

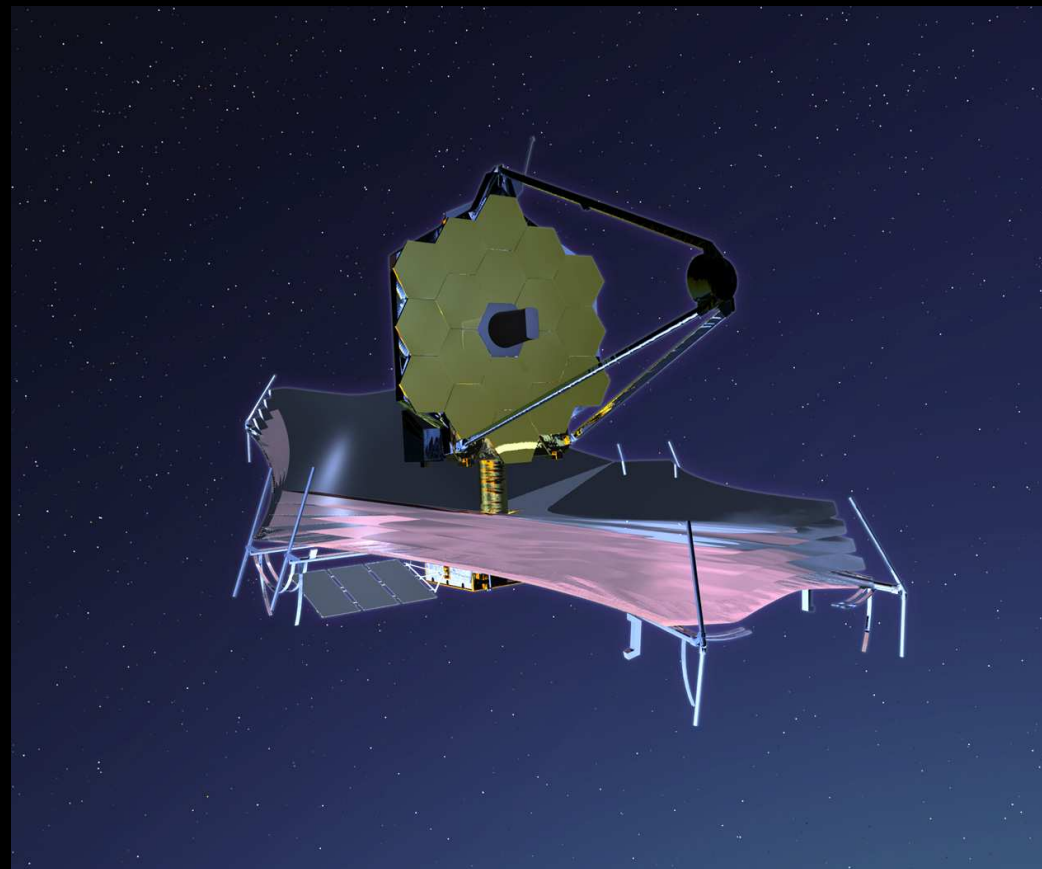
# NASA's James Webb Space Telescope (JWST): The new Frontier in the Cosmos after Hubble

---

**Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist**

*Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice, S. Driver (UK), & H. Yan (Carnegie)*

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



*Talk at the STEMnet Teacher Workshop, ASU, Tempe, AZ, Thursday Oct. 29, 2011*

*All presented materials are ITAR-cleared. These are my opinions only, not ASU's.*



# Outline

---

- (1) Recent key aspects of the Hubble Space Telescope (HST) project.
- (2) How has Hubble measured Galaxy Assembly over Cosmic Time?
- (3) What is the James Webb Space Telescope (JWST)?
- (4) How can JWST measure First Light, Reionization, & Galaxy Assembly?
- (5) How can JWST measure Earth-like exoplanets?
- (6) Summary and Conclusions

Sponsored by NASA/HST & JWST





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



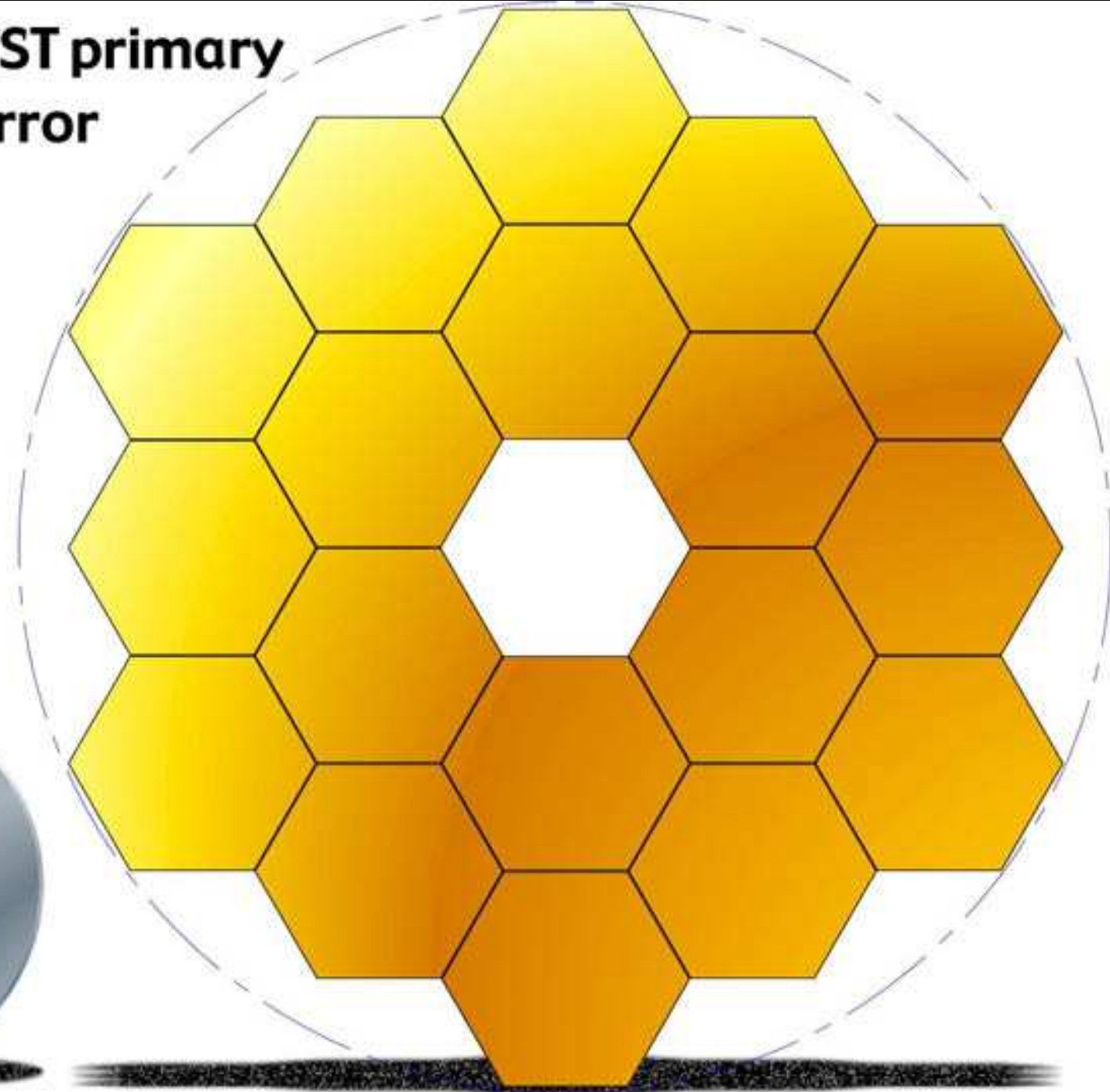
James E. Webb (1906–1992) — Second NASA Administrator

Hubble: Concept in 1970's; Made in 1980's; Operational 1990– $\gtrsim$ 2014

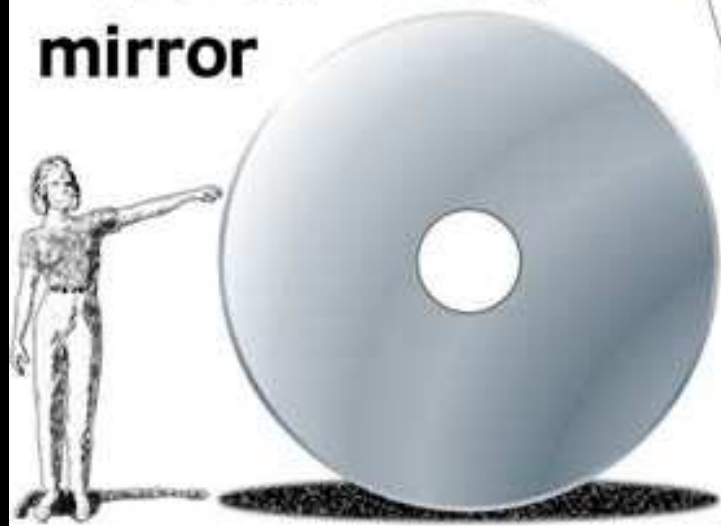
JWST: The infrared sequel to Hubble from 2018–2023 (–2029?)



**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) Recent key aspects of the Hubble Space Telescope (HST) project:



The HST Advanced Camera for Surveys (ACS) — launched 2002 (SM3B).









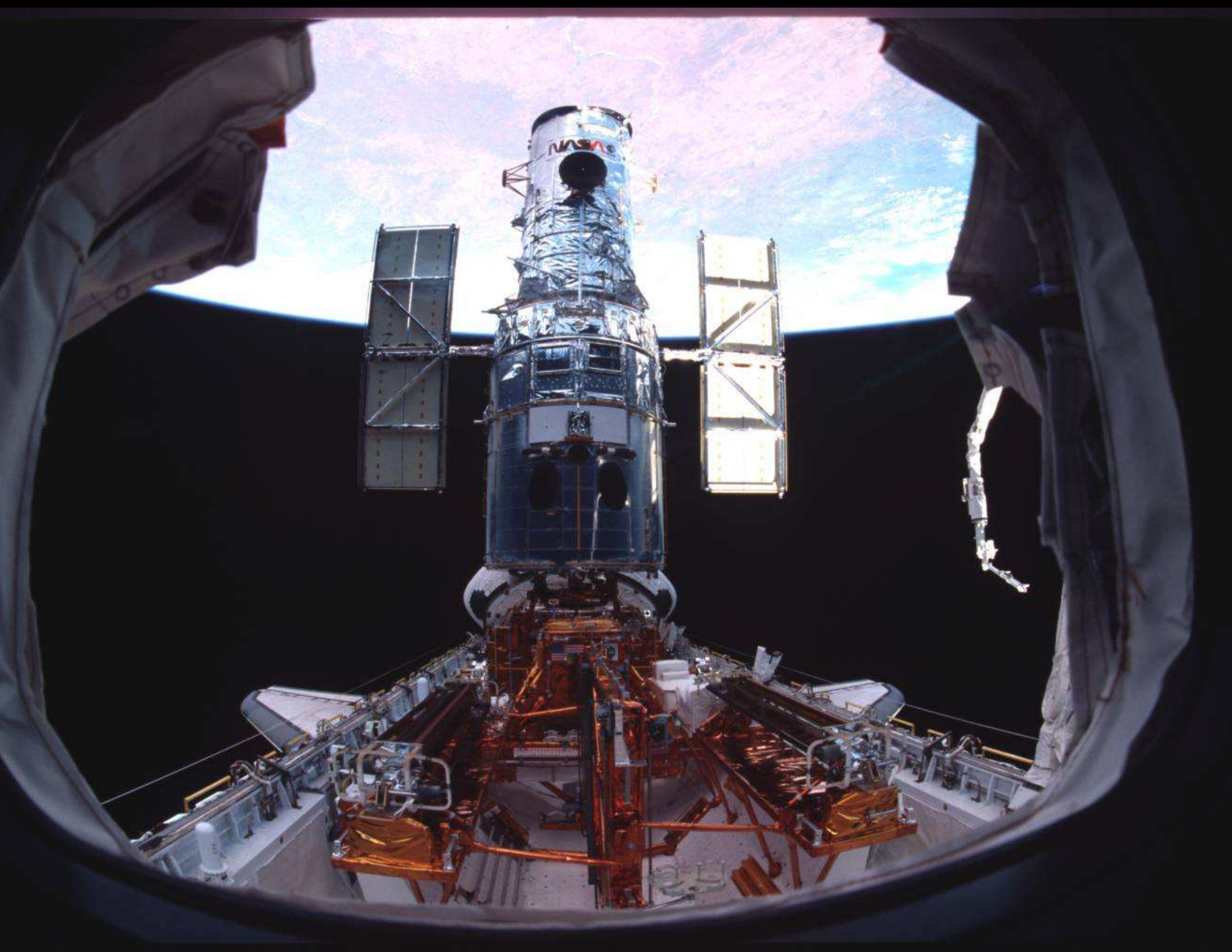








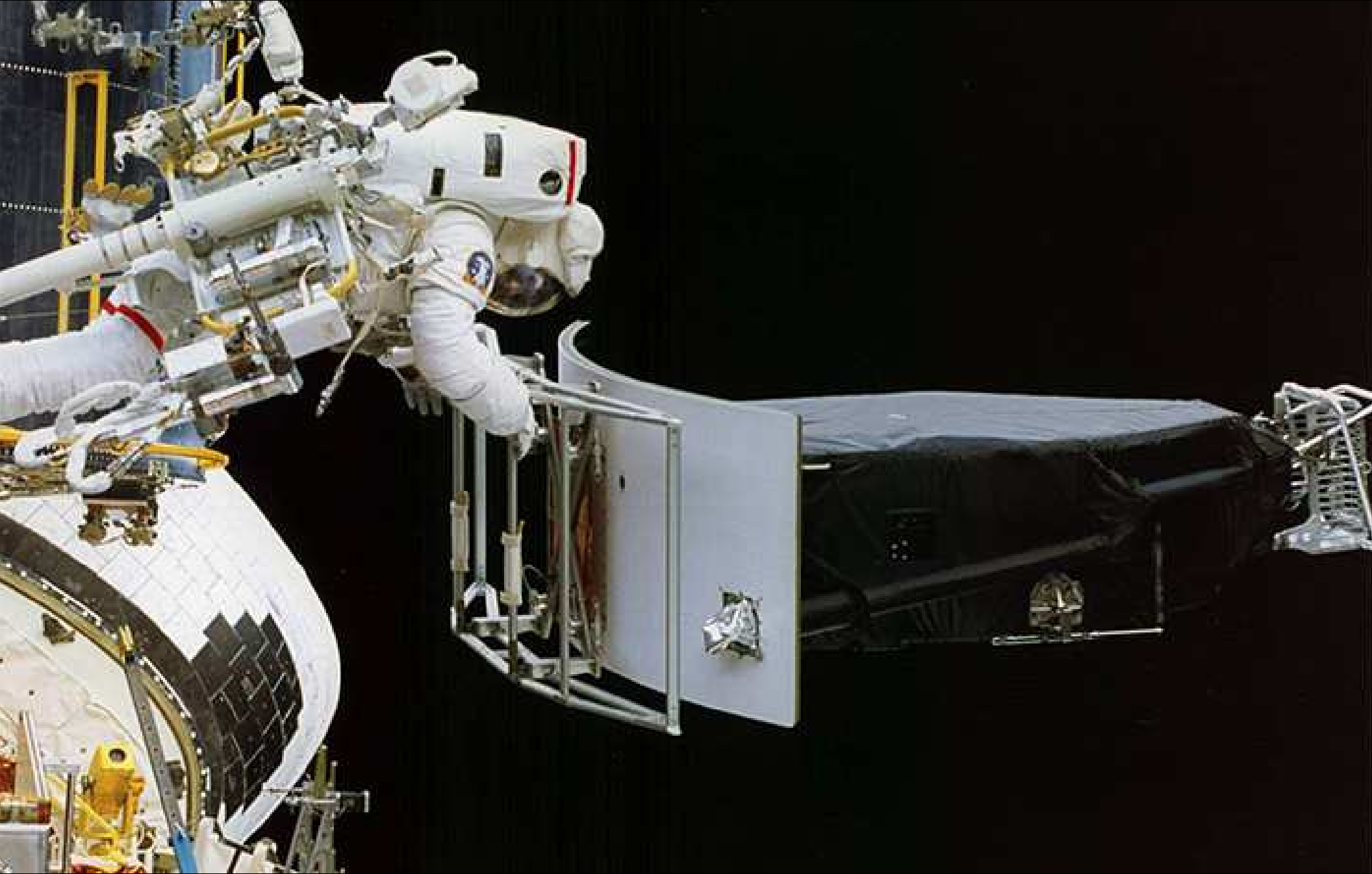






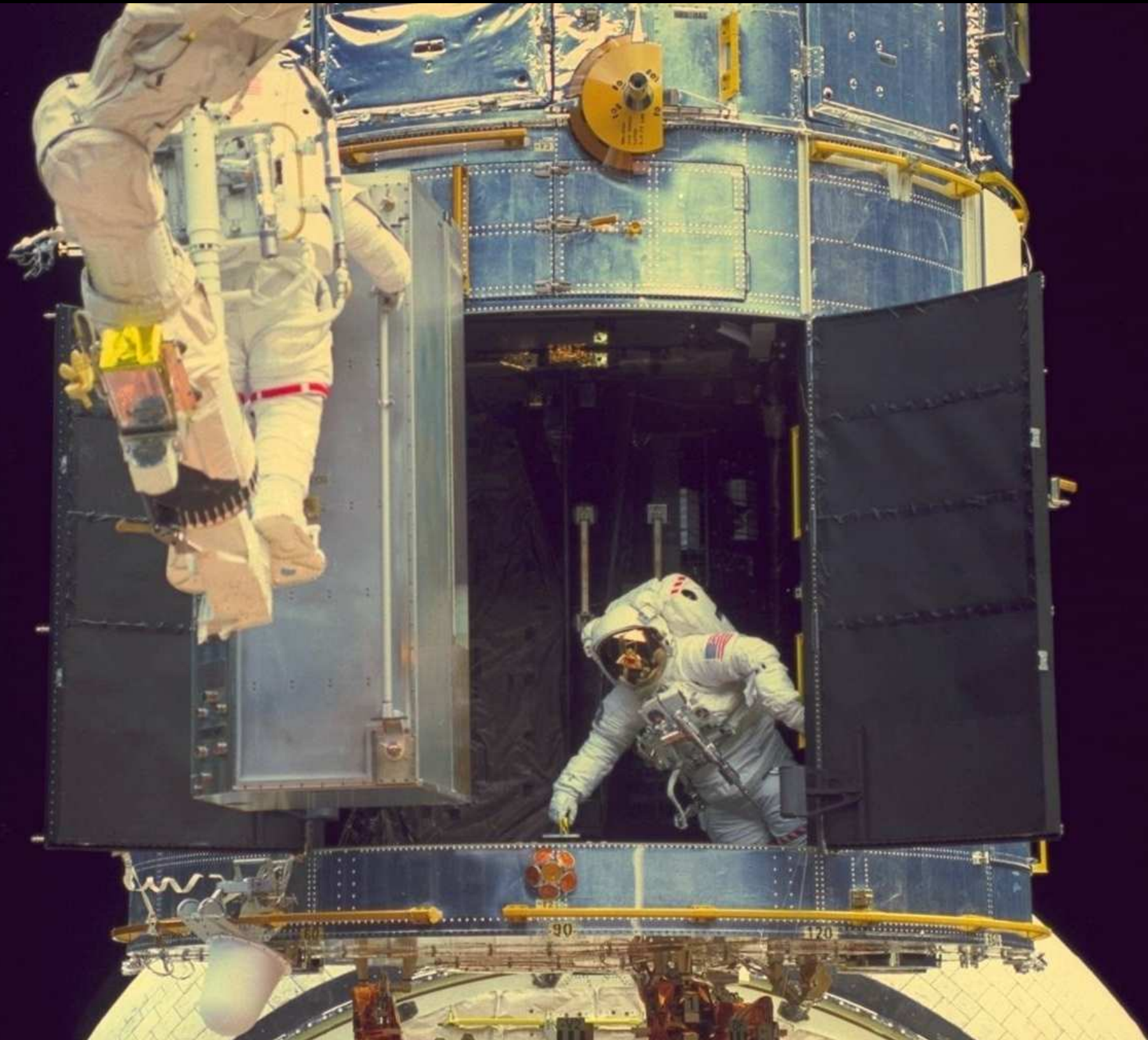






Installing Wide Field Camera 2 (WFPC2) during SM1 in December 1993.  
Similar to what astronauts did with WFC3 during SM4 in May 2009.









New ESA solar panels rolling out during SM1 in December 1993

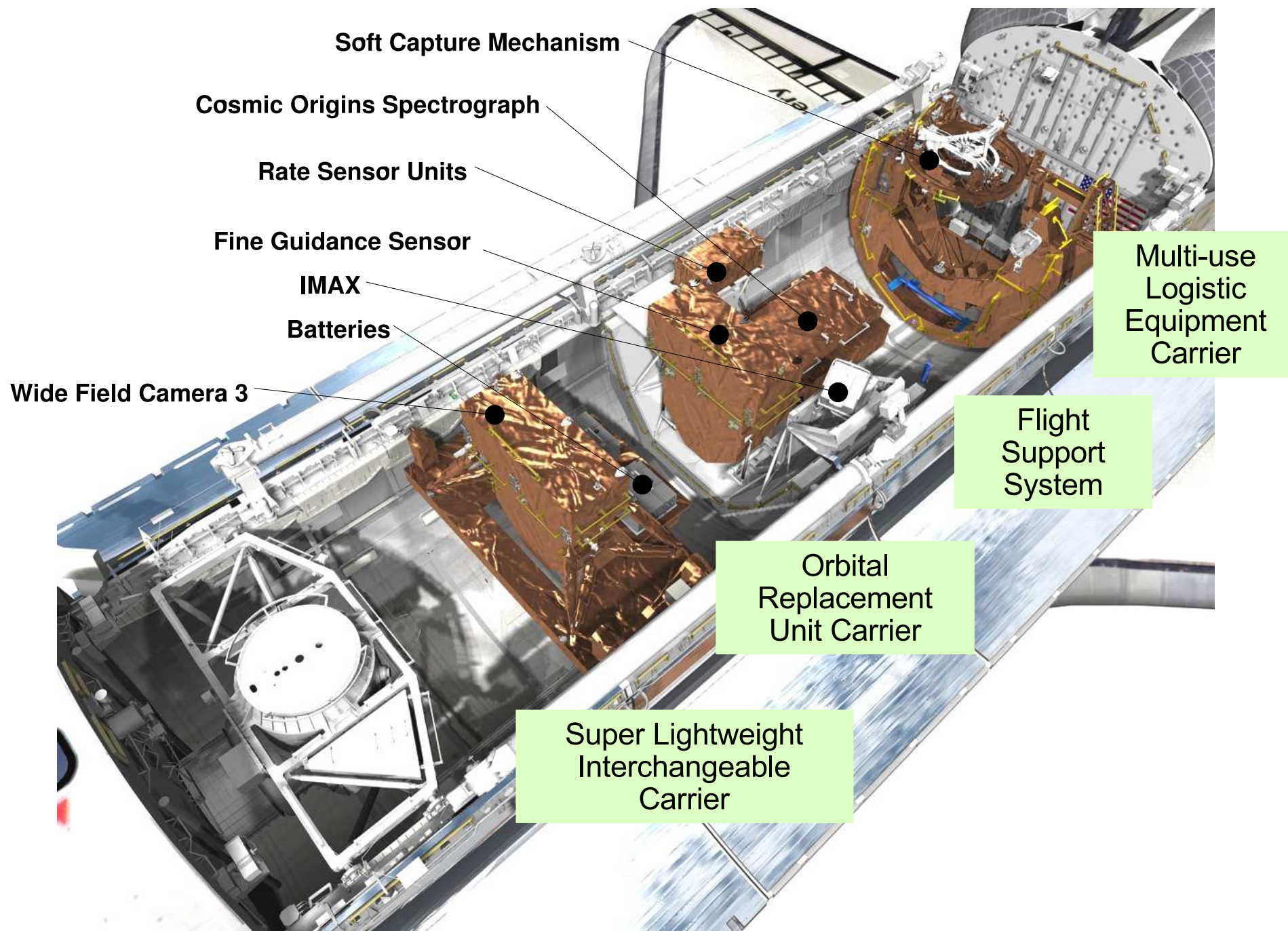








# HST Servicing Mission 4 (SM4) Configuration



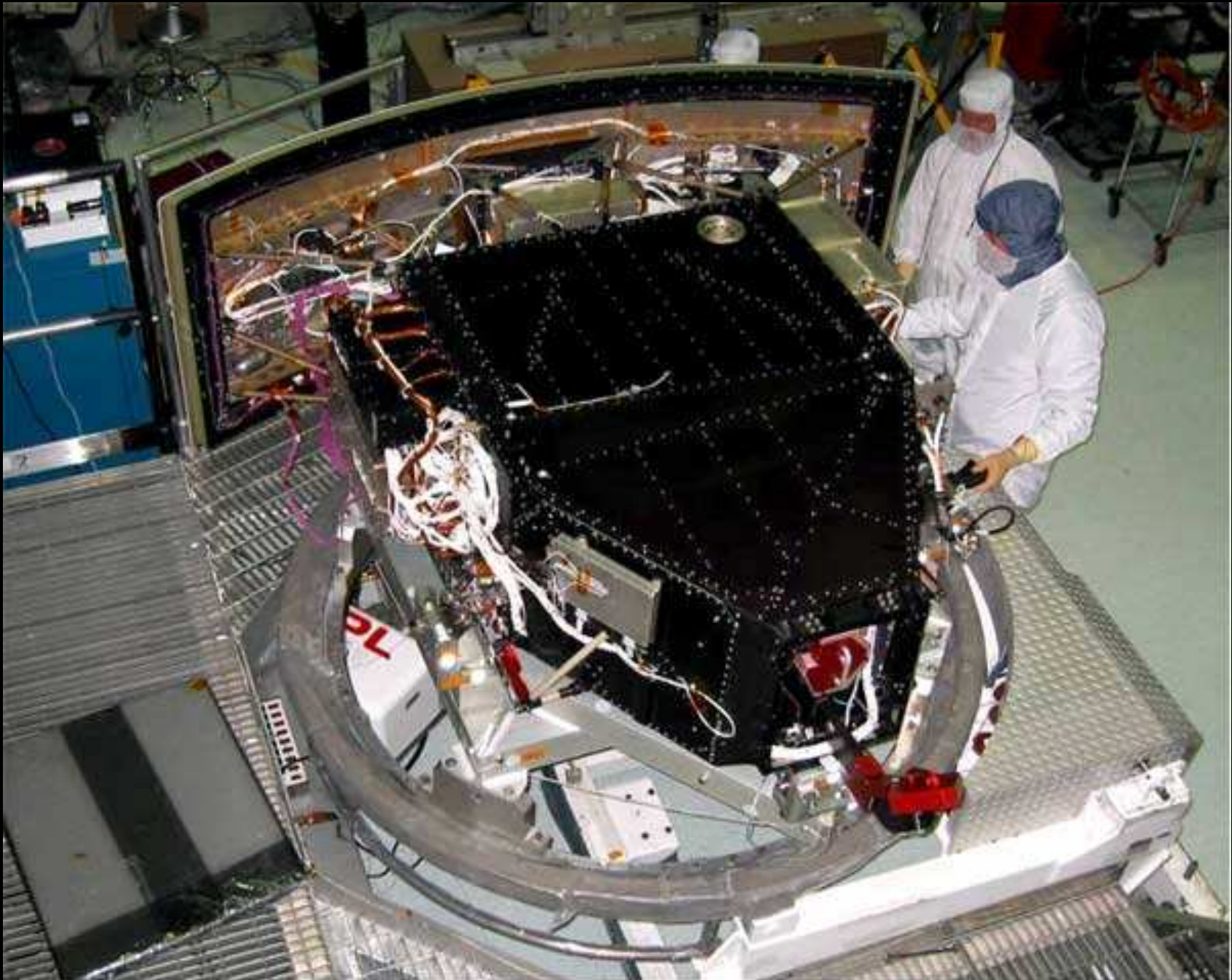




Wide Field Camera 3 for SM4 in 2009: More powerful HST imaging than ever.

