

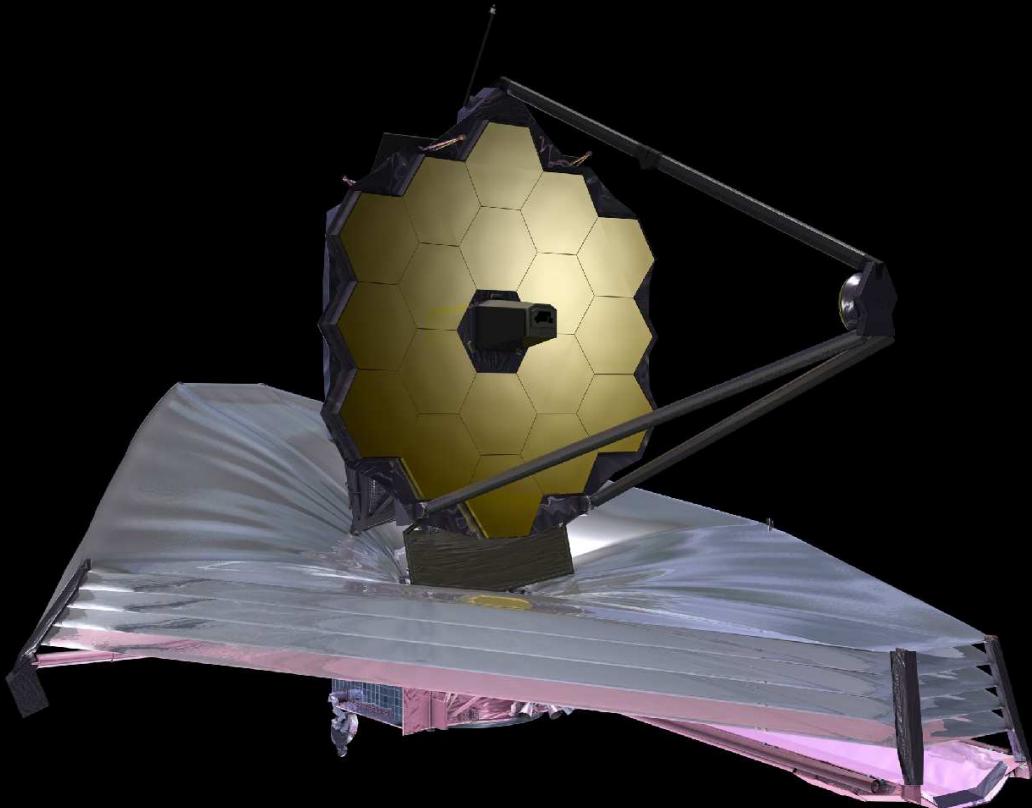
# The Search for First Light: James Webb Space Telescope Hardware Update

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Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

S. Cohen, R. Jansen (ASU), B. Frye (UofA), C. Conselice (UK), S. Driver (OZ), S. Wyithe (OZ), H. Yan (U-MO)

(Ex) ASU Grads: T. Ashcraft, N. Hathi, B. Joshi, D. Kim, M. Mechtley, R. Ryan, B. Smith, & A. Straughn



*Spirit of the Senses — Salon Talk; Gainey Ranch, Scottsdale, AZ*

*Wednesday June 1, 2016; All presented materials are ITAR-cleared.*

# Outline

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- (1) James Webb Space Telescope Hardware Update as of 2016.
- (2) How will JWST measure Galaxy Assembly & Supermassive Blackhole Growth — handshake with 2016 LIGO Gravitational Wave results.
- (3) How will JWST measure the Epoch of First Light (using gravitational lensing) — handshake with Planck 2016 results.
- (4) Summary and Conclusions.

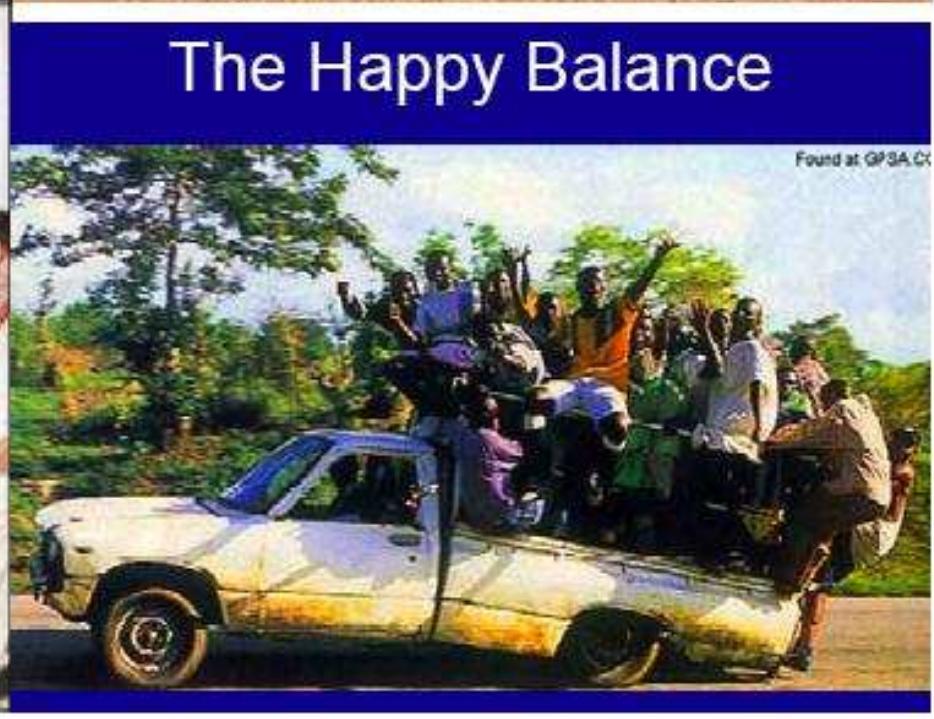


Sponsored by NASA/HST & JWST

Talk is on: <http://www.asu.edu/clas/hst/www/jwst/jwsttalks/spirit16hstjwst.pdf>

What the Scientists See:

What the Project Manager Sees:

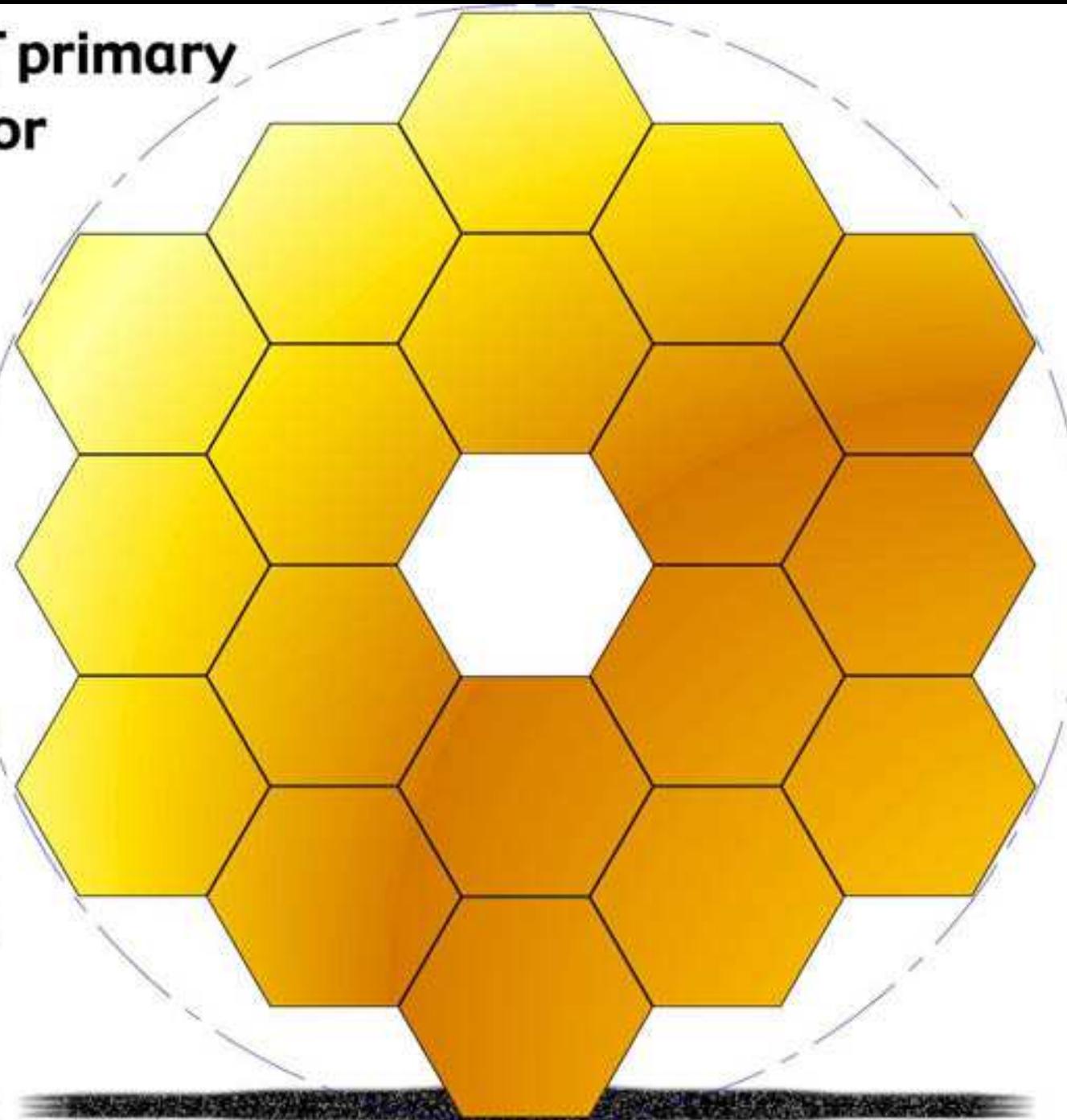


The Happy Balance

Found at GPSA.CX

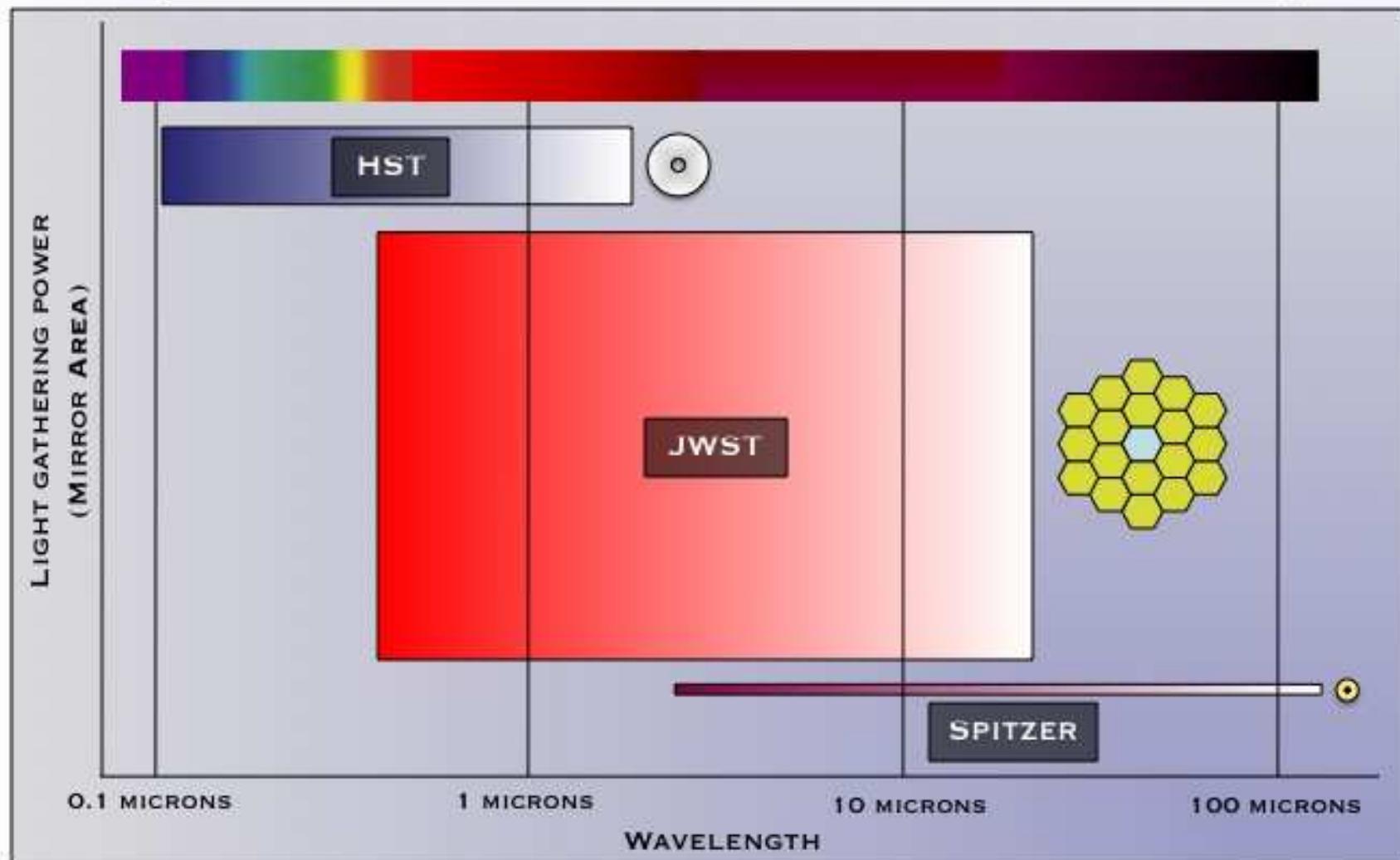
Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

**JWST 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.

# THE JAMES WEBB SPACE TELESCOPE



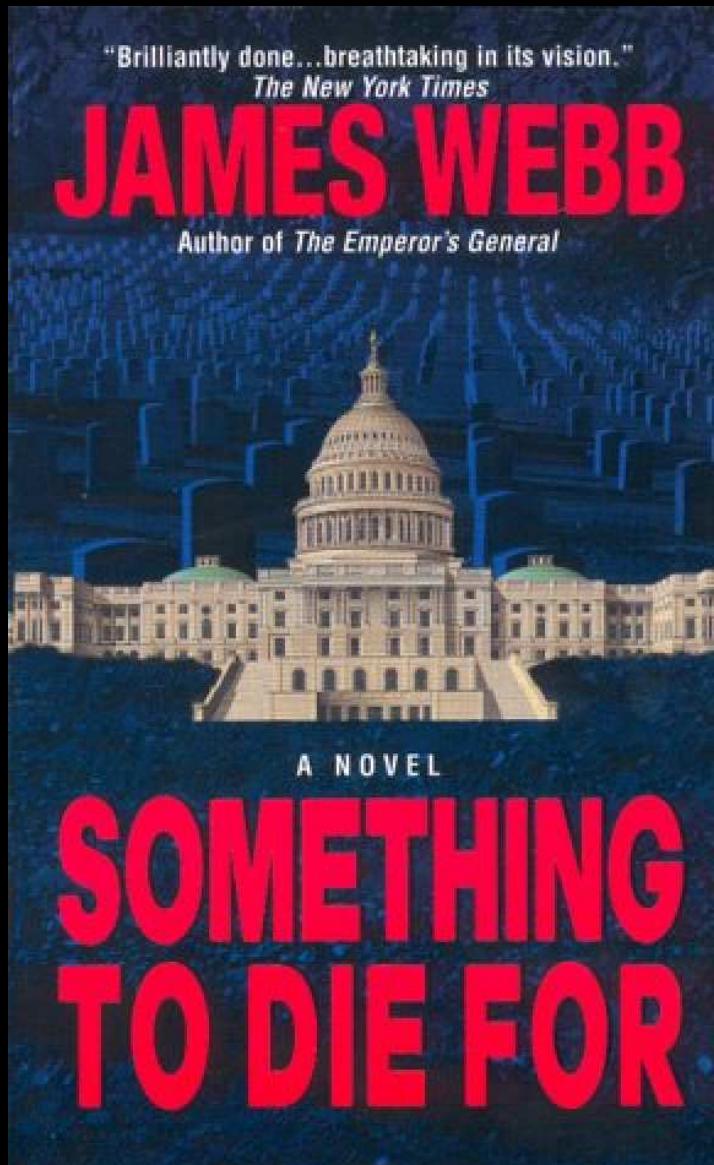
## LIGHT GATHERING POWER

$$\text{JWST} = 25 \text{ m}^2; \text{ Hubble} = 4.5 \text{ m}^2; \text{ Spitzer} = 0.6 \text{ m}^2$$

JWST is the perfect near-mid-IR sequel to HST and Spitzer:

Vastly larger collecting area than HST in UV-optical and Spitzer in mid-IR.

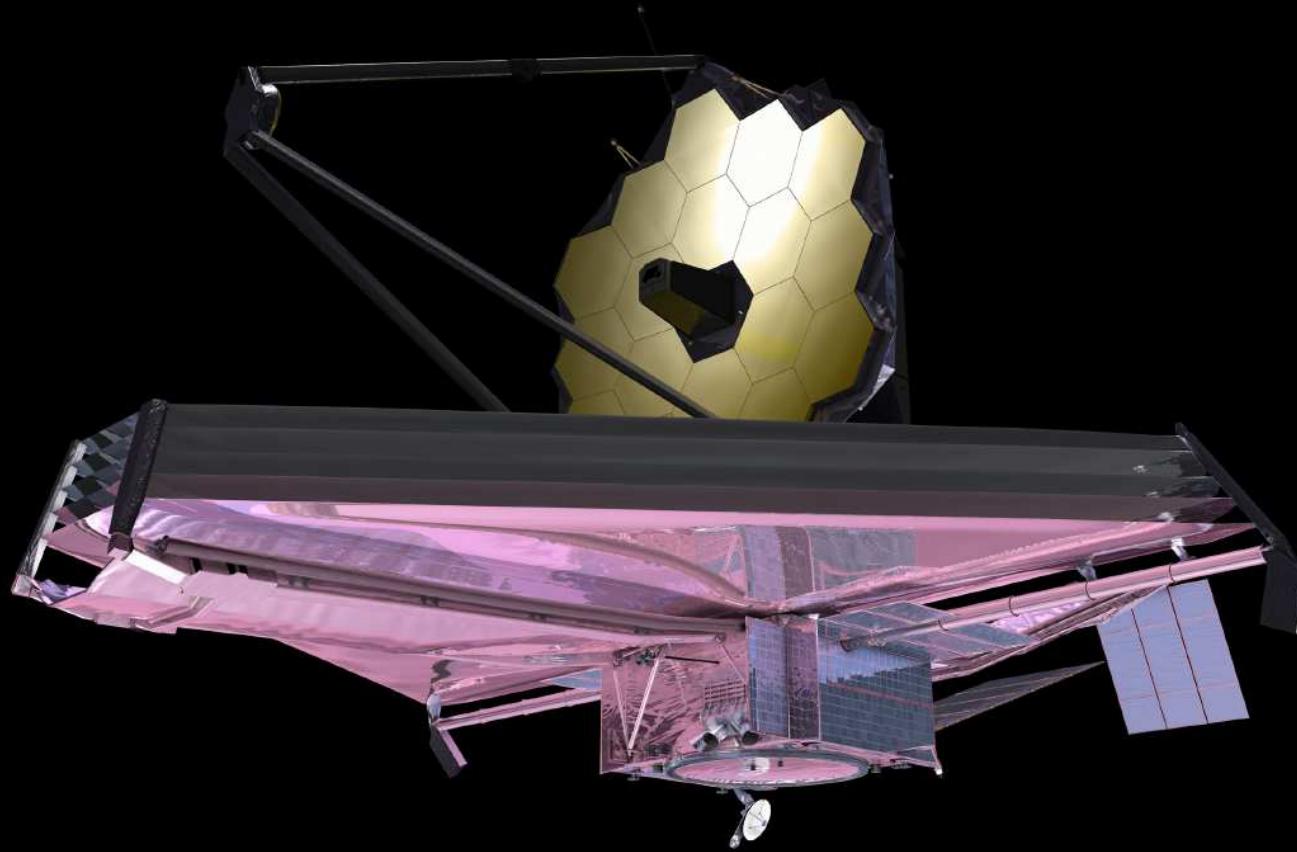
(1) Update of the James Webb Space Telescope (JWST), 2016.



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 2016.



- 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 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.

# THE JAMES WEBB SPACE TELESCOPE

## JWST LAUNCH

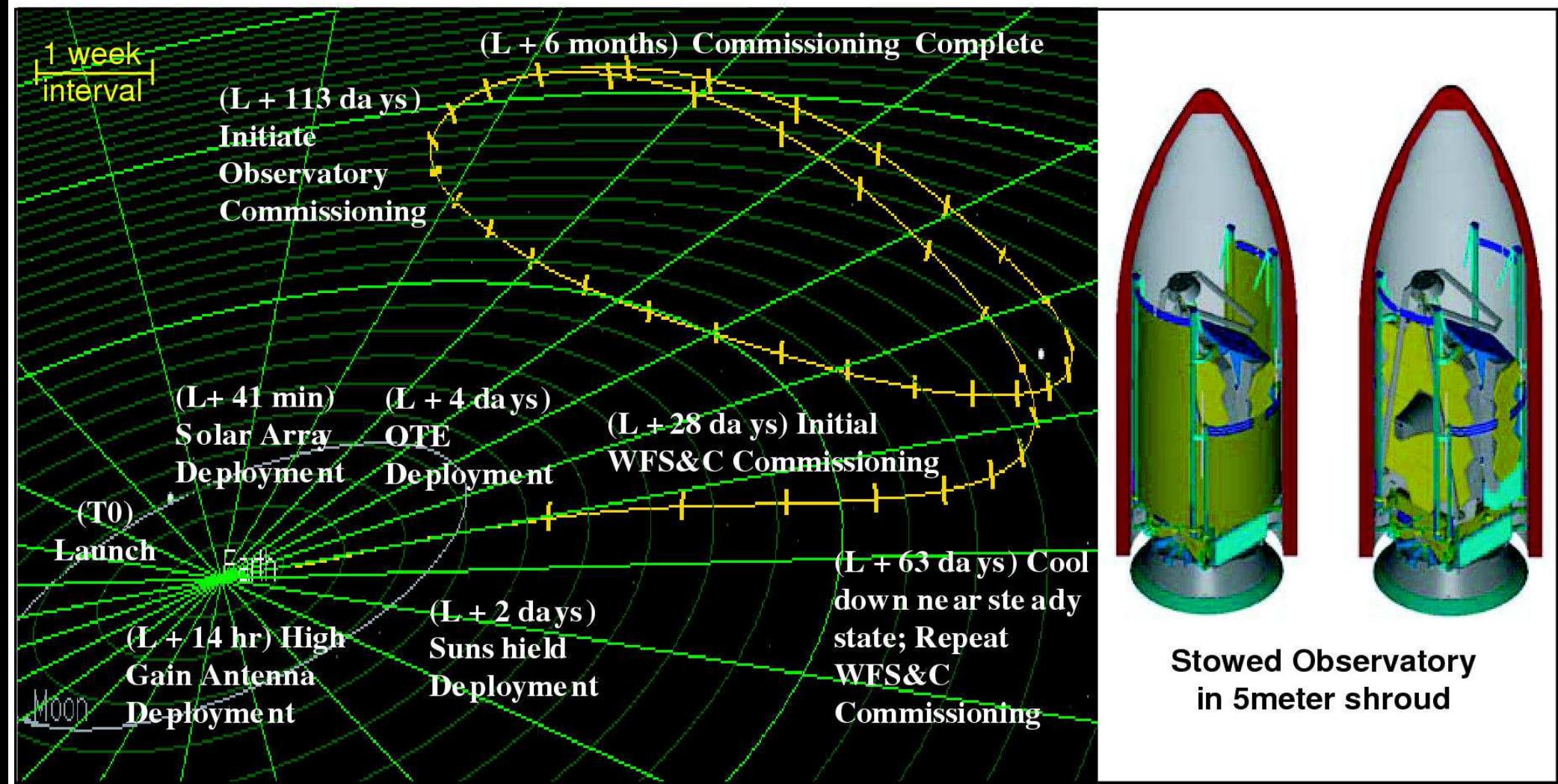
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



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.

