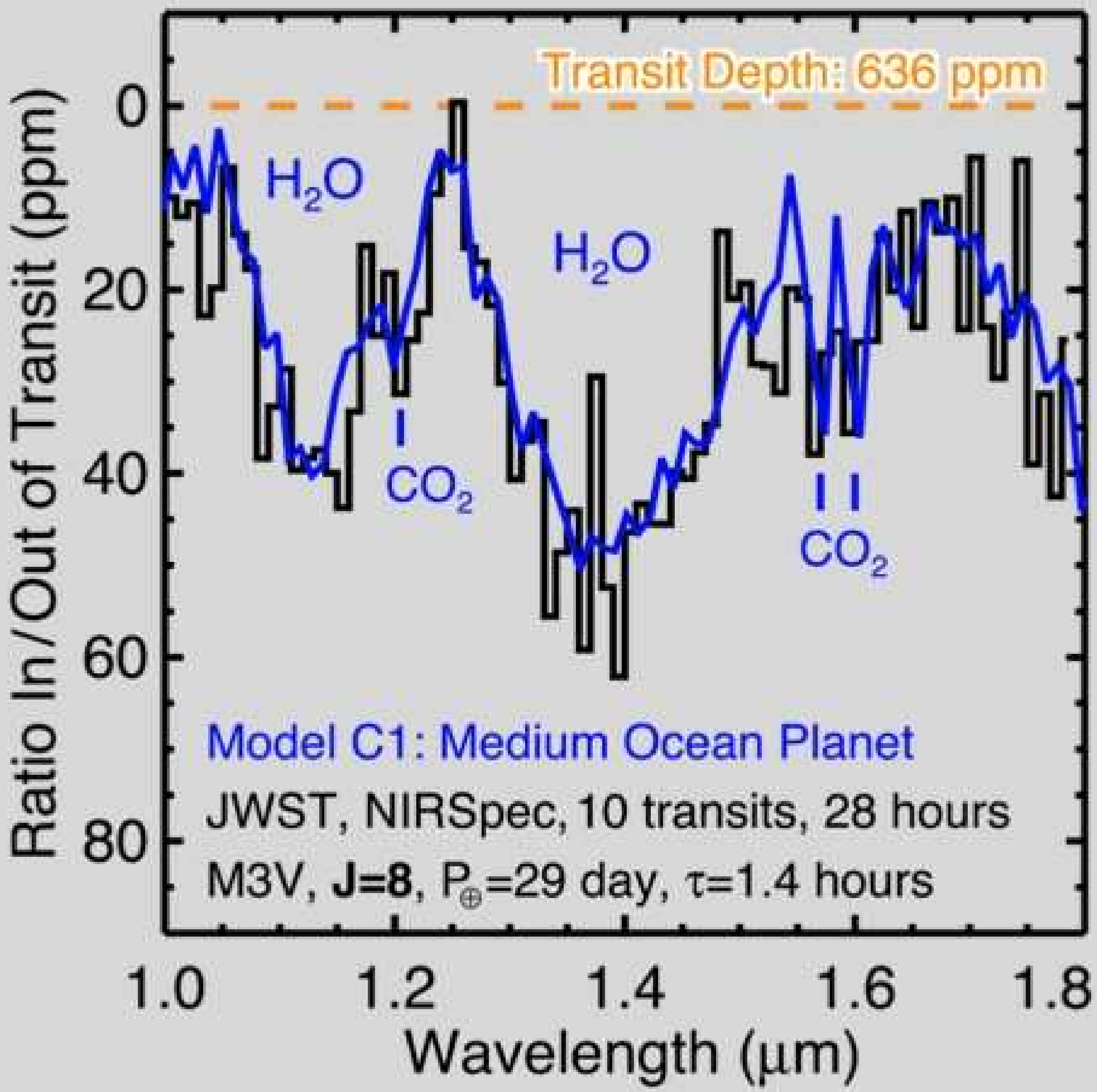


JWST can do very precise photometry of transiting Earth-like exoplanets.

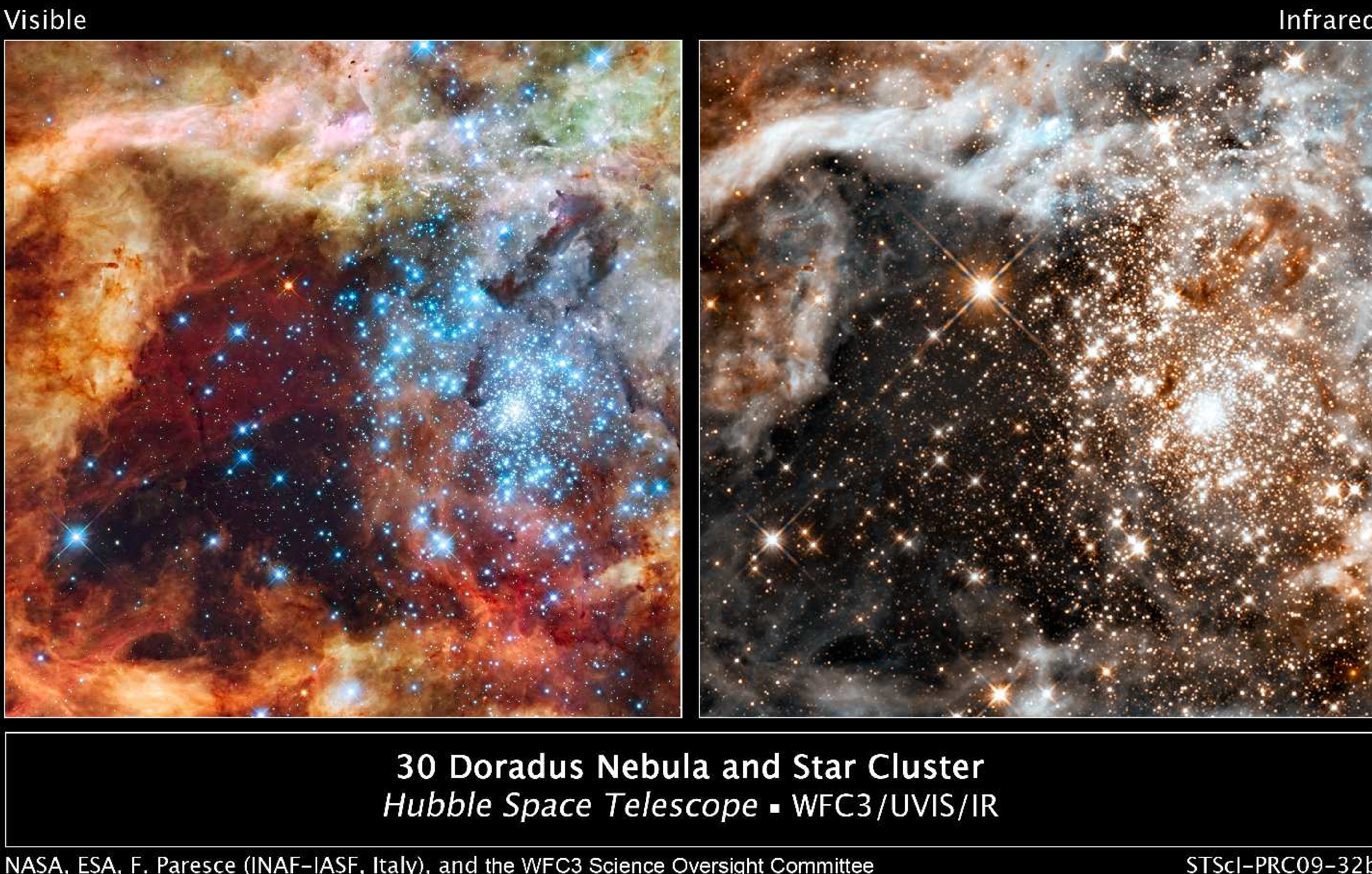


JWST IR spectra can find water and CO_2 in (super-)Earth-like exoplanets.

Transit Spectrum of Habitable “Ocean Planet”

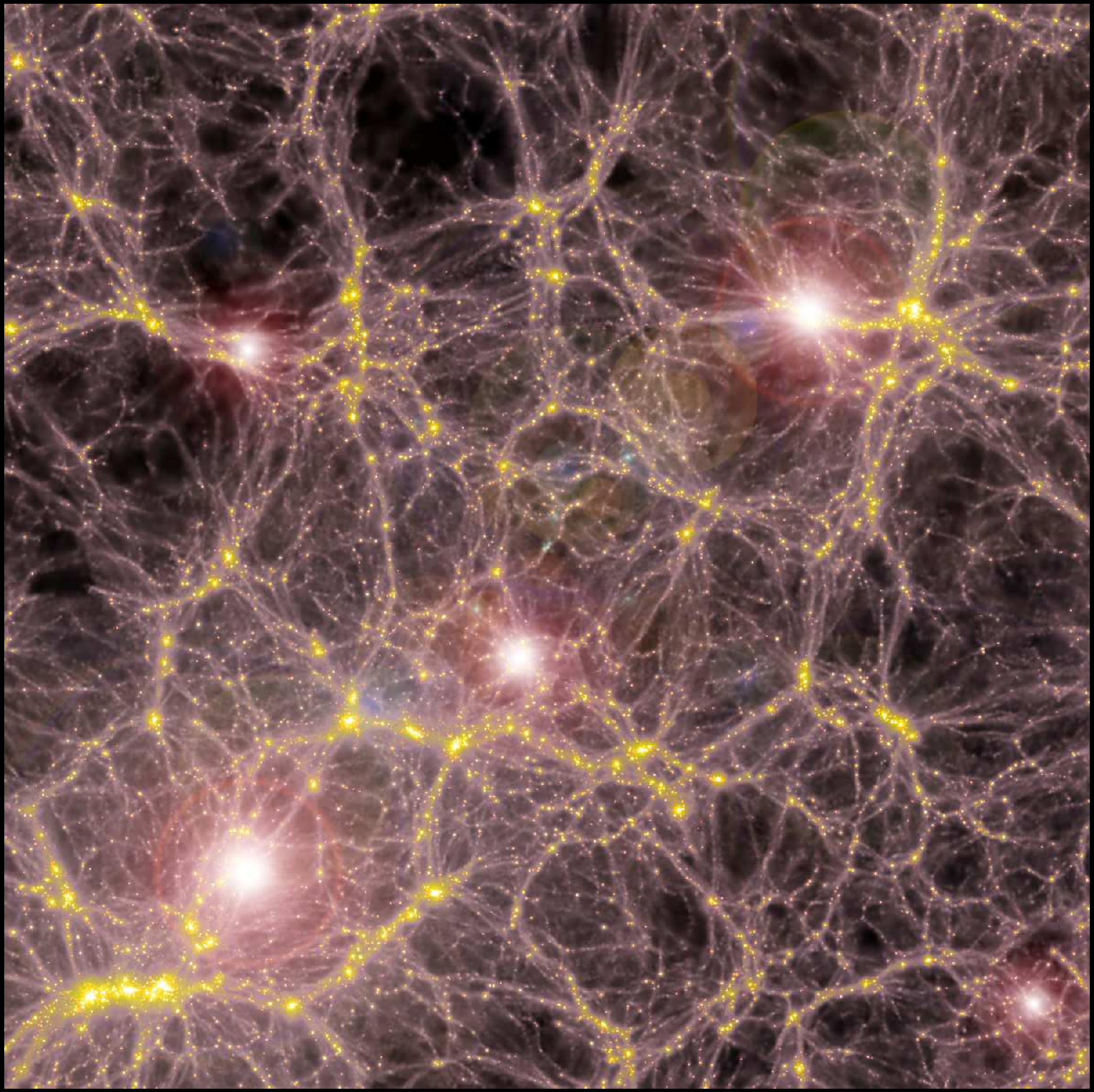


JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.



