The best of Hubble WFC3, and what the James Webb Space Telescope will do after 2018.

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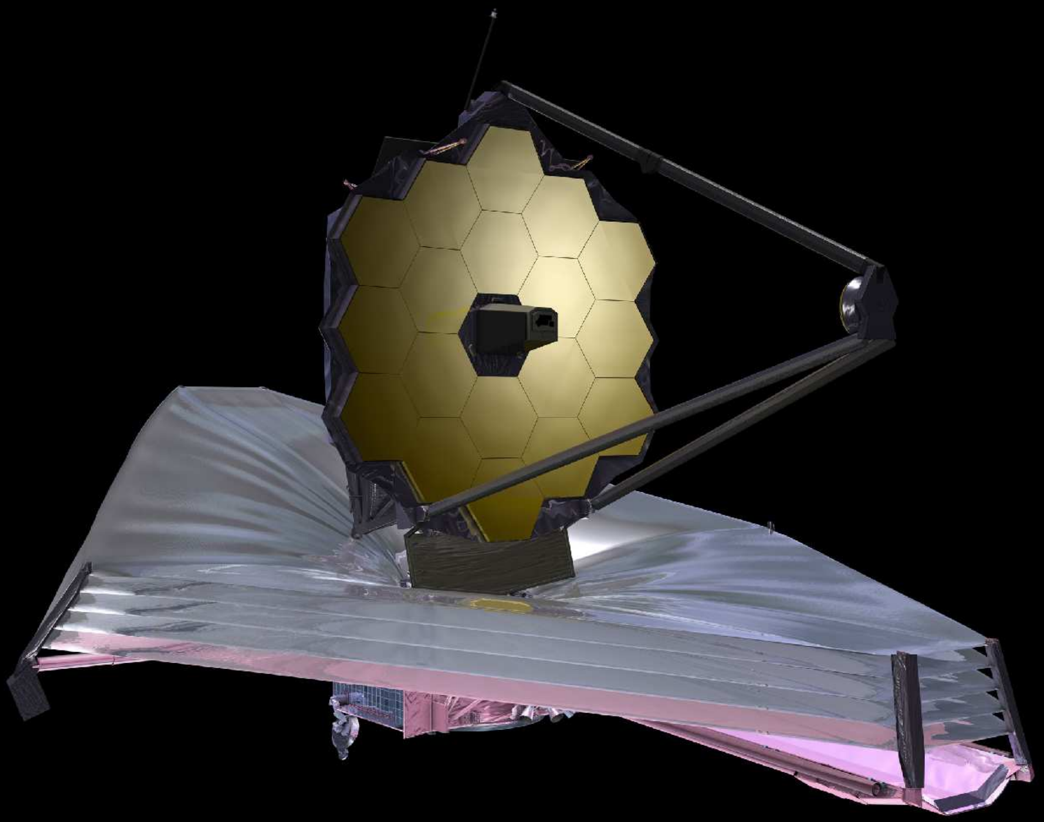
Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice, S. Driver (UK), & H. Yan (Carnegie)

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



ASU SESE Undergraduate Student Seminar, Camp Tontozona, AZ, Saturday, Sept. 7, 2013.

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

WARNING: Asking NASA for images is like drinking from a fire-hydrant!

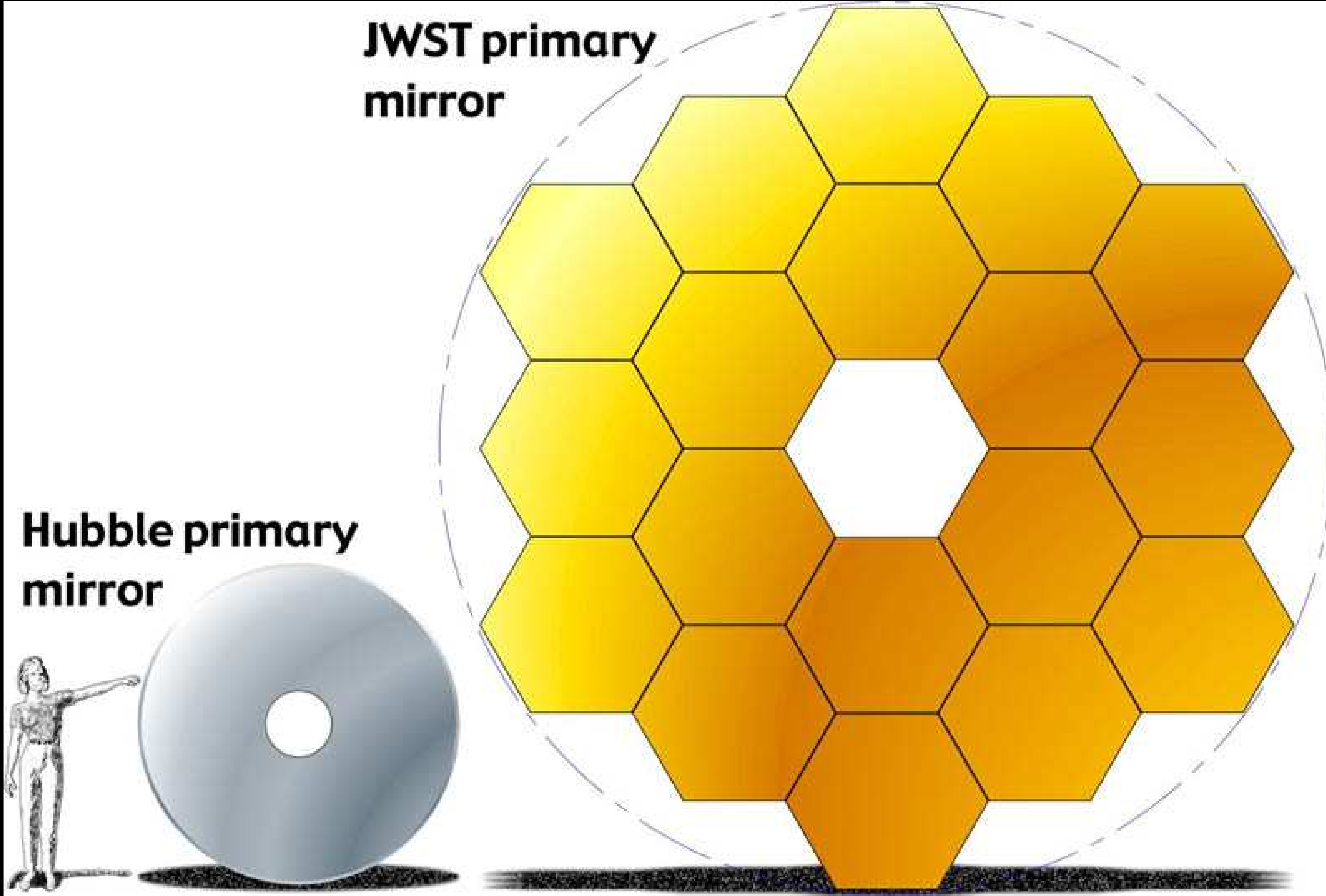
Don't do this at home!! :)

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.

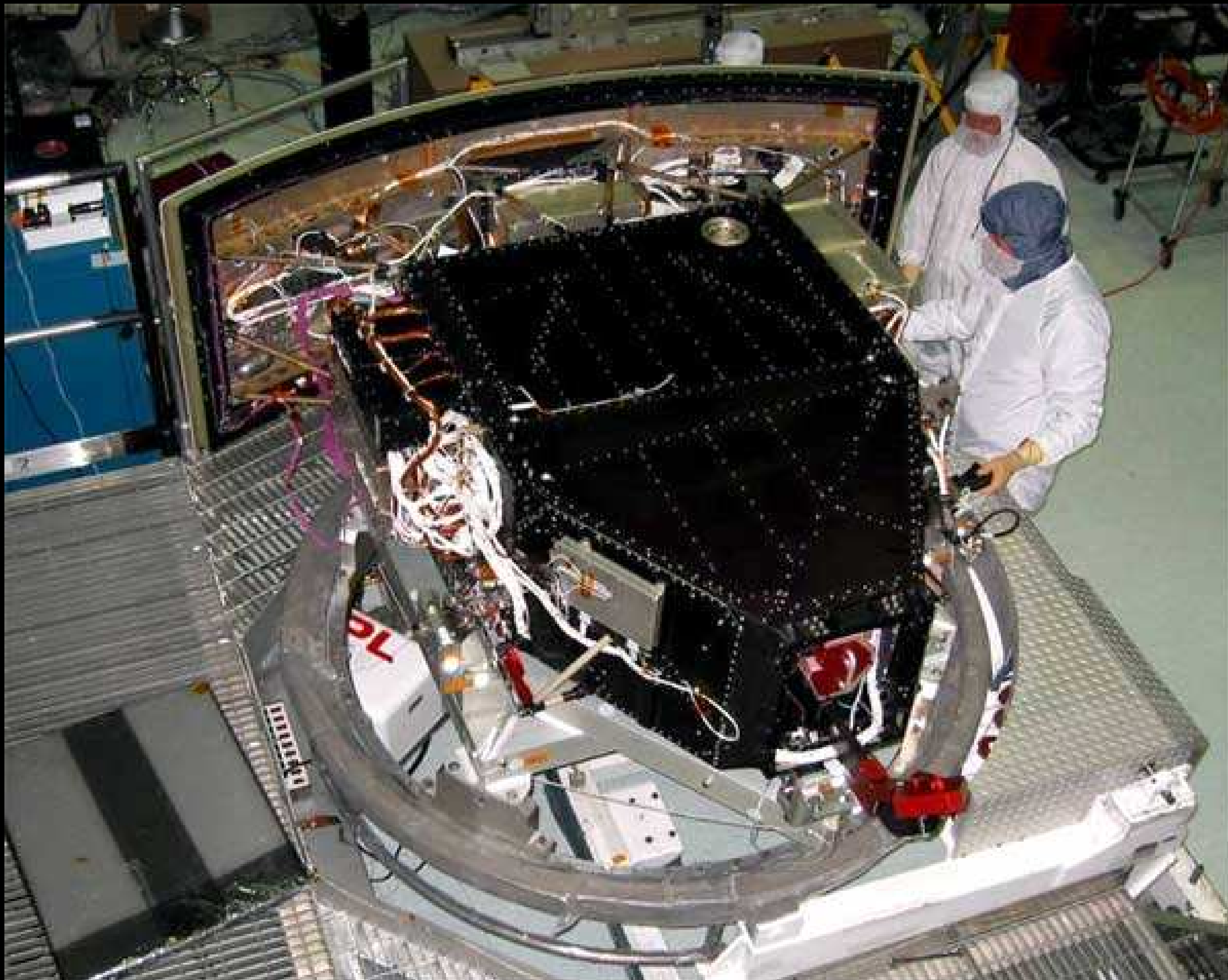
JWST: The infrared sequel to Hubble from 2018–2023 (–2029?).



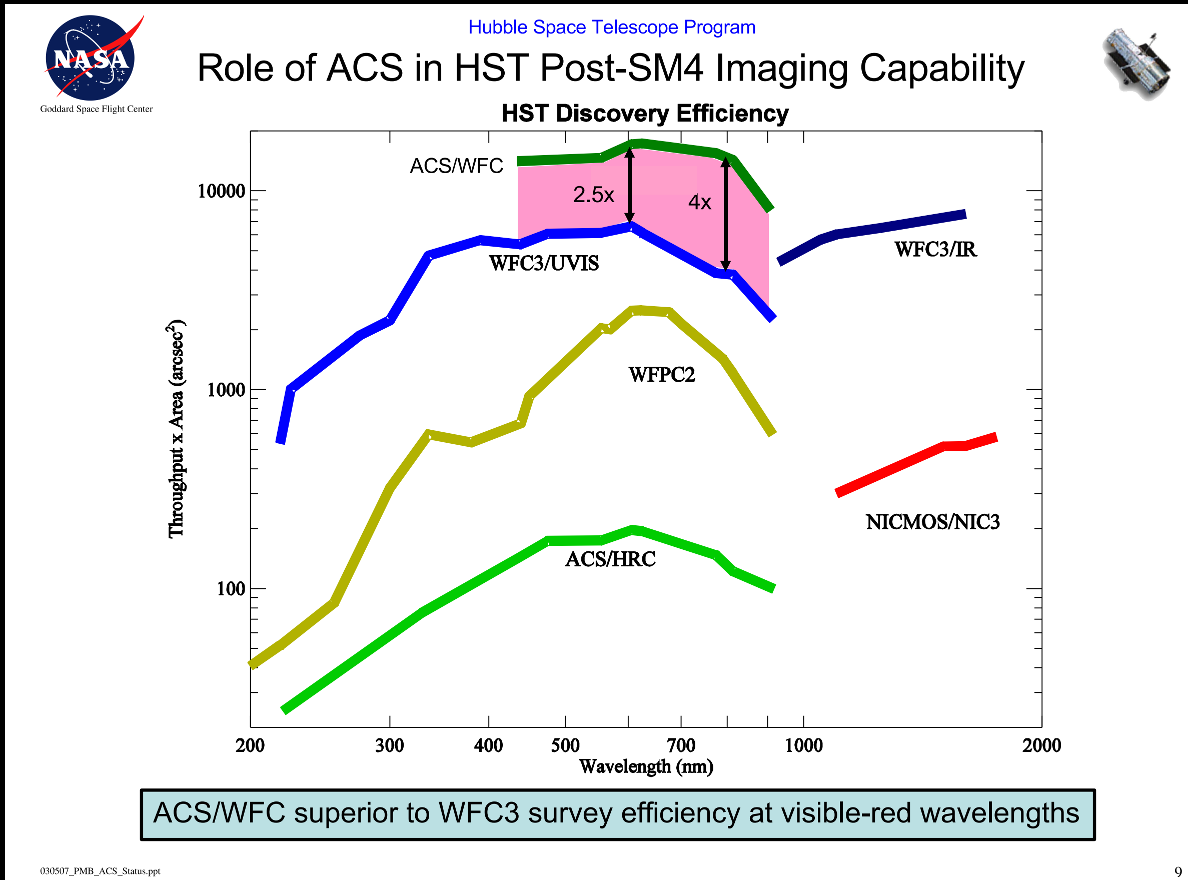
JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.

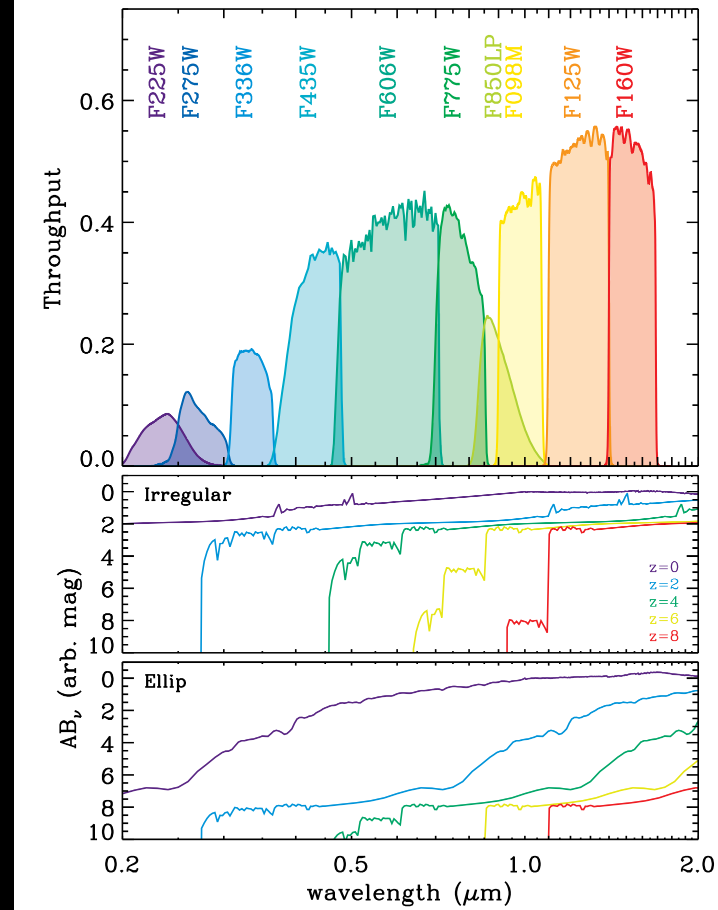
(1) The Best of Hubble: Recent results from the HST and its WFC3

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 & areal coverage:

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

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

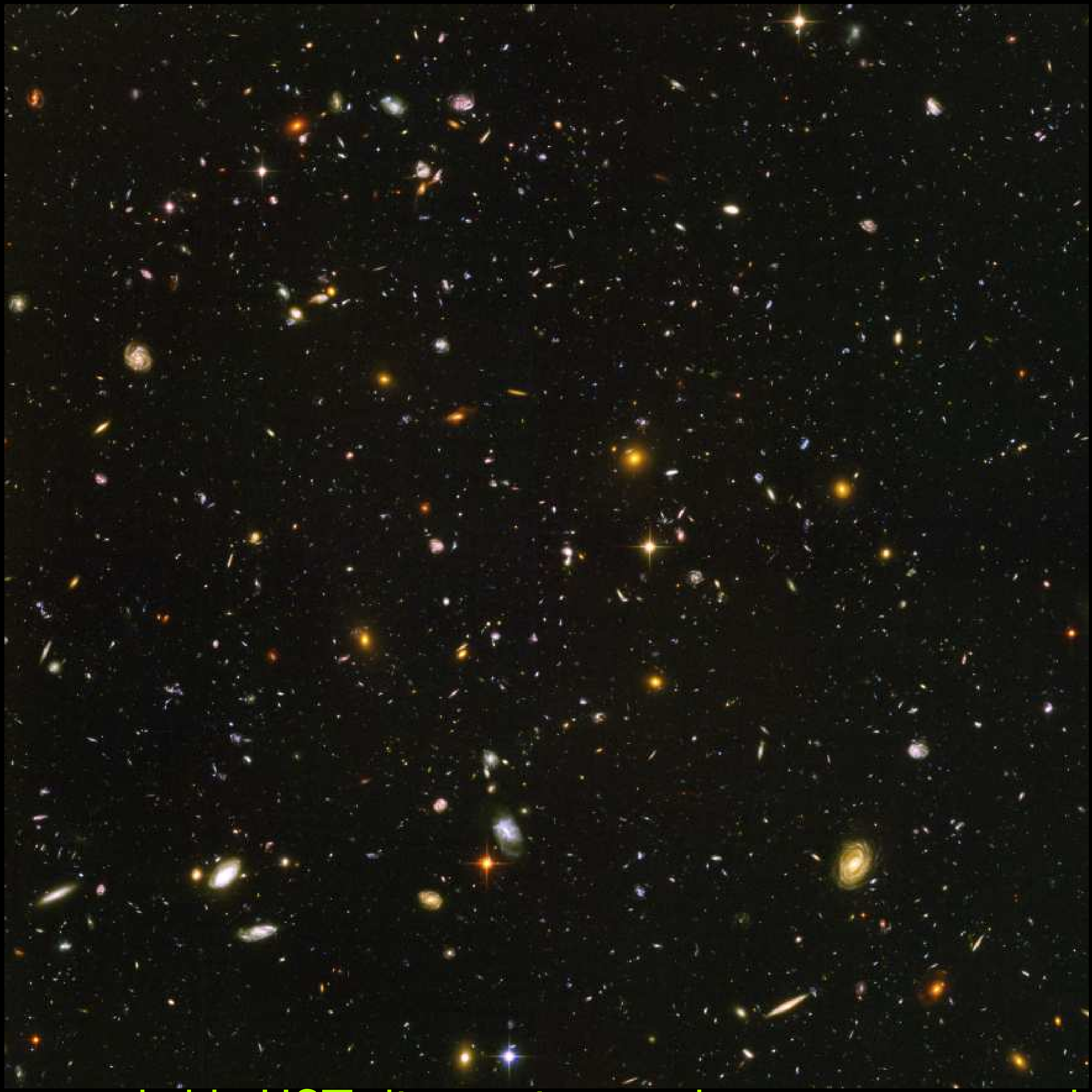
- QE$\gtrsim$70%, 1k×1k array of 0.″13 pixel, FOV $\simeq$ 2.′25 ×2.′25.

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

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

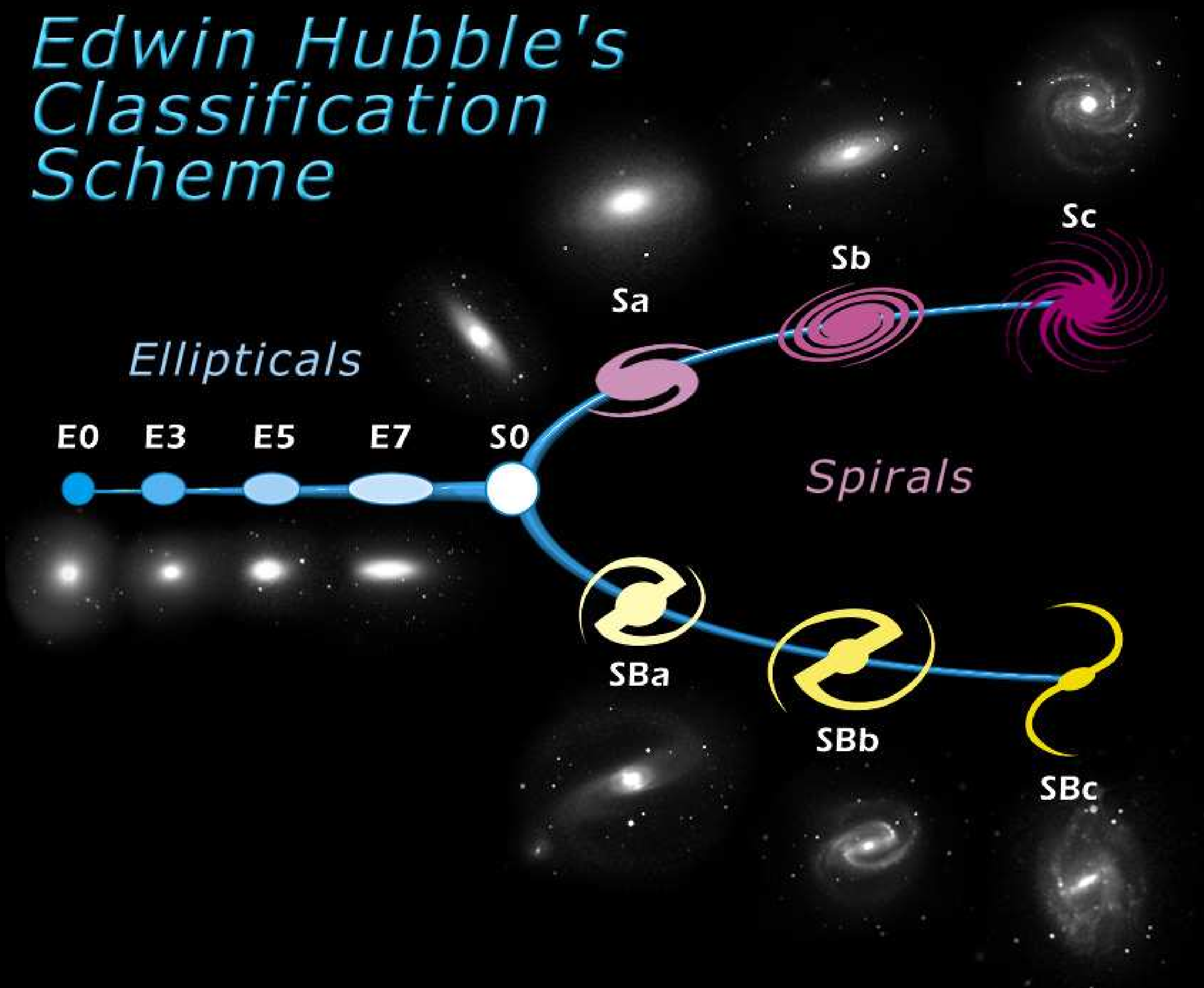
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

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

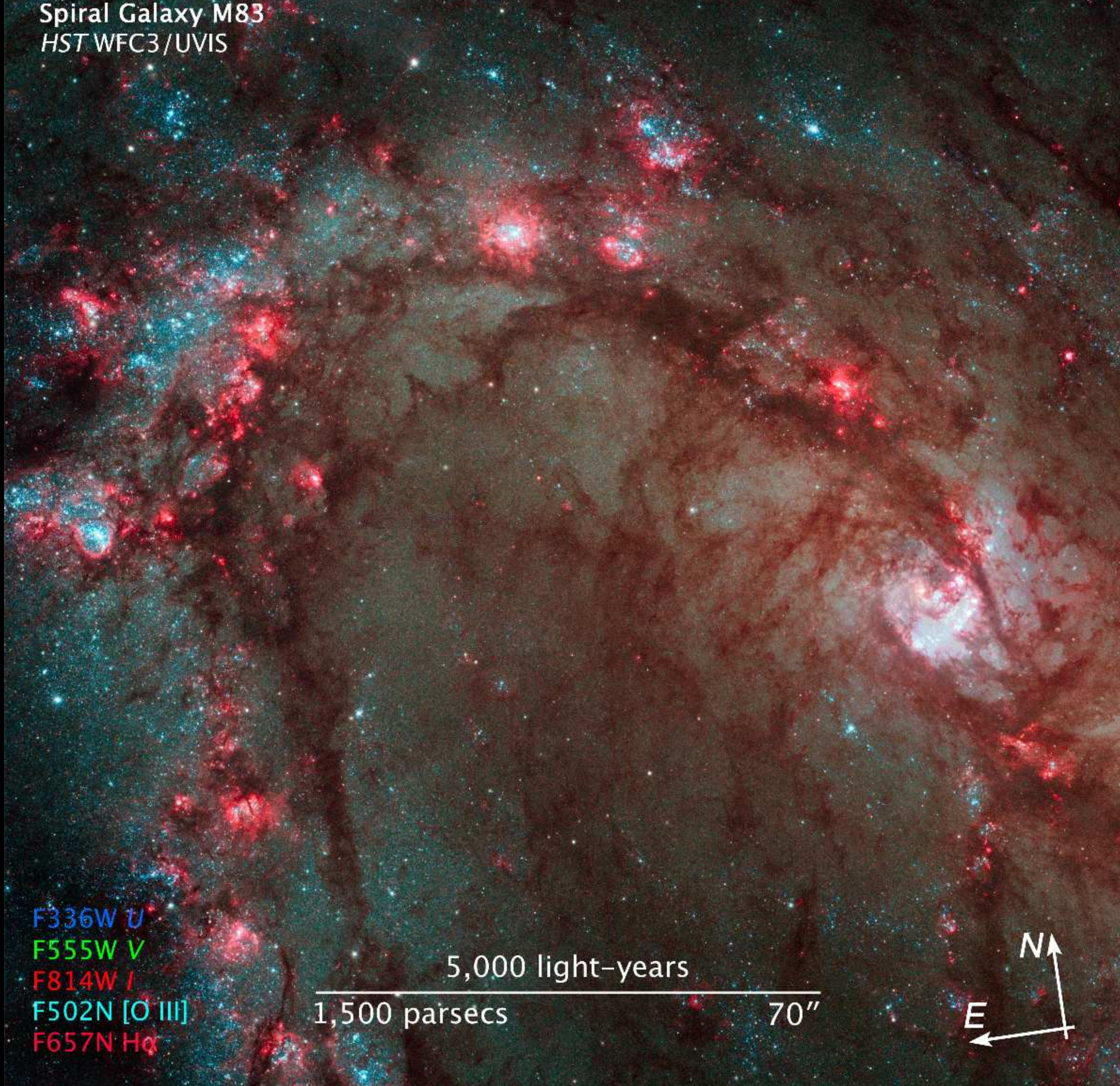


One of the remarkable HST discoveries was how numerous and small faint galaxies are: The building blocks of giant galaxies seen today.

(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

Elliptical Galaxy NGC 1132

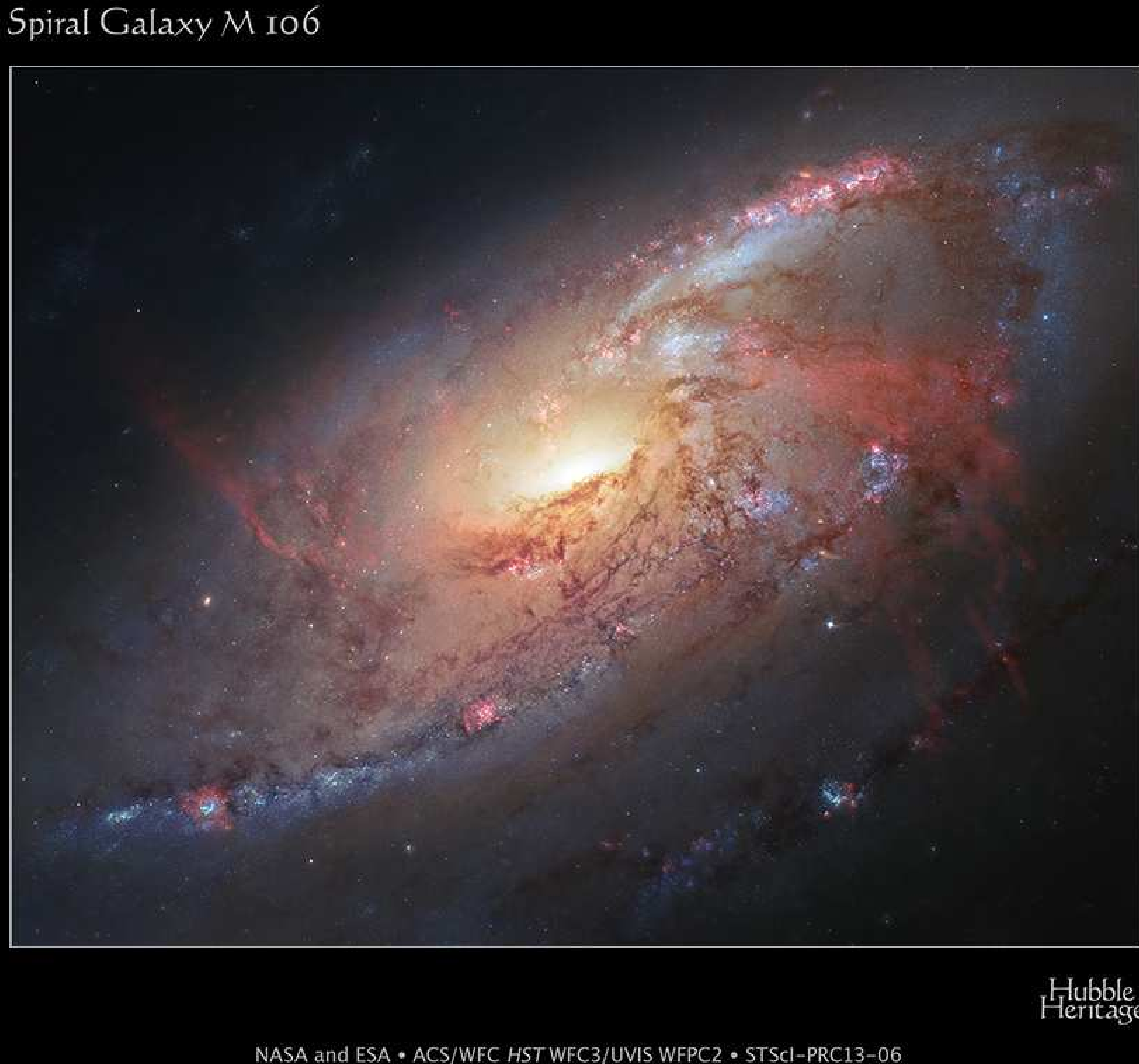
Hubble Heritage

M. Rutkowski (2012, ApJS, 199, 3).

NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration
Hubble Space Telescope ACS • STScI-PRC08-07

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

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



Central $H\alpha$ outflow from the Spiral Galaxy Messier 106.

Hubble image by amateur astronomers Robert Gendler and Jay GaBany!