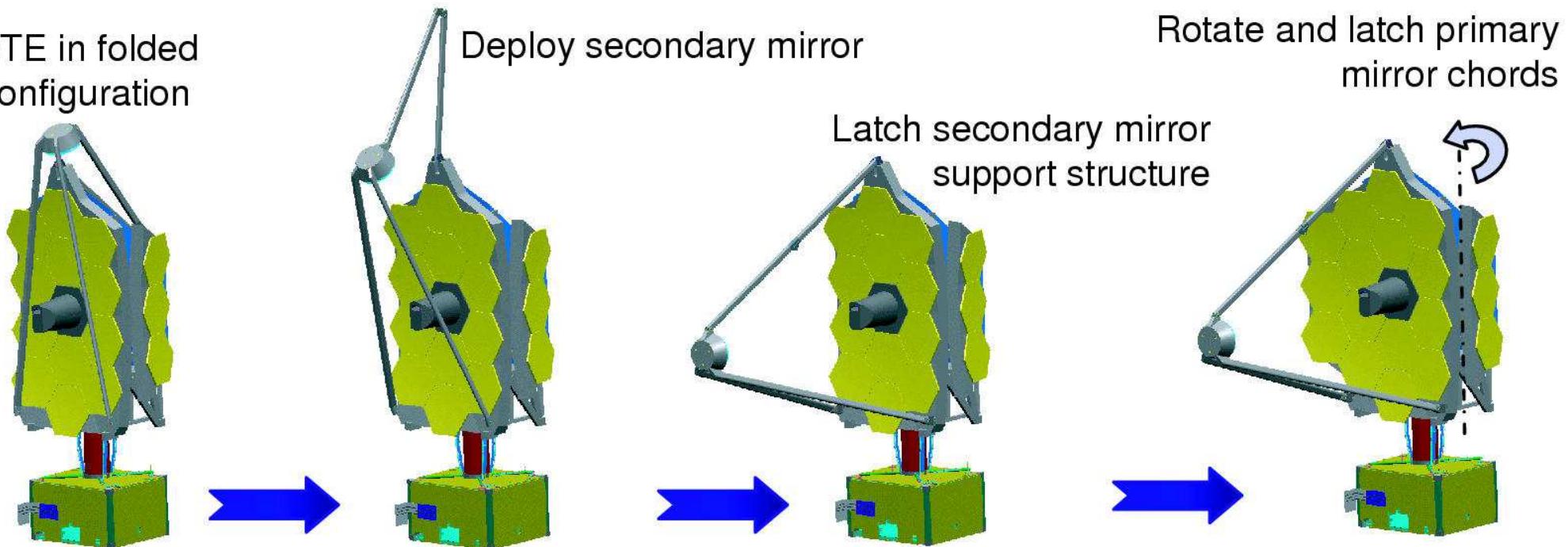
## (1a) How will JWST travel to its L2 orbit?



- 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.

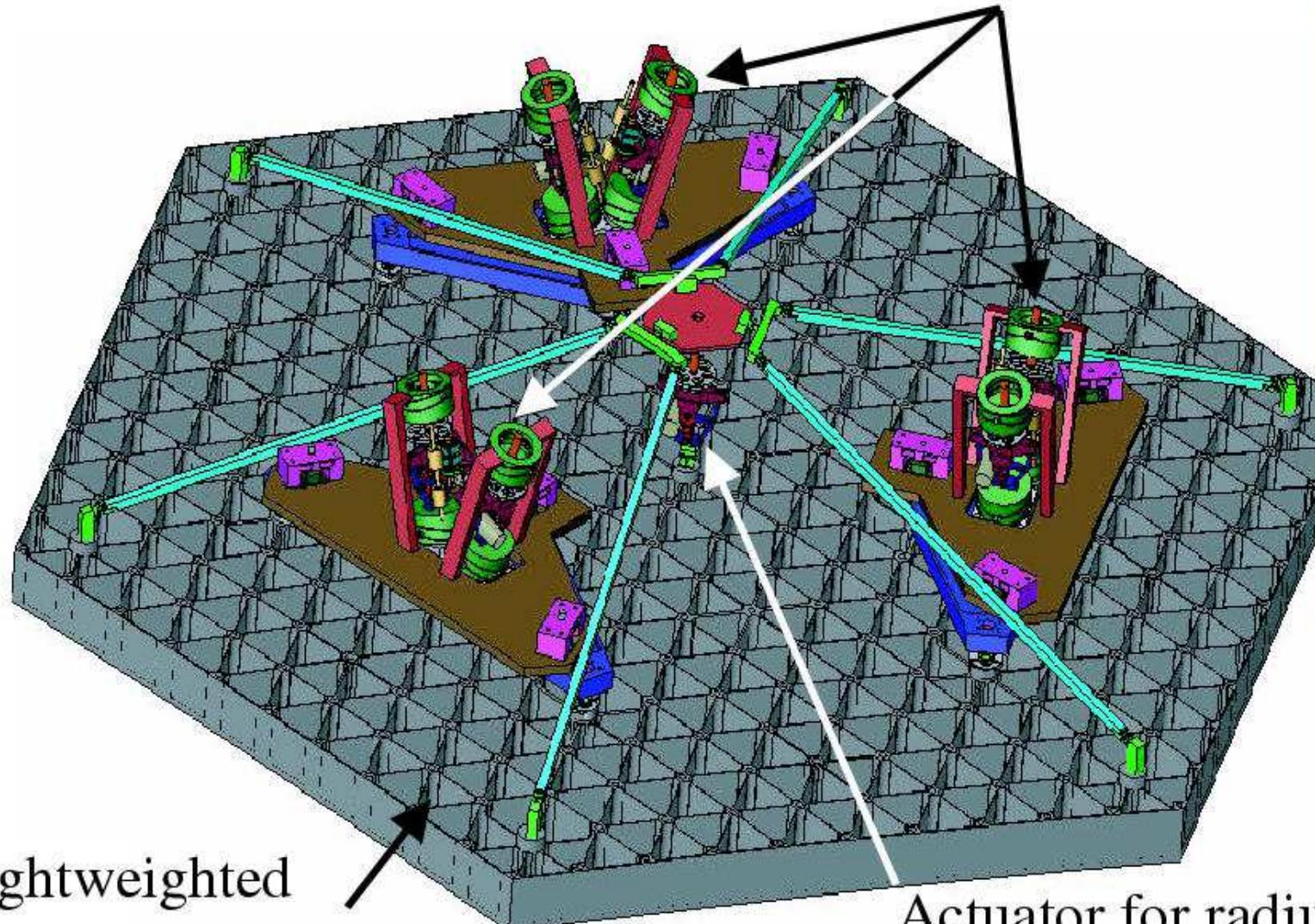
## (1b) How will JWST be automatically deployed?

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 2014–2017 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.

# 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



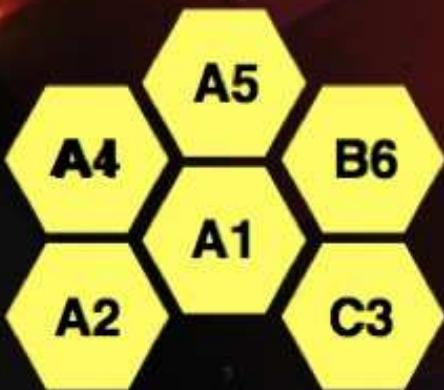
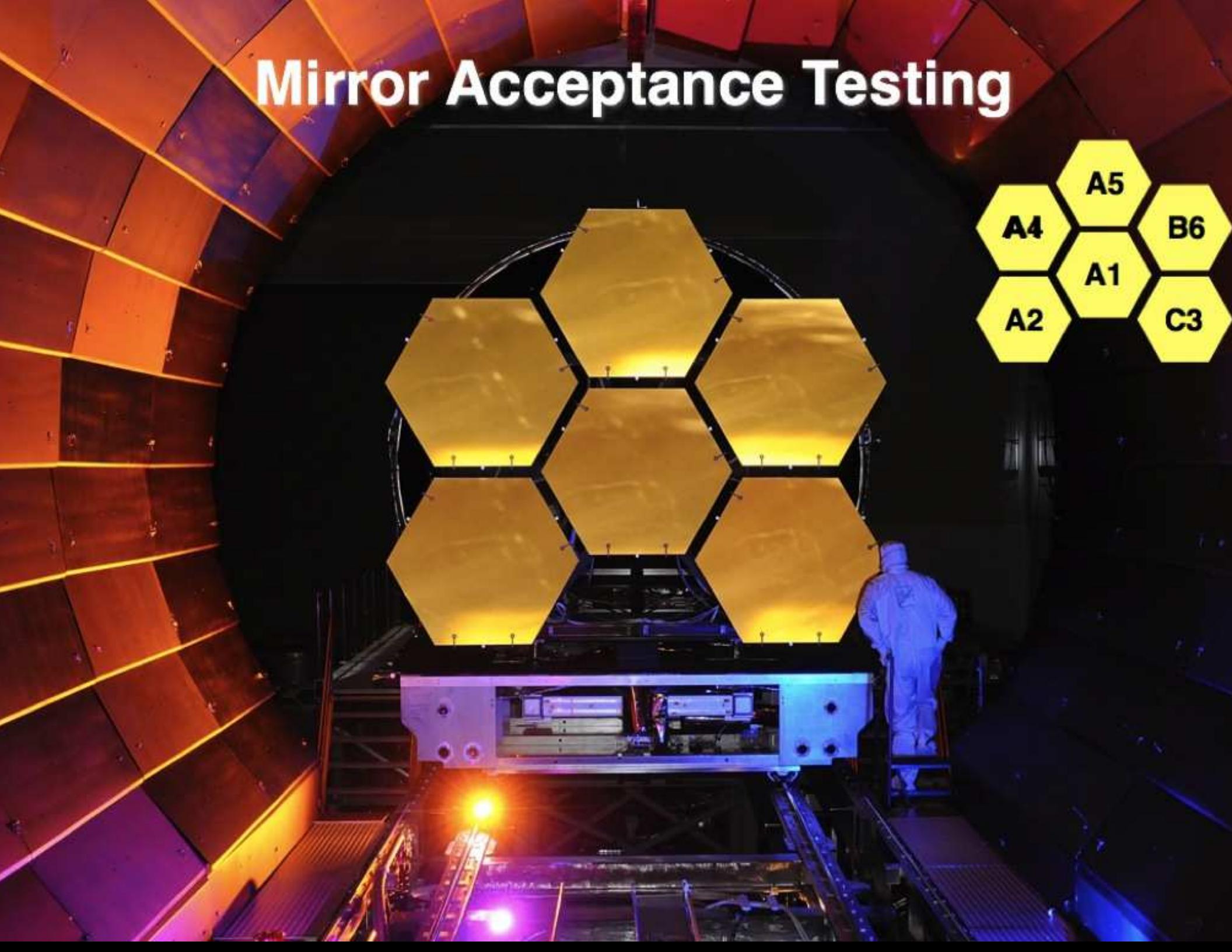
Spacecraft computer Test Unit



Mid-boom Test

Apr. 2016:  $\gtrsim 99\%$  of launch mass designed and built ( $\gtrsim 70\%$  weighed).

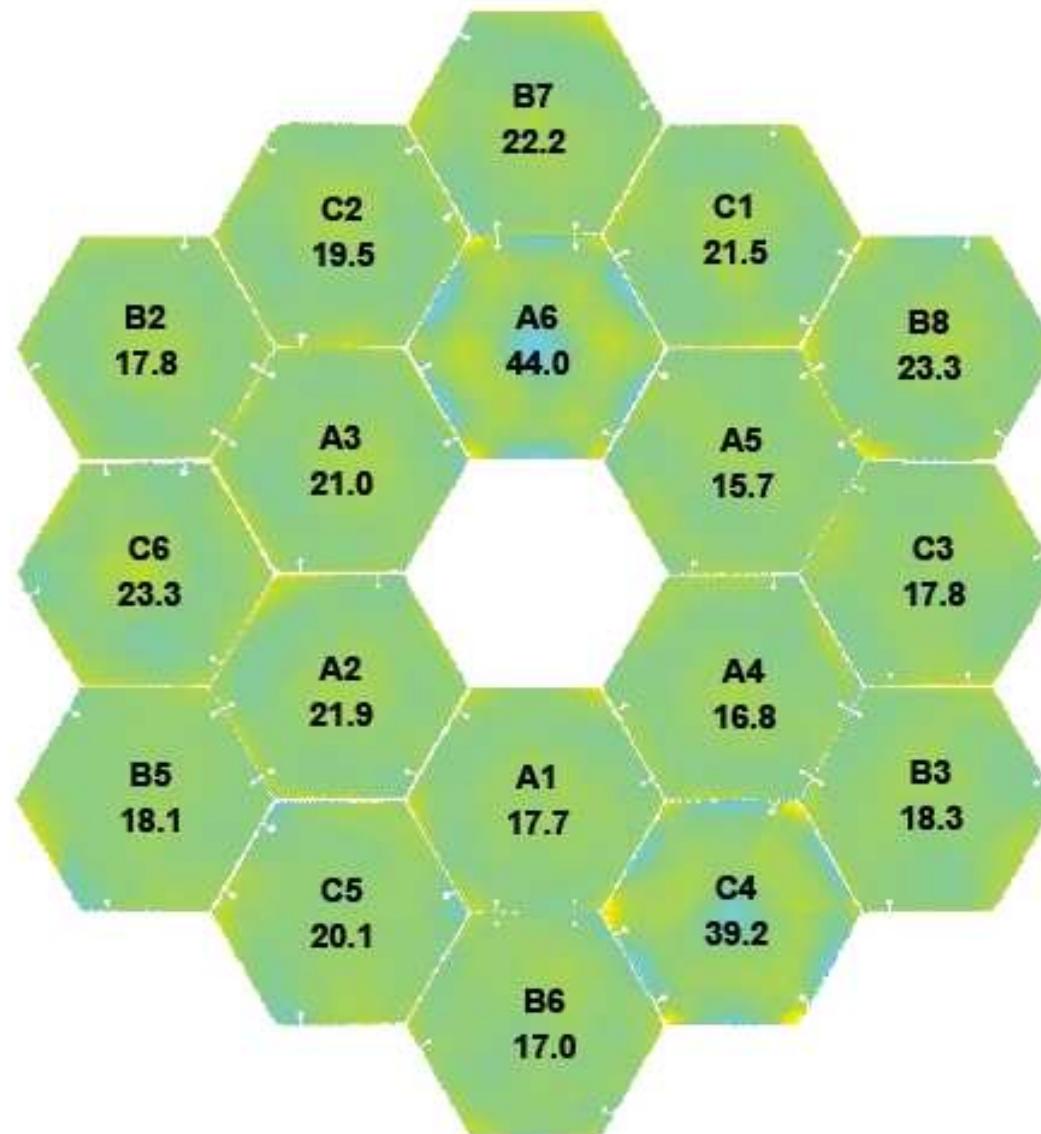
# Mirror Acceptance Testing







# Primary Mirror Composite



RMS:  
**23.2 nm**

PV:  
**515.5 nm**

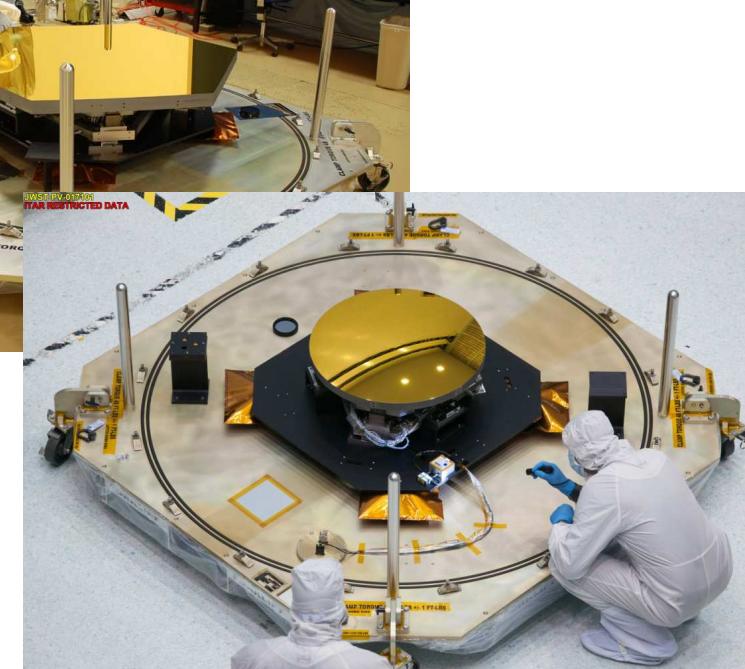
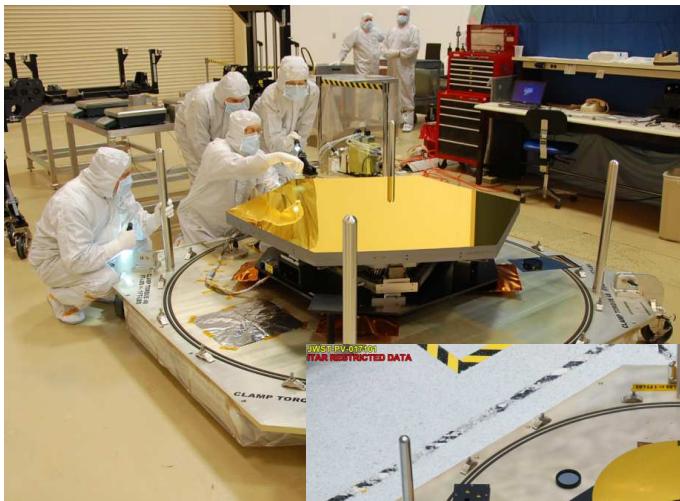




# Mirror Status

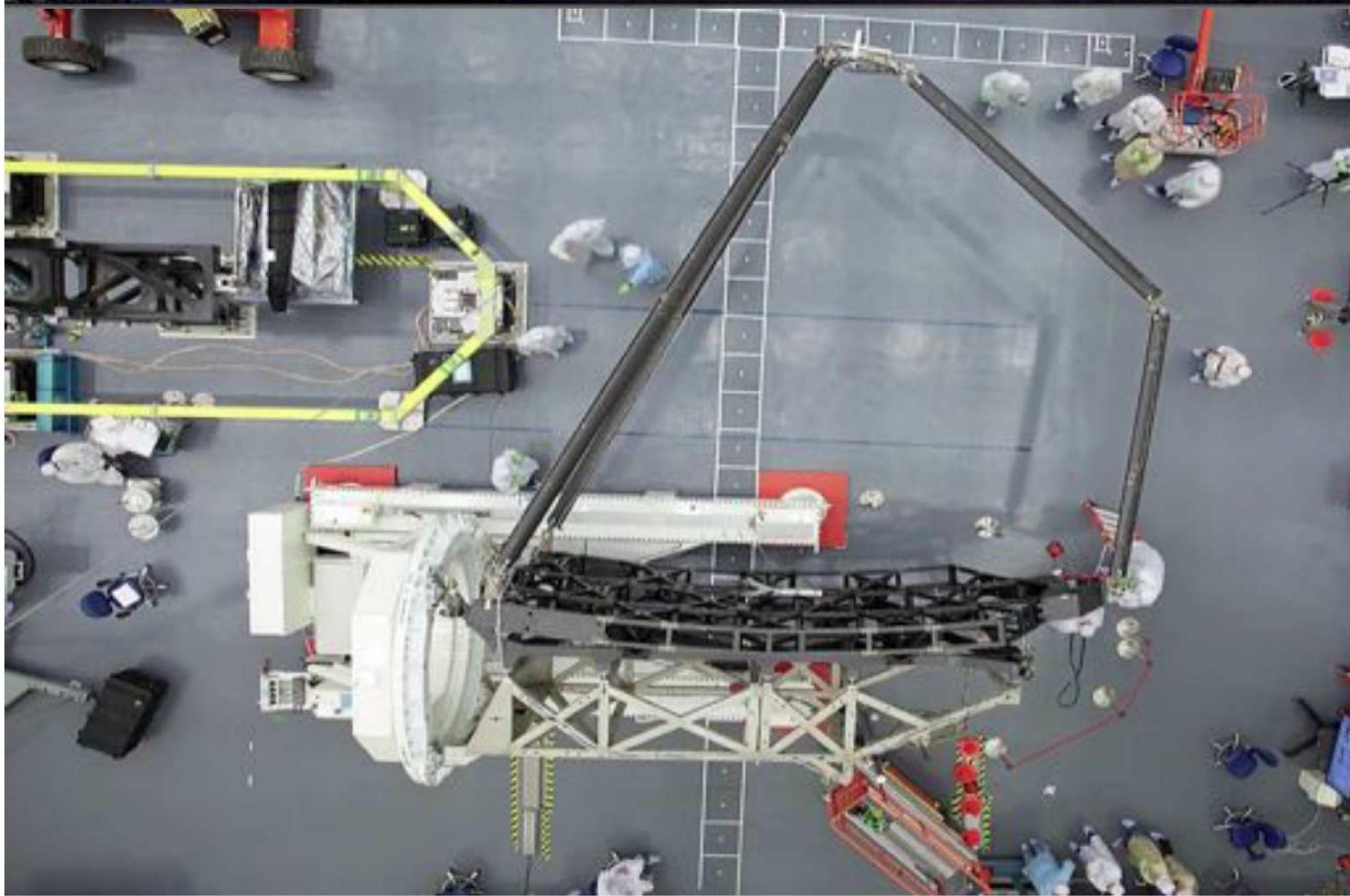


- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC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



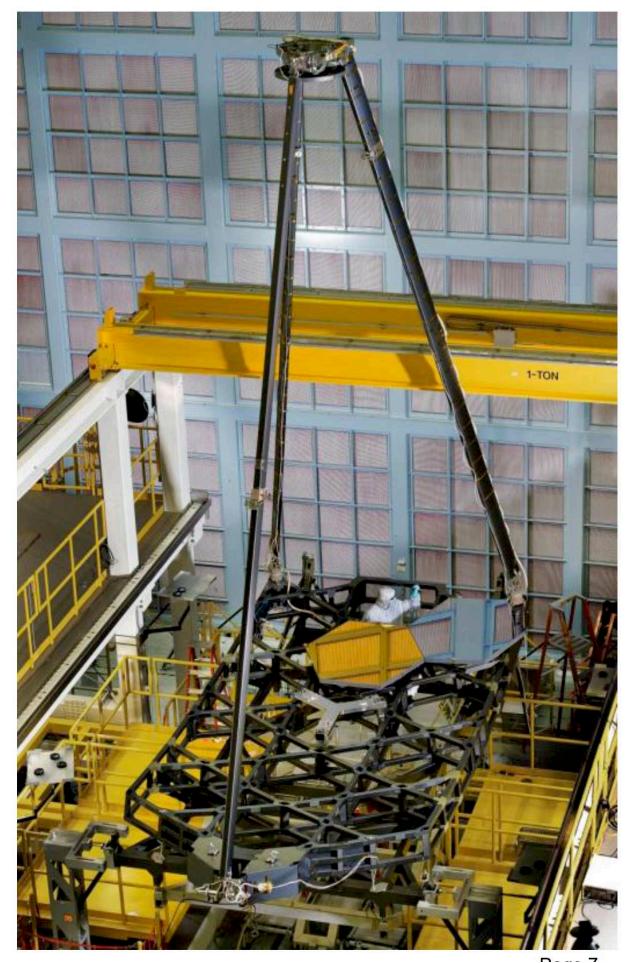
Spring 2014: All 18 flight mirrors delivered to NASA GSFC (MD).

# Pathfinder: Powered Deployment of SMSS



July 2014: Secondary Mirror Support deployment successfully tested.

# (1c) JWST hardware to date, and how to best use it for high redshift lensing.



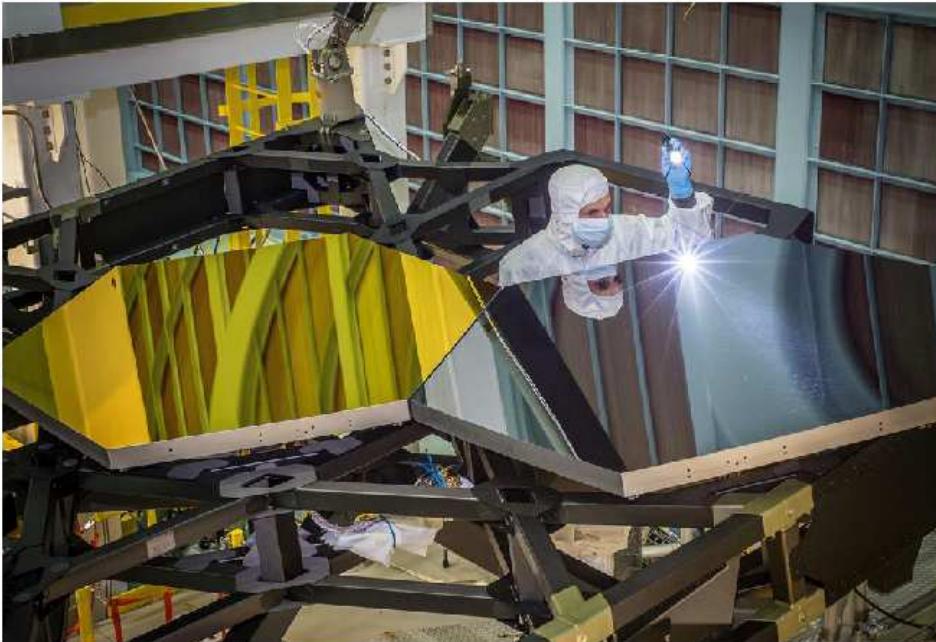
[LEFT]: Aug. 2014: Engineering Kapton Sunshield; 2016: Flight Sunshield.

[RIGHT]: Nov. 2014: First JWST mirrors mounted onto support structure, using Engineering Demo mirrors — Flight mirrors mounted in Jan. 2016.