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

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

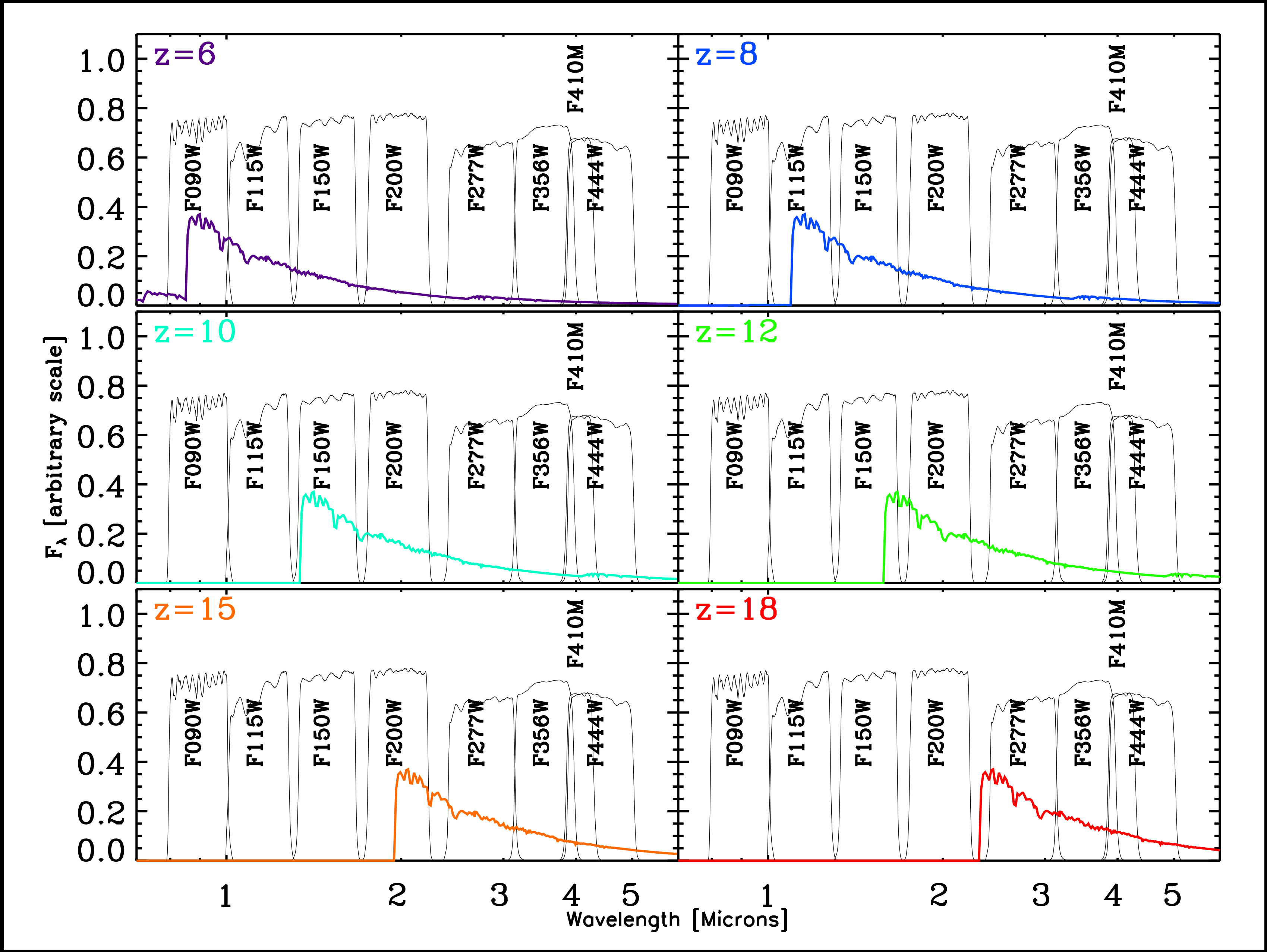


- Detailed cosmological models (V. Bromm) suggest that massive "Pop III" stars ($\gtrsim$100 M_{sun}) started to reionize the universe at z$\lesssim$10–30 (First Light).

- This should be visible to JWST as the first Pop III stars or surrounding (Pop II.5) star clusters, and perhaps their extremely luminous supernovae at z$\simeq$10$\longrightarrow$30.

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

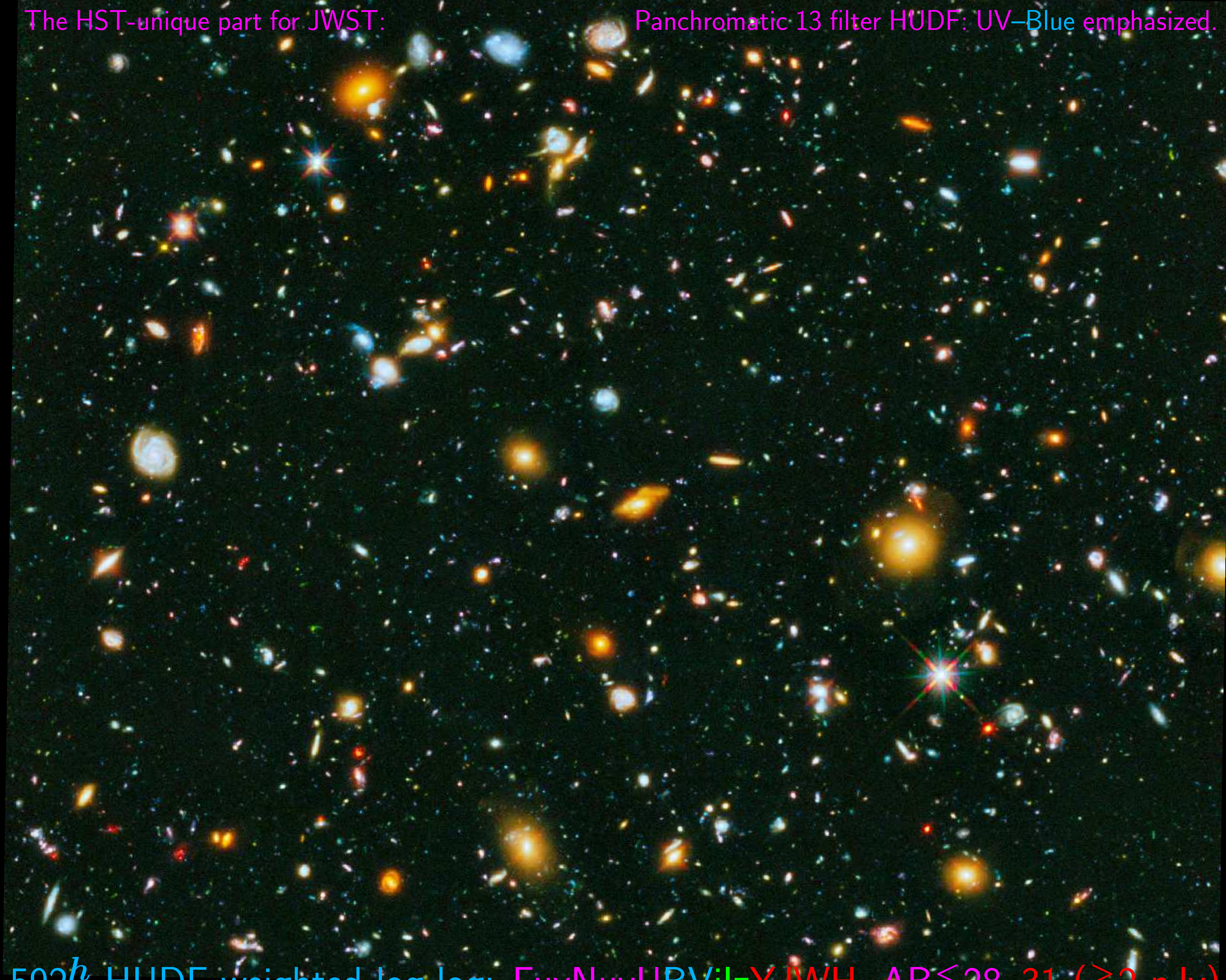
3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



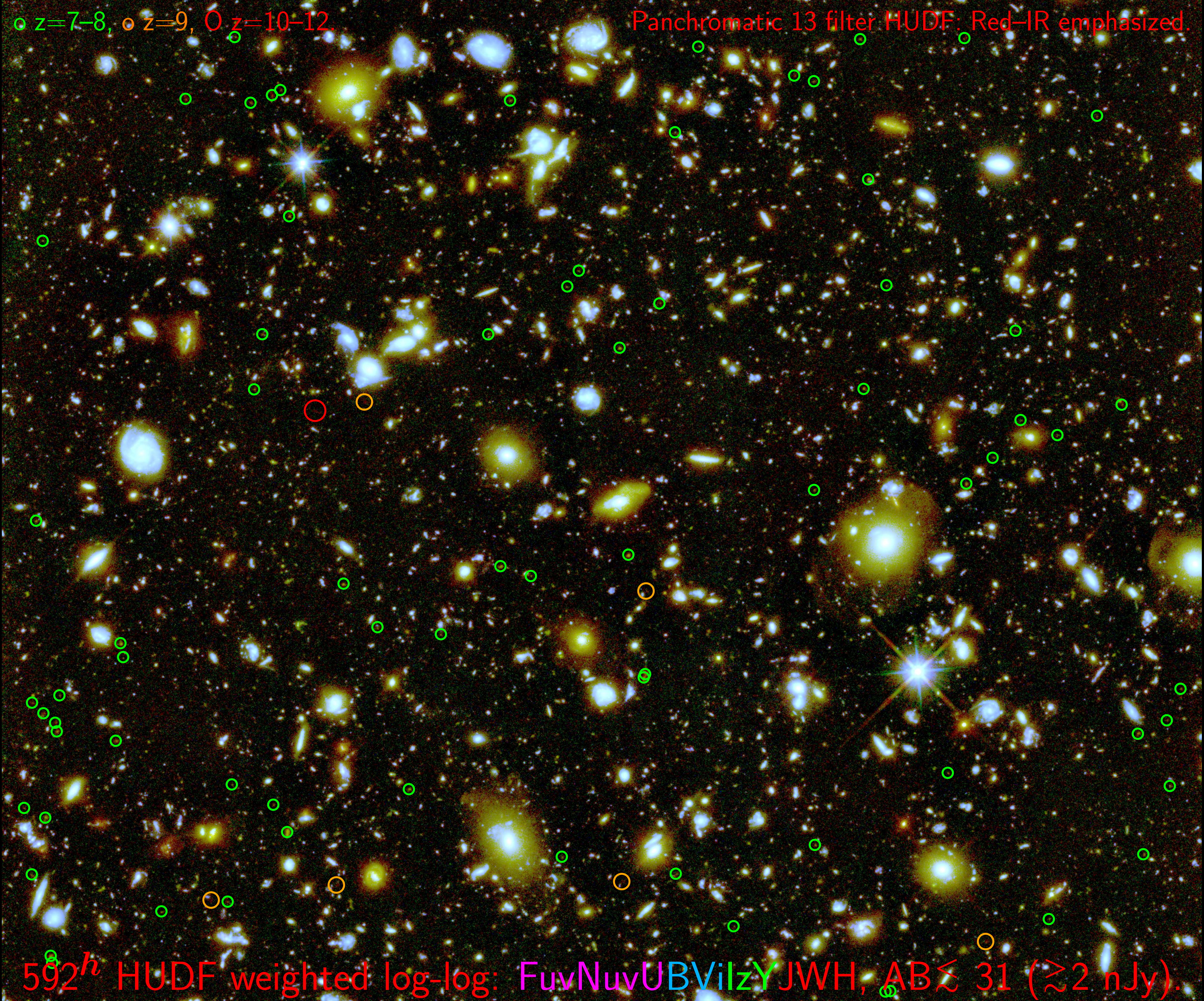
- Can't beat redshift: to see First Light, must observe near–mid IR.

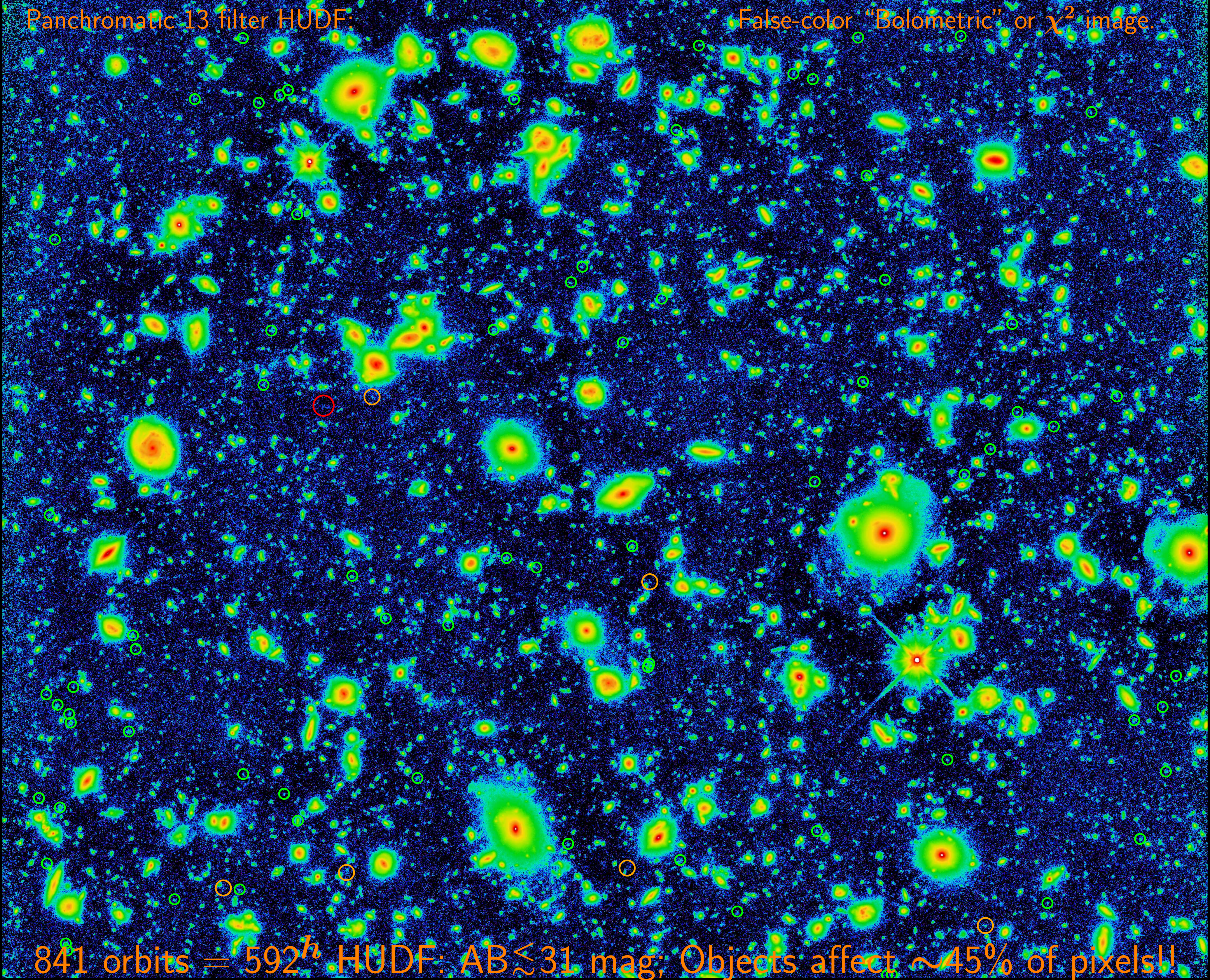
$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