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

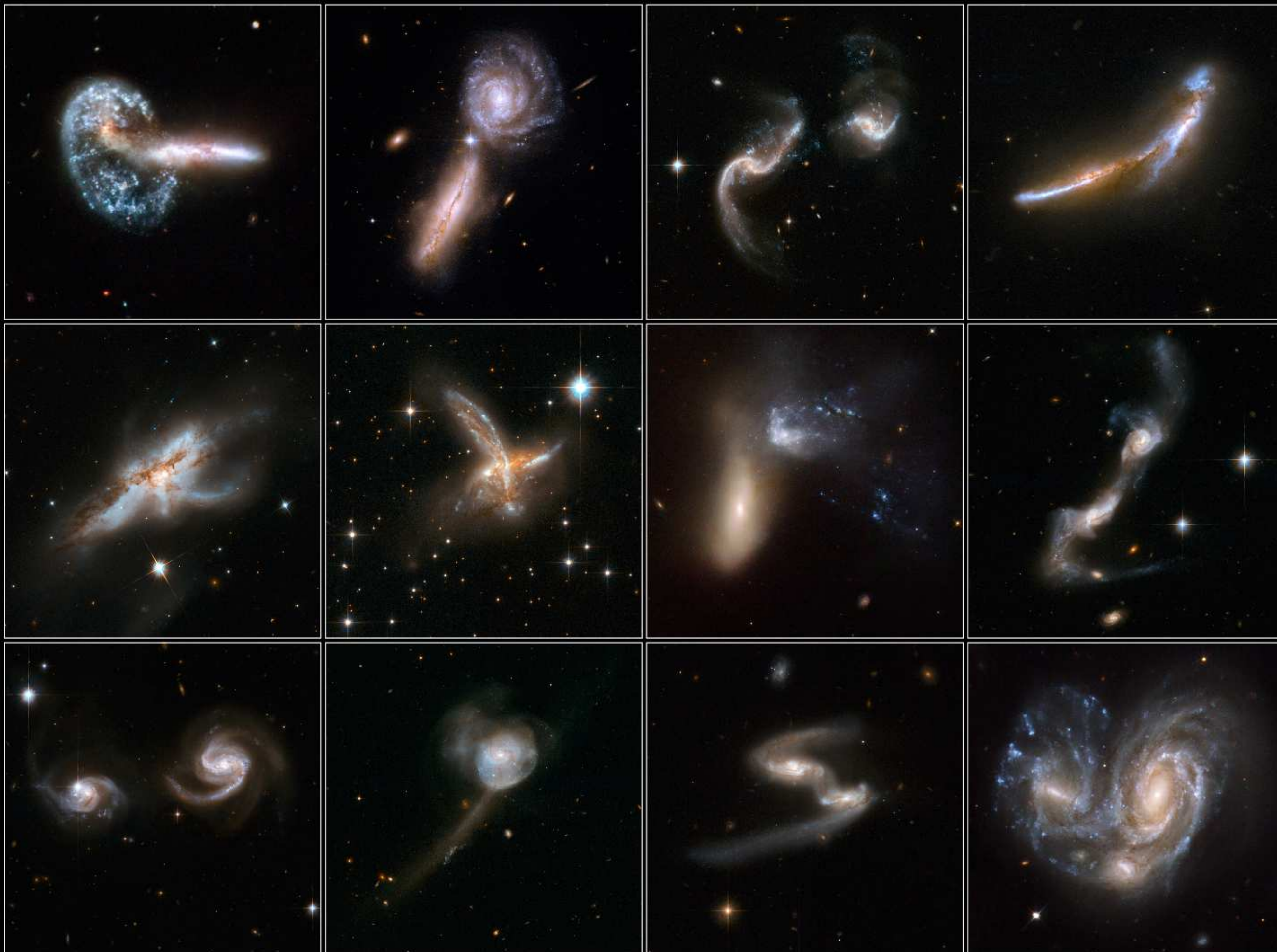
Illustration Sequence of the Milky Way and Andromeda Galaxy Colliding

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.

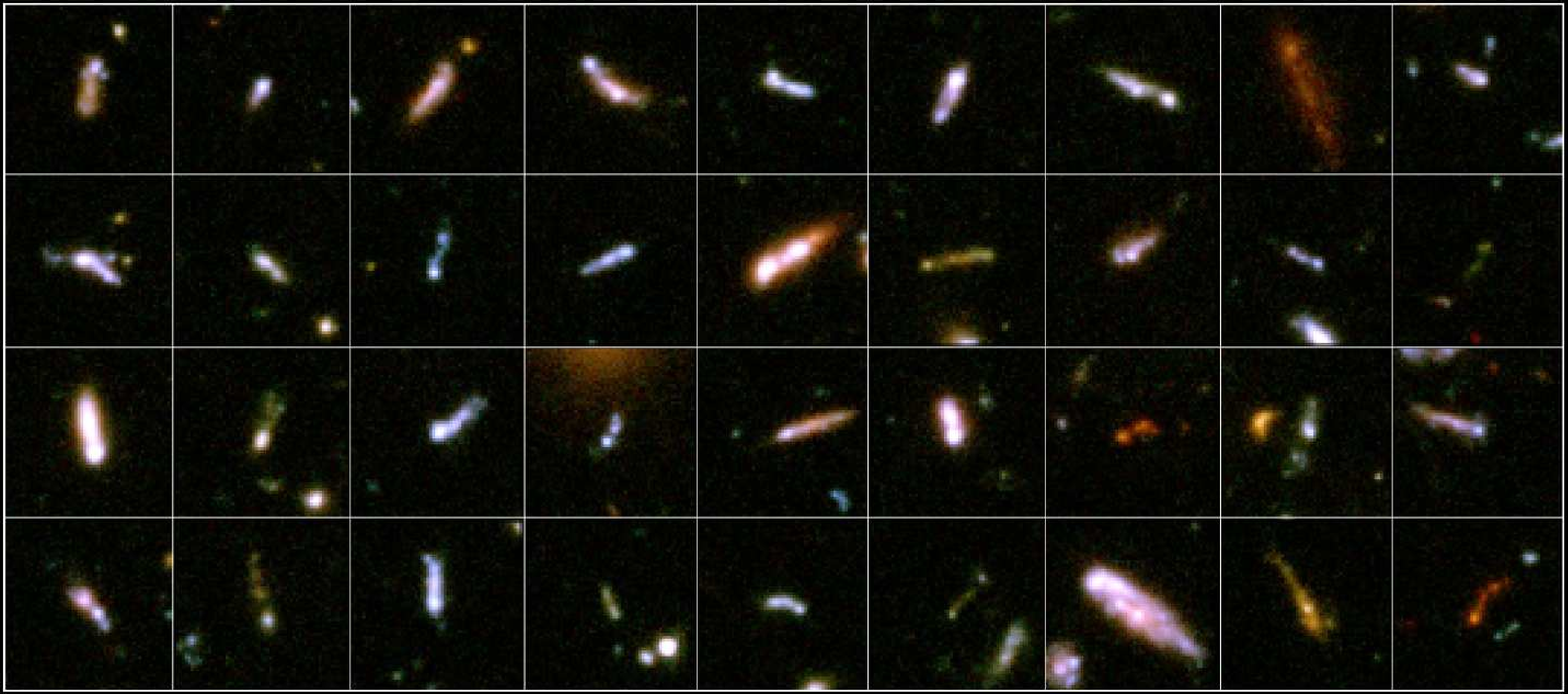
Interacting Galaxies

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

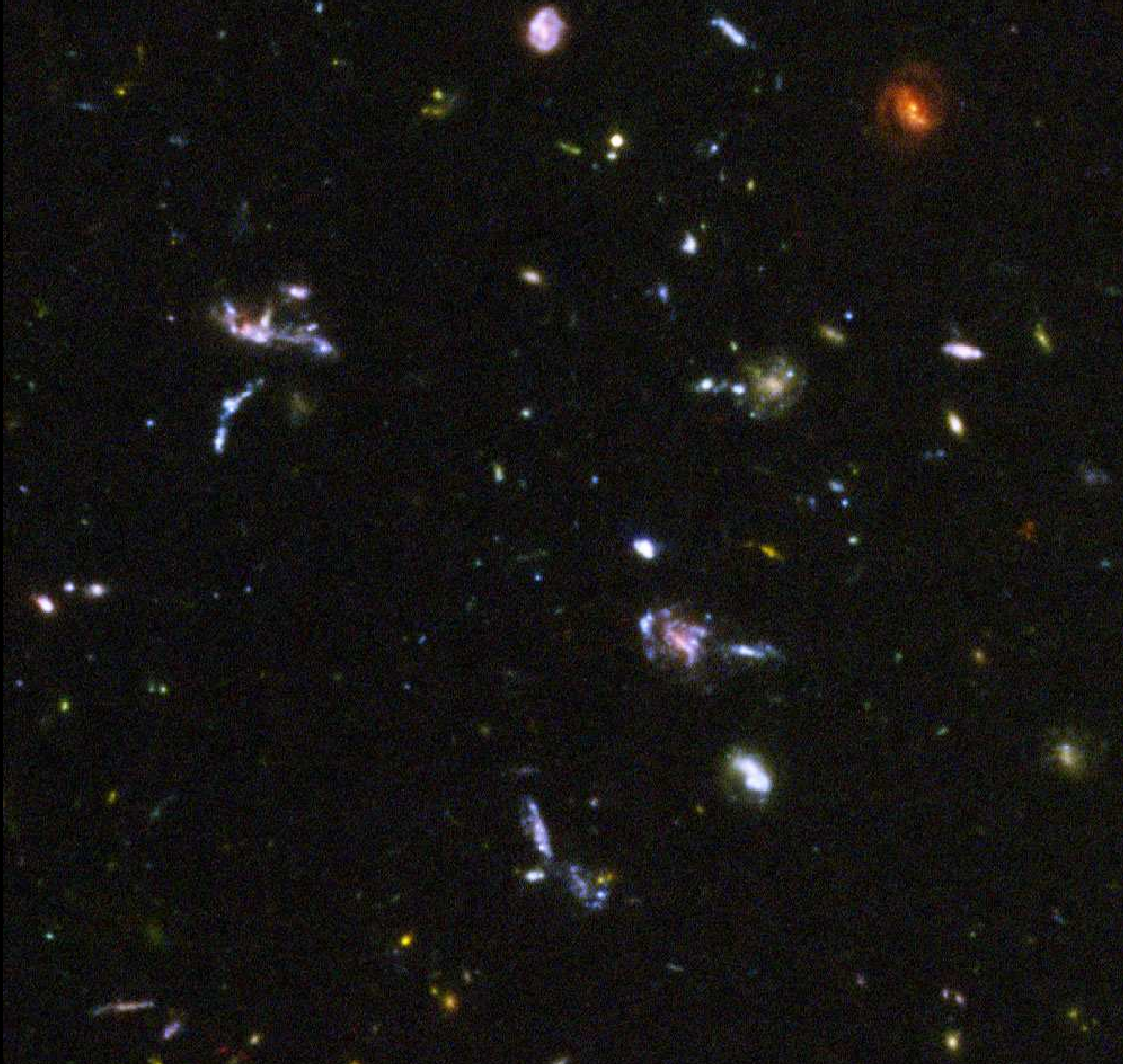
Merging galaxies constitute $\lesssim$1% of Hubble sequence TODAY (age$\gtrsim$12.5 Gyr).

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

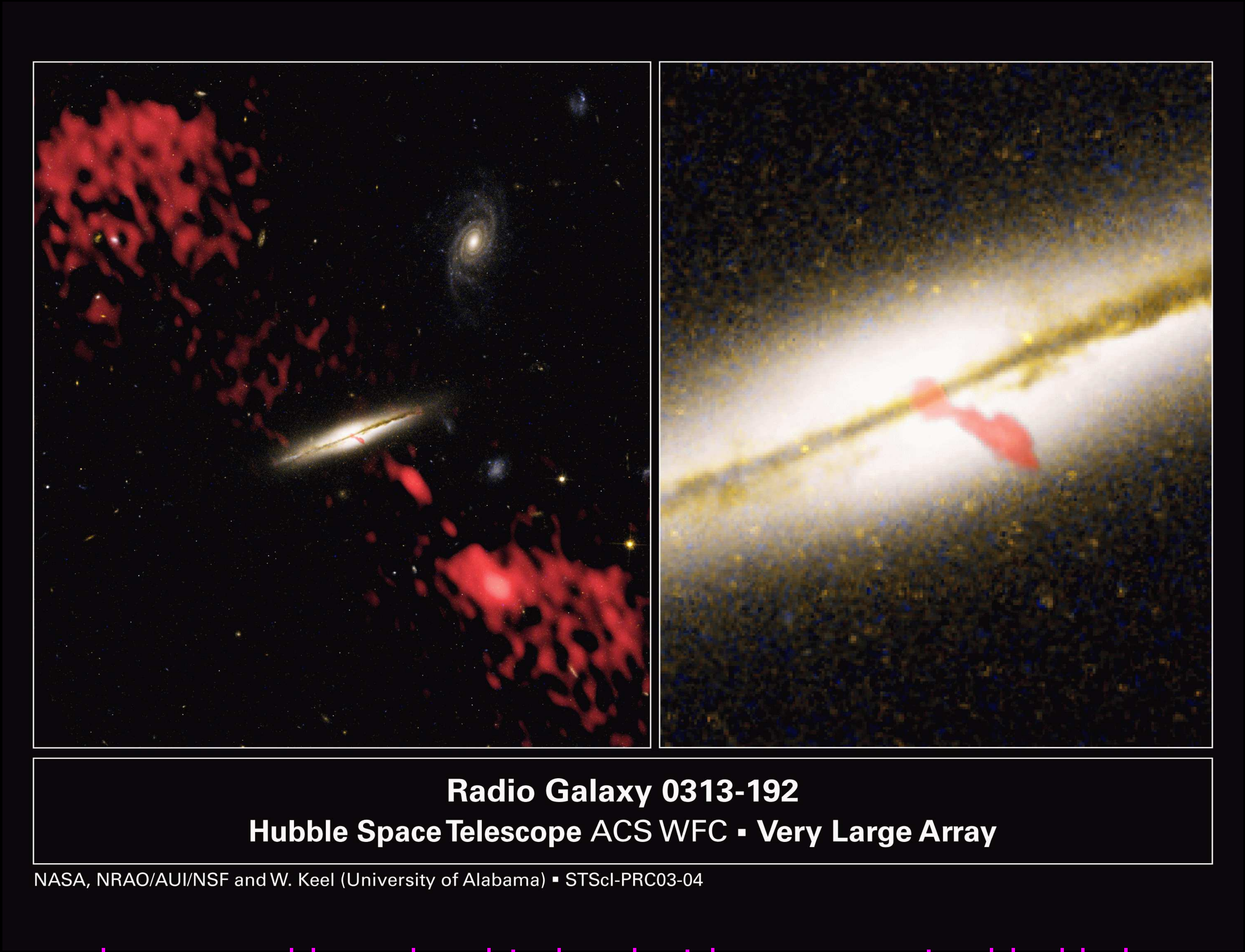
JWST will measure Galaxy Assembly to z$\lesssim$20 (cosmic age $\gtrsim$0.2 Gyr).

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(–29)μm wavelengths, tracing young and old stars + dust.



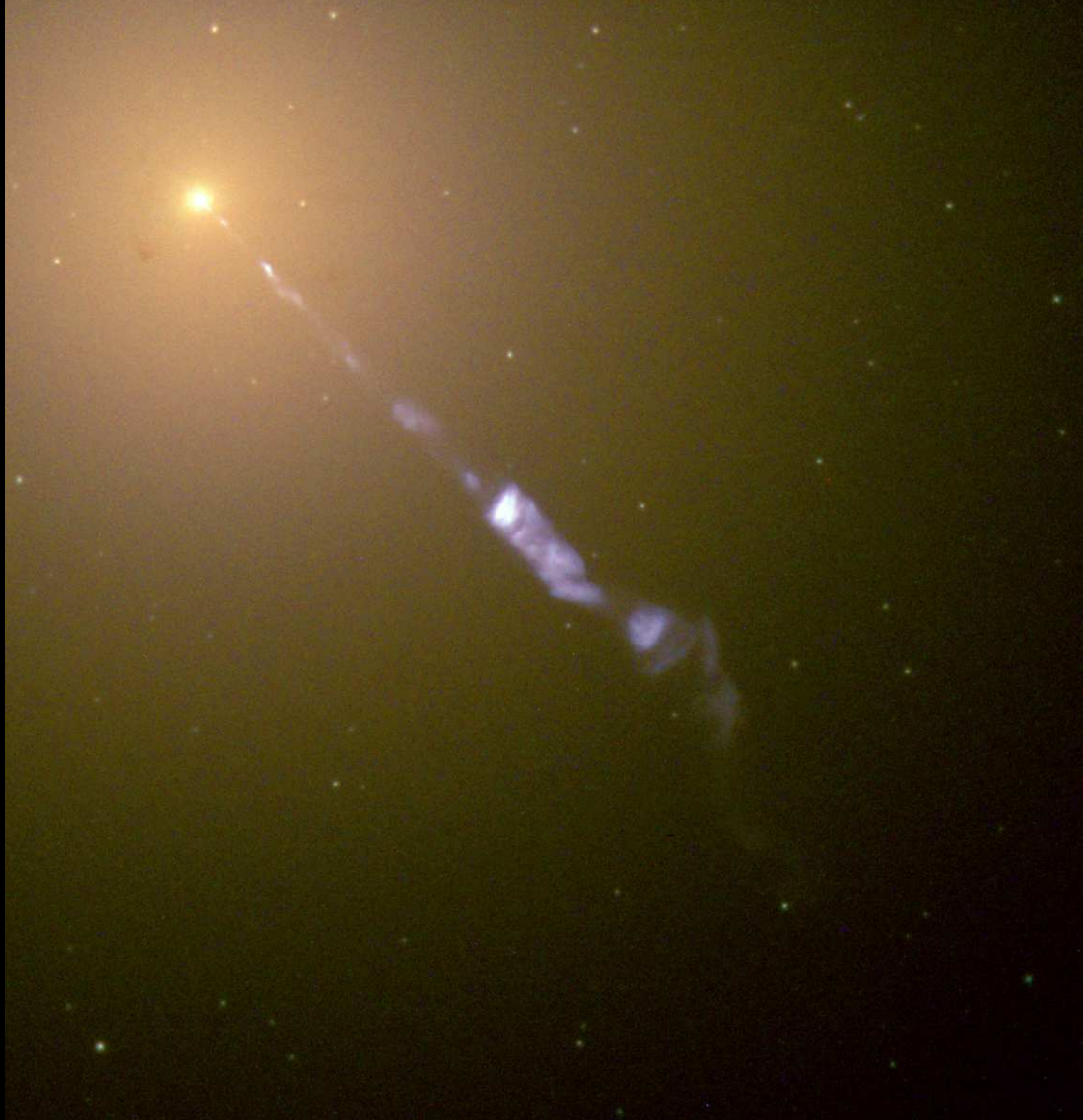
(2) Measuring Galaxy Assembly & Supermassive Blackhole Growth



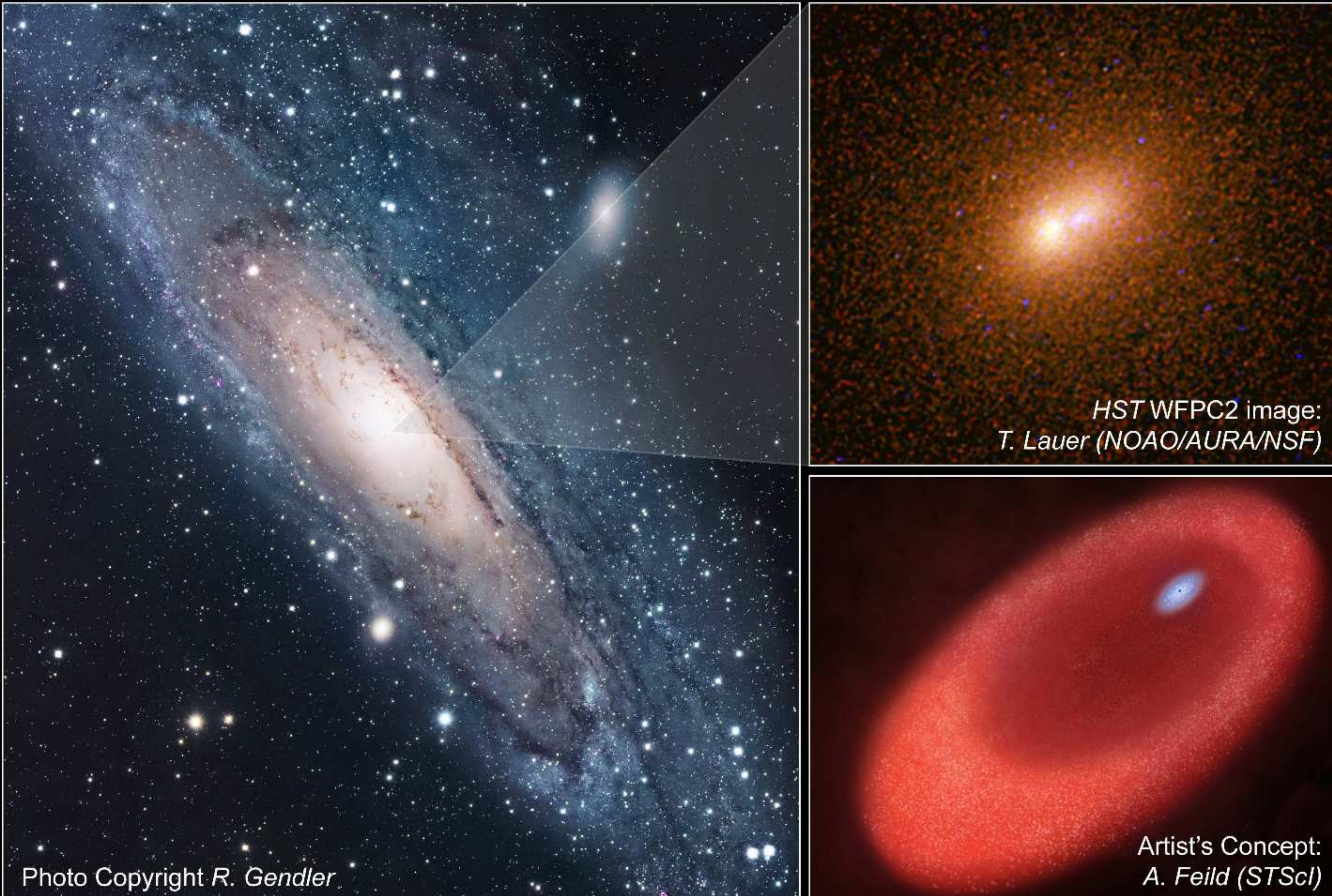
Does galaxy assembly go hand-in-hand with supermassive blackhole growth?

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

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



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

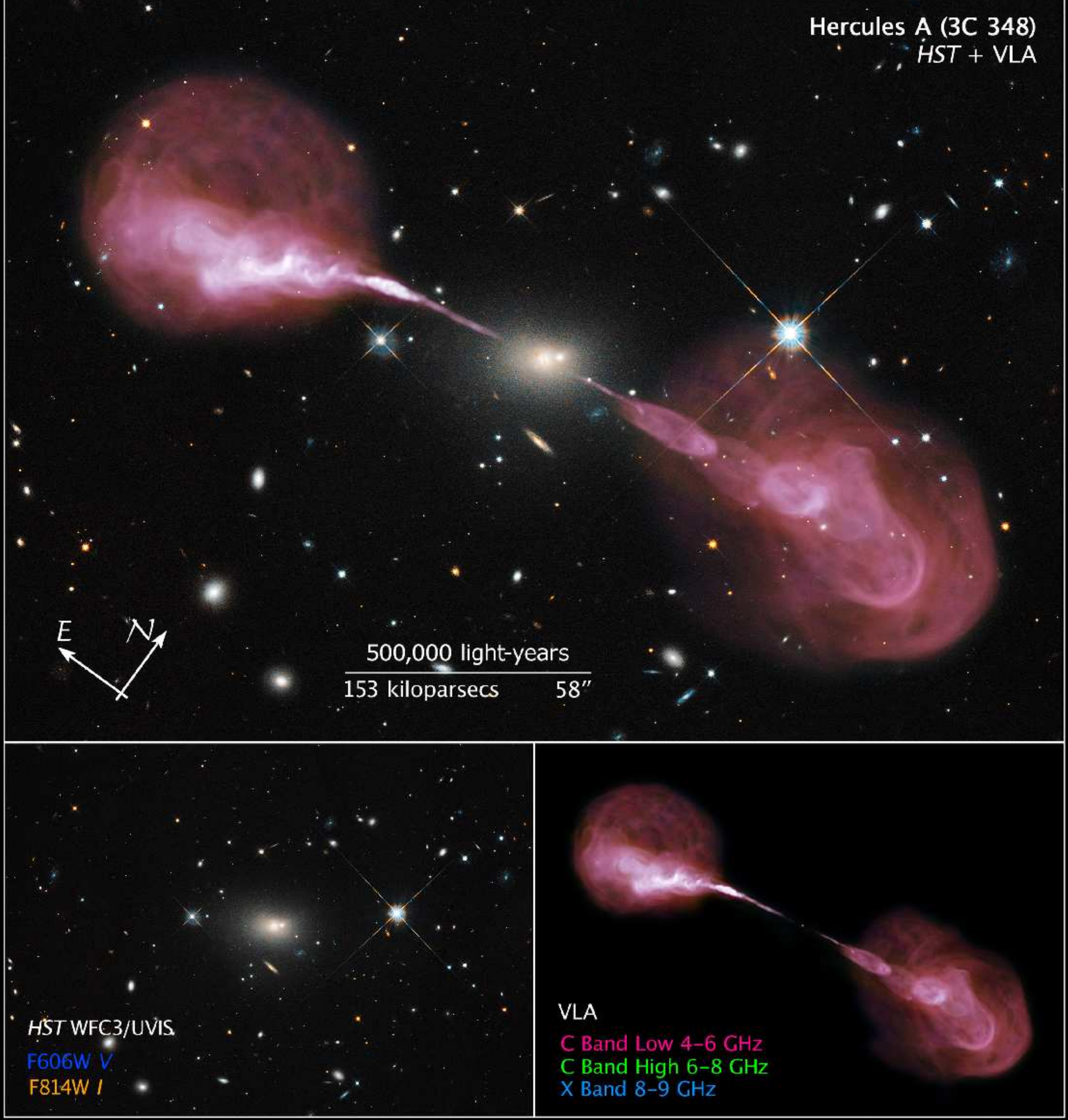


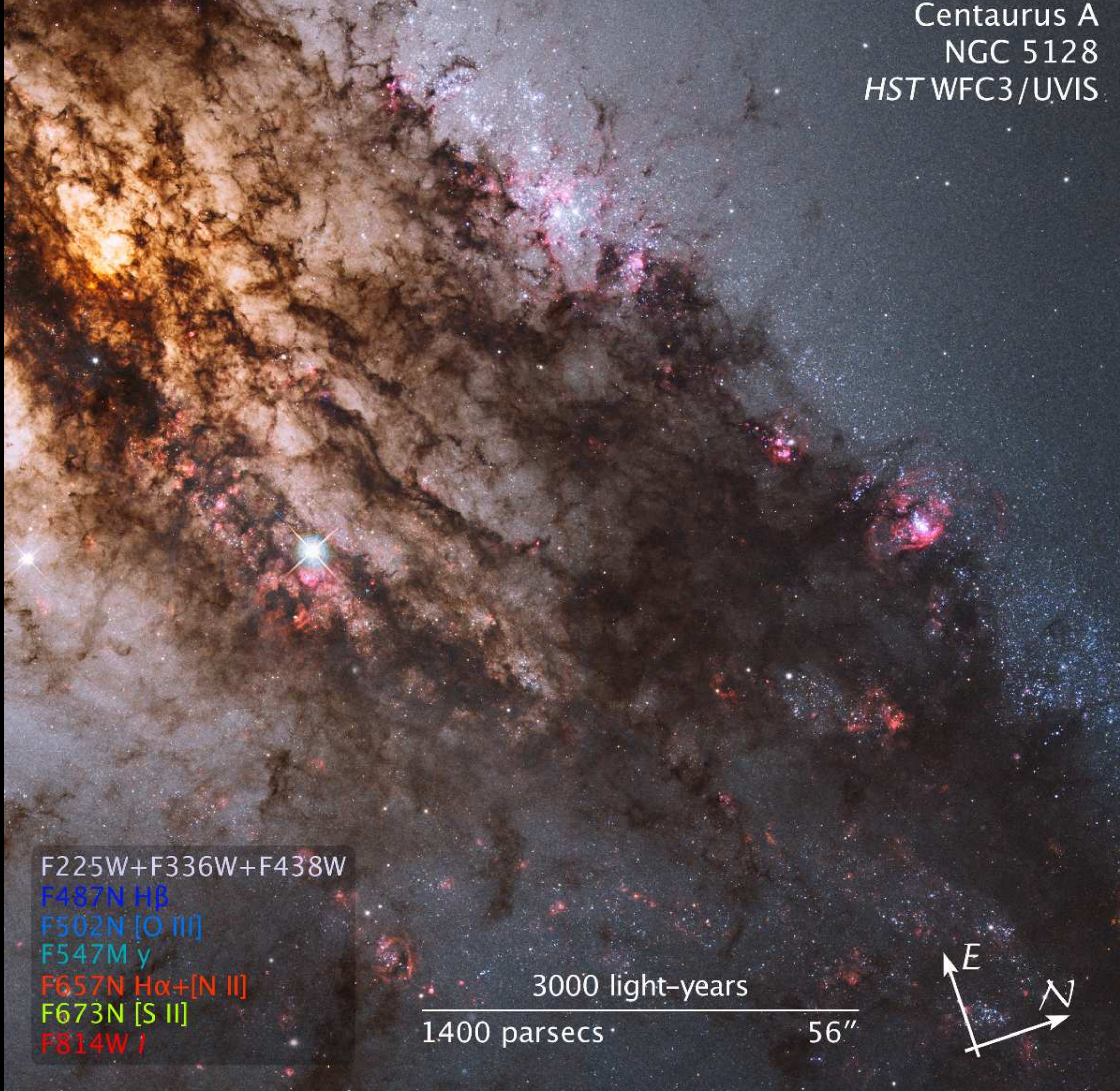
Andromeda Galaxy Nucleus ▪ M31

Hubble Space Telescope ▪ WFPC2

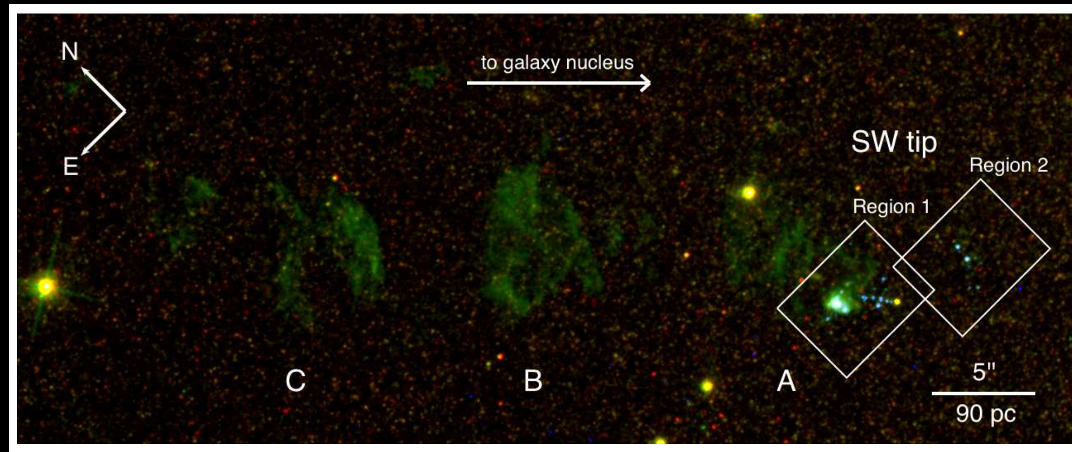
NASA, ESA, R. Gendler, T. Lauer (NOAO/AURA/NSF), and A. Feild (STScI)

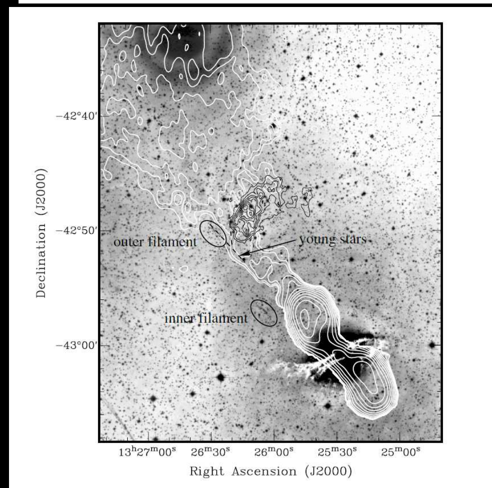
STScI-PRC05-26

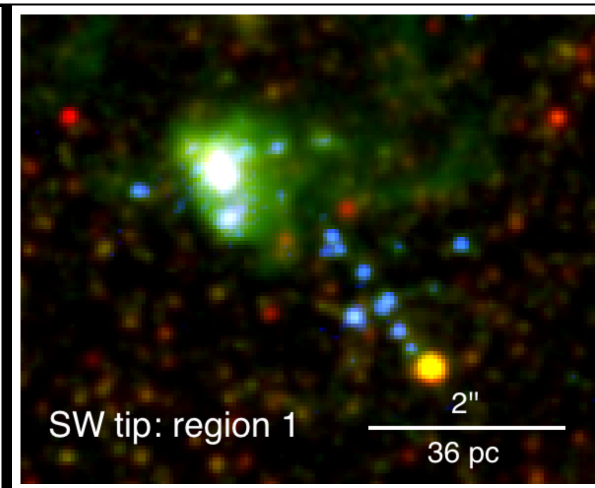

Hercules A (3C 348)
HST + VLA
E
N
500,000 light-years
153 kiloparsecs
58″
HST WFC3/UVIS
F606W V
F814W I
VLA
C Band Low 4–6 GHz
C Band High 6–8 GHz
X Band 8–9 GHz

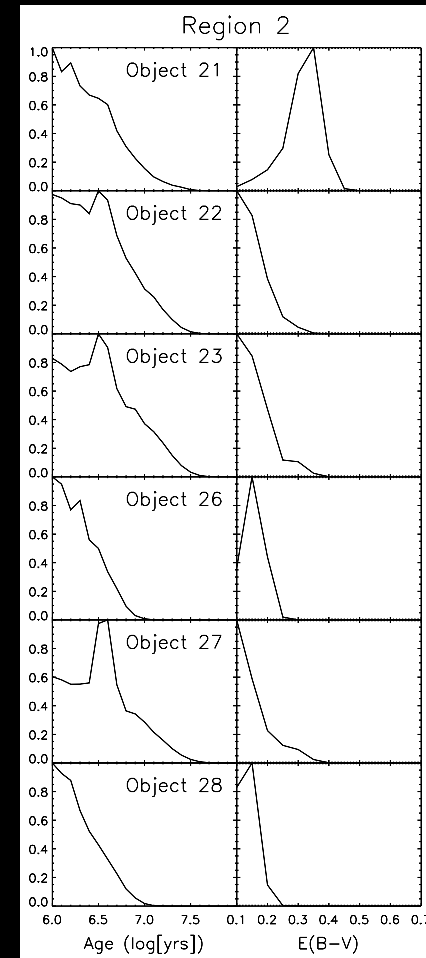


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W I
3000 light-years
1400 parsecs
56″
E
N









[Left] CSIRO/ATNF 1.4 GHz image of Cen A (Feain, Cornwell & Ekers (2009).

