The Search for First Light:

James Webb Space Telescope Hardware Update

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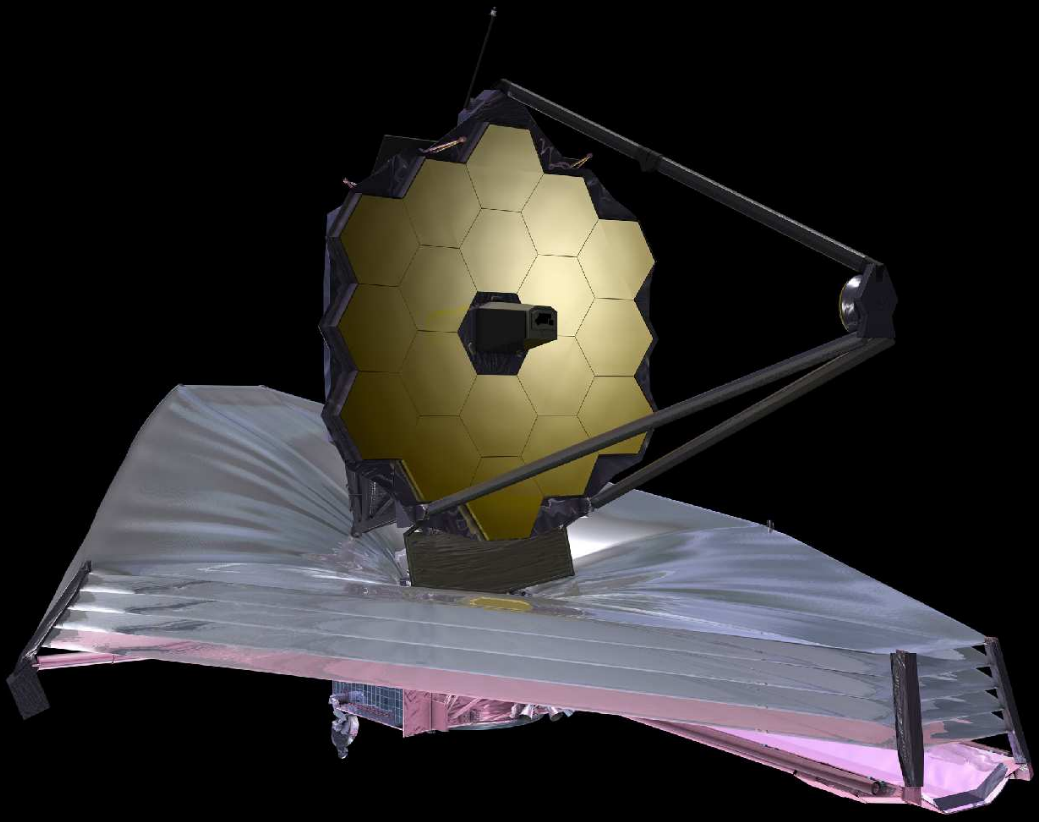


SESE Undergraduate Seminar, Arizona State University, Tempe, AZ

Friday April 22, 2016; All presented materials are ITAR-cleared.

Outline

- (1) James Webb Space Telescope Hardware Update as of 2016.

- (2) How will JWST measure Galaxy Assembly & Supermassive Blackhole Growth — handshake with 2016 LIGO Gravitational Wave results.

- (3) How will JWST measure the Epoch of First Light (using gravitational lensing) — handshake with Planck 2016 results.

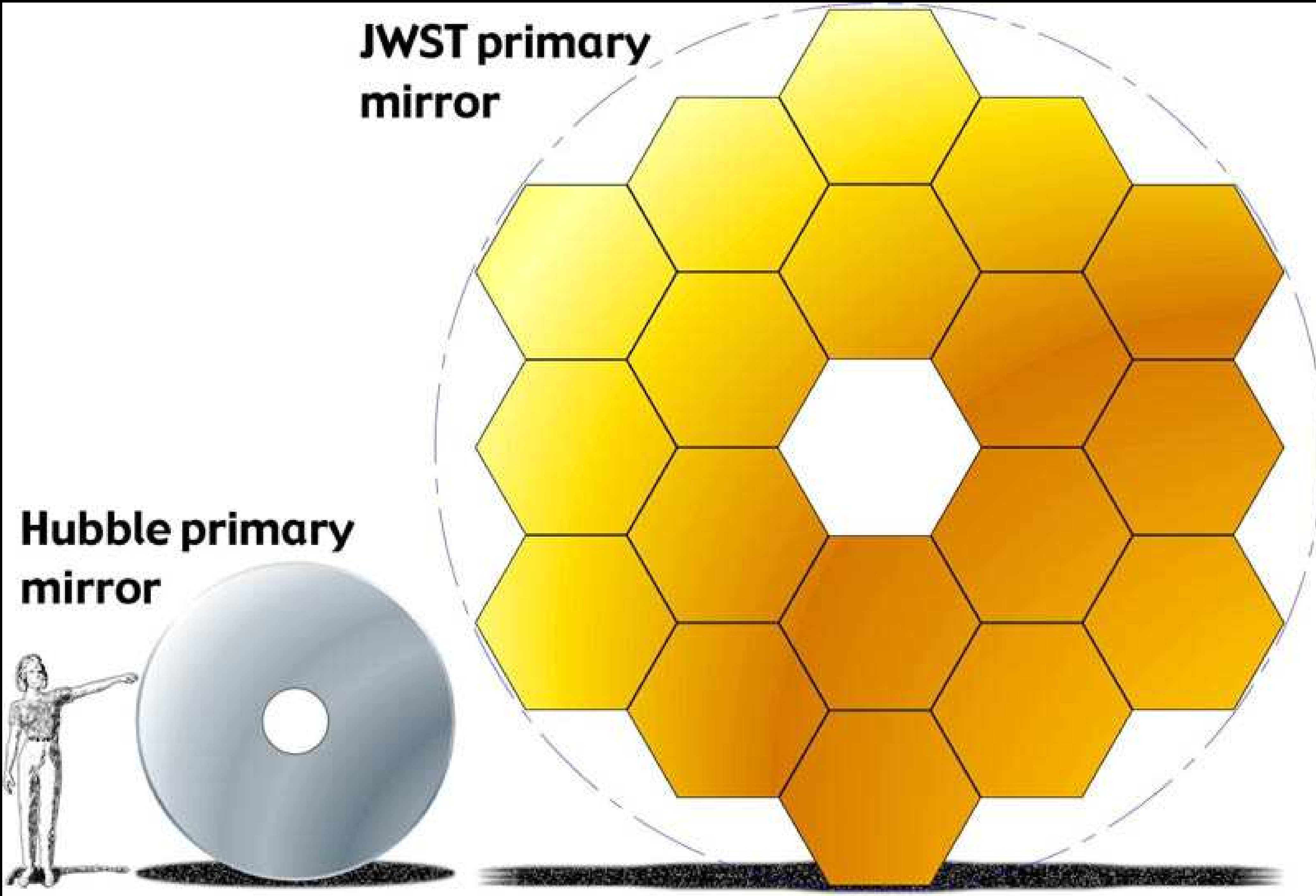
  - (4) Where do our students end-up? Possible NASA Careers

- (5) Summary and Conclusions.

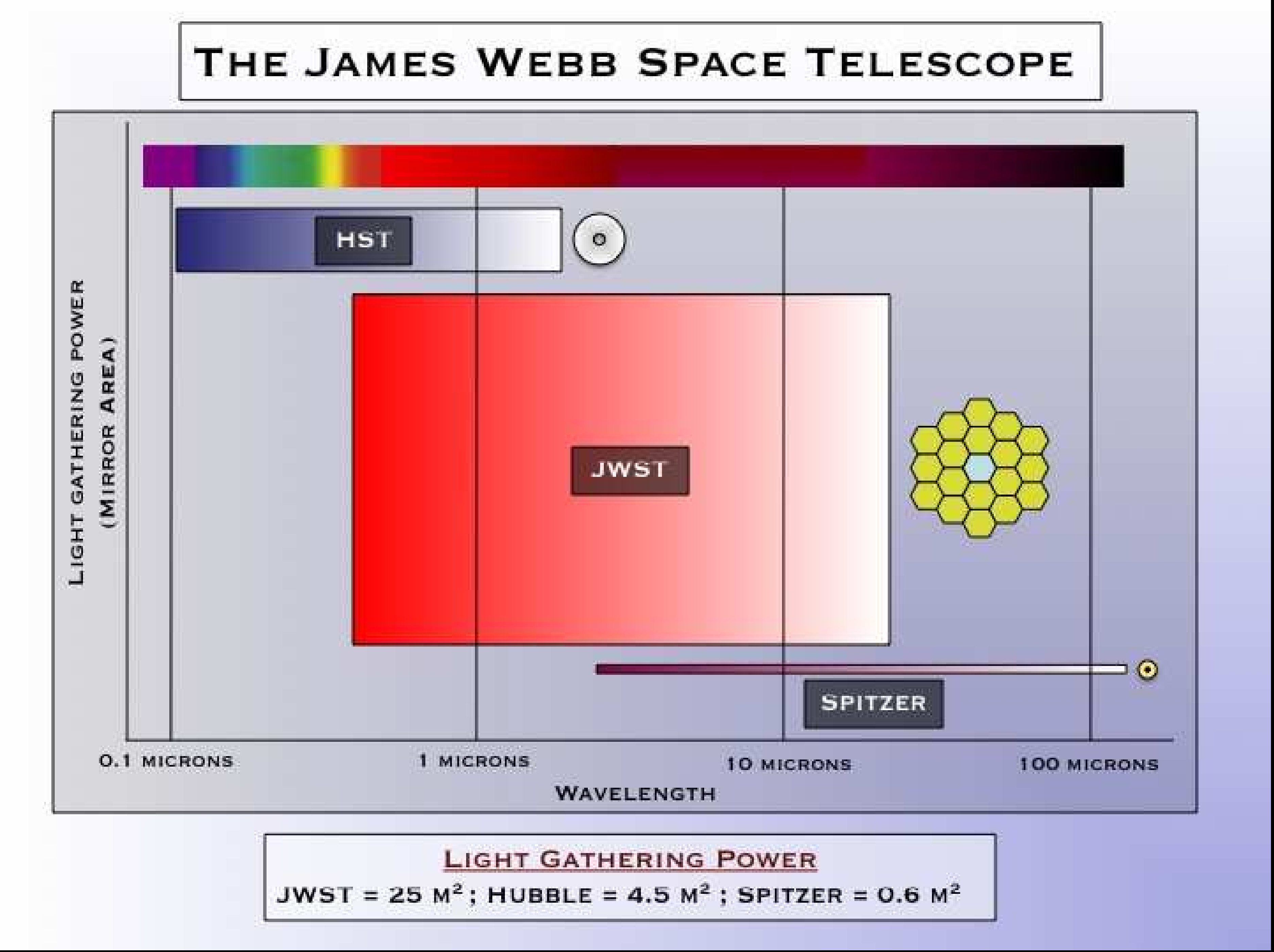
Sponsored by NASA/HST & JWST

Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/asuphysics16_hstjwst.pdf`

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



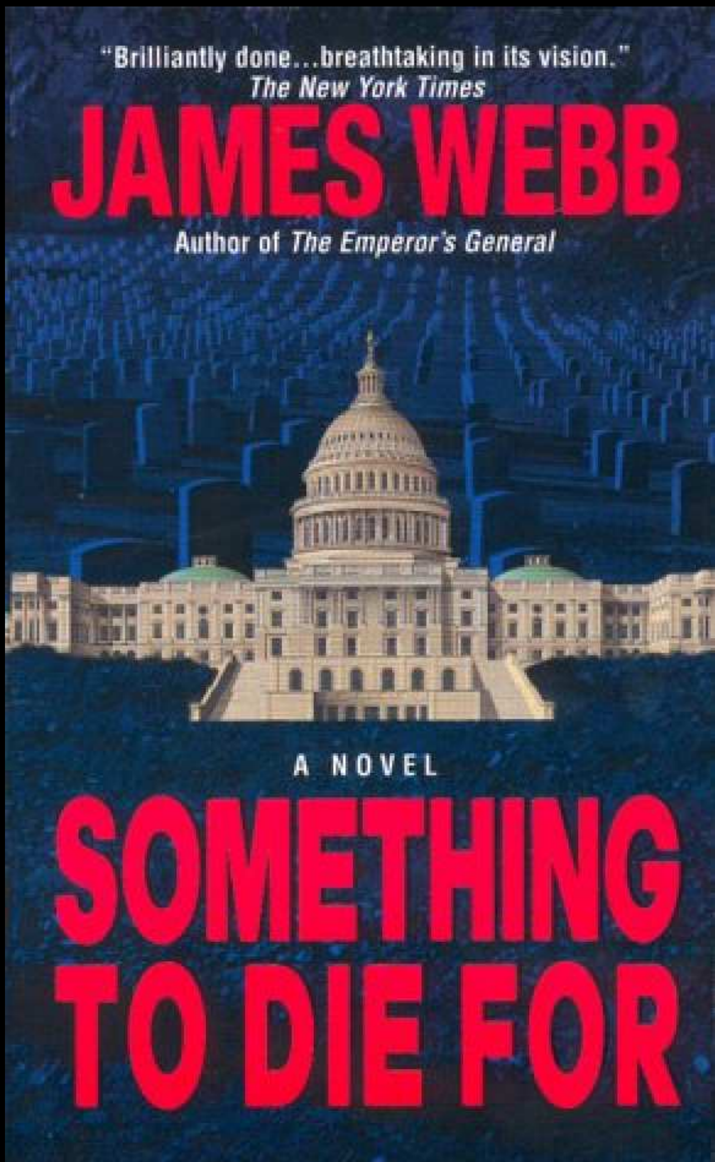
JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.



JWST is the perfect near–mid-IR sequel to HST and Spitzer:

Vastly larger collecting area than HST in UV-optical and Spitzer in mid-IR.

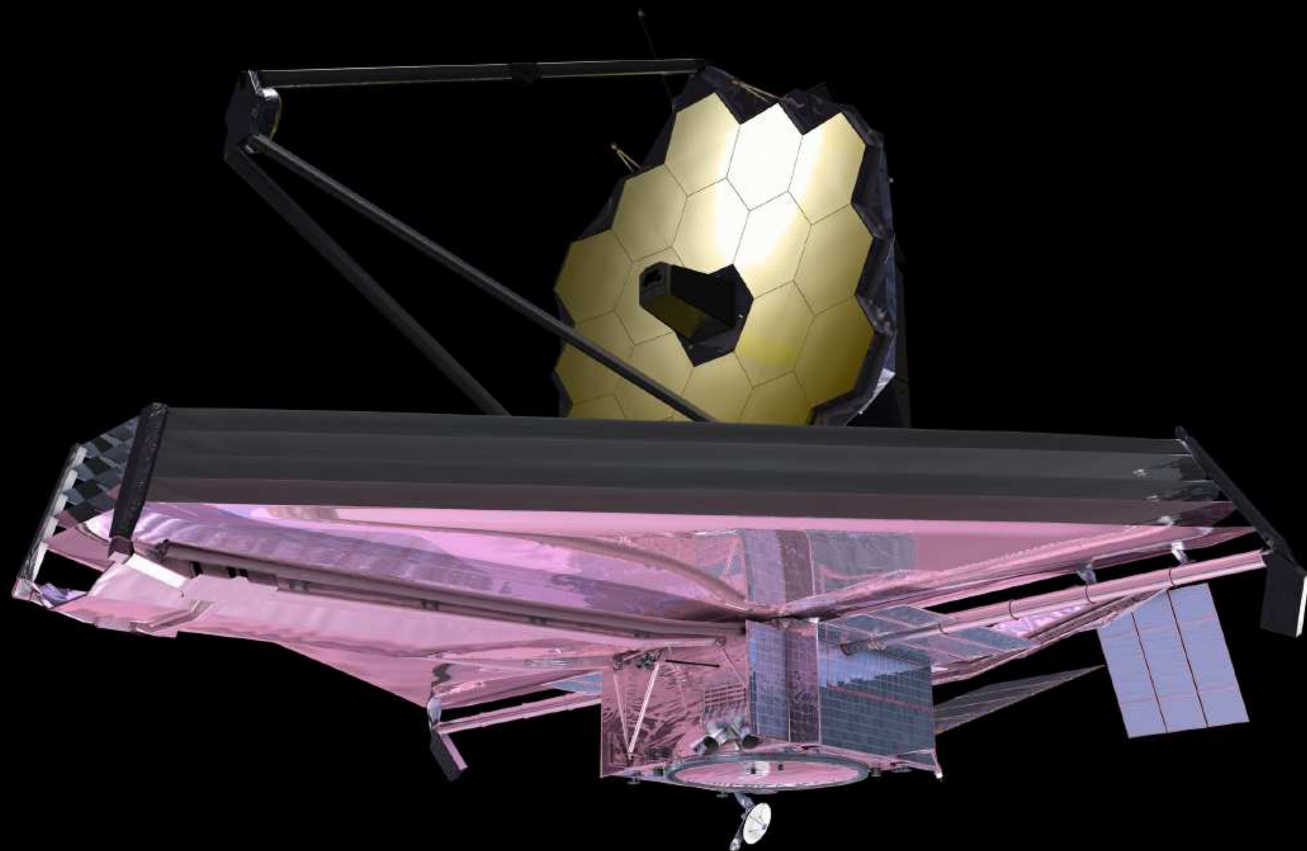
(1) Update of the James Webb Space Telescope (JWST), 2016.



To be used by students & scientists after 2018 ... It'll be worth it.

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

(1) Update of the James Webb Space Telescope as of 2016.



- 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 (AB=31.5 mag) and spectroscopy.

The James Webb Space Telescope

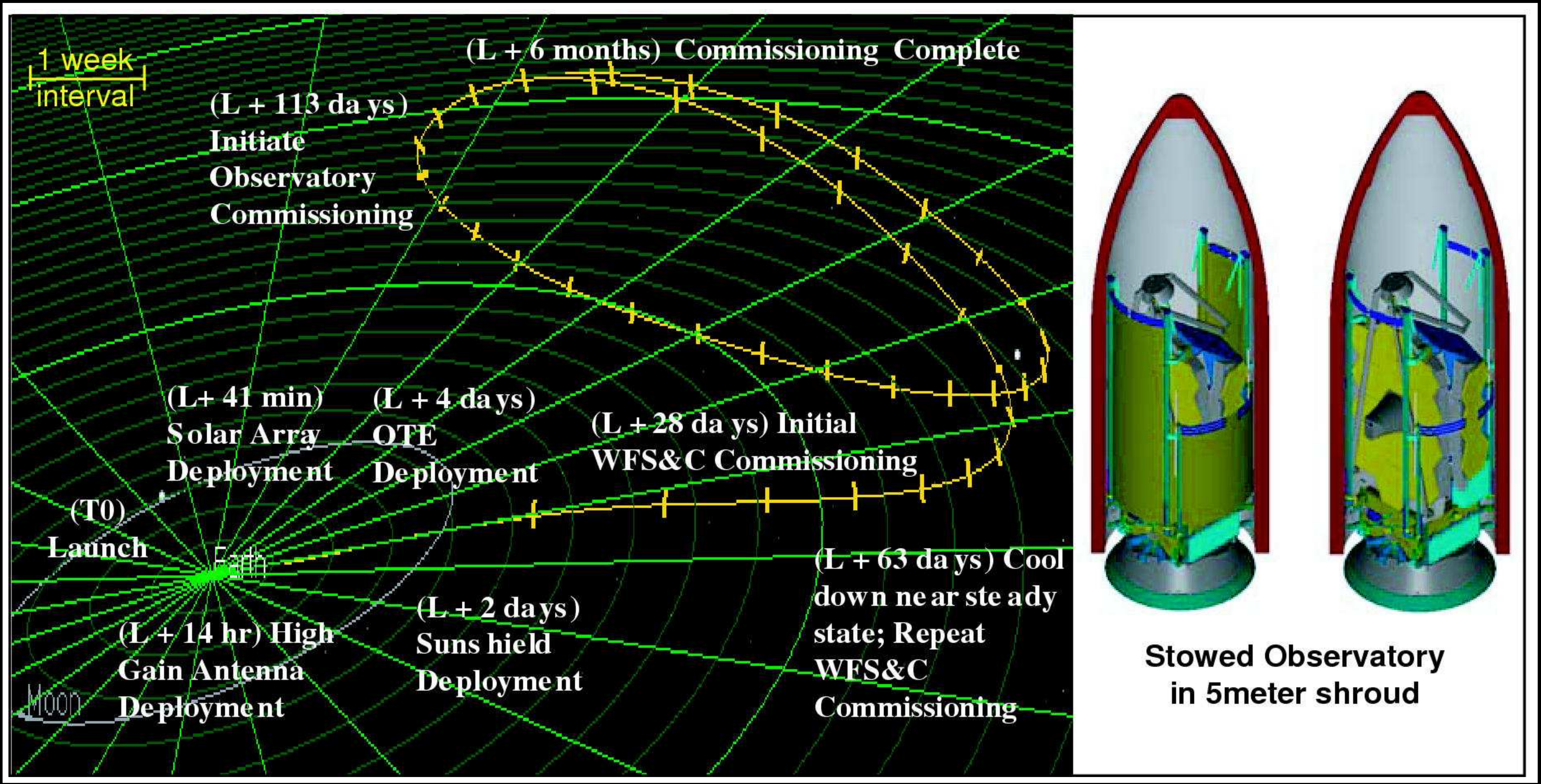
JWST Launch

- 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

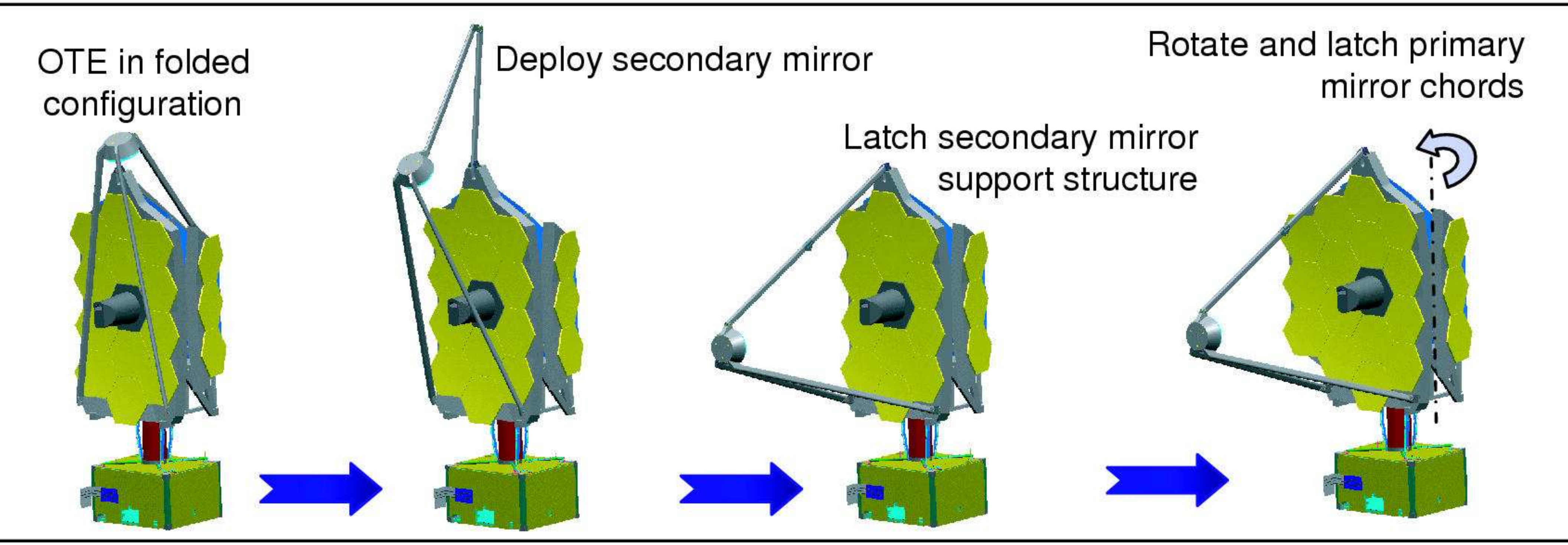
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(1a) How will JWST travel to its L2 orbit?



- After launch in (Oct.) 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.

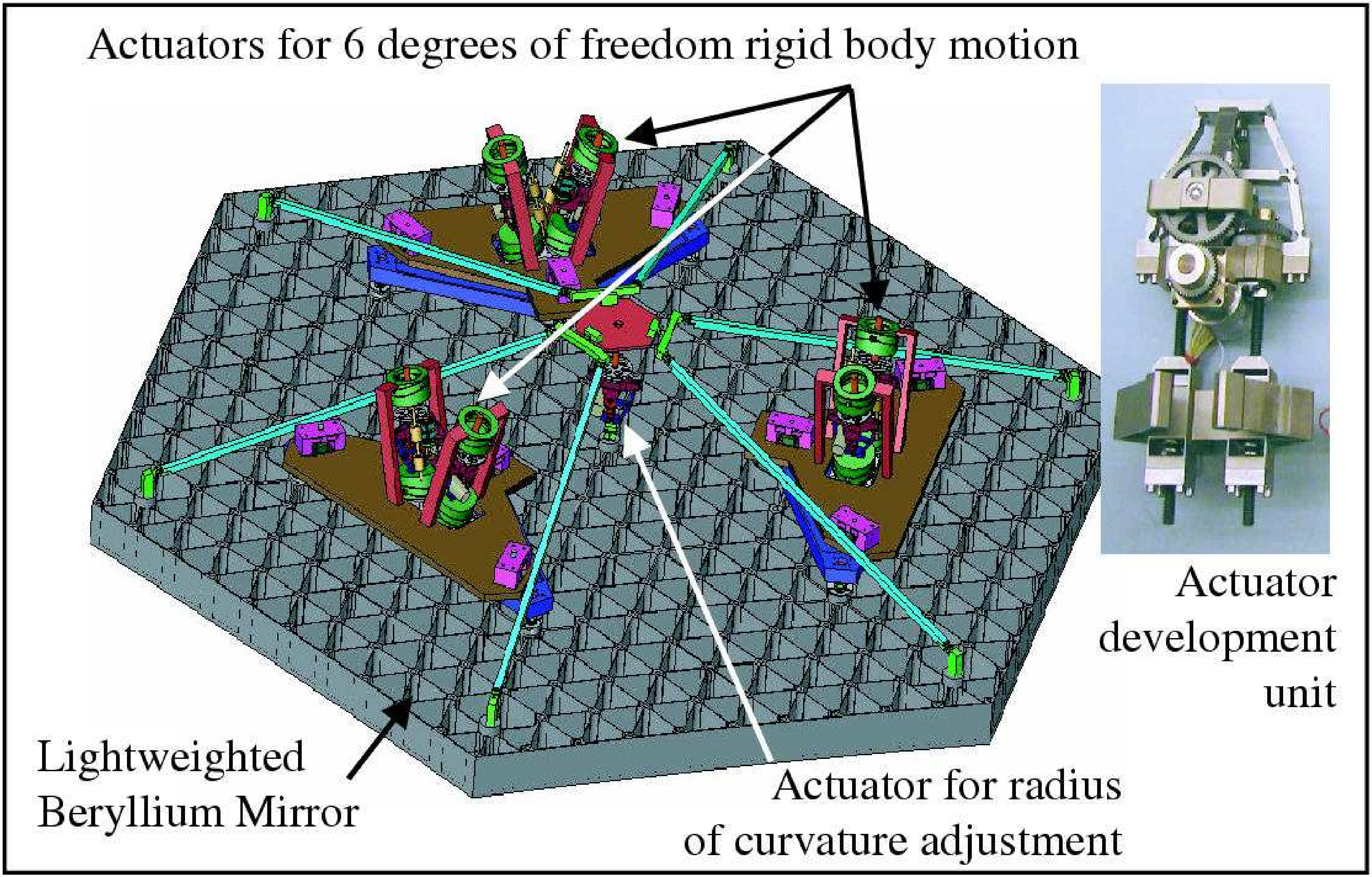
(1b) How will JWST be automatically deployed?



- 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).

