The best of Hubble Wide Field Camera 3, and what the James Webb Space Telescope will do after 2018.

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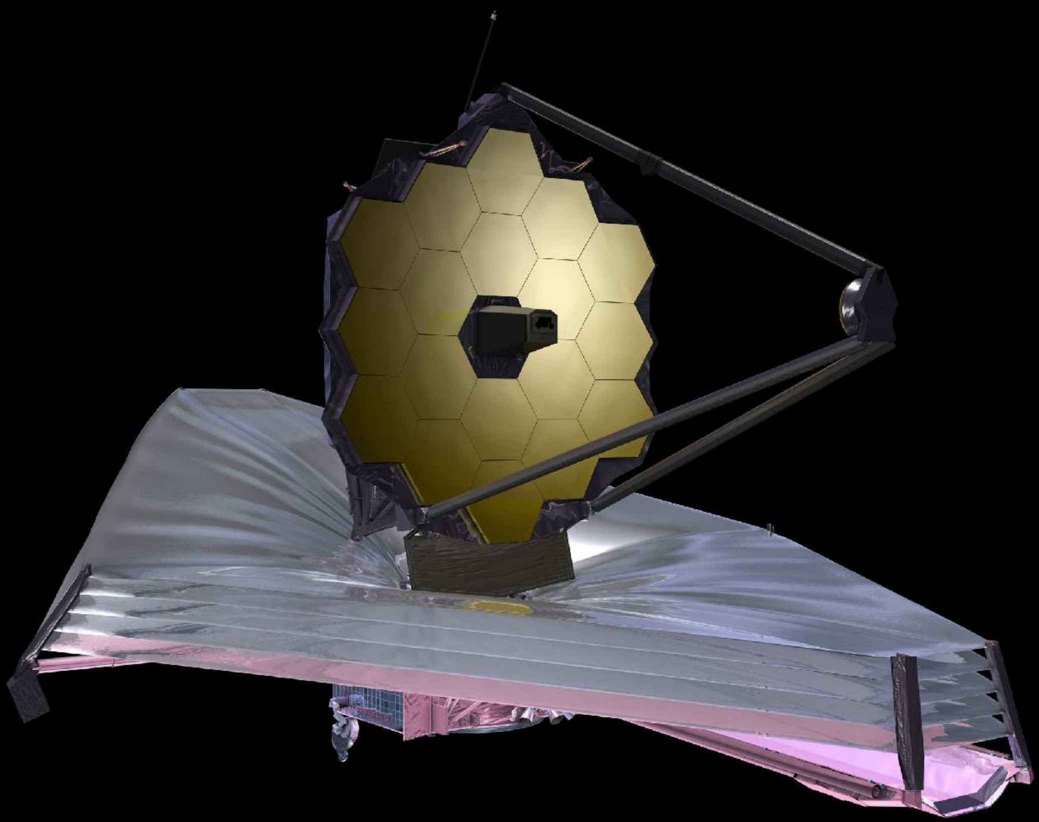
(Ex) ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, A. Straughn & K. Tamura



Colloquium, ASU School of Earth & Space Exploration, Tempe, AZ, Wednesday, Sept. 18, 2013.

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

Outline

- (1) The Best of Hubble: Recent results from the Hubble Space Telescope (HST) and its Wide Field Camera 3 (WFC3).

- (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.

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

- (4) How can JWST measure the Epochs of First Light & Reionization?

- (5) Summary and Conclusions.

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

Sponsored by NASA/HST & JWST

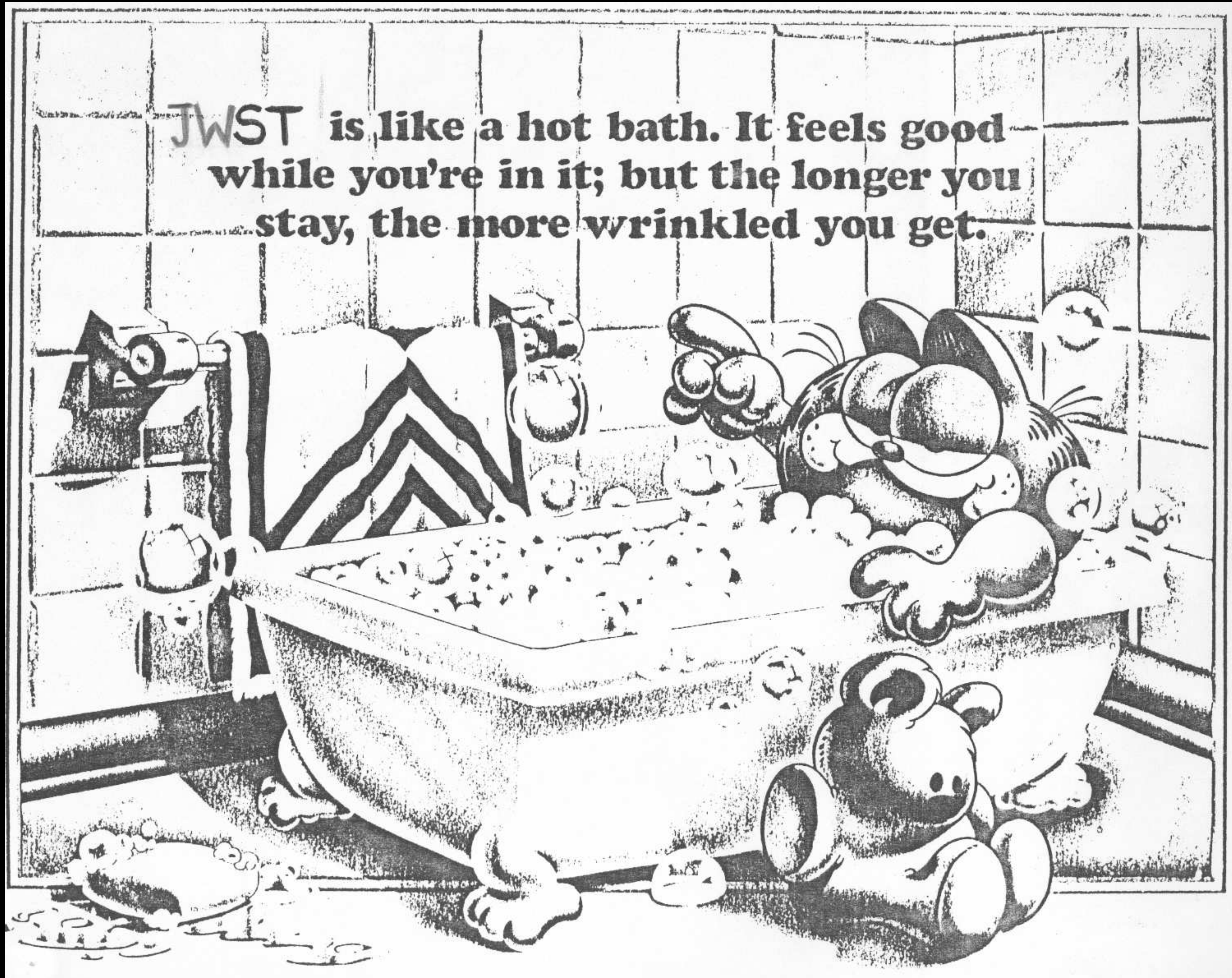
ARIZONA STATE UNIVERSITY

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

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

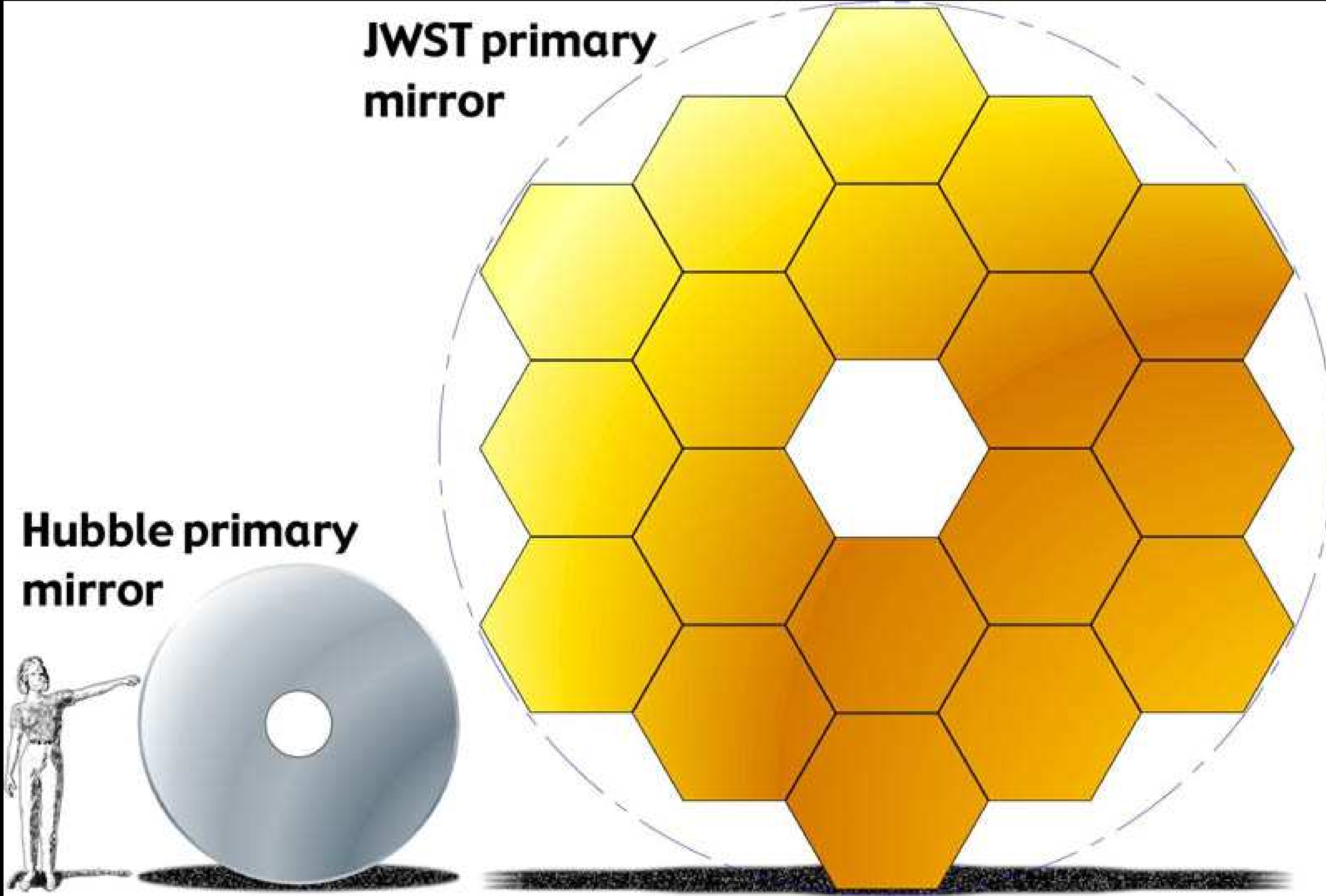
Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2014.

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



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

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

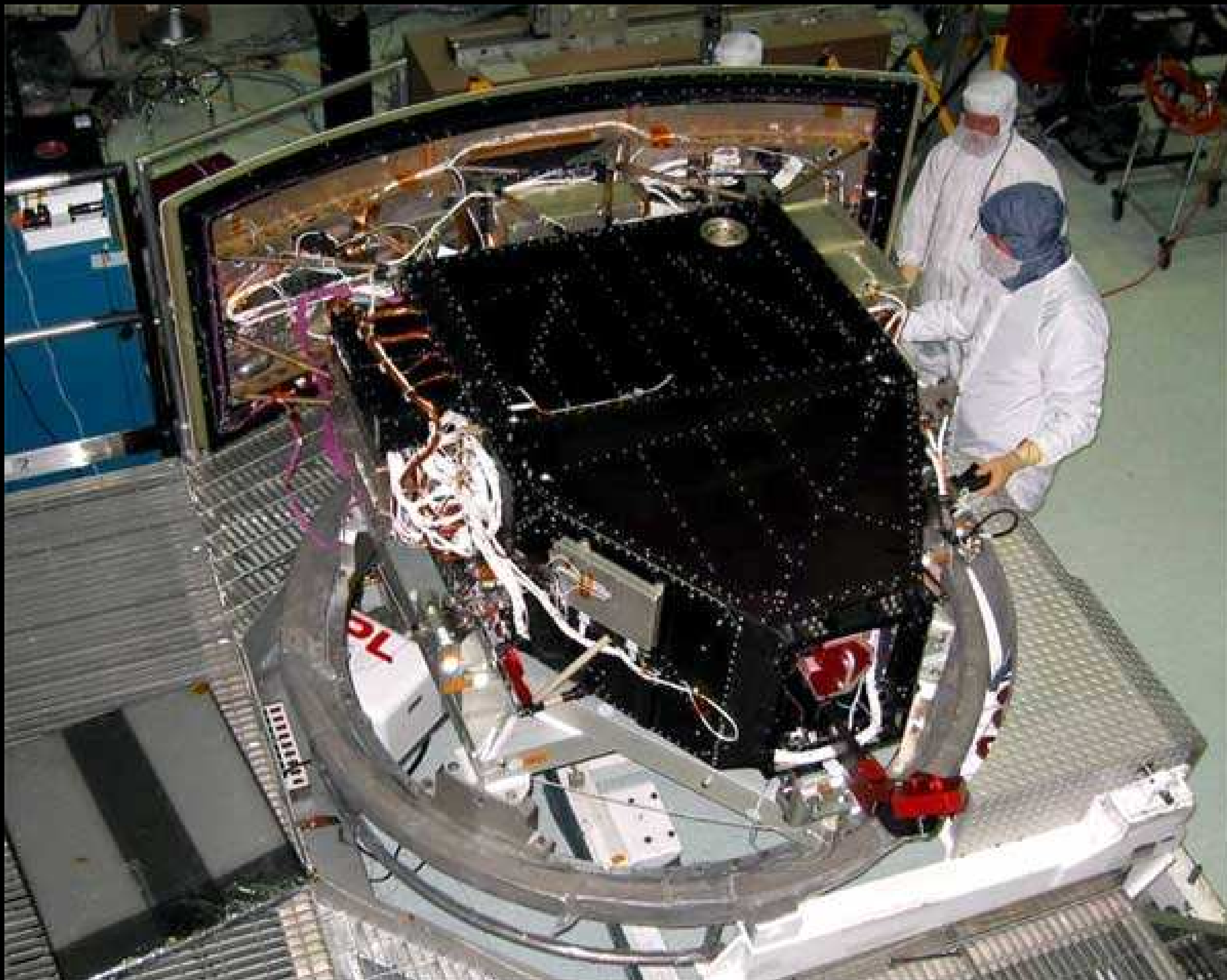


JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:

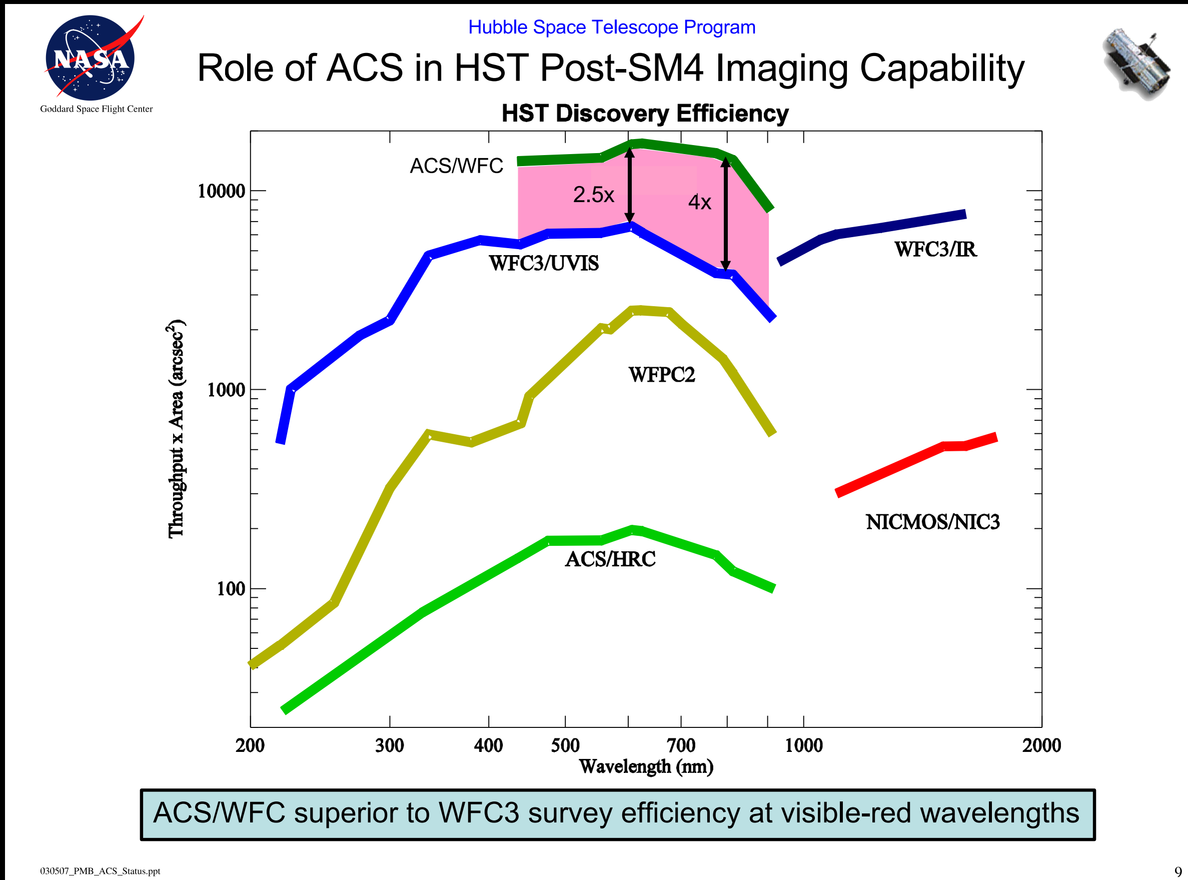
JWST has the same resolution in the near-IR as Hubble in the optical.

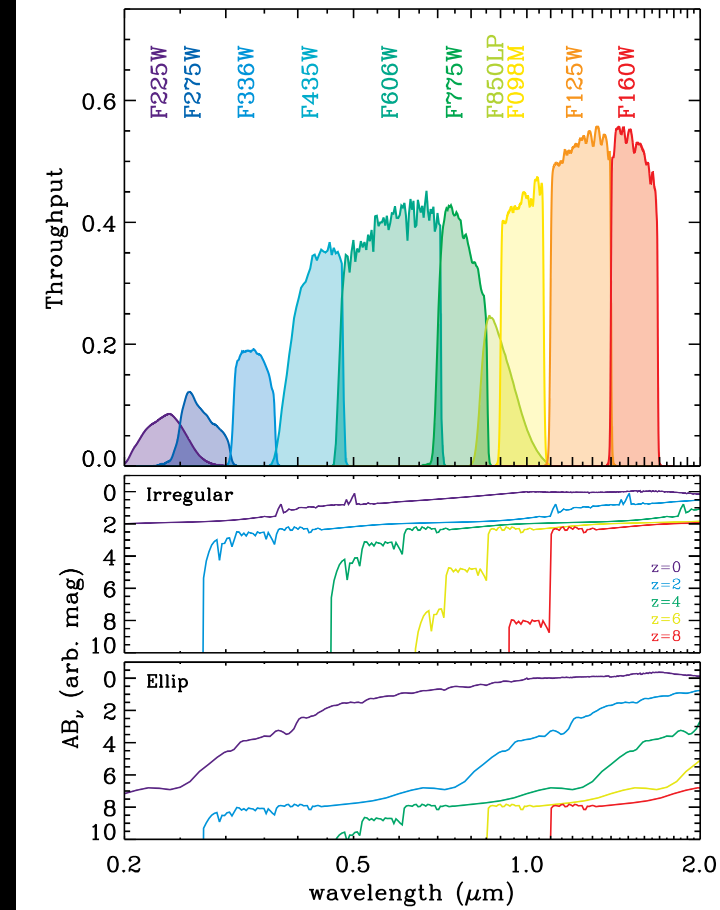
(1) The Best of Hubble: Recent results from the HST and its WFC3

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 & area:

- 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 & area:

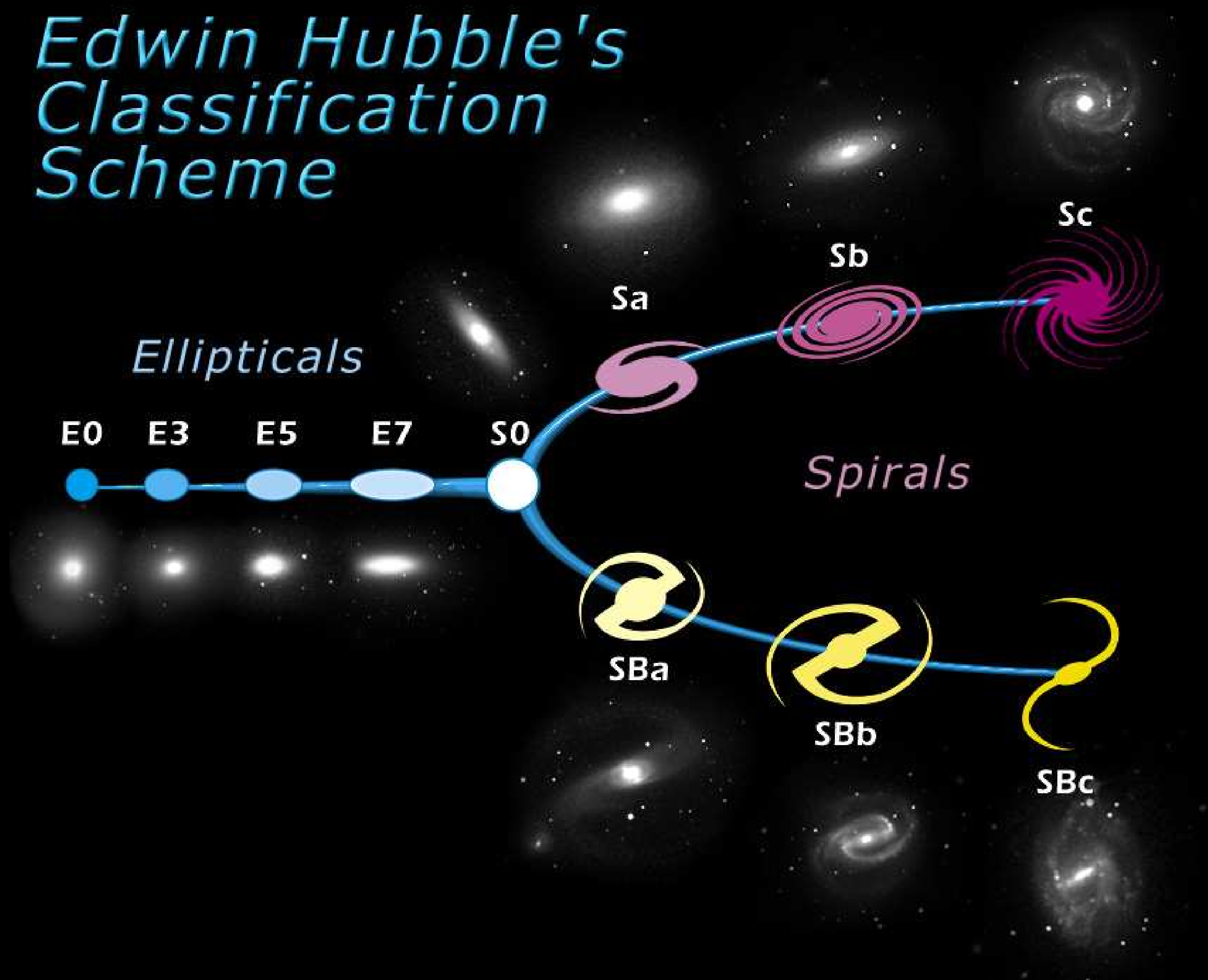
- QE$\gtrsim$70%, 1k$\times$1k array of 0.″13 pixel, FOV $\simeq$ 2.′25 $\times$2.′25.

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

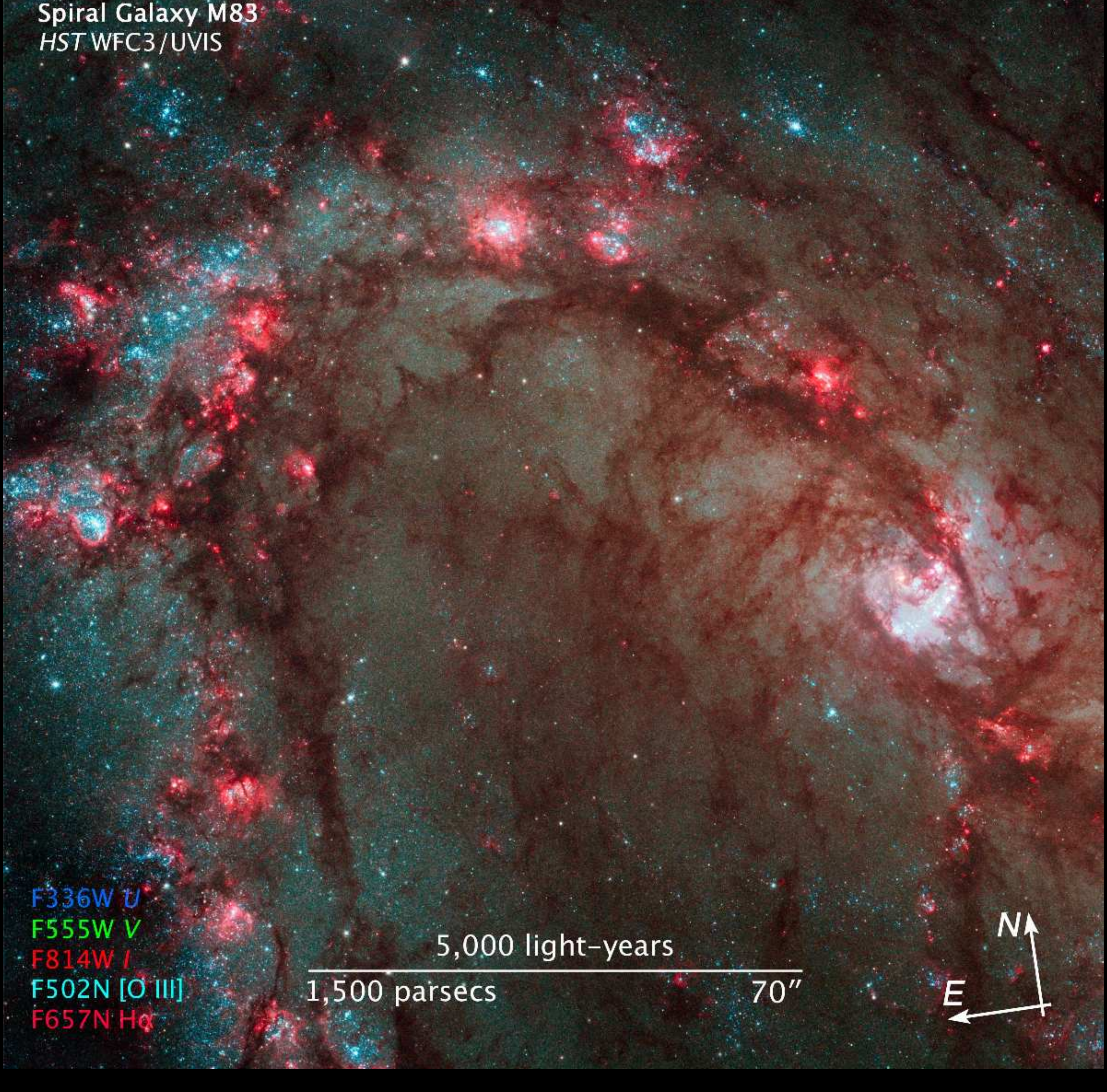
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8:

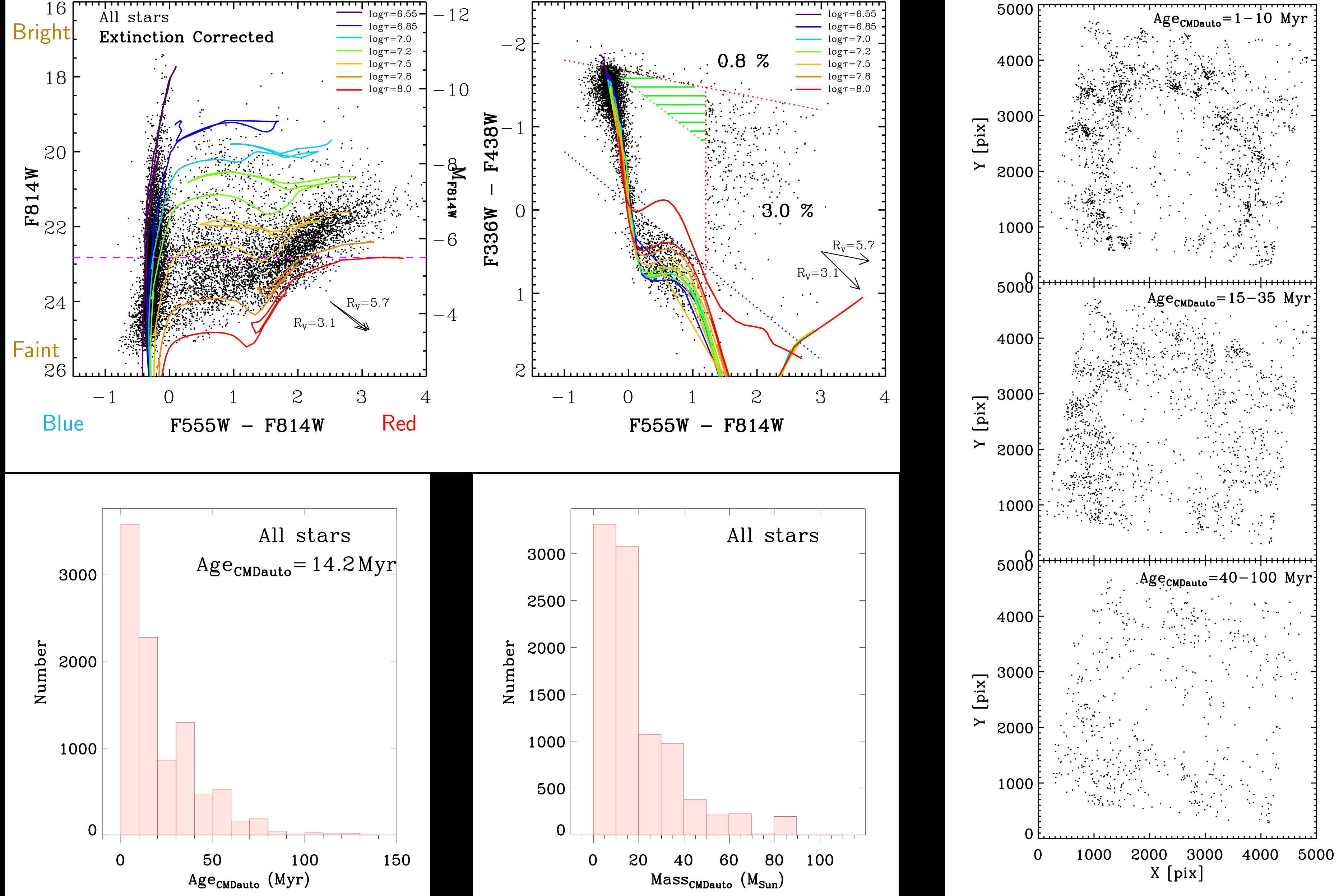
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

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



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% !