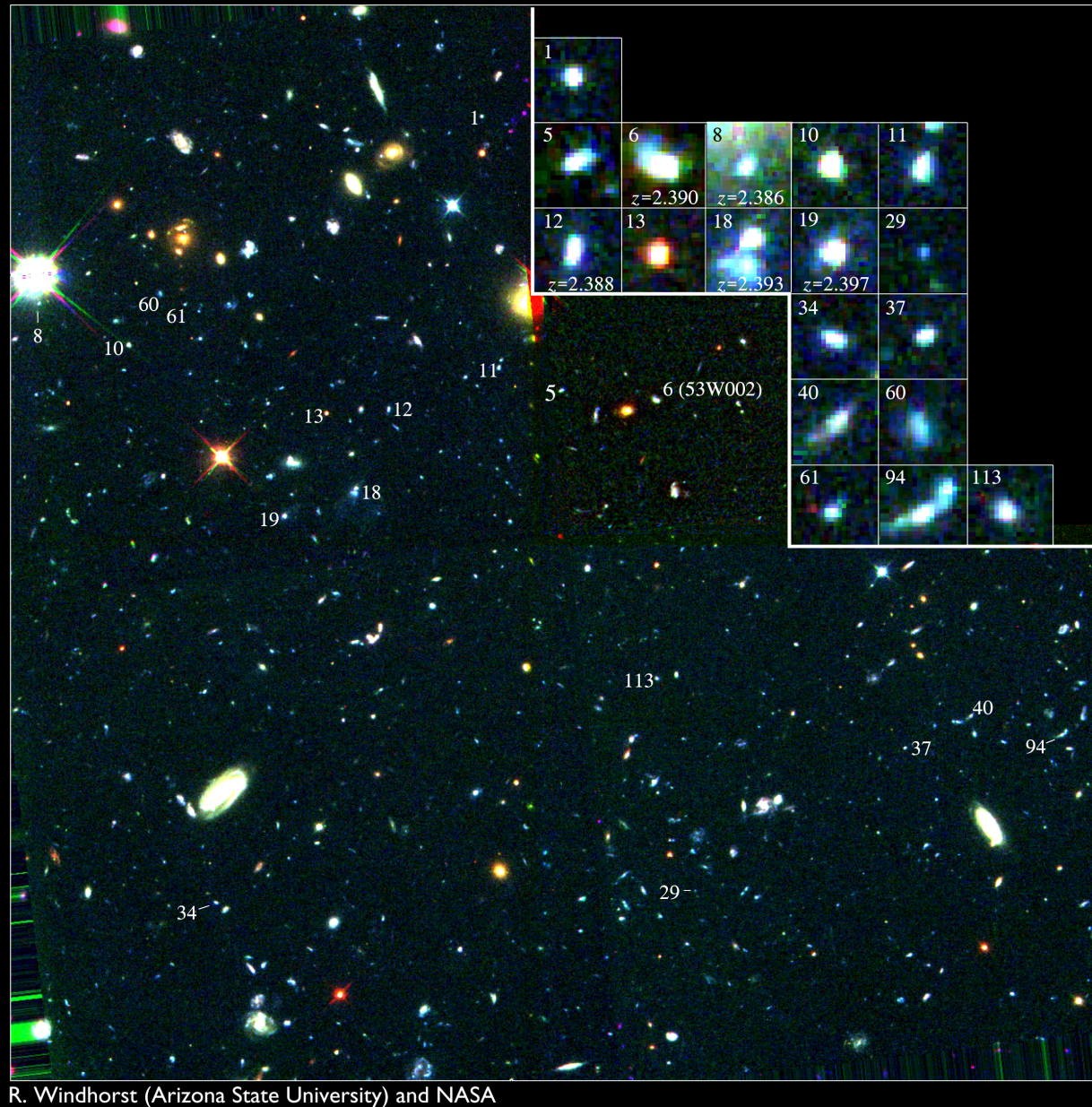


## (2) New studies of the Cosmos with the Hubble Wide Field Camera 3





## (2) How has Hubble measured Galaxy Assembly over Cosmic Time?

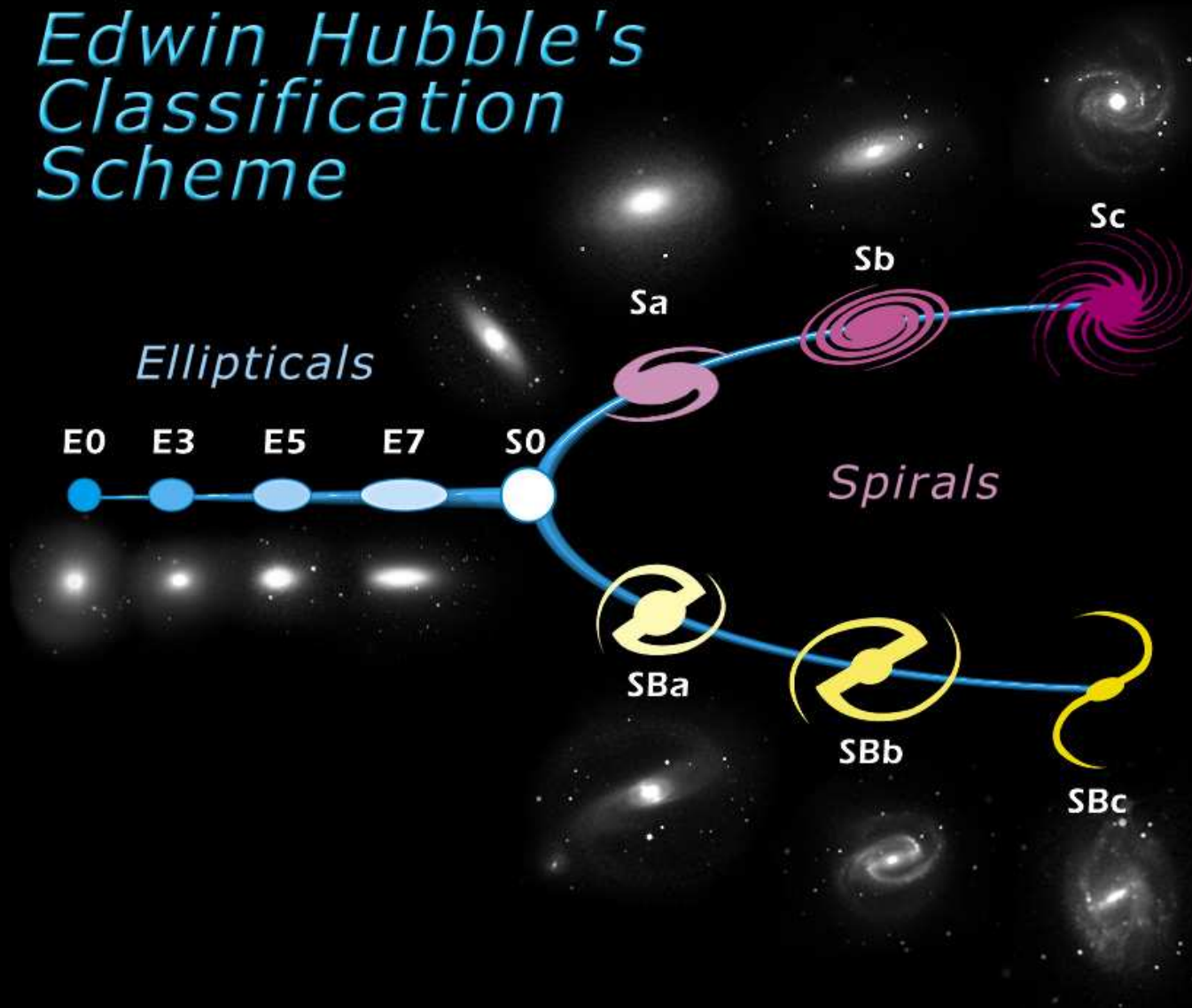


One of the remarkable HST discoveries was how numerous and small faint galaxies are: the building blocks of giant galaxies seen today (T. Ashcraft).



## (2) HST turned the classical Hubble sequence upside down!

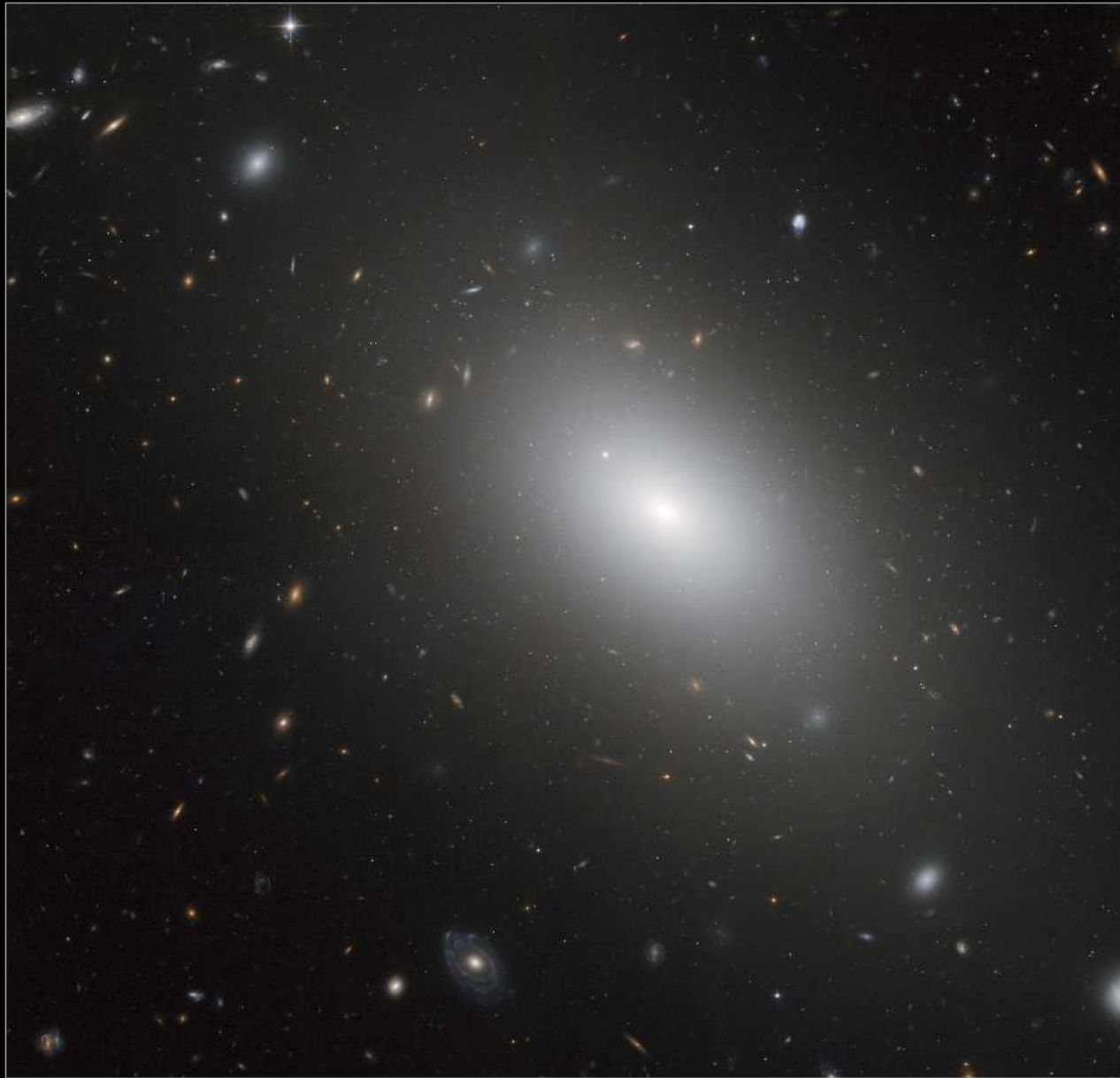
### Edwin Hubble's Classification Scheme



Who (when)	Cosmic Epoch	Ellipticals	Spirals	Irr's/mergers
Hubble (1920's)	$z=0$ (13.73 Gyr)	$\sim 40\%$	$\gtrsim 50\%$	$\lesssim 10\%$
HST (1990's)	$z \simeq 1-2$ (3-6 Gyr)	$\lesssim 15\%$	$\sim 30\%$	$\gtrsim 55\% !$



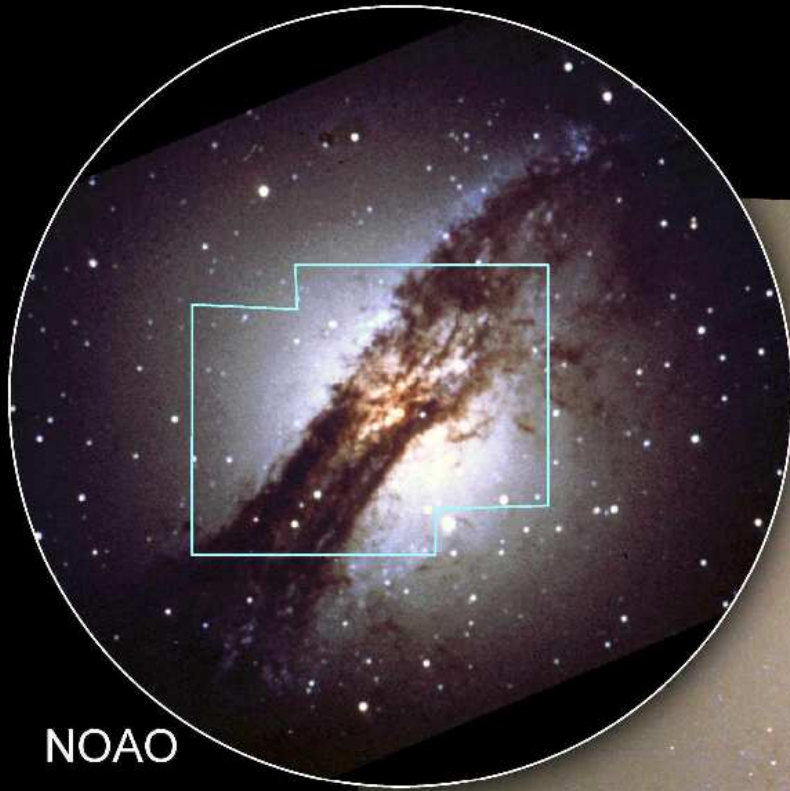
# Elliptical Galaxy NGC 1132



Hubble  
Heritage

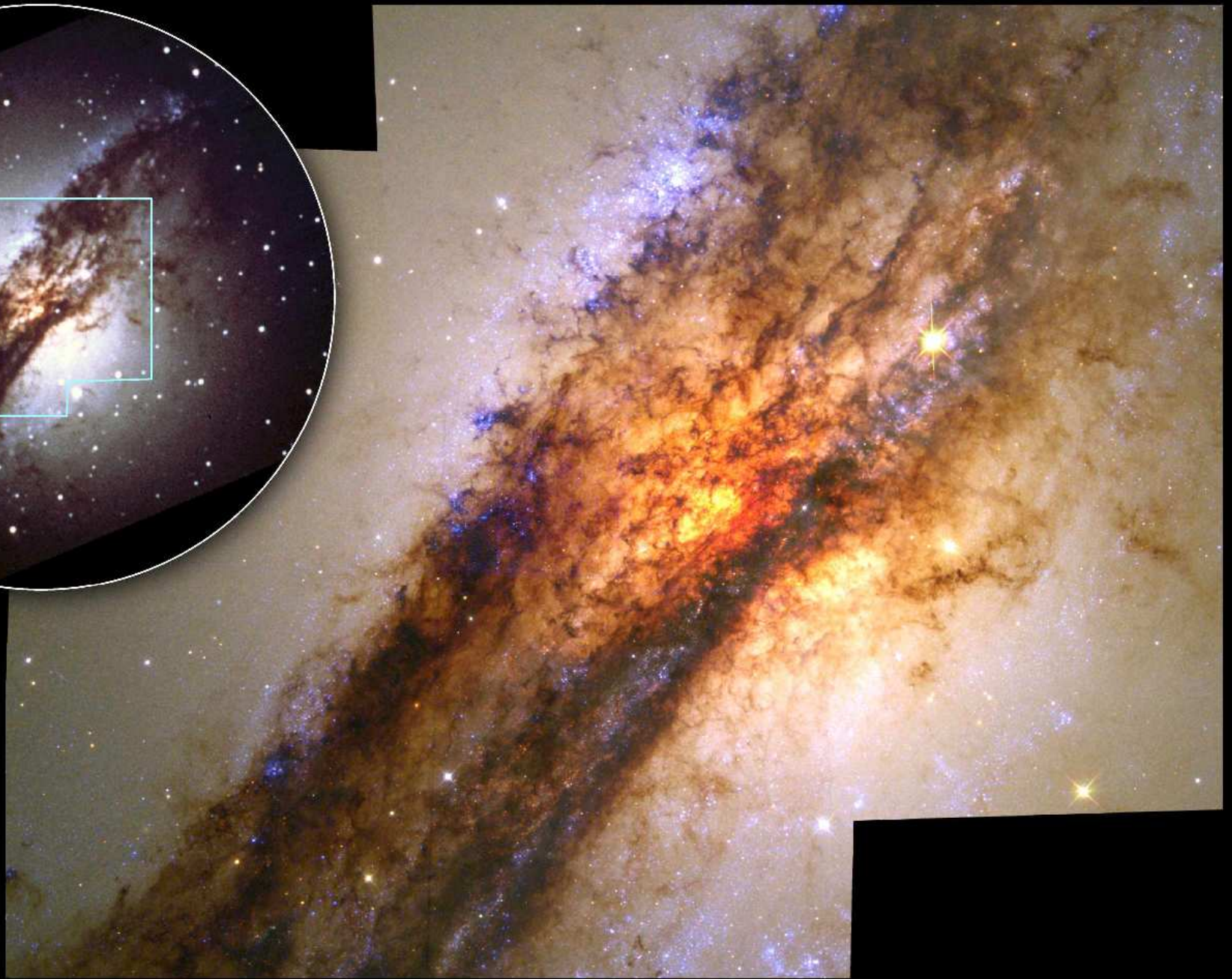
M. Rutkowski (Dissertation).





NOAO

HST



## Active Galaxy Centaurus A

Hubble Space Telescope • Wide Field Planetary Camera 2



Centaurus A  
NGC 5128  
*HST* WFC3/UVIS

F225W+F336W+F438W

F487N H $\beta$

F502N [O III]

F547M  $\gamma$

F657N H $\alpha$ + [N II]

F673N [S II]

F814W I

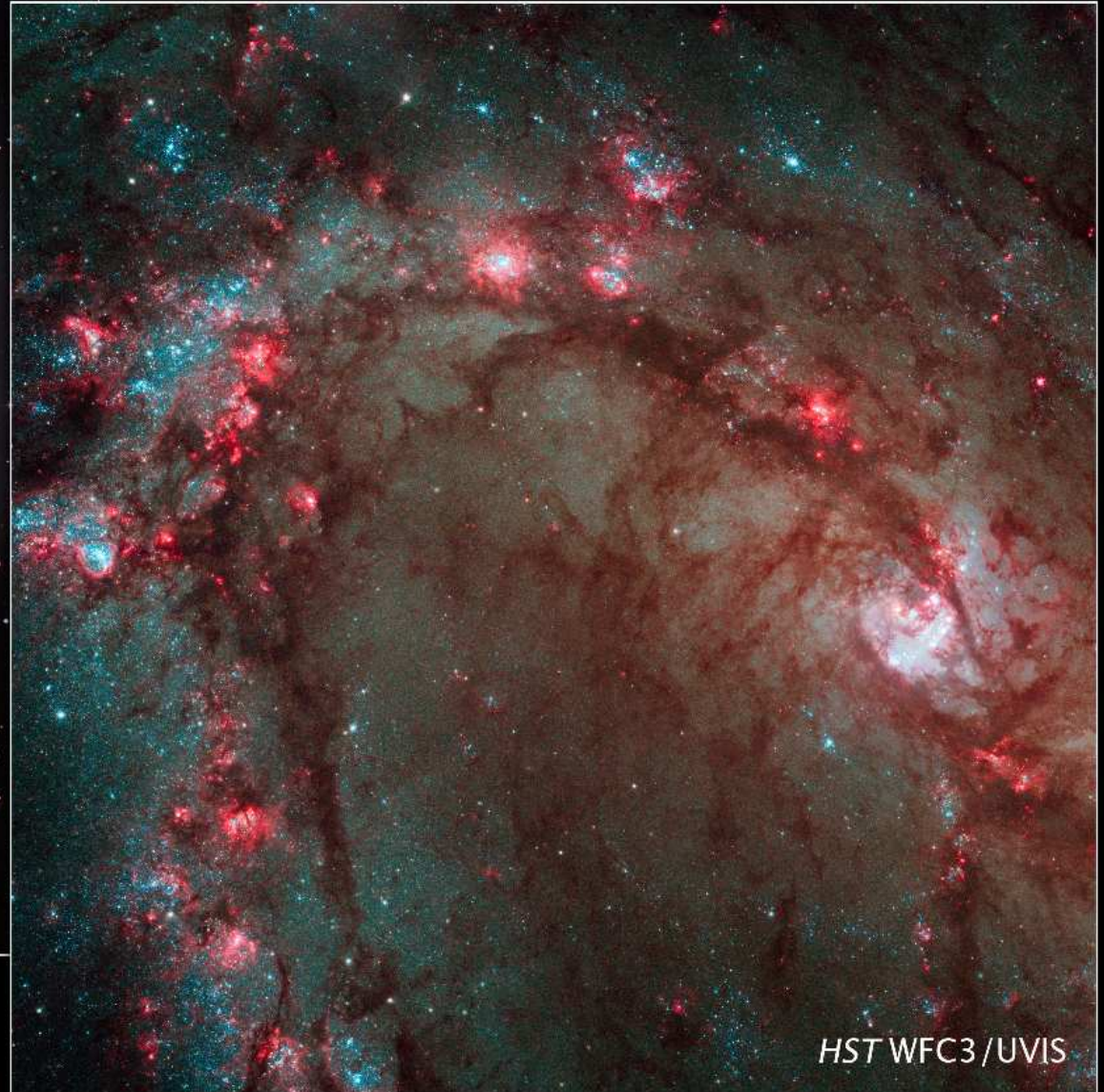
3000 light-years

1400 parsecs

56''







**Spiral Galaxy M83**  
*Hubble Space Telescope ■ WFC3/UVIS*



Spiral Galaxy M83  
HST WFC3/UVIS

F336W U  
F555W V  
F814W I  
F502N [O III]  
F657N H $\alpha$

5,000 light-years  
1,500 parsecs 70"





