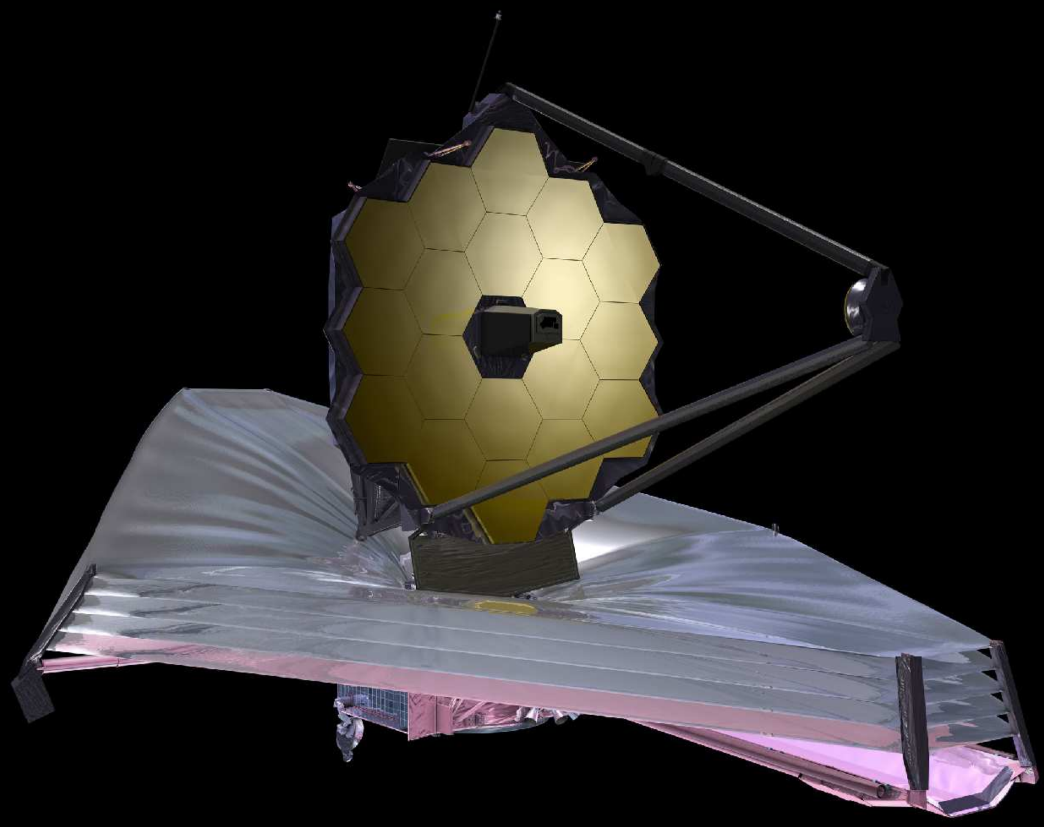
How will the Webb Space Telescope measure First Light Reionization, & Galaxy Assembly in the post Hubble era?

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 ASU Open House, ASU, Tempe, AZ, March 30, 2012

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

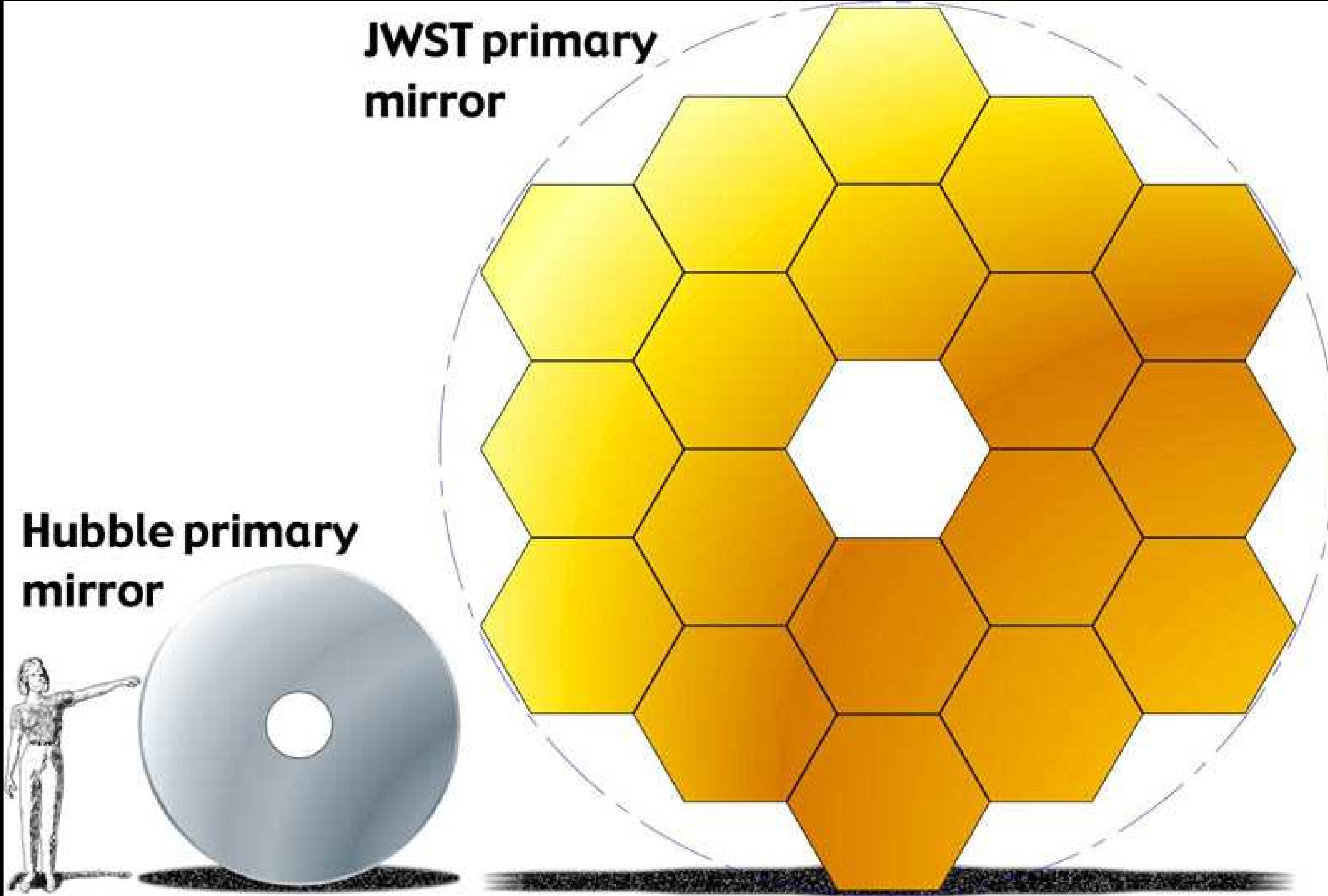
ASU Arizona State University

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

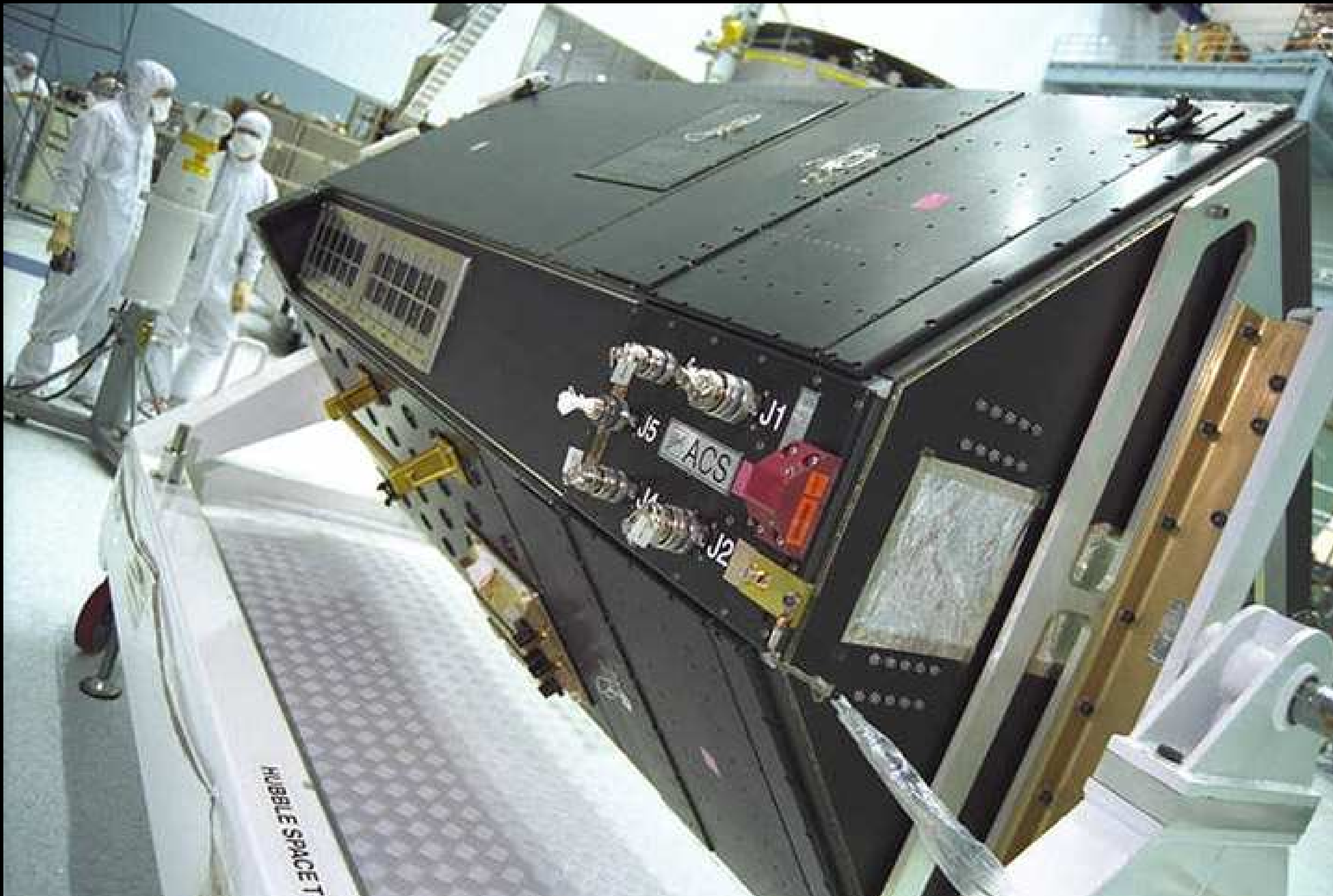
JWST: The infrared sequel to Hubble from 2018–2023 (–2029?)



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

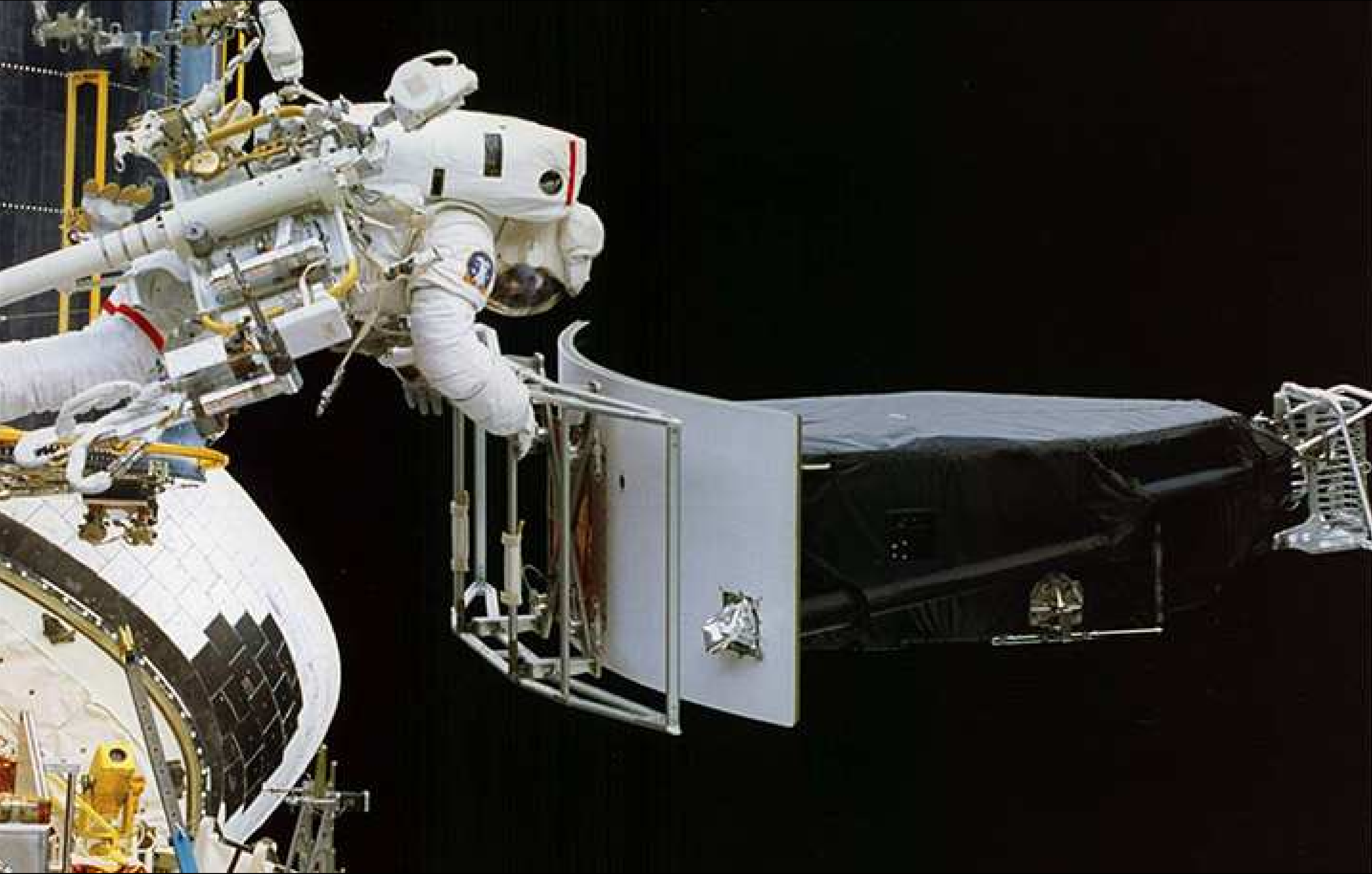
JWST has the same resolution in the near-IR as Hubble in the optical.

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



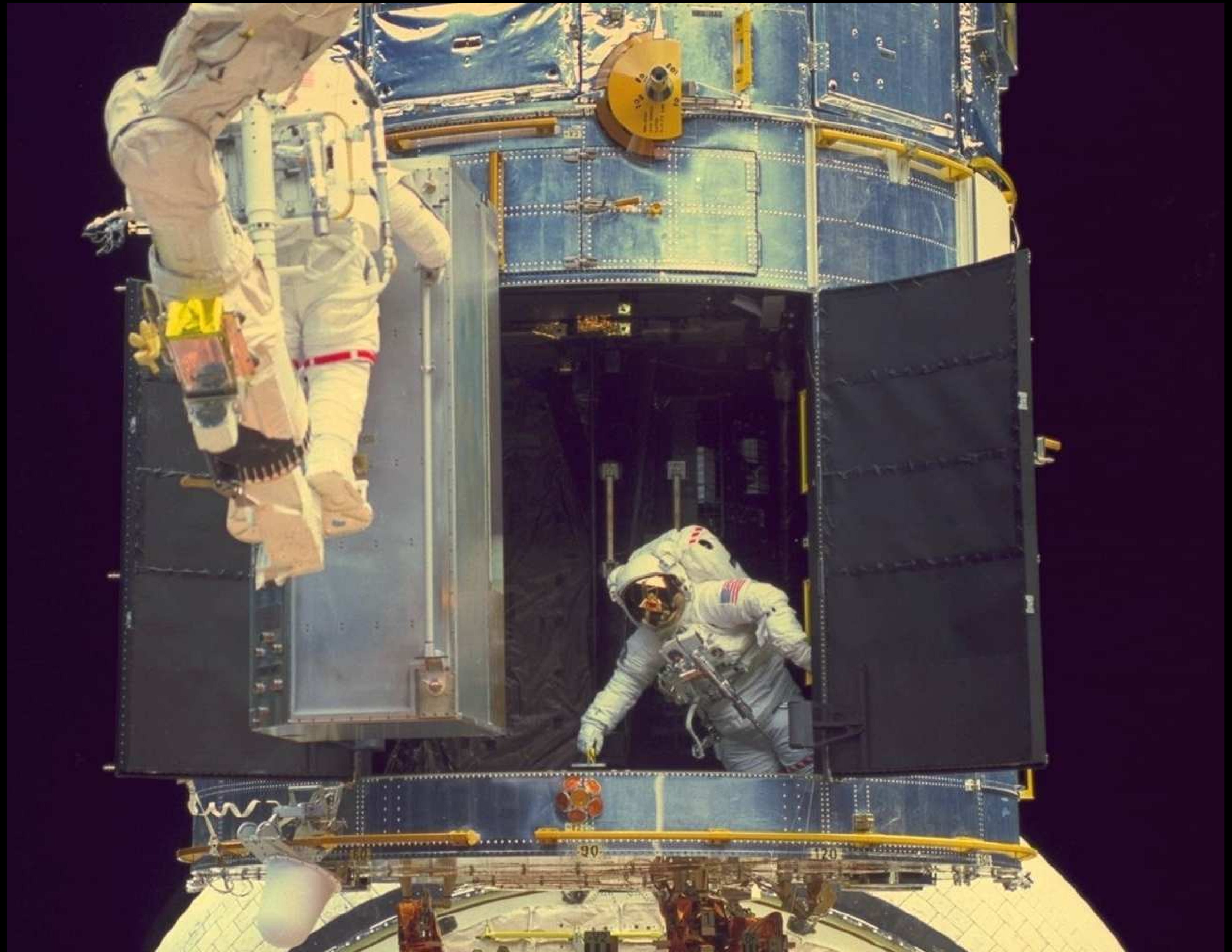
The HST Advanced Camera for Surveys (ACS) — launched 2002 (SM3B).

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

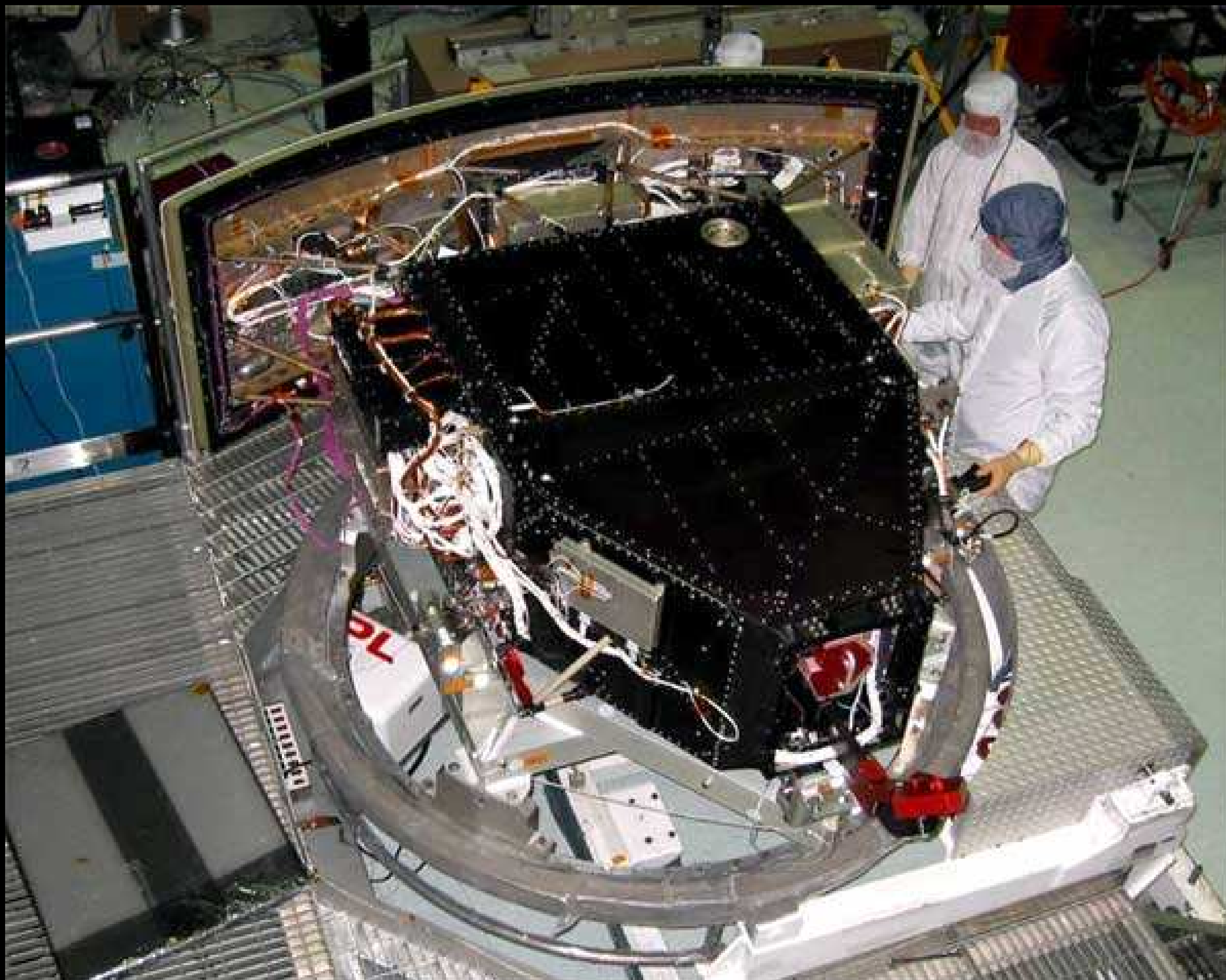


Installing Wide Field Camera 2 (WFPC2) during SM1 in December 1993.

