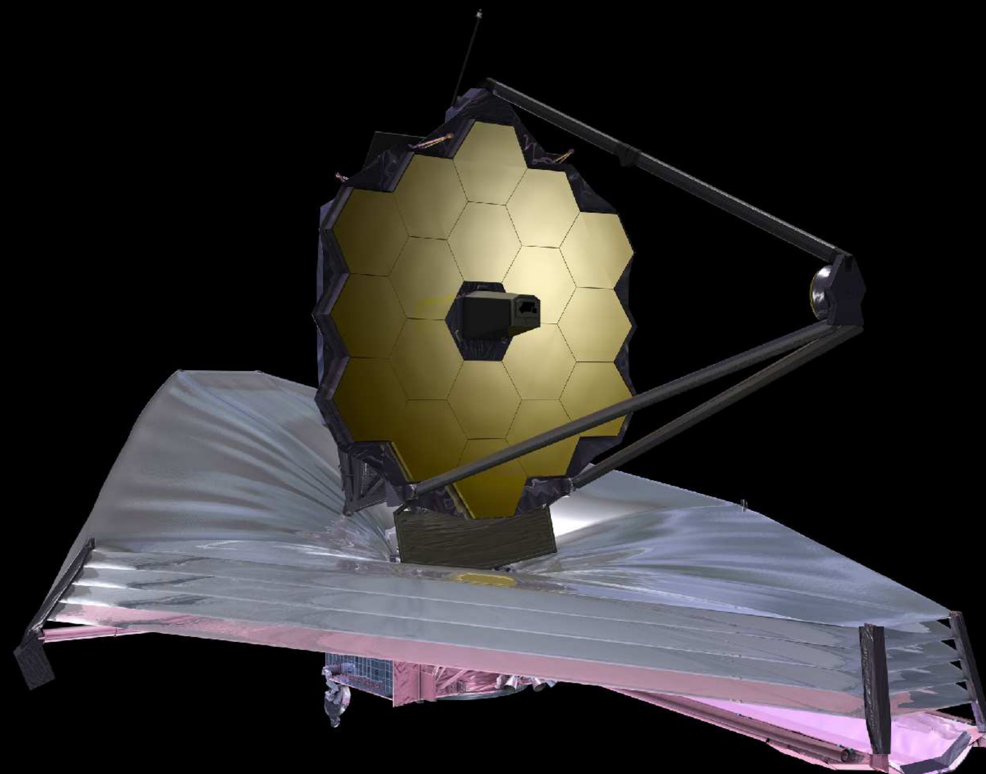
Beyond Hubble: From Exoplanets to the First Stars with the James Webb Space Telescope

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

Collaborators: S. Cohen, L. Jiang, R. Jansen (ASU), C. Conselice (UK), S. Driver (OZ), & H. Yan (U-MO)

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



2014 Bullitt Lecture, University of Louisville, Department of Physics & Astronomy,

and the Gheens Science Hall & Rauch Planetarium (Louisville; KY). Thursday October 16, 2014.

All presented materials are ITAR-cleared.

Outline

- (1) The Best of Hubble: Recent results from the Hubble Space Telescope (HST) and its Wide Field Camera 3 (WFC3).
- (2) Measuring Star-birth and Earth-like exoplanets
- (3) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.
- (4) What is the James Webb Space Telescope (JWST)?
- (5) How can JWST measure the Epochs of First Light & Reionization?
- (6) Summary and Conclusions.

Sponsored by NASA/HST & JWST

ARIZONA STATE UNIVERSITY

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

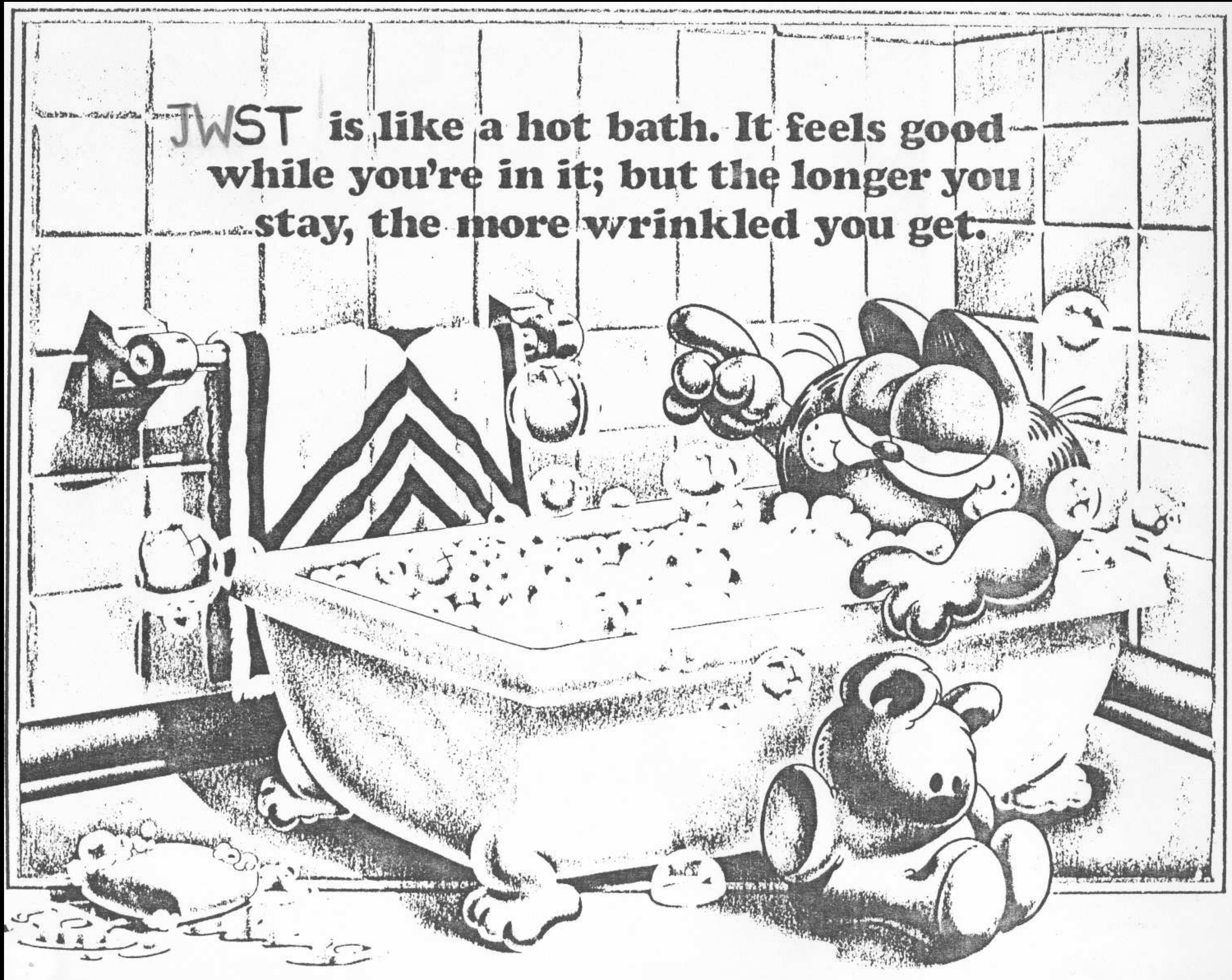
Don't do this at home!! :)

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

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

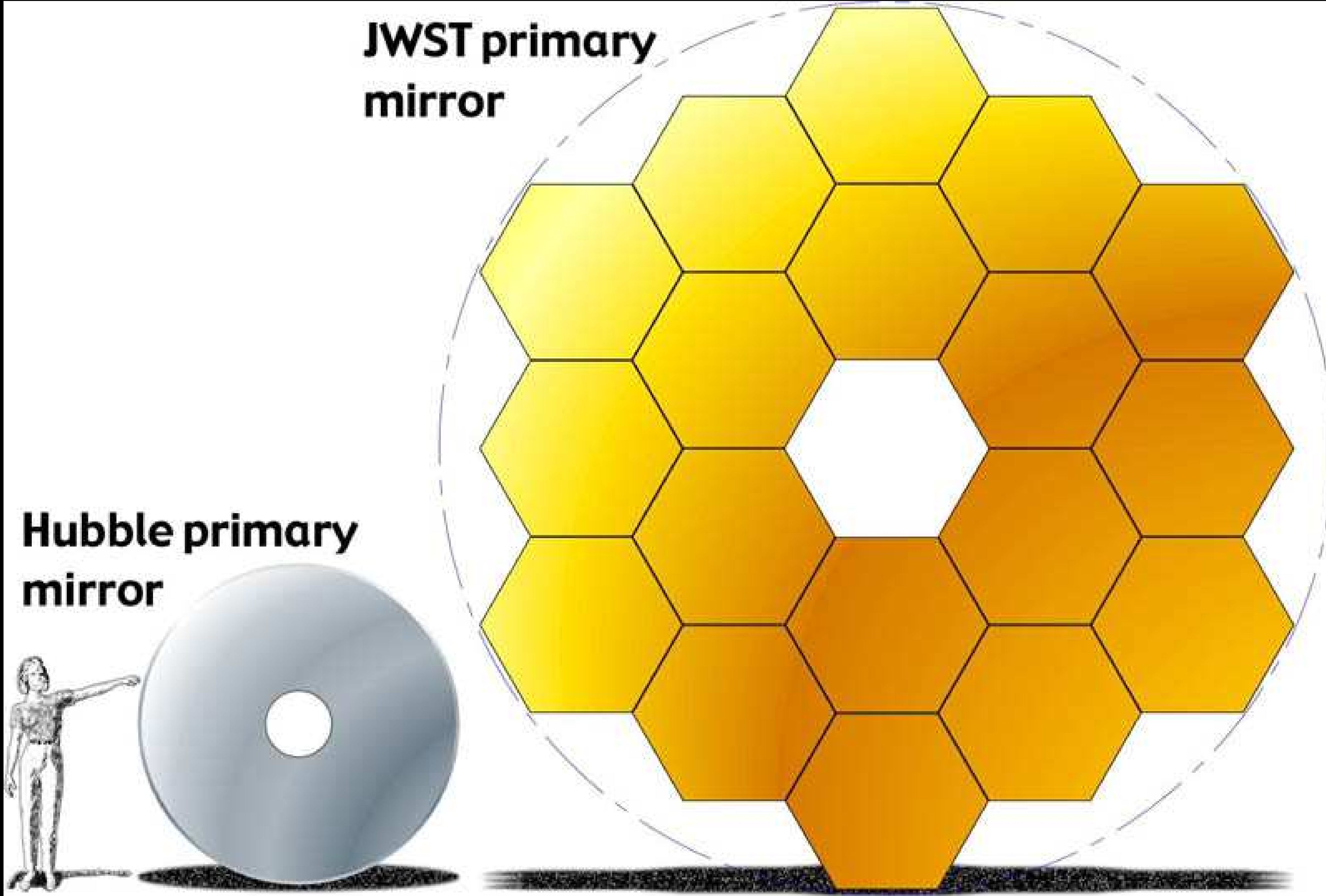
Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2014.

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



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

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

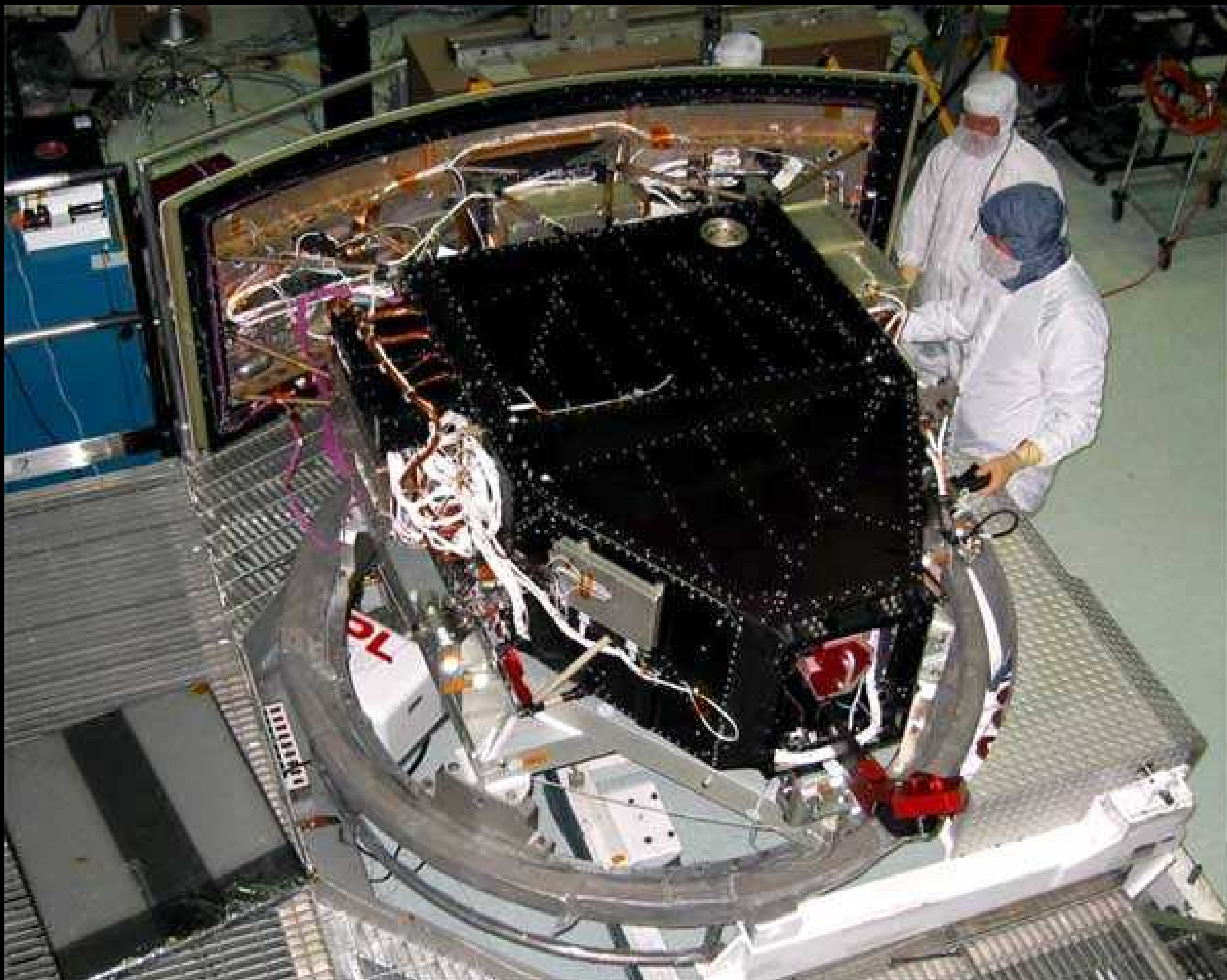


JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:

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

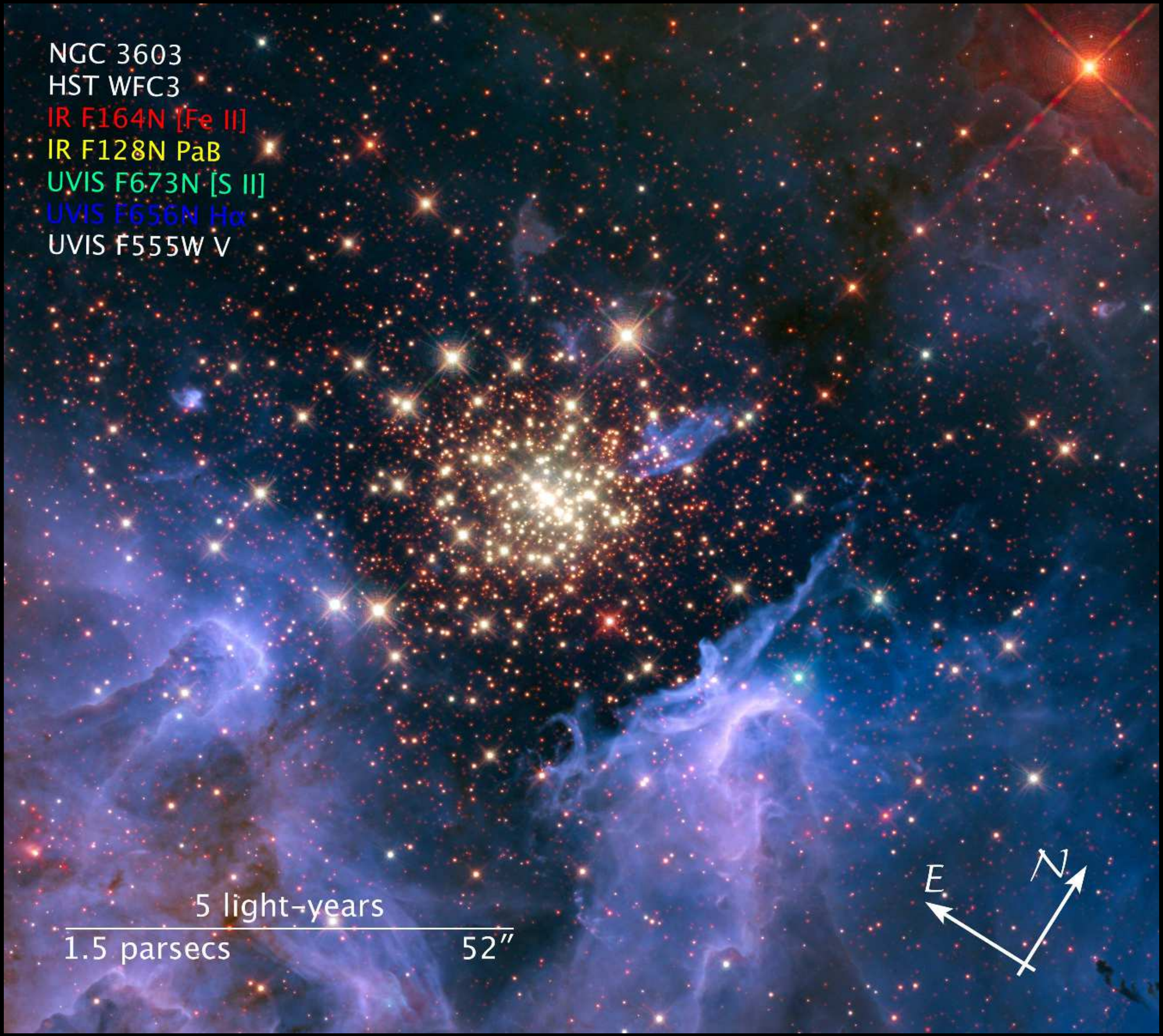
(1) The Best of Hubble: Recent results from the HST and its WFC3

WFC3: Hubble's new Panchromatic High-Throughput Camera

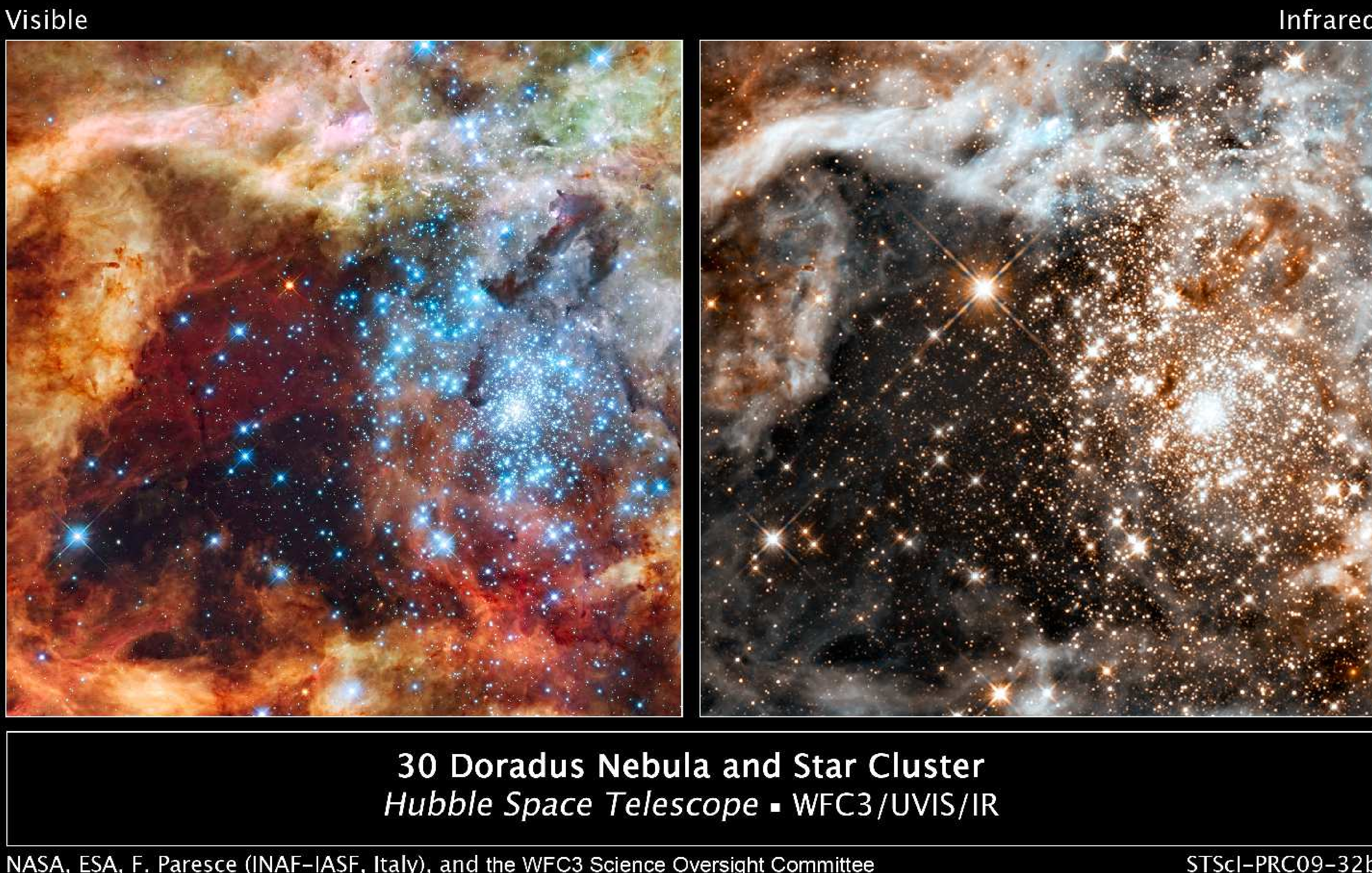


HST WFC3 and its IR channel: a critical pathfinder for JWST science.