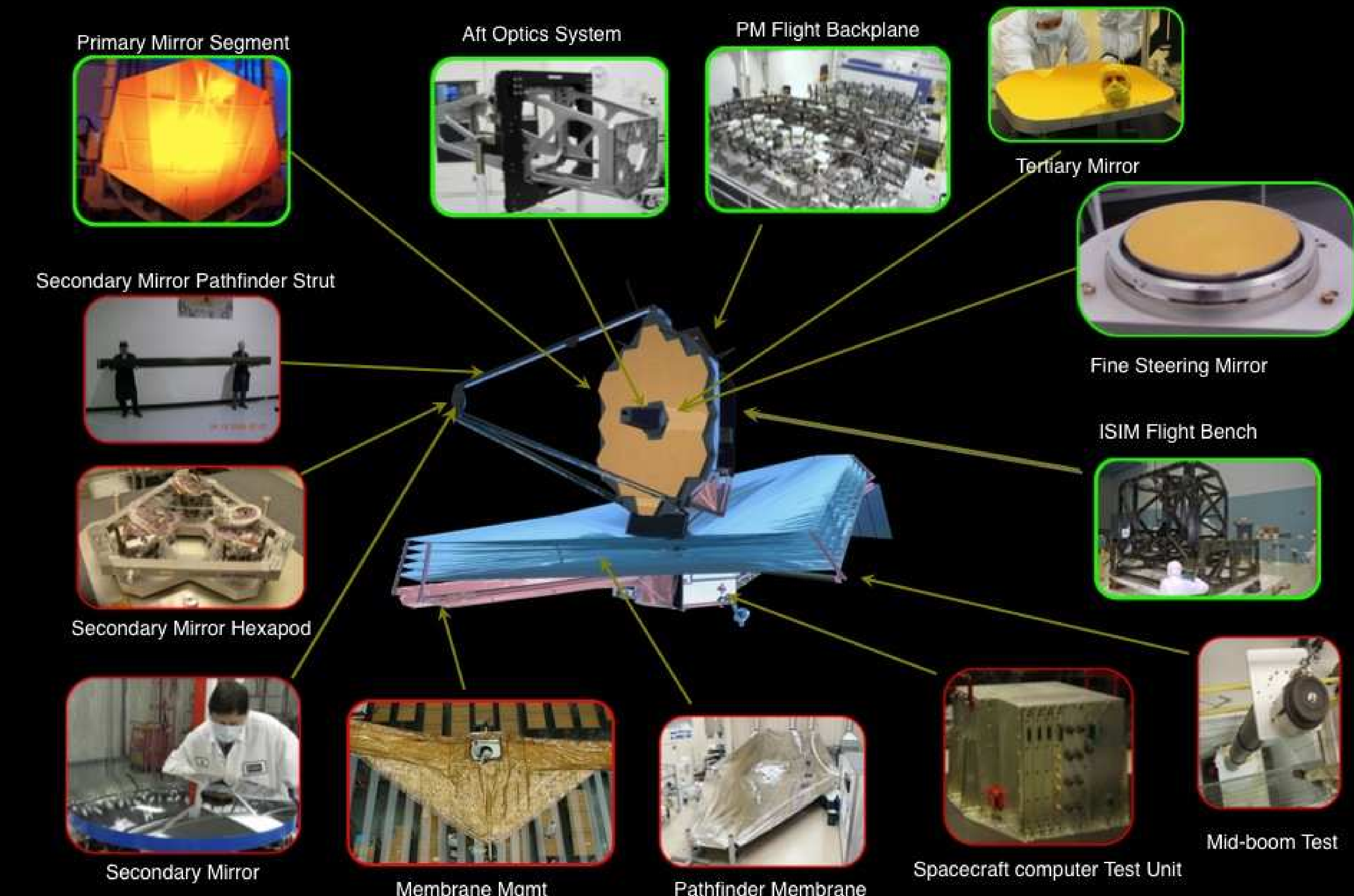
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



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

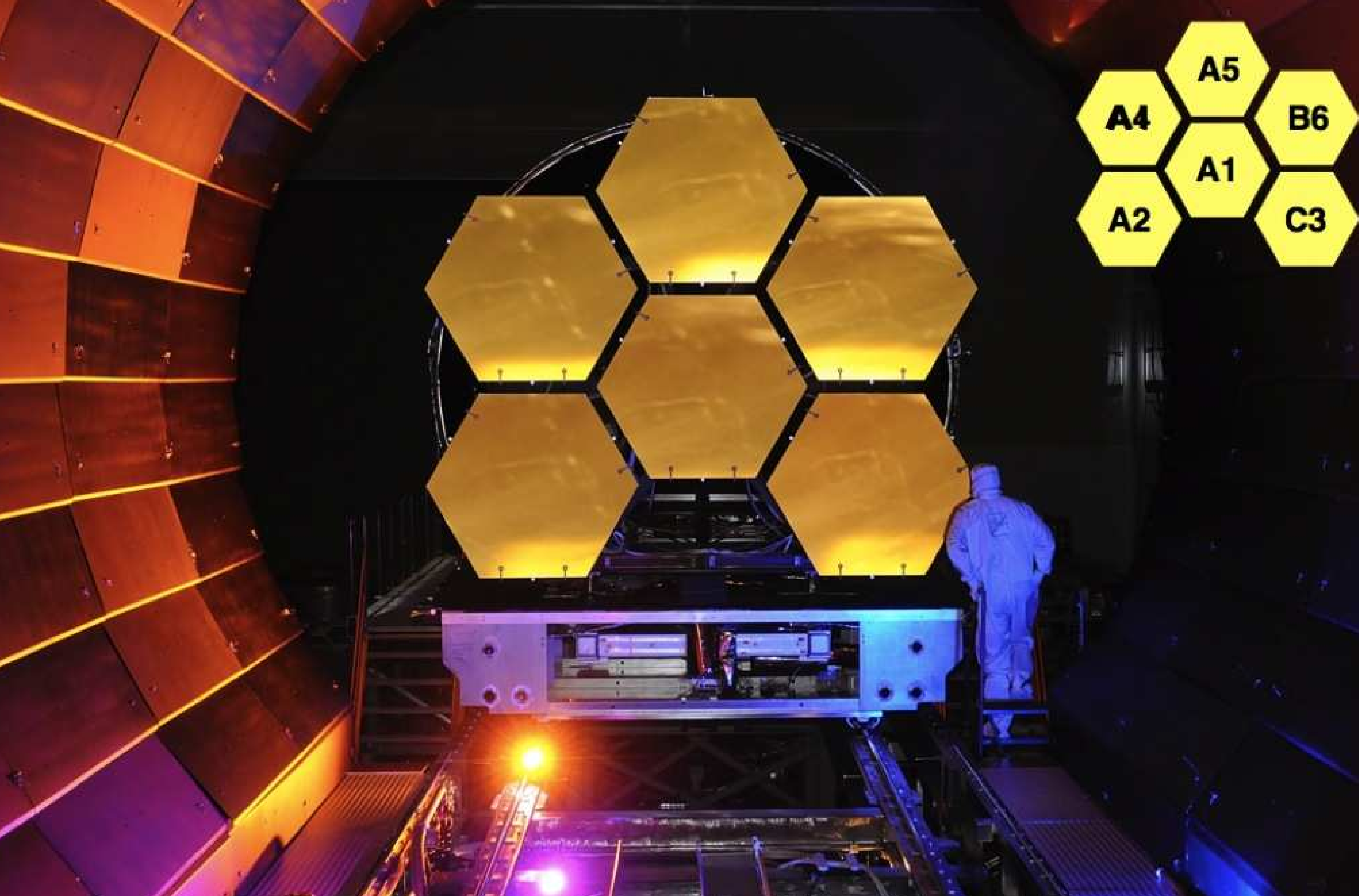
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

JWST Hardware Status



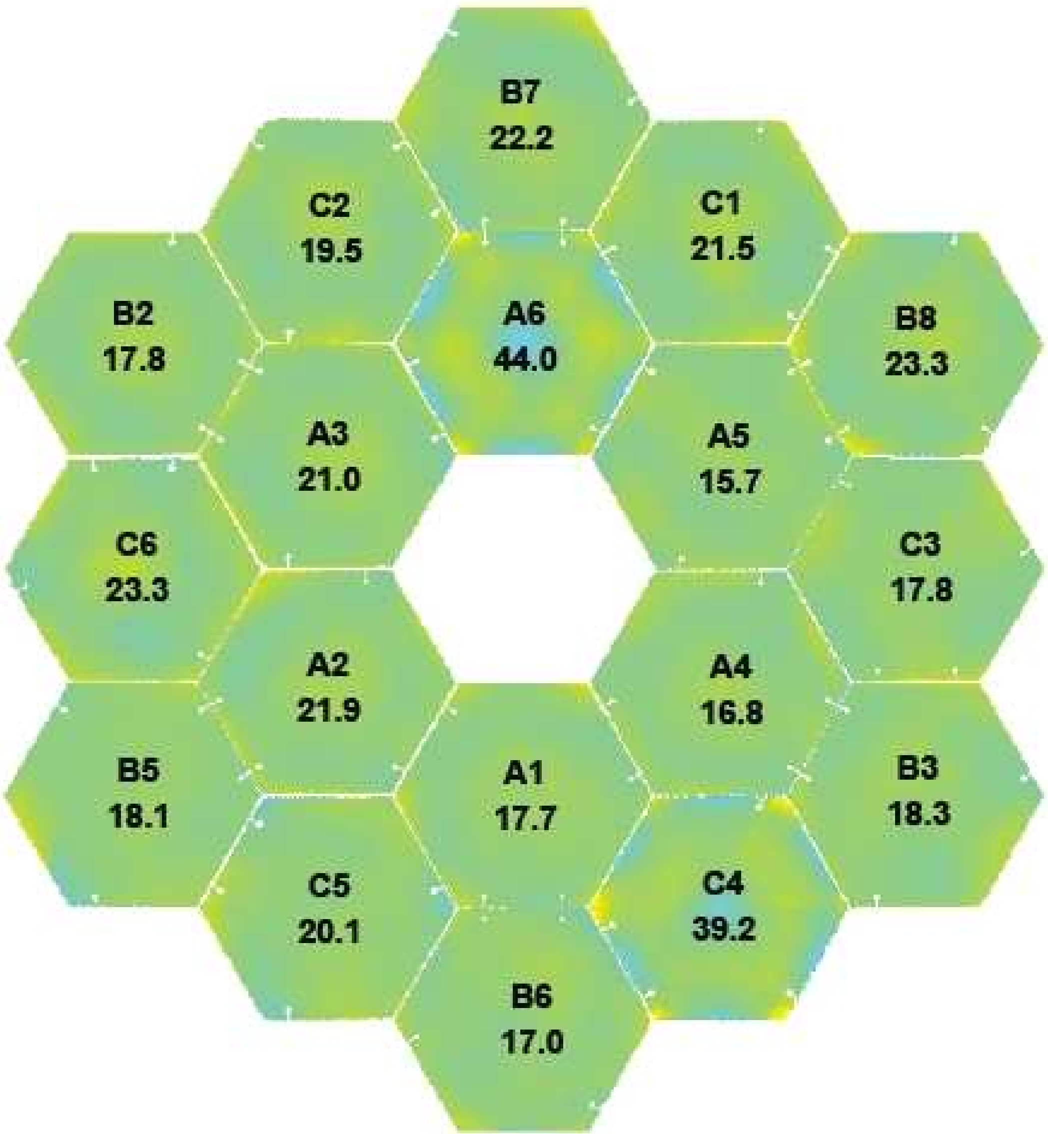
Apr. 2016: $\gtrsim$99% of launch mass designed and built ($\gtrsim$70% weighed).

Mirror Acceptance Testing



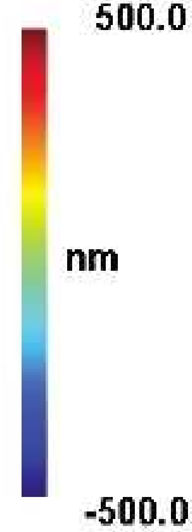

Ball

Primary Mirror Composite



RMS: 23.2 nm

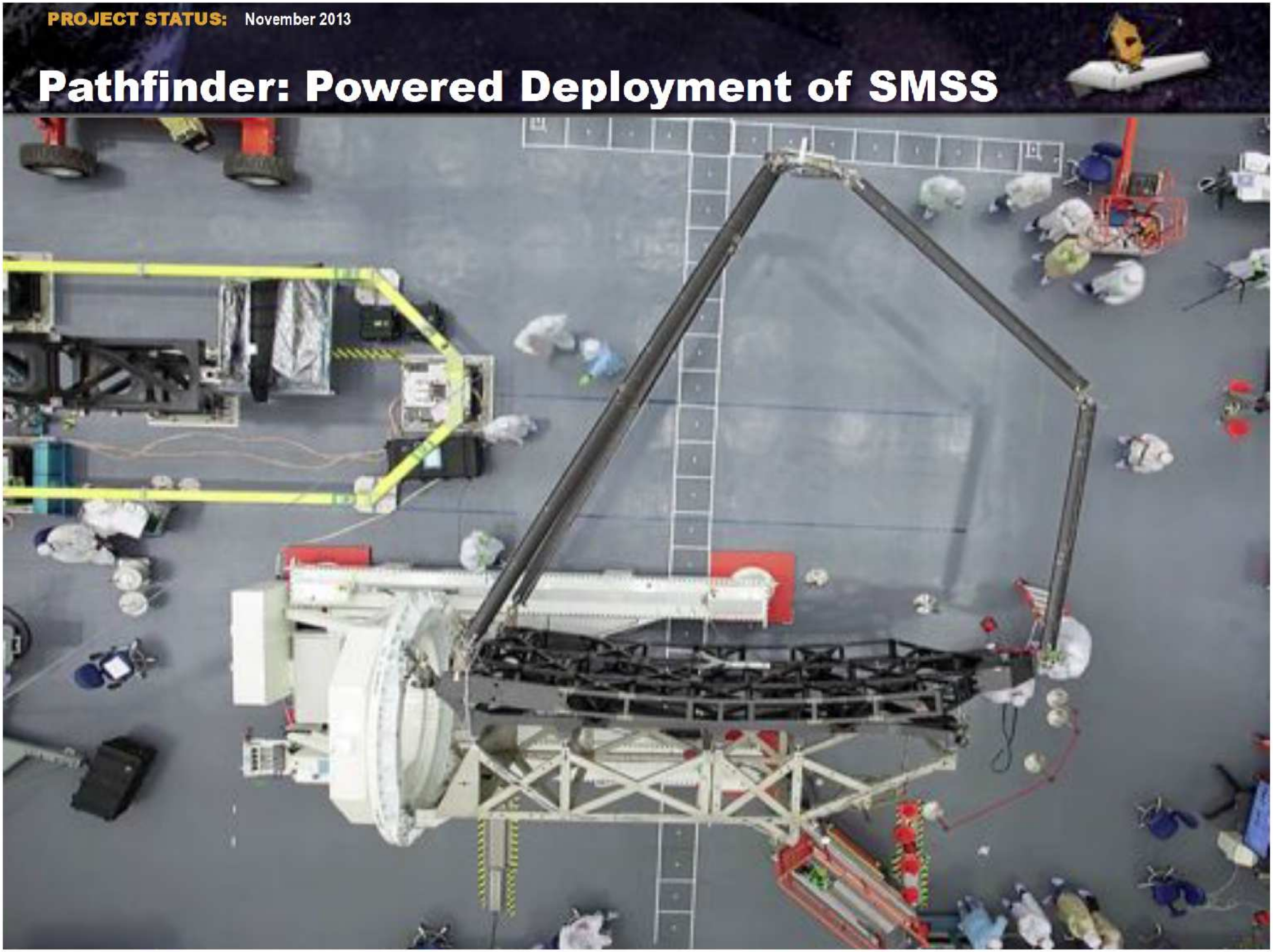
PV: 515.5 nm



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 delivered to NASA GSFC (MD).



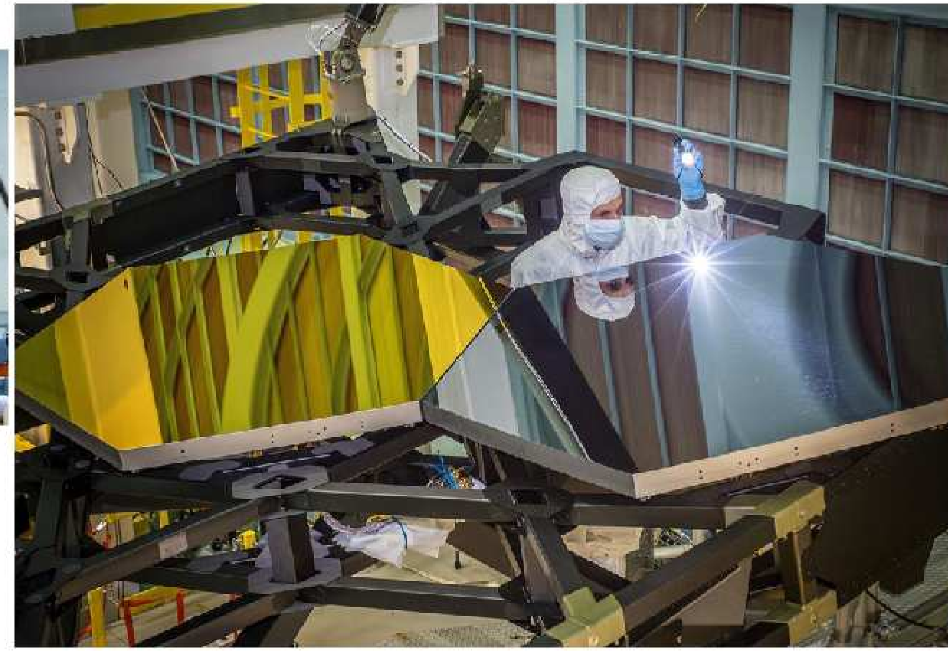
July 2014: Secondary Mirror Support deployment successfully tested.

(1c) JWST hardware to date, and how to best use it for high redshift lensing.

[LEFT]: Aug. 2014: Engineering Kapton Sunshield; 2016: Flight Sunshield.
[RIGHT]: Nov. 2014: First JWST mirrors mounted onto support structure, using Engineering Demo mirrors — Flight mirrors mounted in Jan. 2016.

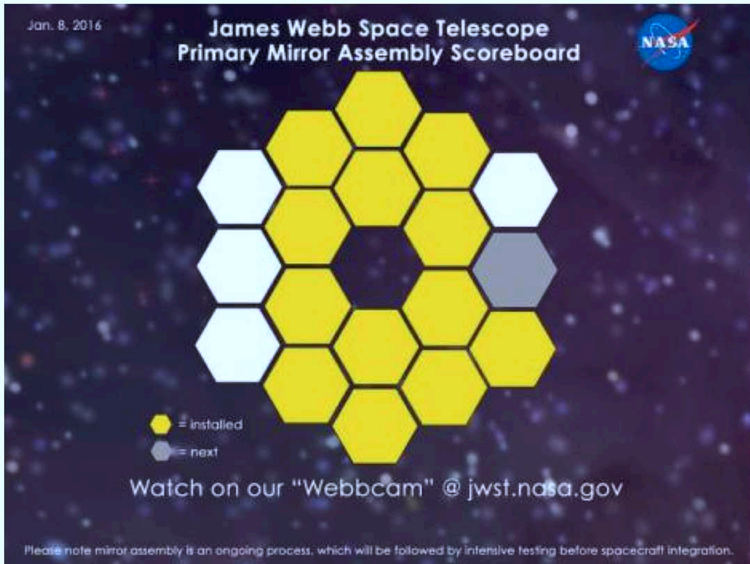
- Our Galaxy is a bright IR source at $\lambda \gtrsim 1$–5μm: In certain directions of the sky, some straylight can hit secondary mirror via Sunshield.
- This can effect JWST (lensing) studies of First Light objects.

Telescope Pathfinder – Risk Reduction

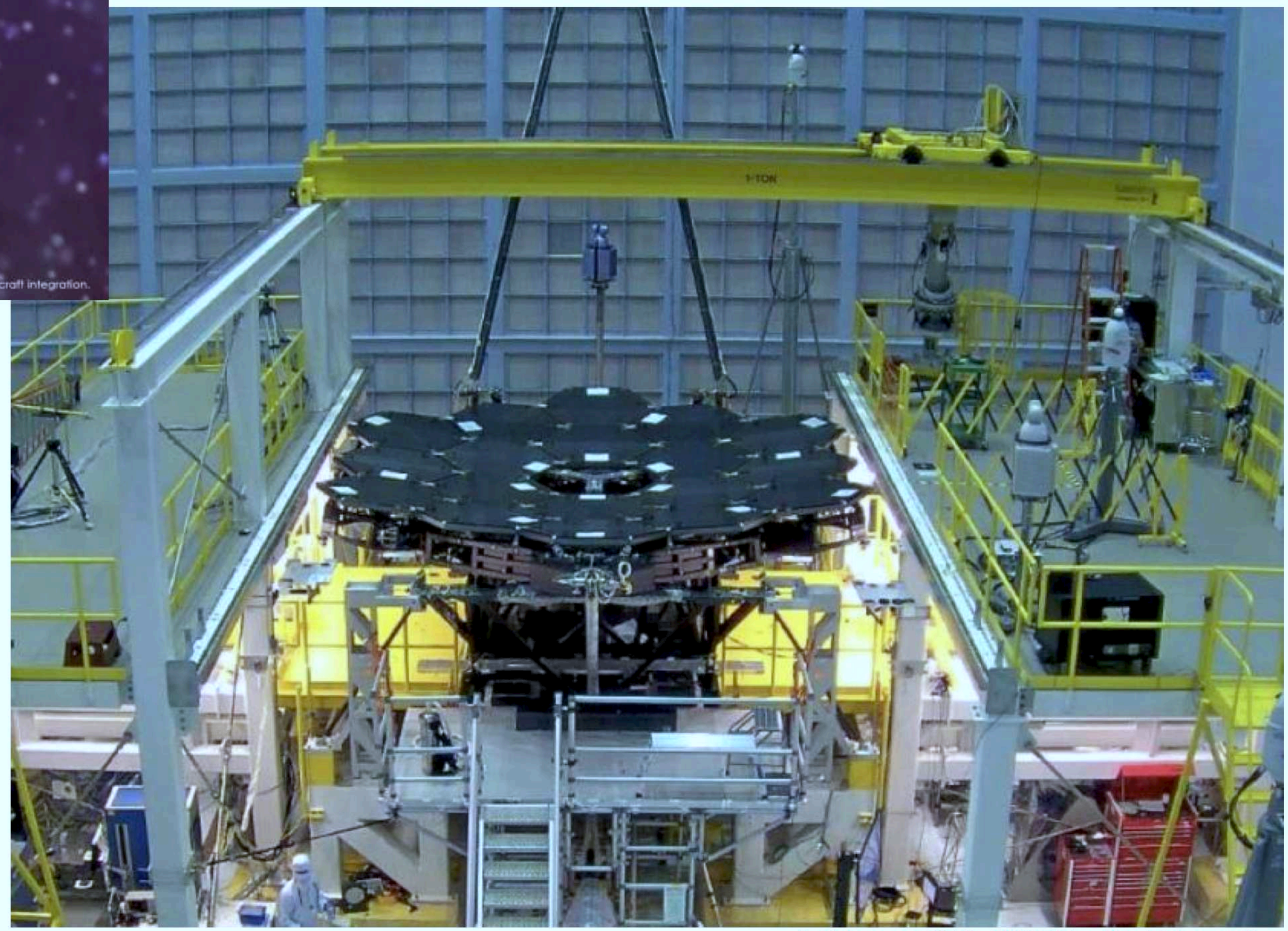


JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

Much progress has been made in OTE integration



Where we were at last month's call

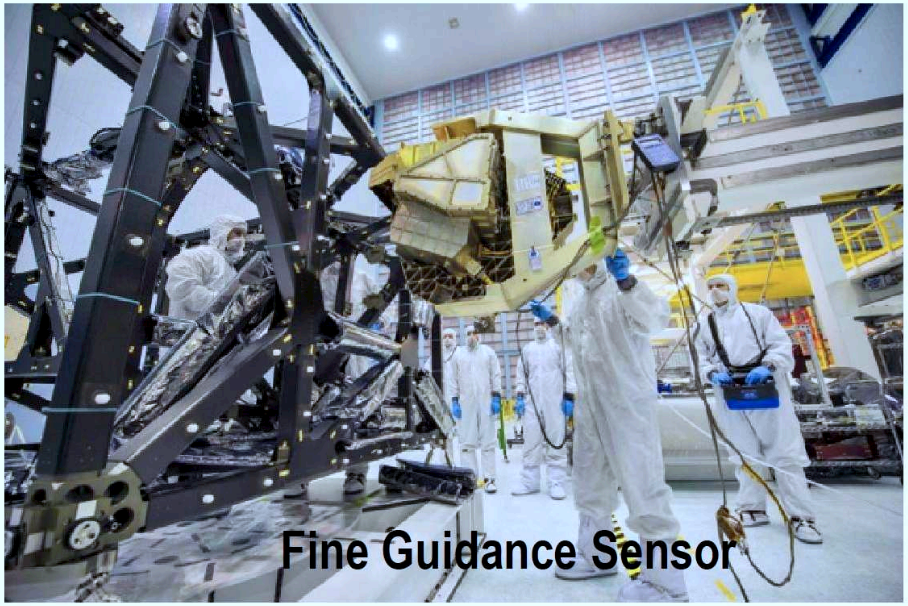


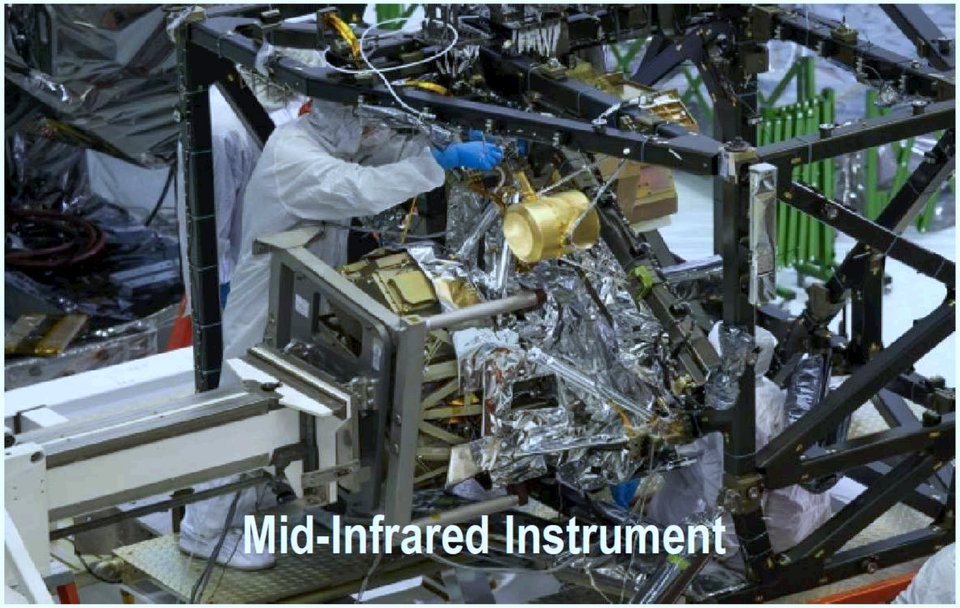
<u>Current</u>: all 18 PMSAs installed, liquid-shim-cured, & metrologized. Alignments meet specifications, and actuator motions verified

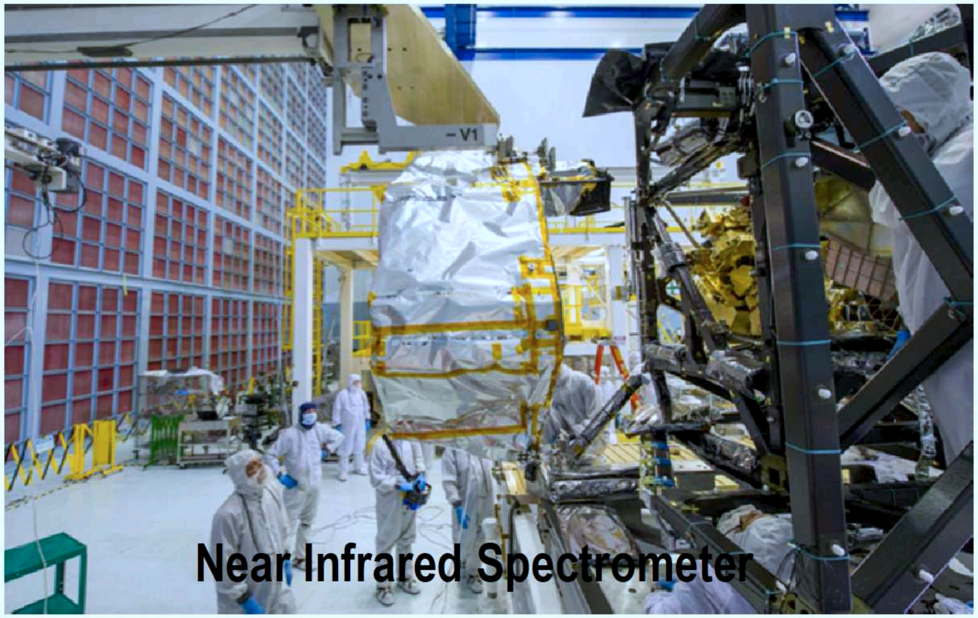
Big milestone!

JWST lifetime: Requirement: 5 yrs; Goal: 10 yrs; Propellant: 14 yrs.