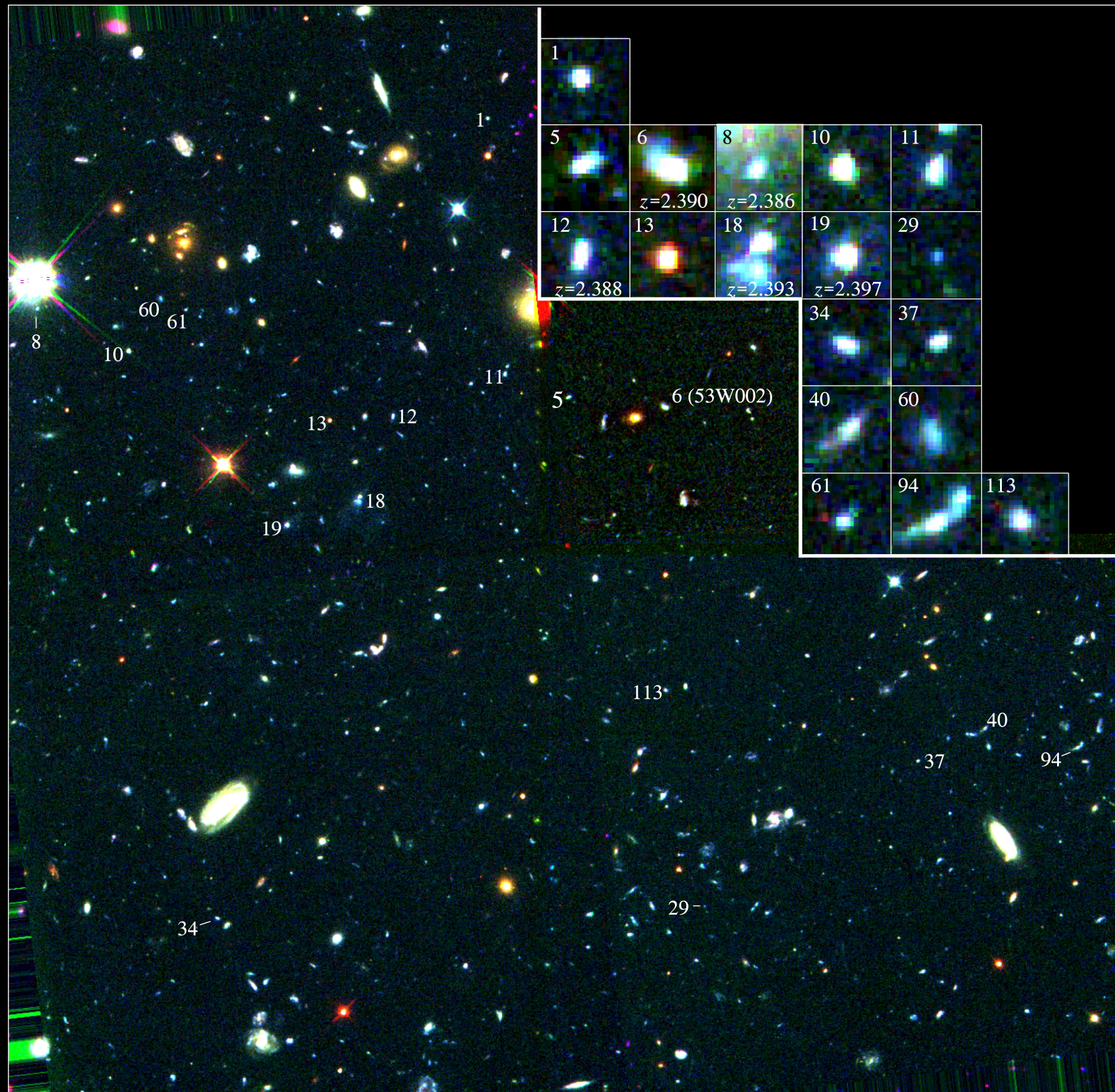
Similar to what astronauts did with WFC3 during SM4 in May 2009.


60
90
120

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



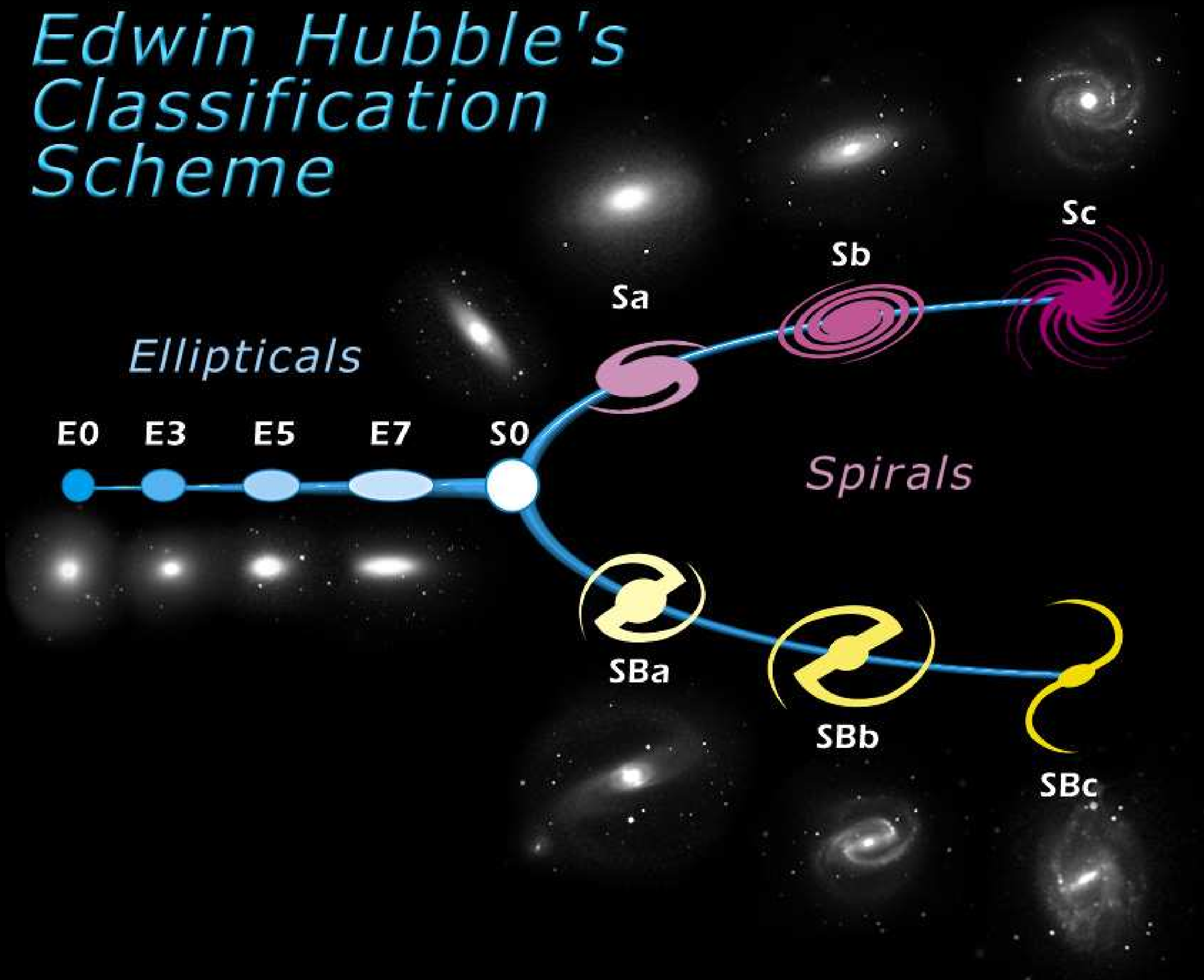
(2) How has Hubble measured Galaxy Assembly over Cosmic Time?



R. Windhorst (Arizona State University) and NASA

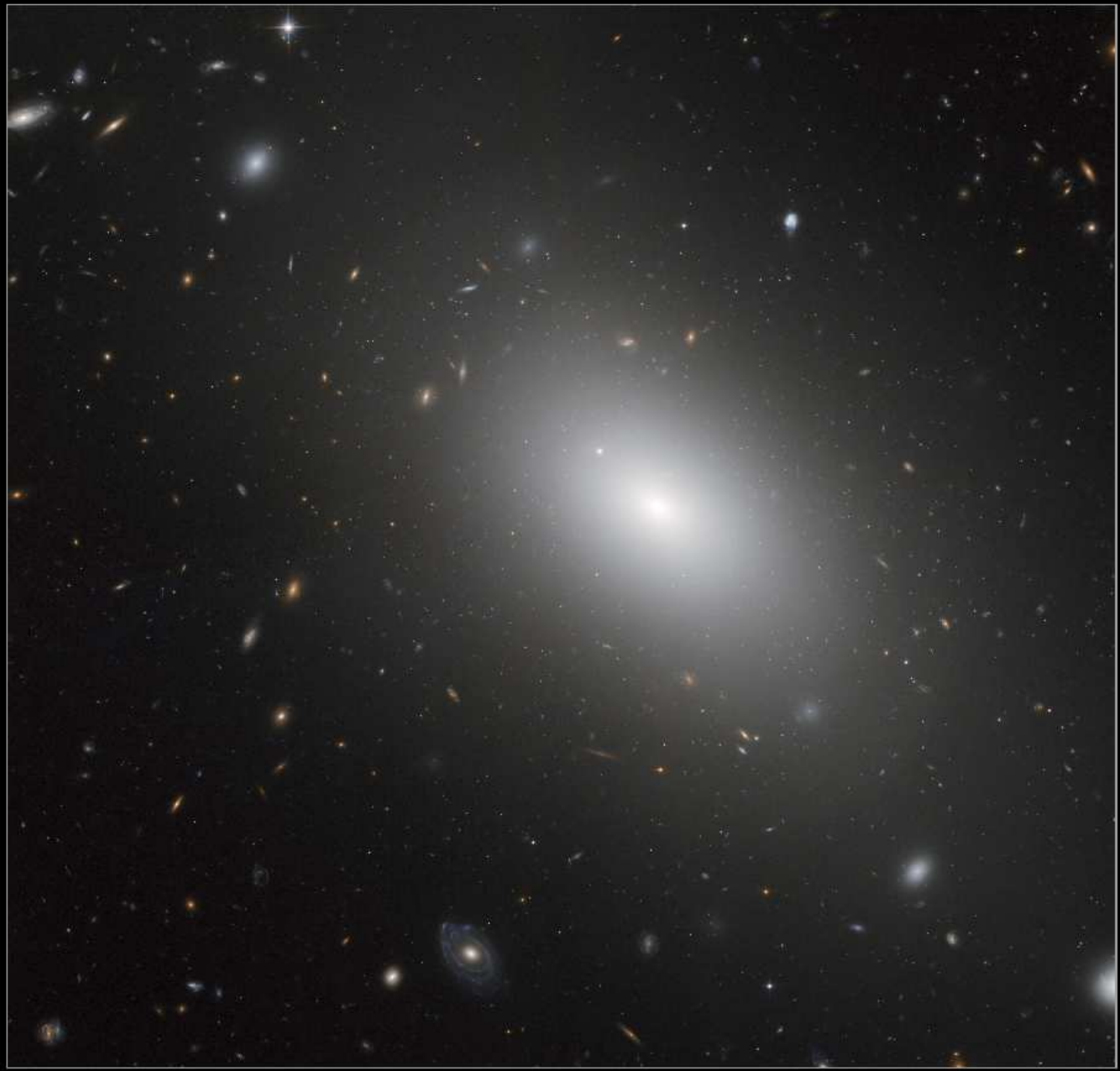
One of the remarkable HST discoveries was how numerous and small faint galaxies are: the building blocks of giant galaxies seen today (T. Ashcraft).

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



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).

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

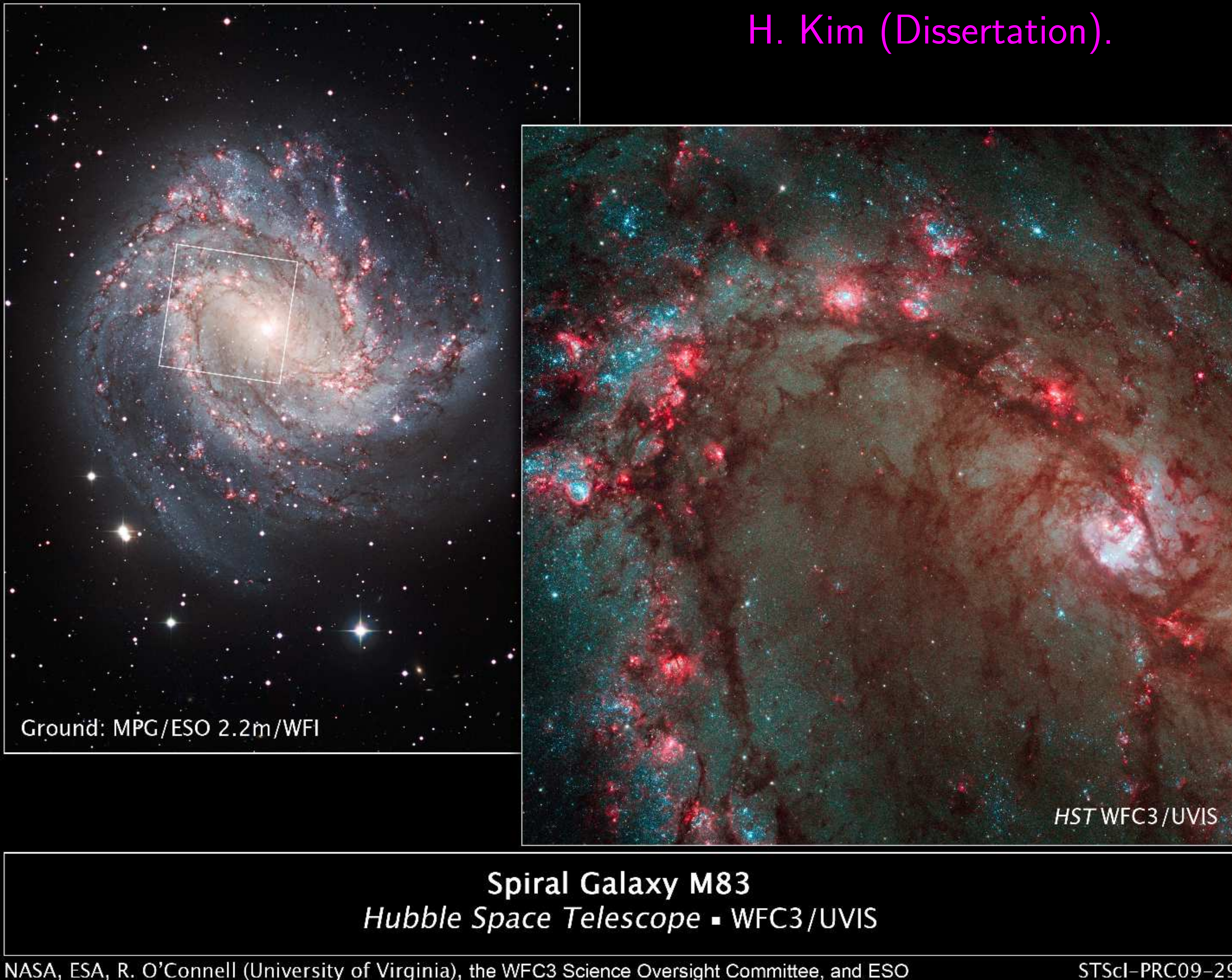
Active Galaxy Centaurus A

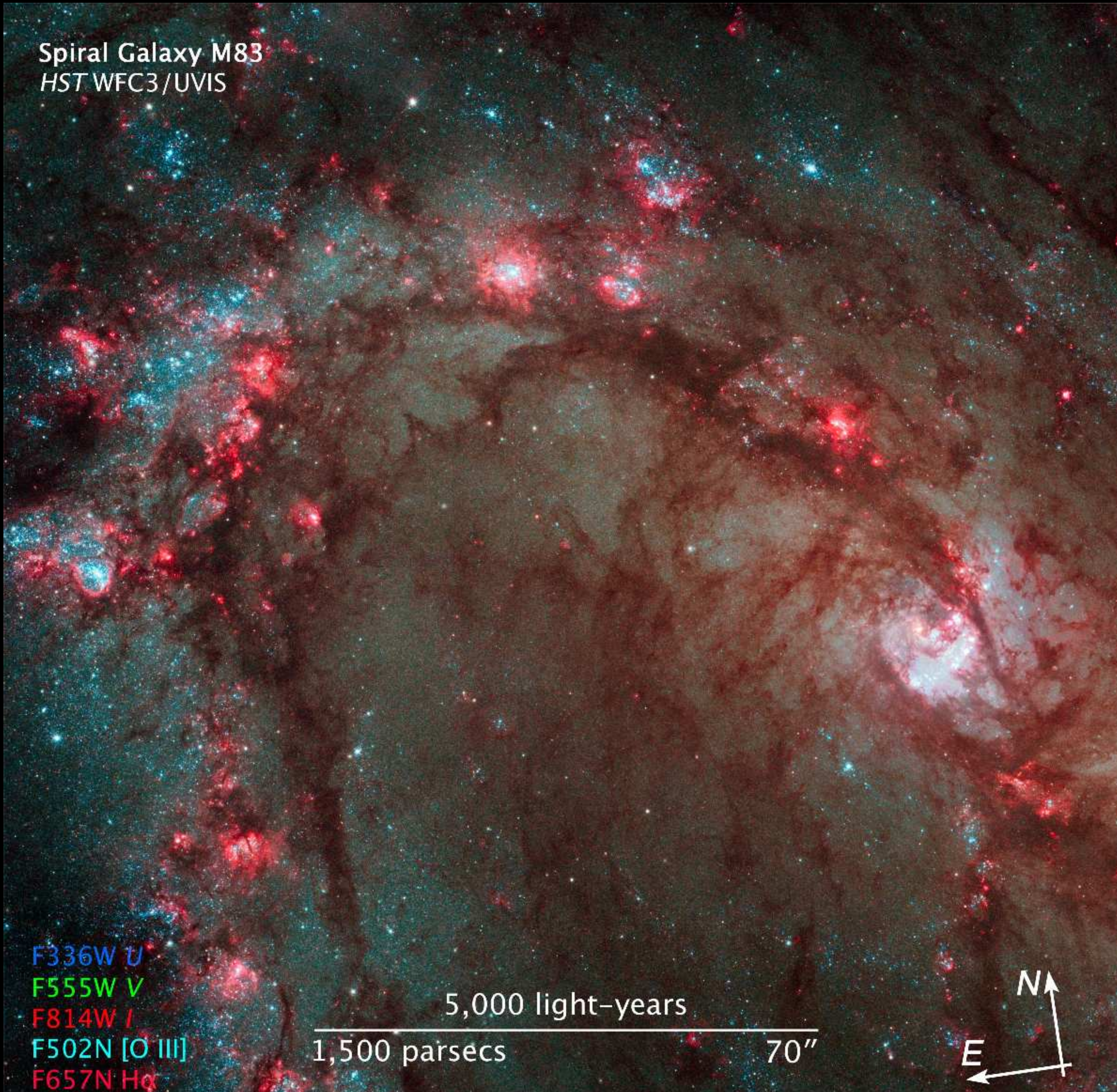
Hubble Space Telescope • Wide Field Planetary Camera 2

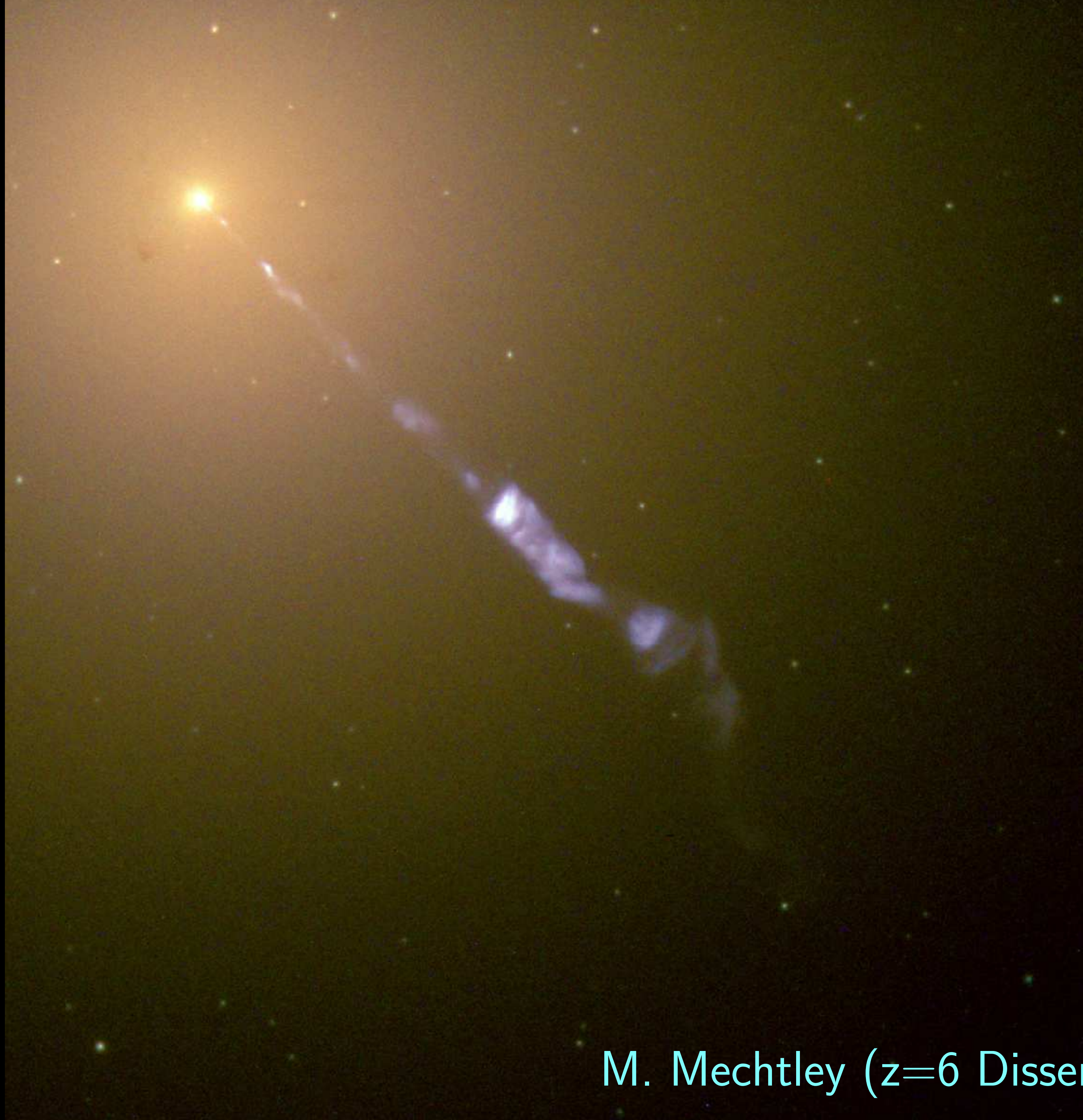
PRC98-14a • ST ScI OPO • May 14, 1998 • E. Schreier (ST ScI) and NASA


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

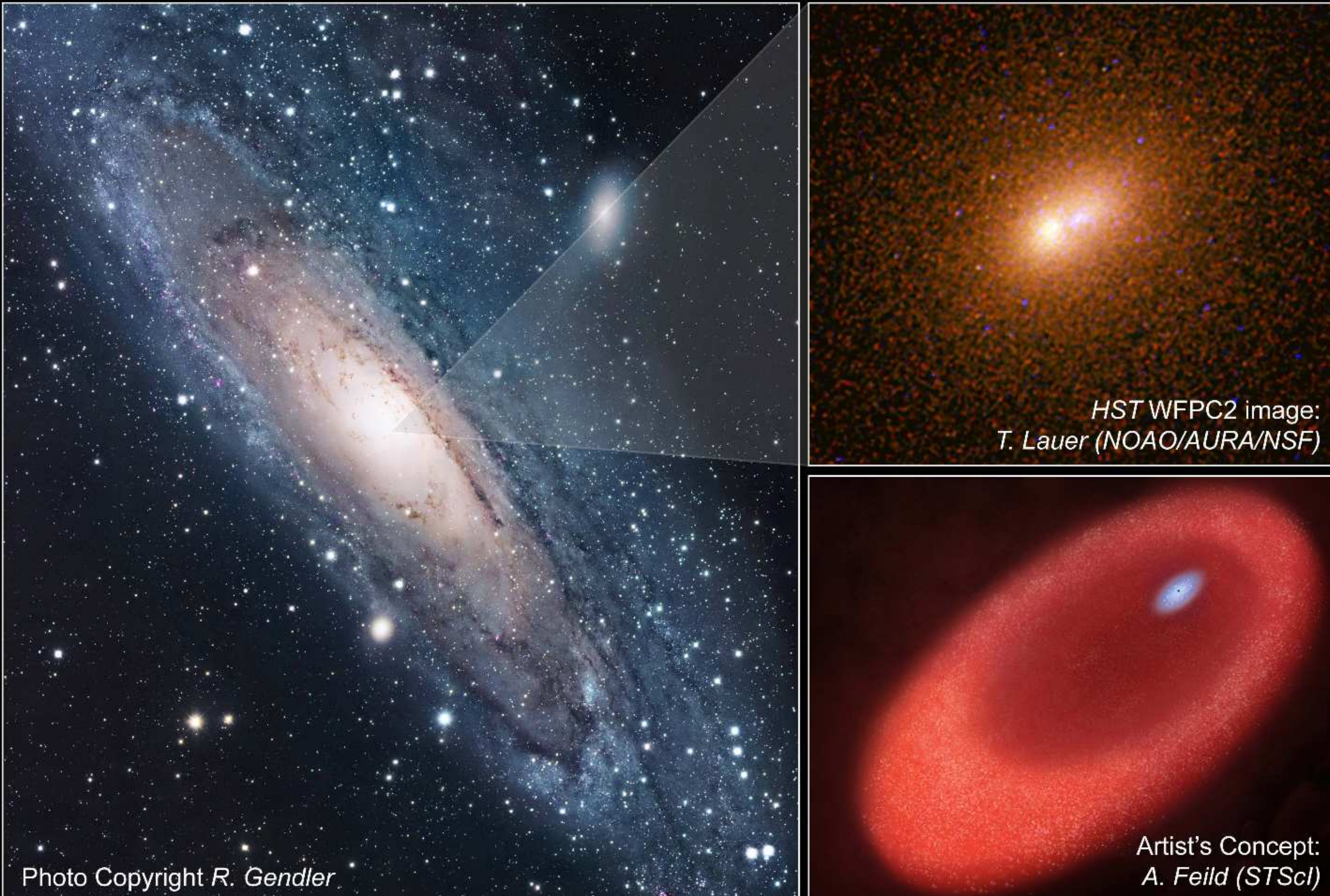
H. Kim (Dissertation).