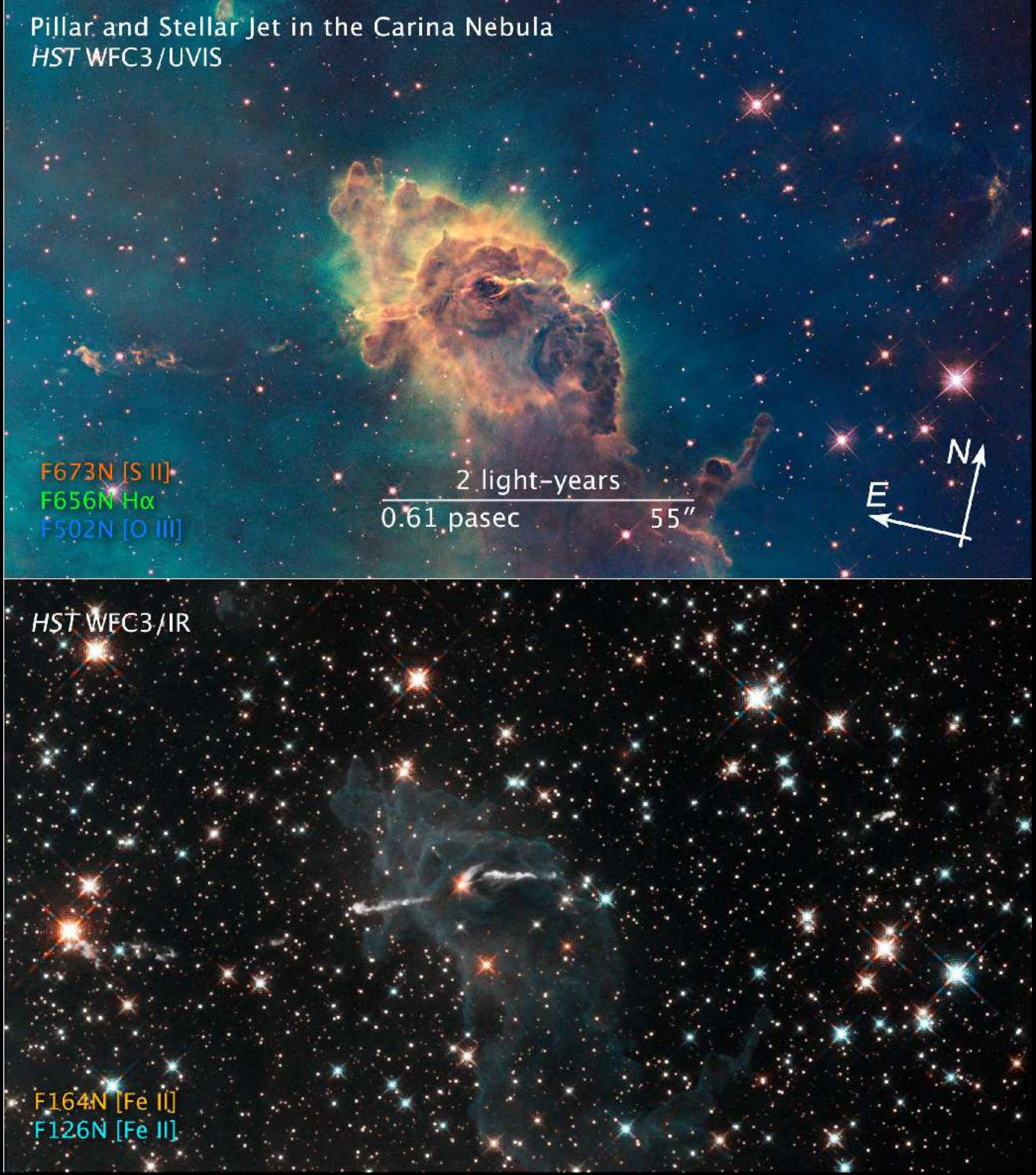
(2) Measuring Star-birth and Earth-like exoplanets

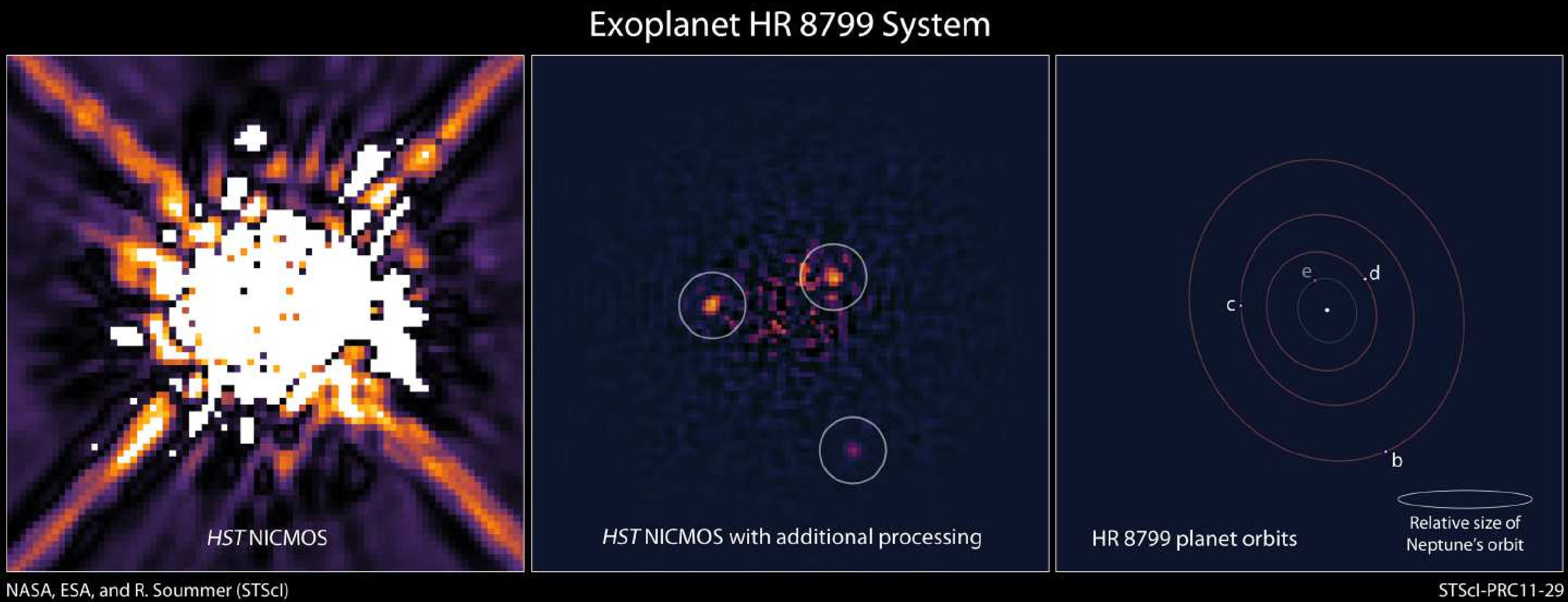


NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"



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

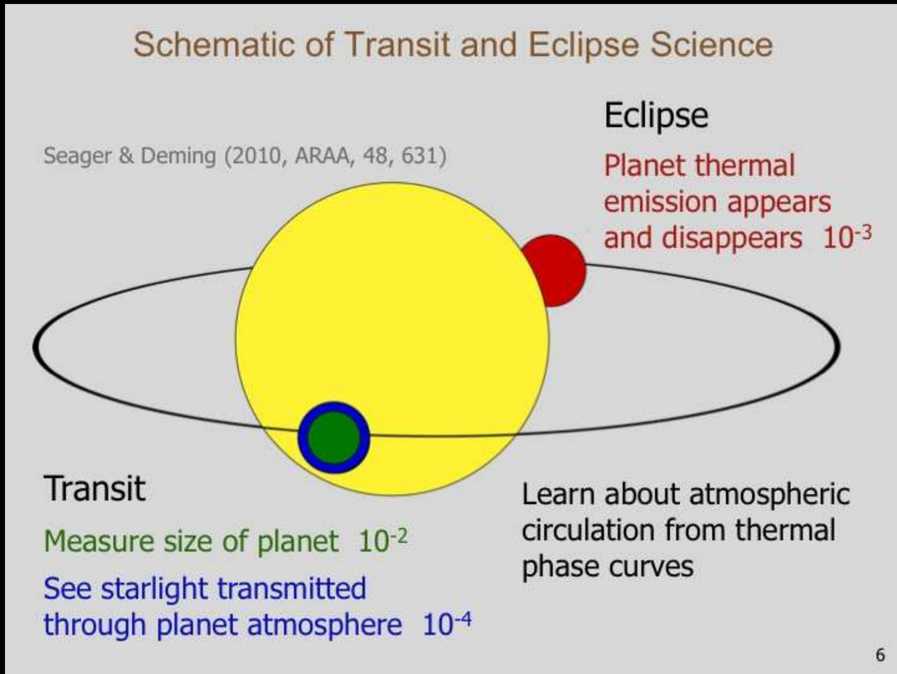

Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS
F673N [S II]
F656N Hα
F502N [O III]
2 light-years
0.61 pasec
55″
N
E
HST WFC3/IR
F164N [Fe II]
F126N [Fe II]

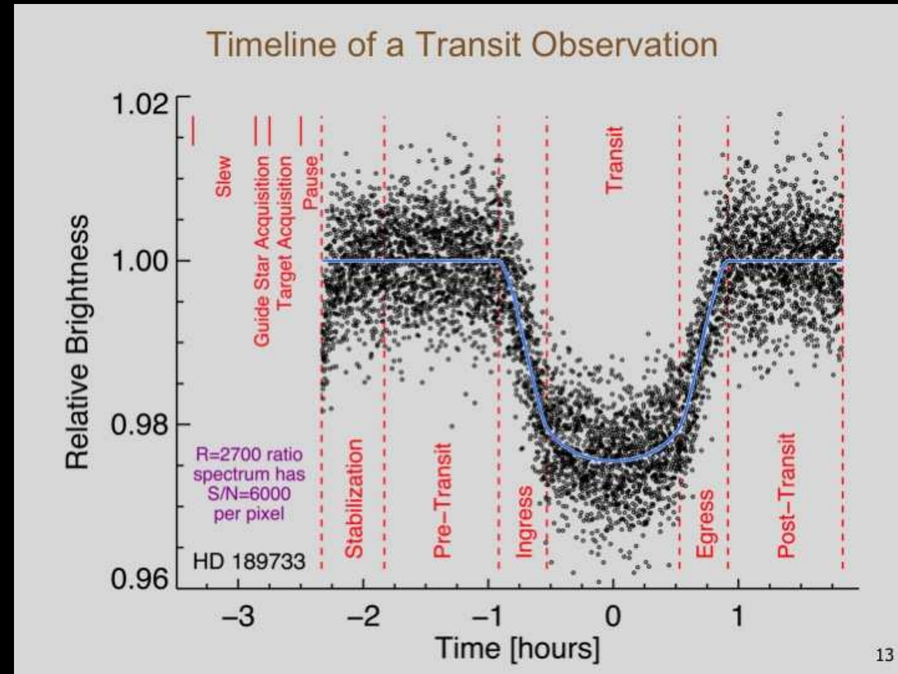


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star!

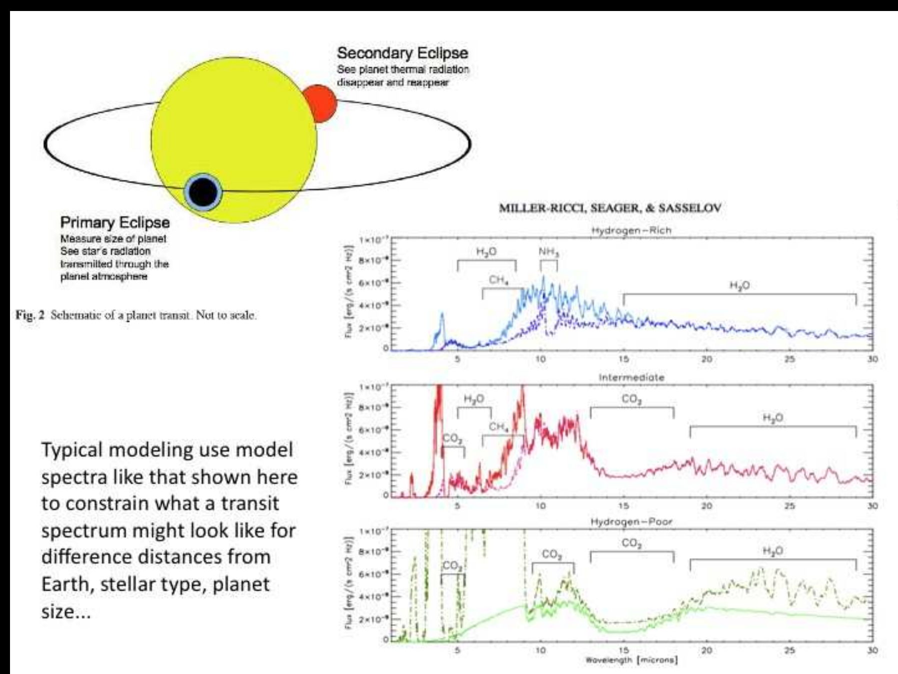
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



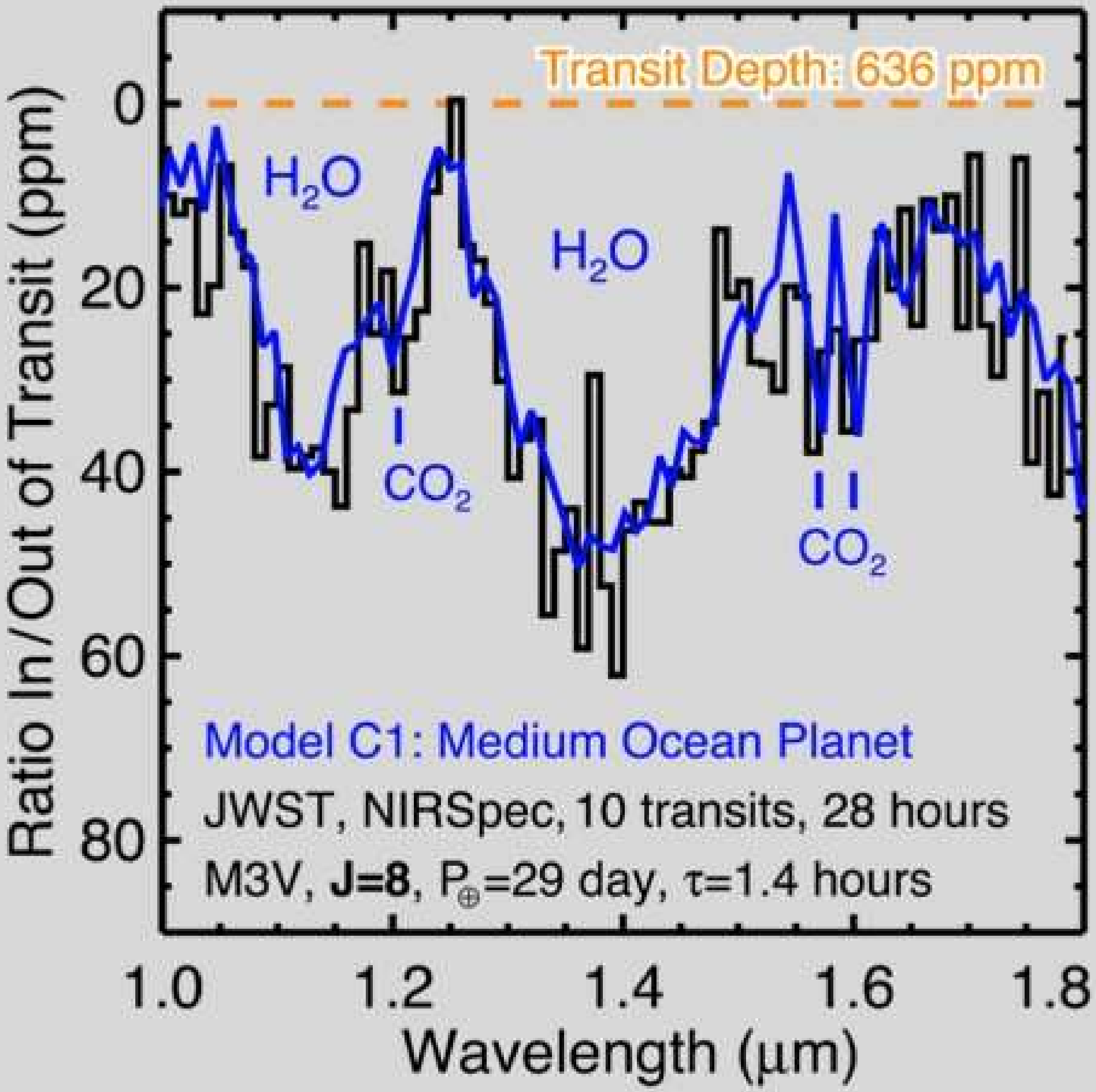


JWST can do very precise photometry of transiting Earth-like exoplanets.



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

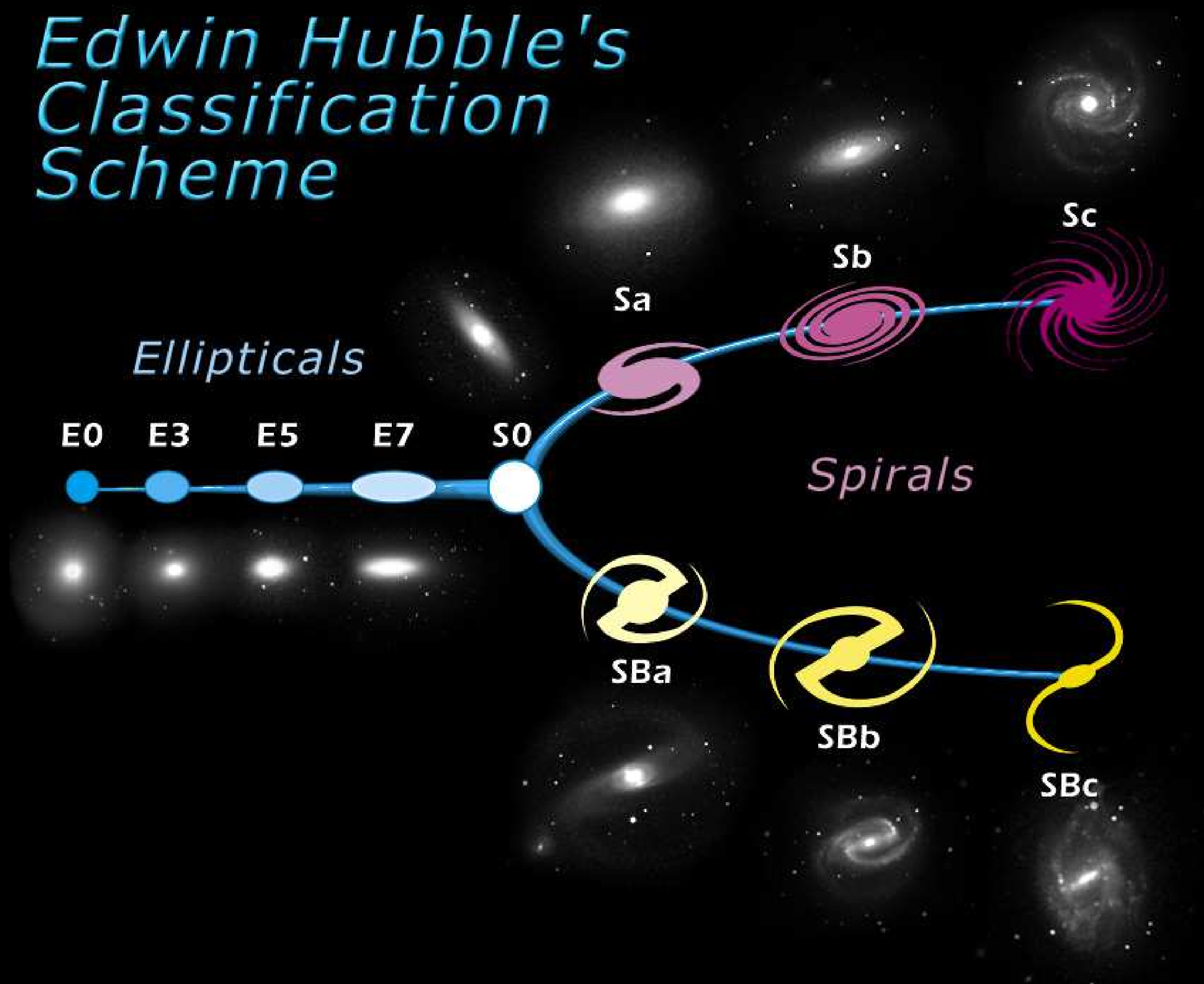
Transit Spectrum of Habitable "Ocean Planet"



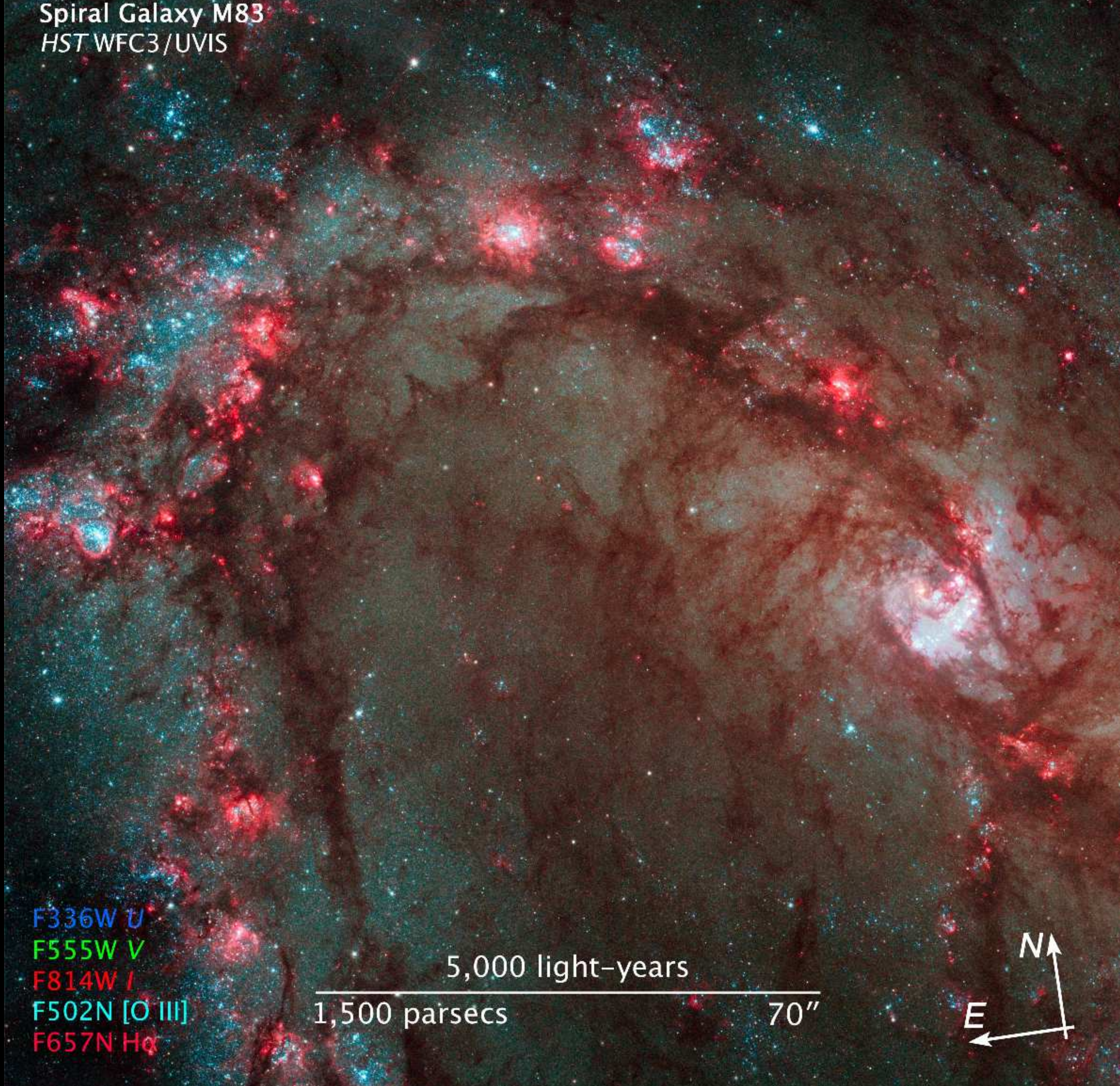
JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.

This is currently the Holy Grail of Exoplanet science.

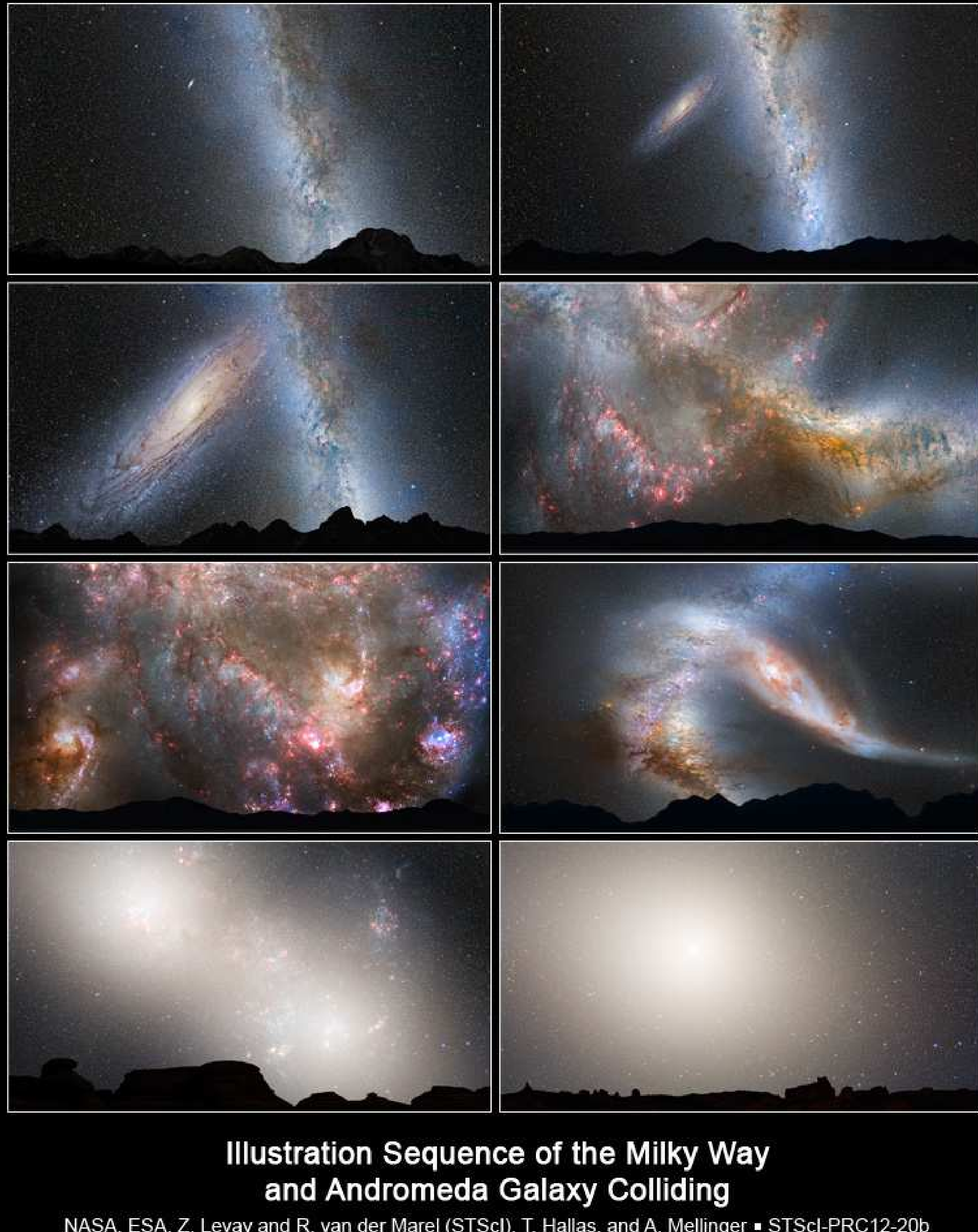
(3) HST turned the classical Hubble sequence upside down!