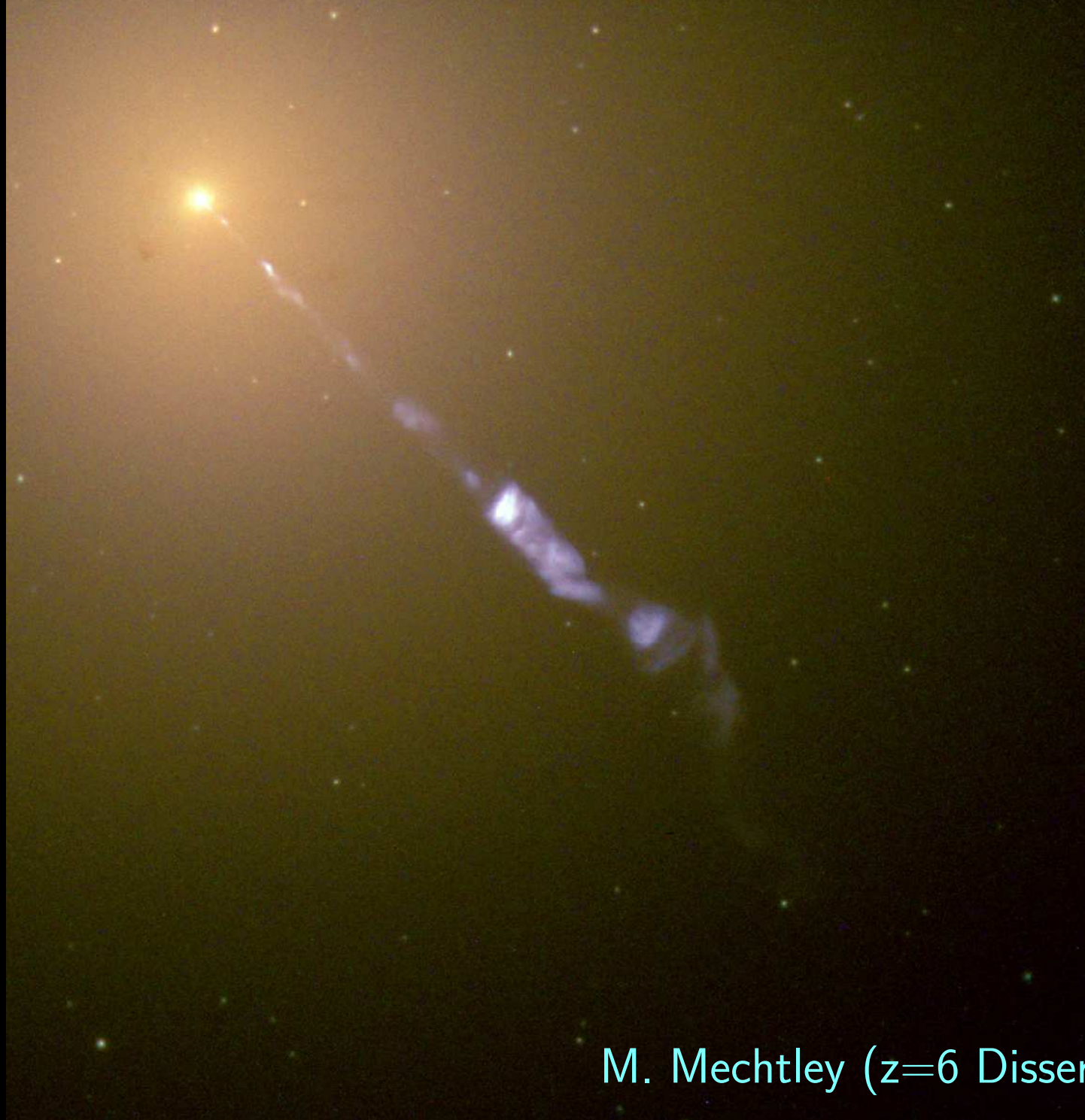
# Active Galaxy M82



Hubble  
Heritage

NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS/WFC • STScI-PRC06-14a





M. Mechtley (z=6 Dissertation).

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





Photo Copyright *R. Gendler*



*HST WFPC2 image:  
T. Lauer (NOAO/AURA/NSF)*



*Artist's Concept:  
A. Feild (STScI)*

**Andromeda Galaxy Nucleus ■ M31**  
**Hubble Space Telescope ■ WFPC2**



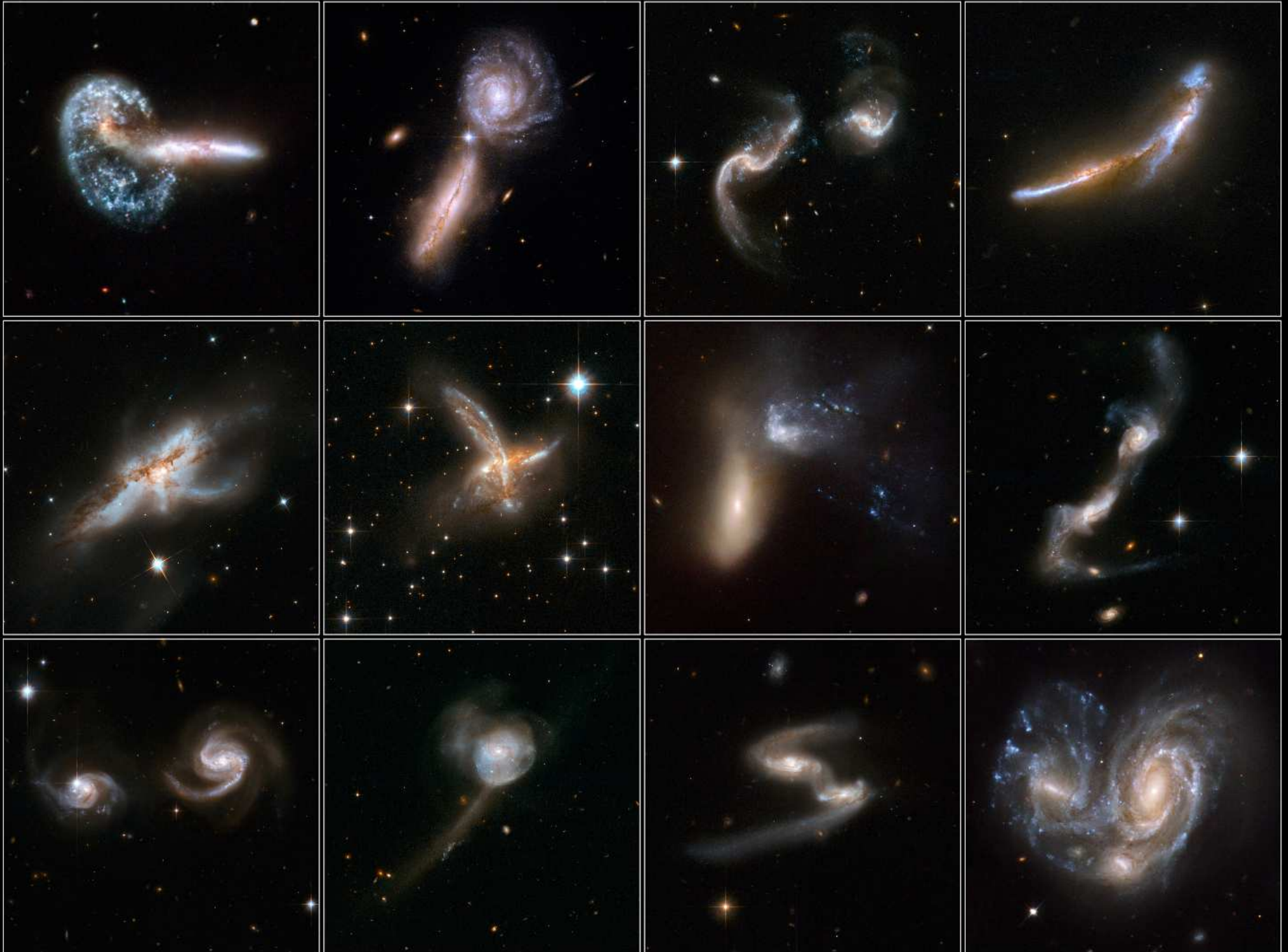


HST Antenna galaxy: Prototype of high redshift, star-forming, major merger?

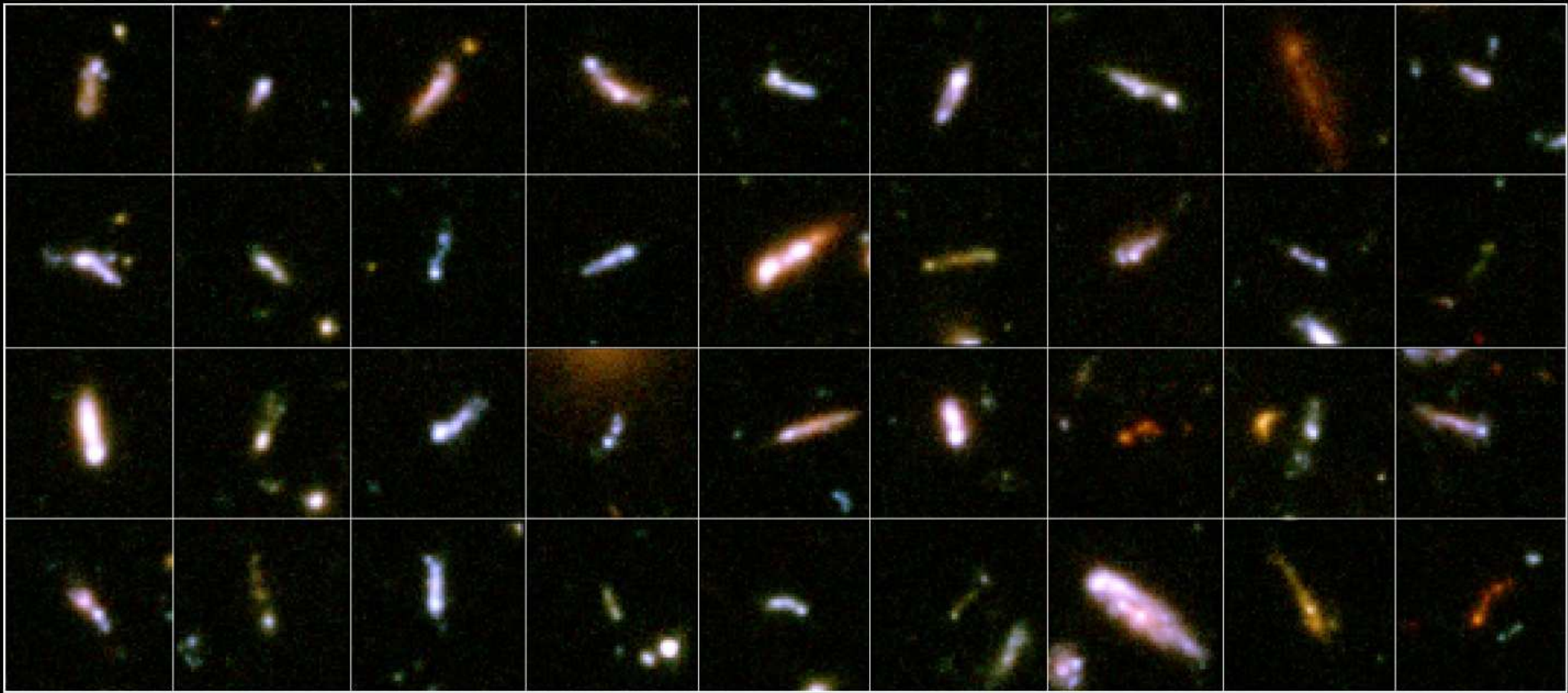


# Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2







“Tadpole” Galaxies in the Hubble Ultra Deep Field  
*Hubble Space Telescope* ■ ACS/WFC

NASA, ESA, A. Straughn, S. Cohen and R. Windhorst (Arizona State University), and the HUDF team (STScI)

STScI-PRC06-04

Merging galaxies constitute  $\lesssim 1\%$  of Hubble sequence today (age  $\gtrsim 12.5$  Gyr).

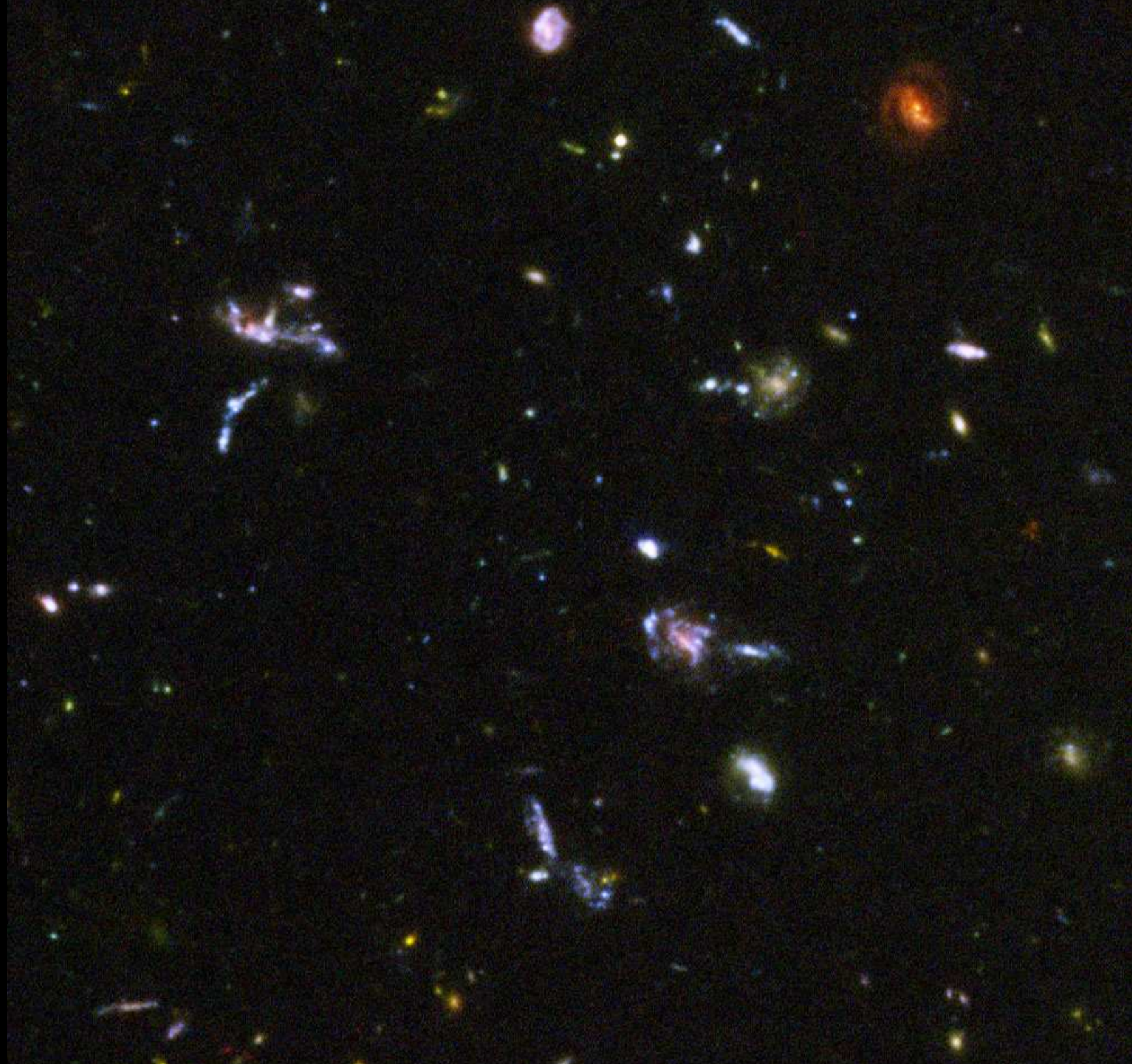
Tadpole galaxies are early stage mergers, very common at  $z \gtrsim 2$  (age  $\lesssim 3$  Gyr).

JWST will measure galaxy assembly to  $z \lesssim 20$  (age  $\simeq 0.2$  Gyr).



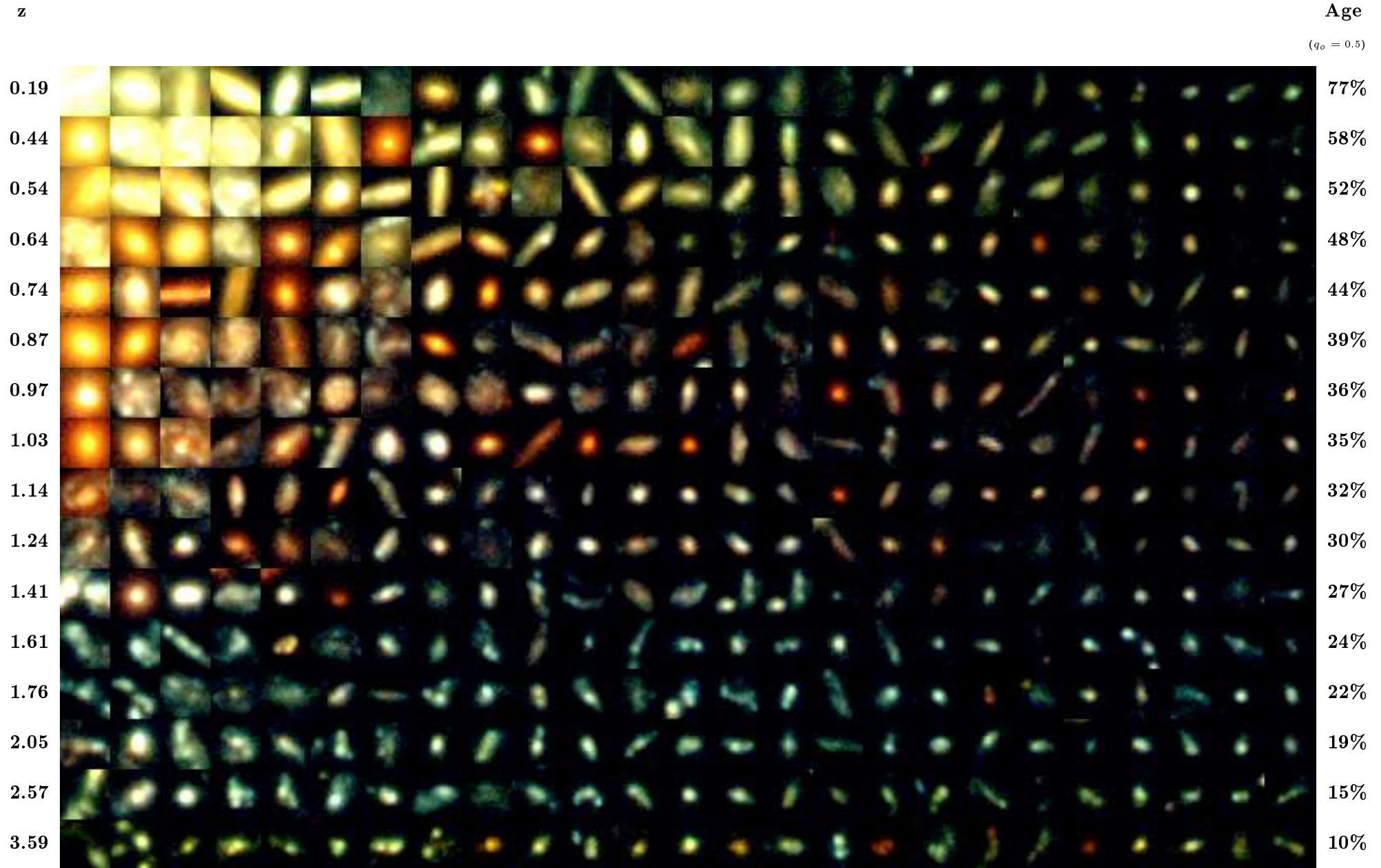






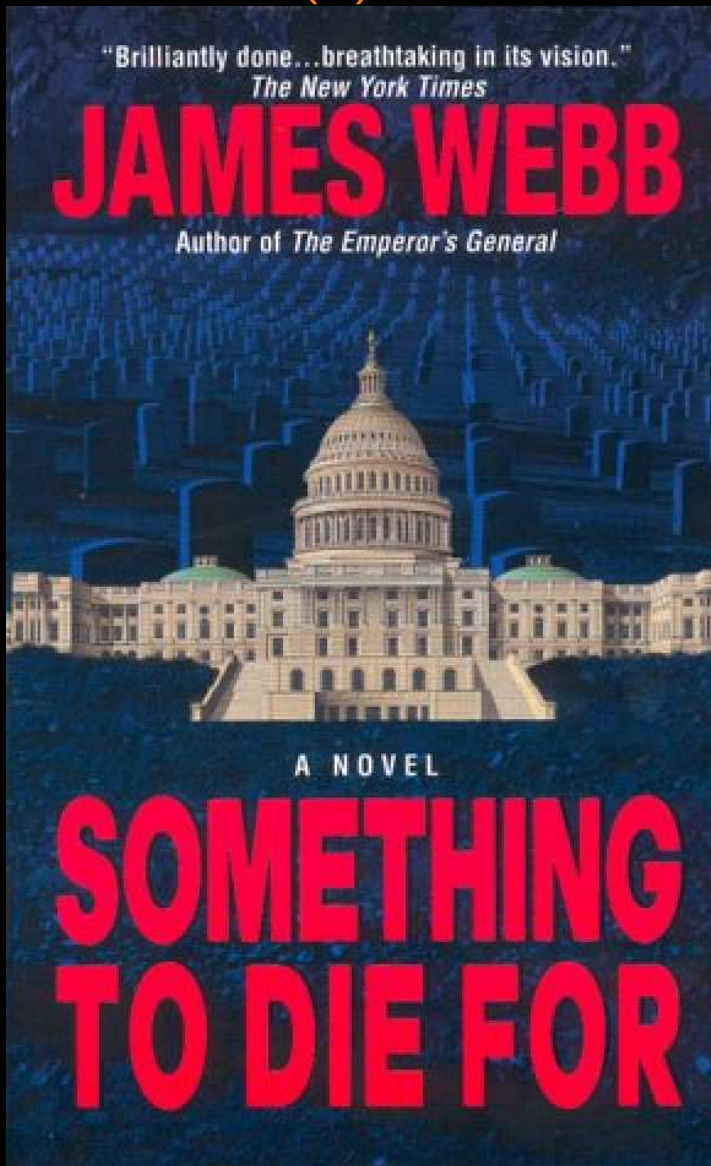


# THE HUBBLE DEEP FIELD CORE SAMPLE ( $I < 26.0$ )





### (3) What is the James Webb Space Telescope (JWST)?



Need young generation of students & scientists after 2018 ... It'll be worth it!

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



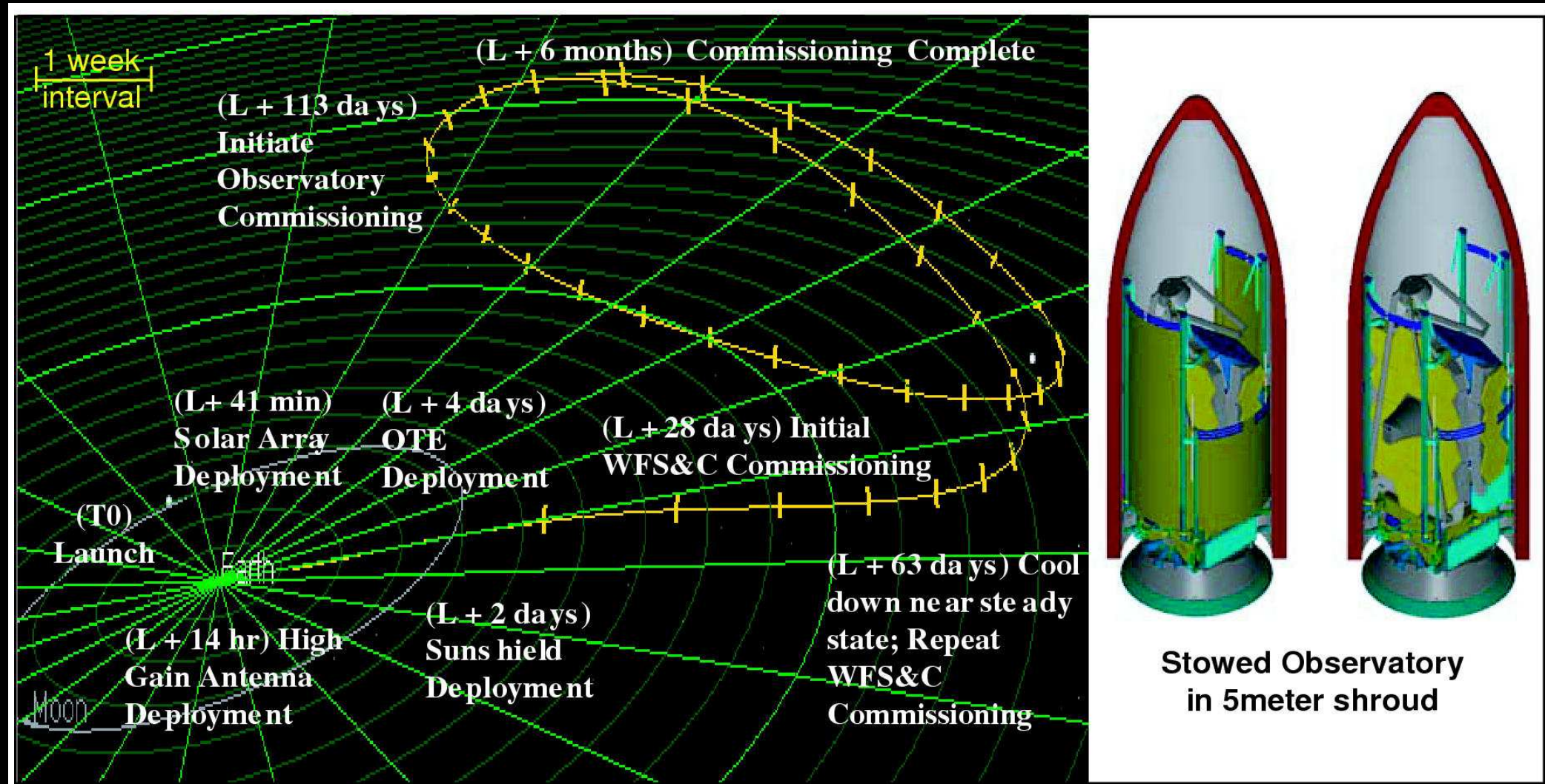
### (3) What is the James Webb Space Telescope (JWST)?



- A fully deployable 6.5 meter ( $25 \text{ m}^2$ ) segmented IR telescope for imaging and spectroscopy at  $0.6\text{--}28 \text{ }\mu\text{m}$  wavelength, to be launched in 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (31.5 mag = firefly from Moon!) and spectroscopy.