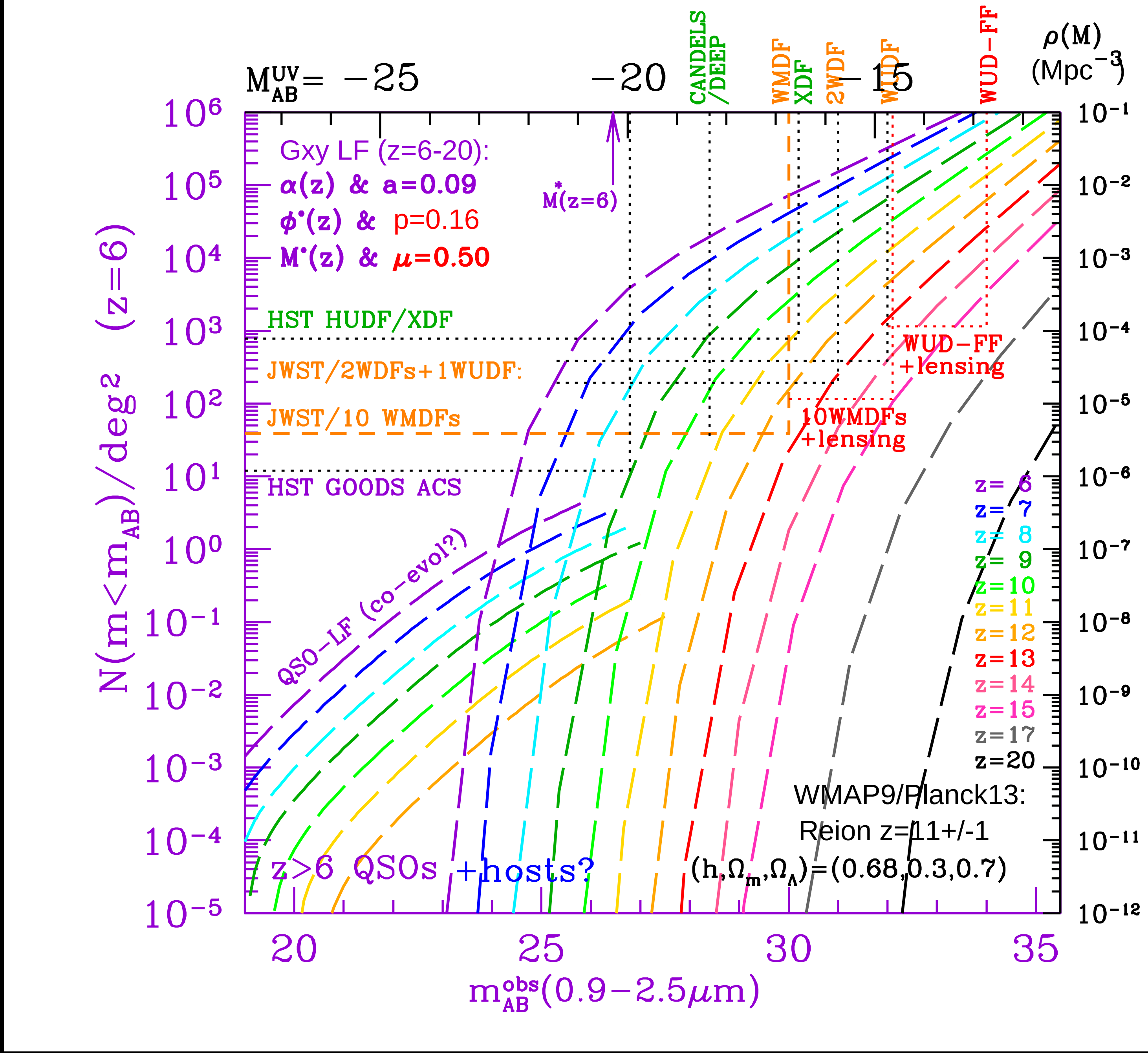
The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.



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


o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB≲ 31 (≳2 nJy).


Panchromatic 13 filter HUDF:
False-color "Bolometric" or χ^2 image.
841 orbits = 592^h HUDF: AB$\lesssim$31 mag; Objects affect ~45% of pixels!!

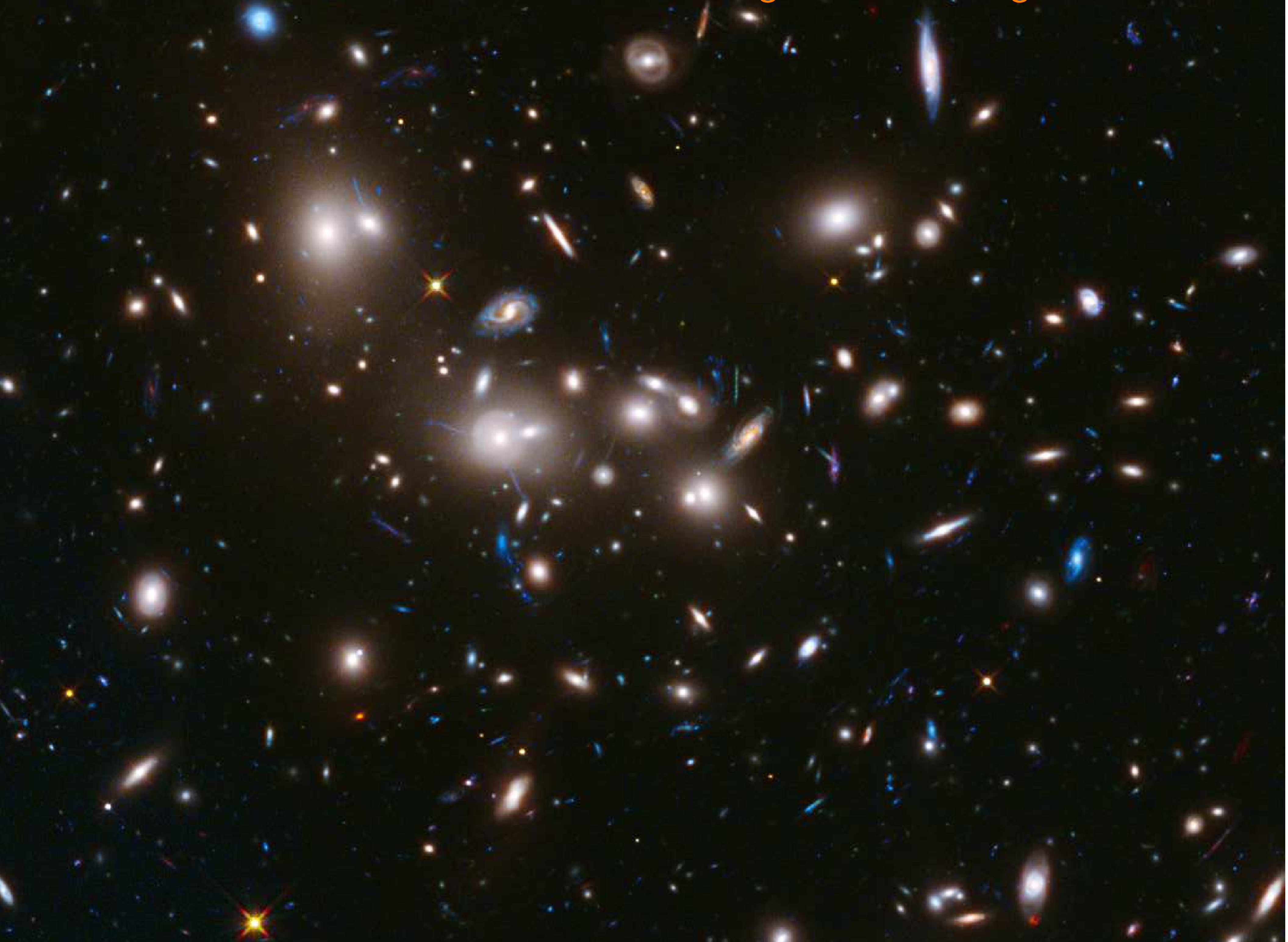


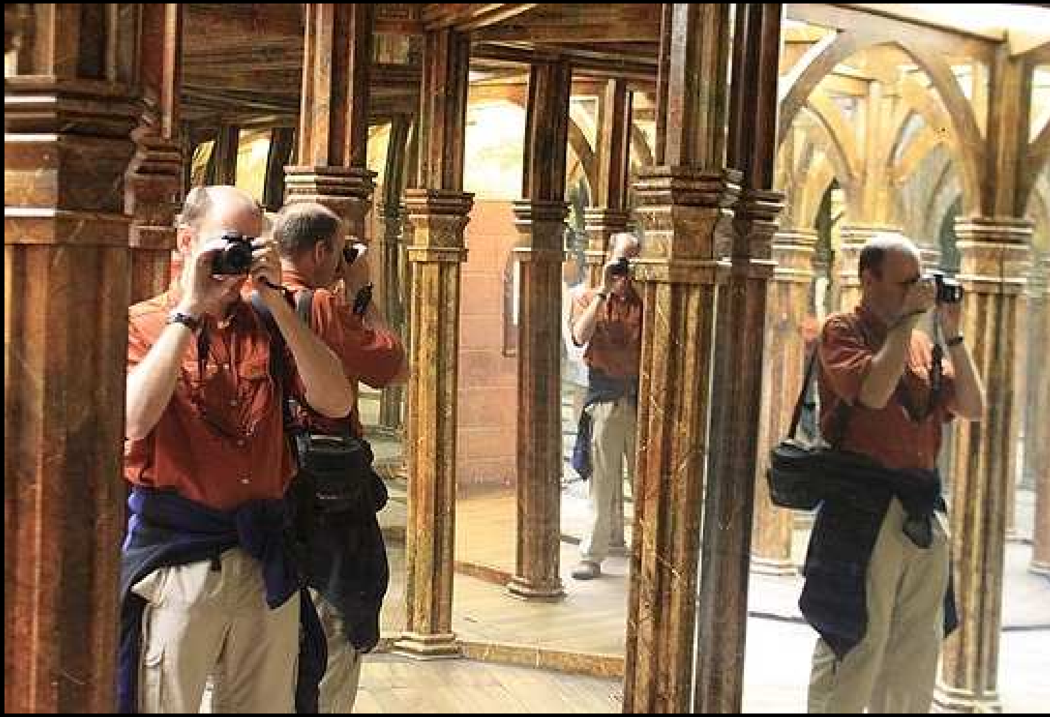
Schechter LF (z≲6≲20) with best-fit α(z), Φ^* (z), M^* (z) & μ=0.50.

Area/Sensitivity for: HUDF/XDF, **10 WMDFs**, 2 WDFs, & 1 WUDF.

- May need lensing targets for WMDF–WUDFF to see z≃14–16 objects!

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



Two fundamental limitations may determine ultimate JWST image depth:

(1) Cannot-see-the-forest-for-the-trees effect [Natural Confusion limit]:

Background objects blend into foreground because of their own diameter
$\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ deblending algorithms.