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

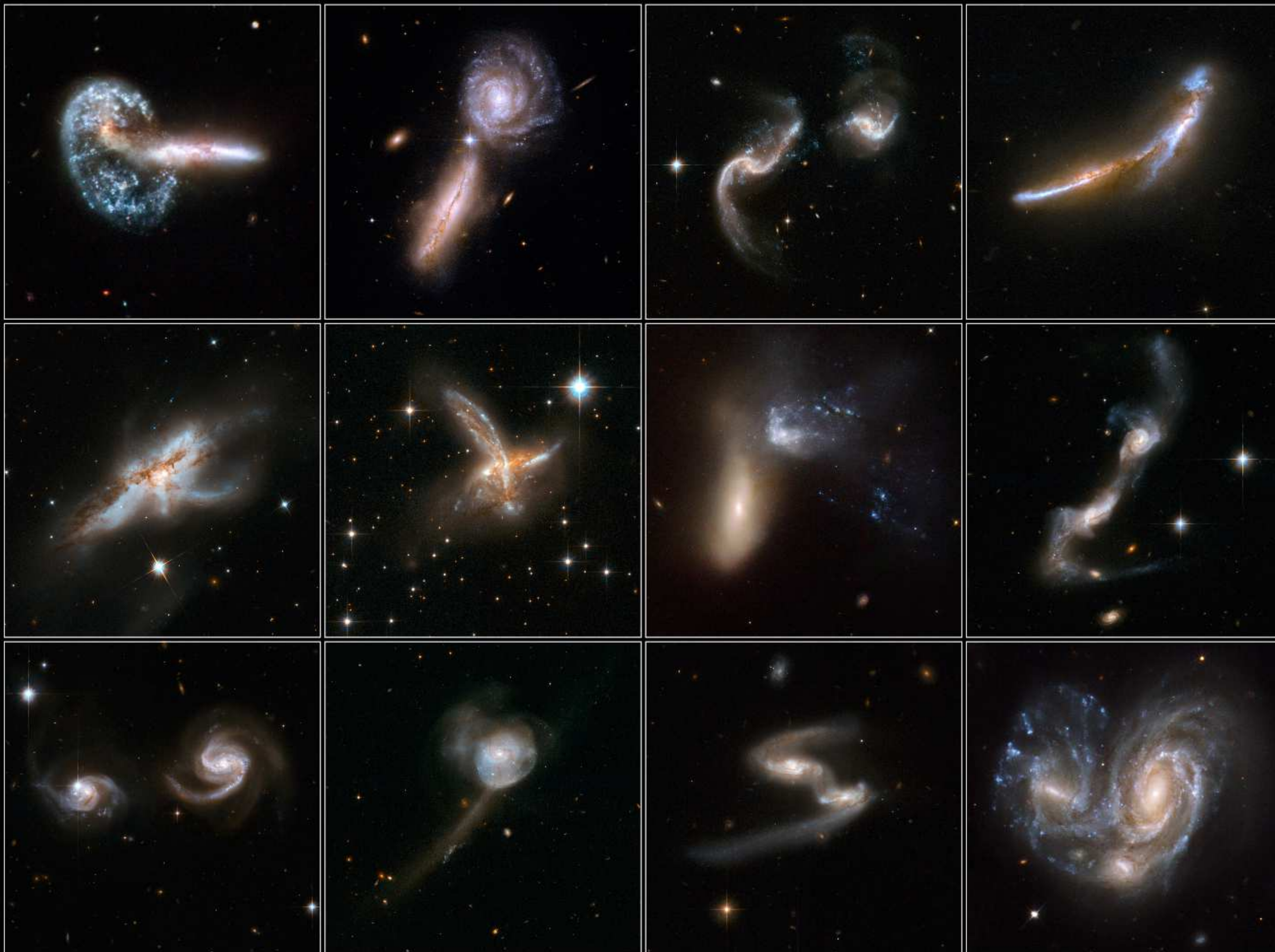
HST Antenna galaxy: Prototype of high redshift, star-forming, major merger?



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

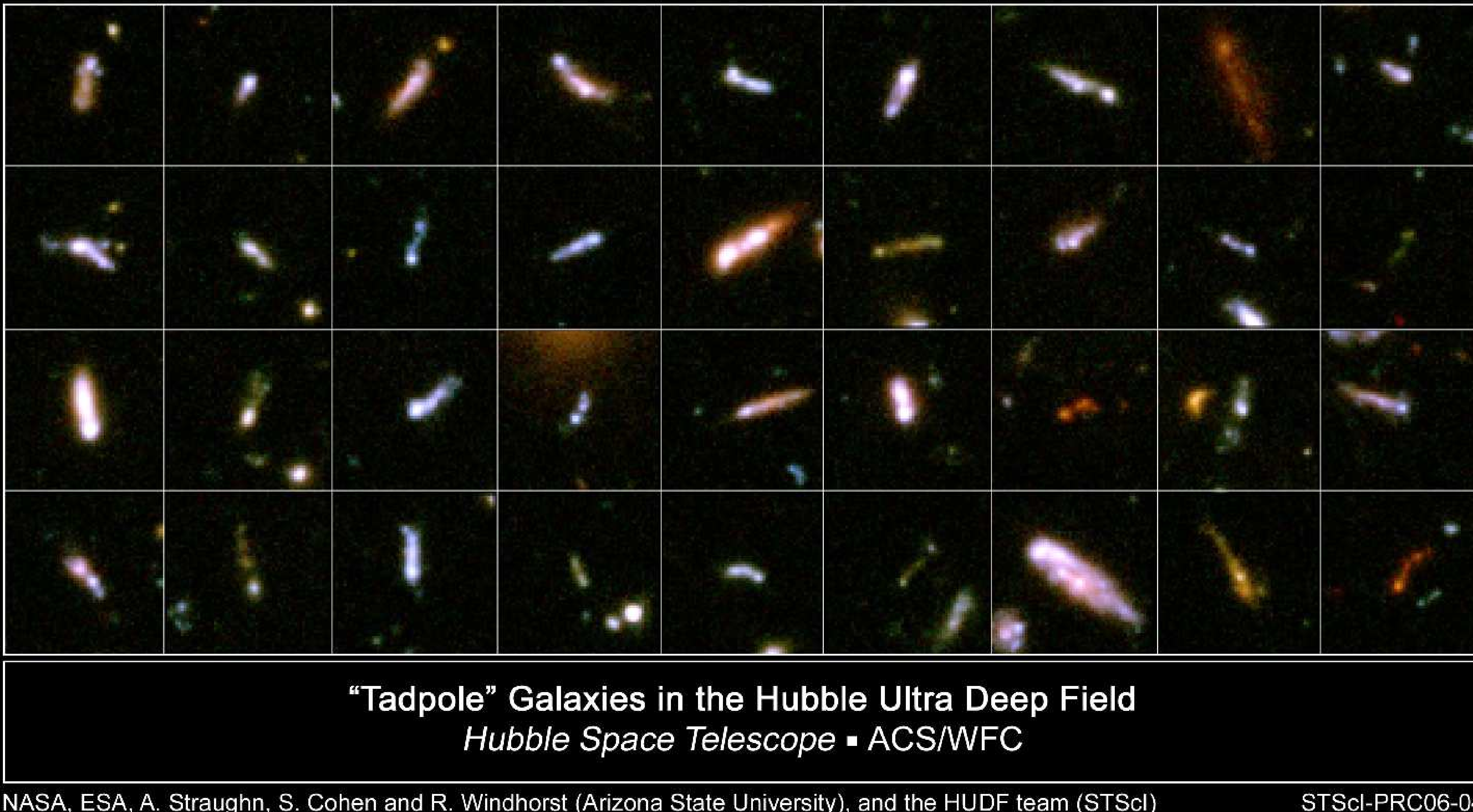
Interacting Galaxies

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



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

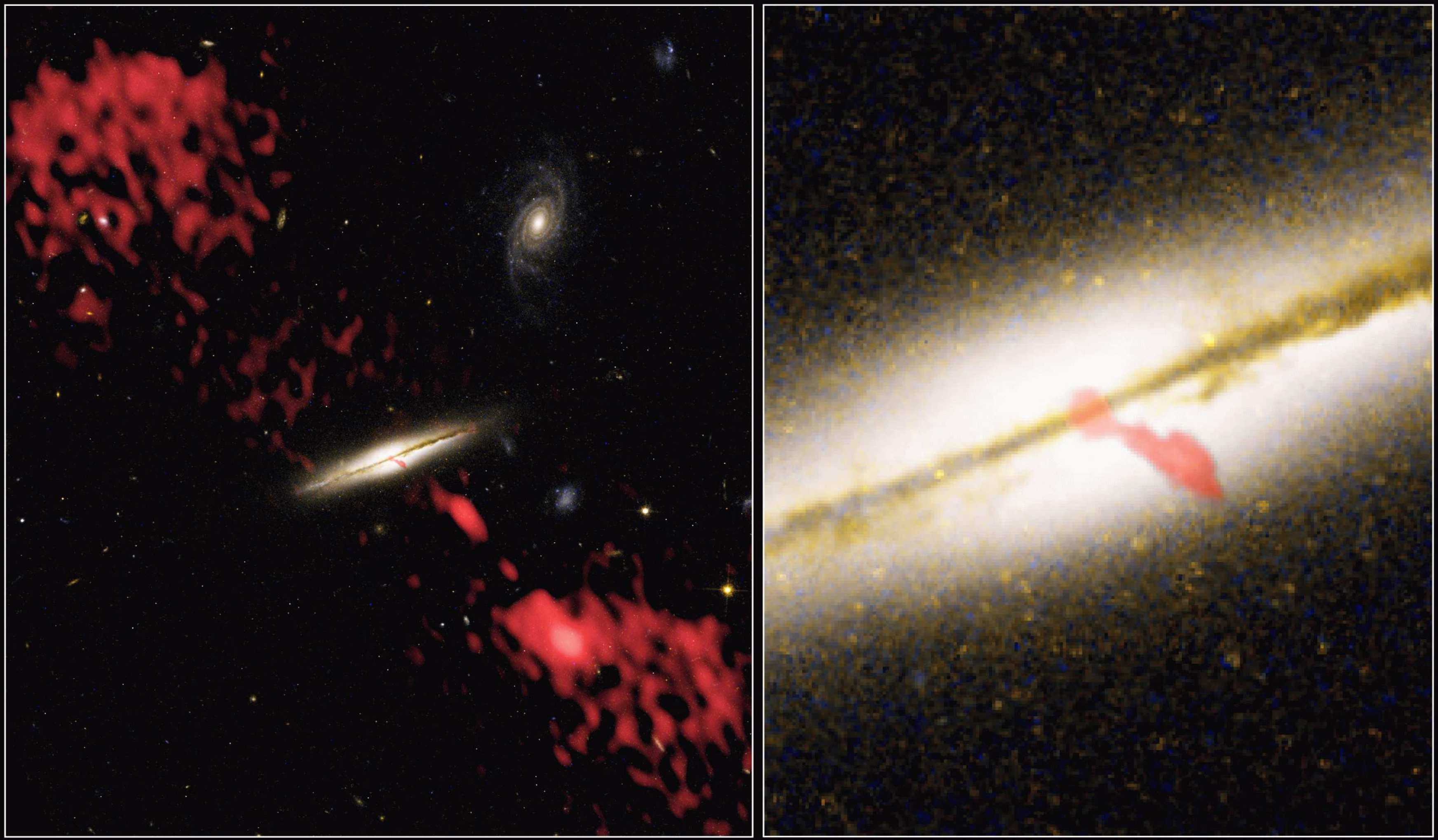
Tadpole galaxies are early stage mergers, very common at z$\gtrsim$2 (age$\lesssim$3 Gyr).

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

Hubble WFC3 reaches 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.

Webb 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.

(3) Measuring Galaxy Assembly & Supermassive Blackhole Growth



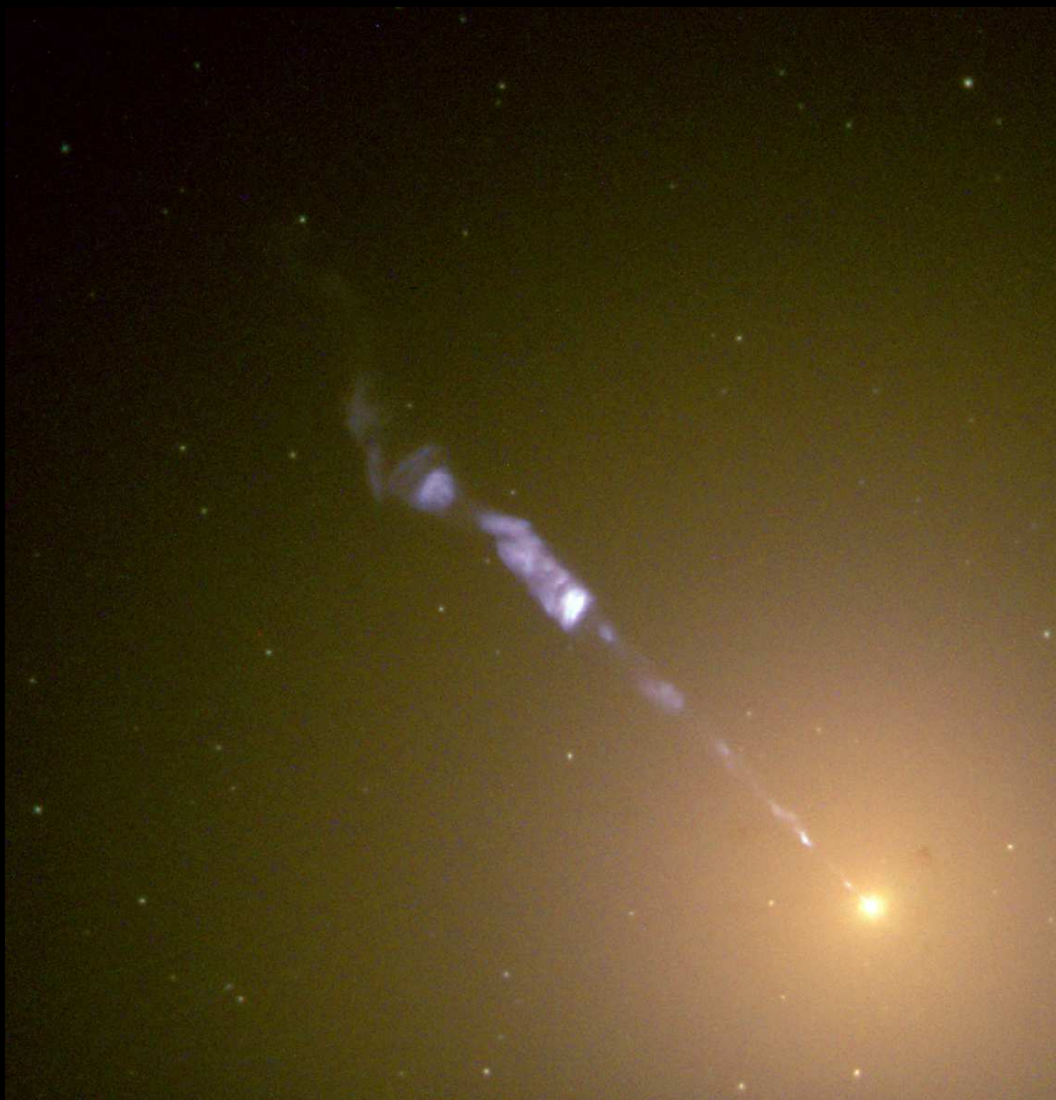
Radio Galaxy 0313-192

Hubble Space Telescope ACS WFC ▪ **Very Large Array**

NASA, NRAO/AUI/NSF and W. Keel (University of Alabama) ▪ STScI-PRC03-04

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

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



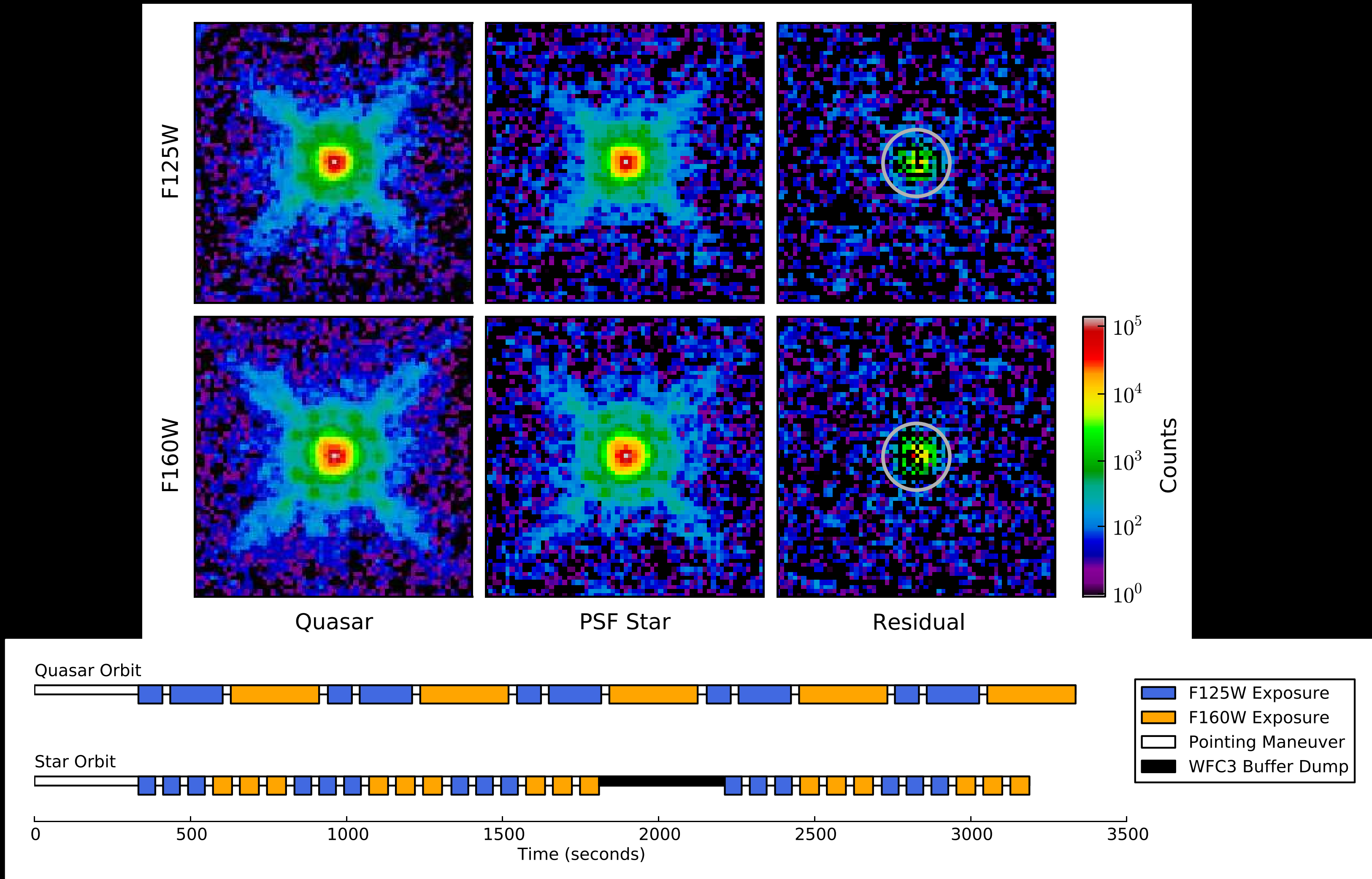
"For God's sake, Edwards. Put the laser pointer away."

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

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

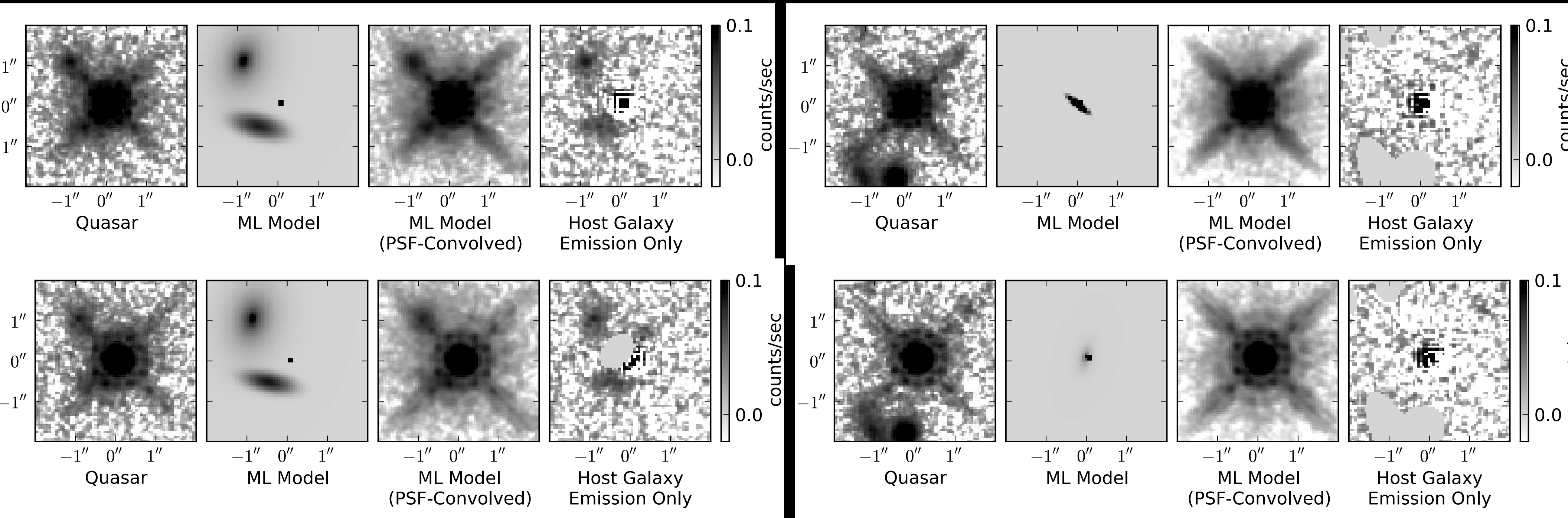

Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N

(3) HST WFC3 observations of QSO host galaxies at z≃6 (age≲1 Gyr)



- Careful contemporaneous orbital "Star-light" subtraction: Removes most of Hubble's "Spacecraft Breathing" (Mechtley et al. 2012, ApJL, 756, L38).
- Star-template (PSF) subtracts Quasar at redshift z≃6 (age ≲1 Gyr) nearly to the noise-limit: NO host galaxy detected 100× fainter.

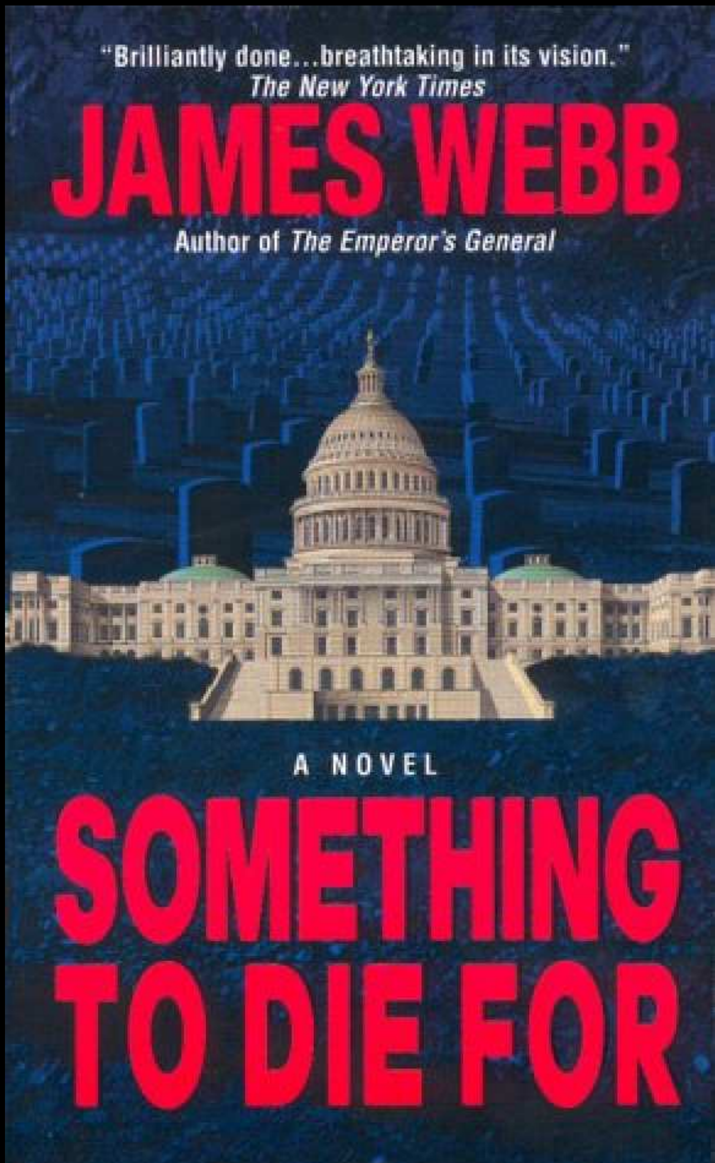
(3) WFC3: First detection of a Quasar Host Galaxy at z≃6 (Giant merger?)