Spiral Galaxy M83
HST WFC3/UVIS
F336W *U*
F555W *V*
F814W *I*
F502N [O III]
F657N Hα
5,000 light-years
1,500 parsecs
70″
N
E



Well determined dust-corrected ages for stars in M83, with formation and dissipation along/across spiral arms (Hwihyun Kim et al. 2012, ApJS).

JWST can do this in much dustier environments and for older stellar populations. But must do all we can with HST in UV–blue before JWST flies!

NGC 3032: “Boring old elliptical galaxy” with residual ongoing star-formation!

Central star-formation could be feeding central super-massive black-hole!

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

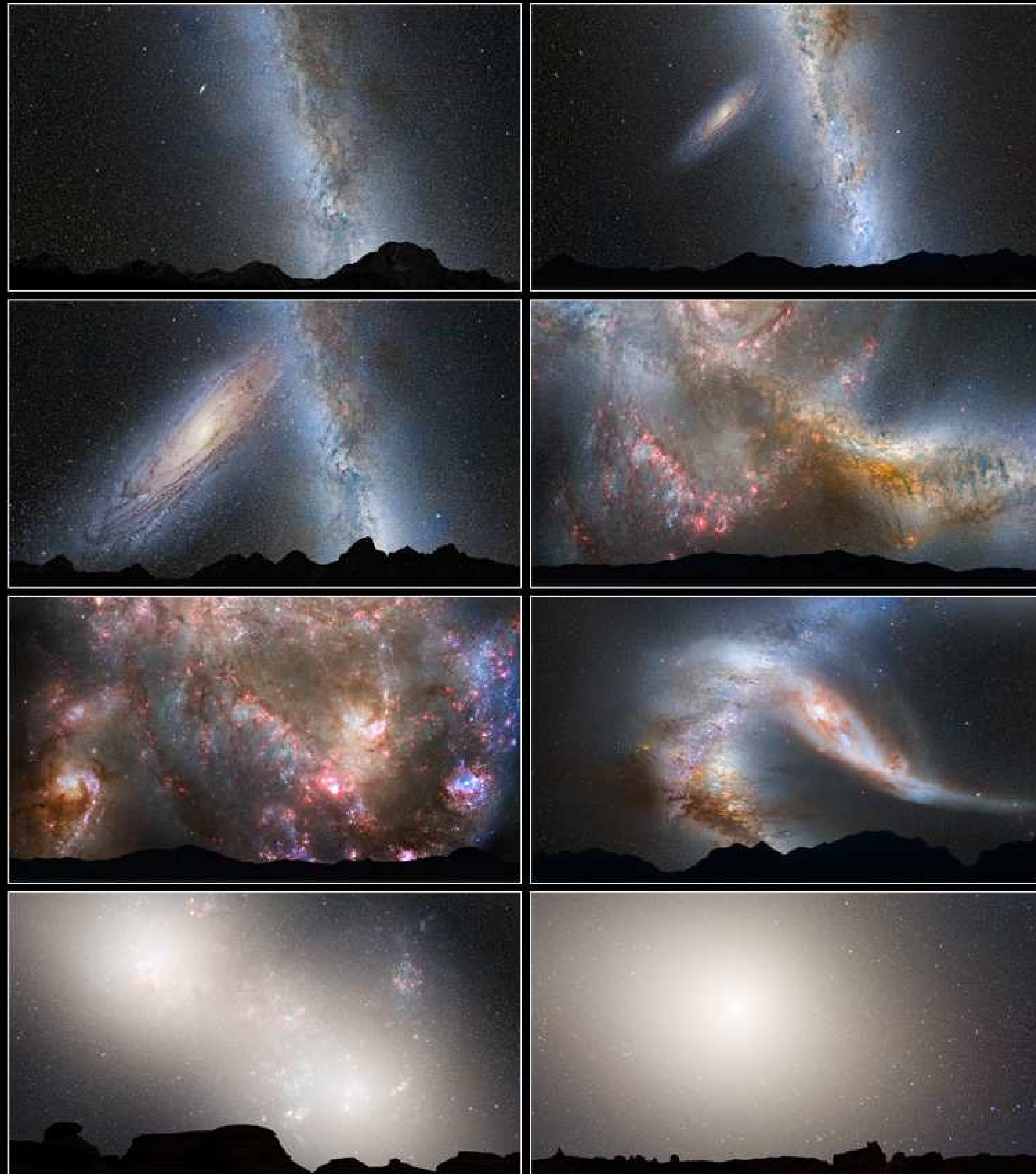


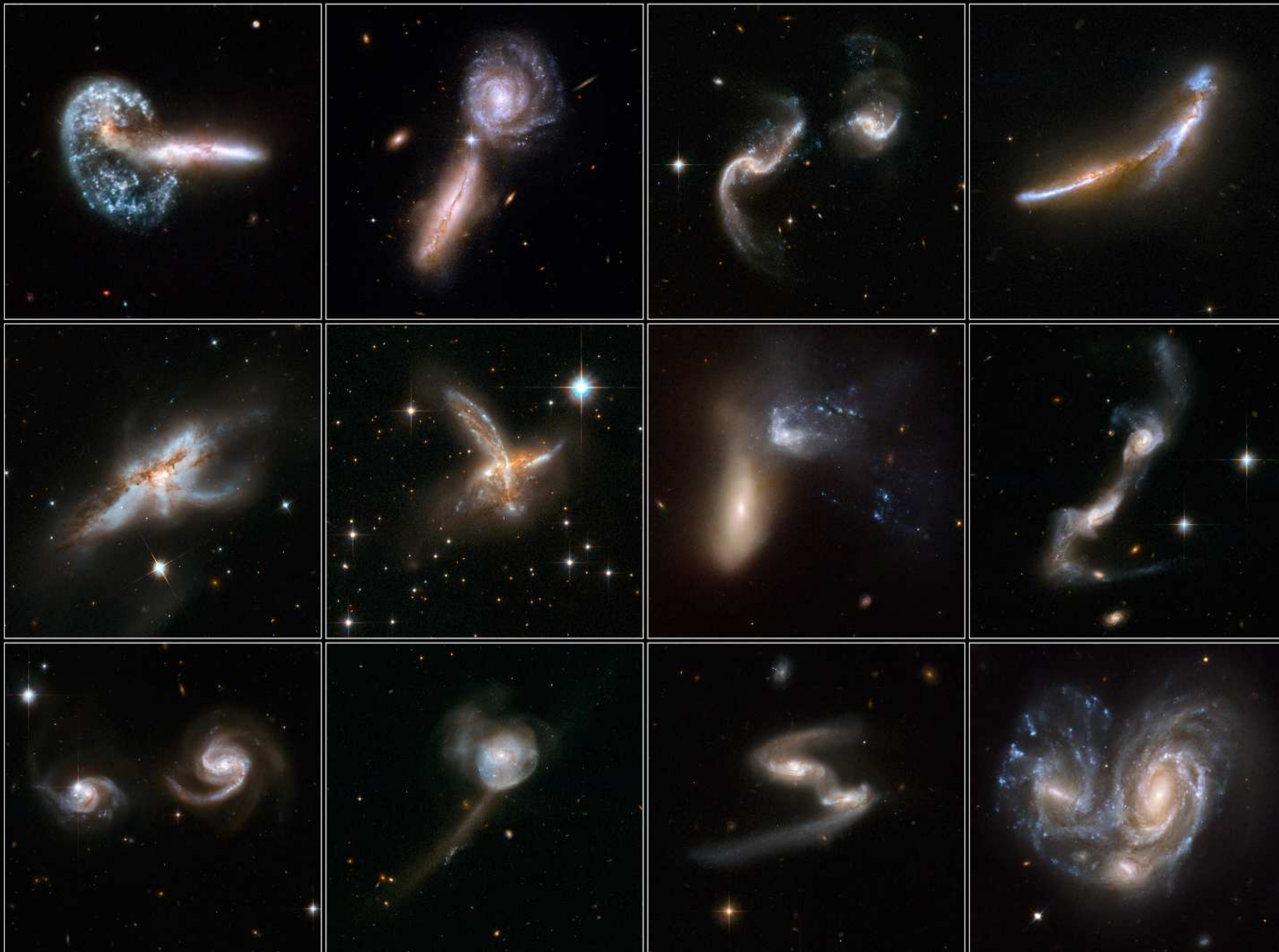
Illustration Sequence of the Milky Way
and Andromeda Galaxy Colliding

NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger ▪ STScI-PRC12-20b

Merger of Andromeda galaxy (M31) with Milky Way about 4 Gyr from now.

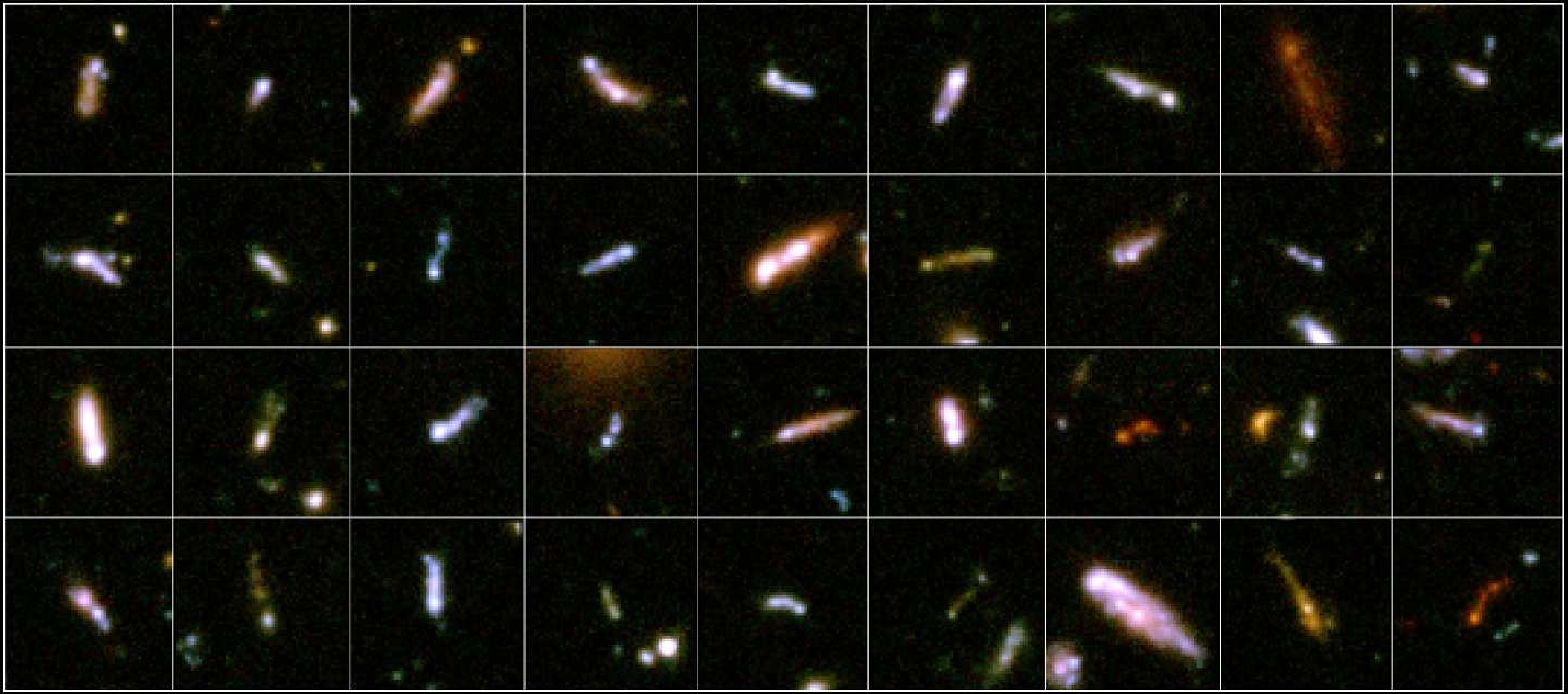
Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2



NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a



“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

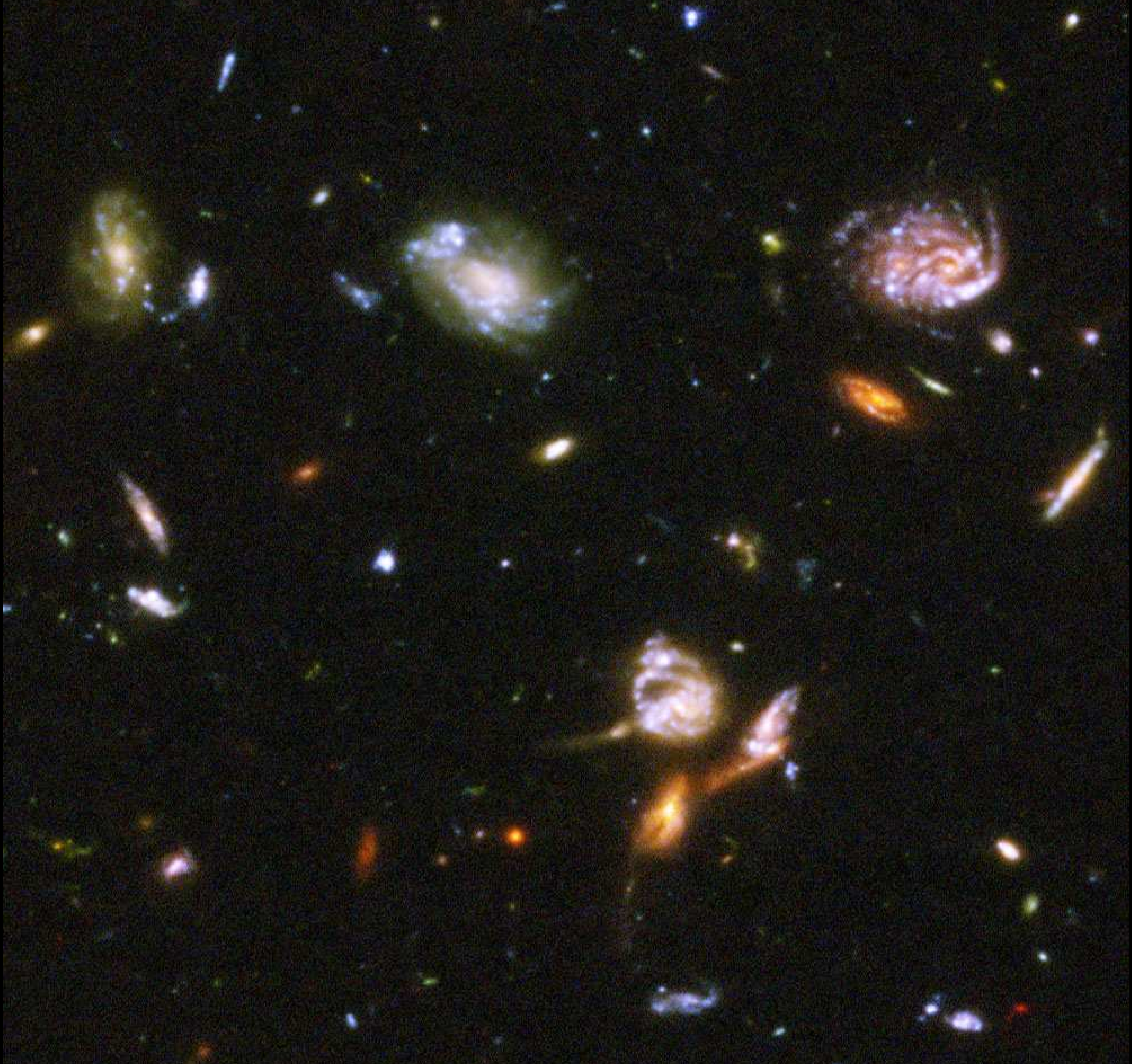
Merging galaxies constitute $\lesssim$1% of Hubble sequence TODAY (age$\gtrsim$12.5 Gyr).

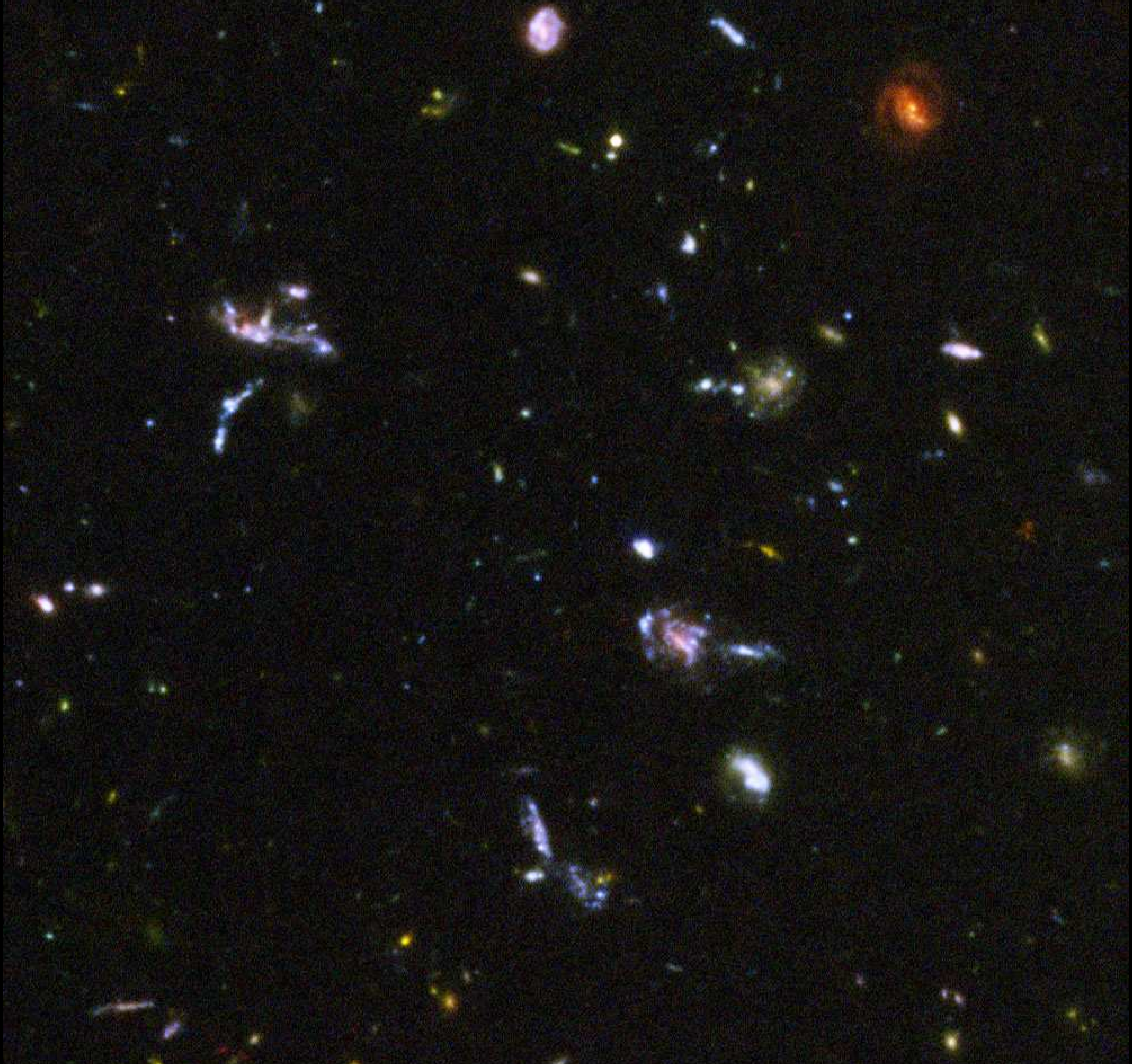
Tadpole galaxies are early stage mergers, very common at z$\gtrsim$2 (age$\lesssim$3 Gyr).

JWST will measure Galaxy Assembly to z$\lesssim$20 (cosmic age $\gtrsim$0.2 Gyr).

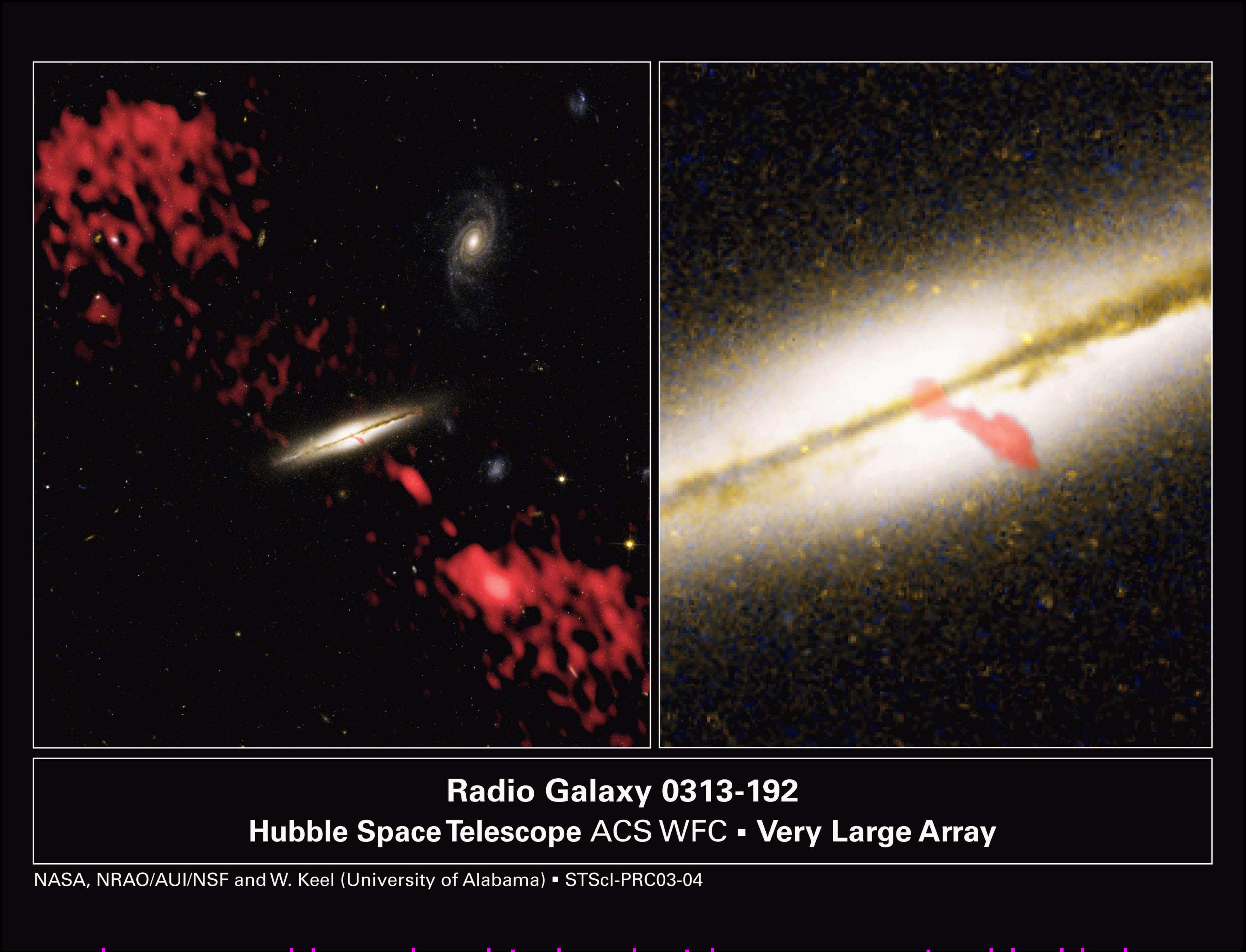
HST/WFC3 & ACS reach AB=26.5-27.0 mag ($\sim$100 fireflies from Moon) over 0.1$\times$full Moon area in 10 filters from 0.2–2μm wavelength.

JWST has 3$\times$sharper imaging to AB$\simeq$31.5 mag ($\sim$1 firefly from Moon) at 1–5μm wavelengths, tracing young and old stars + dust.

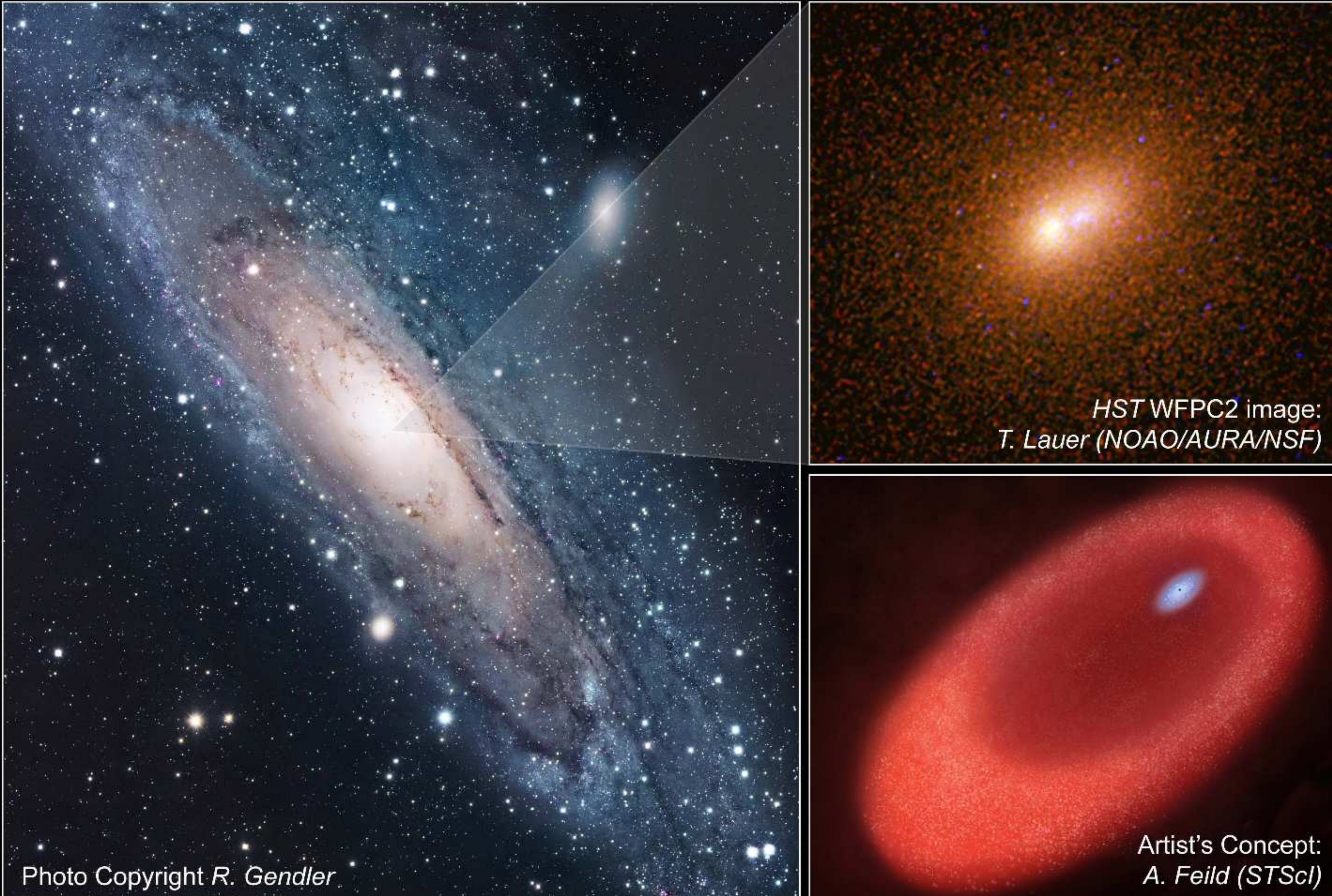




(2) Measuring Galaxy Assembly & Supermassive Blackhole Growth



Does galaxy assembly go hand-in-hand with supermassive blackhole growth?