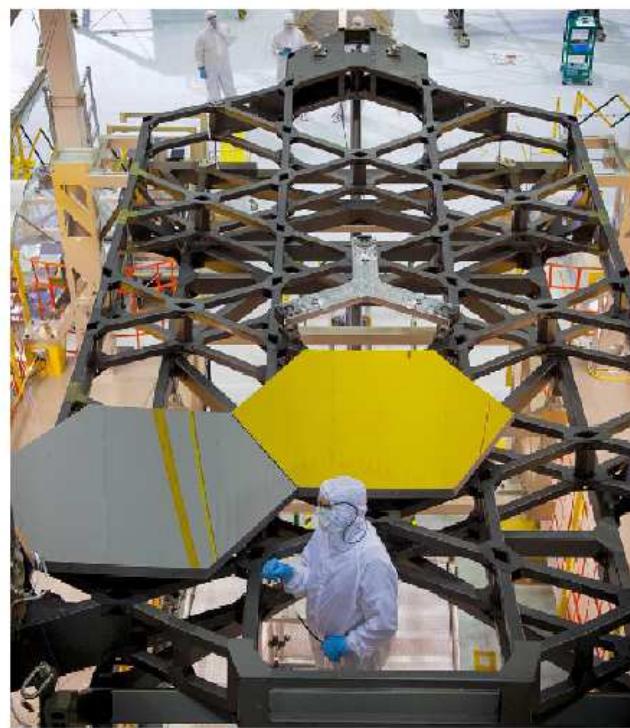
- Our Galaxy is a bright IR source at  $\lambda \gtrsim 1-5\mu\text{m}$ : In certain directions of the sky, some straylight can hit secondary mirror via Sunshield.
- This can effect JWST (lensing) studies of First Light objects.



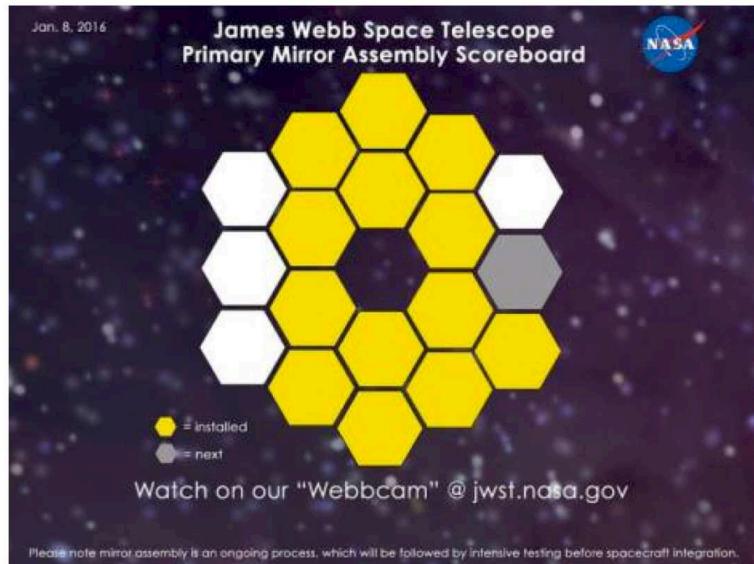
# Telescope Pathfinder – Risk Reduction



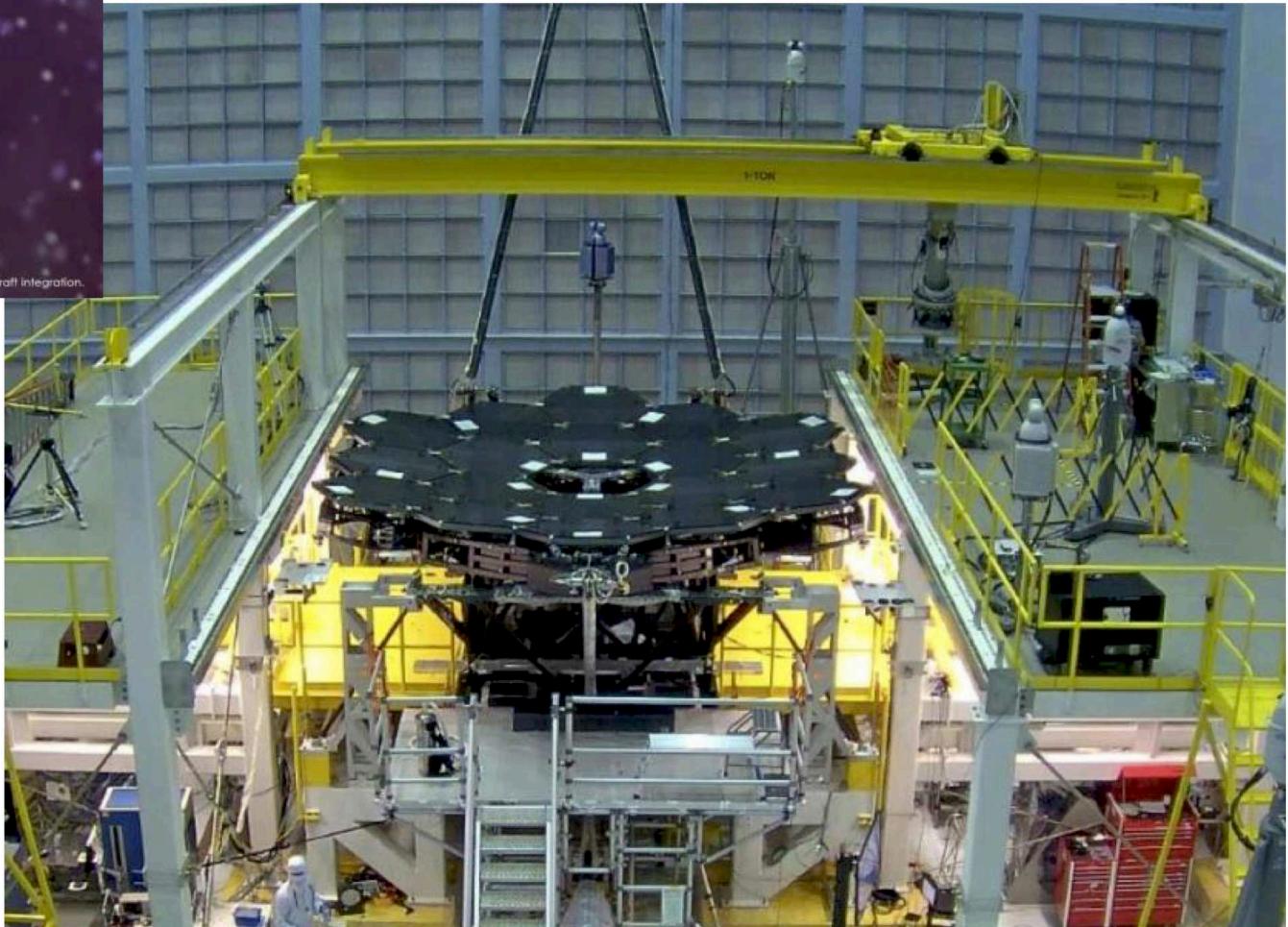
JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly



# Much progress has been made in OTE integration



Where we were at last month's call



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



8 February 2016 JWST Monthly Telecon 8

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



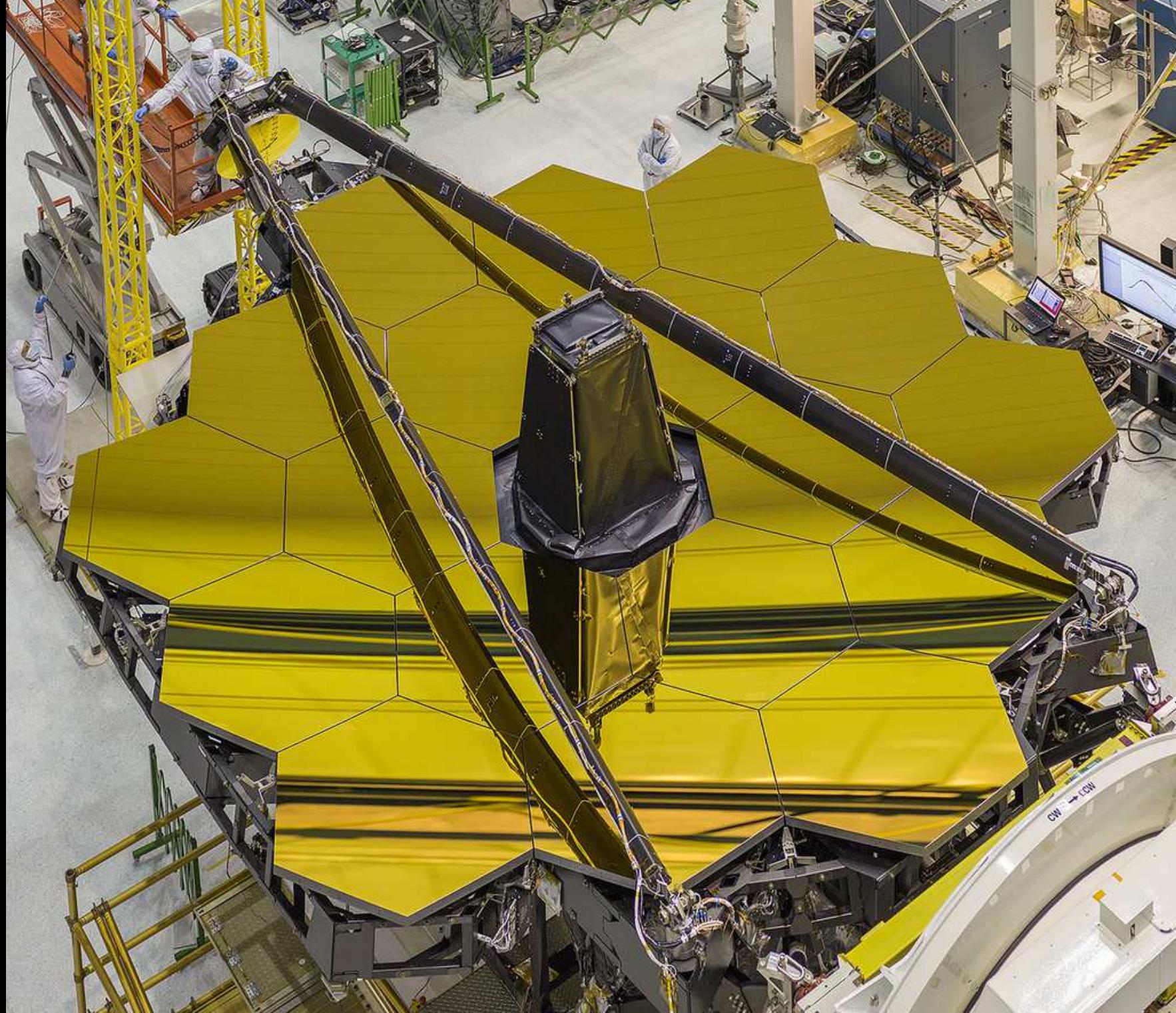
April 2016: NASA team-work to take JWST mirror covers off!



May 2016: Webb mirrors finally mounted and ready!



May 2016: JWST being tilted into the right position



May 2016: JWST stowed for further instrument mounting



# All Instruments Integrated



Fine Guidance Sensor



Mid-Infrared Instrument



Near Infrared Camera



Near Infrared Spectrometer

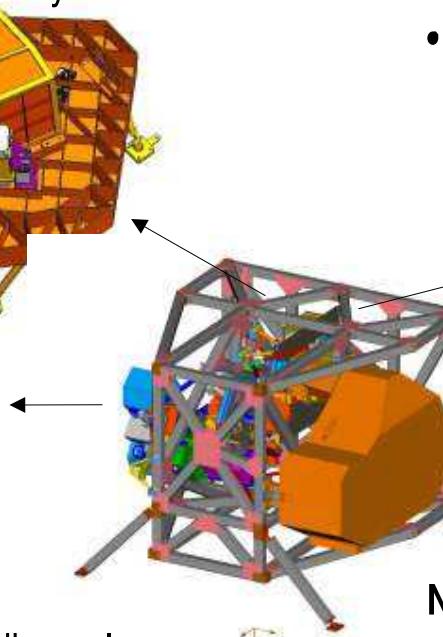
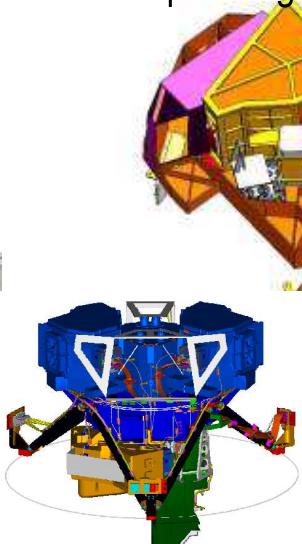


# Instrument Overview



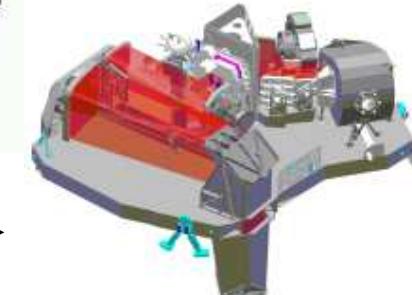
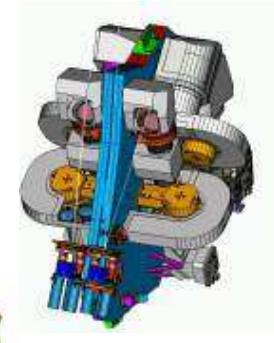
## Fine Guidance Sensor (FGS)

- 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



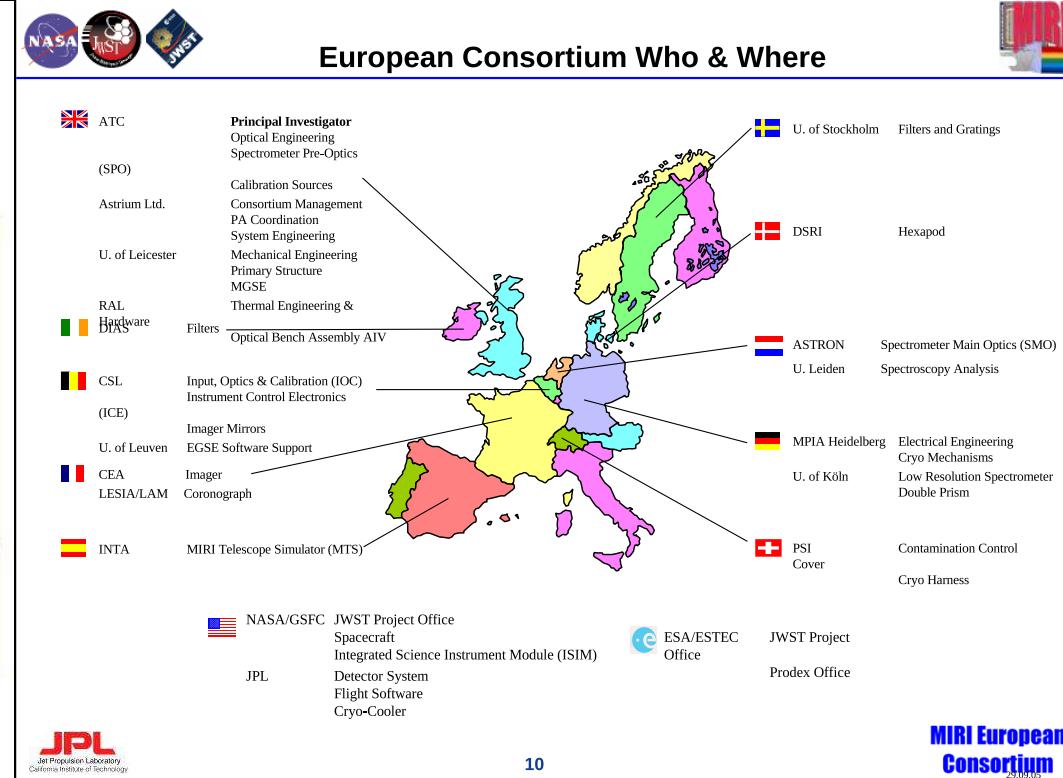
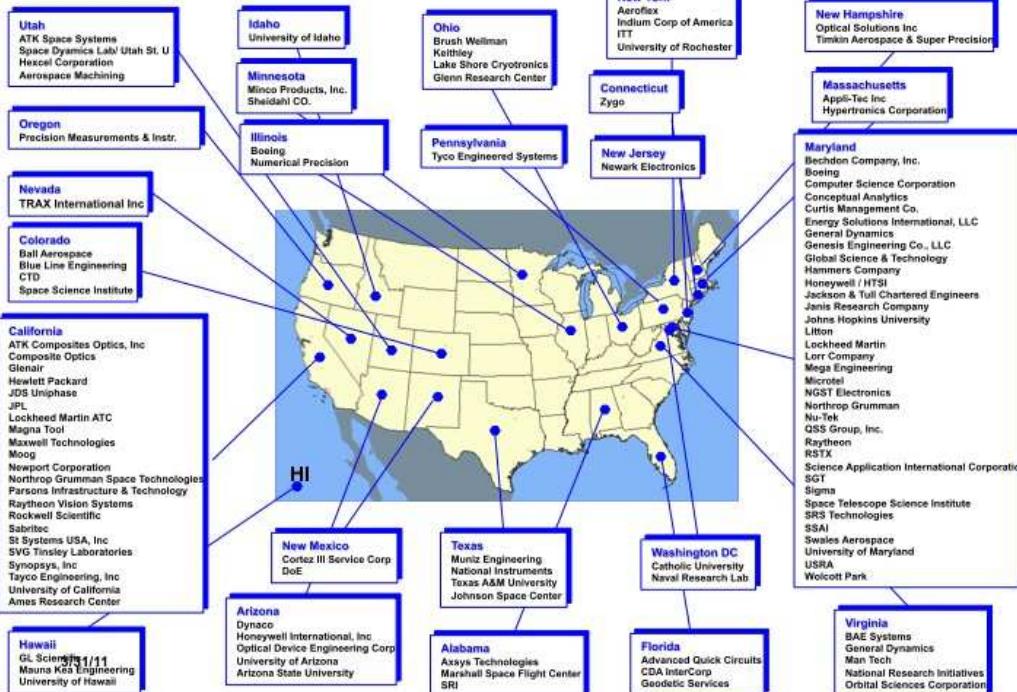
## Mid-Infra-Red Instrument (MIRI)

- 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

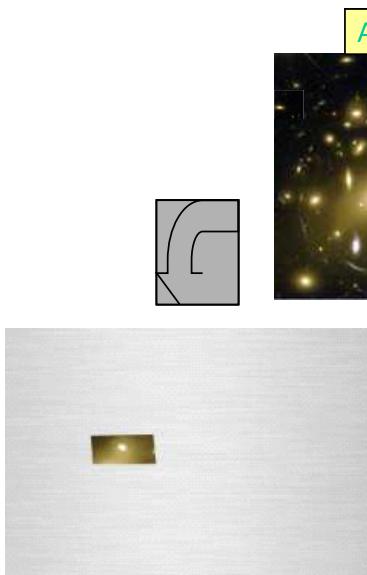
# JWST: A Product of the Nation



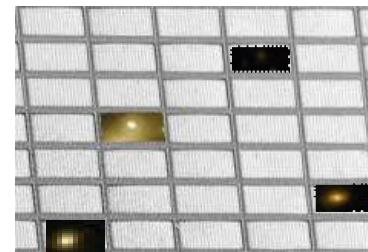
- JWST hardware made in 27 US States:  $\gtrsim 99\%$  of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

This nationwide + international coalition was critical for project survival!

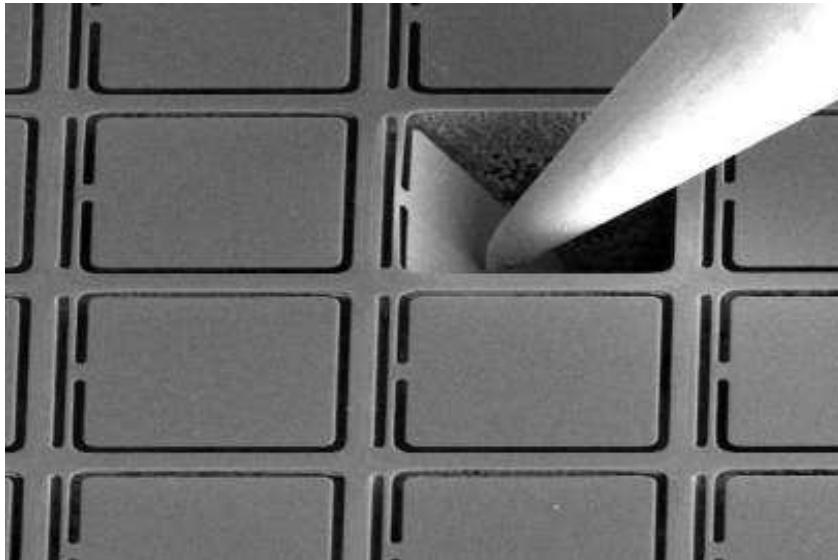
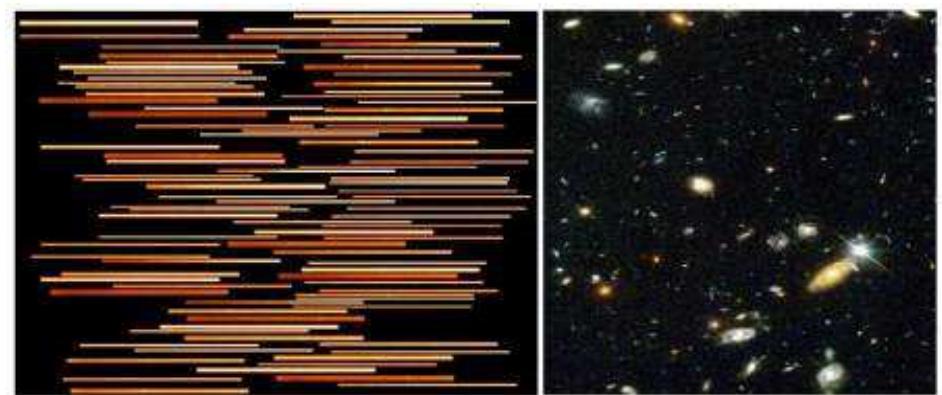
# Micro Shutters