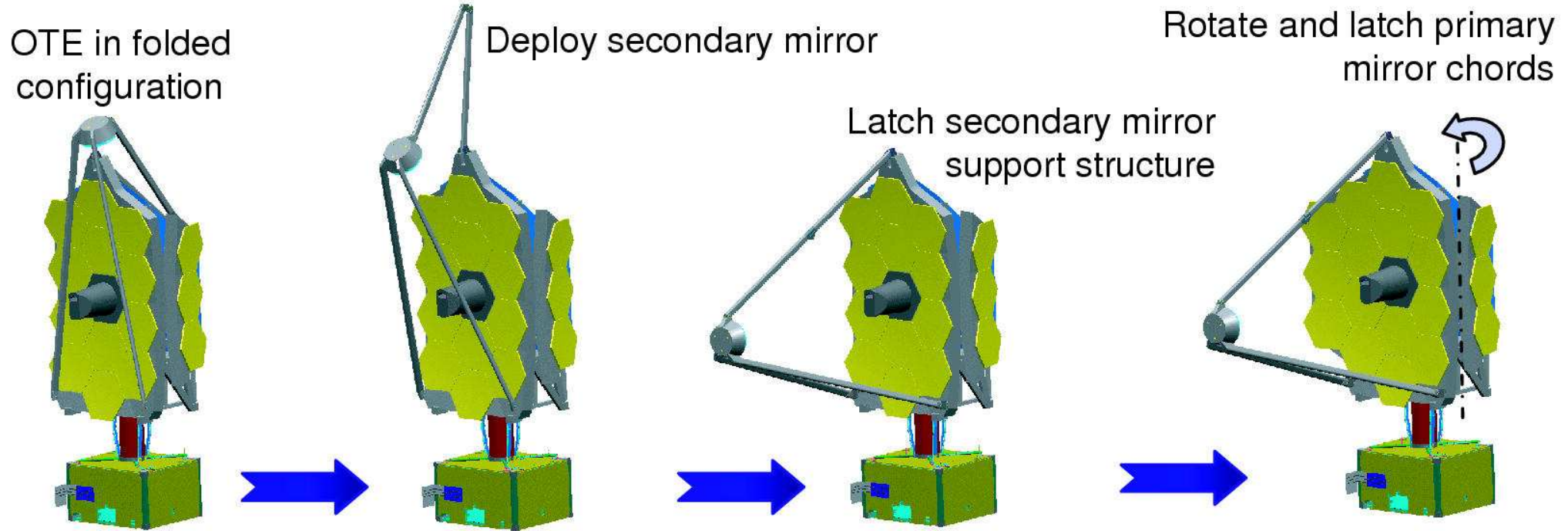
### (3a) How will JWST travel to its L2 orbit?



- After launch in 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.

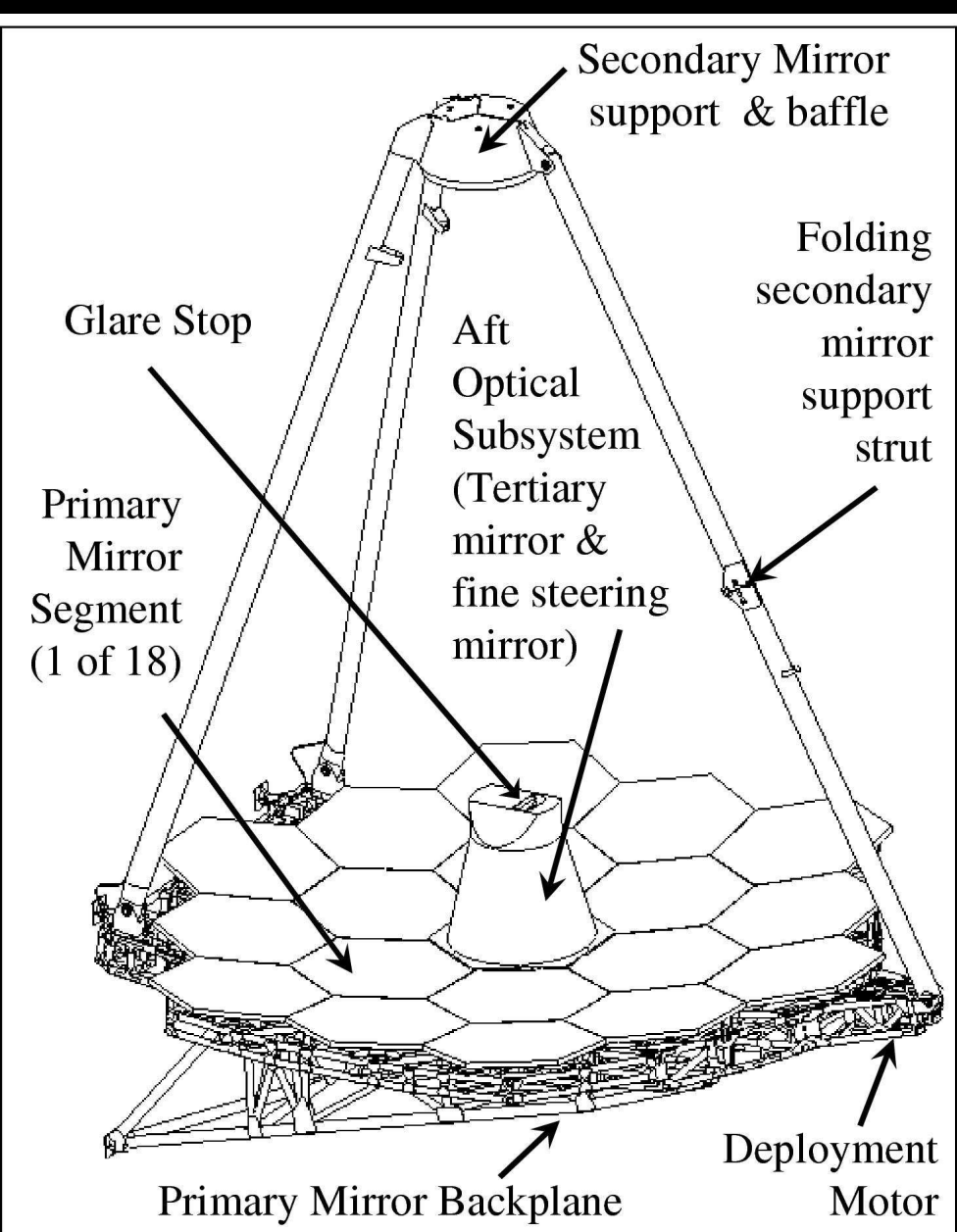


- (3b) How will JWST be automatically deployed?



- 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 will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.
- Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meeting the 40K specifications!

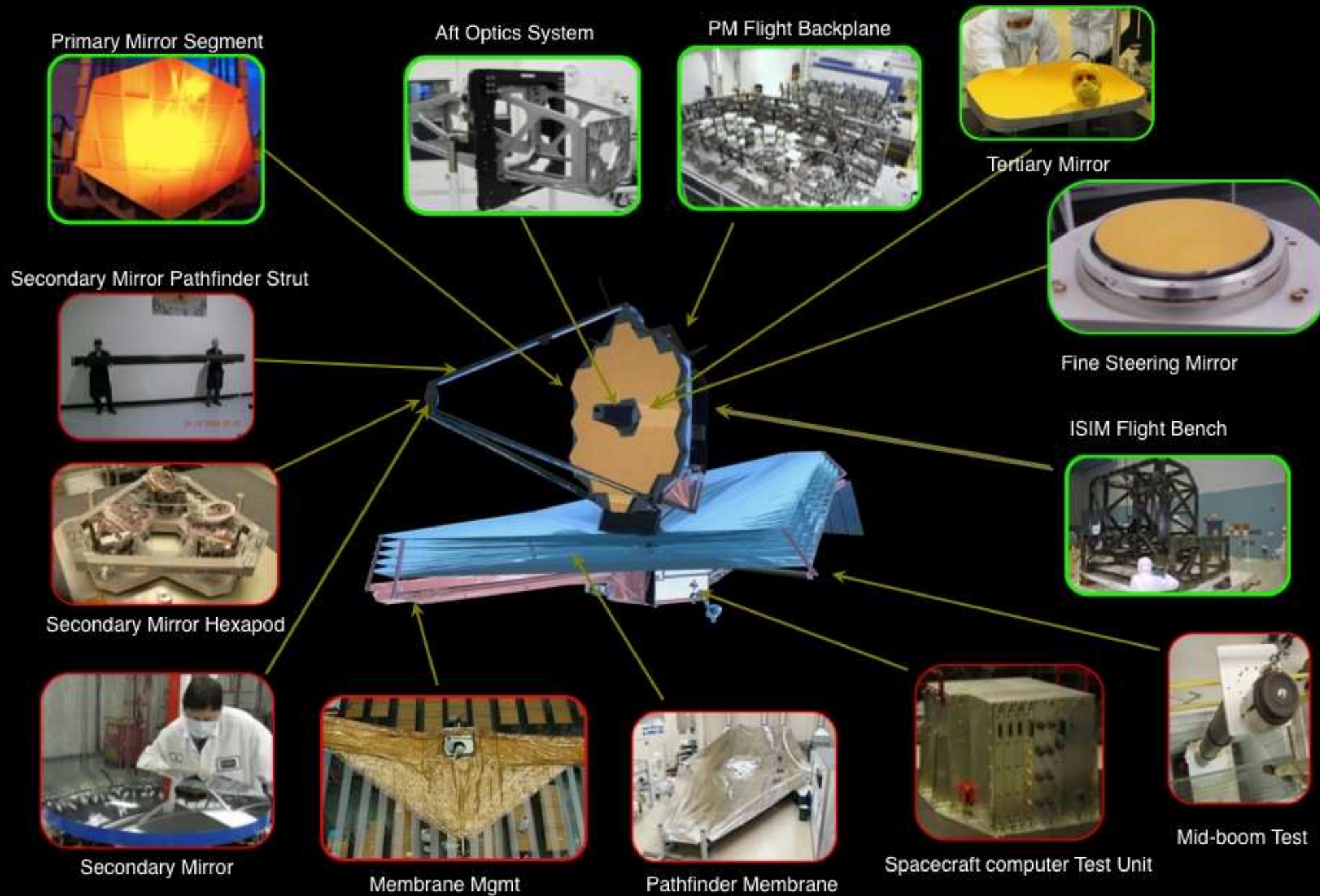




Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2013-2015.  
 Ball 1/6 scale-model for WFS: produces diffraction-limited  $2.0 \mu\text{m}$  images.

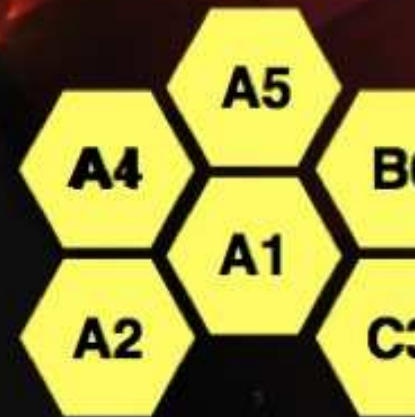


# JWST Hardware Status

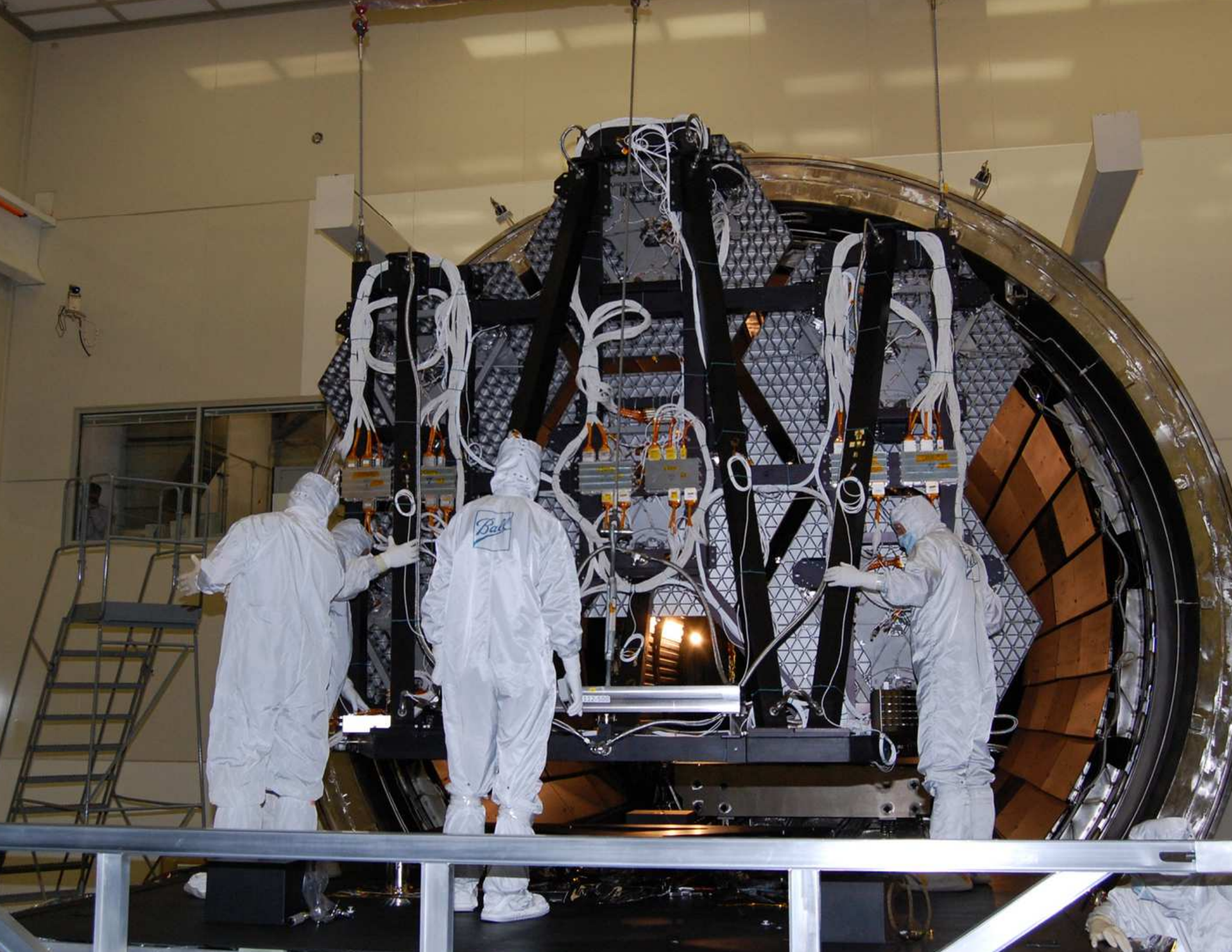




# Mirror Acceptance Testing











# JWST Flight Mirrors Have Completed Polishing



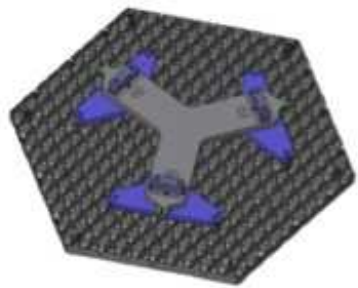
Tinsley Final Measurement Requirements  
Total Figure  $< 17 \text{ nm}$

FLIGHT COMPOSITE RMS:

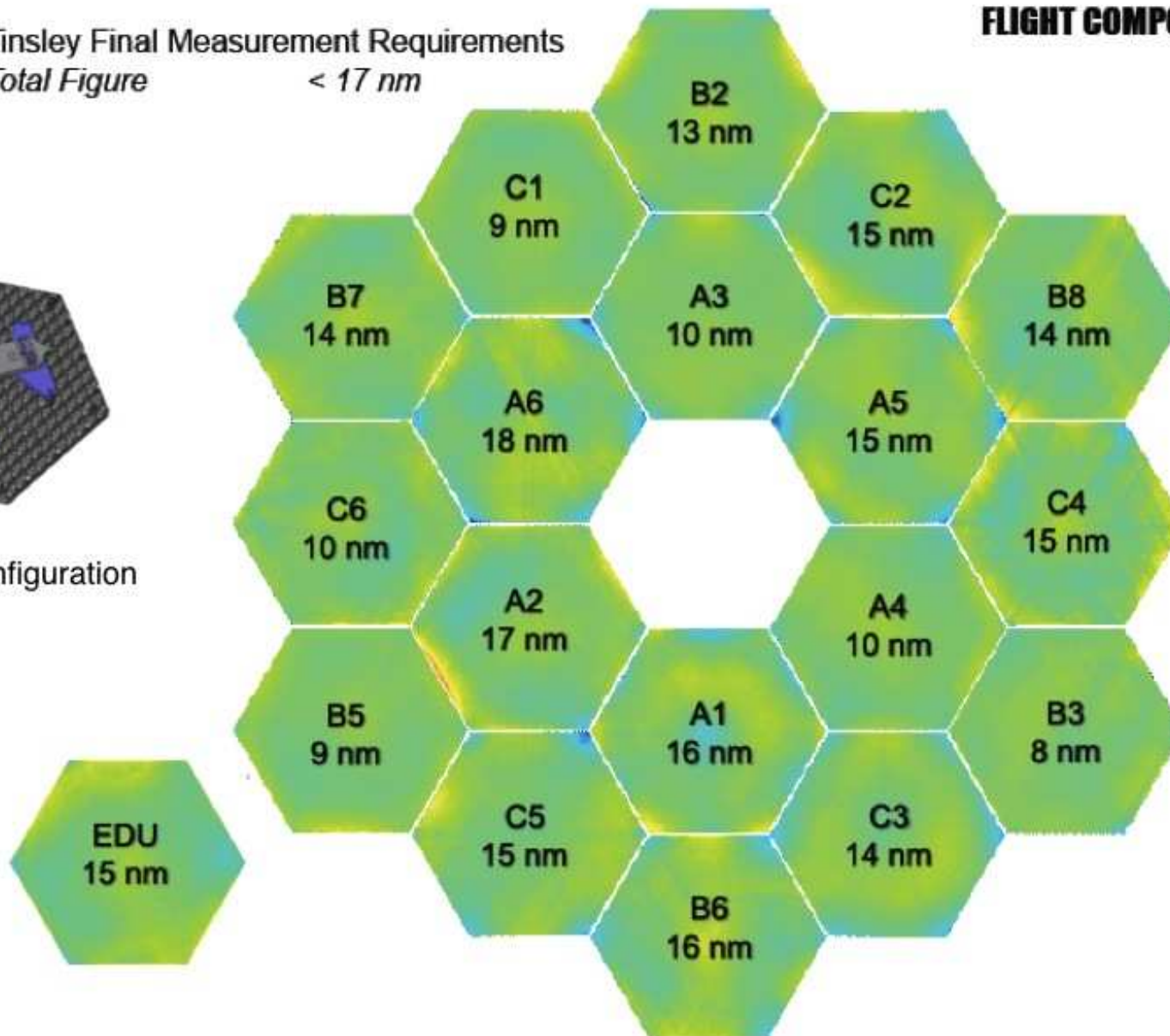
**13.3 nm**

PV:

**976.4 nm**



Mirror test configuration



200.0

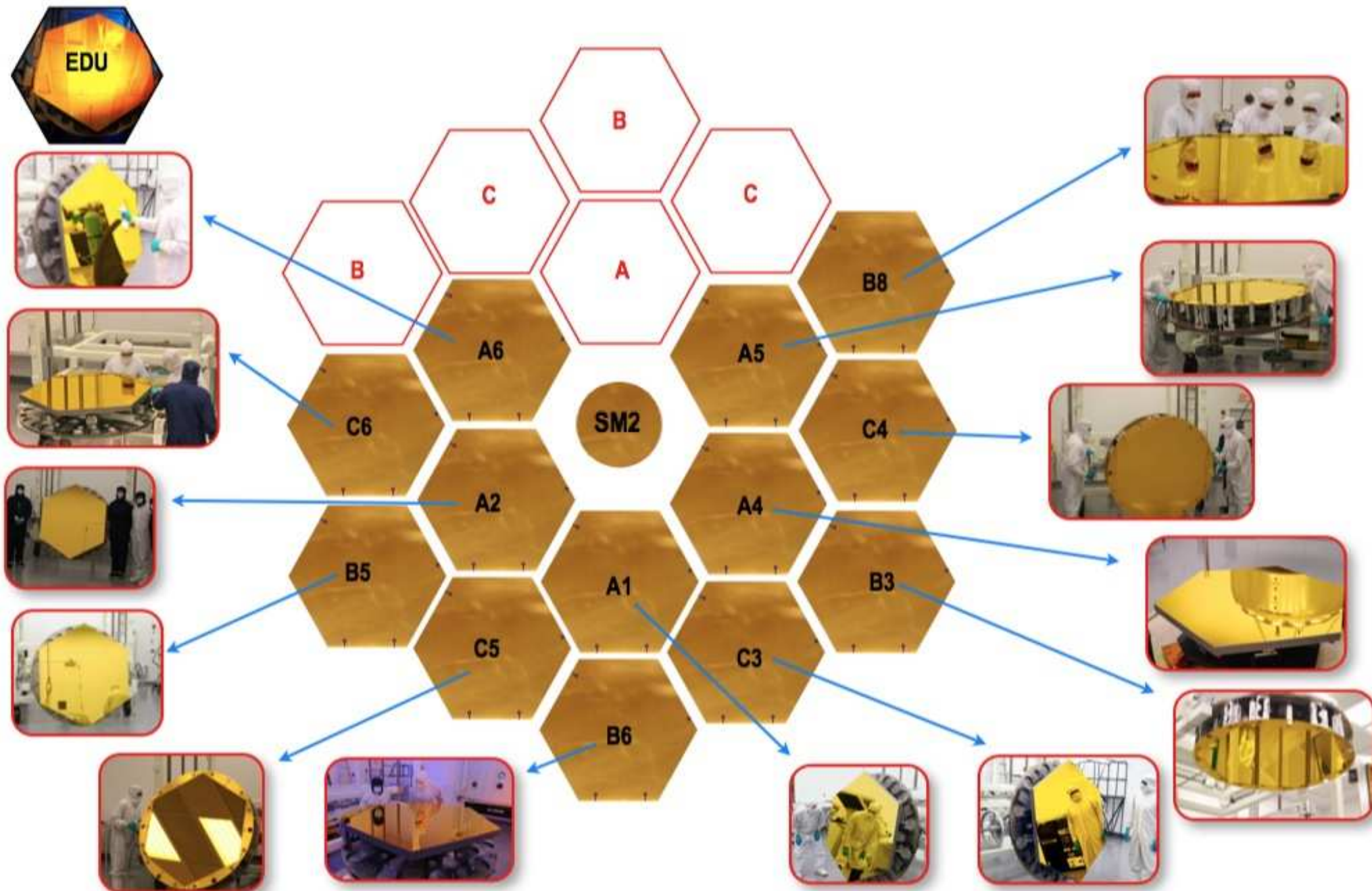
nm

-200.0





# 13 Gold-Coated Flight PMSAs





# (3b) JWST instrument update: US (UofA, JPL), ESA, & CSA.



## Instrument Overview

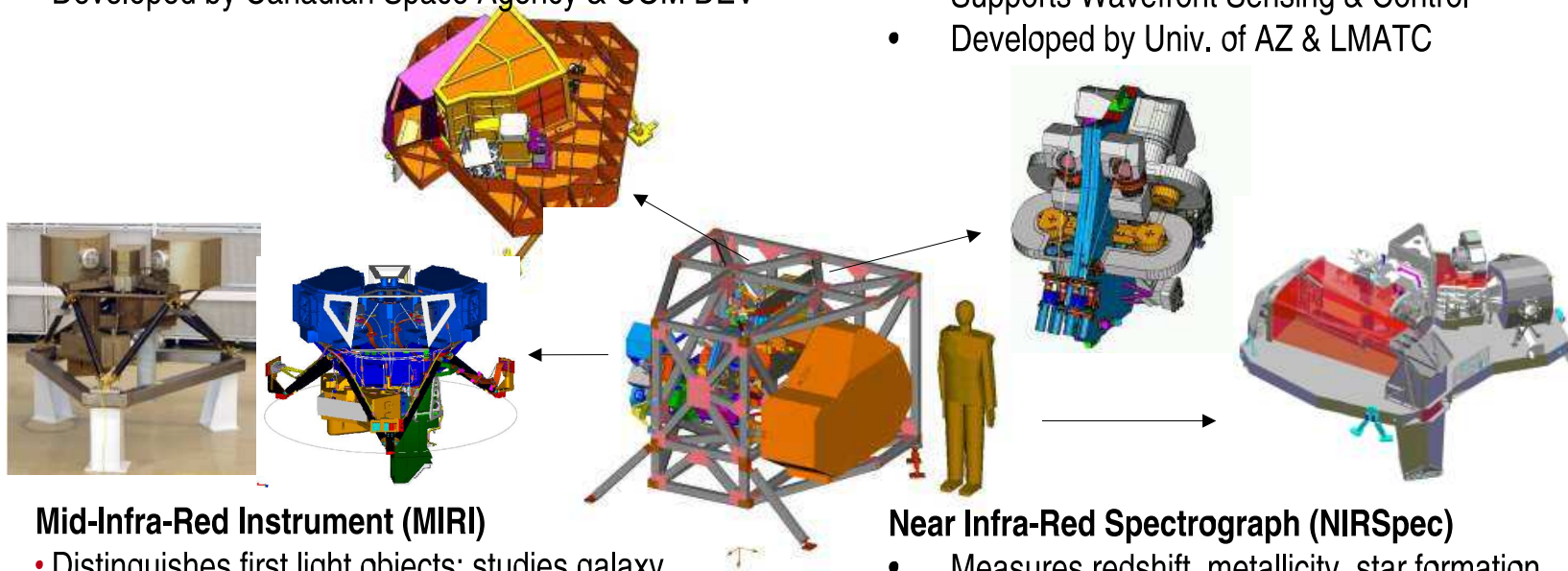


### Fine Guidance Sensor (FGS)

- 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

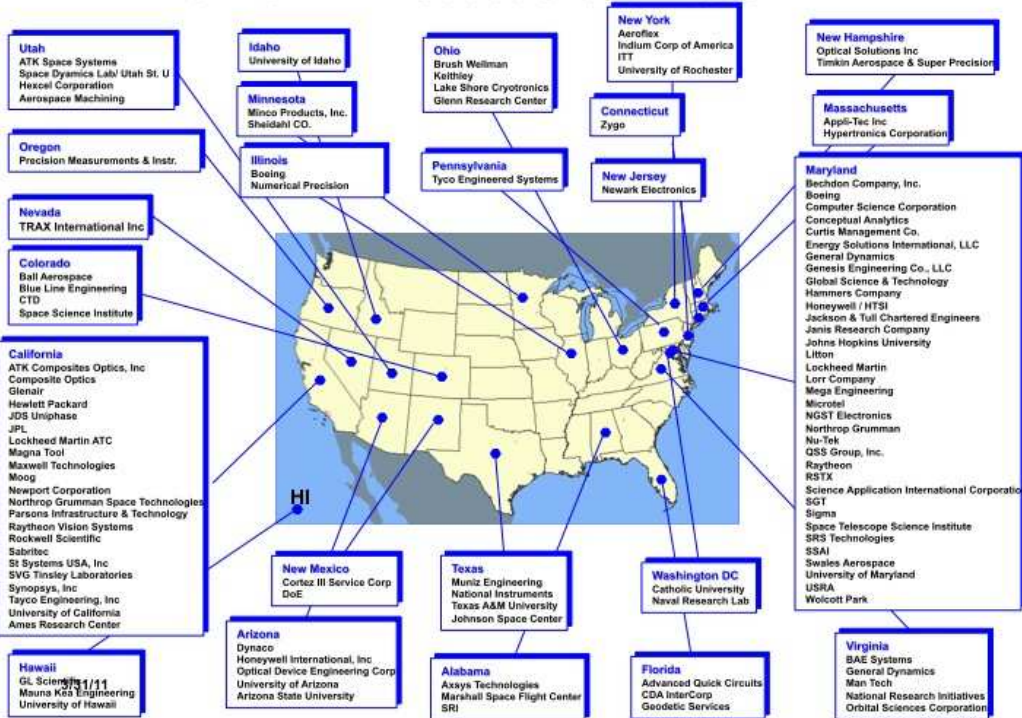
### Near Infra-Red Spectrograph (NIRSpec)

- 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

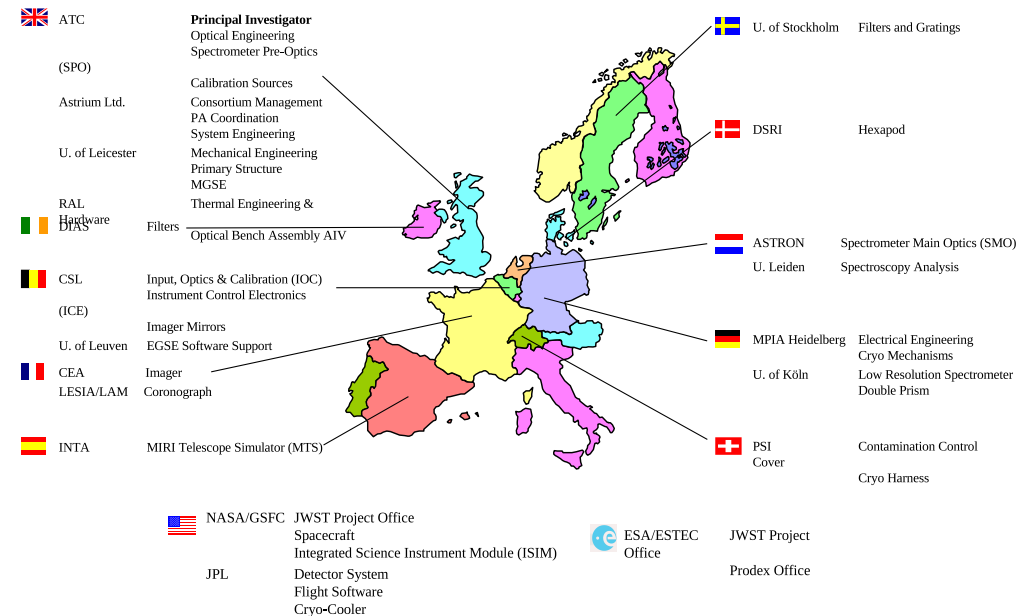
MIRI & NIRSpec completed 9/11; NIRCam & FGS delivery to GSFC 12/11.