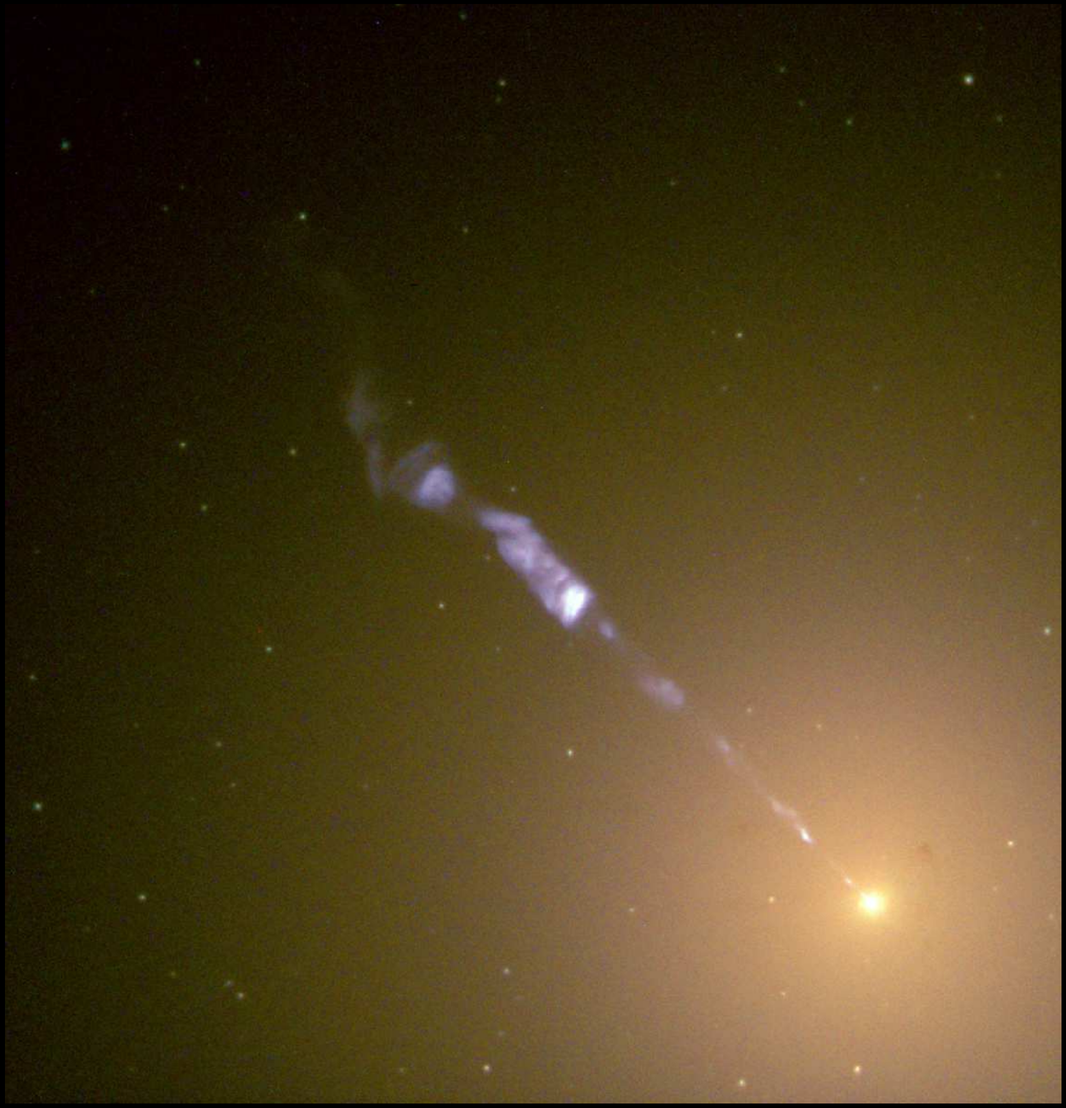
Andromeda Galaxy Nucleus ▪ M31

Hubble Space Telescope ▪ WFPC2

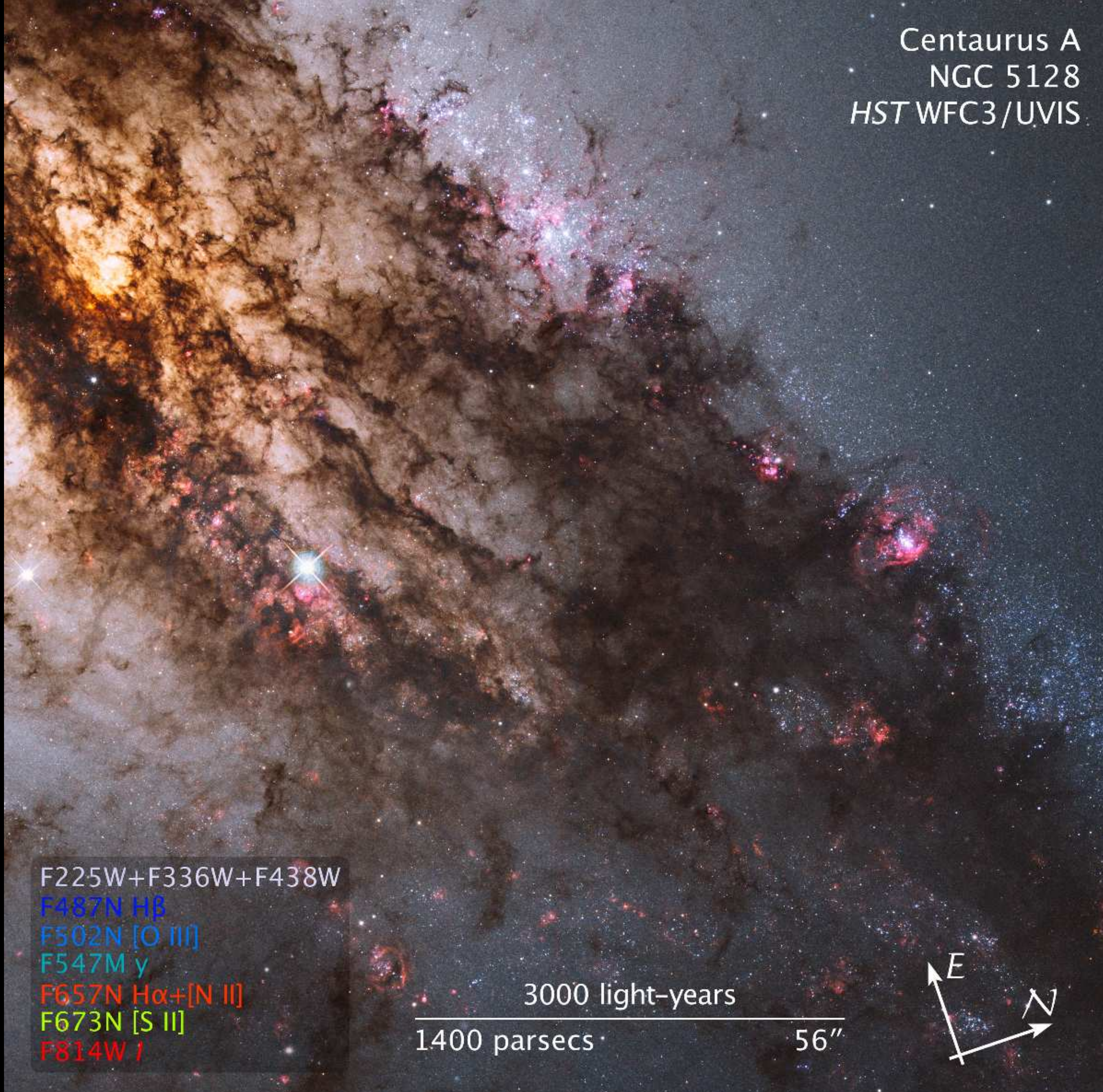
NASA, ESA, R. Gendler, T. Lauer (NOAO/AURA/NSF), and A. Feild (STScI)

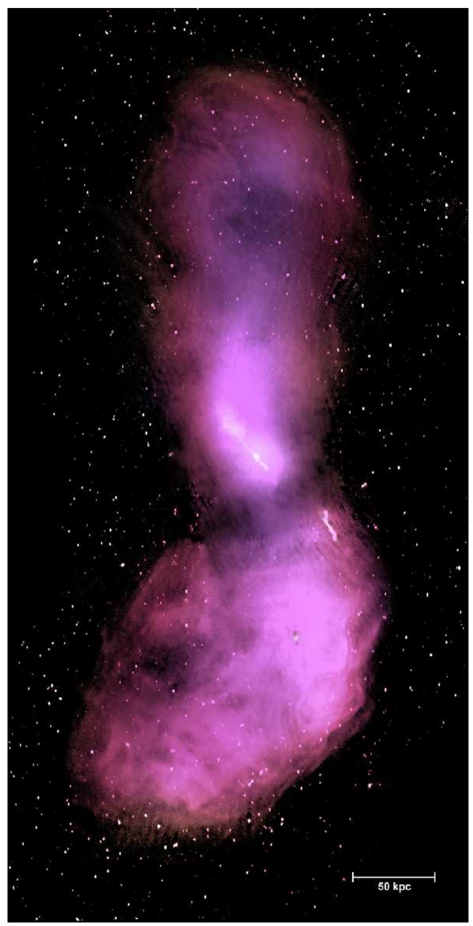
STScI-PRC05-26

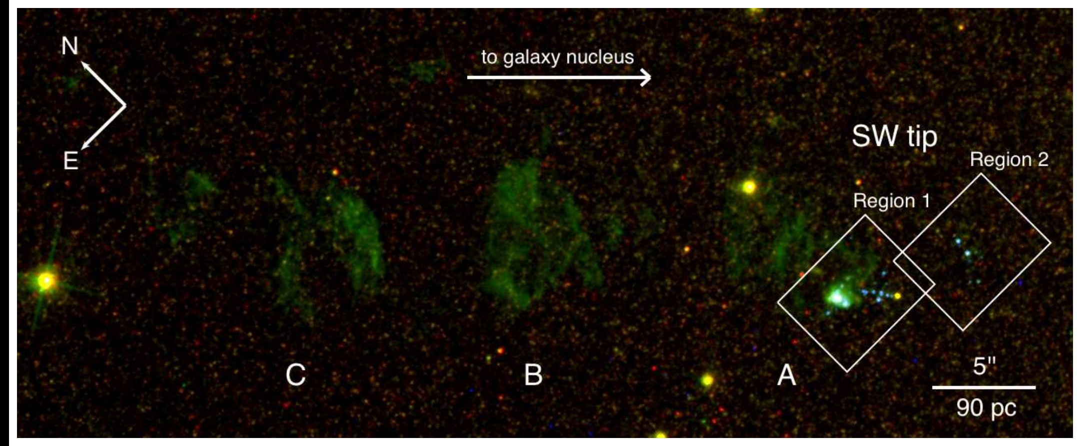
Elliptical galaxy M87 with Active Galactic Nucleus (AGN) and relativistic jet:

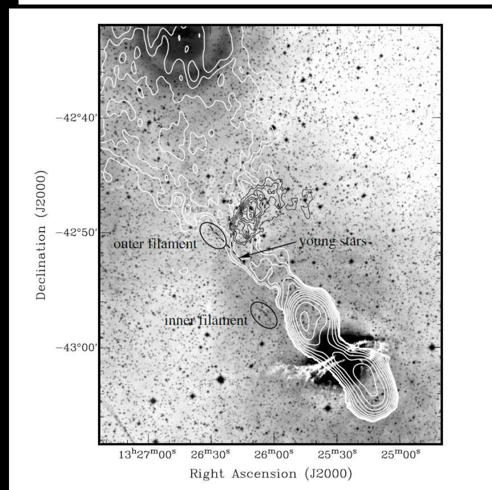


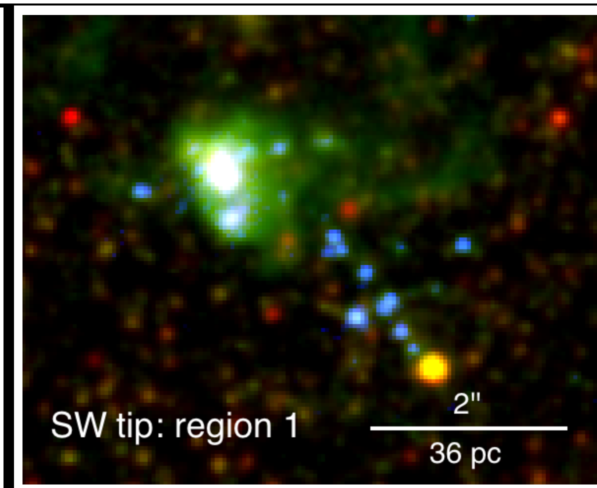
The danger of having Quasar-like devices too close to home ...

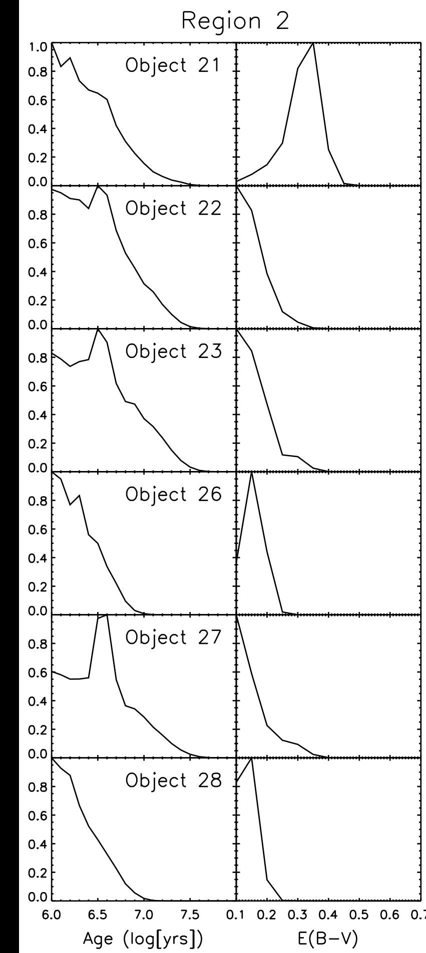

Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W I
3000 light-years
1400 parsecs
56″
E
N











[Left] ATNF 1.4 GHz radio image of Cen A (Feain et al. 2009).

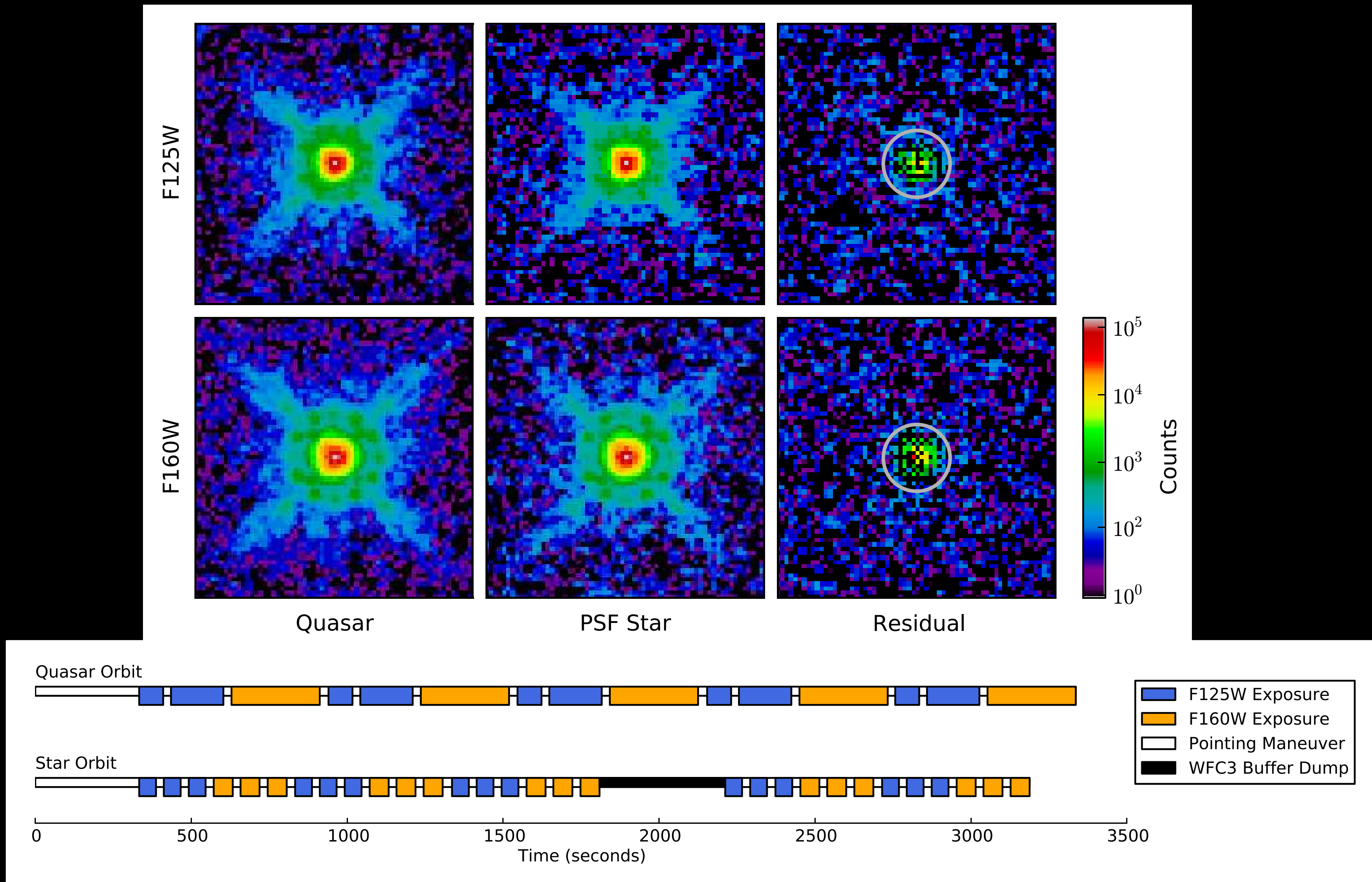
Fermi GeV source (Yang$^+$ 12) & Auger UHE Cosmic Rays (Abreu$^+$ 2010).

[Middle] SF in Cent A jet's wake (Crockett$^+$ 2012, MNRAS, 421, 1602).

[Right] Well determined ages for young ($\sim$2 Myr) stars near Cen A's jet.

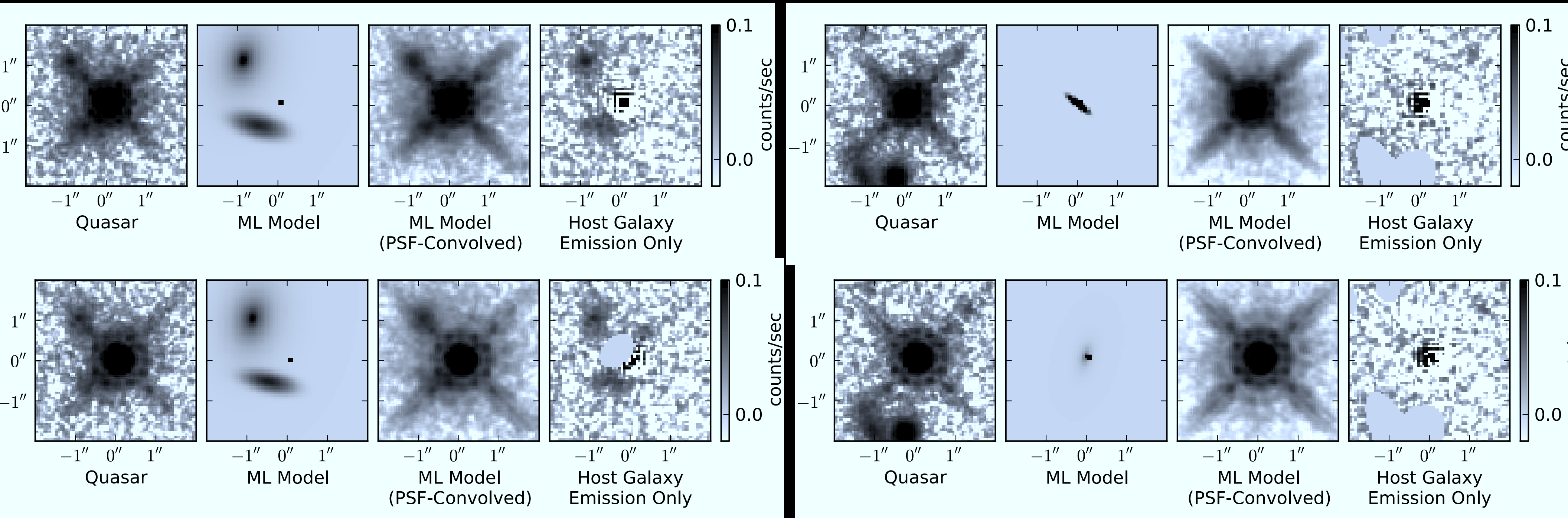
- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV–blue before JWST flies.

(2) HST WFC3 observations of QSO host galaxies at z$\simeq$6 (age$\lesssim$1 Gyr)



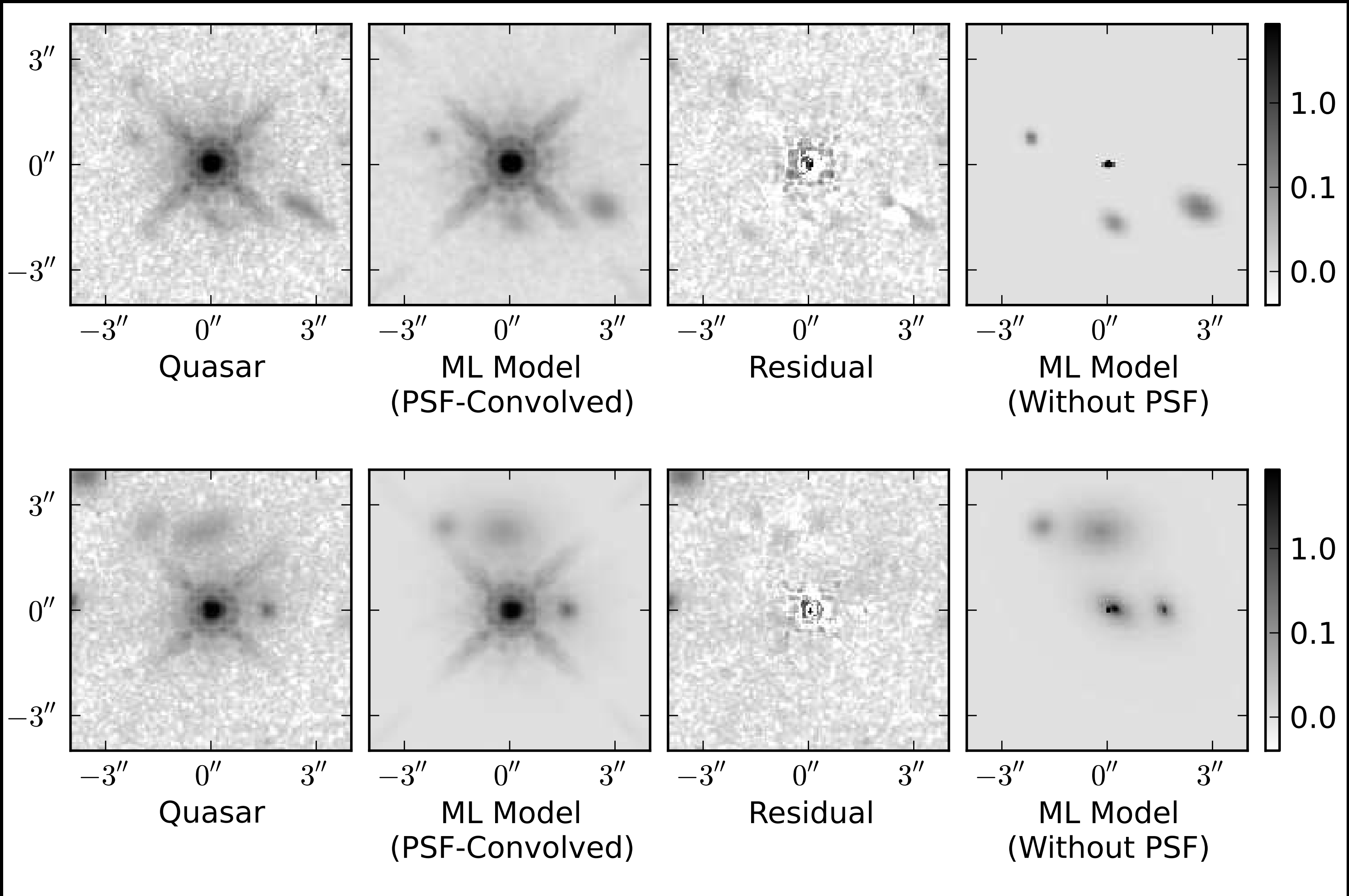
- Careful contemporaneous orbital PSF-star subtraction: Removes most of "OTA spacecraft breathing" effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star (AB$\simeq$15 mag) subtracts z=6.42 QSO (AB$\simeq$18.5) nearly to the noise limit: NO host galaxy detected 100$\times$fainter (AB$\gtrsim$23.5 at r$\gtrsim$0$''$.3).

(2) WFC3: First detection of one QSO Host Galaxy at $z \simeq 6$ (Giant merger?)



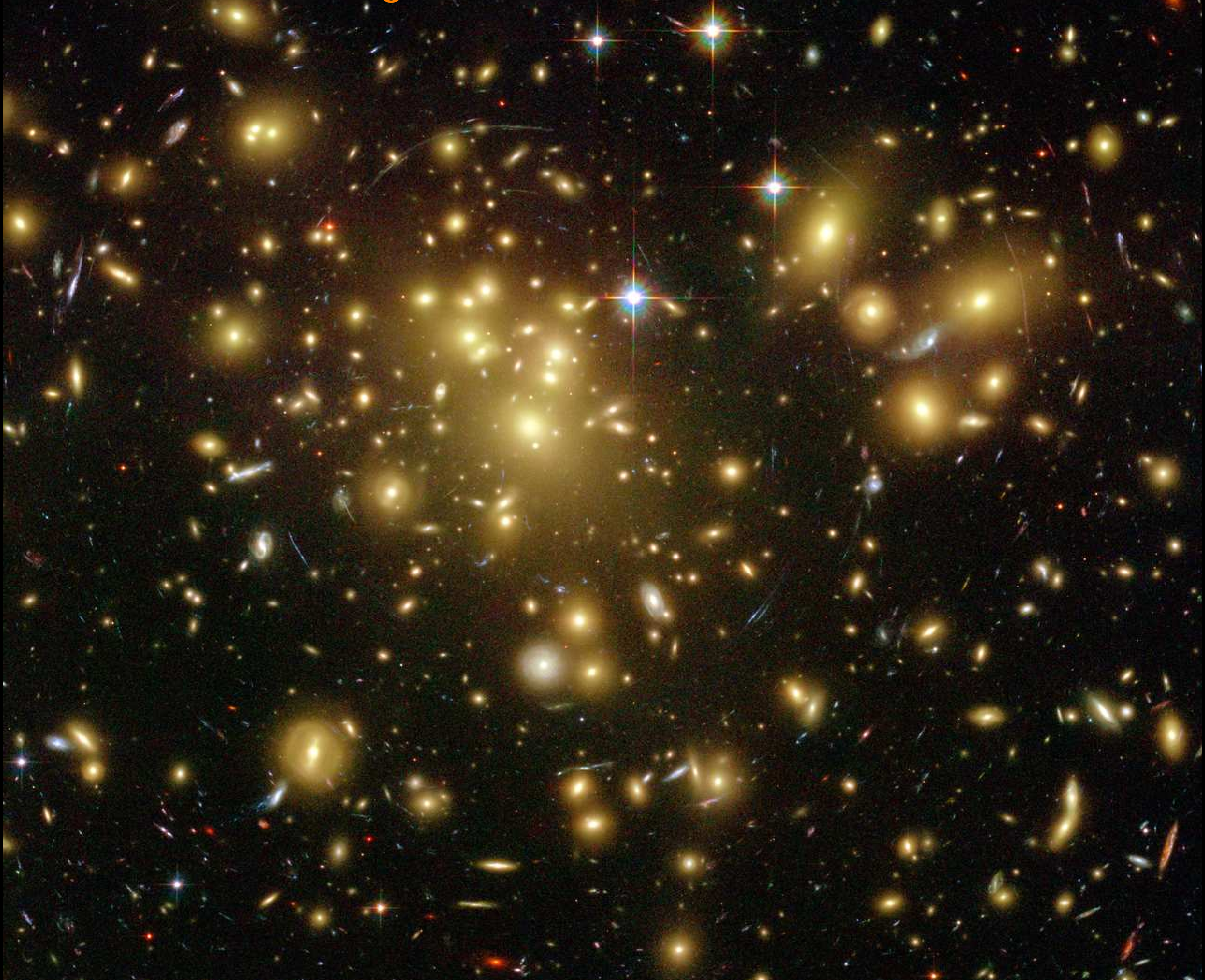
- Monte Carlo Markov-Chain of PSF-star + Sersic ML light-profile: (Mechtley, Jiang, Windhorst et al. 2013; Mechtley 2013, PhD):
- FIRST solid detection out of four $z \simeq 6$ QSOs [3 more to be observed].
- One $z \simeq 6$ QSO host galaxy: Giant merger morphology + tidal structure??
- Same J+H-band structure! Blue UV spectrum: Constrains dust.
- Starburst-like spectrum from rest-frame UV to far-IR ($A_{FUV} \sim 1$ mag).
- L($z \simeq 6$ host galaxy)$\simeq 6\times$ brighter than typical L*: Monster!
- Quasar duty cycle could be $\lesssim 10^{-2}$ ($\lesssim$10 Myrs): Eats like a beast!

(2) WFC3 observations of QSO host galaxies at z≃2 (evidence for mergers?)



- Monte Carlo Markov-Chain runs of PSF-star + Sersic light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, Koekemoer, Windhorst et al. 2013).
- JWST Coronagraphs can do this 10–100× fainter (& for $z \lesssim 20$, $\lambda \lesssim 28\mu m$).

Massive clusters as gravitational Lenses: cosmic House-of-Mirrors:

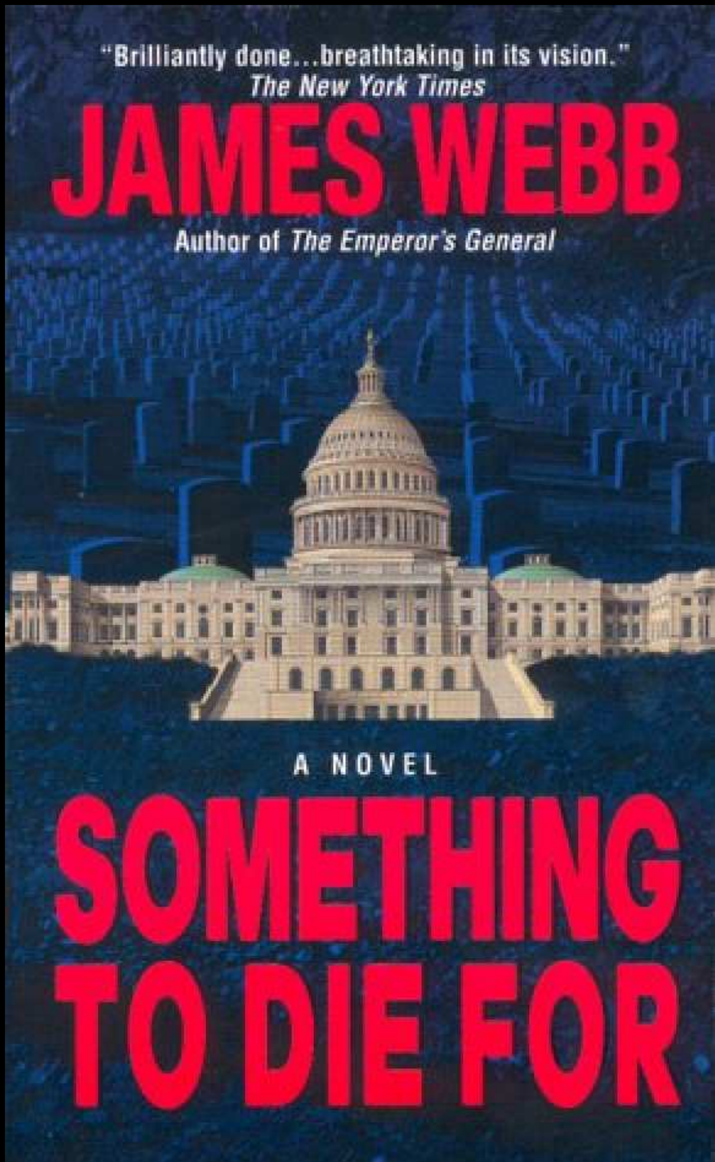


Galaxy Cluster RCS2 032727-132623
Hubble Space Telescope • WFC3/UVIS/IR

NASA, ESA, J. Rigby (NASA GSFC), and K. Sharon (Kavli Institute for Cosmological Physics, University of Chicago) STScI-PRC12-08a

- See Prof. Malhotra et al.'s Herschel work of such objects: CII + dust!