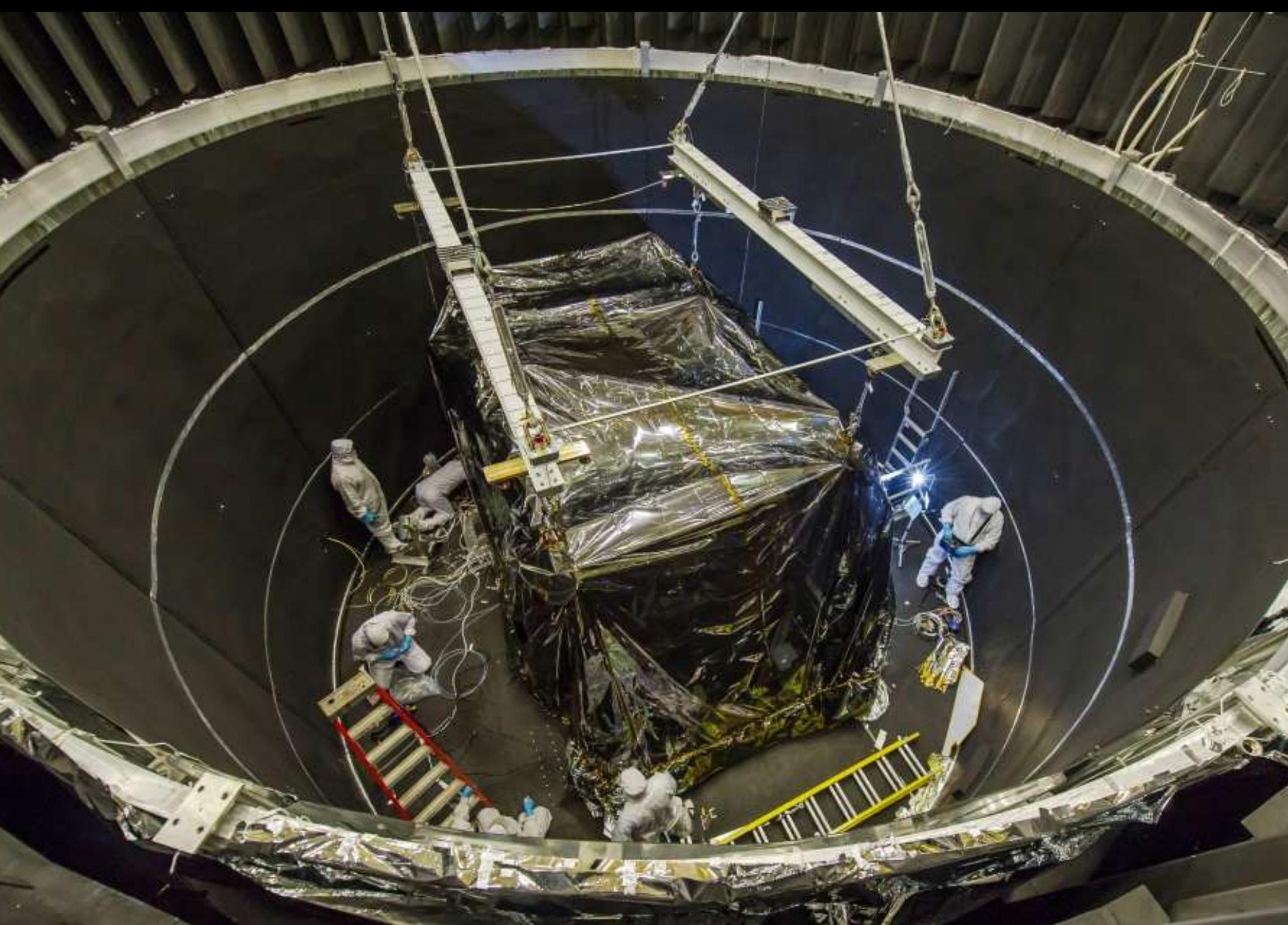


Metal Mask/Fixed Slit



Shutter Mask

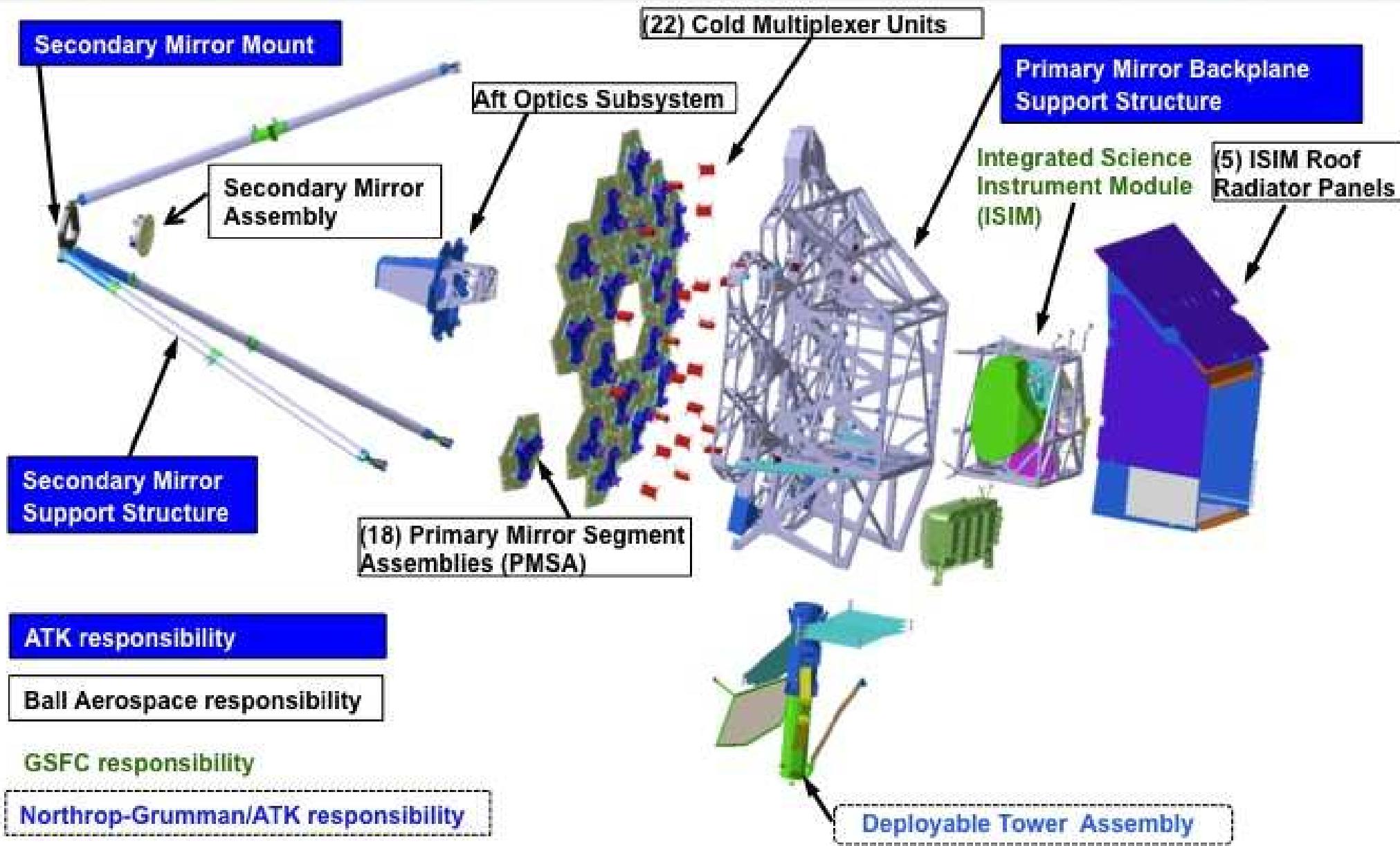




2014: Flight ISIM (all 4 instruments) in test; Oct. 15-Feb. 2016: CryoVac3.



# TELESCOPE ARCHITECTURE



3/31/11

2014–2016: Complete system integration at GSFC and Northrop.



# OTIS Test GSE Architecture and Subsystems



## Chamber Isolator Units

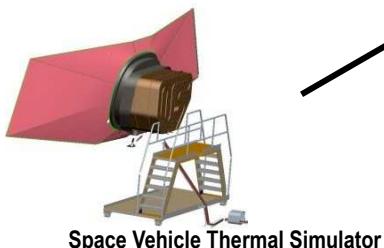
Dynamically isolates OTIS Optical Test  
– Integration 6 units complete



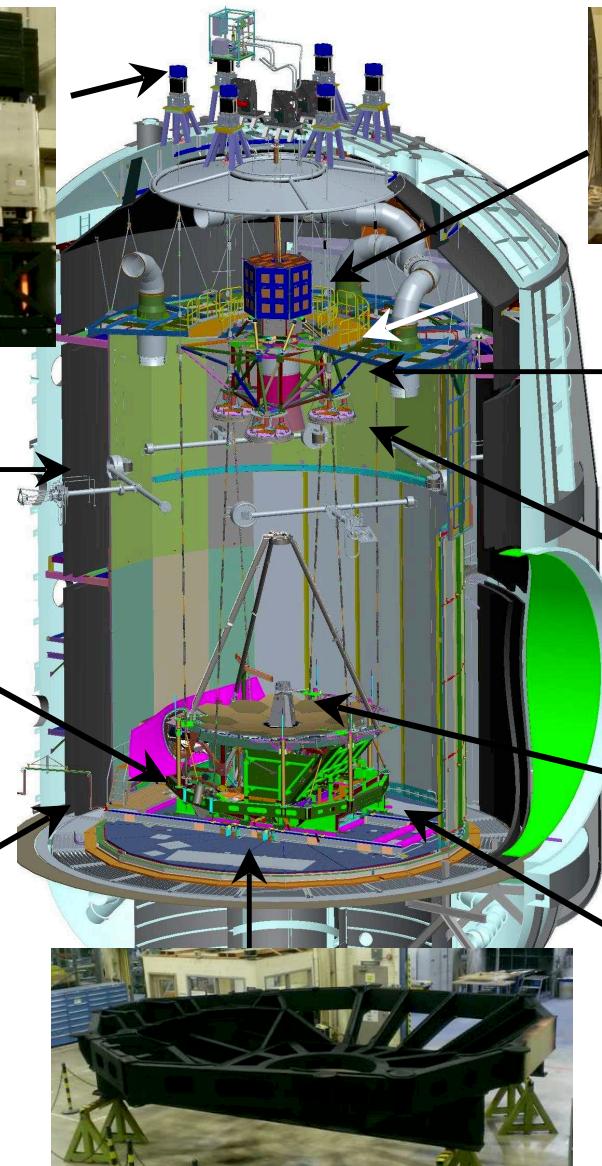
Cryo Position Metrology (CPM)  
Photogrammetry System  
Integration Complete



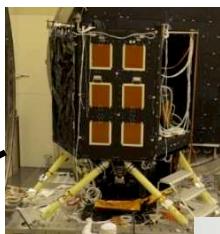
ADM - new Leica  
delivered and under  
test



Passed design review and started  
Procurements and fab subcontracts



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



## Center of Curvature Optical Assembly (COCOA)

- Multiwavelength interferometer (MWIF), null, calibration equipment, coarse/fine PM phasing tools, Displacement Measuring Interferometer – COCOA was exercised at MSFC in December



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



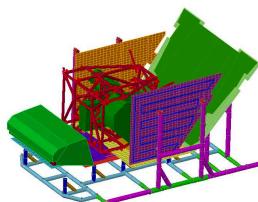
3 Auto collimating Flat Mirrors (ACFs)  
1.5 M Plano for Pass and Half Testing  
Cryo testing underway, ACF 1 complete, ACF 4 in  
Cryo test complete , ACF 5 ready for Cryo.



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



Mag Damper Cryo  
Test  
Article  
Fabrication started

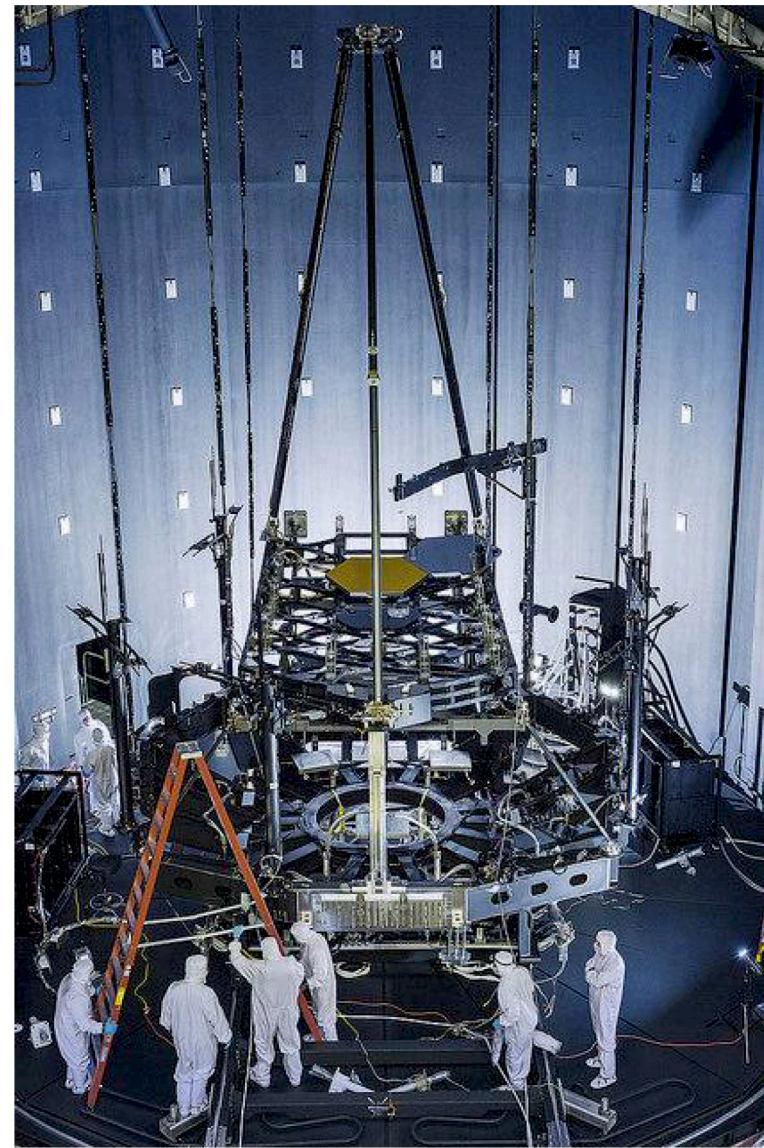
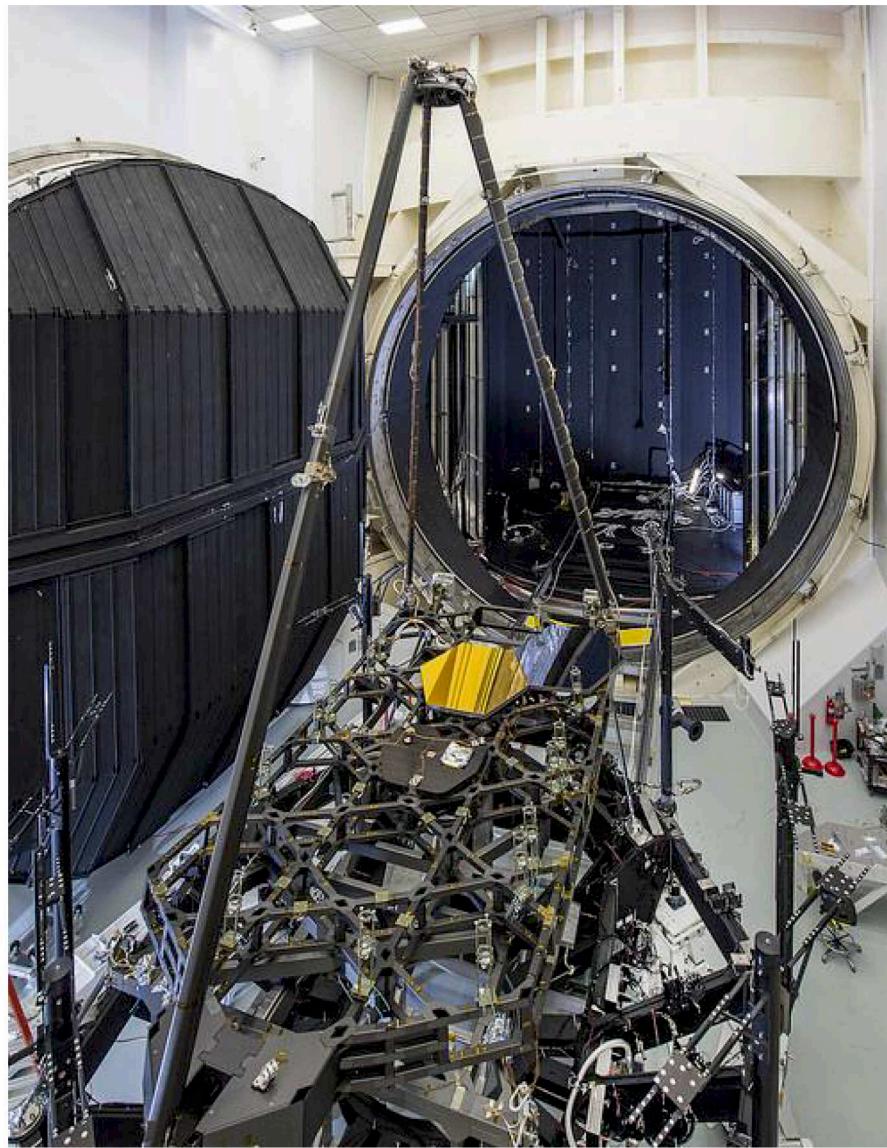


## Deep Space Edge Radiation Sink (DSERS)

Thermal modeling of payload and DSERS  
started

World's largest TV chamber OTIS: will test whole JWST in 2016–2017.

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



April 2015: Testing OTIS chamber with the JWST Engineering model.

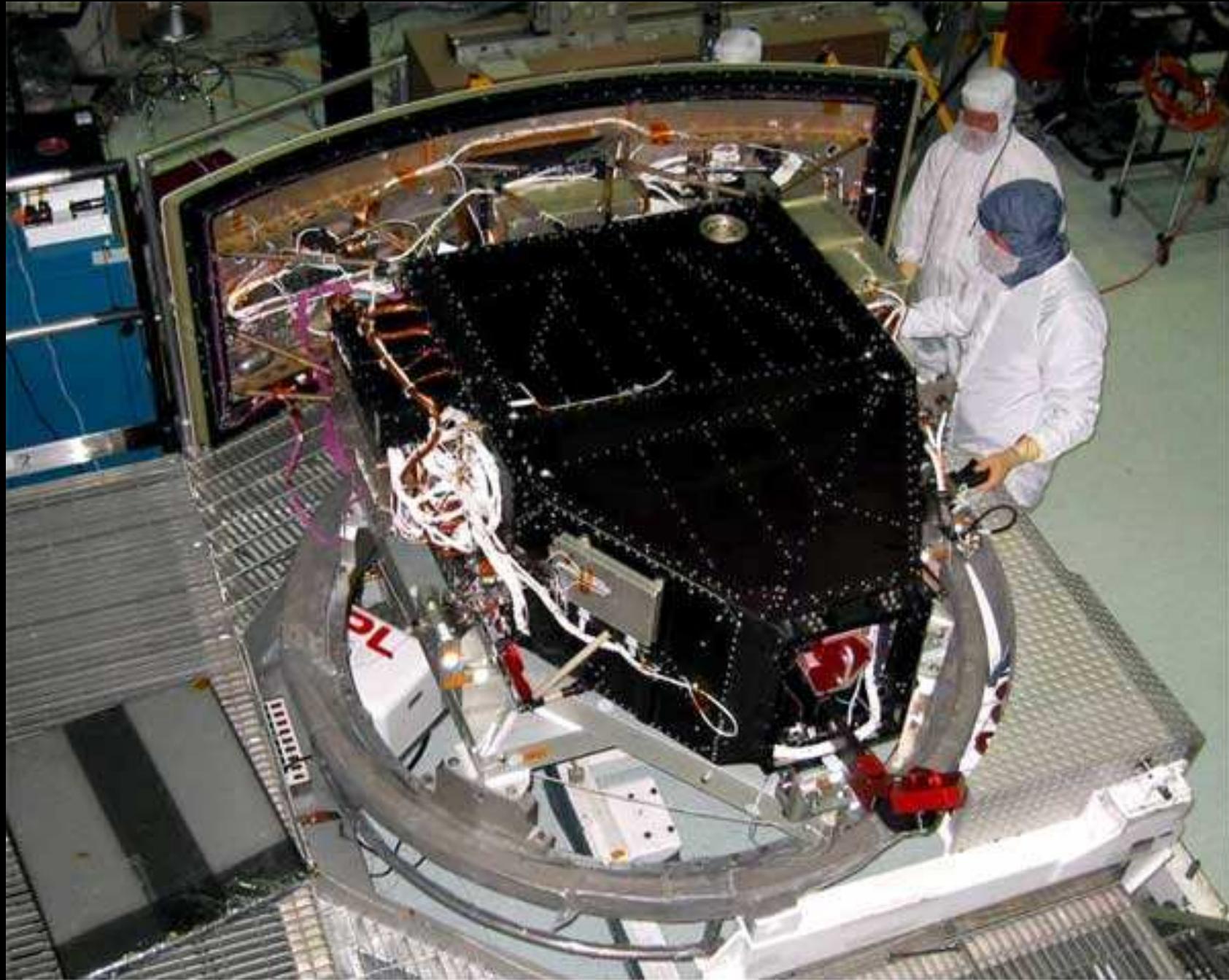
## (2) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?



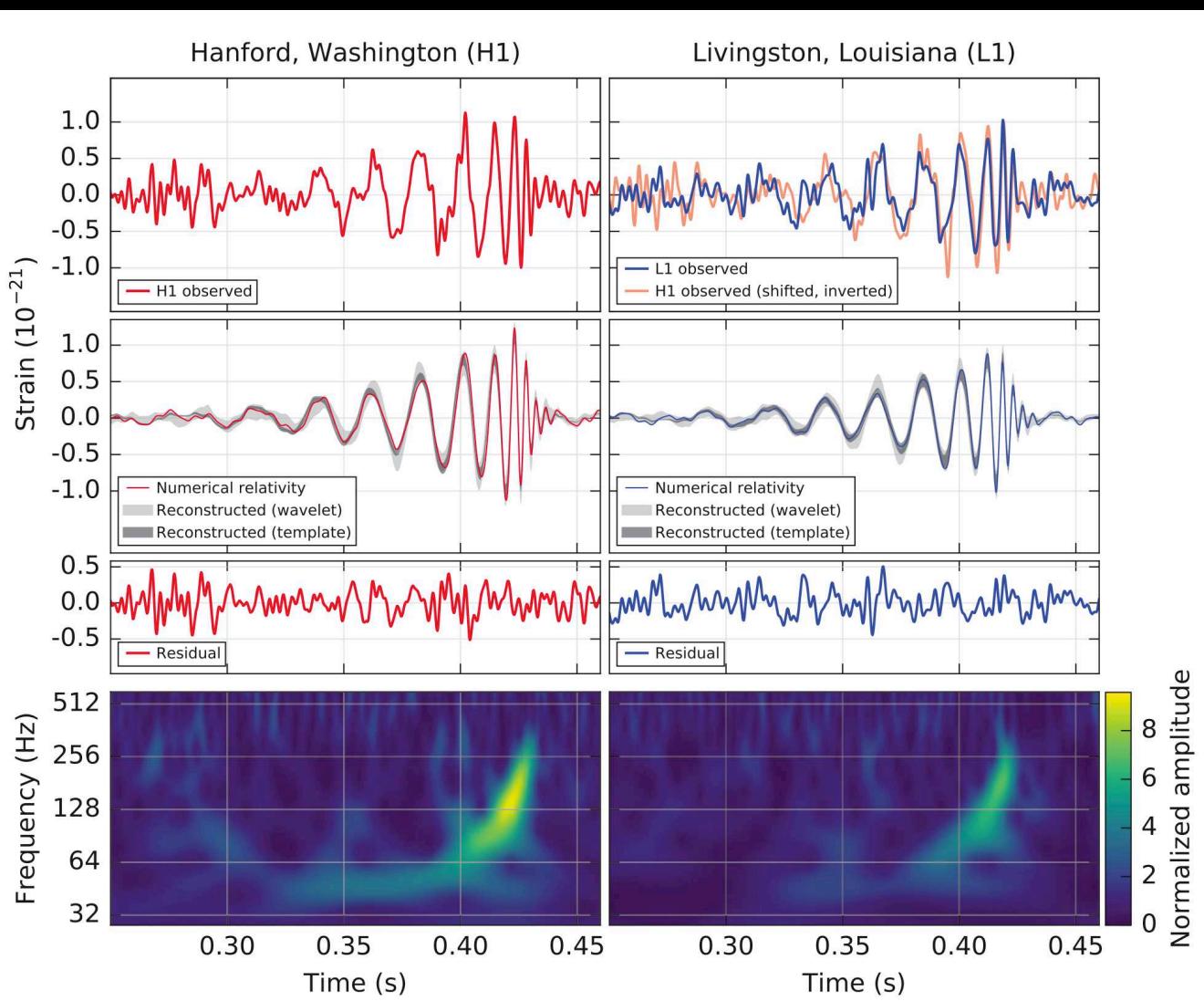
HST (WFC3 & ACS) reach 26.5-27.0 mag ( $\sim$ 100 fireflies from Moon) over 0.1 $\times$ full Moon area in 10 filters from 0.2–2  $\mu\text{m}$  wavelength.

JWST has 3 $\times$ sharper imaging to  $\sim$ 31.5 mag ( $\sim$ 1 firefly from Moon) at 1–29  $\mu\text{m}$  wavelength, tracing young and old stars + dust.

