The Search for First Light:
James Webb Space Telescope Hardware Update 2017.

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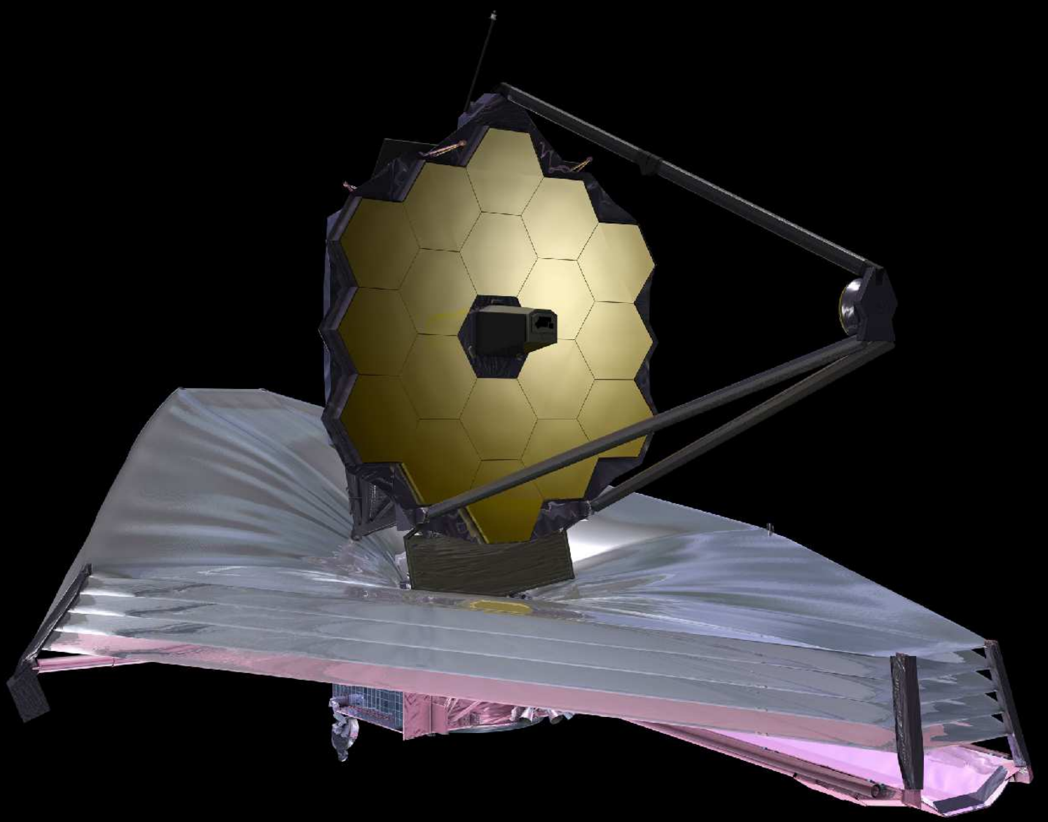


Colloquium at the Kapteyn Astronomical Institute, University of Groningen; Groningen, The Netherlands.

Monday, July 3, 2017; All presented materials are ITAR-cleared.

Outline

- (1) James Webb Space Telescope Hardware Update as of 2017.

- (2) How will JWST measure Galaxy Assembly & Supermassive Blackhole Growth?

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

- (4) Summary and Conclusions.

Sponsored by NASA/HST & JWST

ARIZONA STATE UNIVERSITY

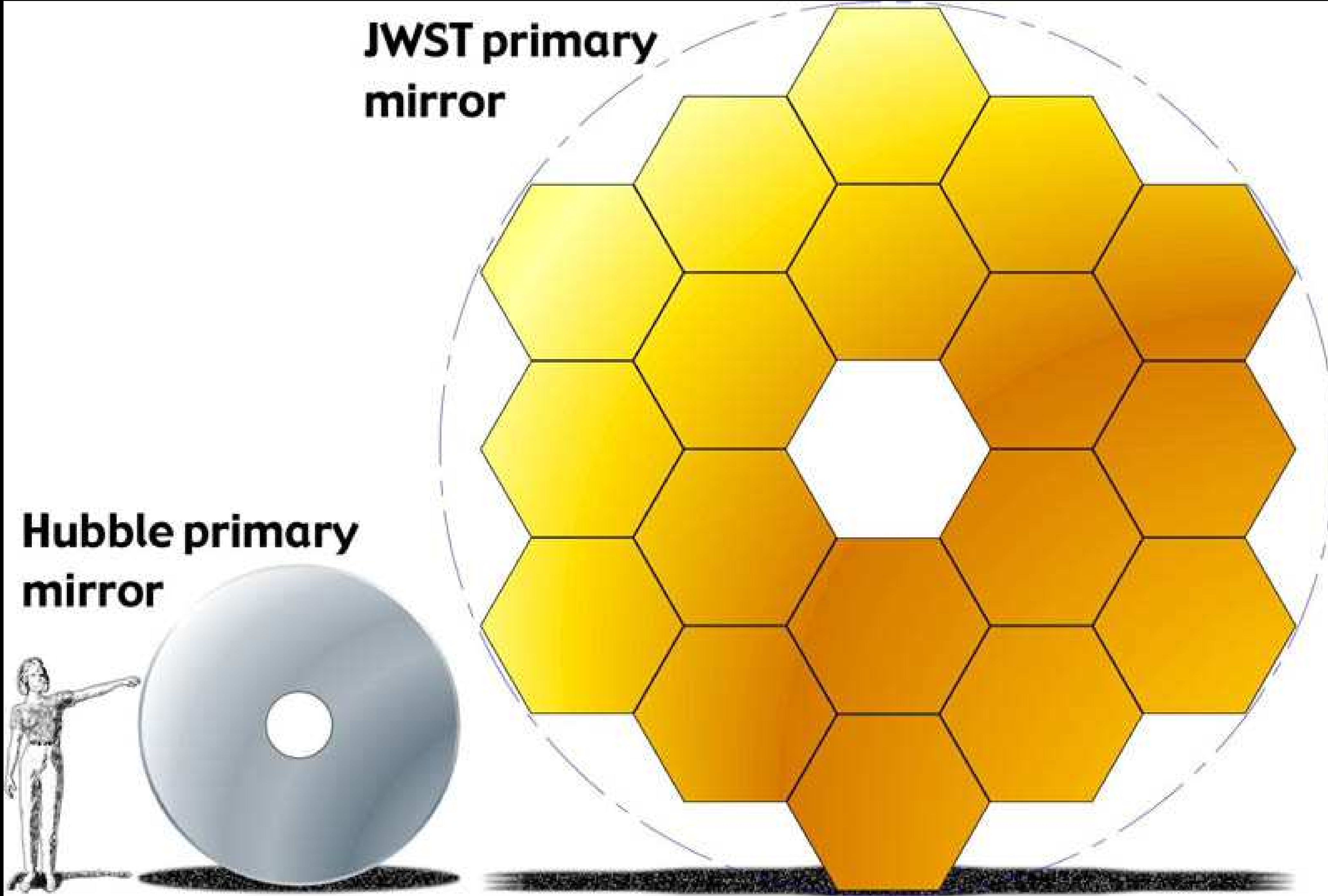
Talk is on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/groningen17_jwst.pdf

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

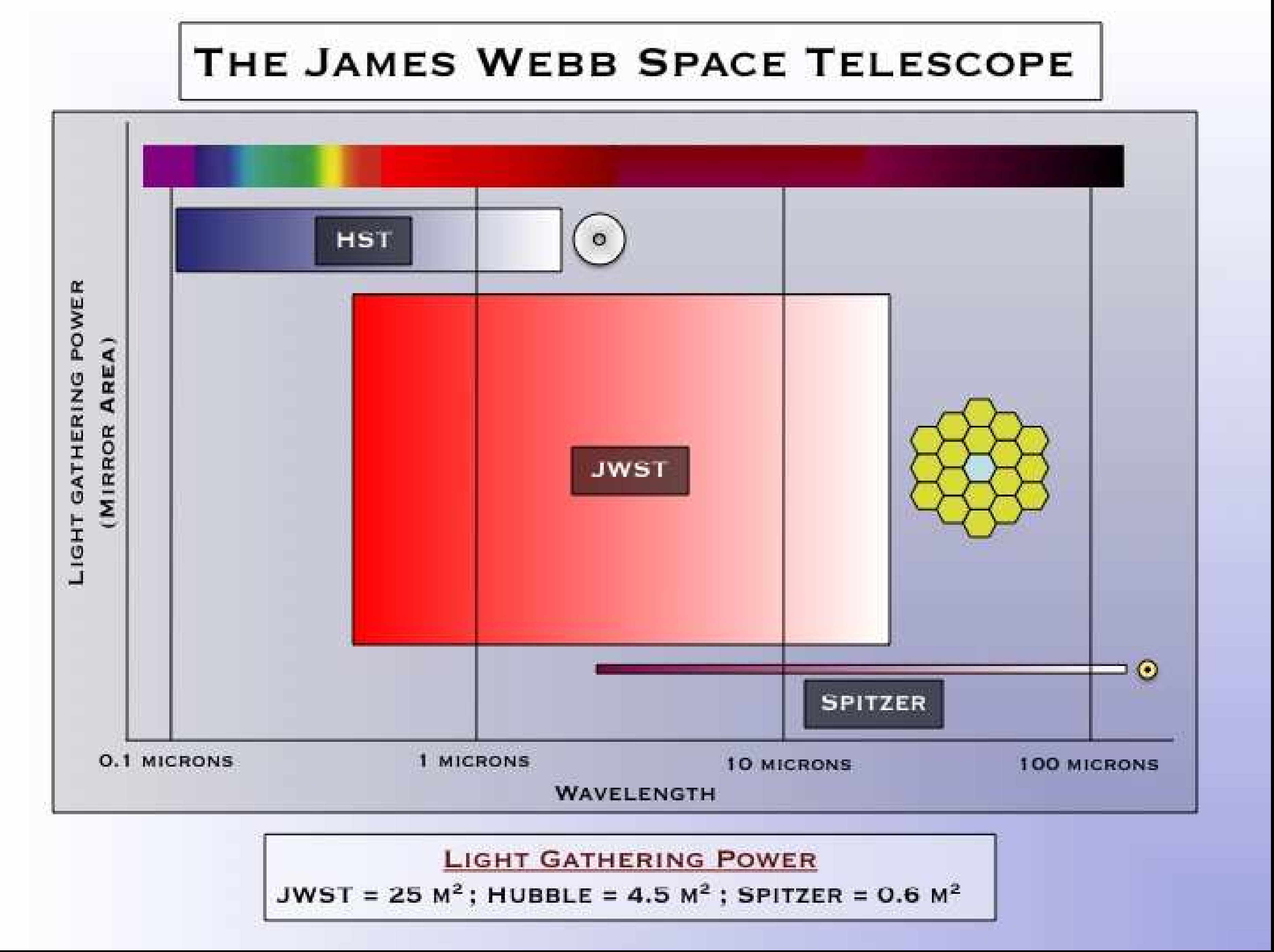
James E. Webb (1906–1992) — Second NASA Administrator

Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2018?.

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



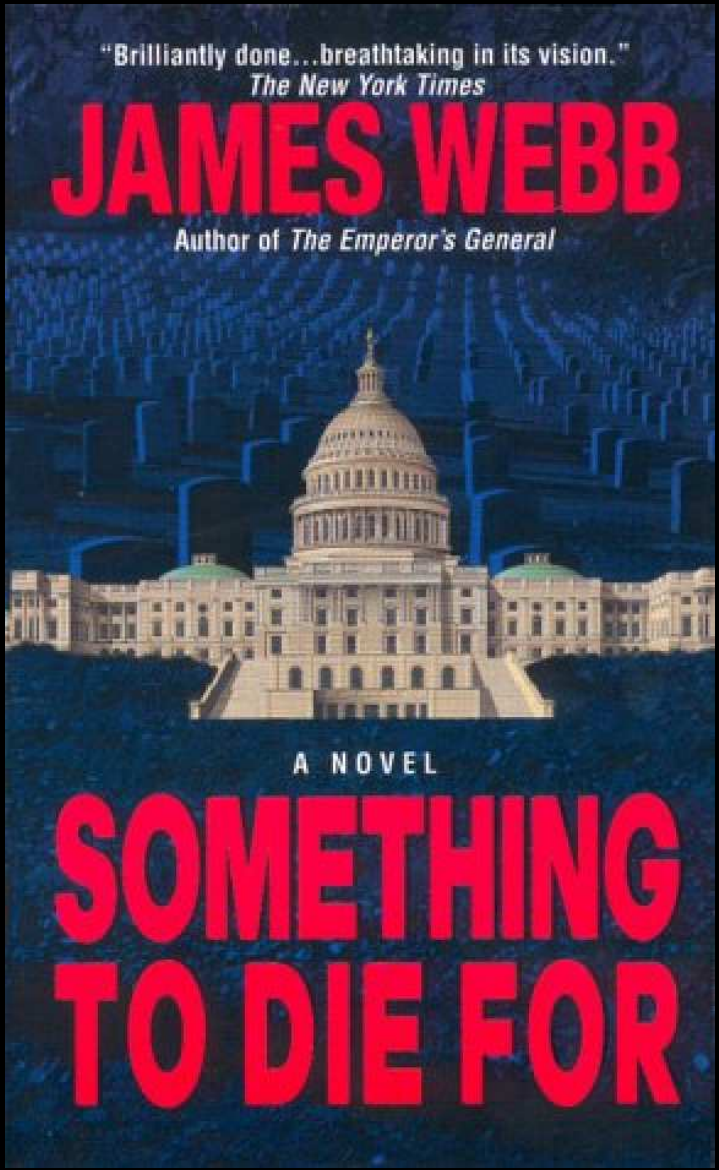
JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.



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.

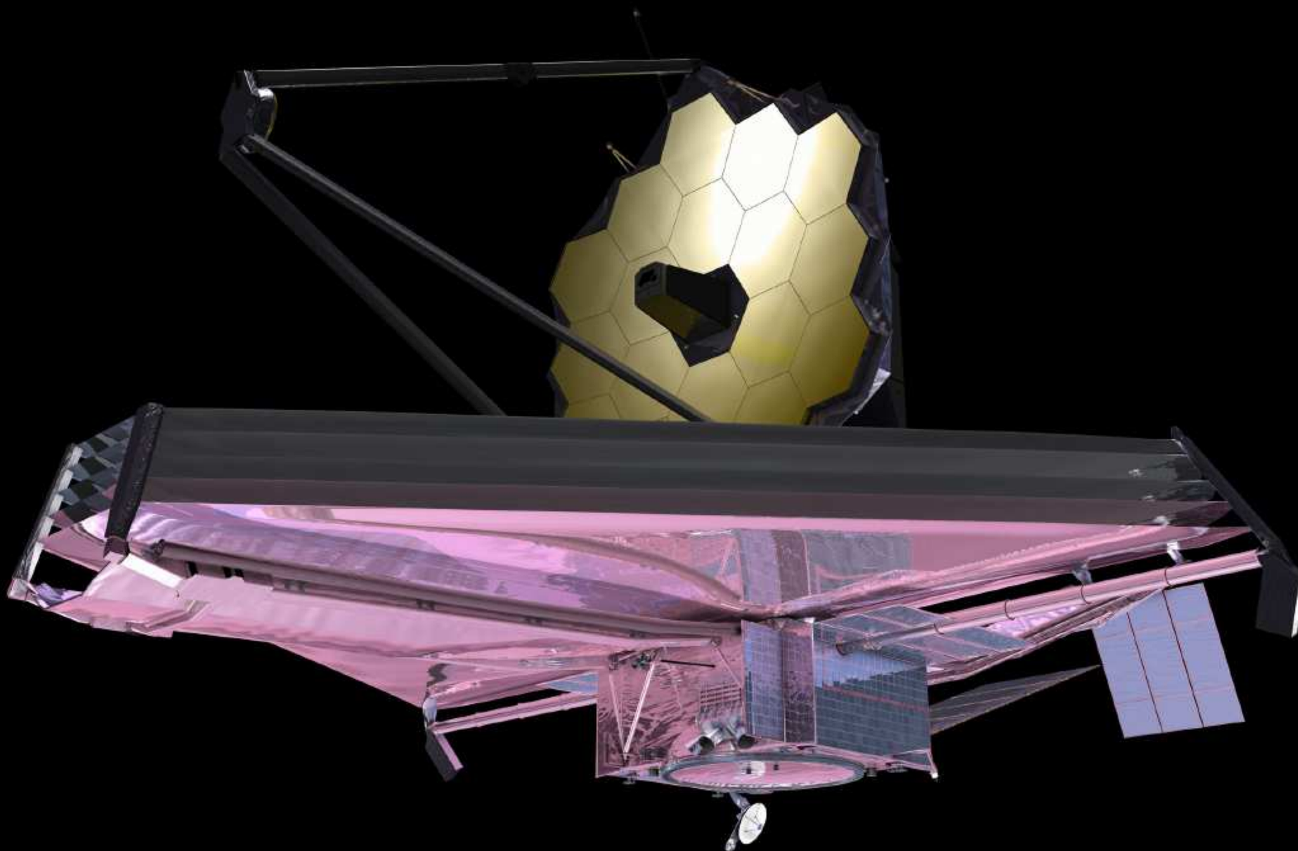
(1) Update of the James Webb Space Telescope (JWST), 2017.



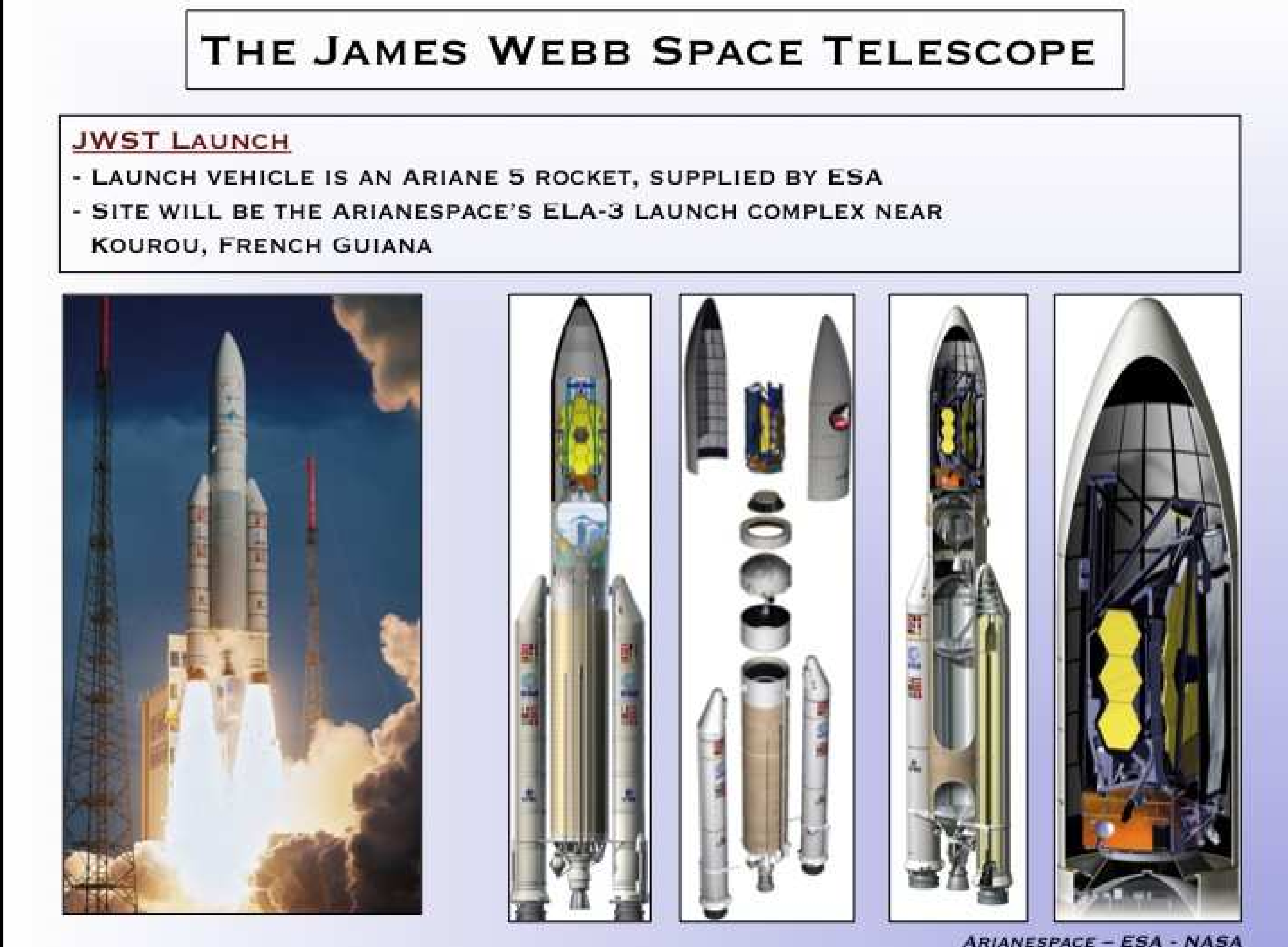
To be used by students & scientists after 2018 ... It'll be worth it.

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

(1) Update of the James Webb Space Telescope as of 2017.