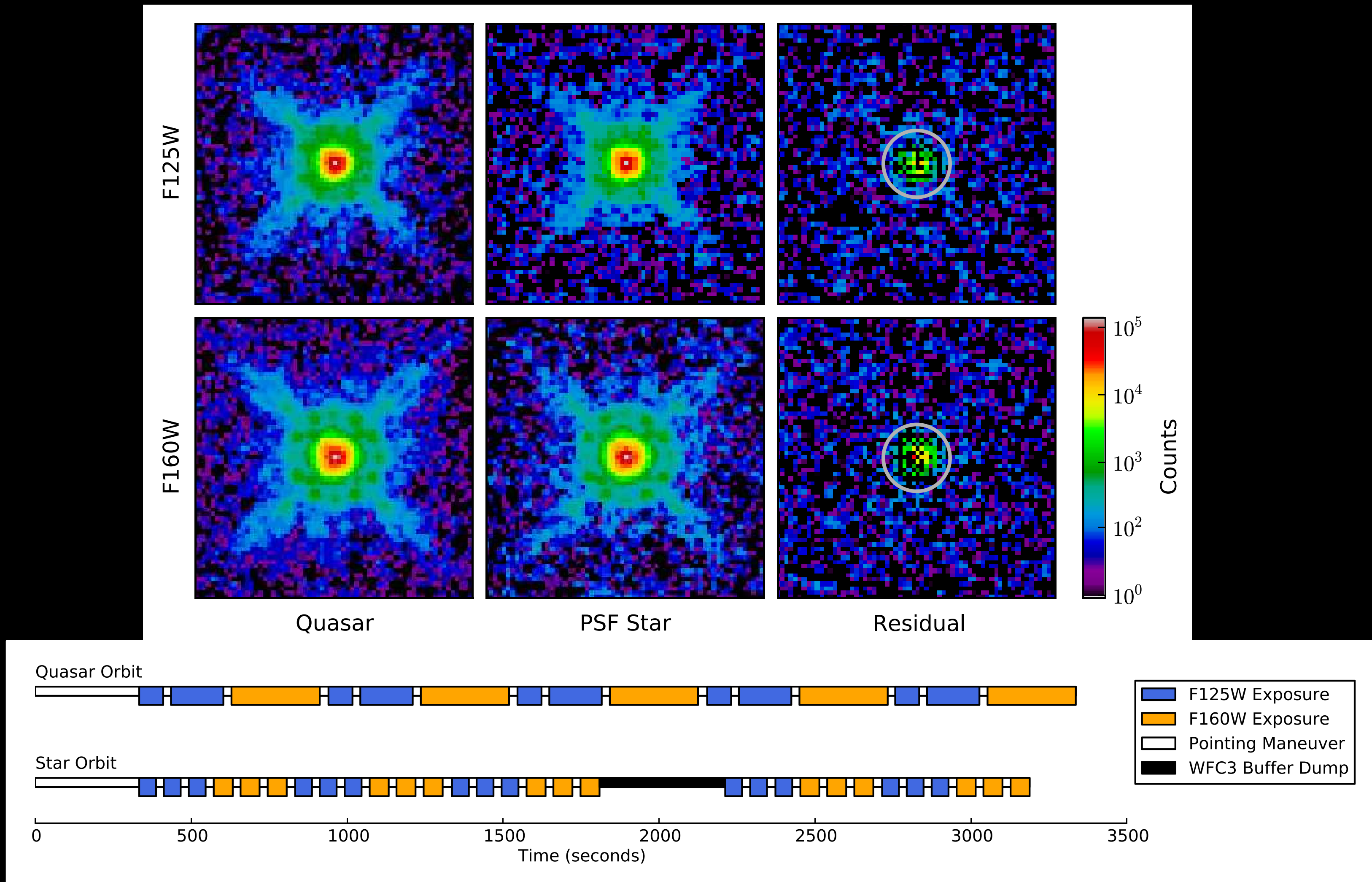
Fermi GeV source (Yang+ 12); & Auger UHE Cosmic Rays (Abreu+ 2010).

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

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

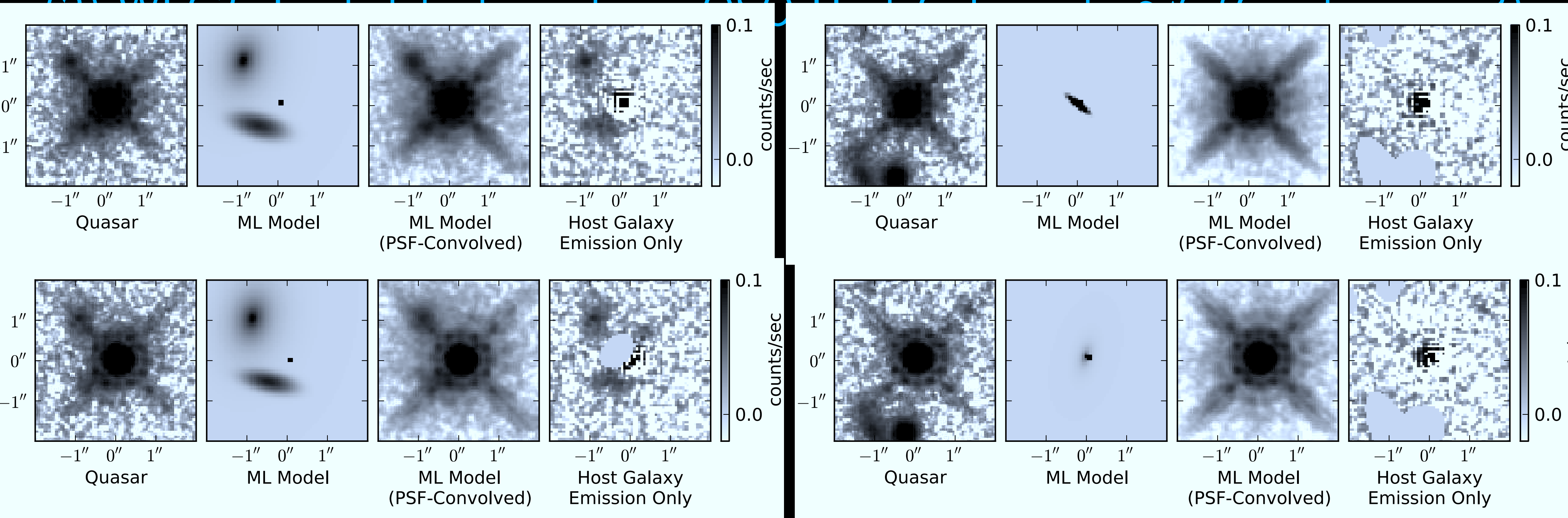
- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV–blue before JWST flies.

(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 a QSO Host Galaxy at z≃6 (Giant merger?)

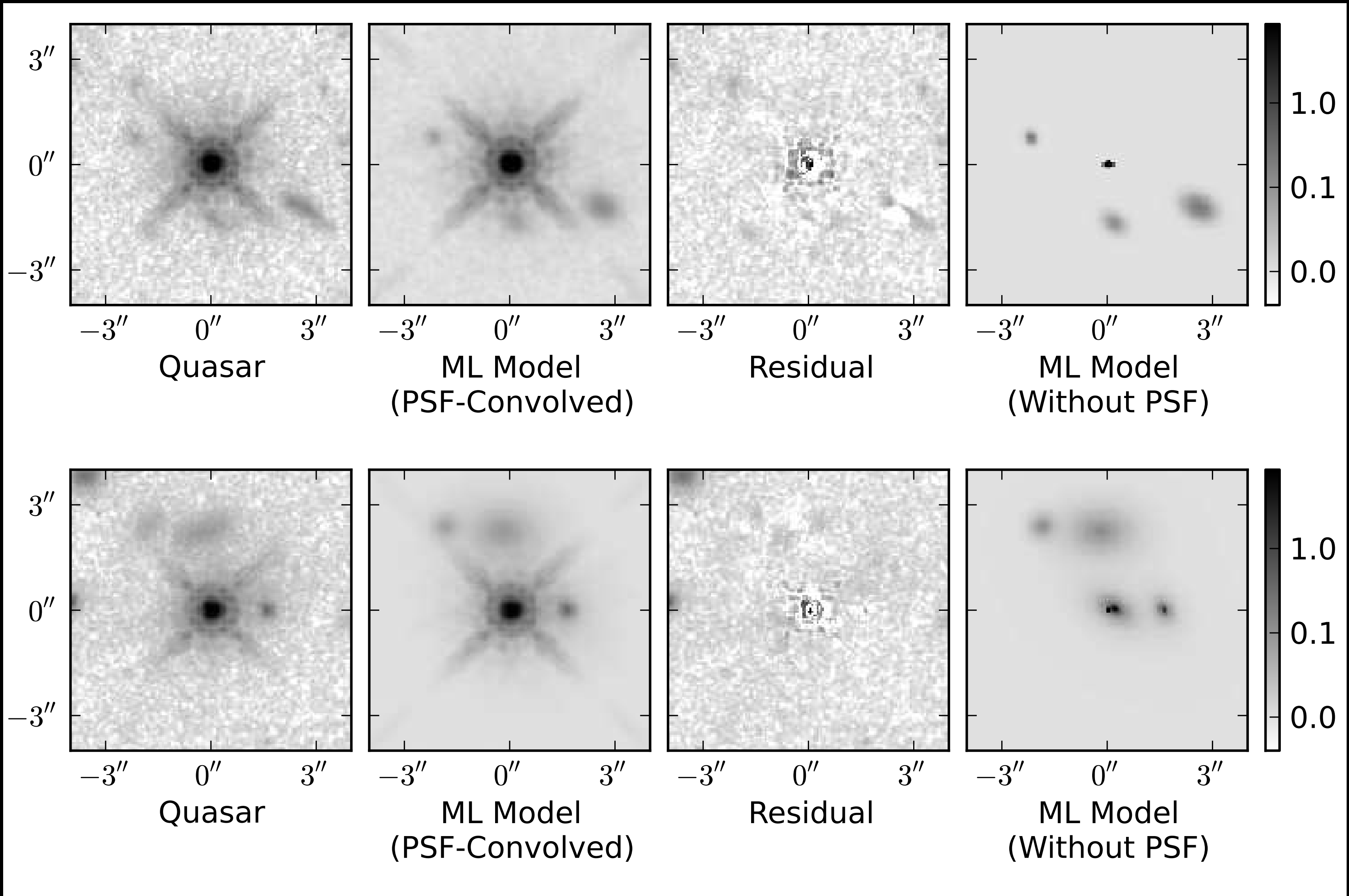


- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO data critical for PSF stars (Mechtley+ 2013).
- First solid detection out of four z≃6 QSOs [3 more to be observed].
- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure??

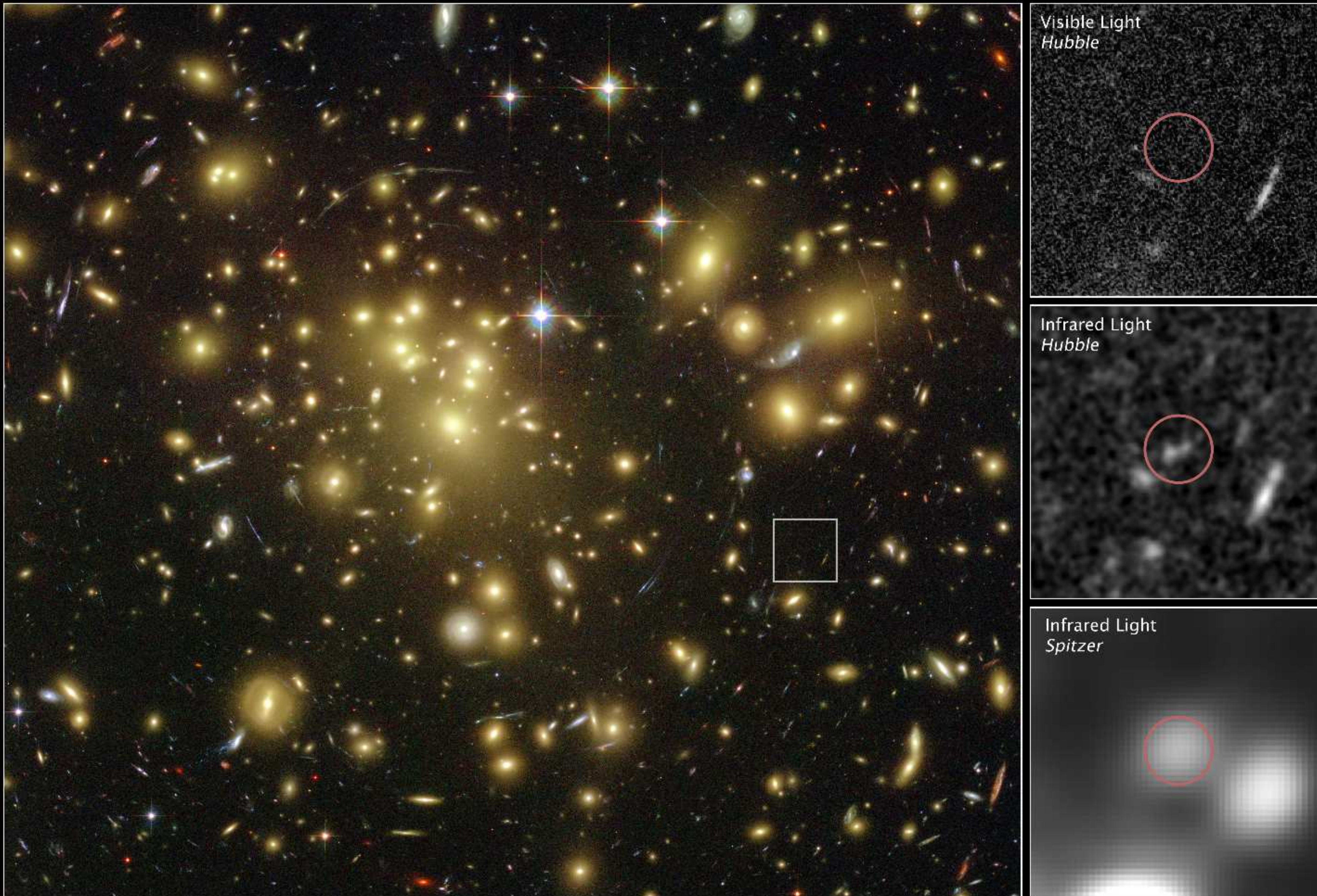
- Same J+H structure! Blue UV-SED colors: (J–H)≃0.19, constrains dust.
  - IRAS starburst-like SED from rest-frame UV–far-IR, A_{FUV}∼1 mag.
- M_{AB}^{host}(z≃6)$\lesssim$–23.0 mag, i.e., ∼2 mag brighter than L*(z≃6)!

⇒ z≃6 QSO duty cycle $\lesssim 10^{-2}$ ($\lesssim$10 Myrs); 1/4 QSO's close to Magorrian.

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



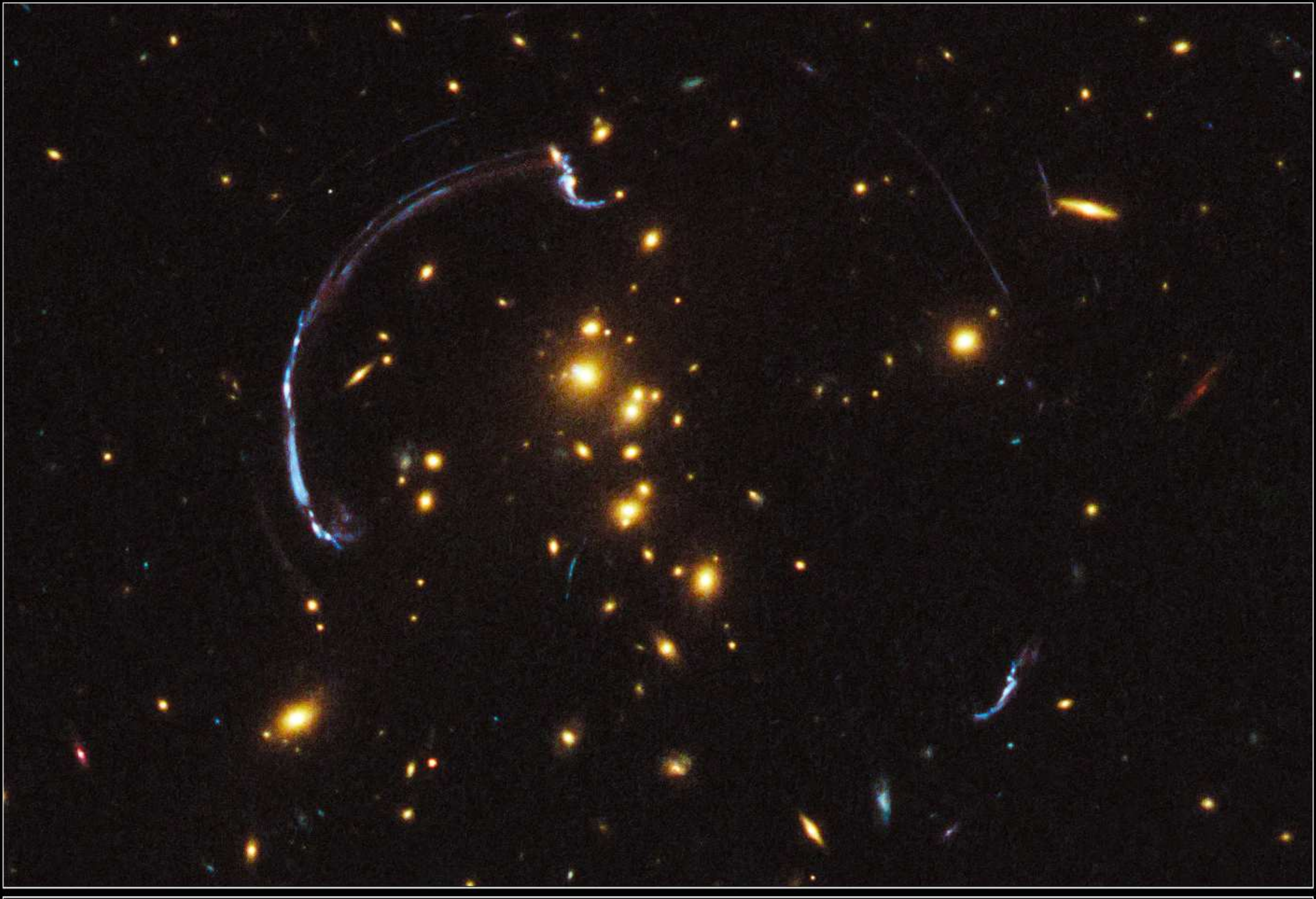
- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, Koekemoer, Windhorst et al. 2013).
- JWST Coronagraphs can do this 10–100× fainter (& for $z \lesssim 20$, $\lambda \lesssim 28\mu$m).



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

NASA, ESA, and L. Bradley (JHU), R. Bouwens (UCSC), H. Ford (JHU), and G. Illingworth (UCSC)

STScI-PRC08-08a

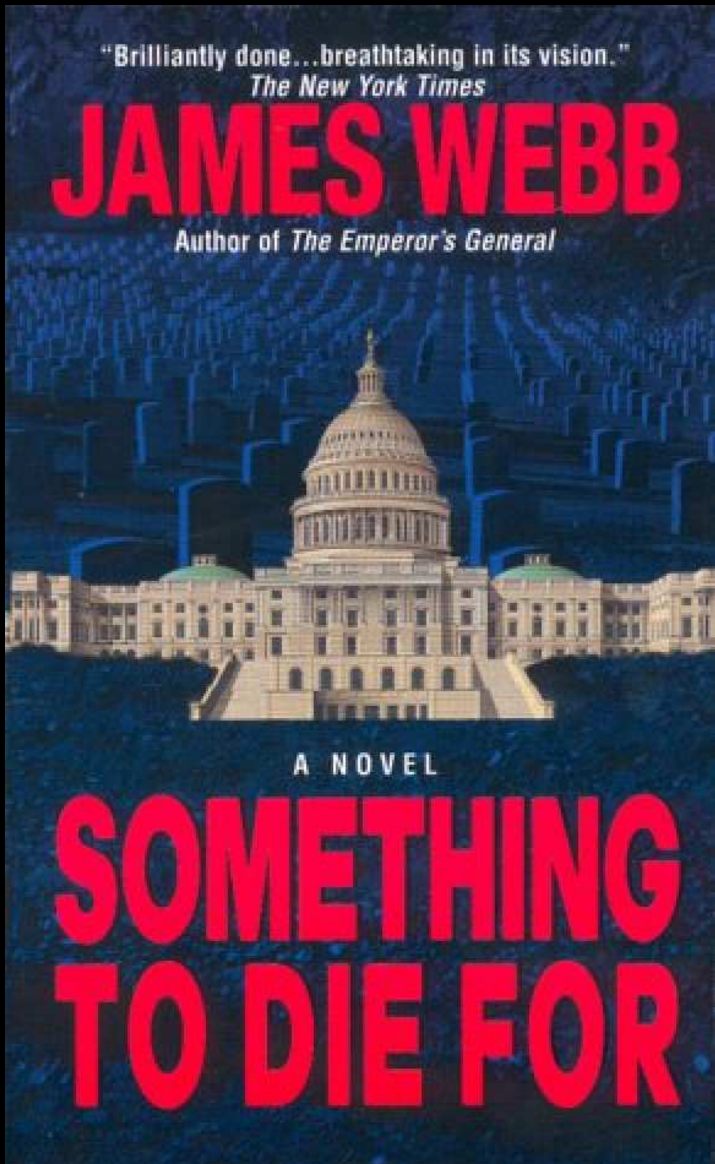


Galaxy Cluster RCS2 032727-132623
Hubble Space Telescope • WFC3/UVIS/IR

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

STScI-PRC12-08a

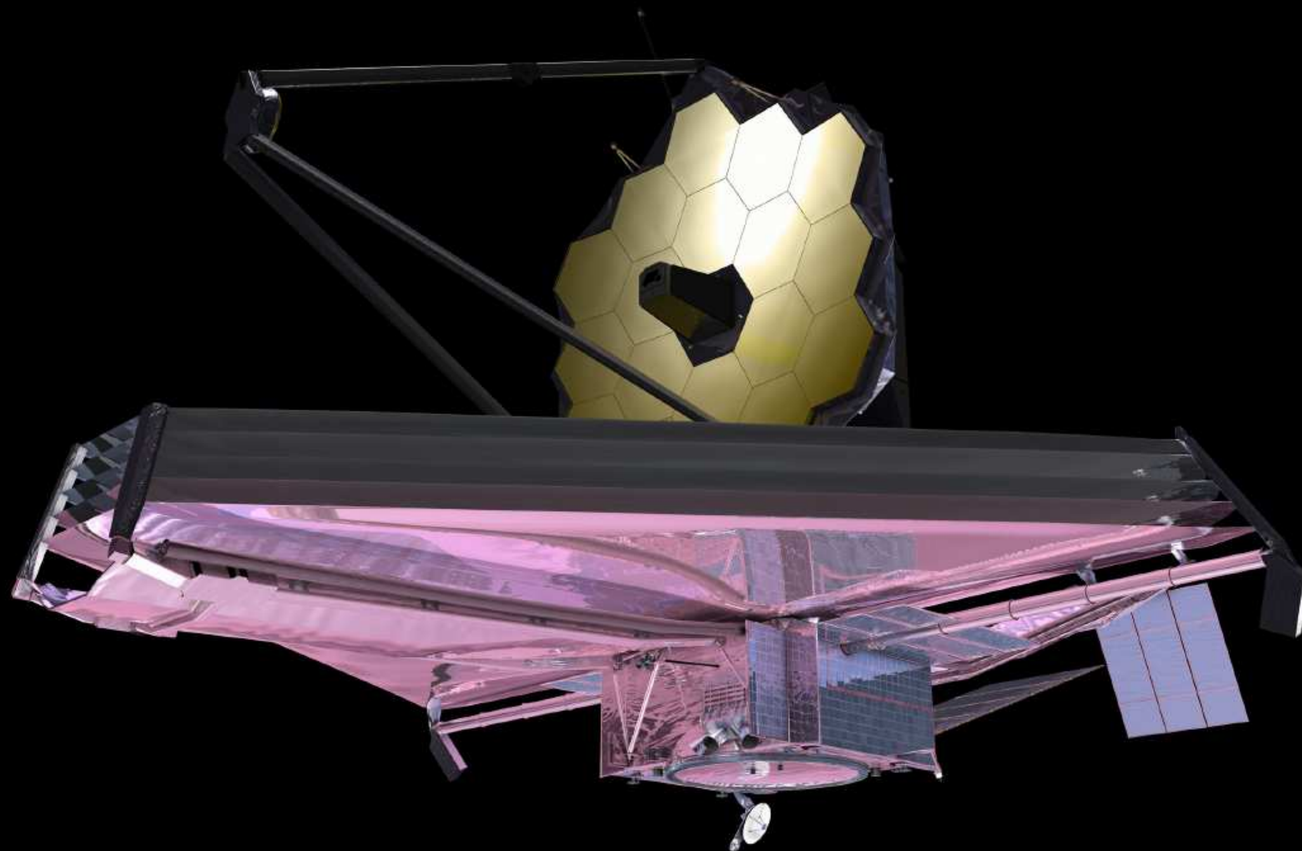
(3) What is the James Webb Space Telescope (JWST)?



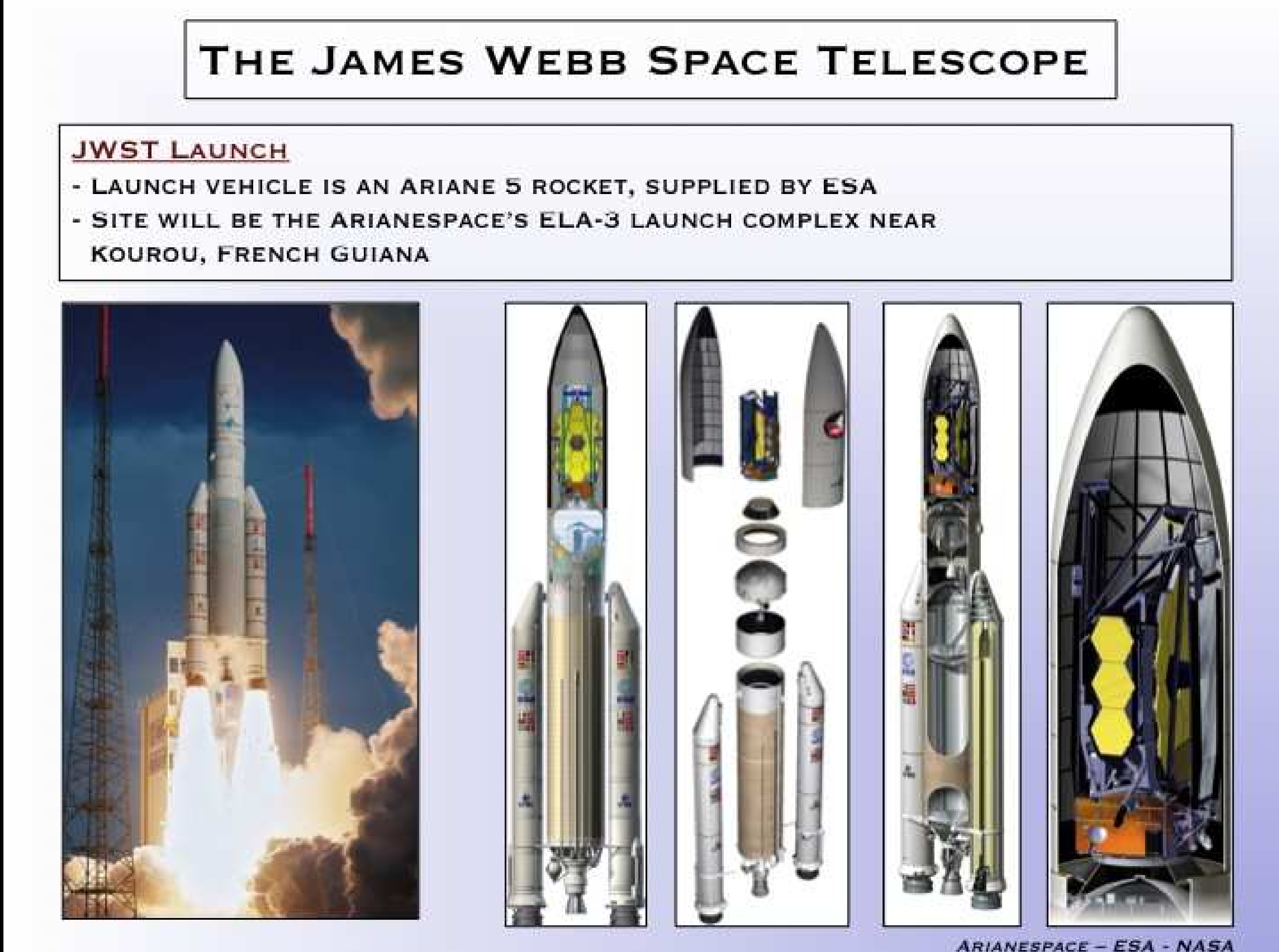
Need young generation of students & scientists after 2018 ... It'll be worth it!