- FIRST solid host galaxy detection out of four quasars at redshift ≃6:
- Morphology of a giant merging galaxy system [LEFT panels].
- Rather blue near-IR colors: Constrains dusty content.
- Host Galaxy ∼6× brighter than typical galaxy: Monster!
- Quasar duty cycle could be ≲10 Myrs: Blackhole eats like a beast!
- JWST Coronagraphs can do this 10–100× fainter (& for z≲20, $\lambda \lesssim 28 \mu$m).

G. Williger & L. Haberzettl [U-Louisville] found many such quasars at z≃2–3.

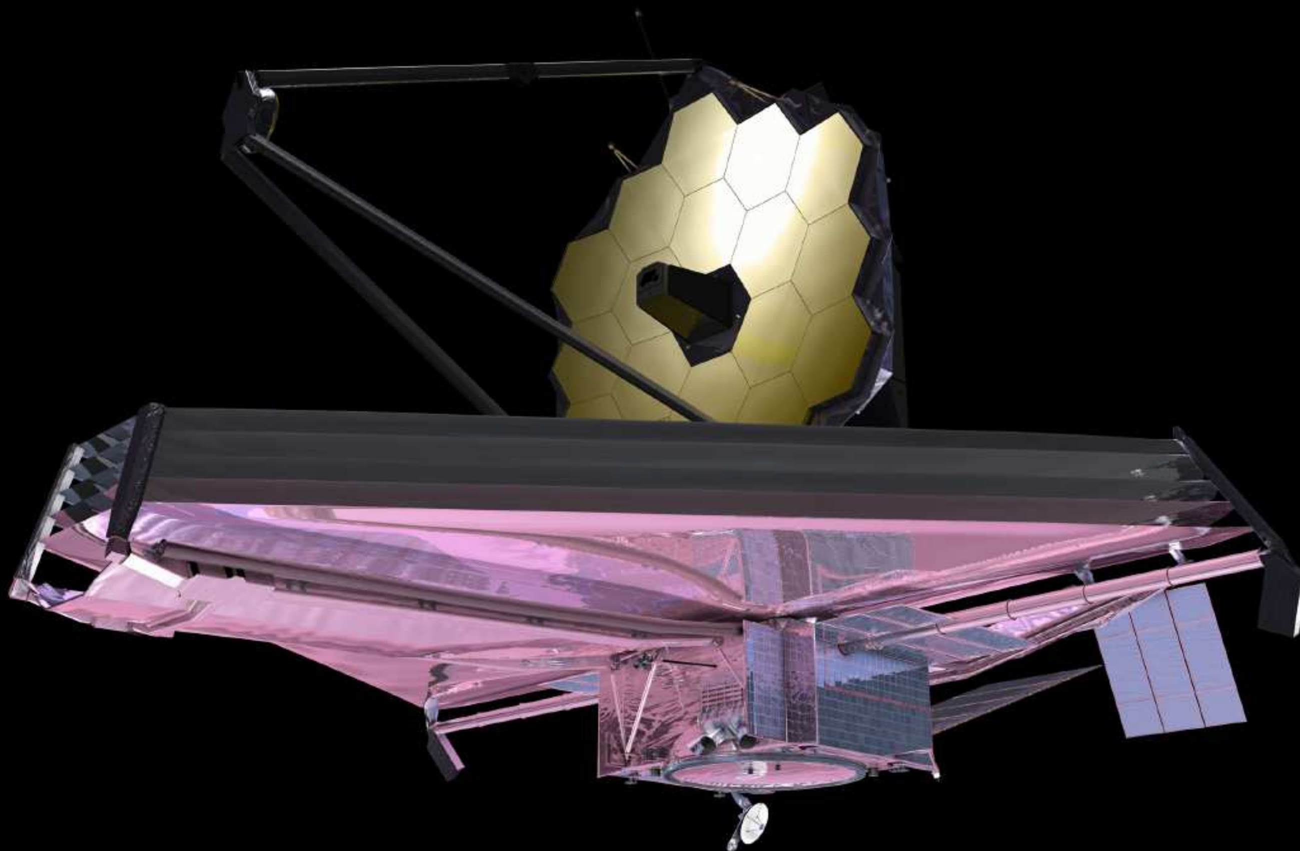
(4) What is the James Webb Space Telescope (JWST)?



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

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

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

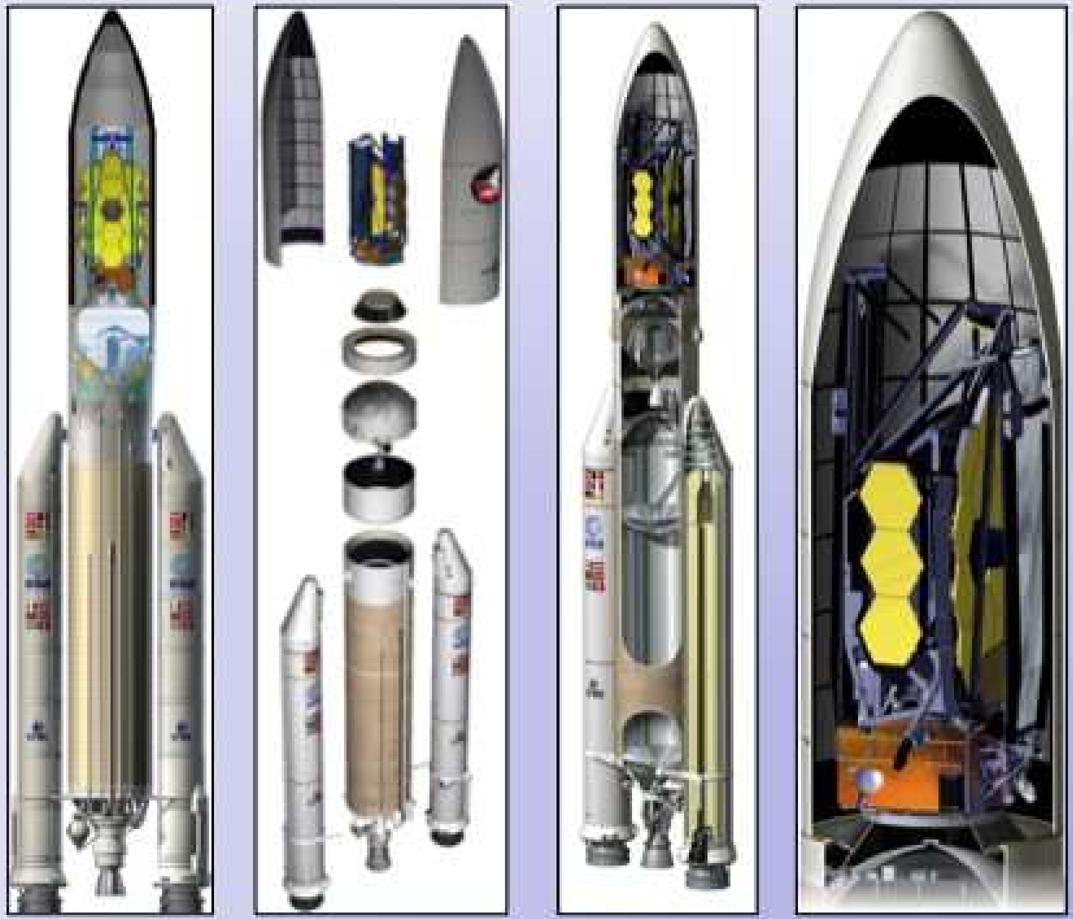


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (31.5 mag = firefly from Moon!) and spectroscopy.

THE JAMES WEBB SPACE TELESCOPE

JWST LAUNCH

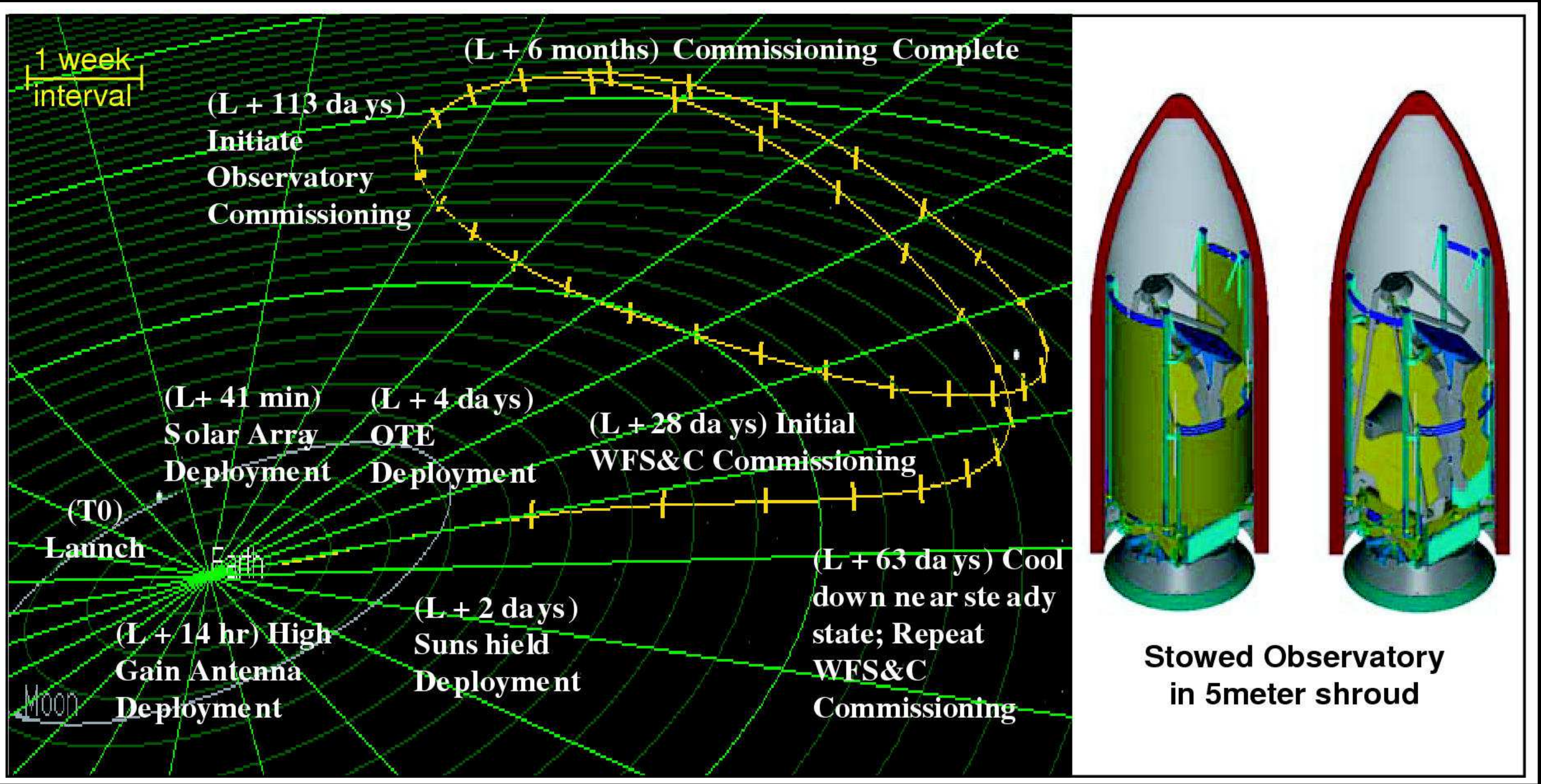
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



ARIANESPACE – ESA - NASA

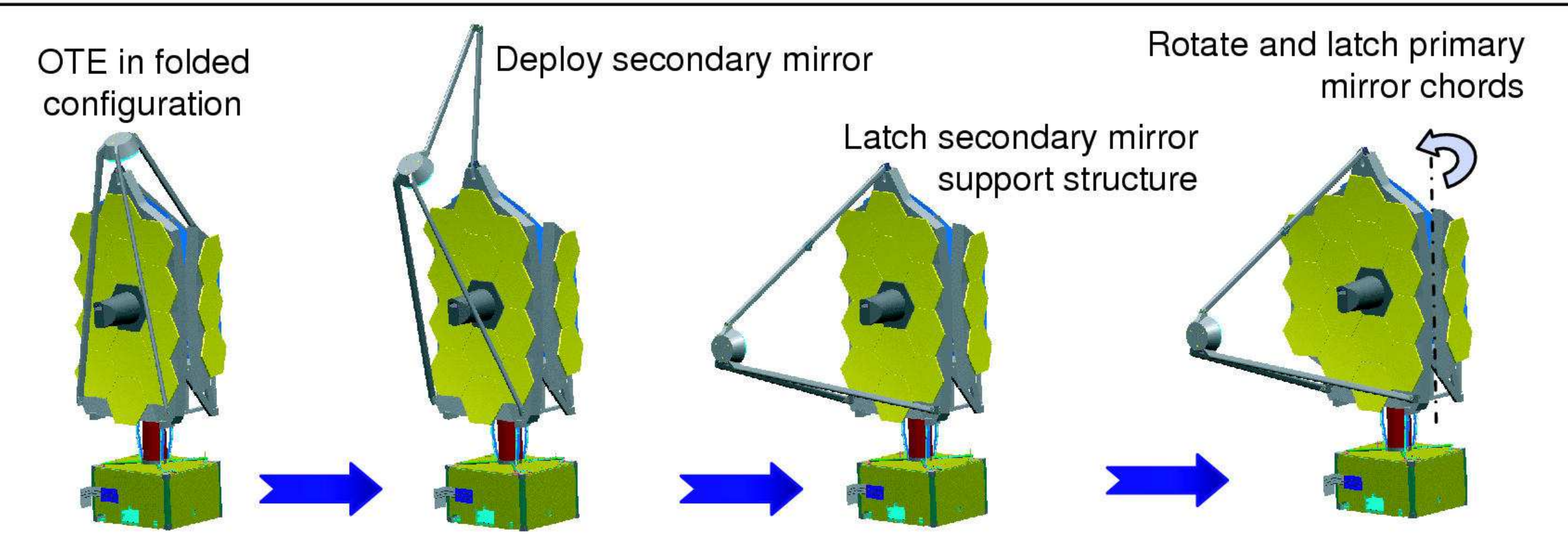
• The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(4a) 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.

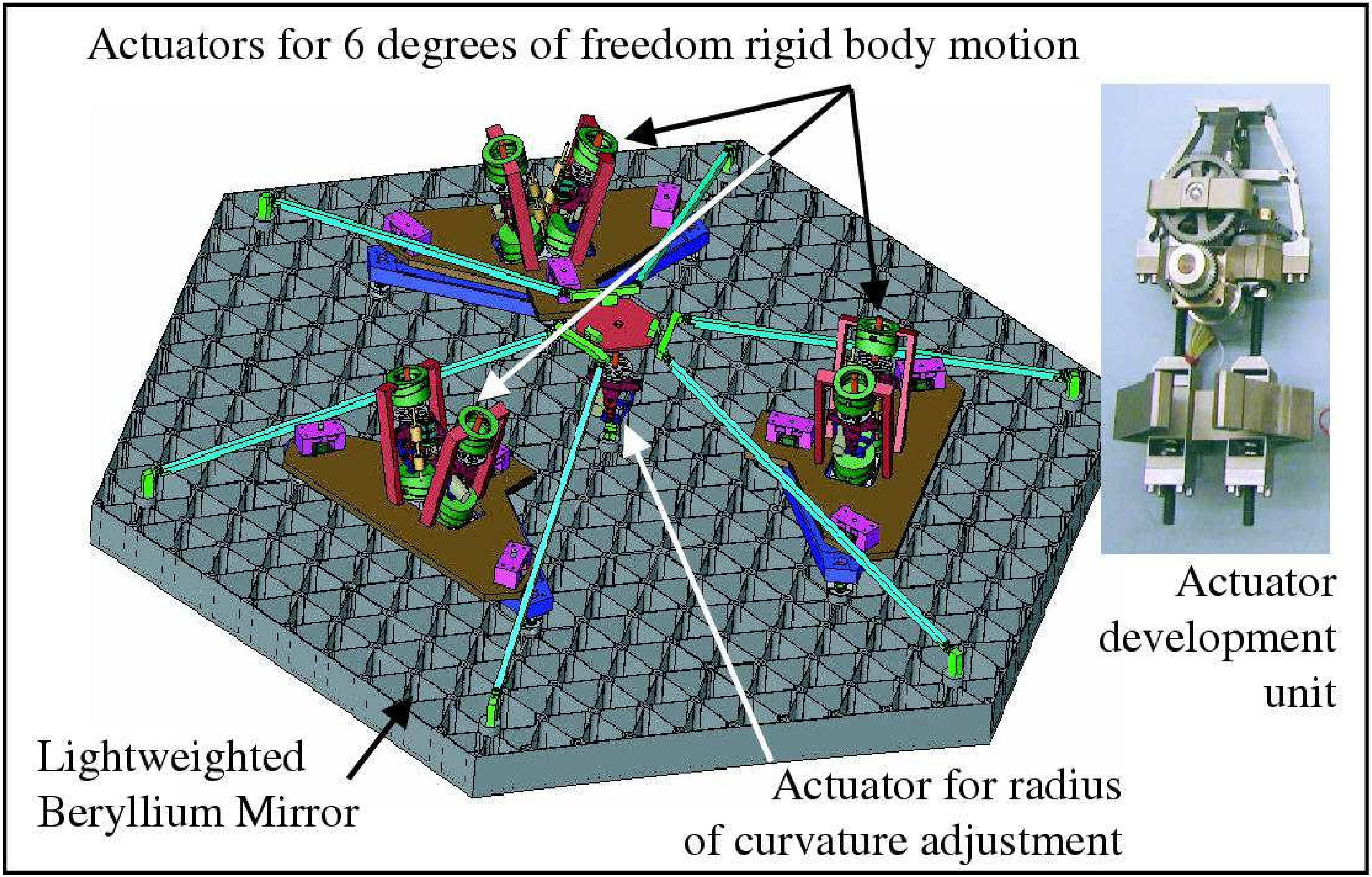
• (4b) How will JWST be automatically deployed?



• 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 is being tested several times on the ground — but only in 1-G: component and system tests in 2014–2017 at GSFC (MD), Northrop (CA), and JSC (Houston).

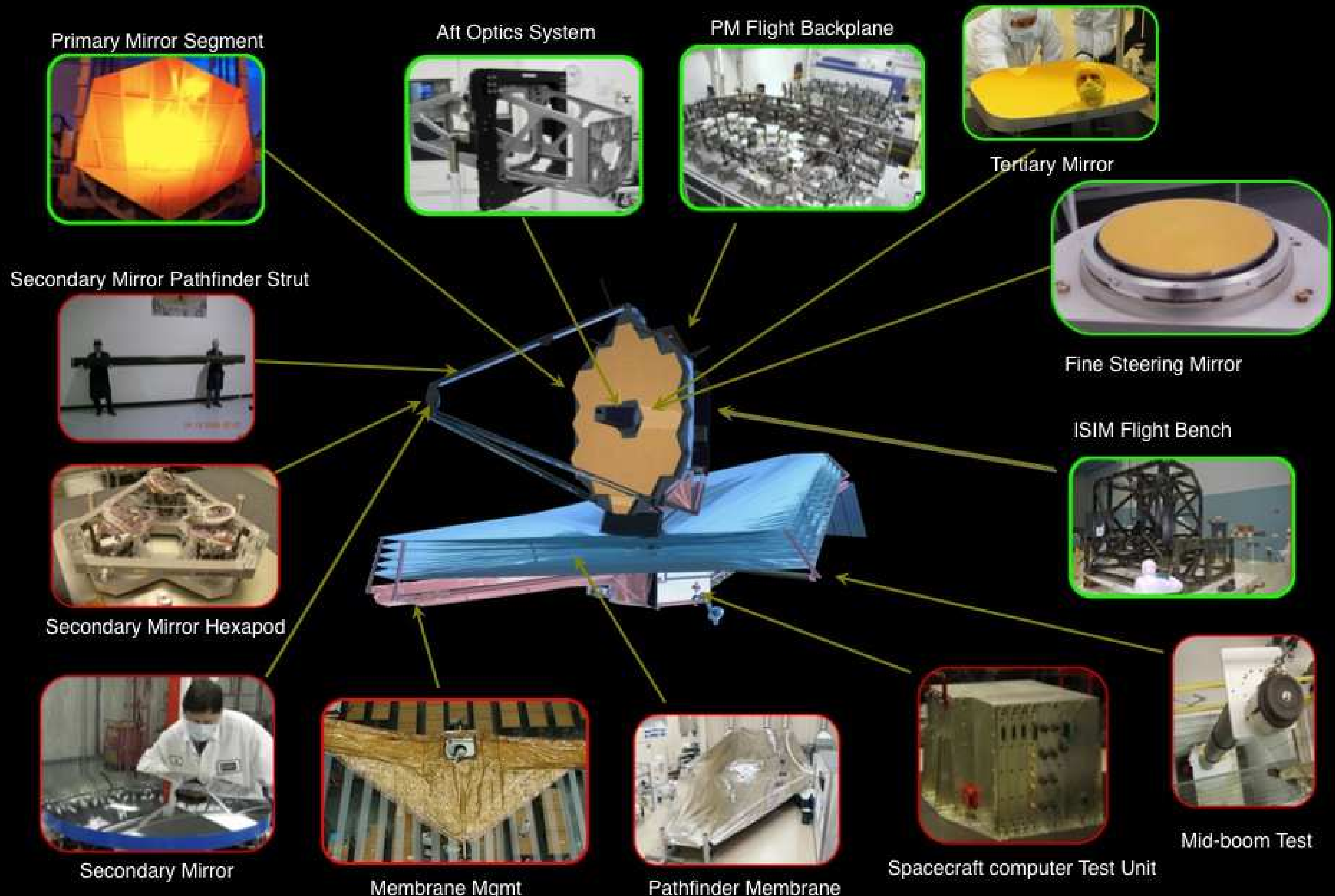
• Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications!