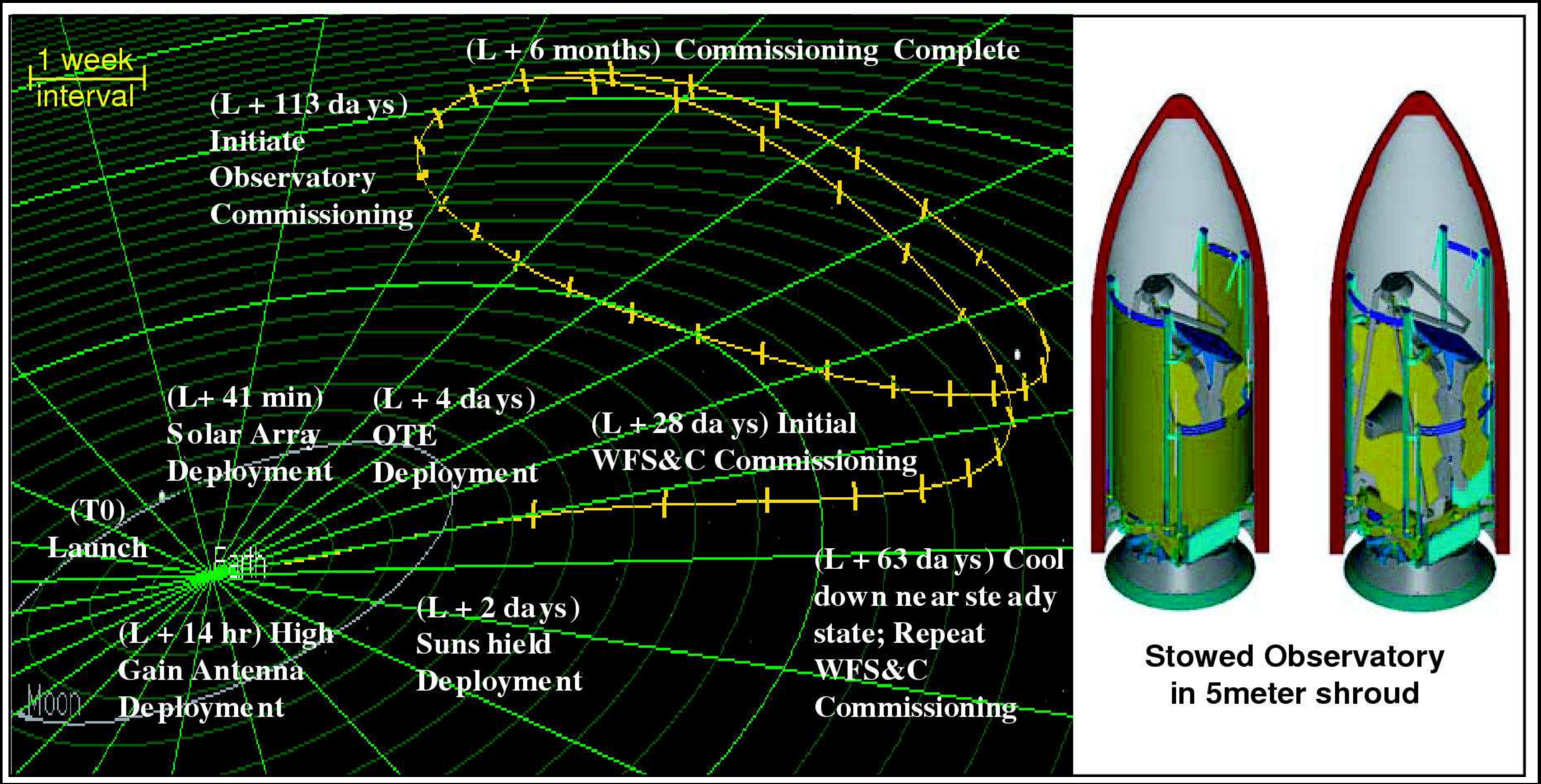


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.



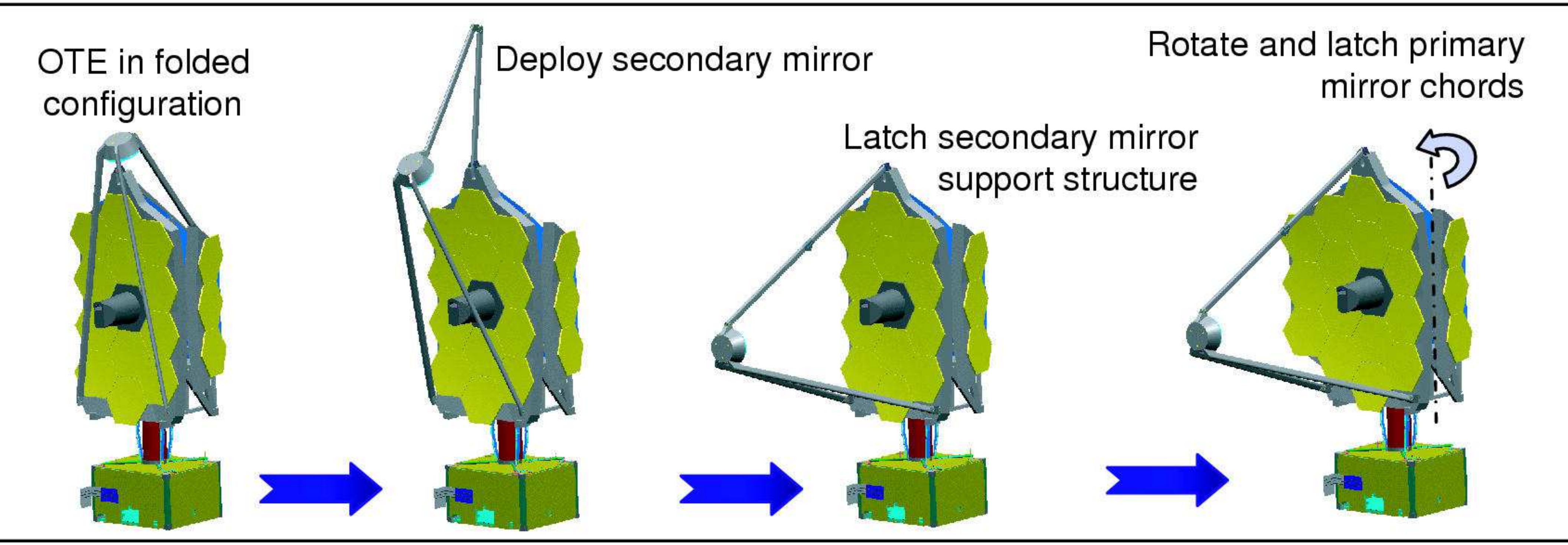
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(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.

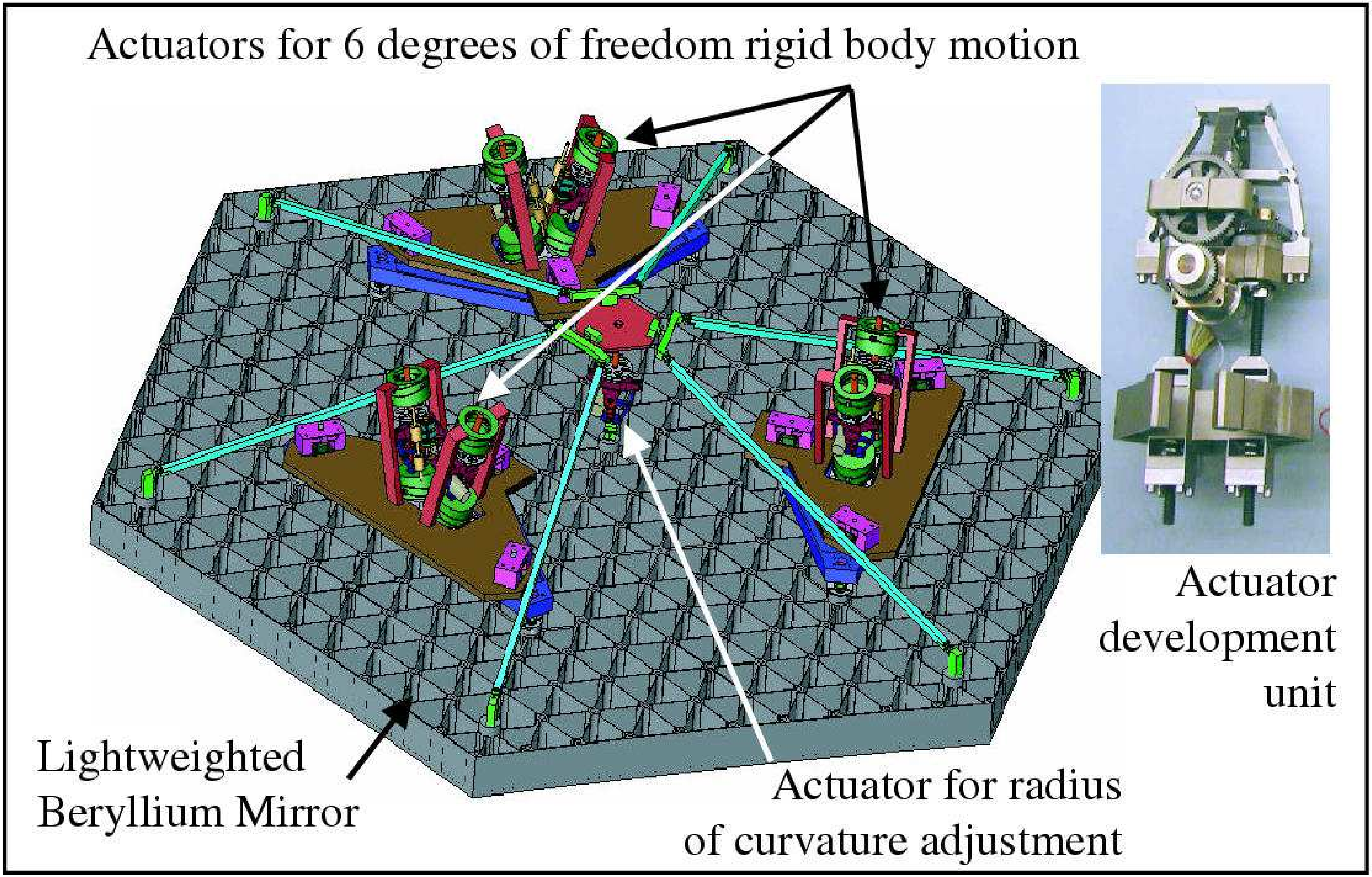
(1b) How will JWST be automatically deployed?



- 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).

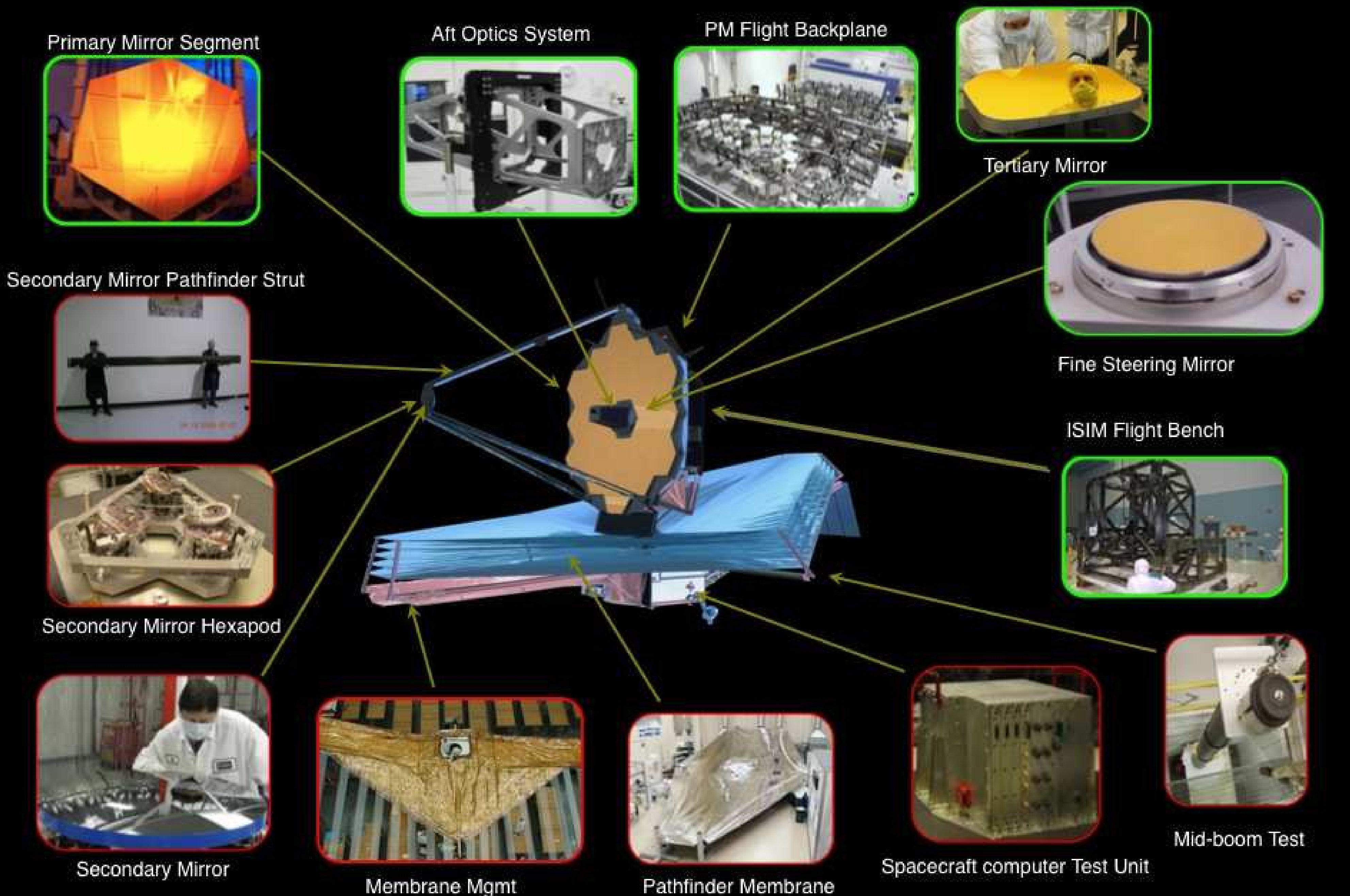
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



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

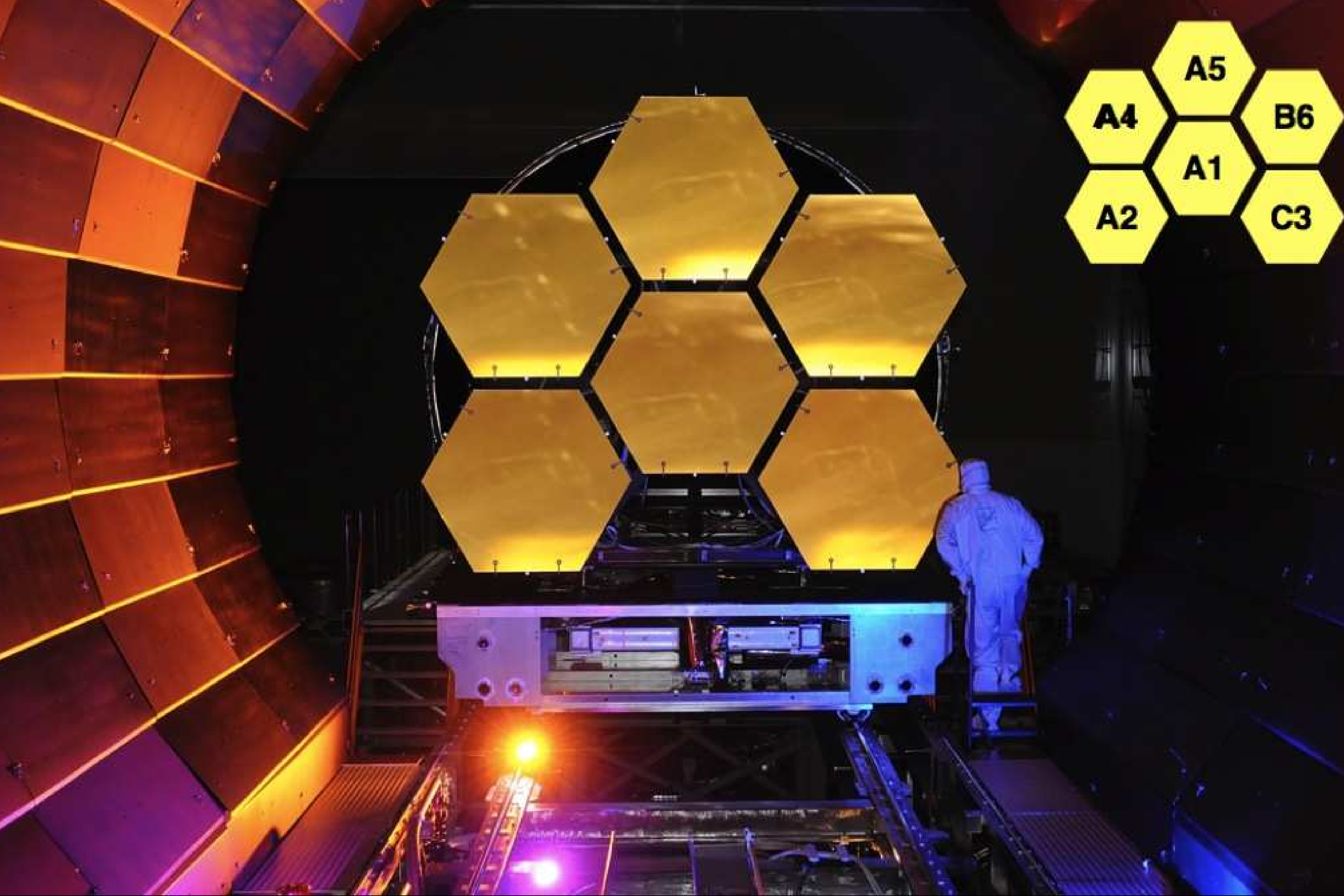
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

JWST Hardware Status



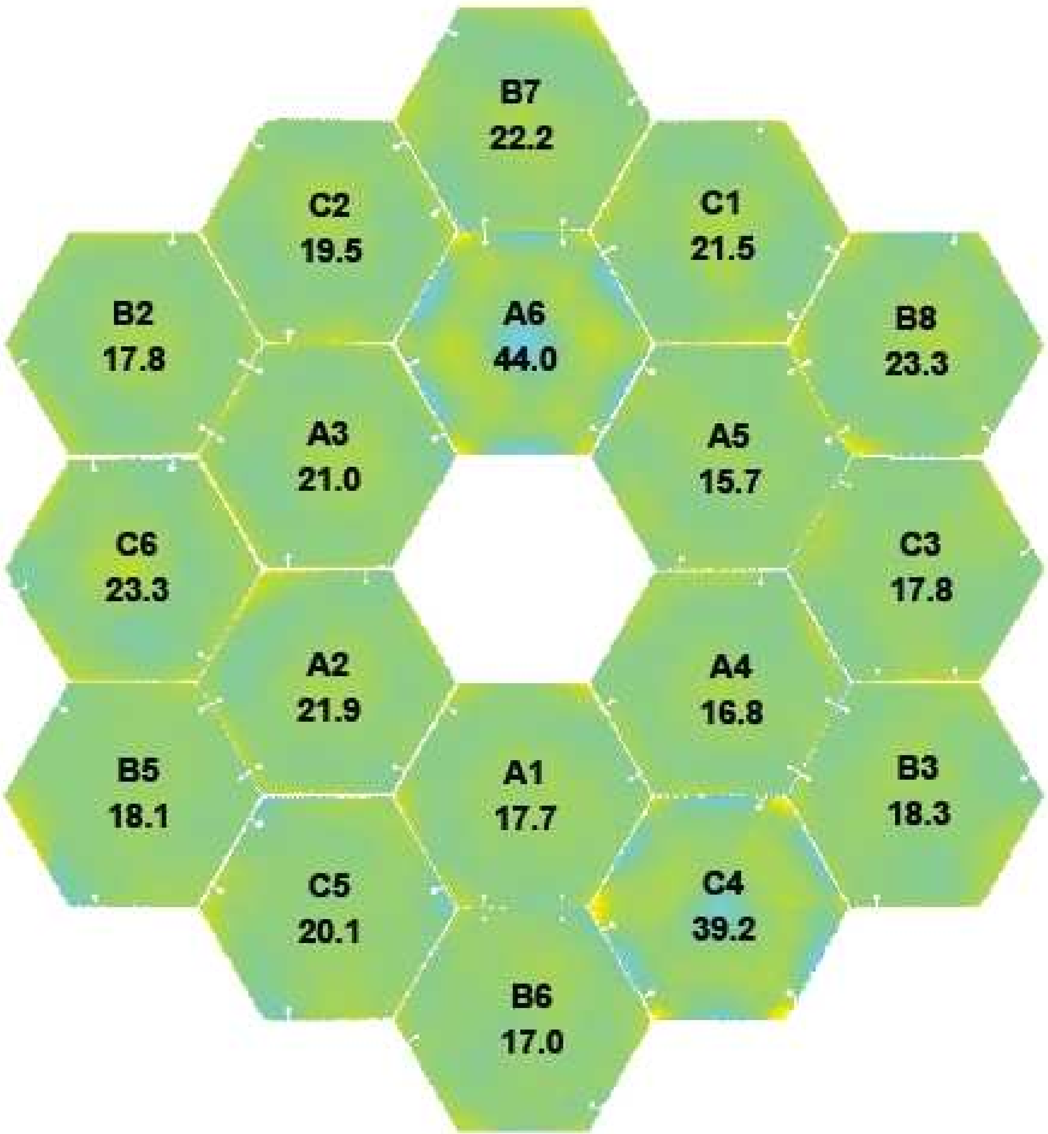
July 2017: $\gtrsim$99.9% of launch mass designed and built ($\gtrsim$90% weighed).