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



Andromeda Galaxy Nucleus ▪ M31

Hubble Space Telescope ▪ WFPC2

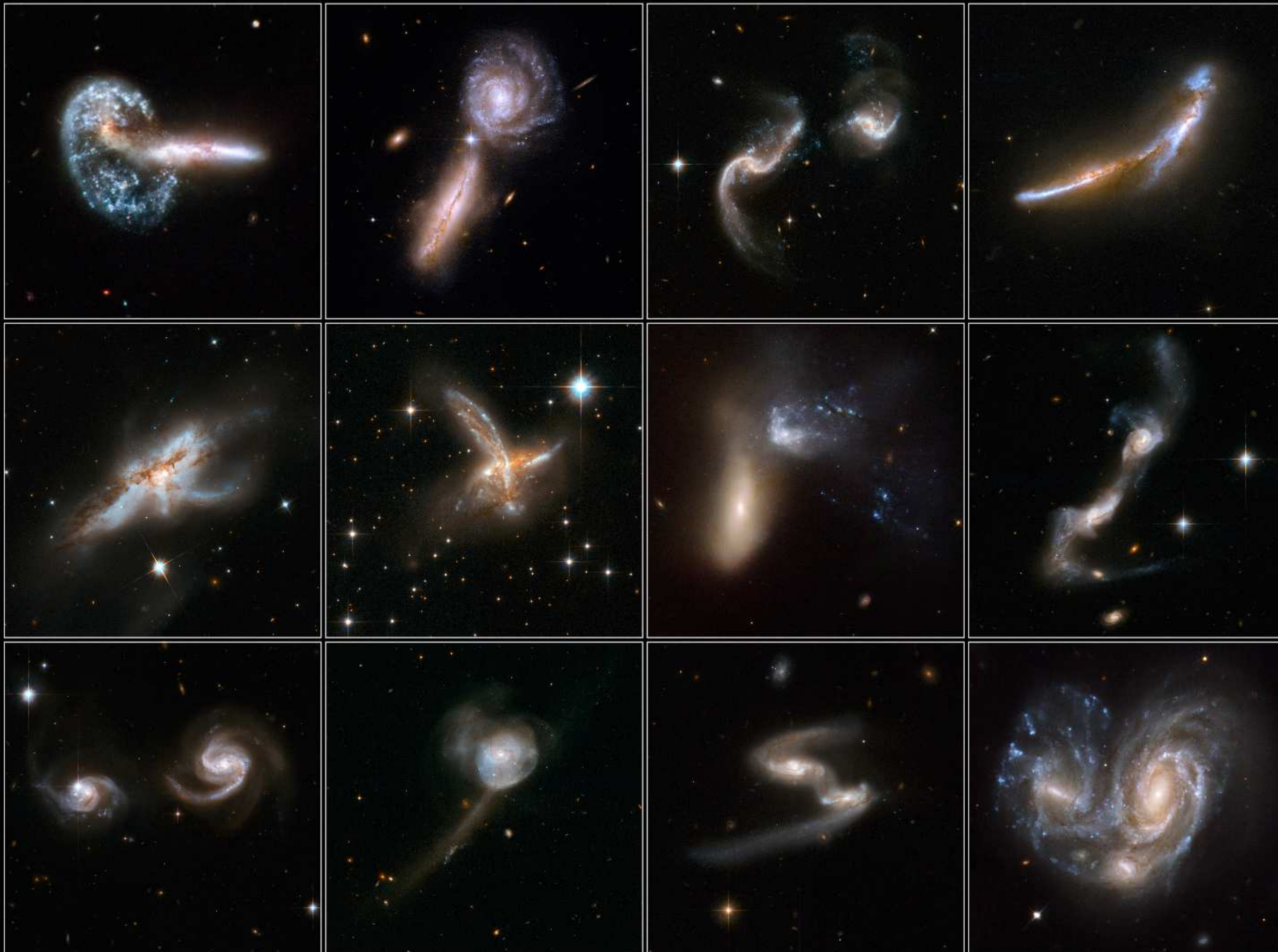
NASA, ESA, R. Gendler, T. Lauer (NOAO/AURA/NSF), and A. Feild (STScI)

STScI-PRC05-26

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

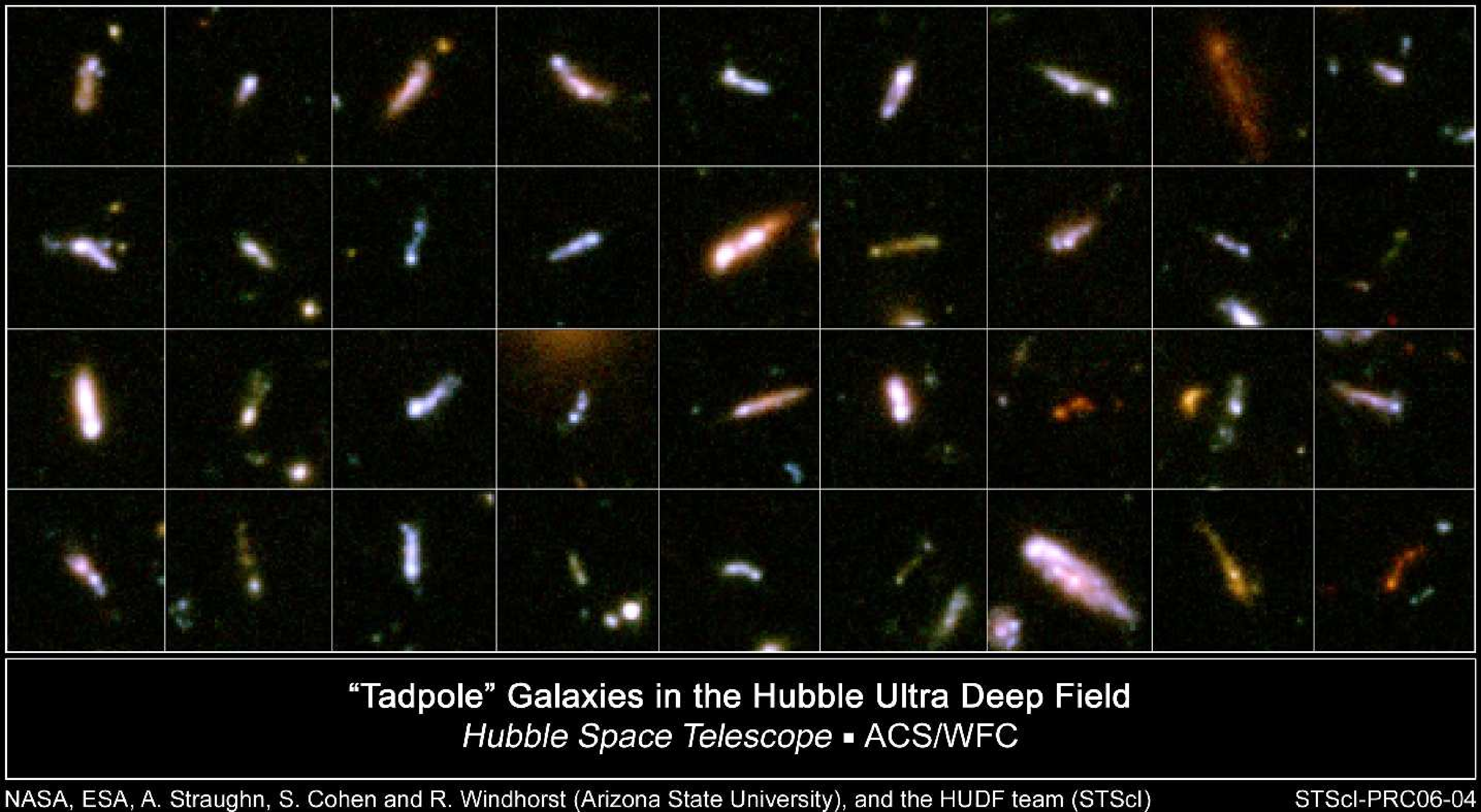
Interacting Galaxies

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)

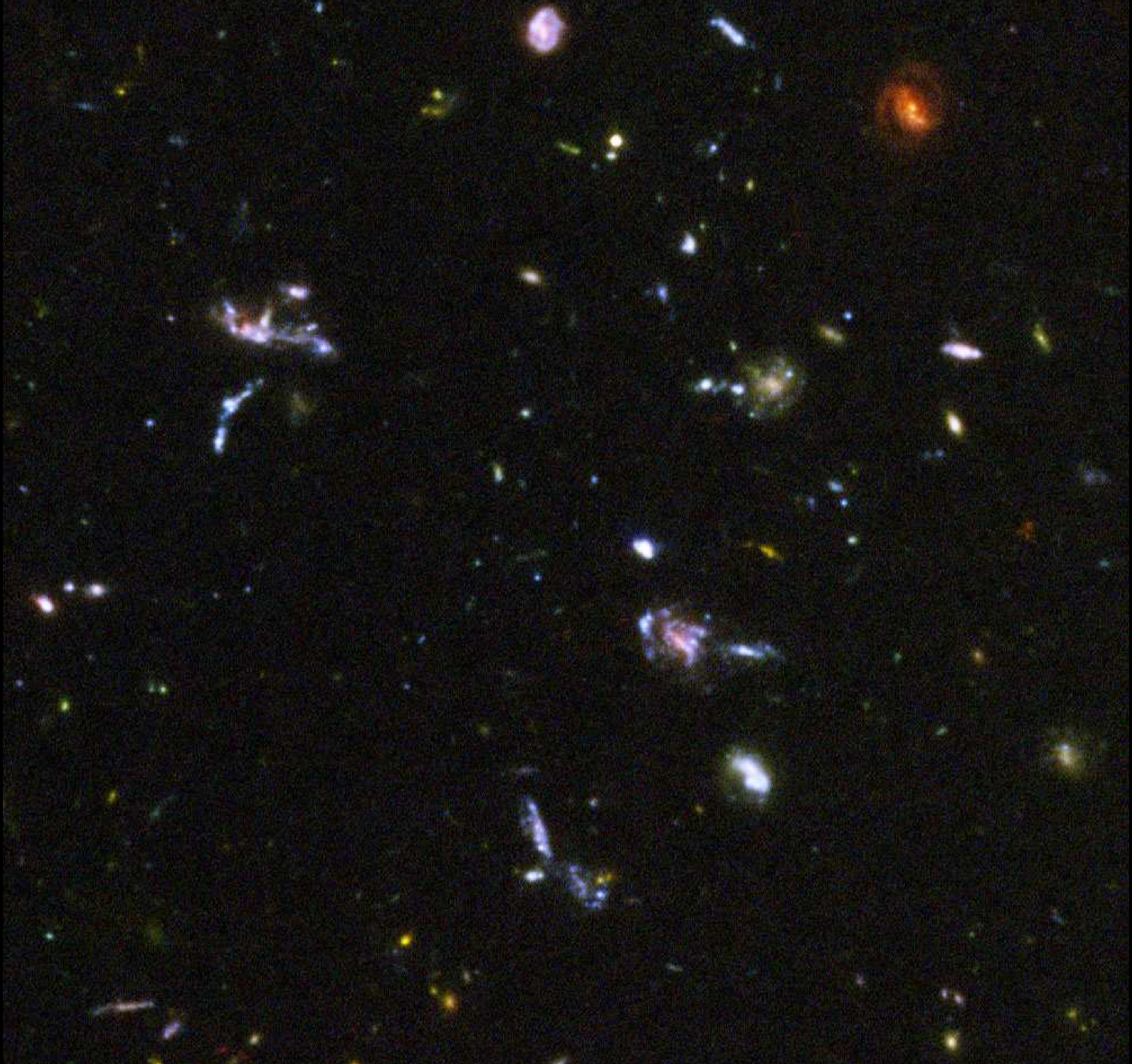
STScI-PRC08-16a



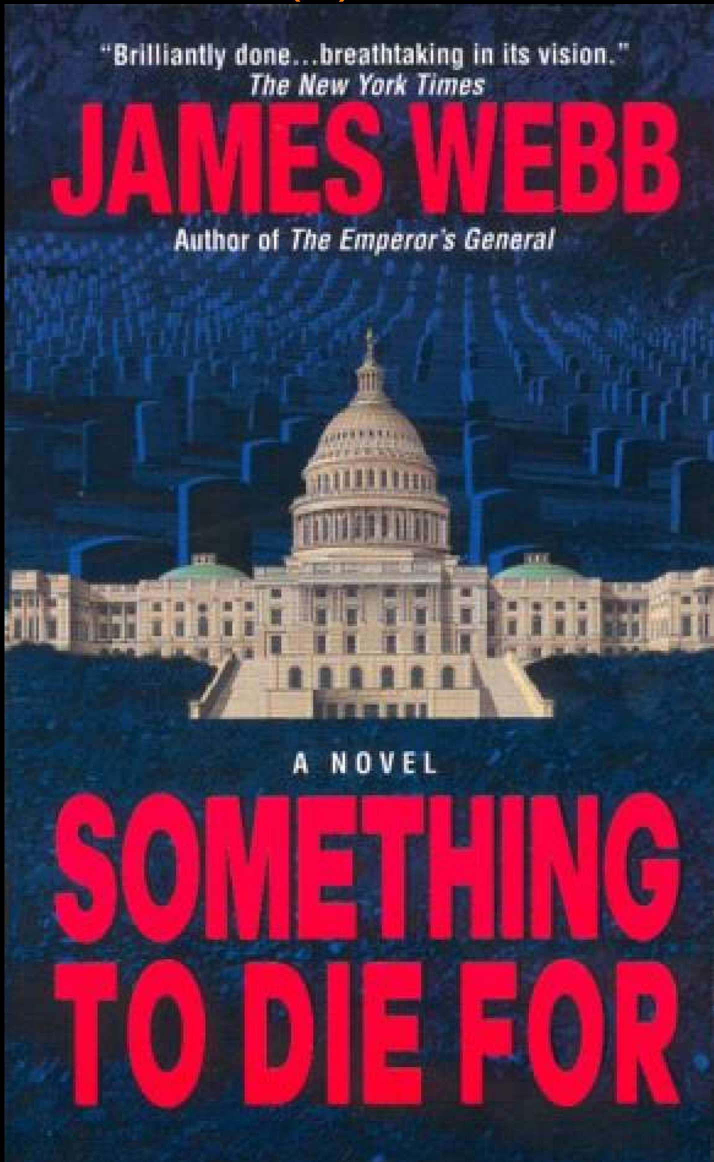
Merging galaxies constitute $\lesssim$1% of Hubble sequence today (age$\gtrsim$12.5 Gyr).

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).



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



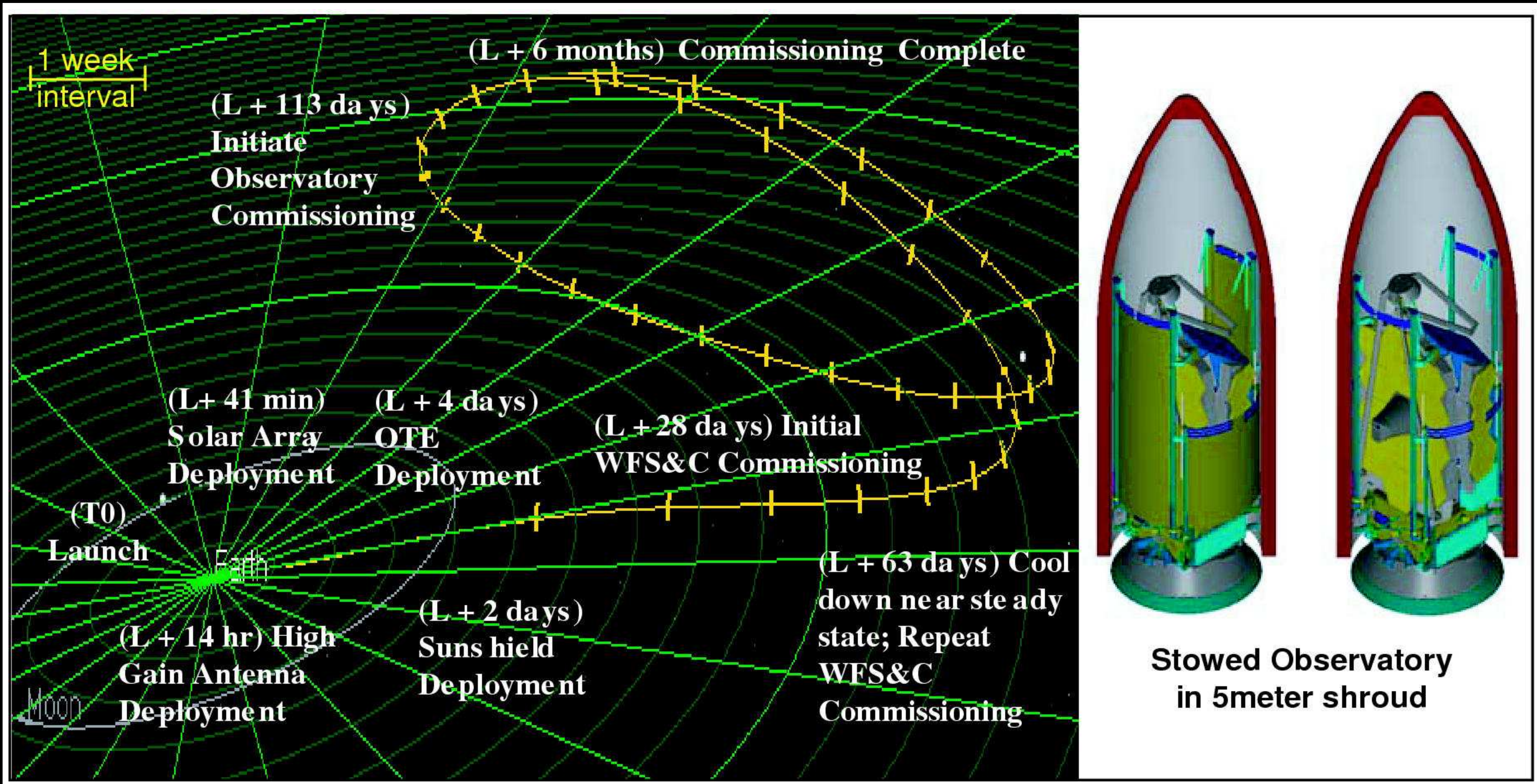
Need young generation of students & scientists after 2018 ... It'll be worth it!

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

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

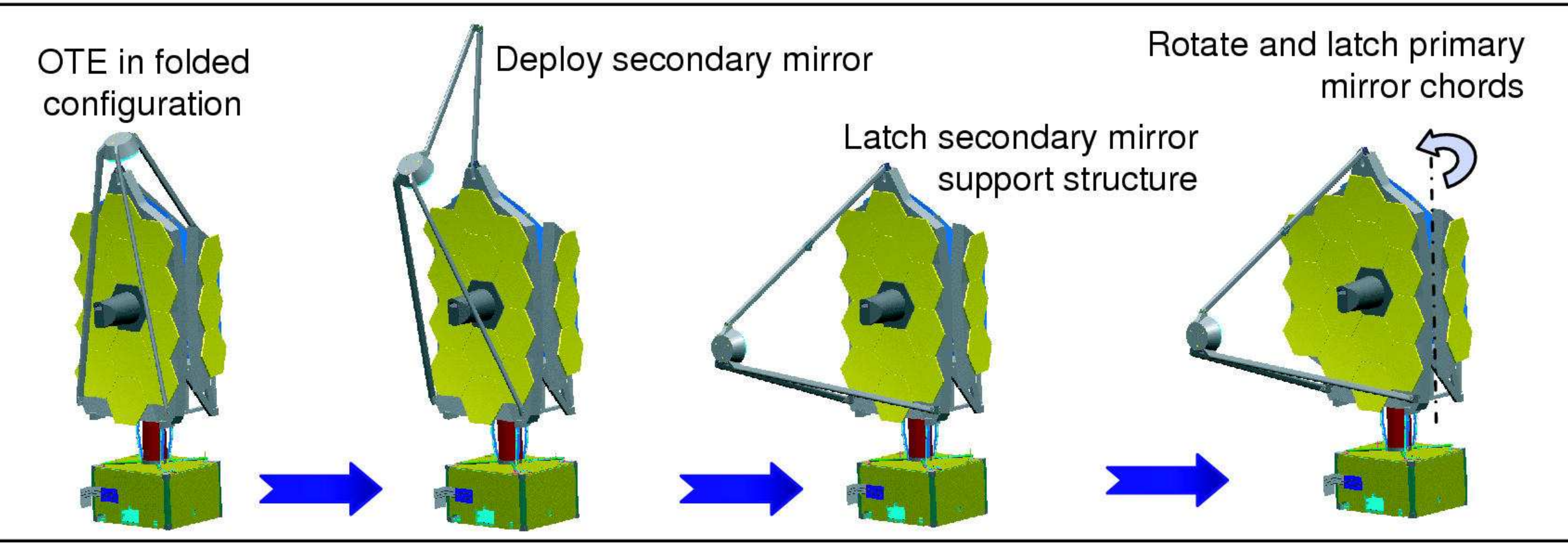
- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (31.5 mag = firefly from Moon!) and spectroscopy.

(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.