# JWST: A Product of the Nation



## European Consortium Who & Where



10

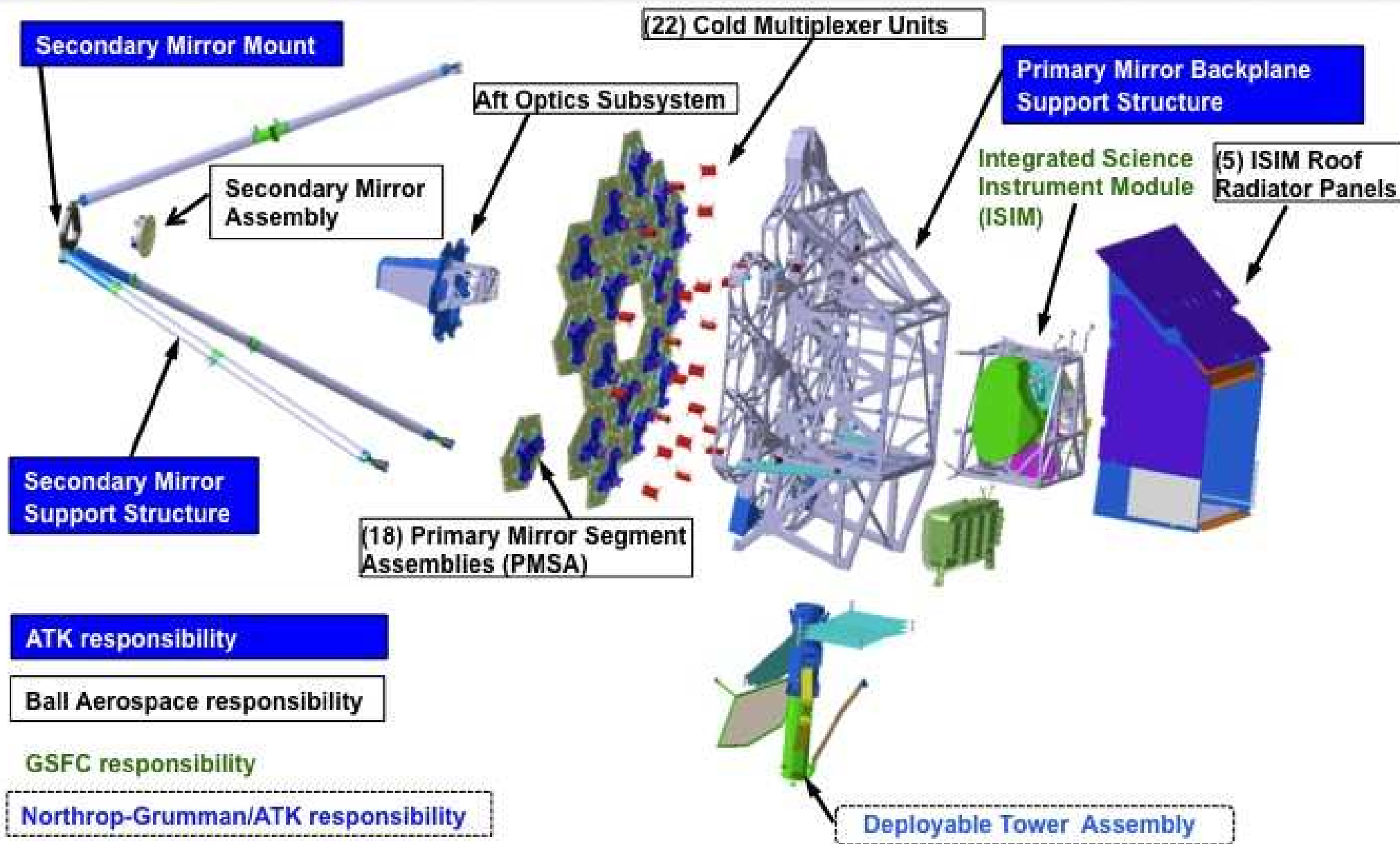
**MIRI European Consortium**  
25.05.05

- JWST hardware made in 27 US States:  $\geq 75\%$  of launch-mass finished.
- Launch Vehicle (Ariane V), NIRSpec, & MIRI provided by ESA.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.





# TELESCOPE ARCHITECTURE







Despite NASA's CAN-do approach: Must find all the cans-of-worms ...



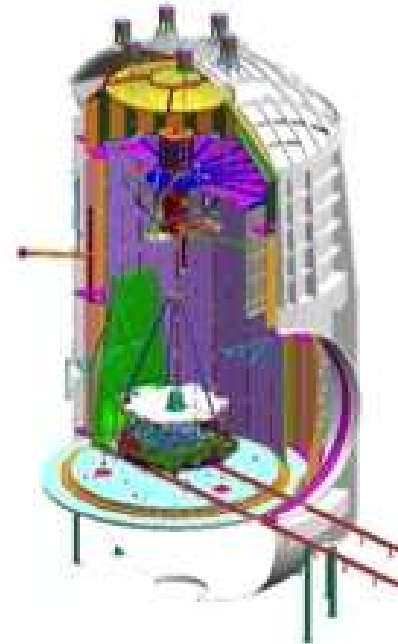


# TELESCOPE TESTING CHAMBER AT JOHNSON SPACE CENTER



Notice people for scale

**Largest simulation of deep space ever attempted will be done here**



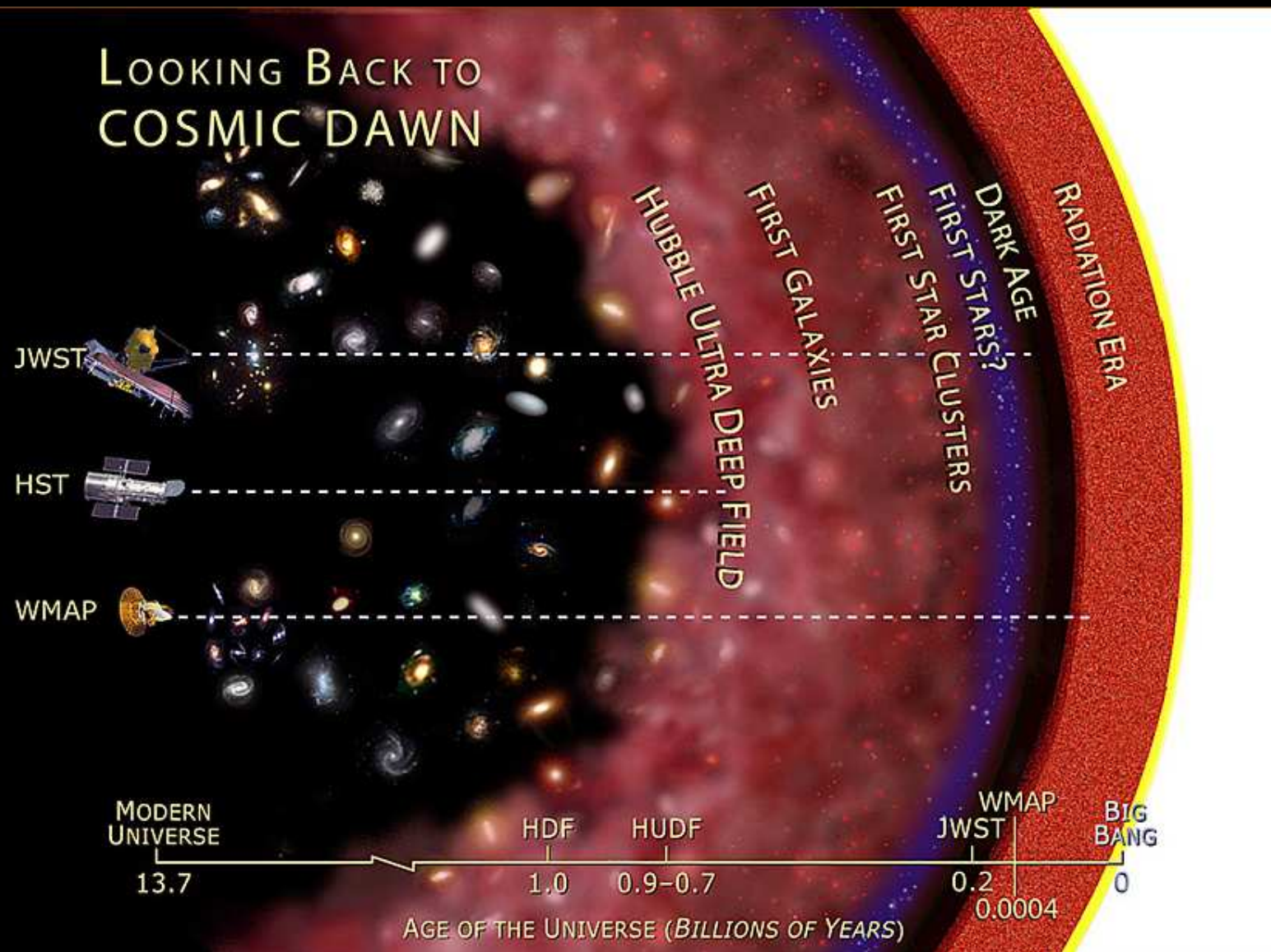
**Telescope and science instruments installed in the test chamber**

Element Progress





#### (4) What is First Light, Reionization, and Galaxy Assembly?



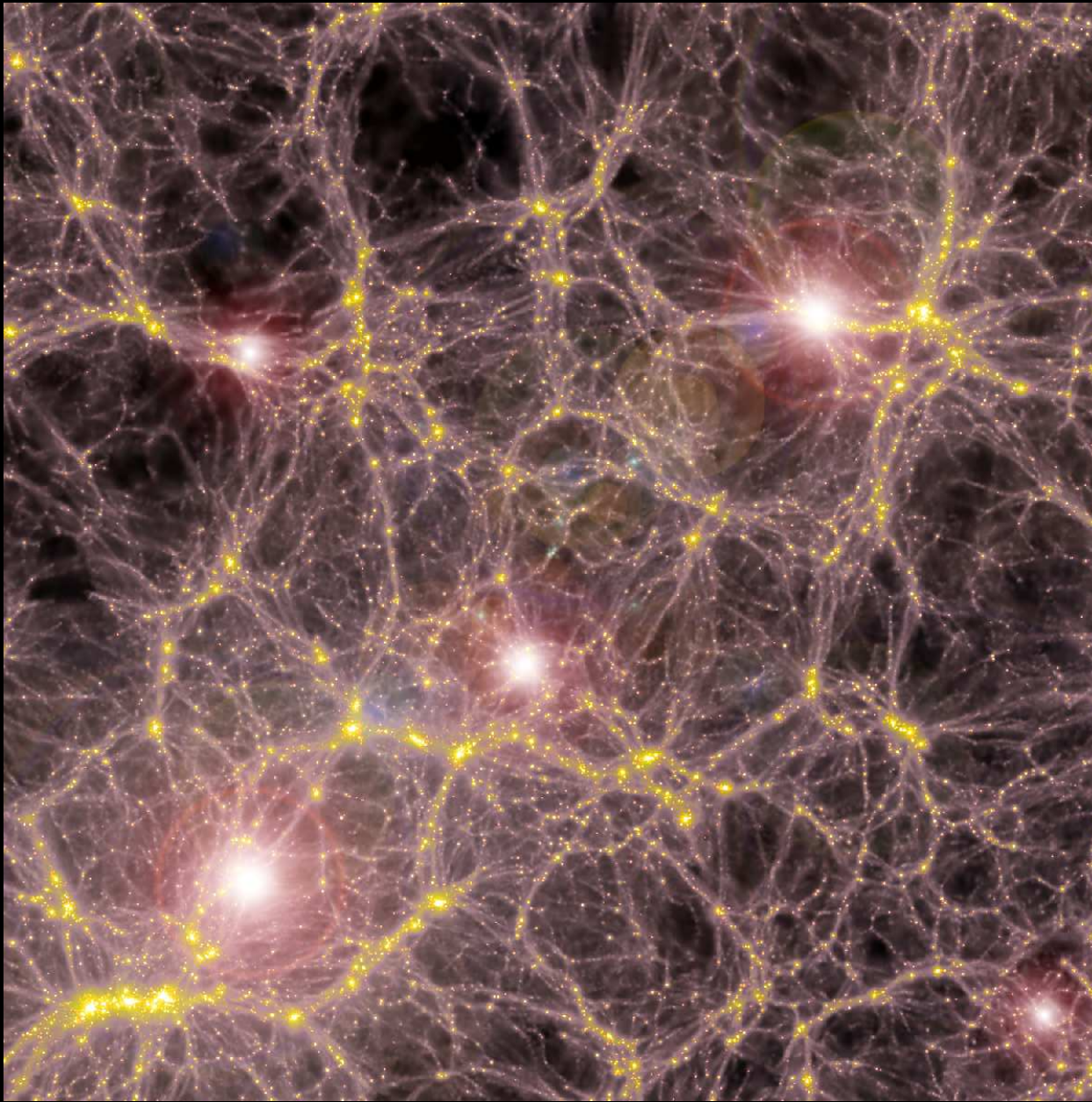
HST: Hubble sequence & galaxy evolution at  $z \lesssim 7-8$  (age  $\gtrsim 0.7$  Gyr).

JWST: First Light, Reionization, & Galaxy Assembly  $z \gtrsim 8-20$  (0.2-0.7 Gyr).

WMAP: Neutral Hydrogen first forms at  $z=1091$  (age  $\simeq 0.378$  Myr).



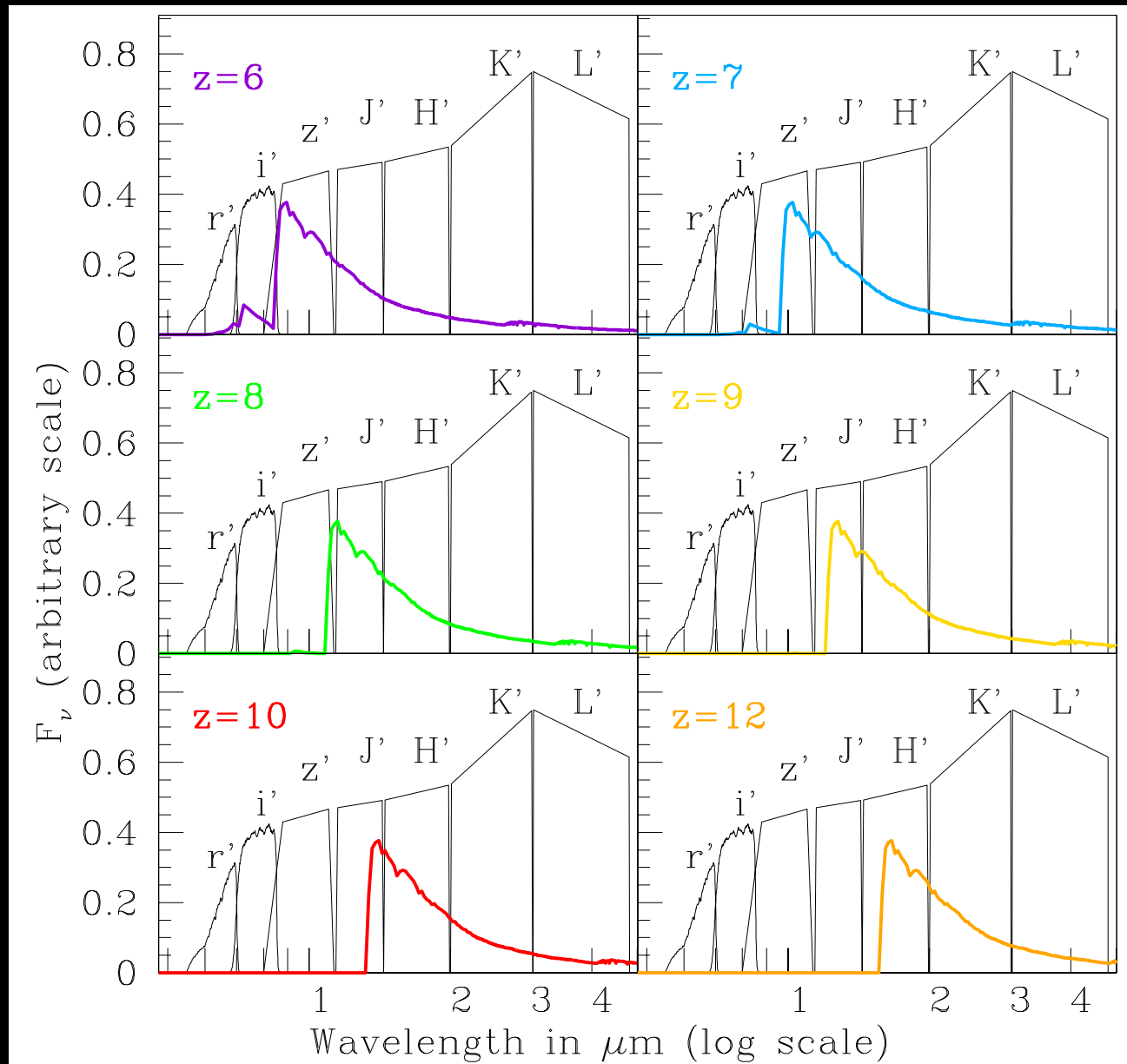
## (4a) How will JWST Observe First Light and Reionization?



- Detailed hierarchical models (Dr. V. Bromm) show that formation of Pop III stars reionized universe for the first time at  $z \simeq 10-30$  (First Light, age  $\simeq 500-100$  Myr).
- This should be visible to JWST as the first massive stars and surrounding star clusters, and perhaps their extremely luminous supernovae at  $z \simeq 10 \rightarrow 30$ .