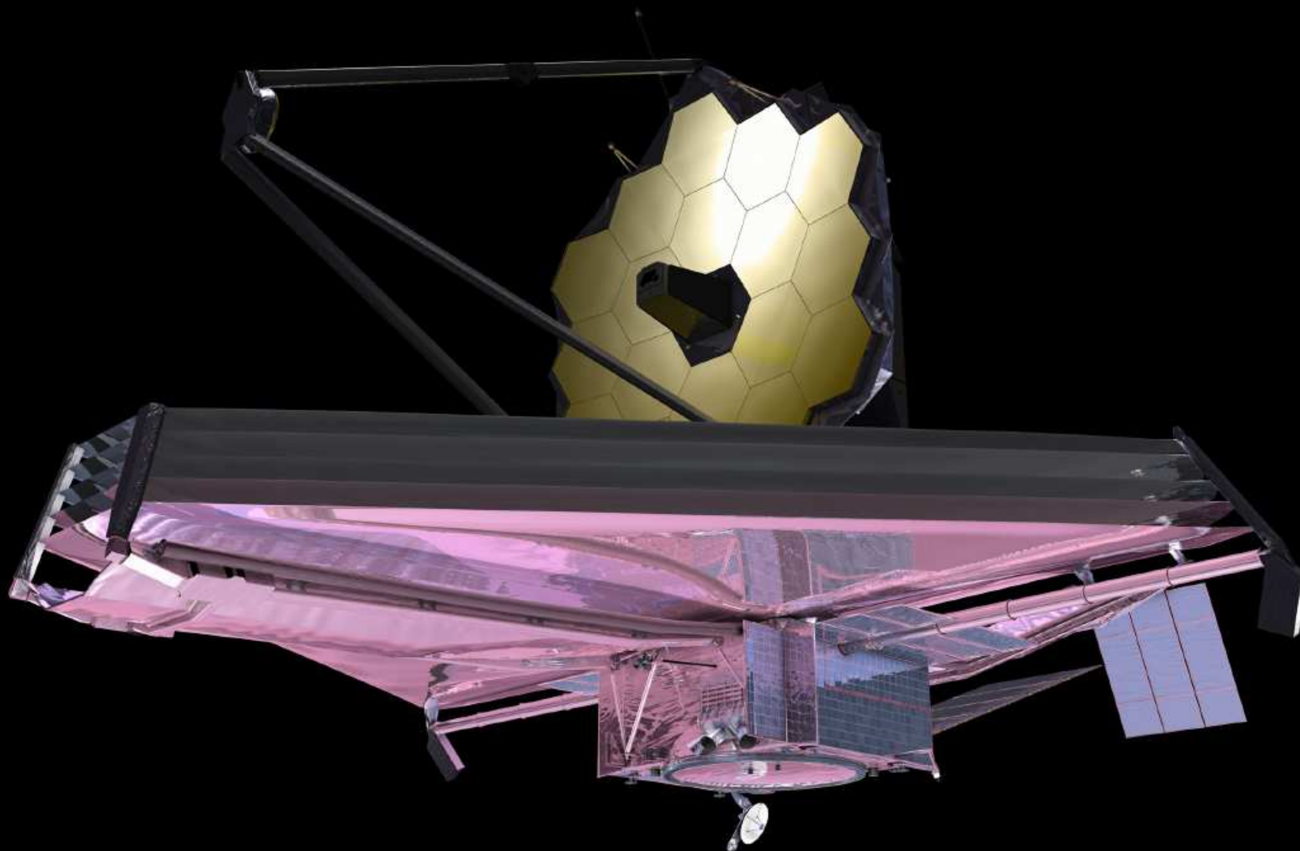
(3) What is the James Webb Space Telescope (JWST)?



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 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 = firefly from Moon!) and spectroscopy.

The James Webb Space Telescope

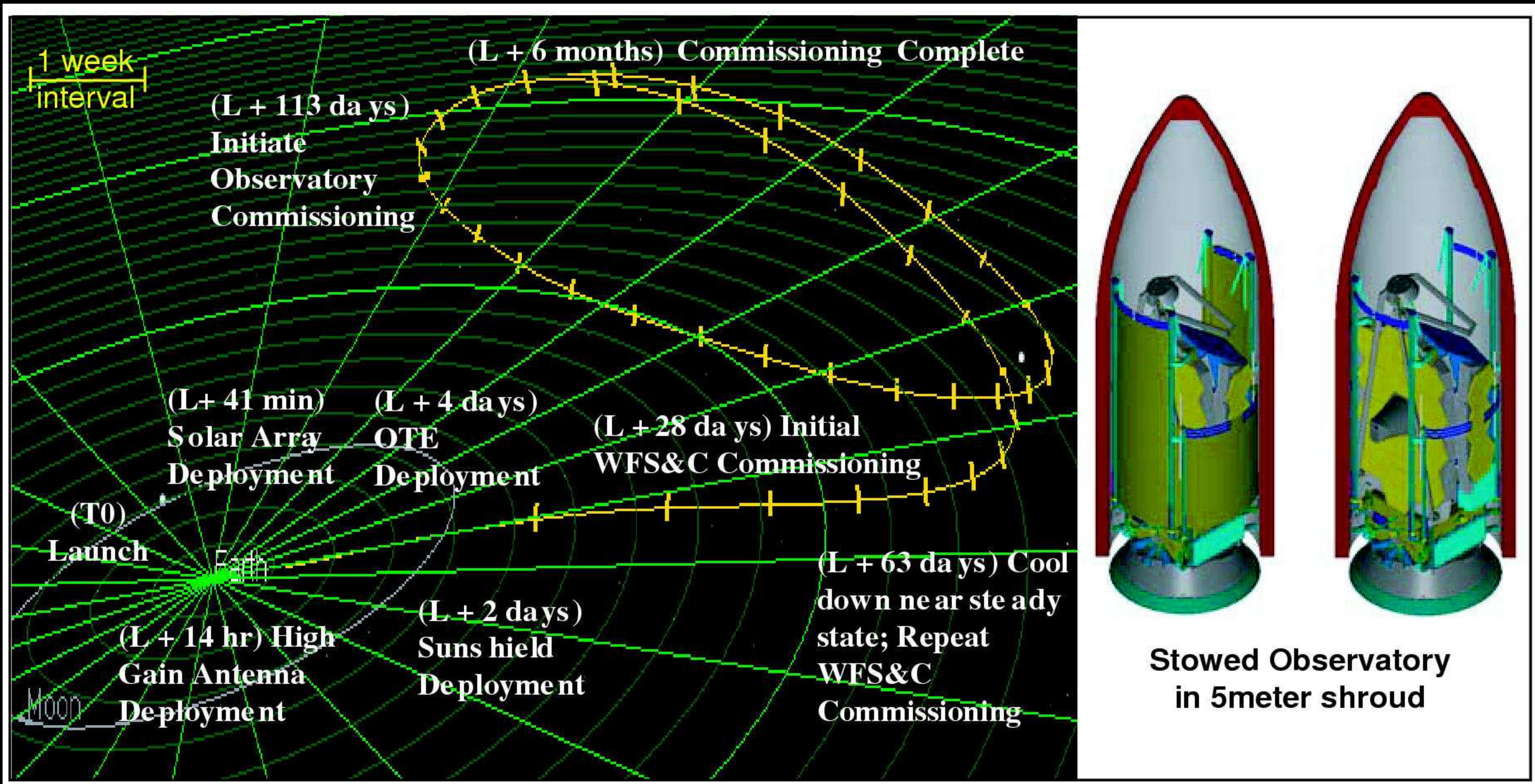
JWST Launch

- 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

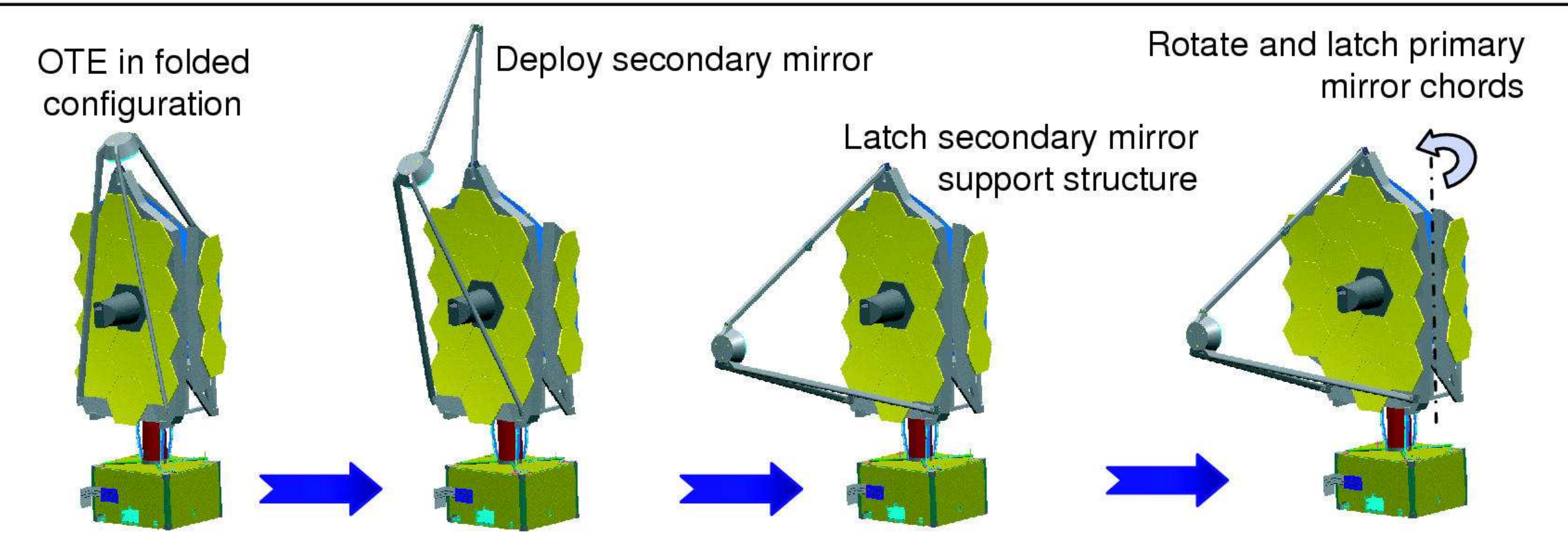
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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

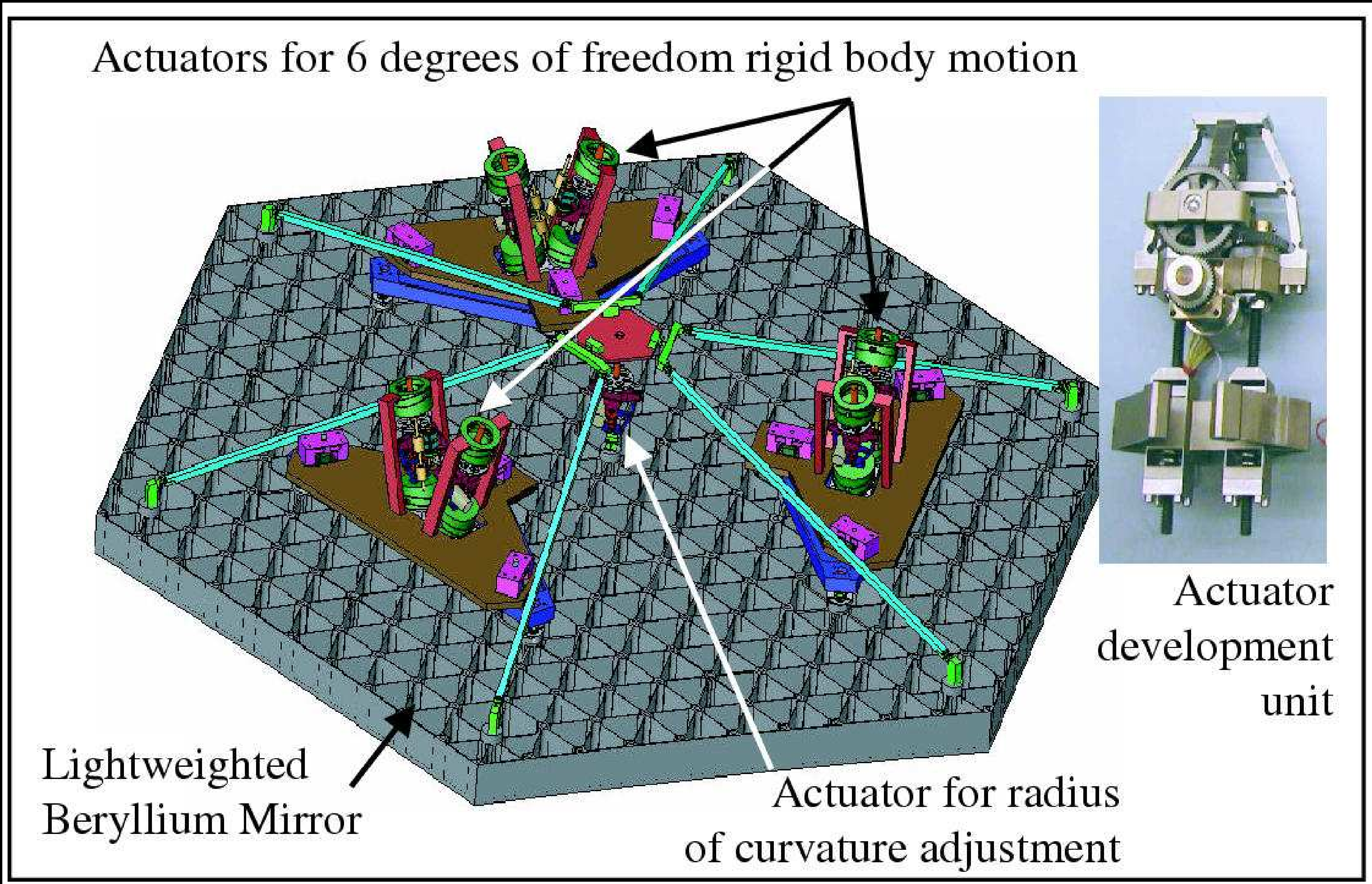


- After launch in 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

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



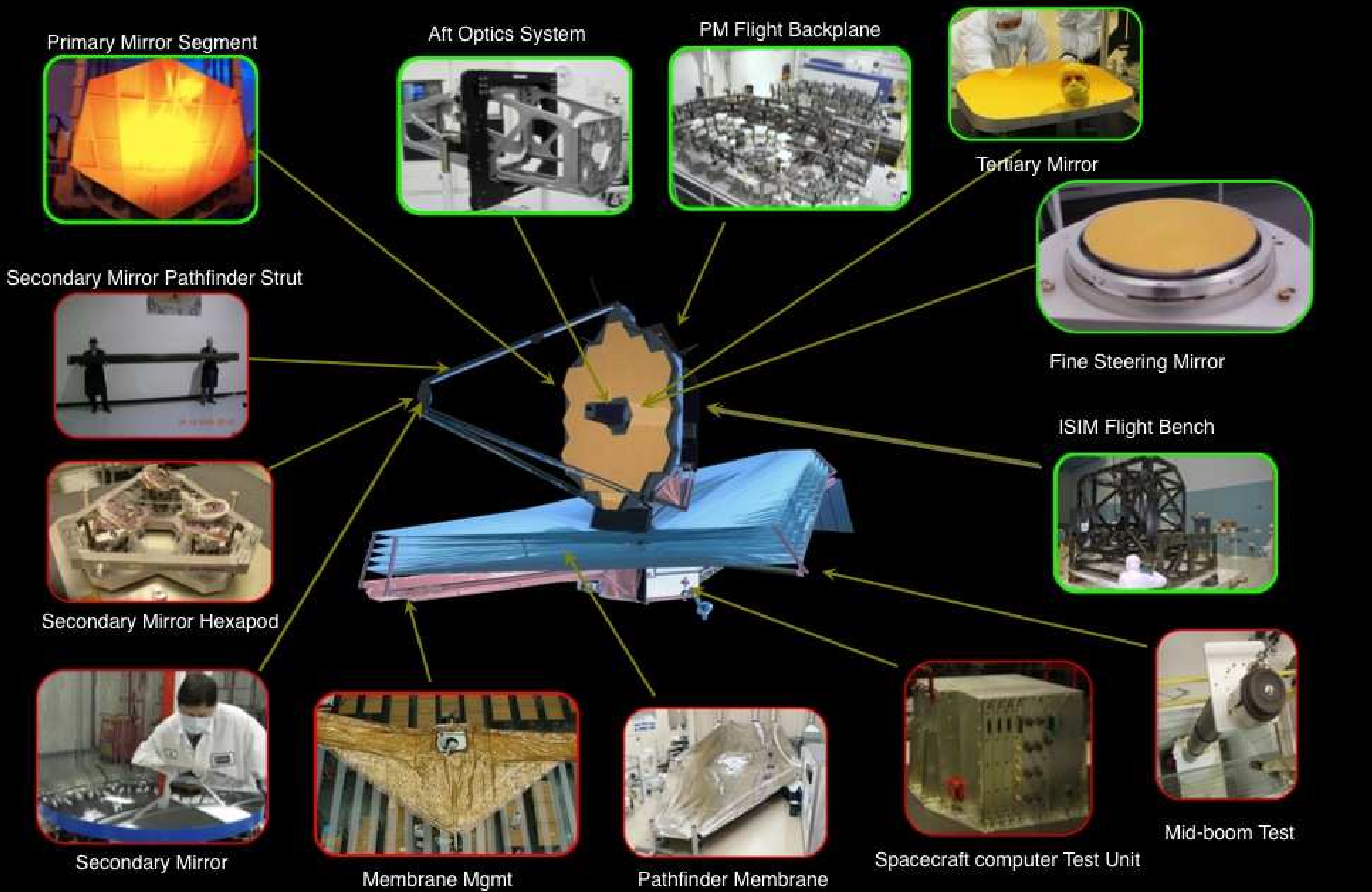
- During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.
- Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications!



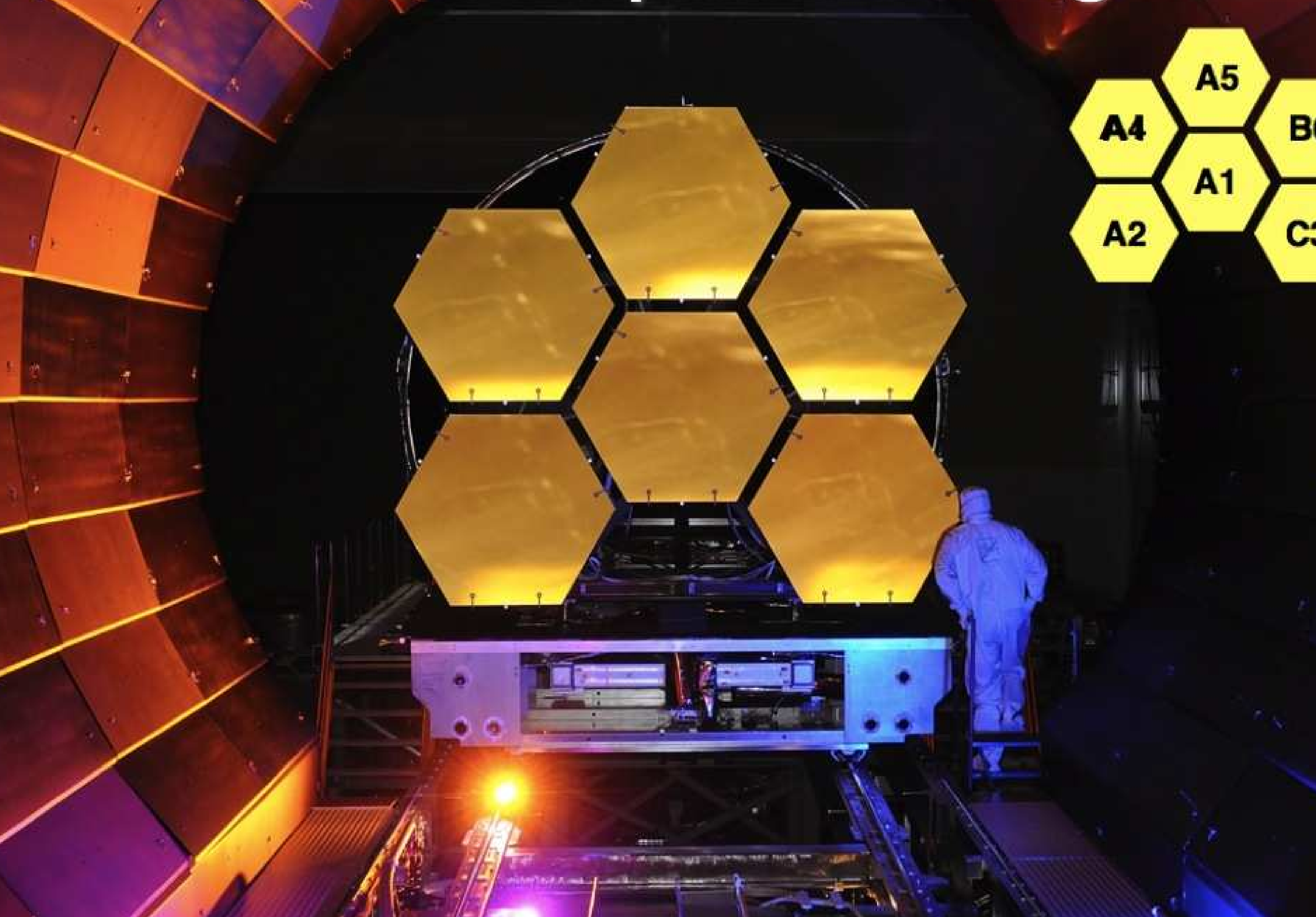
Active mirror segment support through “hexapods”, similar to Keck.

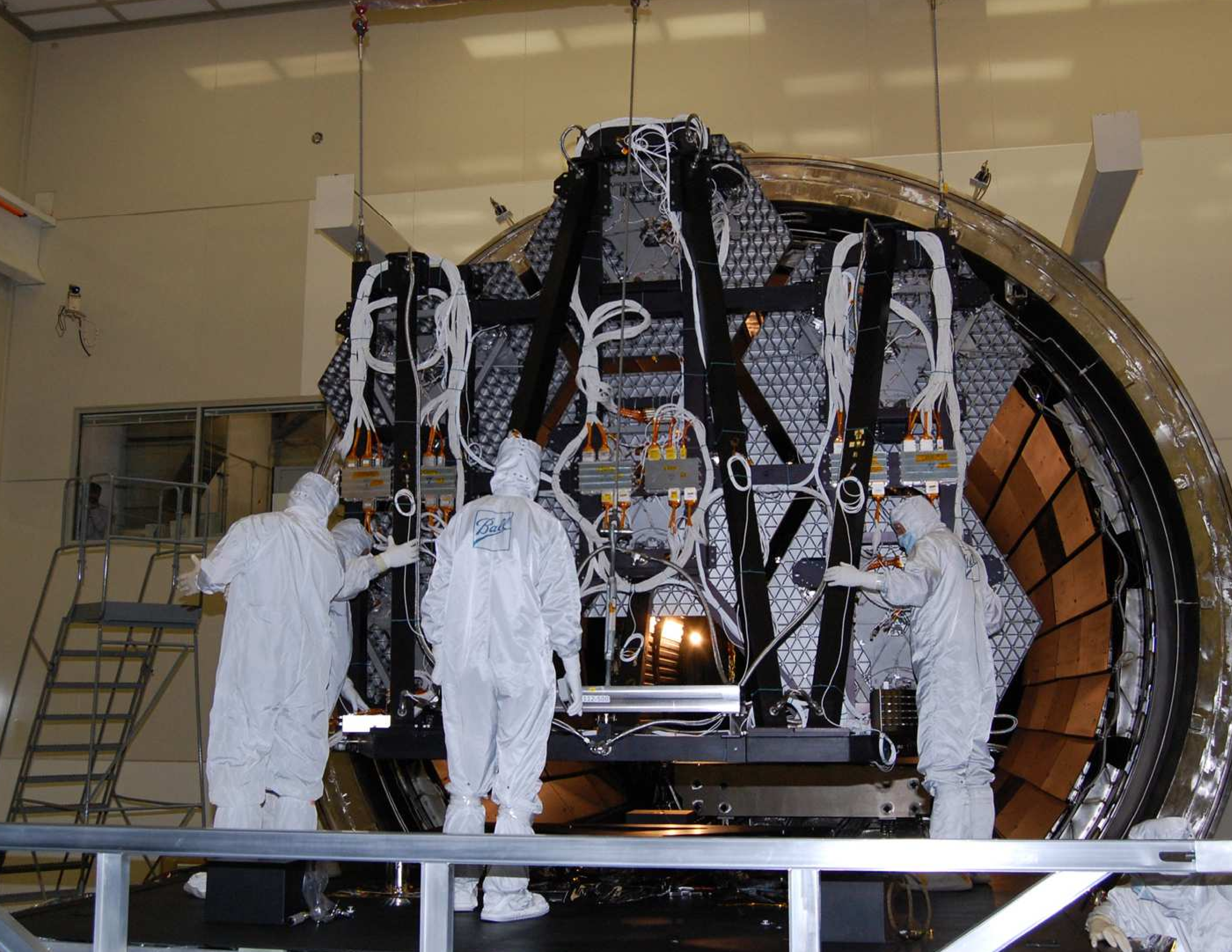
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