Mirror Acceptance Testing



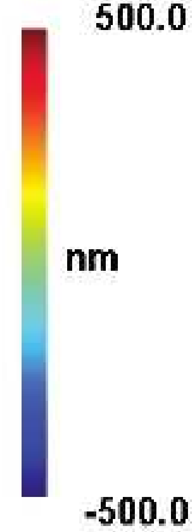

Ball

Primary Mirror Composite



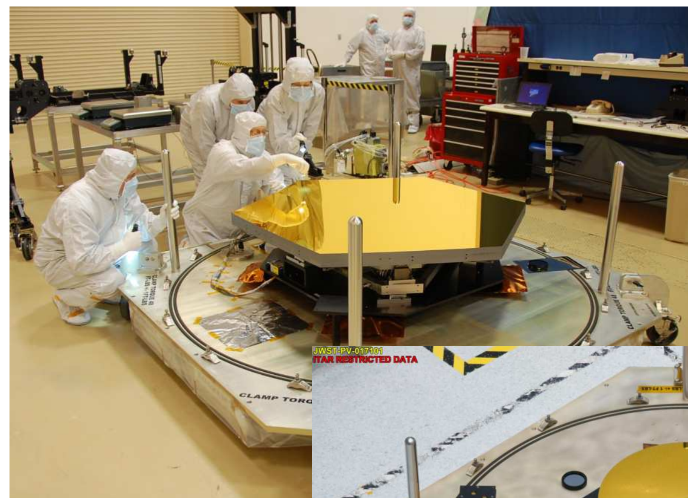
RMS: 23.2 nm

PV: 515.5 nm



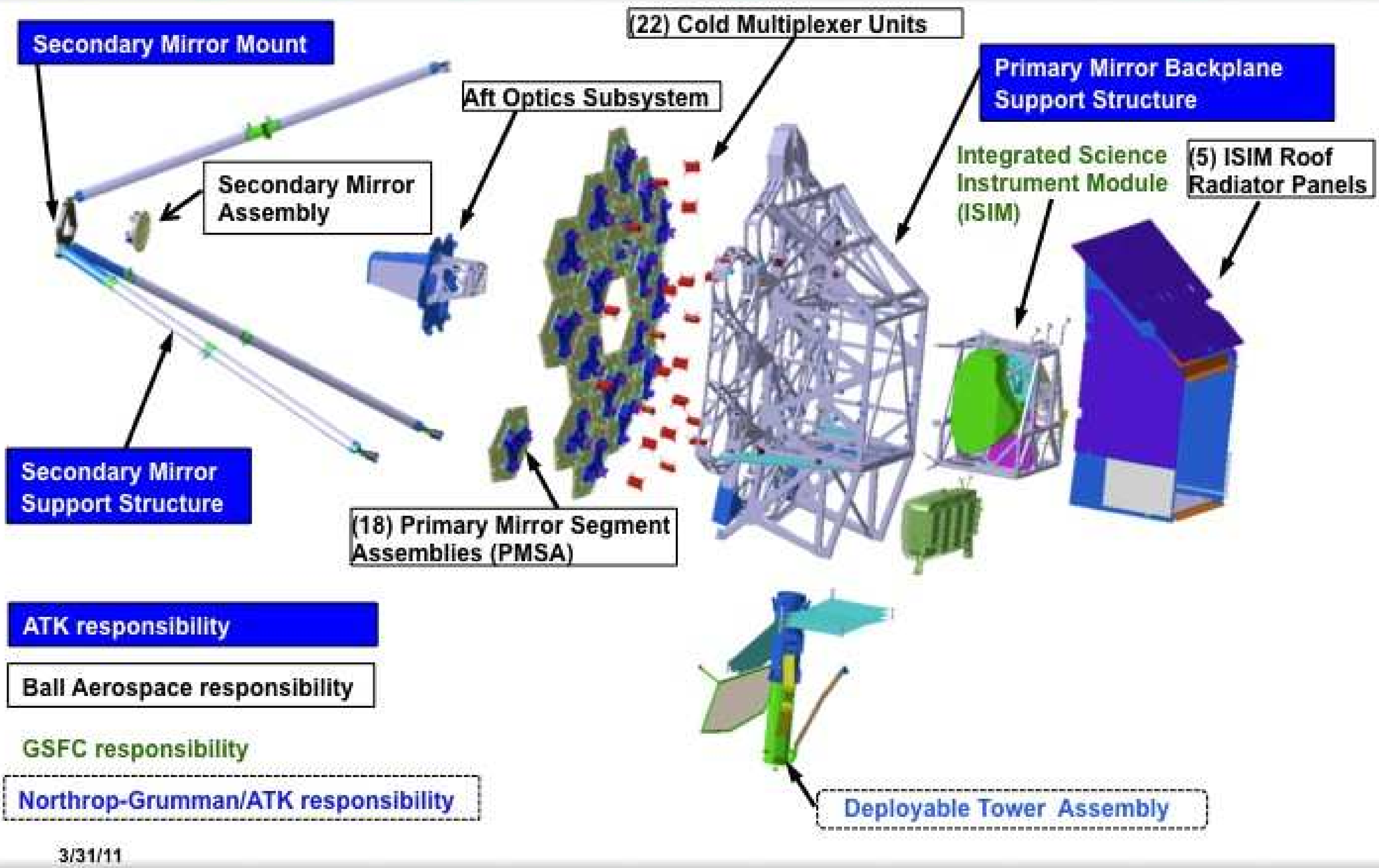
Mirror Status

- **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

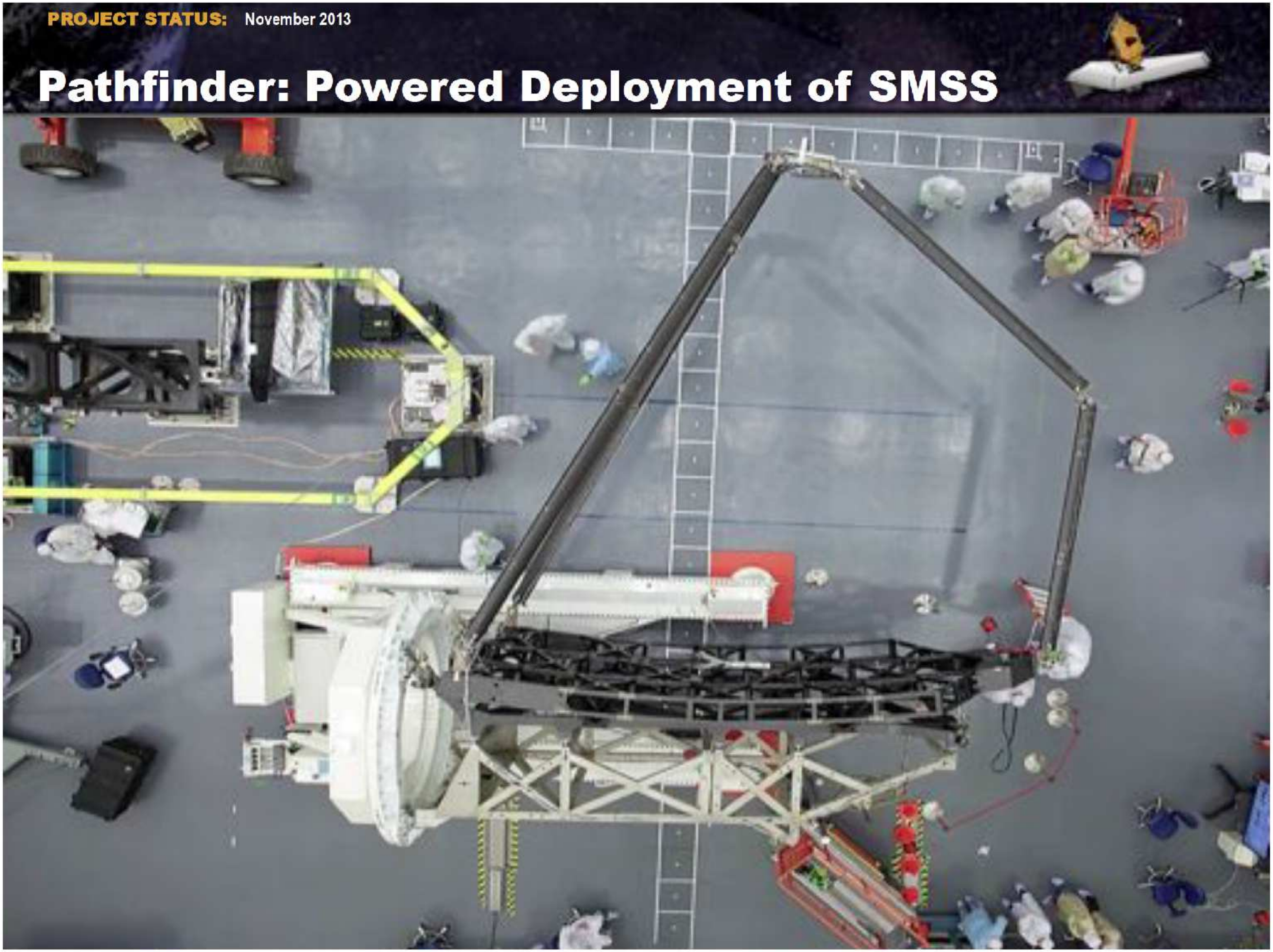


Spring 2014: All 18 flight mirrors delivered to NASA GSFC (MD).

TELESCOPE ARCHITECTURE



2014–2017: Complete system integration at GSFC and Northrop.



July 2014: Secondary Mirror Support deployment successfully tested.

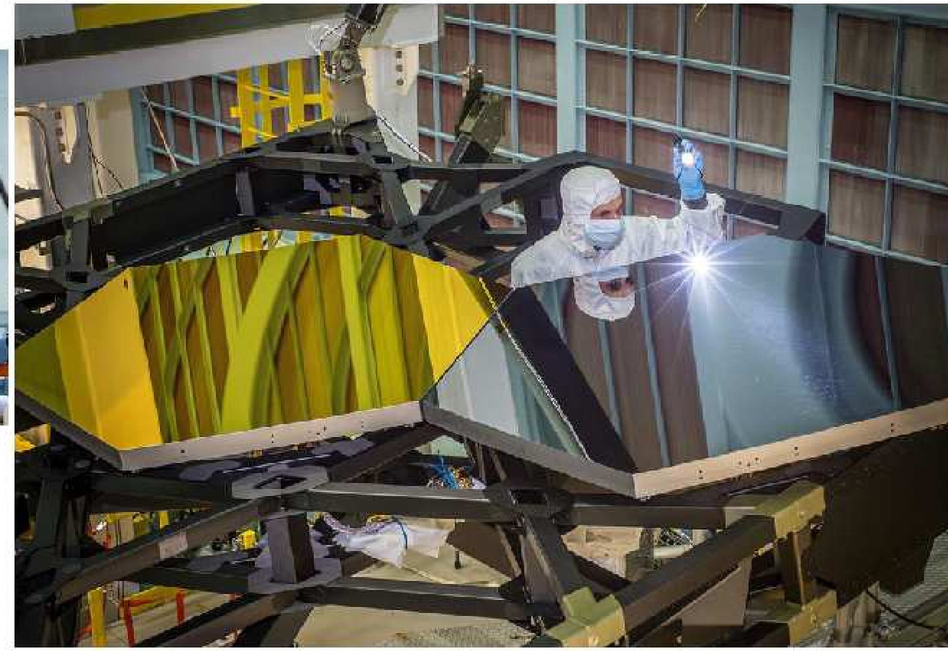
(1c) JWST hardware to date, and how to best use it for high redshift lensing.

[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.

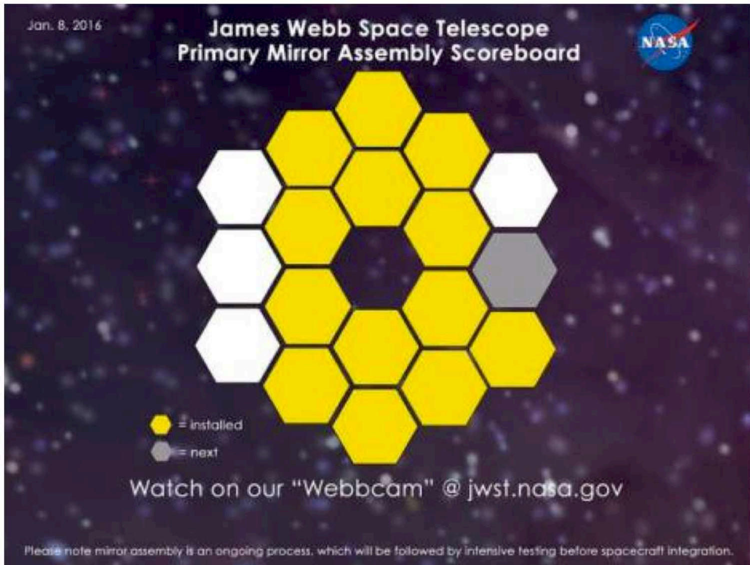
- Our Galaxy is a bright IR source at $\lambda \gtrsim 1$–5μm: In certain directions of the sky, some straylight can hit secondary mirror via Sunshield.
- This can effect JWST (lensing) studies of First Light objects.

Telescope Pathfinder – Risk Reduction

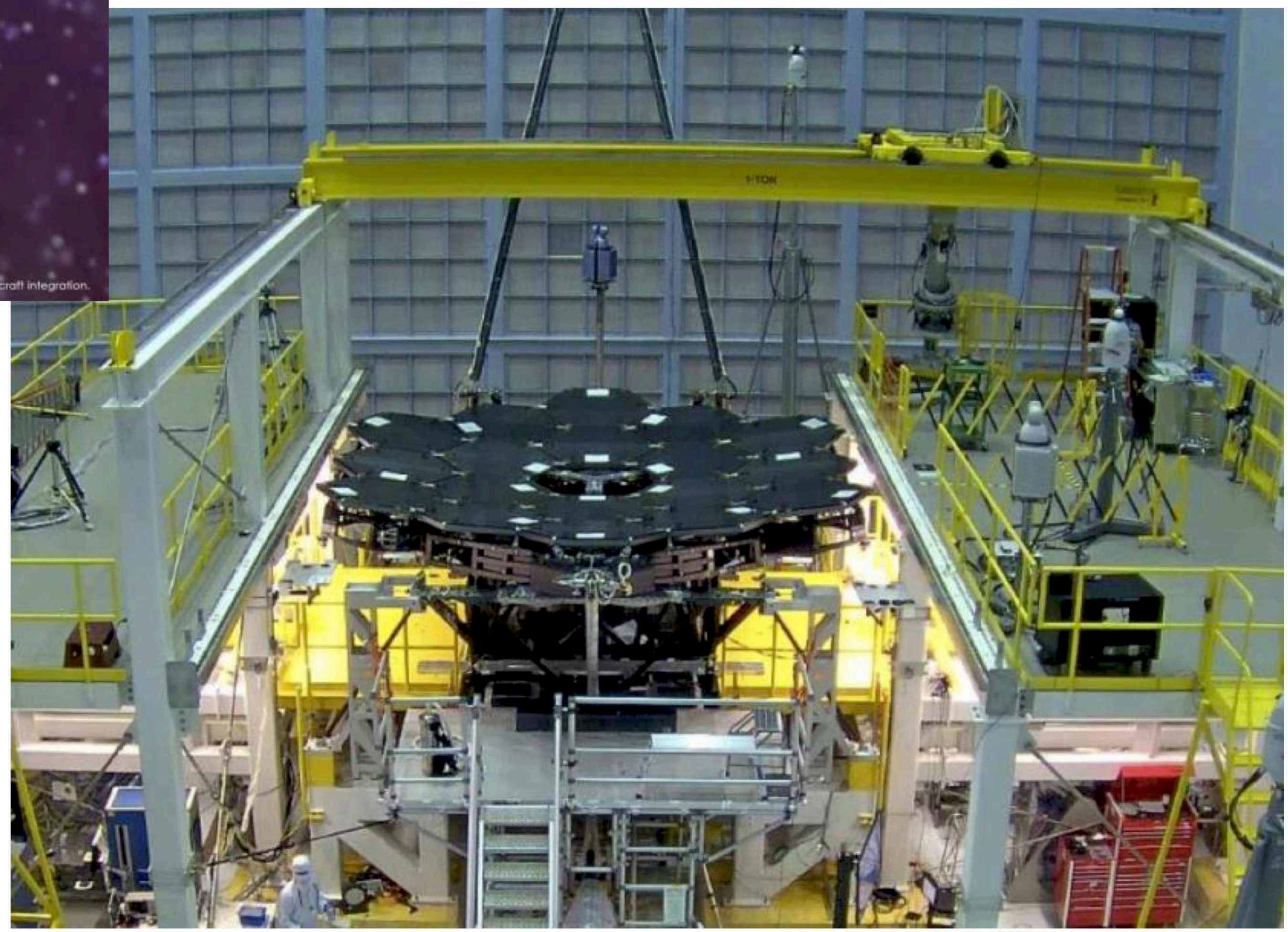


JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

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 →

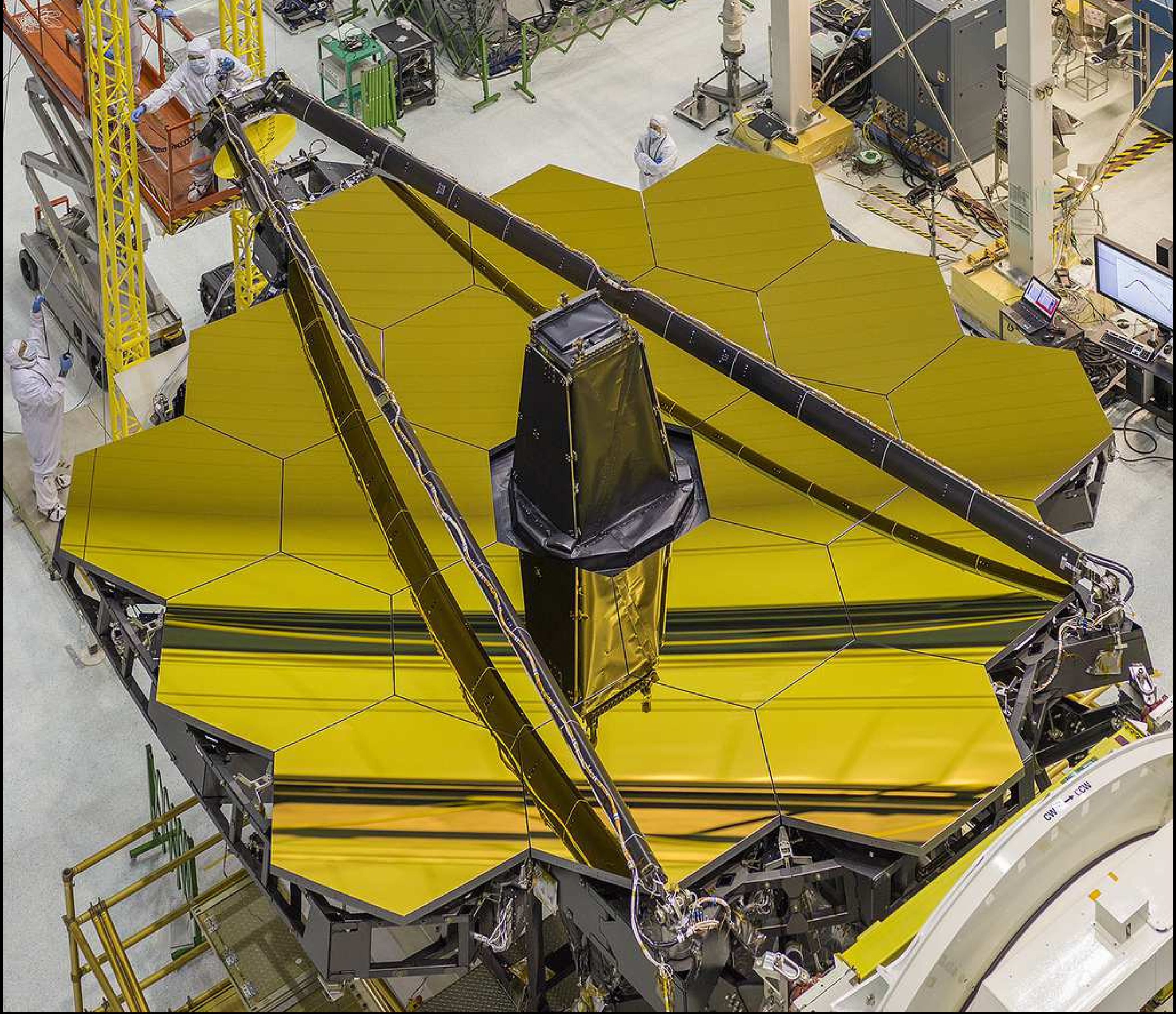
Big milestone!

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

April 2016: NASA team-work to take JWST mirror covers off!

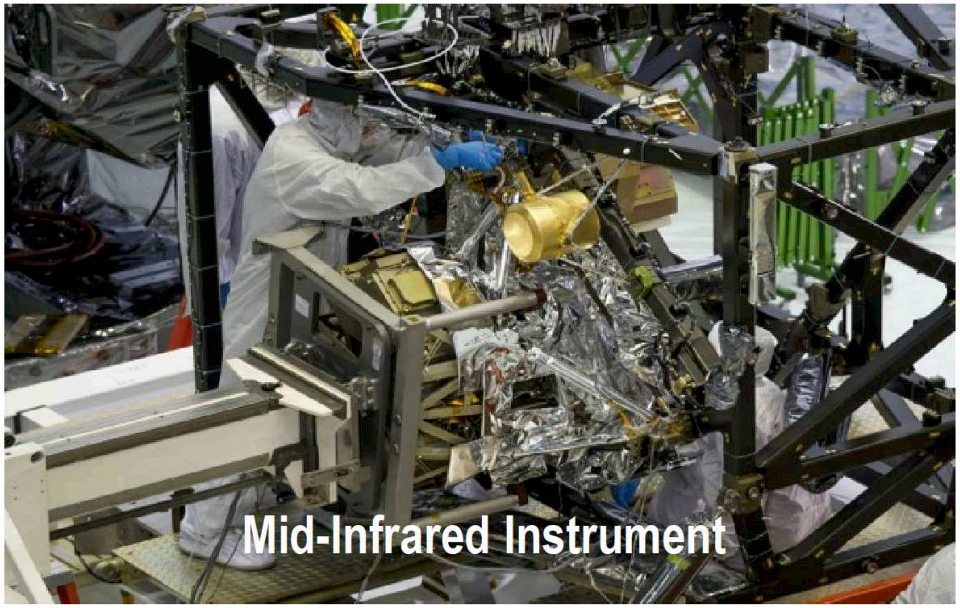
May 2016: JWST being tilted into the right position

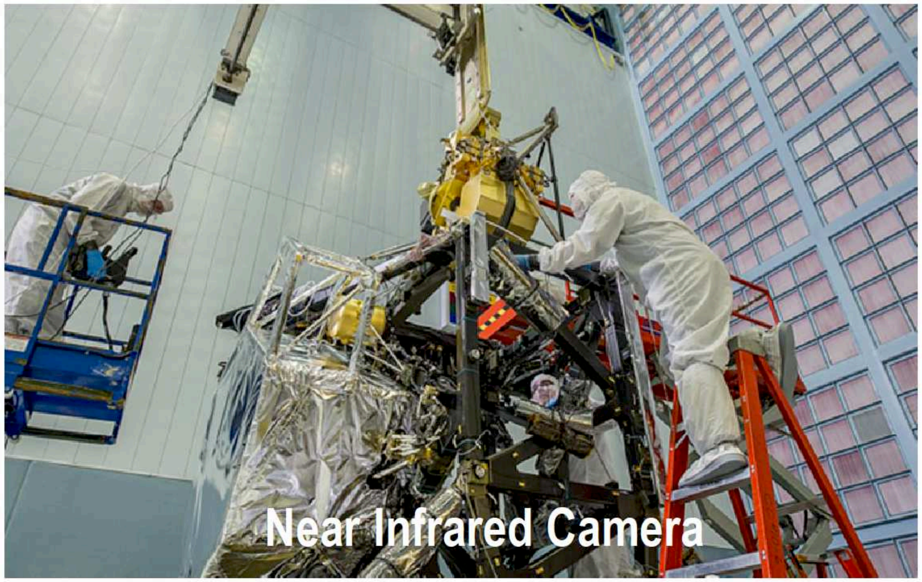
May 2016: Webb mirrors finally mounted and ready!