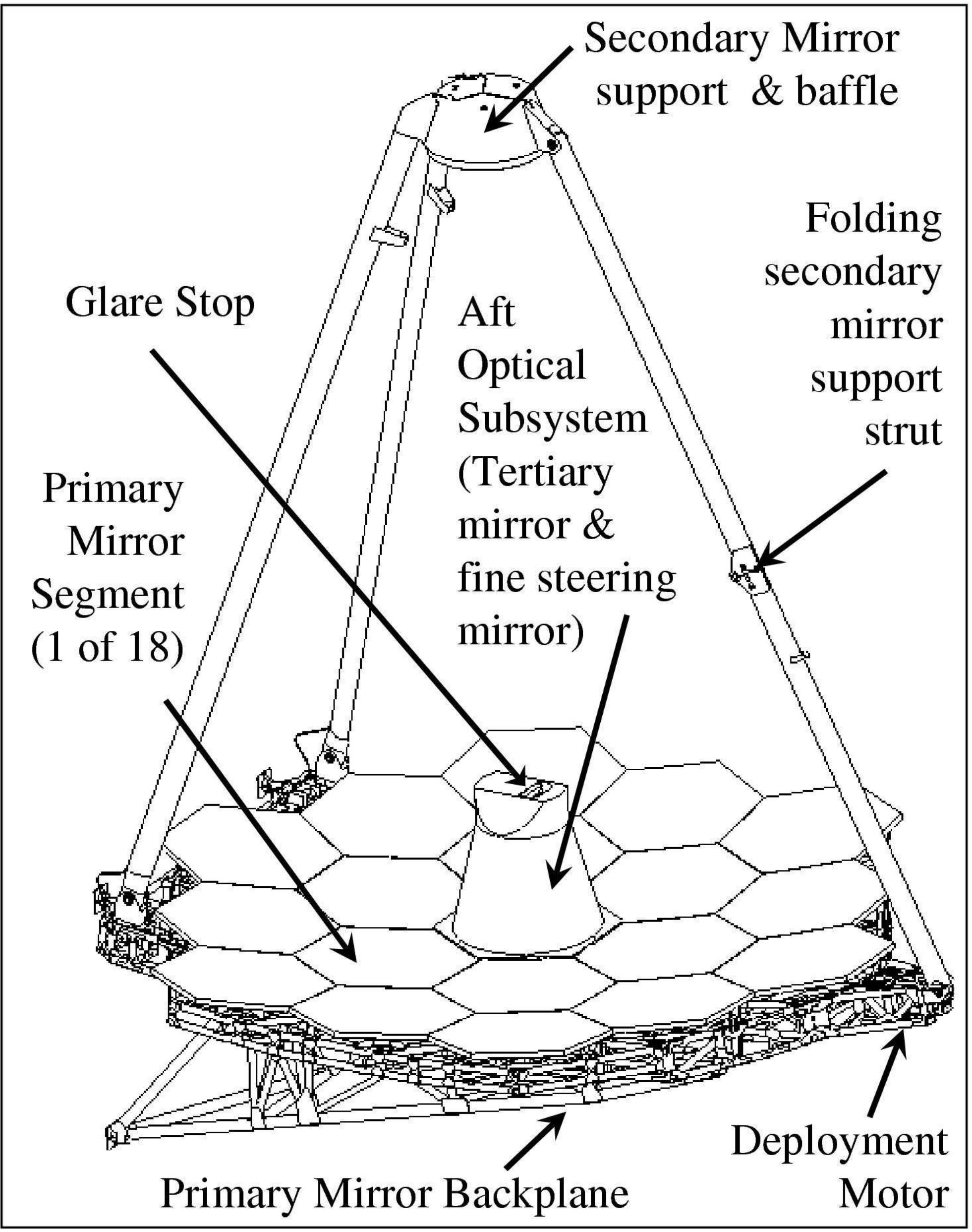
• (3b) How will JWST be automatically deployed?



• 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.

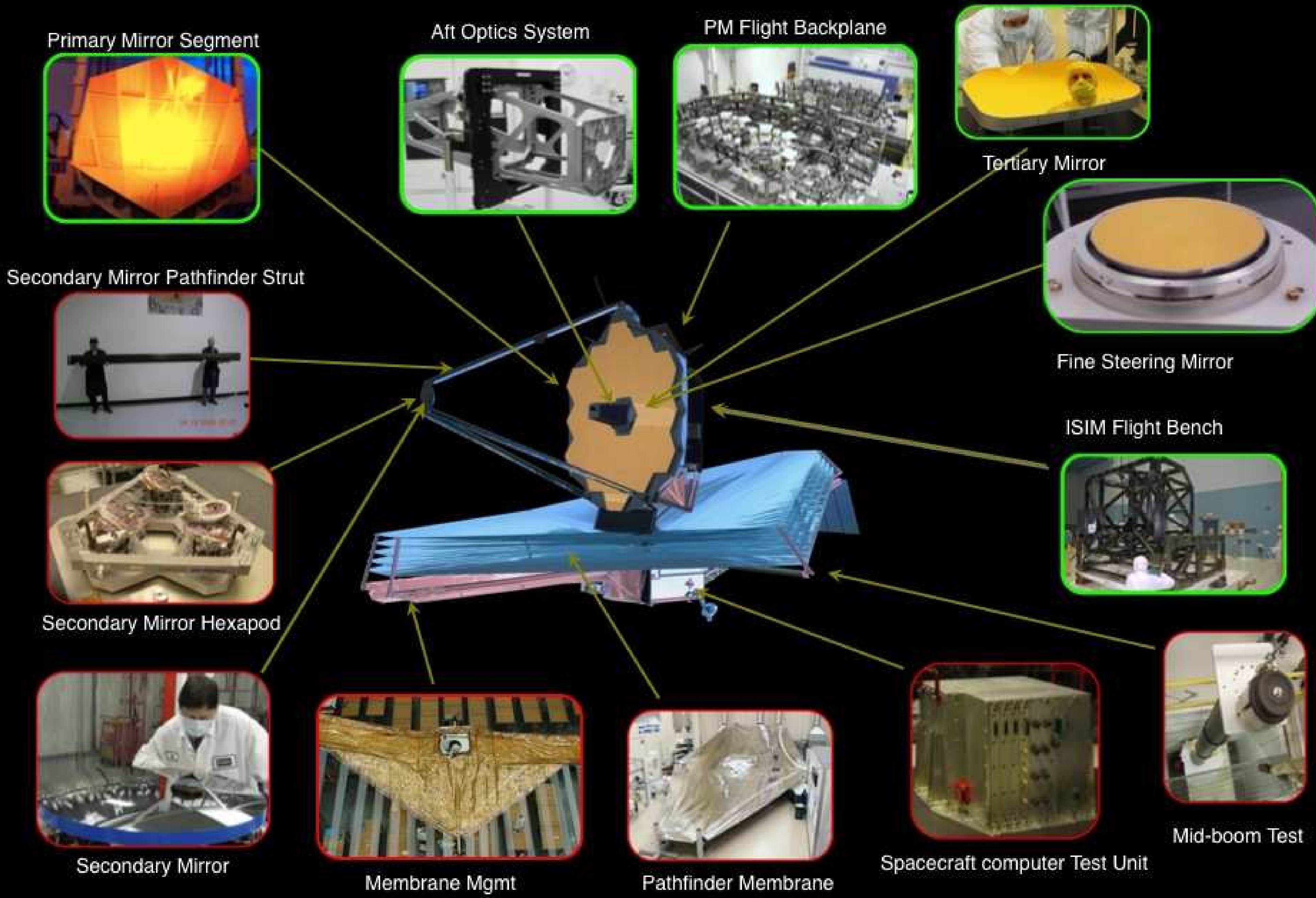
• Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meeting the 40K specifications!



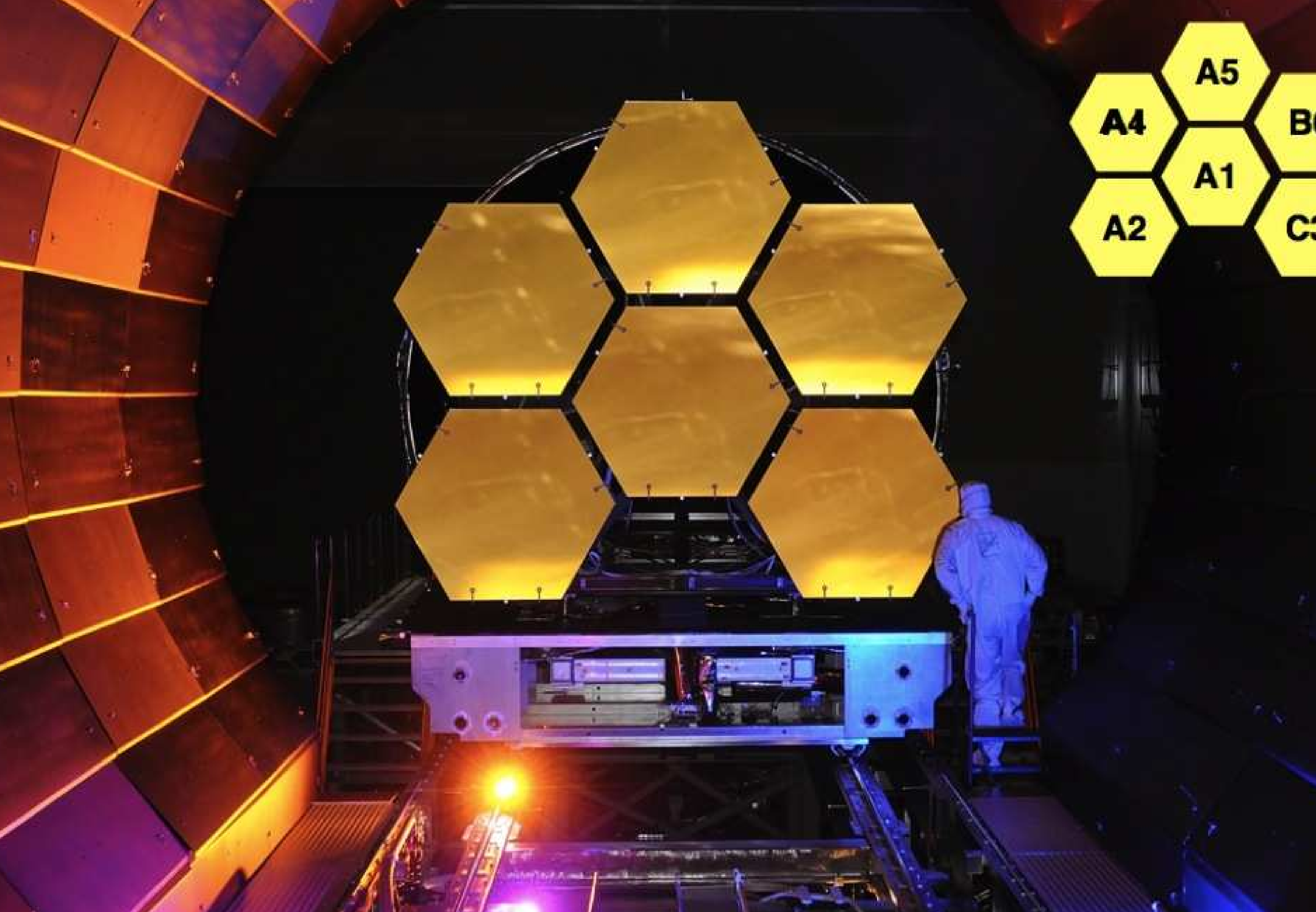
Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2014-2015.

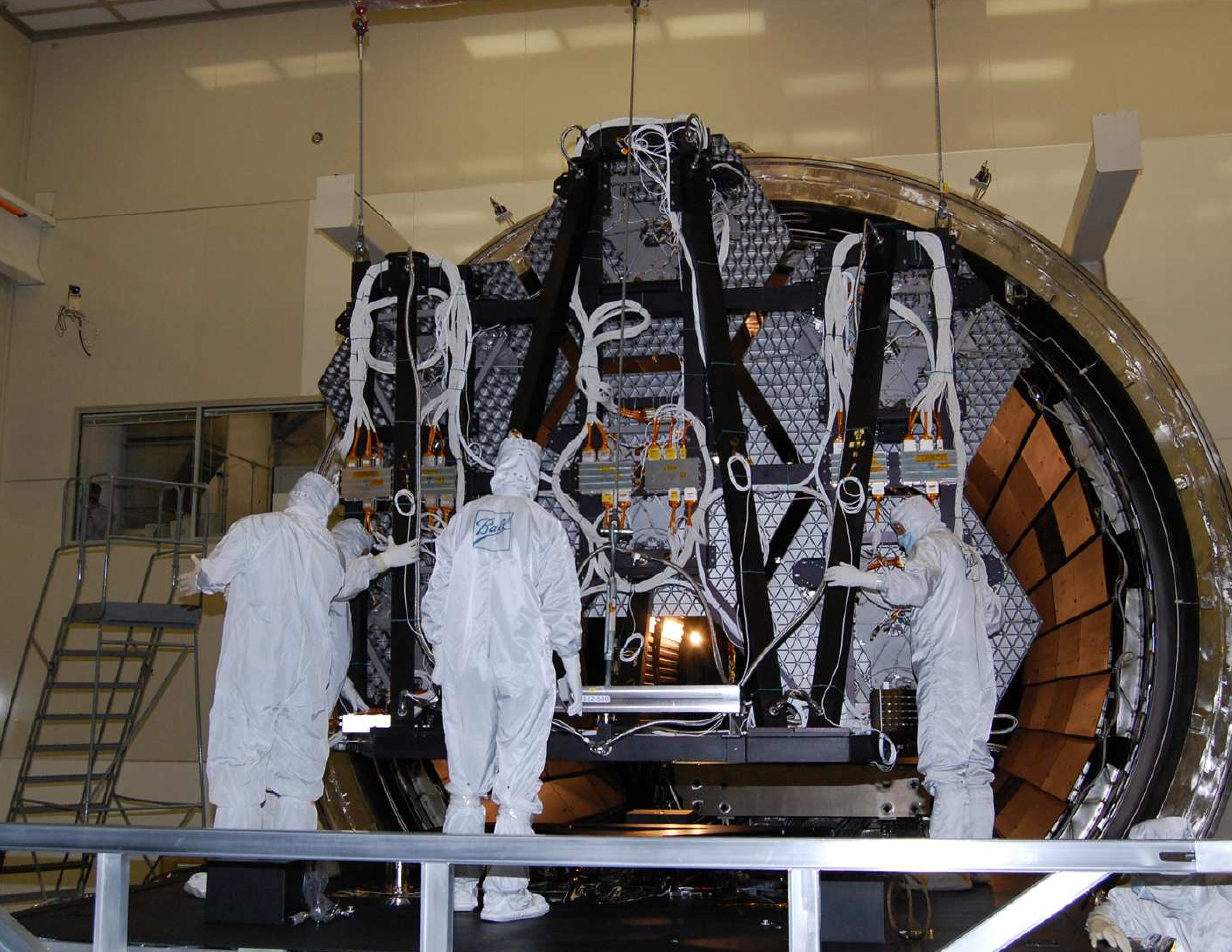
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.

JWST Hardware Status



Mirror Acceptance Testing



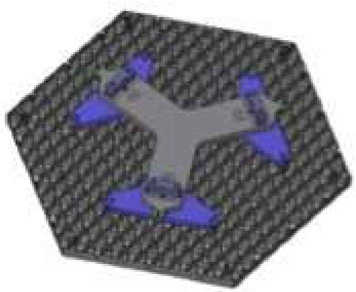

Ball

JWST Flight Mirrors Have Completed Polishing

Tinsley Final Measurement Requirements
Total Figure < 17 nm

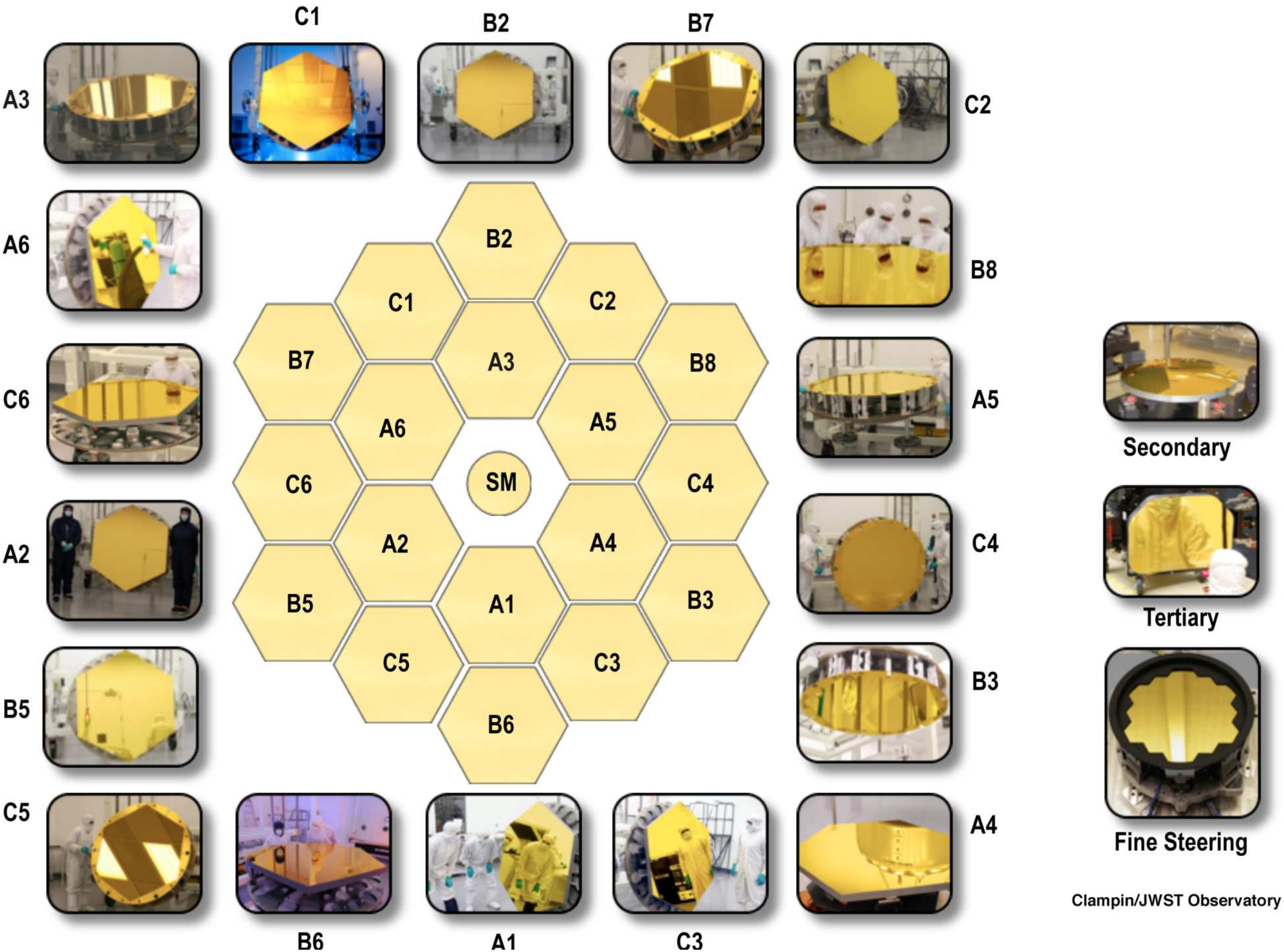
FLIGHT COMPOSITE RMS: **13.3 nm**

PV: **976.4 nm**



Mirror test configuration

All mirrors are gold-coated



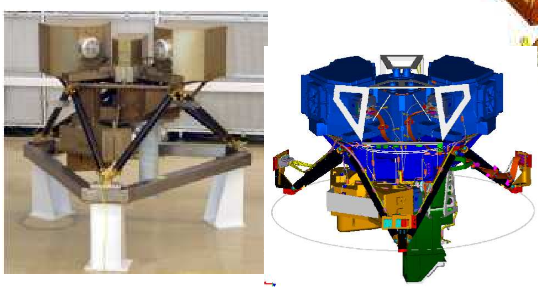
Clampin/JWST Observatory

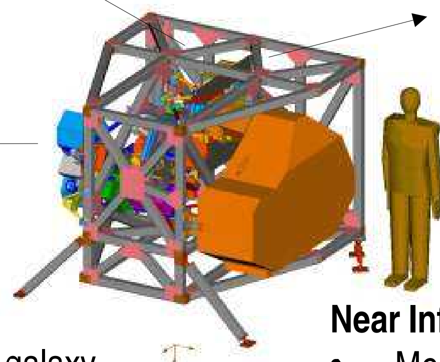
(3b) JWST instrument update: US (UofA, JPL), ESA, & CSA.

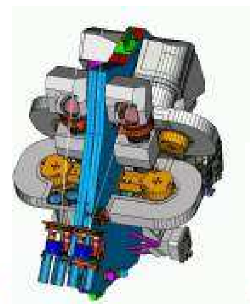
Instrument Overview

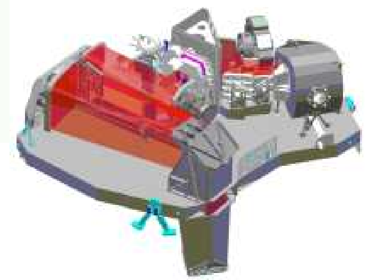
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

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





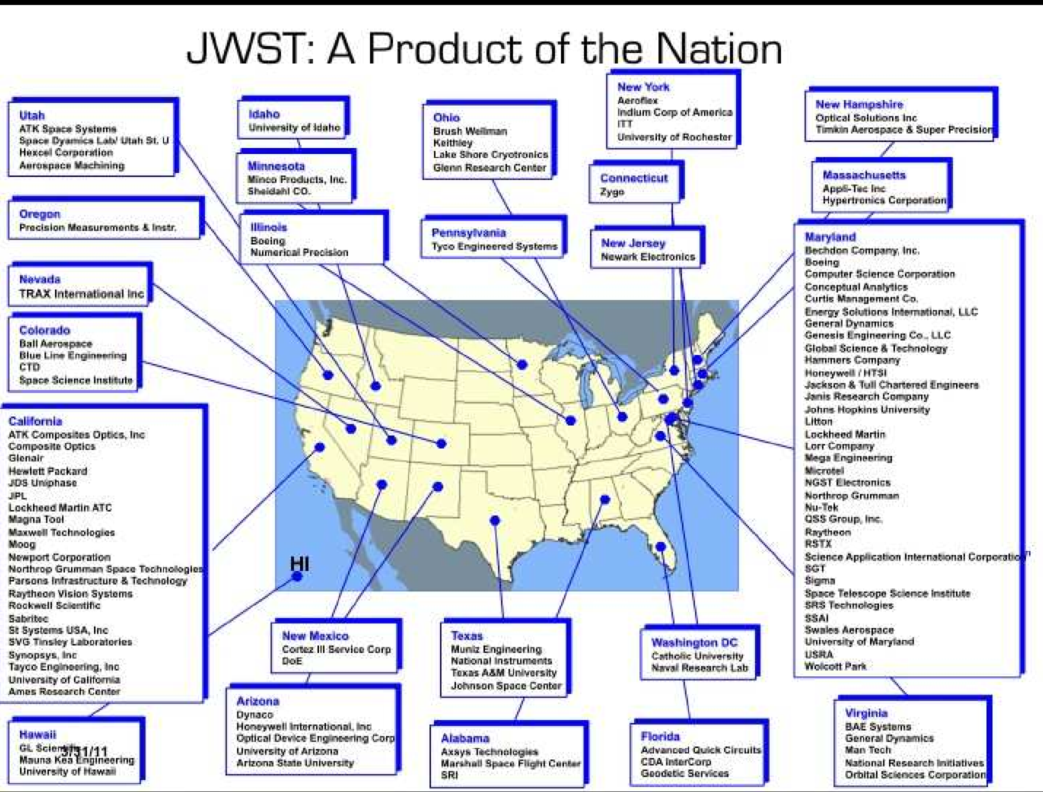


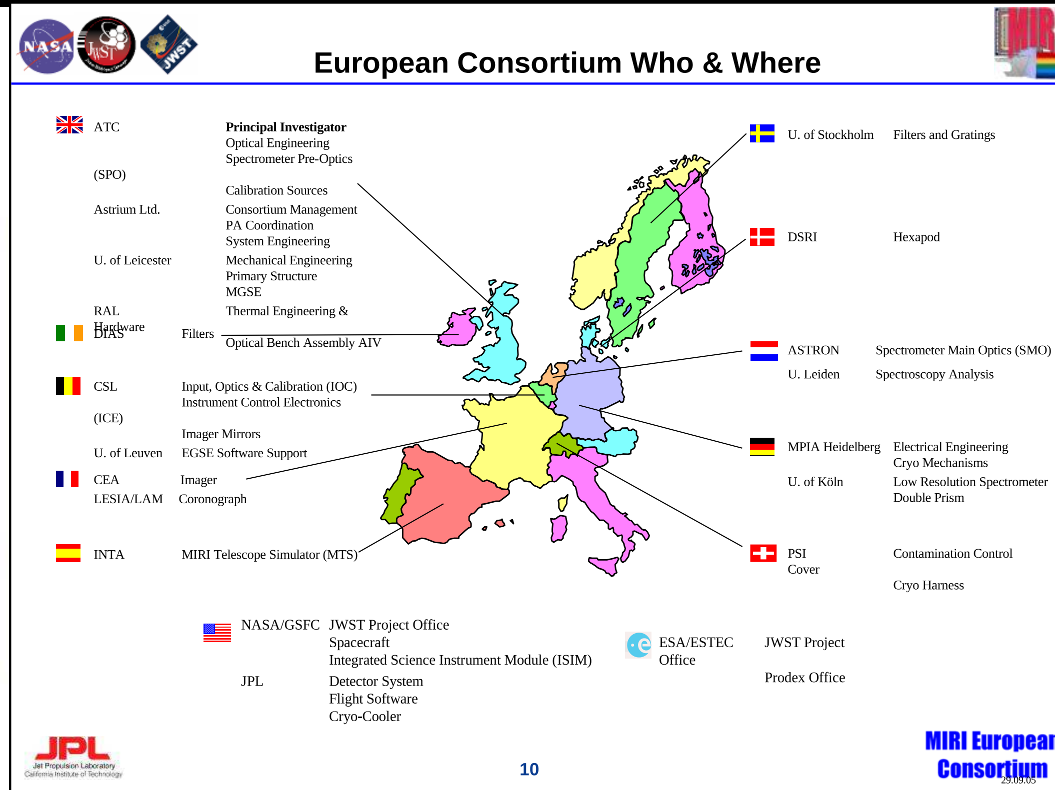


Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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 completed 2011; NIRSpec, NIRCam & FGS delivery to GSFC 2012.