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

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

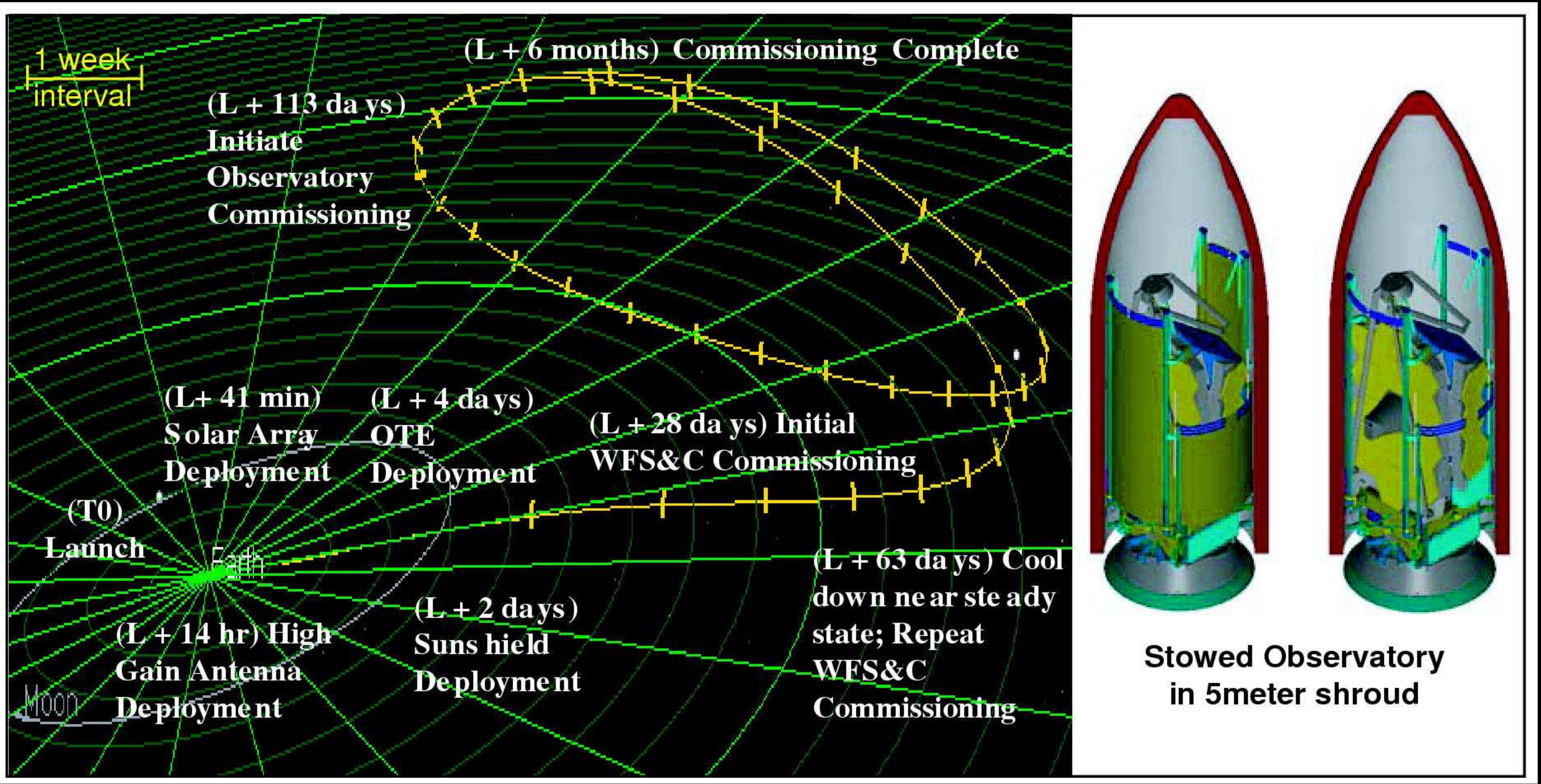


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (31.5 mag = firefly from Moon!) and spectroscopy.



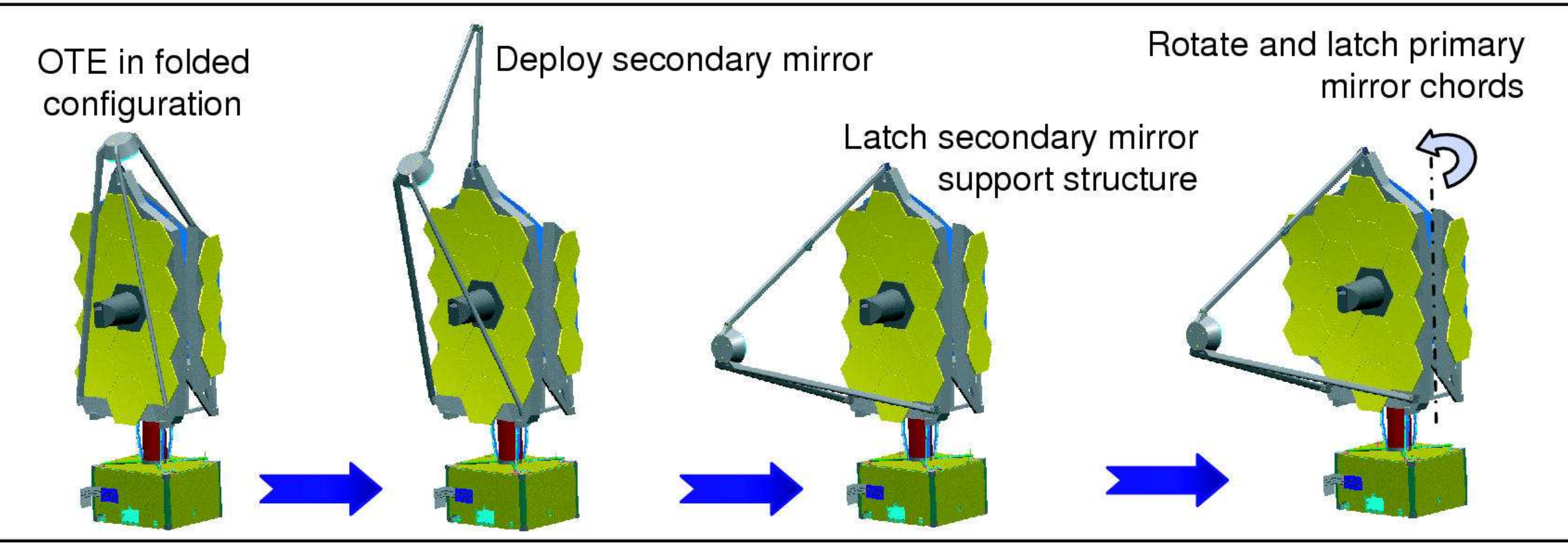
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(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.

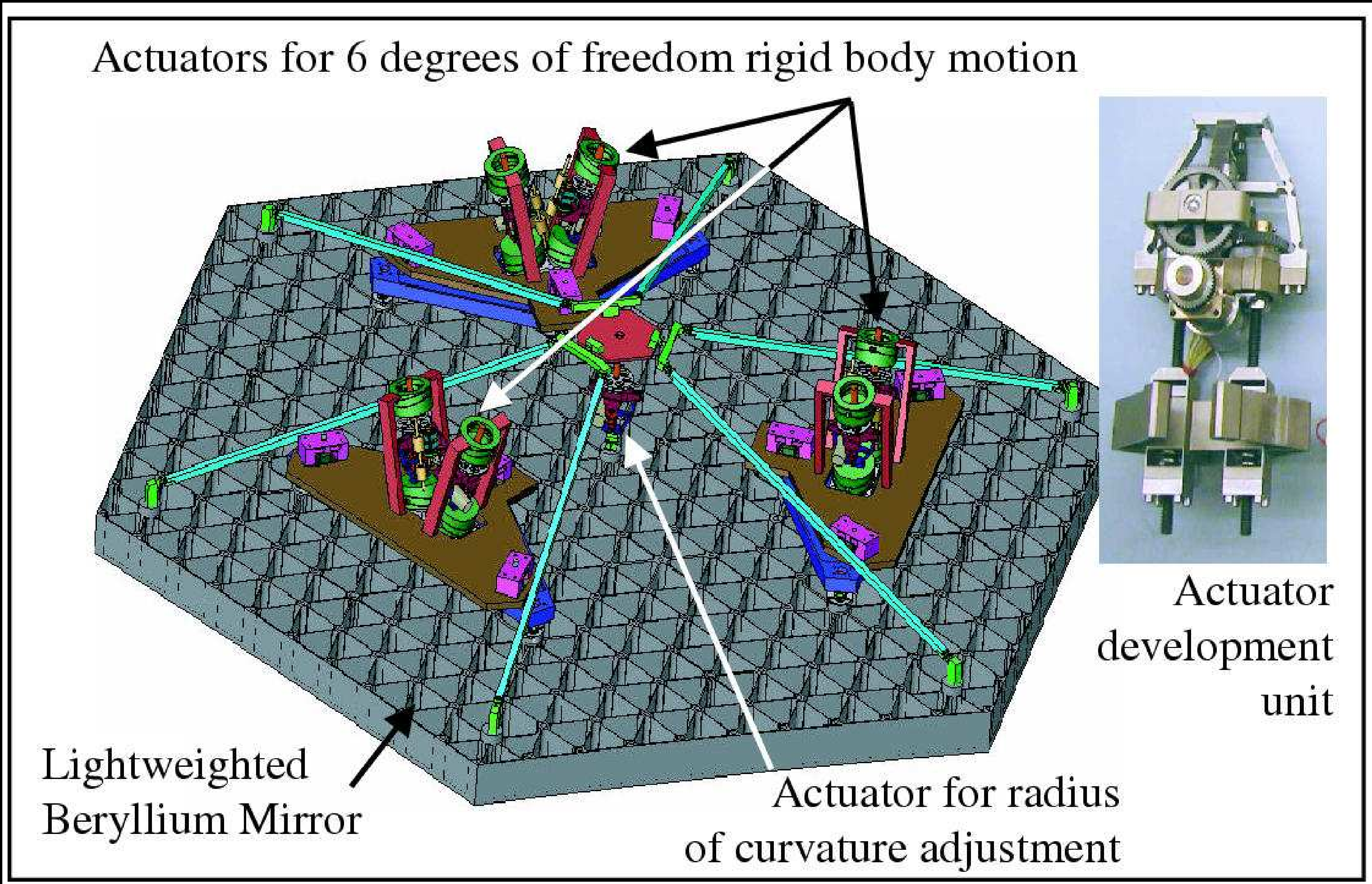
• (3b) How will JWST be automatically deployed?



• 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.

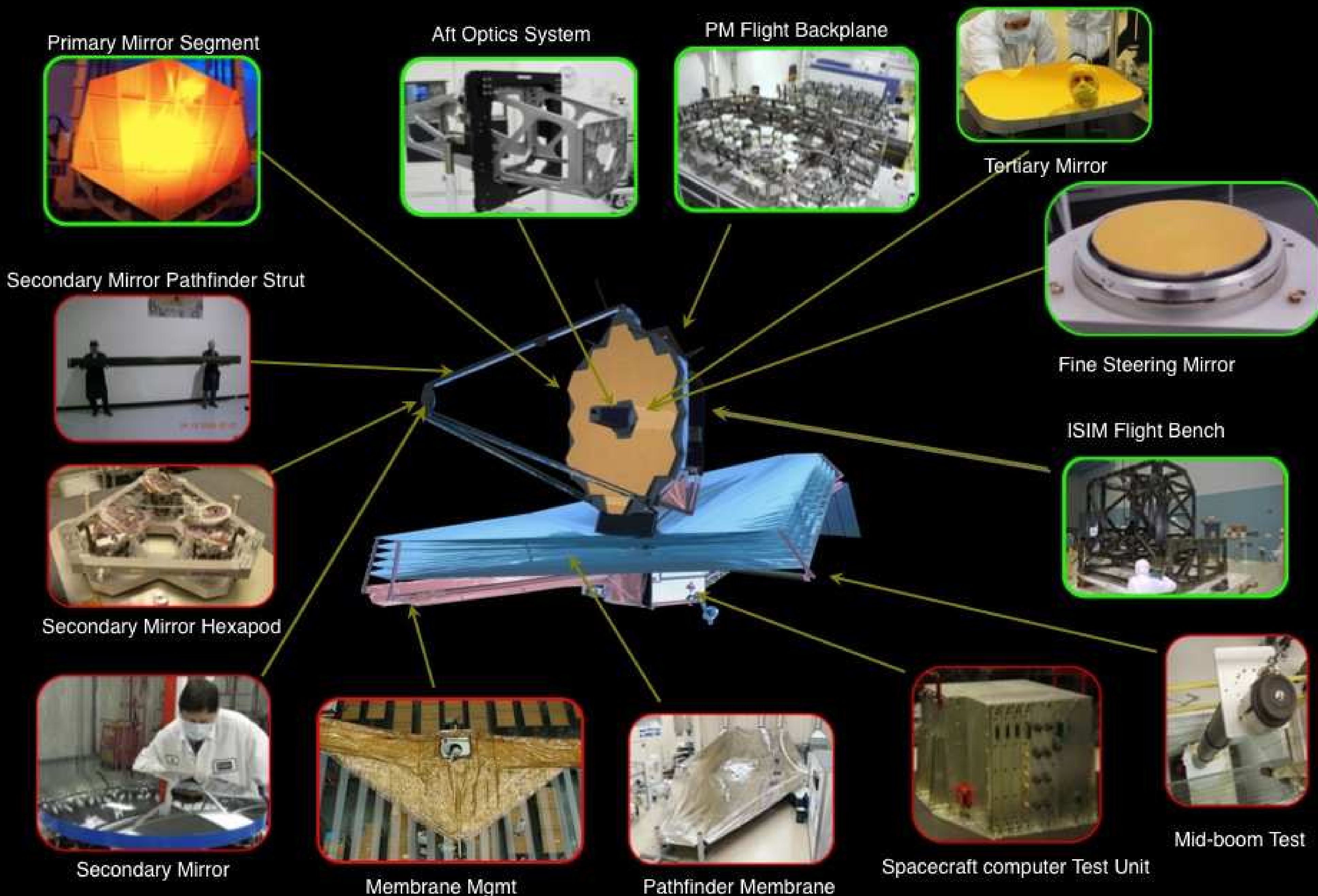
• Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications!



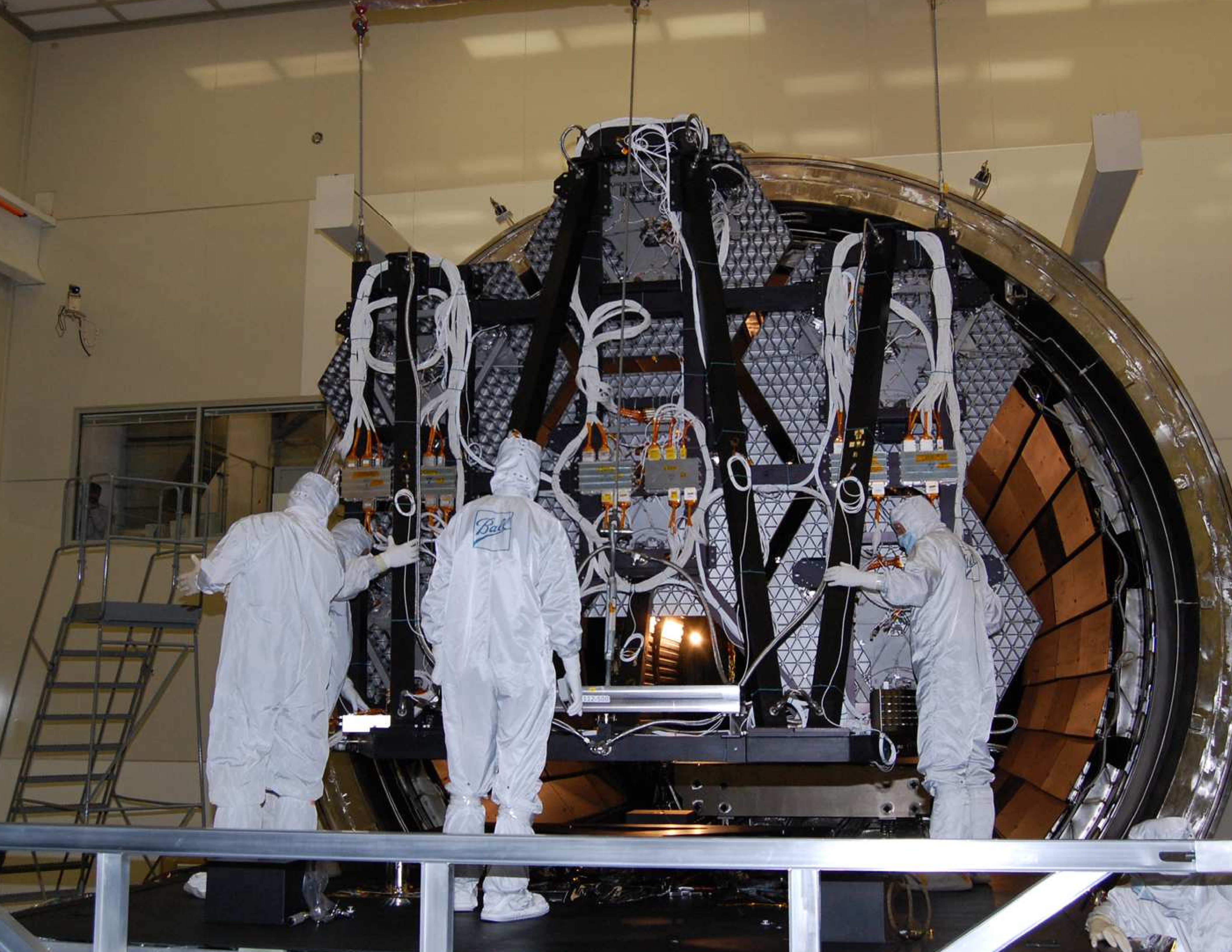
Active mirror segment support through “hexapods”, similar to Keck.

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

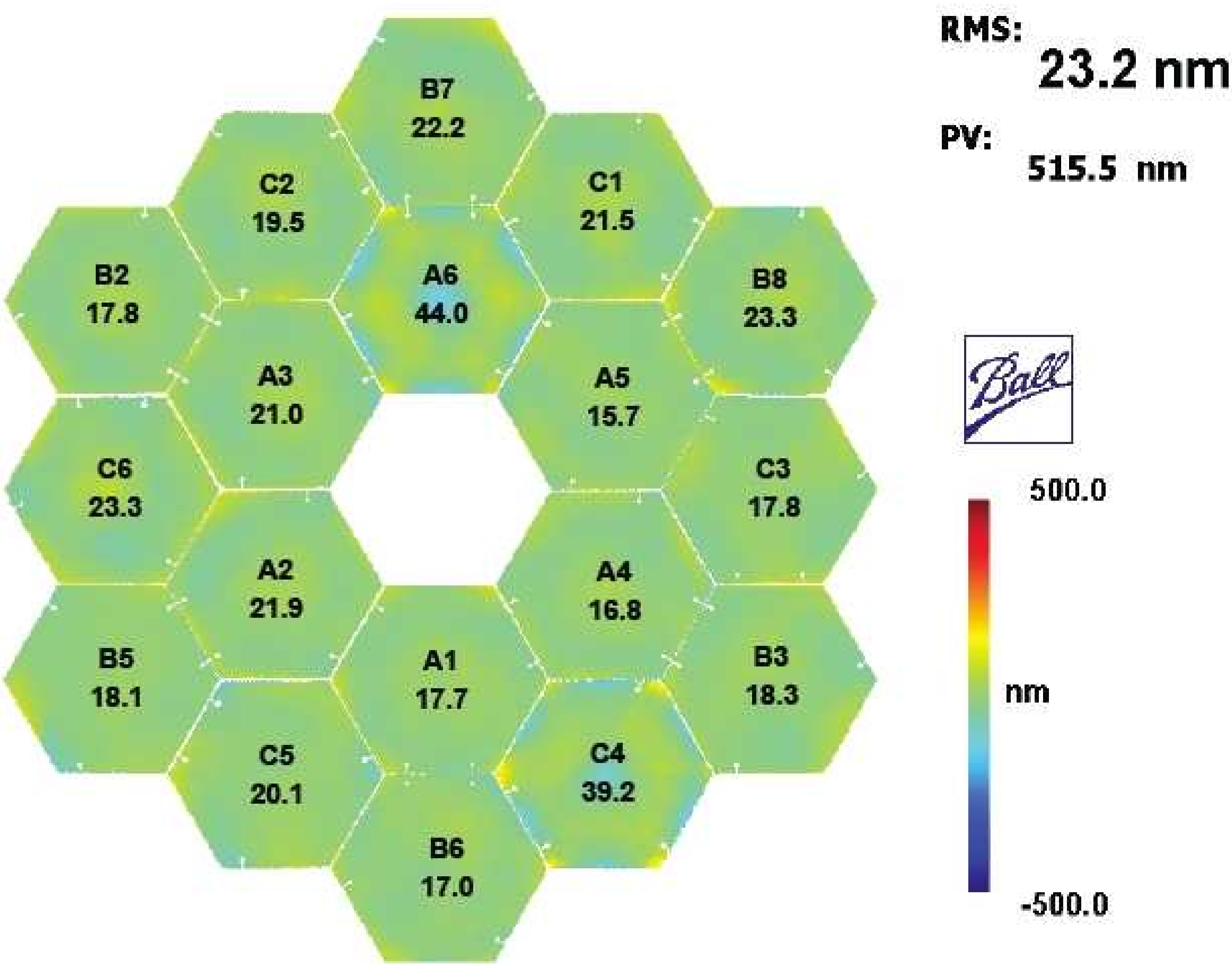
JWST Hardware Status



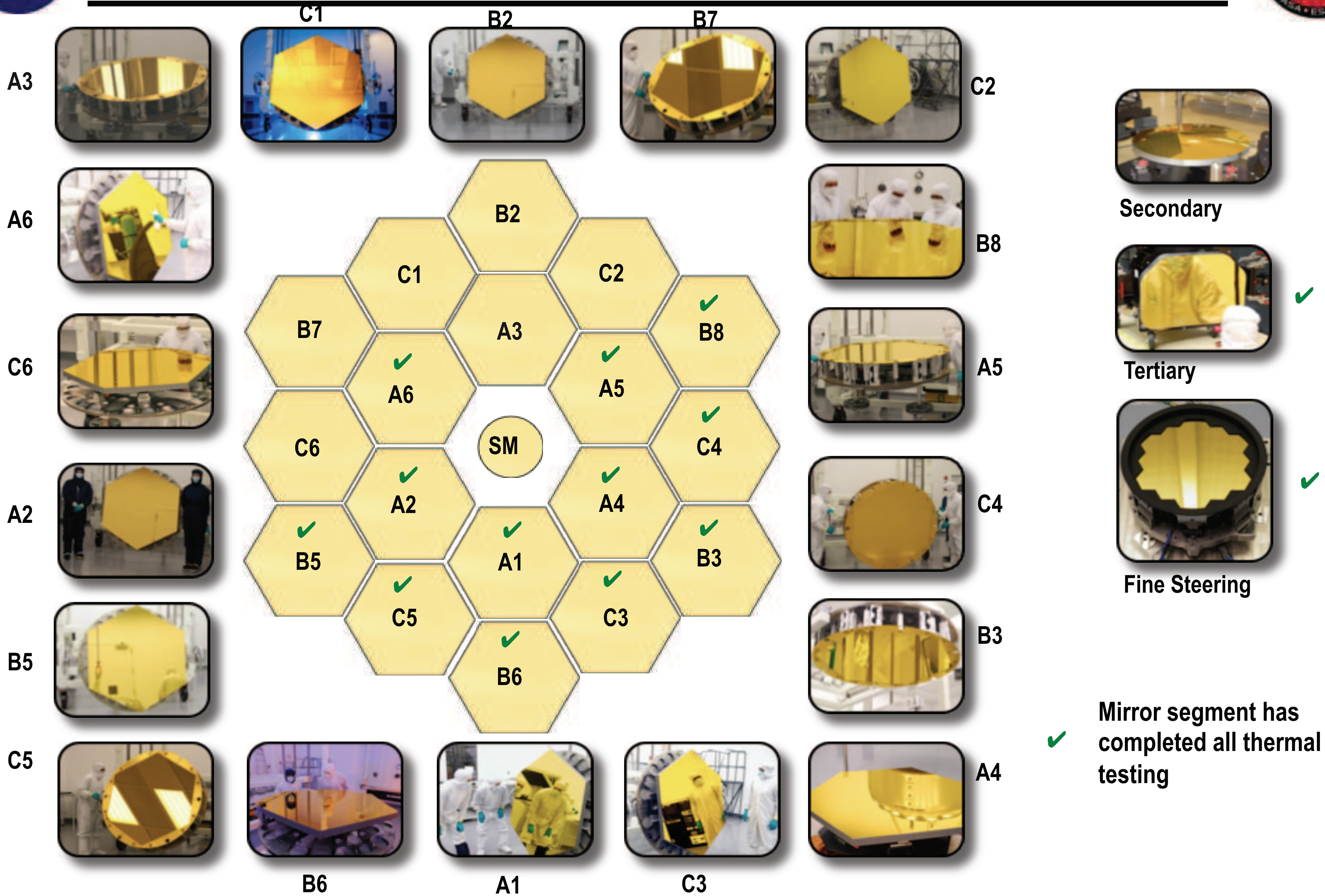
Mirror Acceptance Testing


Ball

Primary Mirror Composite

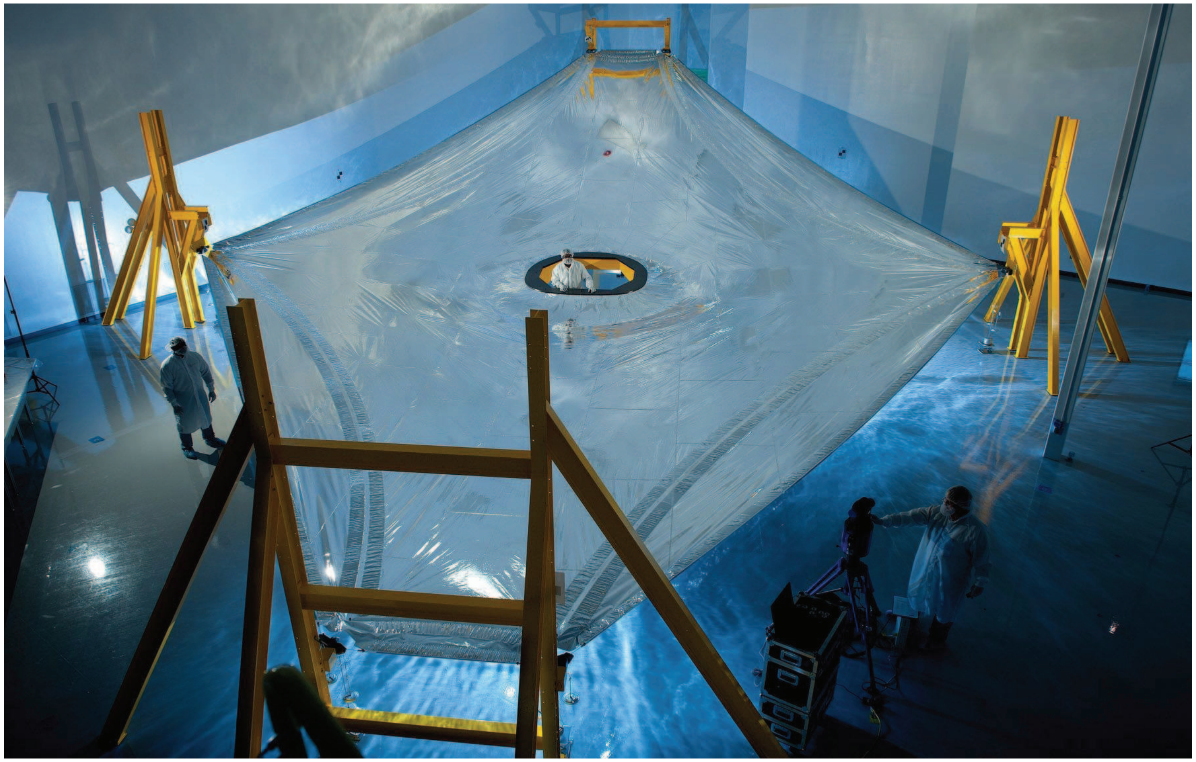


Family Portrait



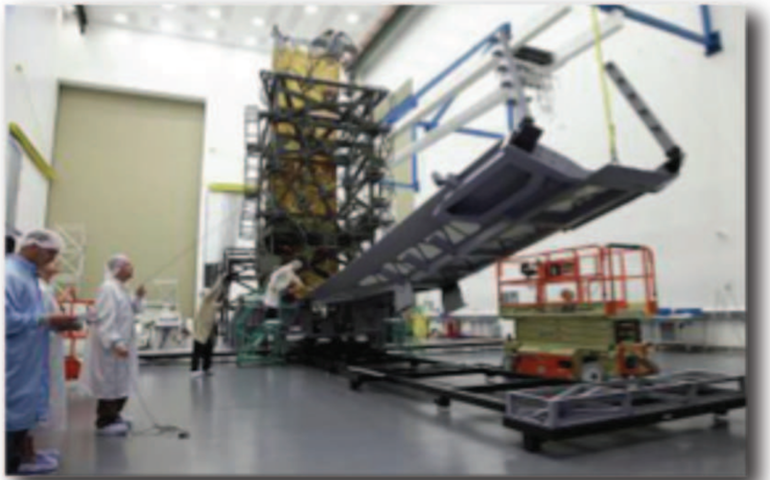
Sunshield

- **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



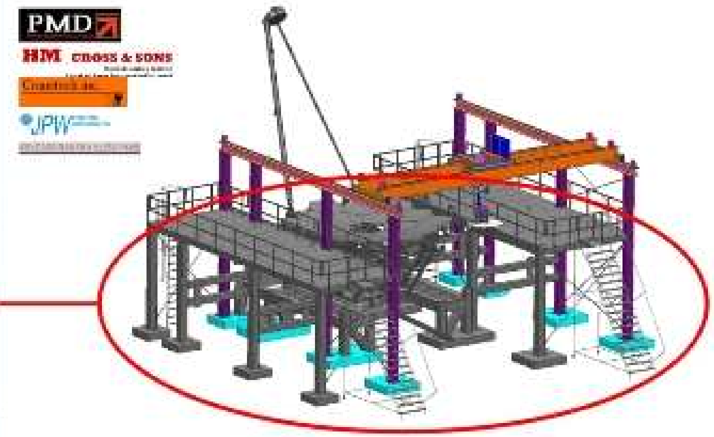
←Layer-3 template membrane under tension for 3-D shape measurements at Mantech

Full-scale JWST mockup with sunshield pallette ↓



Telescope Assembly Ground Support Equipment

Ambient Optical Alignment Stand Complete



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

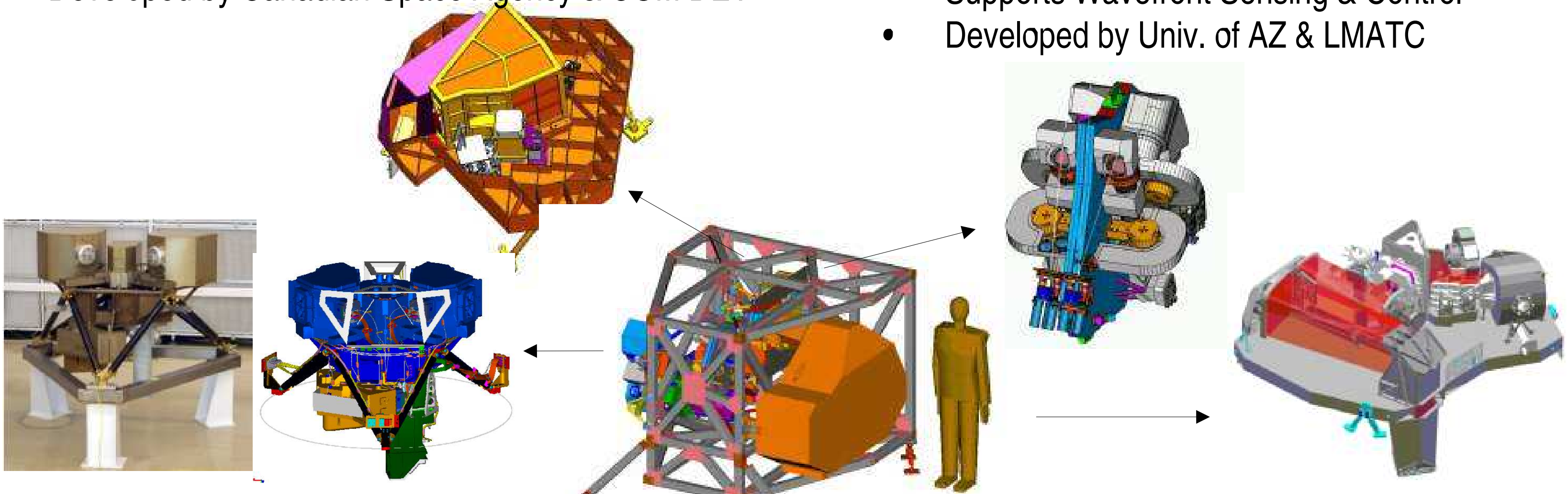
Landing a mirror onto backplane simulator