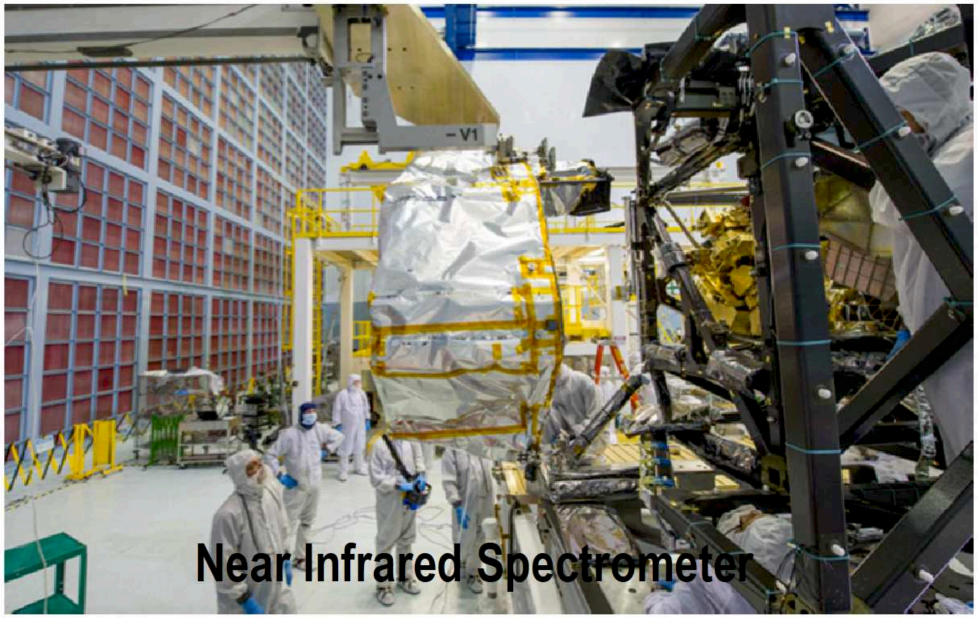


May 2016: JWST stowed for further instrument mounting

All Instruments Integrated





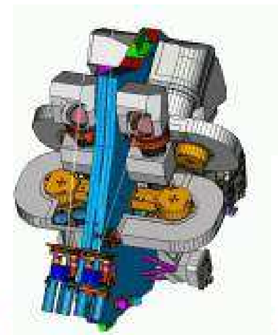


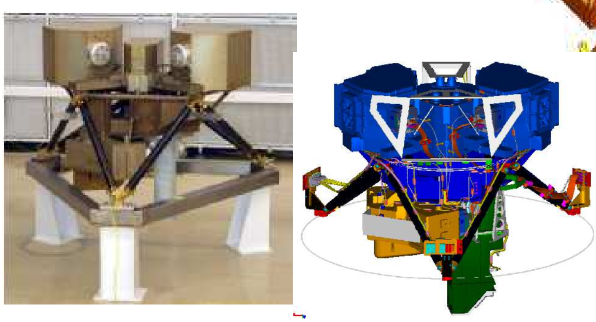
(1d) JWST instruments: USA (UofA, JPL), ESA, & CSA.

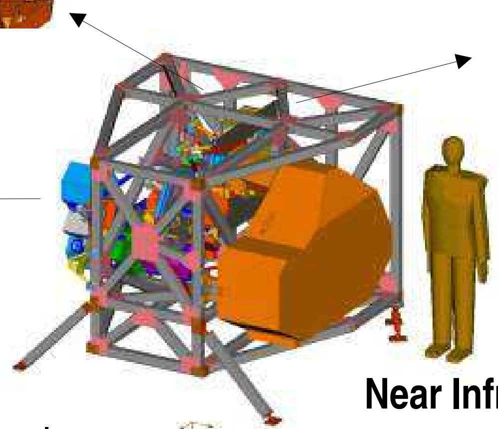
Instrument Overview

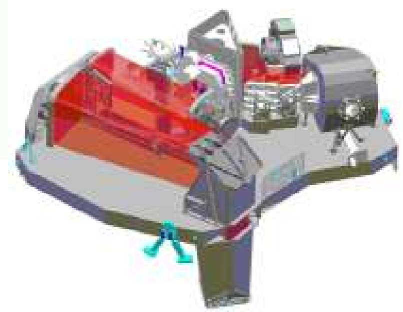
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

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



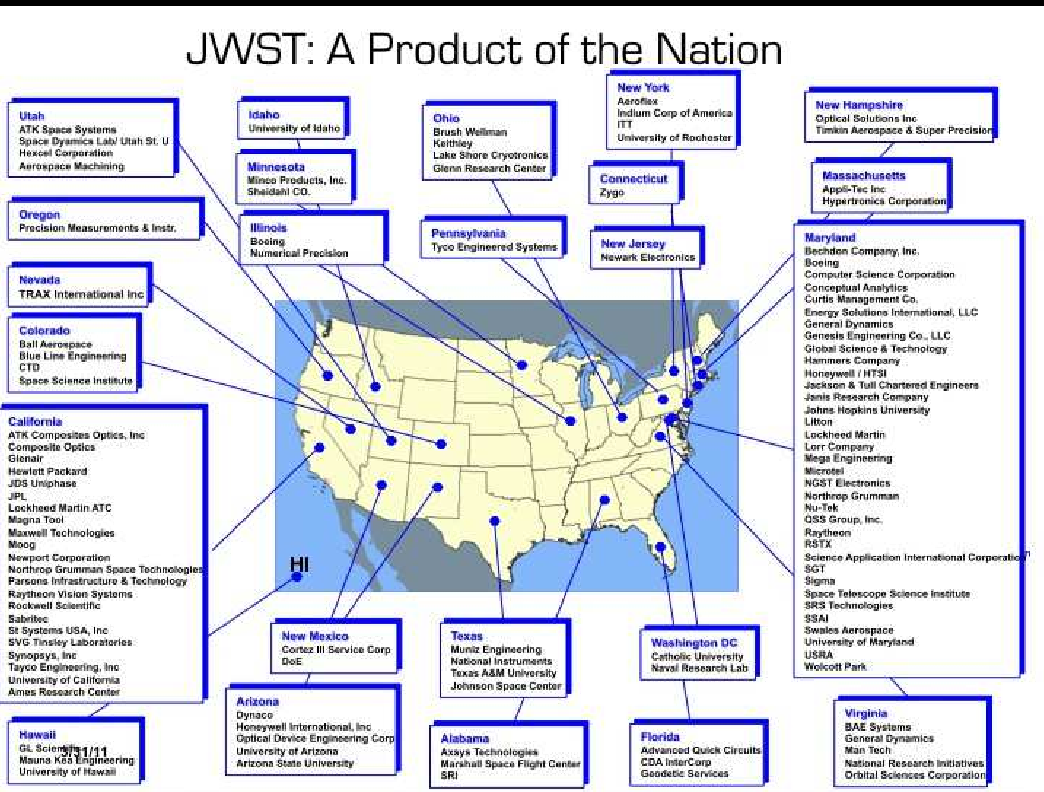


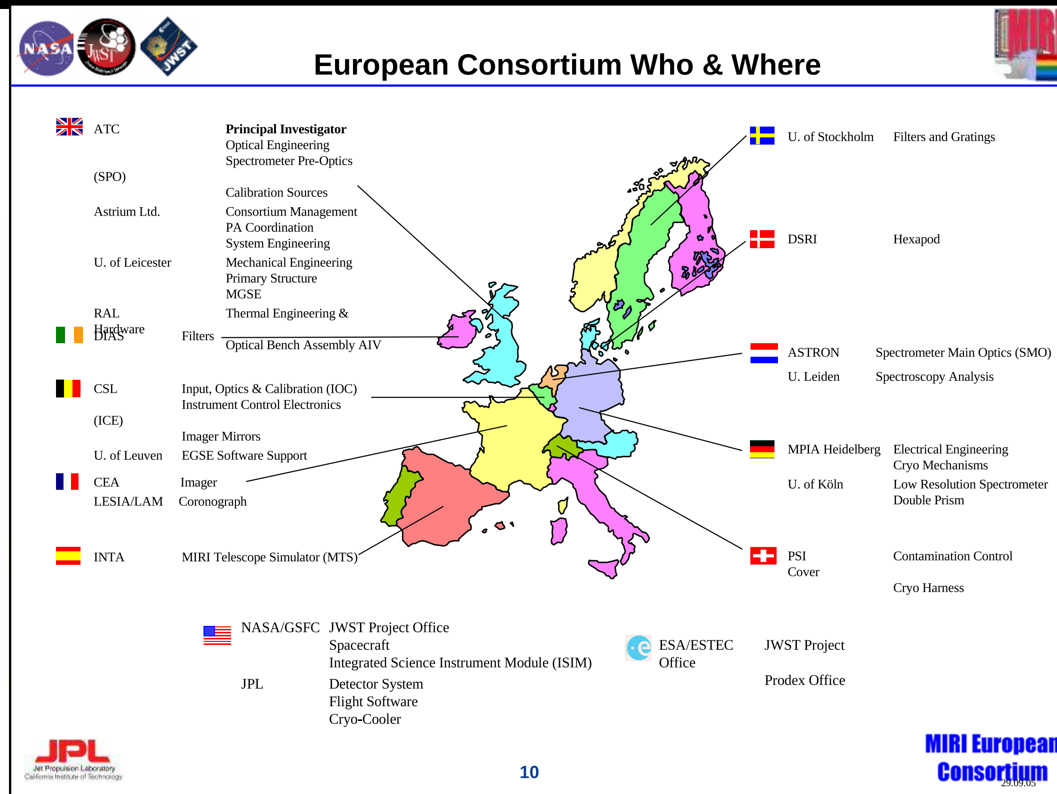




Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

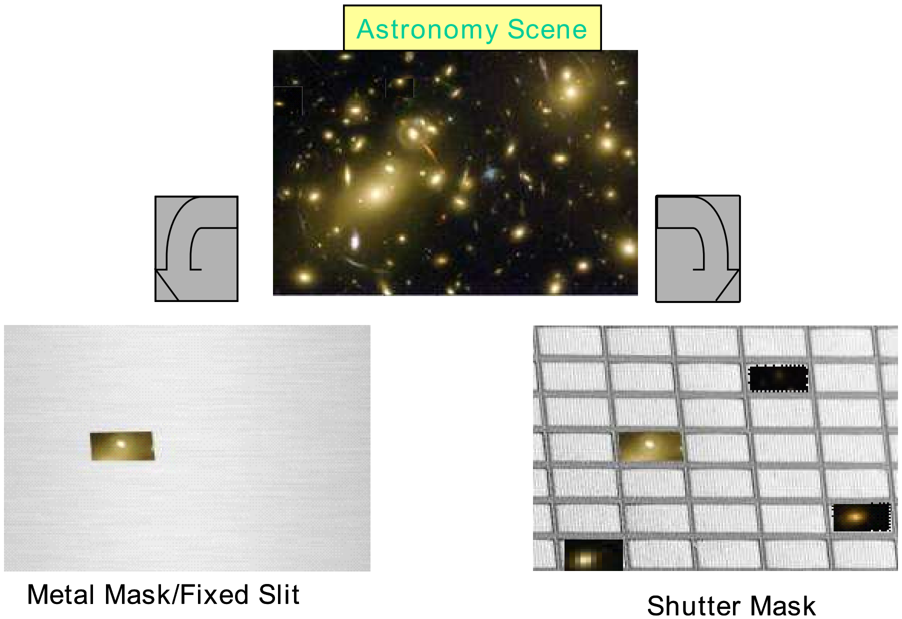


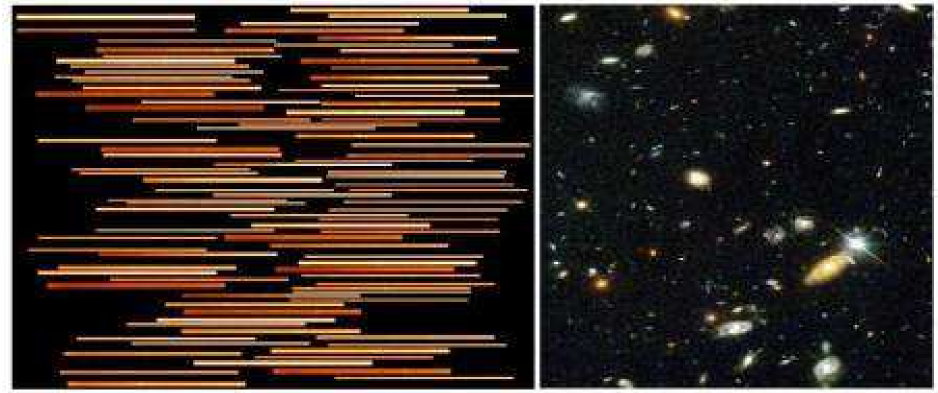


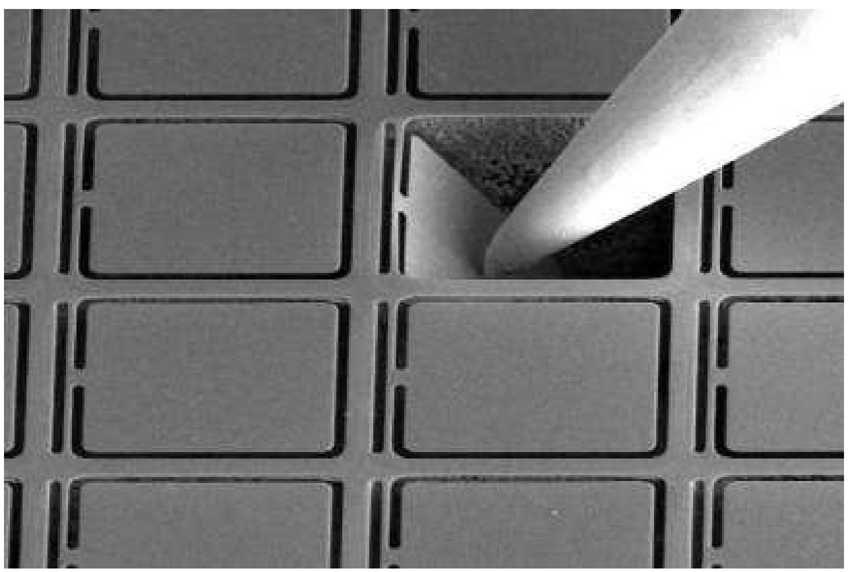
- JWST hardware made in 27 US States: $\gtrsim$99% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

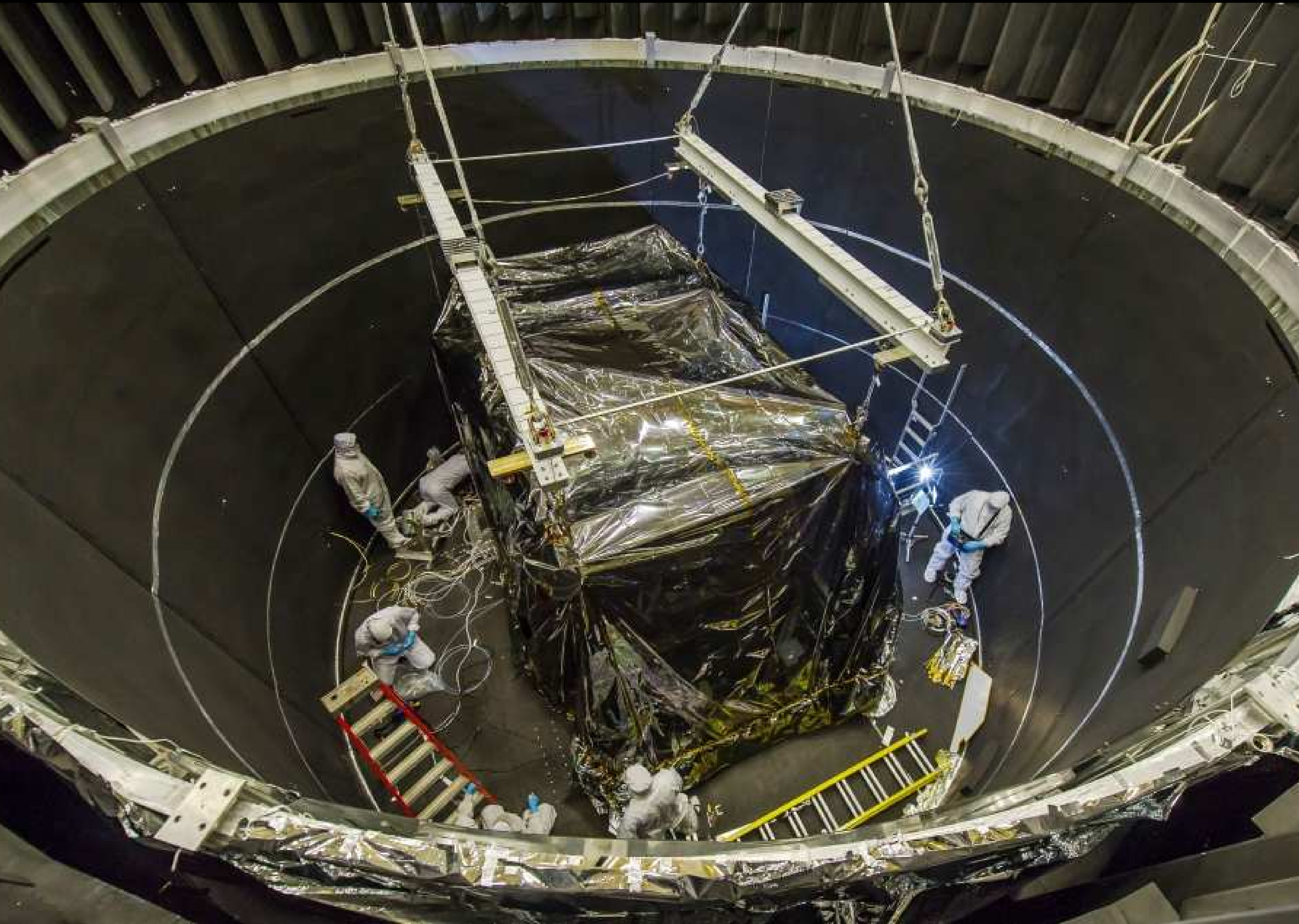
This nationwide + international coalition was critical for project survival!

Micro Shutters





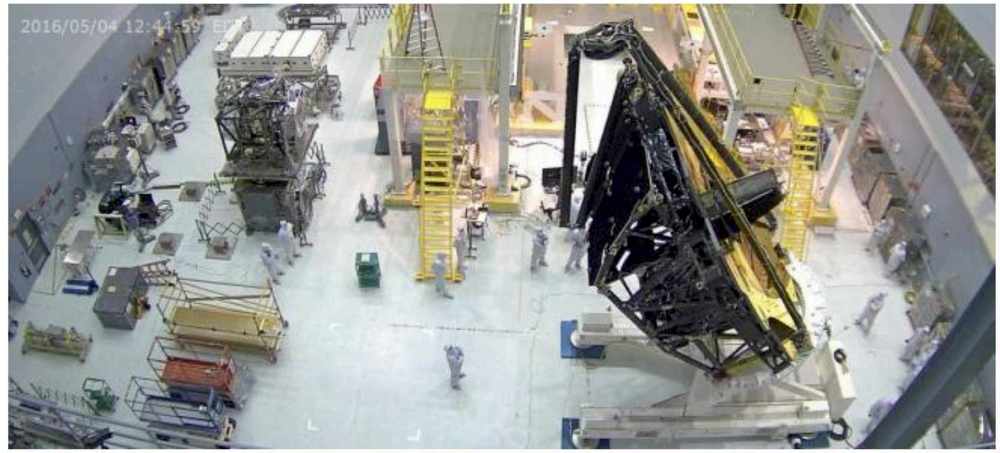


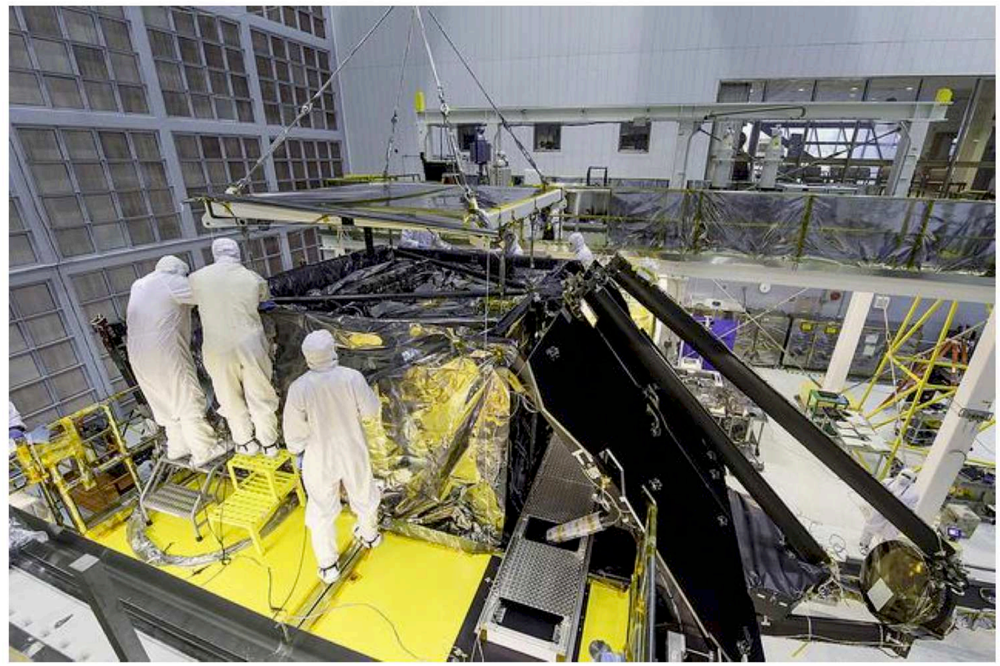


2014: Flight ISIM (all 4 instruments) in test. Oct. 15–Feb. 2016: CryoVac3.