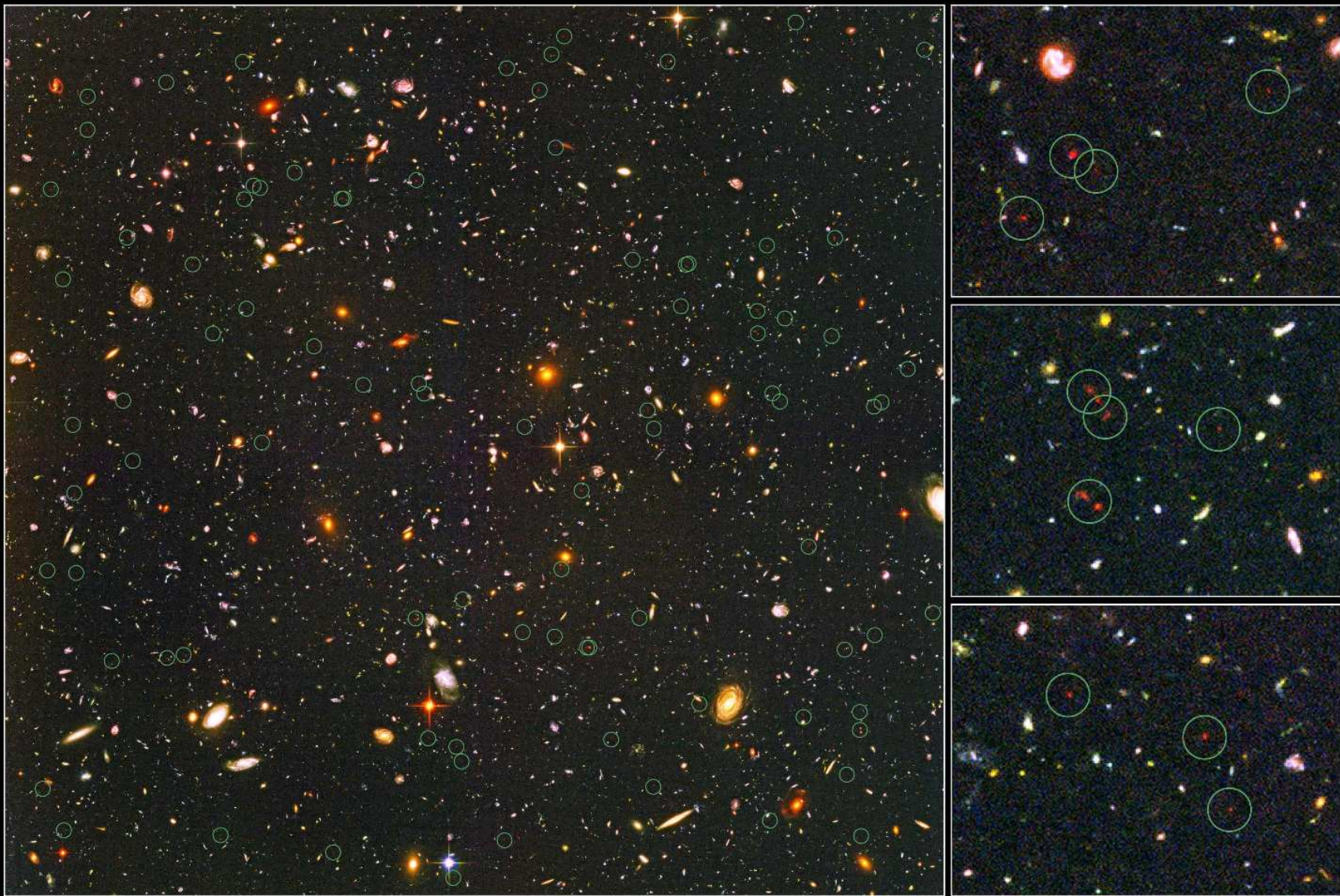


## (4) How will JWST measure First Light & Reionization?



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





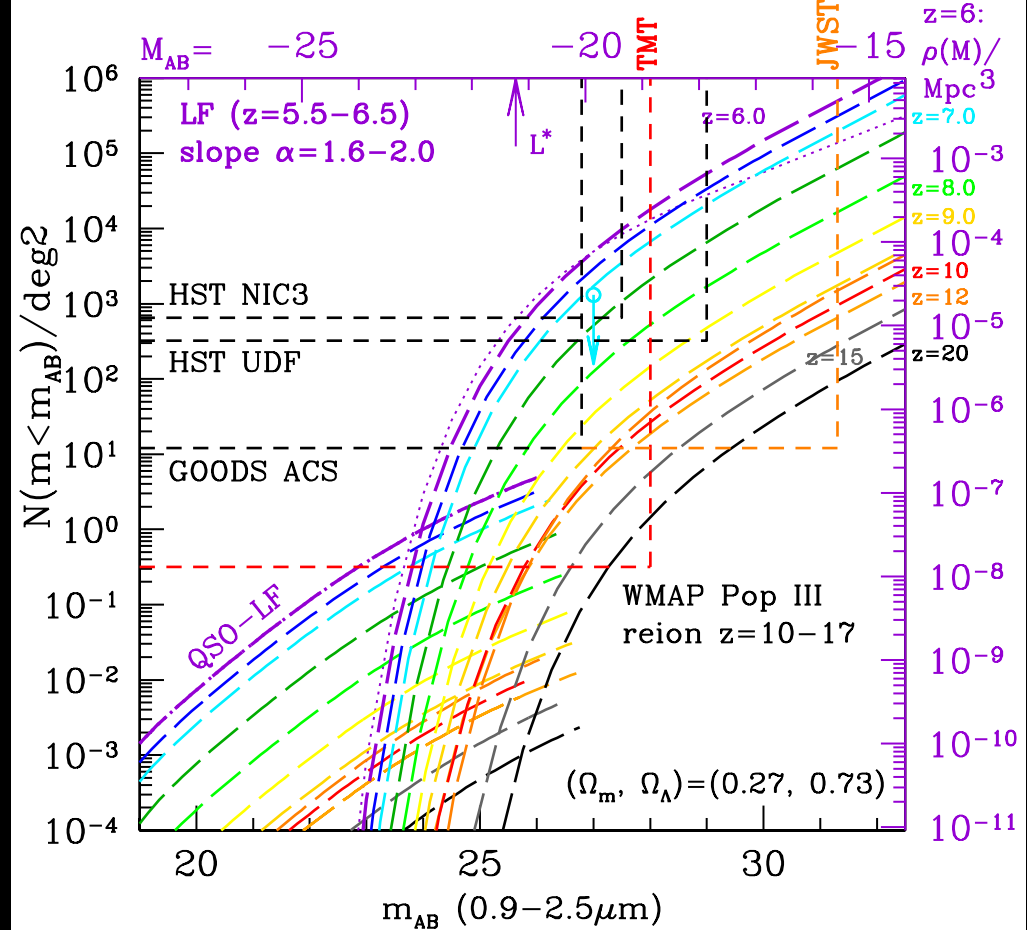
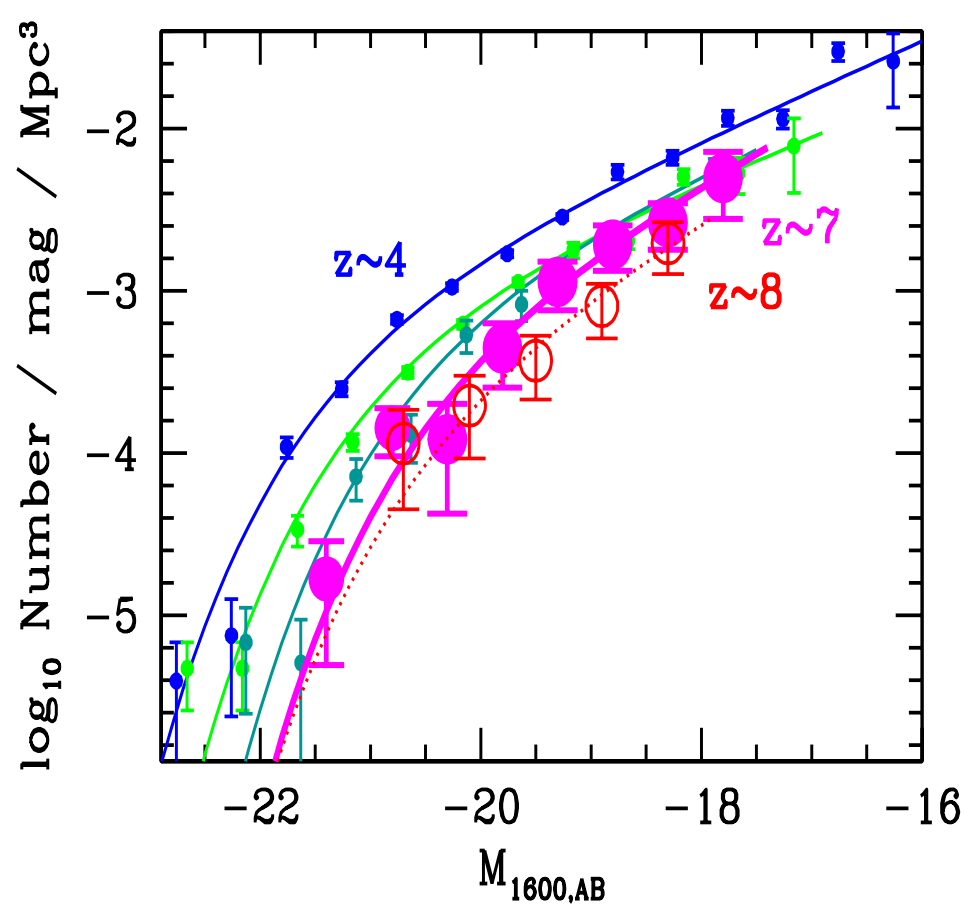
**Distant Galaxies in the Hubble Ultra Deep Field**  
**Hubble Space Telescope • Advanced Camera for Surveys**

NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

STScI-PRC04-28

Hubble UltraDeep Field: Dwarf galaxies at  $z \simeq 6$  (age  $\simeq 1$  Gyr; Yan & Windhorst 2004), many confirmed by spectra at  $z \simeq 6$  (Malhotra et al. 2005).





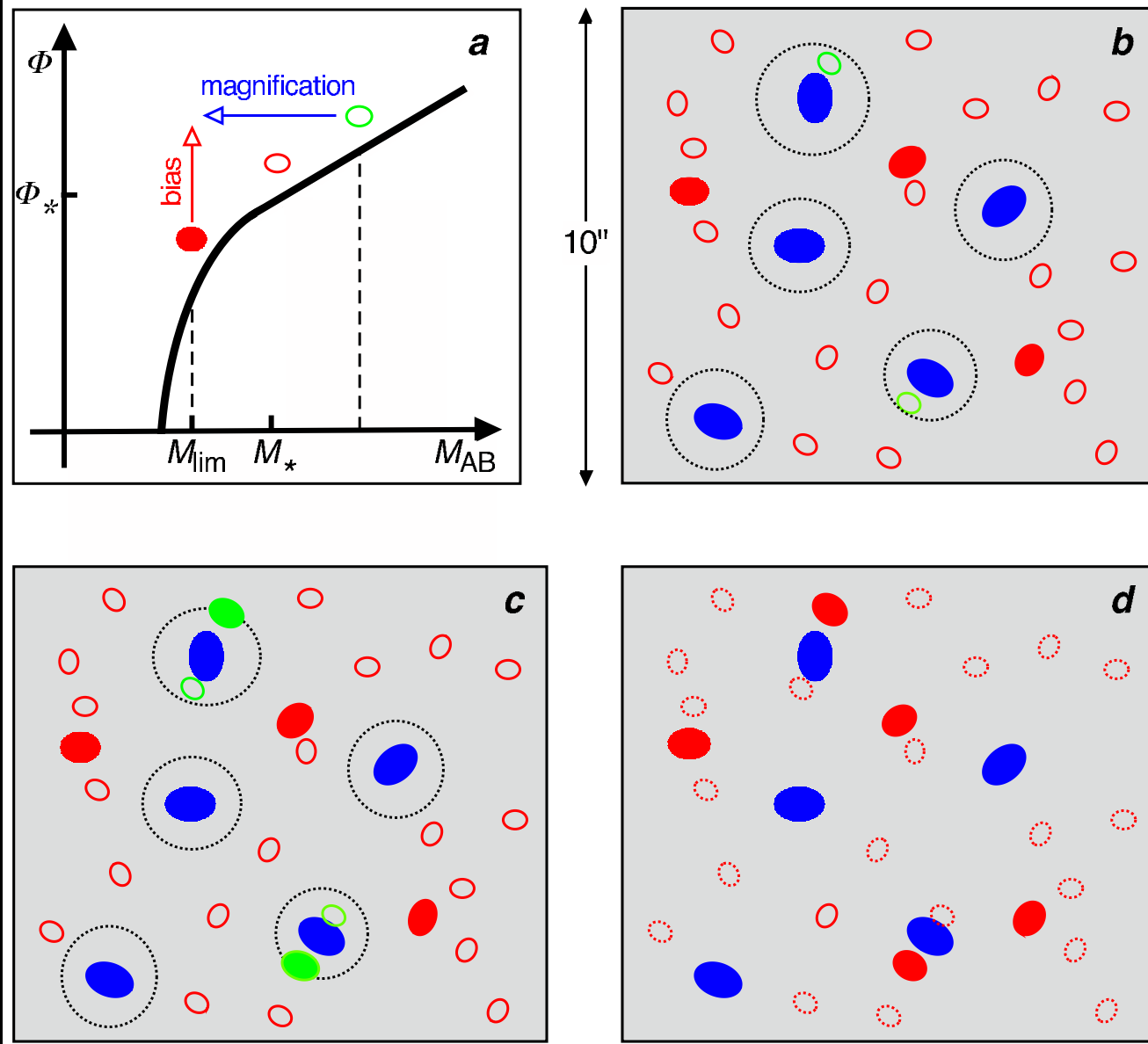
The “Cosmic Stock Market chart of galaxies: Very few big bright objects in the first Gyr, but lots of dwarf galaxies at  $z \gtrsim 6$  (age  $\lesssim 1$  Gyr).

- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- JWST can also trace Super-Massive Black Holes as faint Quasars in young galaxies (M. Mechtley Dissertation).







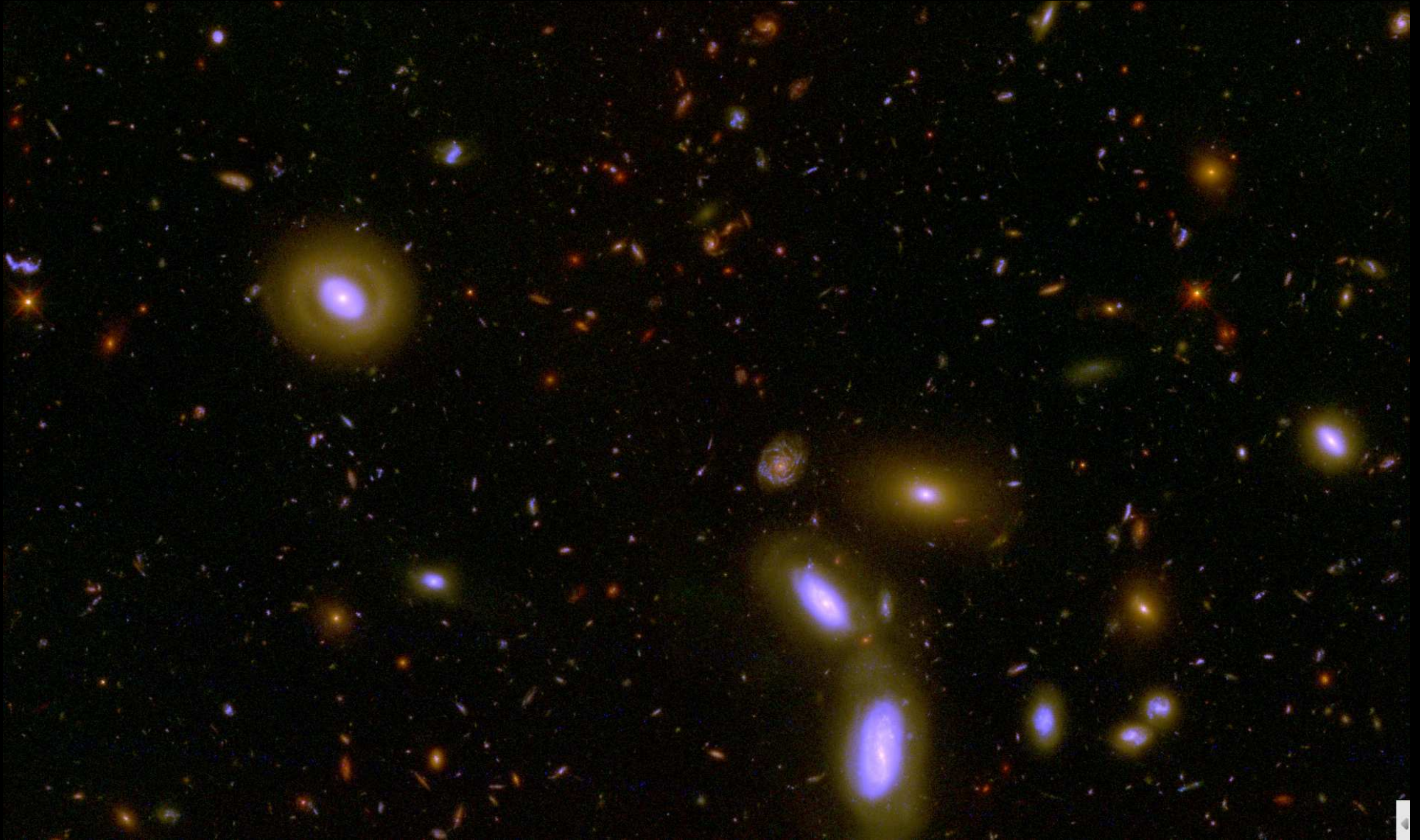


Hard to see the forest for the trees in the first 0.5 Gyrs?:

- Foreground galaxies ( $z \simeq 1-2$  or age  $\simeq 3-6$  Gyr) may gravitationally lens or amplify galaxies at  $z \gtrsim 8-10$  (age  $\lesssim 0.5$  Gyr; Wyithe et al. 2011).
- This could change the landscape for JWST observing strategies.



- (4) How can JWST measure Galaxy Assembly?

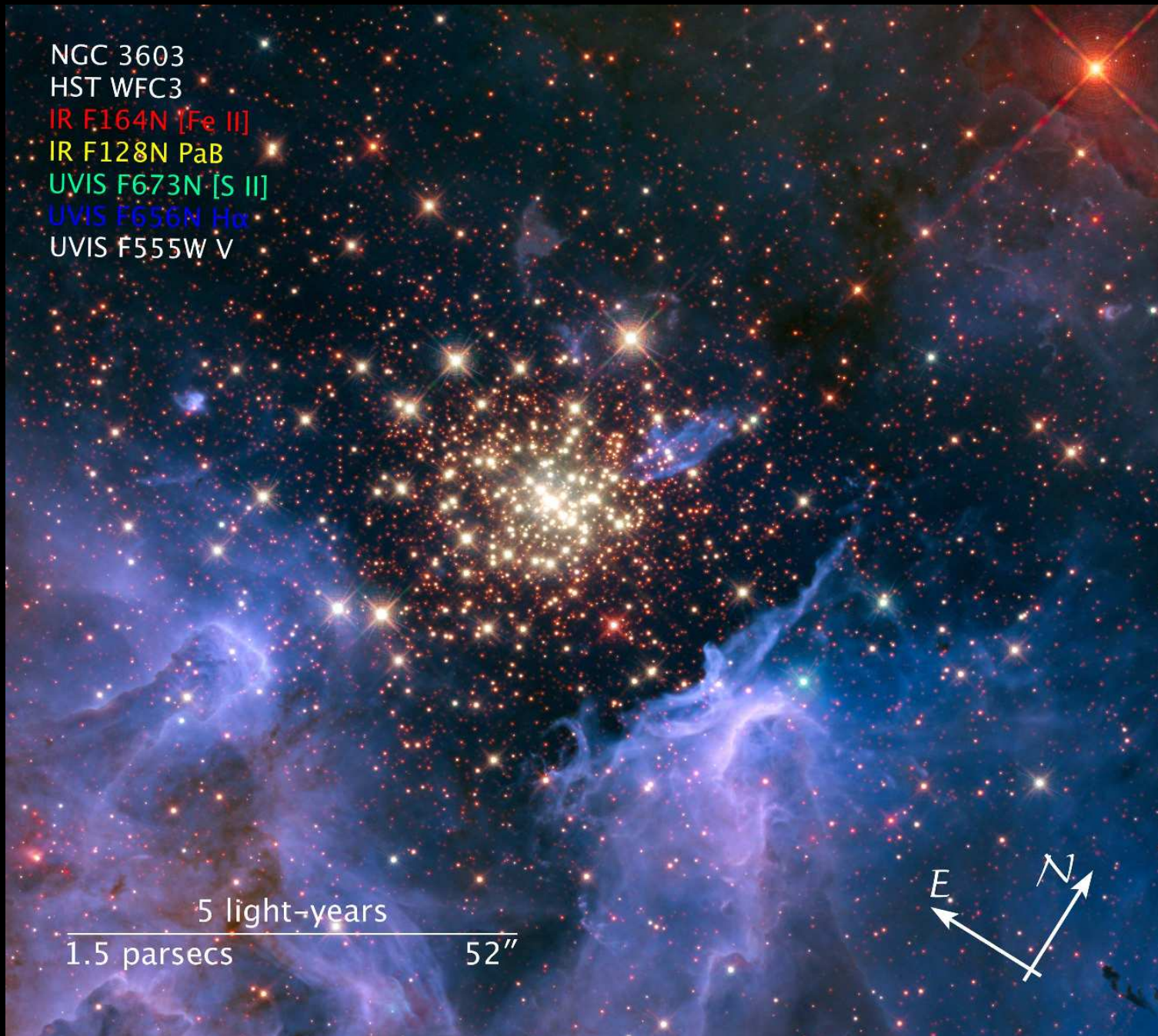


HST/WFC3 & ACS reach  $AB=26.5-27.0$  mag (100 fireflies from Moon) over  $0.1 \times$  full Moon area in 10 filters from  $0.2-2\mu\text{m}$  wavelength.

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



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

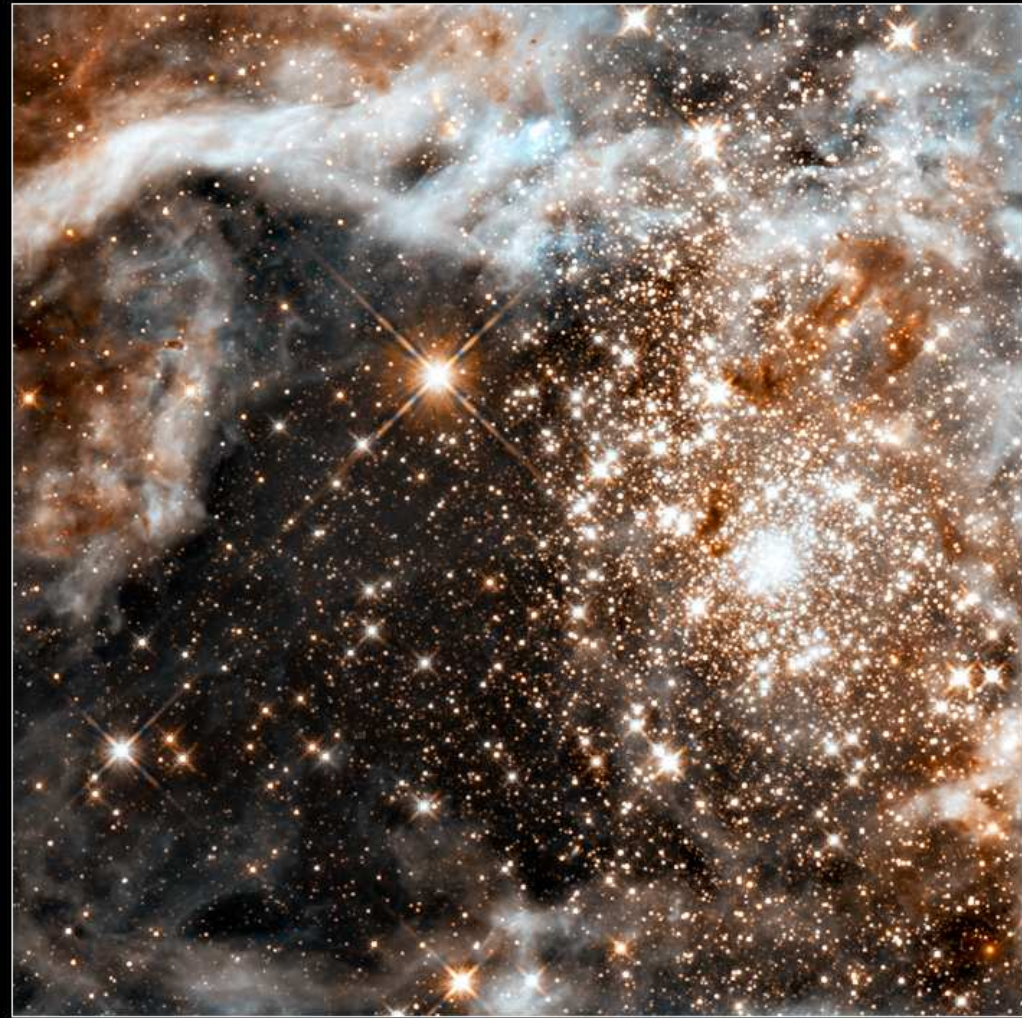
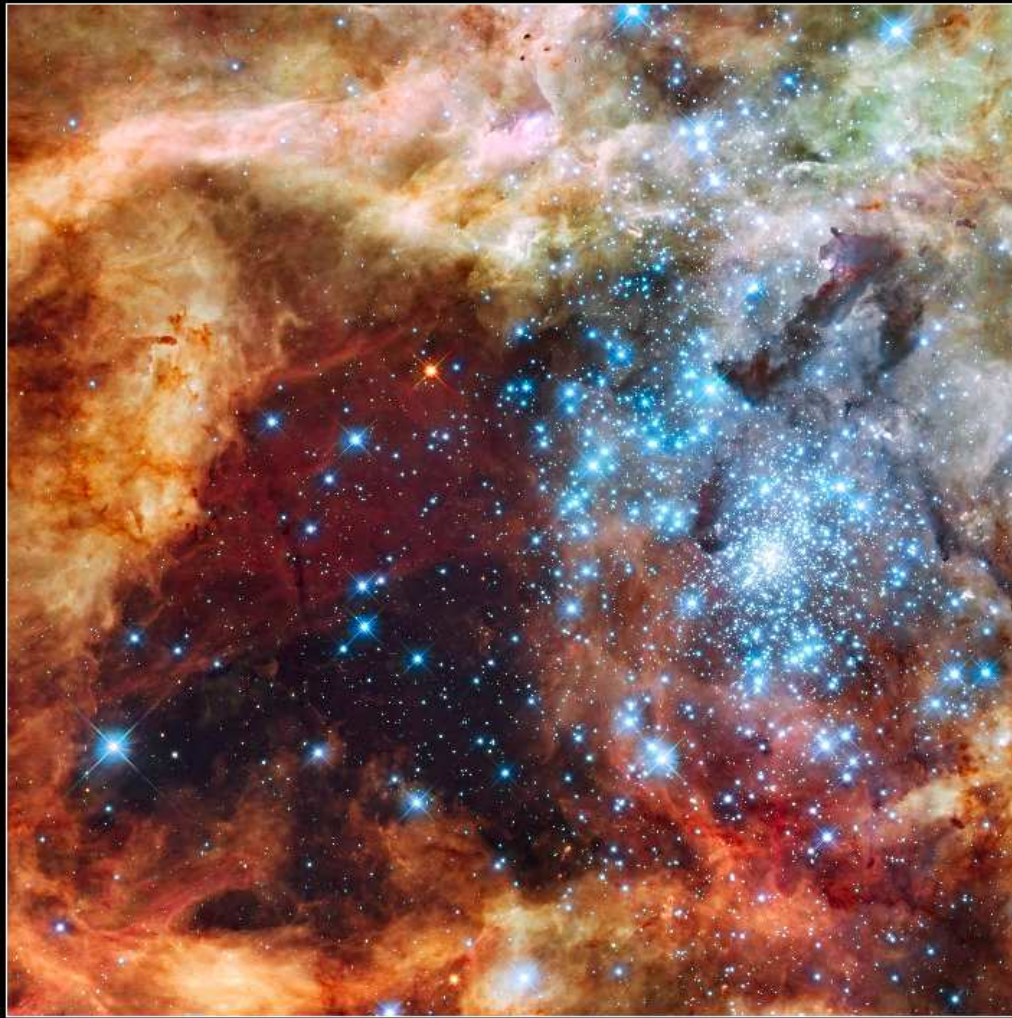


NGC 3603: Young star-cluster triggering star-birth in “Pillars of Creation”



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 stars like the Sun.