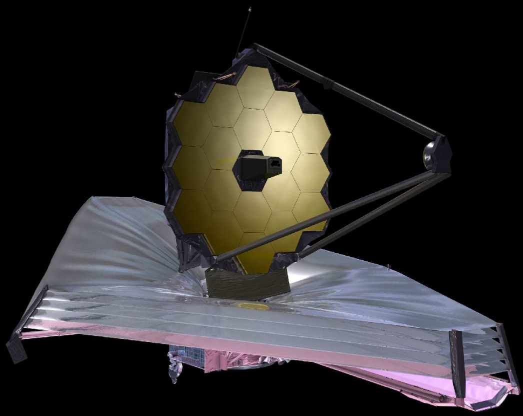
(2) House-of-mirrors effect ["Gravitational Confusion"]: Most First Light objects at z$\gtrsim$12–14 may need to be found by cluster or group lensing.

$\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ object-finder that works on sloped backgrounds.

$\Rightarrow$ If $M^*(z\gtrsim10)\gtrsim-18$, need to use & model gravitational foreground.

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

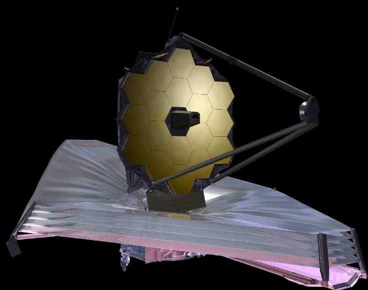
True relative size: Hubble, James Webb, & Giant Magellan Telescope

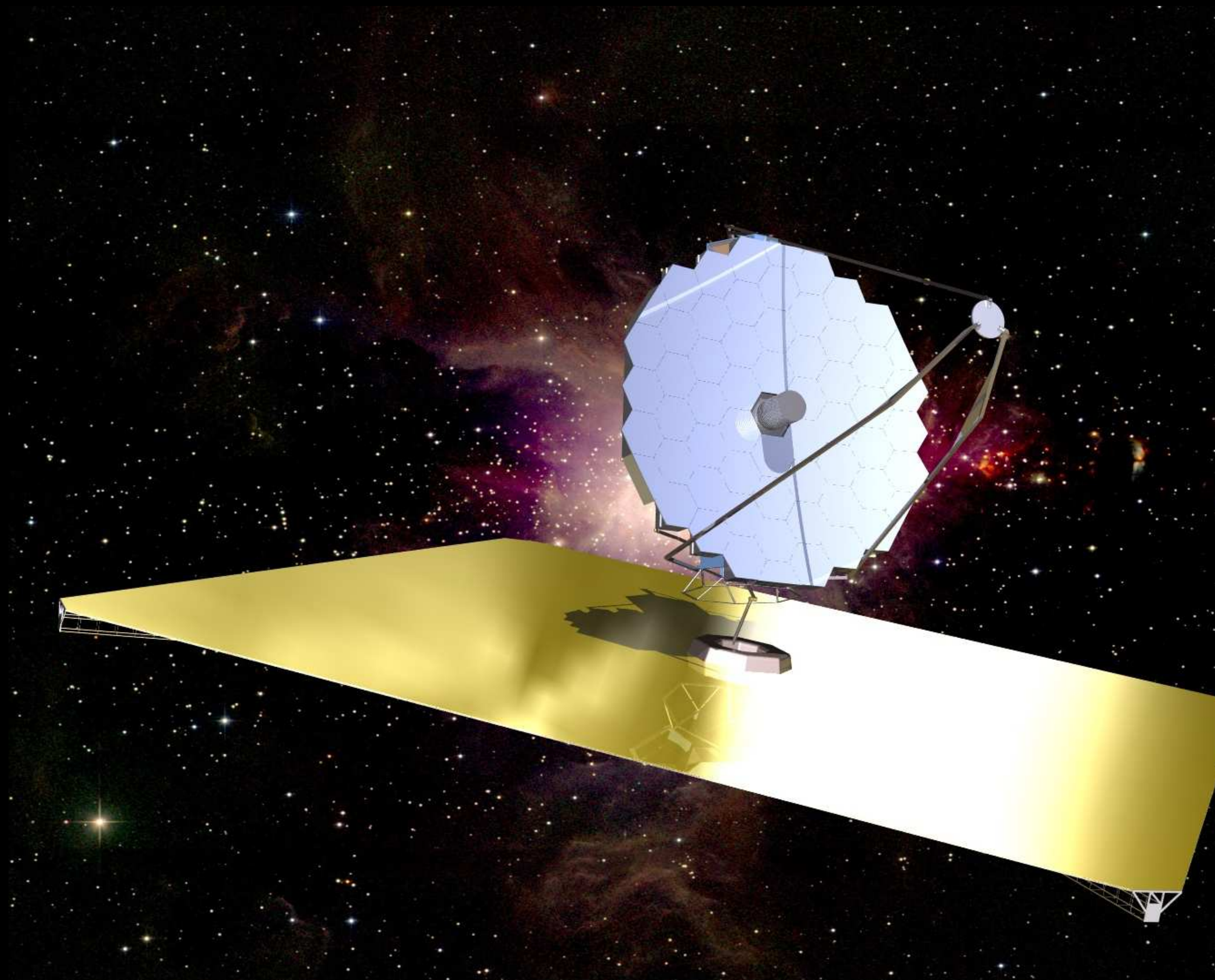


18 B\$ (1973∼2018); 9 B\$ (1996∼2029); ∼1 B\$ (2000∼2050^{+}).

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

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





18 B$ (1973∼2018); 9 B$ (1996∼2029); 15–20 B$ (2020∼2050$^+$?).

(5) 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.

(6) What do our Astrophysics College Graduates do?

Future Careers at NASA:

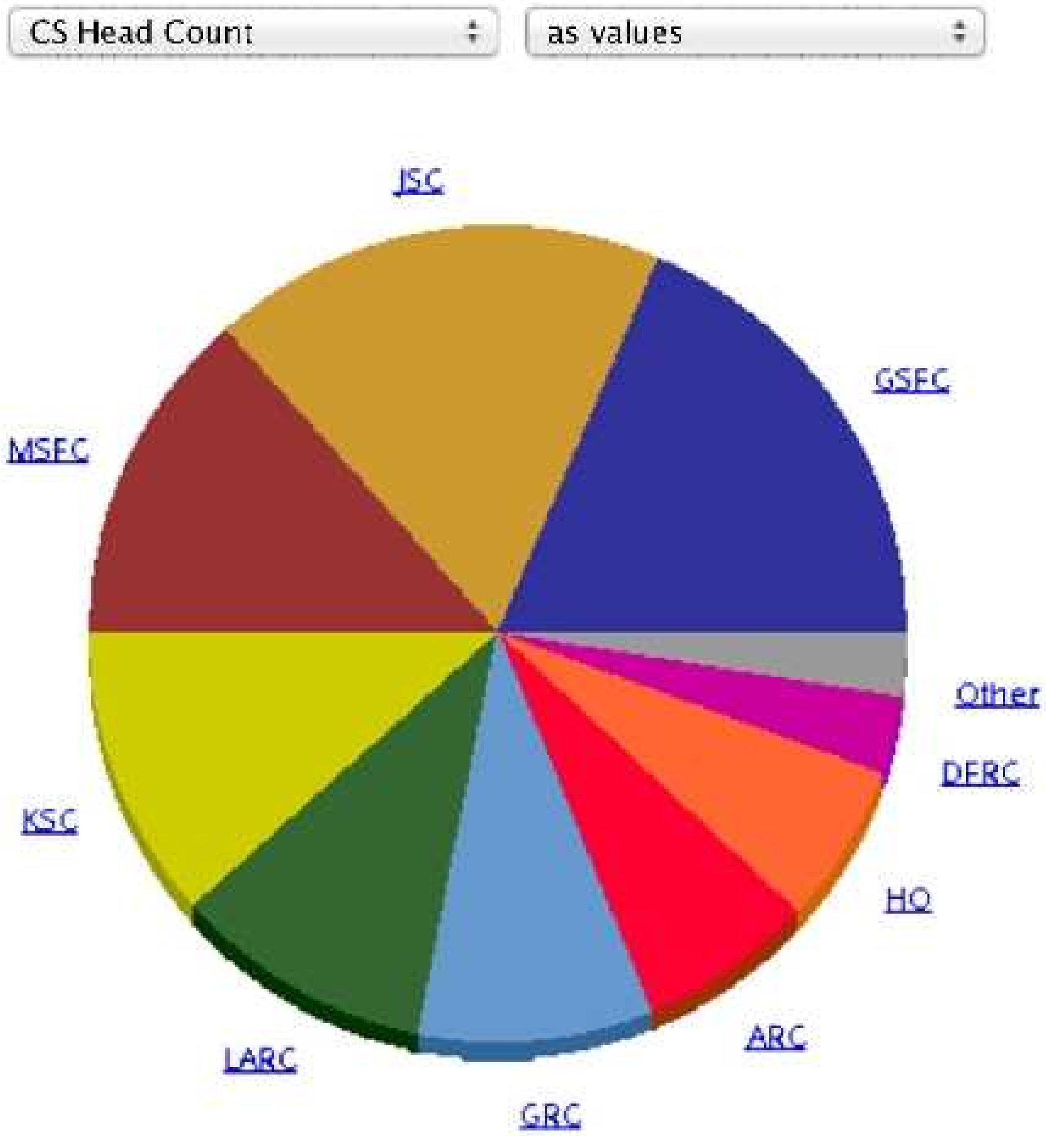
- Over the last 25 years, (ASU) Astrophysics College Graduates typically:
- (0) Have very low unemployment ($\lesssim$few %).
- (1) About 30% are faculty at Universities or 4-year colleges.
- (2) About 30% are researchers at NASA or other government centers.
- (3) About 20% work in Aerospace or related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

(7) Summary and Conclusions

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

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

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

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

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

- Formation and evolution of the first star-clusters after 0.2 Gyr.
- How dwarf galaxies formed and reionized the Universe after 1 Gyr.

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

- IR sequel to HST after 2018: Training the 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

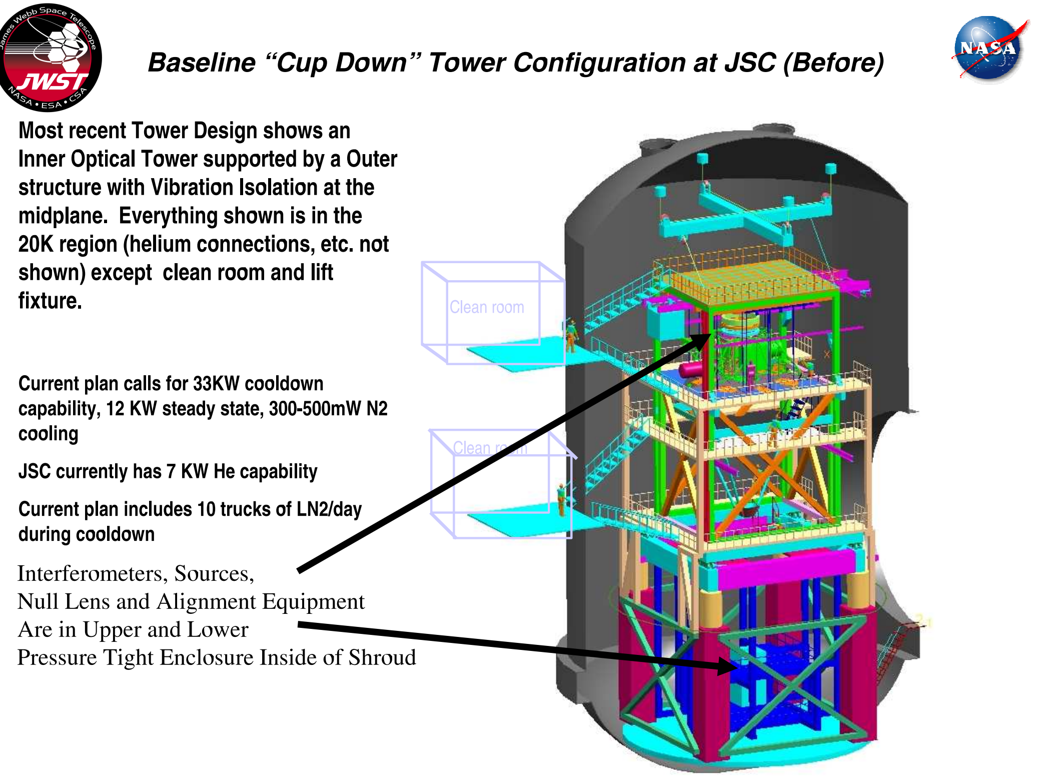
Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