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

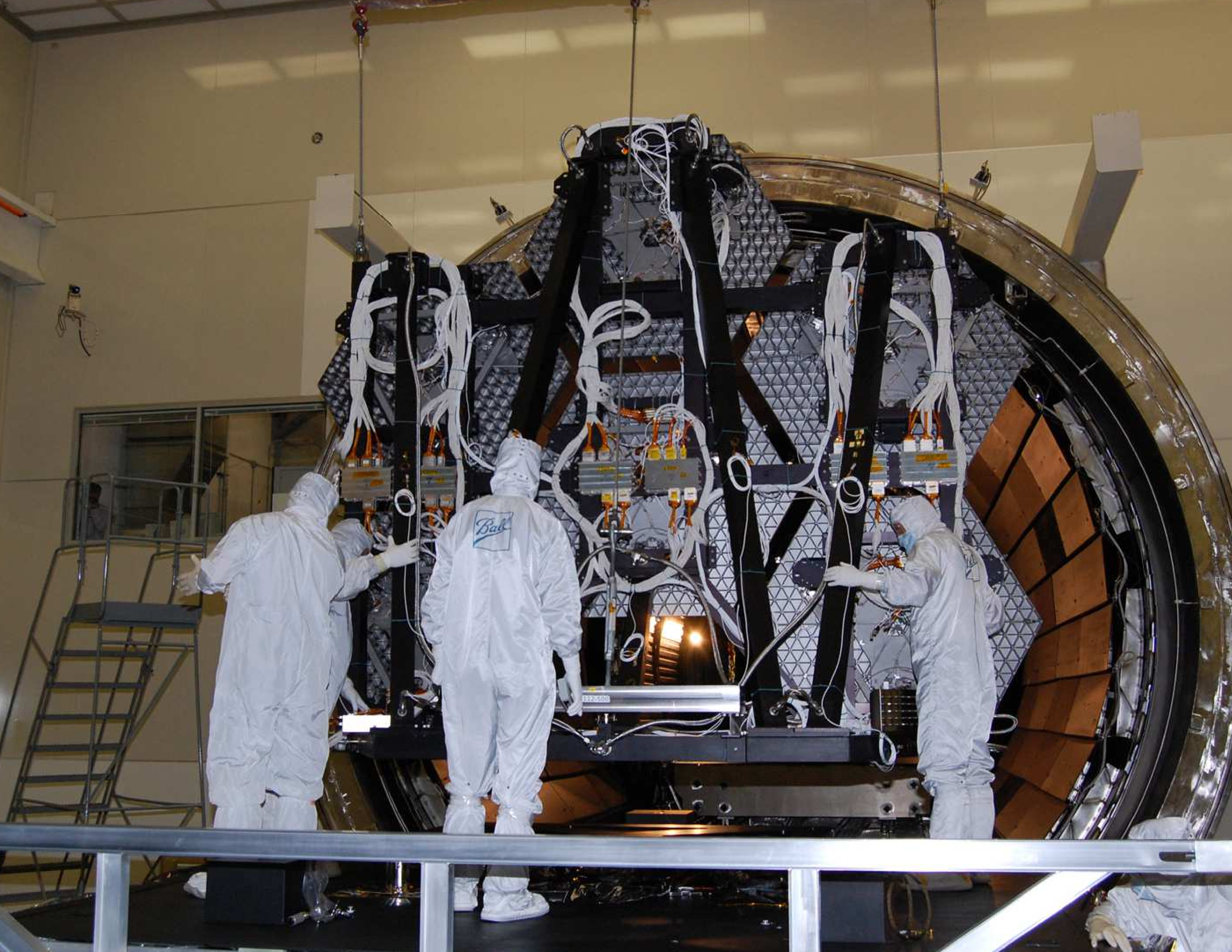
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

JWST Hardware Status

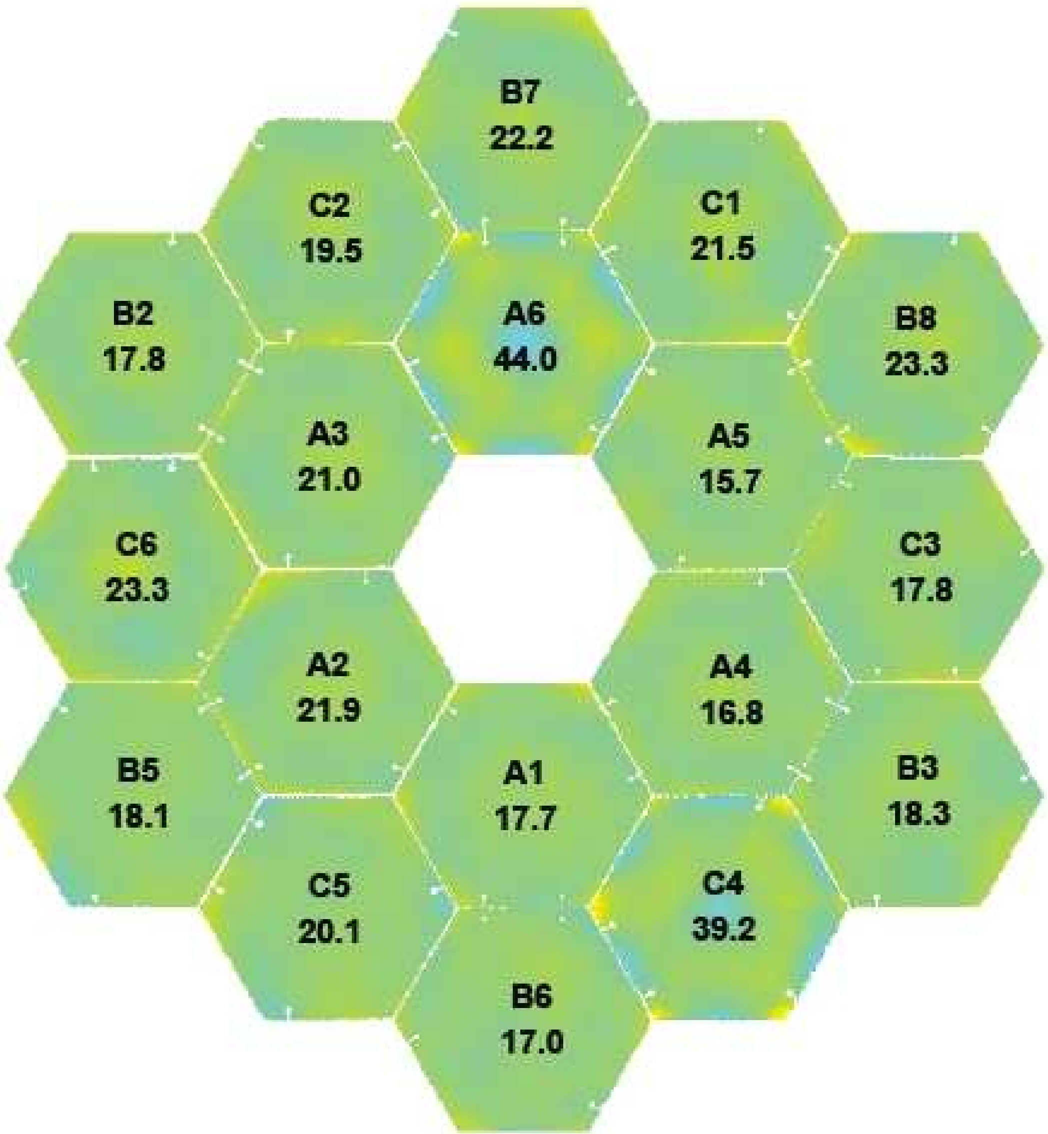


July 2014: $\gtrsim$97.4% of launch mass designed and built ($\gtrsim$60 weighed).


Mirror Acceptance Testing
A5
A4
A1
A2

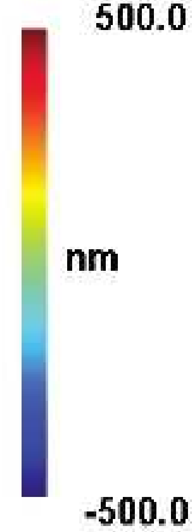


Primary Mirror Composite



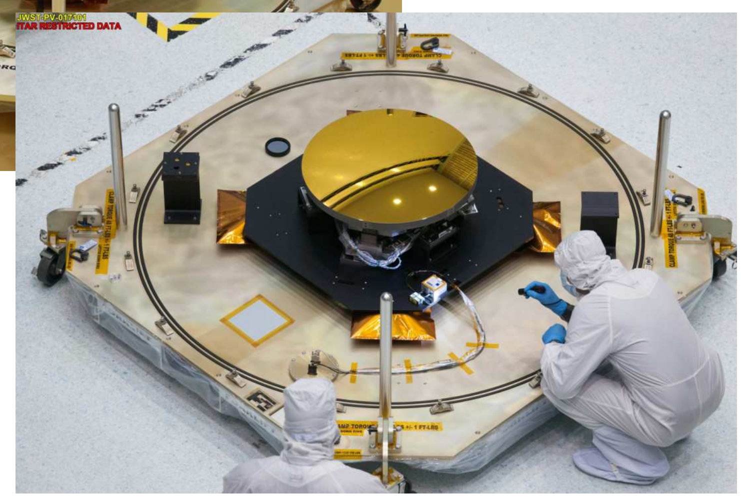
RMS: 23.2 nm

PV: 515.5 nm

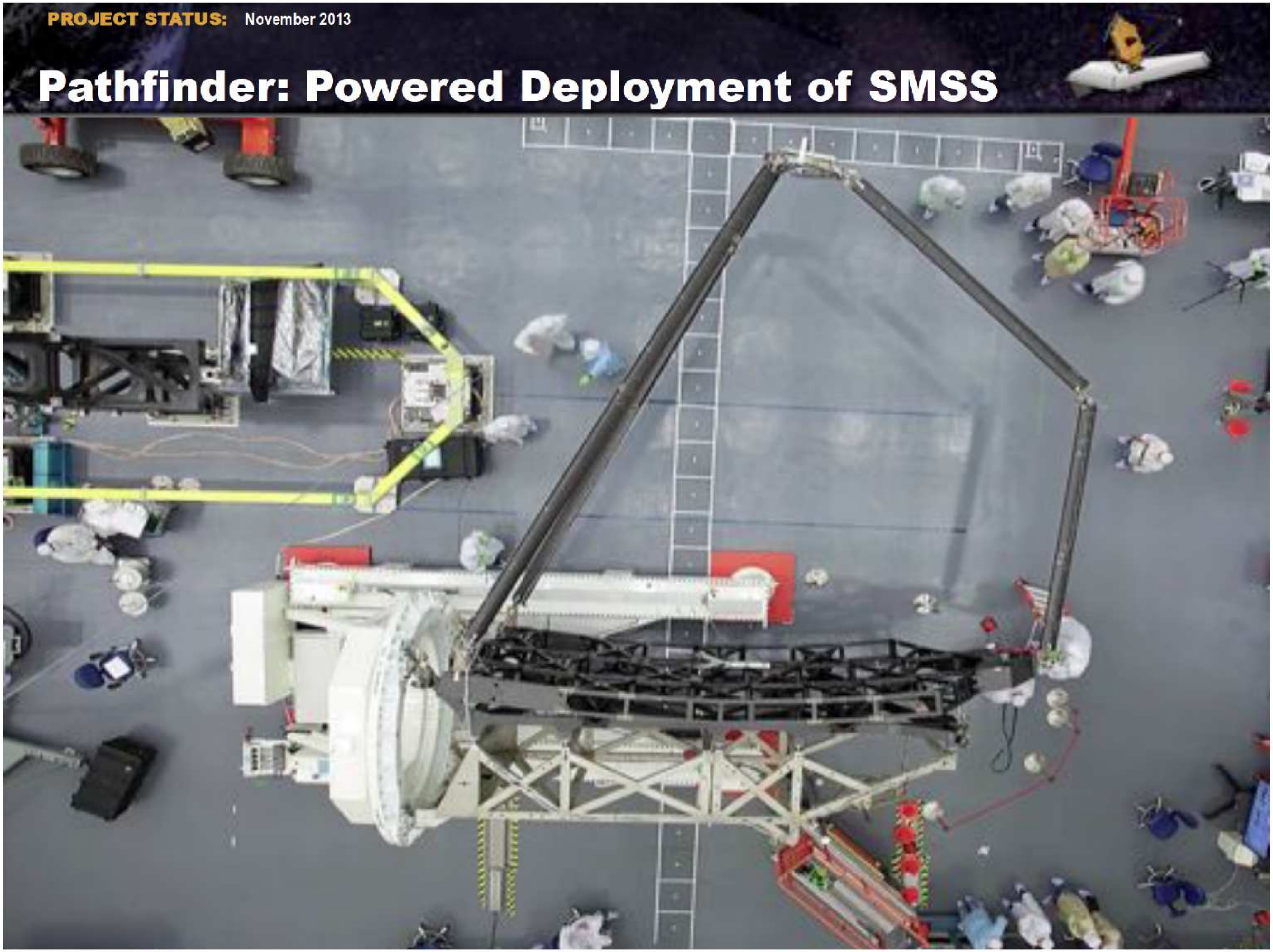


Mirror Status

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



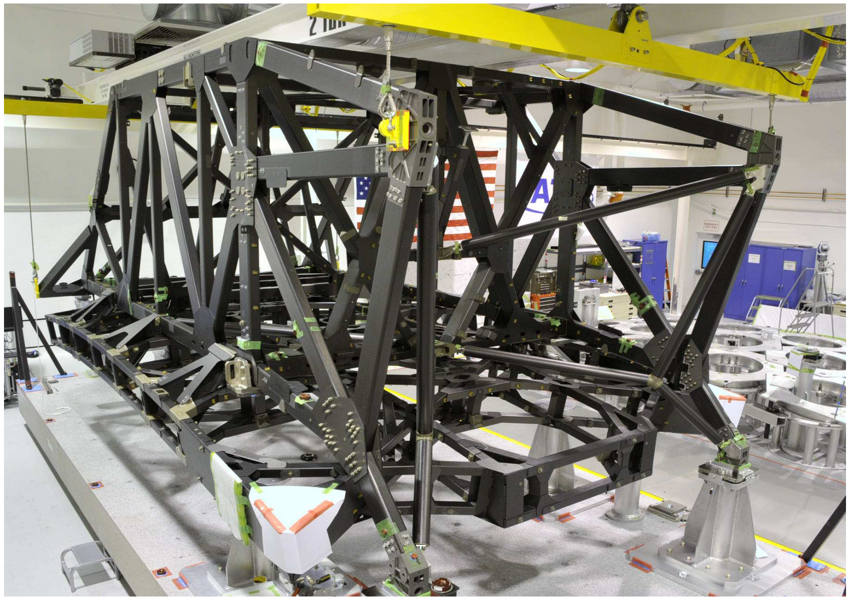
Spring 2014: All 18 flight mirrors now delivered to NASA GSFC (MD).



July 2014: Secondary Mirror Support deployment successfully tested.

Backplane Support Frame, Center Section, & Wings

- Center Section is complete
- Wings and cryo cycling is complete
- BSF assembly is complete
- Integration of the BSF to Center Section Complete
  - Cryo Cycling at MSFC XRCF complete

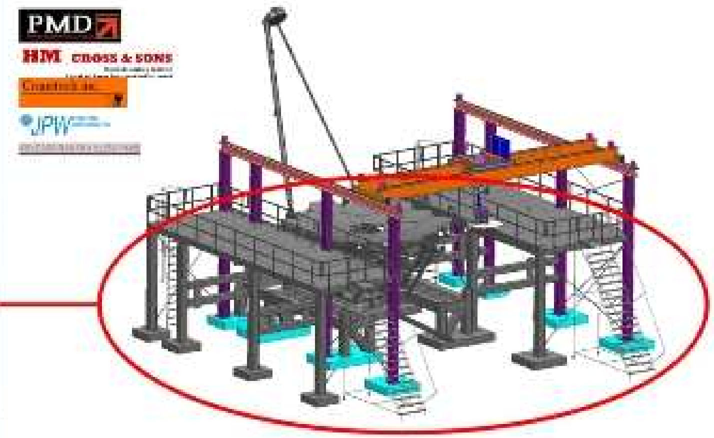


BSF and Center Section

BSF/Center Section coming out of

Jan 2014: Flight back-plane ready to receive mirrors in 2014.

Telescope Assembly Ground Support Equipment



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

Landing a mirror onto backplane simulator

Sunshield Deployment

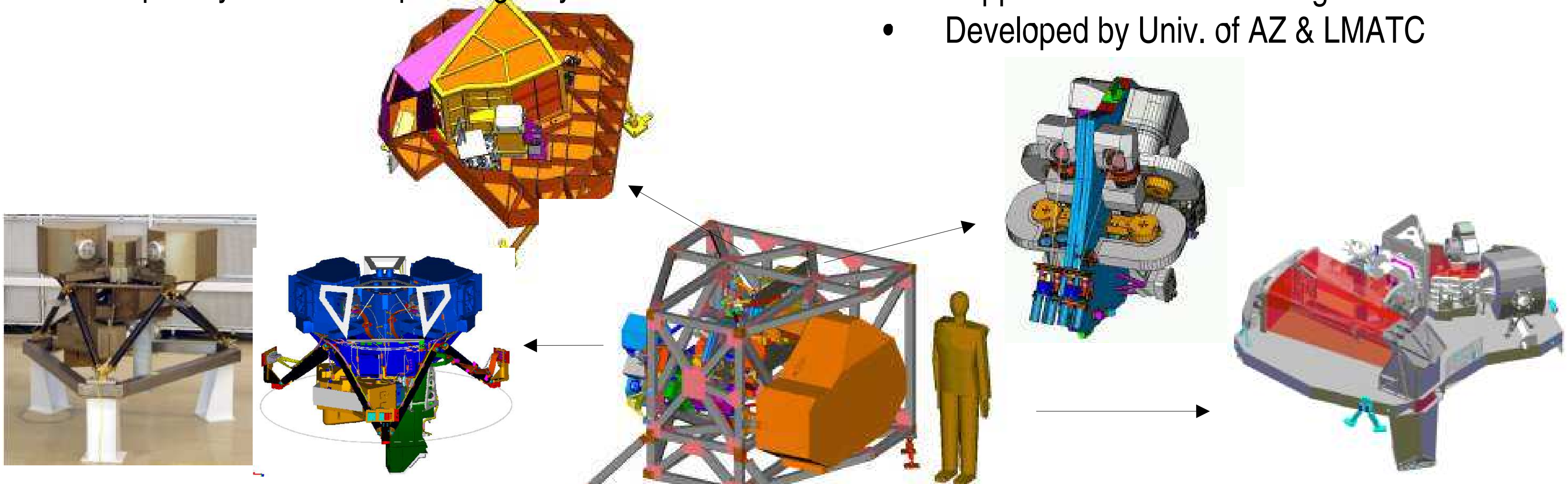
July 2014: Engineering sunshield successfully deployed at Northrop (CA).

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

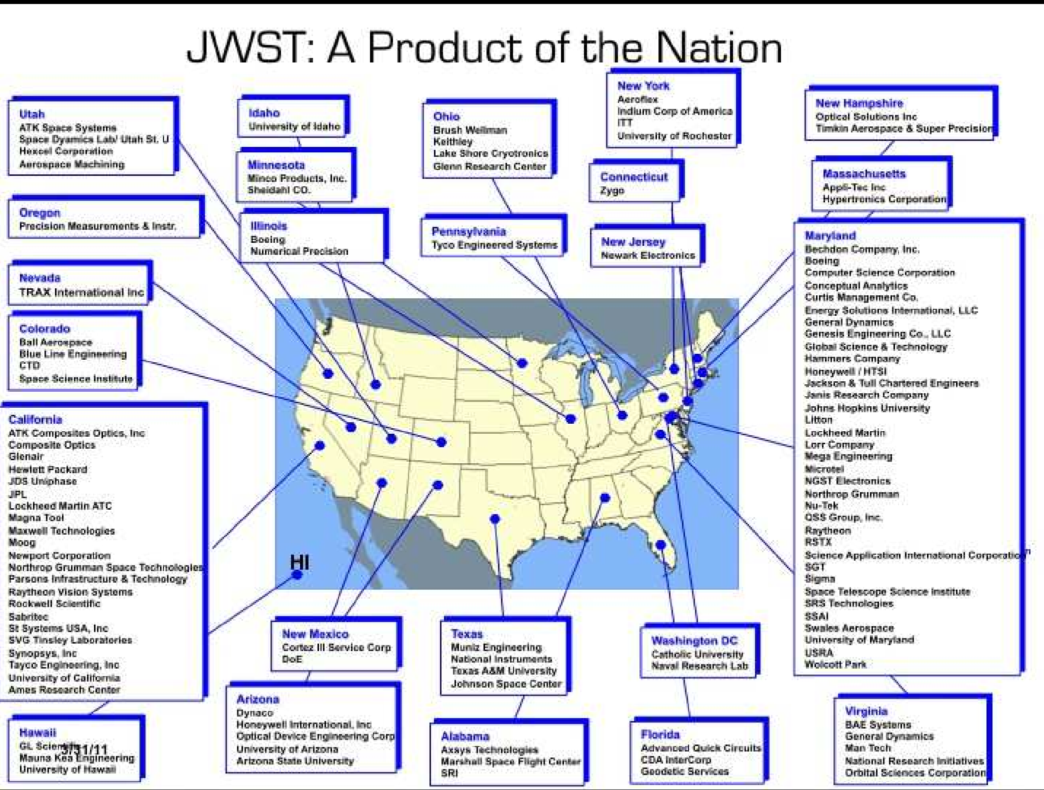
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

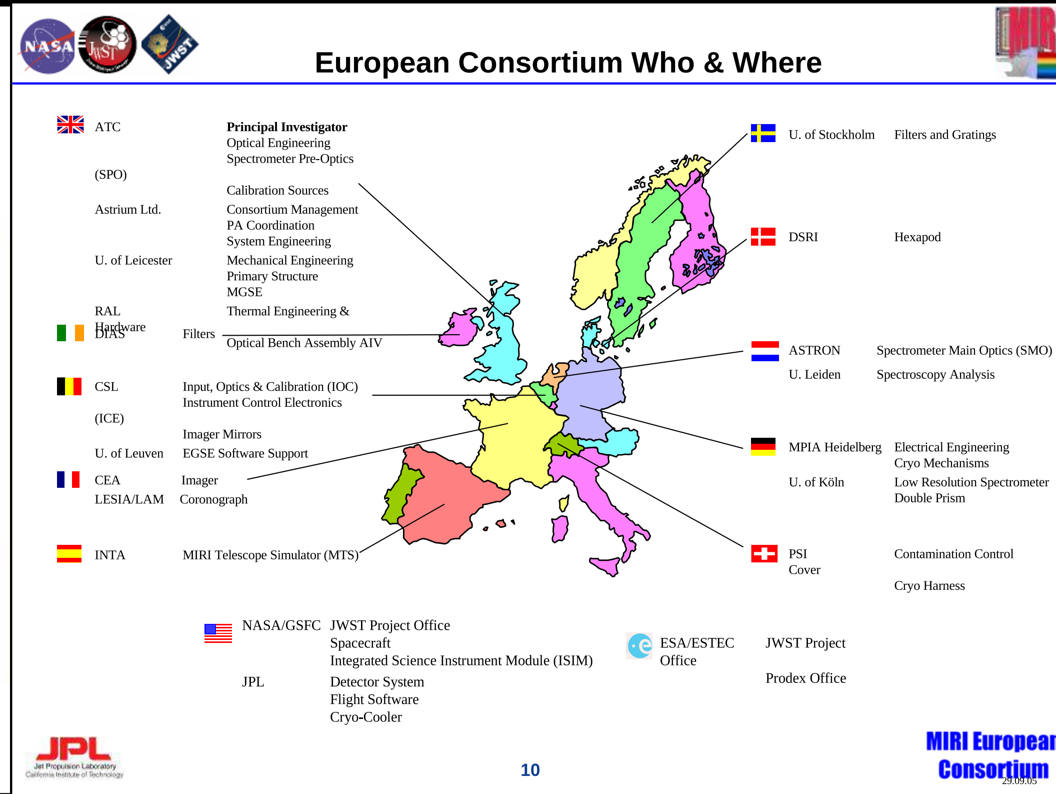


Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

All delivered: MIRI 05/12; FGS 07/12; NIRCam 07/13, NIRSpec 9/13.



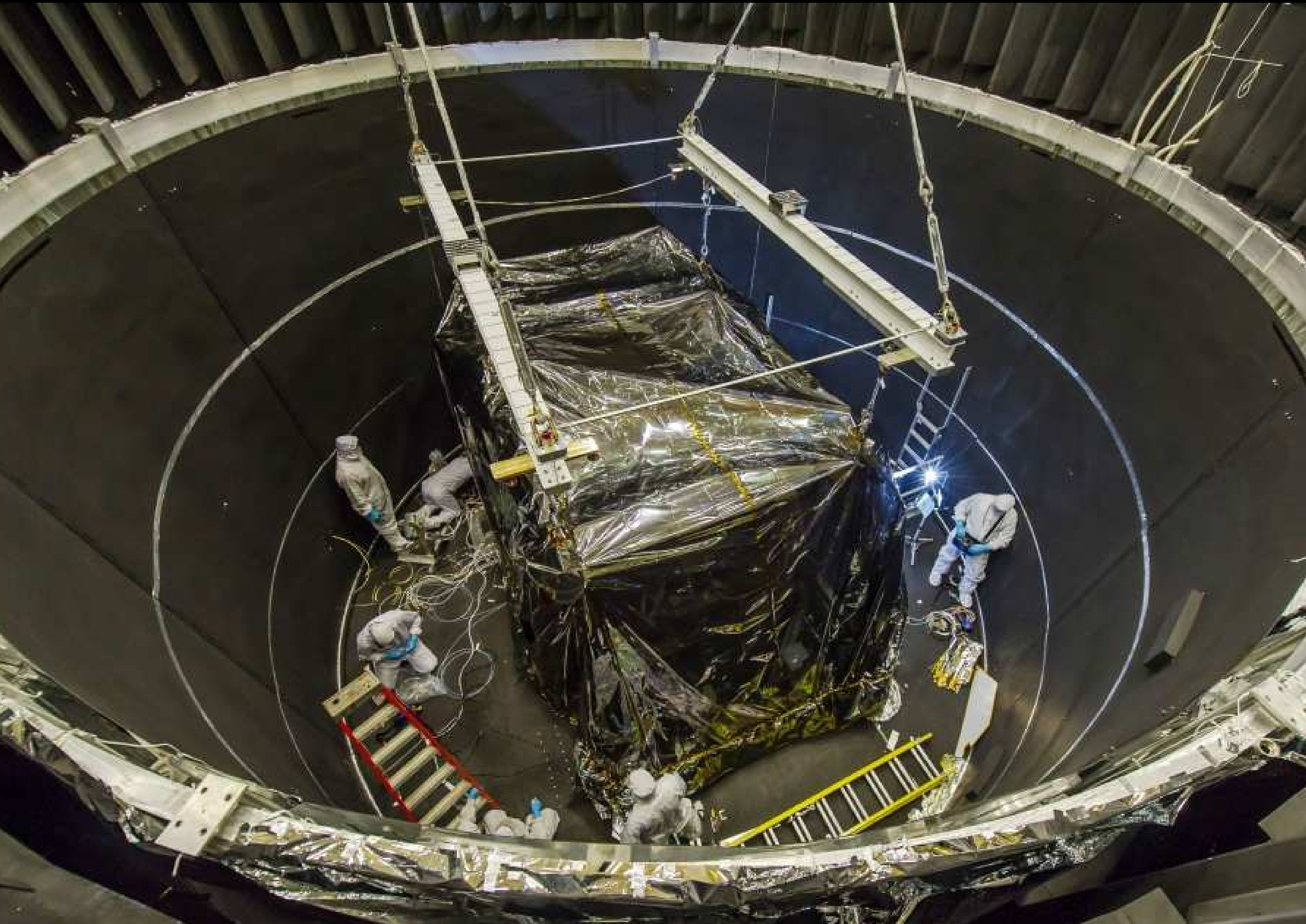


- JWST hardware made in 27 US States: $\gtrsim$97% of launch-mass finished.