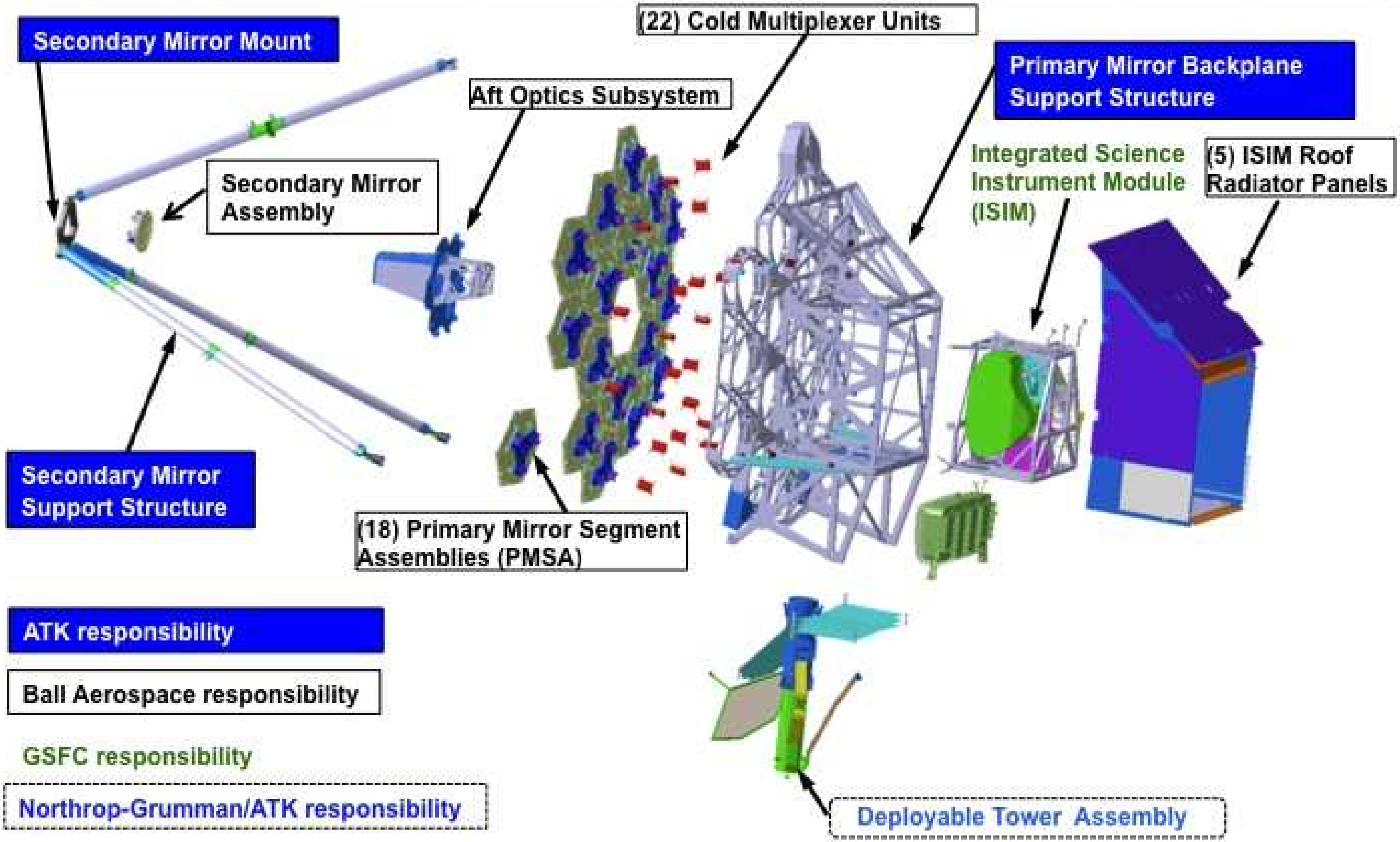


- JWST hardware made in 27 US States: $\gtrsim$75% of launch-mass finished.

- 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

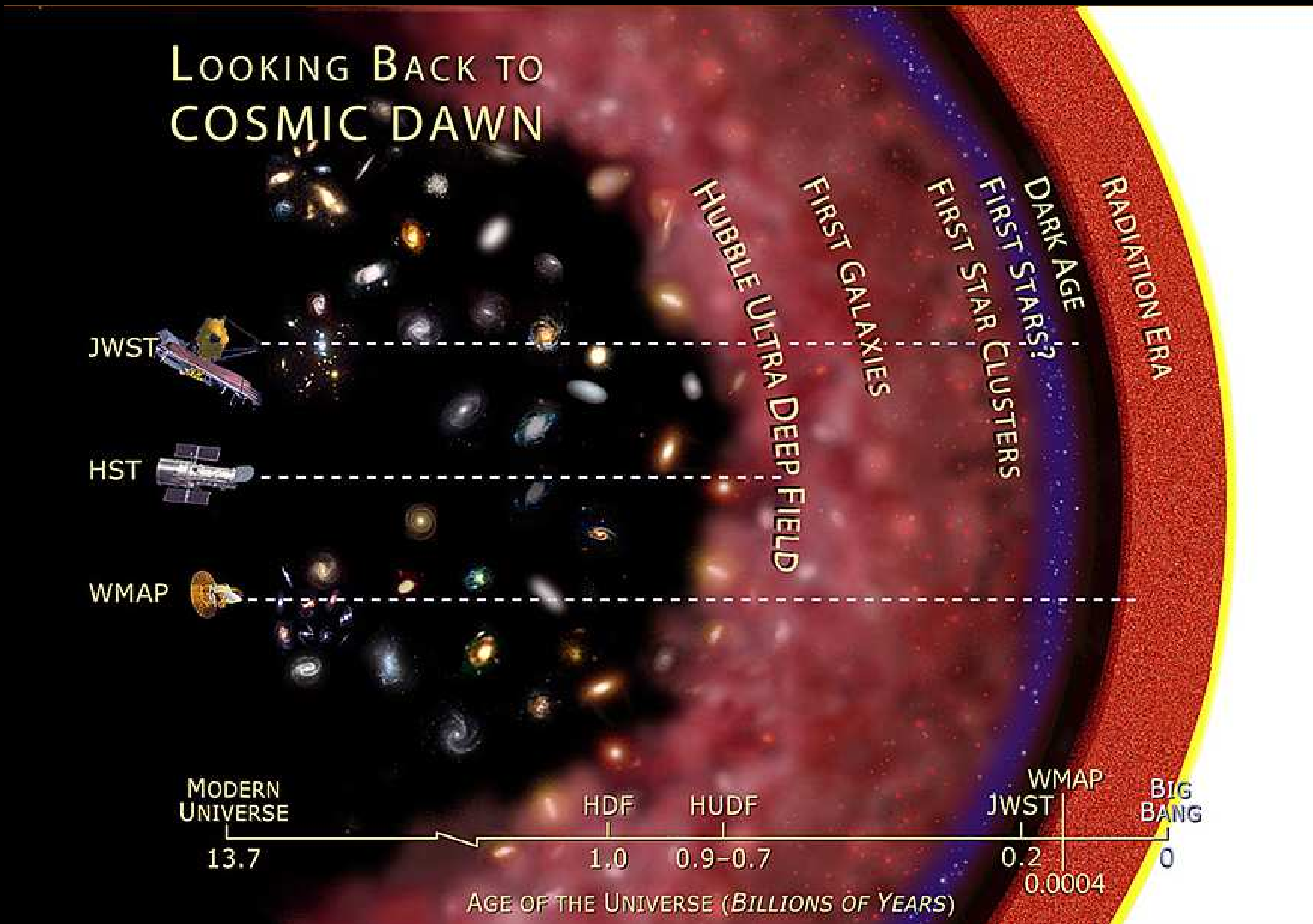
Notice people for scale

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?

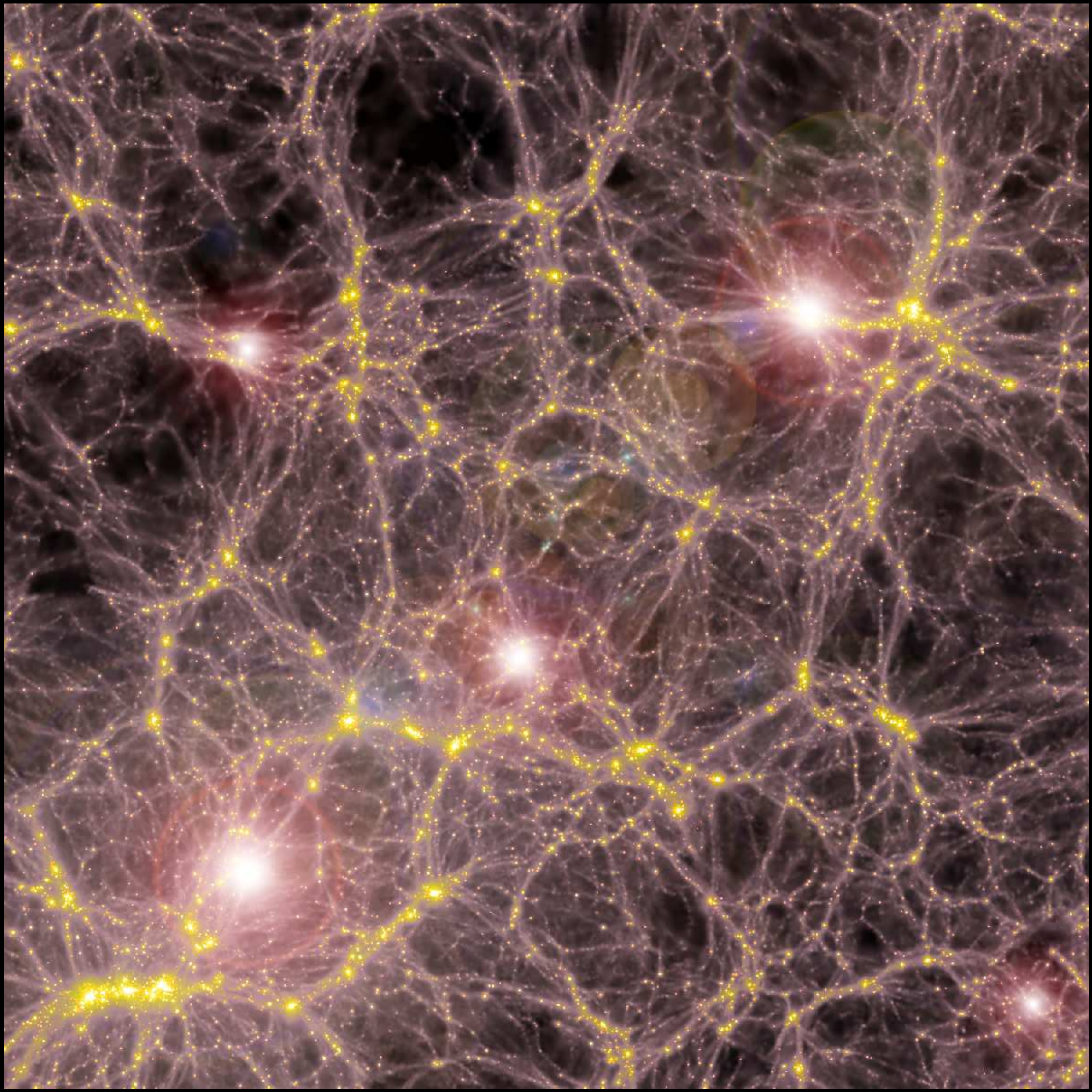


HST: Hubble sequence & galaxy evolution at z$\lesssim$7–8 (age$\gtrsim$0.7 Gyr).

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

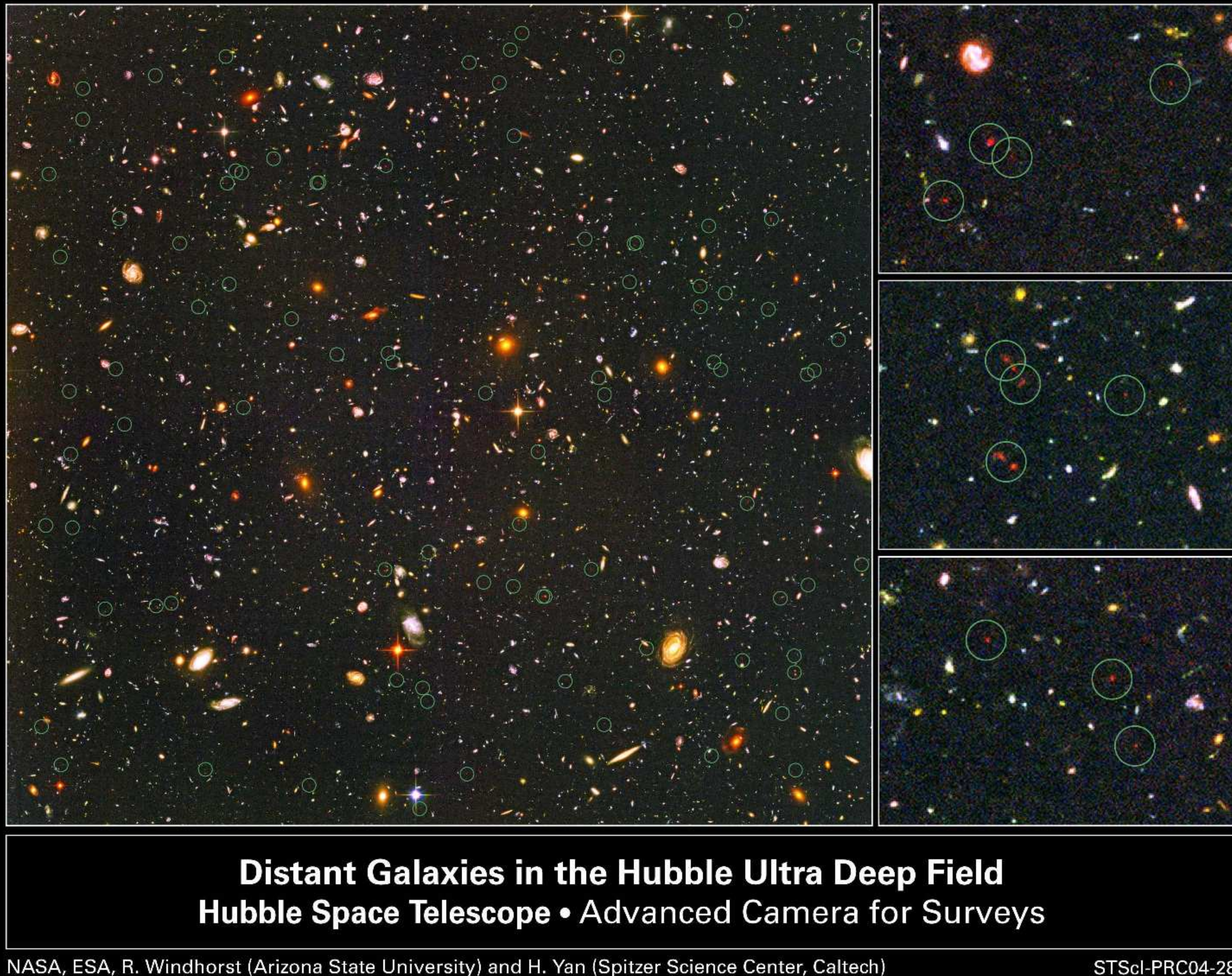
WMAP: Neutral Hydrogen first forms at z=1091 (age$\simeq$0.378 Myr).

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

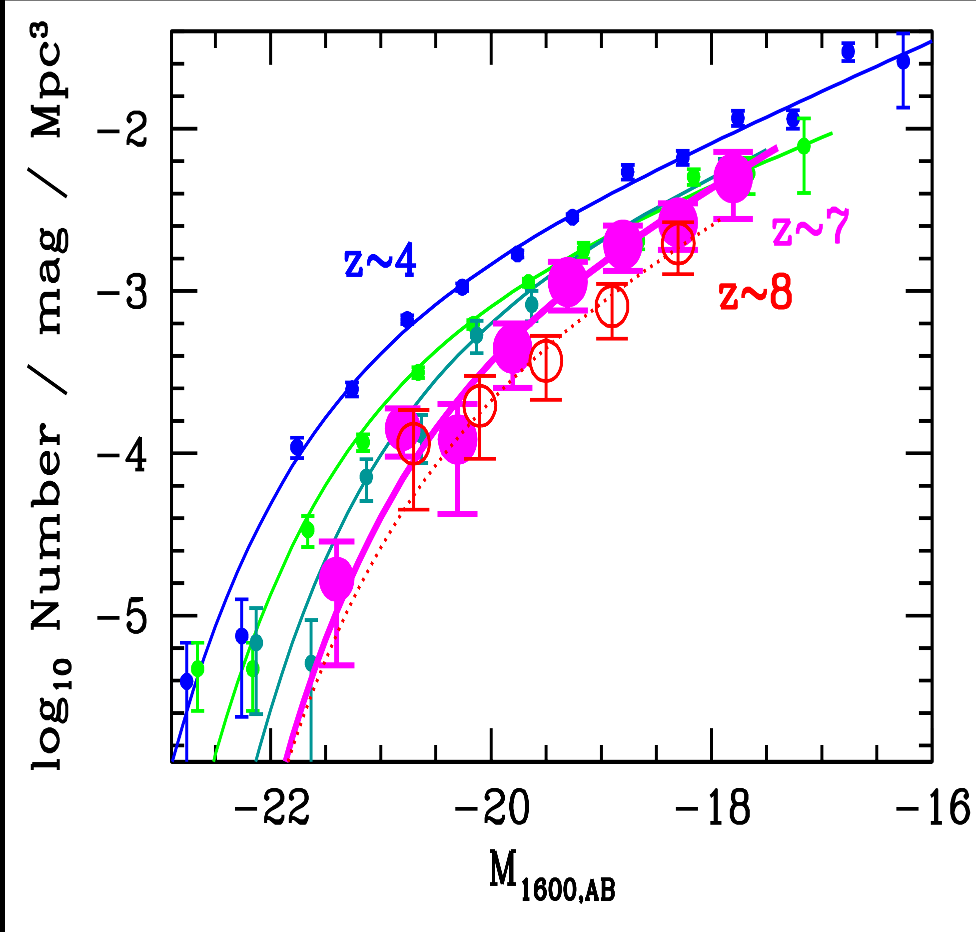


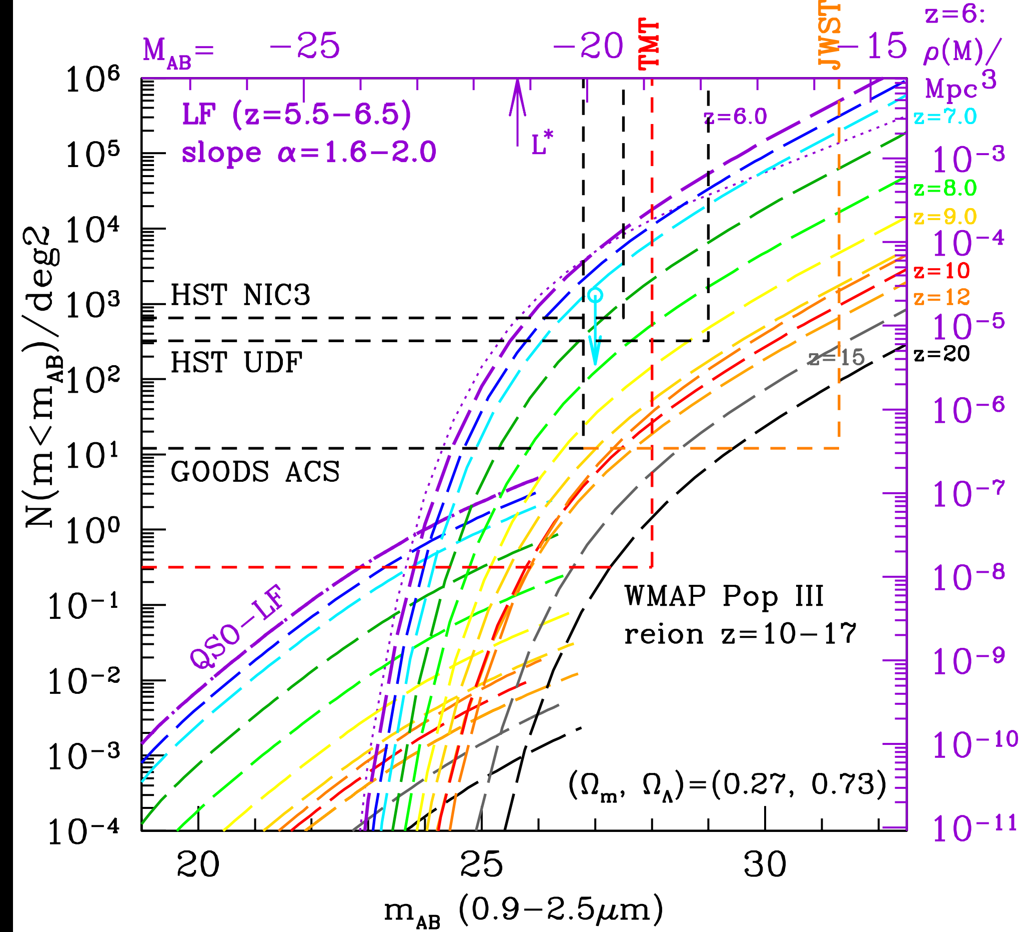
- Detailed hierarchical models (Dr. V. Bromm) show that formation of Pop III stars reionized universe for the first time at z$\simeq$10–30 (First Light, age$\simeq$500–100 Myr).