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



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



(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:



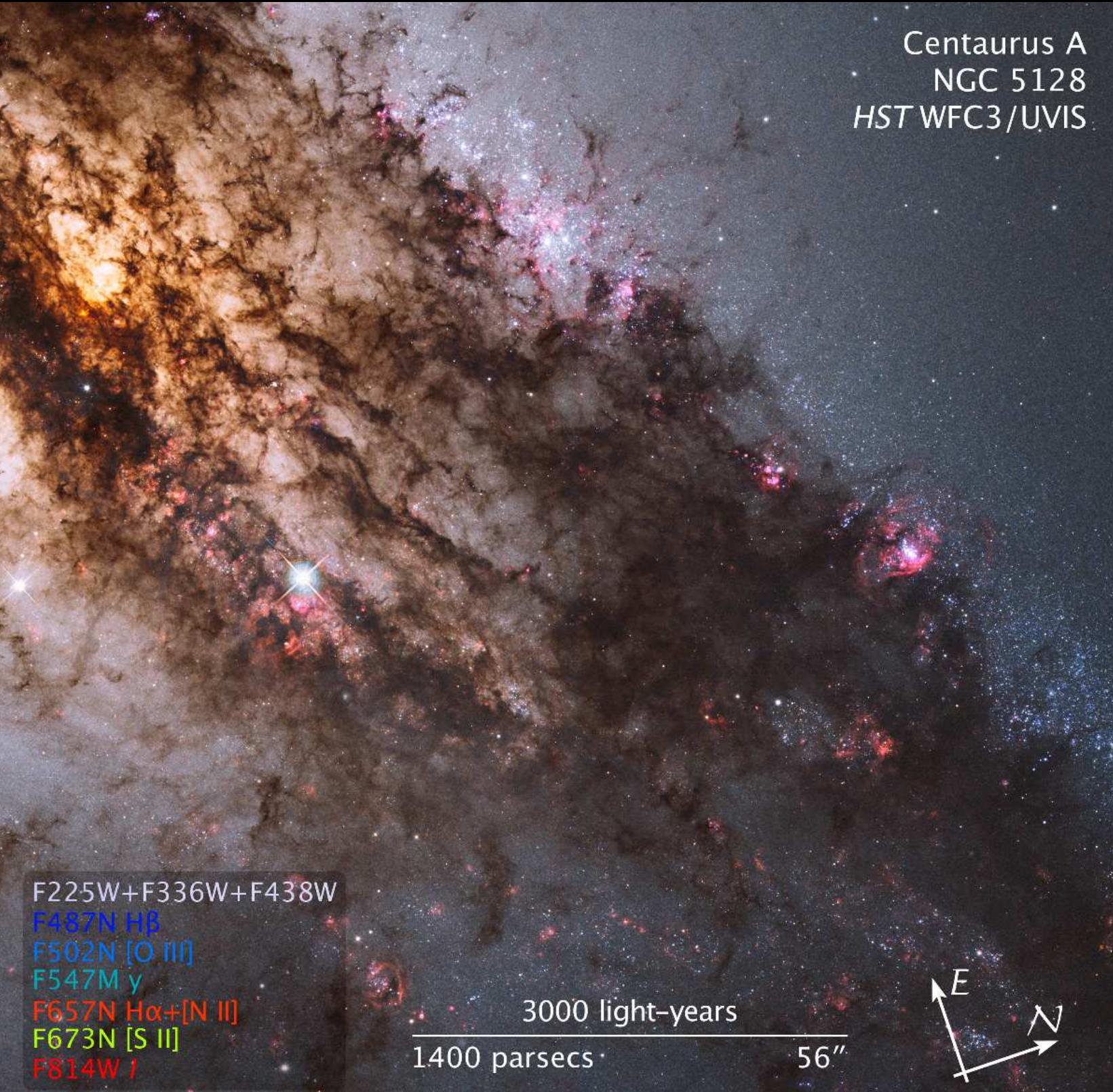
*"For God's sake, Edwards. Put the laser pointer away."*

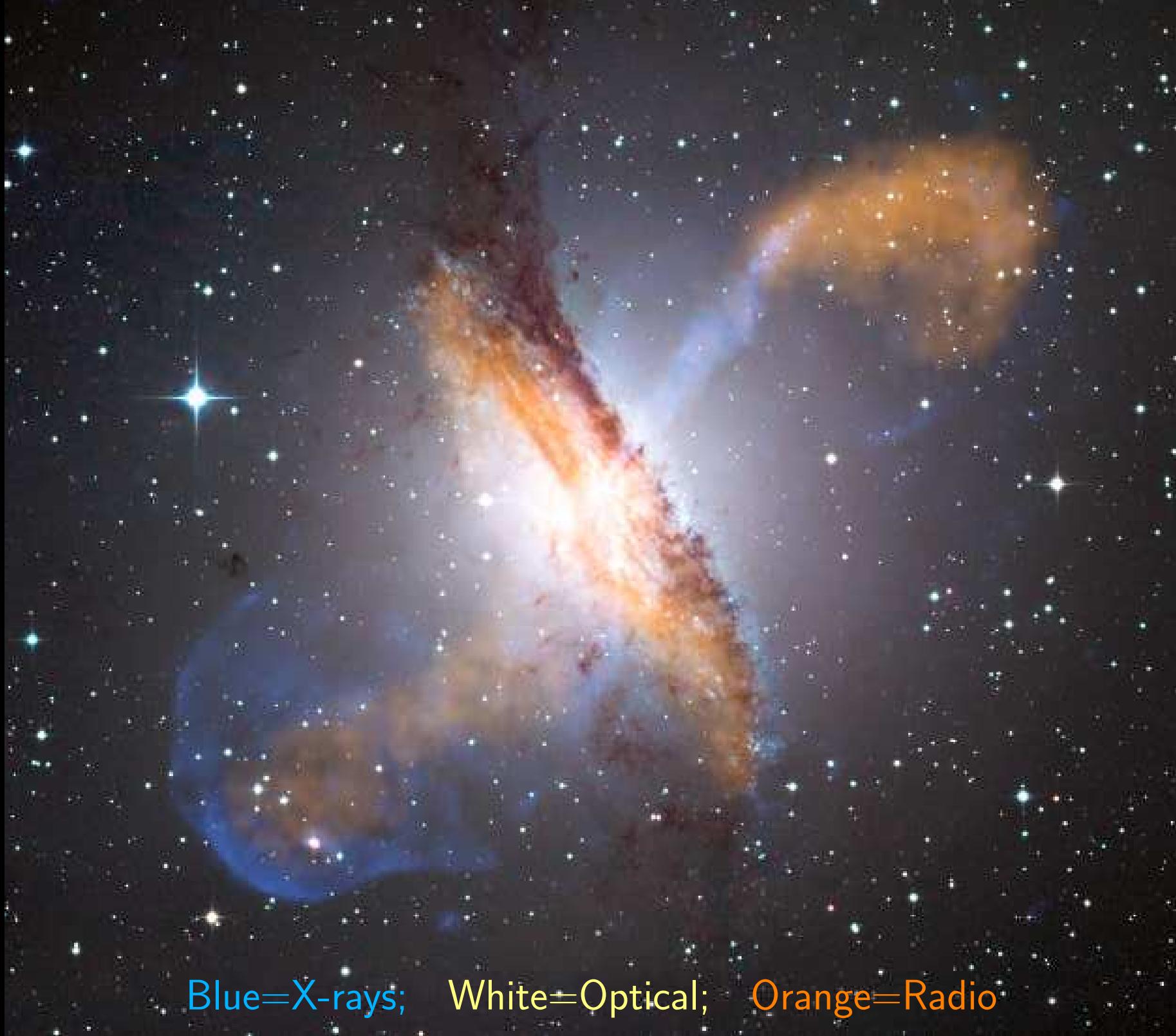
The danger of having Quasar-like devices too close to home ...

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

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

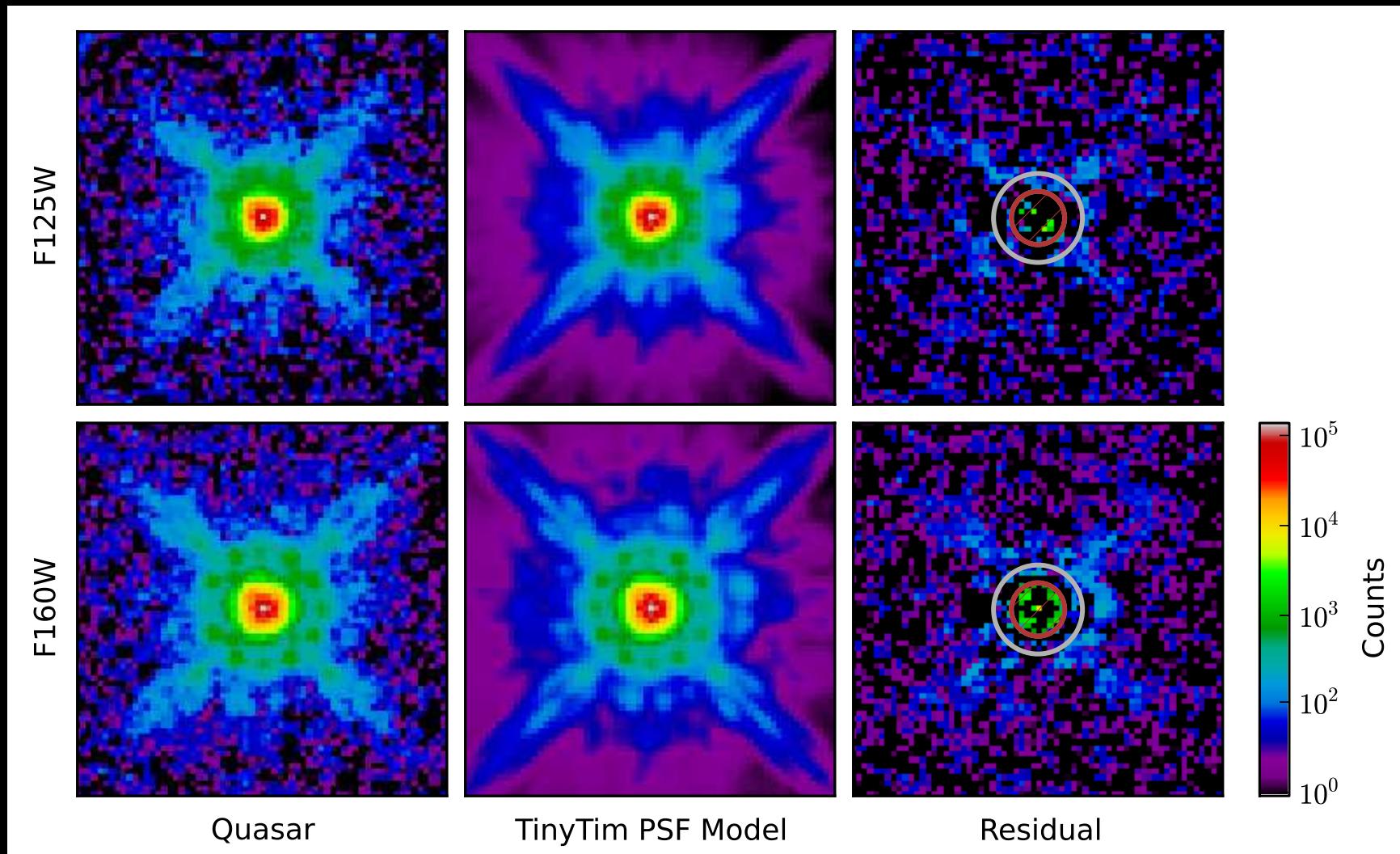
Centaurus A  
NGC 5128  
*HST WFC3/UVIS*





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

- Quasars: Centers of galaxies with feeding supermassive blackholes:

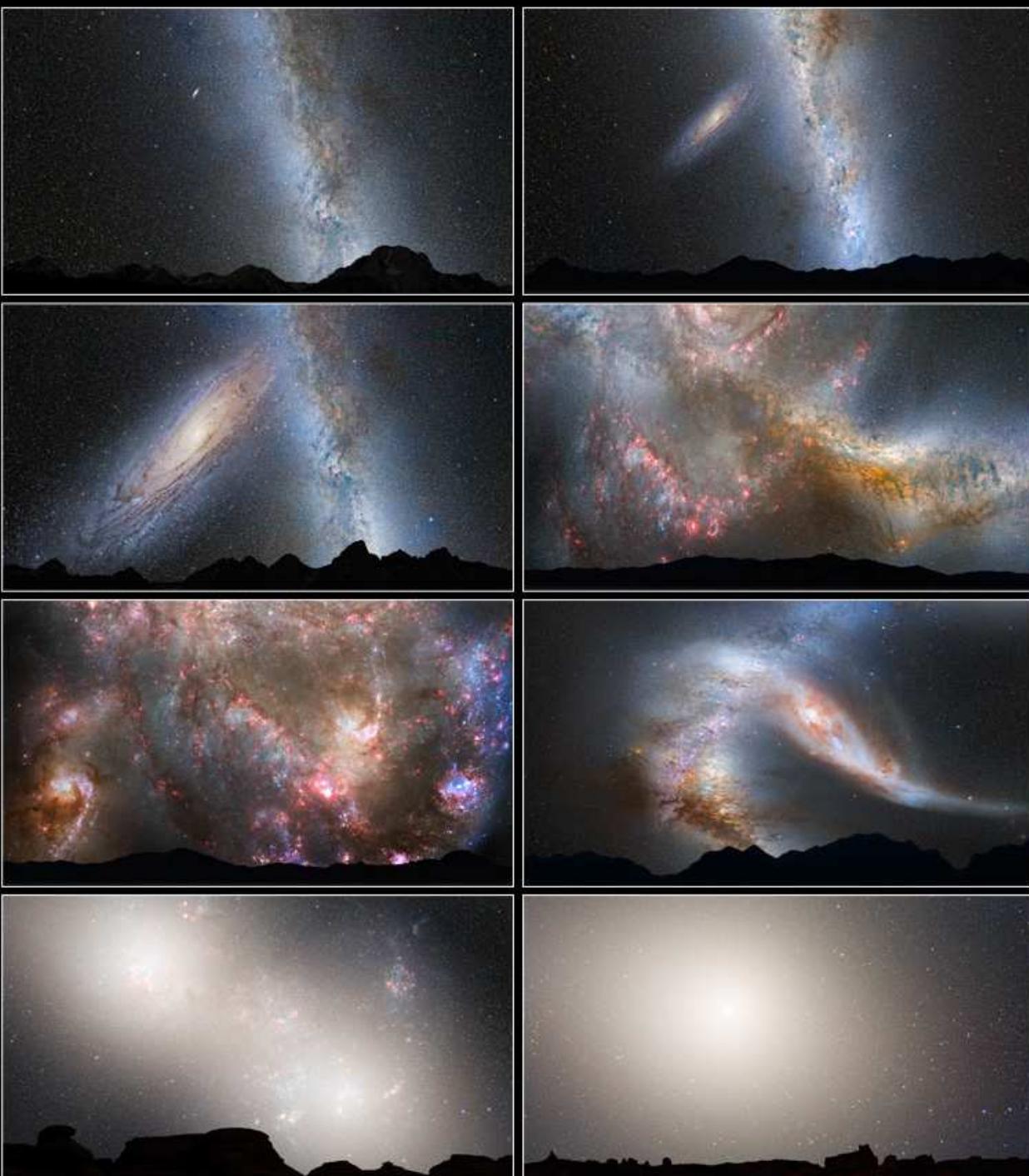


- Hubble IR-images of the most luminous Quasar known in the universe.
- Seen at redshift 6.42 (universe 7.42× smaller than today), 900 Myr old!
- Contains  $10^{14}$  solar luminosities within a region as small as Pluto's orbit!
- A feeding monster blackhole ( $>3 \times 10^9$  solar mass) 900 Myr after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

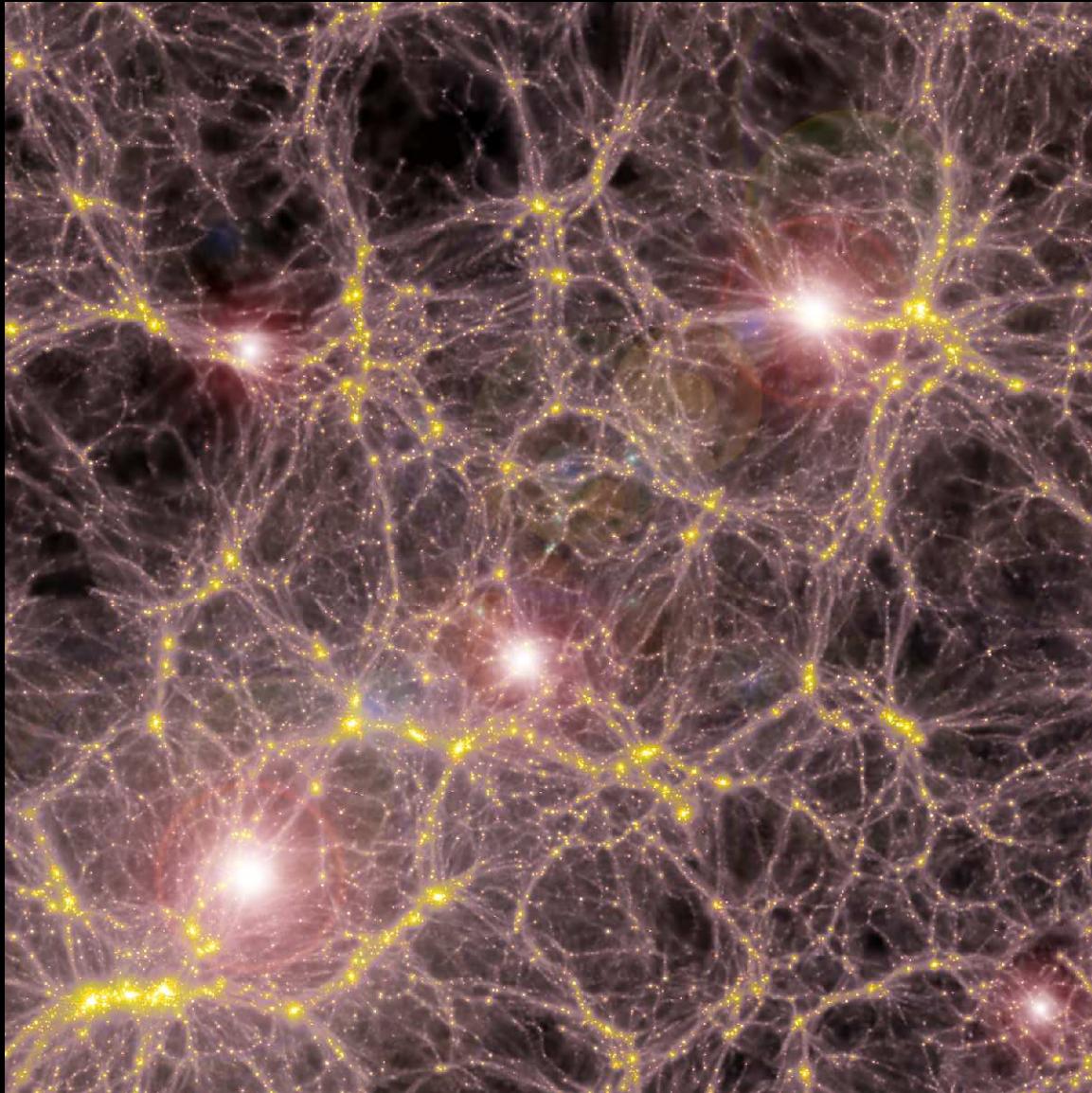
Hence, Andromeda will merge with Milky Way!

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

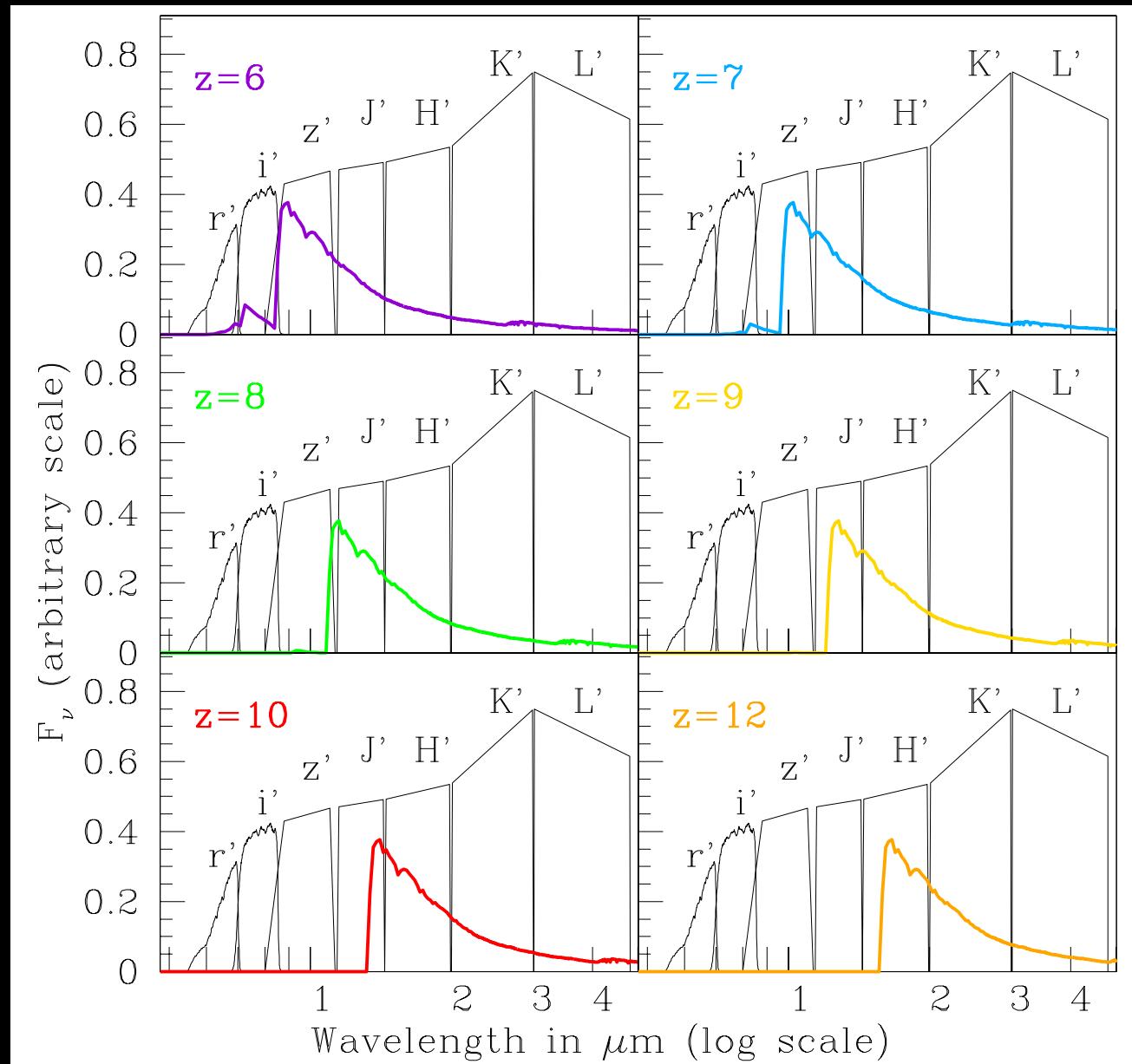
### (3) How will JWST Observe First Light and Reionization?



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

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

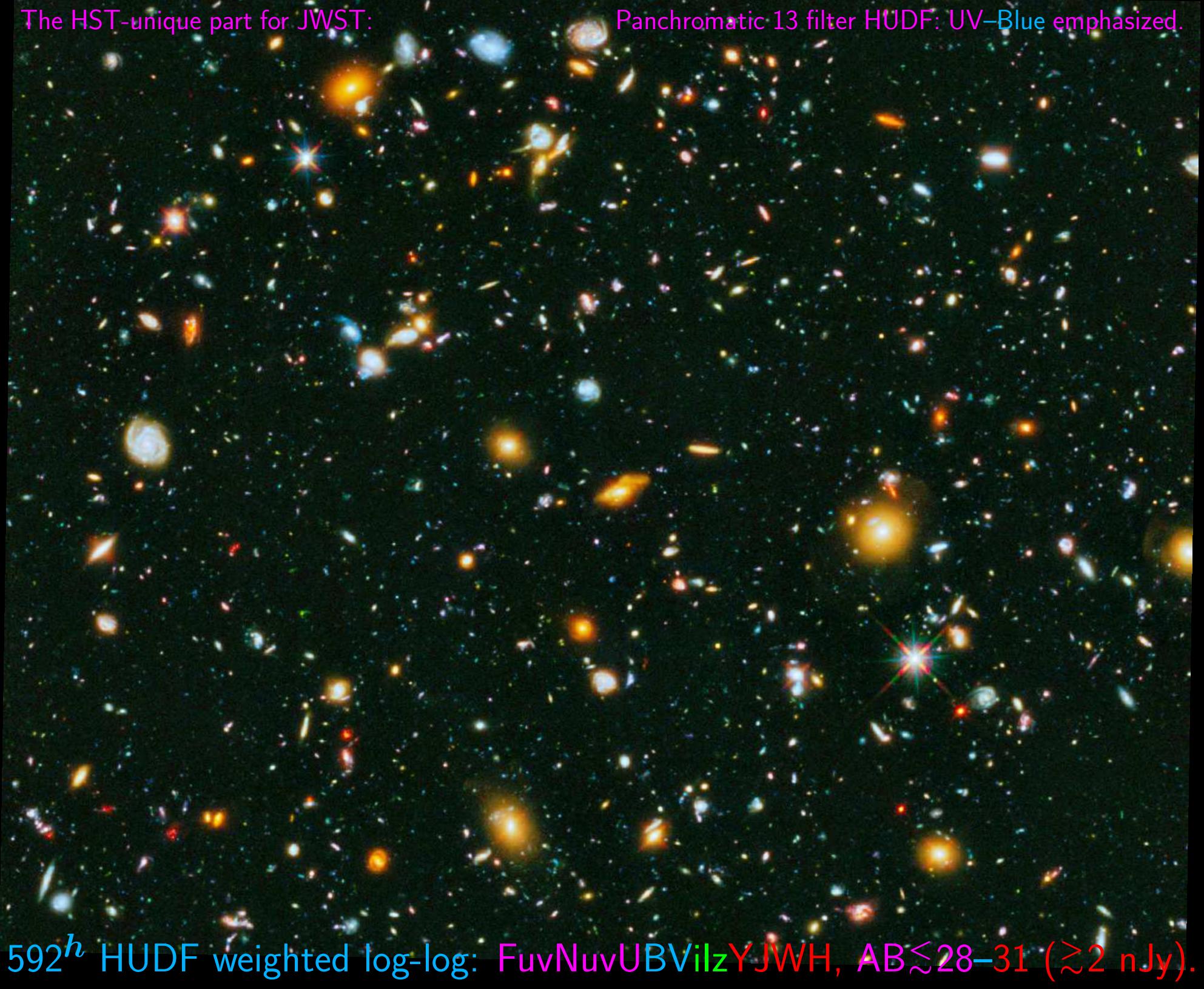
### 3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



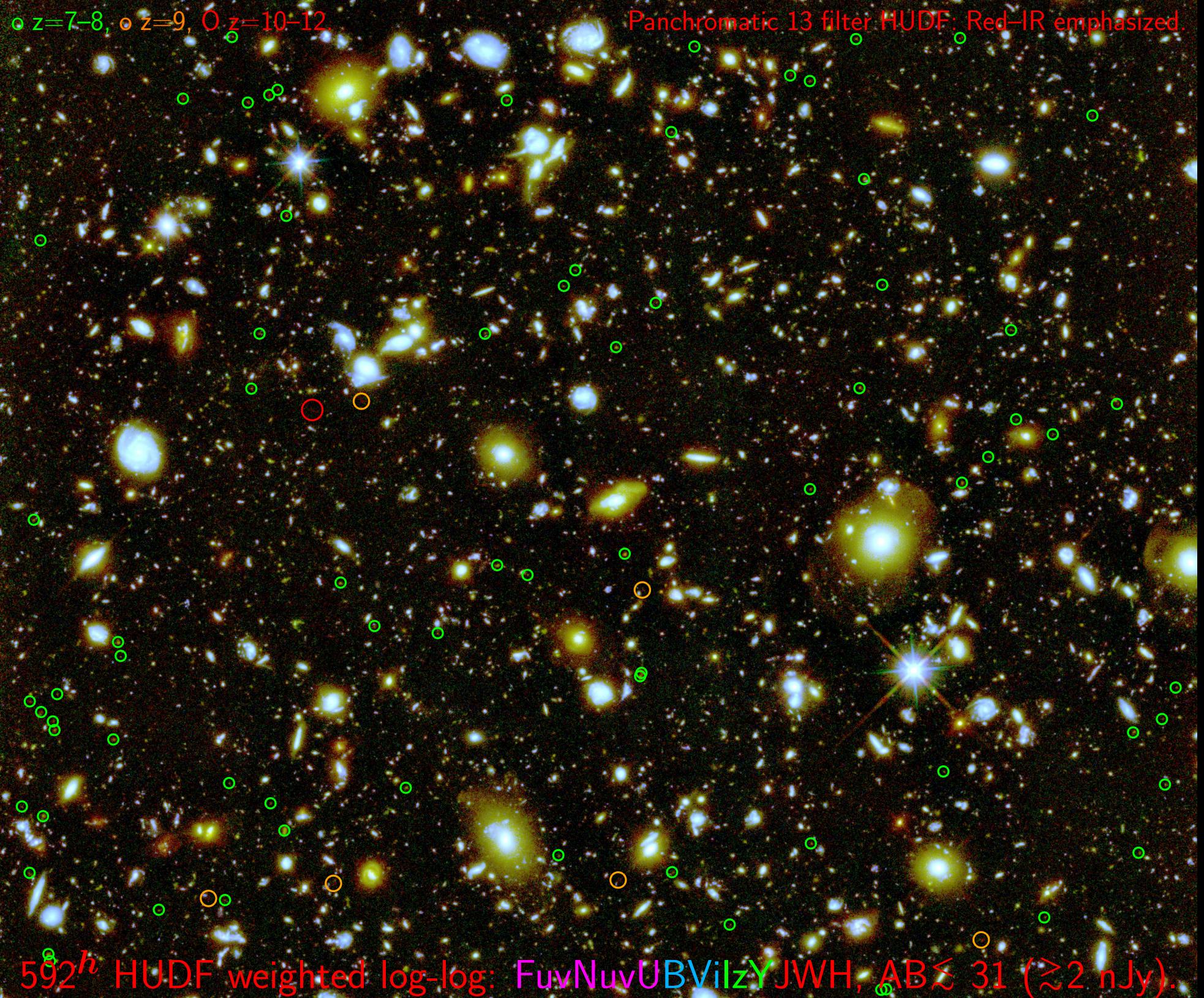
- Can't beat redshift: to see First Light, must observe near-mid IR.  
⇒ This is why JWST needs NIRCam at 0.8–5  $\mu\text{m}$  and MIRI at 5–28  $\mu\text{m}$ .