Program Update: OTE + ISIM = OTIS

NORTHROP GRUMMAN

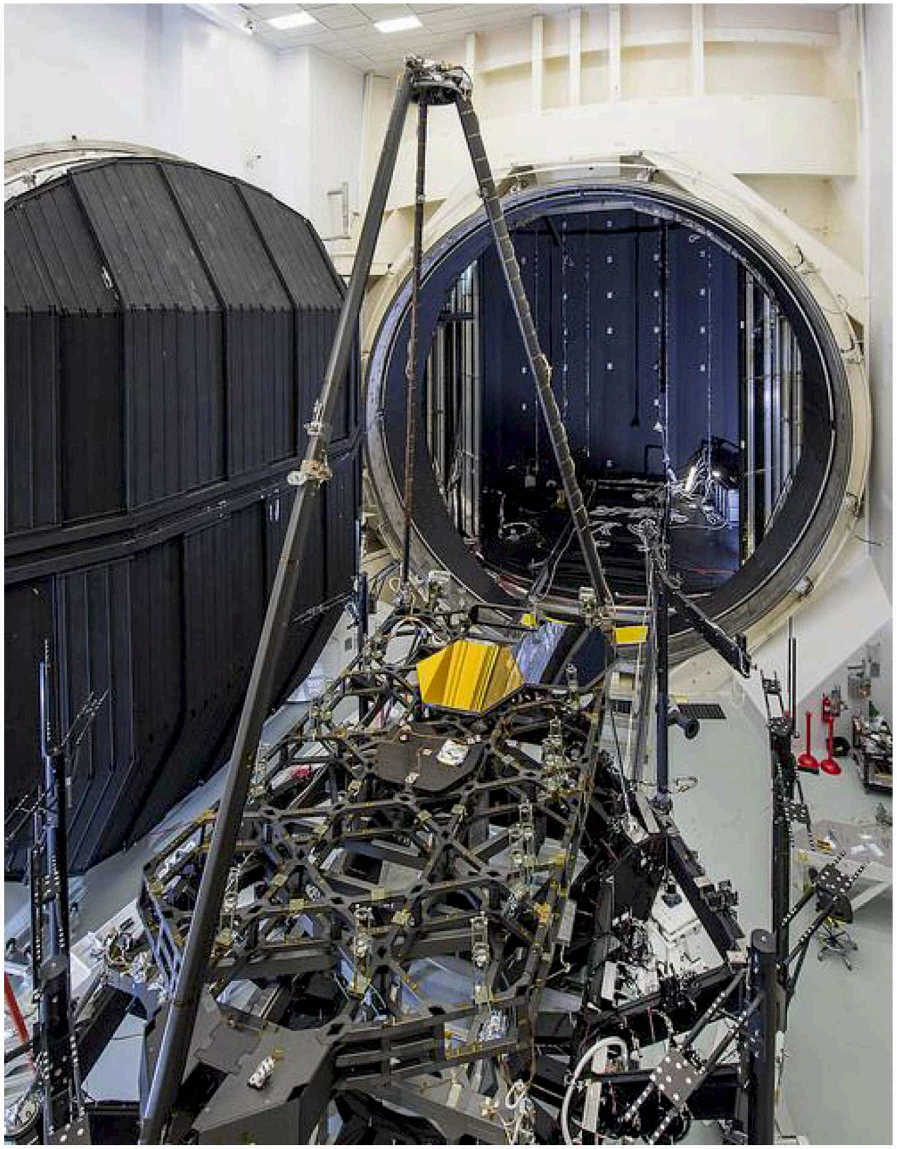


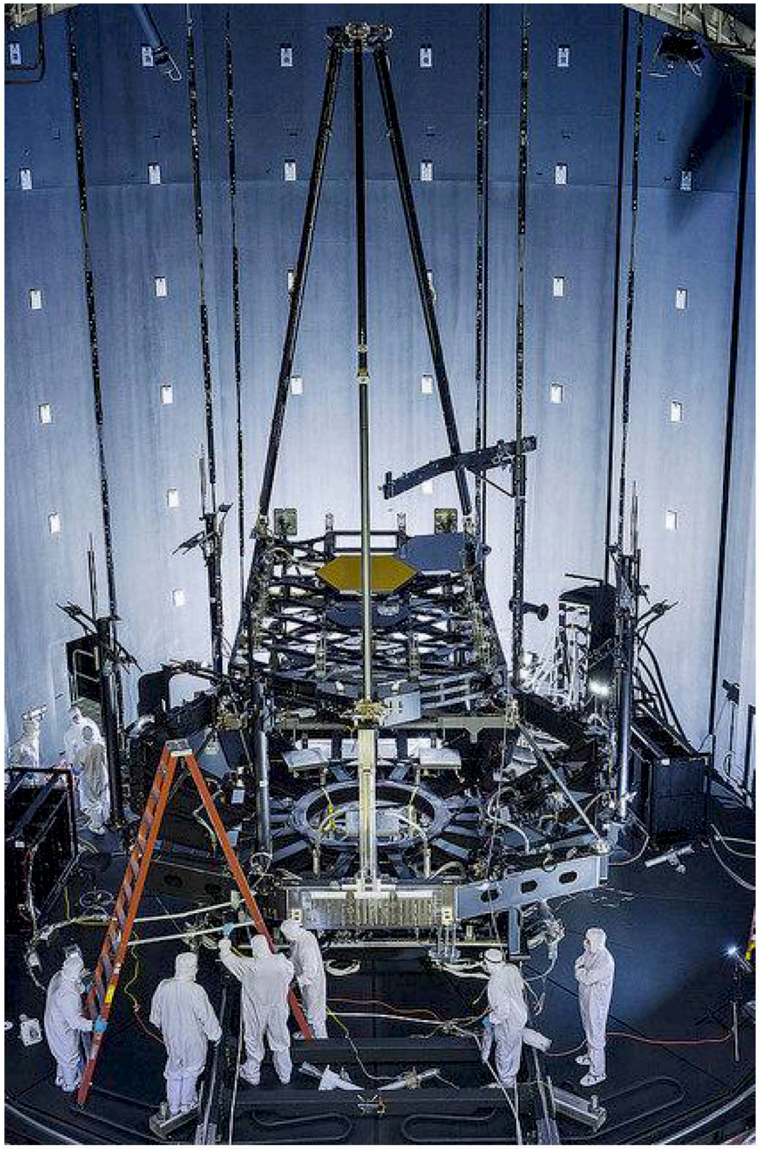


June 2016: Flight ISIM mated with Optical Telescope Element (OTE).
JWST is now a real working telescope (albeit not yet at 40 K & in 0 G)!

April 2017: Last portrait of JWST at Goddard Space Flight Center (MD).

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



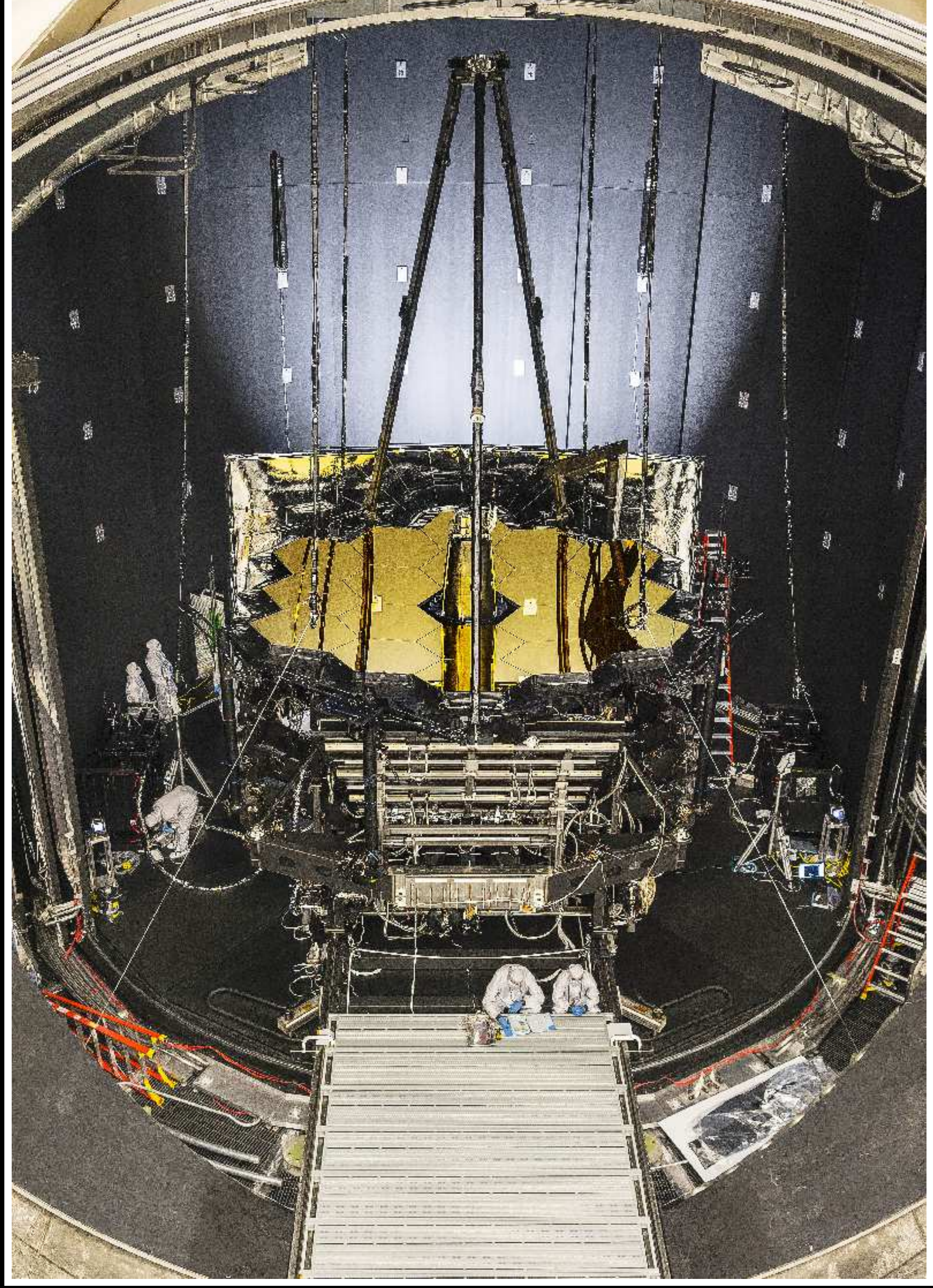


2015–2016: Testing OTIS chamber with the JWST Engineering model.

May 2017: JWST in enclosure at Johnson Space Center in Houston.

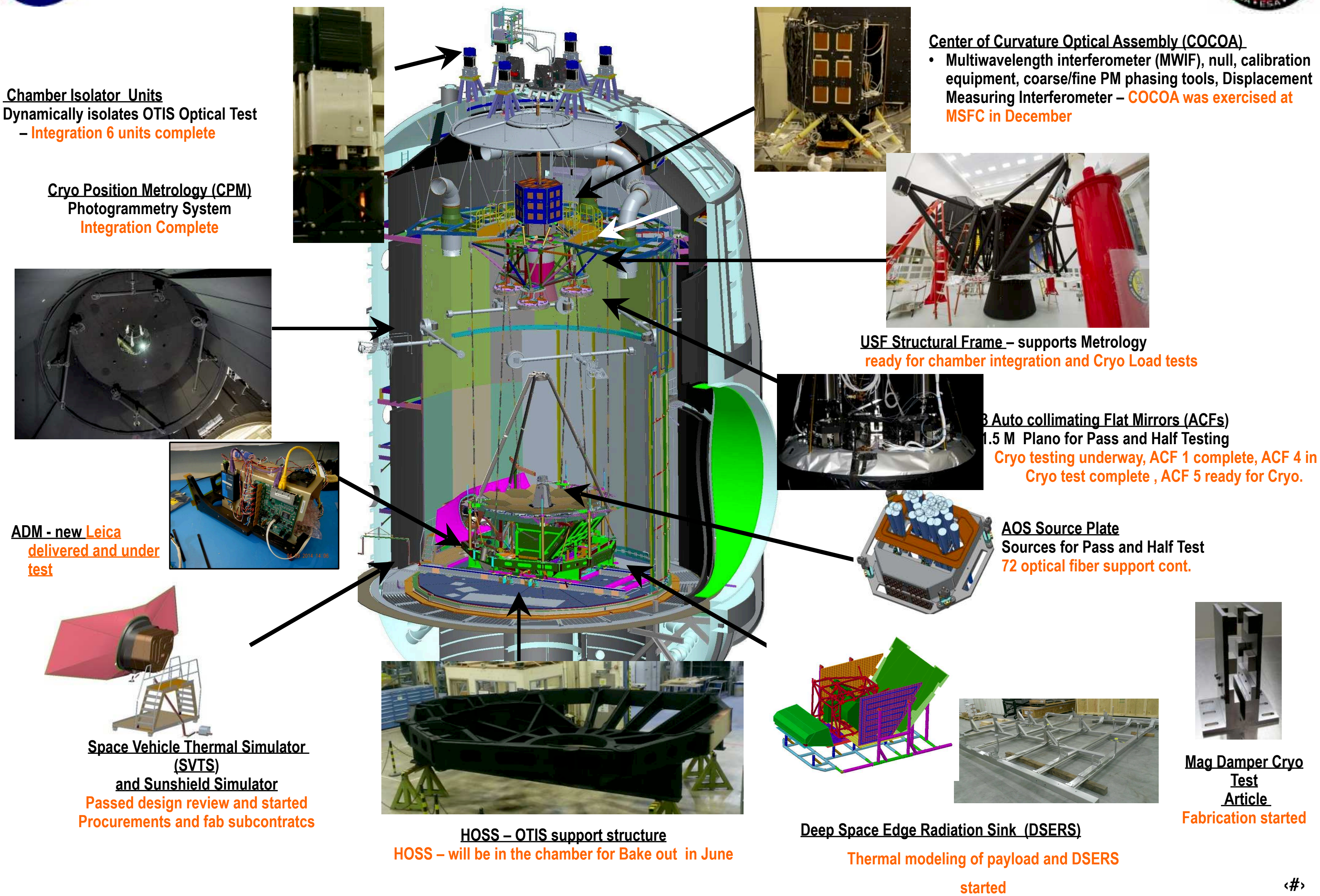
Program Update: OTIS

June 2017: JWST going into Chamber A at Johnson Space Center in Houston.



July 2017: JWST now in Chamber A at Johnson Space Center in Houston.

OTIS Test GSE Architecture and Subsystems



World's largest TV chamber OTIS: will test JWST July–Oct. 2017.

Program Updates: Spacecraft and Sunshield

NORTHROP GRUMMAN

FWD/AFT UPSs Installed

Mid Booms Deployed

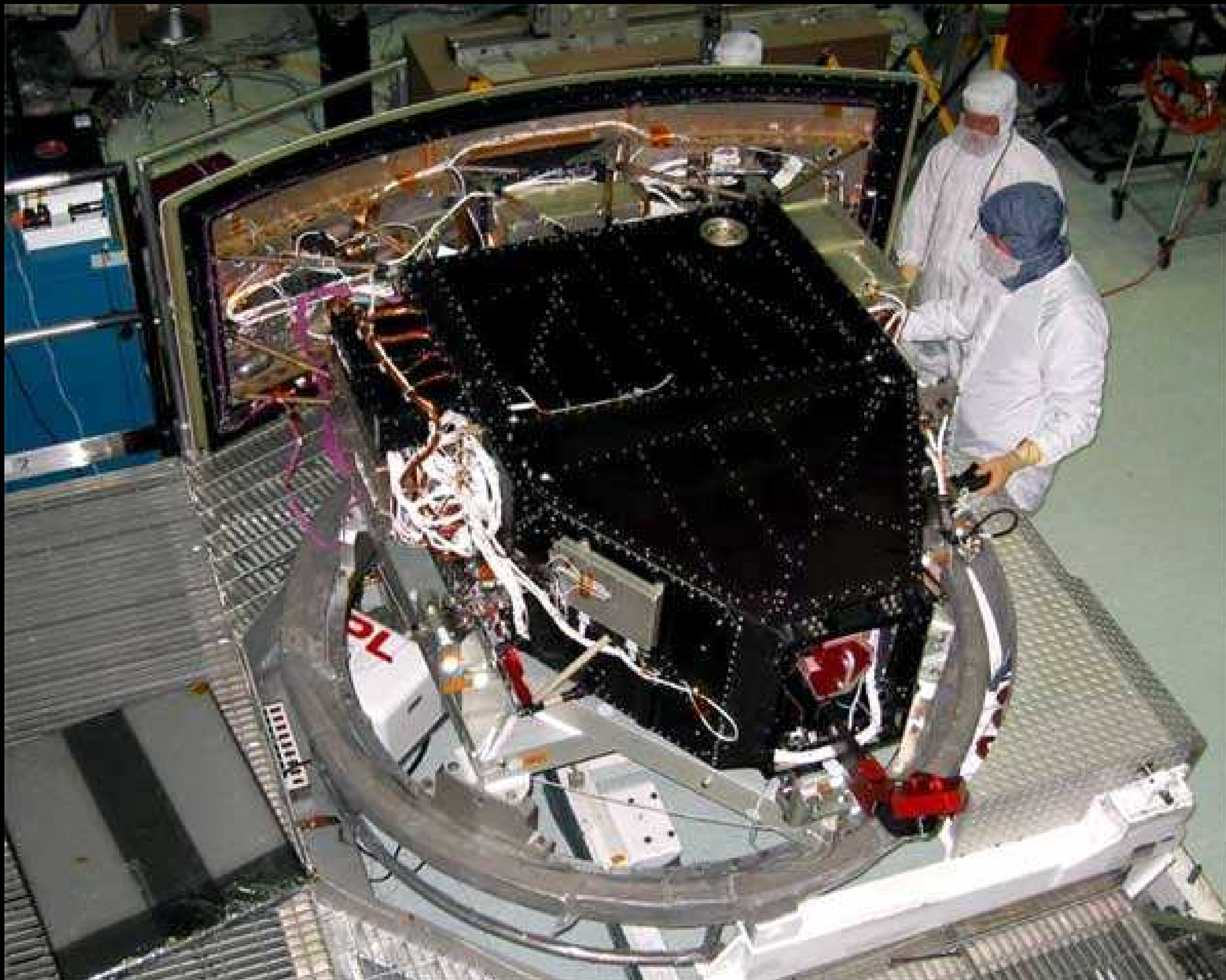
June 2017: JWST Flight Sunshield assembled and tested at Northrop (CA).