(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

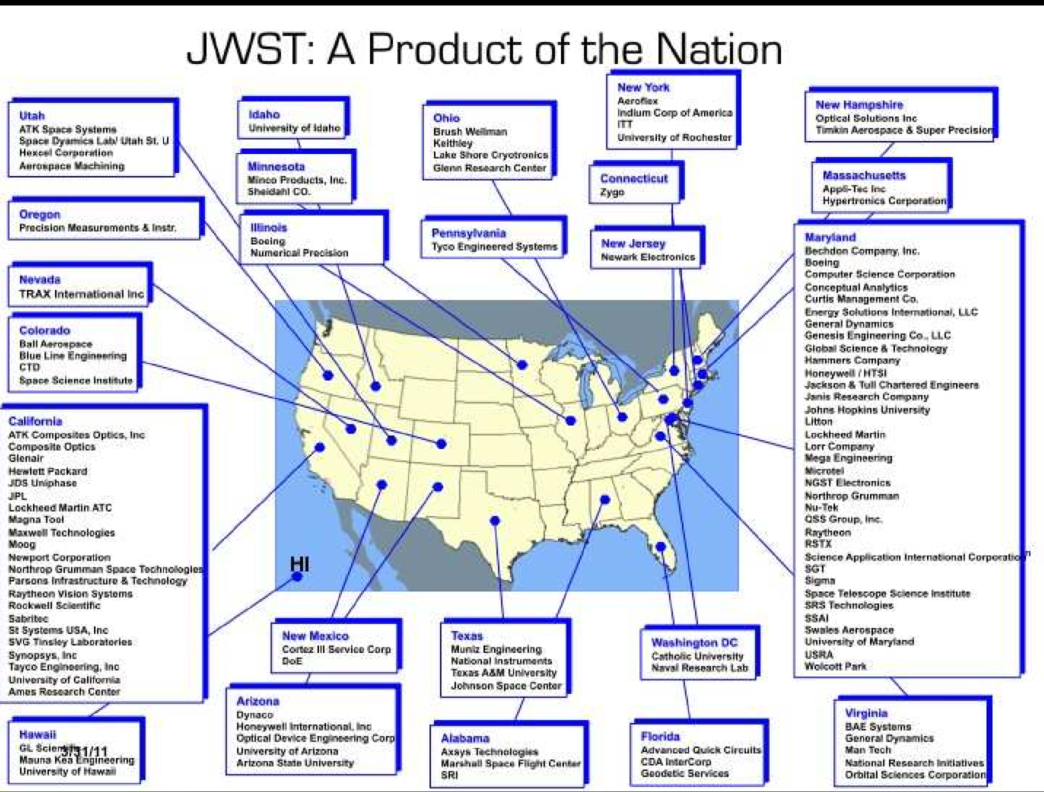
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

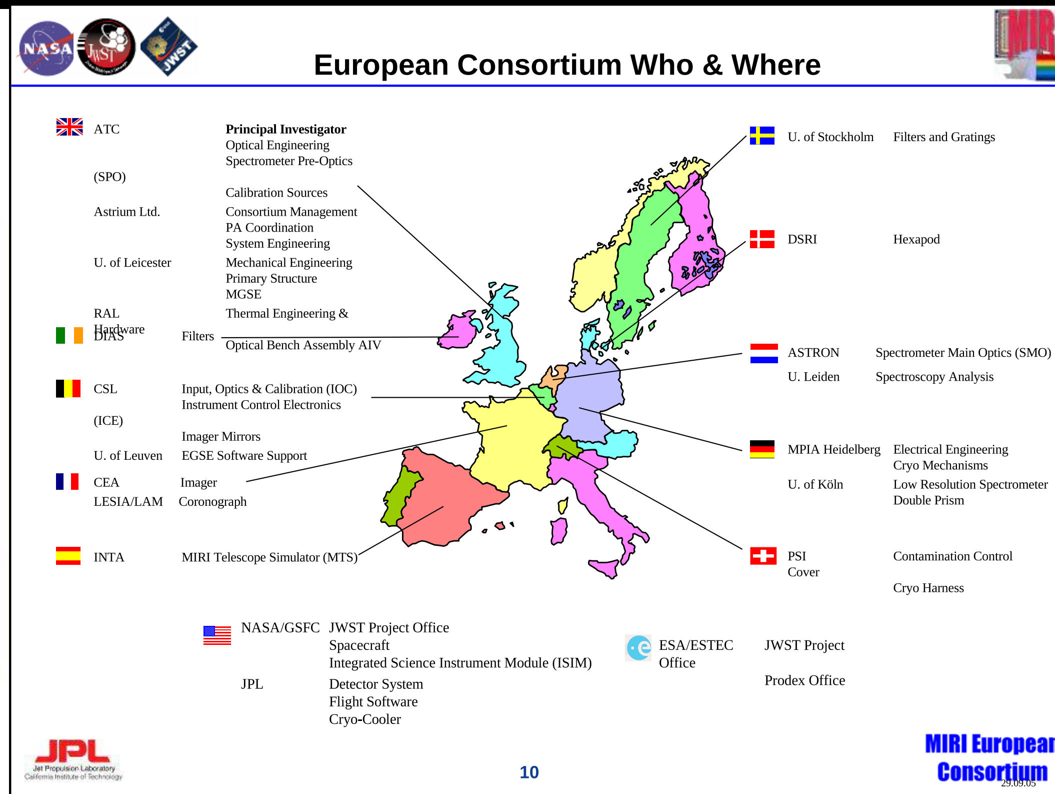


Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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.



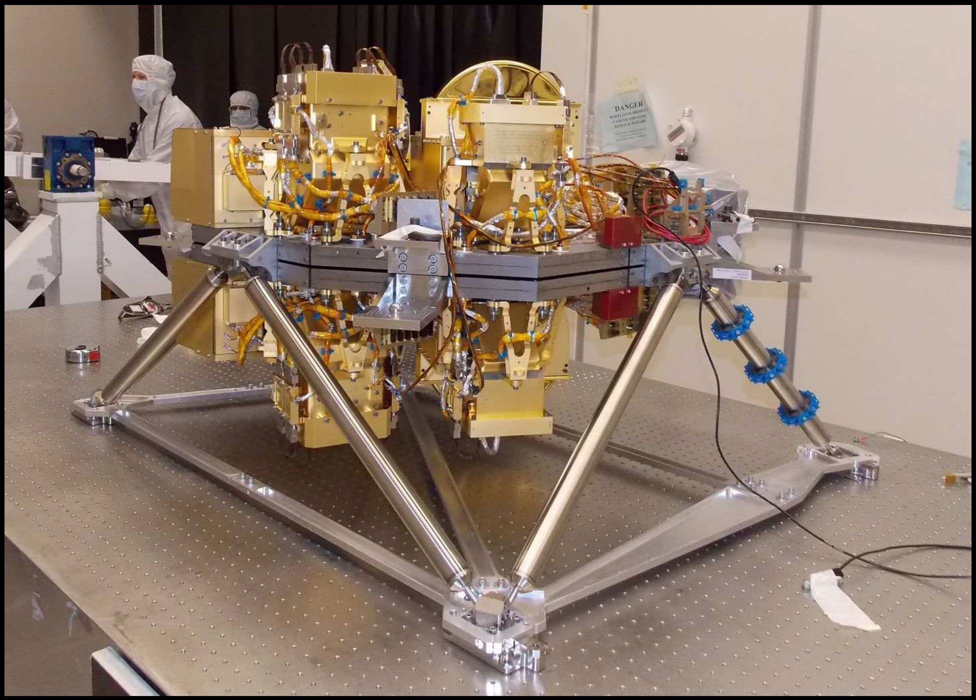


- JWST hardware made in 27 US States: $\gtrsim$80% of launch-mass finished.

- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.

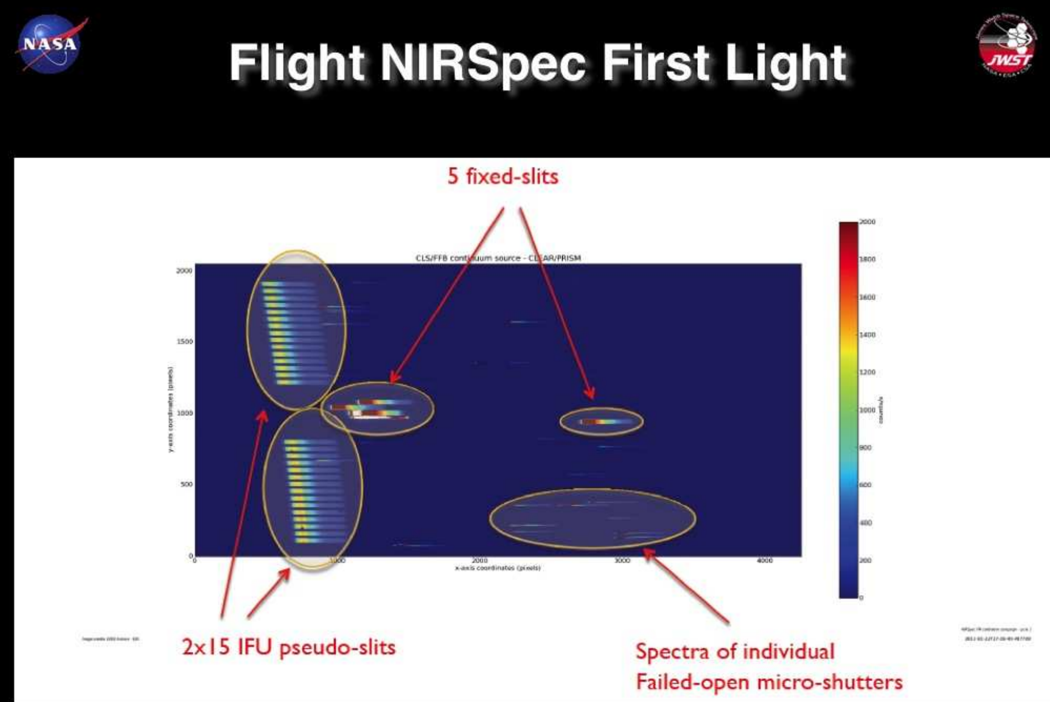
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.

- 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!

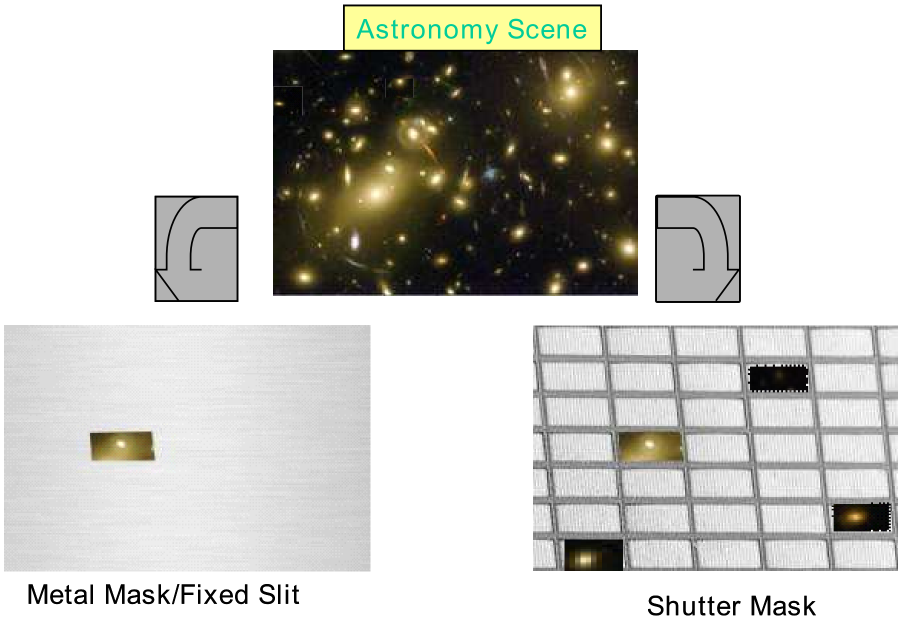


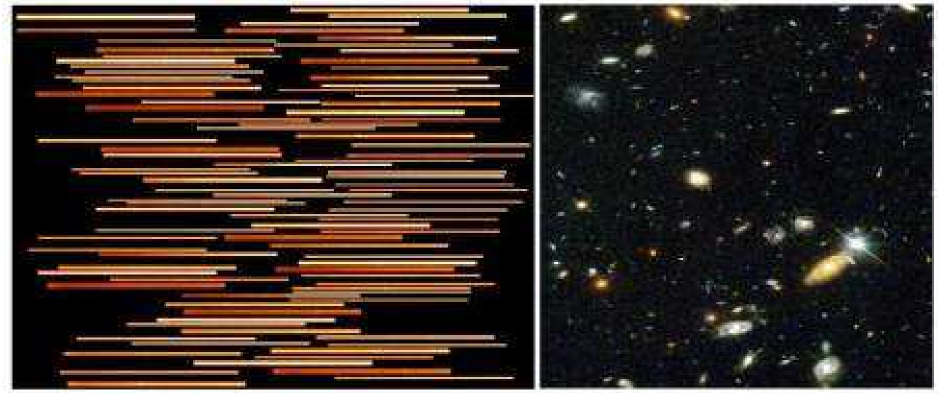
JWST's short-wavelength (0.6–5.0μm) spectrograph:

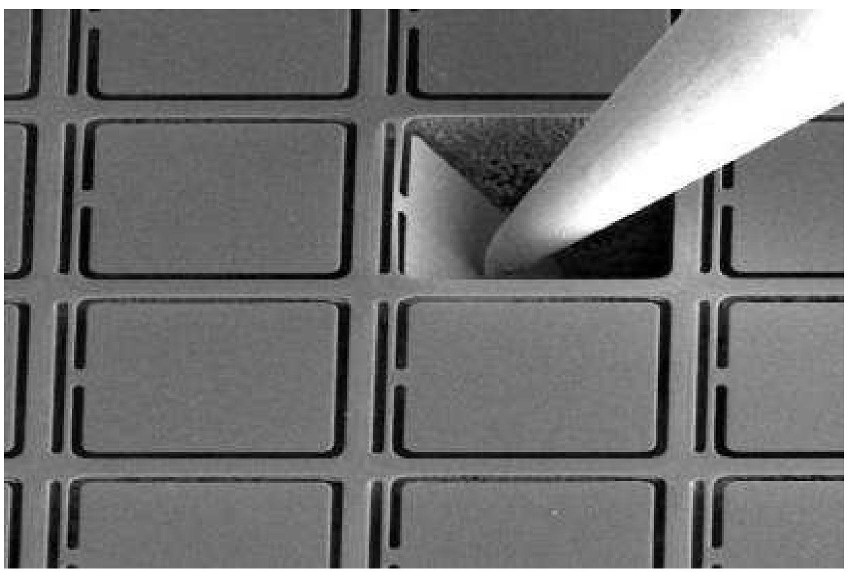
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Fight build completed and tested with First Light in Spring 2011.

NIRSpec delivery to NASA/GSFC scheduled for Fall 2013.

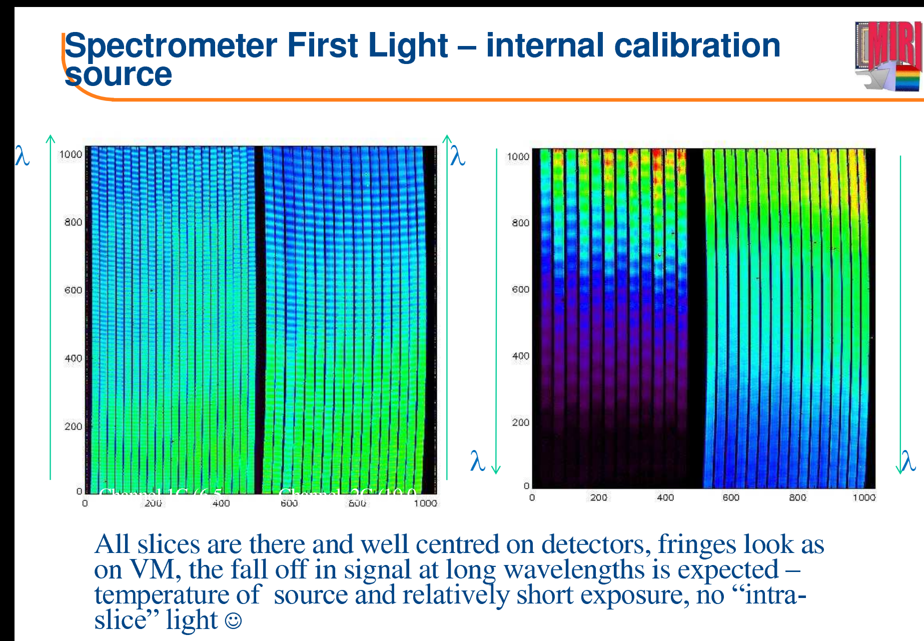
Micro Shutters







Flight MIRI

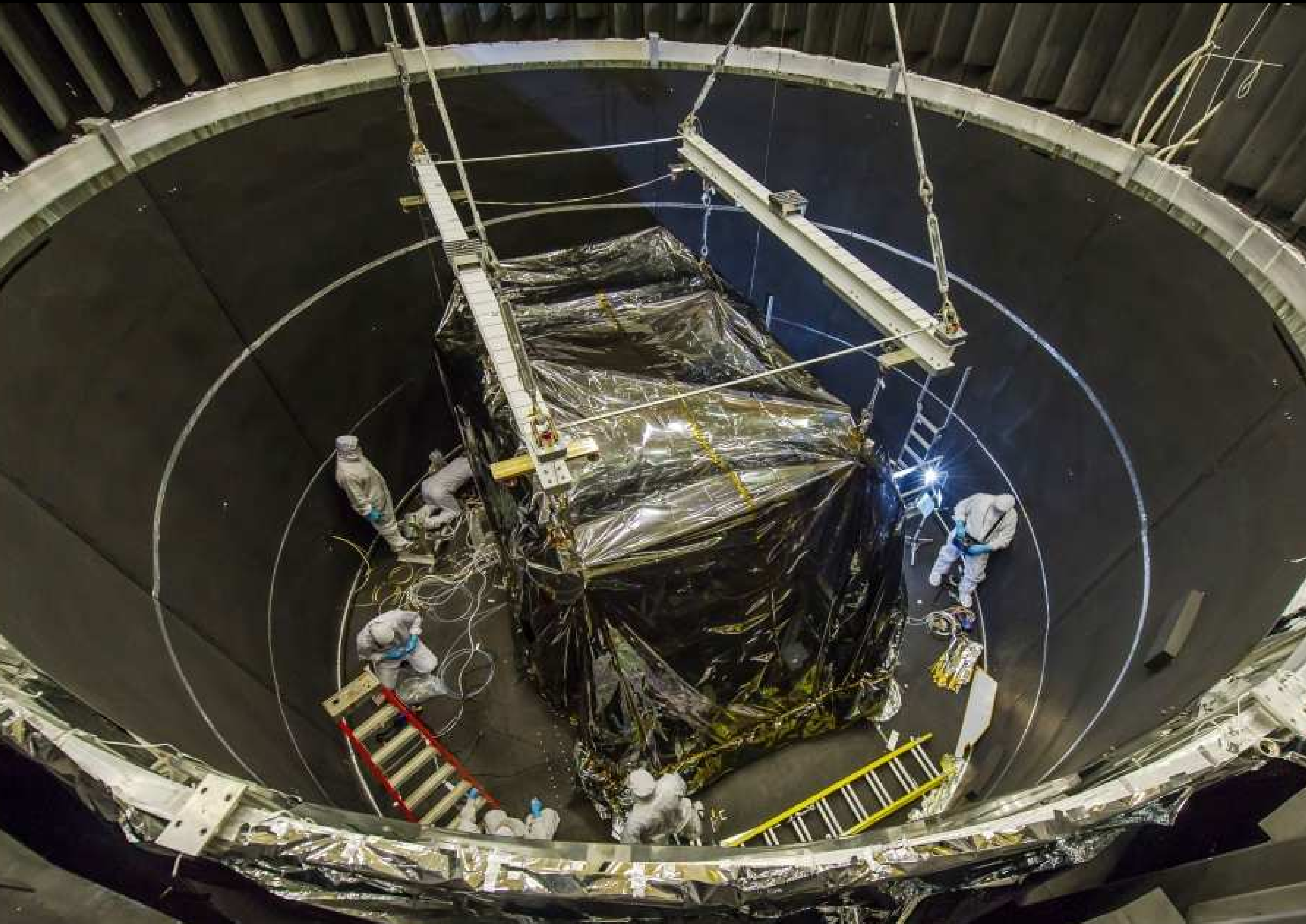


JWST's mid-infrared (5–29μm) camera and spectrograph:

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

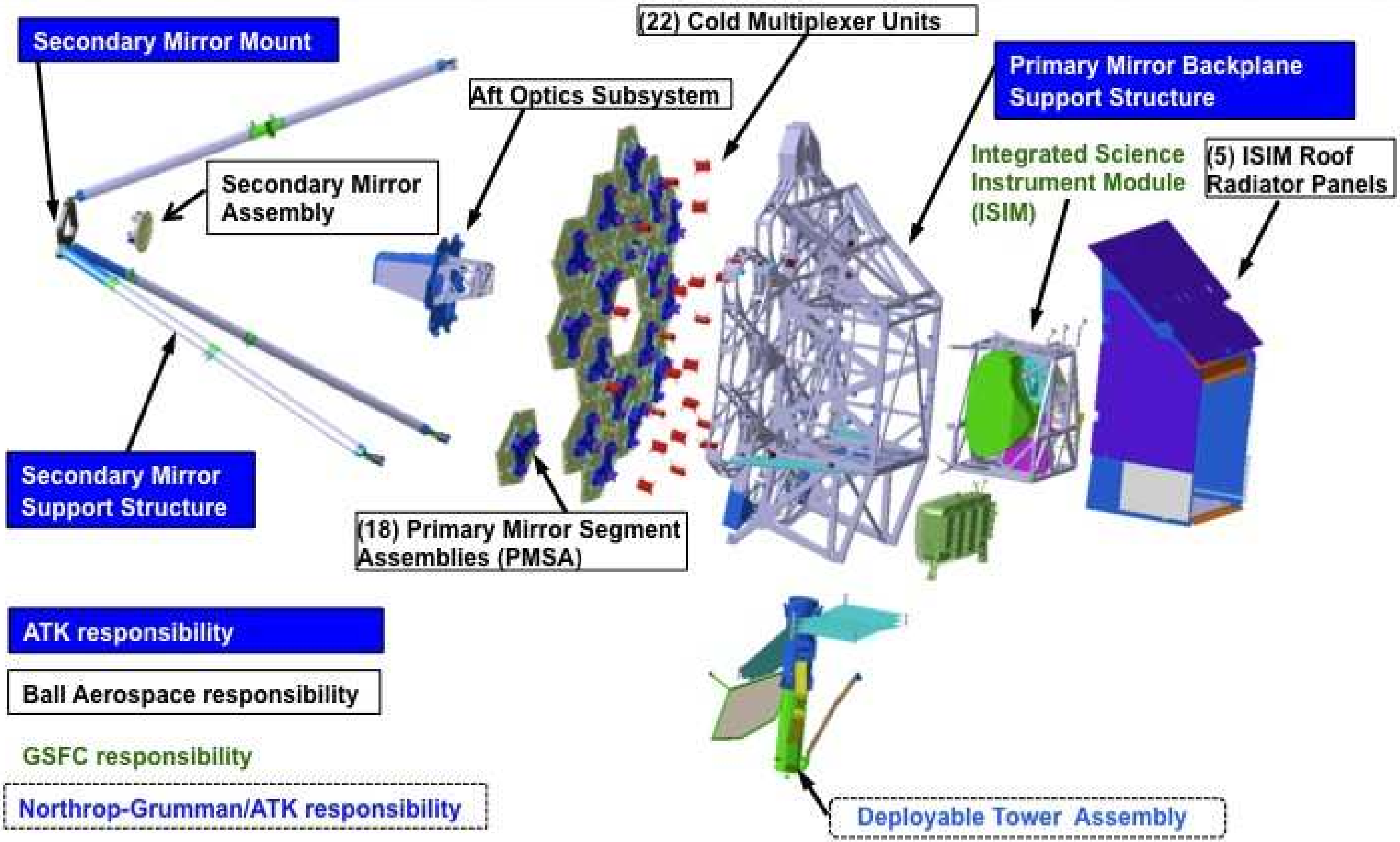
MIRI delivered to NASA/GSFC in early May 2012.

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



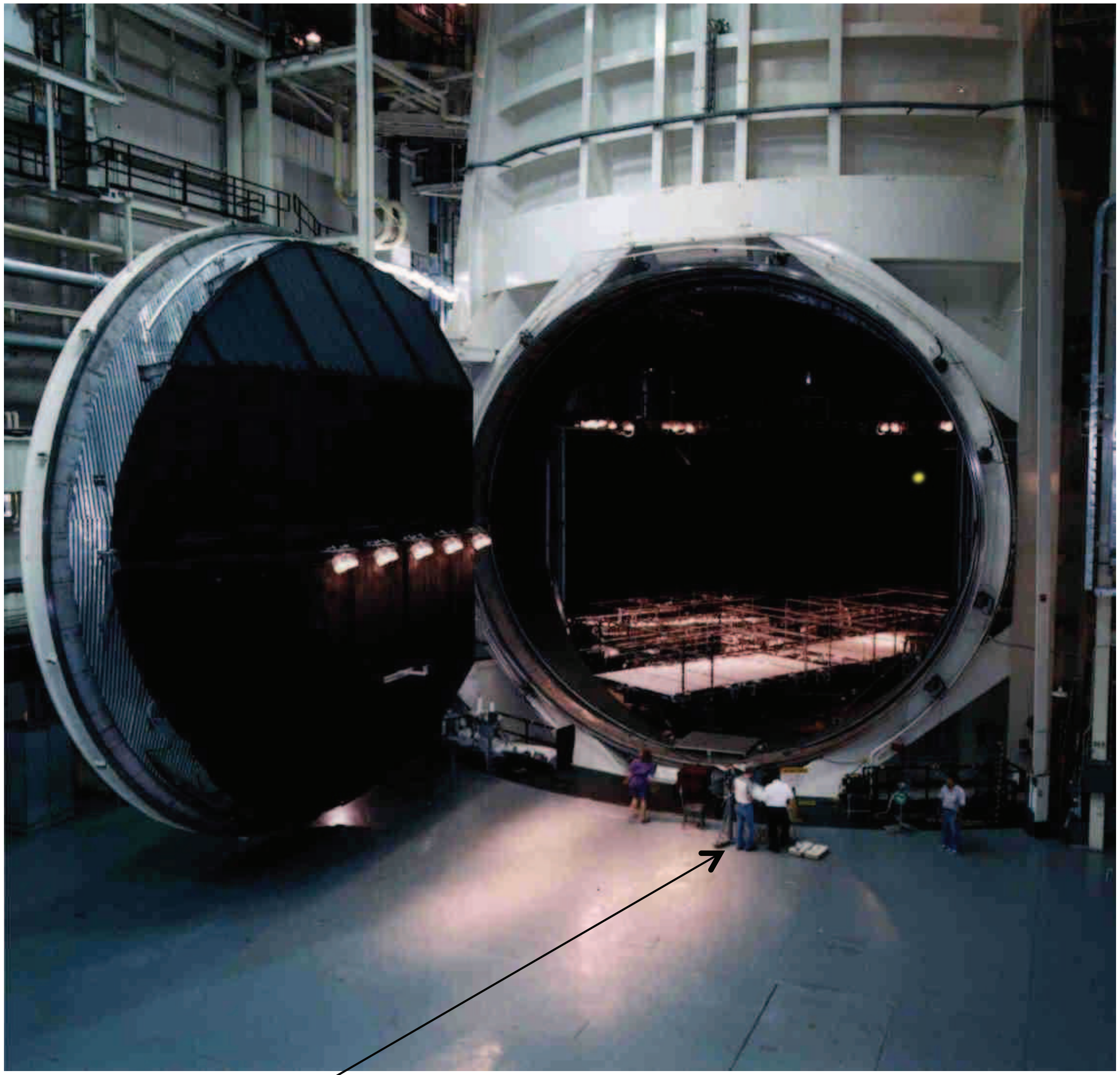
Aug. 2013: Actual Flight ISIM (with MIRI and FGS) lowered into OSIM.

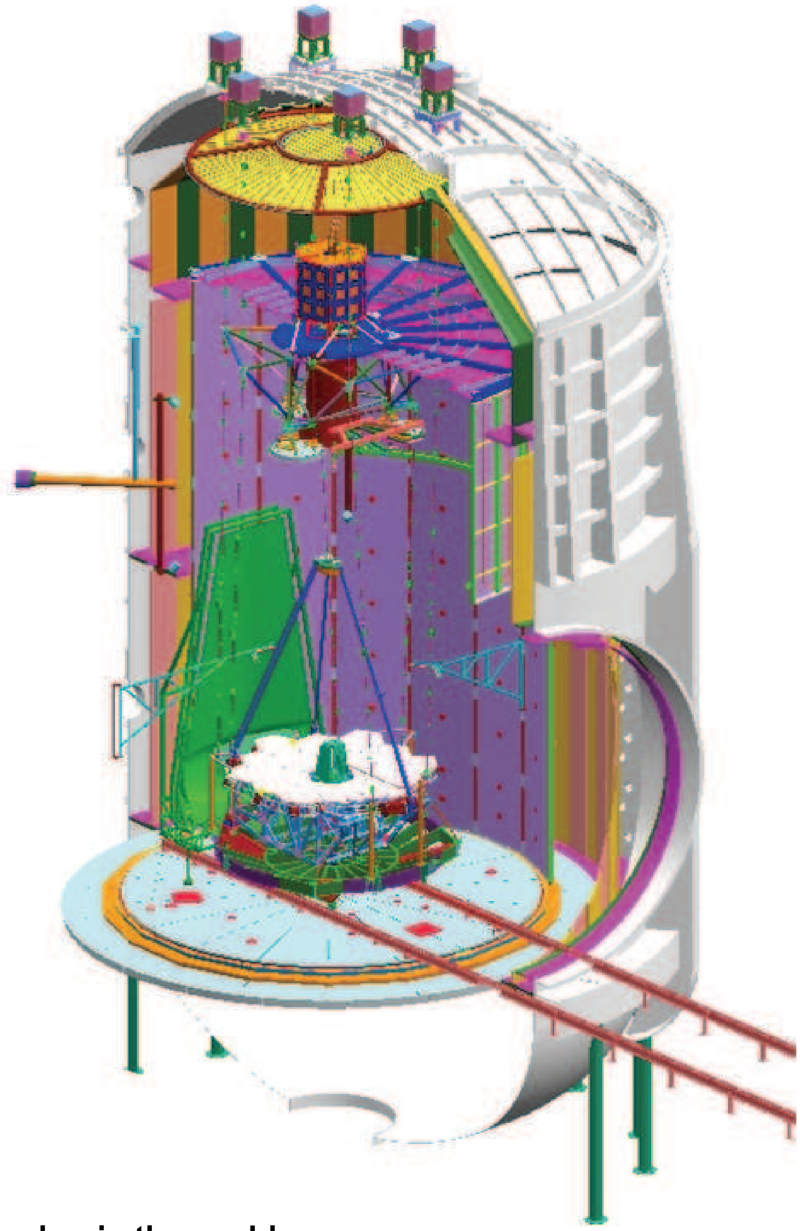
TELESCOPE ARCHITECTURE



3/31/11

OTE Testing – Chamber A at JSC



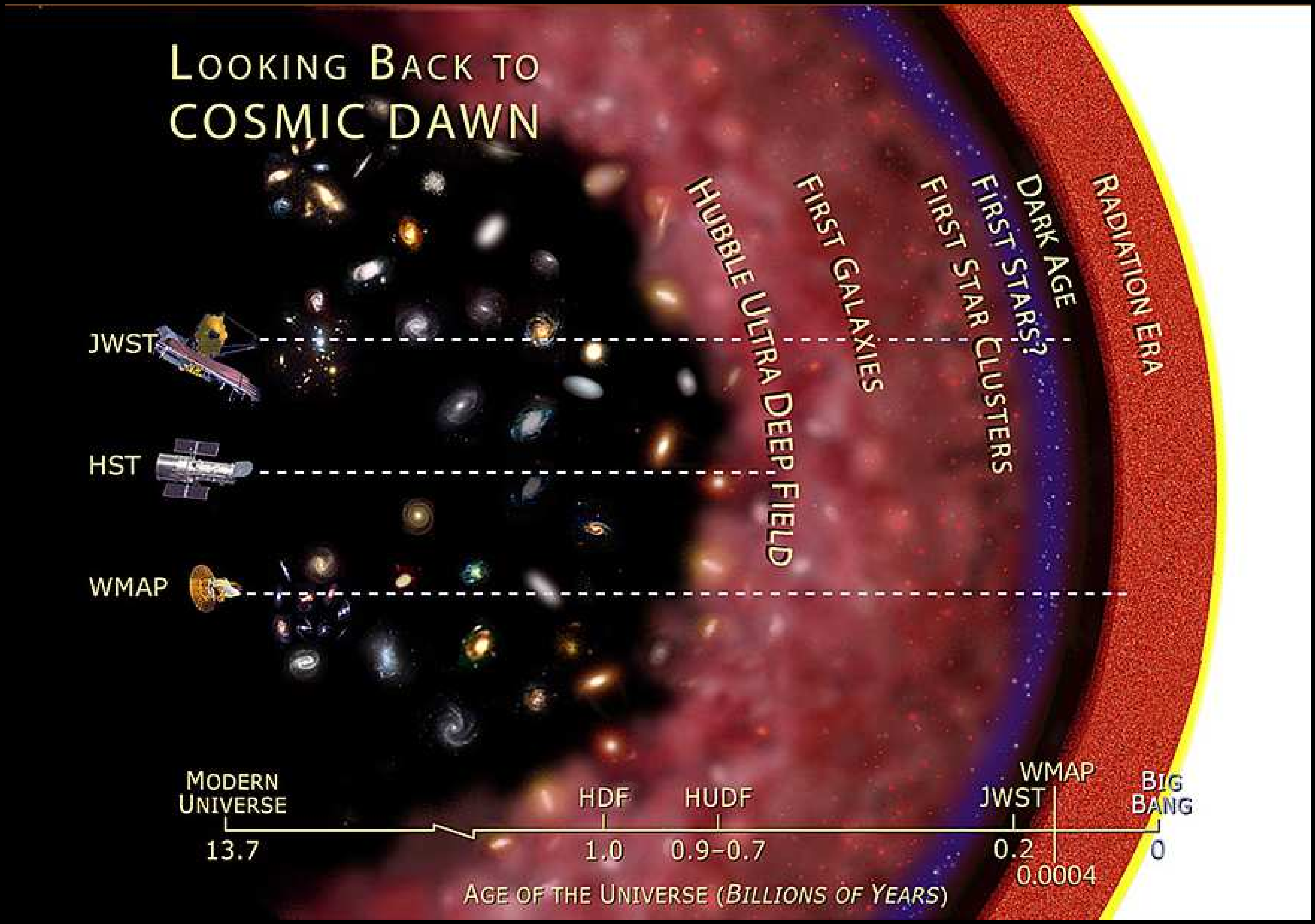


Notice people for scale

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?