JWST Hardware Status



Mirror Acceptance Testing

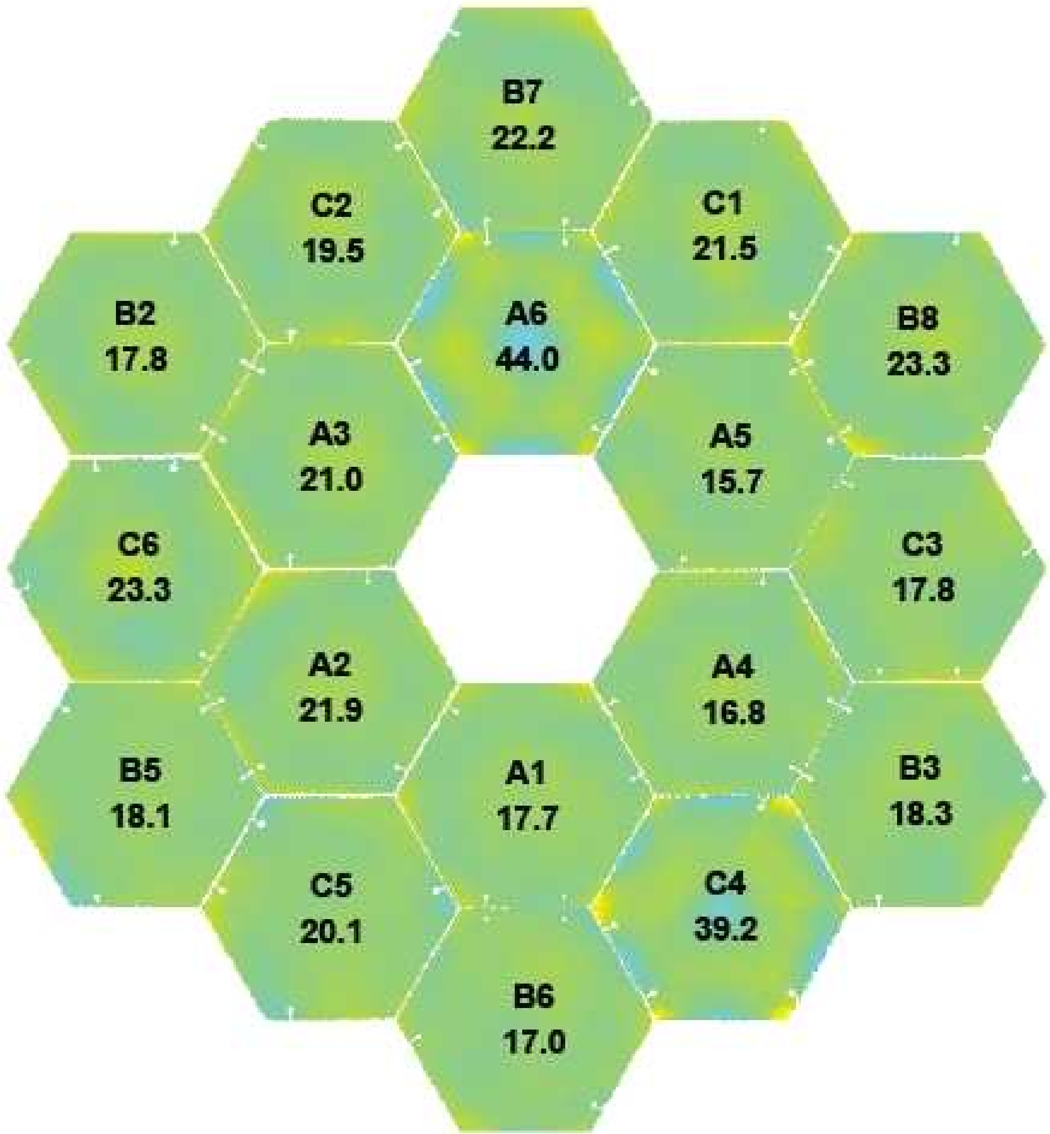


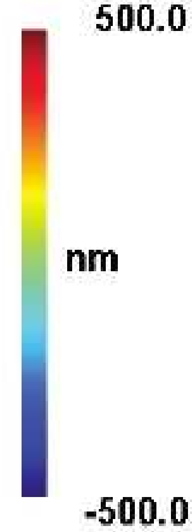

Ball

Primary Mirror Composite

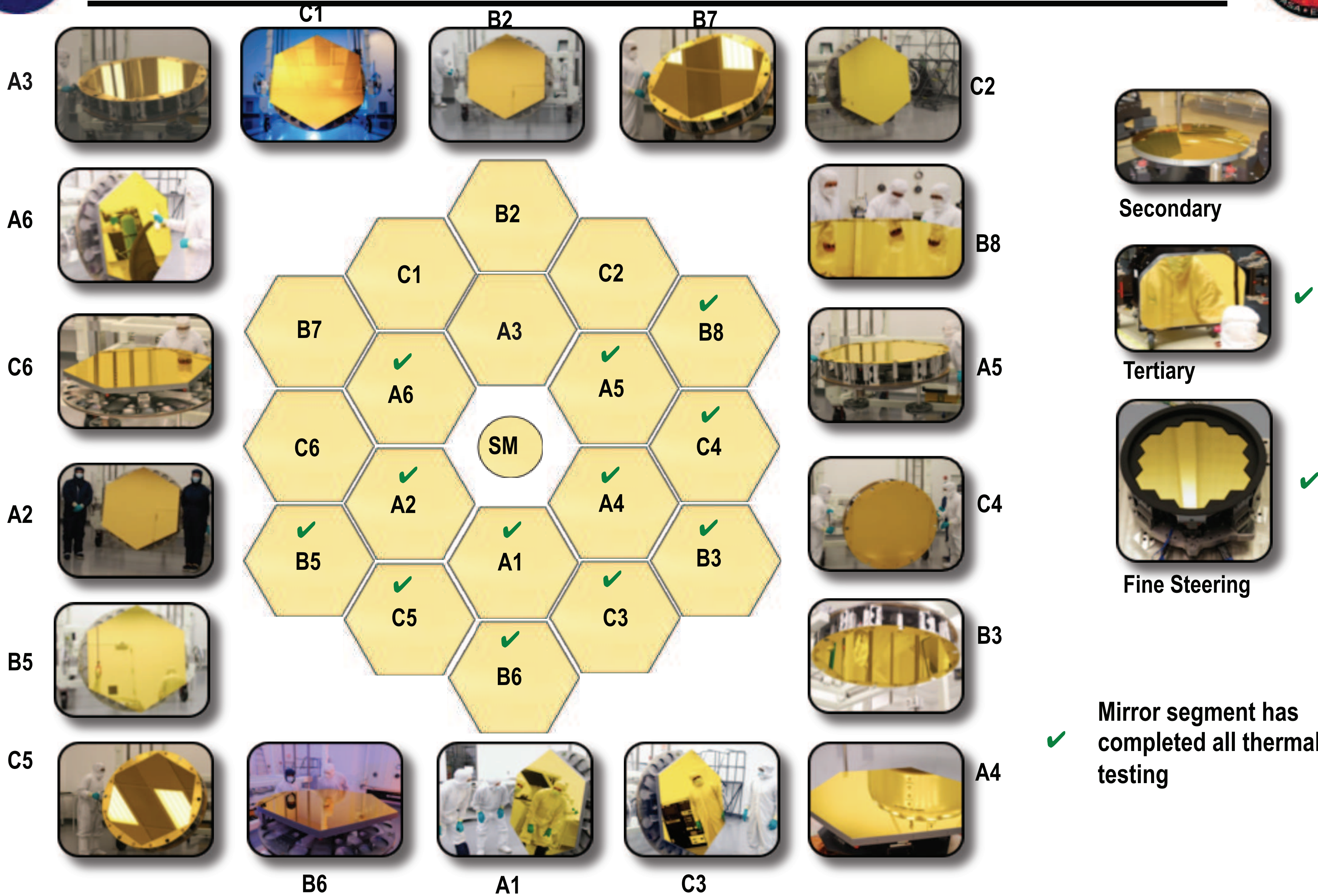
RMS: 23.2 nm

PV: 515.5 nm



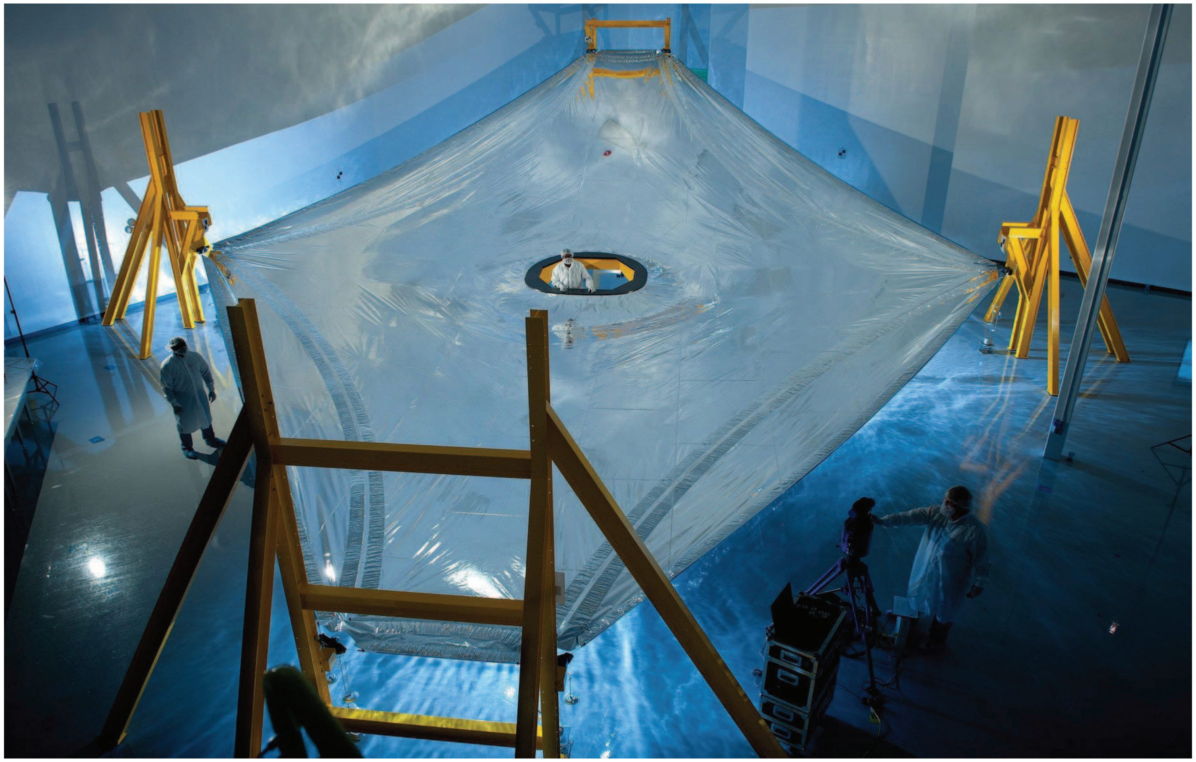


Family Portrait



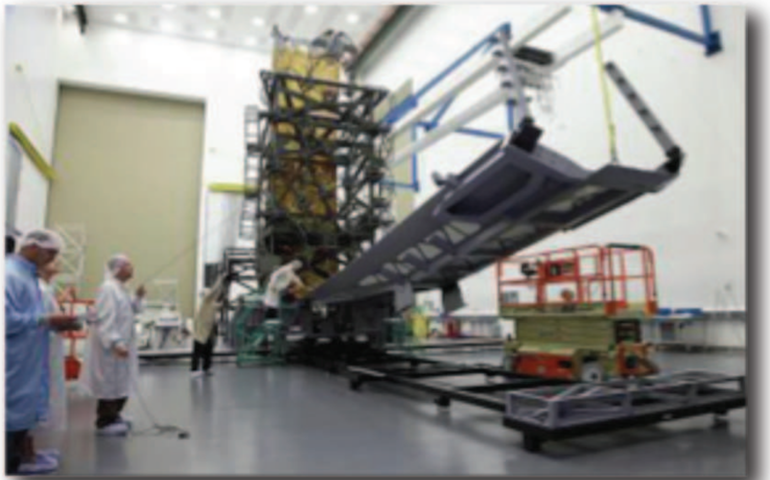
Sunshield

- **Template membrane build to flight-like requirements for verification of:**
  - Shape under tension to verify gradients and light line locations
  - Hole punching & hole alignment for membrane restraint devices (MRD)
  - Verification of folding/packing concept on full scale mockup
  - Layer 3 shape measurements completed



←Layer-3 template membrane under tension for 3-D shape measurements at Mantech

Full-scale JWST mockup with sunshield pallette



Telescope Assembly Ground Support Equipment

Hardware has been installed at GSFC approximately 8 weeks ahead of schedule

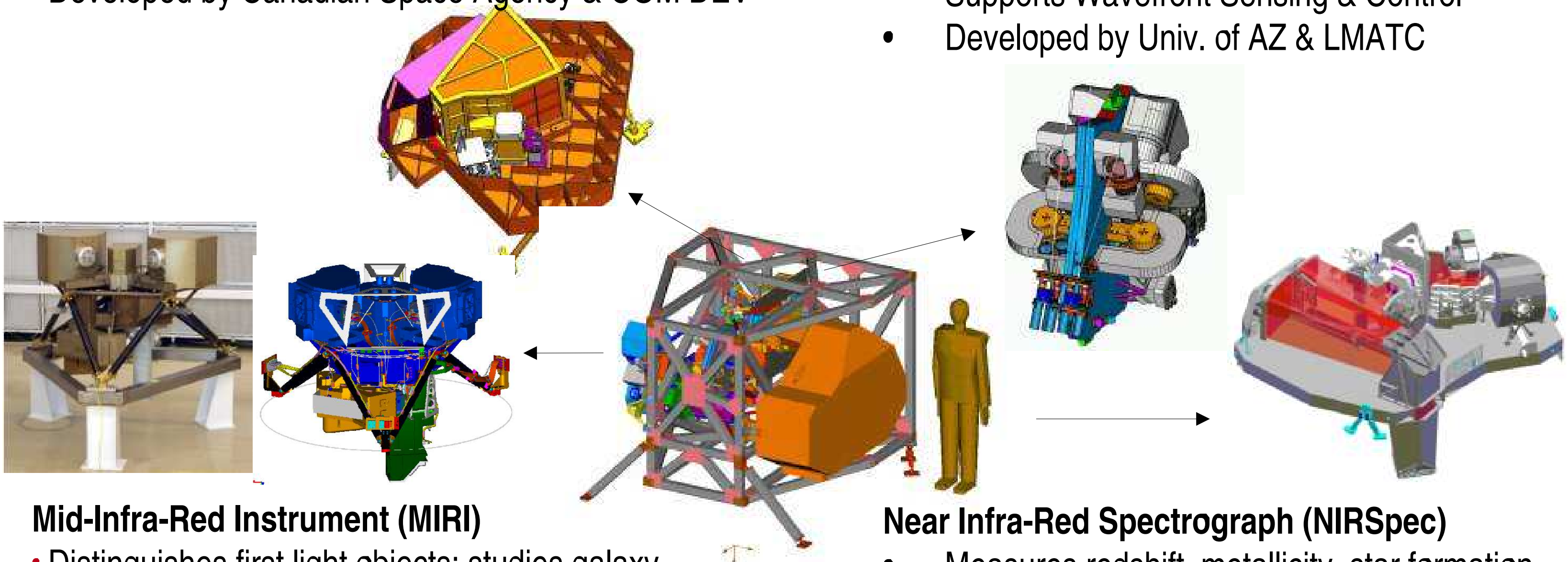
Landing a mirror onto backplane simulator

(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

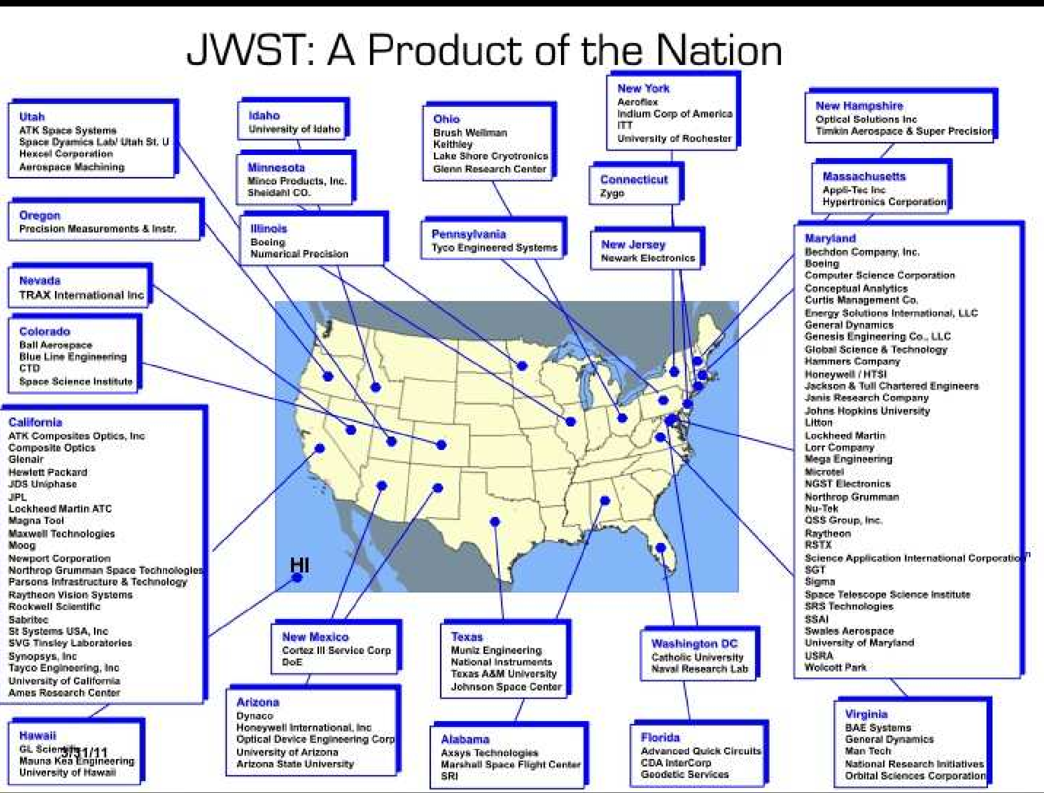
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

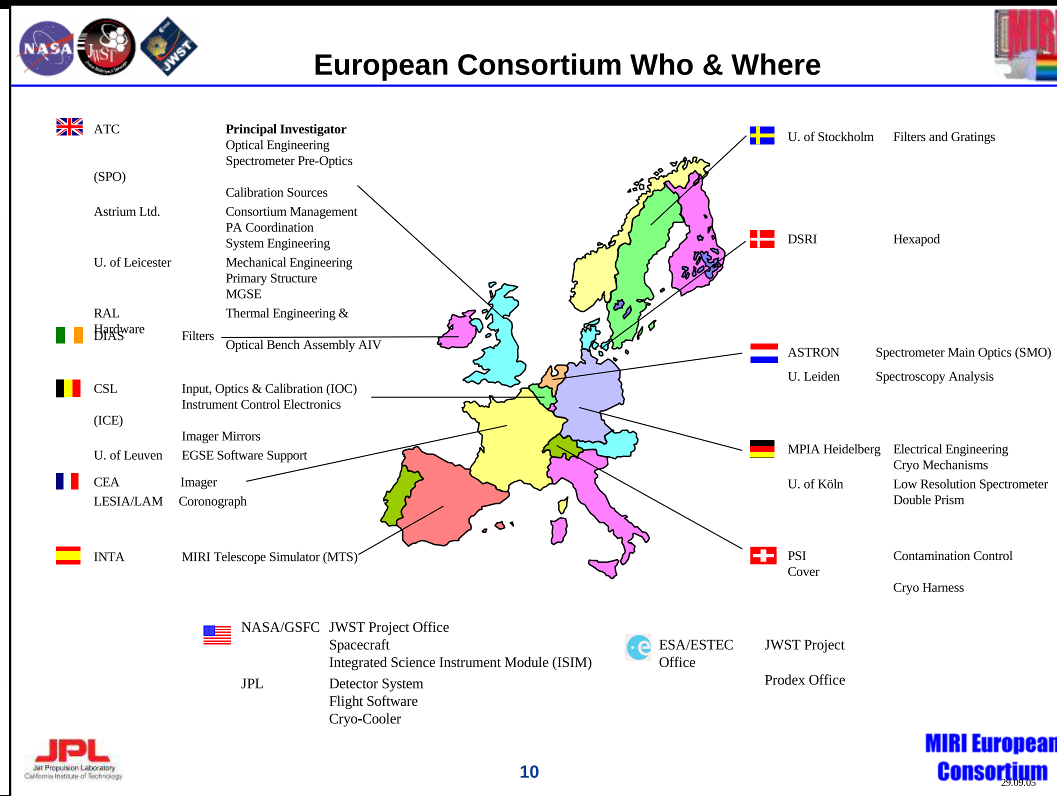


Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

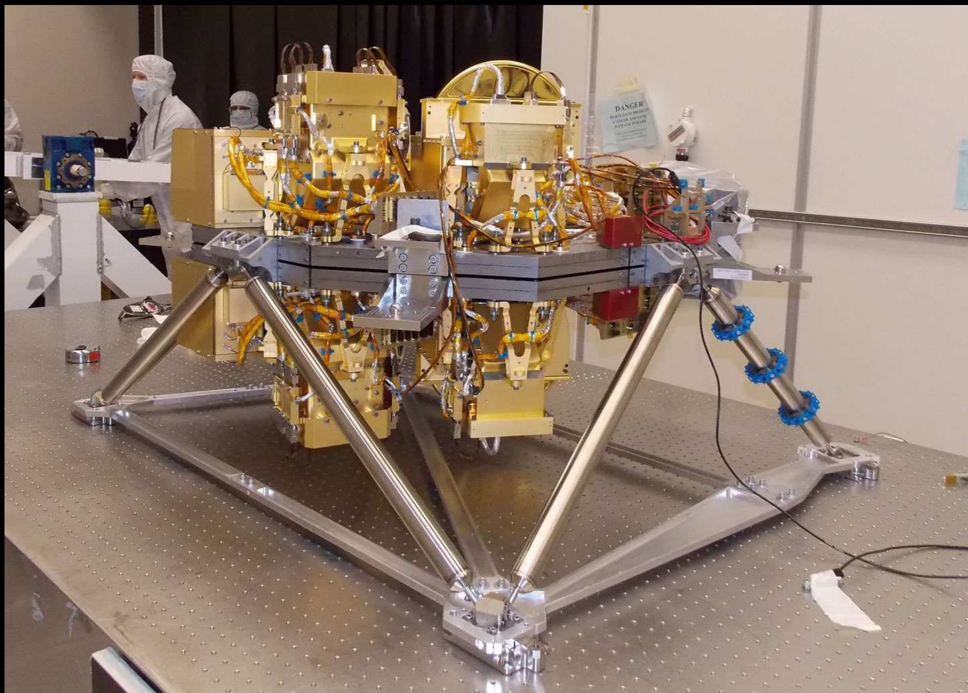
Near Infra-Red Spectrograph (NIRSpec)
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

MIRI delivery 05/12; FGS 07/12; NIRCam 07/28/13, NIRSpec Fall 2013.



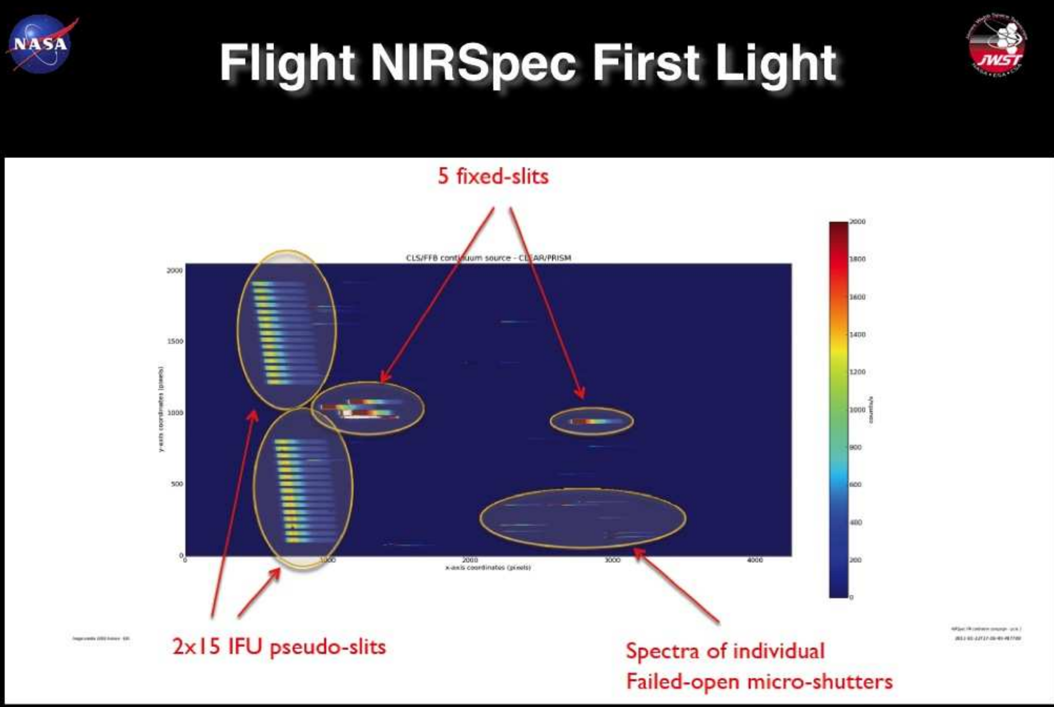


- JWST hardware made in 27 US States: $\gtrsim$80% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.



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
- FGS delivered to GSFC 07/12; NIRCam delivered July 28, 2013.

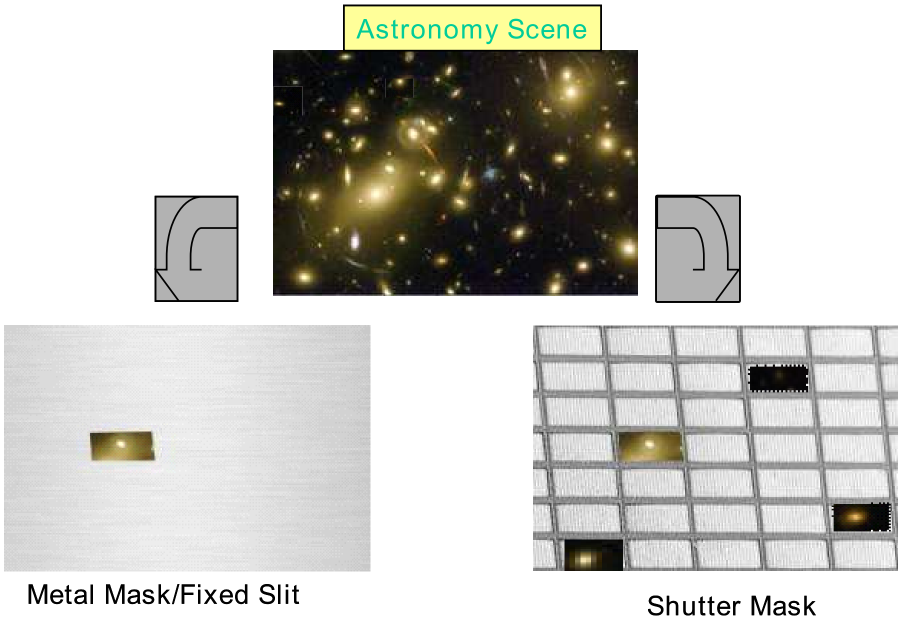


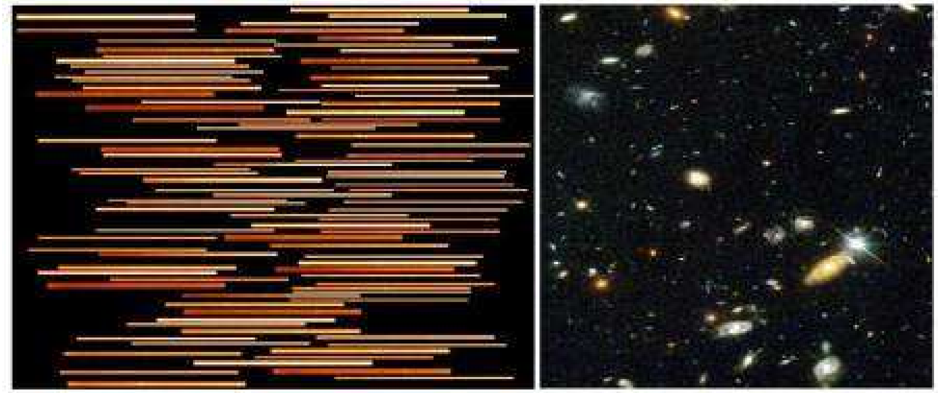
JWST's short-wavelength (0.6–5.0μm) spectrograph:

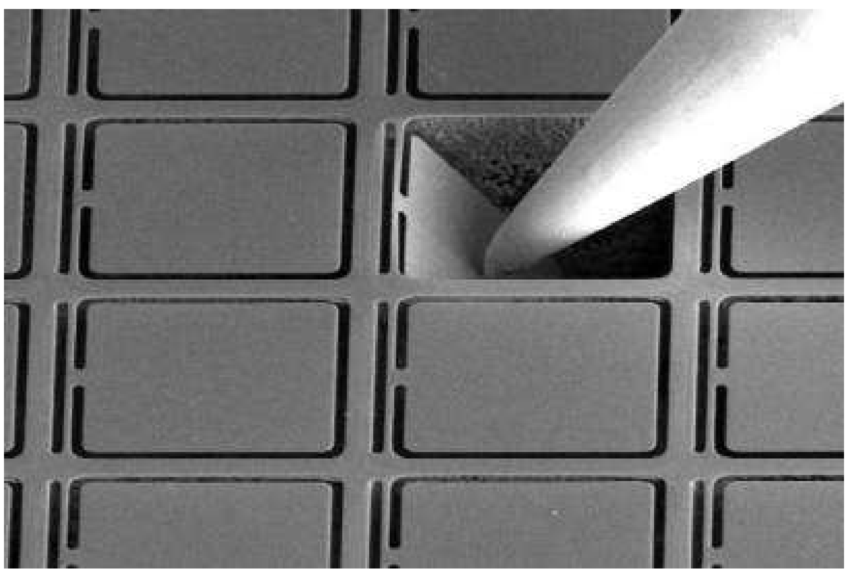
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Fight build completed and tested with First Light in Spring 2011.

NIRSpec delivery to NASA/GSFC scheduled for Fall 2013.

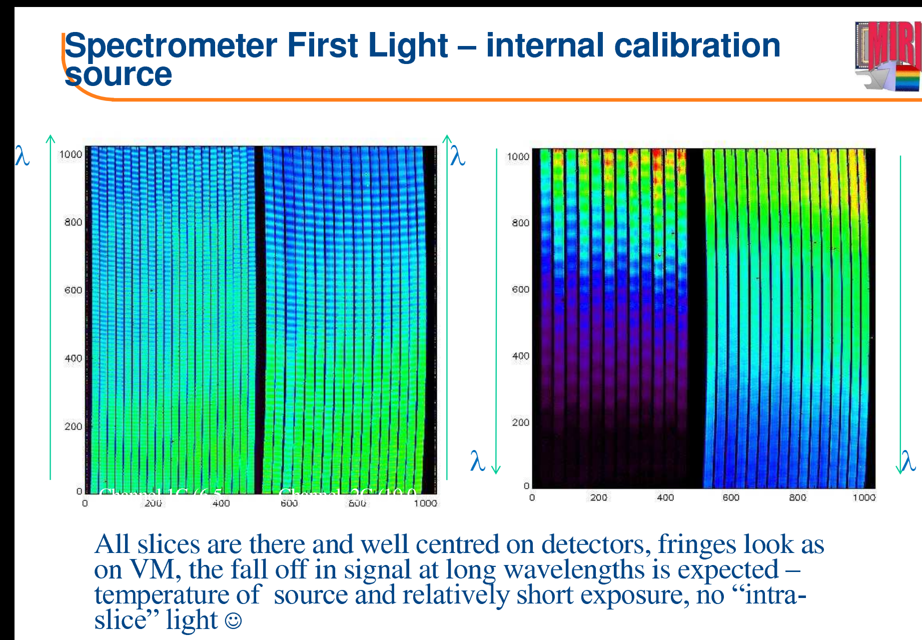
Micro Shutters







Flight MIRI

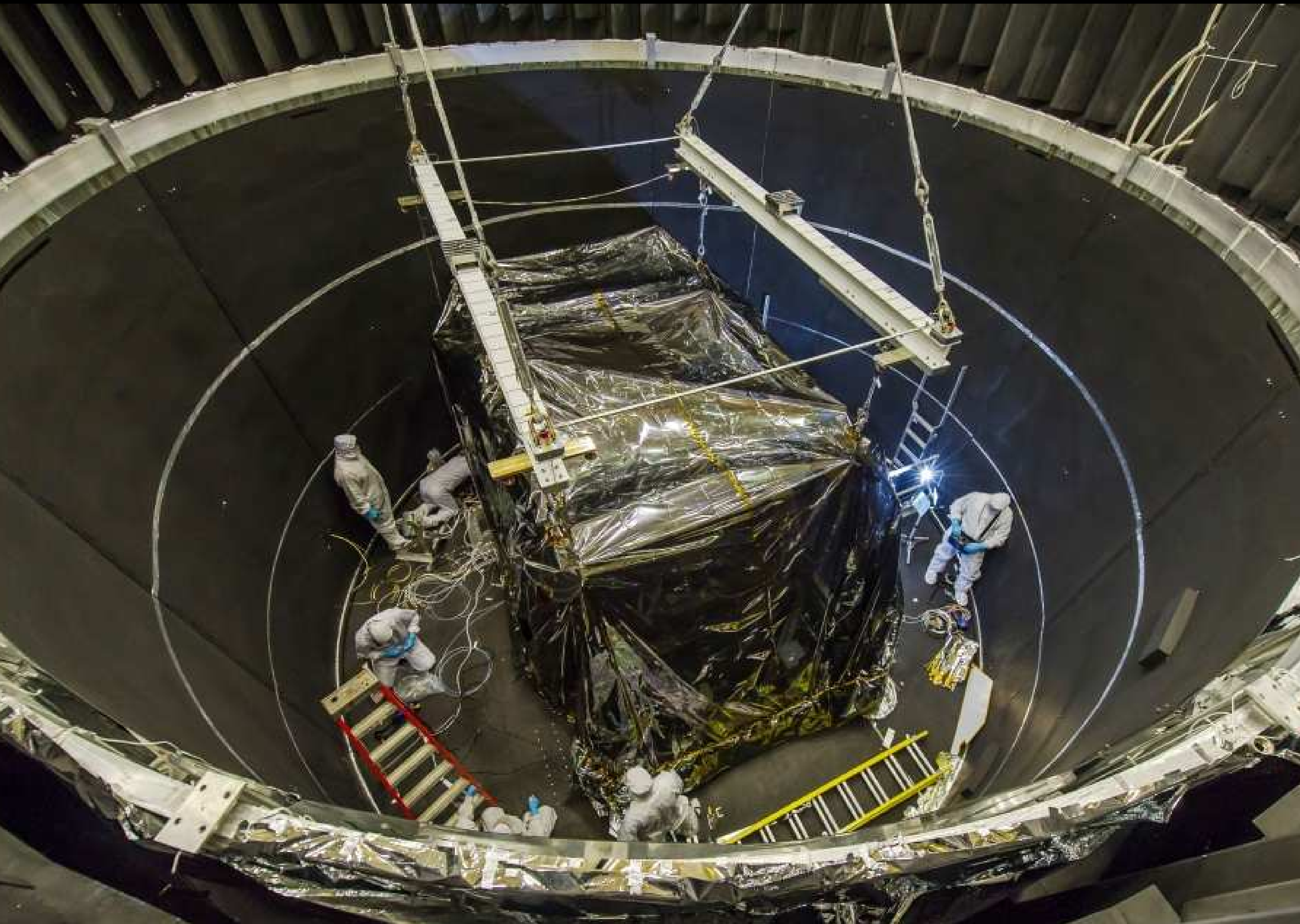


JWST’s mid-infrared (5–29μm) camera and spectrograph:

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

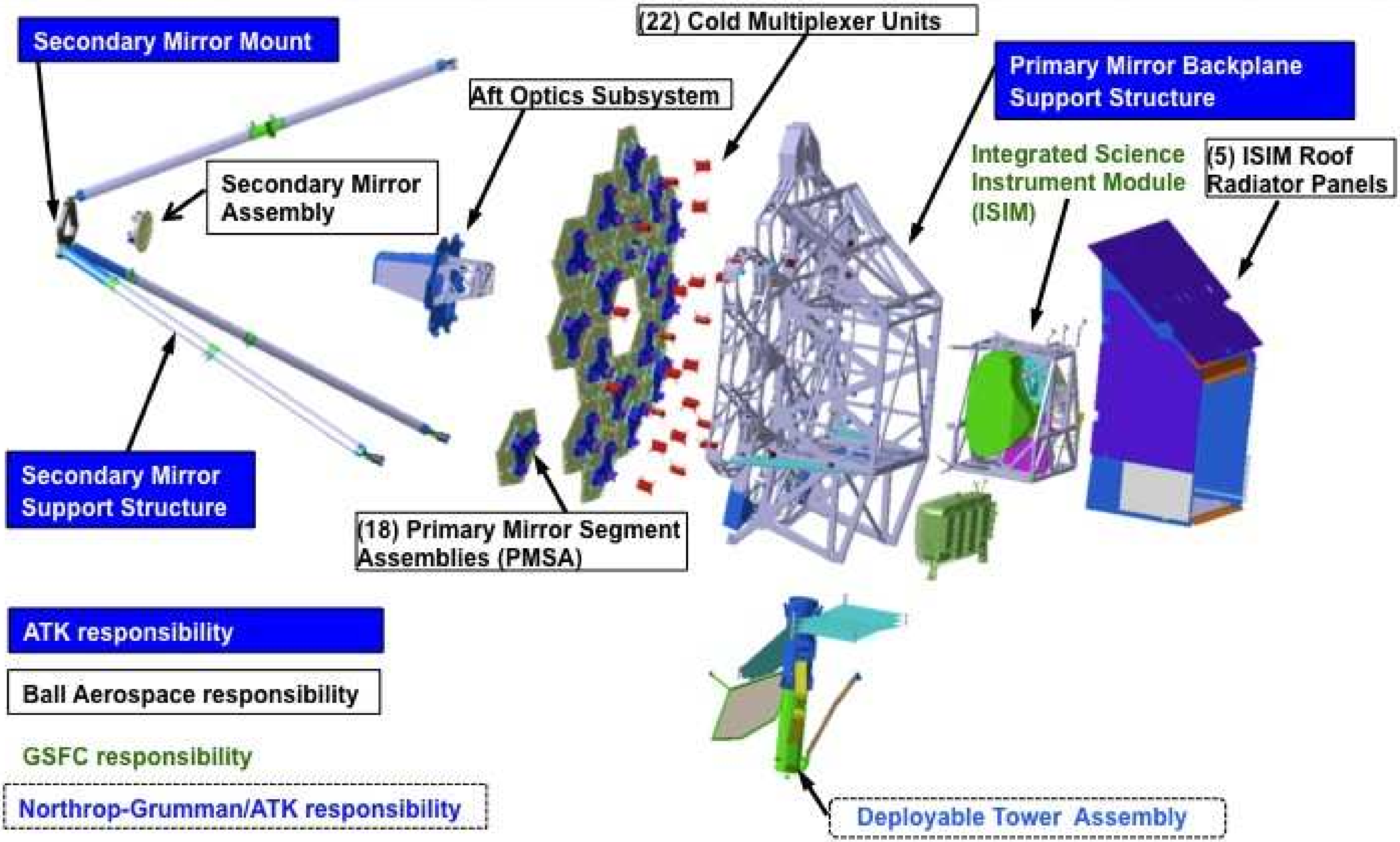
MIRI delivered to NASA/GSFC in May 2012.

OSIM: Here is where Instruments inside ISIM will be tested.



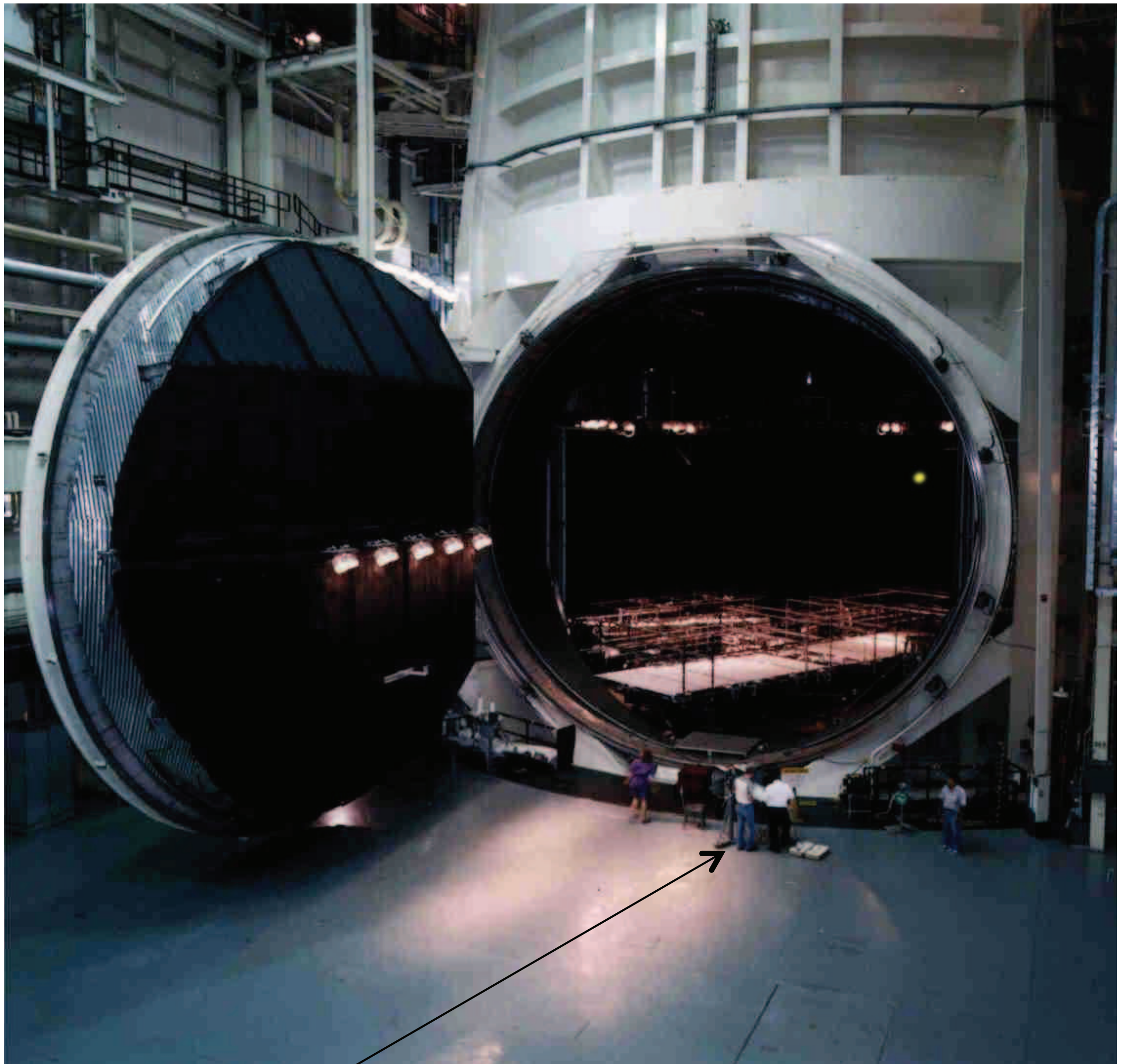
Aug. 2013: Actual Flight ISIM (with MIRI and FGS) lowered into OSIM.

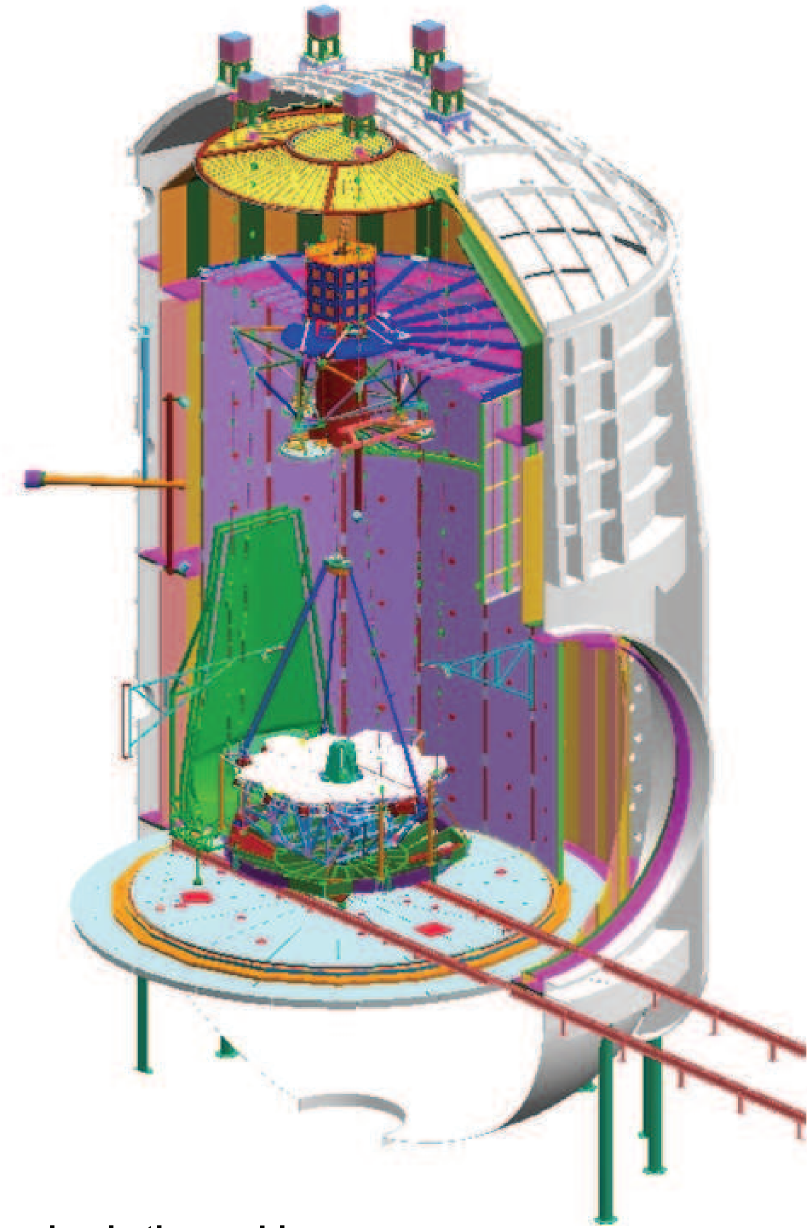
TELESCOPE ARCHITECTURE



3/31/11

OTE Testing – Chamber A at JSC



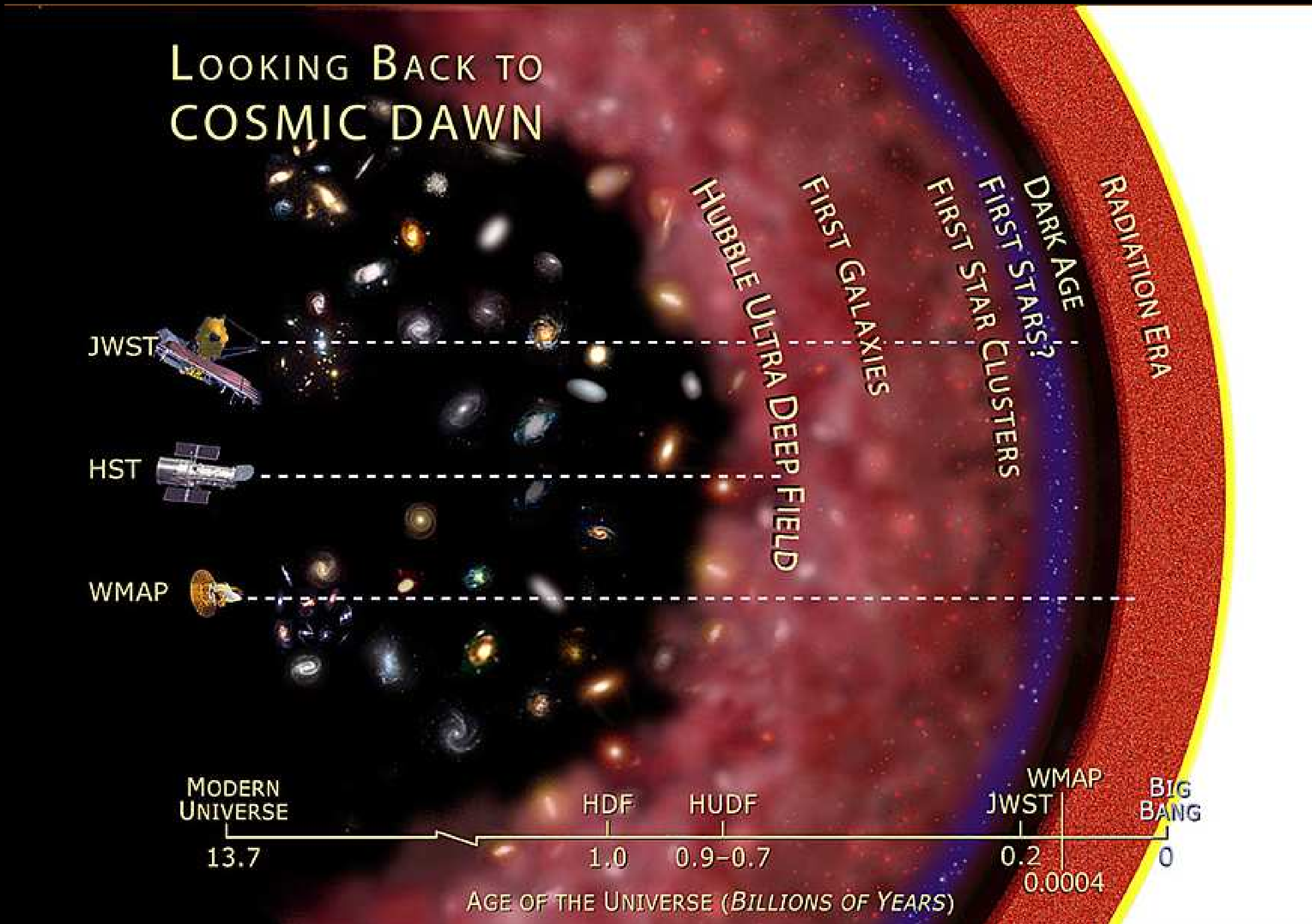


Notice people for scale

Will be the largest cryo vacuum test chamber in the world

OTIS: Largest TV chamber in world: will test whole JWST in 2015–2016.

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

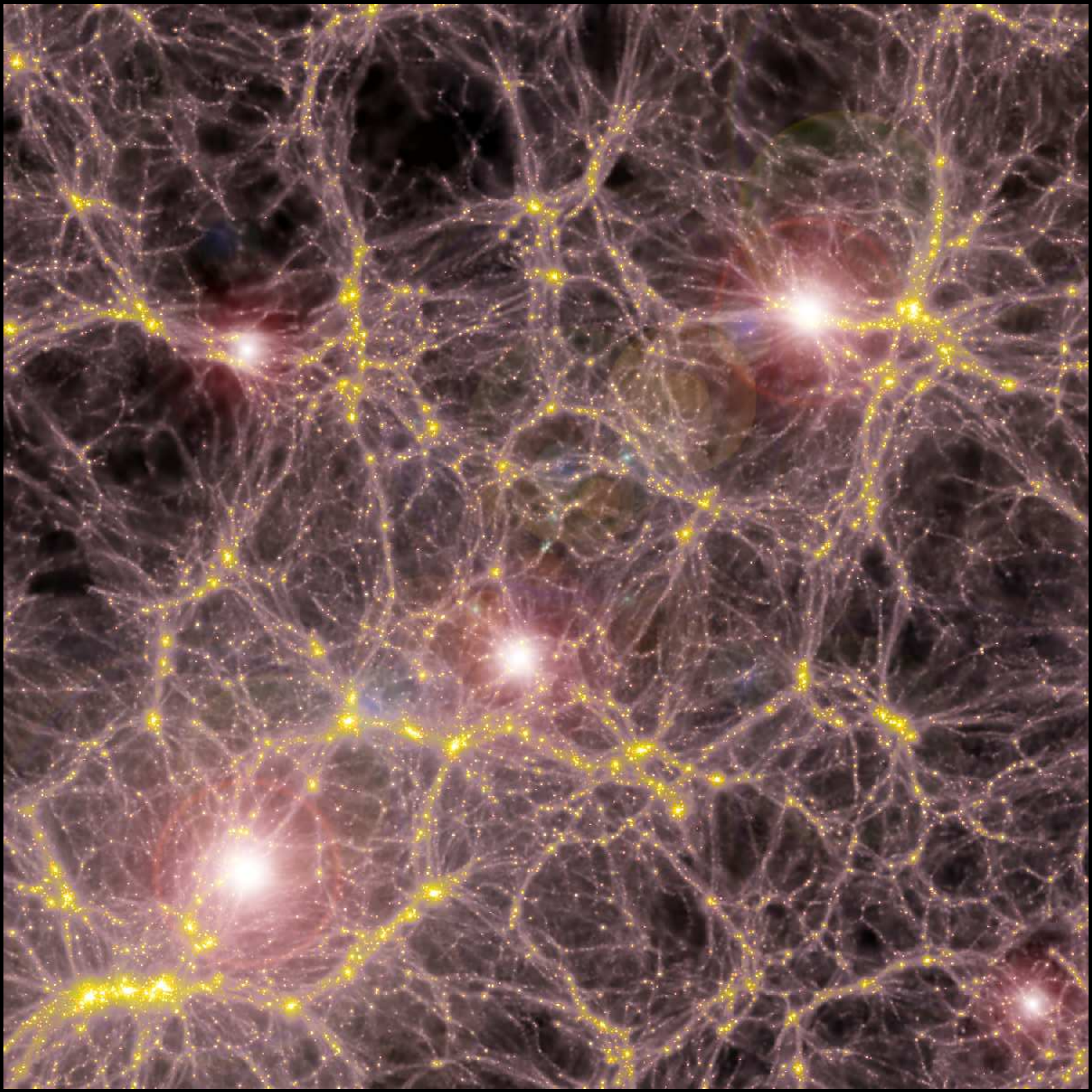


HST: Hubble sequence & galaxy evolution at $z \lesssim 7$–8 (age$\gtrsim$0.7 Gyr).

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

WMAP: Neutral Hydrogen first forms at $z=1090$ (cosmic age$\simeq$0.38 Myr).

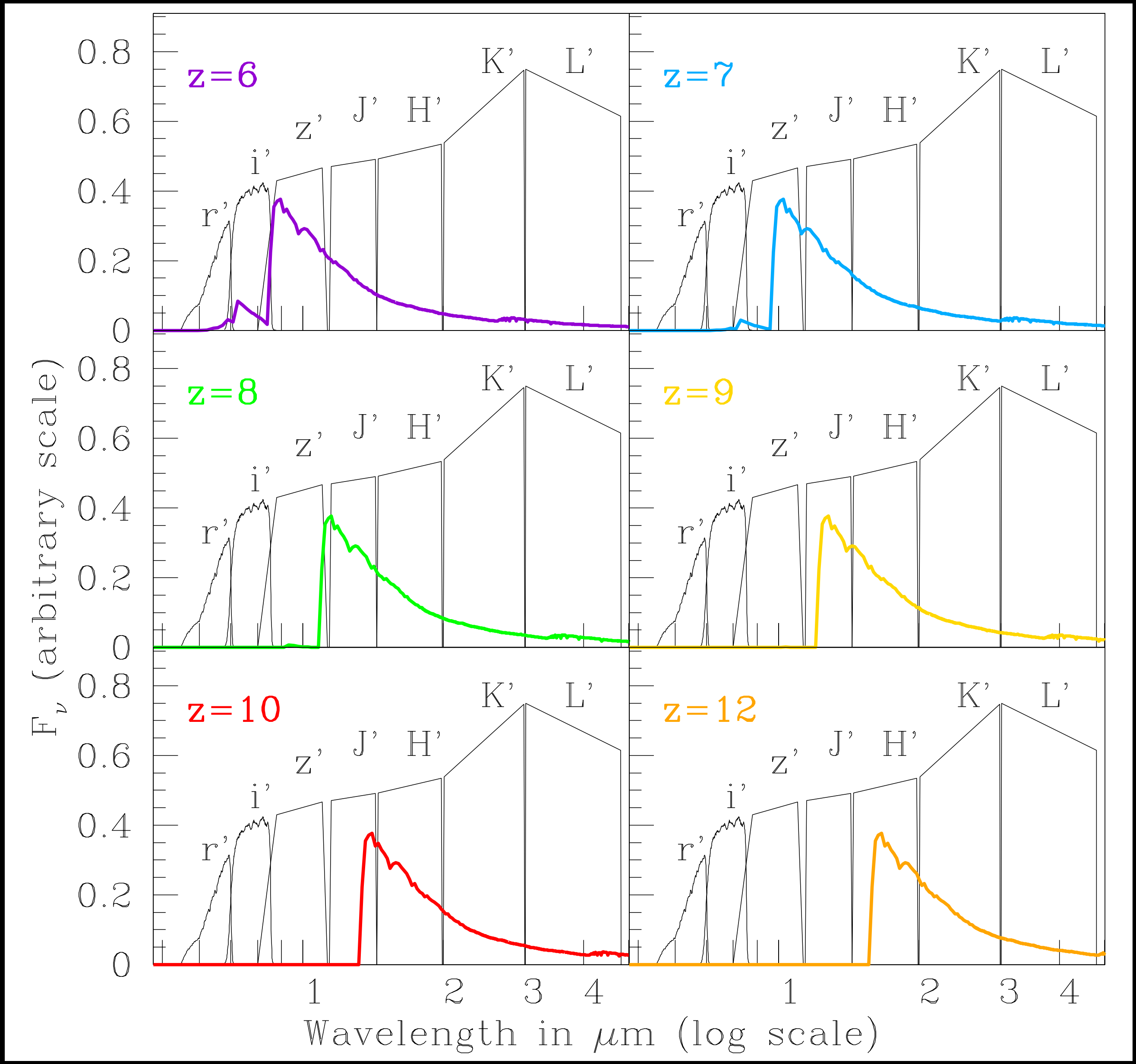
(4a) How will JWST Observe First Light and Reionization?



- 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).

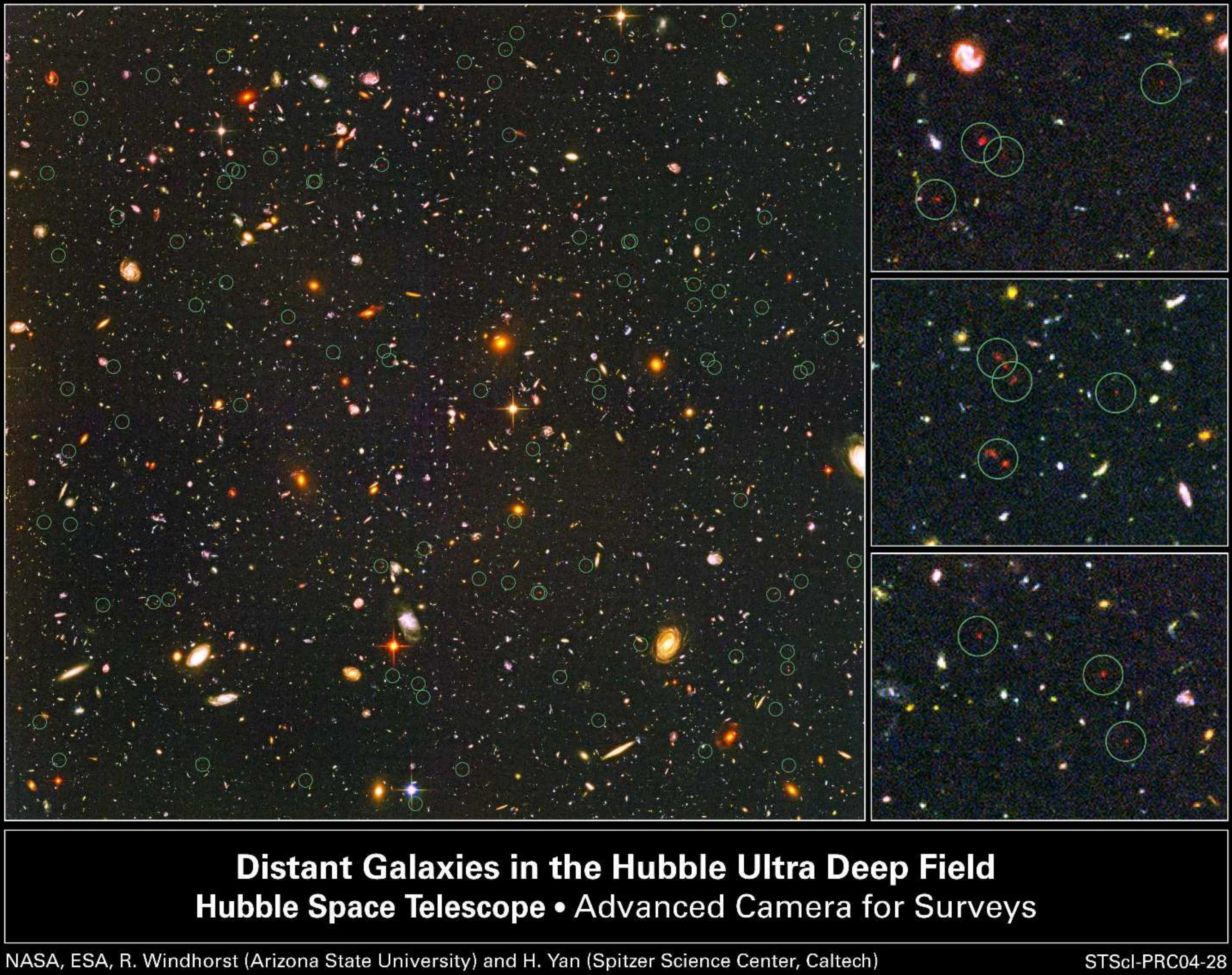
- This should be visible to JWST as the first massive stars and surrounding star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \longrightarrow 30$.

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

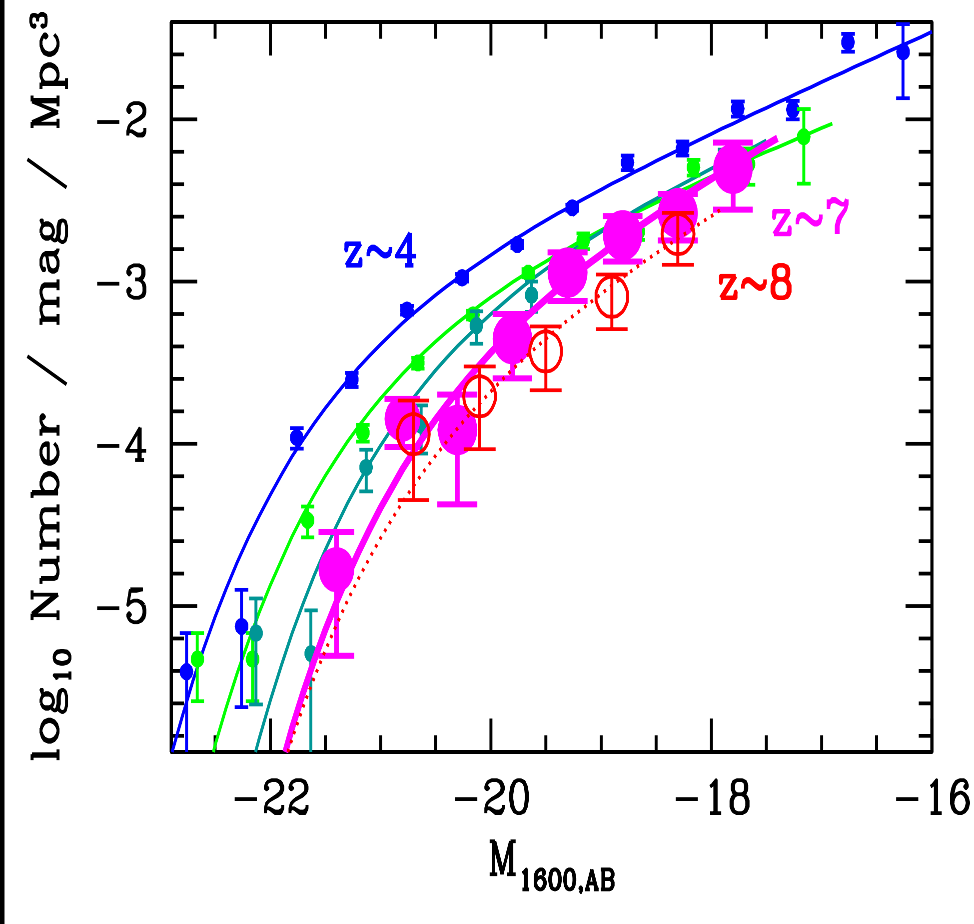


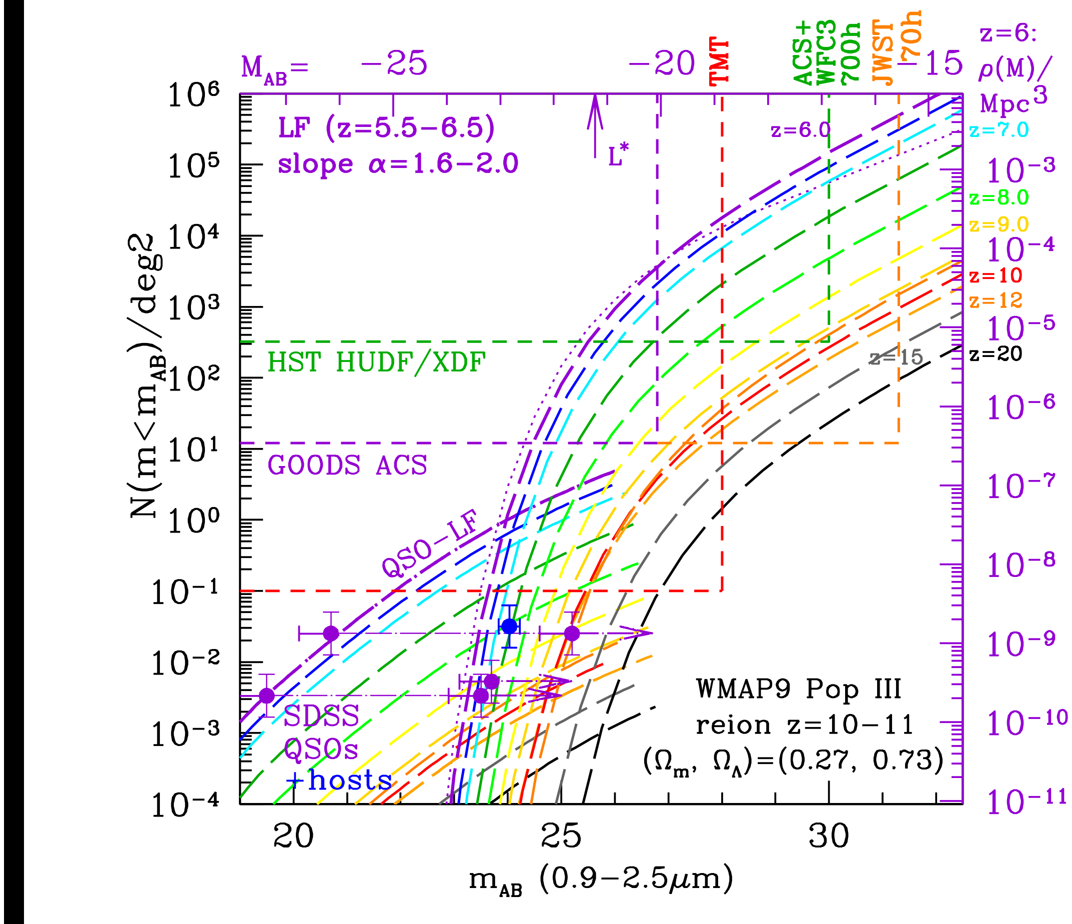
- Can't beat redshift: to see First Light, must observe near–mid IR.