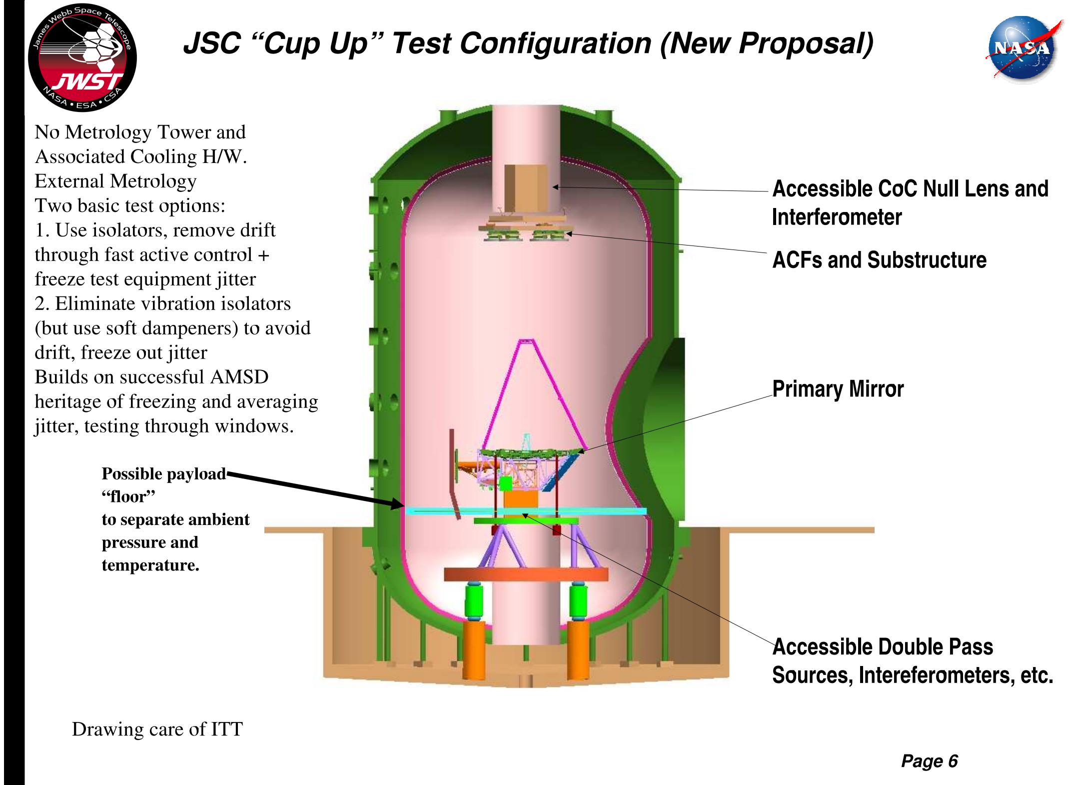
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

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

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

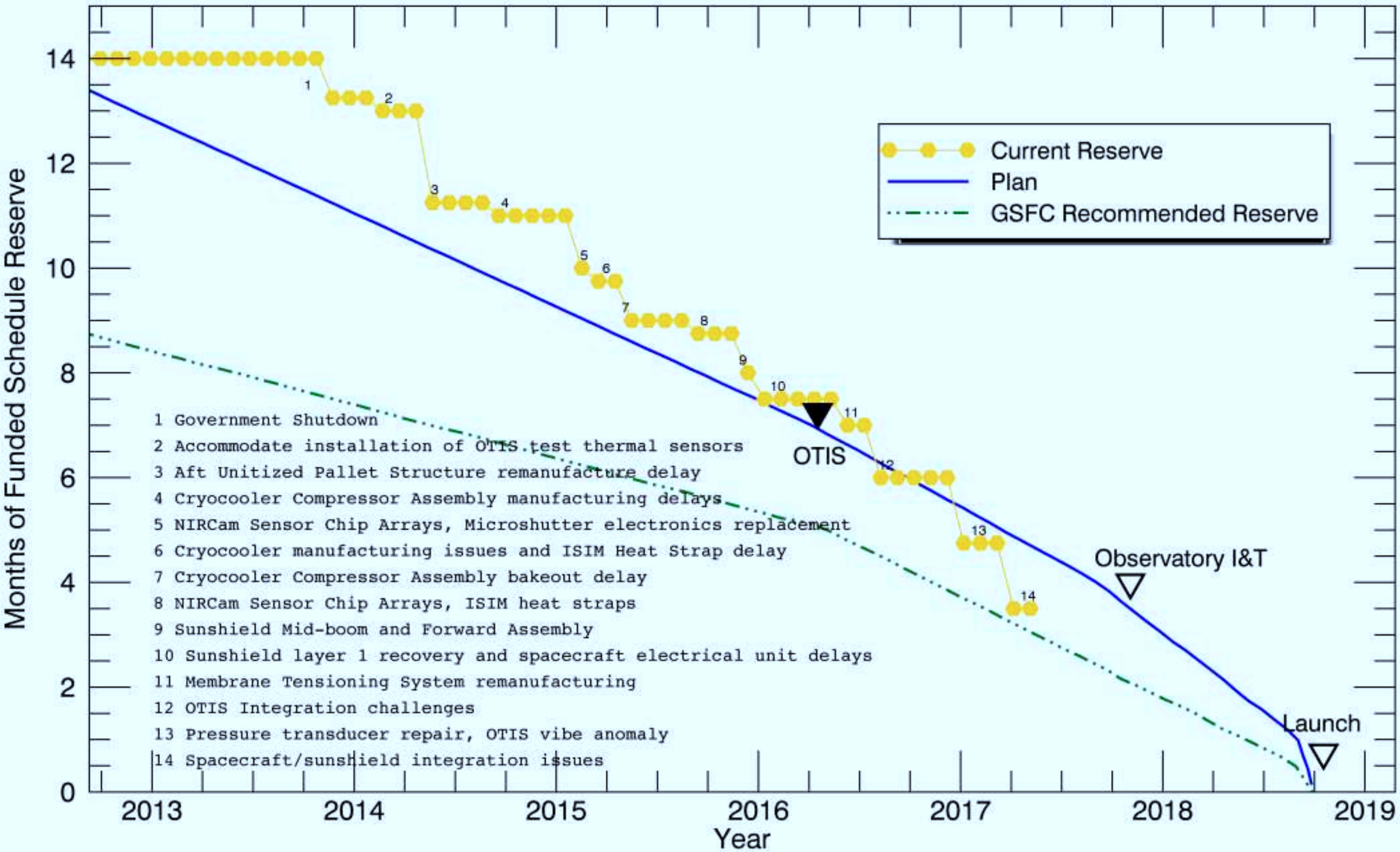




JWST underwent several significant replans and risk-reduction schemes:

- $\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).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.

Funded Schedule Reserve



Keys to stay on schedule: 1) Sufficient Project contingency ($\gtrsim$25% of total).
2) Well replanned and managed Project (starting late summer 2011).

Fiscal Year 2017 JWST HQ Milestones

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

Blue font(underline) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late. "•" denotes 2016 milestones carried forward.

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

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	24	11	17*	3	1

*Late milestones have been completed late within the year or are forecast to complete late within the year. Deferred milestones are not included in the number-completed-late tally.

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

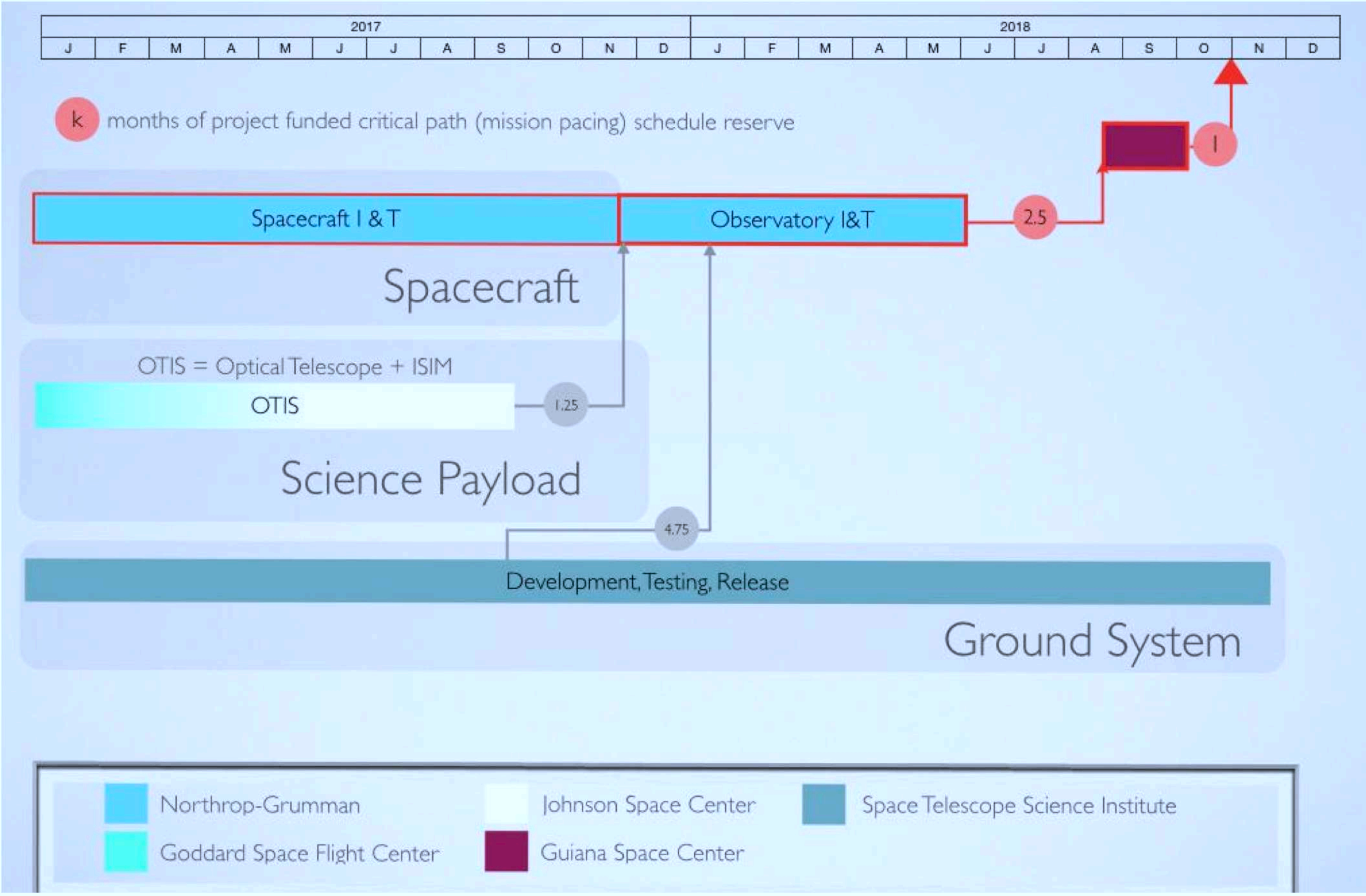
170612 JWST Monthly Telecon 4

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

FY15, F16: Most “Lates” not on critical path, nor cause a launch delay.

FY17: “Lates” anticipated to finish with FY, not causing launch delay.

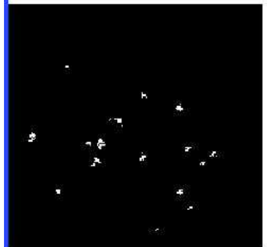
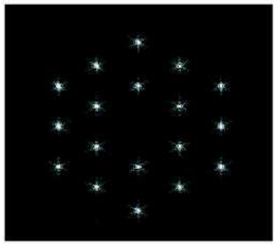
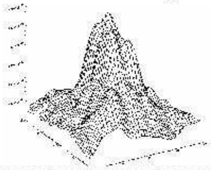
Simplified Schedule