All Instruments Integrated







(1c) JWST instruments: USA (UofA, JPL), ESA, & CSA.

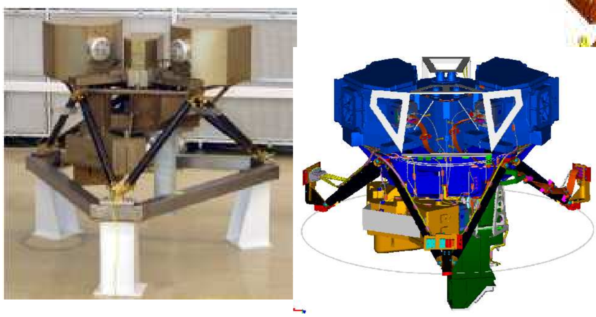
Instrument Overview

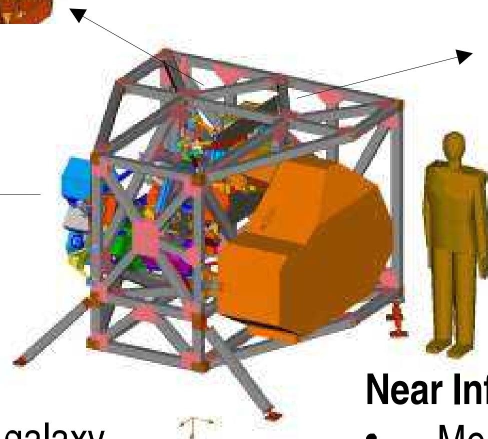
Fine Guidance Sensor (FGS)

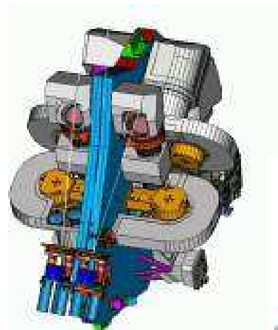
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

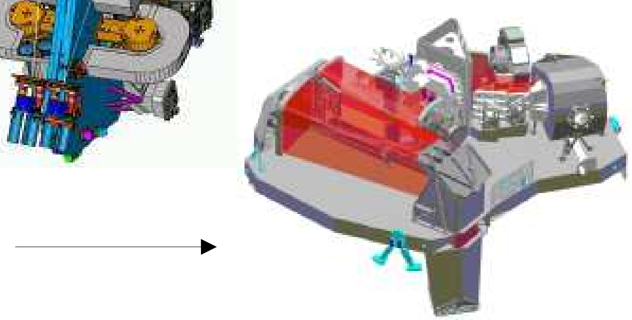
Near Infra-Red Camera (NIRCam)

- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC







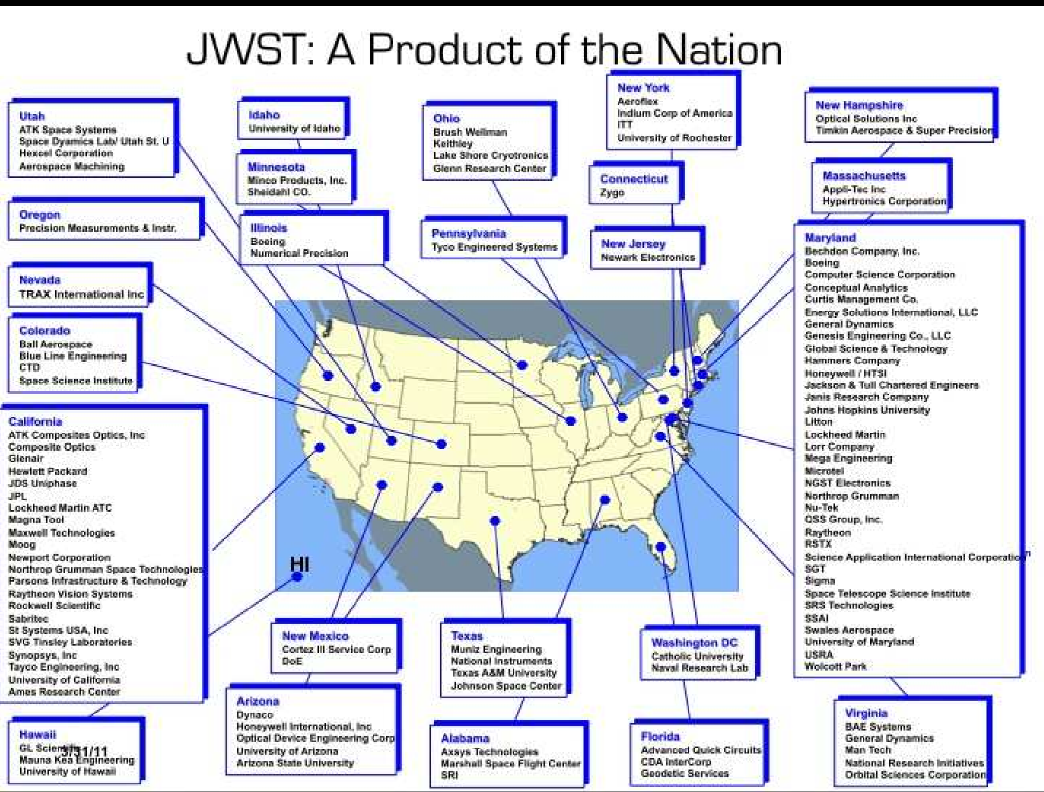


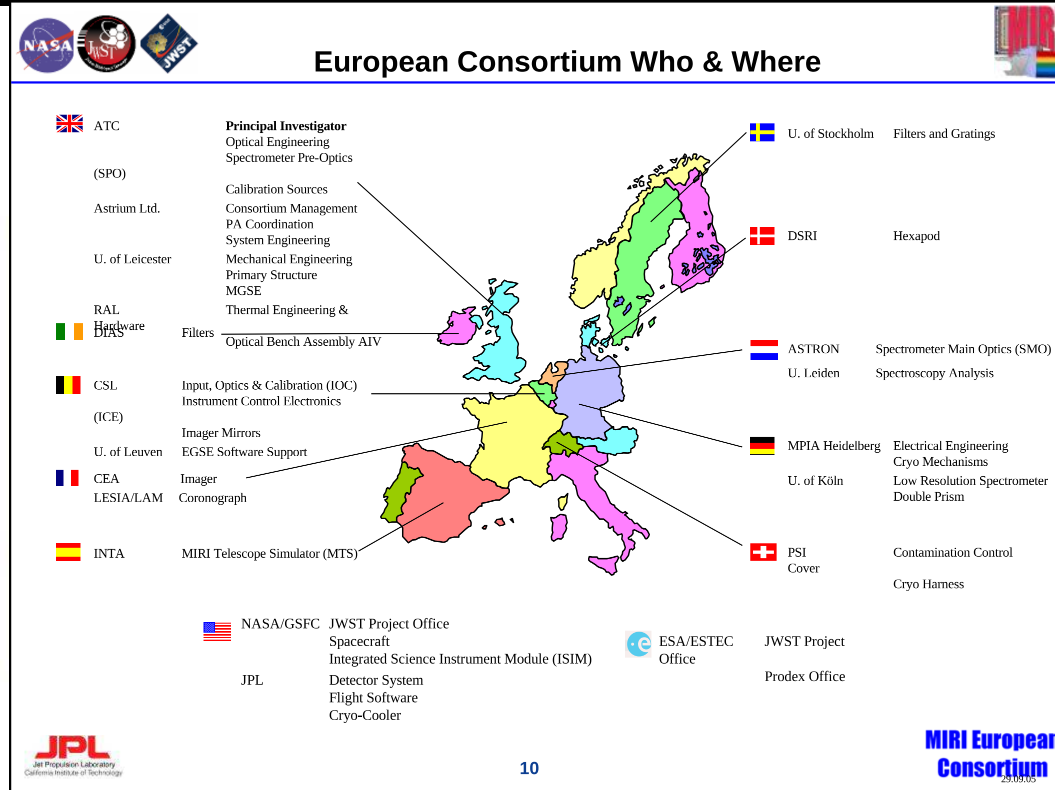
Mid-Infra-Red Instrument (MIRI)

- 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





- JWST hardware made in 27 US States: $\gtrsim$99% of launch-mass finished.

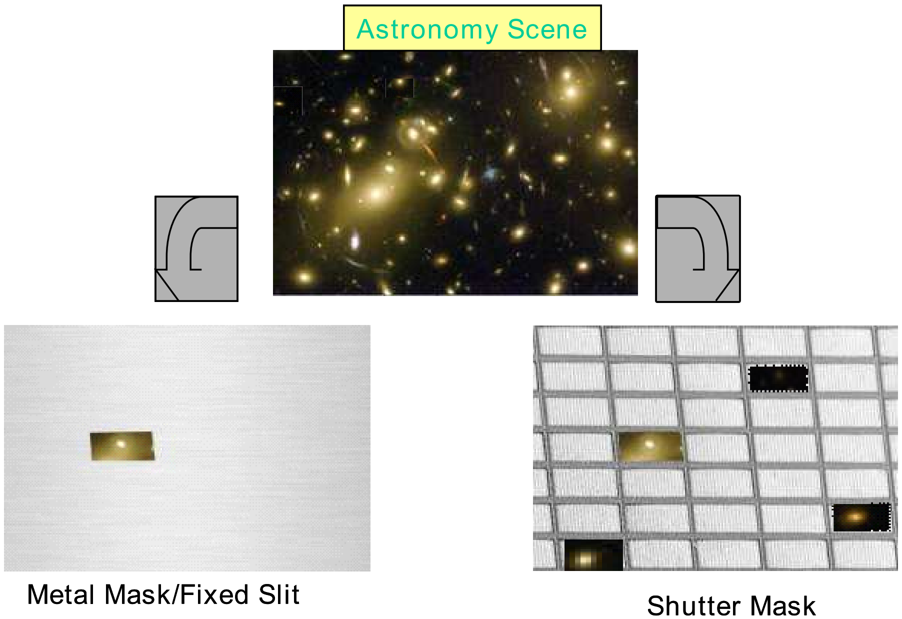
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.

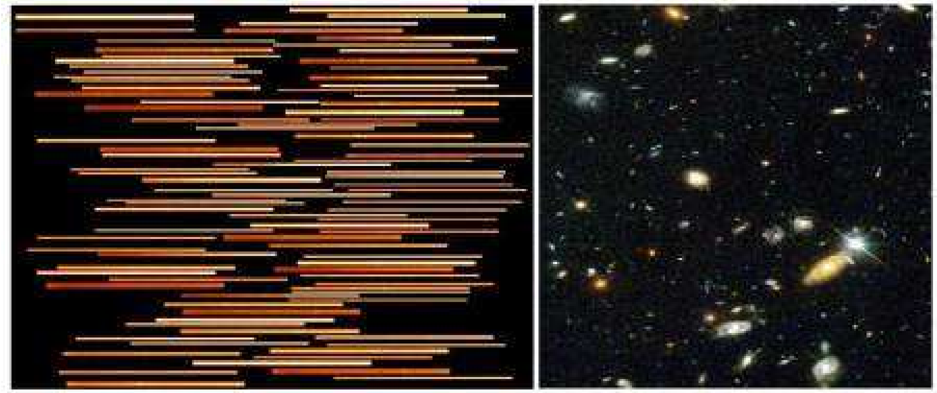
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.

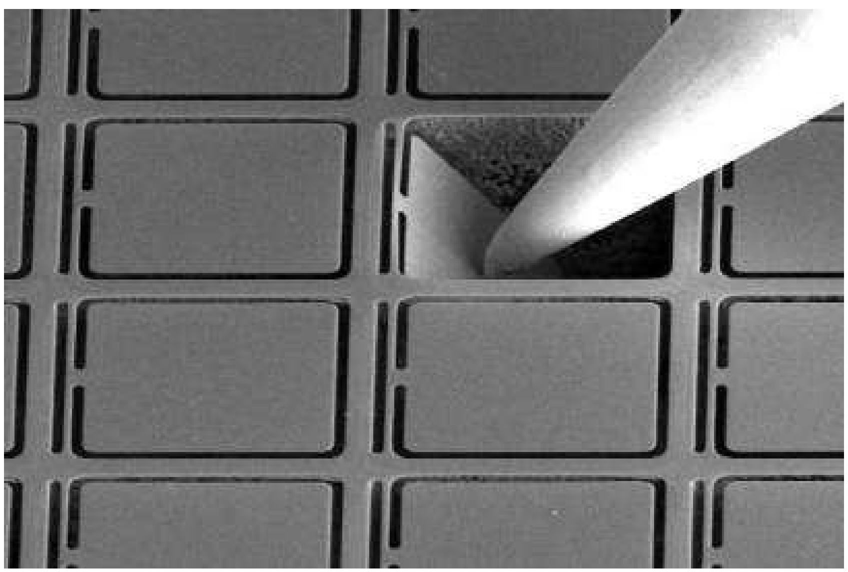
- JWST NIRCam made by UofA and Lockheed.

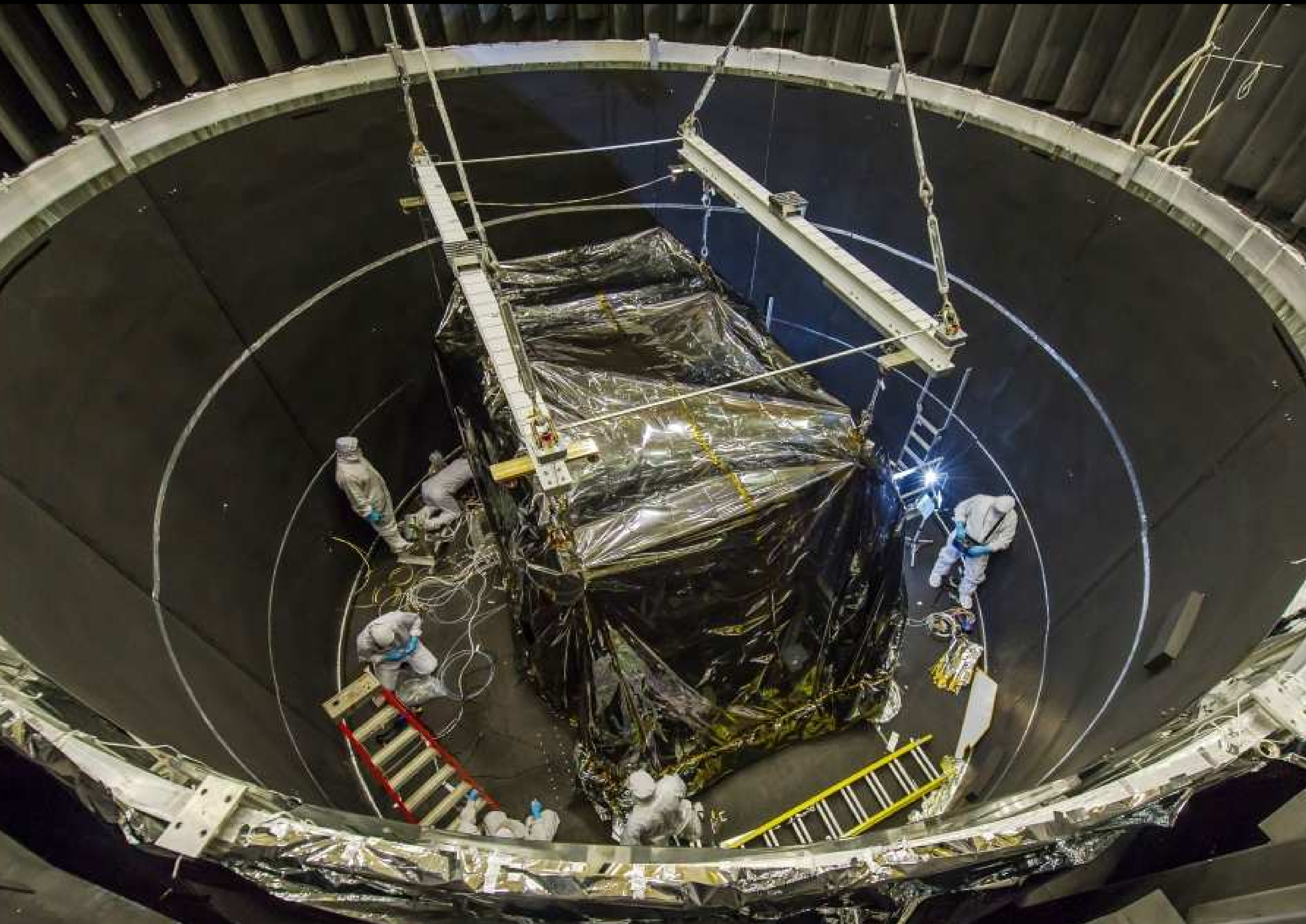
This nationwide + international coalition was critical for project survival!

Micro Shutters



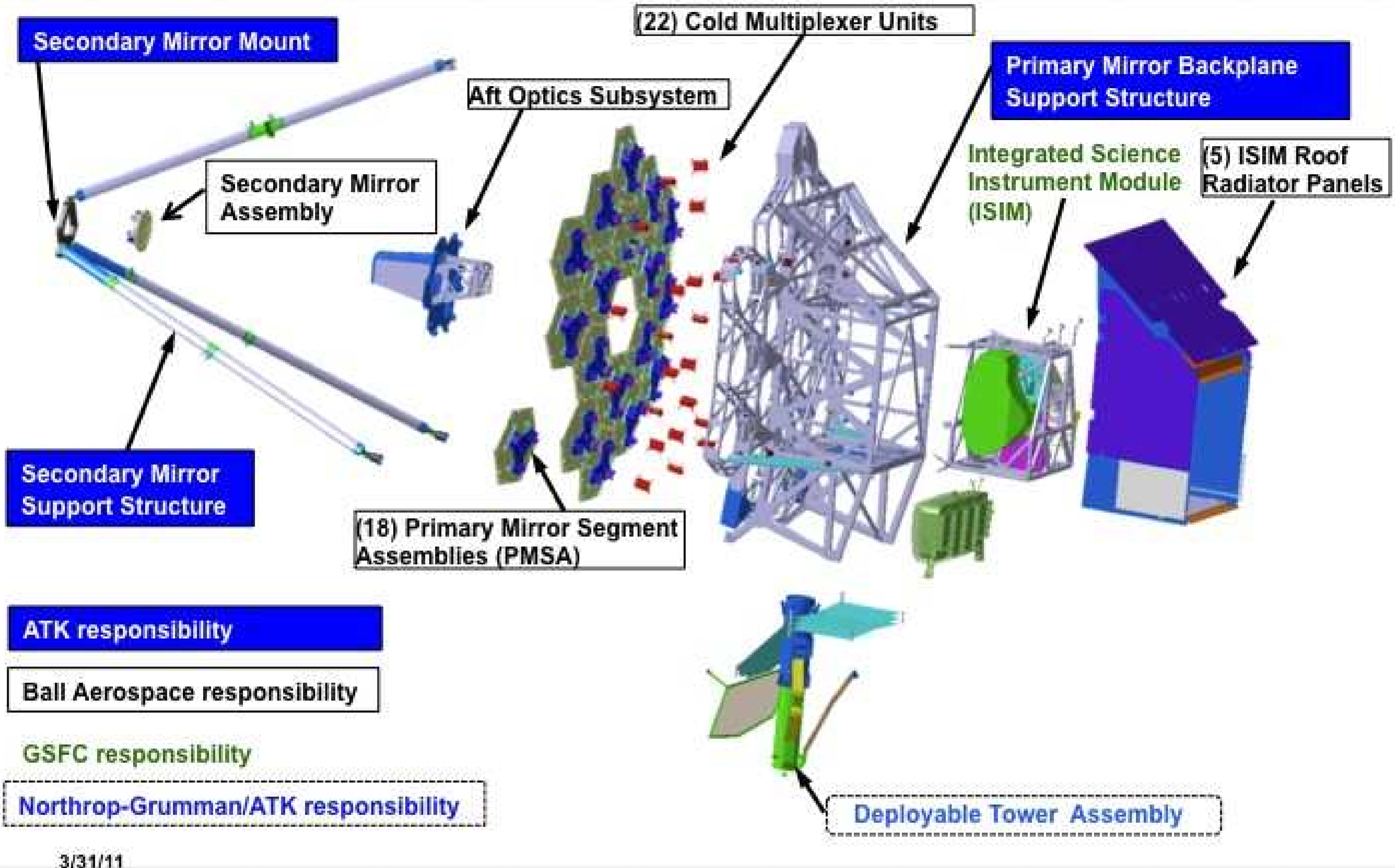




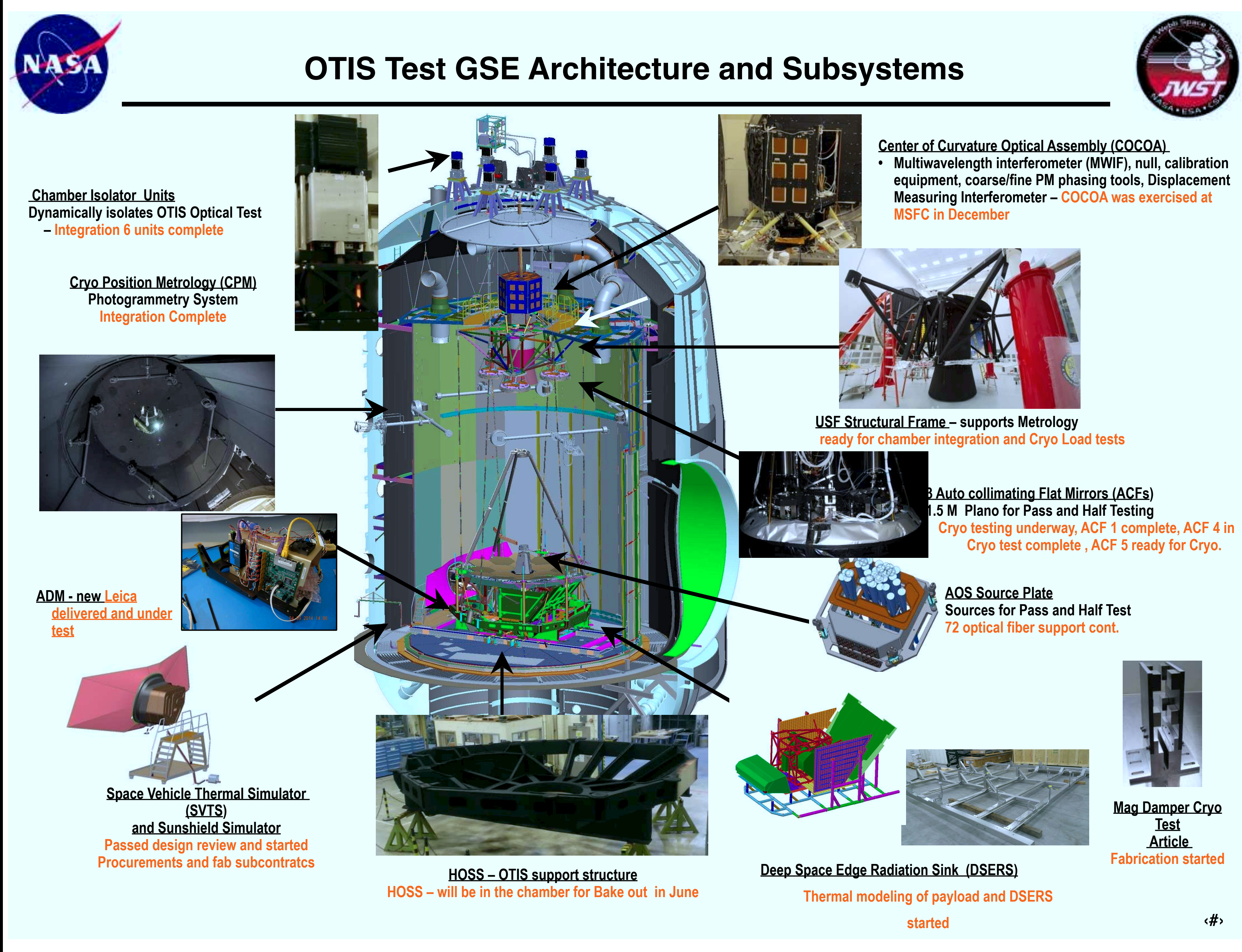


2014: Flight ISIM (all 4 instruments) in test; Oct. 15-Feb. 2016: CryoVac3.

TELESCOPE ARCHITECTURE

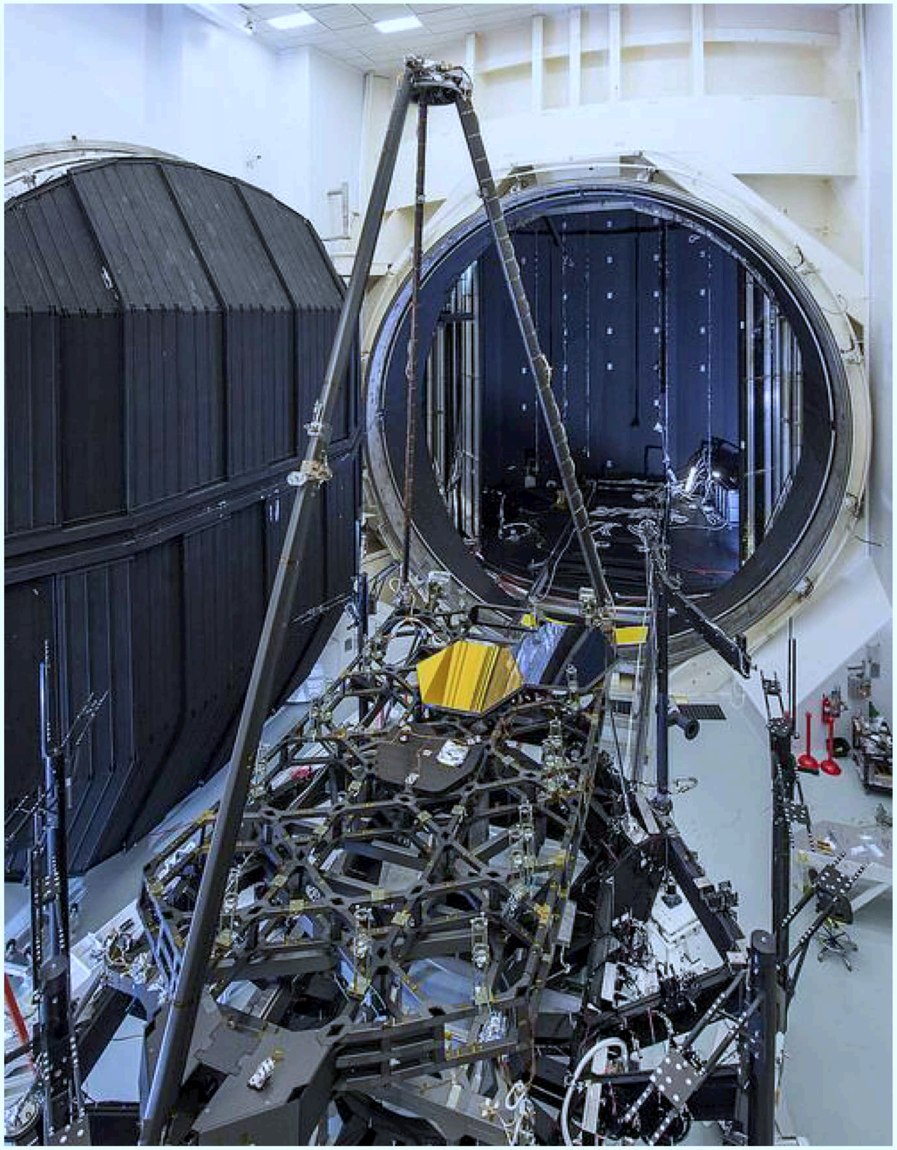


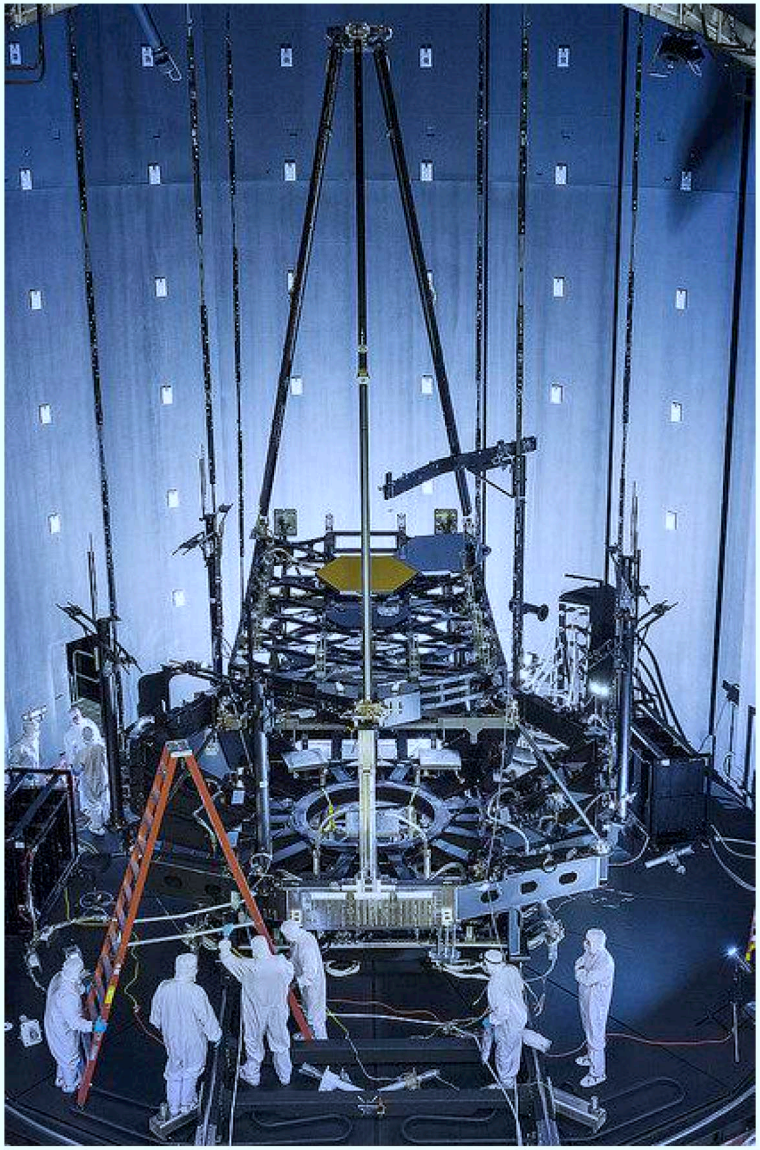
2014–2016: Complete system integration at GSFC and Northrop.