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

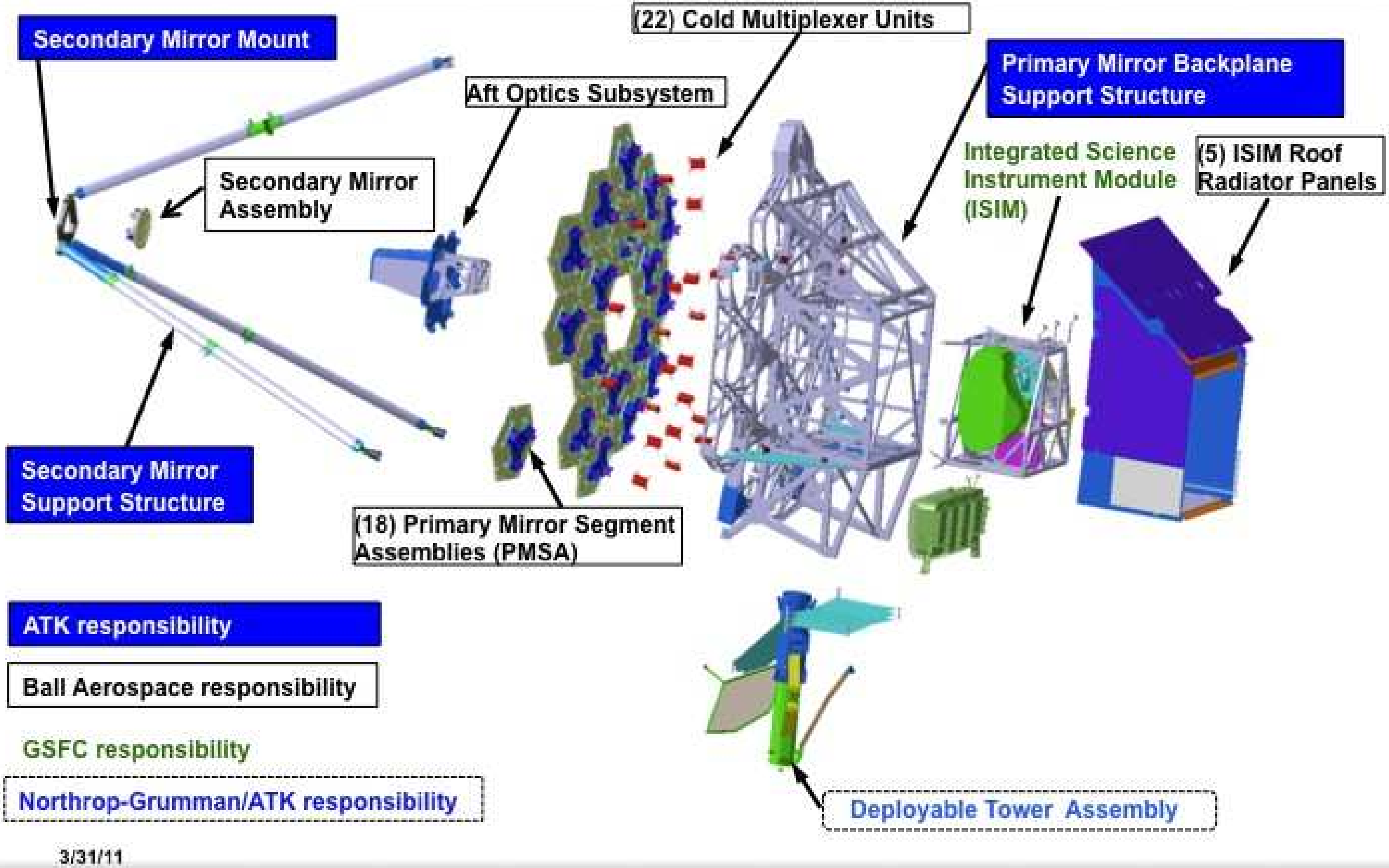
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.

- JWST NIRCam made by UofA and Lockheed.

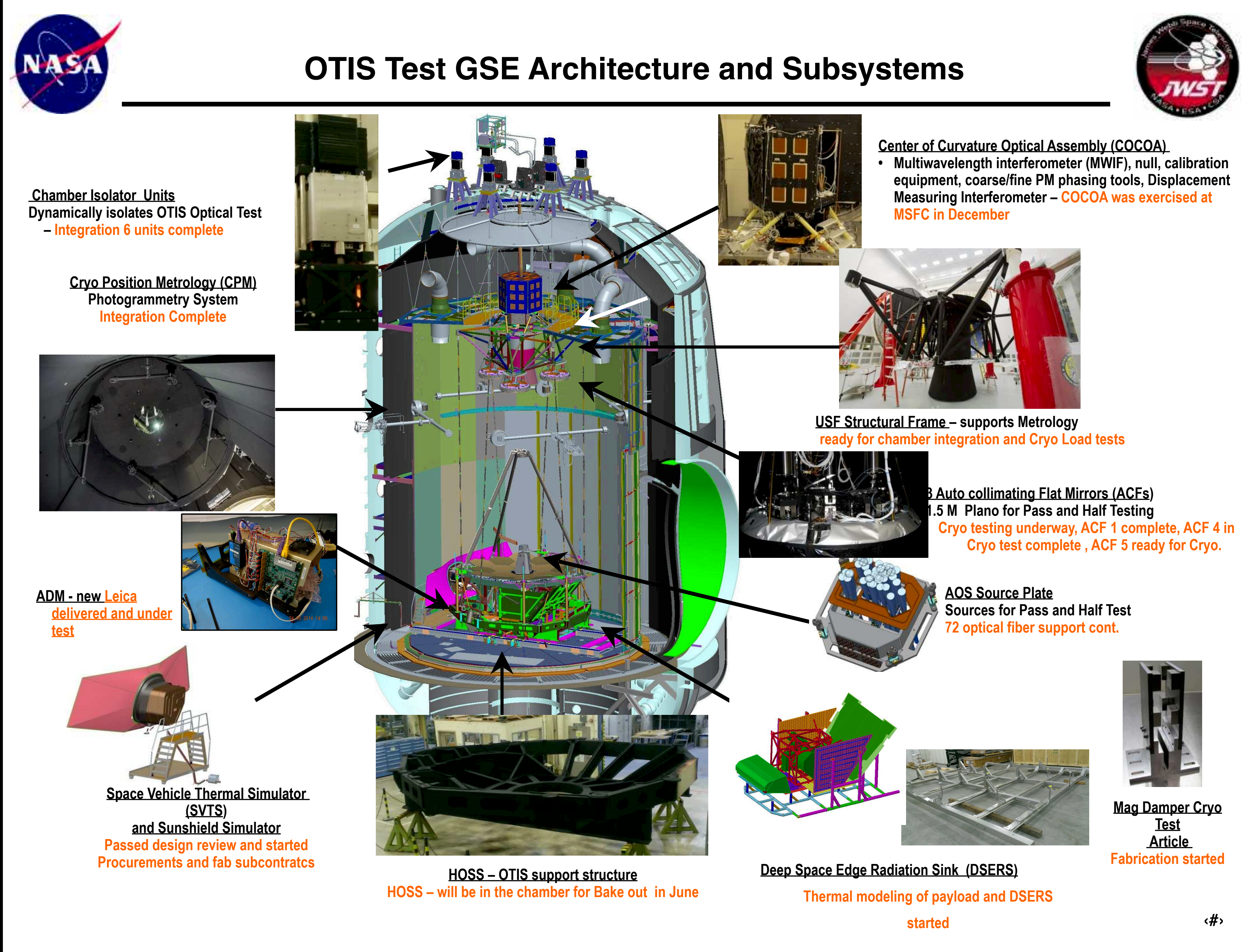


June 2014: Actual Flight ISIM (with MIRI and FGS) lowered into OSIM.

TELESCOPE ARCHITECTURE

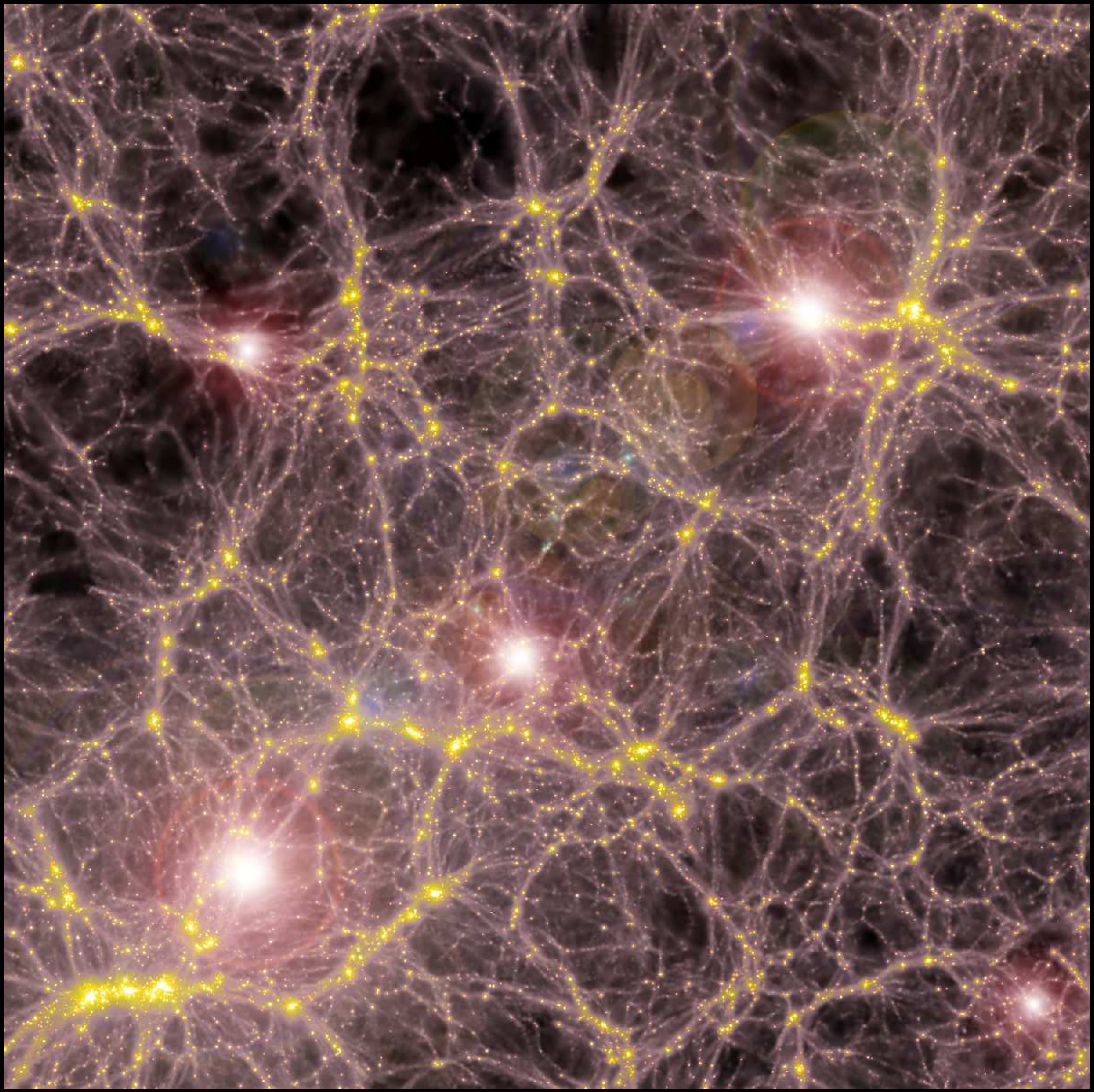


2014–2016: Complete system integration at GSFC and Northrop.



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

(5) How will JWST Observe First Light and Reionization?

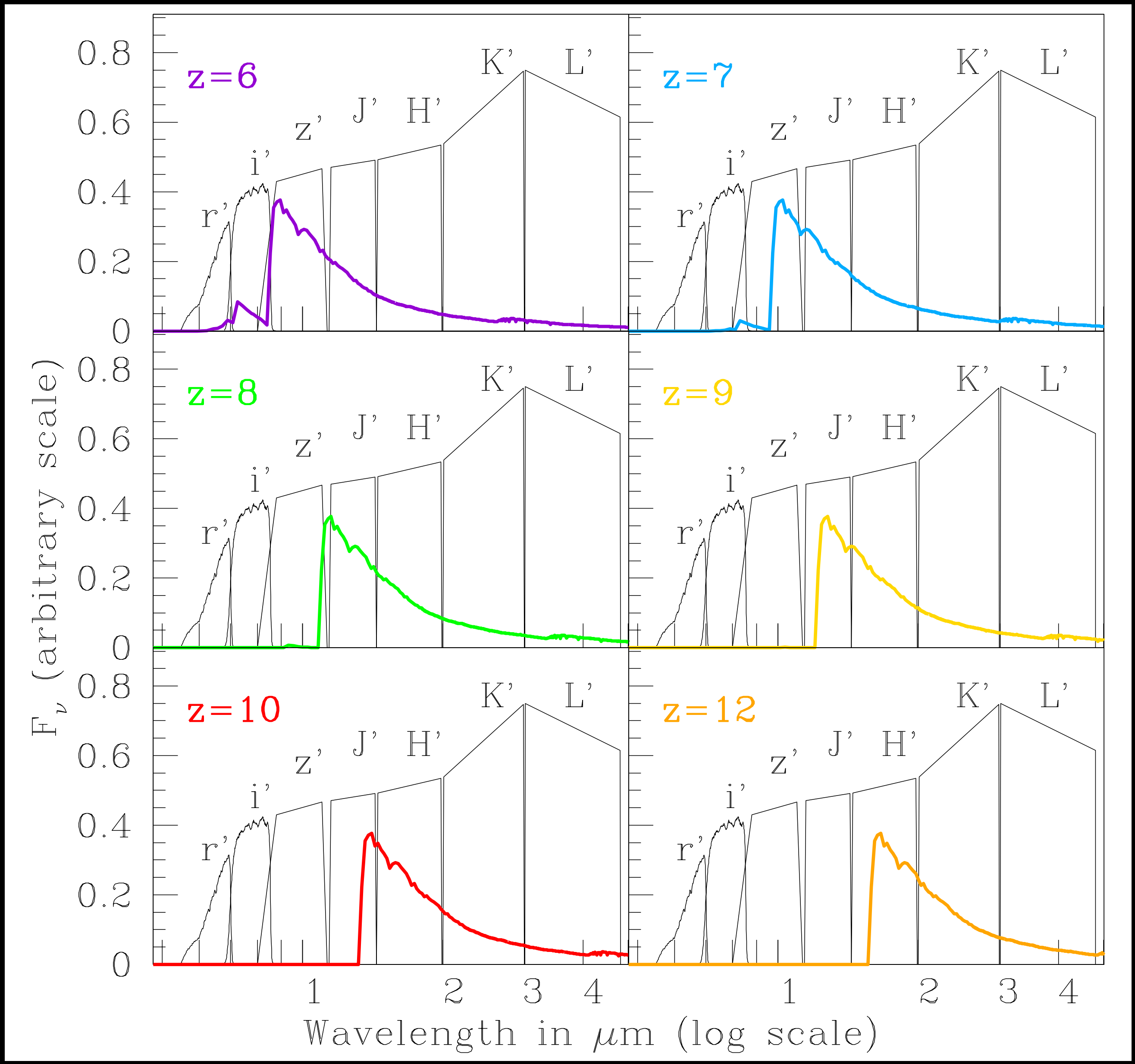


- Detailed cosmological models (V. Bromm) suggest that massive "Population III" stars ($M \gtrsim 100\ M_{sun}$) started to "reionize" the universe at redshifts $z \lesssim 10$–30 (First Light).

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

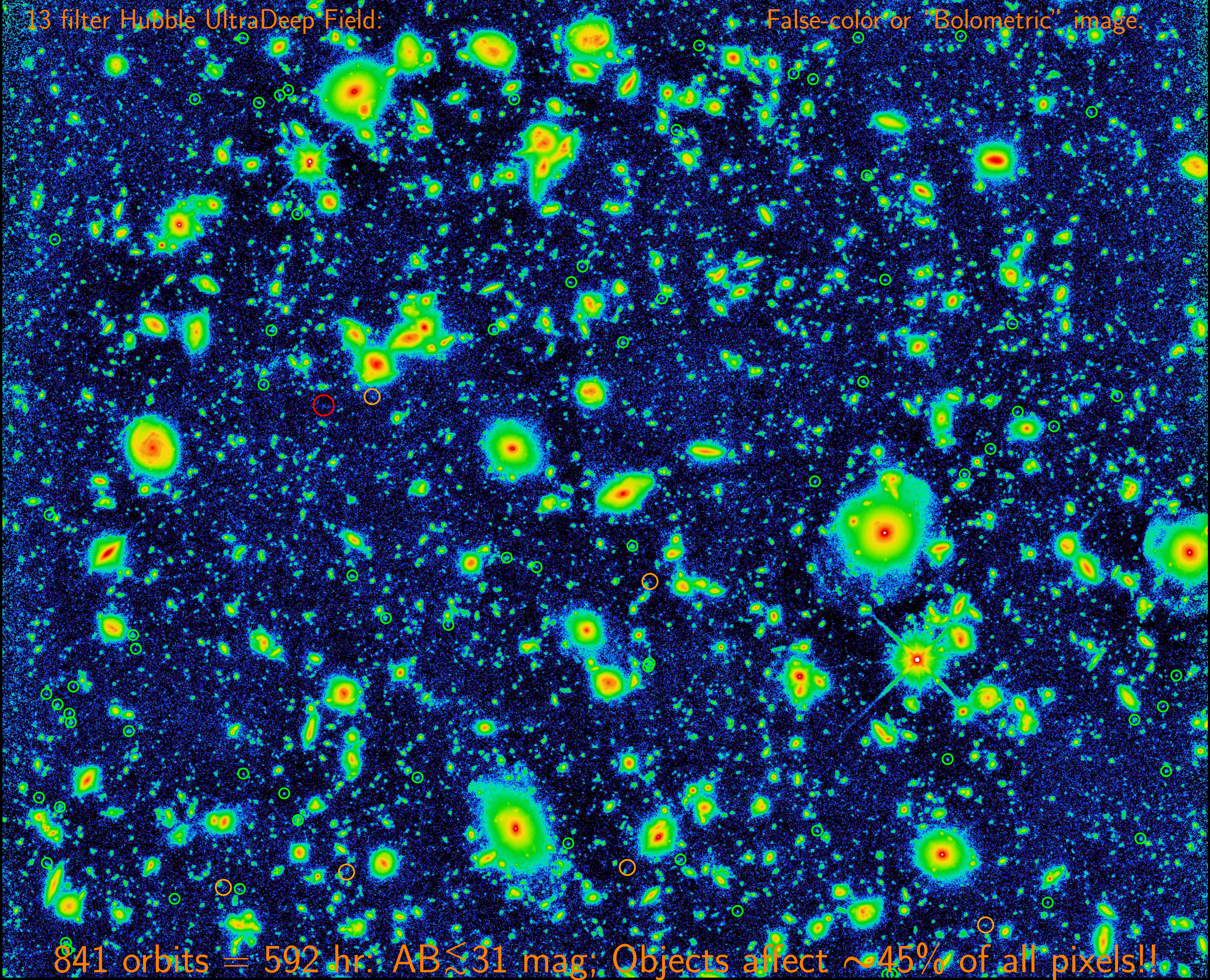
- We must make sure that we theoretically understand the likely mass distribution of these Pop III stars, their clustering properties, supernova-rates, etc., before Webb flies, so we will know what to look for.

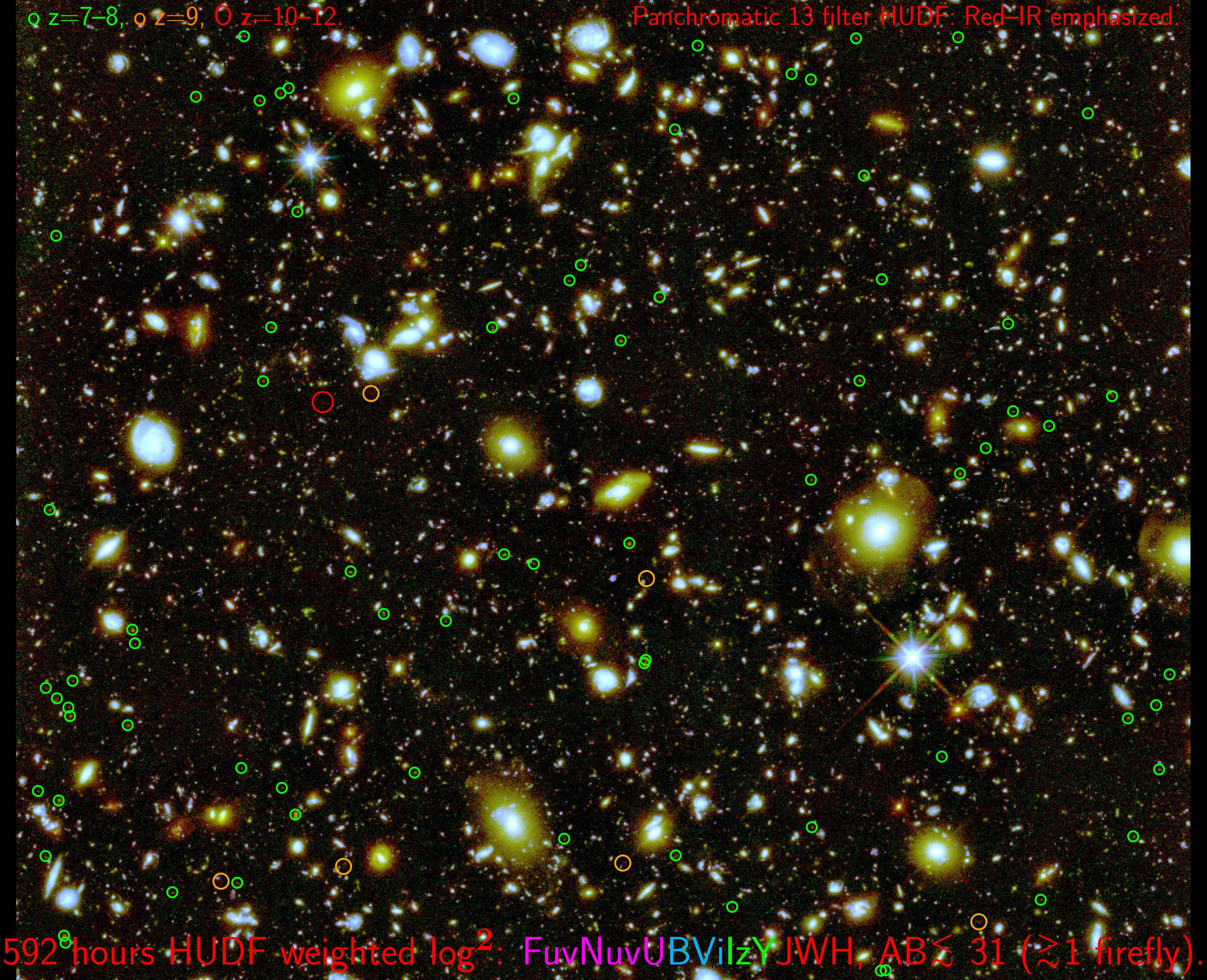
(5) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



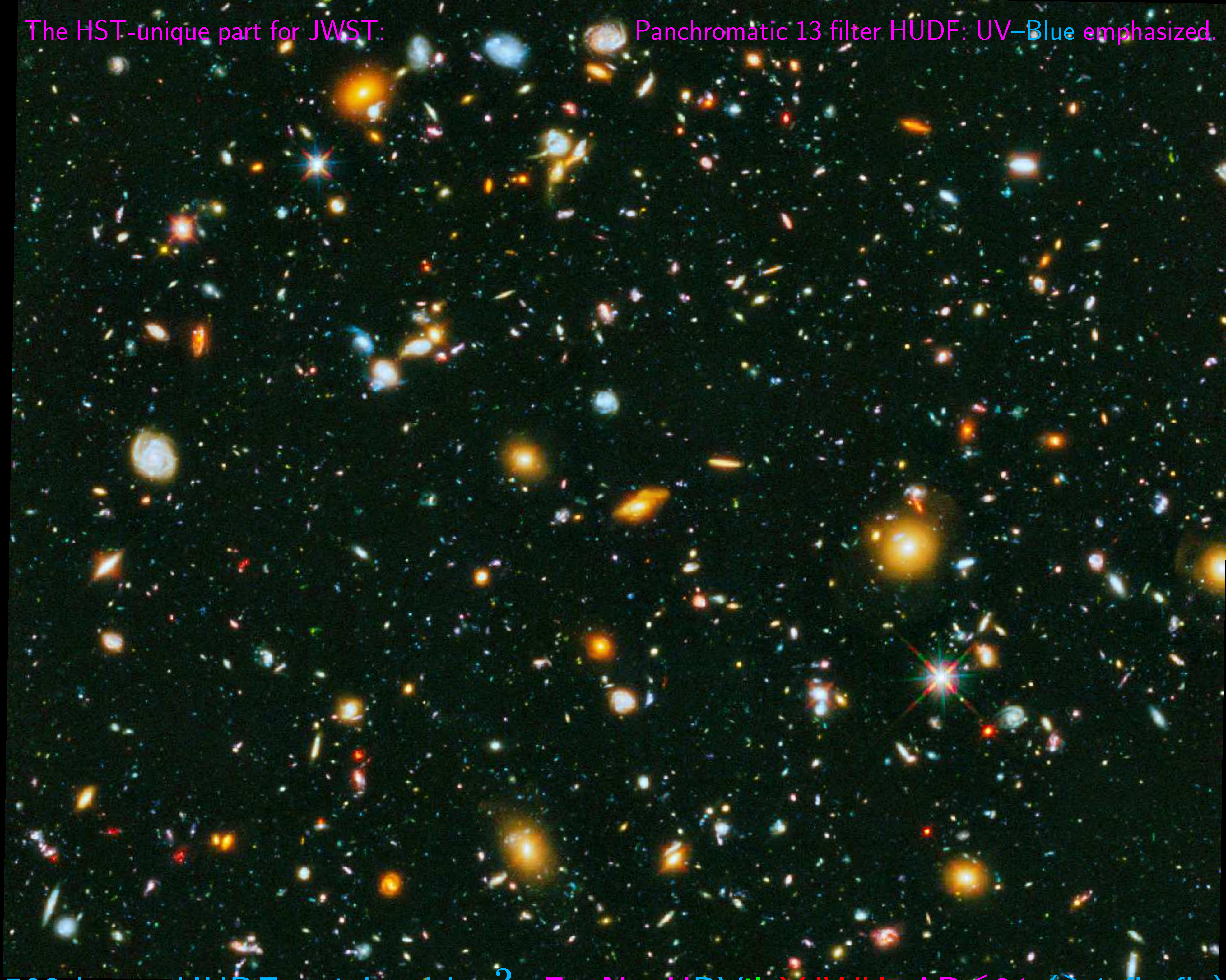
- Can't beat redshift: to see First Light, must observe near–mid IR.