The HST-unique part for JWST:

Panchromatic 13 filter HUDF: UV–Blue emphasized.

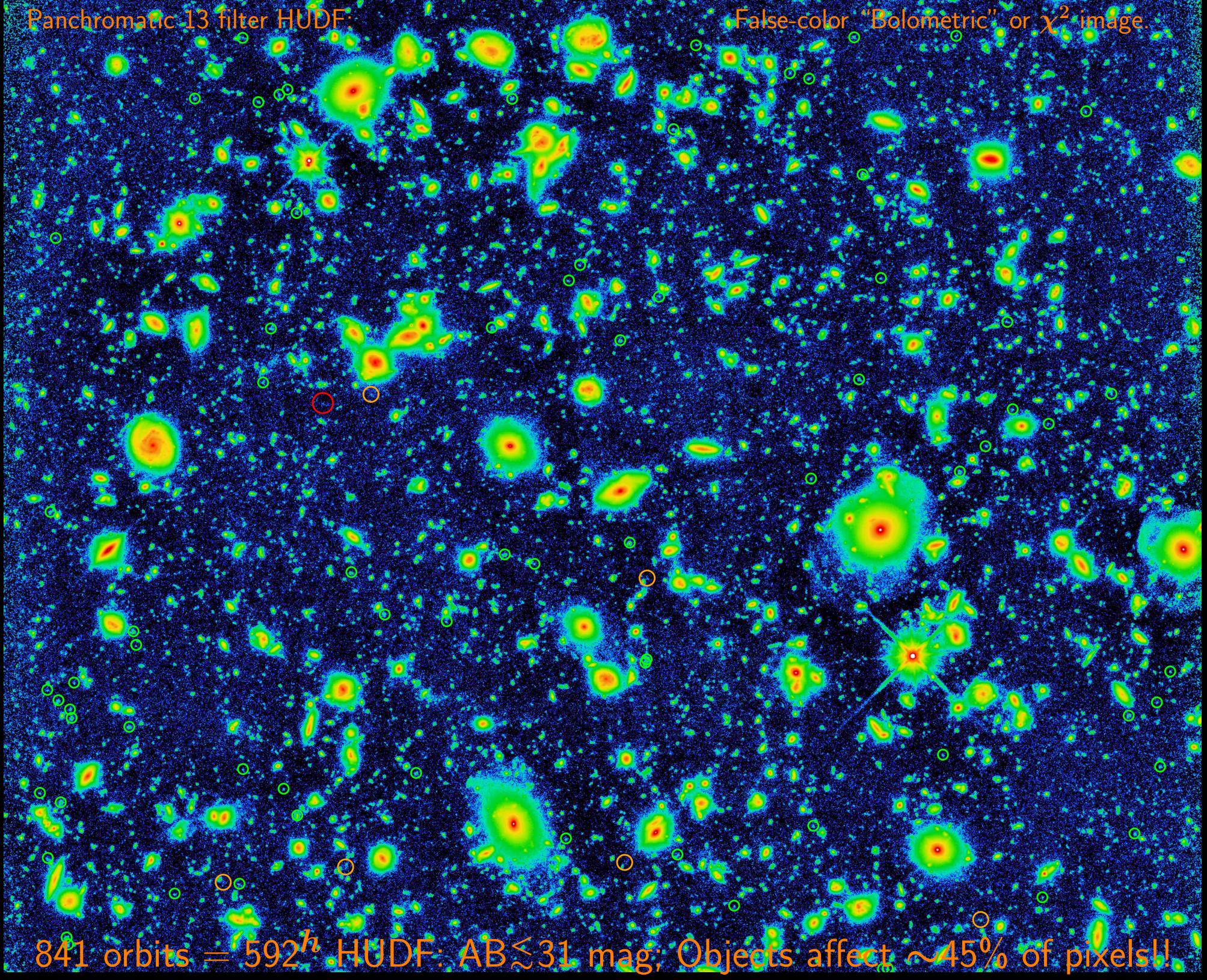


592<sup>h</sup> HUDF weighted log-log: FuvNuvUBViIzYJWH, AB $\lesssim$ 28–31 ( $\gtrsim$ 2 nJy).

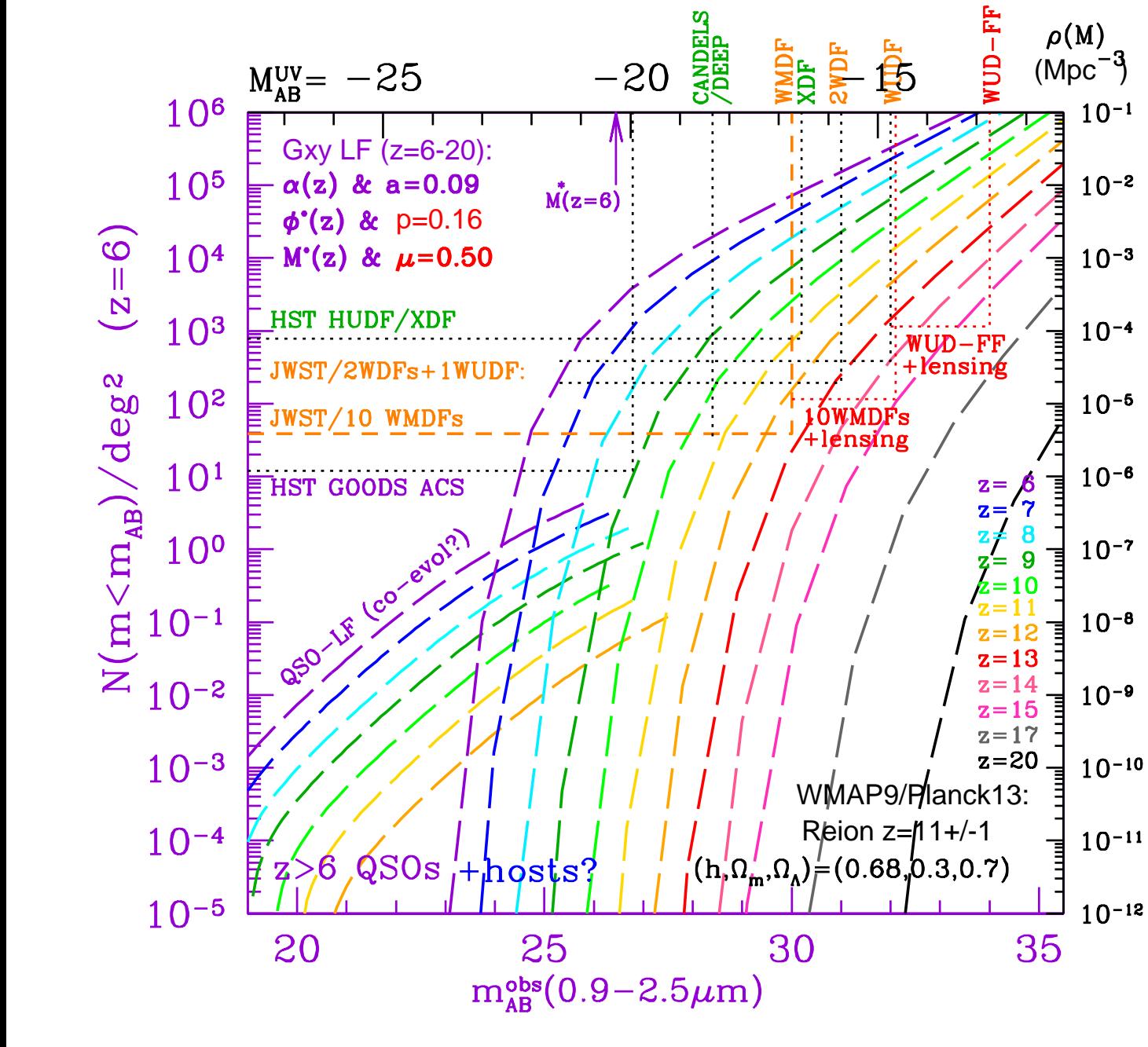


Panchromatic 13 filter HUDF

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

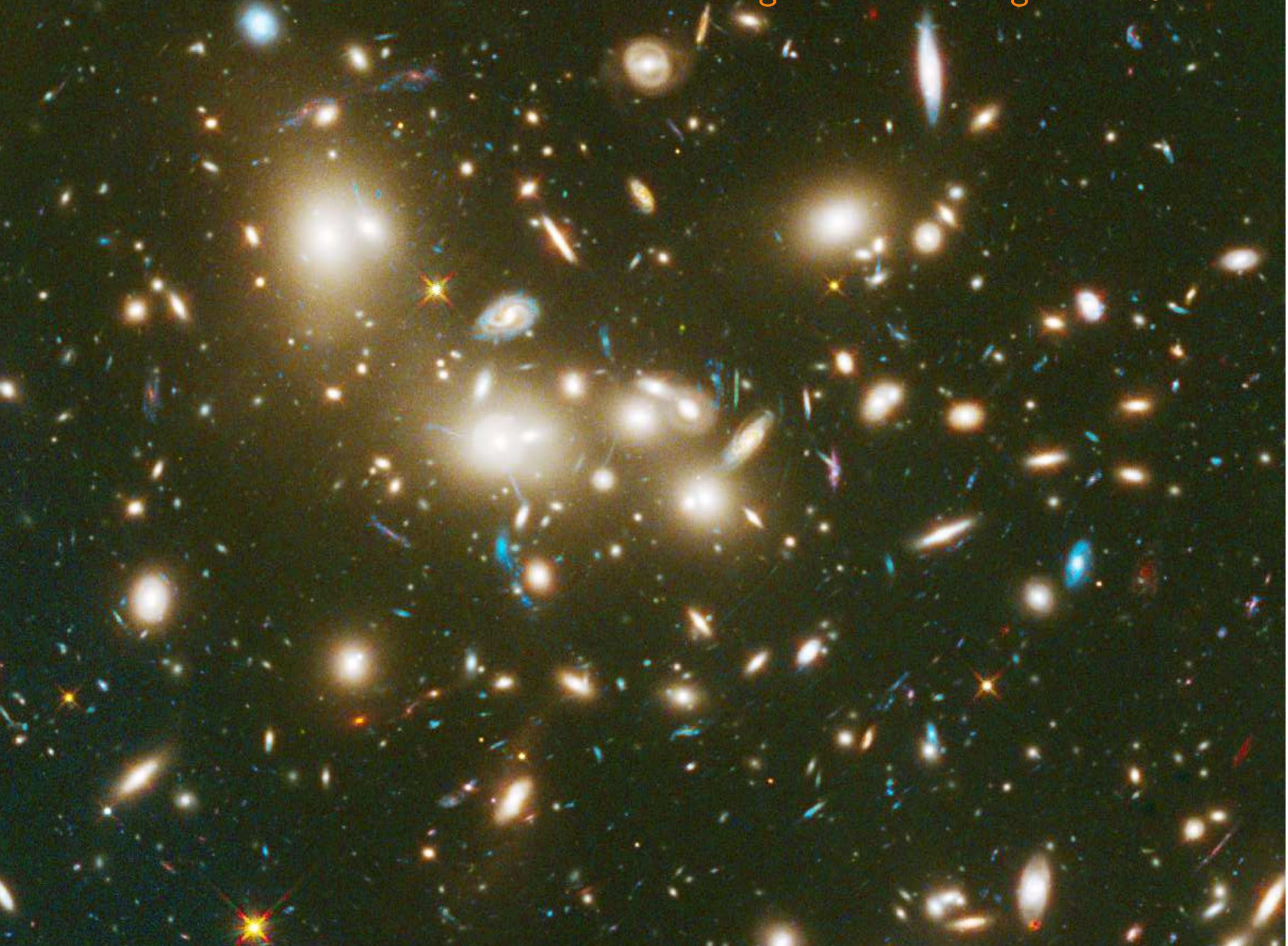


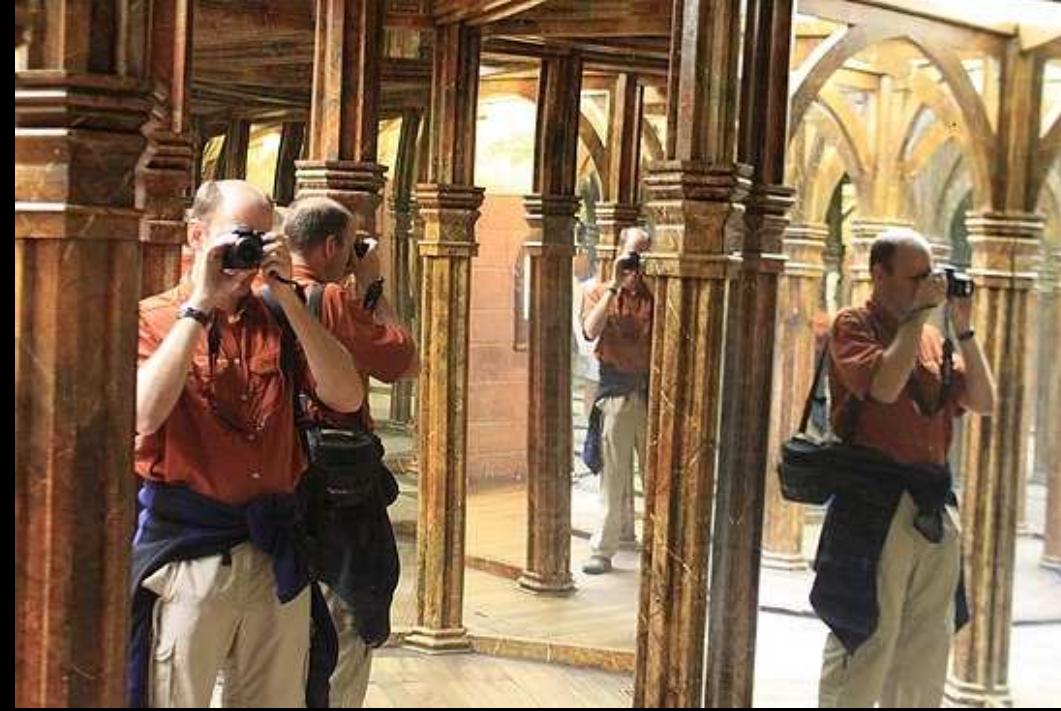
841 orbits =  $592^h$  HUDF: AB  $\lesssim$  31 mag; Objects affect  $\sim 45\%$  of pixels!!



Predicted Schechter Luminosity Function (LF) at redshifts  $6 \lesssim z \lesssim 20$ :  
 Area/Sensitivity for: Hubble UDF, Webb: 10 MDFs, 2 DFs, & 1 UDF.  
 ● JWST need to use lensing targets to see many  $z \simeq 12-15$  objects.

HST Frontier Field A2744: JWST needs lensing to see First Light at  $z \gtrsim 10-15$ .





Conclusion: JWST First Light strategy must consider three aspects:

- (1) The catastrophic drop in the LF (space density) for  $z \gtrsim 8$ .
- (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:
  - Lensing is what Einstein thought was impossible to observe.

## (5) Summary and Conclusions

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

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

- 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.

- Measure rapid growth of first supermassive blackholes & host galaxies.
- To see the most First Light, JWST must cover the best lensing clusters!
- Must *routinely* observe what Einstein thought impossible.

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

- IR sequel to HST after 2018: Training the next generation researchers.
- Your JWST proposals are due  $\lesssim$ 1.8 years from today!

# SPARE CHARTS

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- 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](#)).

# 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)



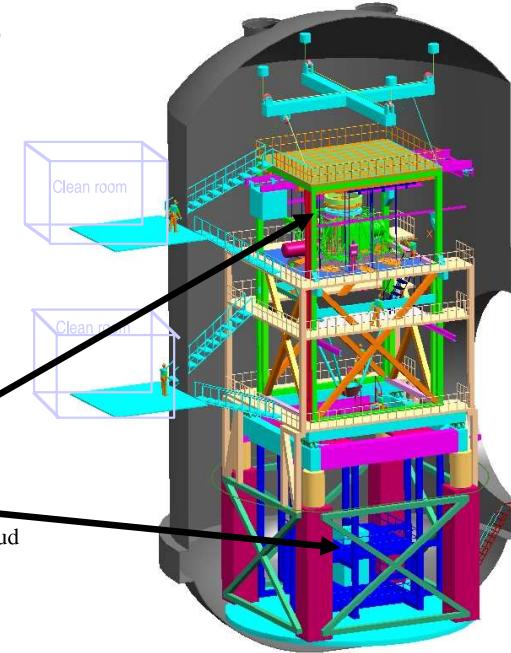
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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)

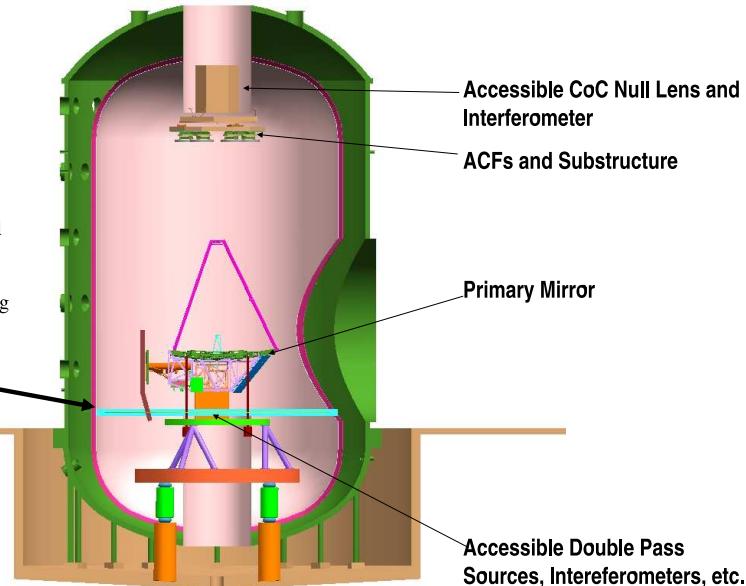


No Metrology Tower and Associated Cooling H/W. External Metrology

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.

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



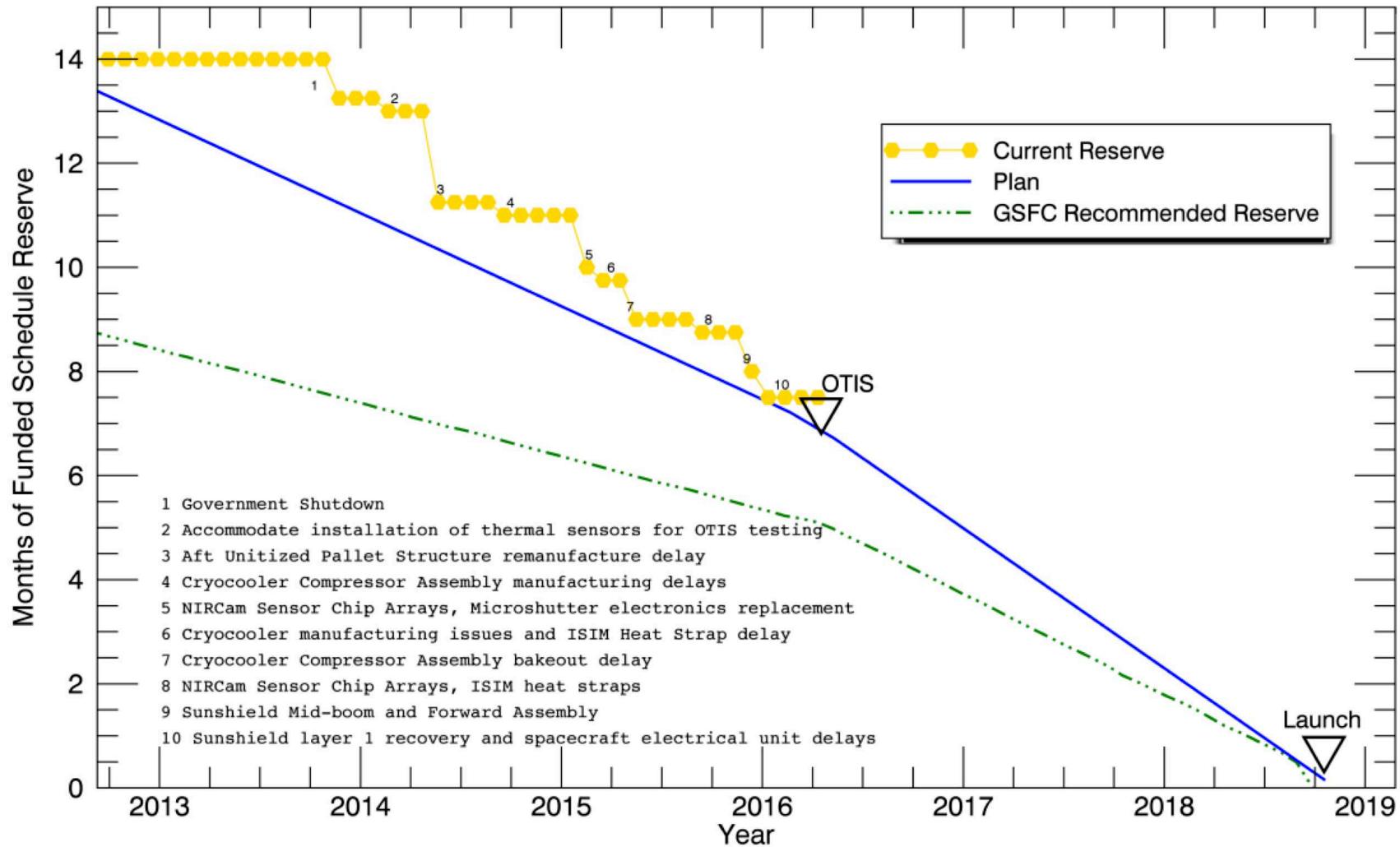
Drawing care of ITT

Page 6

JWST underwent several significant replans and risk-reduction schemes:

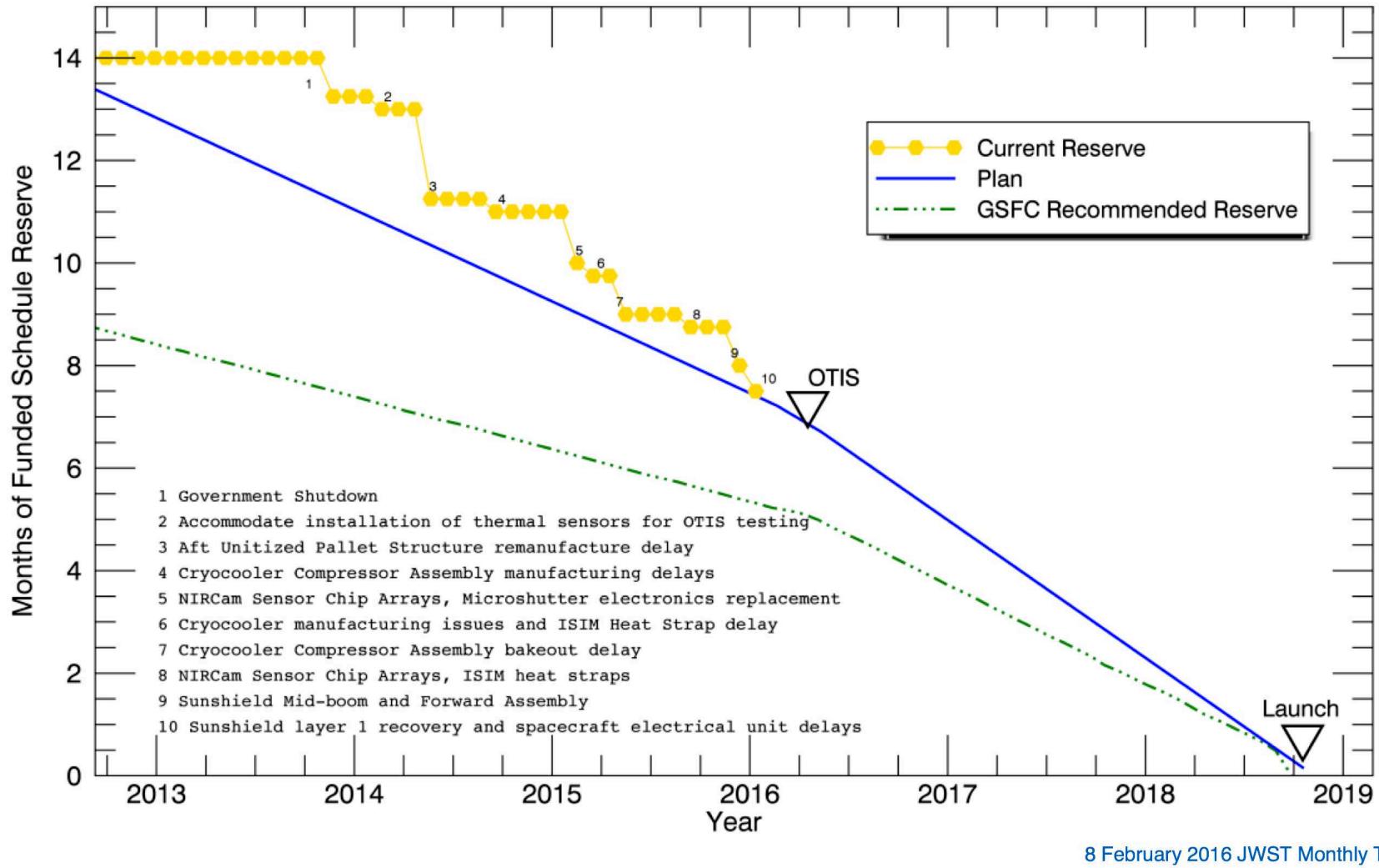
- ≈2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6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

# 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 2016 JWST HQ Milestones

Month	Milestone	FY2015 Deferral	Comment
Oct-15	1 Start Integrated Science Instrument Module (ISIM) cryovacuum test #3 2 Deliver update for launch and activation sequence of events for JWST commissioning		• Completed 10/27/15 <u>Completed 10/29/15</u>
Nov-15	3 Deliver the Observatory Operations Handbook Vol 1&2 updates 4 Deliver new build of the proposal planning software for Telescope plus ISIM (OTIS) testing		<u>Completed 10/30/15</u> <u>Completed 10/30/15</u>
Dec-15	5 Complete second test of Pathfinder Telescope equipment at the JSC Chamber A 6 Complete Solar Array panel #2 cell installation 7 Complete Sunshield Mid-Boom Assembly #1 functional test 8 Complete Delivery of Reaction Wheel Assemblies to Observatory Integration and Test (I&T) 9 Deliver Data Management Subsystem build for basic data search and distribution functionality		<u>Completed 10/31/15</u> Completed 12/24/15 Delayed to <u>May</u> for reassembly of mid-boom #1 Two of 3 wheels delivered in December, 1 in <u>June</u> , being rebuilt, no schedule impact <u>Completed 11/30/15</u>
Jan-16	10 Deliver flight Aft Optics System to Telescope I&T 11 Complete final checkout of new GSFC vibration shaker table 12 Sunshield Flight Layer #4 shipped to Northrop-Grumman 13 Sunshield Forward Cover Assembly shipped to Northrop-Grumman 14 Complete Flight Operations Subsystem System Design Review #2 15 Complete Mission Operations Center construction at STScI		<u>Completed 12/14/15</u> Horizontal shaker table accepted 3/3/2016, Vertical shaker acceptance delayed to May <u>Completed 12/3/15</u> Delayed till <u>June</u> . Nexolve revised schedule to implement NGAS design changes. No anticipated schedule impact <u>Completed 12/17/15</u> <u>Completed 12/29/15</u>
Feb-16	16 Deliver Aft Deployable Instrument Radiator to Observatory I&T 17 Deliver Command & Telemetry computer to Observatory I&T 18 Deliver Secondary Mirror Support Structure verification report to GSFC 19 Complete deliveries of Spacecraft wire harnesses 20 Deliver spare Cryocooler Compressor Assembly to JPL		<u>Completed 2/15/16</u> <u>Completed 4/11/16</u> <u>Completed 1/28/16</u> <u>Completed 1/22/16</u> • Delayed to <u>May 2016</u> , no schedule impact
Mar-16	21 Start Spacecraft Panel Integration 22 Complete Sunshield Mid-Boom Assembly #2 functional test 23 Complete cryocooler thermal performance acceptance testing		<u>Completed 10/26/15</u> Forecasting <u>July</u> completion date due to latch and detent pin redesign and tubesegment rebuild <u>Completed 3/5/16</u>

Blue font(underline) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late. "\*" denotes 2015 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	46	24	19	10*	0	0

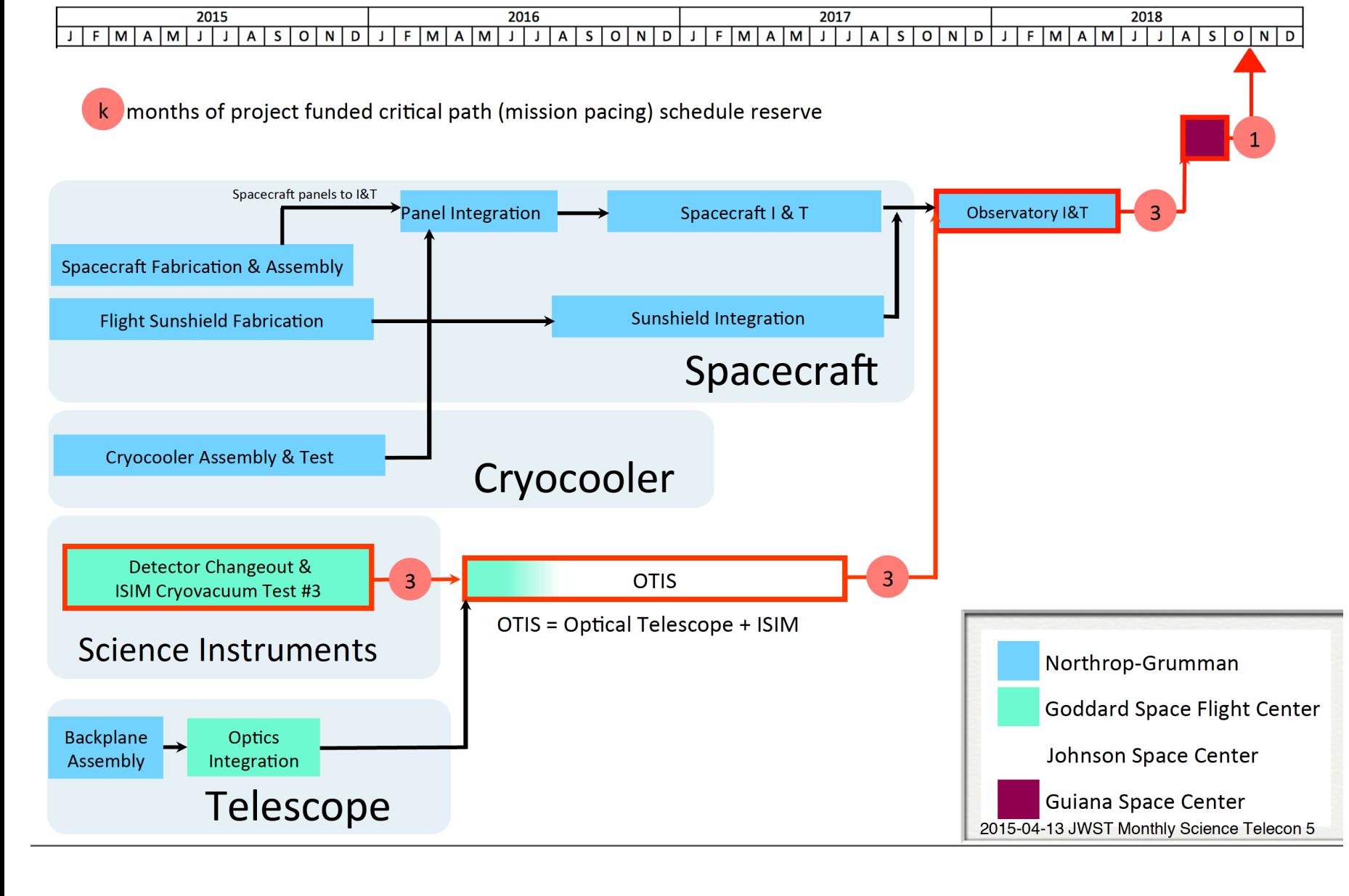
\*Late milestones have been or are forecast to complete within the year. Deferred milestones are not included in the number-completed-late tally.

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

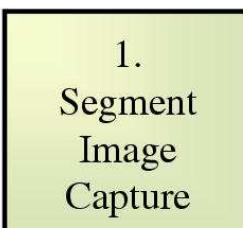
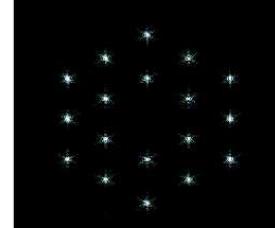
FY14: 8 milestones late by 1 month due to Oct 13 Government shutdown.

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

# Simplified Schedule

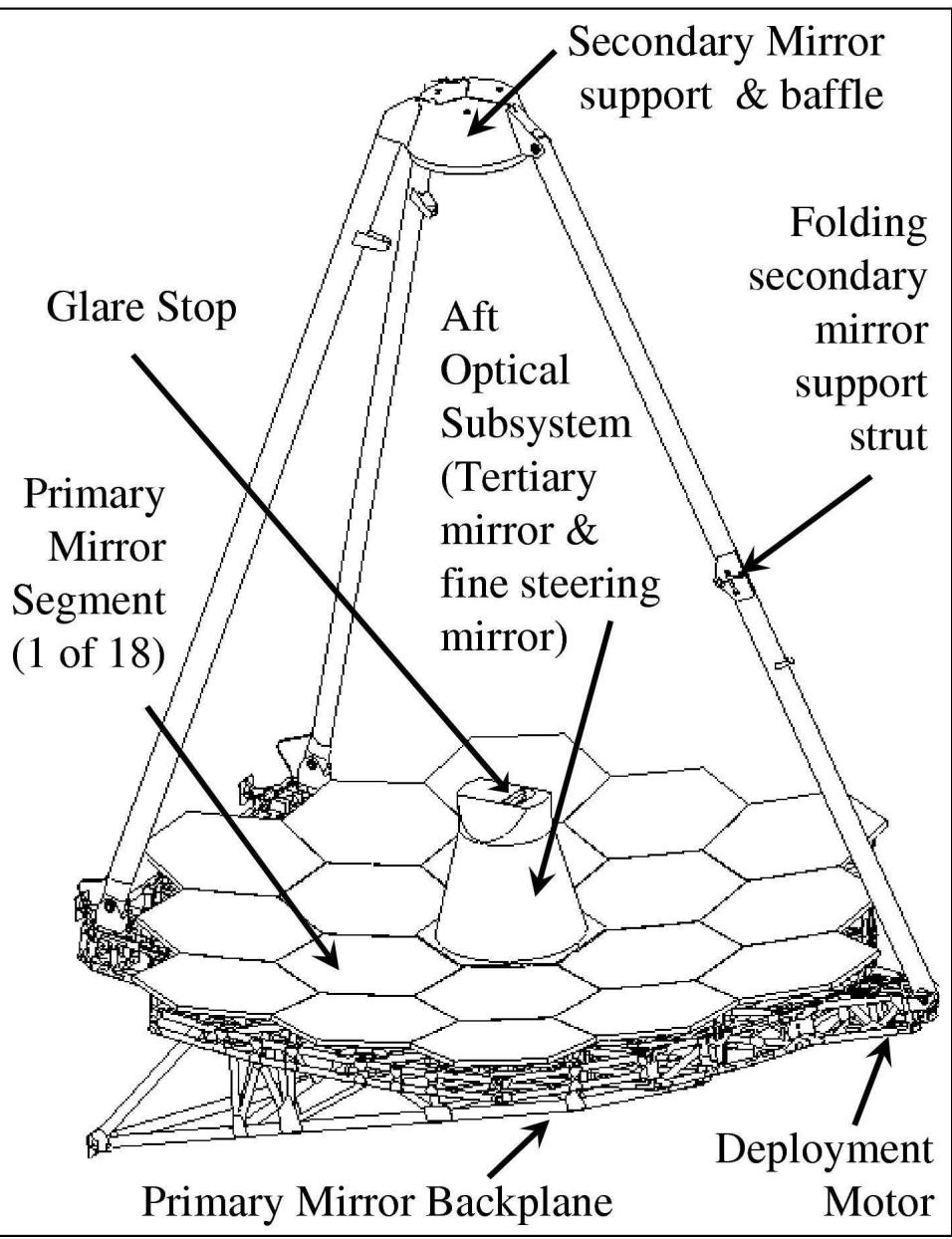


Path forward to Launch (in Oct. 2018): 10 months schedule reserve.  
Instruments+detectors & Optical Telescope Element remain on critical path.

<i>First light NIRCam</i>	<i>After Step 1</i>	<i>Initial Capture</i>	<i>Final Condition</i>
		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 $\mu\text{m}$ , < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
<b>2. Coarse Alignment</b> Secondary mirror aligned Primary RoC adjusted		Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	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)

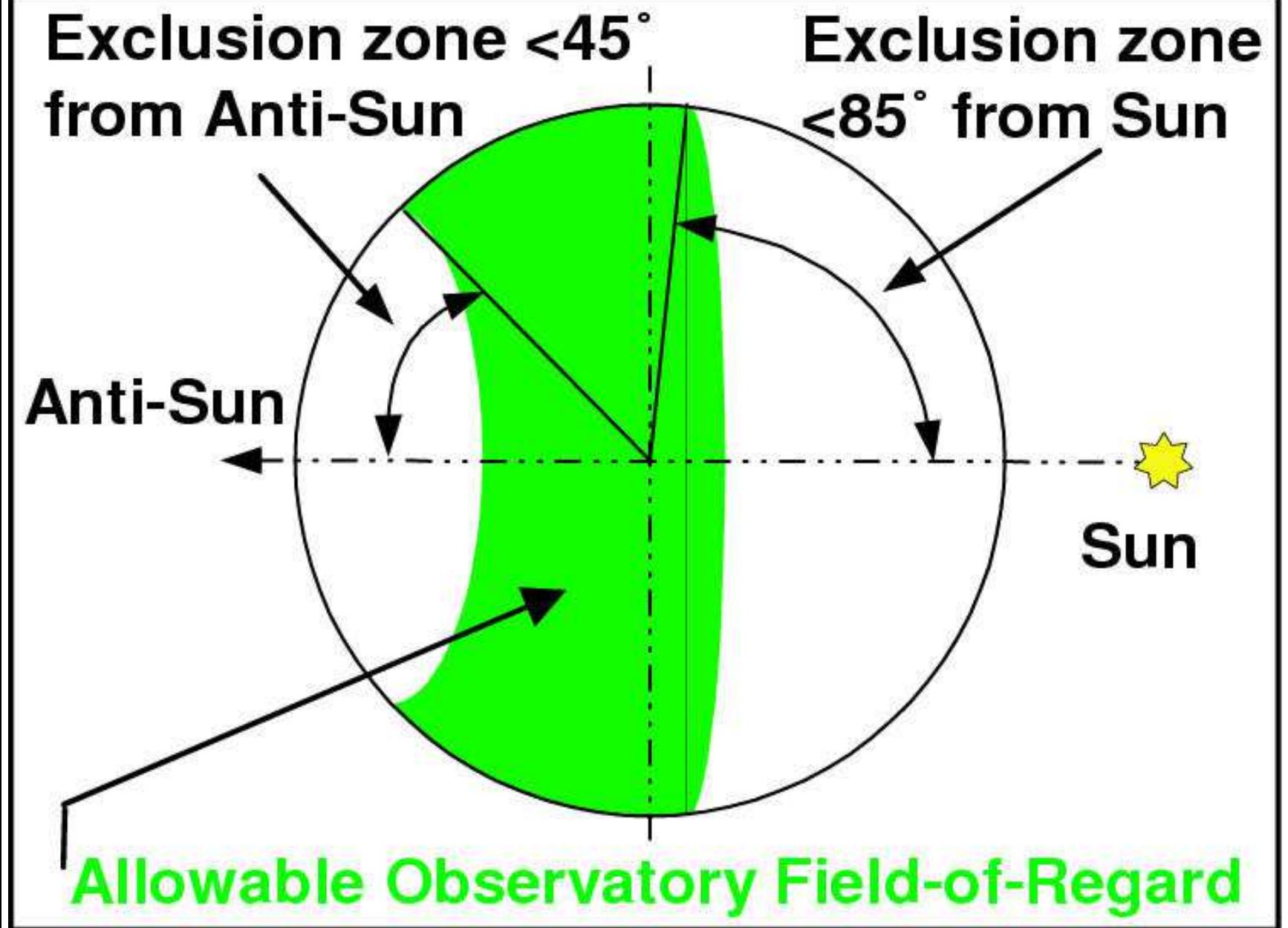
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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 2016–2017.

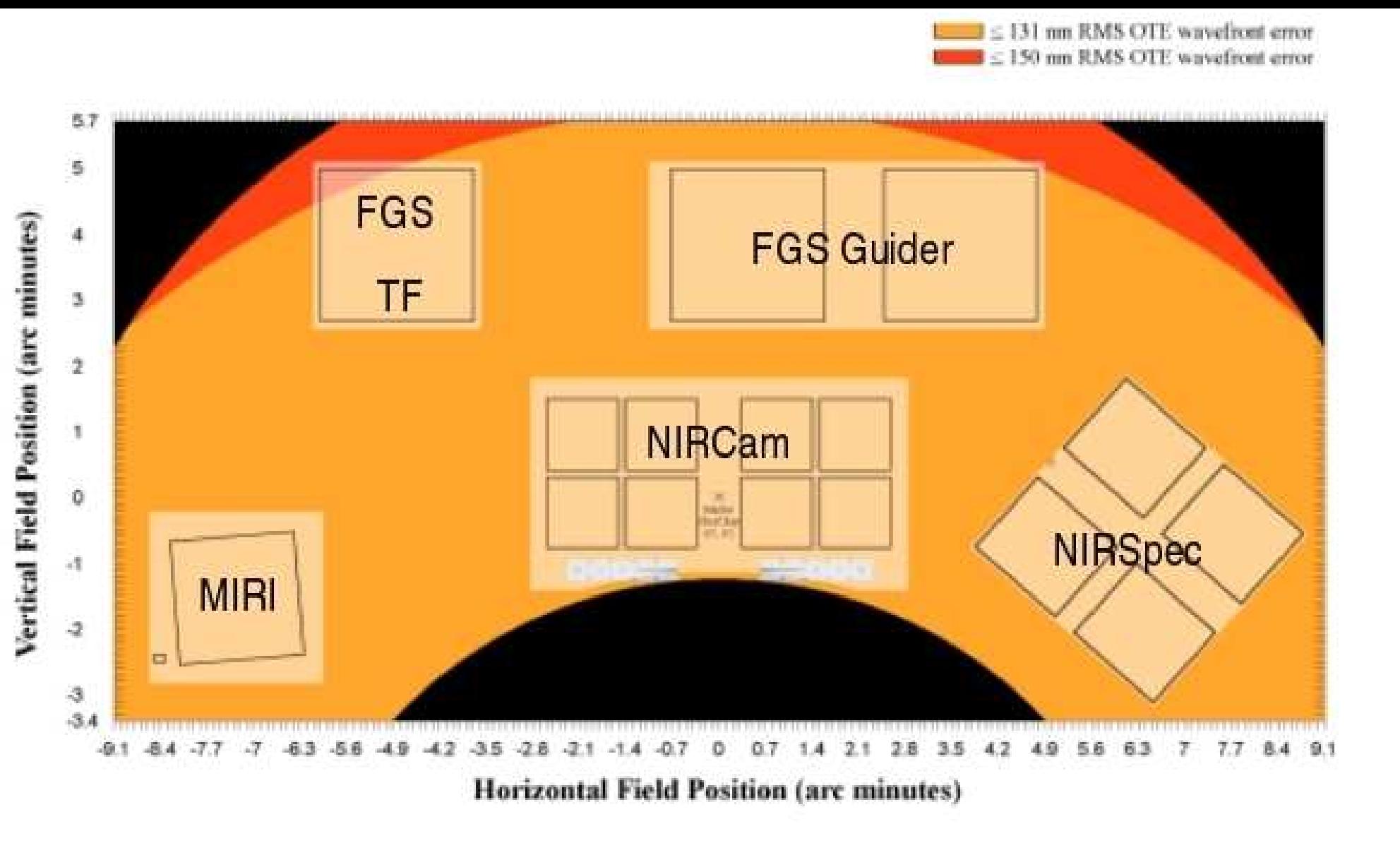
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0  $\mu\text{m}$  images.



JWST can observe North/South Ecliptic pole targets continuously:

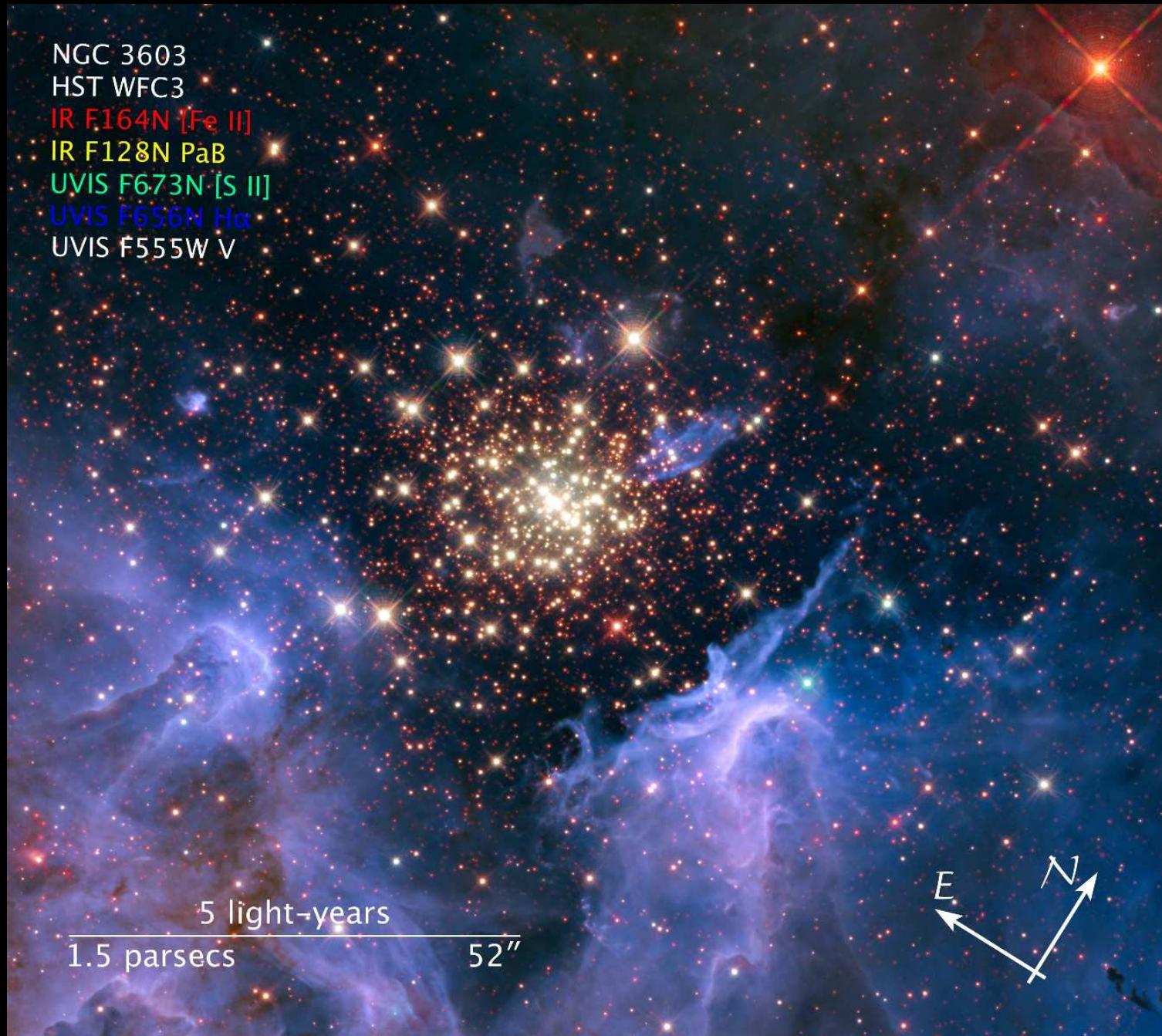
- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- They will rely a lot on Rockwell Collins' (Heidelberg) reaction wheels.