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

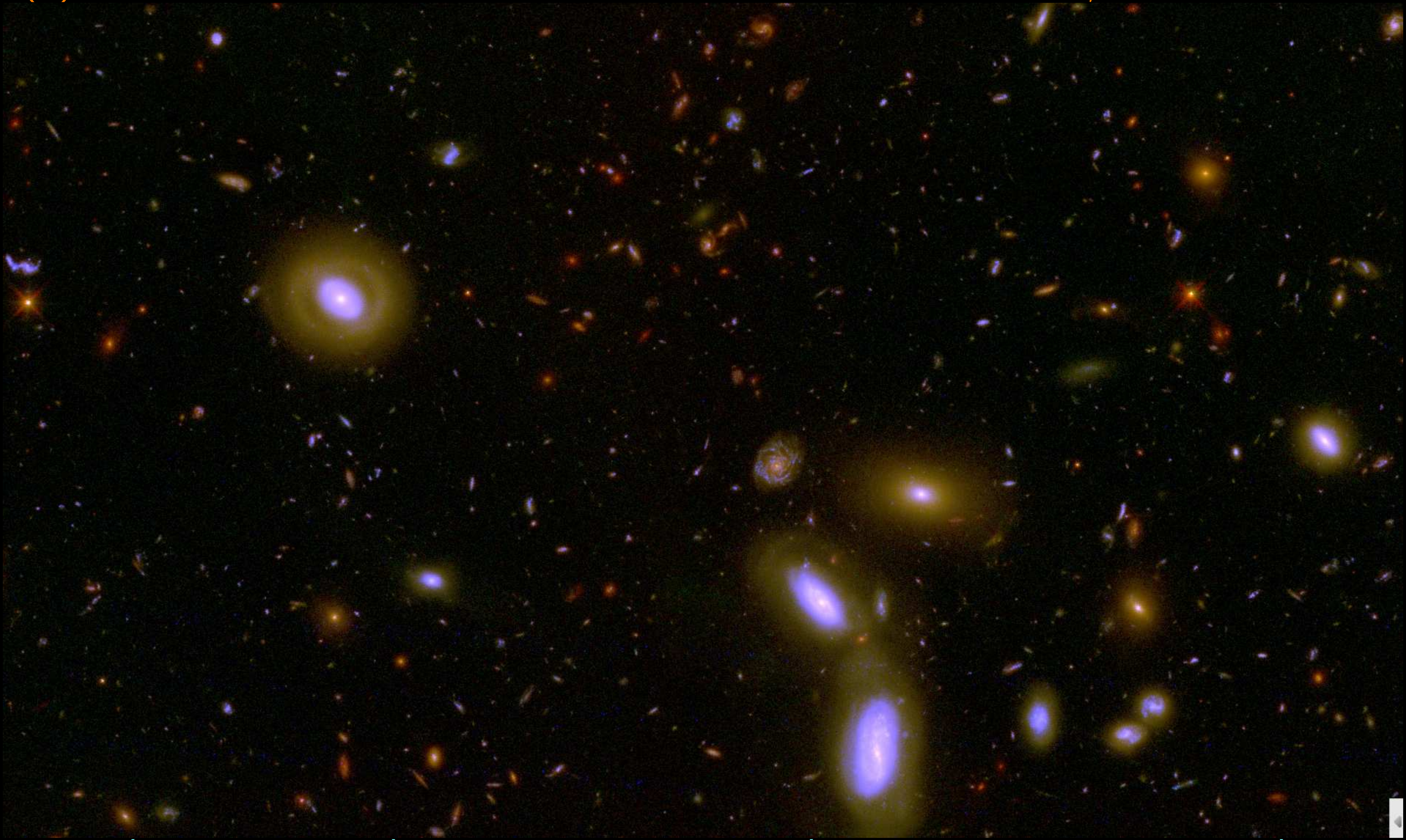
Pathfinder & JSC Chamber A: getting ready for OGSE1 (and eventually OGSE2 & Thermal Pathfinder)





April 2015: Testing OTIS chamber with the JWST Engineering model.

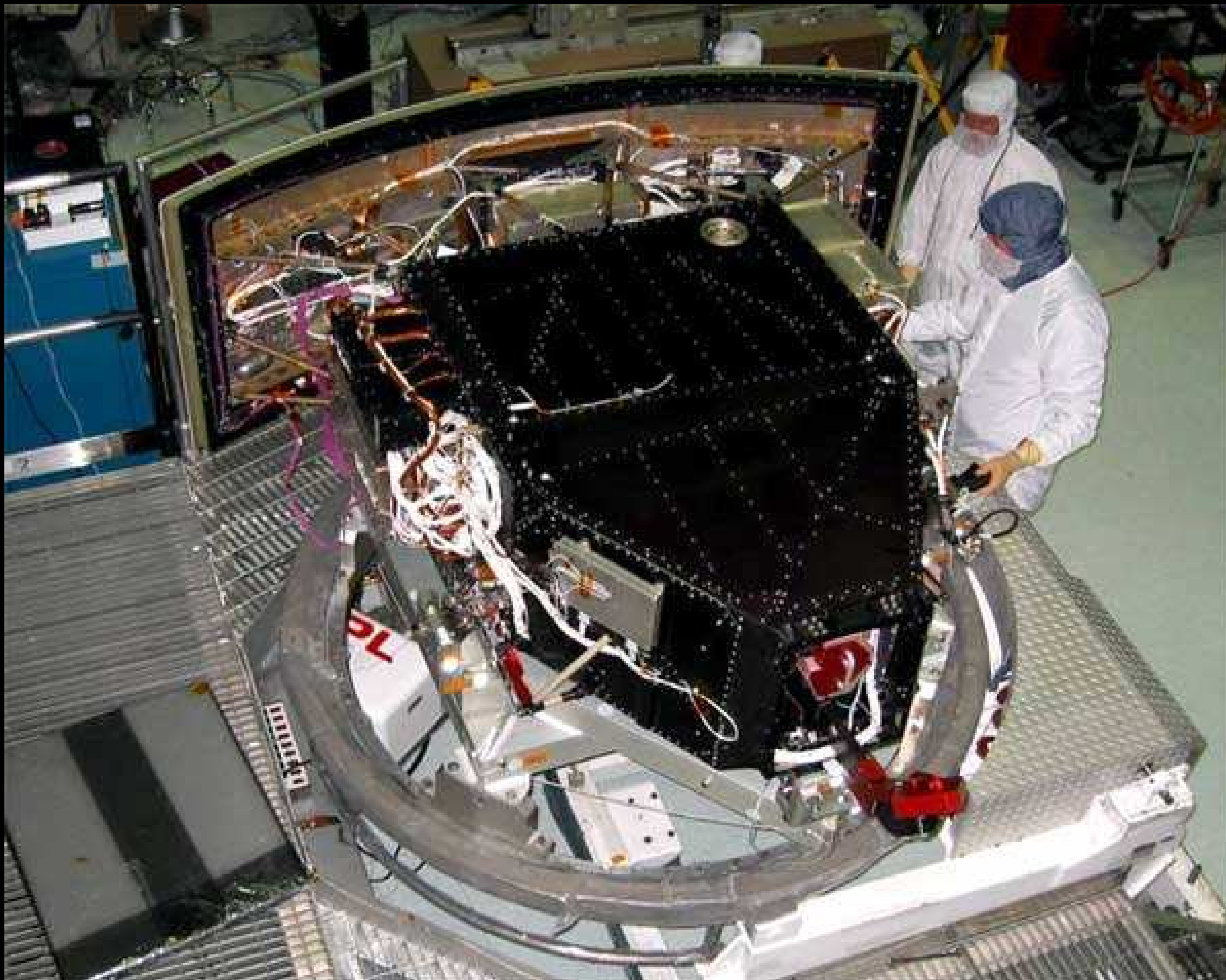
(2) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?



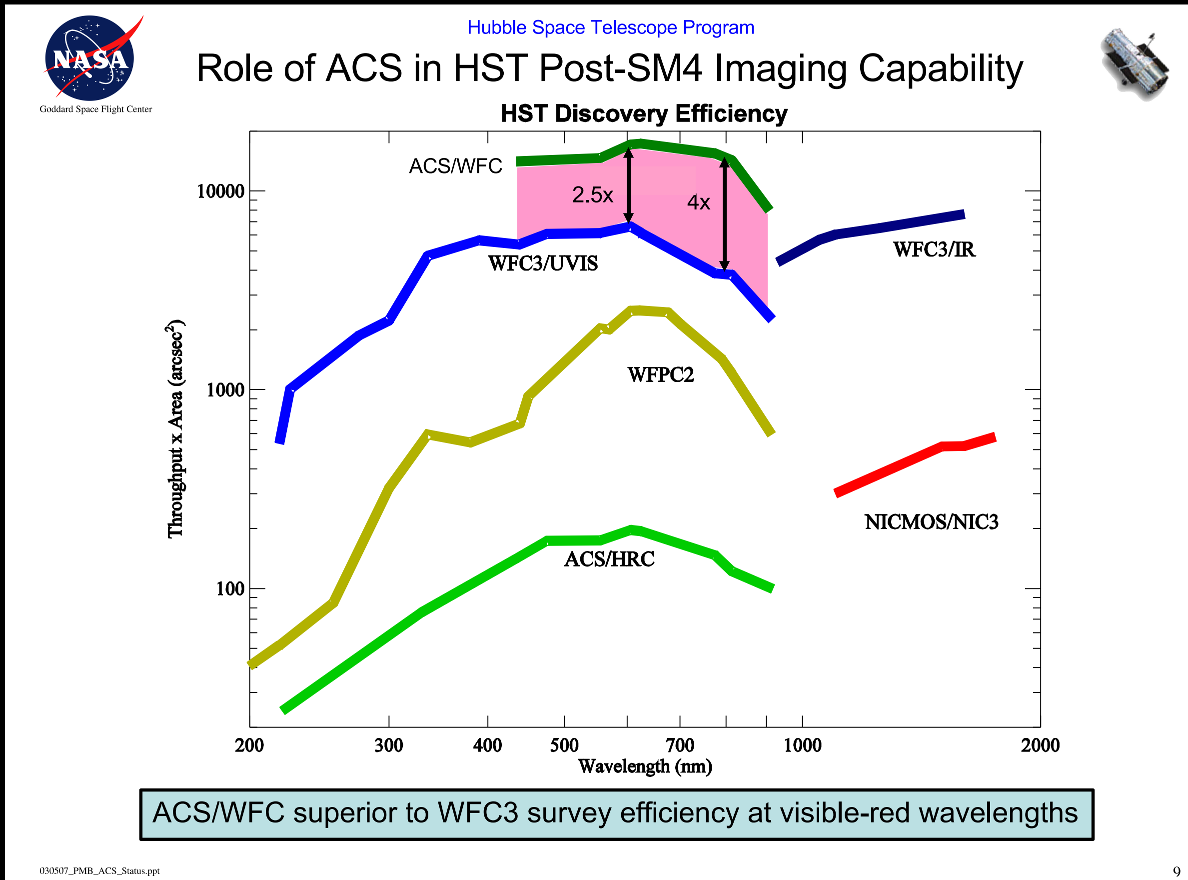
HST (WFC3 & ACS) reach 26.5-27.0 mag ($\sim$100 fireflies from Moon) over $0.1\times$full Moon area in 10 filters from 0.2–2 μm wavelength.

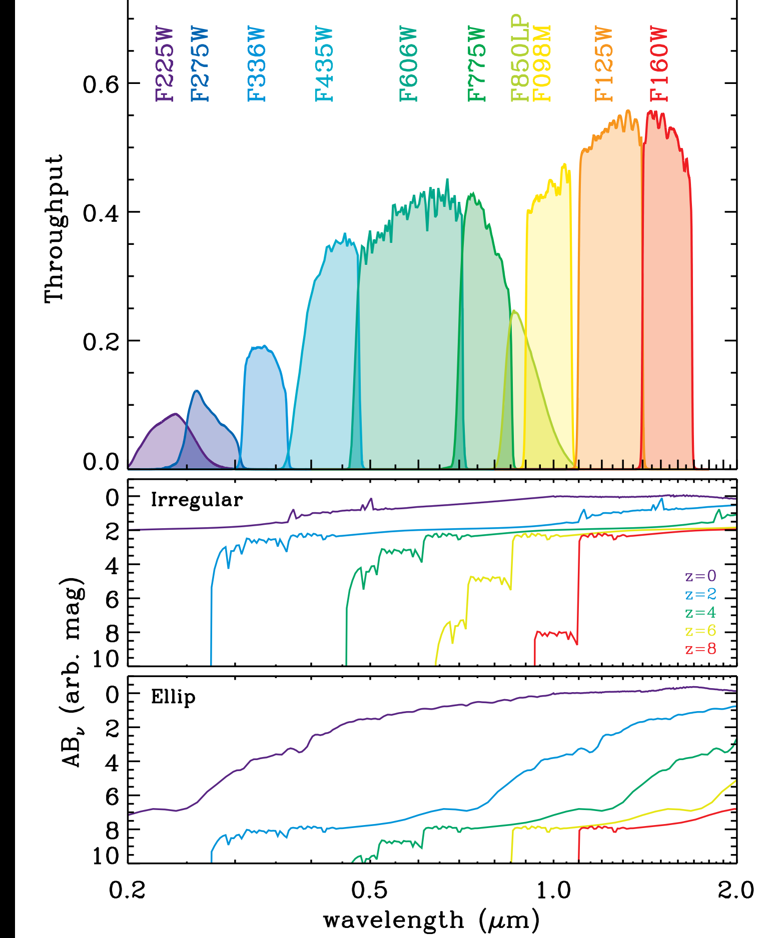
JWST has $3\times$sharper imaging to $\sim$31.5 mag ($\sim$1 firefly from Moon) at 1–29 μm wavelength, tracing young and old stars + dust.

(2a) WFC3: Hubble's new Panchromatic High-Throughput Camera



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





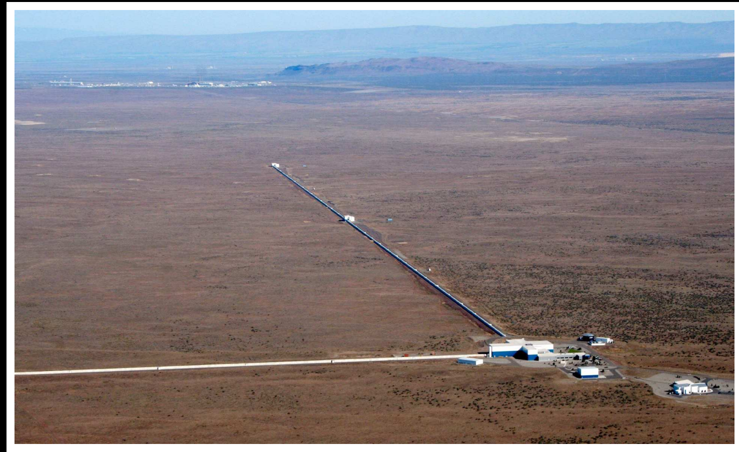
WFC3/UV & IR channels unprecedented throughput & areal coverage:

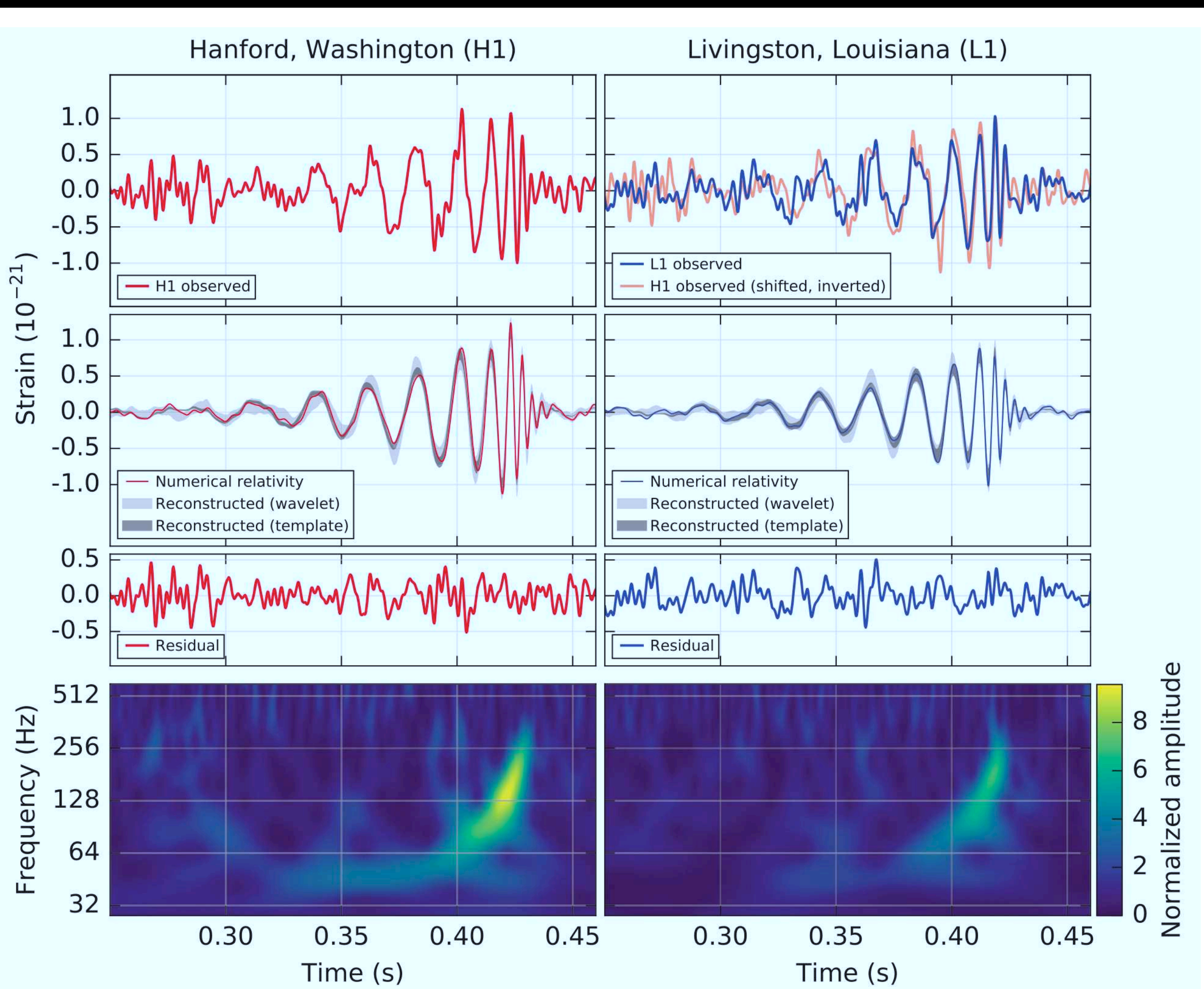
- $QE \gtrsim 70\%$, $4k \times 4k$ array of $0''.04$ pixel, FOV $\simeq 2'.67 \times 2'.67$.
- $QE \gtrsim 70\%$, $1k \times 1k$ array of $0''.13$ pixel, FOV $\simeq 2'.25 \times 2'.25$.

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

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

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





(1) LIGO first observed Gravitational Waves on Sept. 14, 2015.

(2) These were caused by two merging (29+36 $M_\odot$) black holes about 1 Gyr ago!

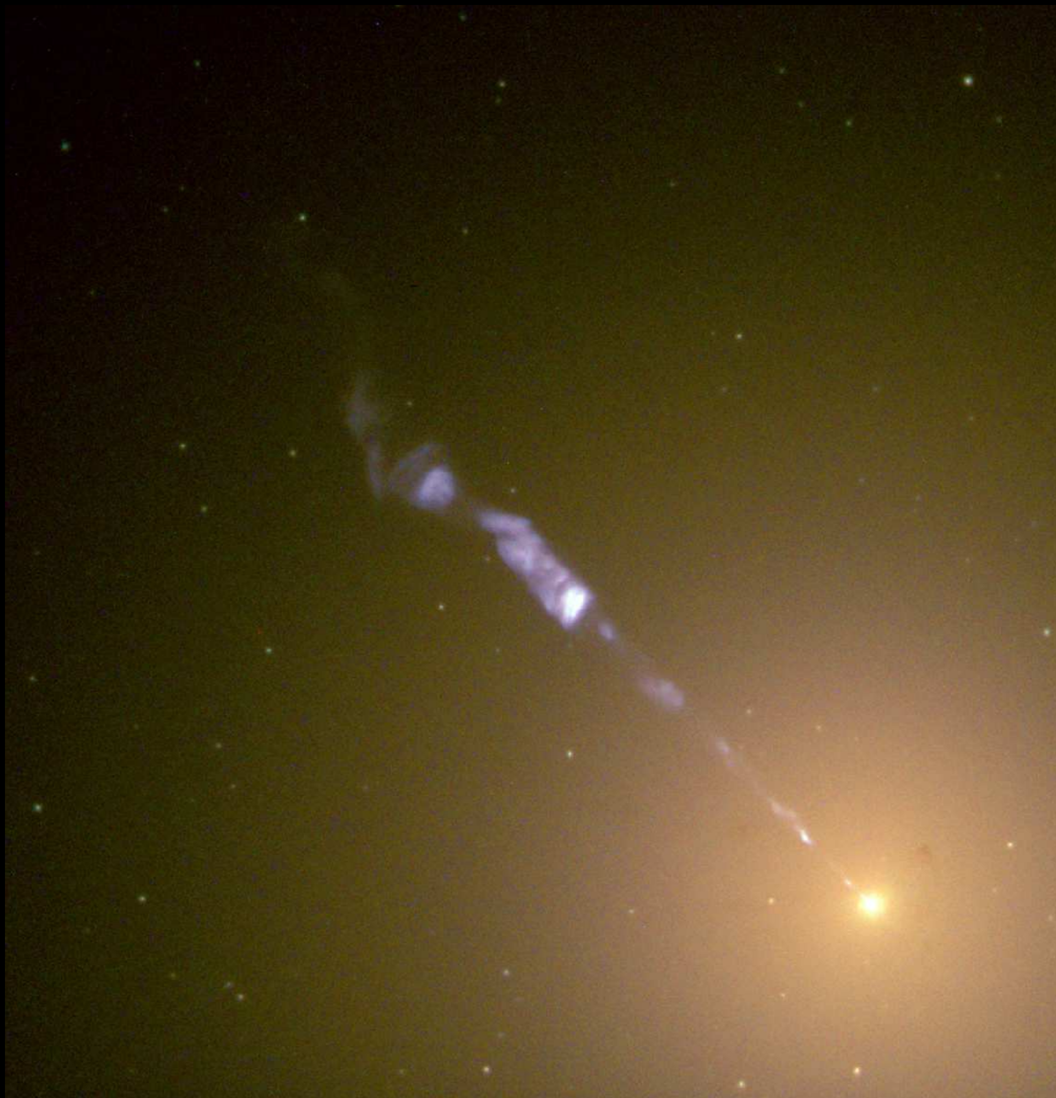
- $E=Mc^2$: 3 $M_\odot$ was converted to energy in a fraction of a second!

Ordinary massive stars (10–30 $M_{\odot}$) leave modest black holes ($\sim$3–10 $M_{\odot}$).

Conclusion 1: Most low-mass black holes today are small, slow eaters:

- 29–36 $M_\odot$ blackholes may be leftover from First Stars (first 500 Myr).
- Likely too massive to be leftover from ordinary Supernova explosions, ...
- How come only now seen merging by LIGO (12.5 Byr after BB)?
- They were likely not fast & efficient eaters, but slow and messy ...