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

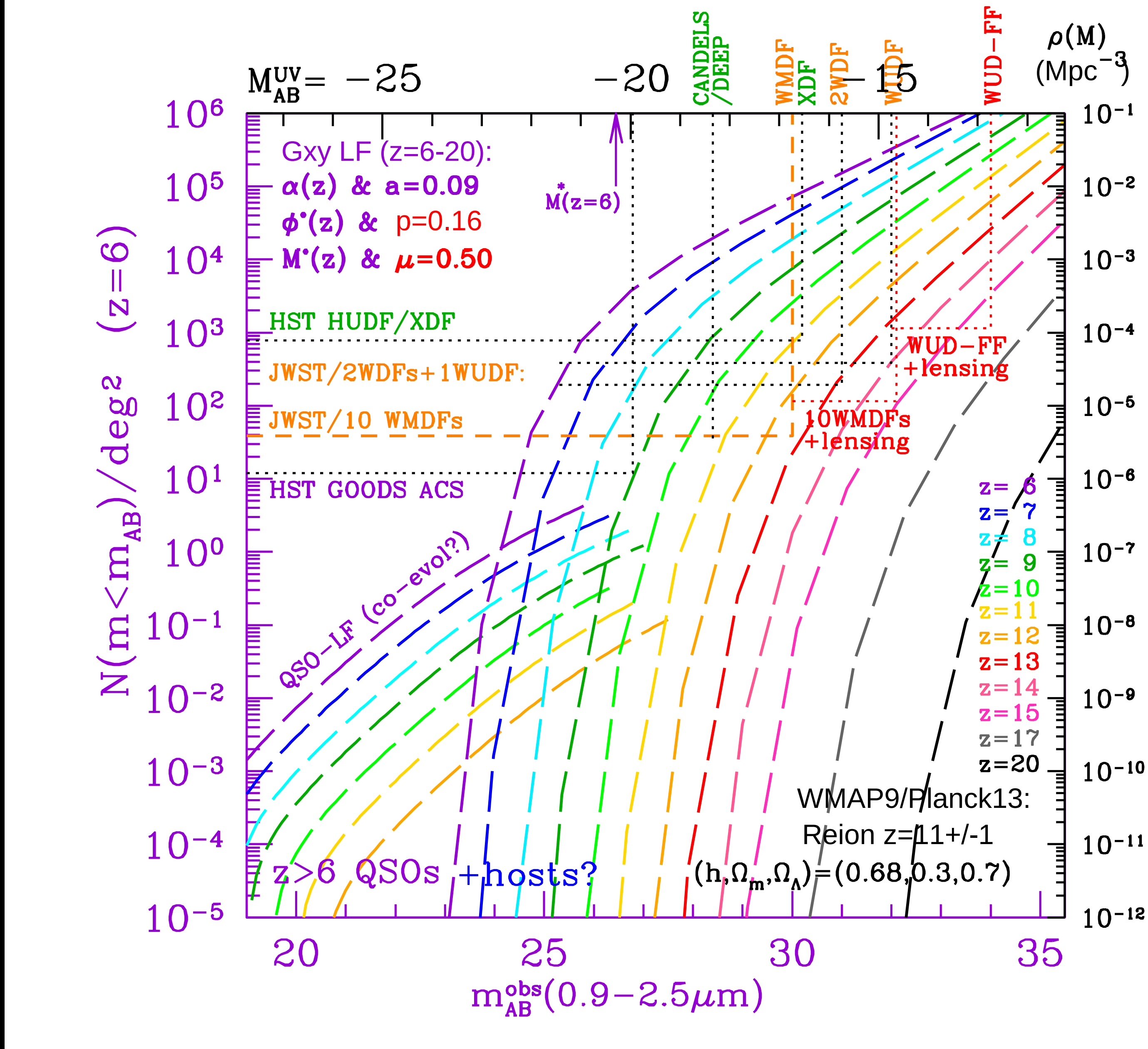

13 filter Hubble UltraDeep Field:
False-color or "Bolometric" image.
841 orbits = 592 hr; AB≲31 mag; Objects affect ~45% of all pixels!!


o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592 hours HUDF weighted log^2: FuvNuvUBViIzYJWH, AB$\lesssim$ 31 ($\gtrsim$1 firefly).

The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.



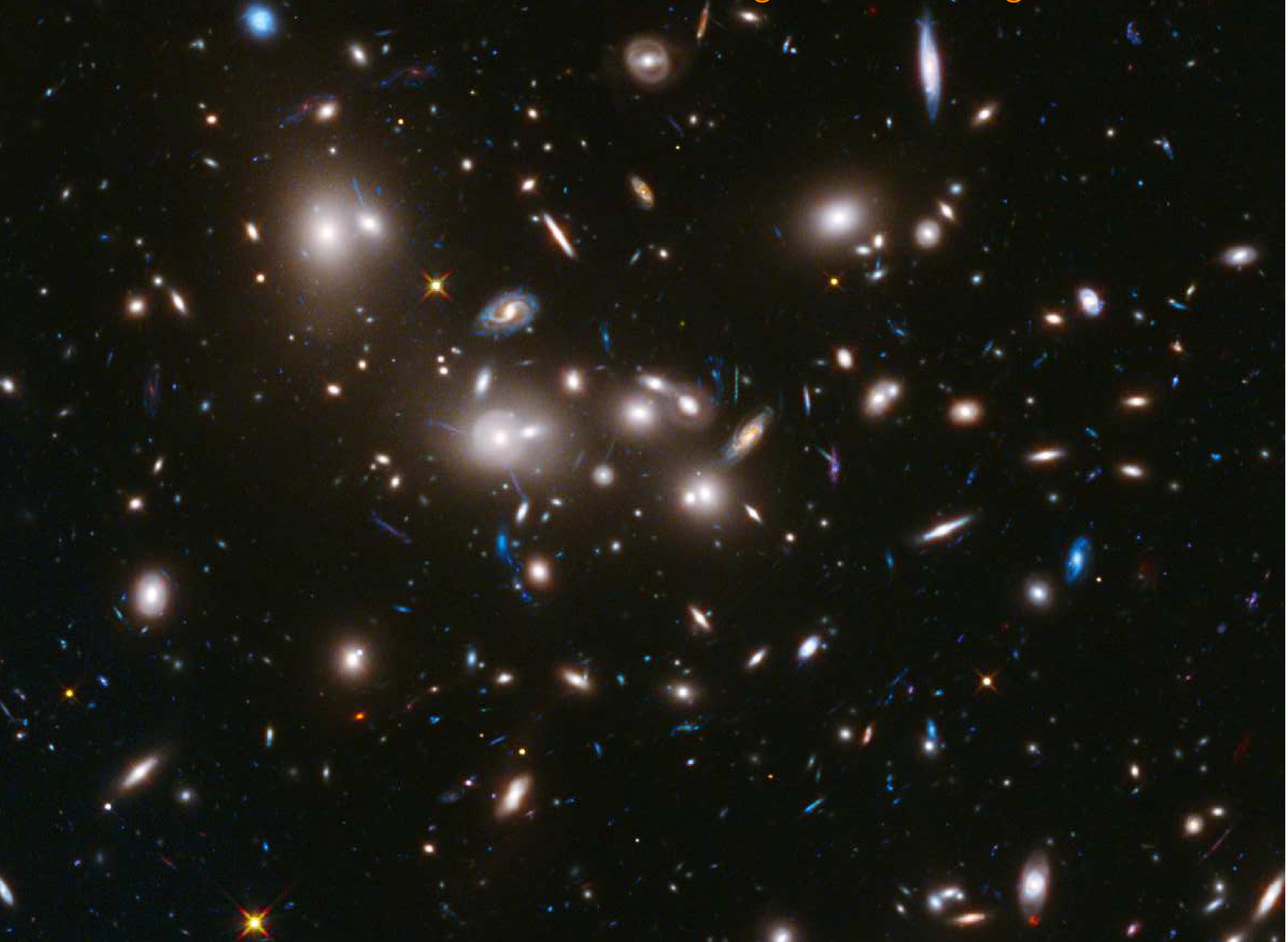
592 hours HUDF weighted log^2: FuvNuvUBViIzYJWH, AB$\lesssim$31 ($\gtrsim$1 firefly).



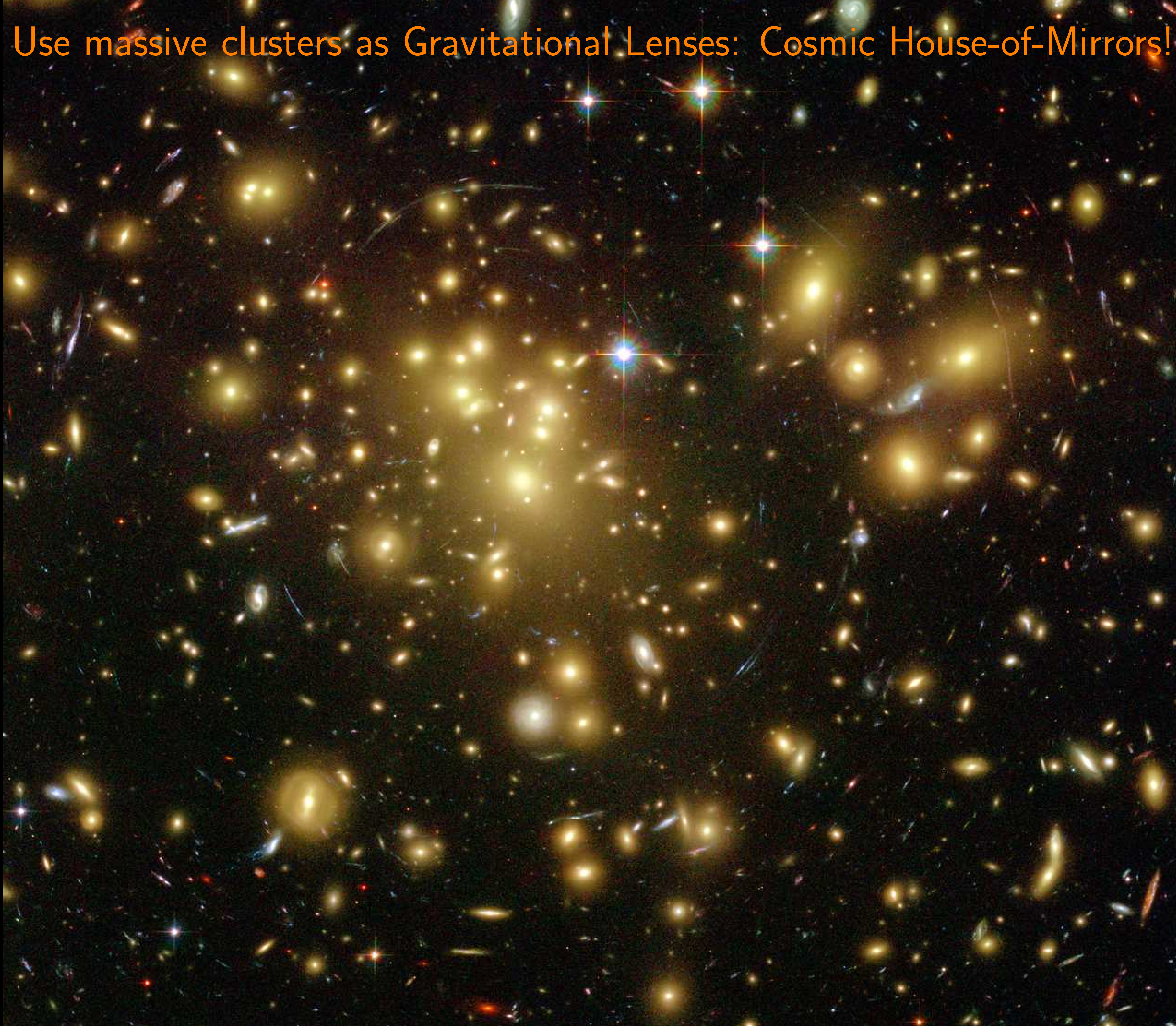
The "Cosmic Stock Market chart of galaxies: Very few big bright objects in the first Gyr, but lots of dwarf galaxies at z$\gtrsim$6 (age$\lesssim$1 Gyr).

- With proper survey strategy (area AND depth), Webb can trace the entire reionization epoch and detect the first star-forming objects.

HST Frontier Field A2744: Webb needs lensing to see First Light at $z \gtrsim 10$–15!



Use massive clusters as Gravitational Lenses: Cosmic House-of-Mirrors!



Two fundamental limitations may determine Webb's ultimate image depth:

(1) Cannot-see-the-forest-for-the-trees effect [Natural Confusion limit]:

Background objects blend into foreground because of their own diameter
$\Rightarrow$ Need multi-wavelength deblending algorithms.

(2) House-of-mirrors effect ["Gravitational Confusion"]: Most First Light objects at z$\gtrsim$12–14 may need to be found by cluster or group lensing.

$\Rightarrow$ Need multi-color object-finders that works on sloped backgrounds.

$\Rightarrow$ May need to use and model the entire gravitational foreground.

(6) 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 97% 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.

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

- IR sequel to HST after 2018: Training the next generation researchers.
- JWST will define the next frontier to explore: the Dark Ages at $z \gtrsim 20$.

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/

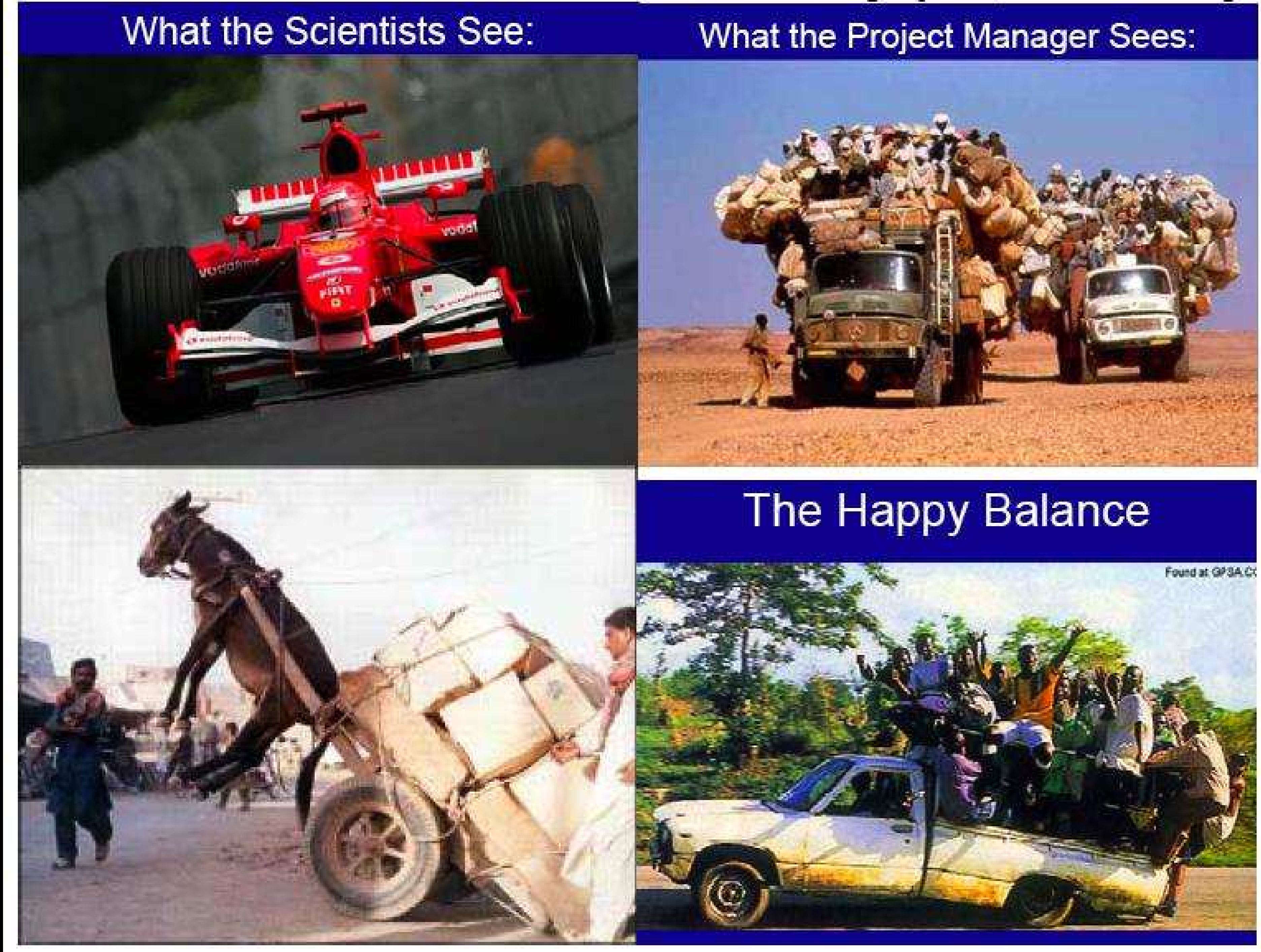
http://www.stsci.edu/jwst/instruments/fgs

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

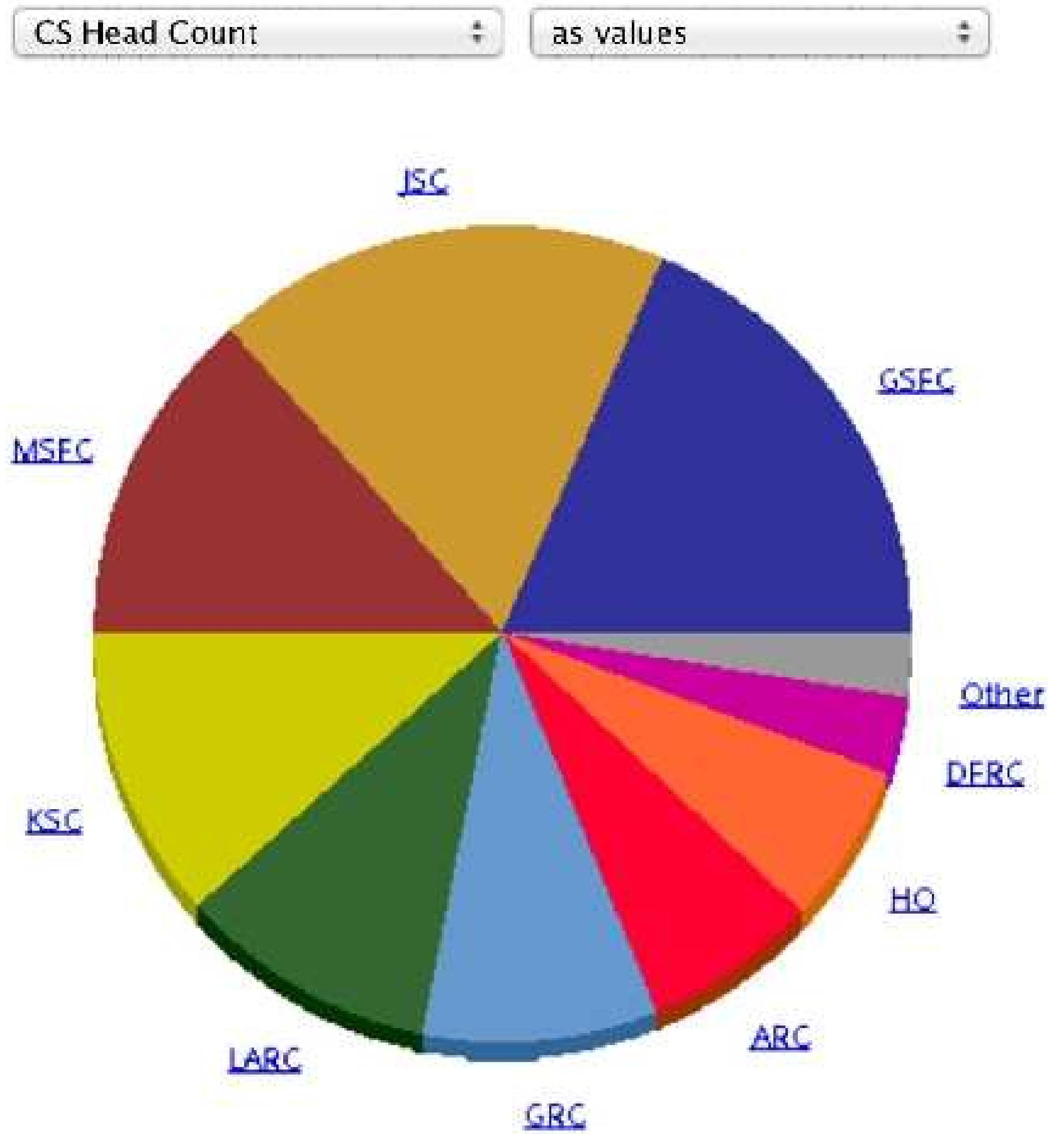
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776)



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



	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`

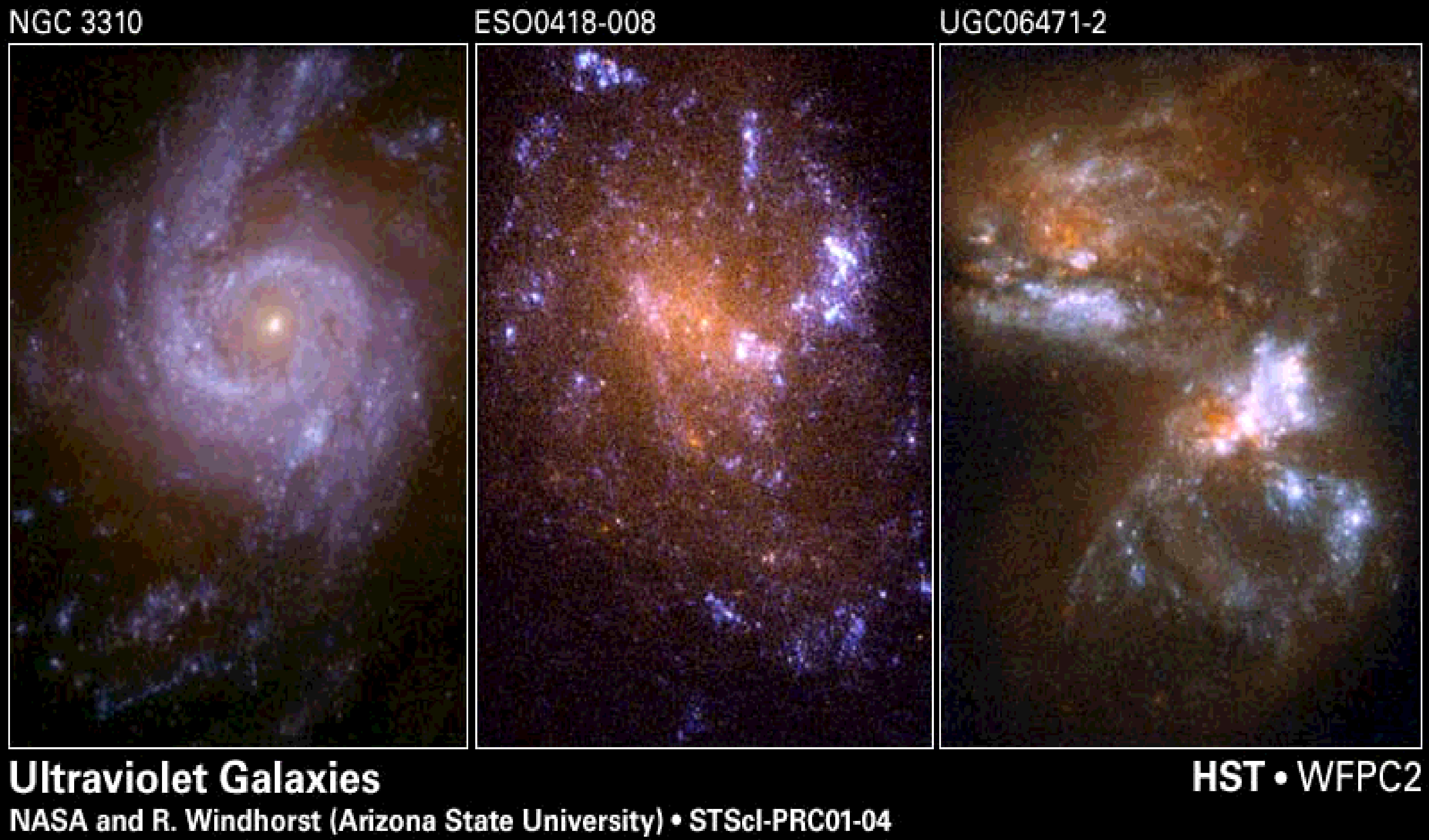
Future Careers at NASA:
What do our Astrophysics College Graduates do?