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

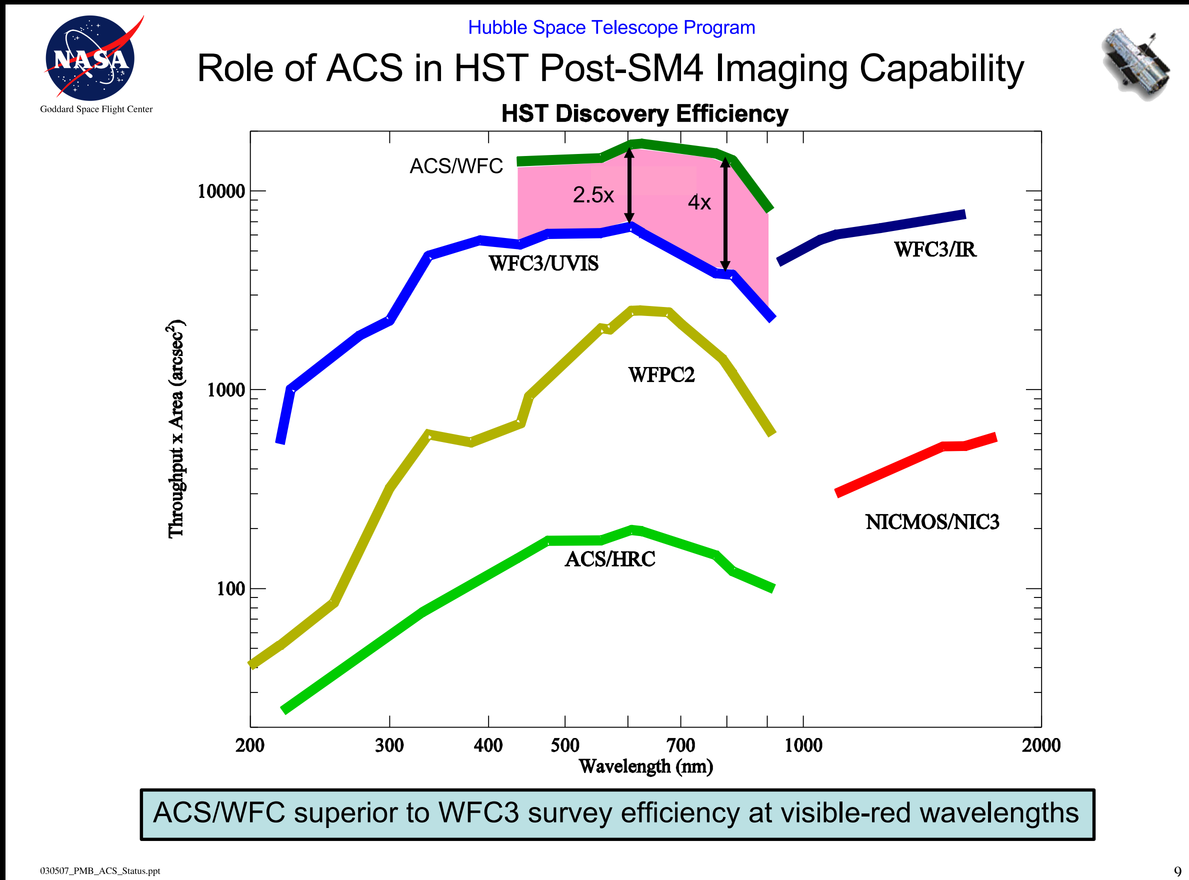
ß10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

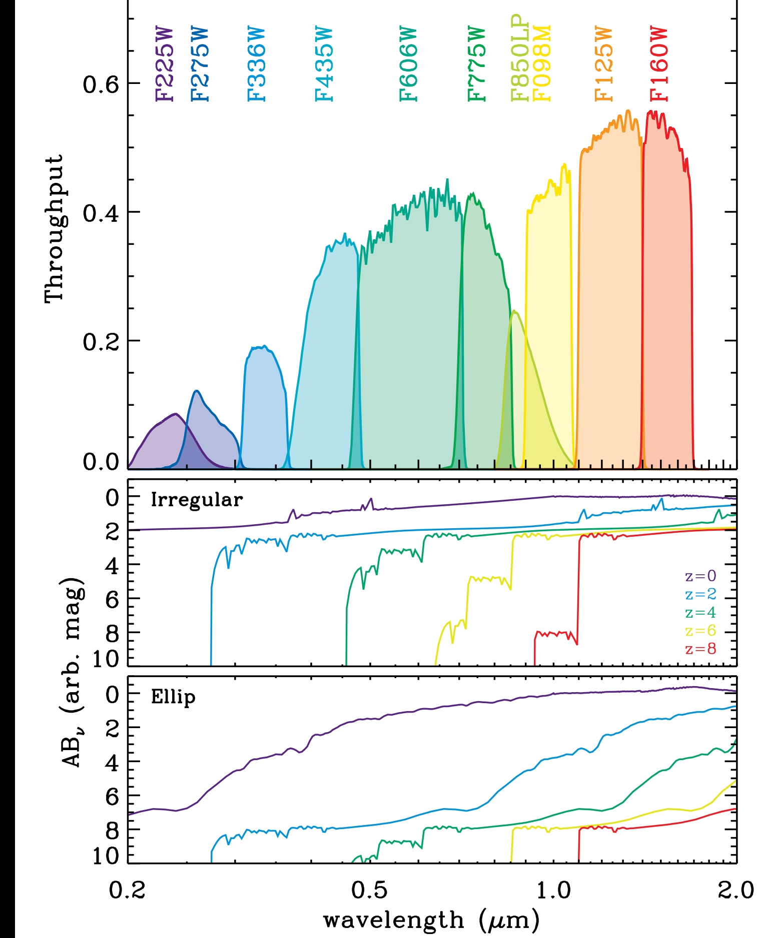
JWST adds 0.05–0.2" FWHM imaging to AB≃31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

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



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





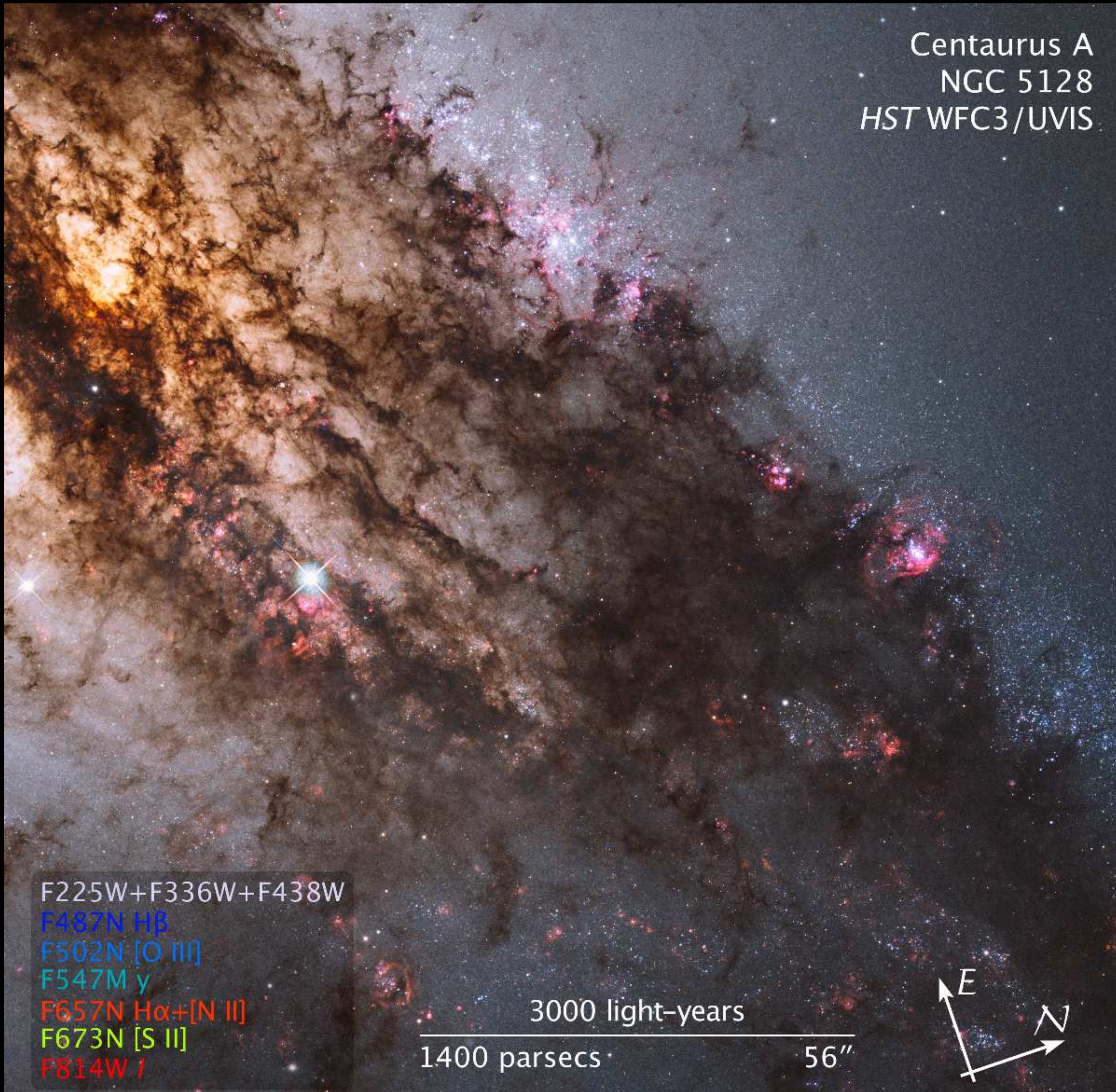
WFC3/UV & IR channels unprecedented throughput & areal coverage:

- 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.

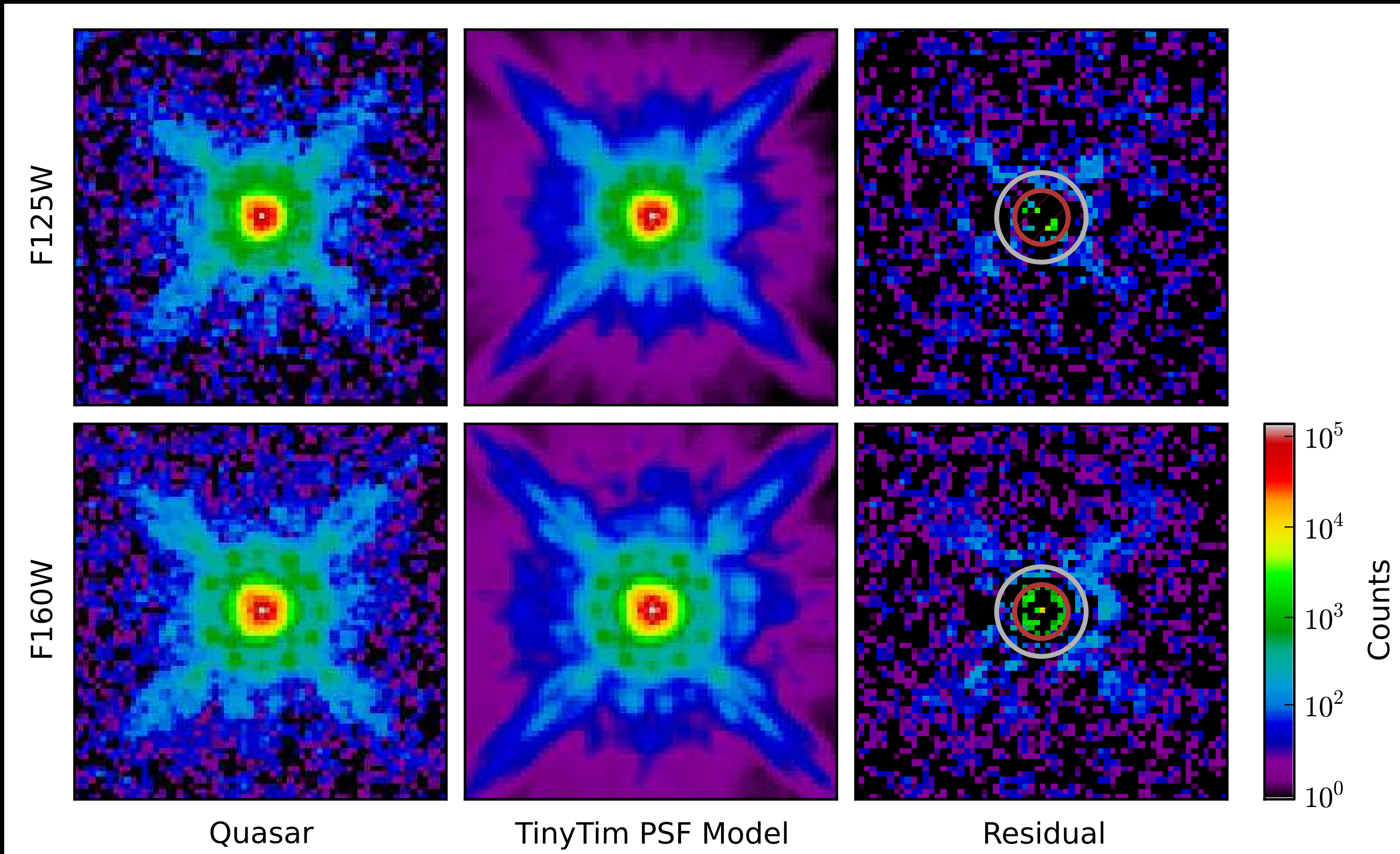
$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:

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.

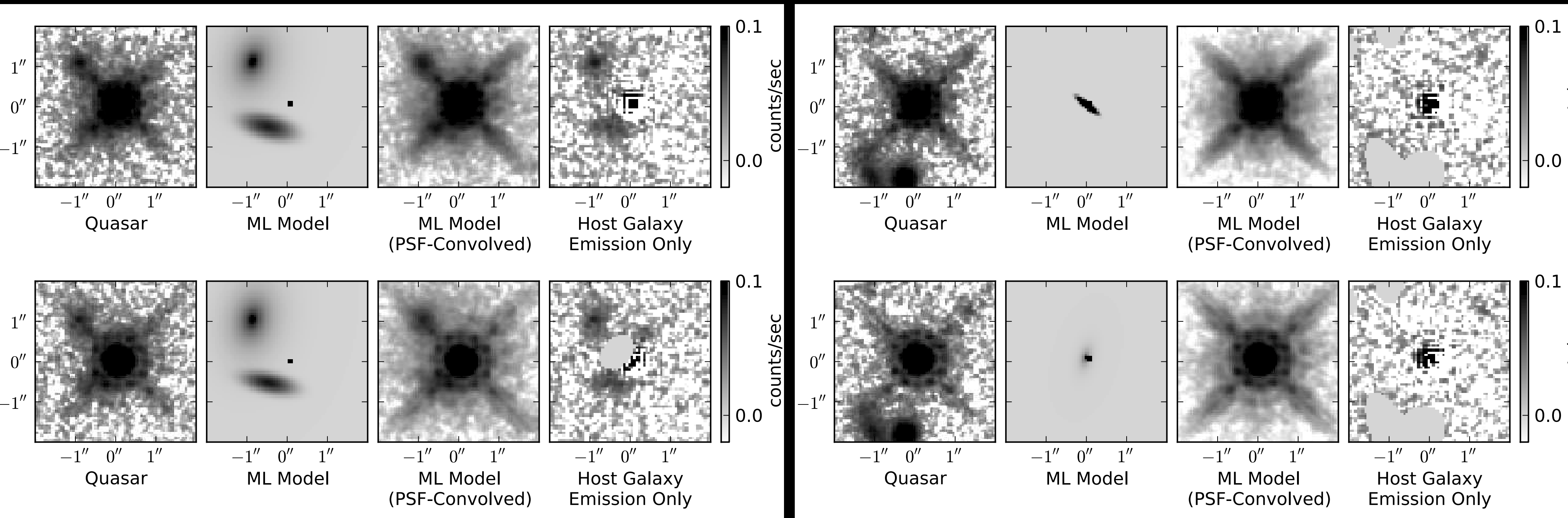

Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N

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



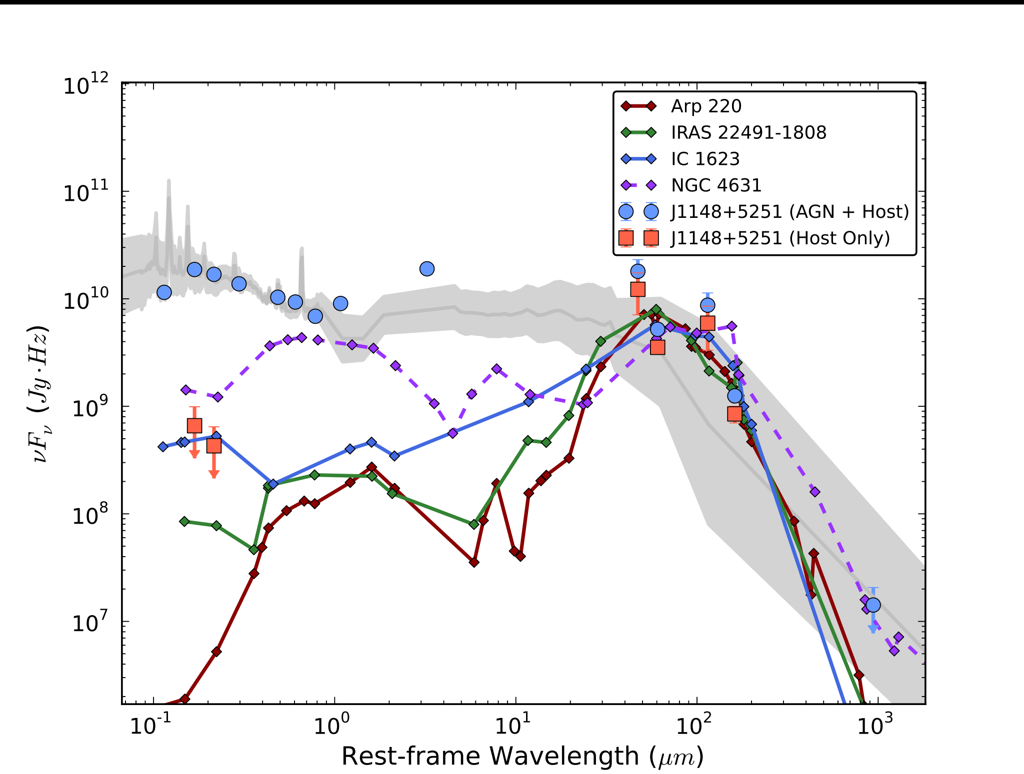
- Careful contemporaneous orbital PSF-star subtraction: Removes most of "OTA spacecraft breathing" effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star (AB$\simeq$15 mag) subtracts z=6.42 QSO (AB$\simeq$18.5) nearly to the noise limit: NO host galaxy detected 100$\times$fainter (AB$\gtrsim$23.5 at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

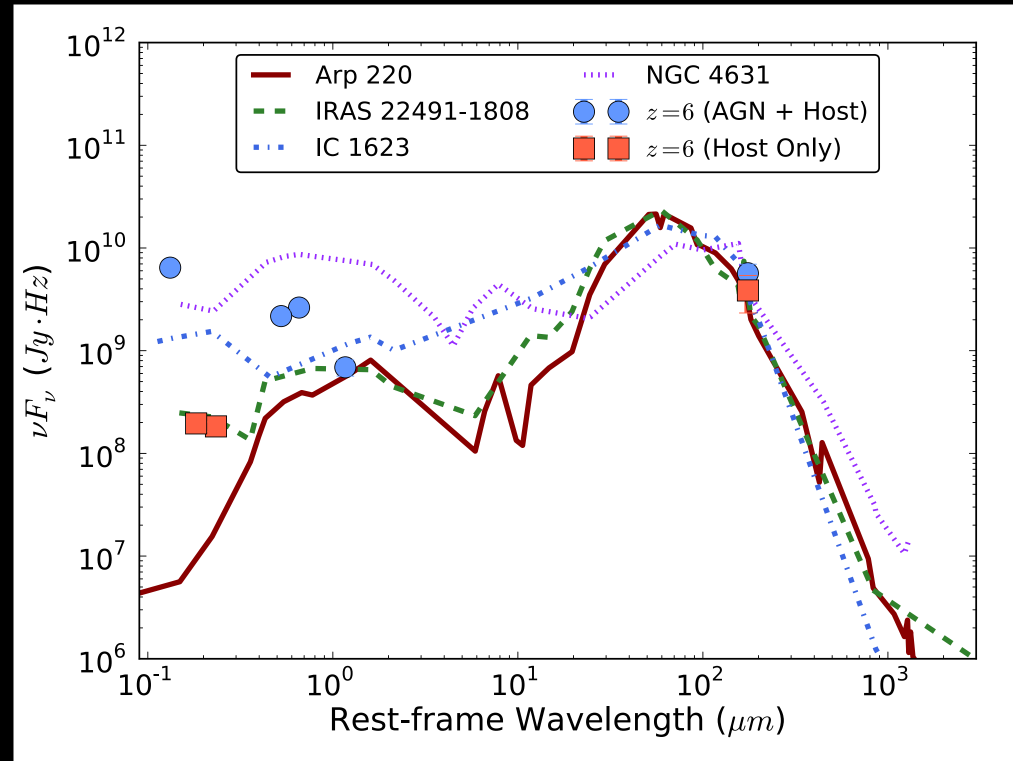
(2b) WFC3: Detection of one QSO Host System at z≃6 (Giant merger?)



- Markov Chain Monte Carlo posterior model of observed PSF-star + Sersic light-profile. Gemini AO images to pre-select PSF stars (Mechtley+ 2014).
- 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. (J–H)≃0.19 color constrains dust.
- IRAS starburst-like SED from rest-frame UV–far-IR: A_{FUV}∼1 mag.
- M_{AB}^{host}(z≃6)$\lesssim$–23.0 mag, i.e., ∼2 mag brighter than L*(z≃6).
- JWST can detect 10–100× fainter dusty hosts (for z$\lesssim$20, $\lambda\lesssim$28μm).