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

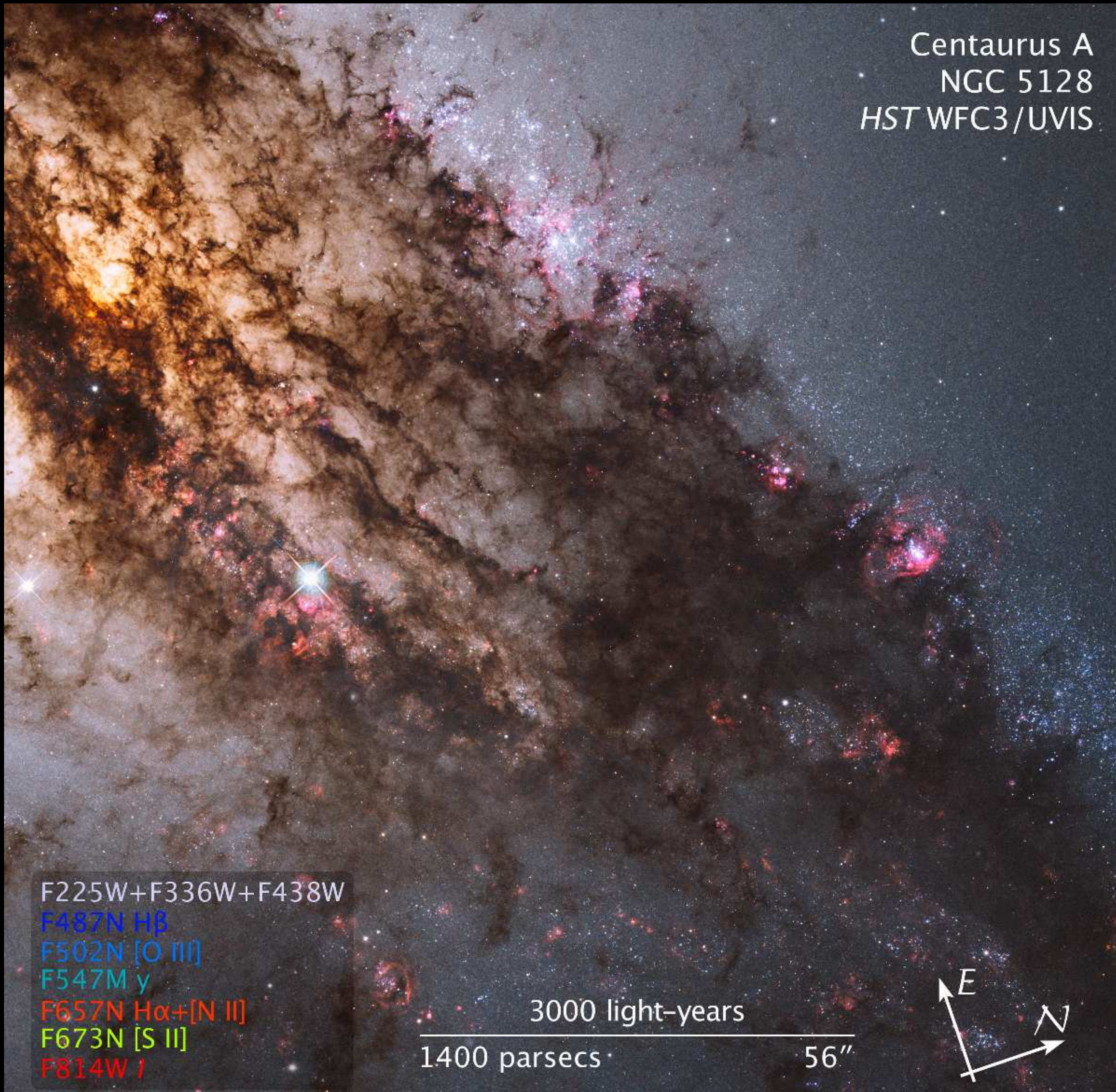


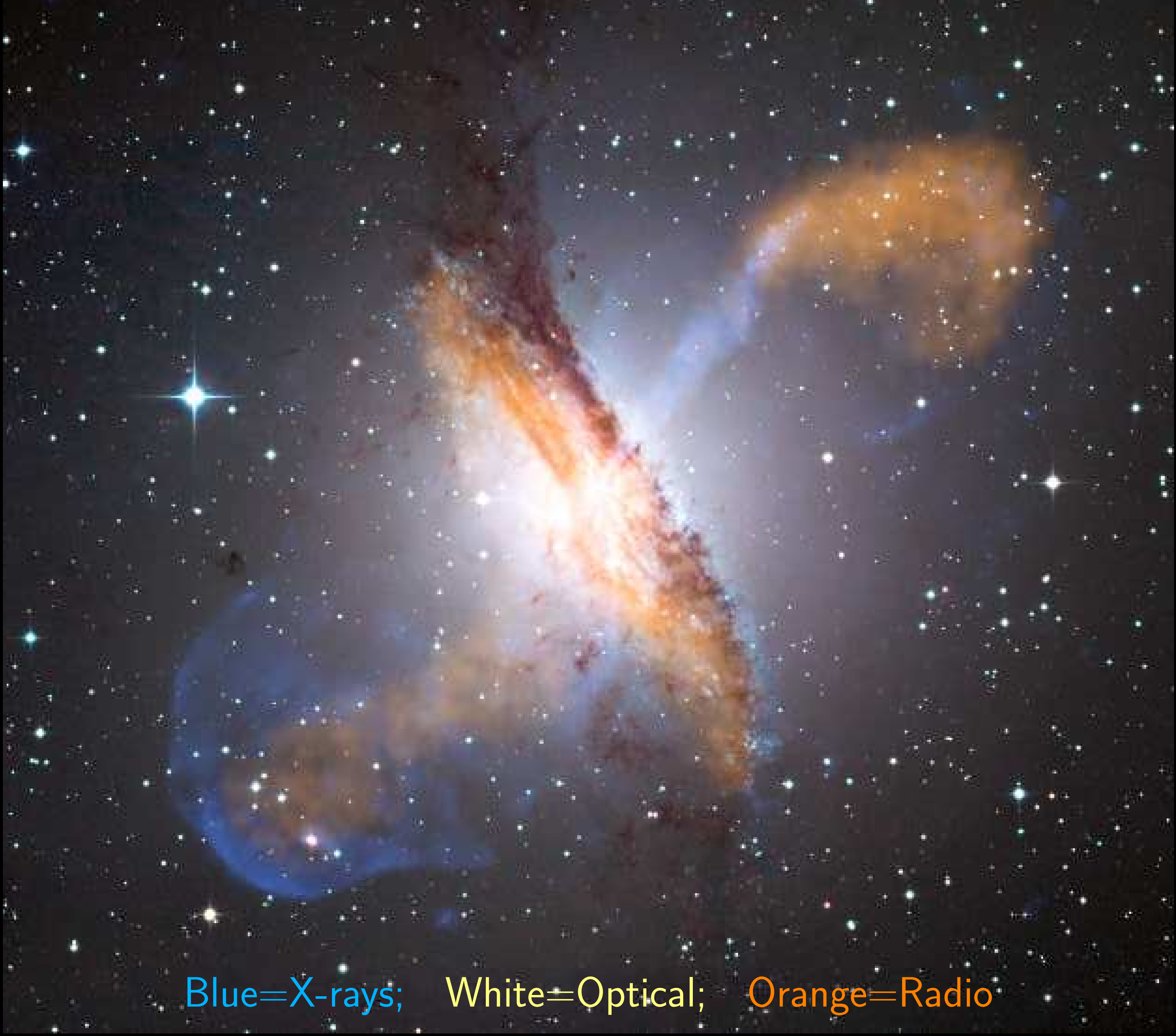
"For God's sake, Edwards. Put the laser pointer away."

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

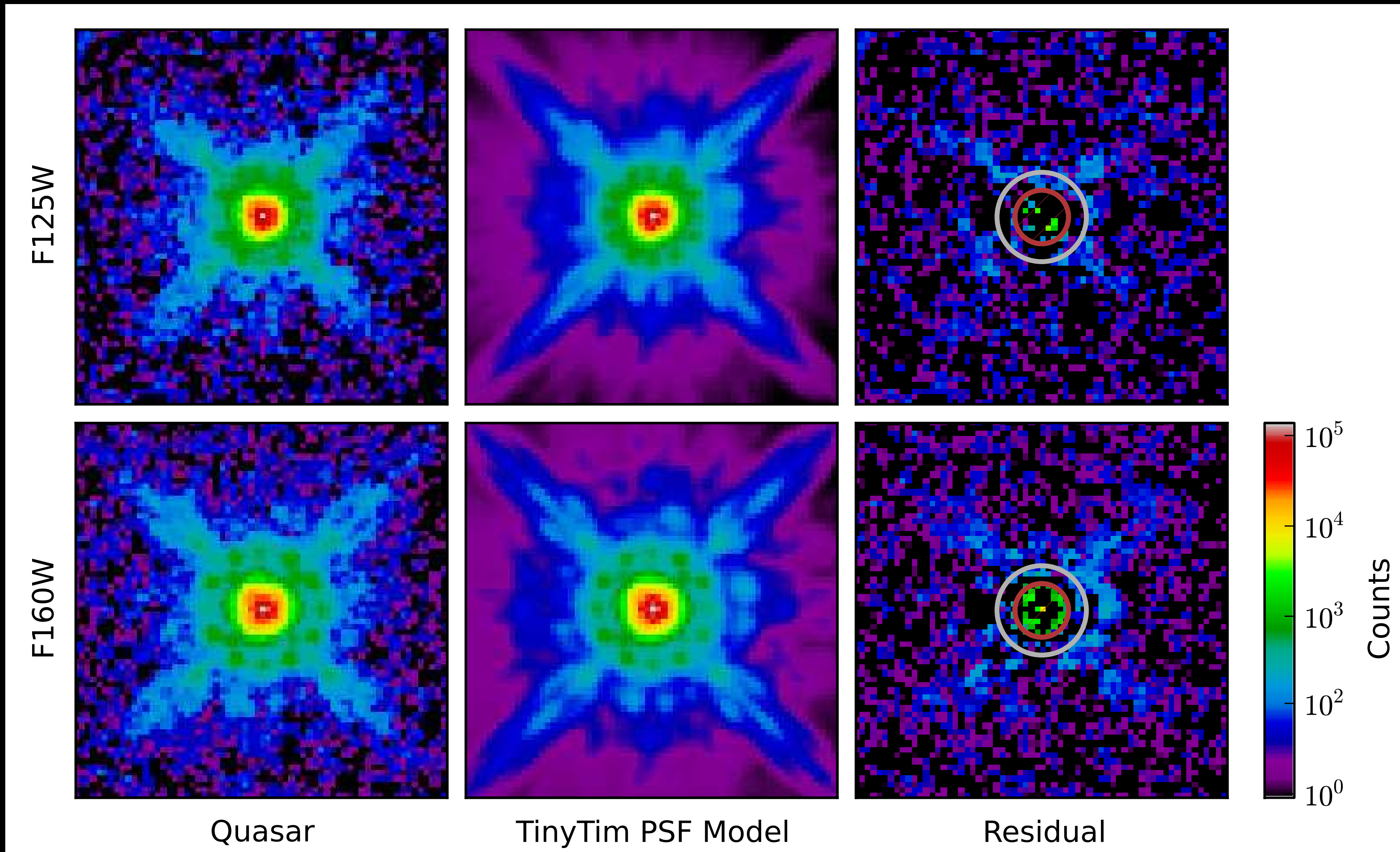
They are EXTREMELY bright sources if viewed "down-the-pipe".

$\sim$0.5% of the baryonic mass, but produce most of the photons!


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

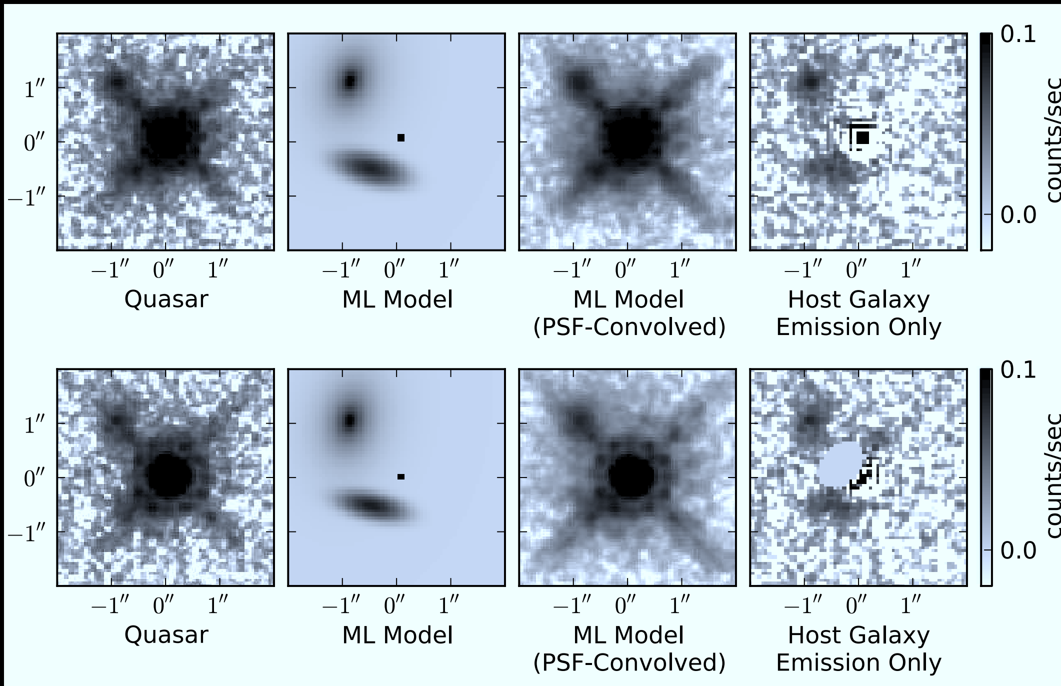

Blue=X-rays; White=Optical; Orange=Radio

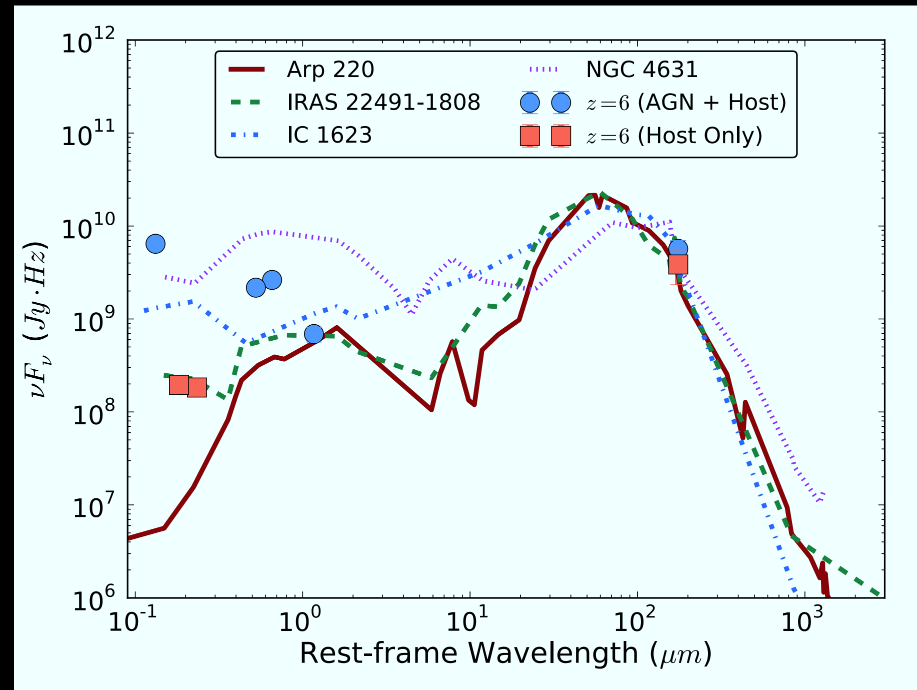
- Quasars: Centers of galaxies with feeding supermassive blackholes:



- Hubble IR-images of the most luminous Quasar known in the universe.
- Seen at redshift 6.42 (universe 7.42× smaller than today), 900 Myr old!
- Contains 10^{14} solar luminosities within a region as small as Pluto's orbit!
- A feeding monster blackhole (>3×10^9 solar mass) 900 Myr after BB!

(2b) WFC3: Detection of one QSO Host System at z≃6 (Giant merger?)





[LEFT]: First detection out of four z≃6 QSOs (Mechtley et al. 2016).

- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure?
- Same λ=1.25 & 1.6 μm structure. Colors constrain dust.

[RIGHT]: Blue dots: z≃6 quasar spectrum, Red: z≃6 host galaxy.

- Host galaxy has dusty starburst-like UV–far-IR spectrum: reddening of A_{FUV}(host)∼1 mag (Mechtley et al. 2014).

- JWST can detect 10–100× fainter dusty hosts (for z≲20, λ≲28μm).

Conclusion 2: Supermassive black holes started early & were very rapid eaters:

- Massive galaxies today contain a super-massive blackhole, no exceptions!
- Masses $\sim 3 \times 10^9$ solar, leftover from the First Stars (first 500 Myr)?
- Must have fed enormously rapidly in the first 1 Byr after the Big Bang.
- Were eating cat-astrophically (and secretly) until they ran out of food ...
- JWST can image the First Quasars to z$\gtrsim$10 (*if* we can find them).

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

Will this ever happen to our own Galaxy?

YES! Hubble showed no lateral motion of Andromeda:

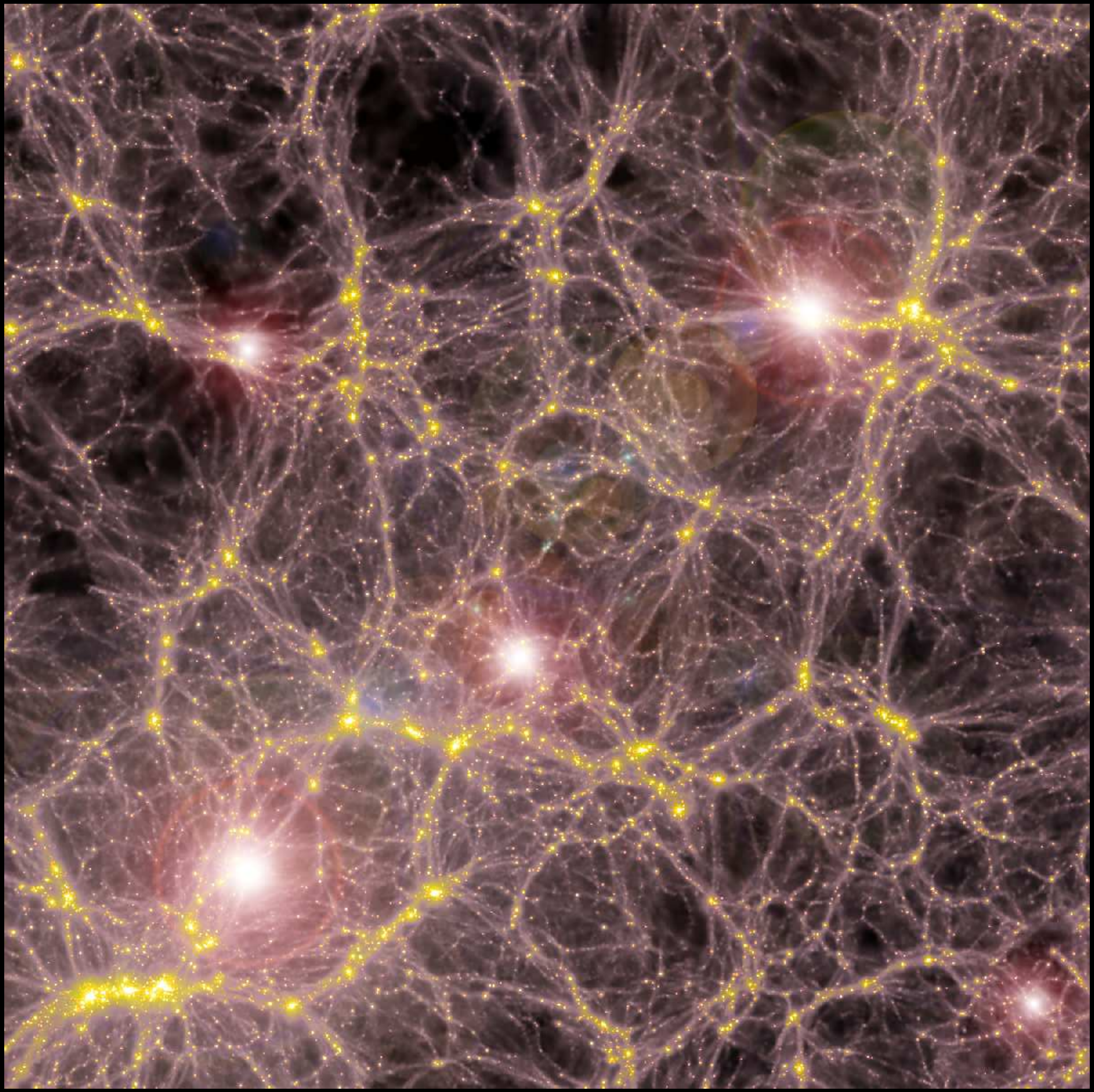
Approaches at –110 km/s.

Hence, Andromeda will merge with Milky Way!

The two blackholes (10^6–10^7 suns) will also merge!

Not to worry: only 4–5 Byr from today!

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

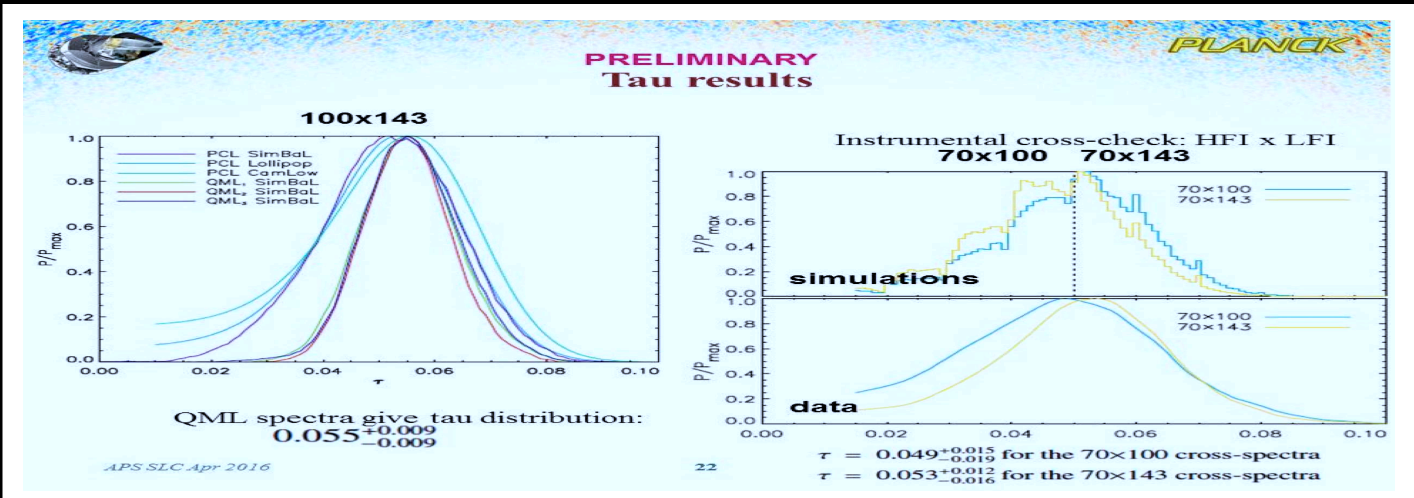


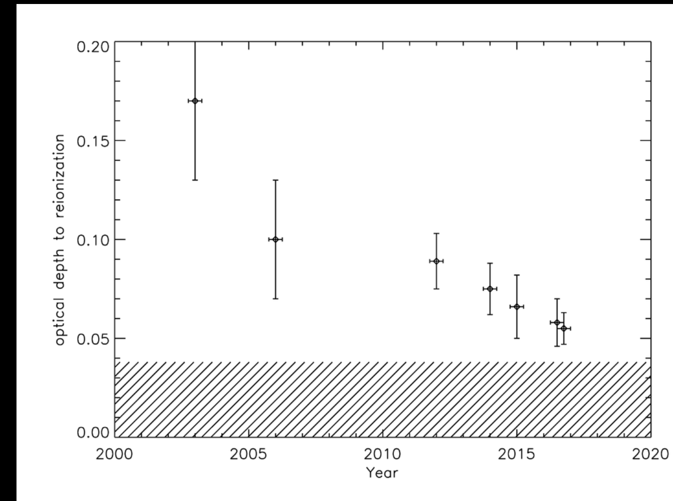
- Detailed cosmological models (V. Bromm) suggest that massive "Pop III" stars ($\gtrsim$100 M_{sun}) started to reionize the universe at z$\lesssim$10–30 (0.1–0.5 Gyr; "First Light").

- This should be visible to JWST as the first Pop III stars or surrounding (Pop II.5) star clusters, and perhaps their extremely luminous supernovae at z$\simeq$10$\longrightarrow$30.

We must make sure that we theoretically understand the likely Pop III mass-range, their mass function, their clustering properties, their SN-rates, etc., before JWST flies, so we know what to look for.

Implications of WMAP year-1—Planck 2016 results for JWST First Light:





HST/WFC3 z$\lesssim$7–9 $\longleftarrow$ $\longrightarrow$ JWST z$\simeq$8–25 (Courtesy: Dr. Bill Jones)

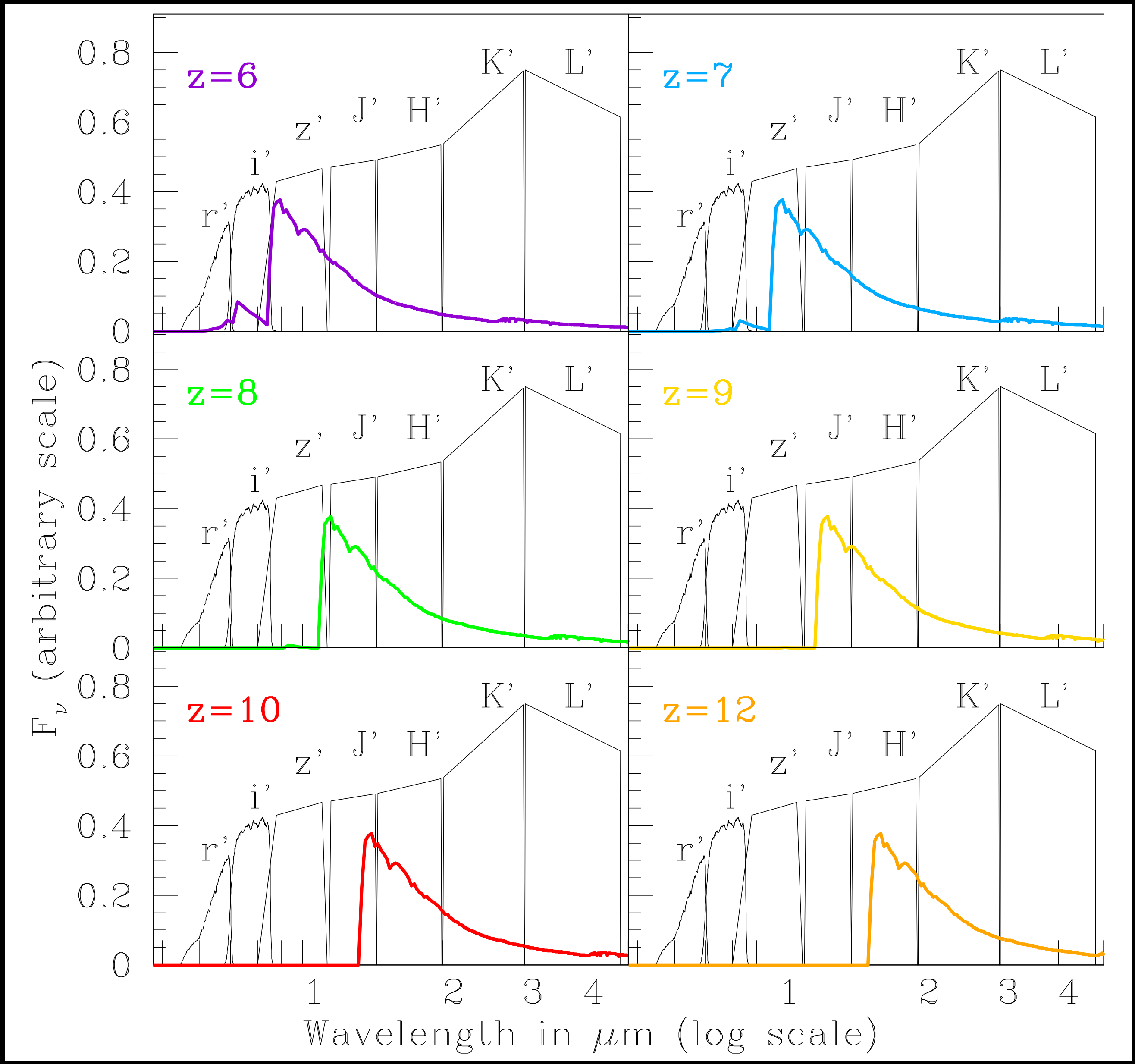
Year-9 WMAP and Planck 2016 data provided better foreground removal (Hinshaw$^+$ 2012; Planck 2016: B. Crill, 2016 APS mtg):

$\Longrightarrow$ (First Light &) Reionization occurred between these extremes:

- (1) Instantaneous: z$\sim$7.5$\pm$1 (pol. optical depth $\tau\simeq$0.055$\pm$0.009), or:
- (2) Inhomogeneous & drawn out: starting at z$\gtrsim$20, peaking at z$\lesssim$9–10, ending at z$\simeq$7.

- Since Planck 2016's polarization τ has come down considerably ($\tau\simeq$0.055), how many reionizers will JWST actually see at z$\simeq$10–15?