170612 JWST Monthly Telecon 5

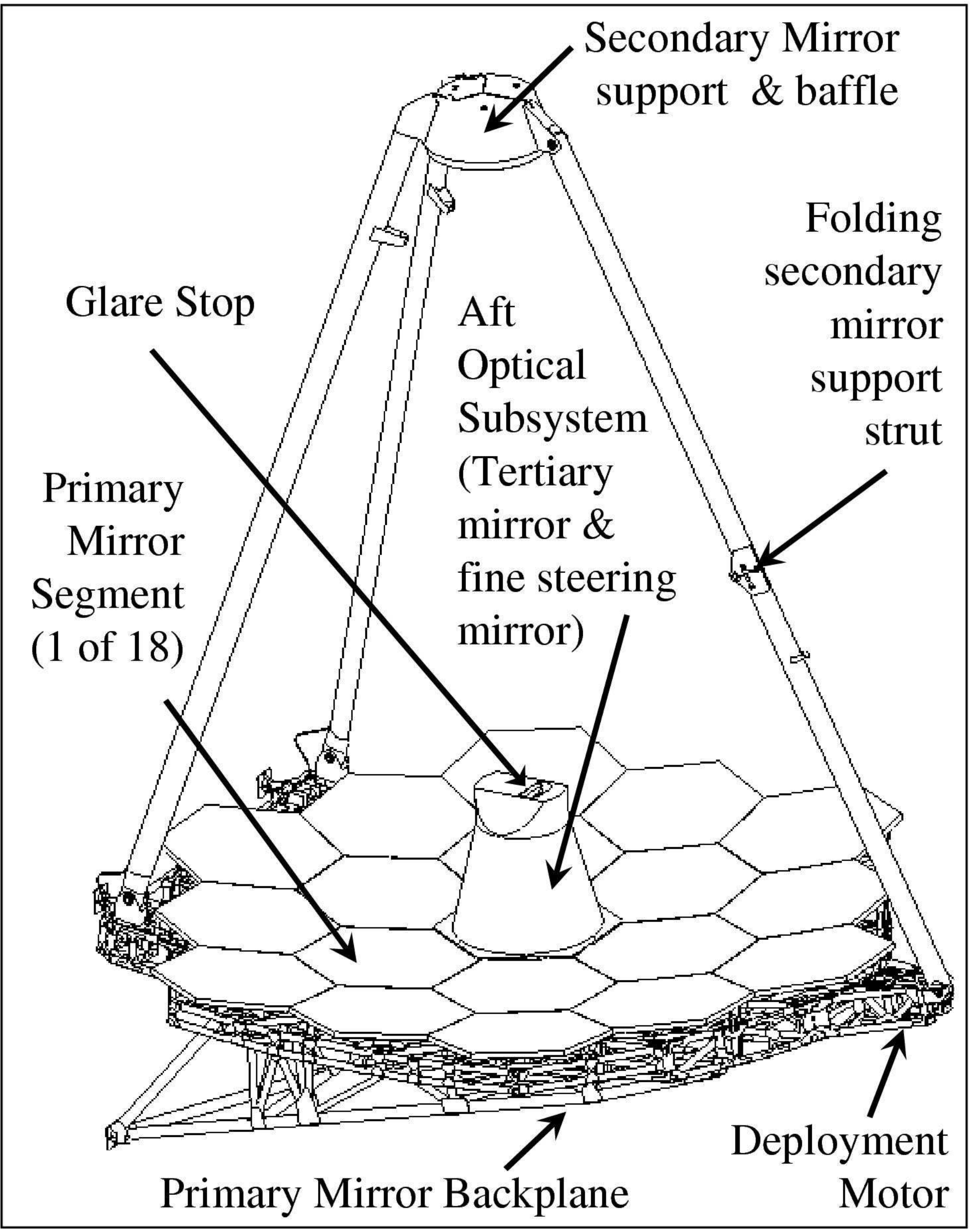
Path forward to Launch (in Oct. 2018): $\lesssim$10 months schedule reserve.

Instruments+detectors & Optical Telescope Element remain on critical path.

			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)

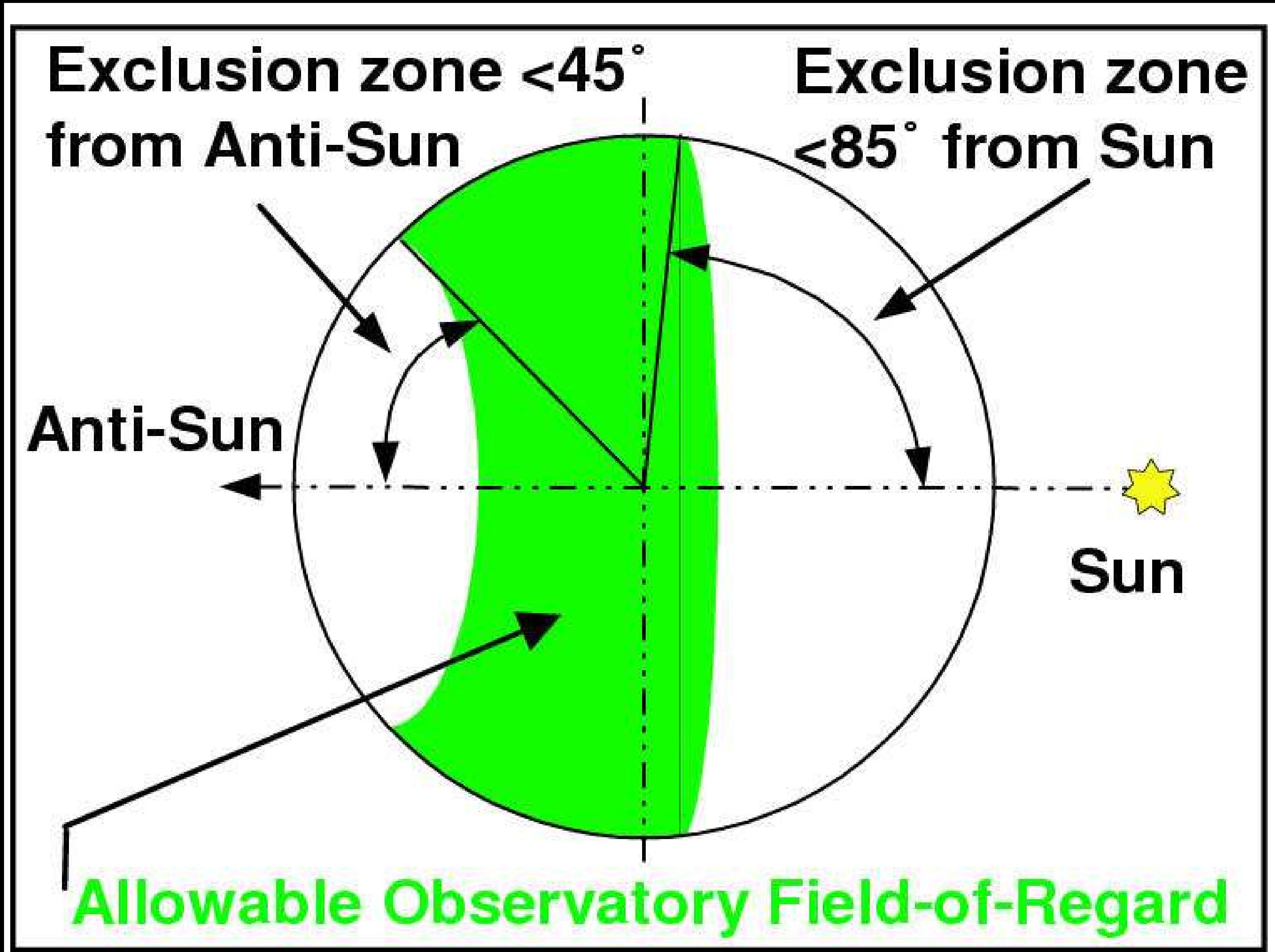
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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.

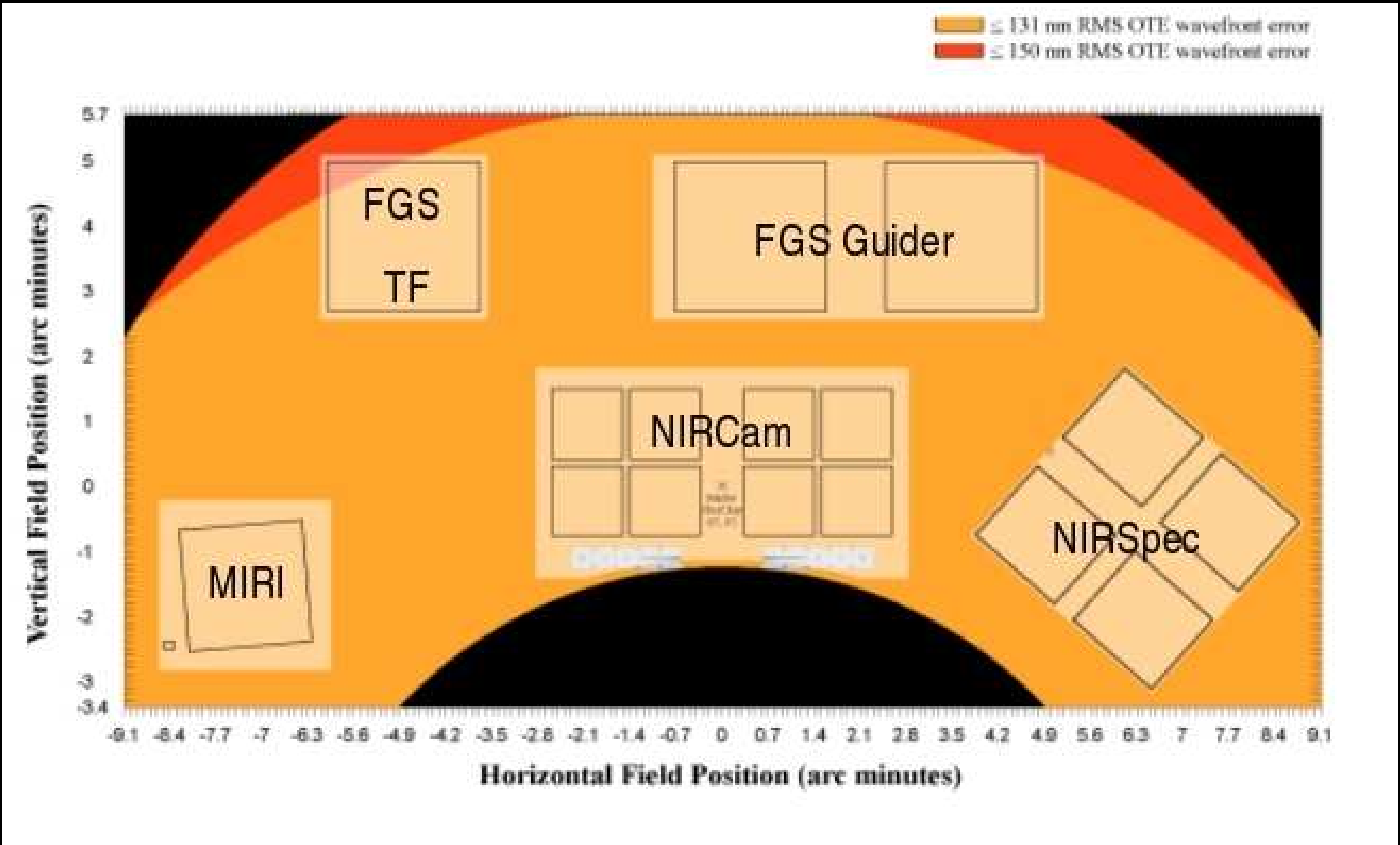
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.



JWST can observe North/South Ecliptic pole targets continuously:

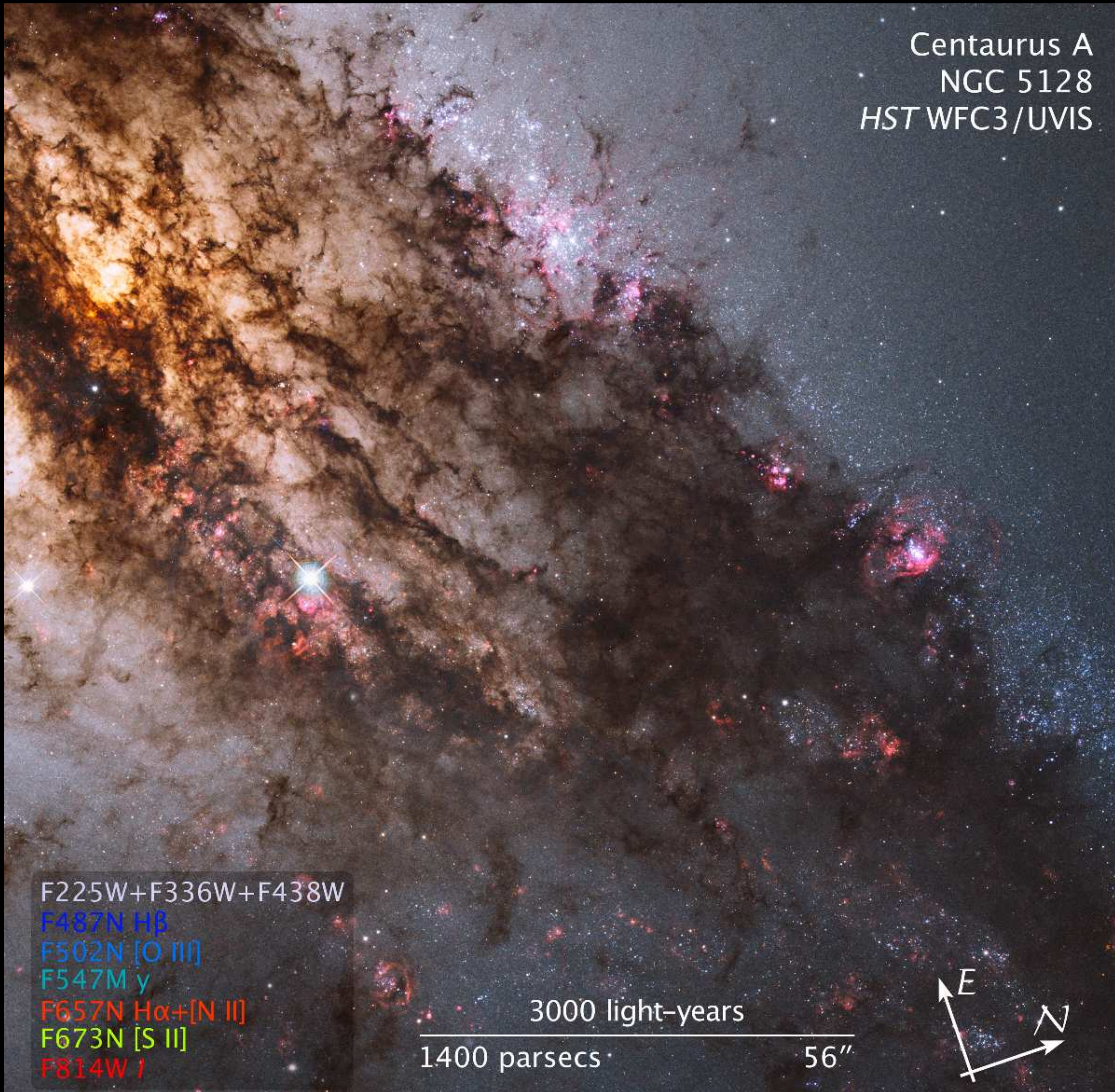
- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- JWST gets the very best reaction wheels (Rockwell Collins; Heidelberg).