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



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.

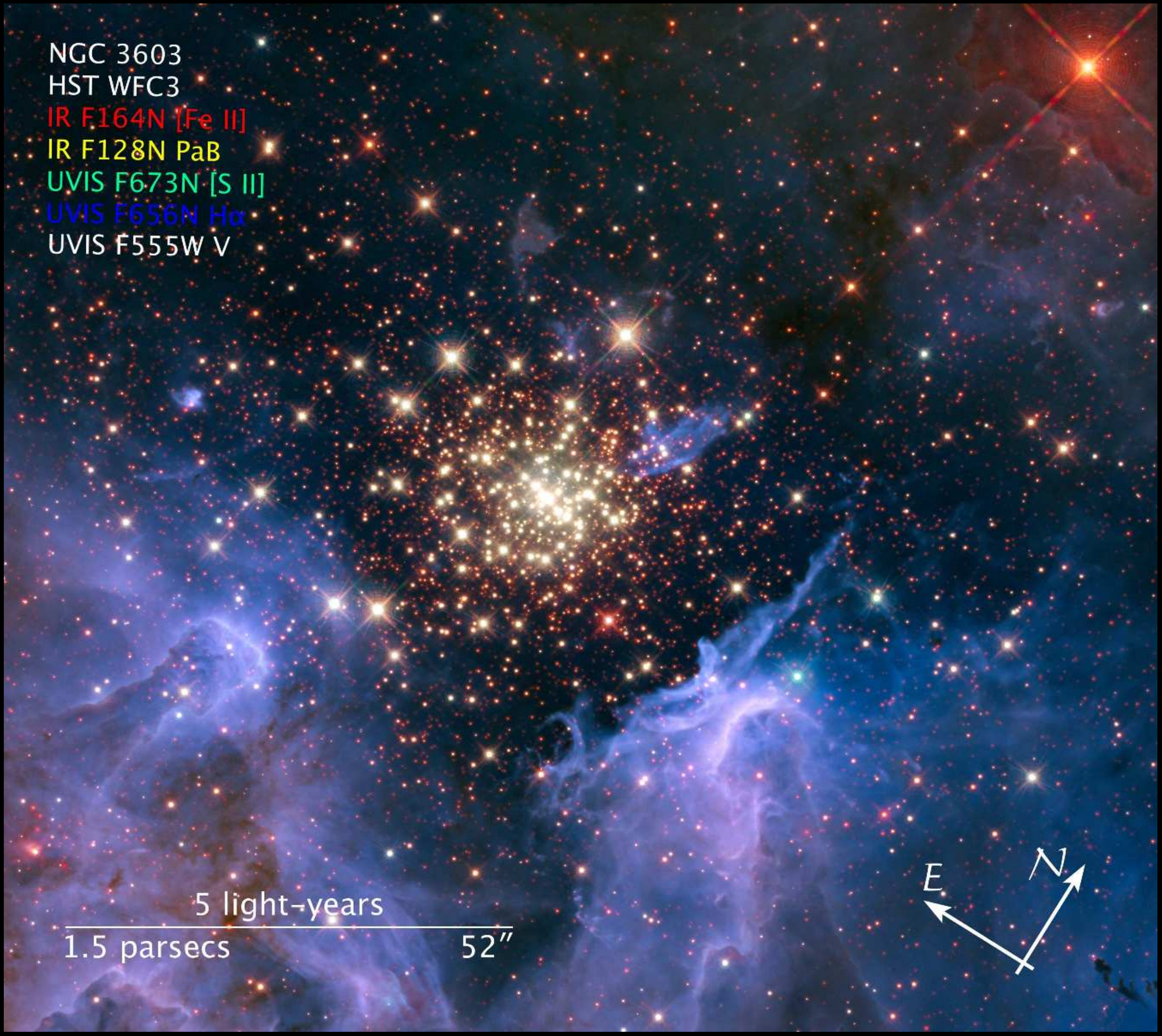
- JWST can also trace Super-Massive Black Holes as faint Quasars in young galaxies (M. Mechtley Dissertation).

• (4) How can JWST measure Galaxy Assembly?

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

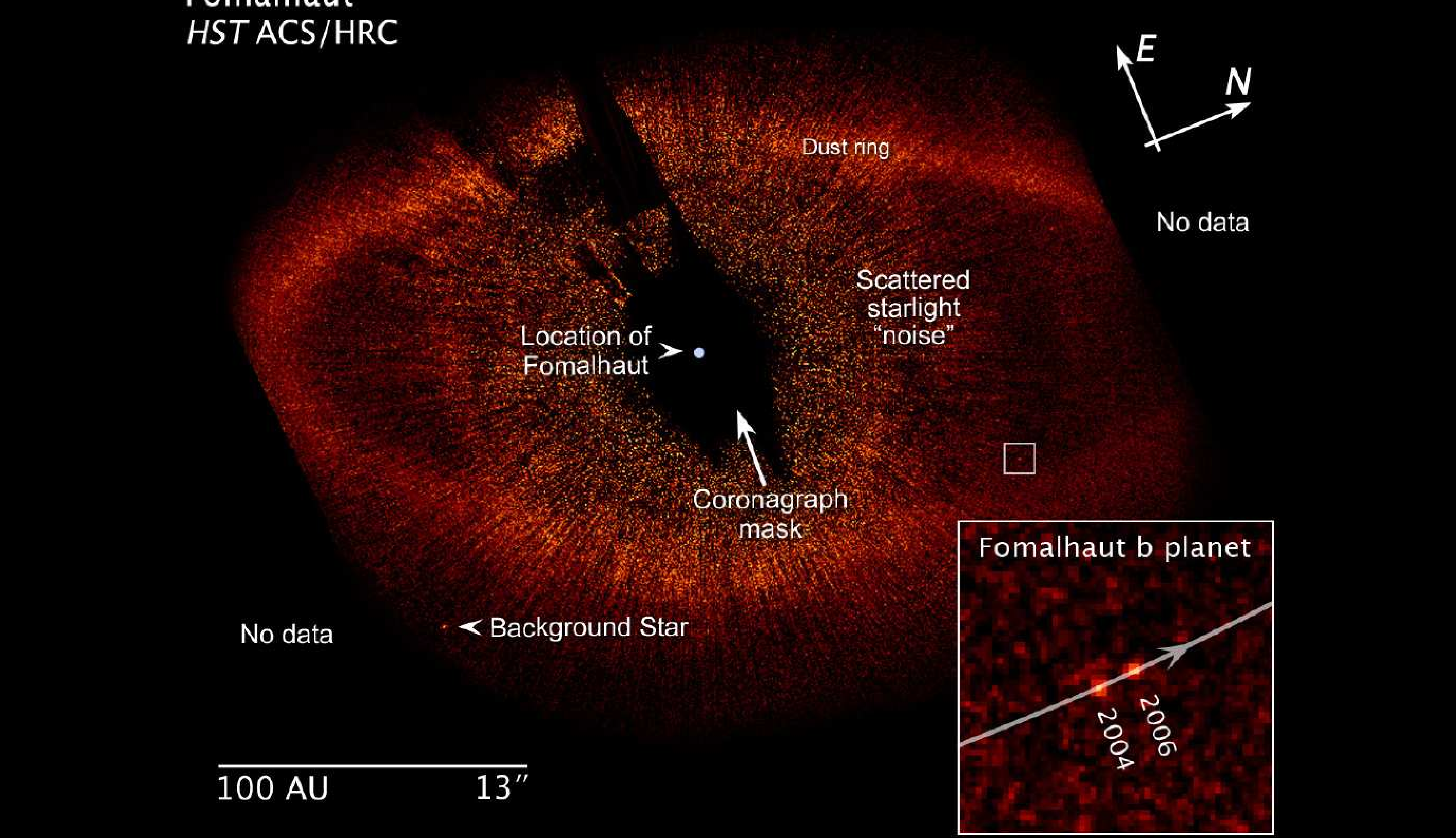
JWST adds 3×sharper imaging to AB≃31.5 mag (1 firefly from Moon) from 1–29μm wavelength, tracing young and old stars + dust.

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



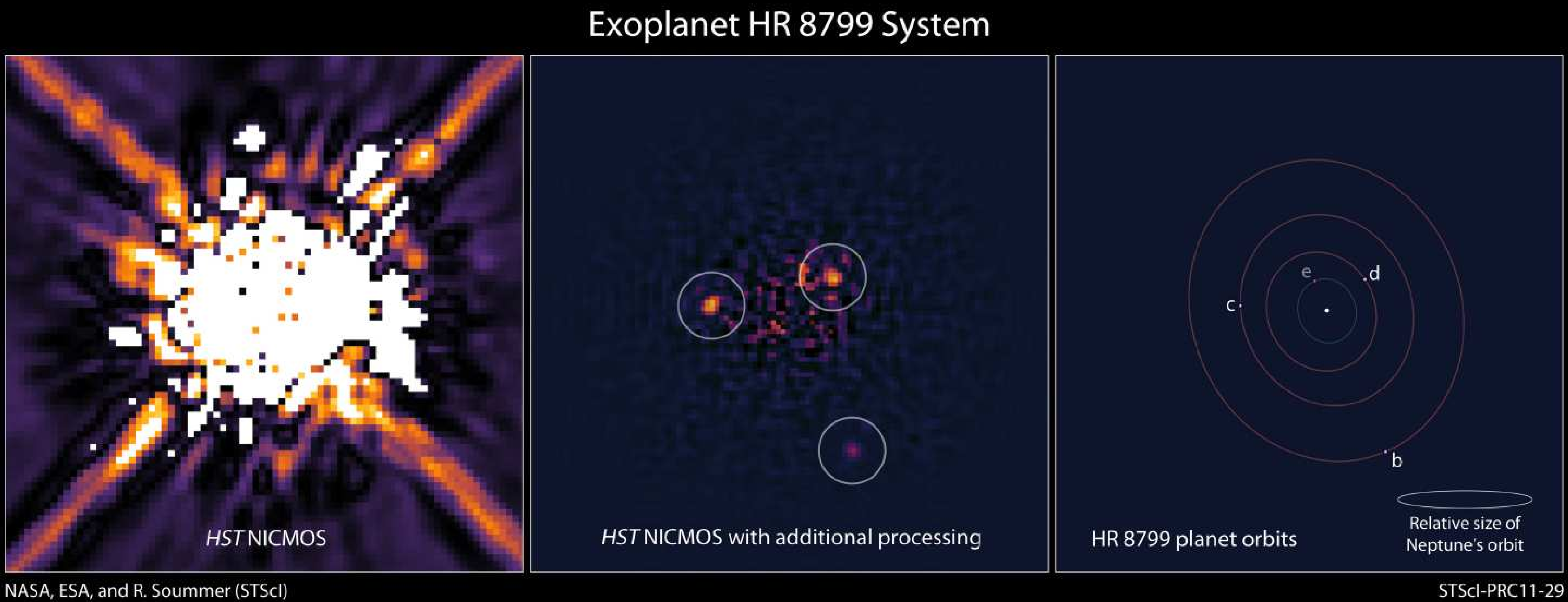
NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"

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



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

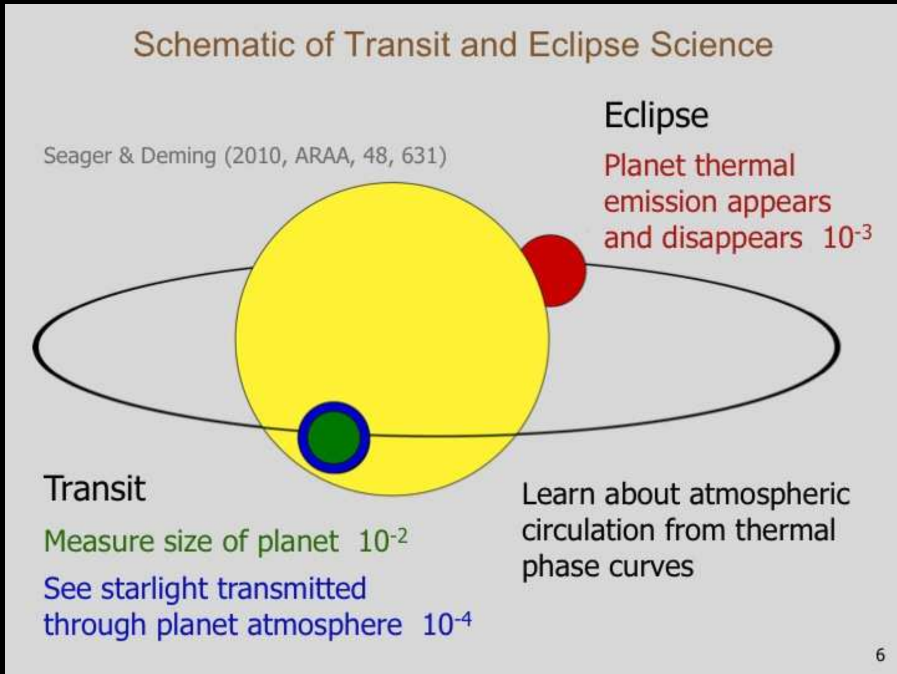
JWST can find such planets much closer in for much farther stars.

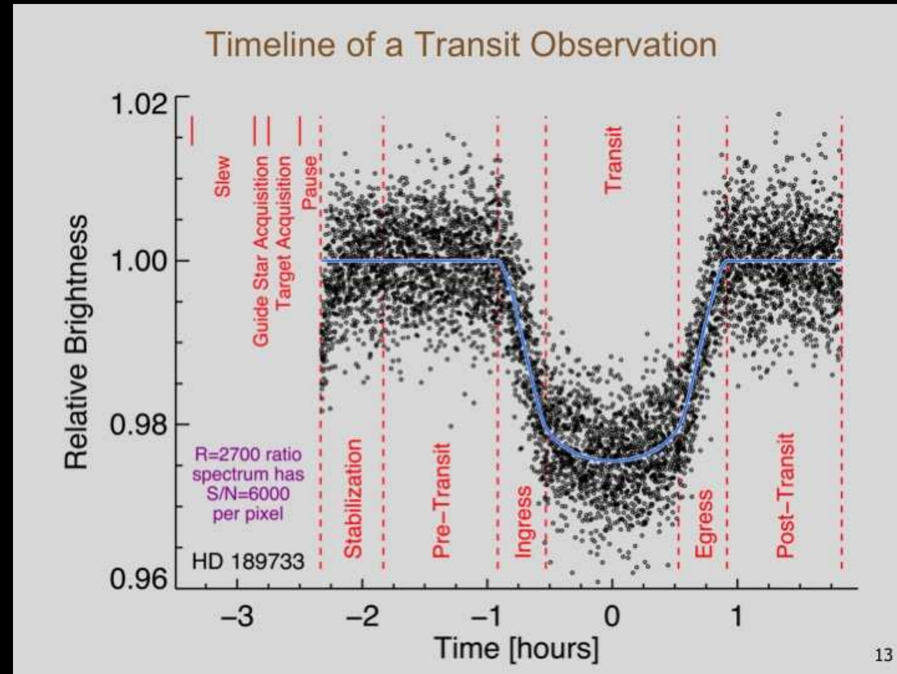


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star!

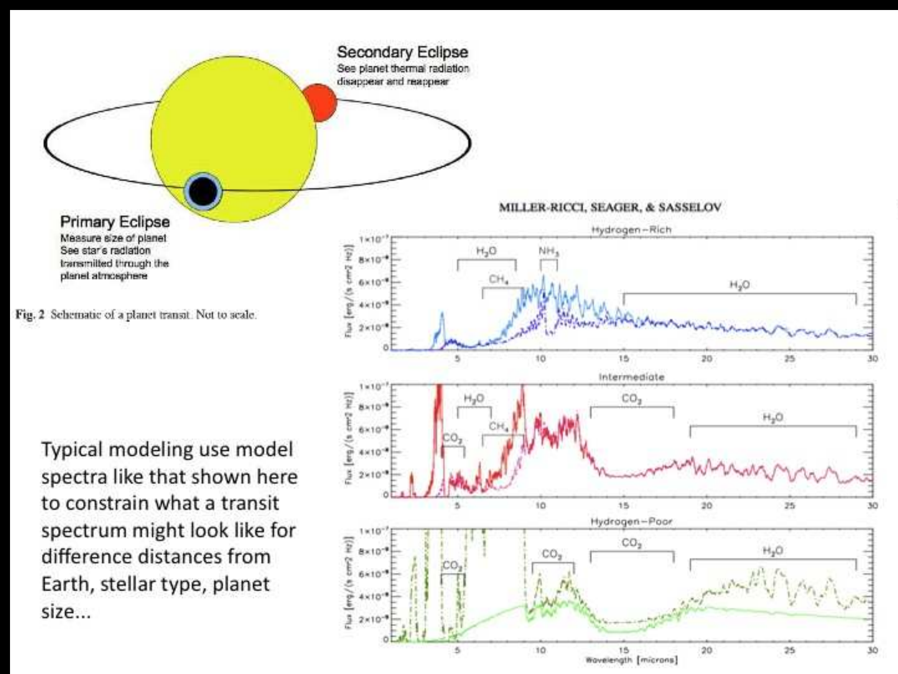
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



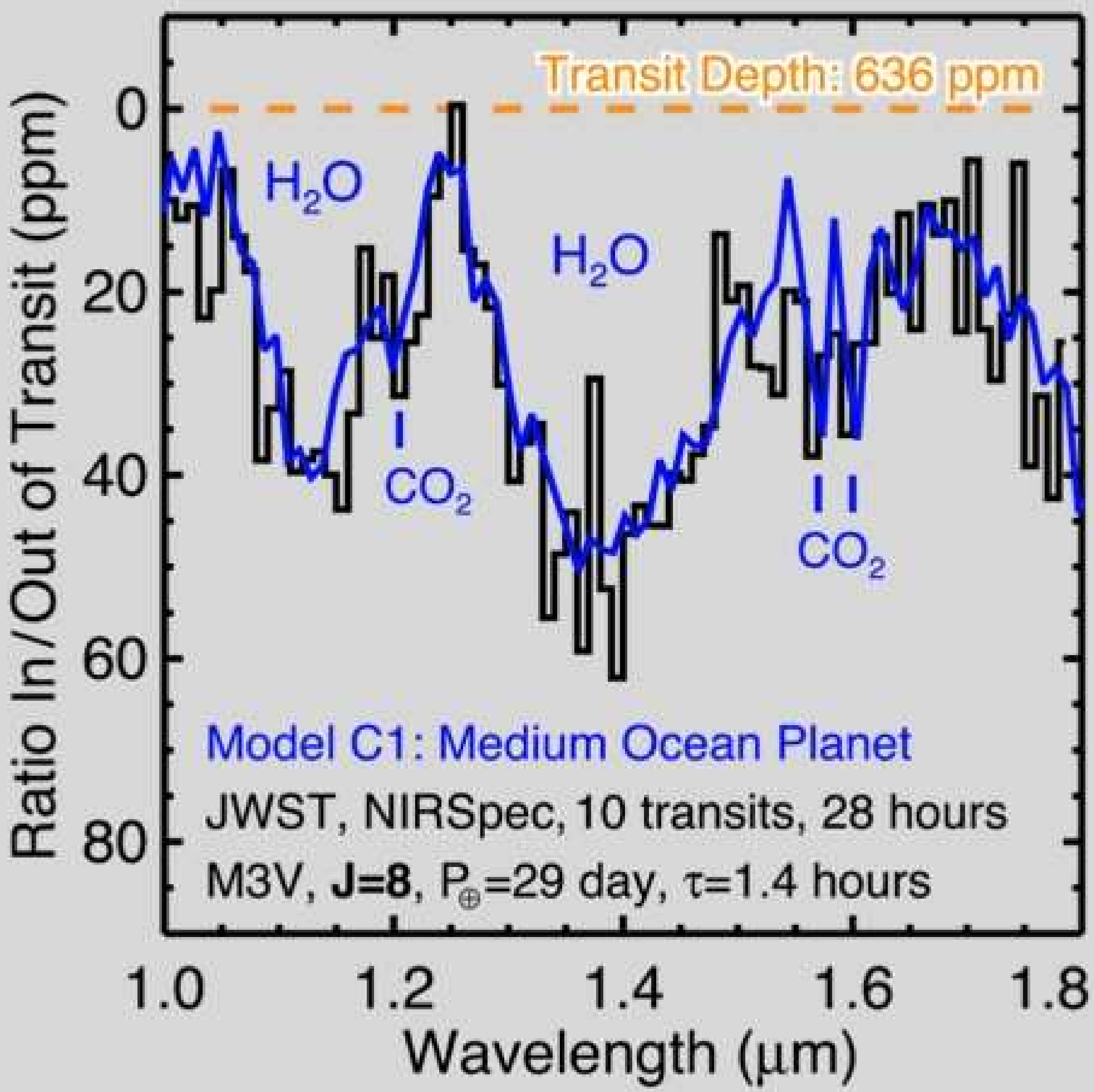


JWST can do very precise photometry of transiting Earth-like exoplanets.



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

Transit Spectrum of Habitable "Ocean Planet"



JWST IR spectra can find water and 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_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, p. 1965 (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

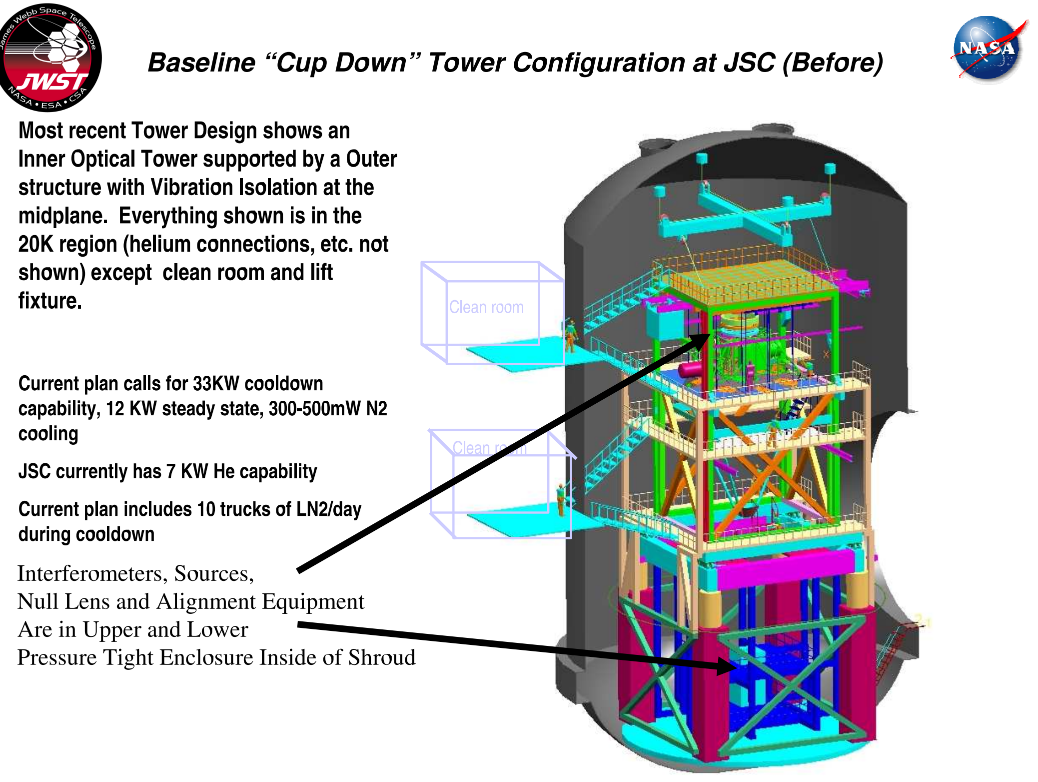
Life-sized JWST model, at NASA/GSFC with the whole JWST Project ...