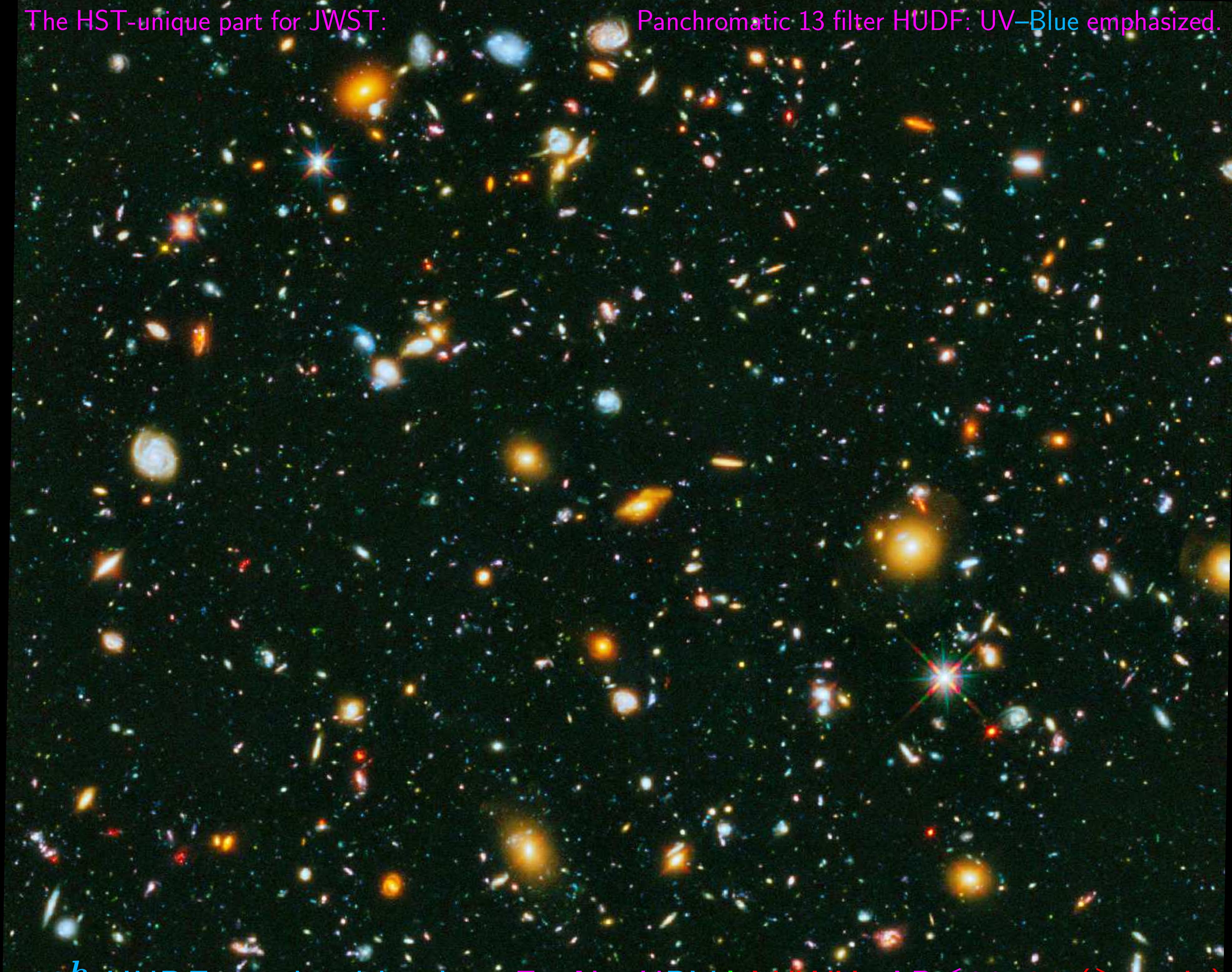
3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



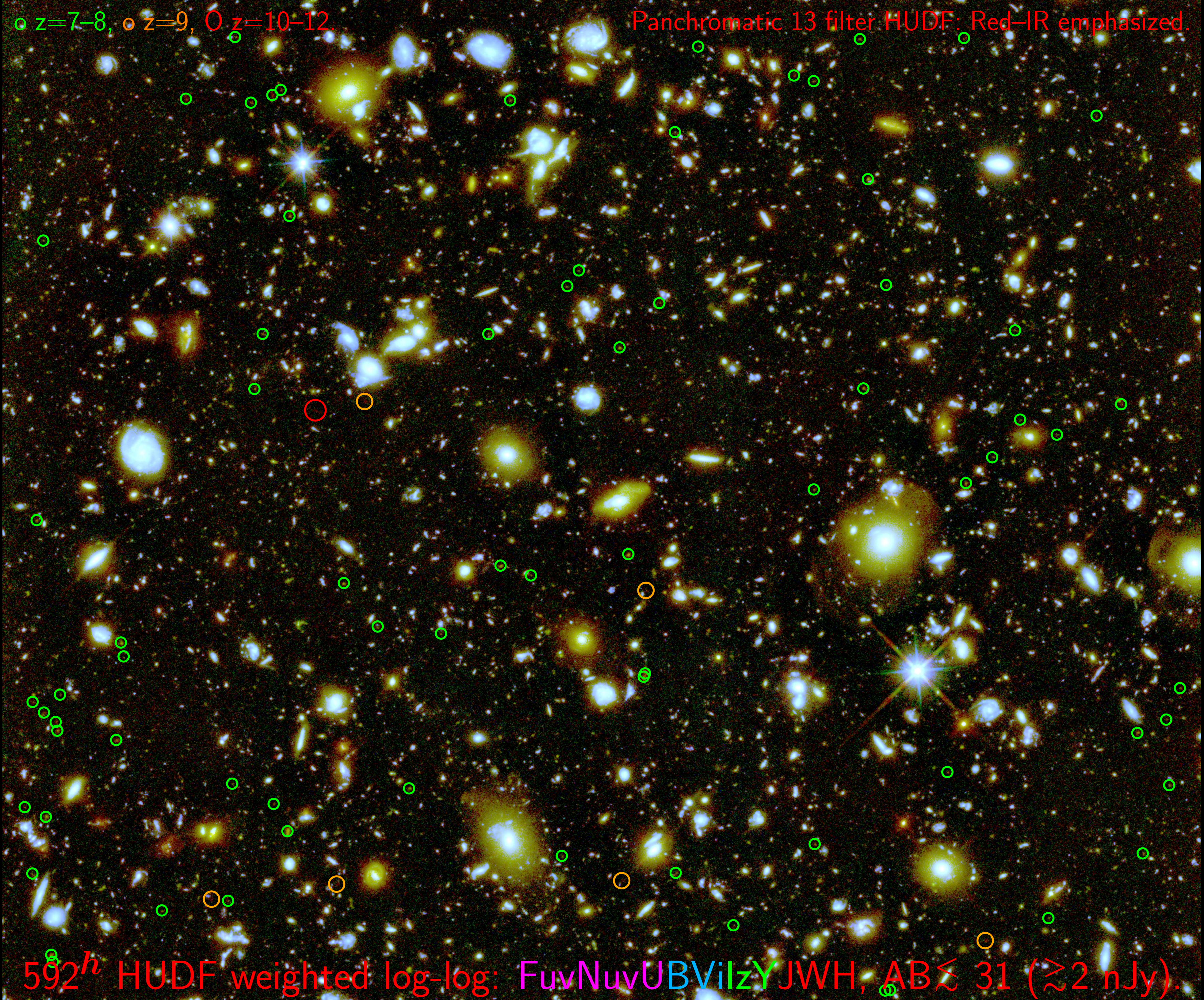
- Can't beat redshift: to see First Light, must observe near–mid IR.

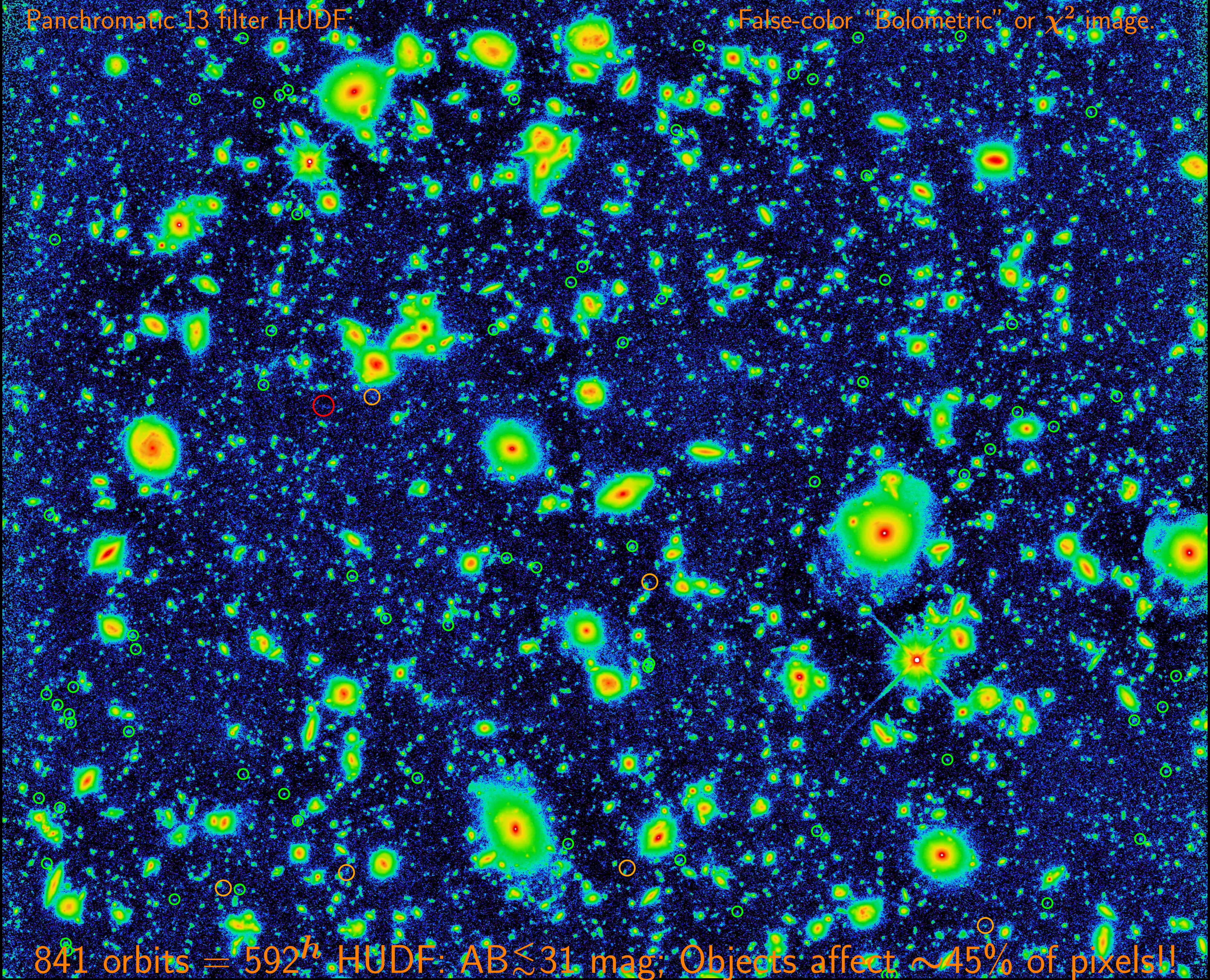
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

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

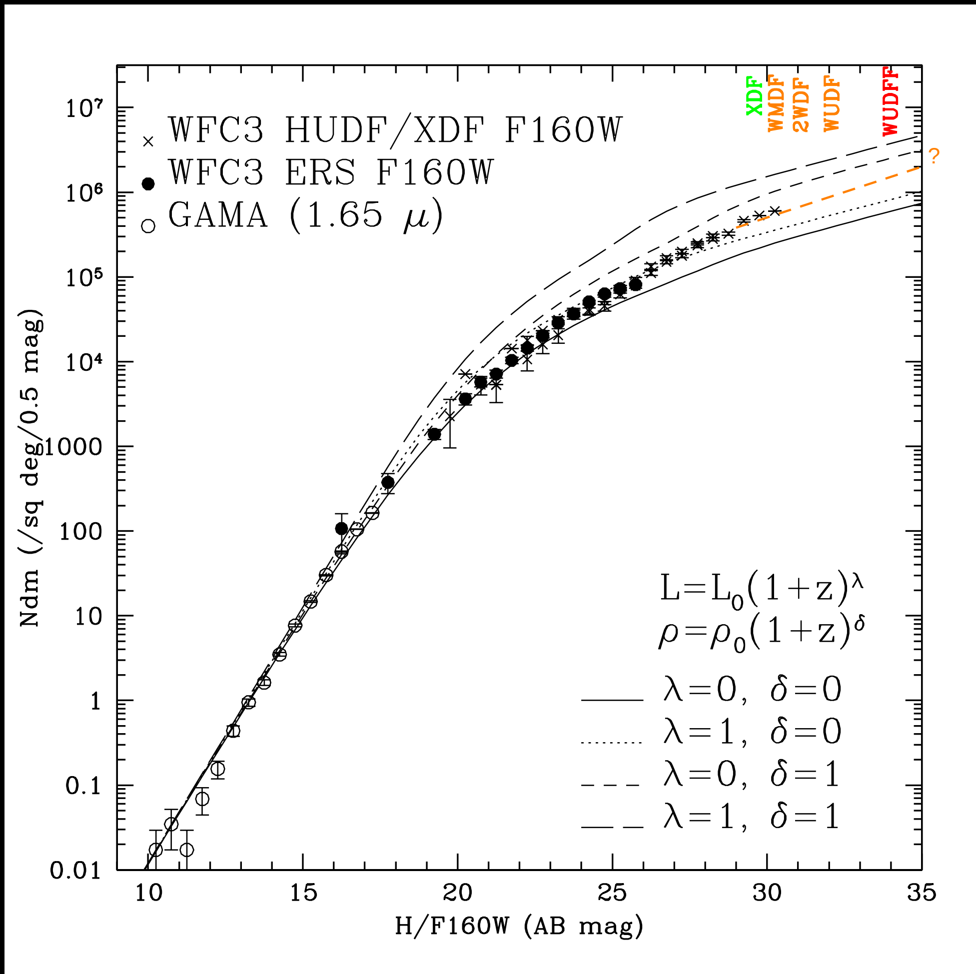


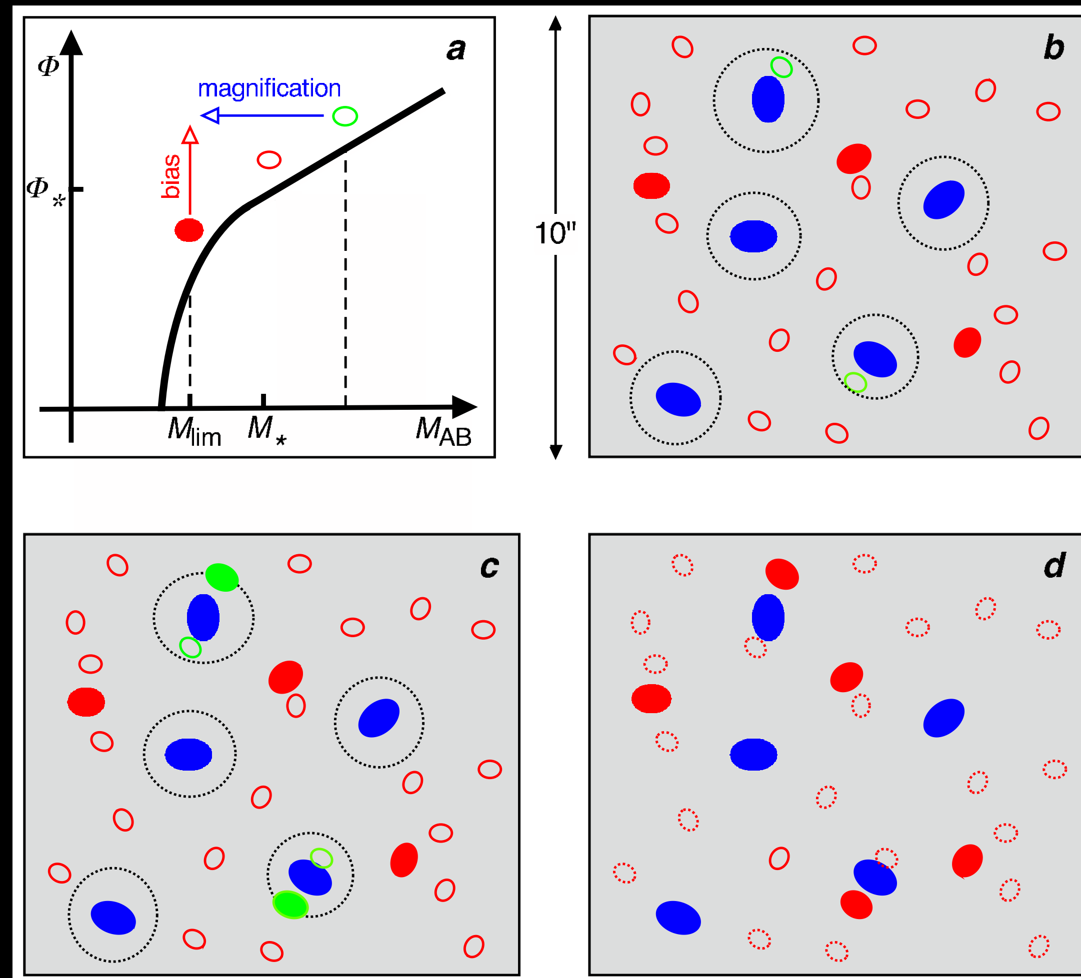
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).


o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB≲ 31 (≳2 nJy).


Panchromatic 13 filter HUDF:
False-color "Bolometric" or χ^2 image.
841 orbits = 592^h HUDF: AB$\lesssim$31 mag; Objects affect ~45% of pixels!!

(3) How can JWST best observe First Light using lensing?



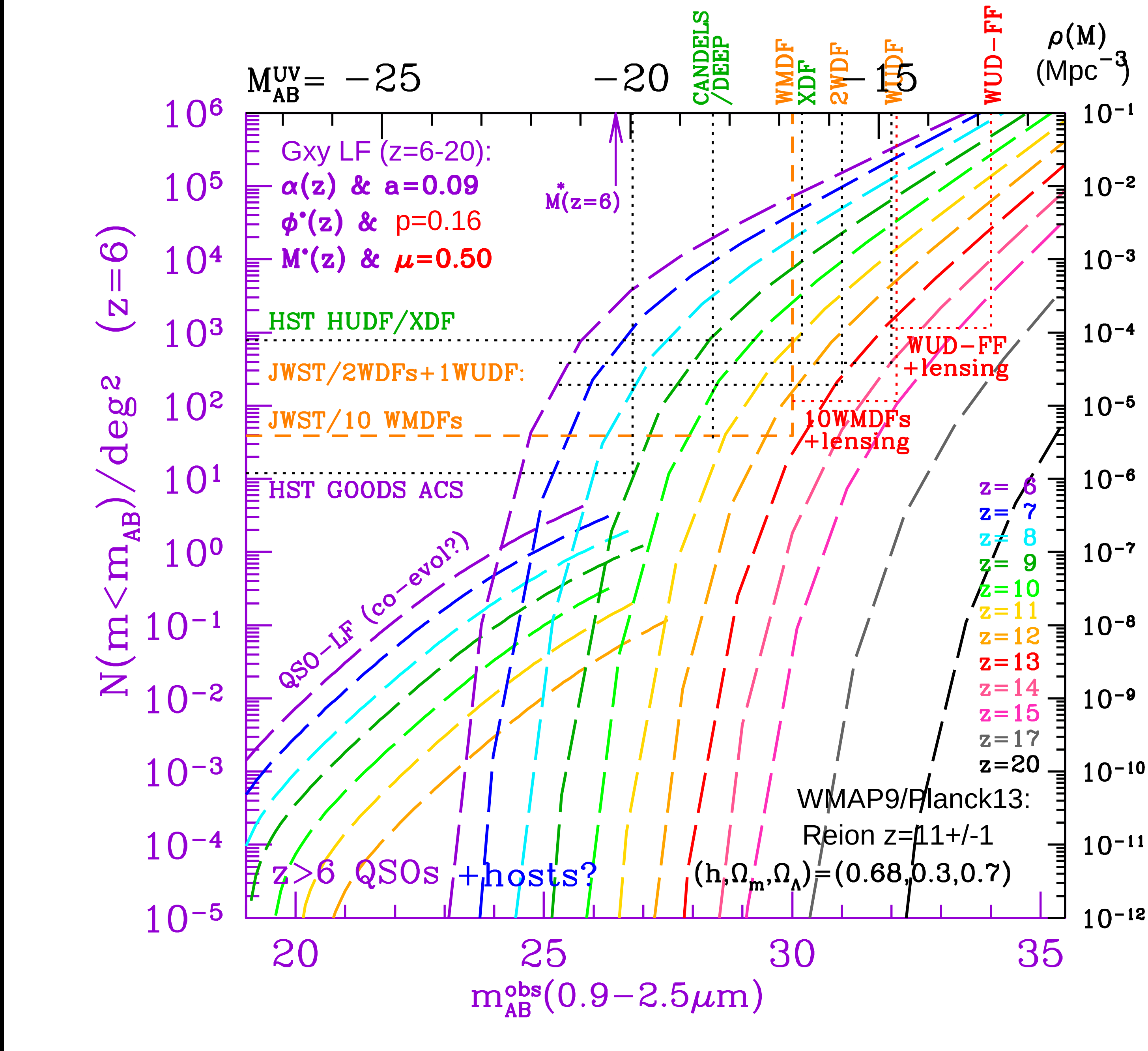


1.6μm counts (Windhorst+2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- Faint-end of near-IR galaxy counts has a steep slope.

⇒ Faint-end of luminosity function at median redshift is also steep.

- In 800-hr JWST can see to ∼32 mag: dwarf galaxy at z≃11!
- Lensing will change the landscape for JWST observing strategies.

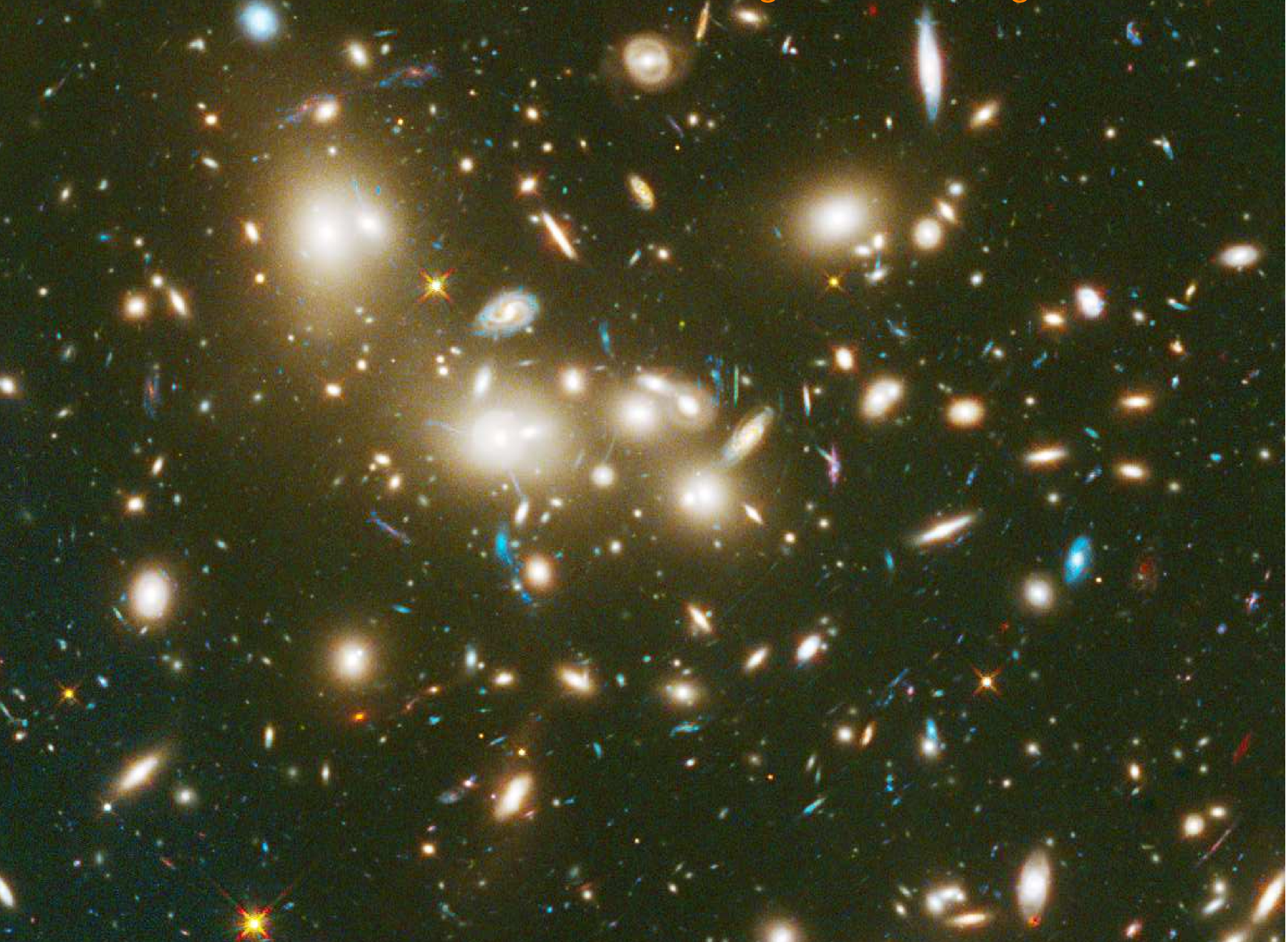


Predicted Schechter Luminosity Function (LF) at redshifts $6 \lesssim z \lesssim 20$:

Area/Sensitivity for: Hubble UDF, **Webb: 10 MDFs**, 2 DFs, & 1 UDF.

- JWST need to use lensing targets to see many $z \simeq 12$–15 objects.

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



Conclusion: JWST First Light strategy must consider three aspects:

(1) The catastrophic drop in the LF (space density) for z$\gtrsim$8.

(2) Cannot-see-the-forest-for-the-trees effect [“Natural Confusion” limit]: Background objects blend into foreground because of their own diameter.

(3) House-of-mirrors effect [“Gravitational Confusion”]:

- JWST needs to find most First Light objects at z$\gtrsim$10–15 through the best cosmic lenses:
- Lensing is what Einstein thought was impossible to observe.

(4) What do our Astrophysics College Graduates do?

Future Careers at NASA:

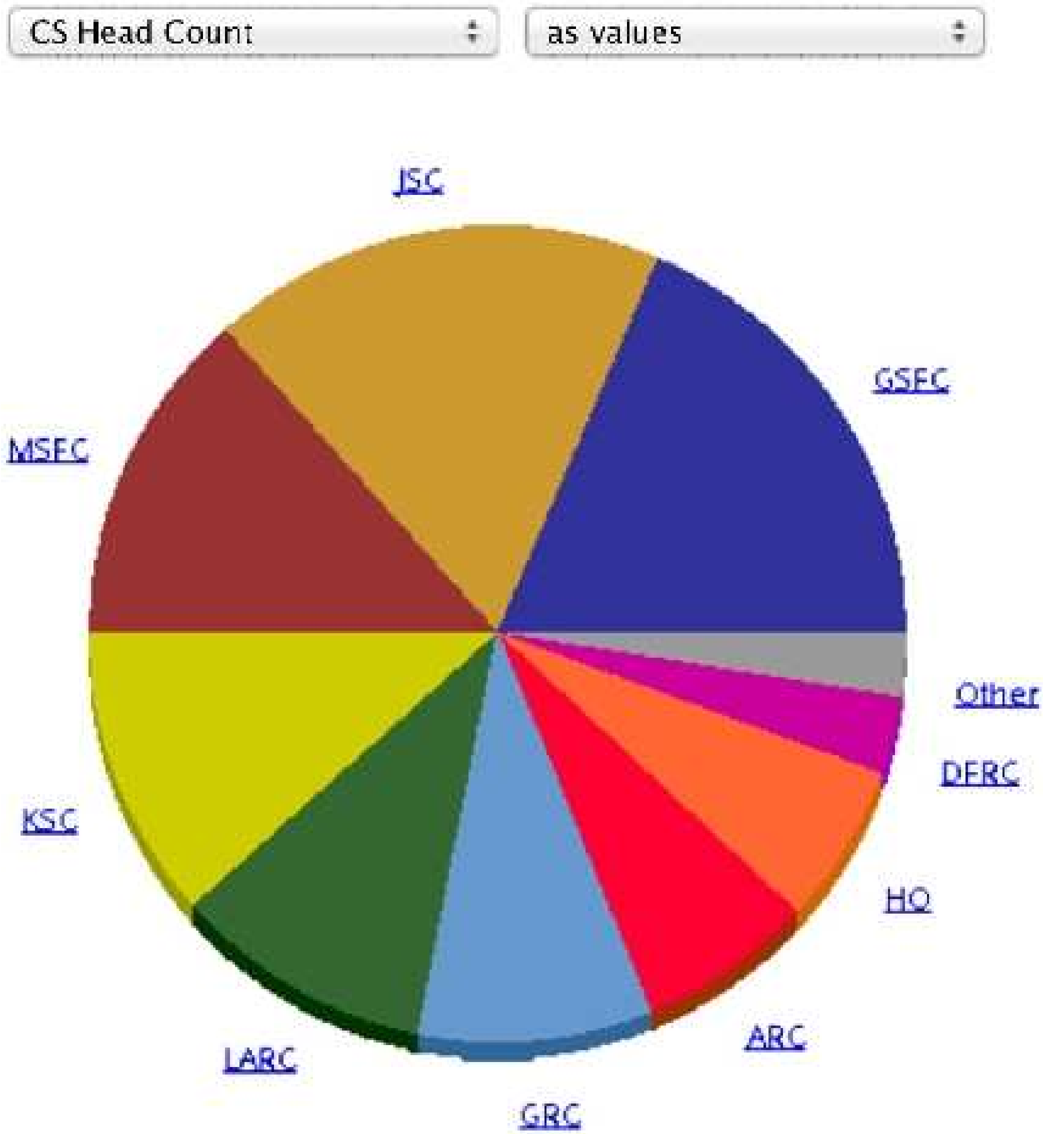
- Over the last 25 years, (ASU) Astrophysics College Graduates typically:
- (0) Have very low unemployment ($\lesssim$few %).
- (1) About 30% are faculty at Universities or 4-year colleges.
- (2) About 30% are researchers at NASA or other government centers.
- (3) About 20% work in Aerospace or related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

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

http://www.aip.org/statistics/astronomy/

https://webapp4.asu.edu/programs/t5/careerdetails/19-2011.00?init=false&nopassive=true

http://scitation.aip.org/content/aip/magazine/physicstoday/article/68/6/10.1063/PT.3.2815



	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`

Some of our ASU grad students do important outreach events:

Annual Girl Scout Stargazing at the White House South lawn (July 2015).

Our own Amber Straughn (right; now at NASA GSFC working for Nobel Laureate Dr. John Mather) informs the Obama's about NASA.