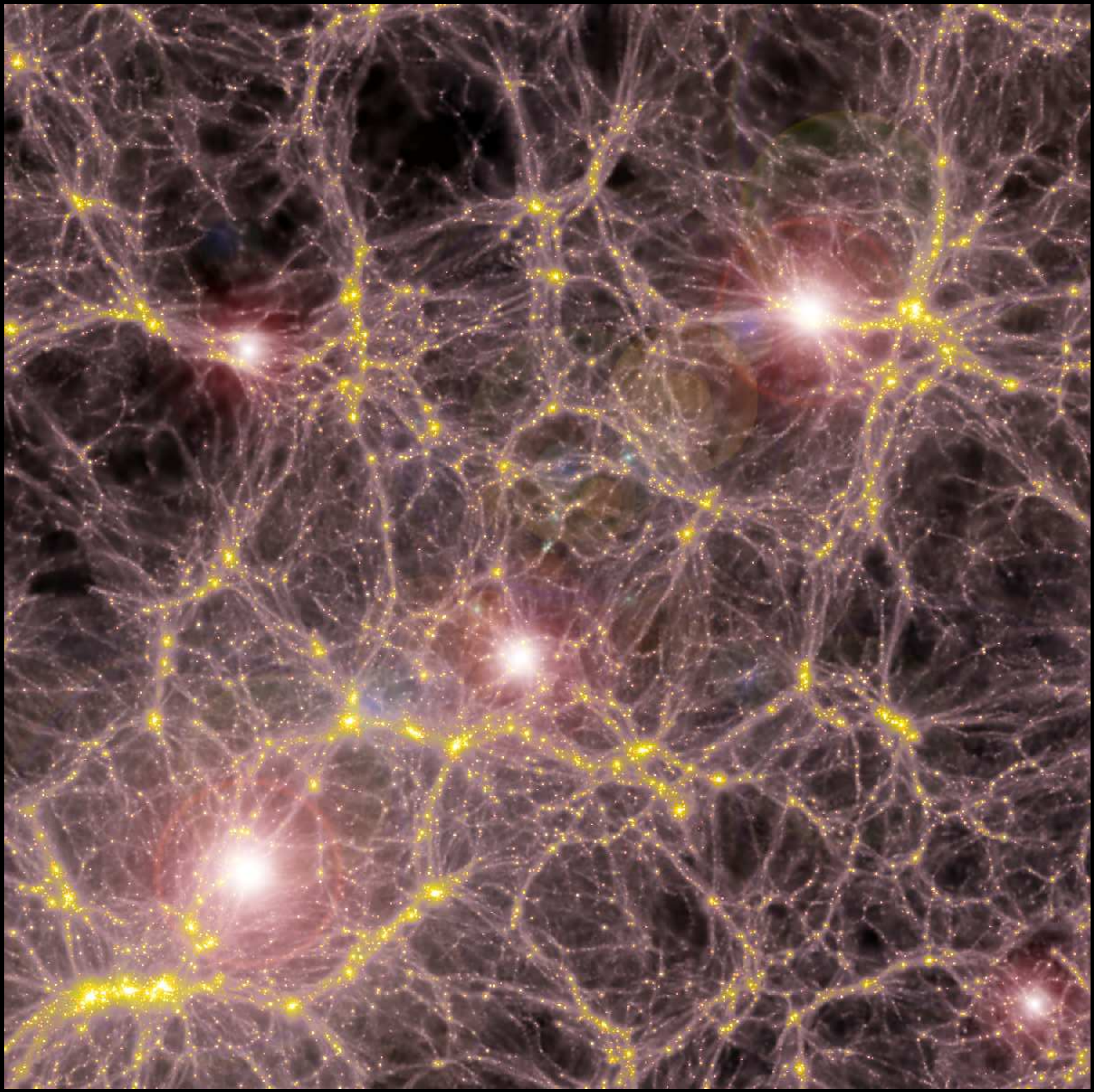


HST: Hubble sequence & galaxy evolution at $z \lesssim 7$–8 (age$\gtrsim$0.7 Gyr).

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).

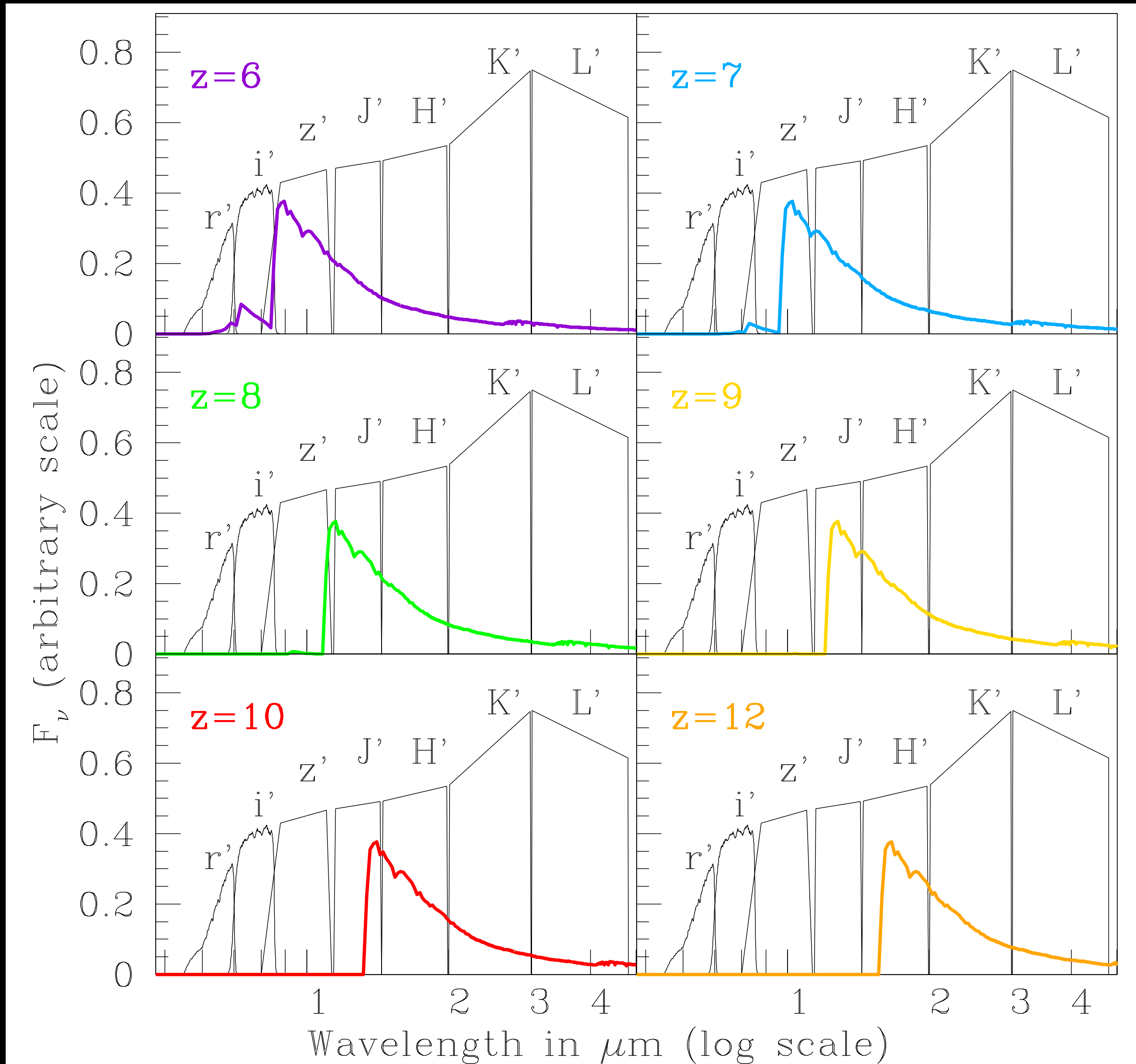
(4a) How will JWST Observe First Light and Reionization?



- 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).

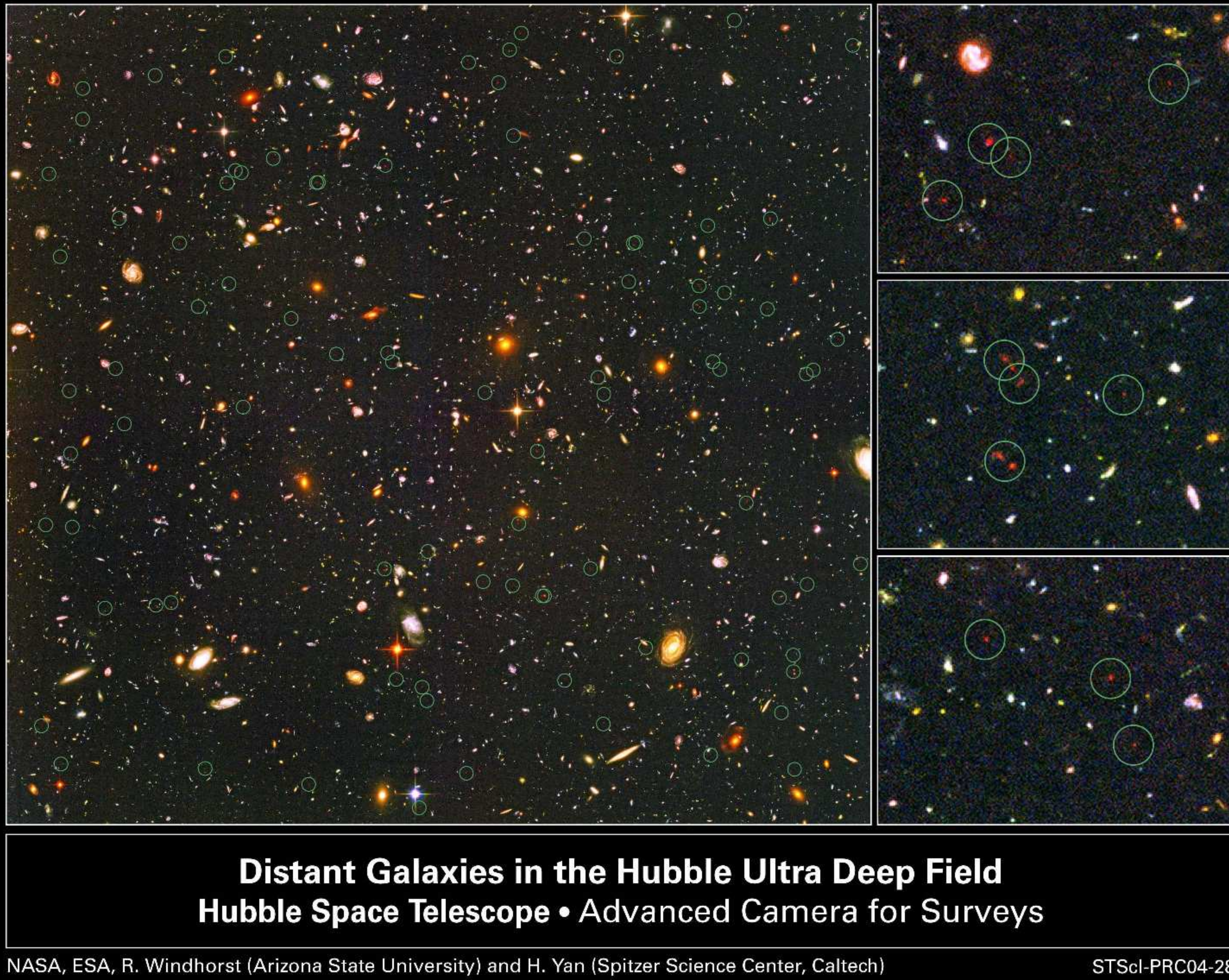
- This should be visible to JWST as the first massive stars and surrounding star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \longrightarrow 30$.

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

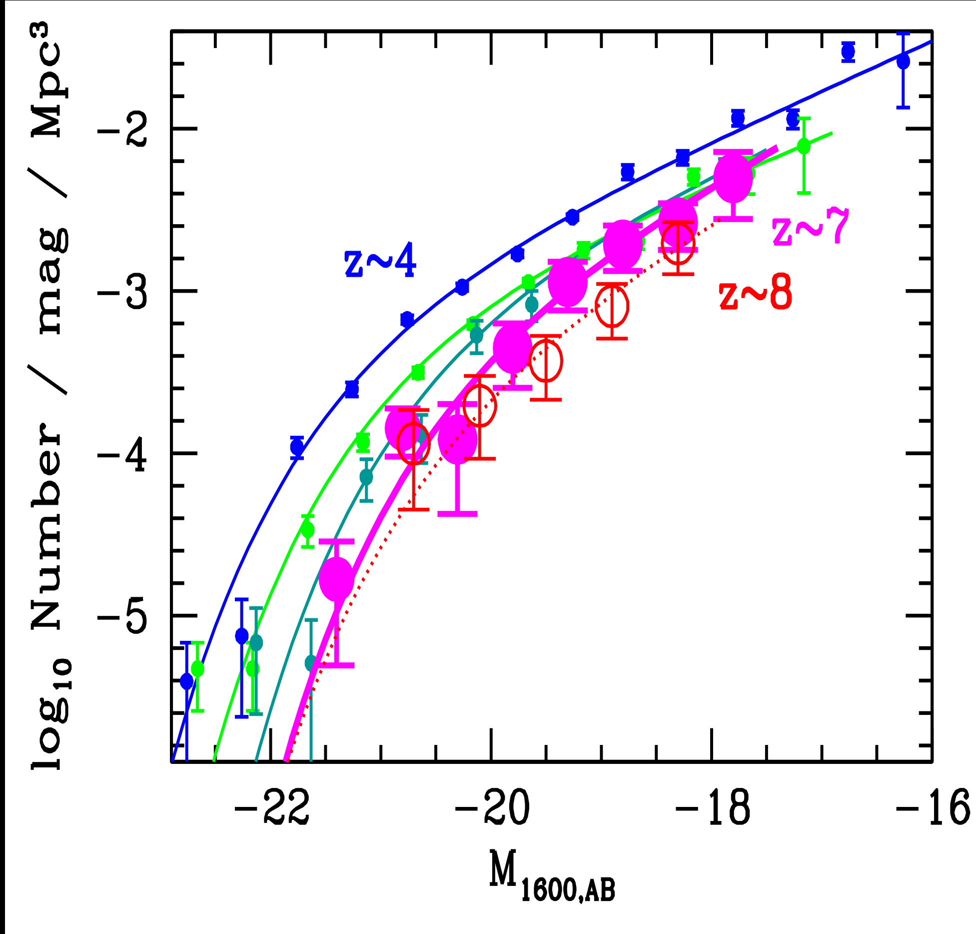


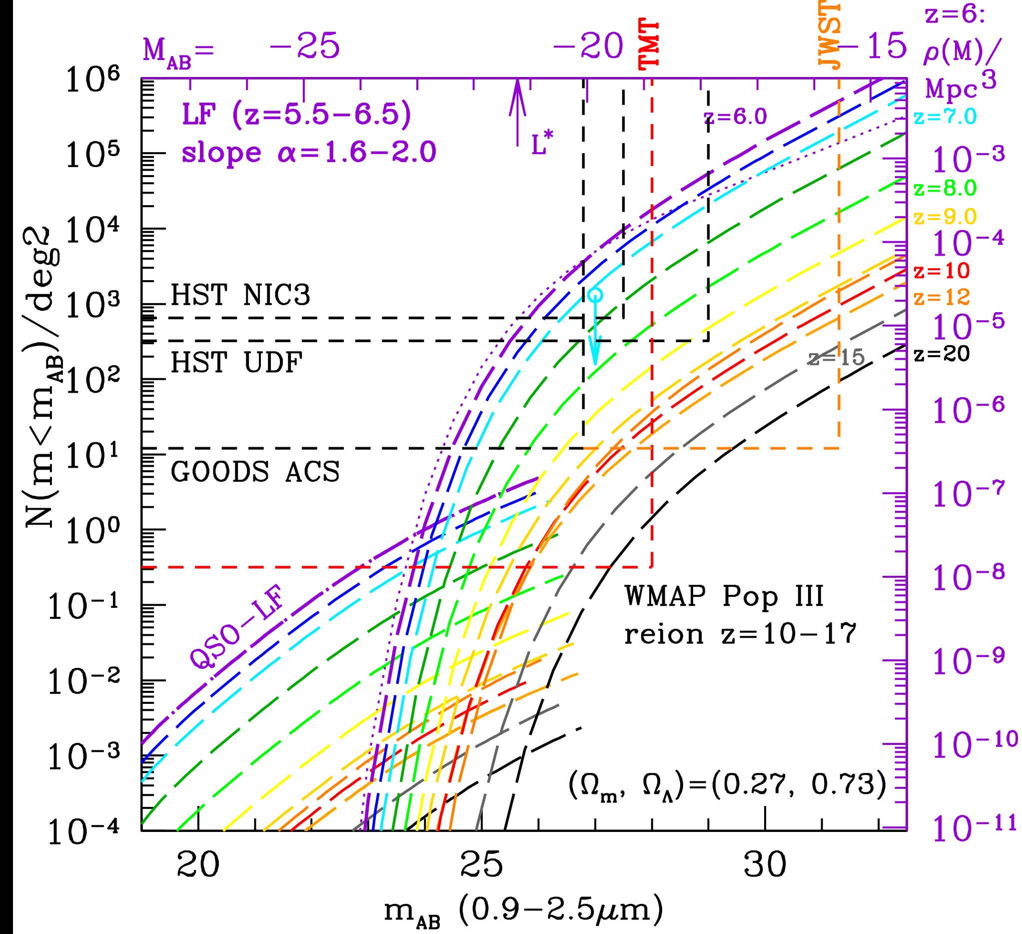
- Can't beat redshift: to see First Light, must observe near–mid IR.

⇒ 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).

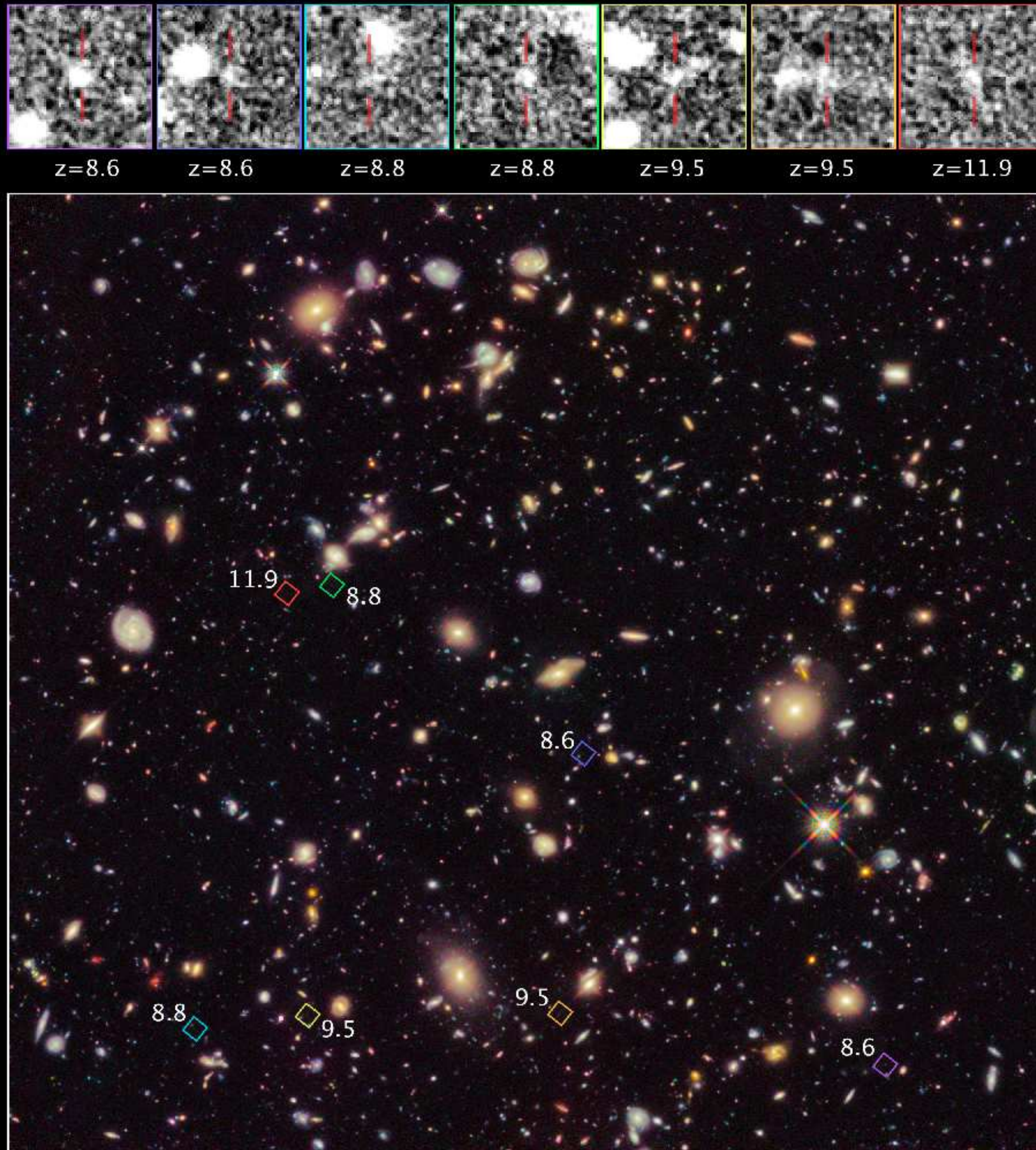




The "Cosmic Stock Market chart of galaxies: Very few big bright objects in the first Gyr, but lots of dwarf galaxies at $z \gtrsim 6$ (age$\lesssim$1 Gyr).

- 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!



Hubble Ultra Deep Field 2012

Hubble Space Telescope WFC3/IR

NASA and ESA

STScI-PRC12-48a

(4) 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.
- Most $z \simeq 6$ QSO host galaxies faint (dusty?), with 1 exception: $L >> L^*$.

(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.
- How to find water and CO_2 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

- 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/

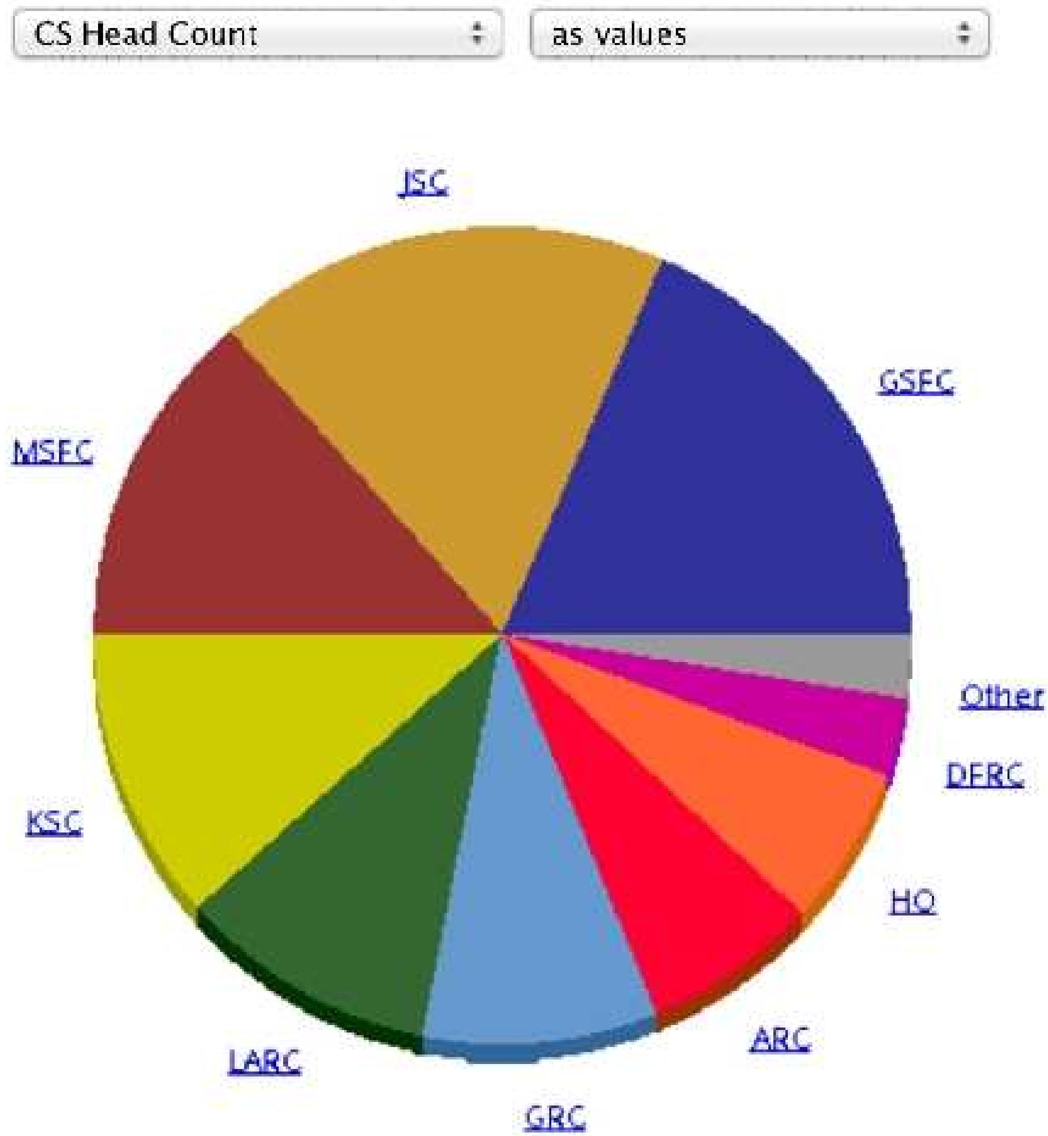
http://www.stsci.edu/jwst/instruments/fgs

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)



	Centers & NSSC	CS Head Count
	GSFC	3,354
	JSC	3,203
	MSFC	2,432
	KSC	2,055
	LARC	1,881
	GRC	1,640
	ARC	1,215
	HQ	1,152
	DFRC	558
	Other	454

NASA workforce as pie-chart and in numbers — 2013 total: about 18,000).

Nation-wide NASA contractors (Northrup, Lockheed, Boeing, etc): 150,000.

See also: `https://wicn.nssc.nasa.gov/generic.html`

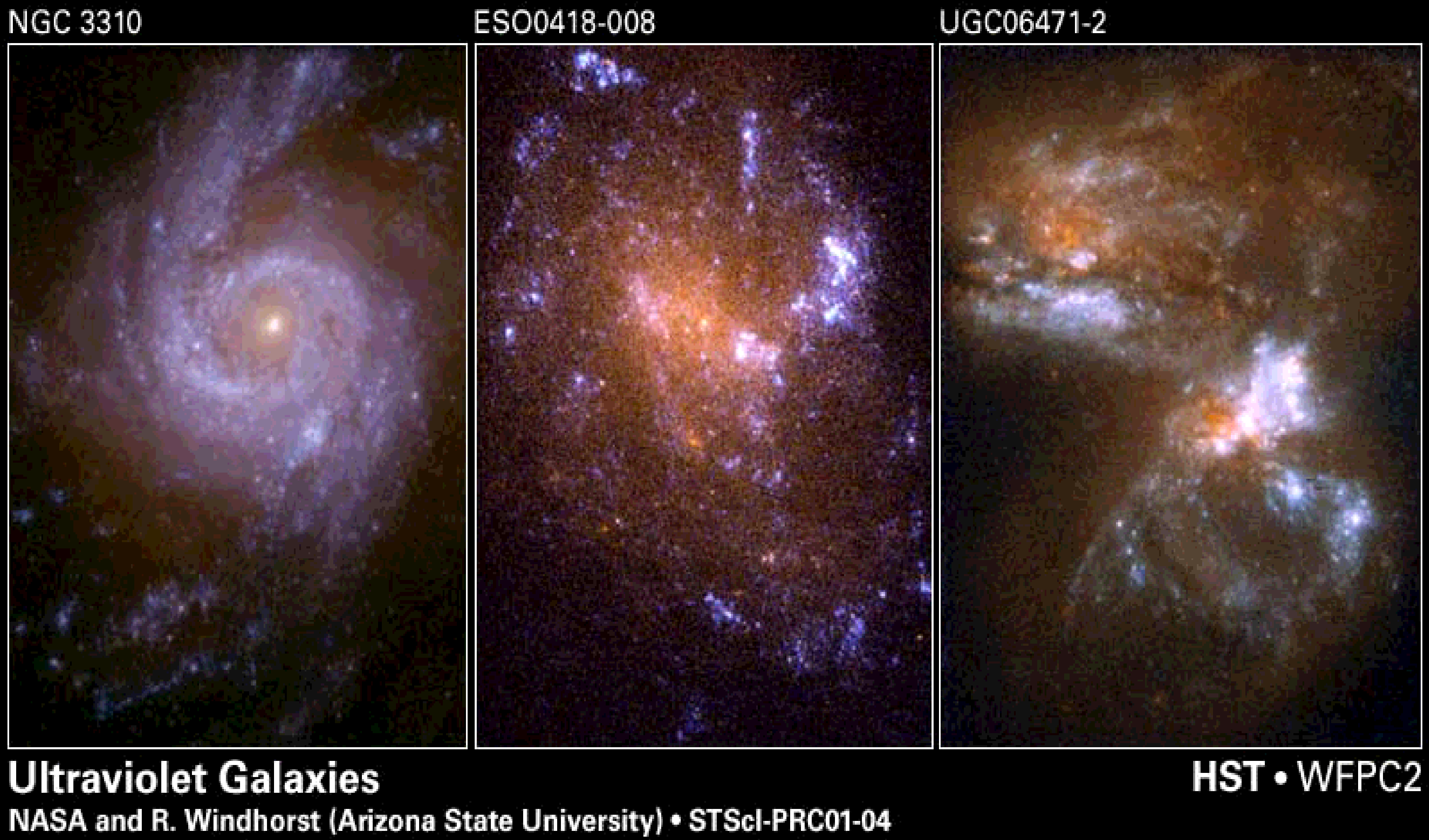
Future Careers at NASA:
What do our Astrophysics College Graduates do?