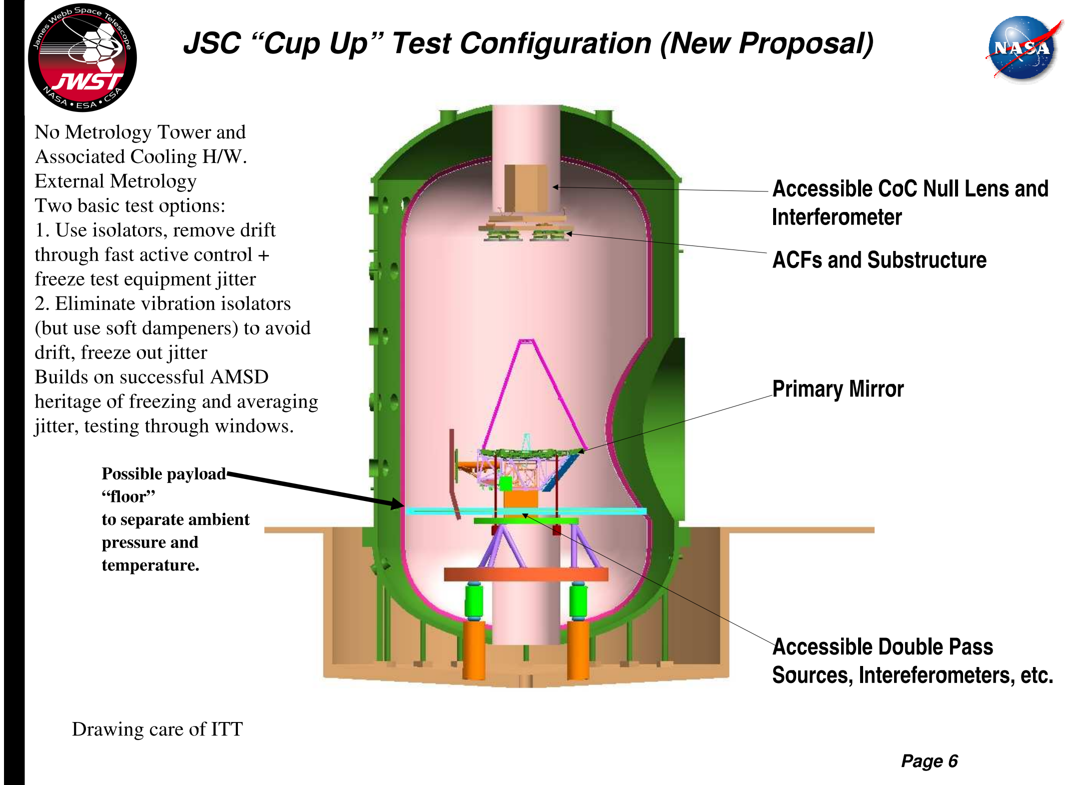
Life-sized JWST model, at NASA/GSFC Friday afternoon after 5 pm ...

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







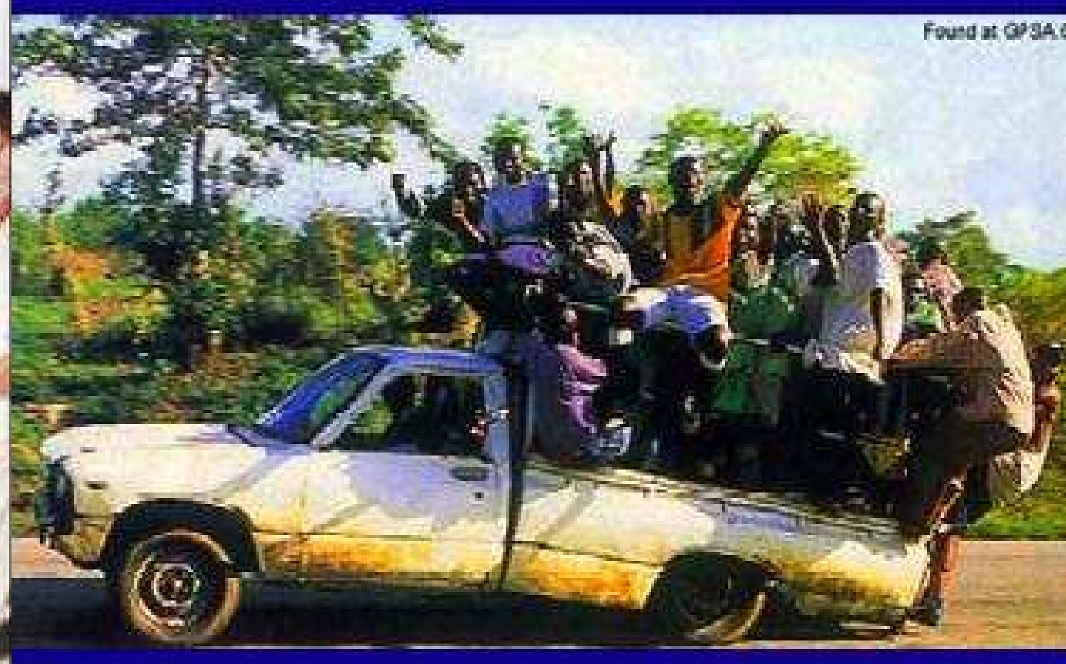
JWST underwent several significant replans and risk-reduction schemes:

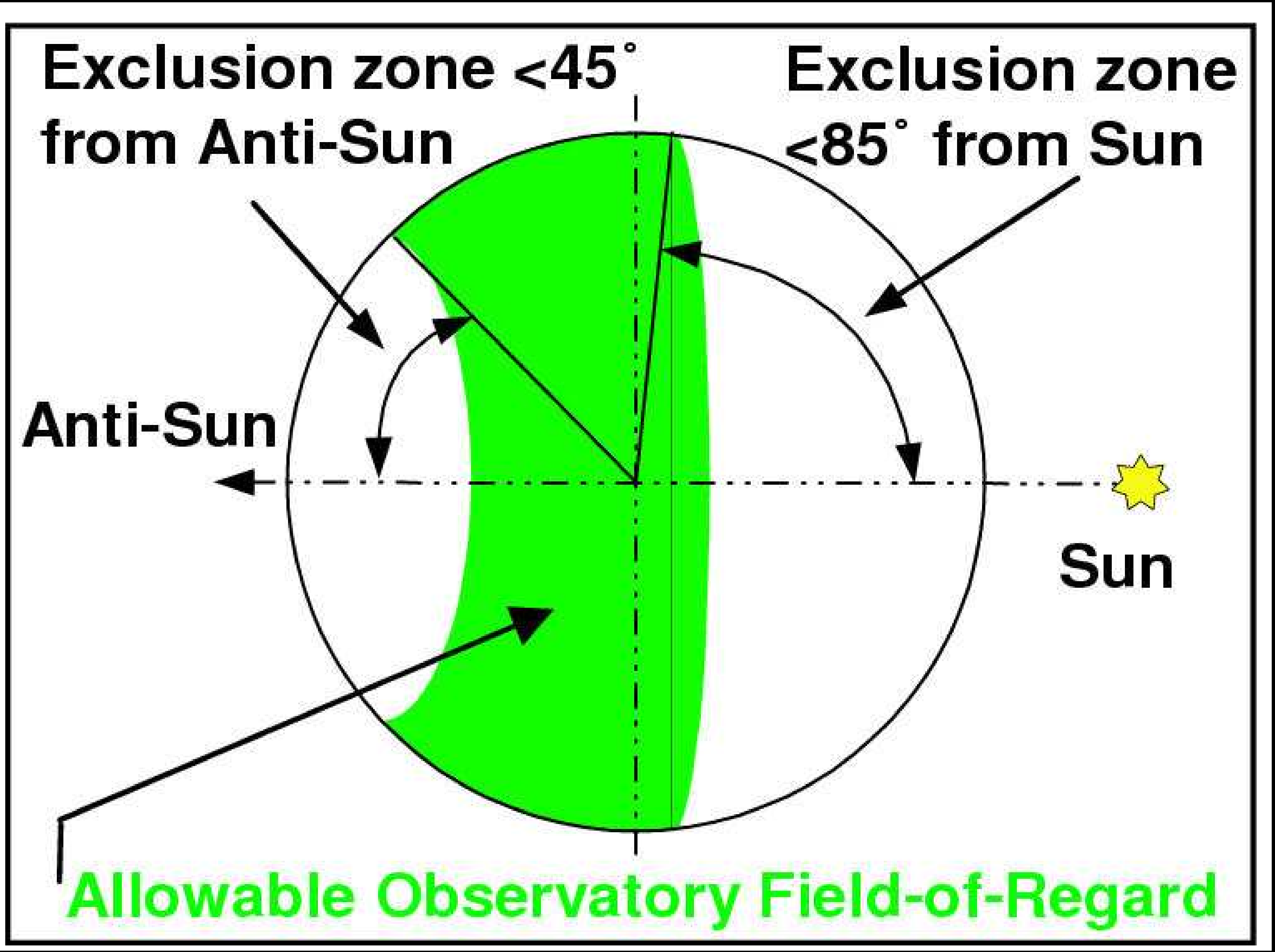
- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: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

What the Scientists See:

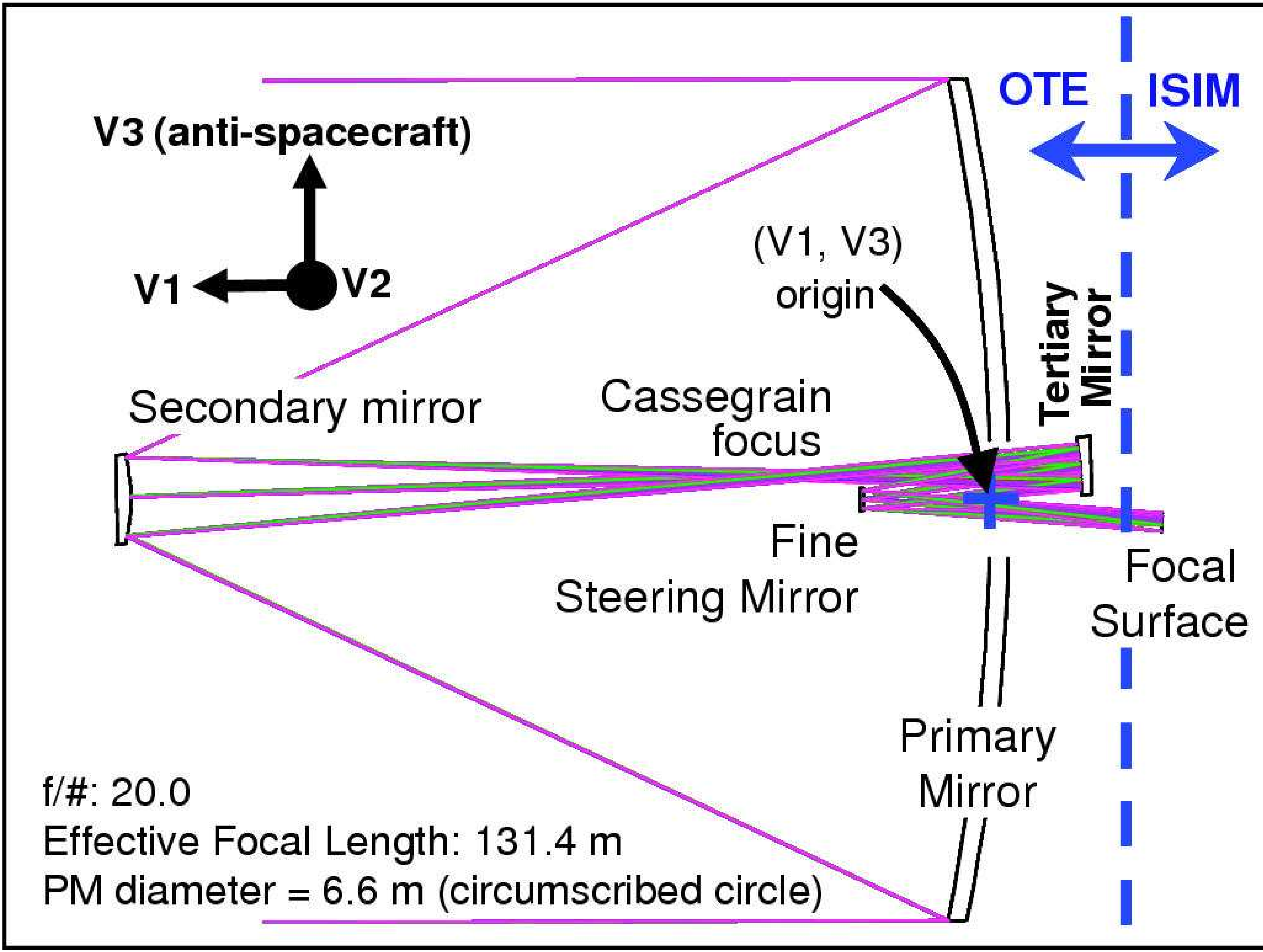
What the Project Manager Sees:

The Happy Balance

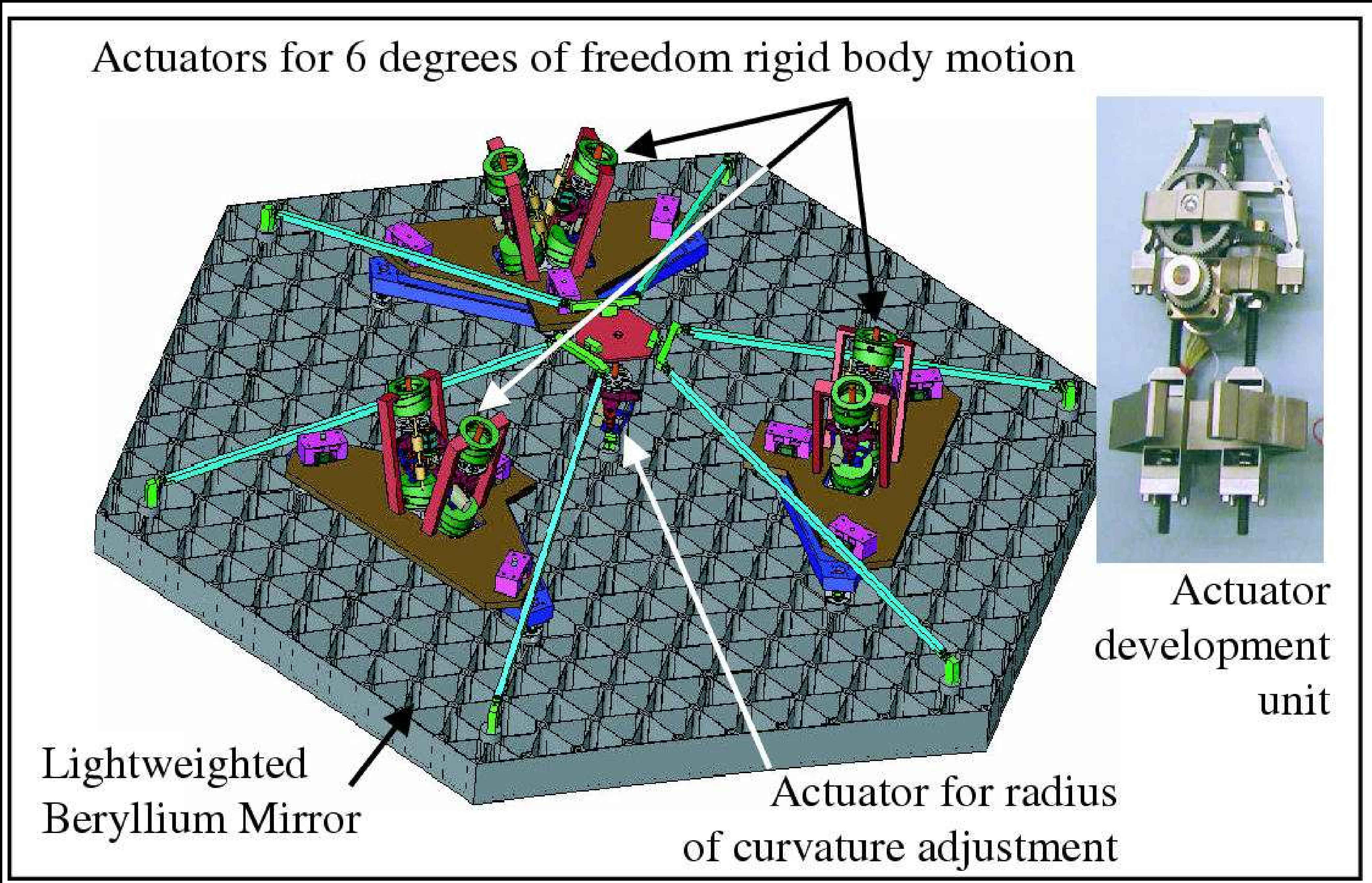




JWST can observe segments of sky that move around as it orbits the Sun.

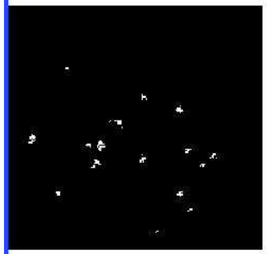
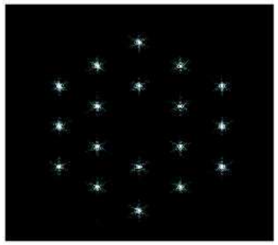
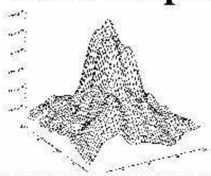
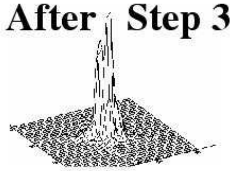
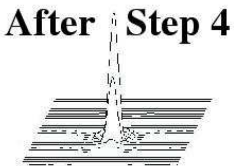


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary
Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)



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

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

		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.

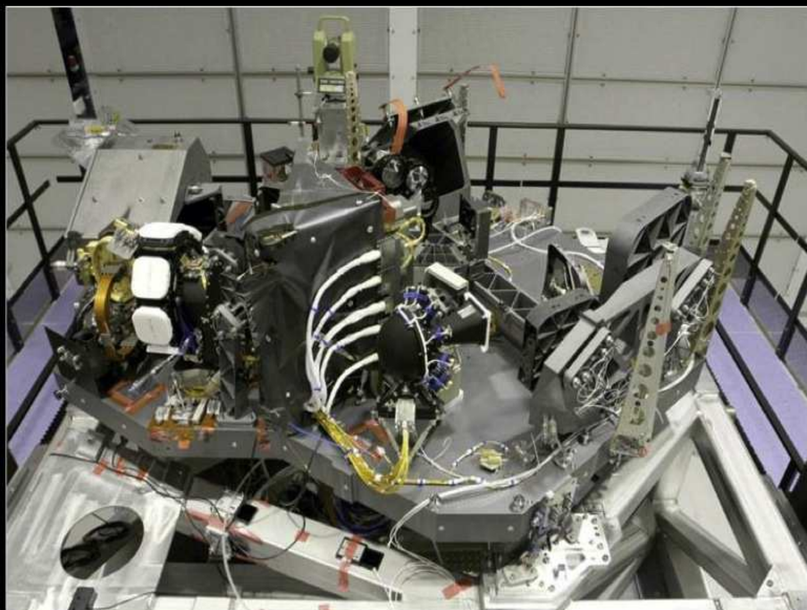
ETU NIRCam

Flight Fine Guidance Sensor

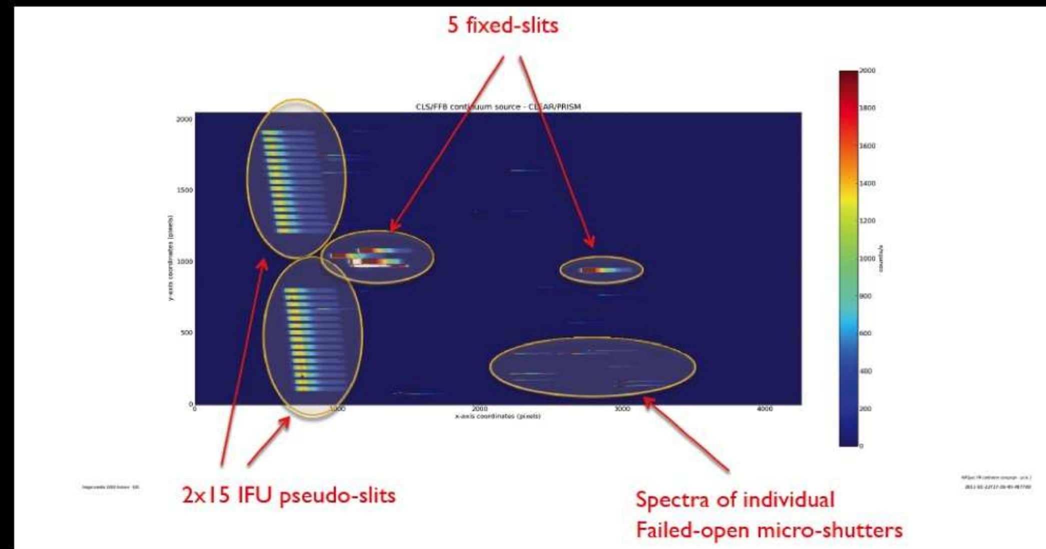
JWST's short-wavelength (0.6–5.0μm) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& 1–5 μm grisms) — built by CSA (Montreal).
- Both to be delivered to GSFC in 2012.