• (3c) What instruments will JWST have?

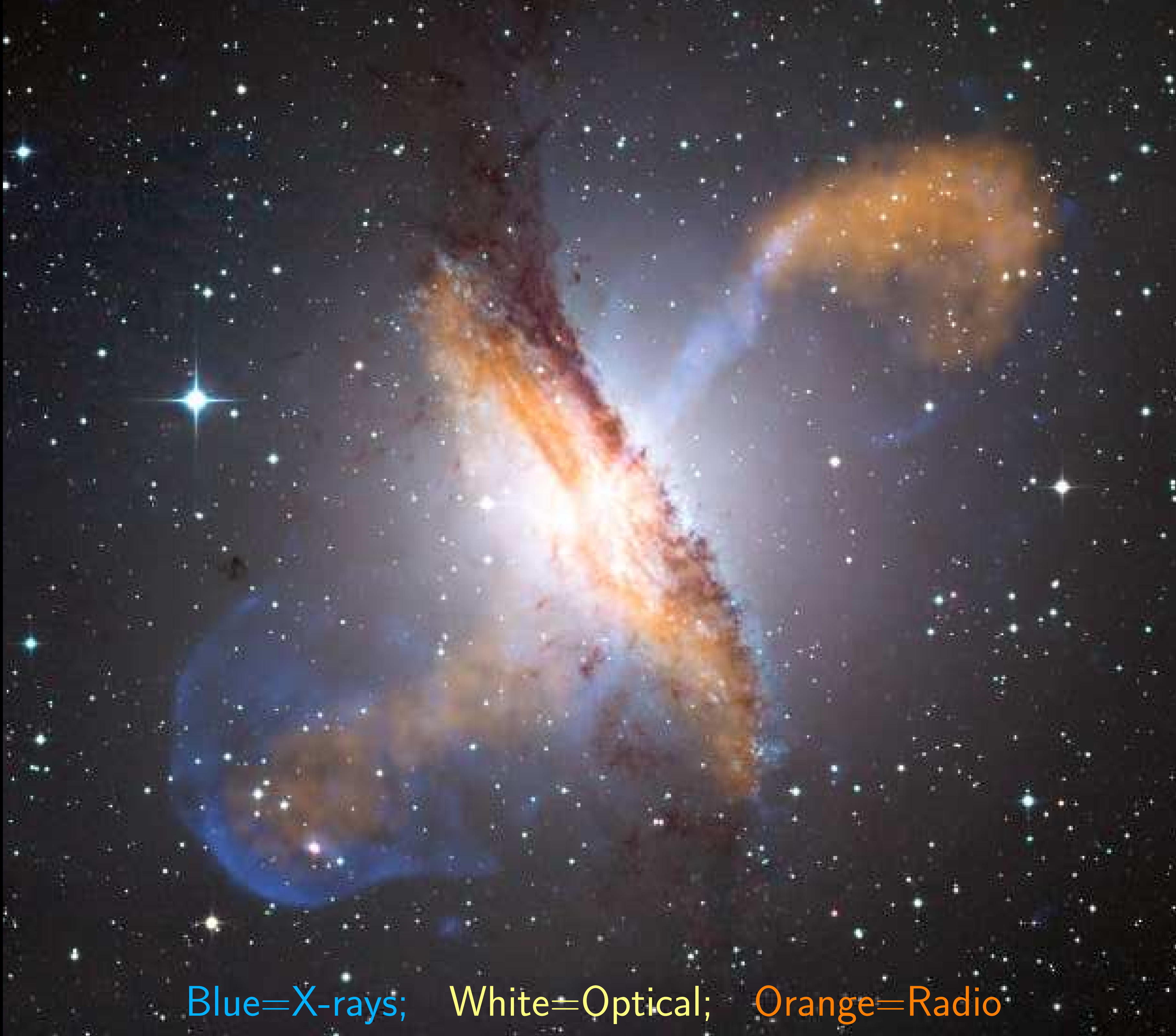


All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations*.

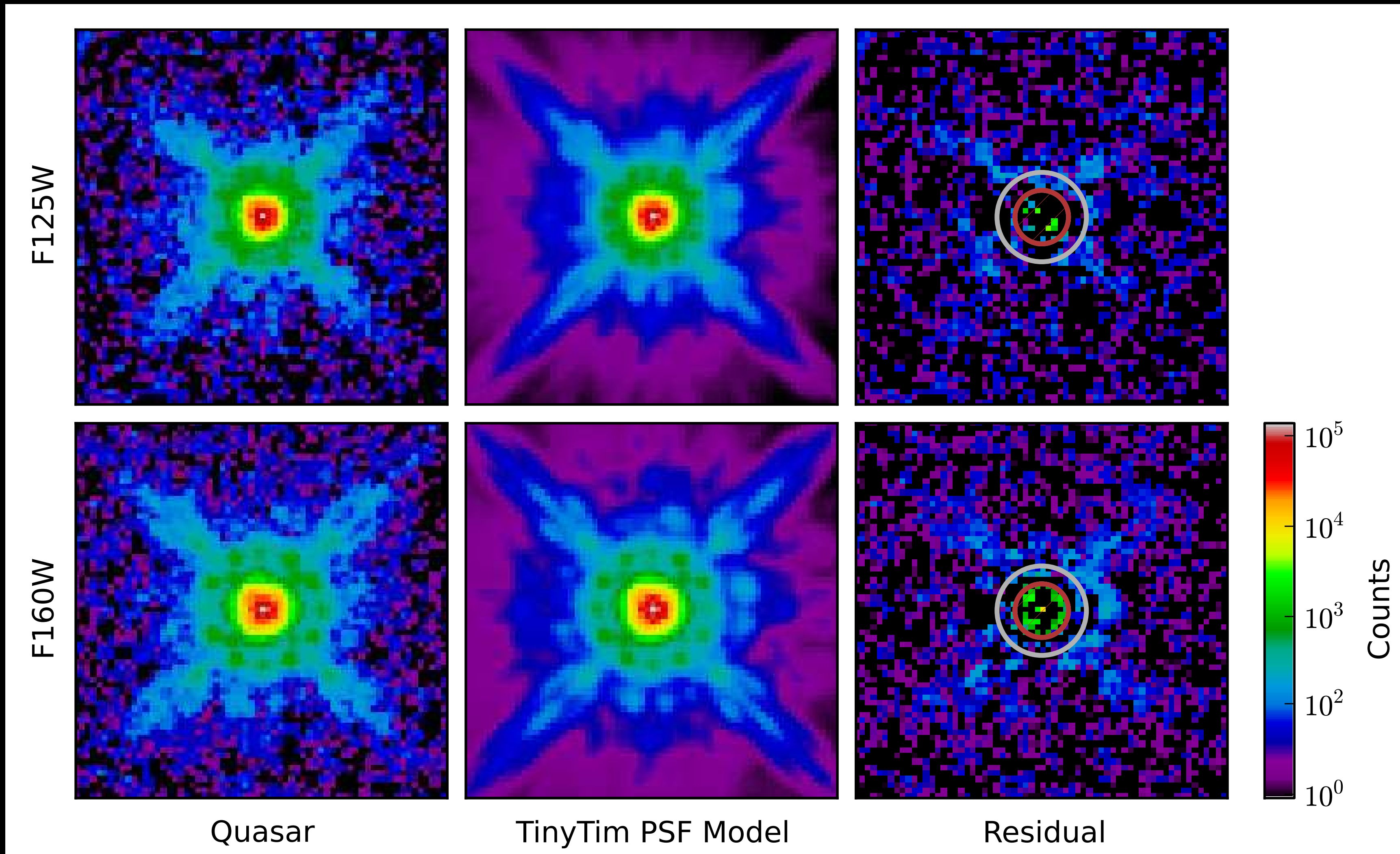


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N



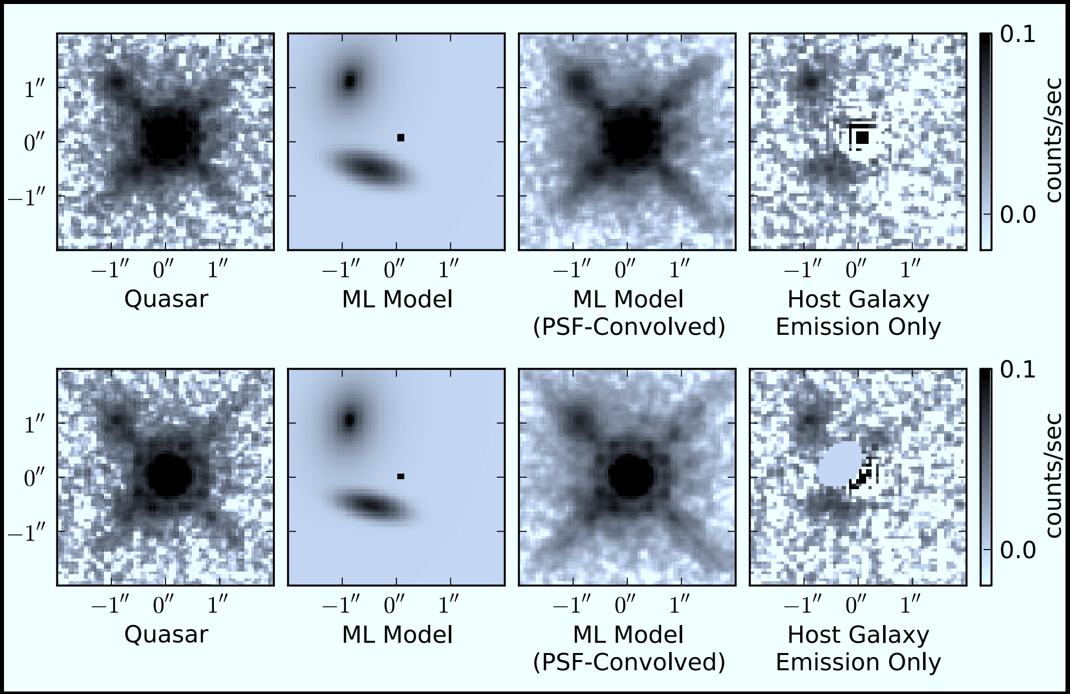
Blue=X-rays; White=Optical; Orange=Radio

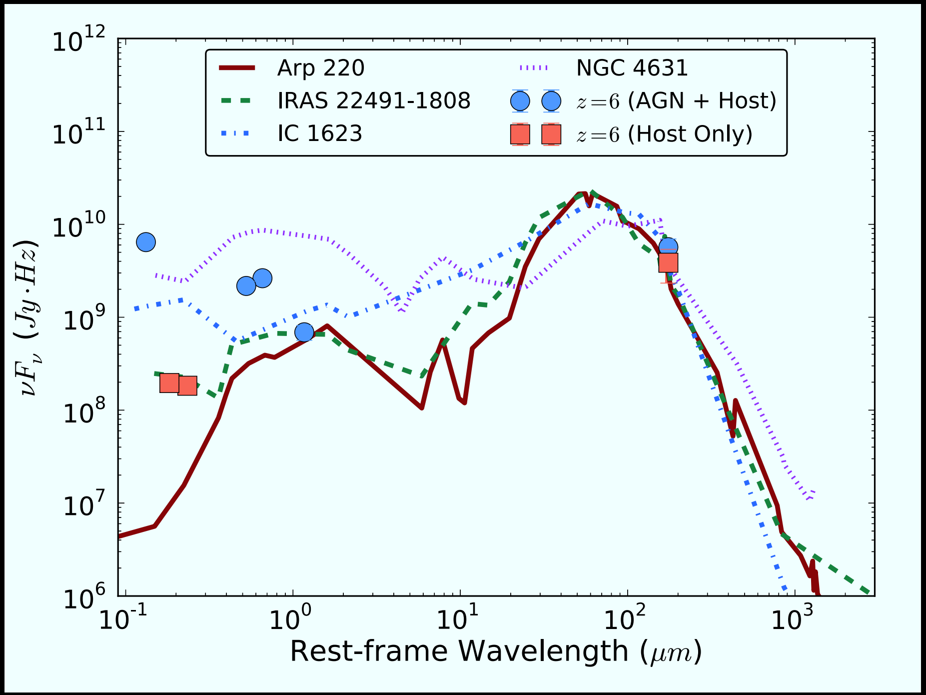
- Quasars: Centers of galaxies with feeding supermassive blackholes:



- 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!