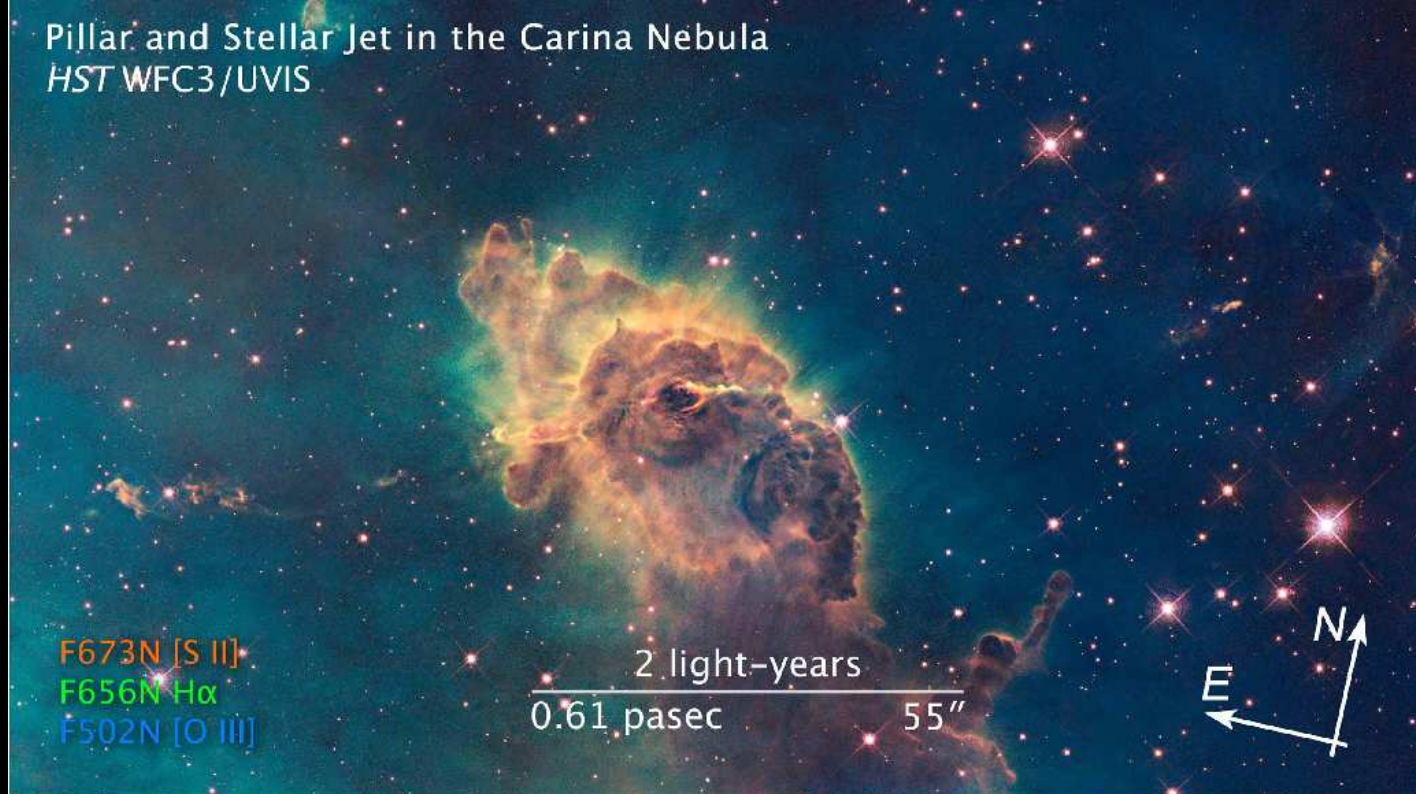








Pillar and Stellar Jet in the Carina Nebula  
*HST* WFC3/UVIS

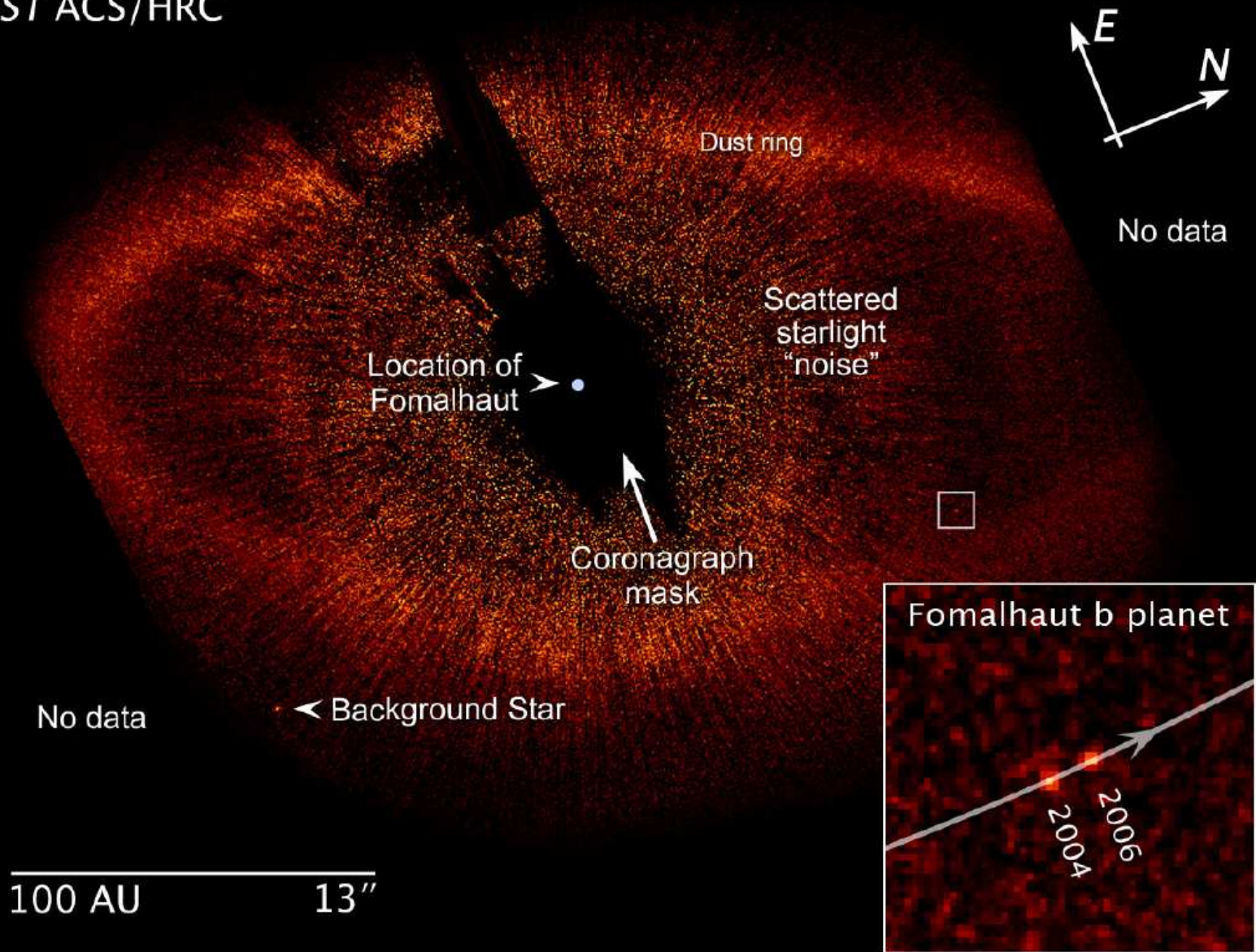


*HST* WFC3/IR





Fomalhaut  
HST ACS/HRC



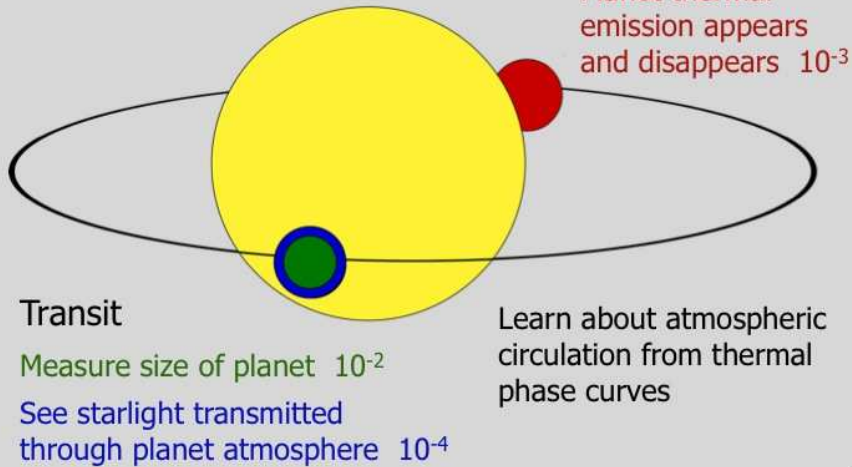
HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut:  
First direct imaging of a moving planet forming around a nearby star!

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



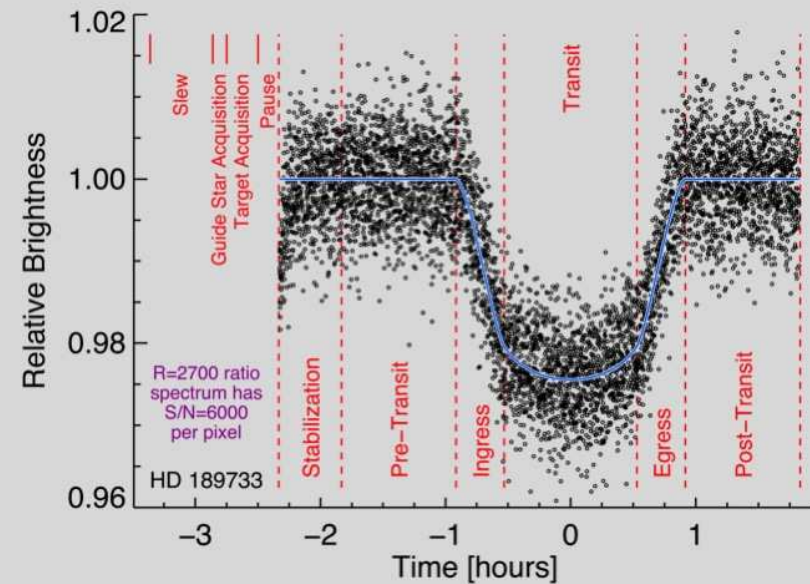
## Schematic of Transit and Eclipse Science

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



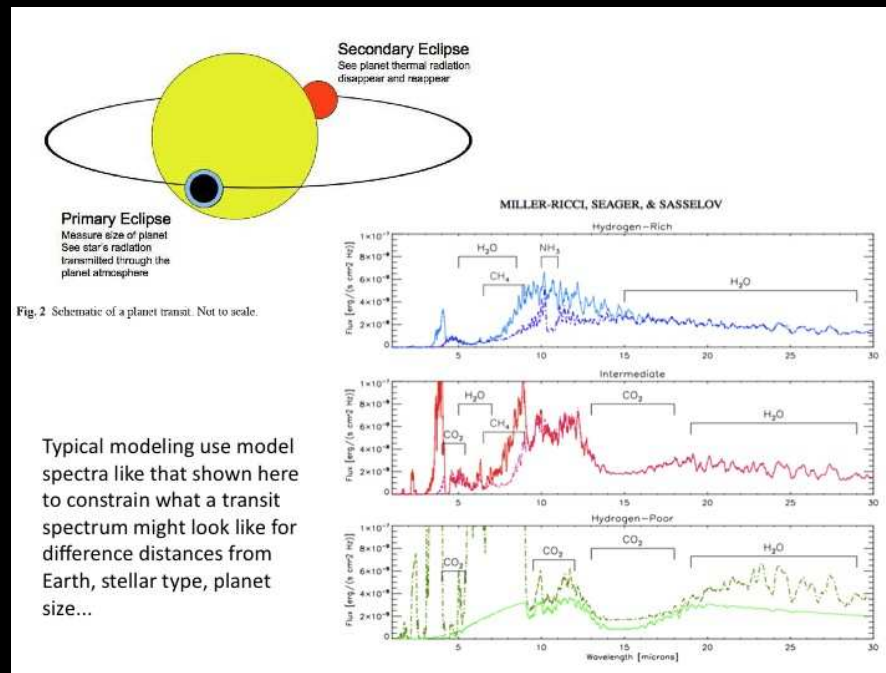
6

## Timeline of a Transit Observation



13

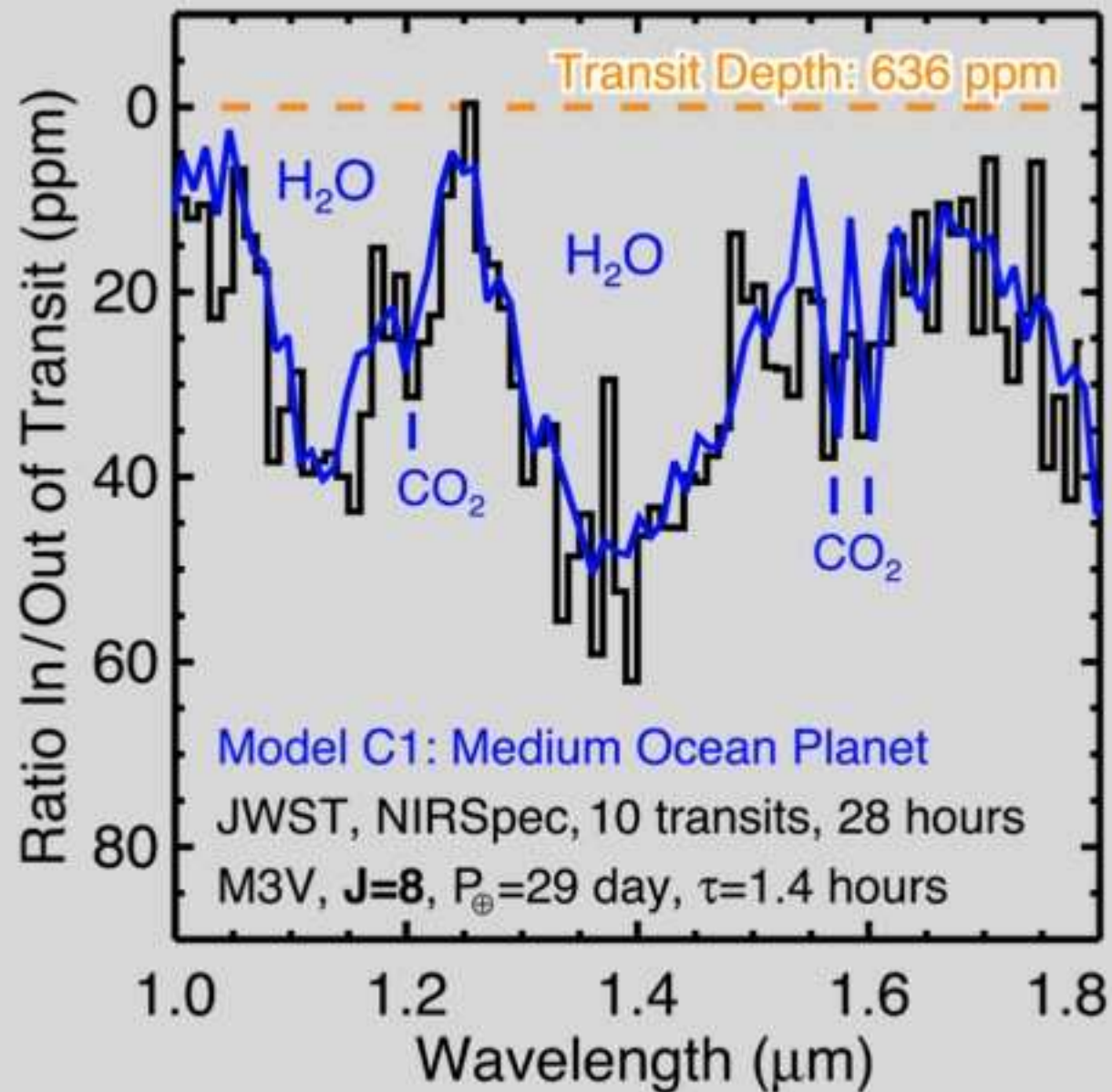
JWST can do very precise photometry of transiting Earth-like exoplanets.



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



# Transit Spectrum of Habitable “Ocean Planet”



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



## (6) Conclusions

(1) HST established how galaxies formed and evolve in the last 12.7 Gyrs:

- Galaxies of all Hubble types formed over a wide range of time, but with a notable transition around  $z \simeq 1-2$  when the Hubble sequence forms.

(2) JWST Project is technologically front-loaded and well on track:

- Passed Preliminary and Critical Design Reviews in 2008 & 2010.

No technical showstoppers. Management replan in 2011.

- More than 75% 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 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.
- How to find water and CO<sub>2</sub> in transiting Earth-like exoplanets.

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

- IR sequel to HST after 2018: Training the next generation researchers.



# SPARE CHARTS

---



## What you can do to help save JWST — Web-links:

<http://capwiz.com/supportjwst/home/>

<http://www.whitehouse.gov/contact>

<http://www.facebook.com/SaveJWST>

<http://twitter.com/#!/saveJWST> or <http://goo.gl/iAR4I>

<http://savethistelescope.blogspot.com/>

<http://www.change.org/petitions/do-not-cancel-funding-for-the-james-webb-space-telescope>

## General JWST Information:

<http://www.aura-astronomy.org/news/news.asp?newsID=264>

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

<http://www.asu.edu/clas/hst/www/jwst/> [Talk, Movie, Java-tool]

Thank you for your time and support!





Life-sized JWST model, at NASA/GSFC with the whole JWST Project ...





Life-sized JWST model, at NASA/GSFC Friday afternoon after 5 pm ...



# 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)



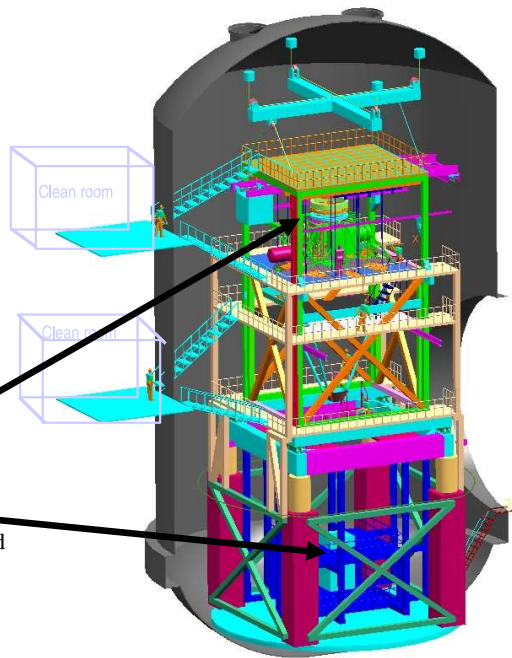
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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)

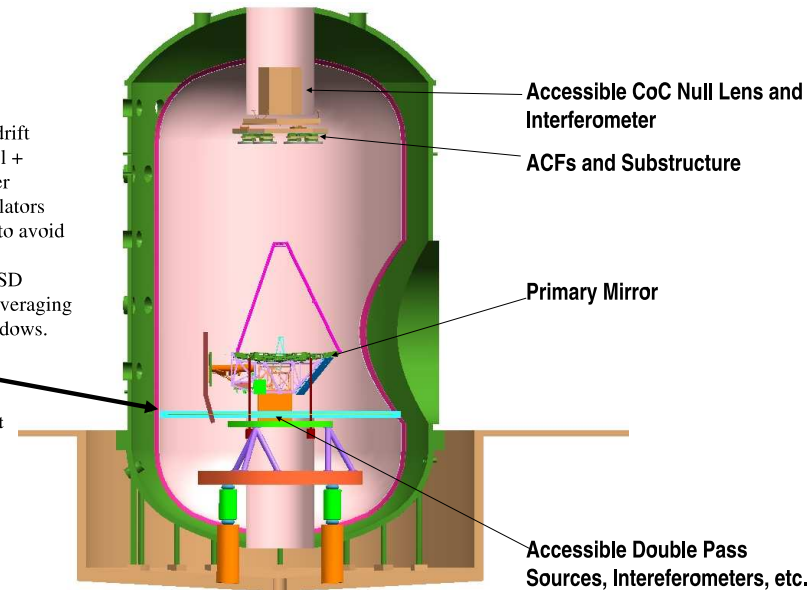


No Metrology Tower and Associated Cooling H/W.  
External Metrology

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.



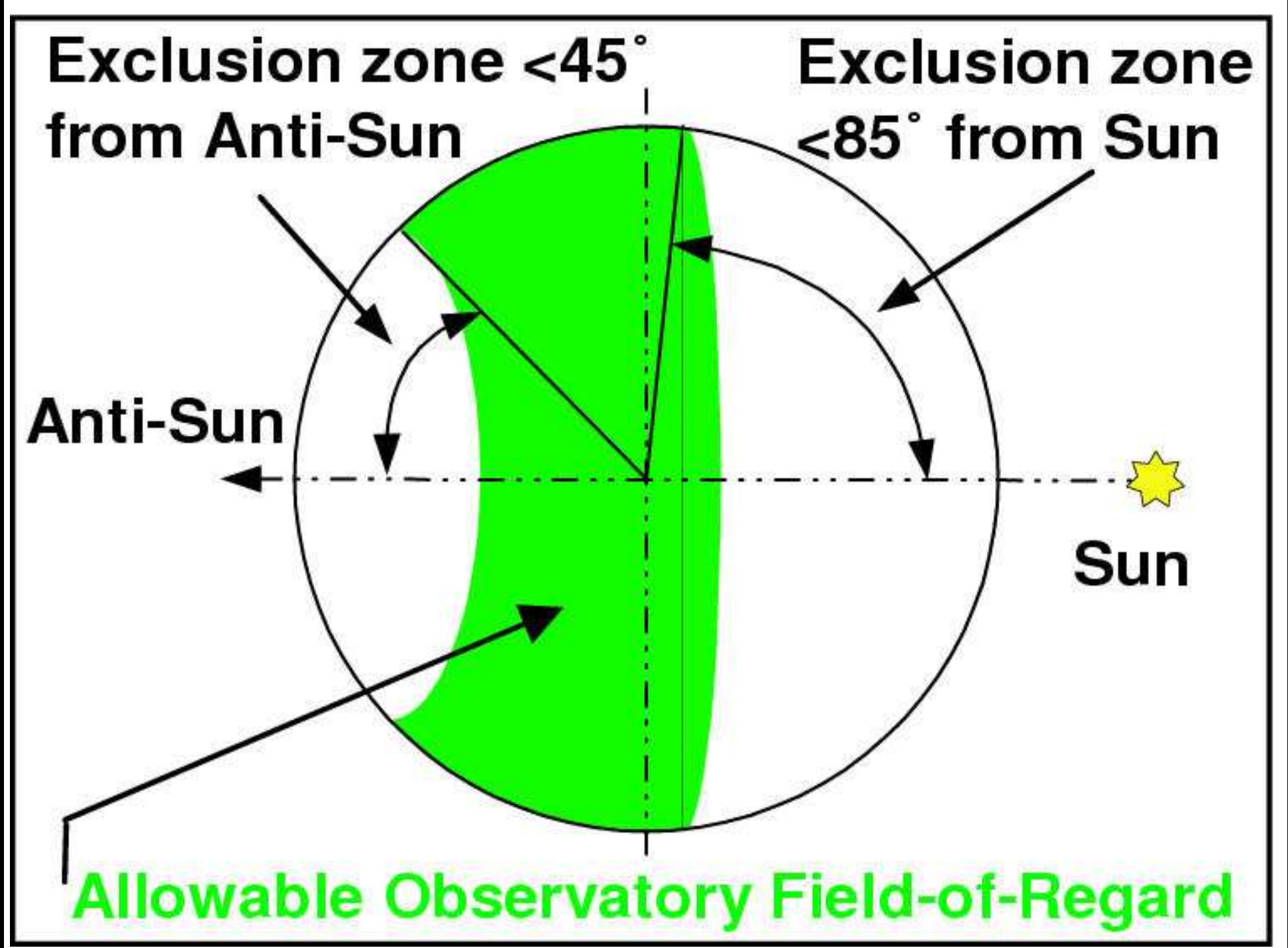
Drawing care of ITT

Page 6

JWST underwent several significant replans and risk-reduction schemes:

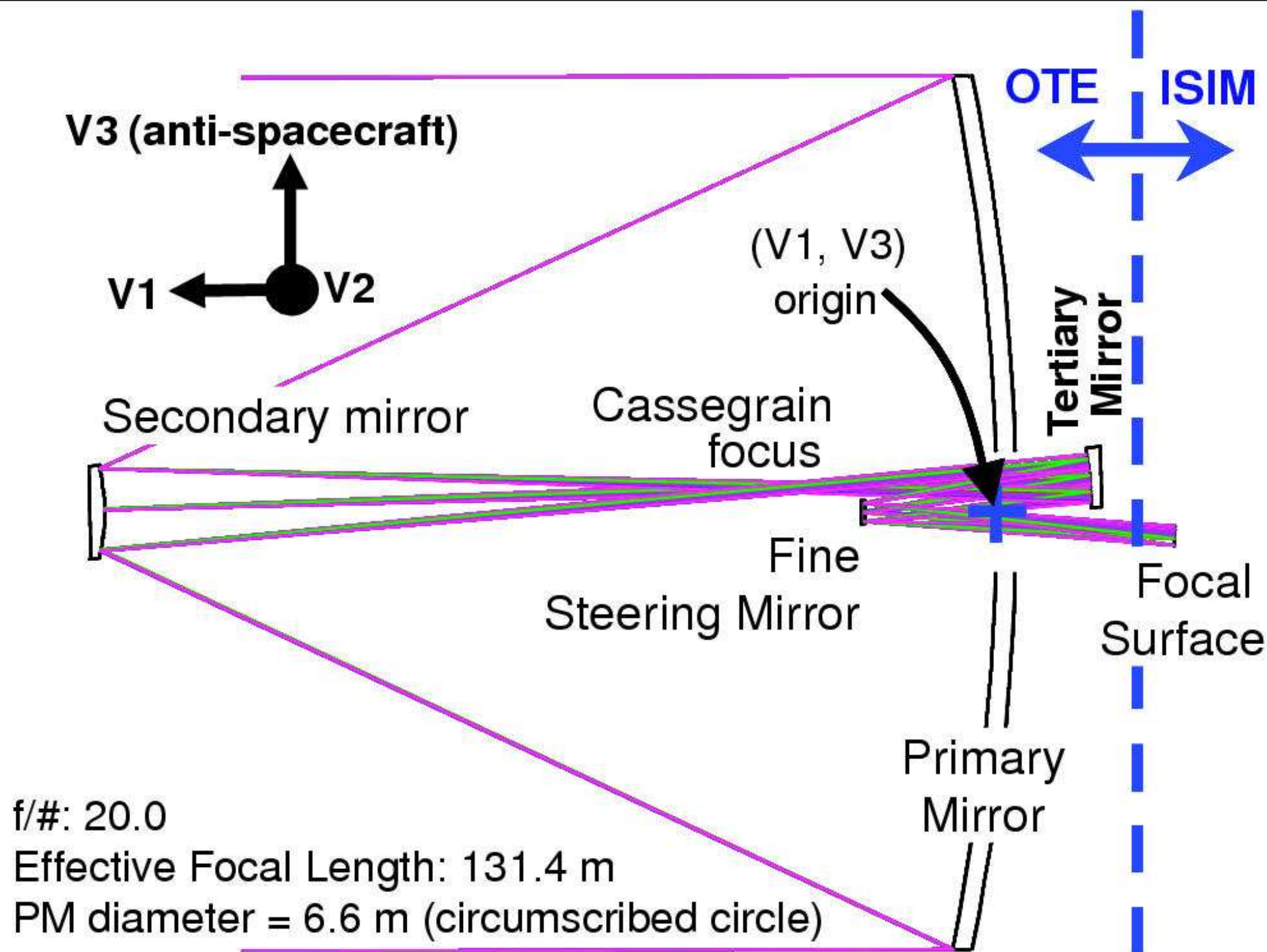
- $\lesssim 2003$ : Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010: Passes Mission Critical Design Review — Replan Int. & Testing.