FLIGHT NIRSpec



Flight NIRSpec First Light

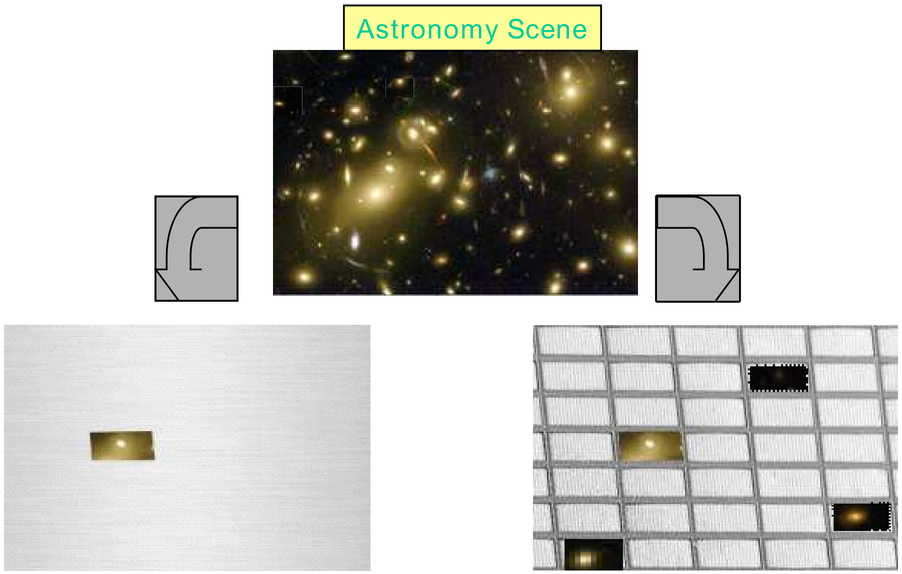


JWST's short-wavelength (0.6–5.0μm) spectrograph:

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

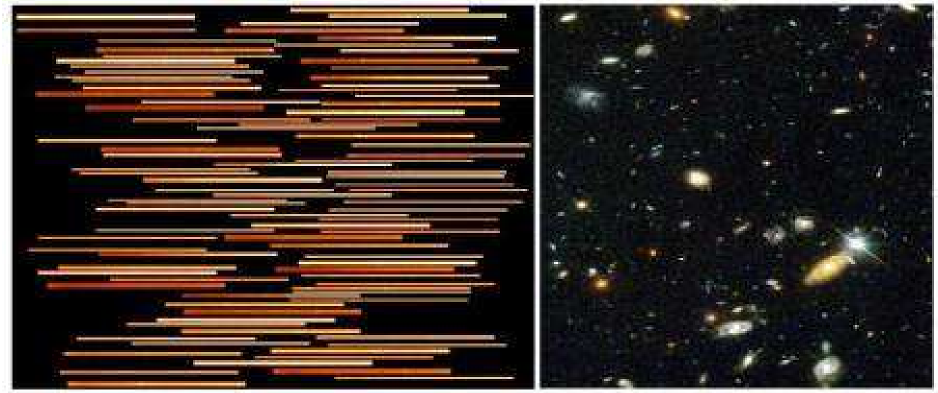
Final delivery to NASA/GSFC in 2012.

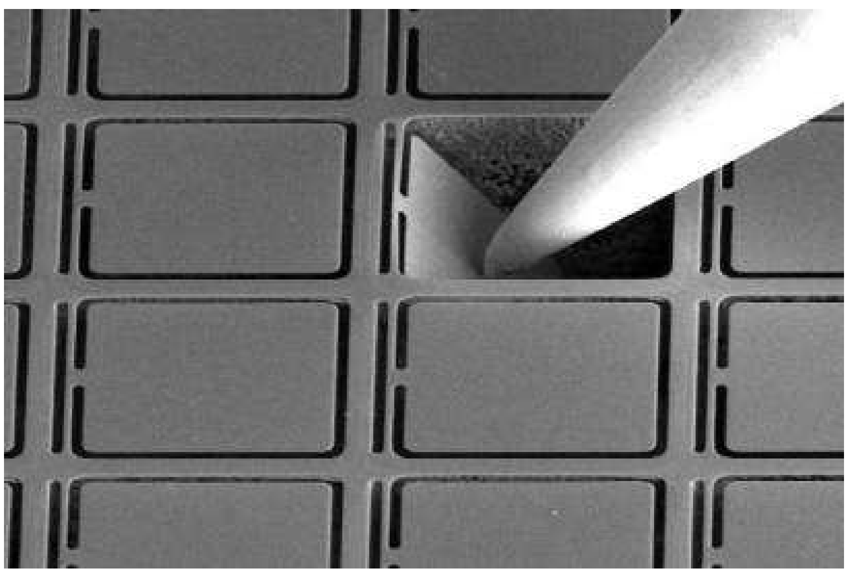
Micro Shutters



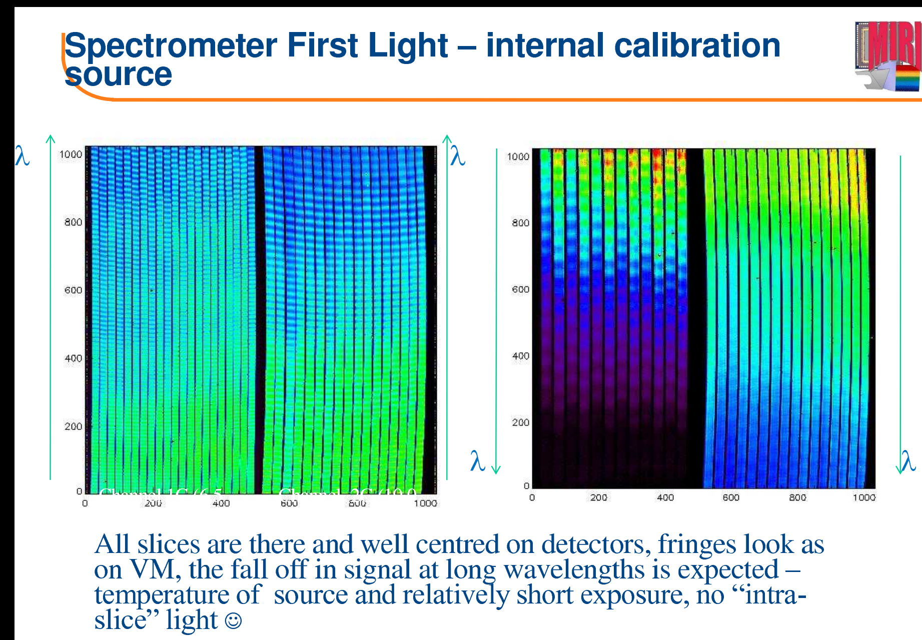
Metal Mask/Fixed Slit

Shutter Mask





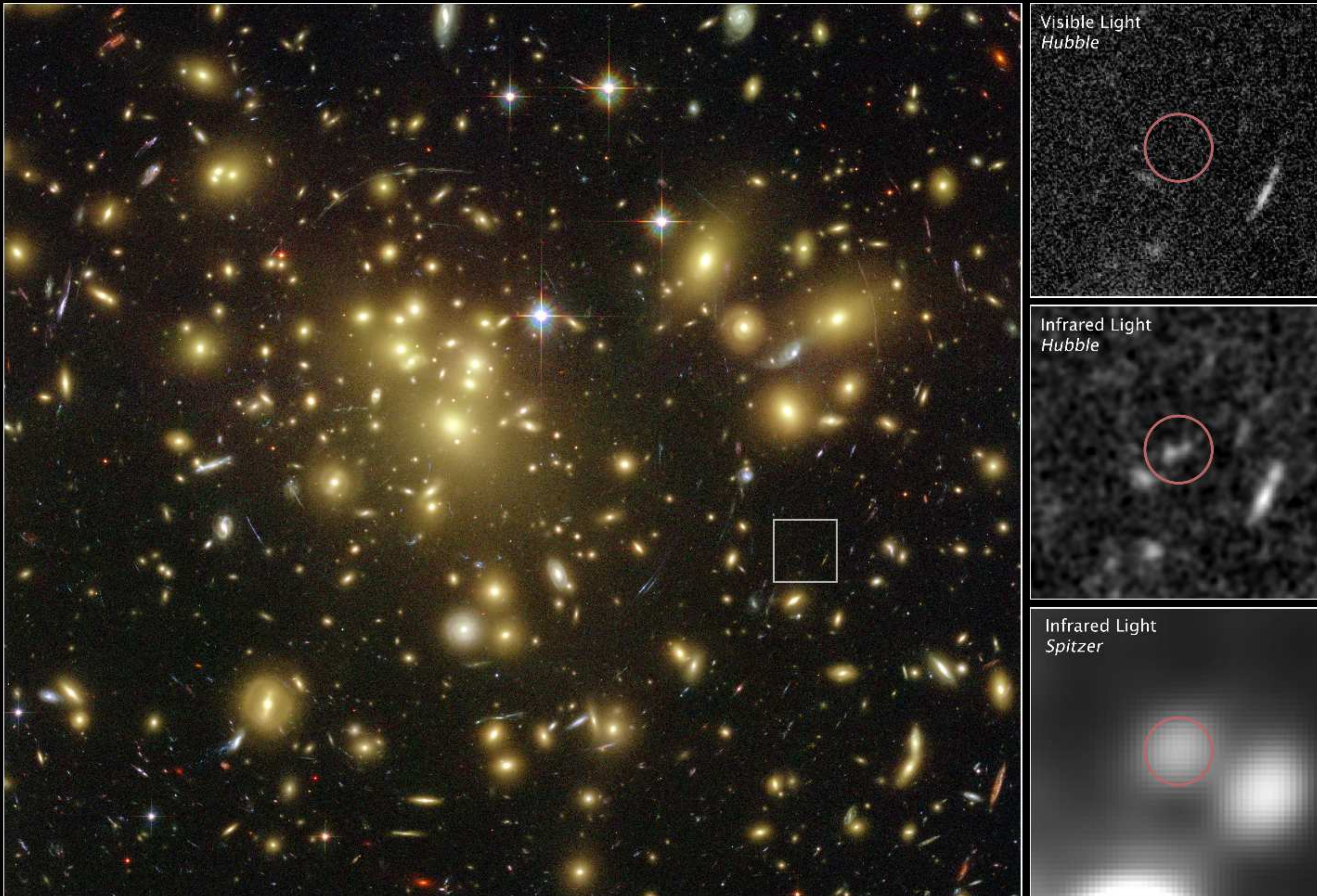
Flight MIRI



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

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

Final delivery to NASA/GSFC in 2011.



Distant Gravitationally Lensed Galaxy ▪ Galaxy Cluster Abell 1689

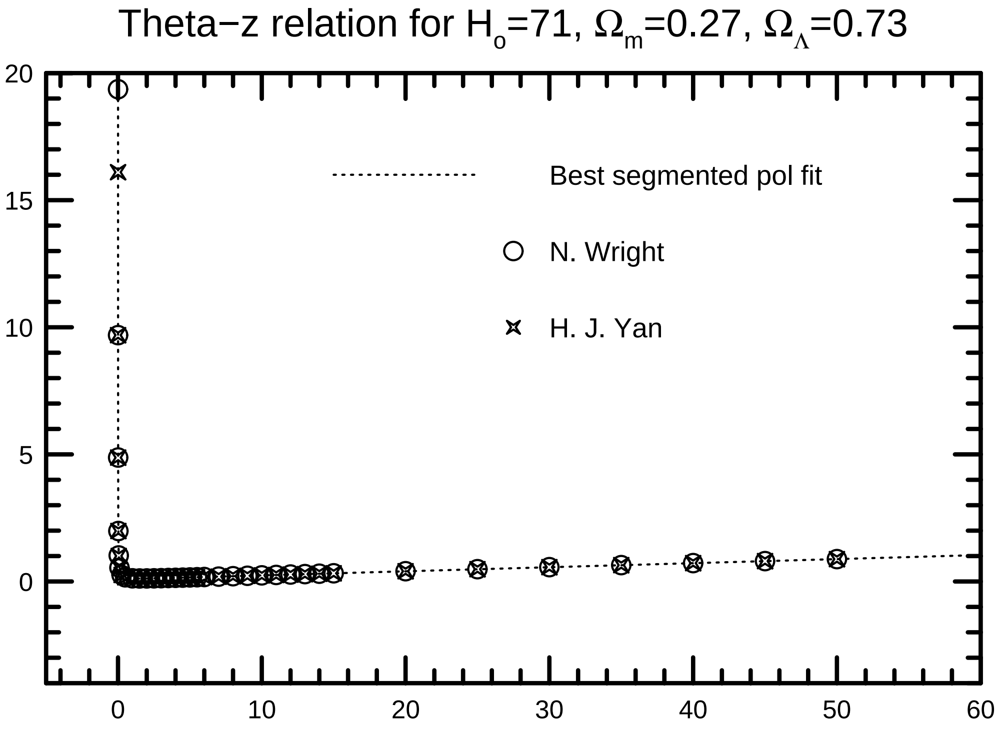
Hubble Space Telescope ▪ ACS/WFC NICMOS

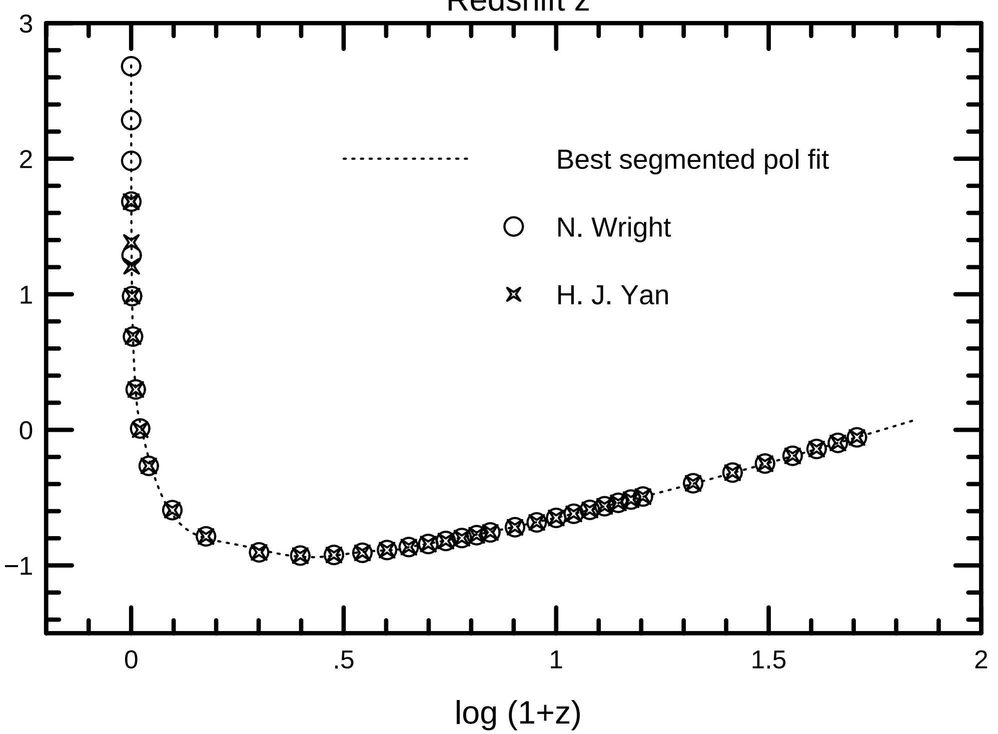
NASA, ESA, and L. Bradley (JHU), R. Bouwens (UCSC), H. Ford (JHU), and G. Illingworth (UCSC)

STScI-PRC08-08a

(0) Intro: Cosmic Expansion and Contents of the Universe

Expansion ⇒ redshift	$\lambda_{obs} = \lambda_{rest} \, . \, (1+z)$
Hubble's Law:	$D \simeq v \, / \, H_o \simeq (c/H_o) \, . \, z = R_o \, . \, z$
Cosmic Content:	inside $R_0=(c/H_0) \simeq 13.73$ Glyr:
	$[\, t_{univ} = (211 \pm 1 \, !) \, . \, (t_{dino}=65 \text{ Myr}) \,]$
Photons (light):	$N_{h\nu} \sim 10^{89}$
Baryons (atoms):	$N_b \sim 10^{80}$
η=Photons/Baryons	$\eta \sim 10^9 \Longrightarrow$ He/H ratio $= 0.235$
Energy Density:	as fraction of critical closure density:
Baryons (atoms):	$\Omega_b = \rho_b/\rho_{crit} \simeq 0.042$
Dark Matter:	$\Omega_d = \rho_d/\rho_{crit} \simeq 0.20$
Dark Energy (Λ):	$\Omega_\Lambda = \rho_\Lambda/\rho_{crit} \simeq 0.76$
(Supermassive) black holes:	$\rho_{smbh}/\rho_{crit} \simeq 0.0001$
Total	$\Omega_{tot}=\rho_{tot}/\rho_{crit} \simeq 1.00 \pm 0.02$





Angular size θ vs. redshift z in Lambda cosmology:

$H_0 = 73$ km/s/Mpc, $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$.

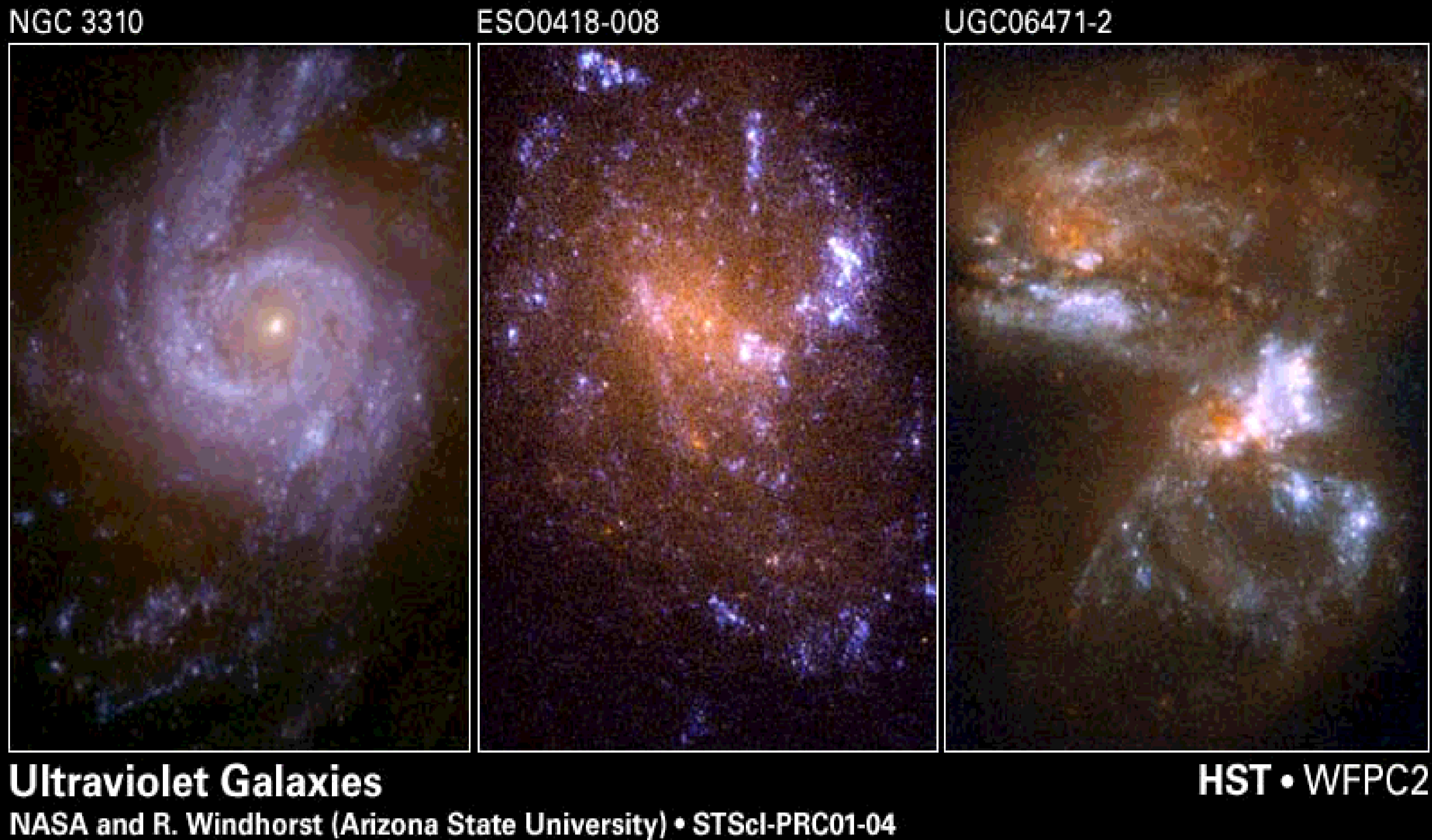
- $\theta \propto 1/\mathrm{z}$ for z$\lesssim$0.05 (small angle approximation).

- $\theta \propto$ z for z $\gtrsim$3 !!

- Objects appear larger with redshift for z$\gtrsim$1.65 !!

But angular sizes of rigid rods are nearly constant for all redshifts 0.5 $\lesssim$z $\lesssim$10 !

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

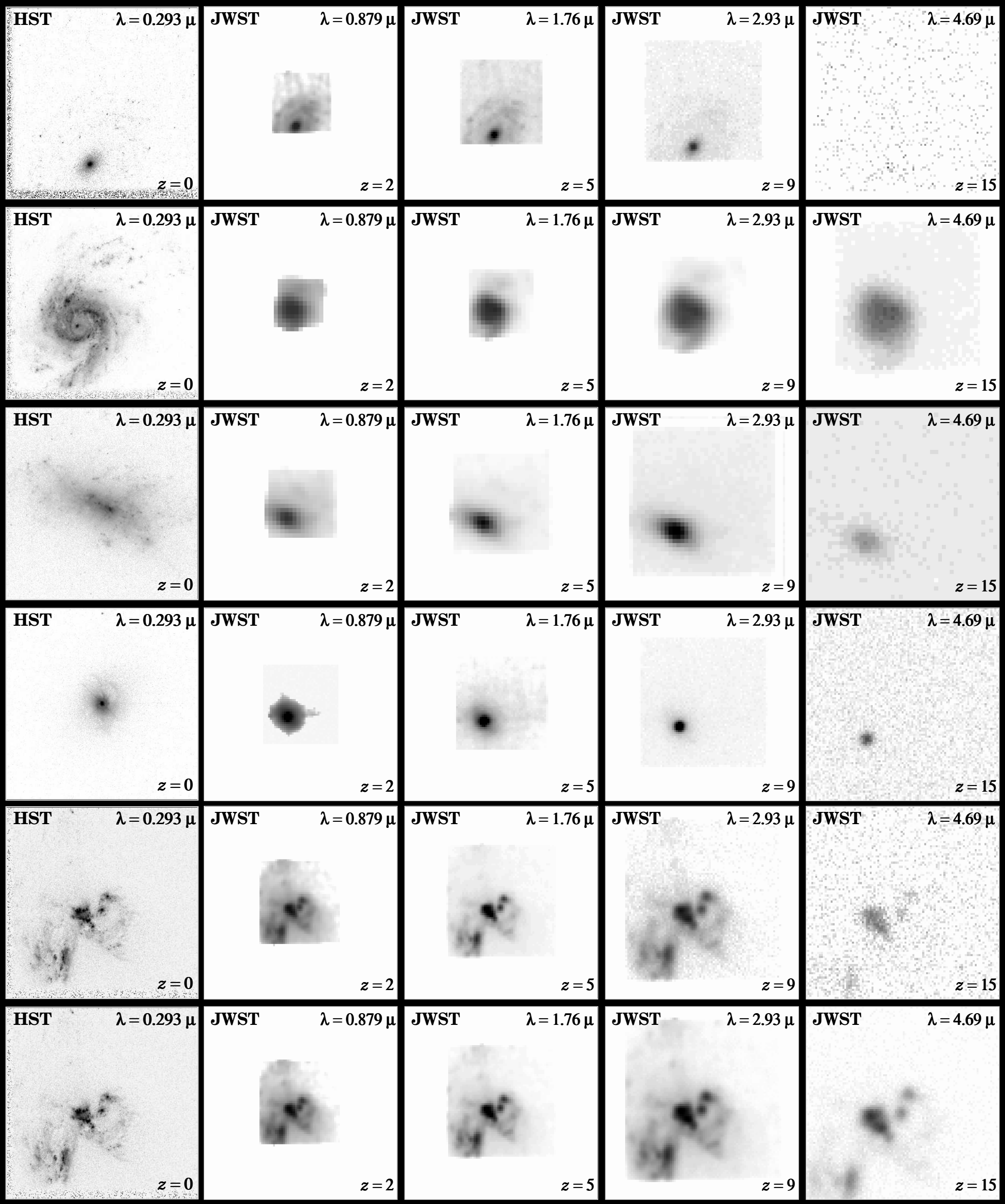


• The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

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

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

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



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

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

Visible to JWST at very high z are:

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