- (3c) What instruments will JWST have?



- All JWST instruments can in principle be used in parallel observing mode:
- As of 2016, now also implemented for parallel *science* observations.

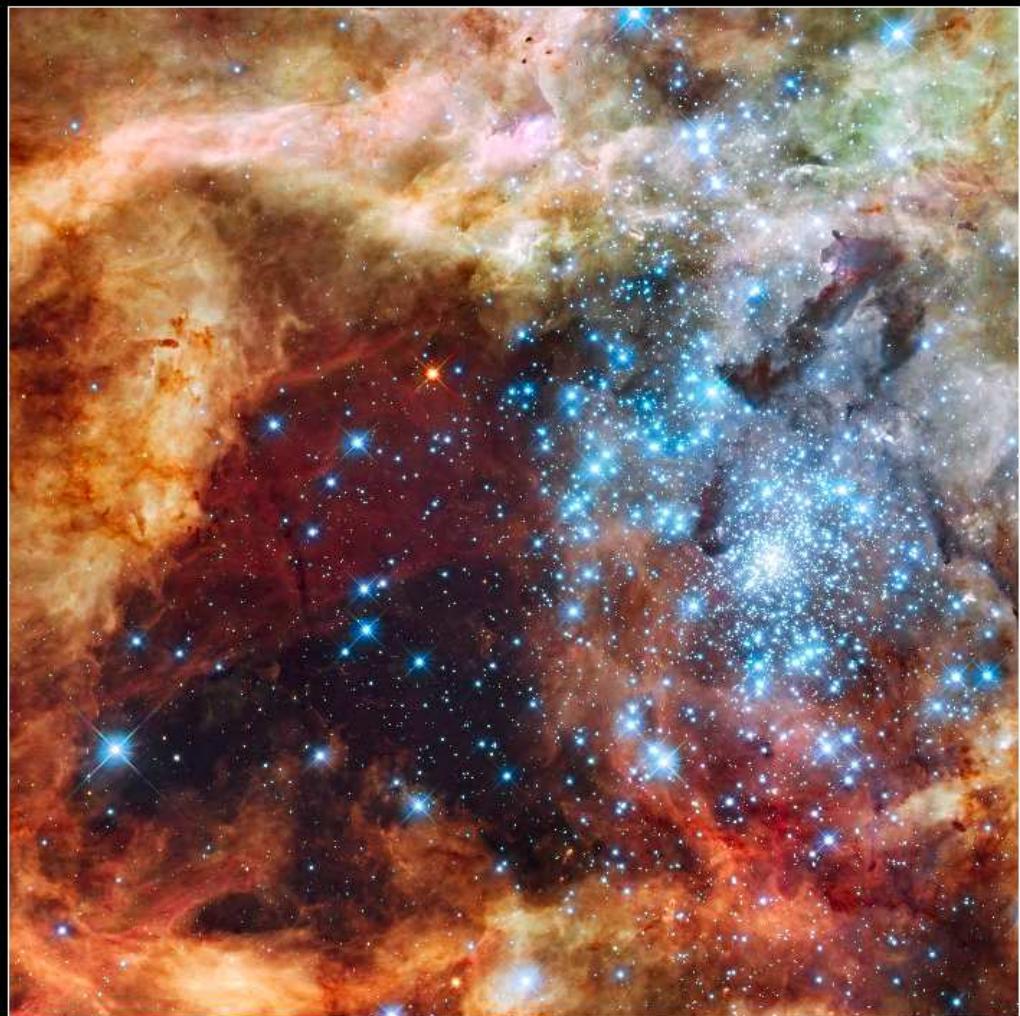
## (6) How can JWST measure Star-Formation and Earth-like exoplanets?



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

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

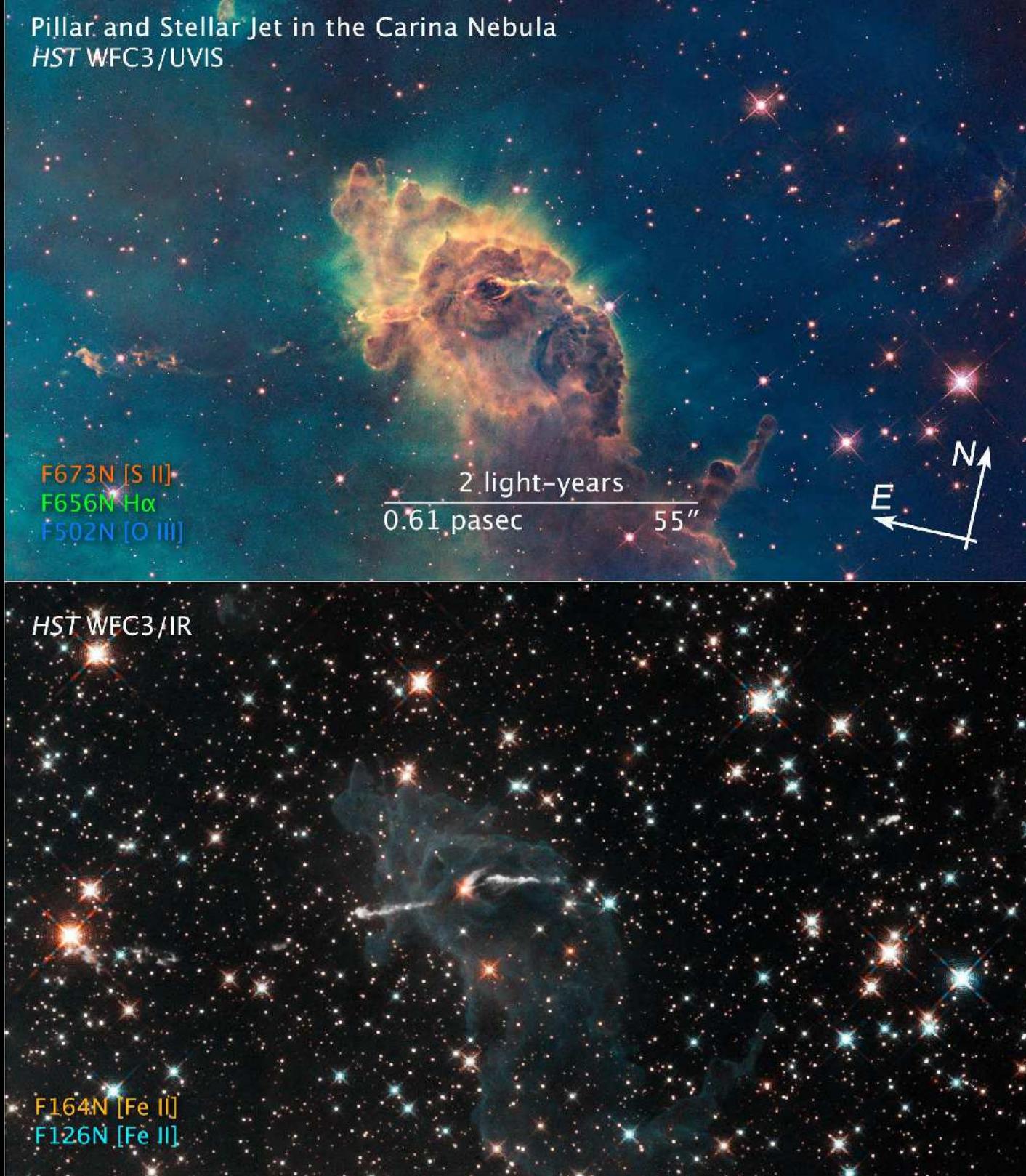
STScI-PRC09-32b

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

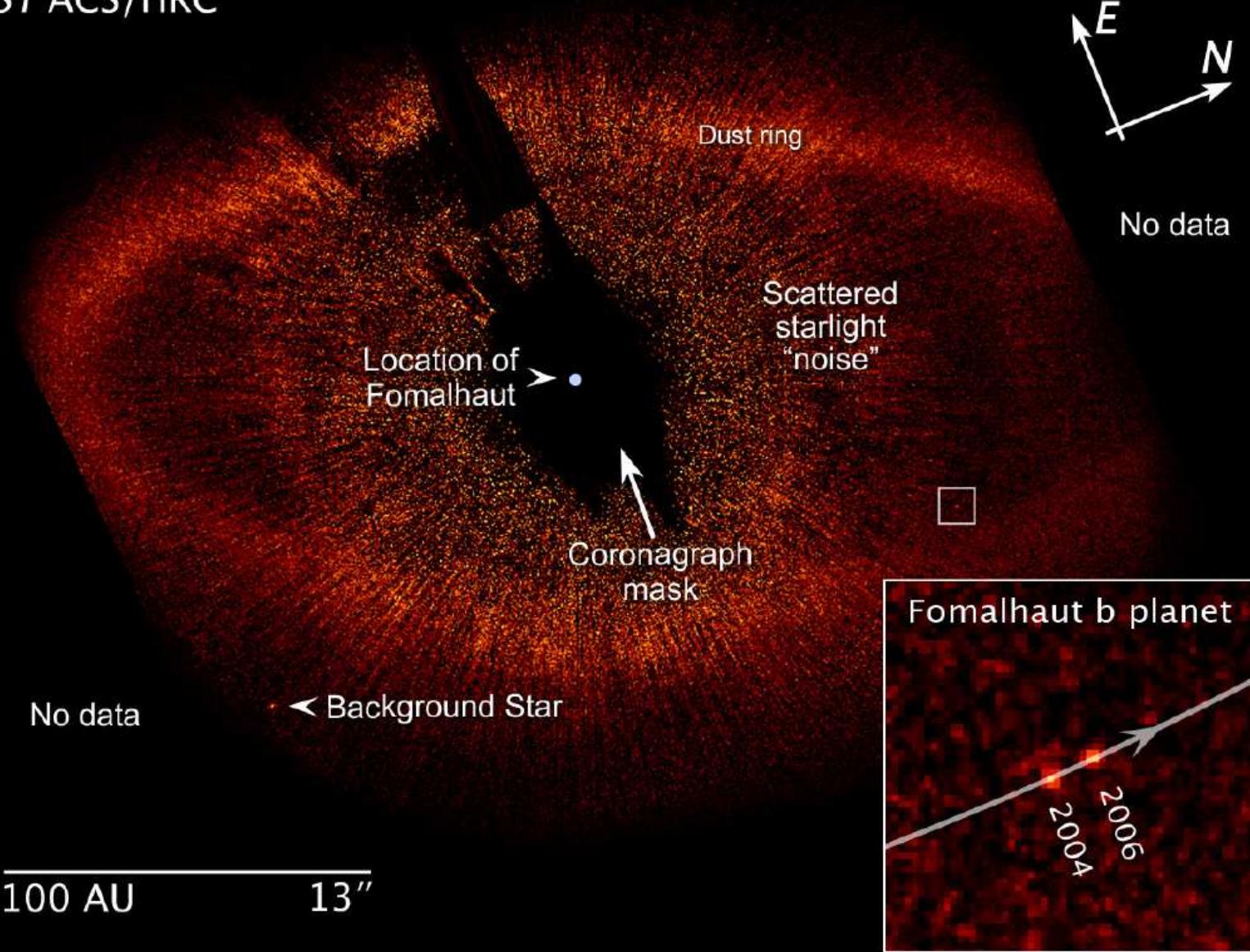




Pillar and Stellar Jet in the Carina Nebula  
*HST WFC3/UVIS*

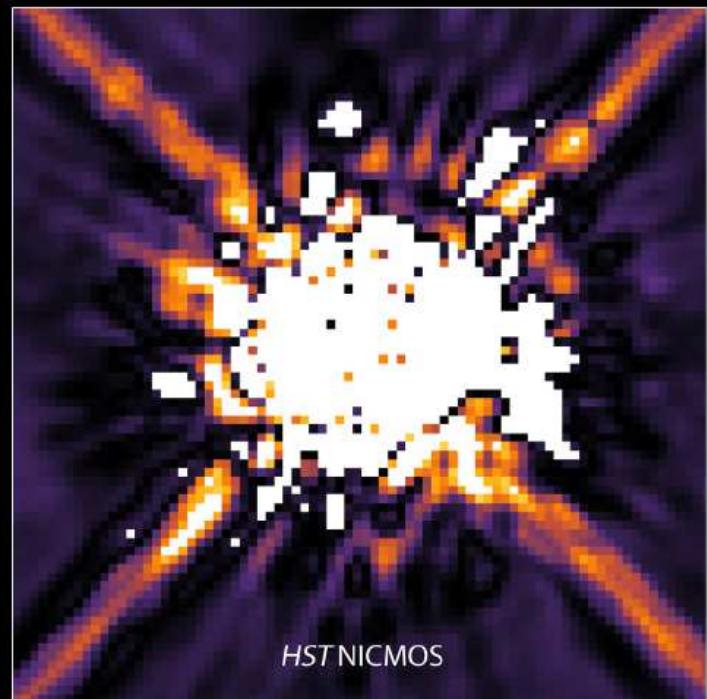


Fomalhaut  
HST ACS/HRC



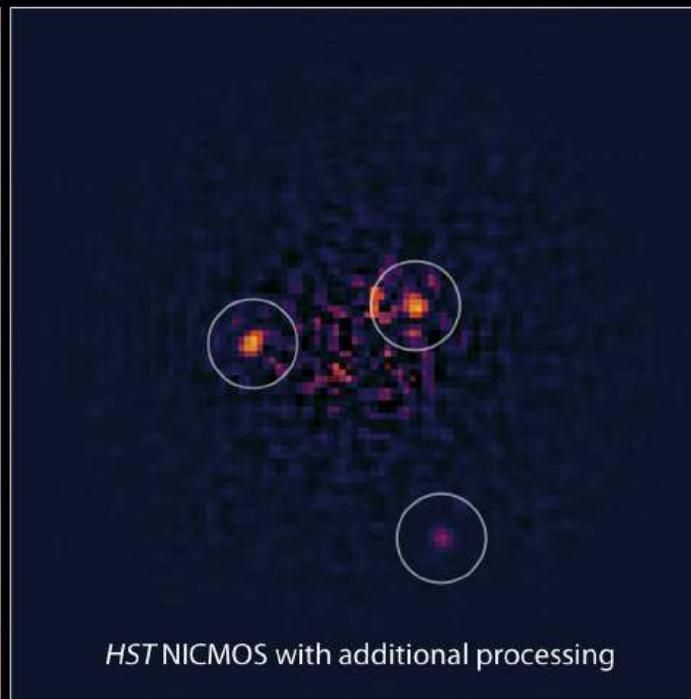
HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut:  
First direct imaging of a moving planet forming around a nearby star!  
JWST can find such planets much closer in for much farther stars.

## Exoplanet HR 8799 System

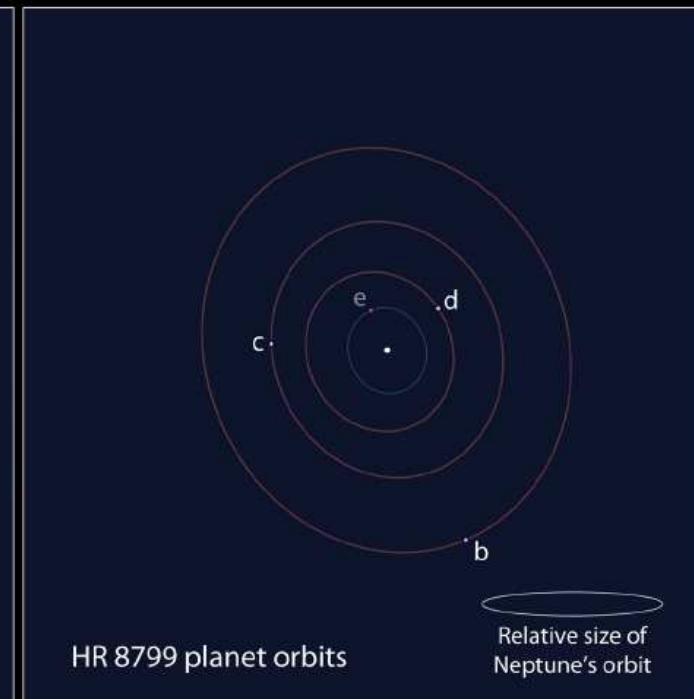


HST NICMOS

NASA, ESA, and R. Soummer (STScI)



HST NICMOS with additional processing



HR 8799 planet orbits

Relative size of  
Neptune's orbit

STScI-PRC11-29

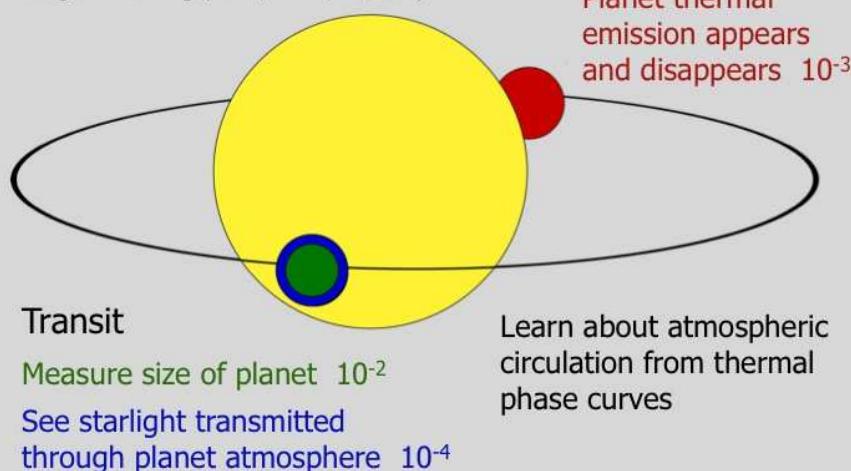
HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

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

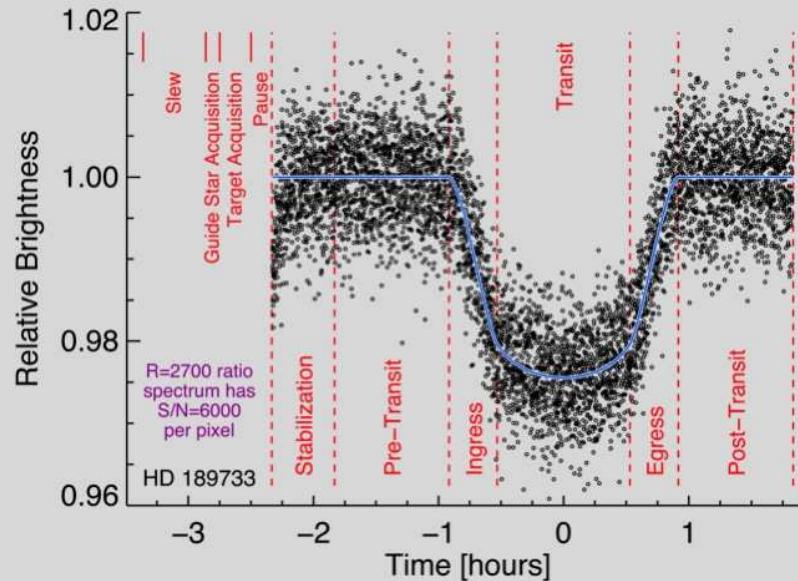
JWST can find such planets much closer in for much farther-away stars.

## Schematic of Transit and Eclipse Science

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



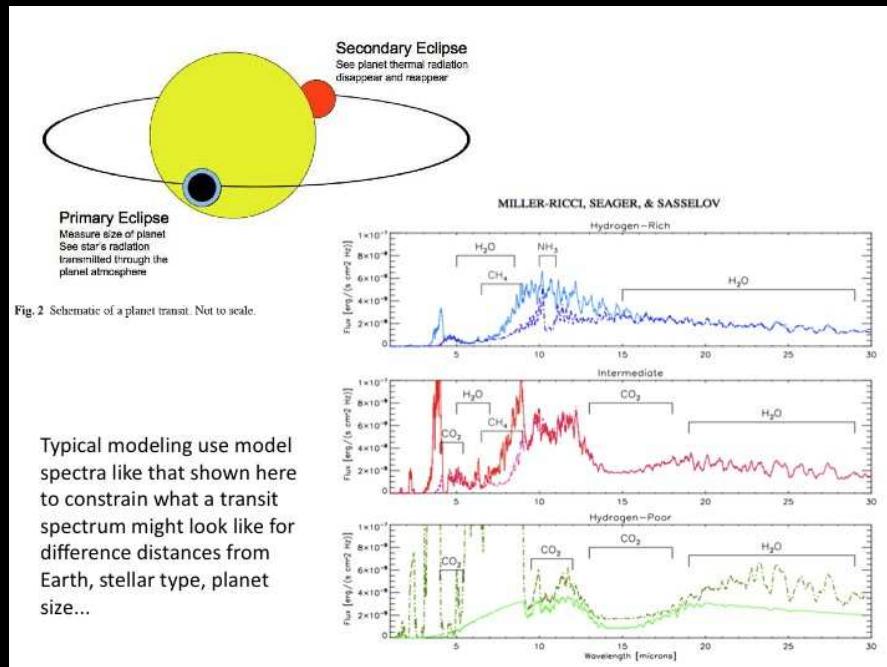
## Timeline of a Transit Observation



6

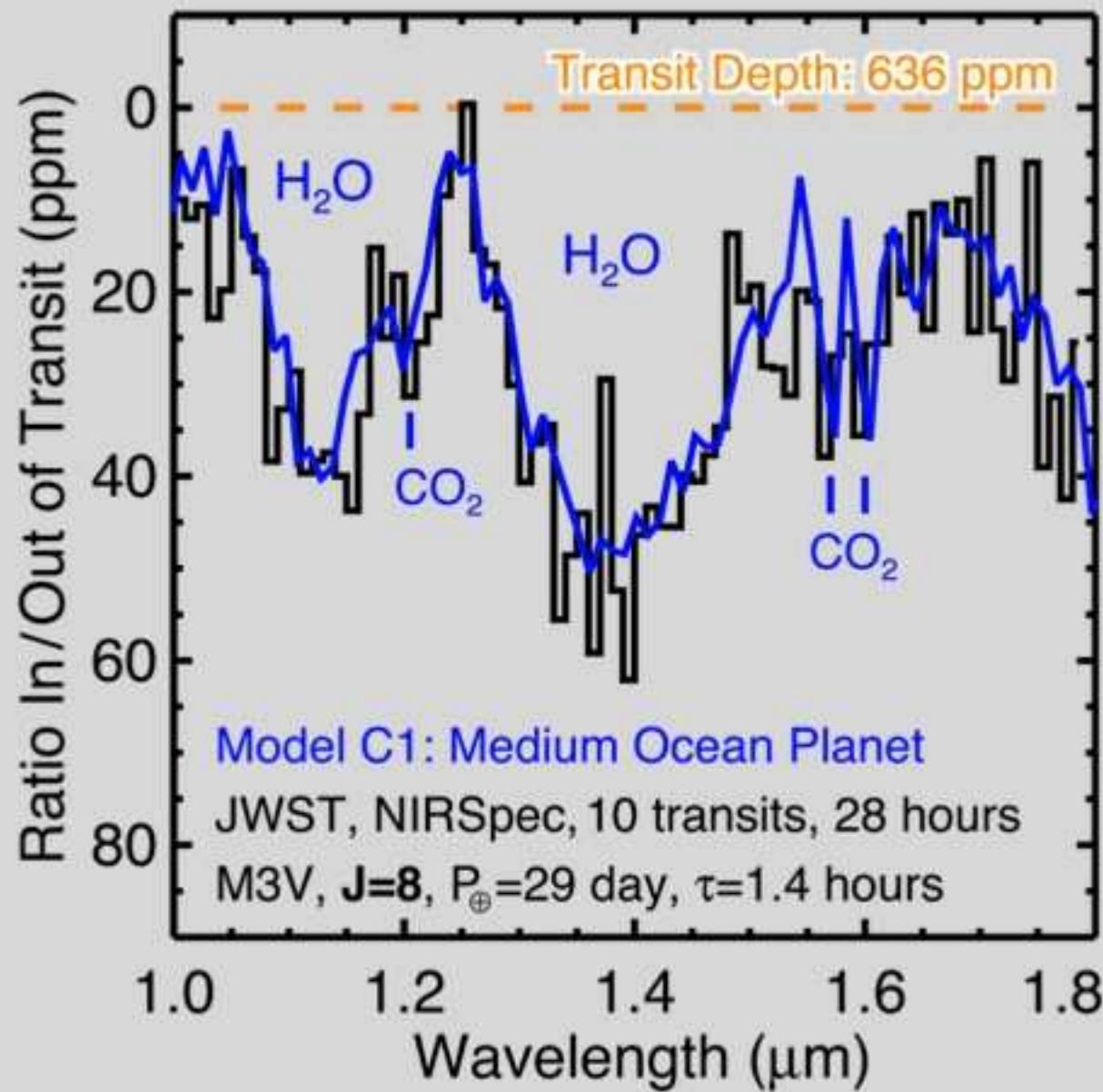
13

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



JWST IR spectra can find water and CO<sub>2</sub> 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.