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



Hubble UltraDeep Field: Dwarf galaxies at z≃6 (age≃1 Gyr; Yan & Windhorst 2004), many confirmed by spectra at z≃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 Coronagraphs can also trace Super-Massive Black Holes as faint Quasars in young galaxies: JWST needs 2.0μm diffraction limit for this!

(4b) Gravitational Lensing to see the Reionizing population at $z \gtrsim 8$?

Two fundamental limitations determine ultimate JWST image depth:

(1) Cannot-see-the-forest-for-the-trees effect: Background objects blend into foreground neighbors $\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ deblending algorithms!

(2) House-of-mirrors effect: (Many?) First Light objects can be gravitationally lensed by foreground galaxies $\Rightarrow$ Must model/correct for this!

- Proper JWST 2.0μm PSF and straylight specs essential to handle this!

(5) Conclusions

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

- Today's Hubble sequence formed 7–10 Gyrs ago.

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

Budget and Management replan in 2011. No technical showstoppers!

- More than 80% 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.
- JWST Cycle 1 proposals due early 2017: in less than 3.5 years!

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

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

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

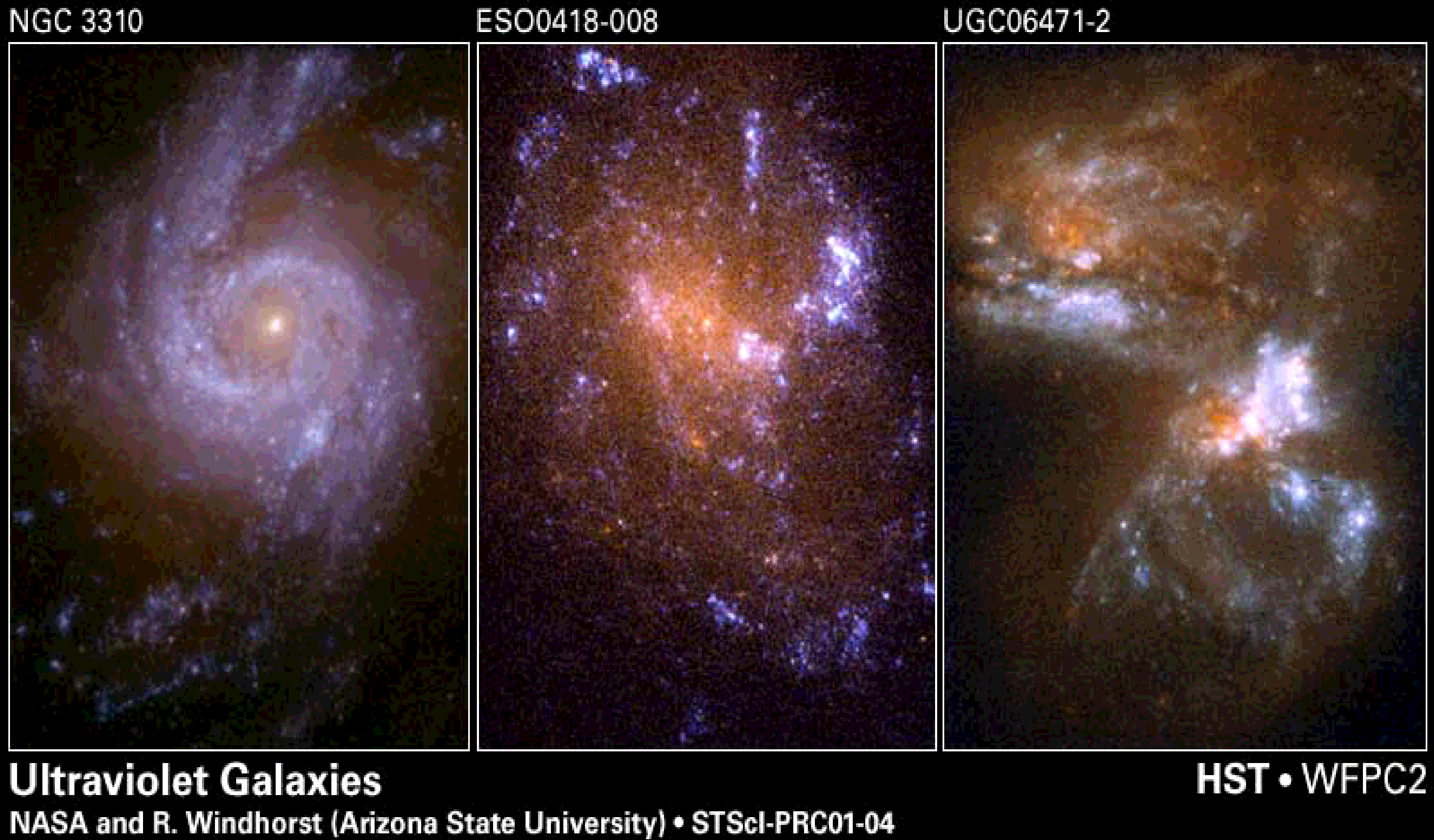
Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

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)

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

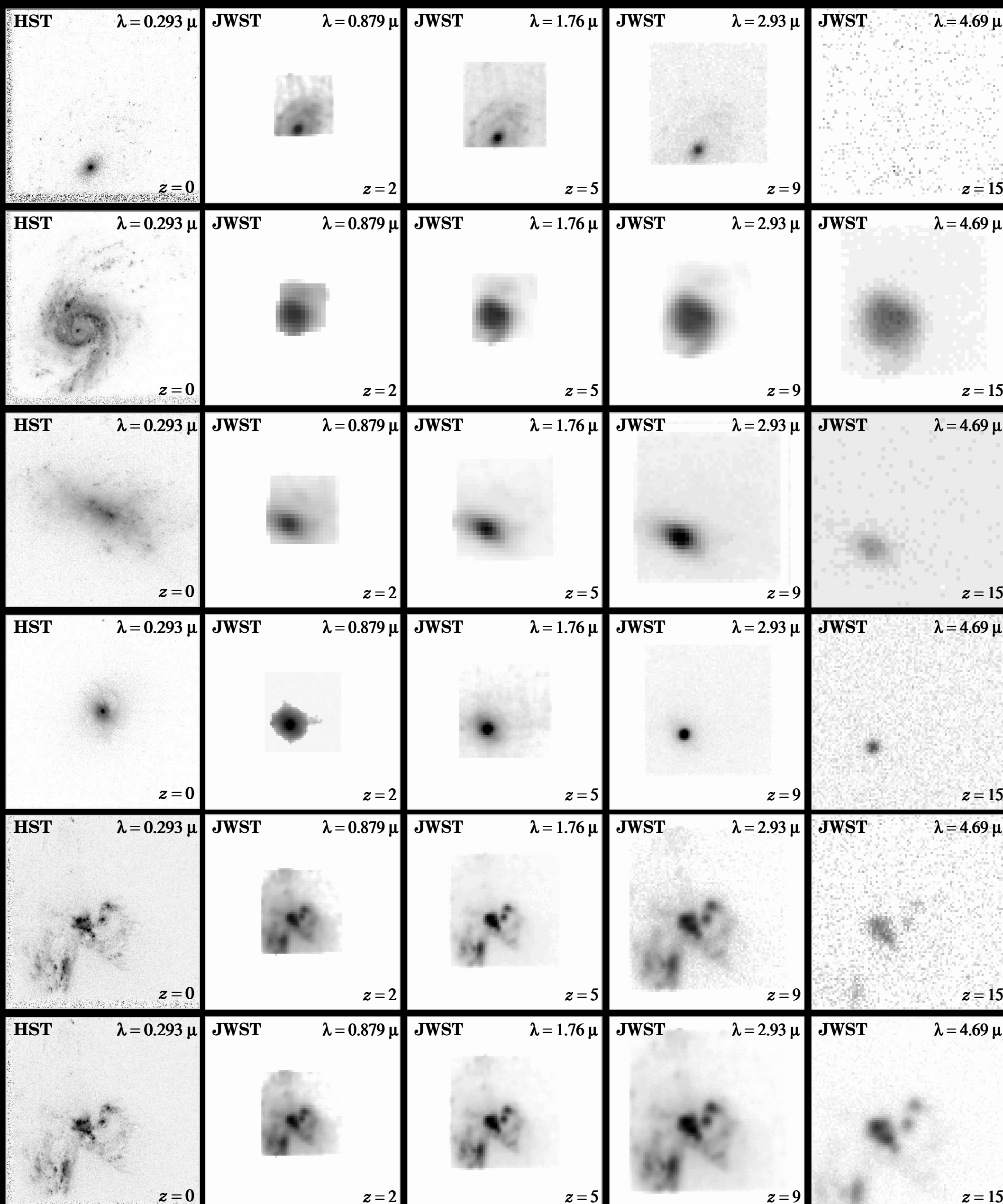


- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

- 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



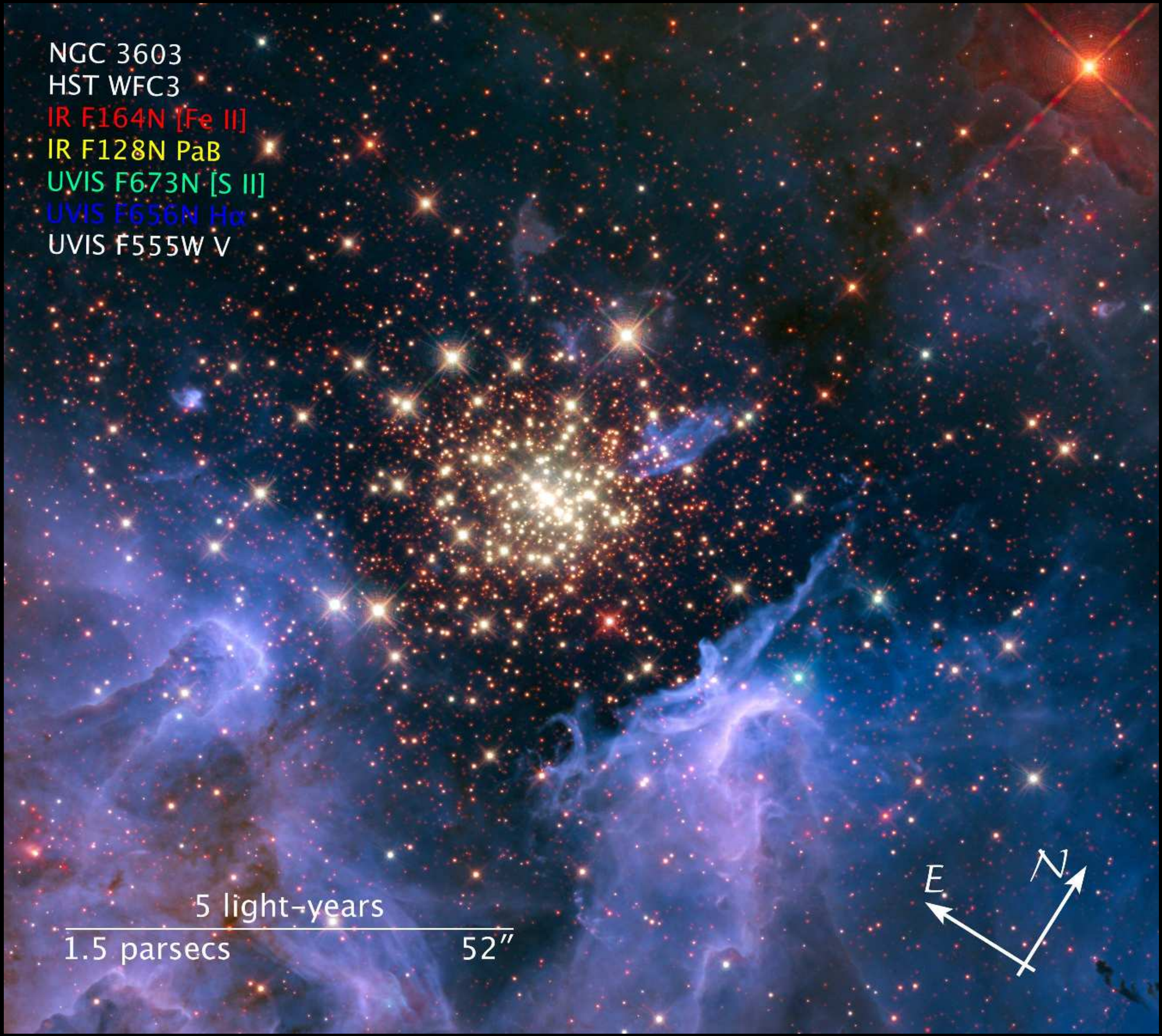
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

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

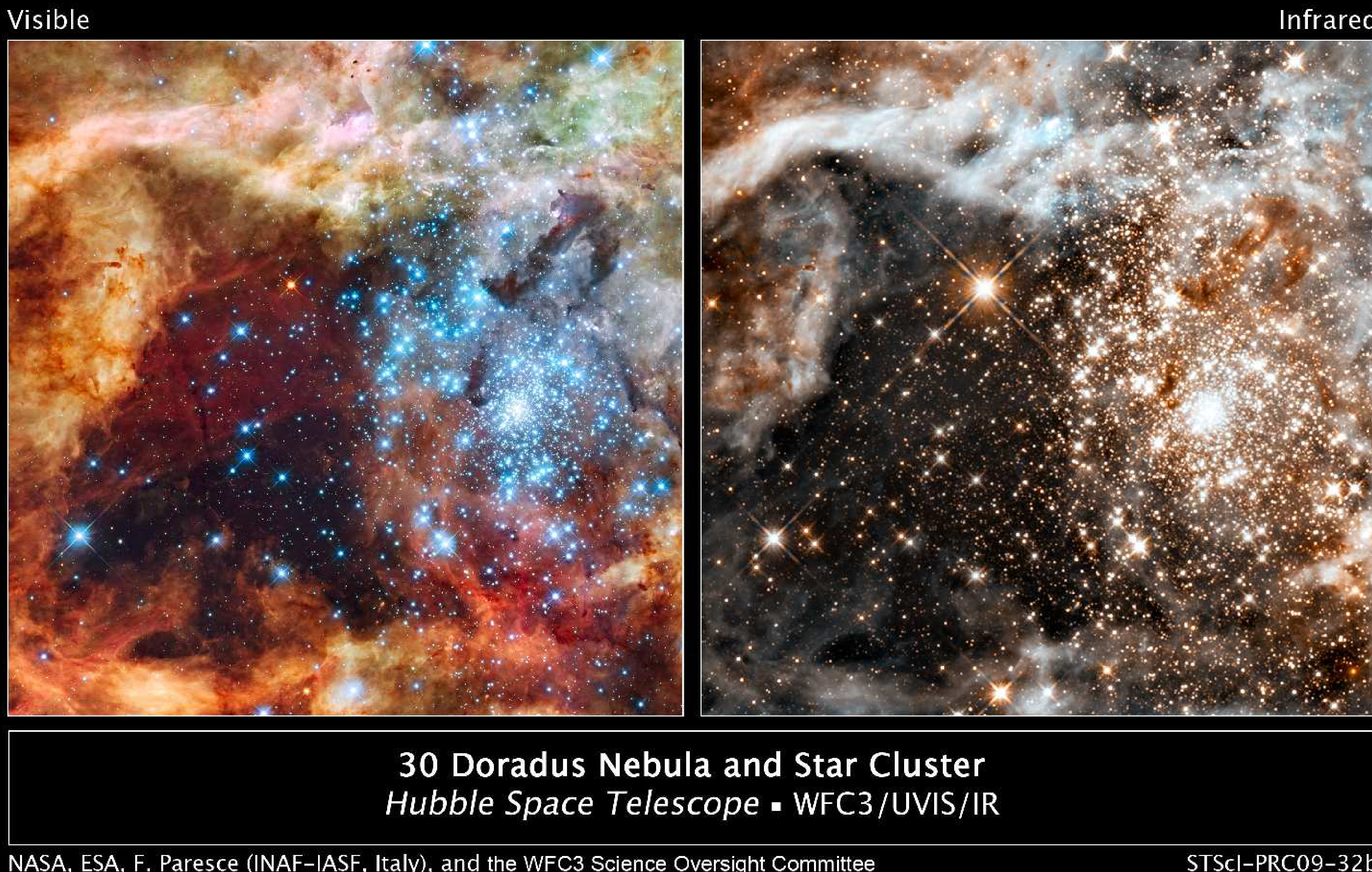
Visible to JWST at very high z are:

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

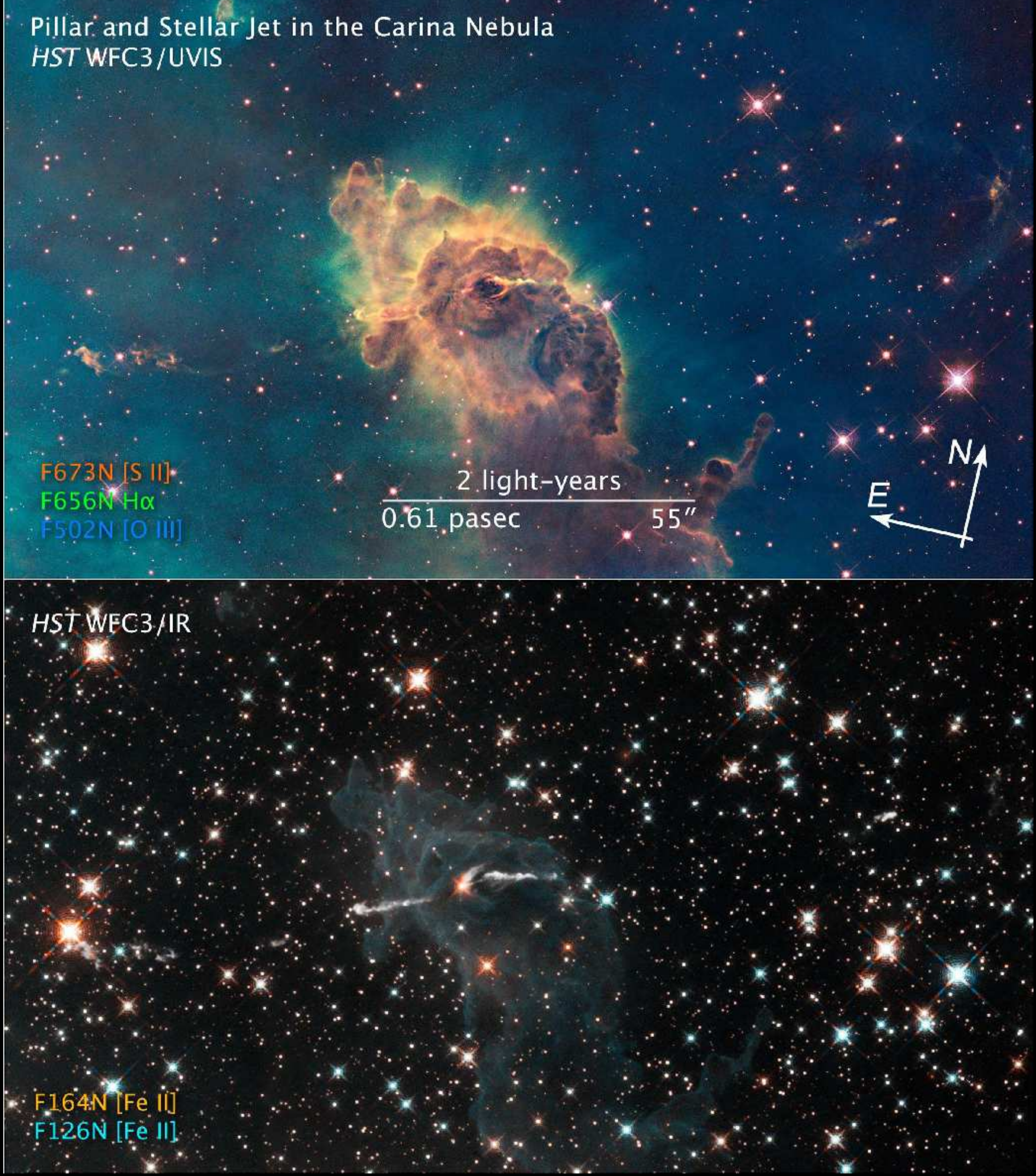
(6) How can JWST measure Star-birth and Earth-like exoplanets?



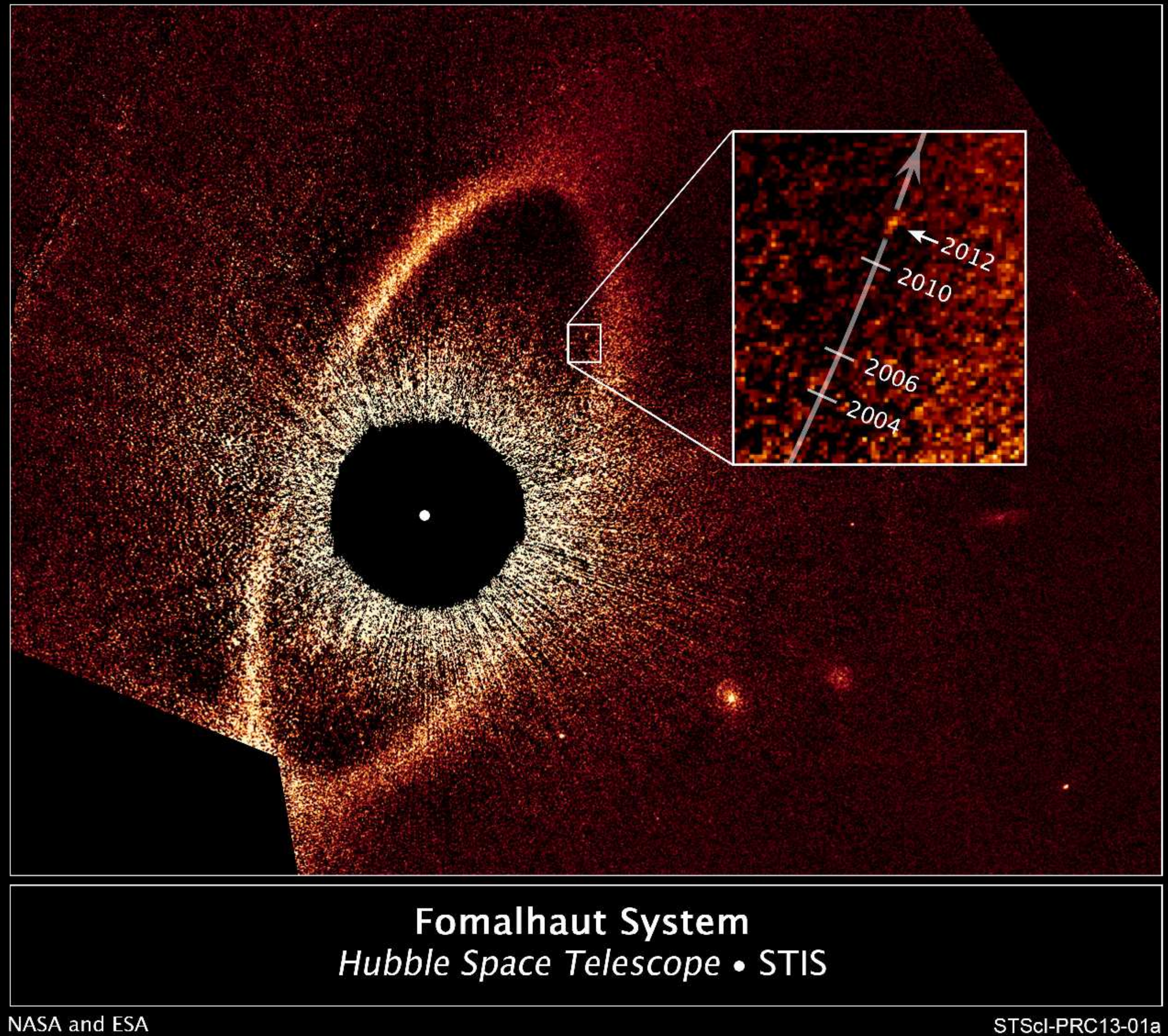
NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"



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

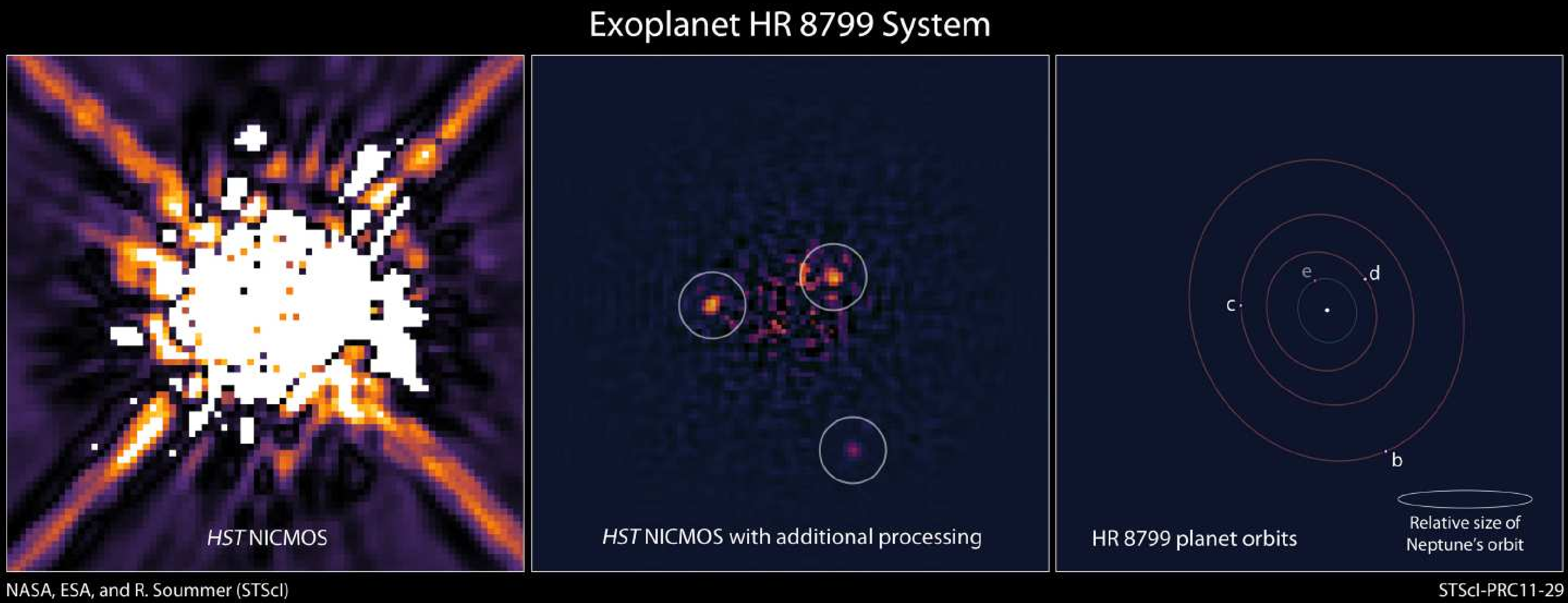


Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS
F673N [S II]
F656N Hα
F502N [O III]
2 light-years
0.61 pasec
55″
N
E
HST WFC3/IR
F164N [Fe II]
F126N [Fe II]



HST/STIS Coronagraph imaging of planetary debris disk around Fomalhaut: Follow-up imaging show moving planet is in highly inclined orbit.