(5) Summary and Conclusions

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

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

- More than 99% 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.

- Measure rapid growth of first supermassive blackholes & host galaxies.
- To see the most First Light, JWST must cover the best lensing clusters!
- Must *routinely* observe what Einstein thought impossible.

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

- IR sequel to HST after 2018: Training the next generation researchers.
- **Your JWST proposals are due $\lesssim$1.8 years from today!**

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

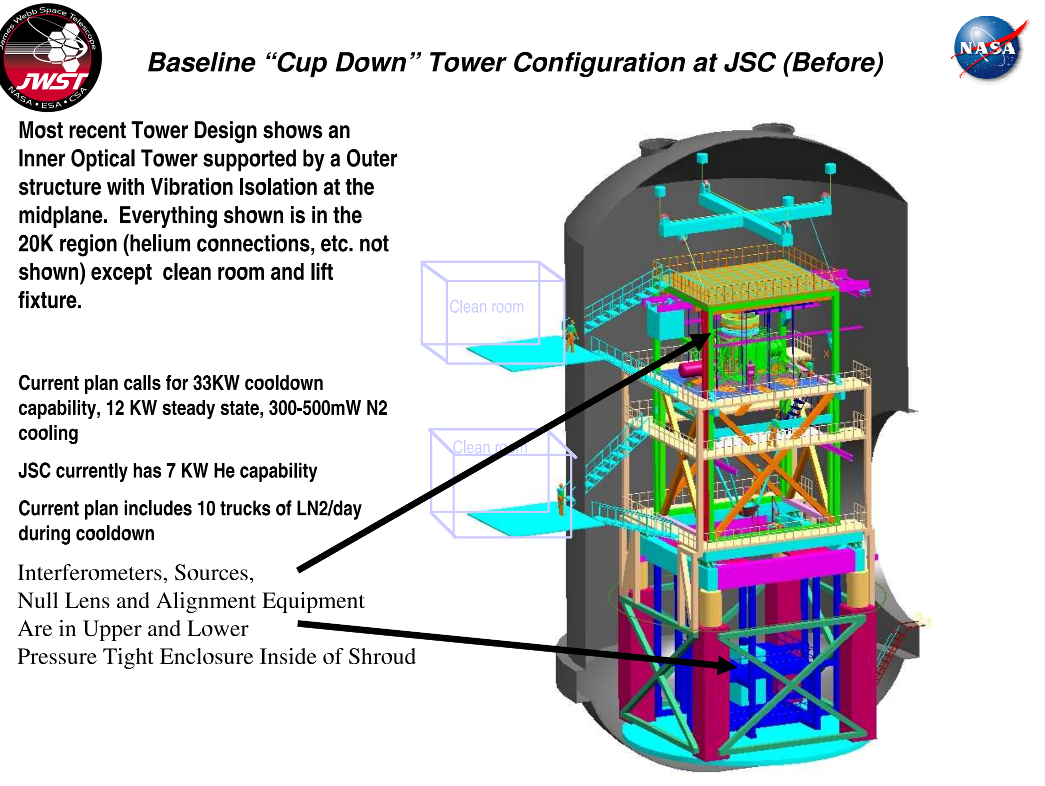
Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

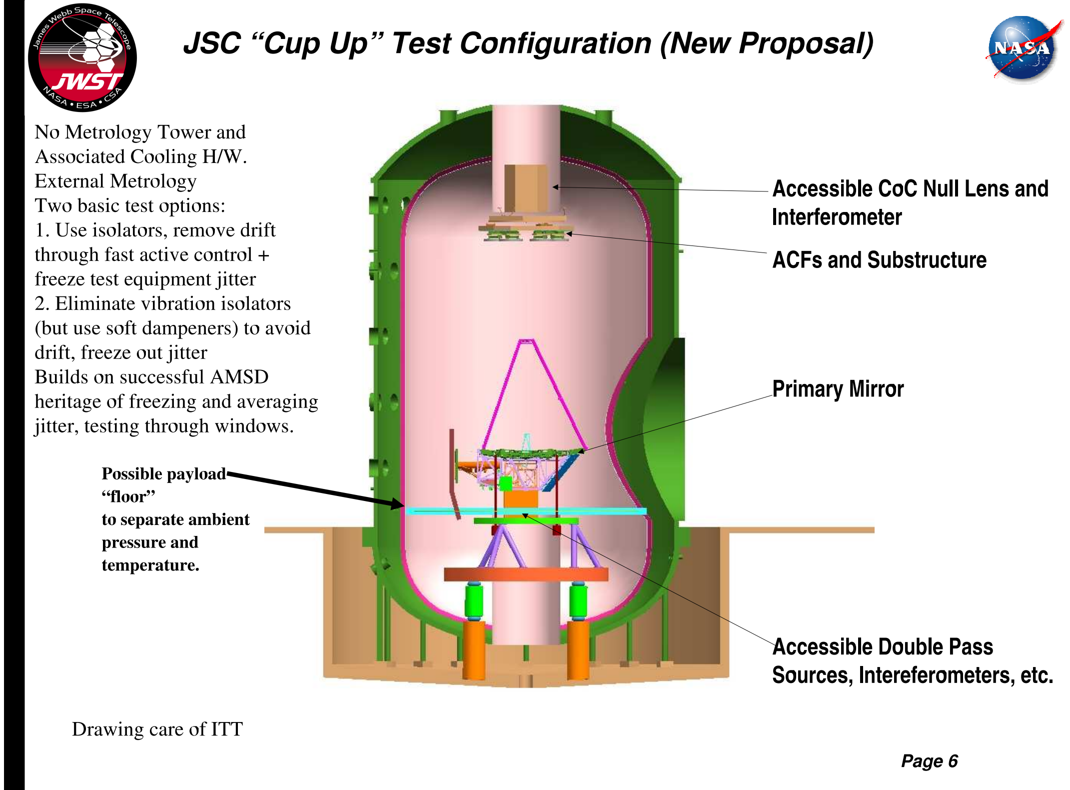
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

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



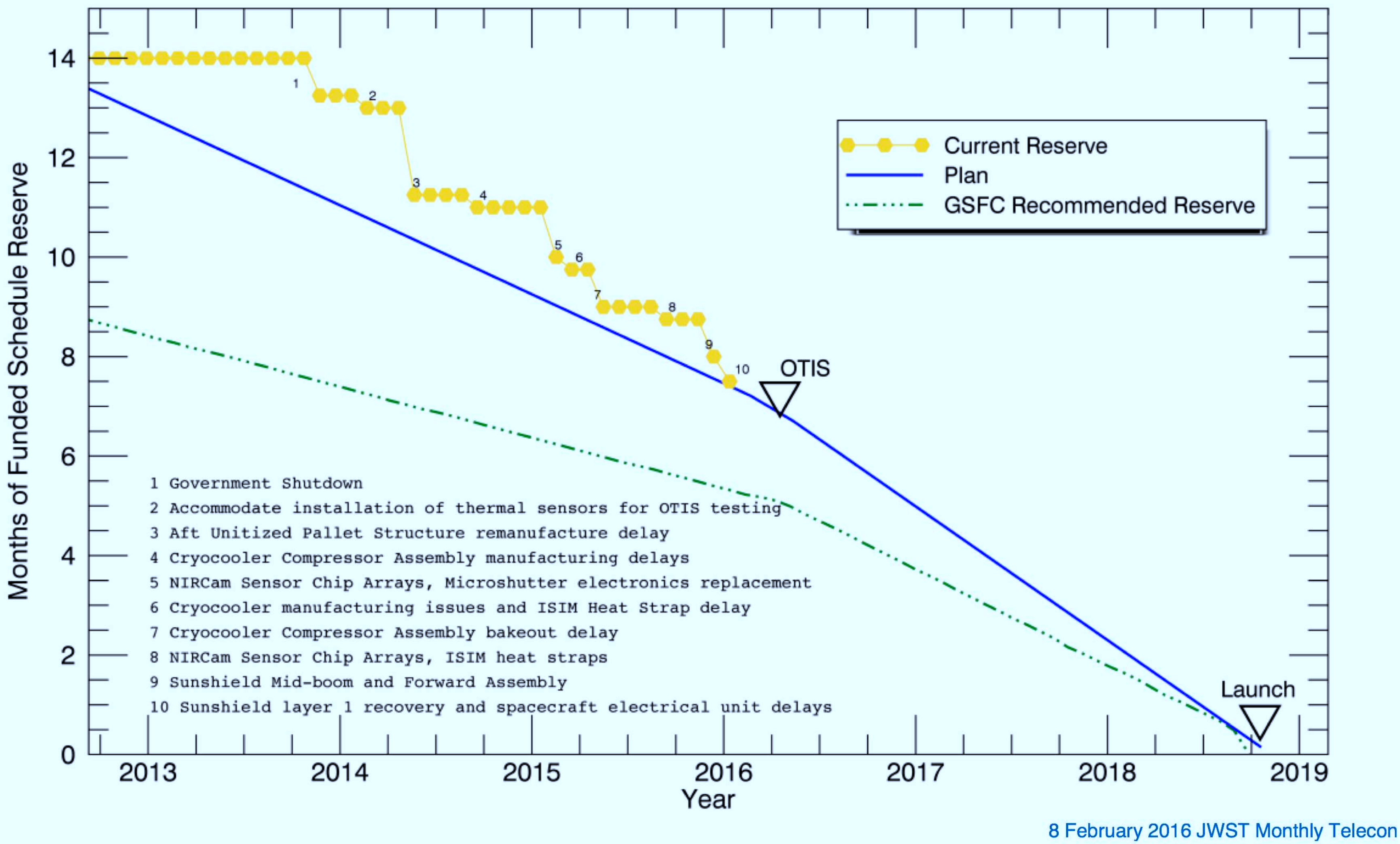




JWST underwent several significant replans and risk-reduction schemes:

- $\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.

Funded Schedule Reserve



Keys to stay on schedule: 1) Sufficient Project contingency ($\gtrsim$25% of total).
& 2) Well replanned and managed Project (starting late summer 2011).

Fiscal Year 2016 JWST HQ Milestones

Month	#	Milestone	FY2015 Deferral	Comment
Oct-15	1	Start Integrated Science Instrument Module (ISIM) cryovacuum test #3	•	Completed 10/27/15
Nov-15	2	Deliver update for launch and activation sequence of events for JWST commissioning		Completed 10/29/15
	3	Deliver the Observatory Operations Handbook Vol 1&2 updates		Completed 10/30/15
	4	Deliver new build of the proposal planning software for Telescope plus ISIM (OTIS) testing		Completed 10/30/15
Dec-15	5	Complete second test of Pathfinder Telescope equipment at the JSC Chamber A		Completed 10/31/15
	6	Complete Solar Array panel #2 cell installation		Completed 12/24/15
	7	Complete Sunshield Mid-Boom Assembly #1 functional test		Delayed to April for reassembly of mid-boom #1
	8	Complete Delivery of Reaction Wheel Assemblies to Observatory Integration and Test (I&T)	•	Two of 3 wheels delivered in December, 1 in May, being rebuilt, no schedule impact
	9	Deliver Data Management Subsystem build for basic data search and distribution functionality		Completed 11/30/15
Jan-16	10	Deliver flight Aft Optics System to Telescope I&T		Completed 12/14/15
	11	Complete final checkout of new GSFC vibration shaker table		Delayed till March, vertical shaker issues
	12	Sunshield Flight Layer #4 shipped to Northrop-Grumman		Completed 12/3/15
	13	Sunshield Forward Cover Assembly shipped to Northrop-Grumman	•	Delayed till June. Nexolve revised schedule to implement NGAS design changes. No anticipated schedule impact
	14	Complete Flight Operations Subsystem System Design Review #2		Completed 12/17/15
	15	Complete Mission Operations Center construction at STScI		Completed 12/29/15
Feb-16	16	Deliver Aft Deployable Instrument Radiator to Observatory I&T		
	17	Deliver Command & Telemetry computer to Observatory I&T		Delayed till March to re-run testing
	18	Deliver Secondary Mirror Support Structure verification report to GSFC		Completed 1/28/16
	19	Complete deliveries of Spacecraft wire harnesses		Completed 1/22/16
	20	Deliver spare Cryocooler Compressor Assembly to JPL	•	
Mar-16	21	Start Spacecraft Panel Integration		Completed 10/26/15
	22	Complete Sunshield Mid-Boom Assembly #2 functional test		Forecasting June completion date due to latch and detent pin redesign and tubessegment rebuild
	23	Complete cryocooler thermal performance acceptance testing		

Milestones: How the Project reports its progress monthly to Congress.

Milestone Performance

- Since the September 2011 replan JWST reports high-level milestones monthly to numerous stakeholders

	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year	Deferred more than one quarter
FY2011	21	21	6	3	0	0
FY2012	37	34	16	2	3	3
FY2013	41	38	20	5	3	2
FY2014❖	36	23	10	8	11	10
FY2015	48	44	22	12	4	3
FY2016	46	15	13	7*	0	0

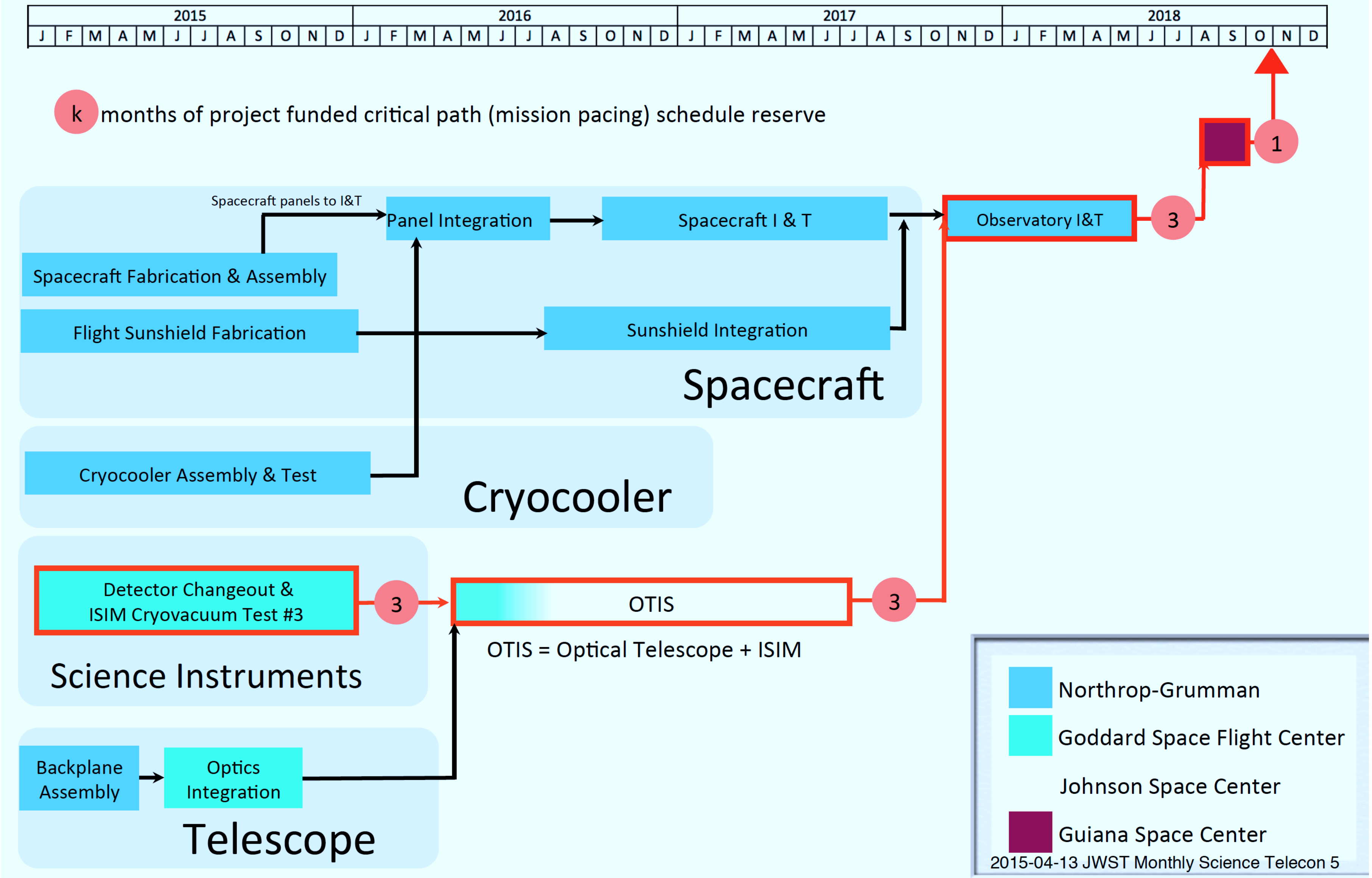
*Late milestones have been or are forecast to complete within the year. Deferred milestones are not included in the number-completed-late tally.

❖ Milestone accounting in FY2014 was complicated by the government shutdown and multicomponent milestones

FY14: 8 milestones late by 1 month due to Oct 13 Government shutdown.

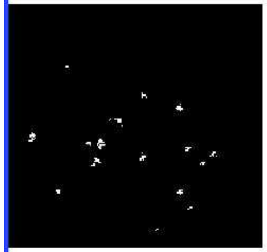
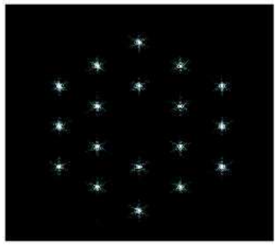
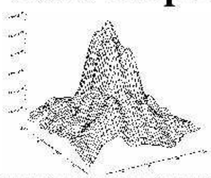
FY15: Most the "Lates" not on critical path, causing no launch delay.

Simplified Schedule



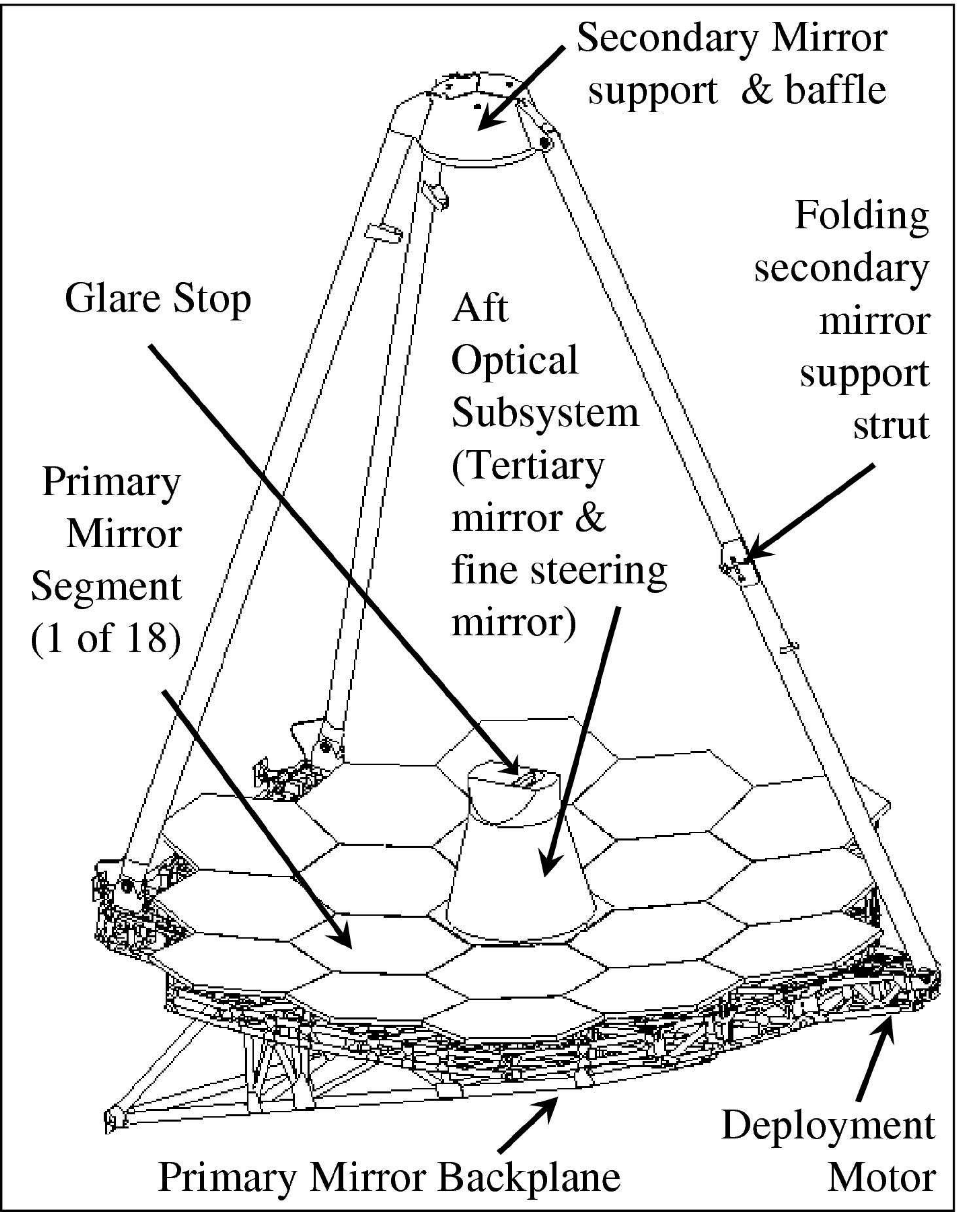
Path forward to Launch (in Oct. 2018): 10 months schedule reserve.

Instruments+detectors & Optical Telescope Element remain on critical path.

Step	Image	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)

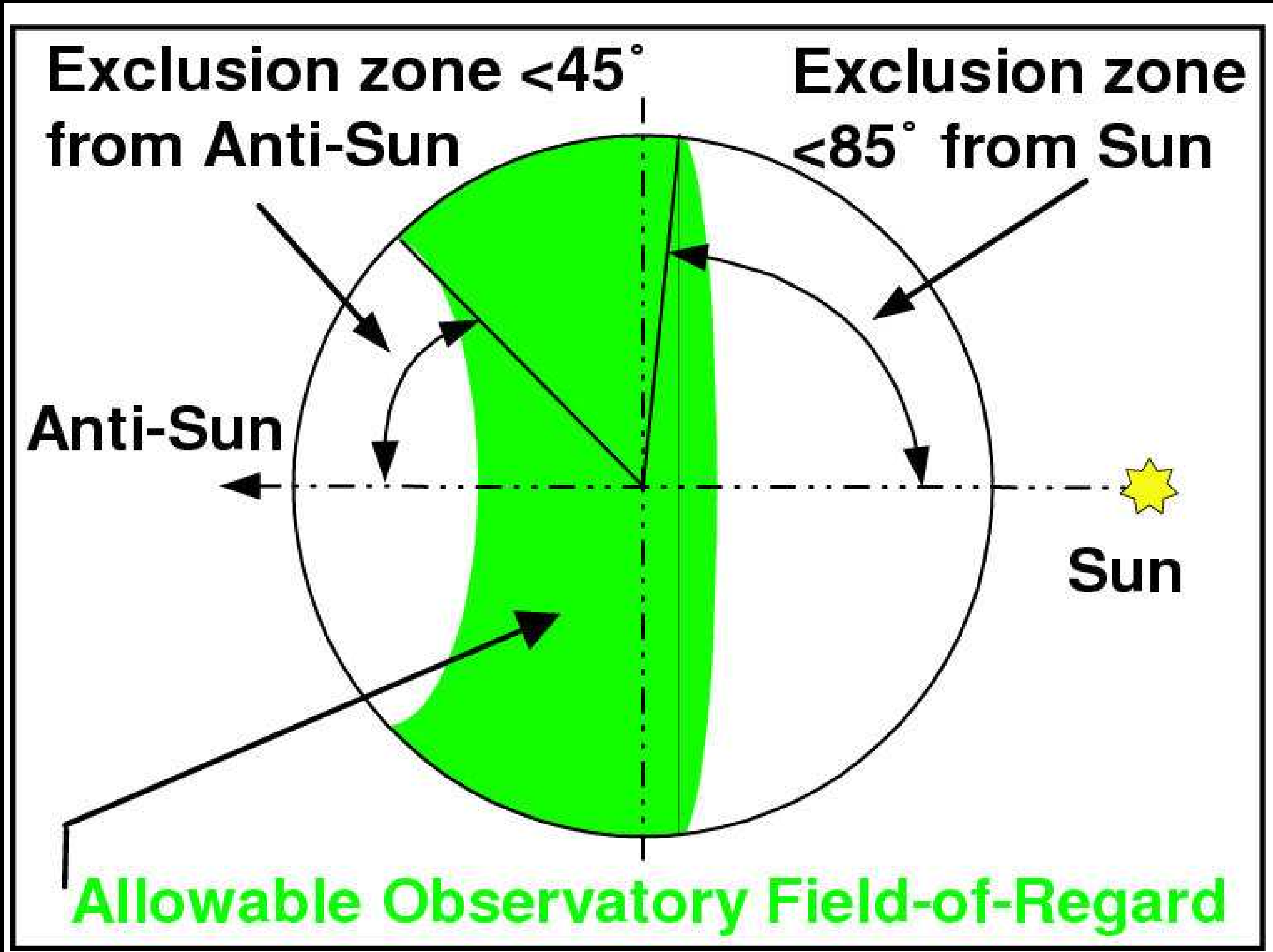
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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 2016–2017.

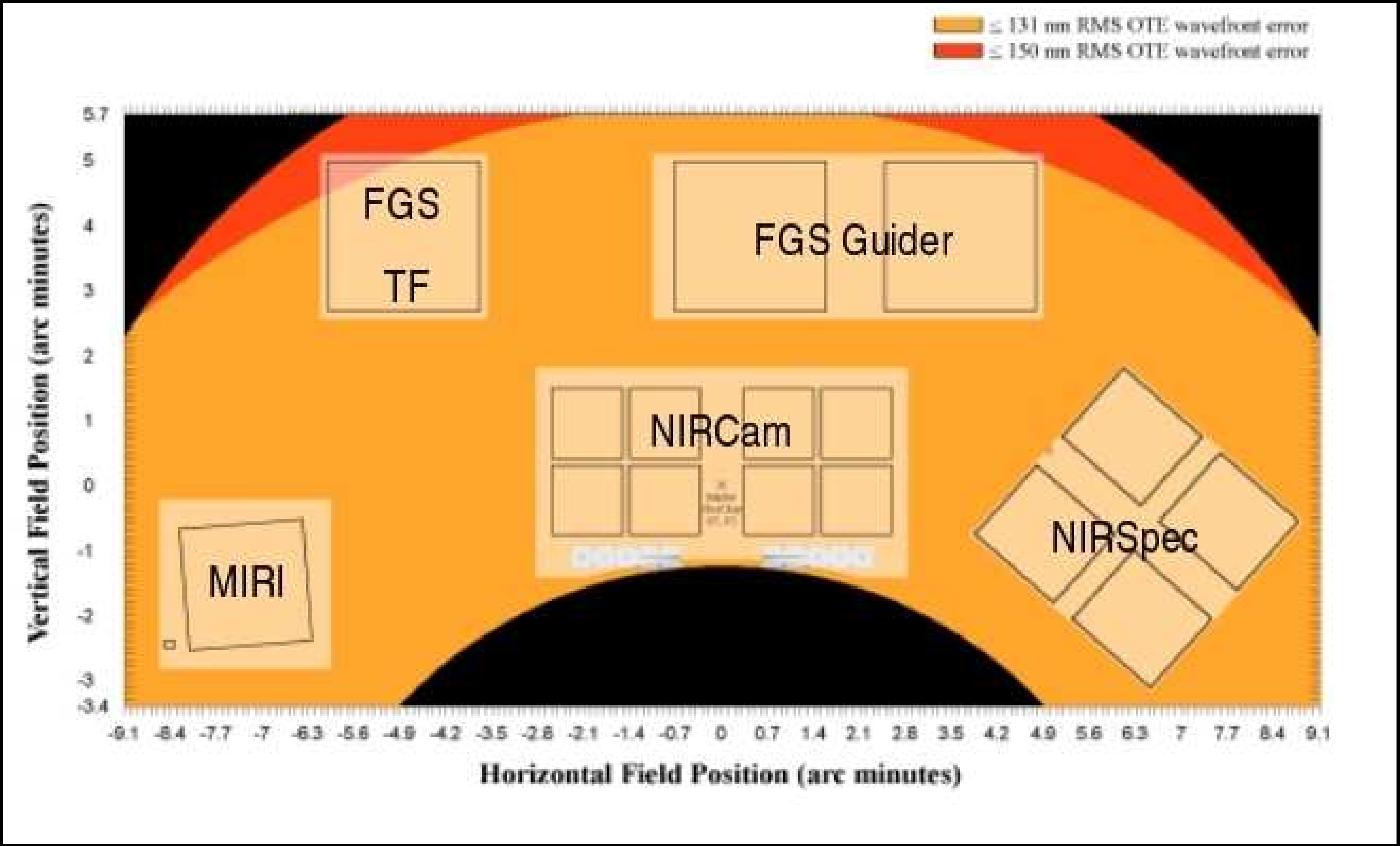
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.