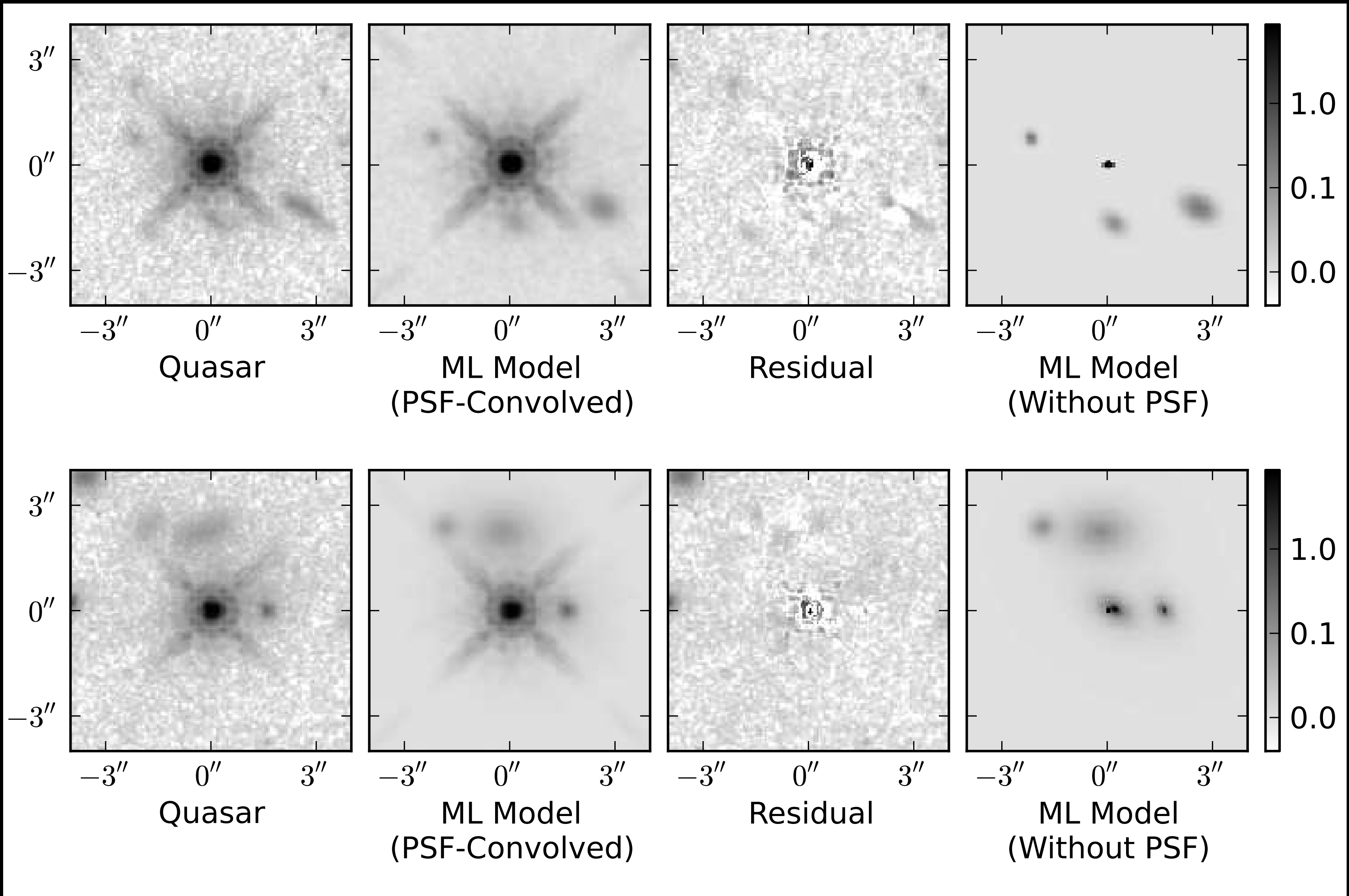
(2b) HST WFC3 observations of dusty QSO host galaxies at z≃6





- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5μ). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100μm: [LEFT] Rules out z=6.42 spiral or bluer host galaxy SEDs for 1148+5251. (U)LIRGs & Arp 220s permitted (Mechtley et al. 2012, ApJL, 756, L38). [RIGHT] Detected QSO host has IRAS starburst-like SED from rest-frame UV–far-IR, A_{FUV}(host)∼1 mag (Mechtley 2013 PhD; et al. 2016).
- JWST (+Coronagraphs) can do this ≳10× fainter: in restframe V for z≳6.

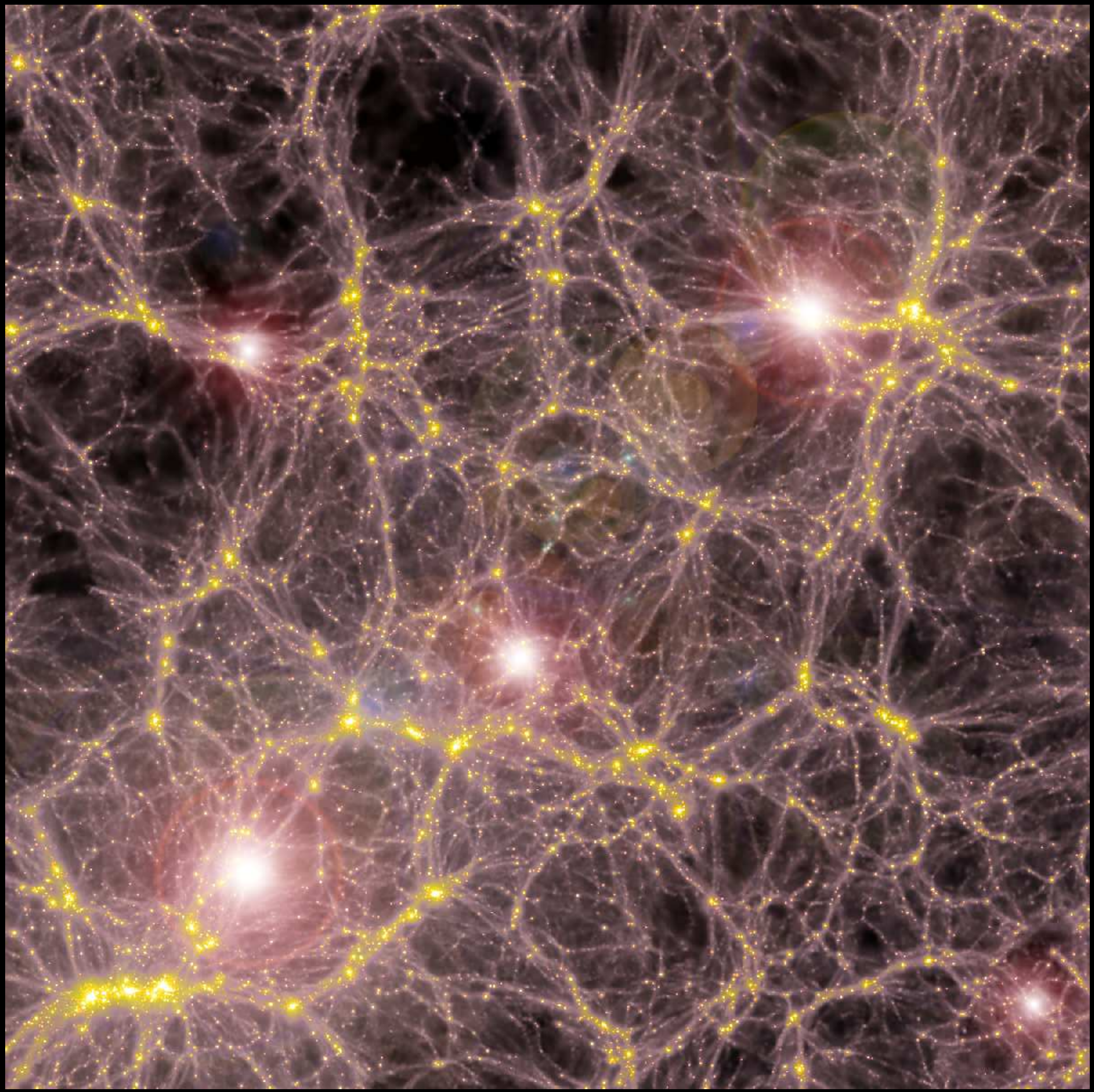
(2b) WFC3 observations of QSO host galaxies at z≃2 (evidence for mergers?)



- Markov Chain Monte Carlo posterior model of observed PSF-star + Sersic light-profile: merging neighbors (some with tidal tails?; Mechtley, M., Jahnke, K., Windhorst, R. A., et al. 2016, ApJ, 830, 156.

- JWST (+Coronagraphs) can do this $\gtrsim$10× fainter: in restframe V for z$\gtrsim$6.

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

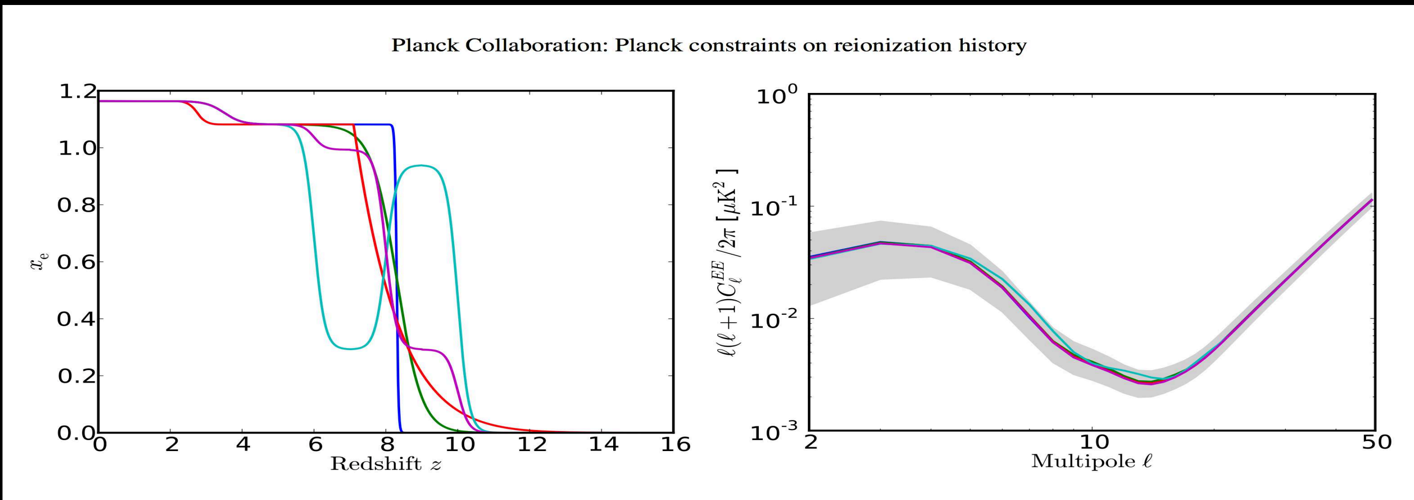


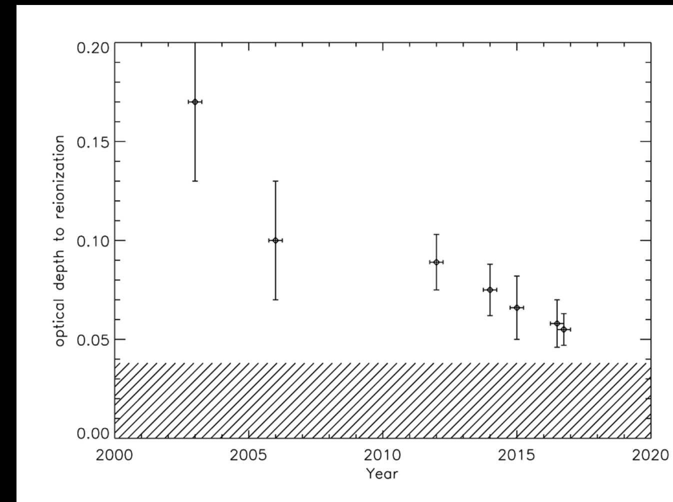
- Detailed cosmological models (V. Bromm) suggest that massive "Pop III" stars ($\gtrsim$100 M_{sun}) started to reionize the universe at z$\lesssim$10–30 (0.1–0.5 Gyr; "First Light").

- 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.

(3a) Implications of Planck 2016 results for JWST First Light:





WFC3 $z \lesssim 7$–9 $\longleftarrow$ $\longrightarrow$ JWST $z \simeq 8$–25

(Courtesy: Dr. Bill Jones).

Planck 2016 data provided better foreground removal (Planck 2016 papers XLVIII & XLVII; astro-ph/1605.02985 & astro-ph/1605.03507):

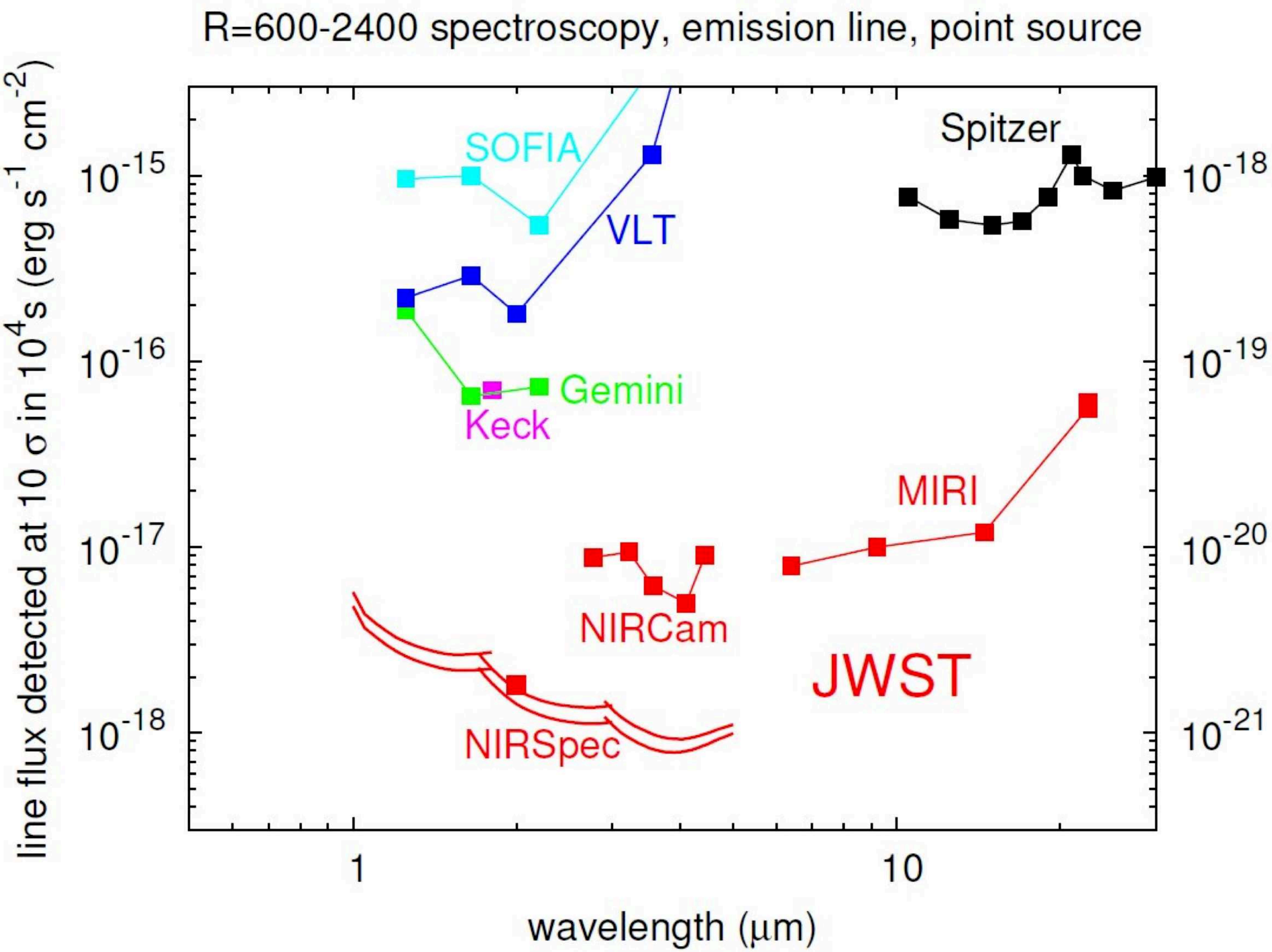
Reionization appears to have occurred between these extremes:

(1) Instantaneous: $z \sim 8.2 \pm 0.9$ (optical depth $\tau \simeq 0.055 \pm 0.009$; 0.058 ± 0.012)

(2) or Inhomogeneous & drawn out: starting at $z \gtrsim 12$?, peaking at $z \sim 8$, ending at $z \simeq 6$–7. The differences between both are now very small.

- Since Planck 2016's polarization τ has come down considerably ($\tau \simeq 0.055$–0.058), how many reionizers will JWST actually see at $z \simeq 10$–15?

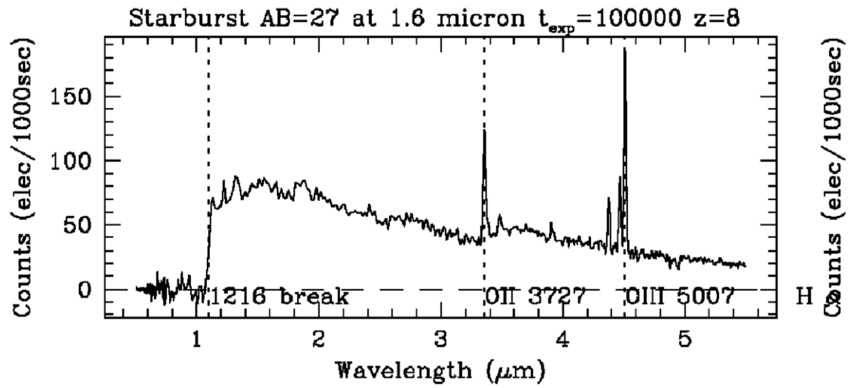
Sensitivities - spectroscopy

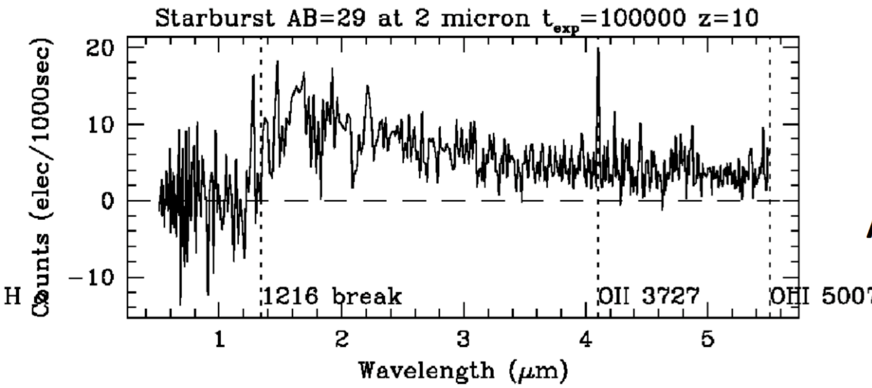


NIRCam, NIRSpec and MIRI sensitivity (cgs) compared to VLT, Keck, Spitzer.

What NIRSPEC can do !

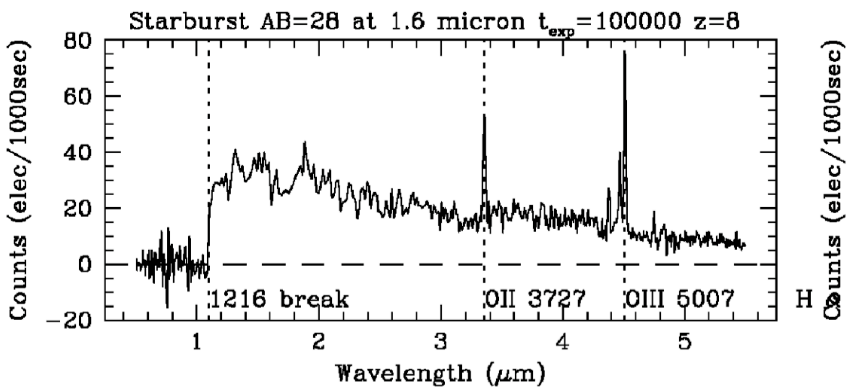
AB=27

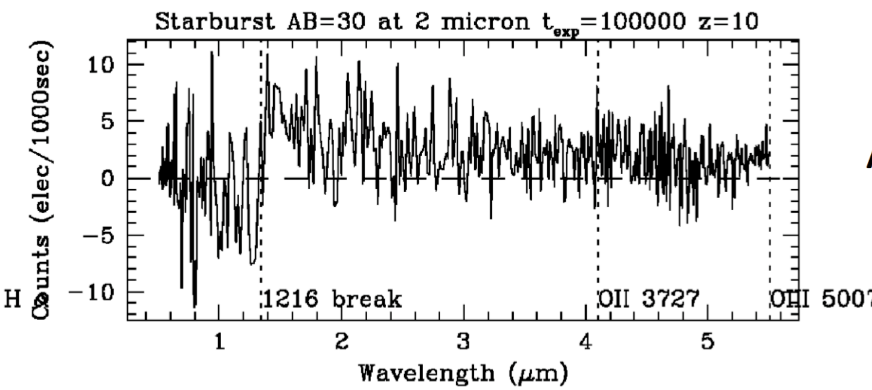




AB=29

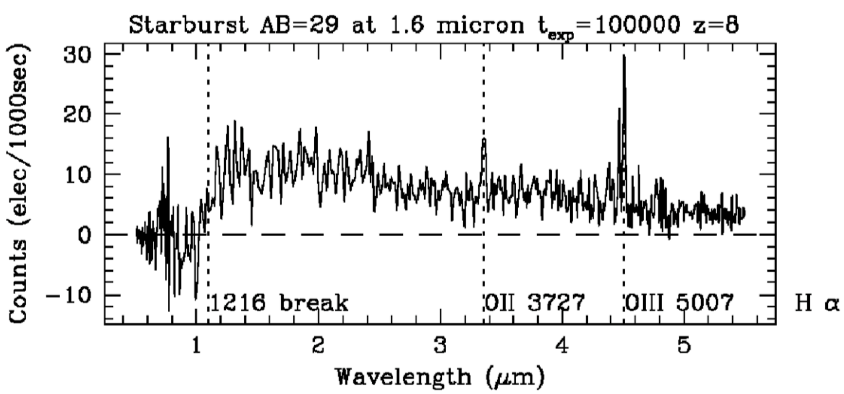
AB=28





AB=30

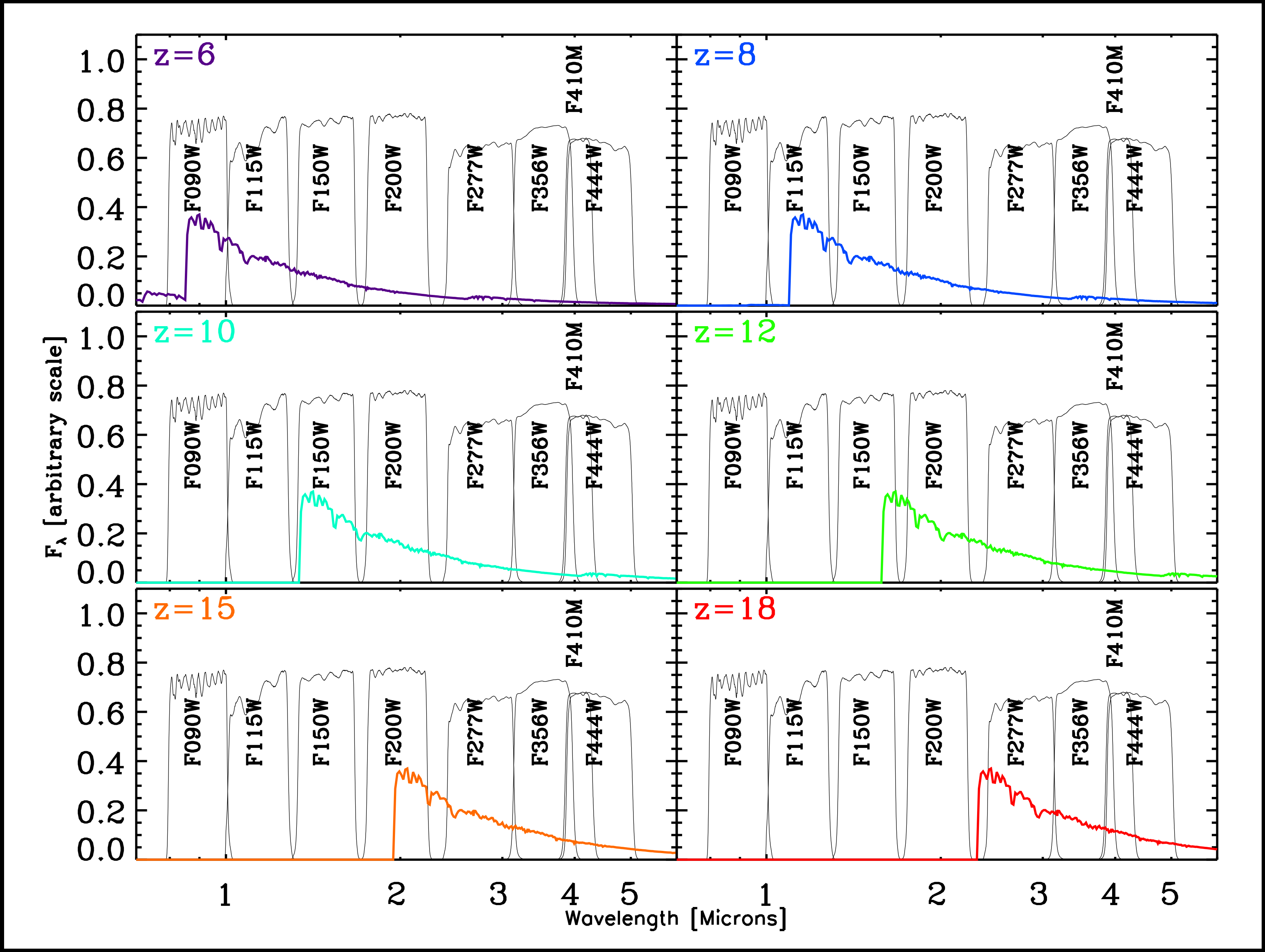
AB=29



Derive redshifts, stellar masses, stellar ages, gas ionization and metallicities, star formation rates, kinematics, pop III stars, Ly-α LF to z=10, etc.