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

See: `http://aas.org/learn/careers-astronomy`

and: `http://www.aip.org/statistics/`

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

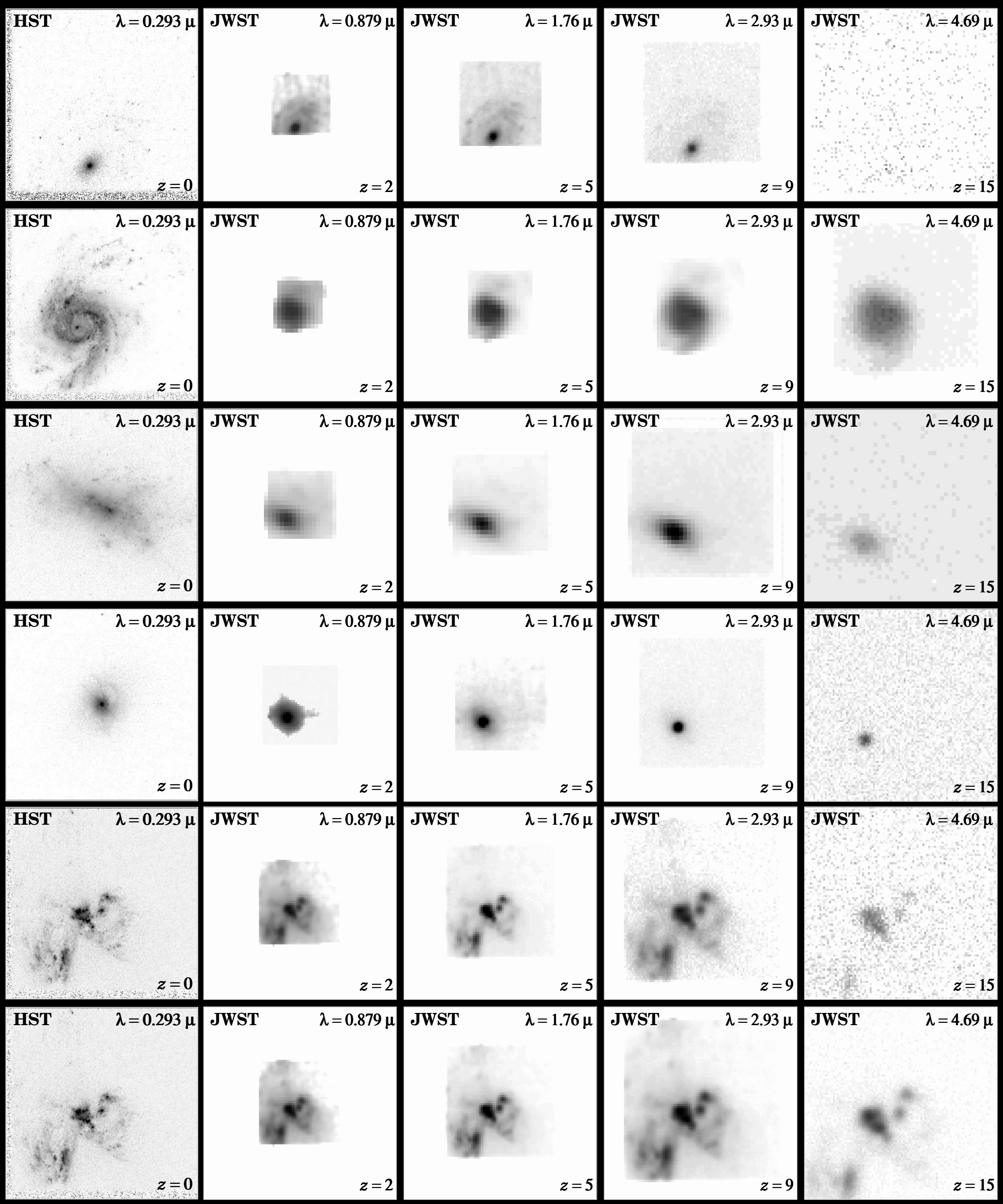


- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

- 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



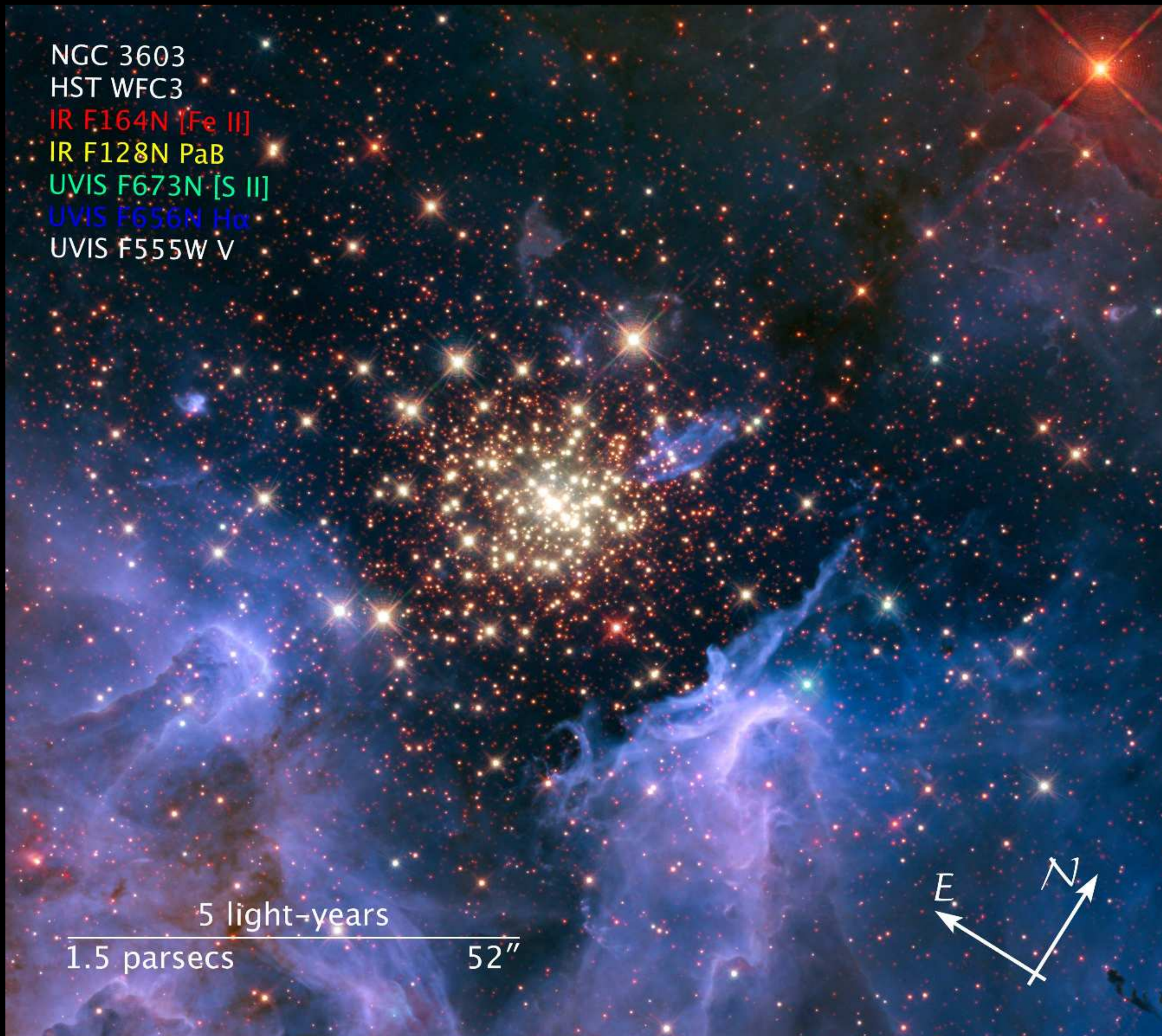
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

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

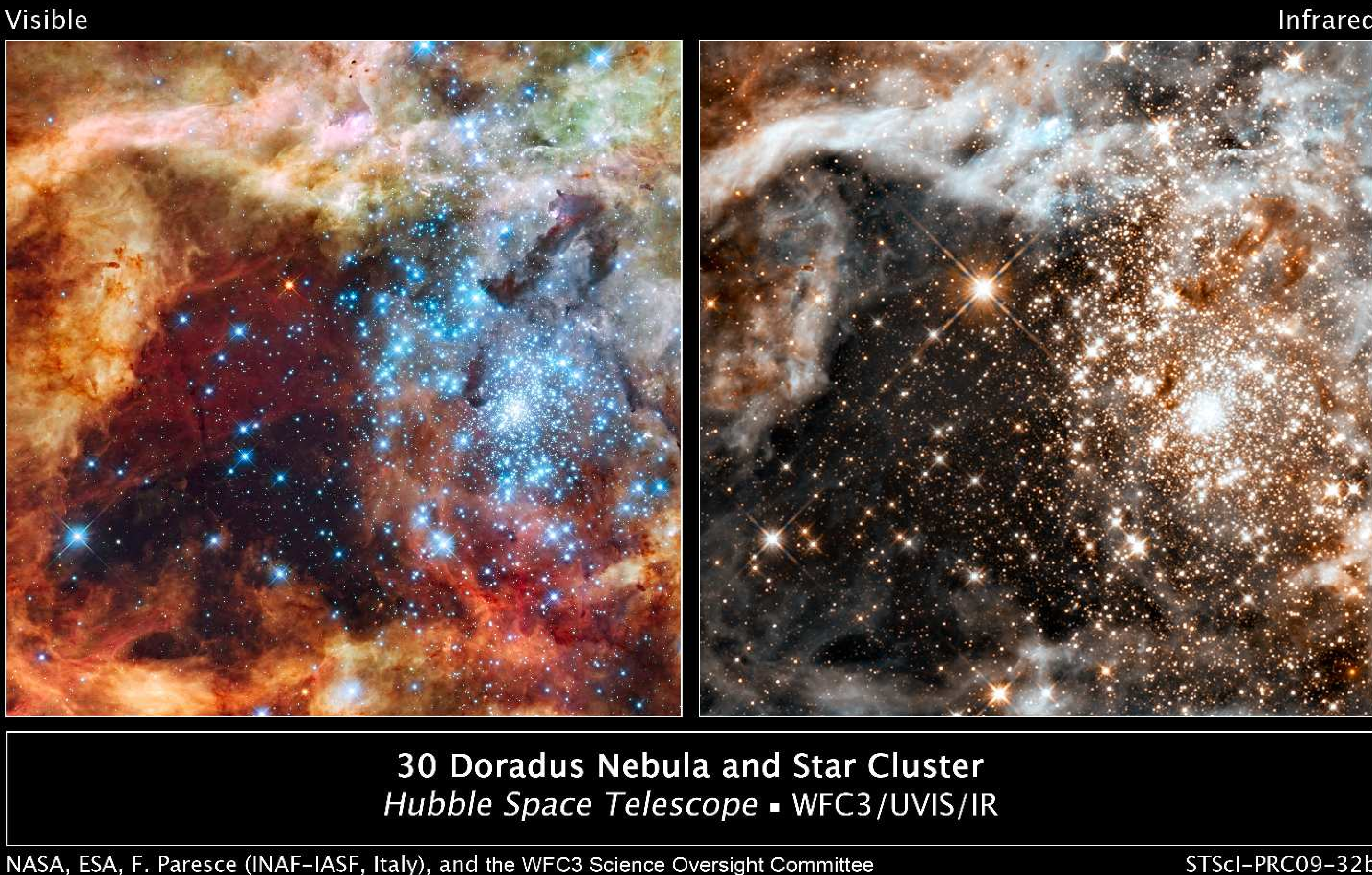
Visible to JWST at very high z are:

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

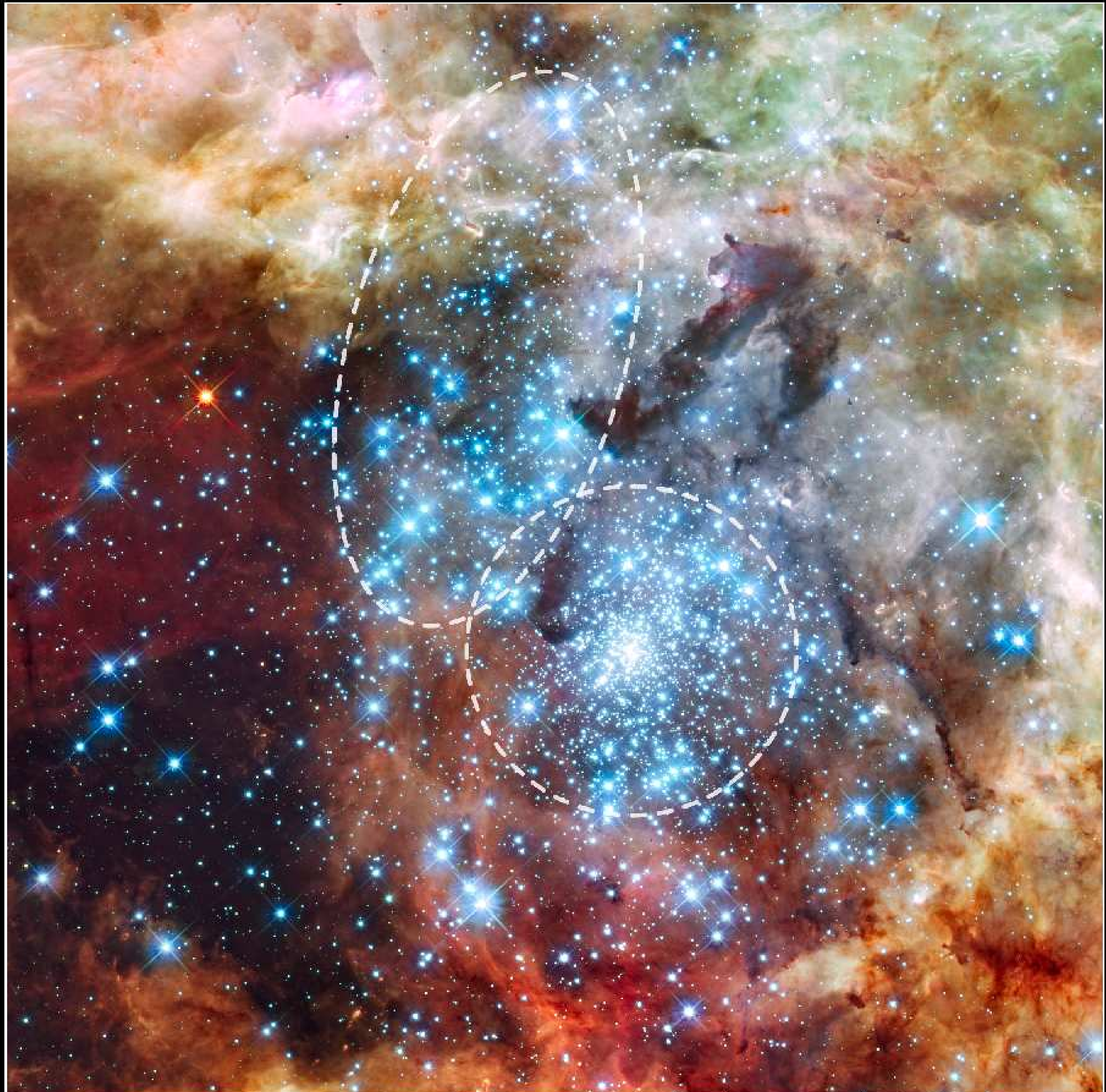
(6) How can JWST measure Star-birth and Earth-like exoplanets?



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).

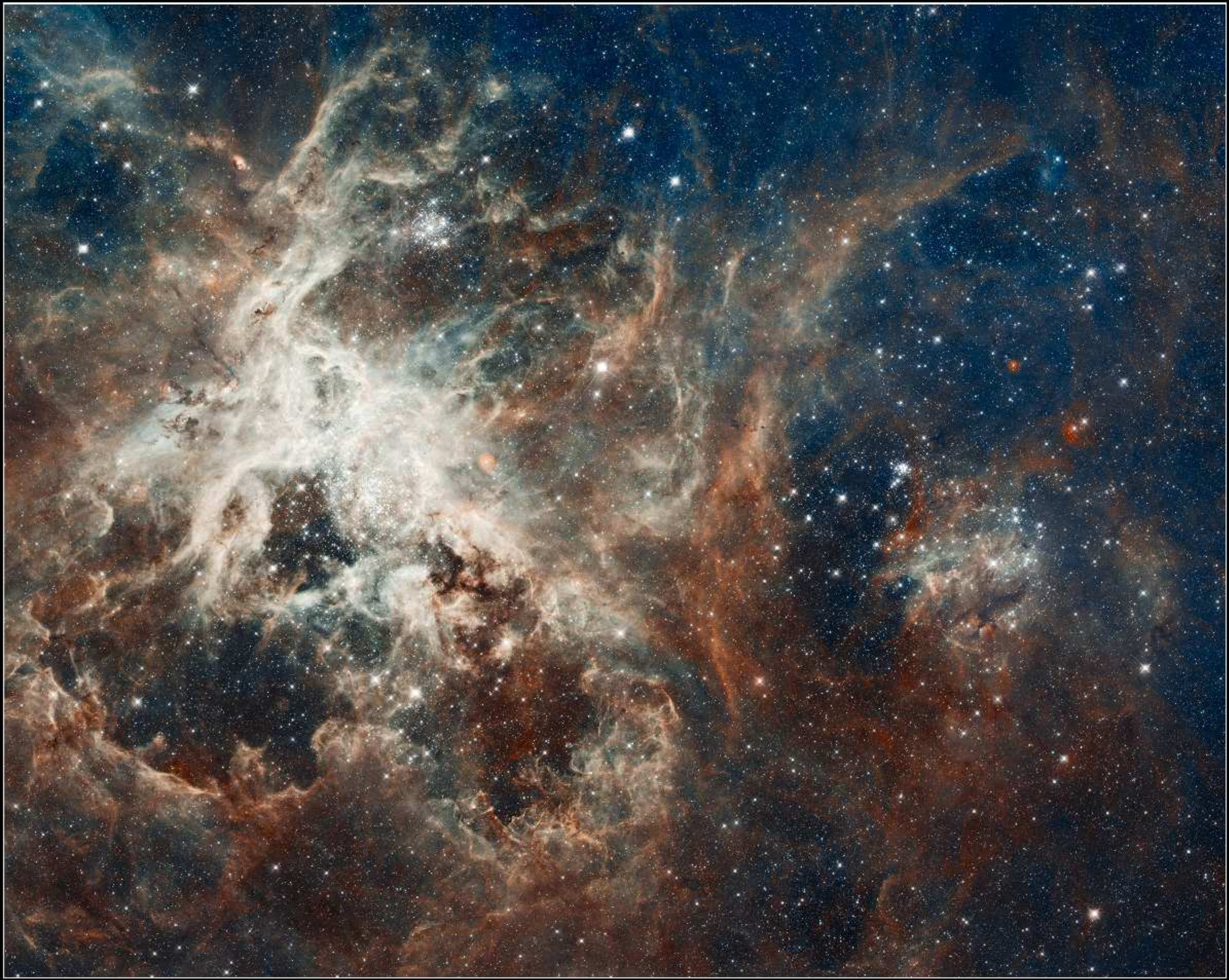


Merging Clusters in 30 Doradus

Hubble Space Telescope ▪ WFC3/UVIS

NASA, ESA, and E. Sabbi (ESA/STScI) STScI-PRC12-35a

Acknowledgment: R. O'Connell (University of Virginia)



Tarantula Nebula • 30 Doradus

HST WFC3/UVIS ACS/WFC • ESO 2.2m

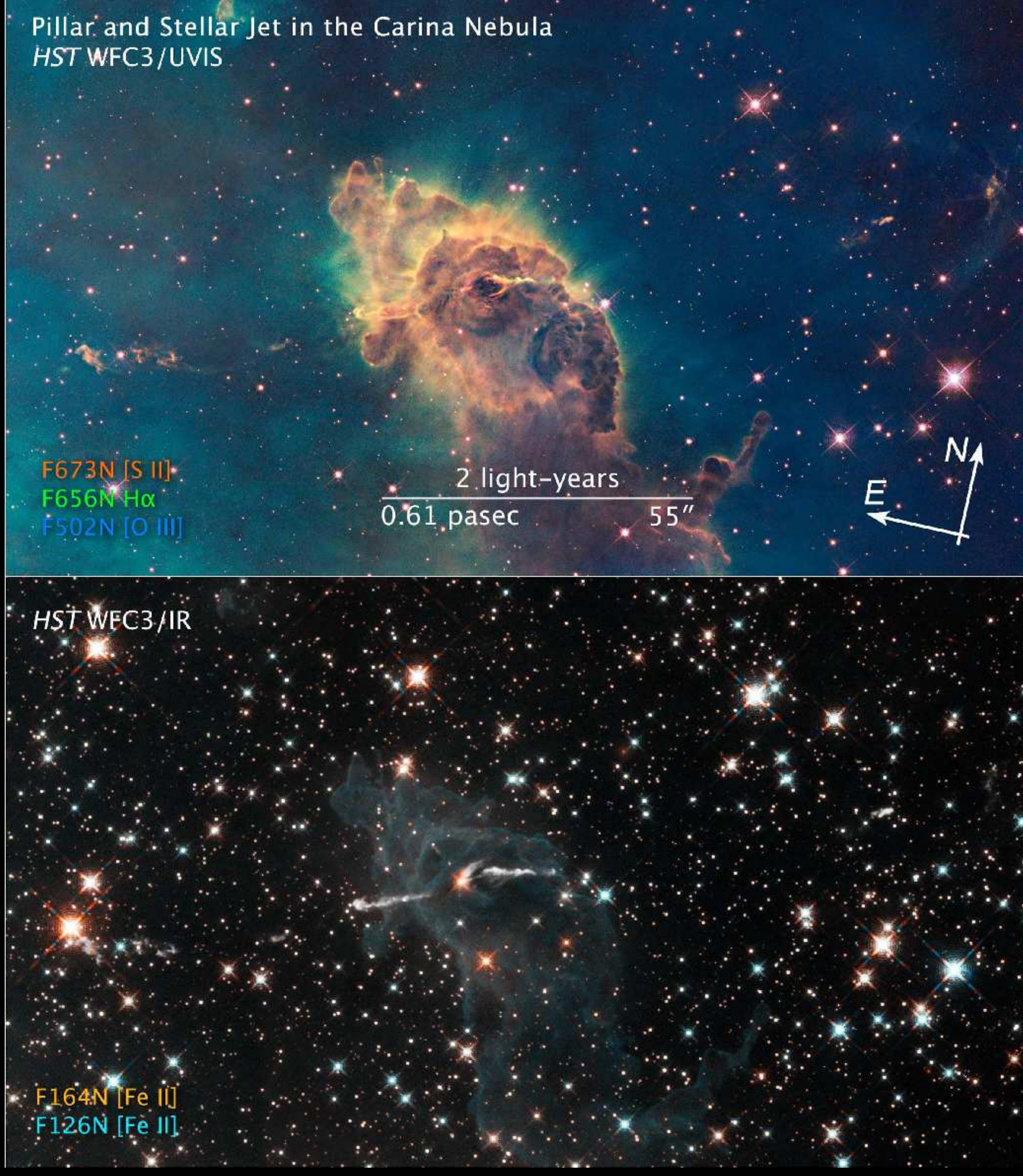
NASA, ESA, and D. Lennon (ESA/STScI)

STScI-PRC12-01a

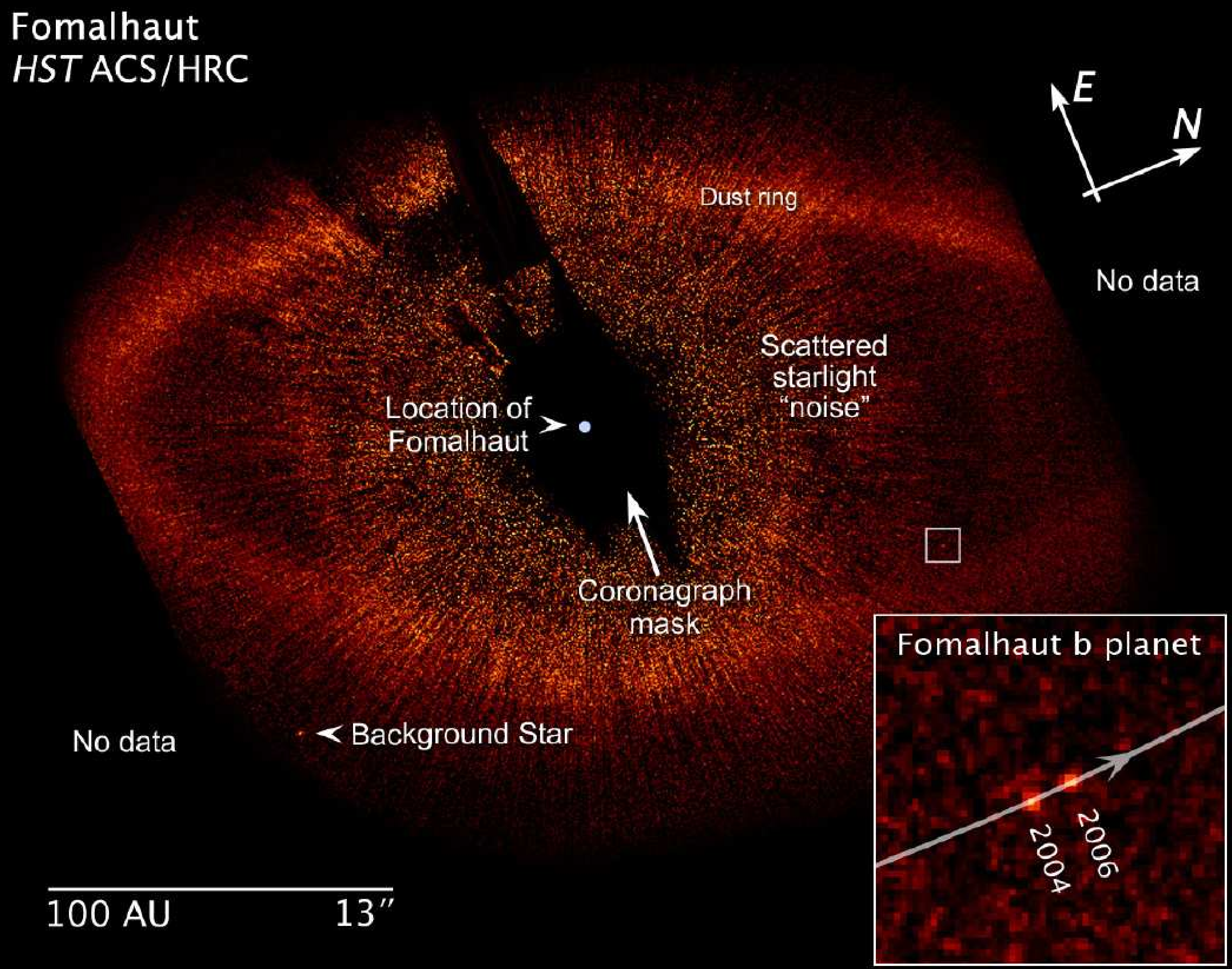
Star-Forming Region S106

Hubble Heritage

NASA, ESA, and the Hubble Heritage Team (STScI/AURA) • *HST* WFC3/UVIS • STScI-PRC11-38

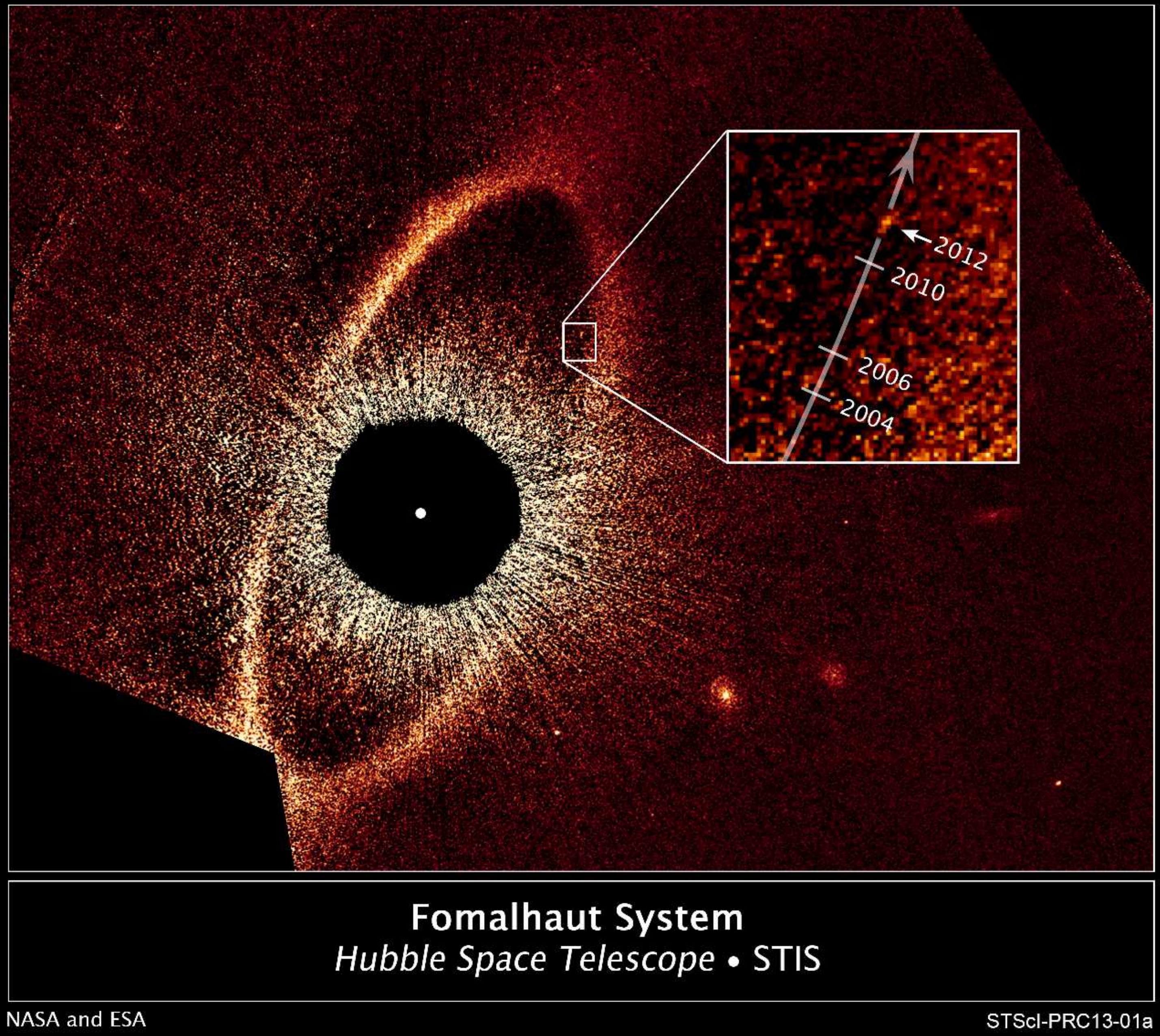


Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS
F673N [S II]
F656N Hα
F502N [O III]
2 light-years
0.61 pasec
55″
N
E
HST WFC3/IR
F164N [Fe II]
F126N [Fe II]



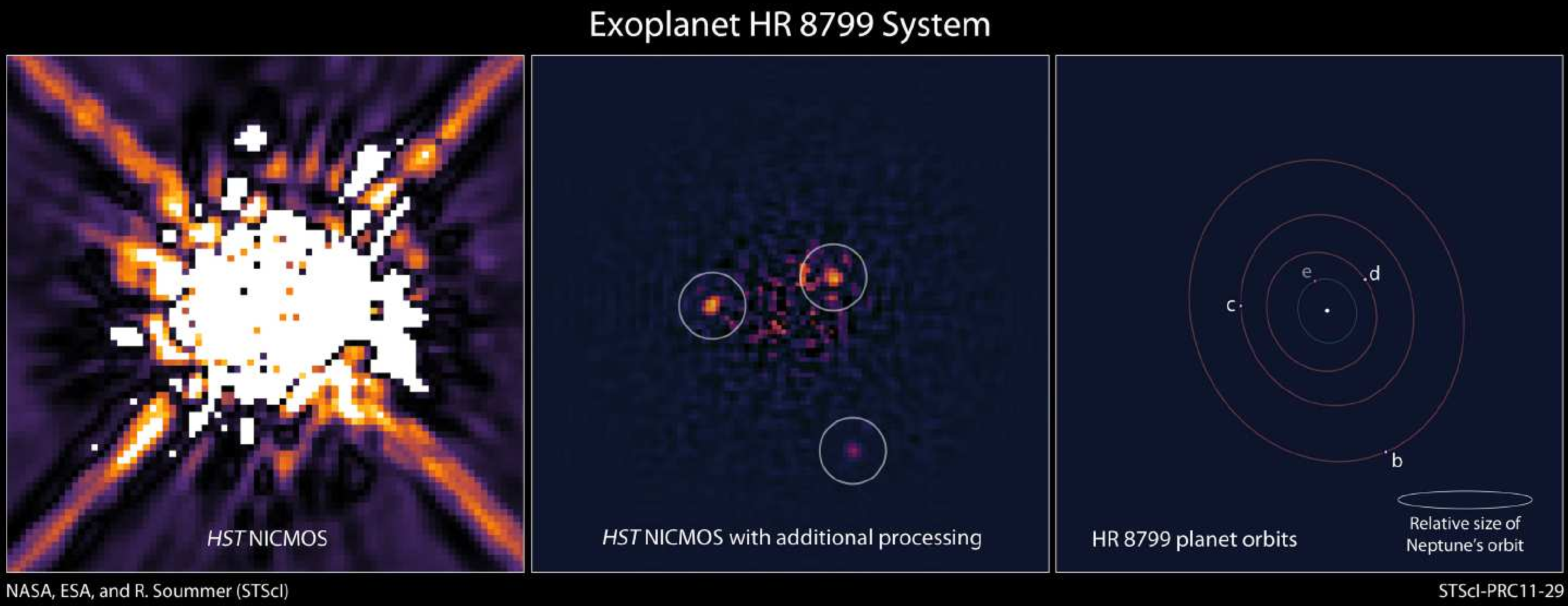
HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut: First direct imaging of a moving planet forming around a nearby star!