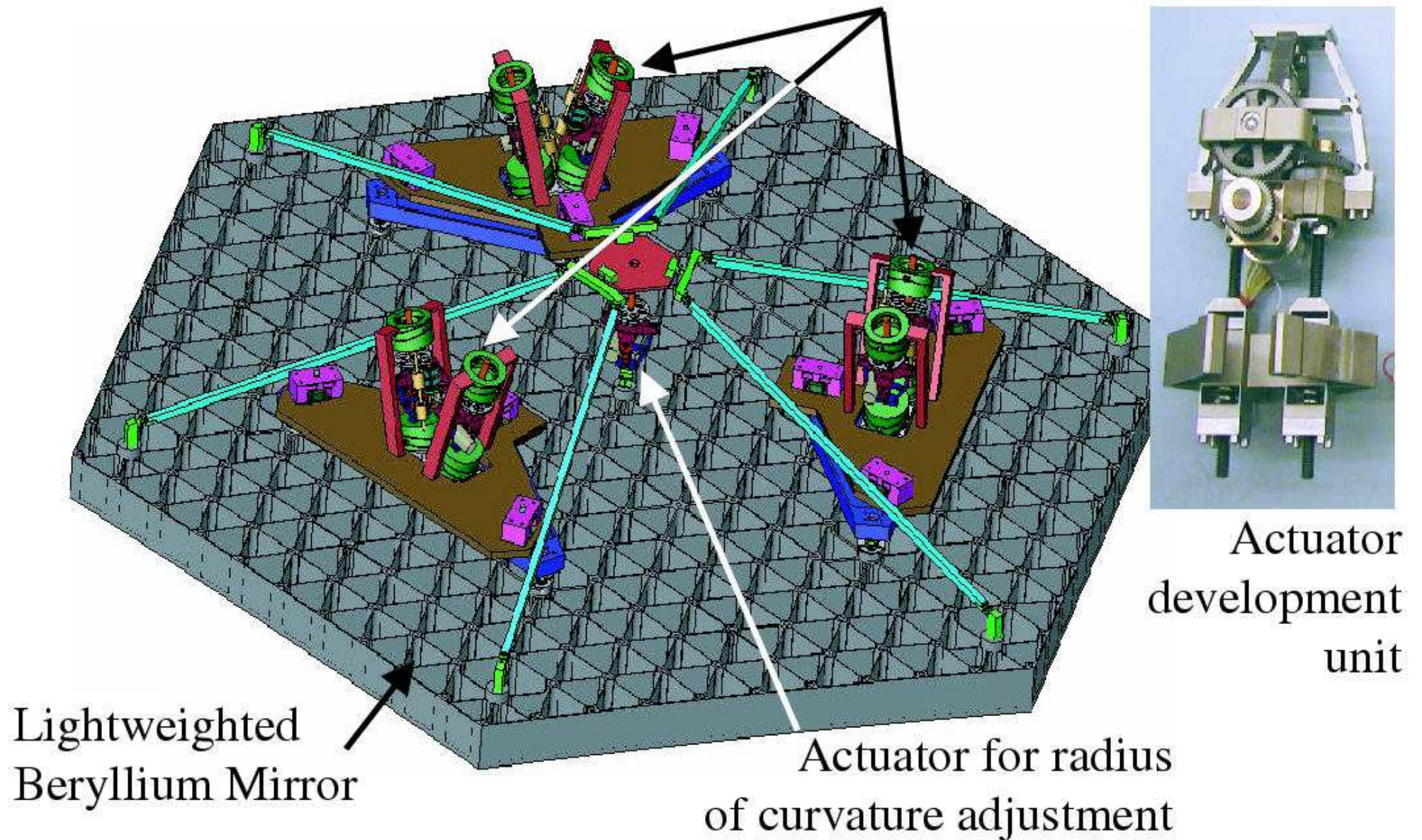
JWST can observe segments of sky that move around as it orbits the Sun.







# Actuators for 6 degrees of freedom rigid body motion

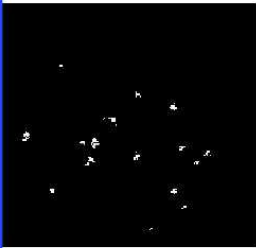


Active mirror segment support through "hexapods", similar to Keck.

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

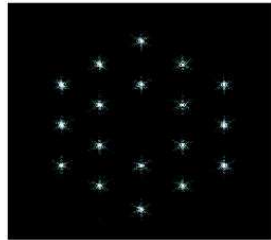


**First light  
NIRCam**



1.  
Segment  
Image  
Capture

**After Step 1**



**Initial Capture**

18 individual 1.6-m diameter aberrated  
sub-telescope images  
PM segments: < 1 mm, < 2 arcmin tilt  
SM: < 3 mm, < 5 arcmin tilt

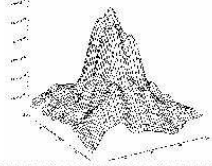
**Final Condition**

PM segments:  
< 100  $\mu\text{m}$ ,  
< 2 arcsec tilt  
SM: < 3 mm,  
< 5 arcmin tilt

## 2. Coarse Alignment

Secondary mirror aligned  
Primary RoC adjusted

**After Step 2**

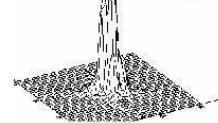


Primary Mirror segments:  
< 1 mm, < 10 arcsec tilt  
Secondary Mirror :  
< 3 mm, < 5 arcmin tilt

WFE < 200  $\mu\text{m}$  (rms)

## 3. Coarse Phasing - Fine Guiding (PMSA piston)

**After Step 3**

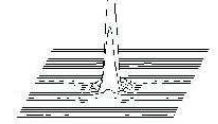


WFE: < 250  $\mu\text{m}$  rms

WFE < 1  $\mu\text{m}$  (rms)

## 4. Fine Phasing

**After Step 4**



WFE: < 5  $\mu\text{m}$  (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.





## ETU NIRCam



## Flight Fine Guidance Sensor



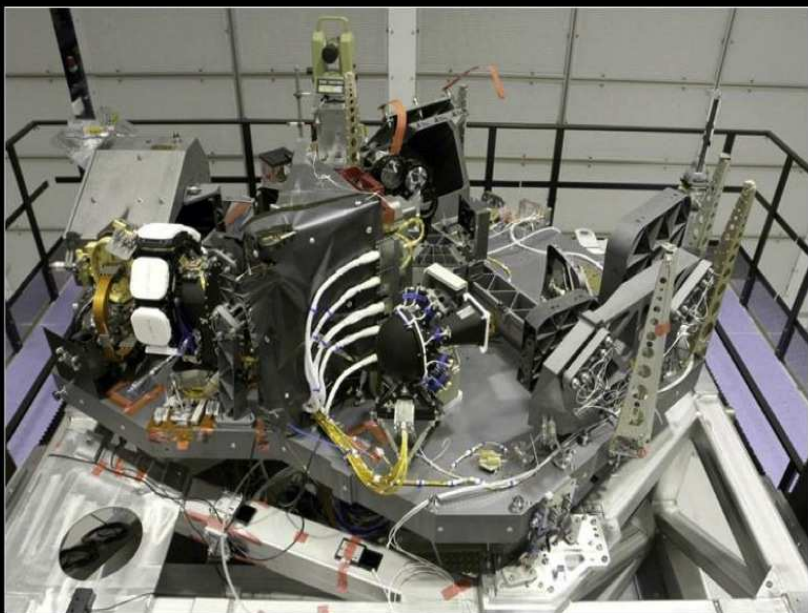
JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (&  $1\text{--}5\mu\text{m}$  grisms) — built by CSA (Montreal).
- Both to be delivered to GSFC late Fall 2011.

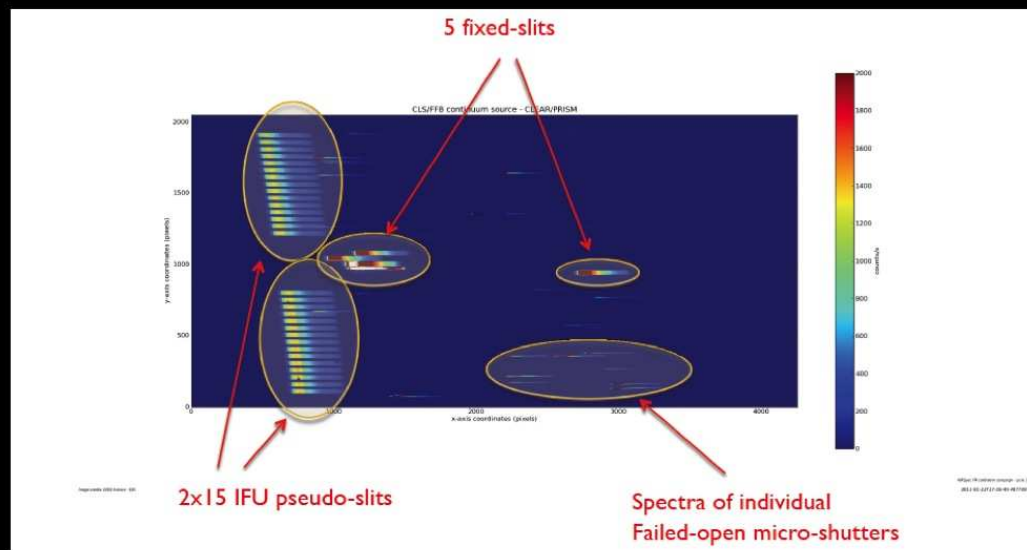




## FLIGHT NIRSpec



## Flight NIRSpec First Light



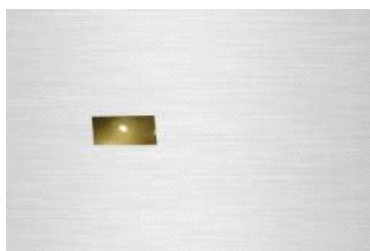
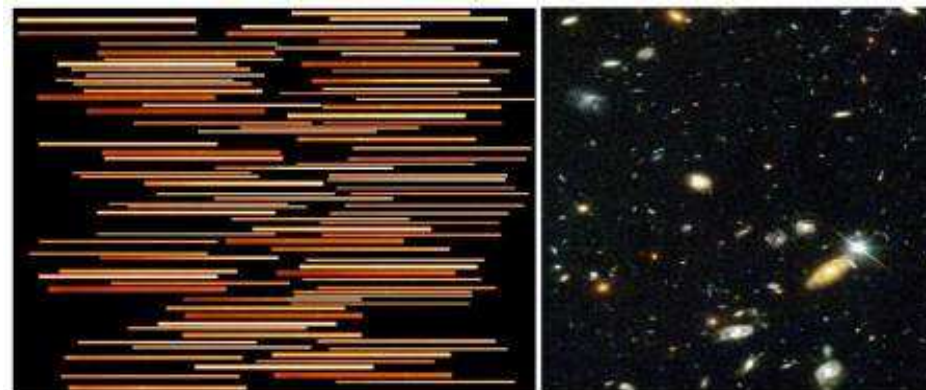
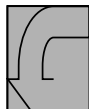
JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) spectrograph:

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

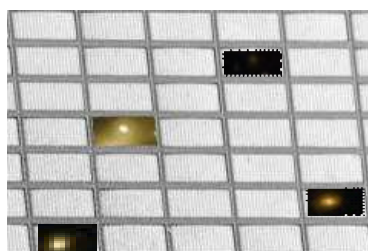
Final delivery to NASA/GSFC in early Fall 2011.



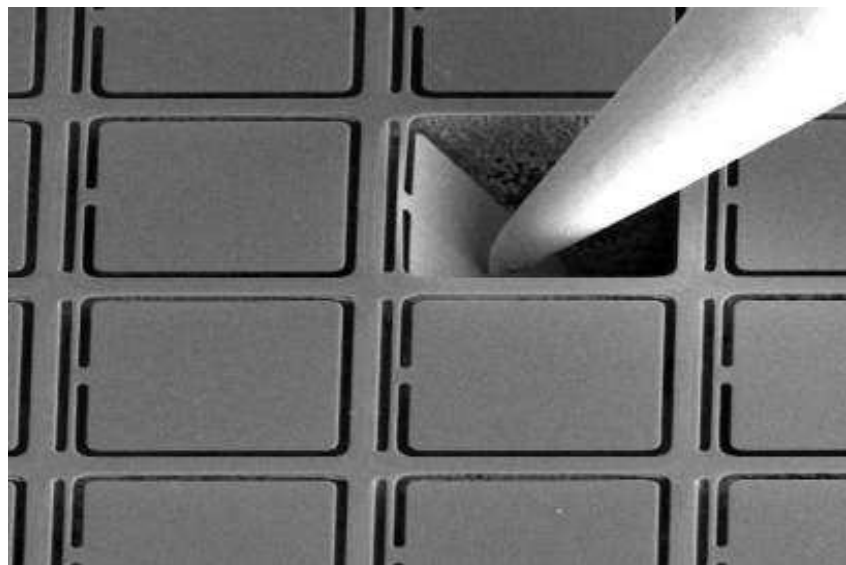
Astronomy Scene



Metal Mask/Fixed Slit



Shutter Mask



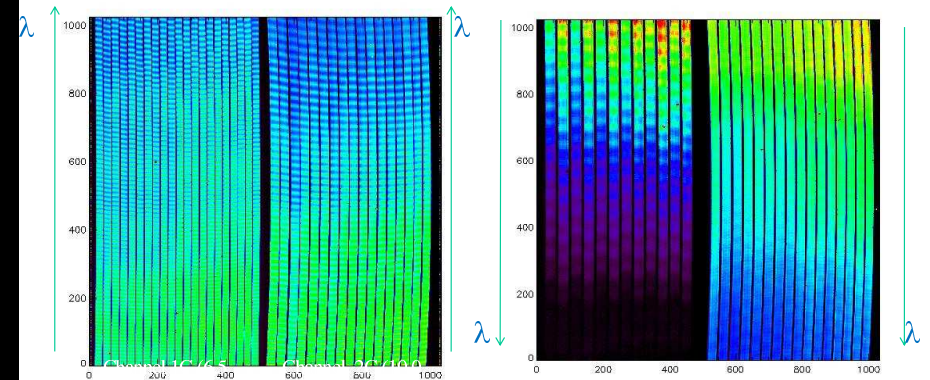




## Flight MIRI



### Spectrometer First Light – internal calibration source



All slices are there and well centred on detectors, fringes look as on VM, the fall off in signal at long wavelengths is expected – temperature of source and relatively short exposure, no “intra-slice” light ☺

JWST's mid-infrared (5–29 $\mu\text{m}$ ) camera and spectrograph:

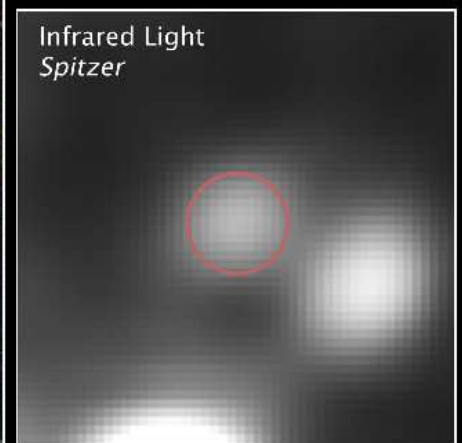
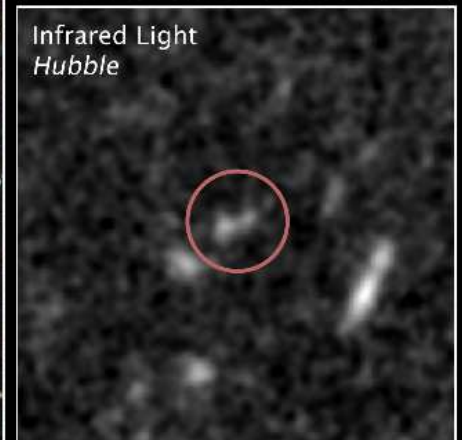
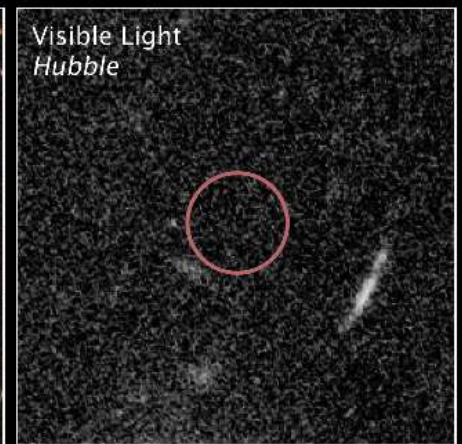
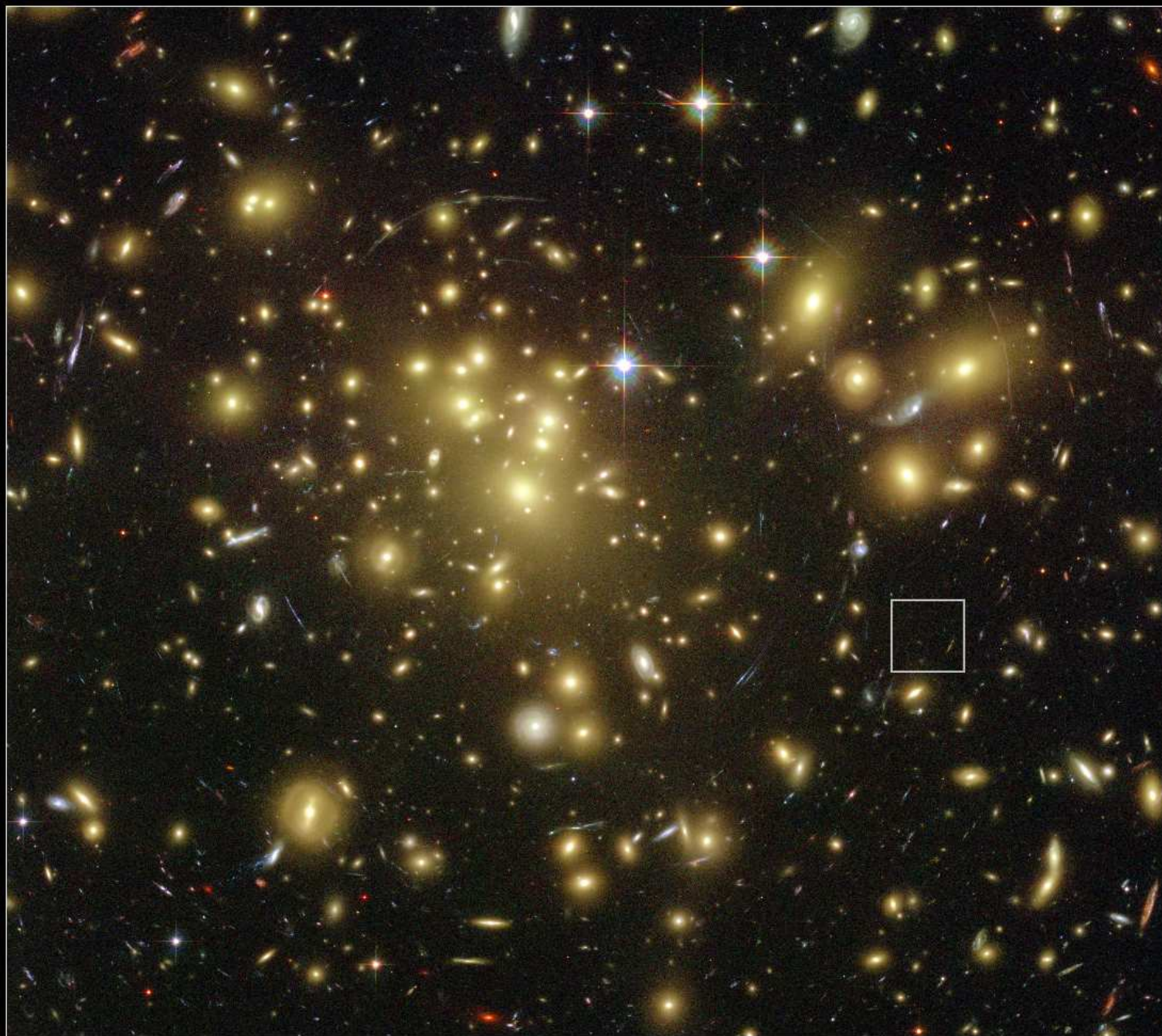
- MIRI — built by ESA consortium of 10 ESA countries & JPL.
- Flight build completed and tested with First Light in July 2011.

Final delivery to NASA/GSFC in early Fall 2011.







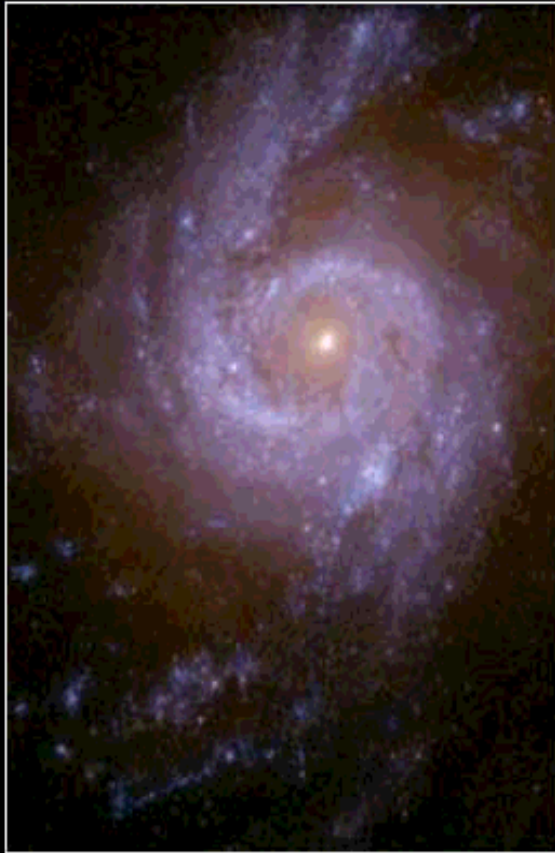


Distant Gravitationally Lensed Galaxy ■ Galaxy Cluster Abell 1689  
*Hubble Space Telescope* ■ ACS/WFC NICMOS



## (4) Predicted Galaxy Appearance for JWST at $z \simeq 1-15$

NGC 3310



ESO0418-008



UGC06471-2



**Ultraviolet Galaxies**

**HST • WFPC2**

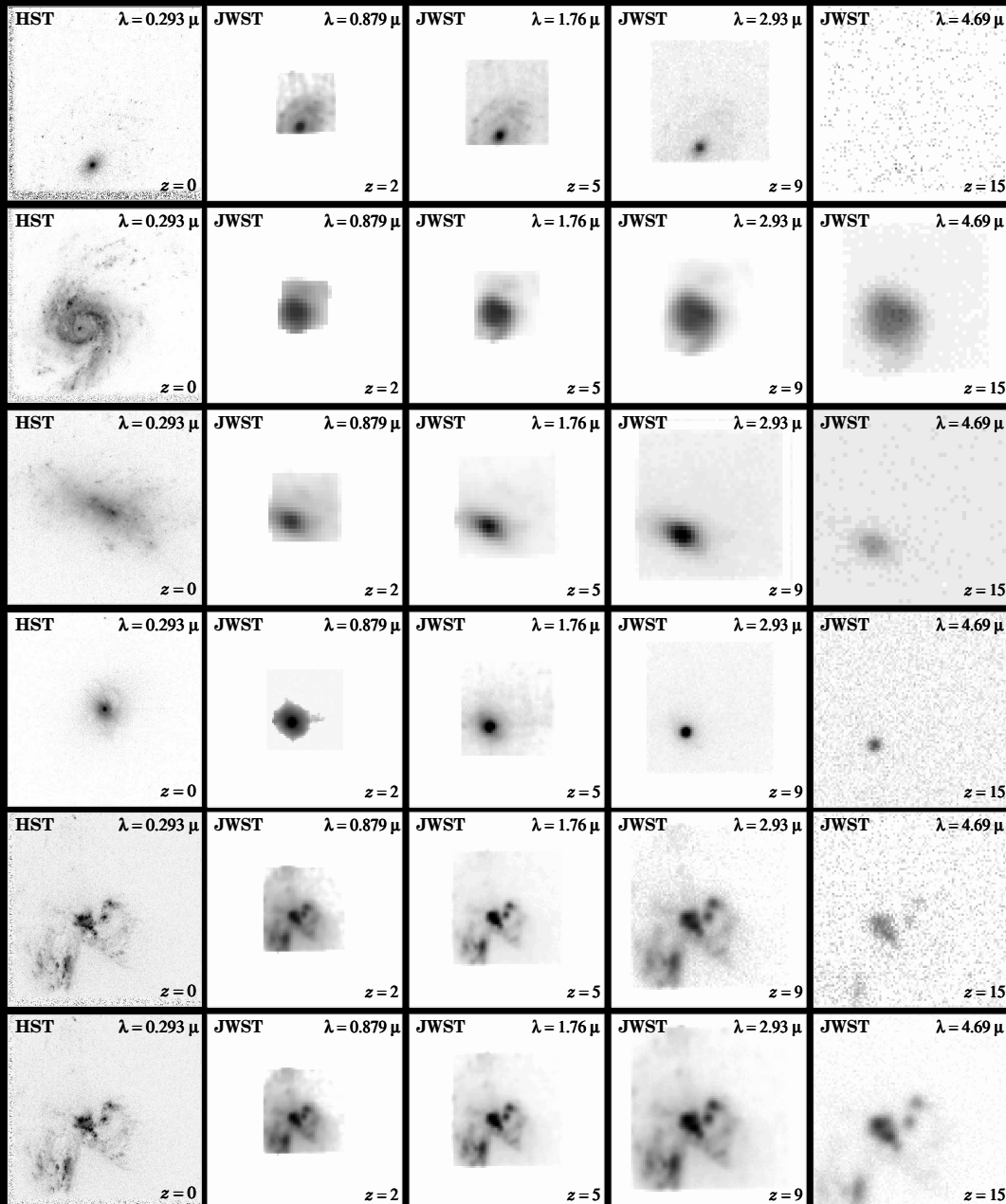
NASA and R. Windhorst (Arizona State University) • STScI-PRC01-04

- 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.



## (4) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1-15$

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.



- 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, p. 1965  
(astro-ph/0703171) “High Resolution Science with High Redshift Galaxies”