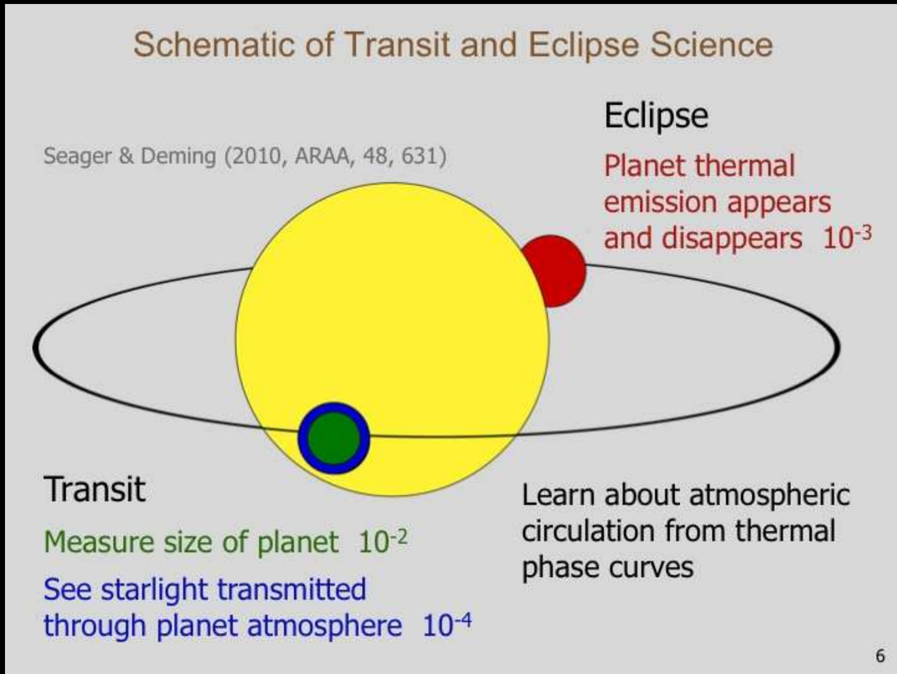
JWST can find such planets much closer in for much farther stars.

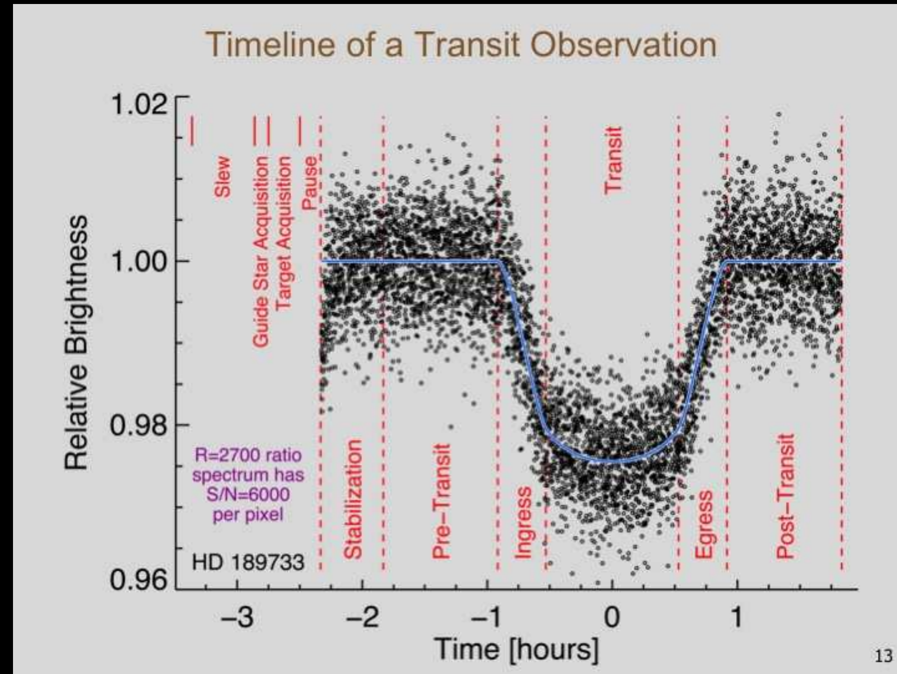


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star!

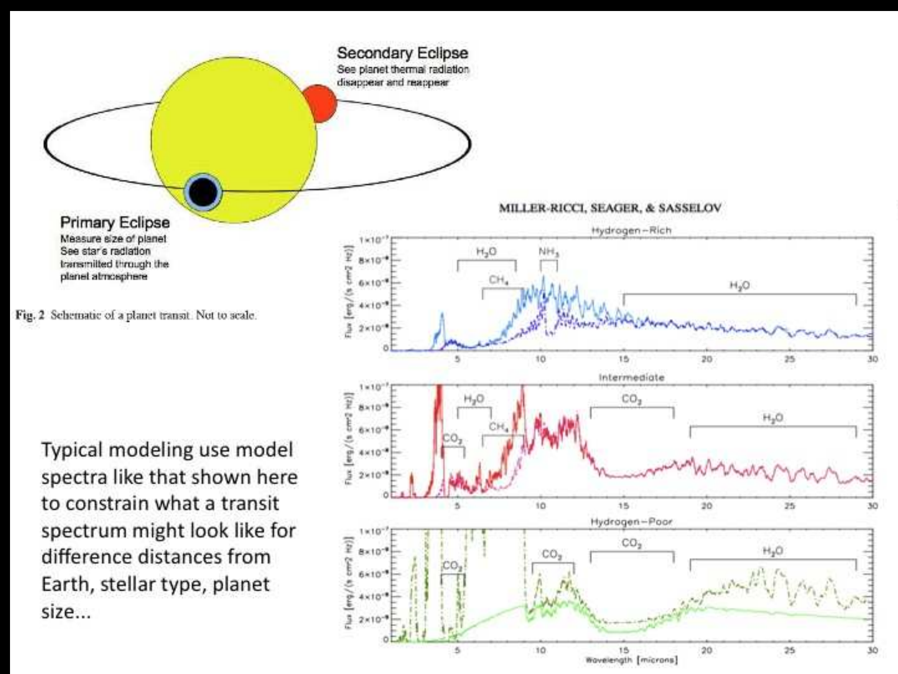
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



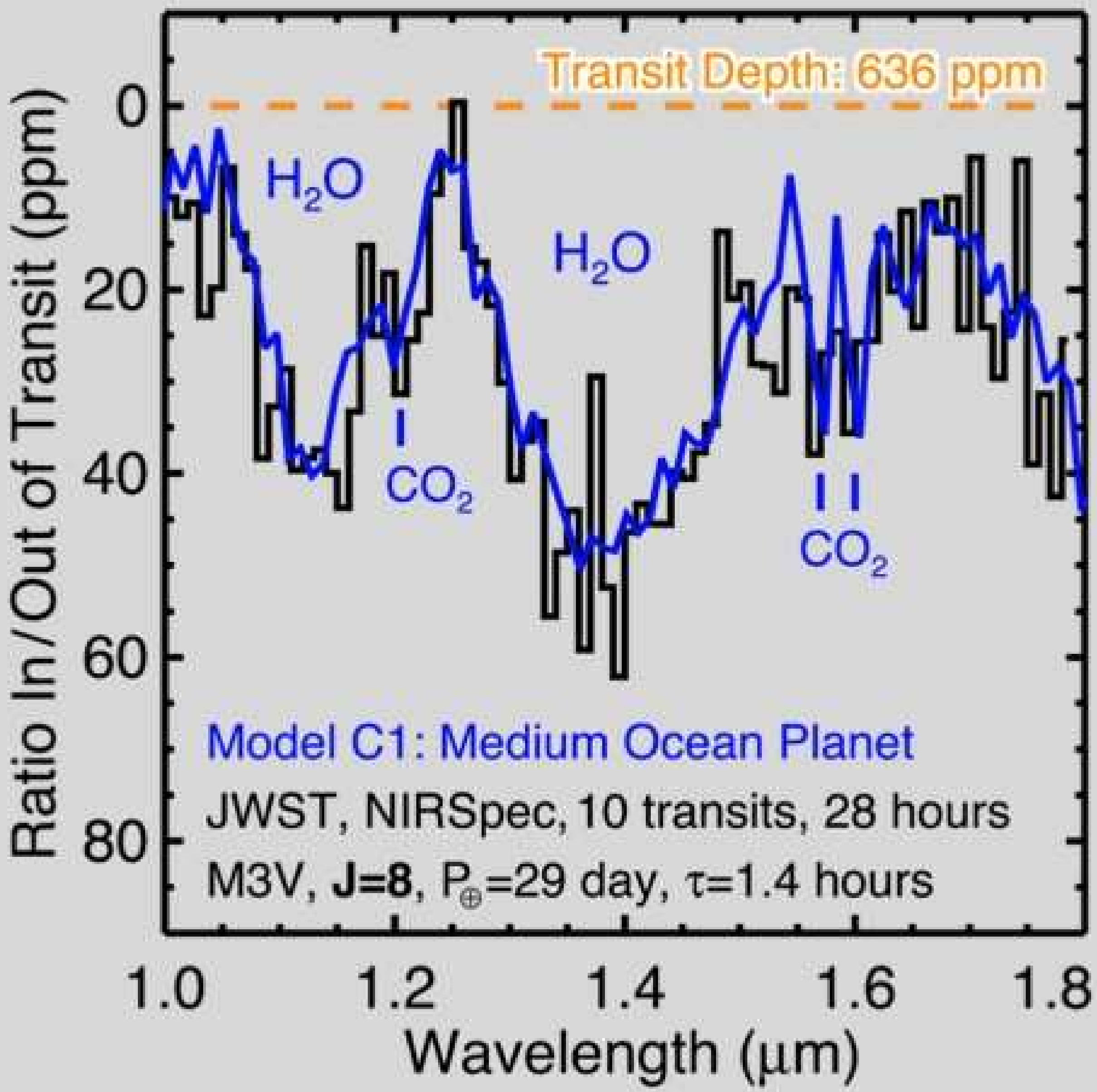


JWST can do very precise photometry of transiting Earth-like exoplanets.



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

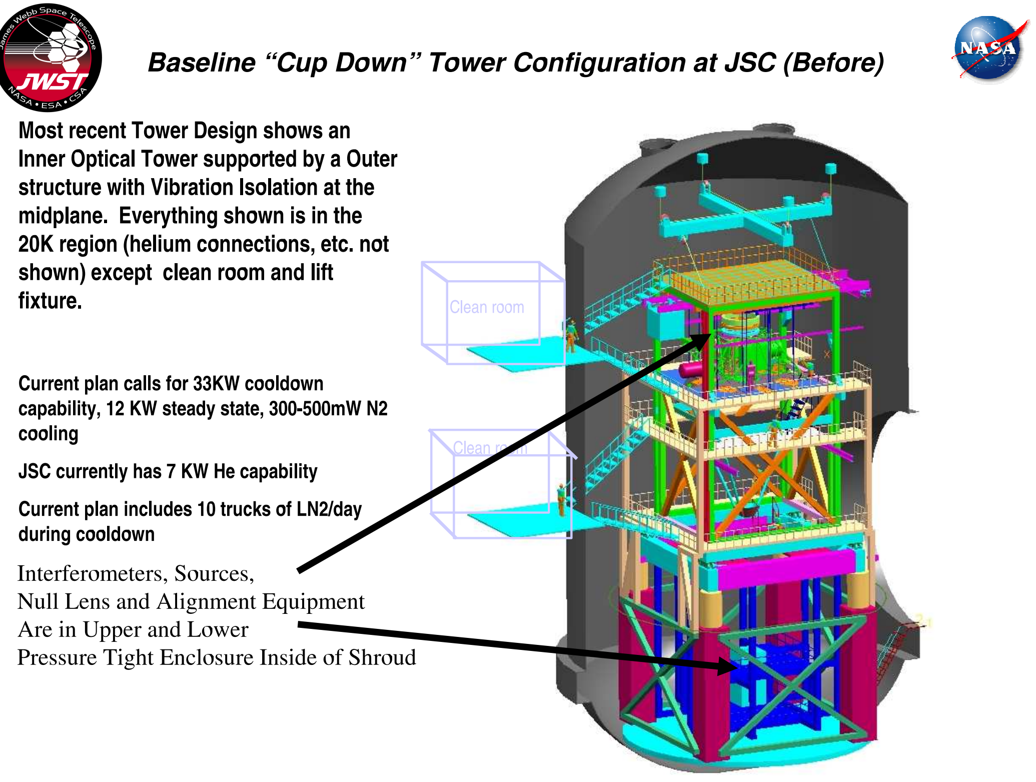
Transit Spectrum of Habitable “Ocean Planet”

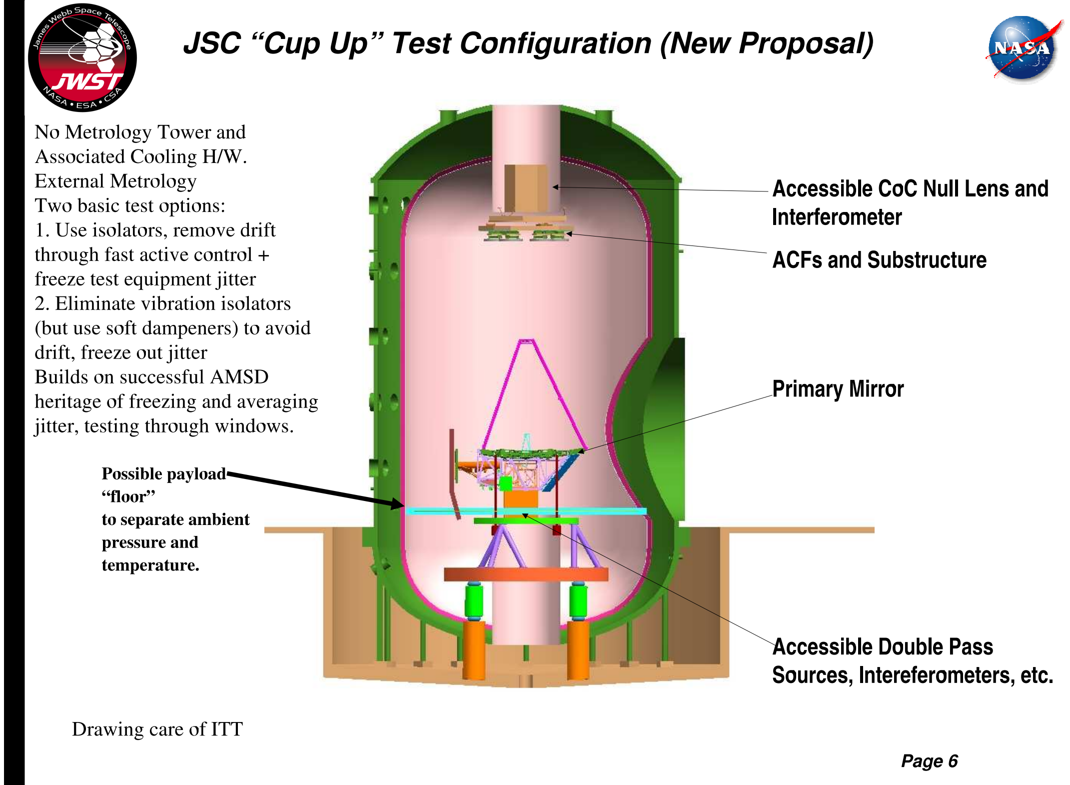


JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.

Northrop Grumman Expertise in Space Deployable Systems

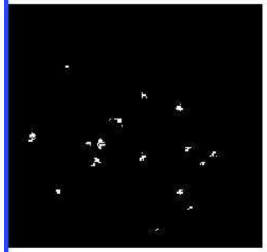
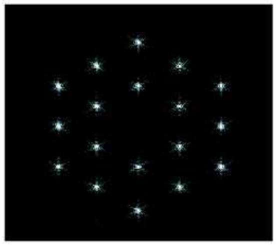
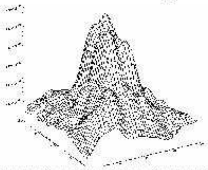
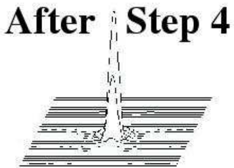
- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements





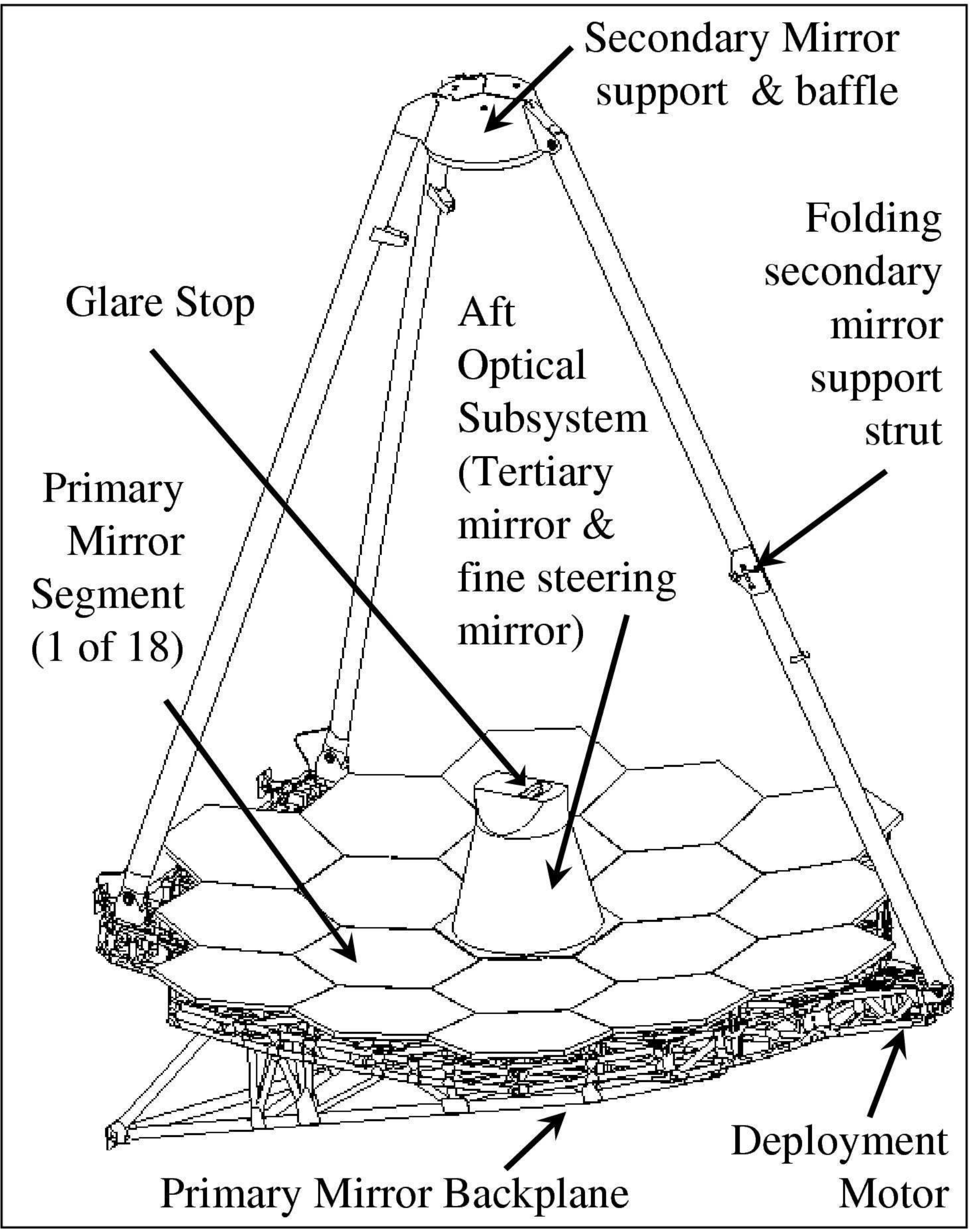
JWST underwent several significant replans and risk-reduction schemes:

- $\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.
- 2011: Passes Mission Critical Design Review — Replan Int. & Testing.

Step	After step	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)

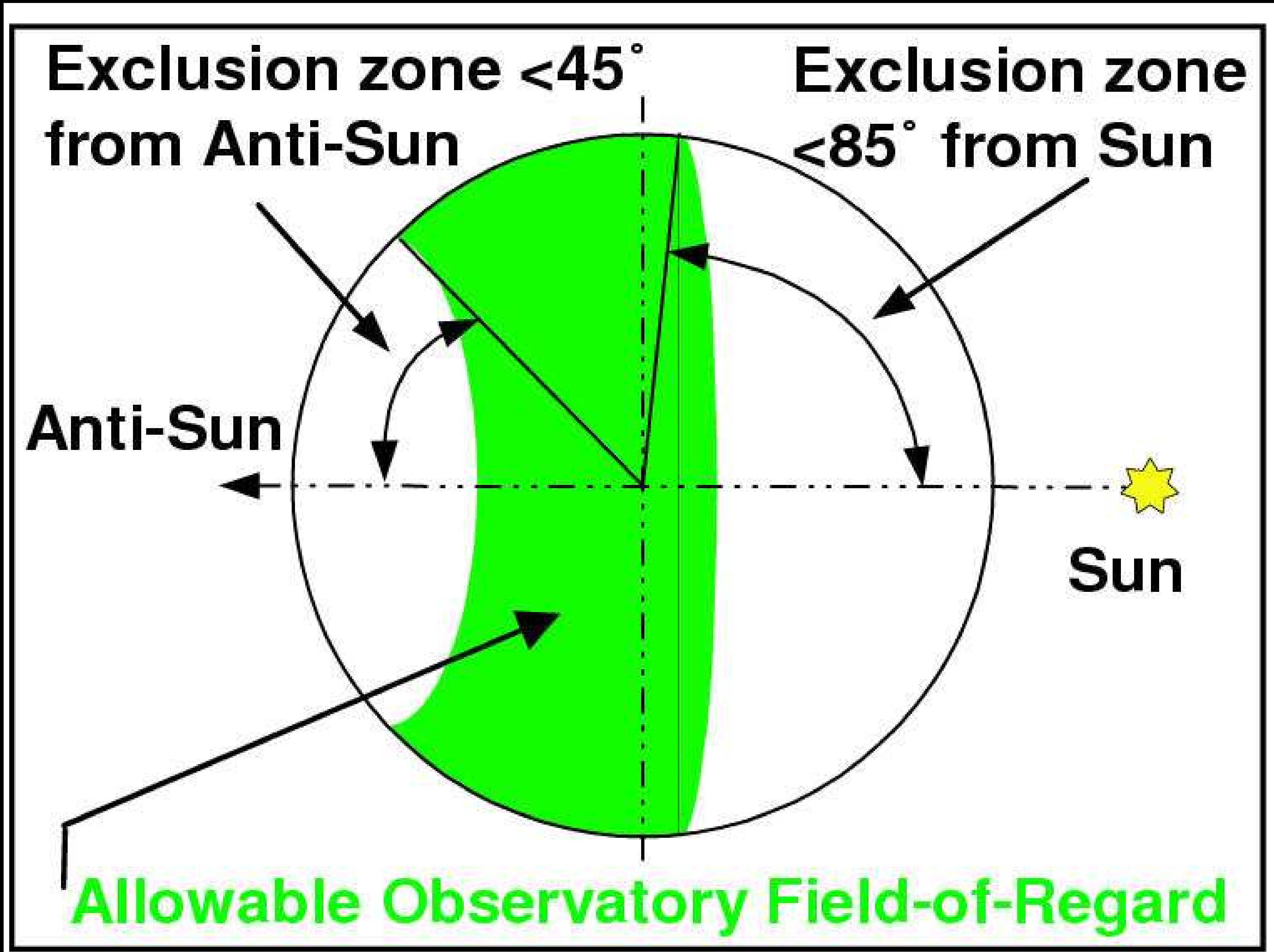
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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

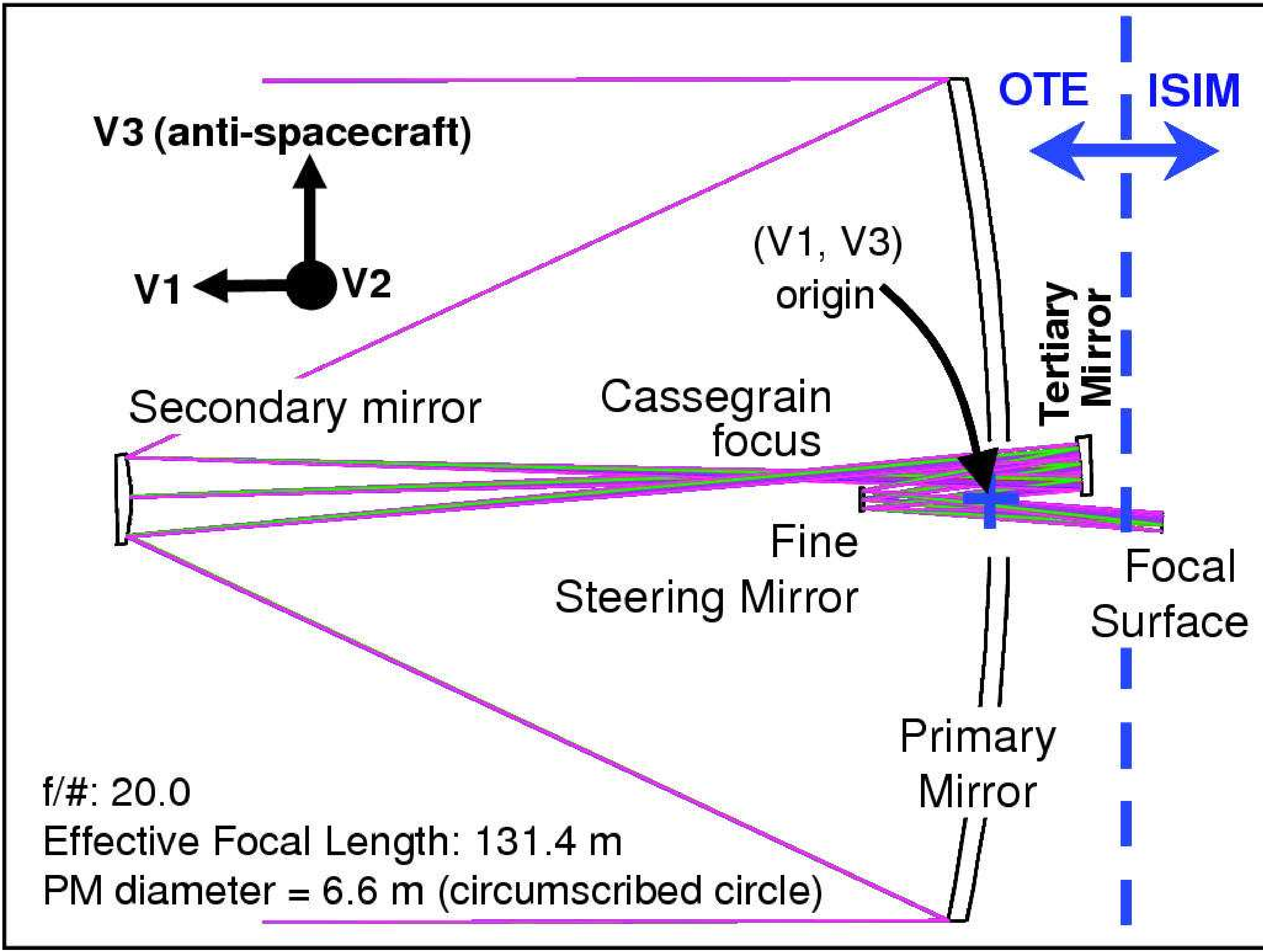


Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015-2016.

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



JWST can observe NEP+SEP continuously: Think of 1000-hr proposals!


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary Mirror
Secondary mirror
Cassegrain focus
Fine Steering Mirror
Focal Surface
Primary Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)

One day we will need a UV-optical sequel to Hubble:

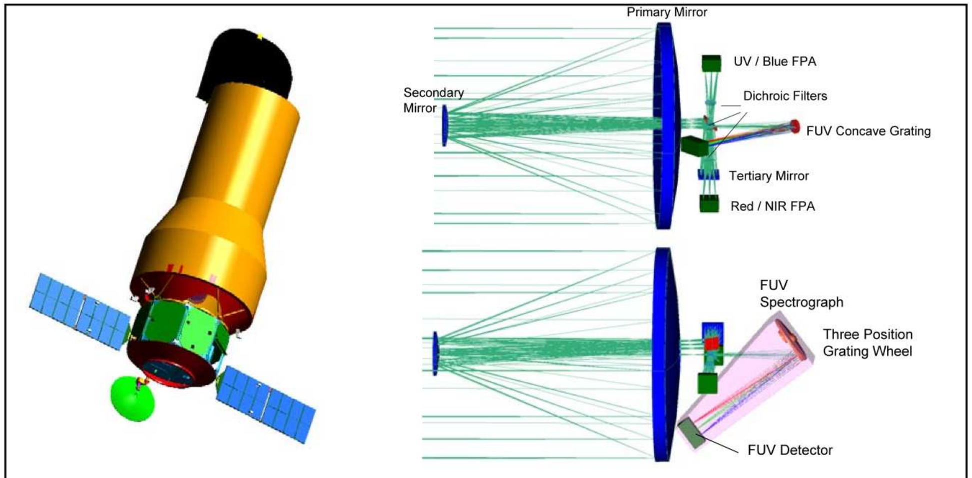
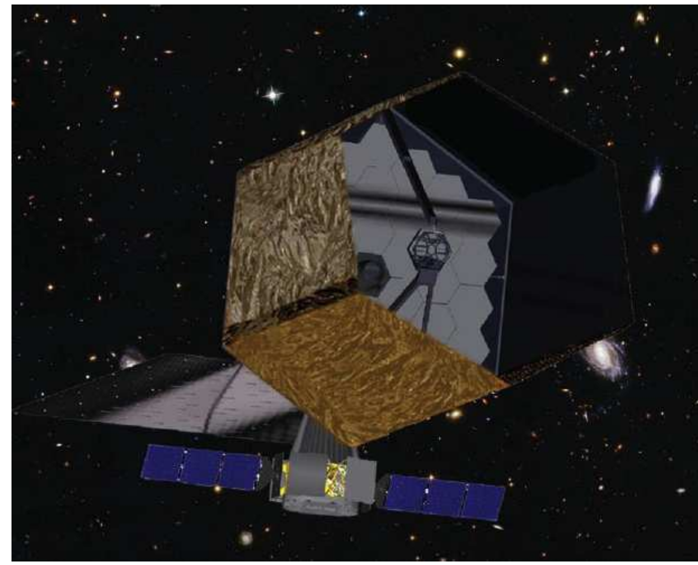


Figure 2.5.3 - *HORUS* Observatory and Optical Ray Trace



[Left] One of two spare 2.4 m NRO mirrors: one will become WFIRST.

- NASA may look for partners to turn 2nd NRO into UV-opt HST sequel.

[Middle] HORUS: 3-mirror anastigmat NRO as UV-opt HST sequel.

- Can do wide-field ($\sim$0.25 deg) UV-opt $0\farcs06$ FWHM imaging to AB$\lesssim$30 mag, and high sensitivity (on-axis) UV-spectroscopy (Scowen et al. 2012).

[Right] ATLAST: 8–16 m UV-opt HST sequel, with JWST heritage.

- Can do same at 9 m.a.s. FWHM routinely to AB$\lesssim$32-34 mag, [and an ATLAST-UDF to AB $\lesssim$38 mag $\sim$1 pico-Jy].

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

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