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



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

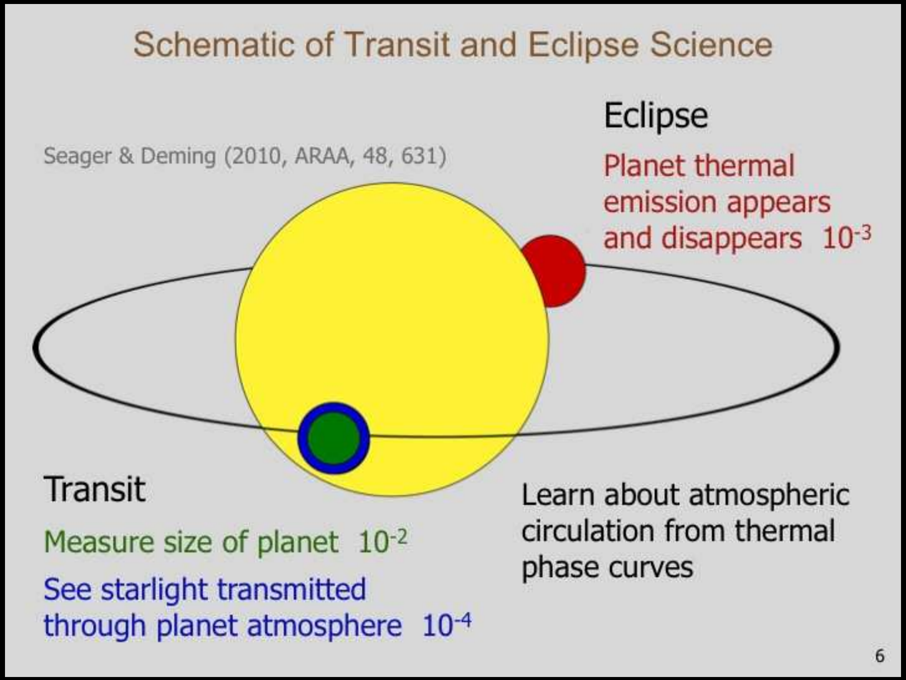
JWST can find such planets much closer in for much farther stars.

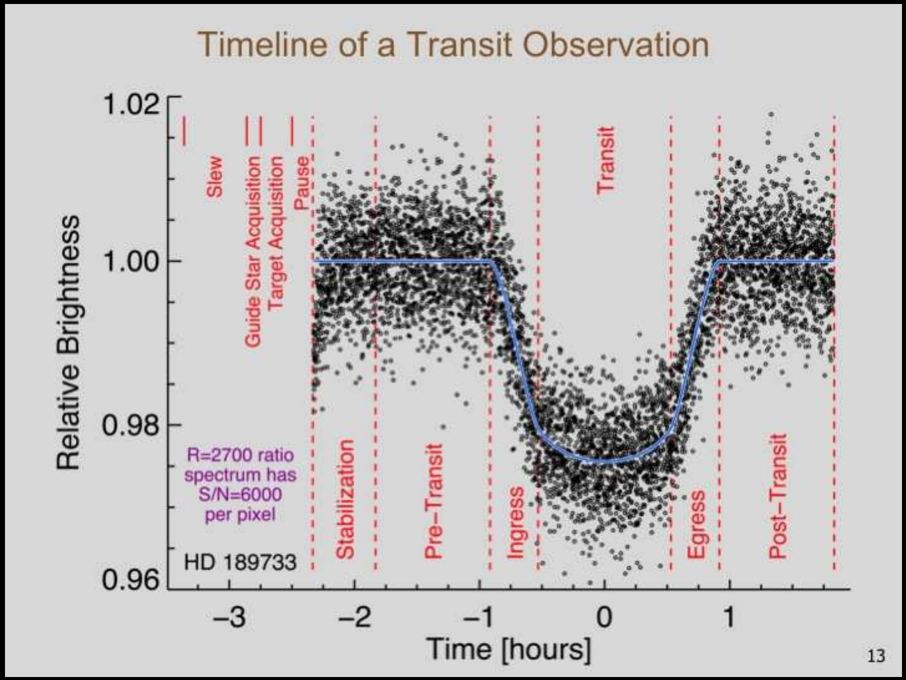


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star!

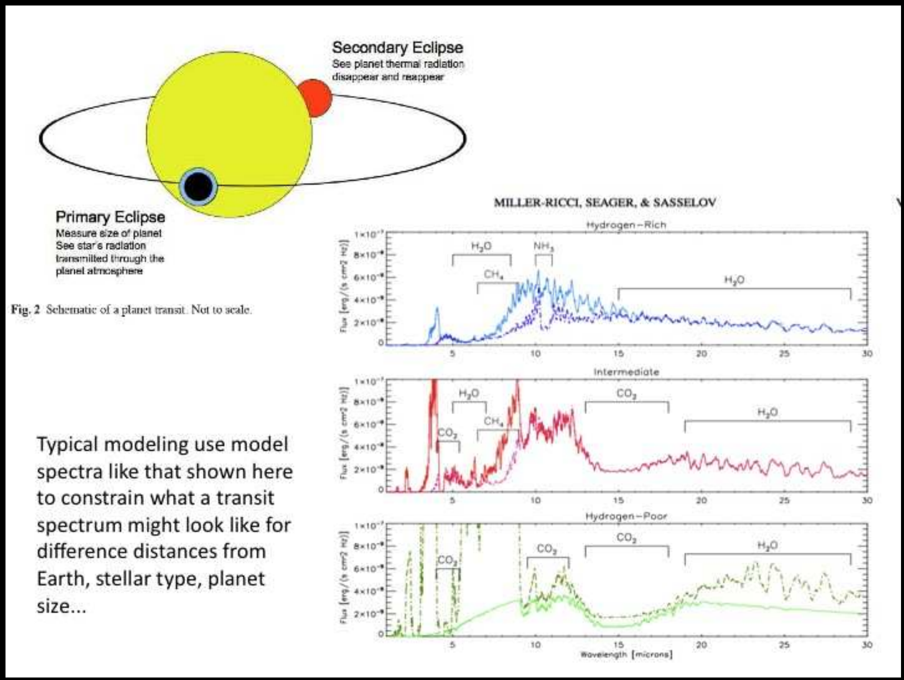
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



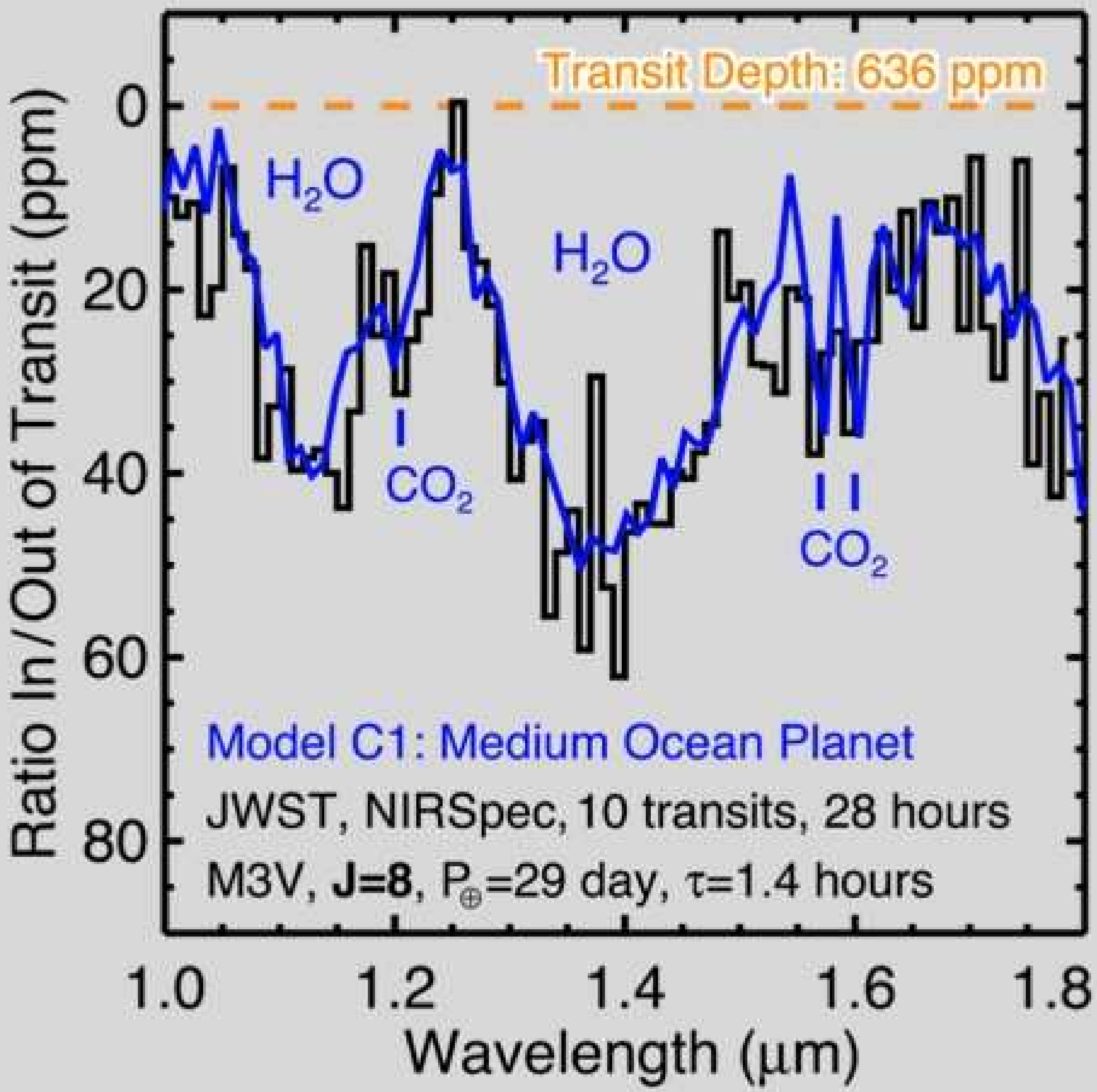


JWST can do very precise photometry of transiting Earth-like exoplanets.



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

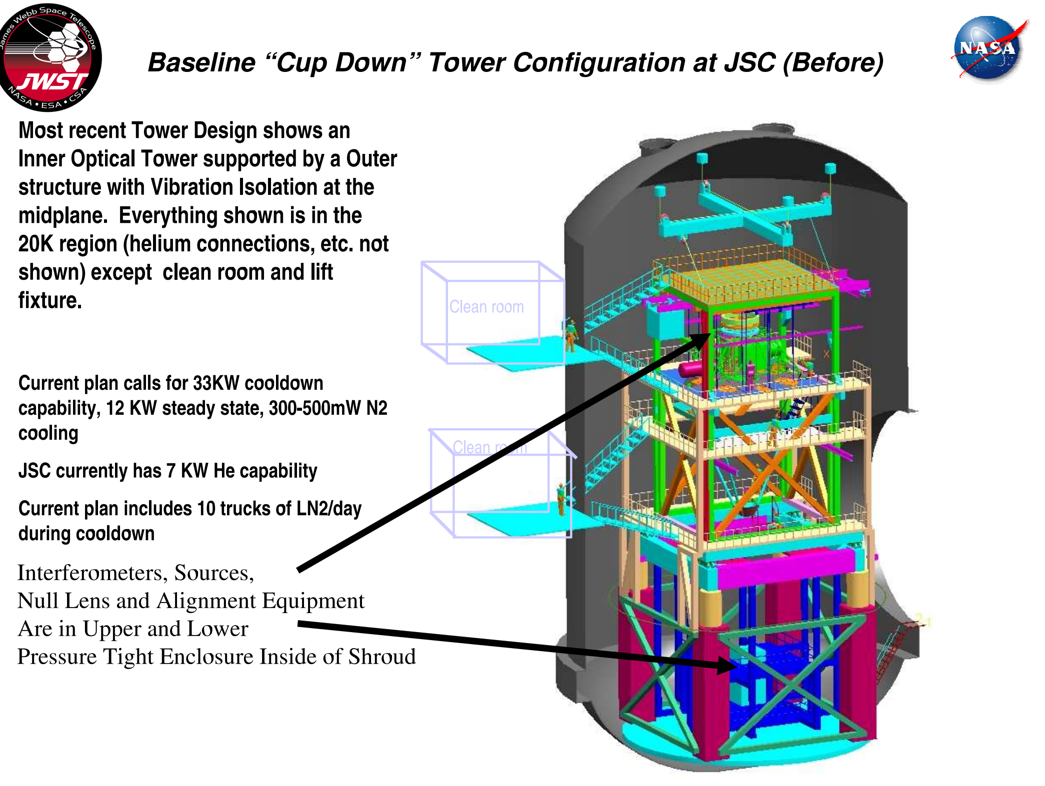
Transit Spectrum of Habitable "Ocean Planet"

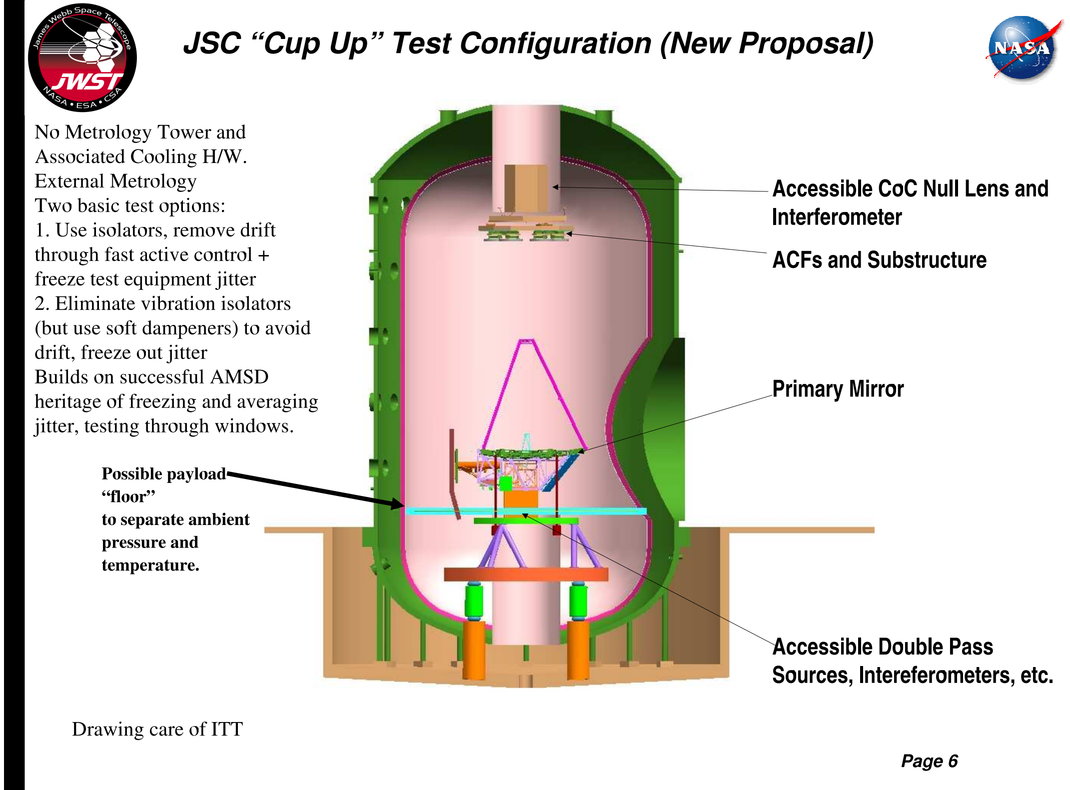


JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.

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

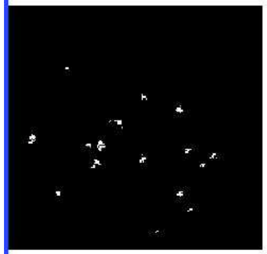
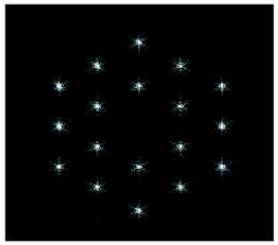
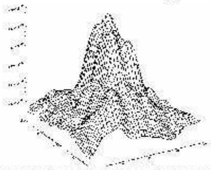
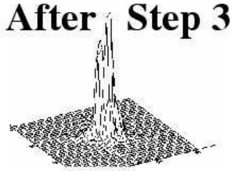
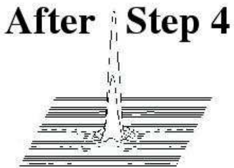




JWST underwent several significant replans and risk-reduction schemes:

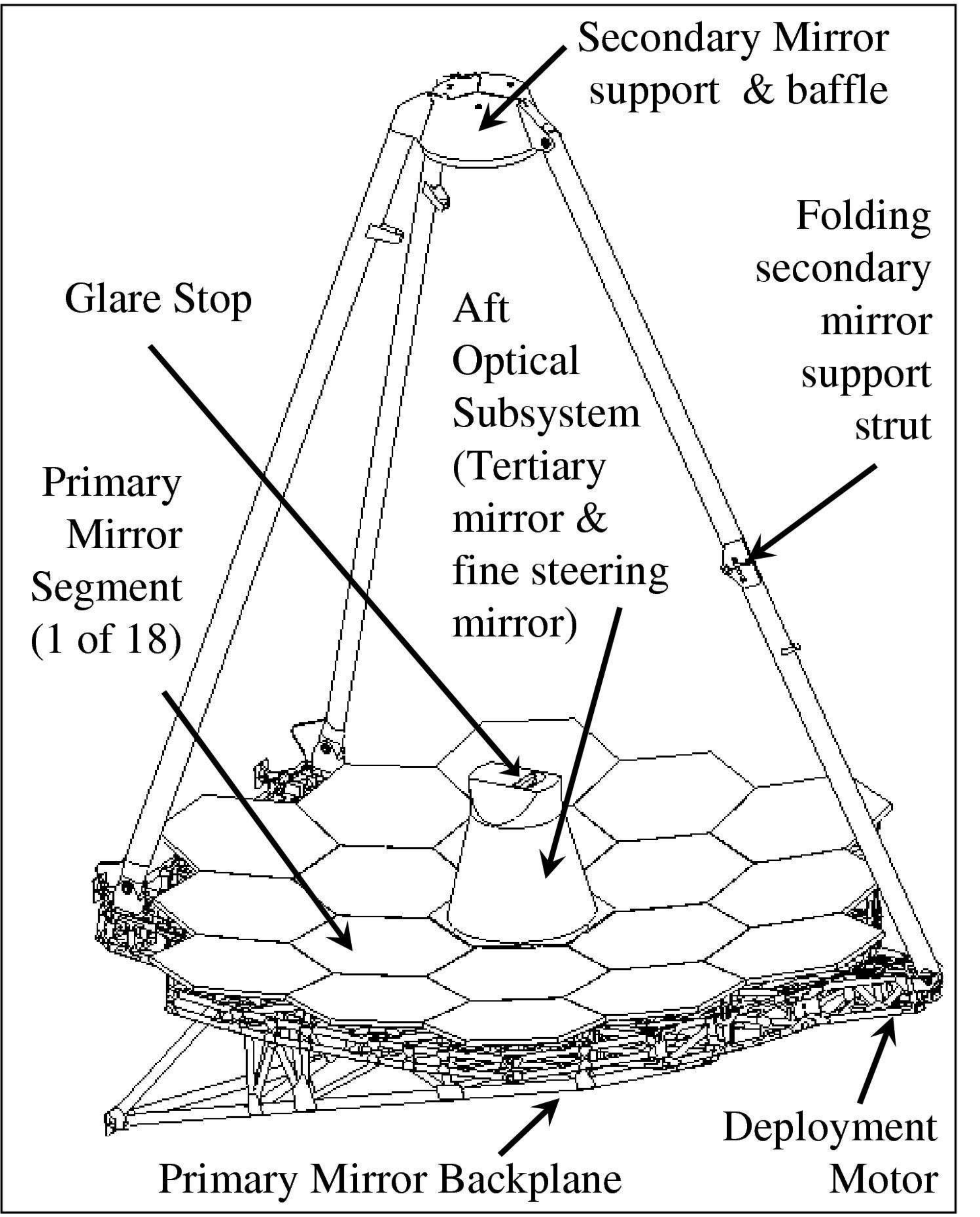
- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: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

- 2010, 2011: Passes Mission Critical Design Review — Replan Int. & Testing.

First light NIRCam / Step	After Step	Initial Capture	Final Condition
 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.

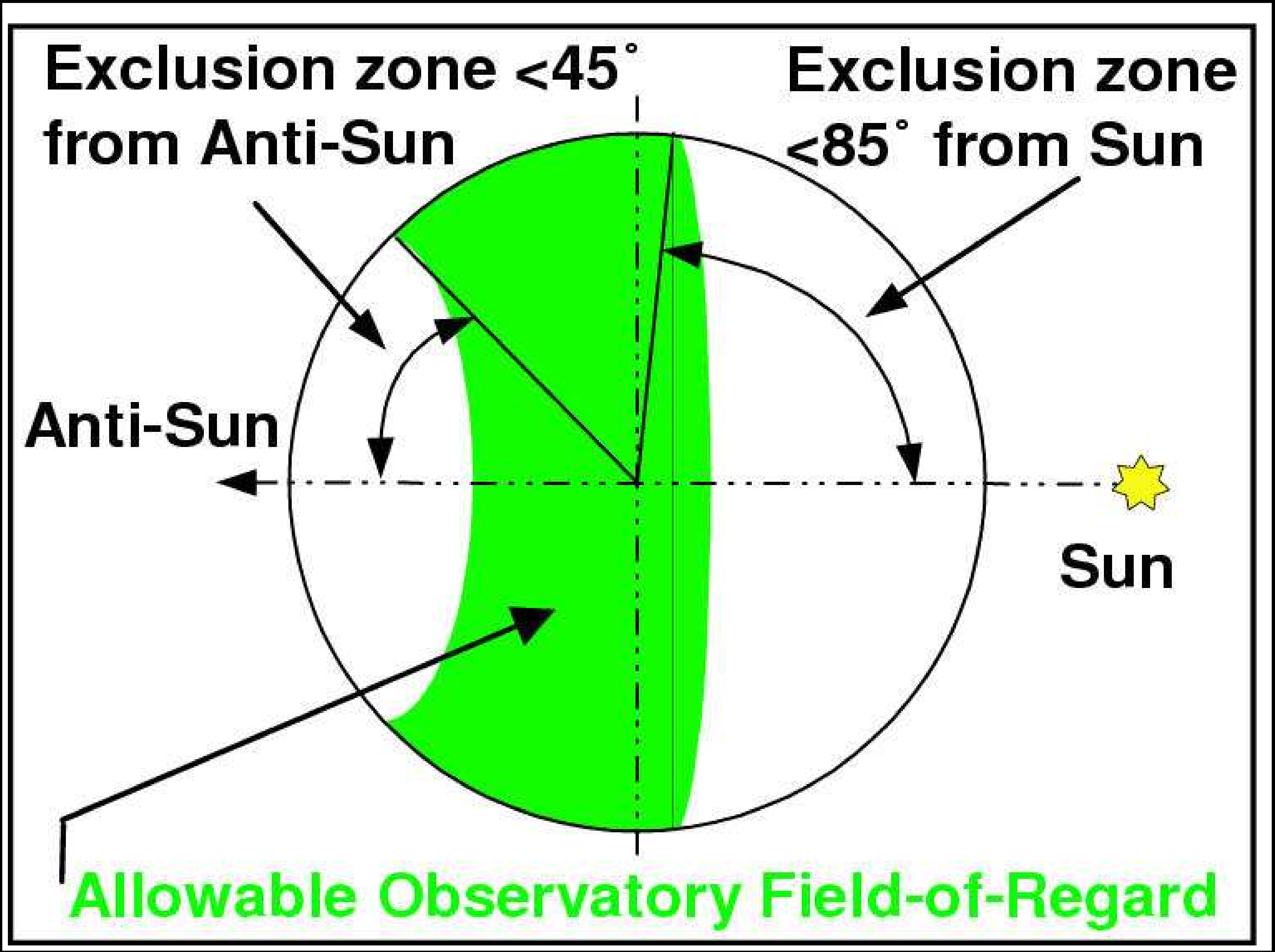


Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015-2016.

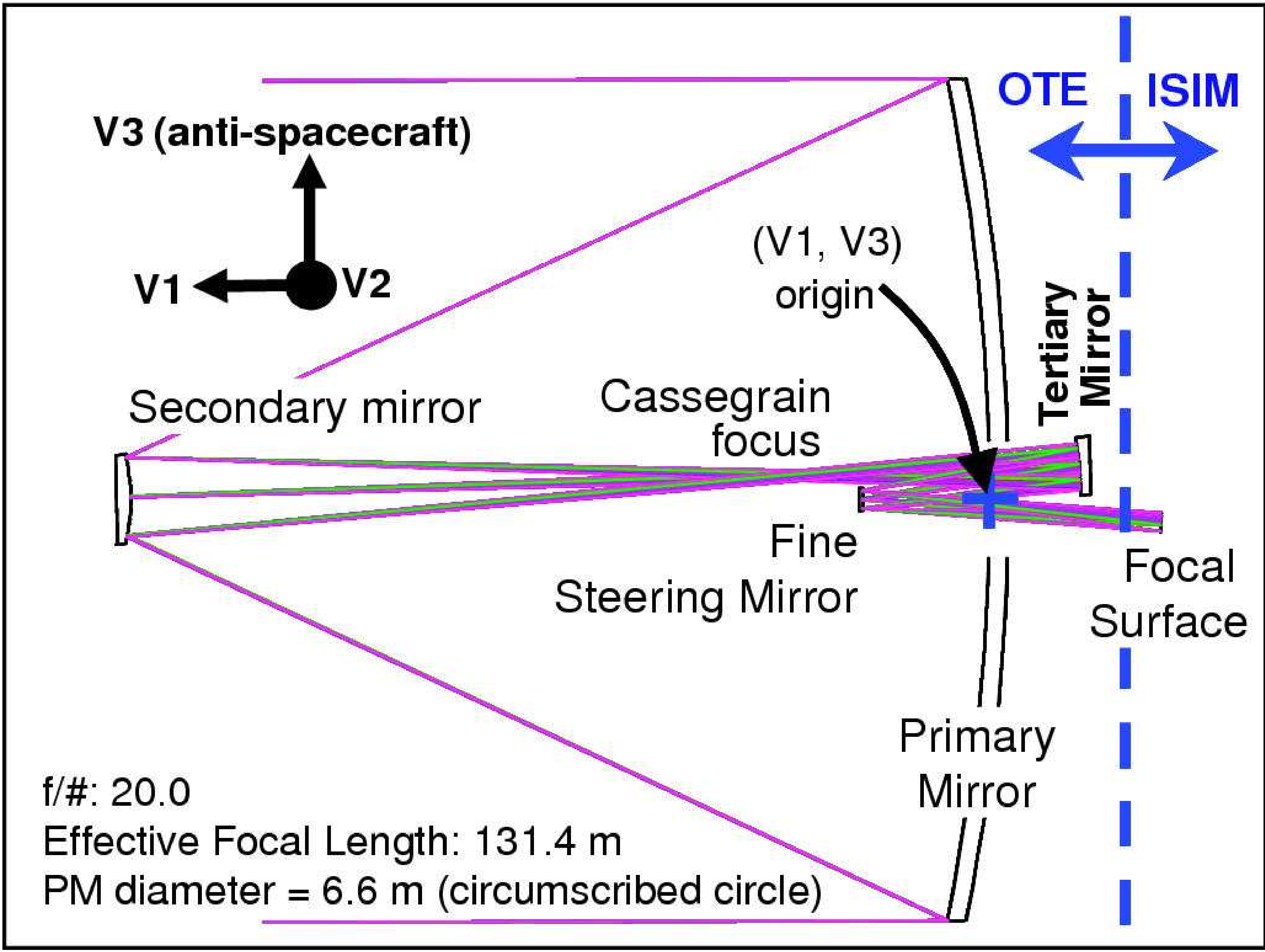
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.

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

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



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:

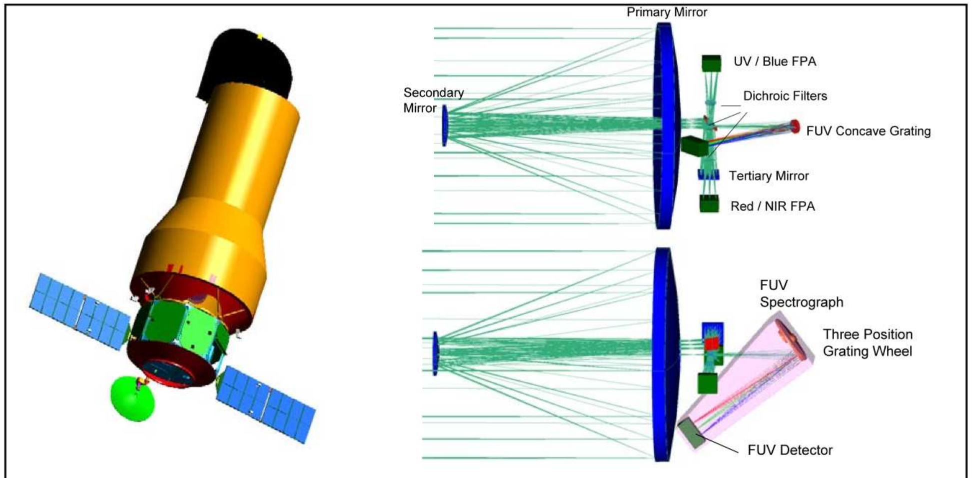
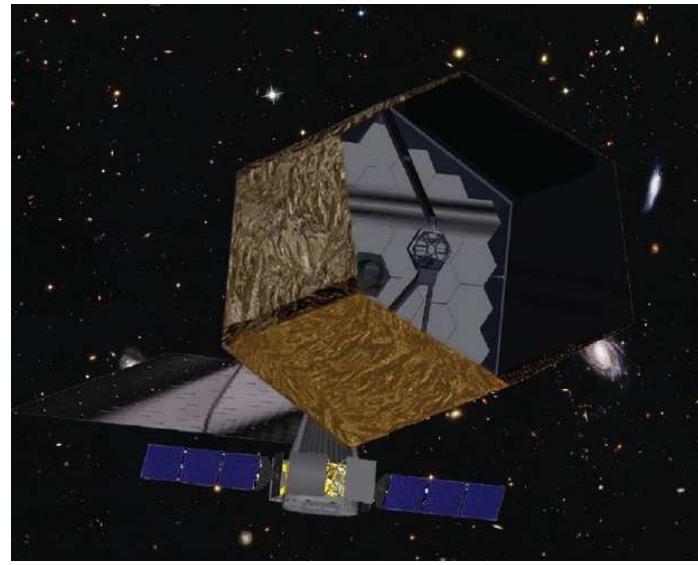


Figure 2.5.3 - *HORUS* Observatory and Optical Ray Trace



[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$29-30 mag, and high sensitivity (on-axis) UV-spectroscopy.

[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].