JWST can observe North/South Ecliptic pole targets continuously:

- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- They will rely a lot on Rockwell Collins' (Heidelberg) reaction wheels.

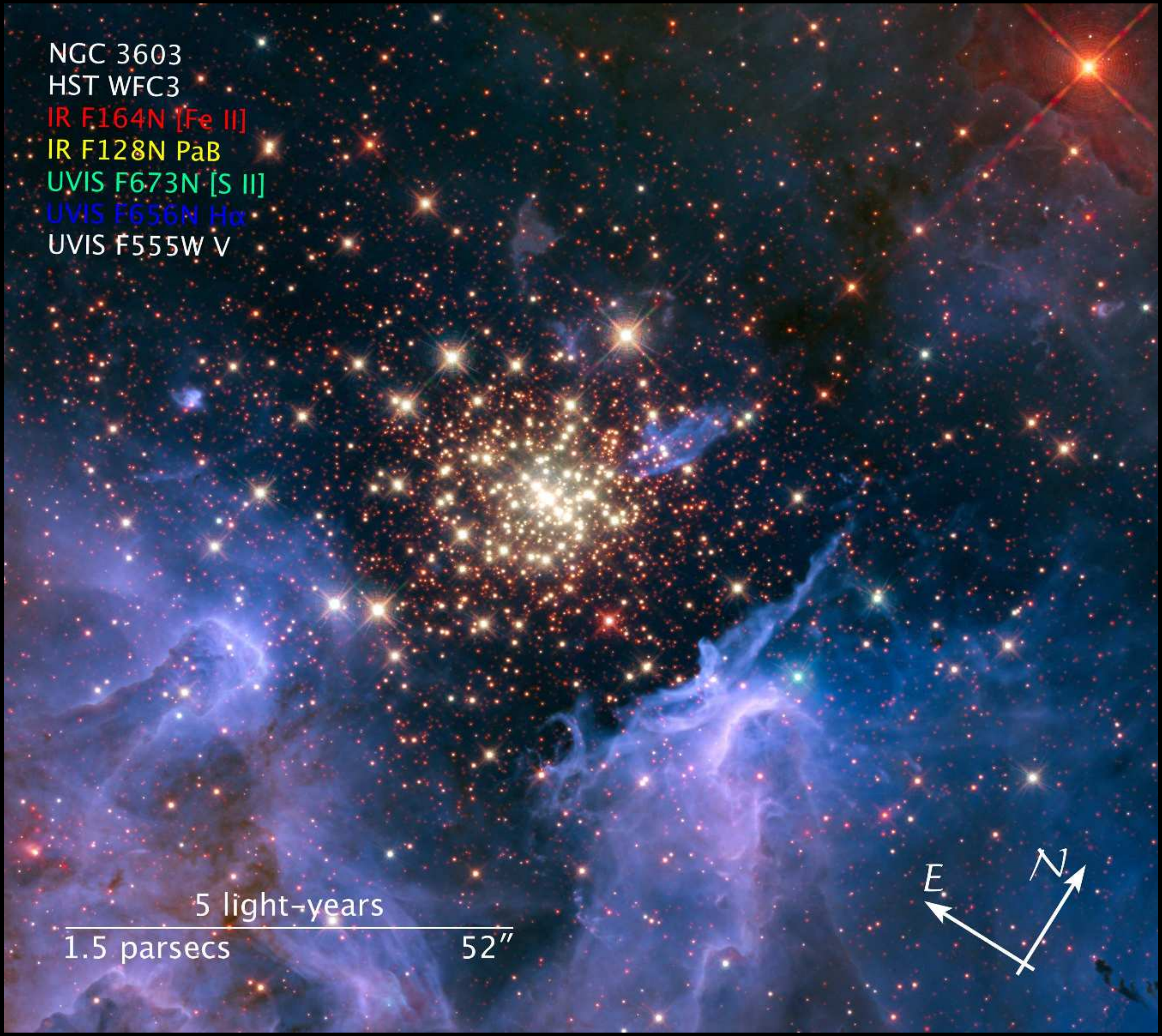
• (3c) What instruments will JWST have?



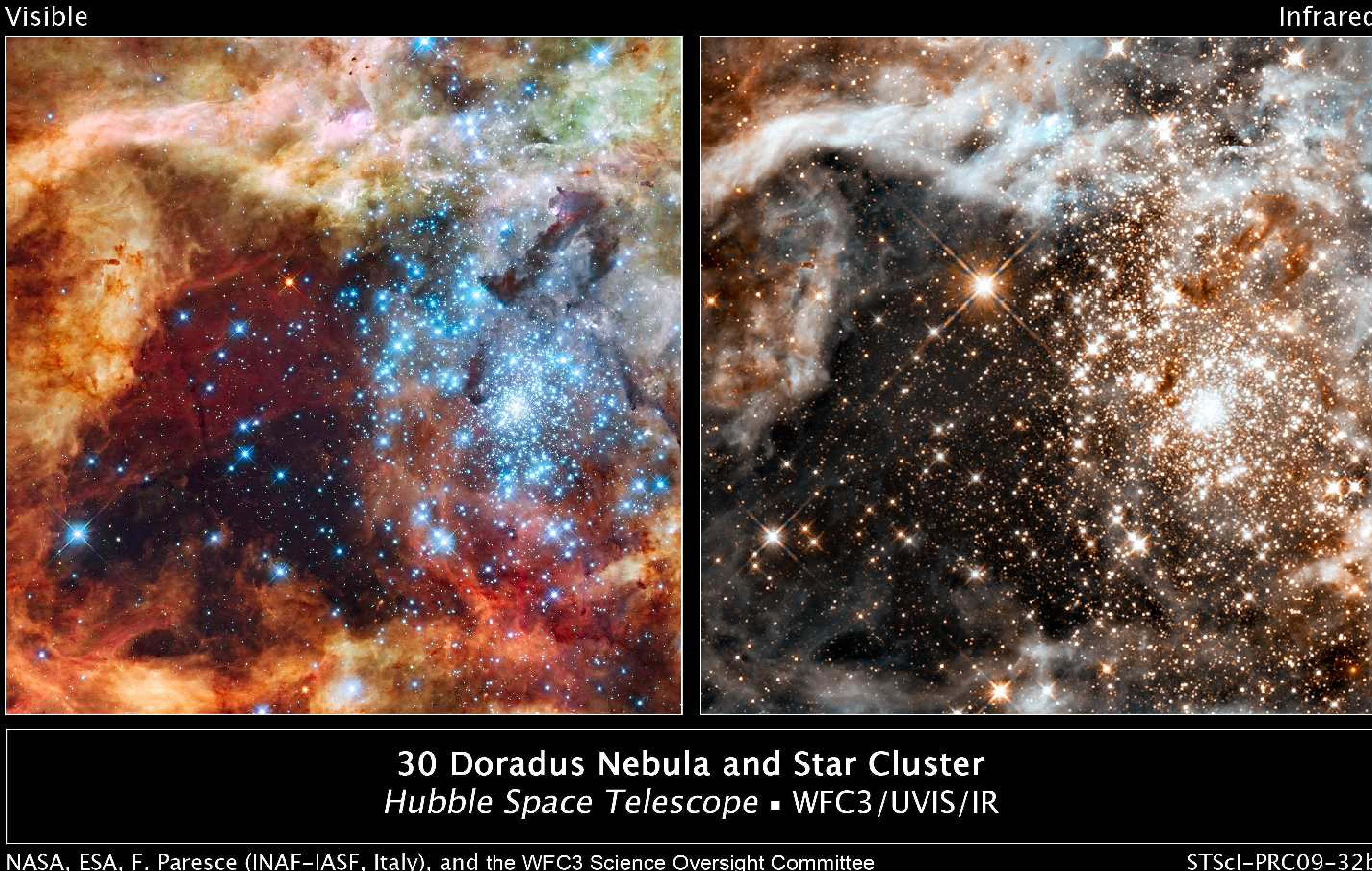
All JWST instruments can in principle be used in parallel observing mode:

- As of 2016, now also implemented for parallel *science* observations.

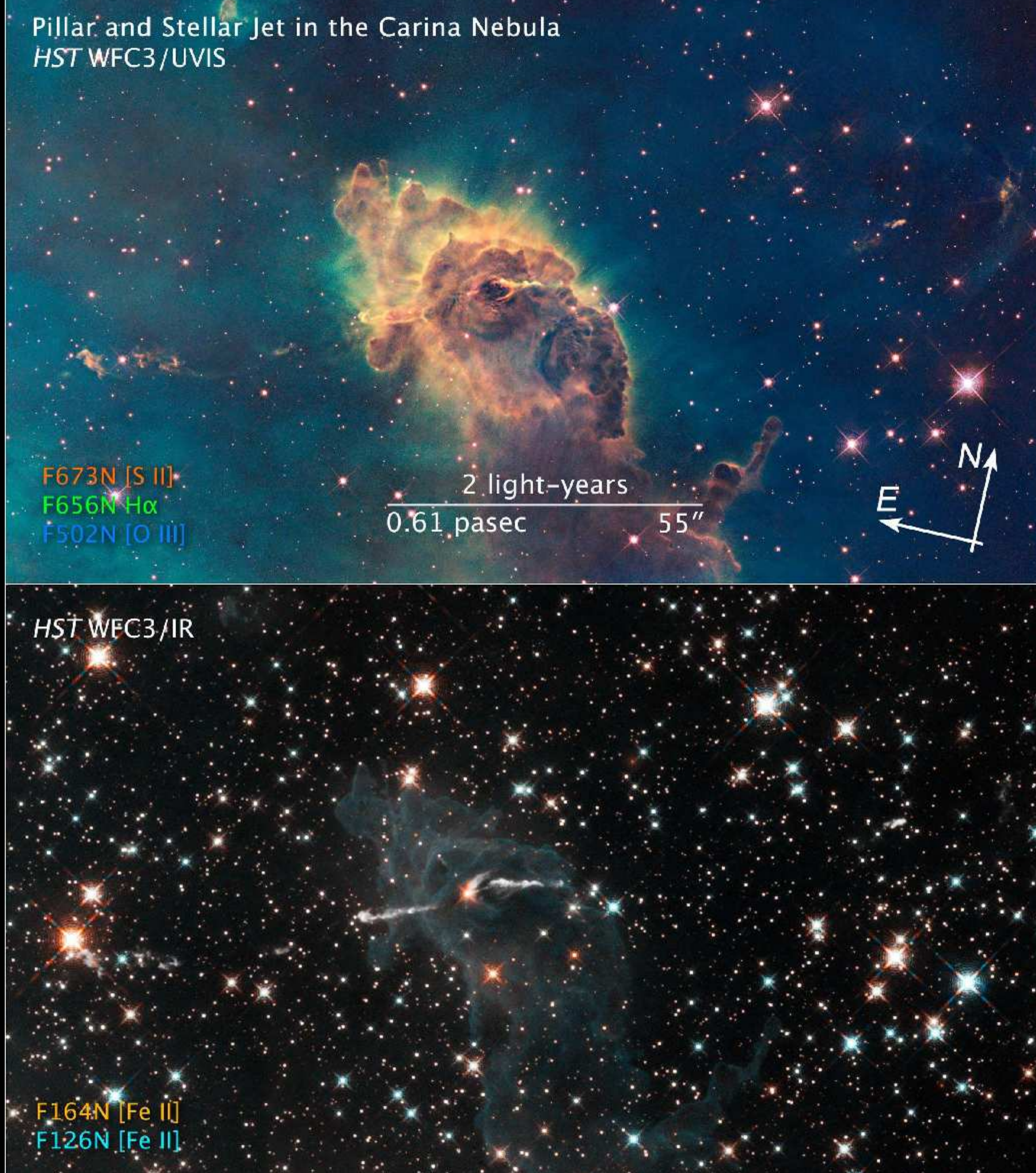
(6) How can JWST measure Star-Formation and Earth-like exoplanets?

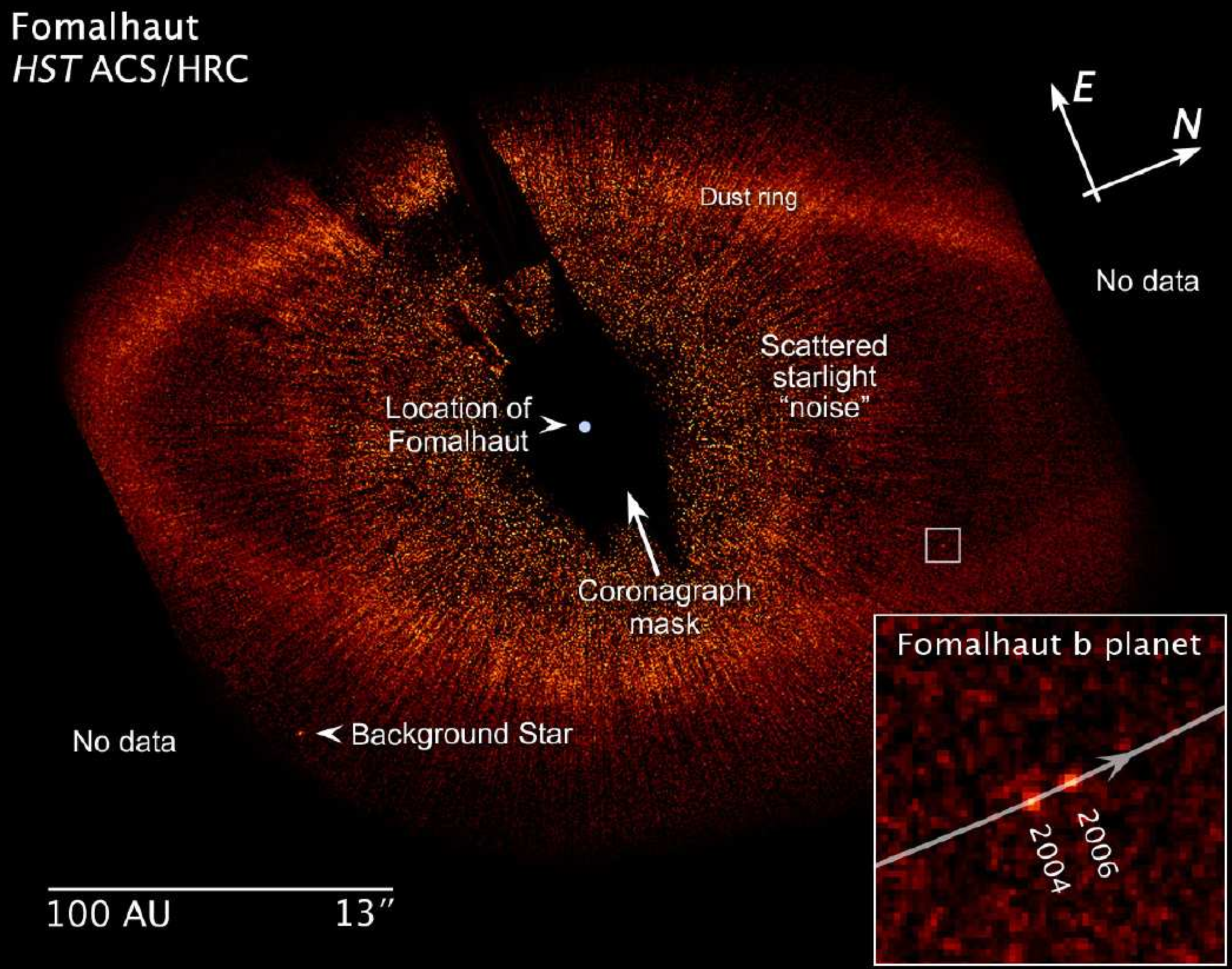


NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"



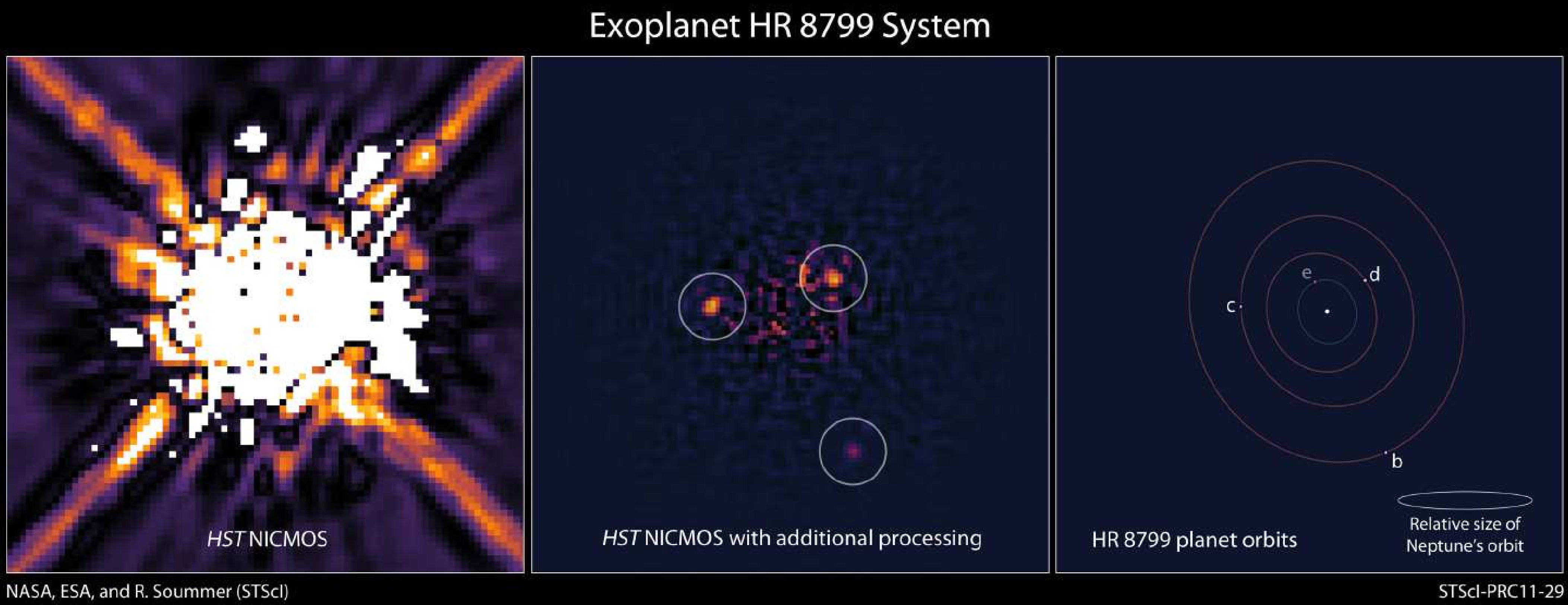
30 Doradus: Giant young star-cluster in Large Magellanic Cloud (150,000 ly), triggering birth of Sun-like stars (and surrounding debris disks).


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



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

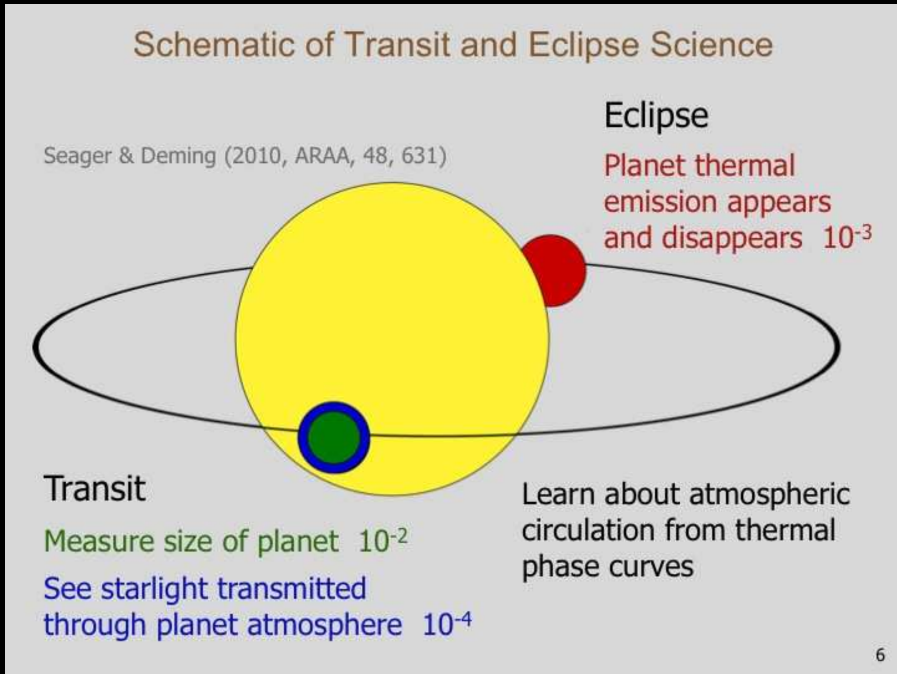
JWST can find such planets much closer in for much farther stars.

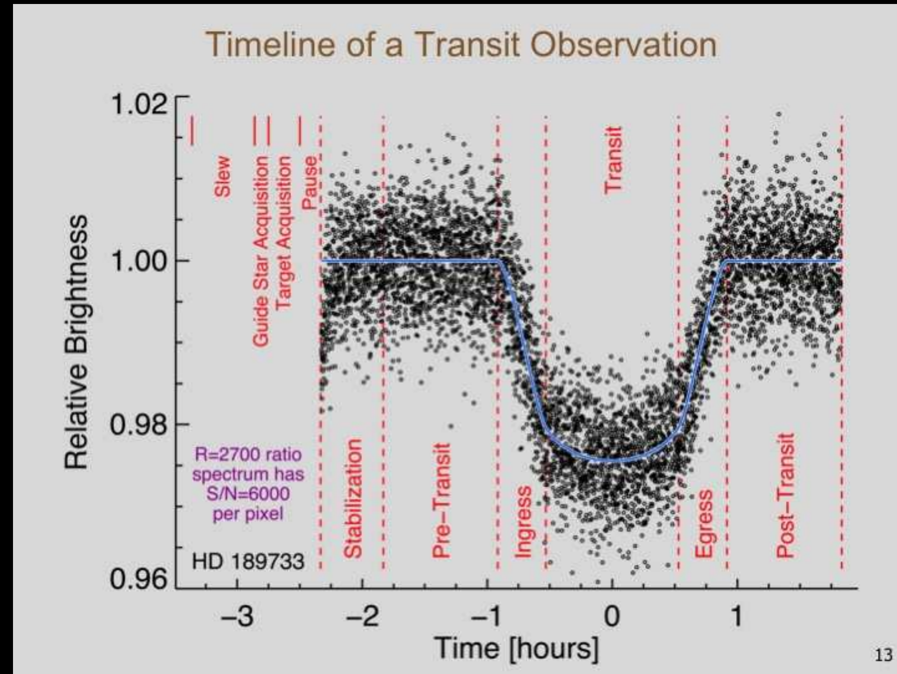


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

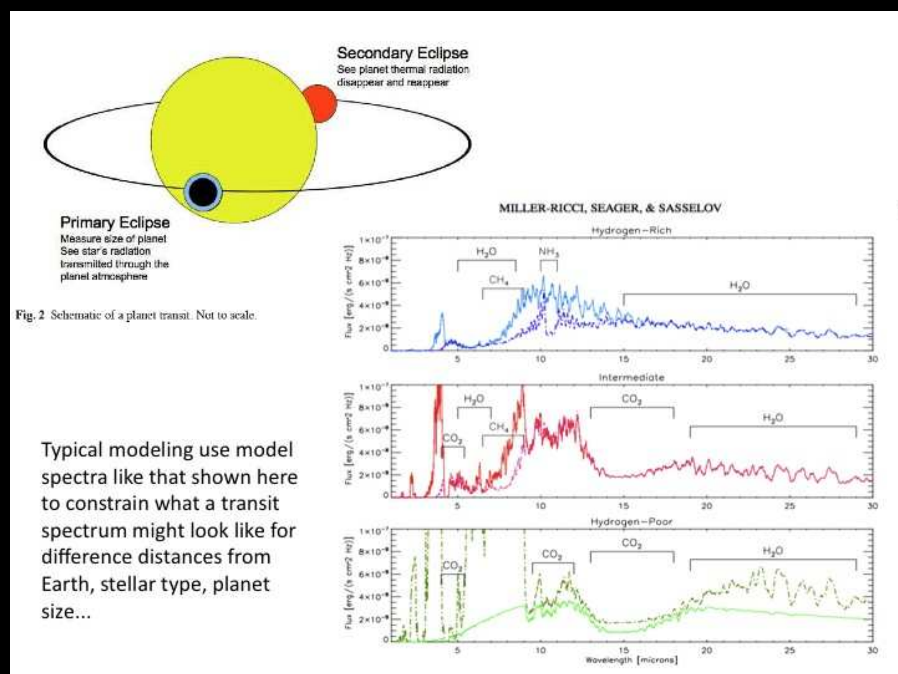
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

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



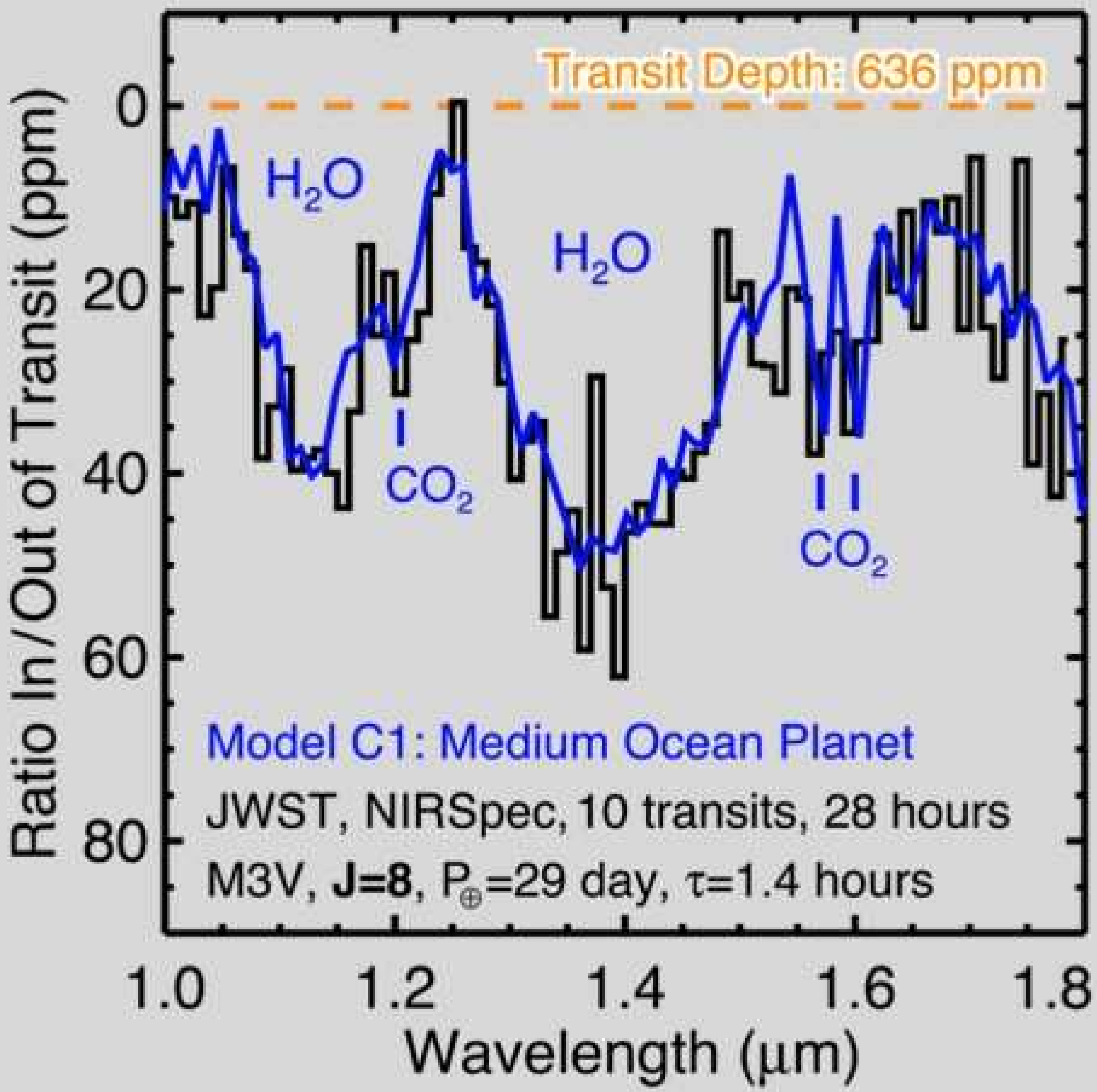


JWST can do very precise photometry of transiting Earth-like exoplanets.



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.