(2b) WFC3: Detection of one QSO Host System at z≃6 (Giant merger?)





[LEFT]: First detection out of four z≃6 QSOs (Mechtley et al. 2016).

- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure?
- Same λ=1.25 & 1.6 μm structure. Colors constrain dust.

[RIGHT]: Blue dots: z≃6 quasar spectrum, Red: z≃6 host galaxy.

- Host galaxy has dusty starburst-like UV–far-IR spectrum: reddening of A_{FUV}(host)∼1 mag (Mechtley et al. 2014).

- JWST can detect 10–100× fainter dusty hosts (for z≲20, λ≲28μm).

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).

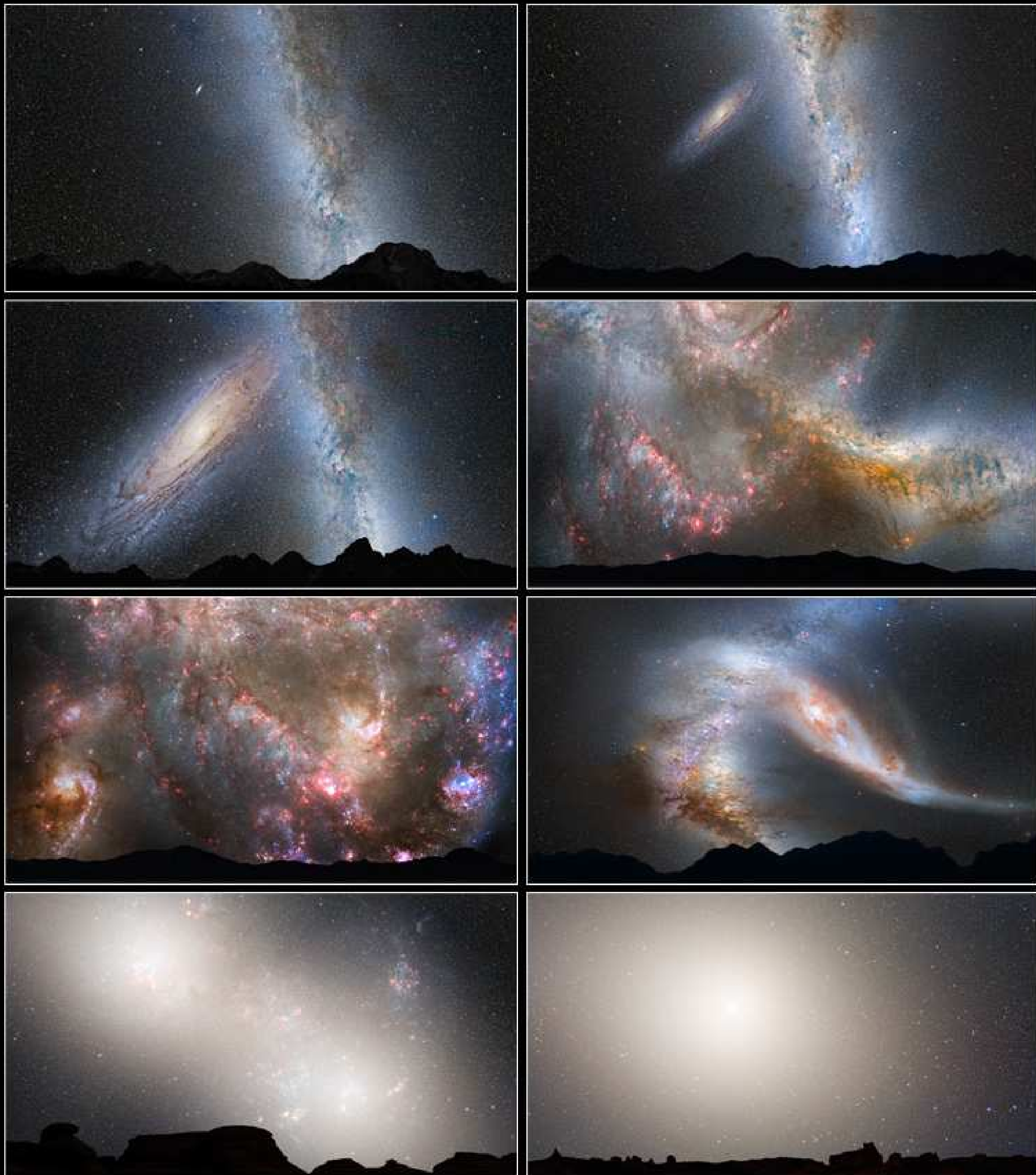


Illustration Sequence of the Milky Way and Andromeda Galaxy Colliding

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:

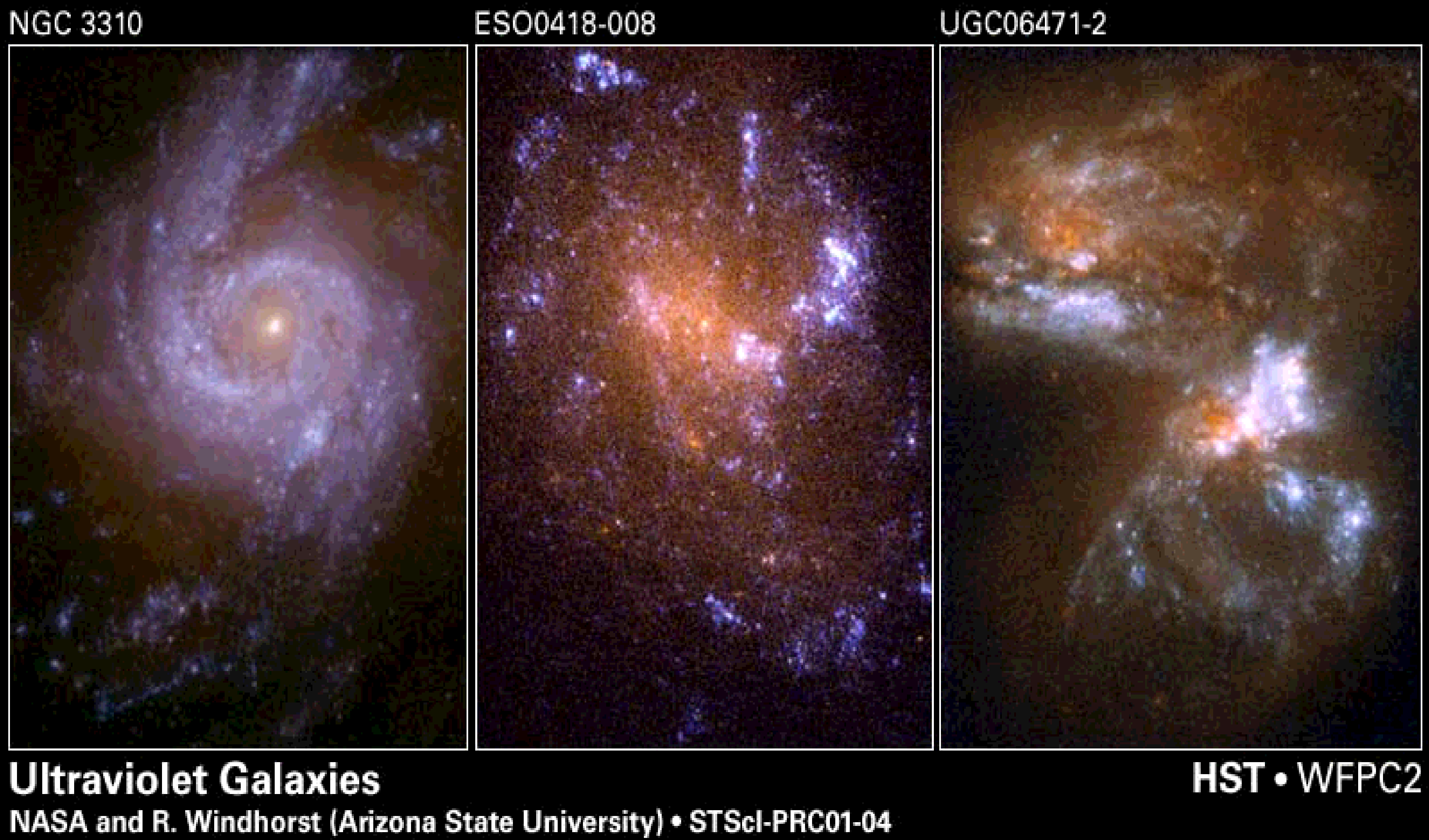
Approaches at –110 km/s.

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!

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

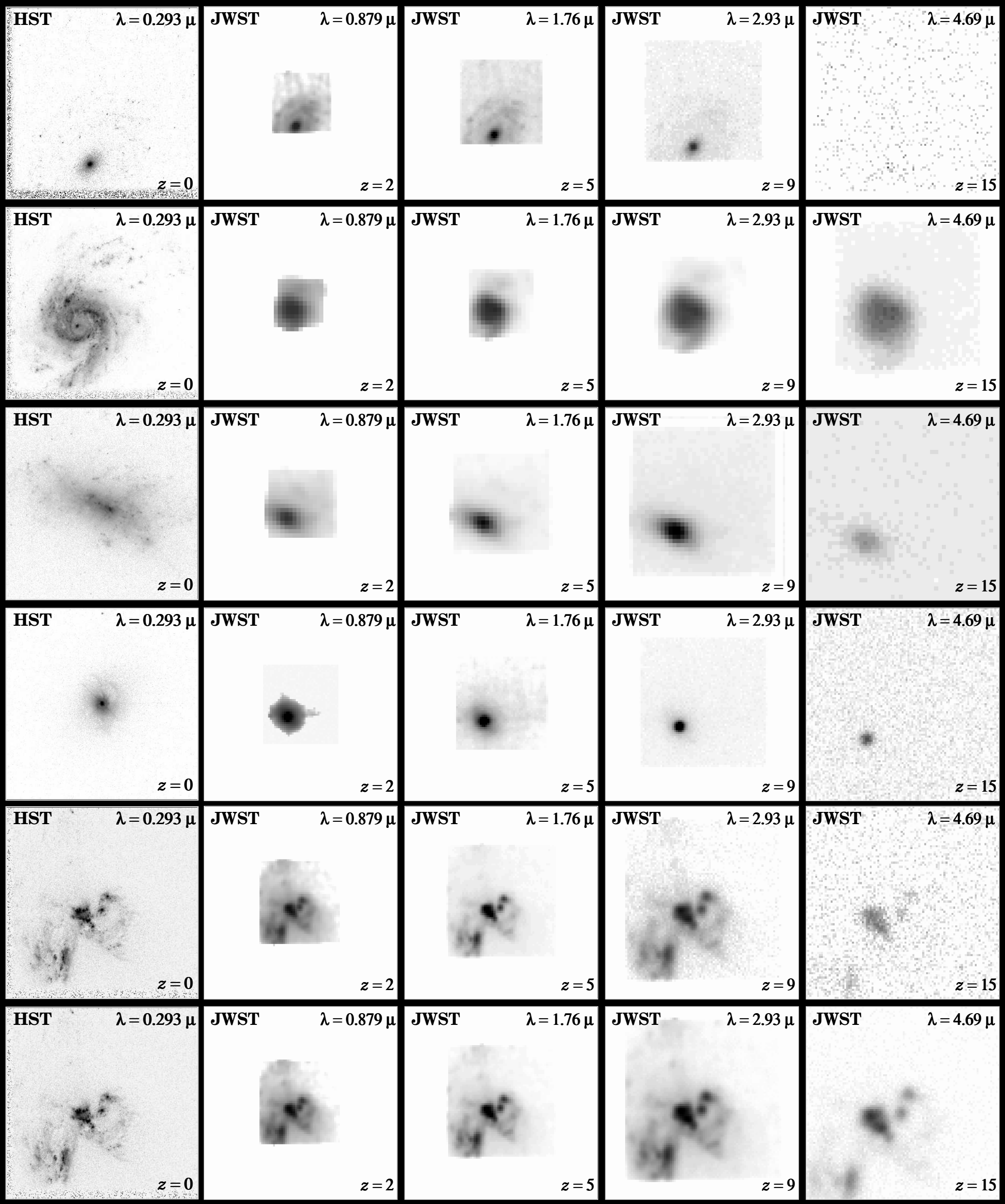


- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

- High-resolution HST ultraviolet images are benchmarks for comparison with very high redshift galaxies seen by JWST.

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

HST z=0 JWST z=2 z=5 z=9 z=15



With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most spiral disks will dim away at high redshift, but most formed at z$\lesssim$1–2.

Visible to JWST at very high z are:

- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.