- 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

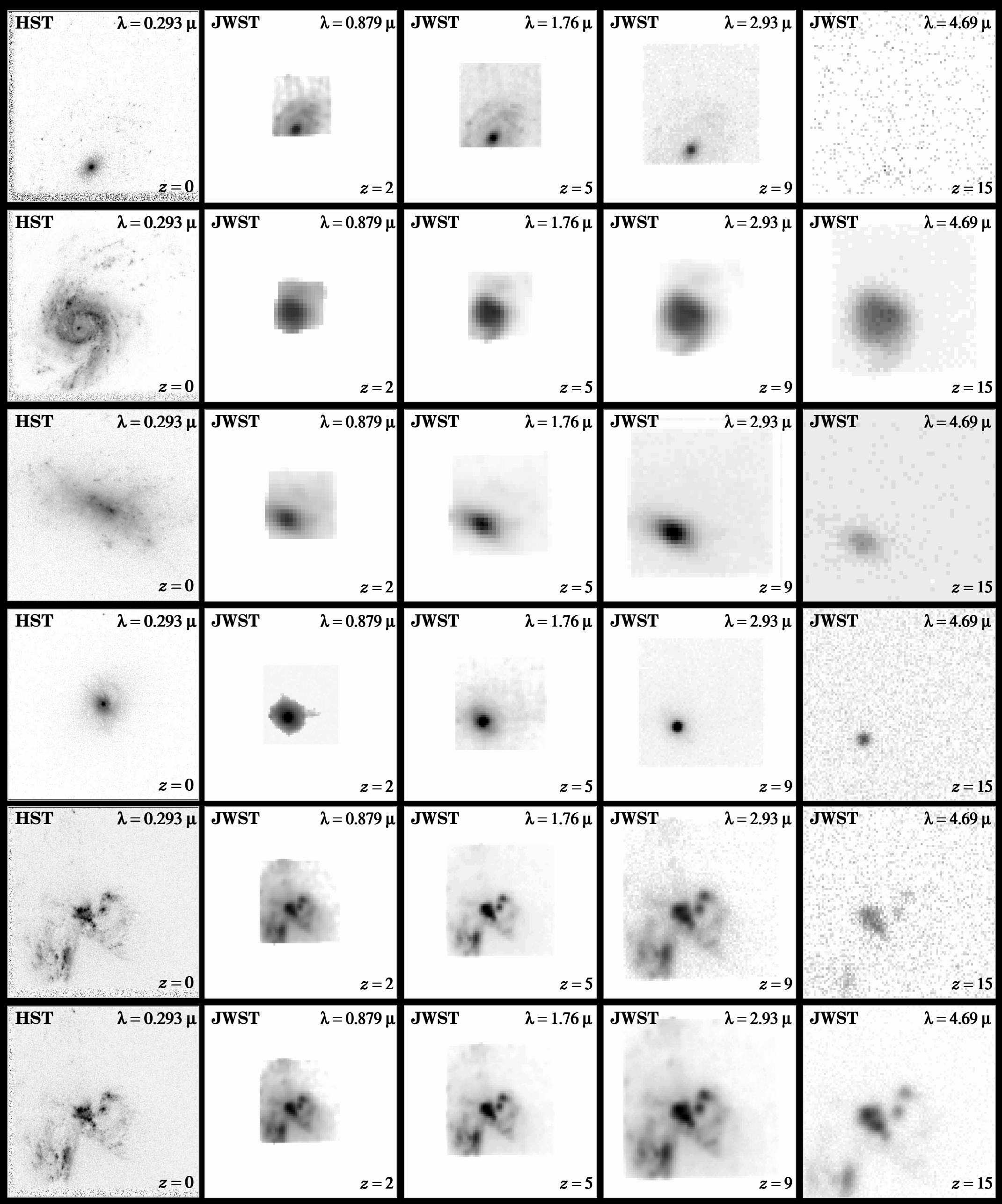


• The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

• 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.

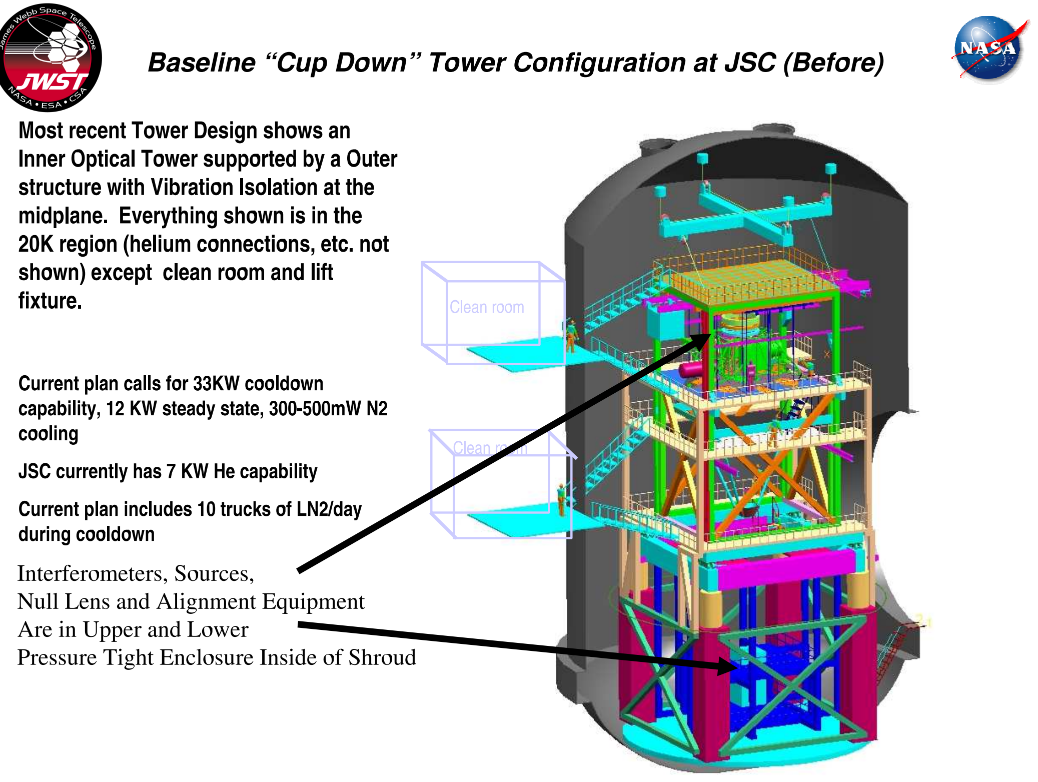
Visible to JWST at very high z are:

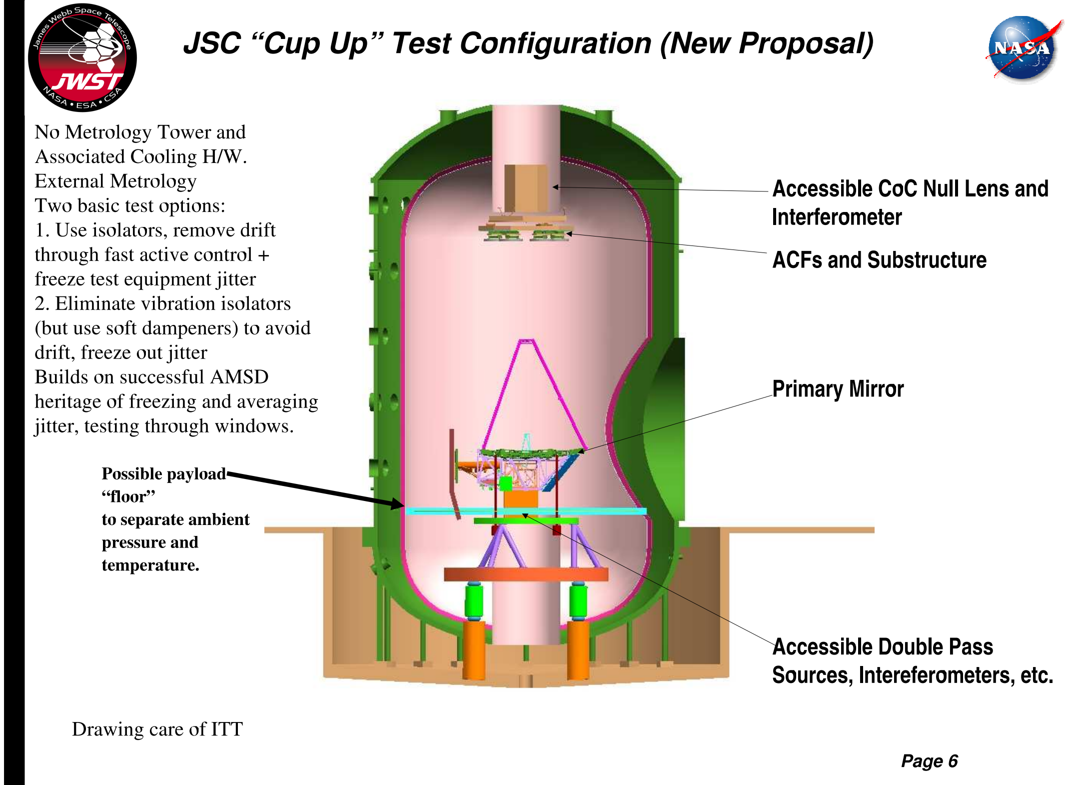
- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.

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

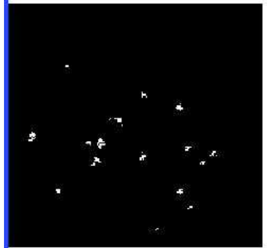
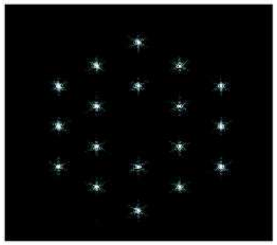
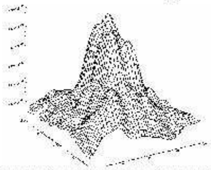
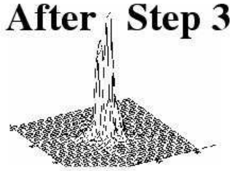






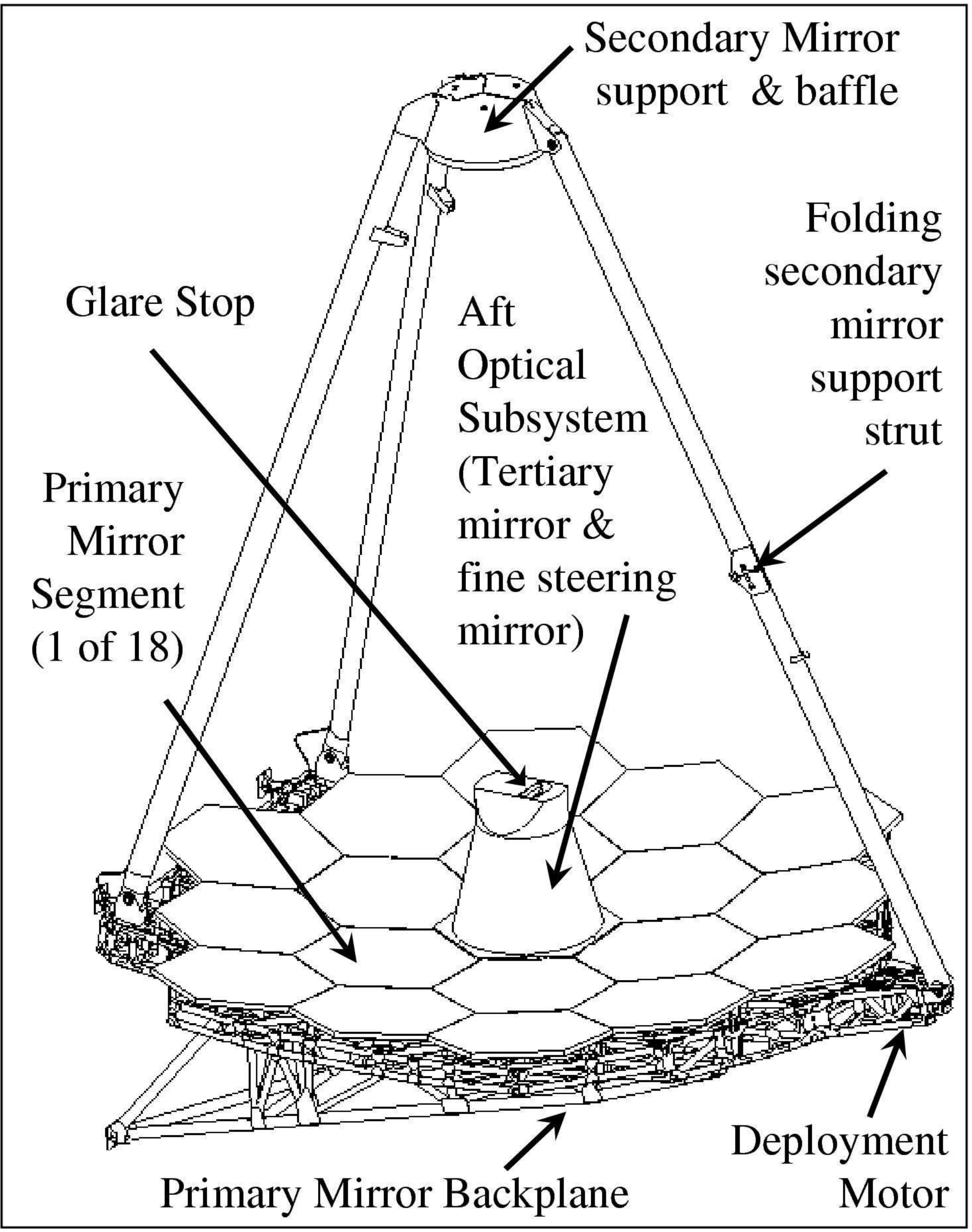
JWST underwent several significant replans and risk-reduction schemes:

- $\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		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)

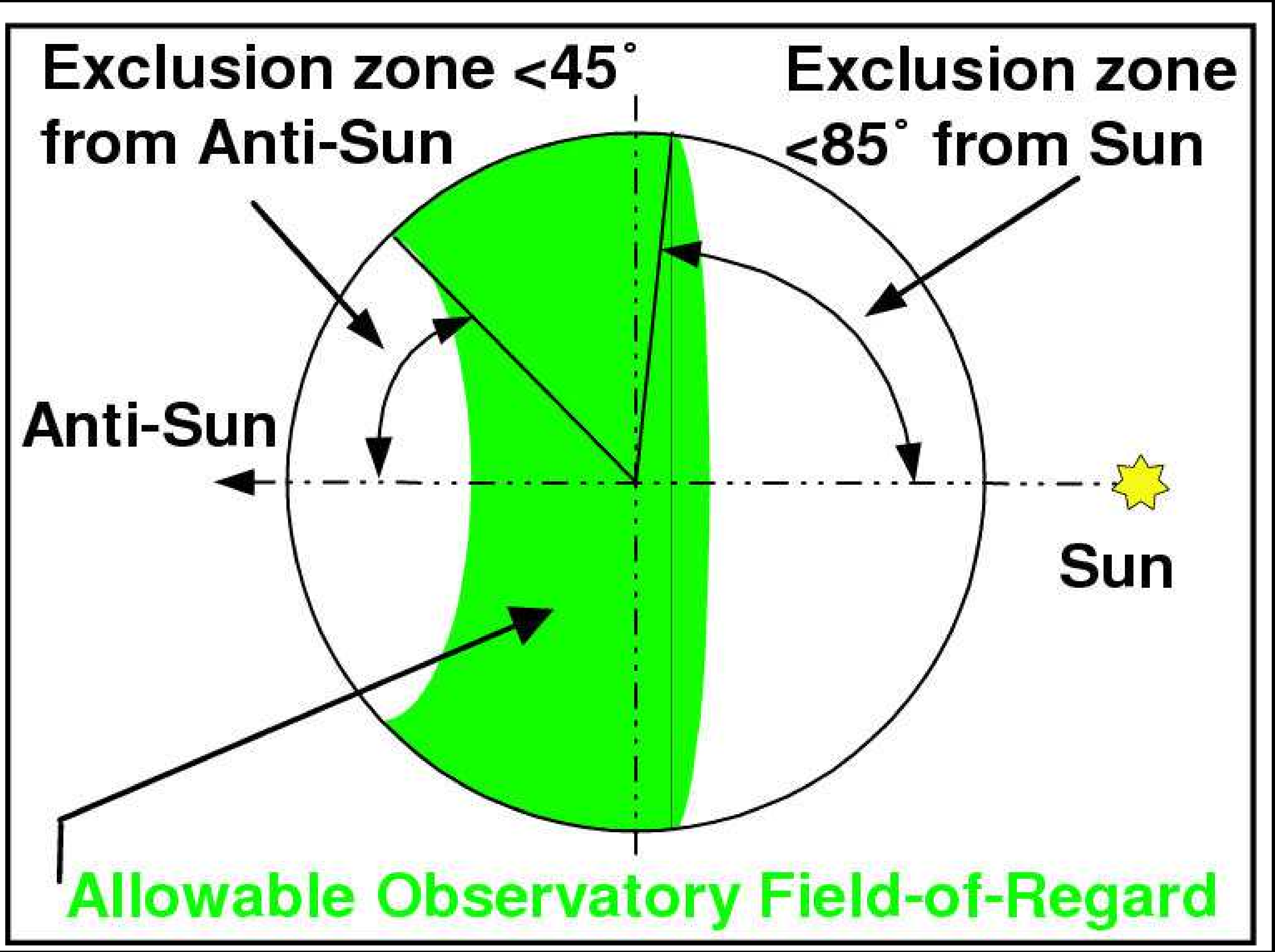
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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

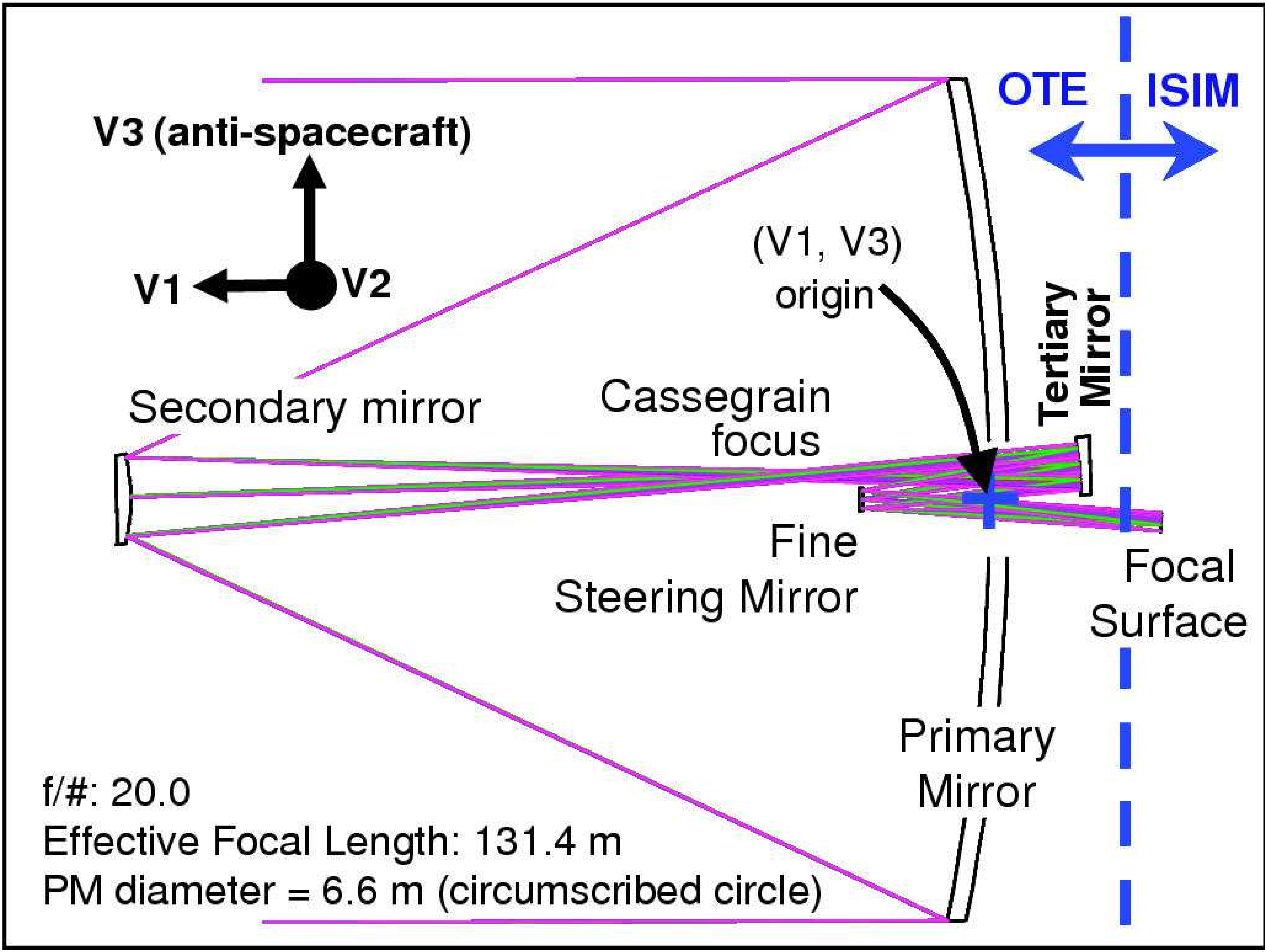


Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015-2016.

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:

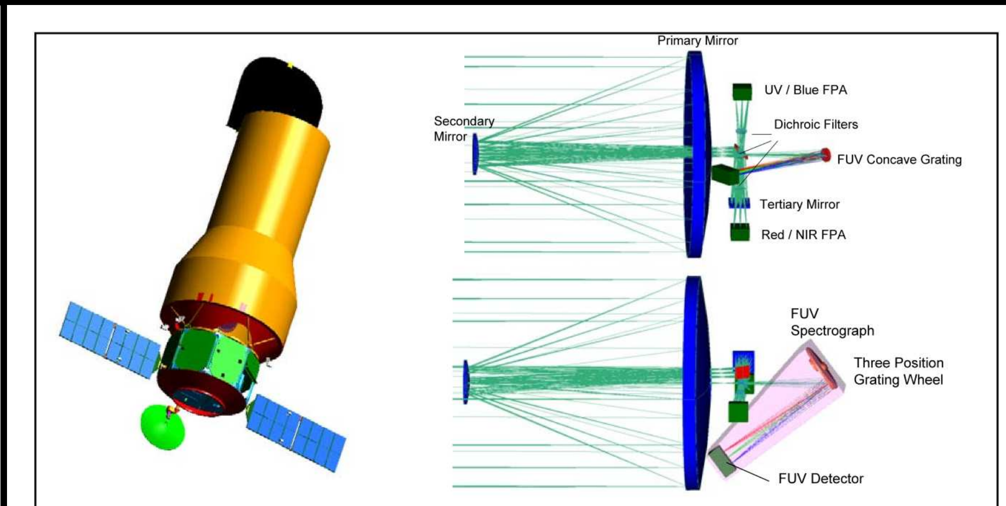
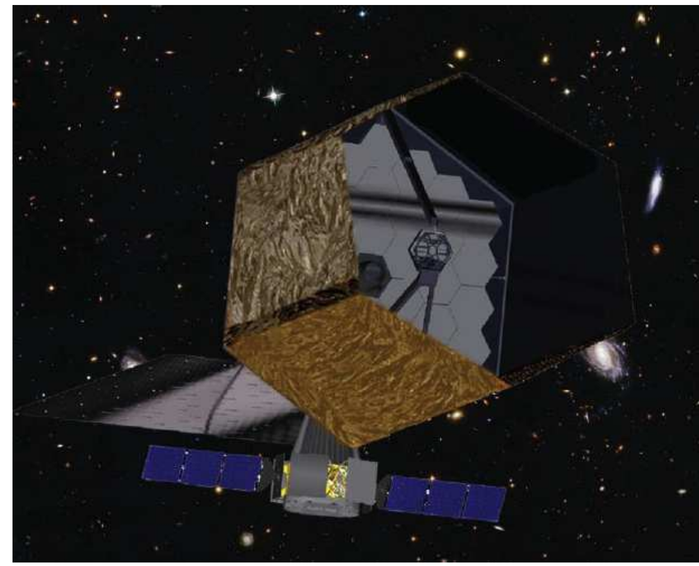


Figure 2.5.3 - *HORUS* Observatory and Optical Ray Trace



[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$0.25 deg) UV-opt 0″.06 FWHM imaging to AB$\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 ...