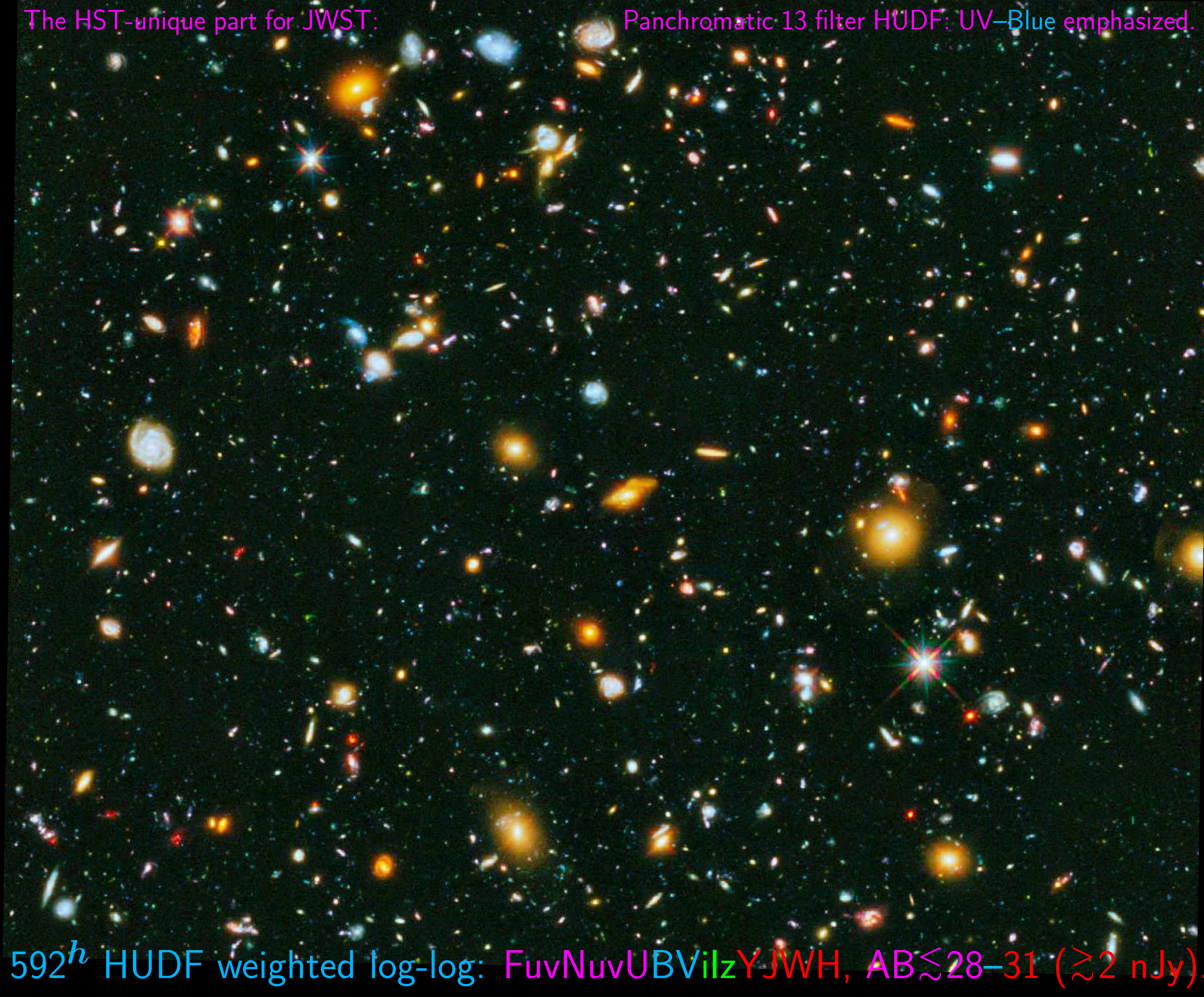
JWST NIRSpec sensitivity to SF reionizers at z=8–10, AB≃27–30 mag.

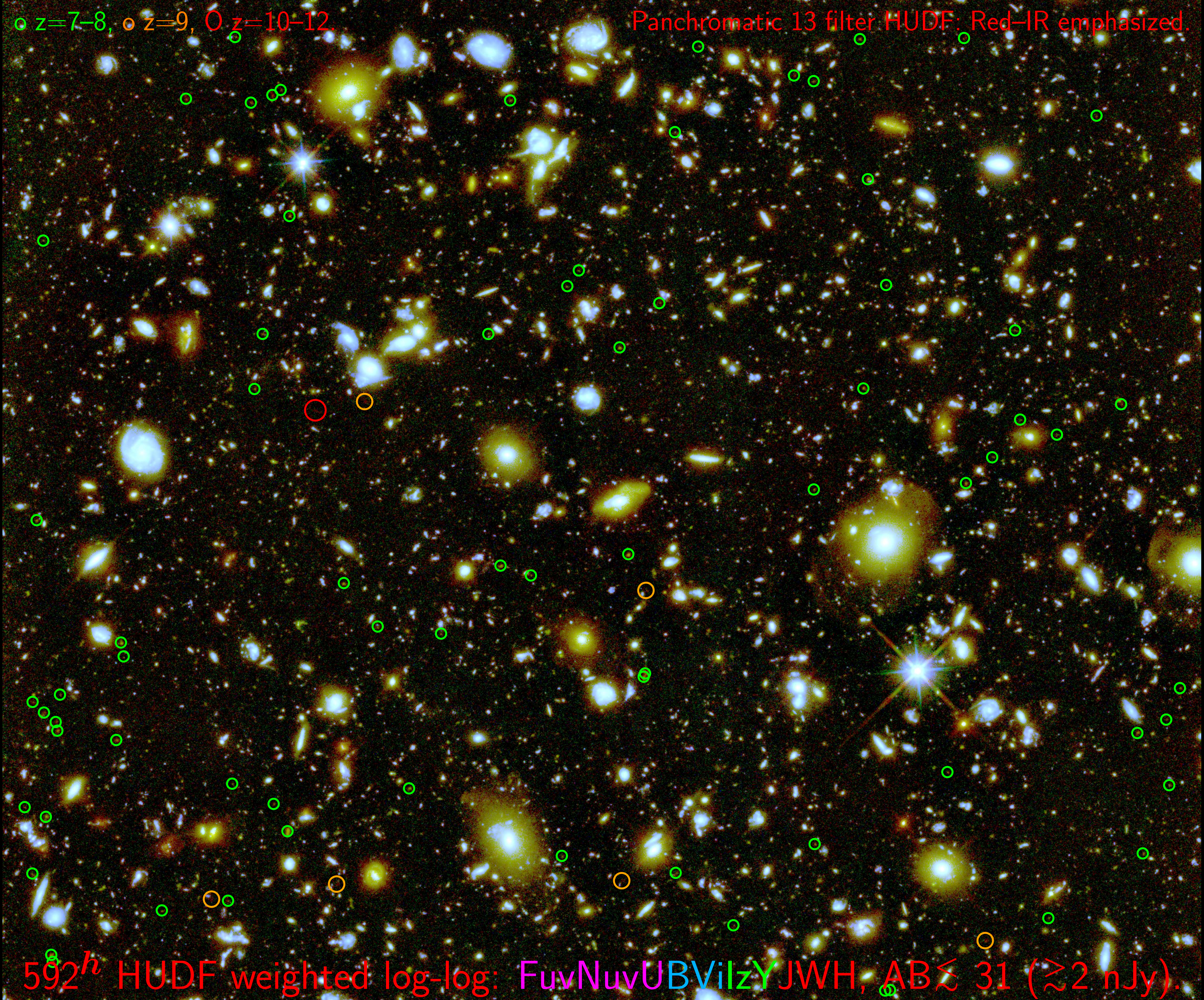
(3b) How will Webb measure First Light: what to expect in (Ultra)Deep Fields?



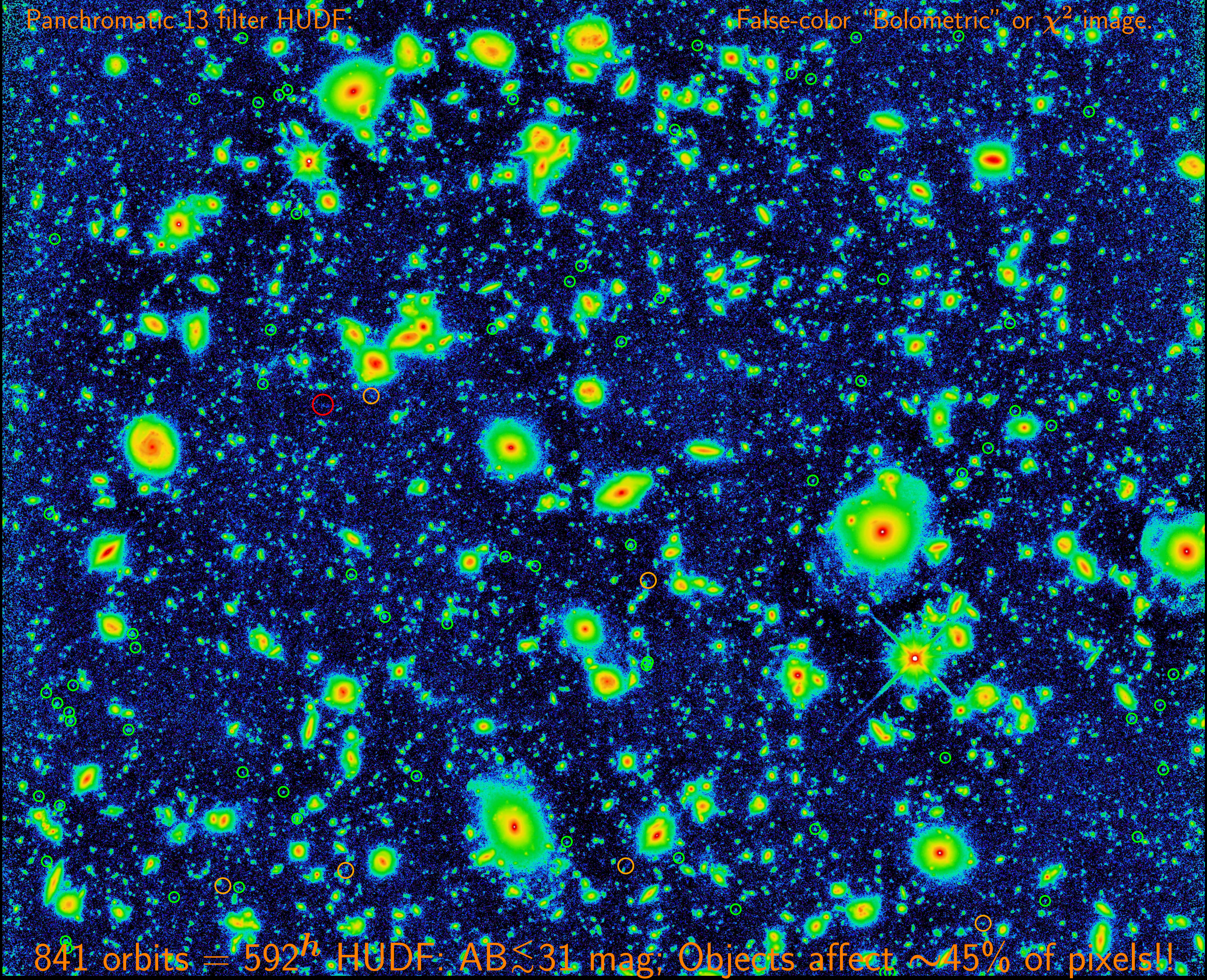
- Can't beat redshift: to see First Light, must observe near–mid IR.

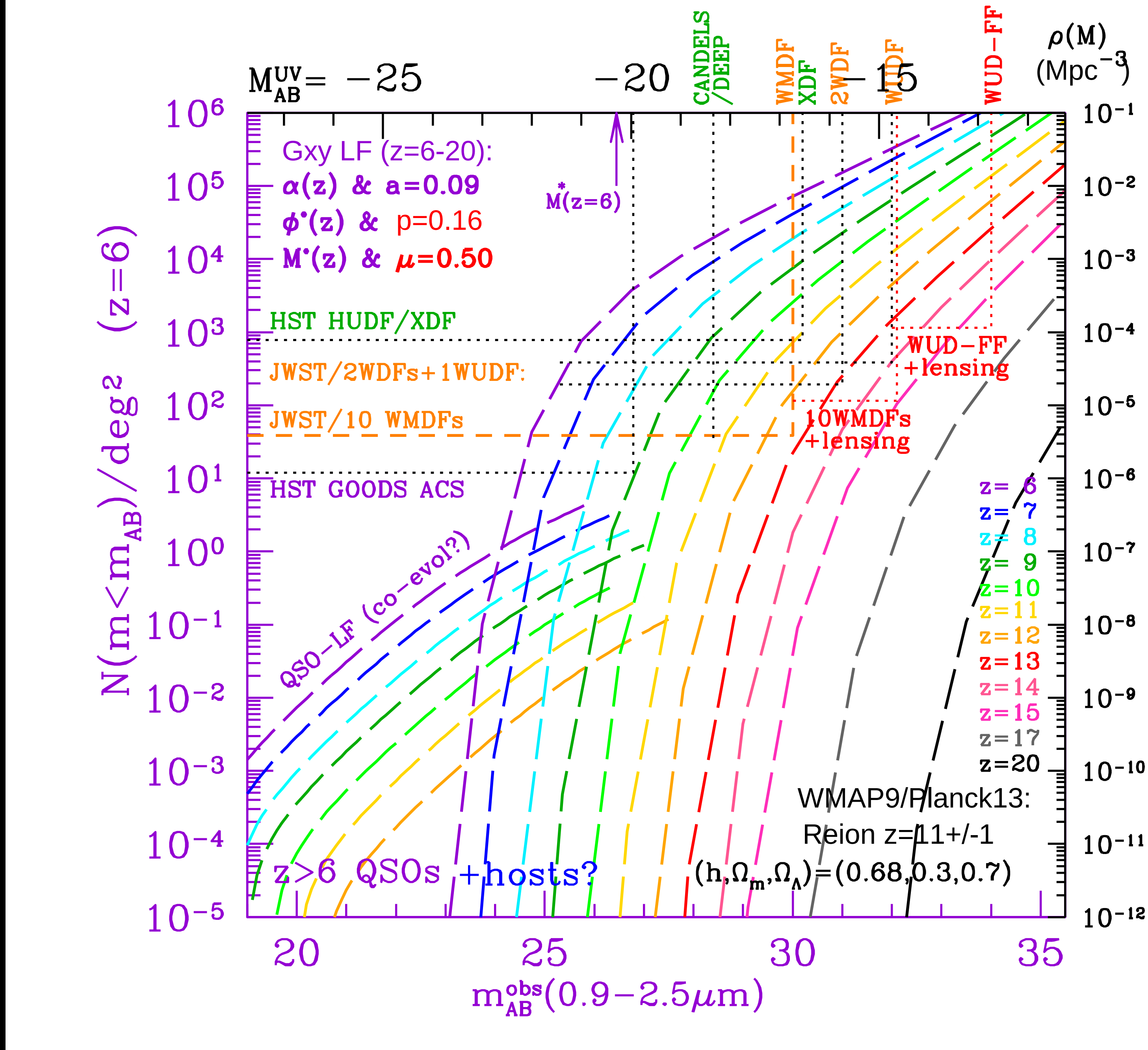
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.


The HST-unique part for JWST:
Panchromatic 13 filter HUDF: UV–Blue emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB≲28–31 (≳2 nJy).



○ z=7–8, ○ z=9, ○ z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$ 31 ($\gtrsim$2 nJy).


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

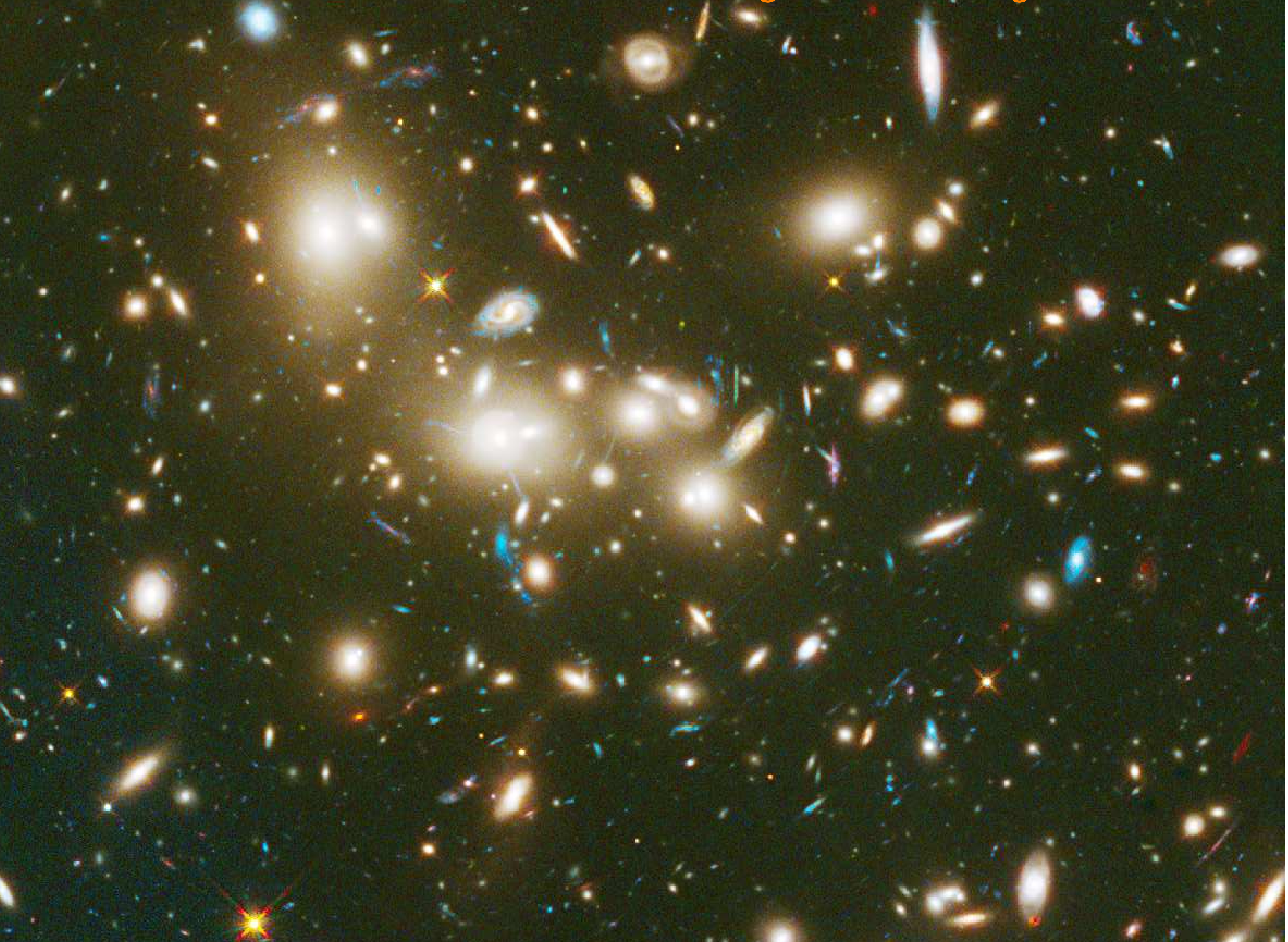


Predicted Schechter Luminosity Function (LF) at redshifts $6 \lesssim z \lesssim 20$:

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

- JWST needs 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 (this will make the images even more crowded):
- Lensing is needed to see what Einstein thought was impossible to observe!

(4) 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.

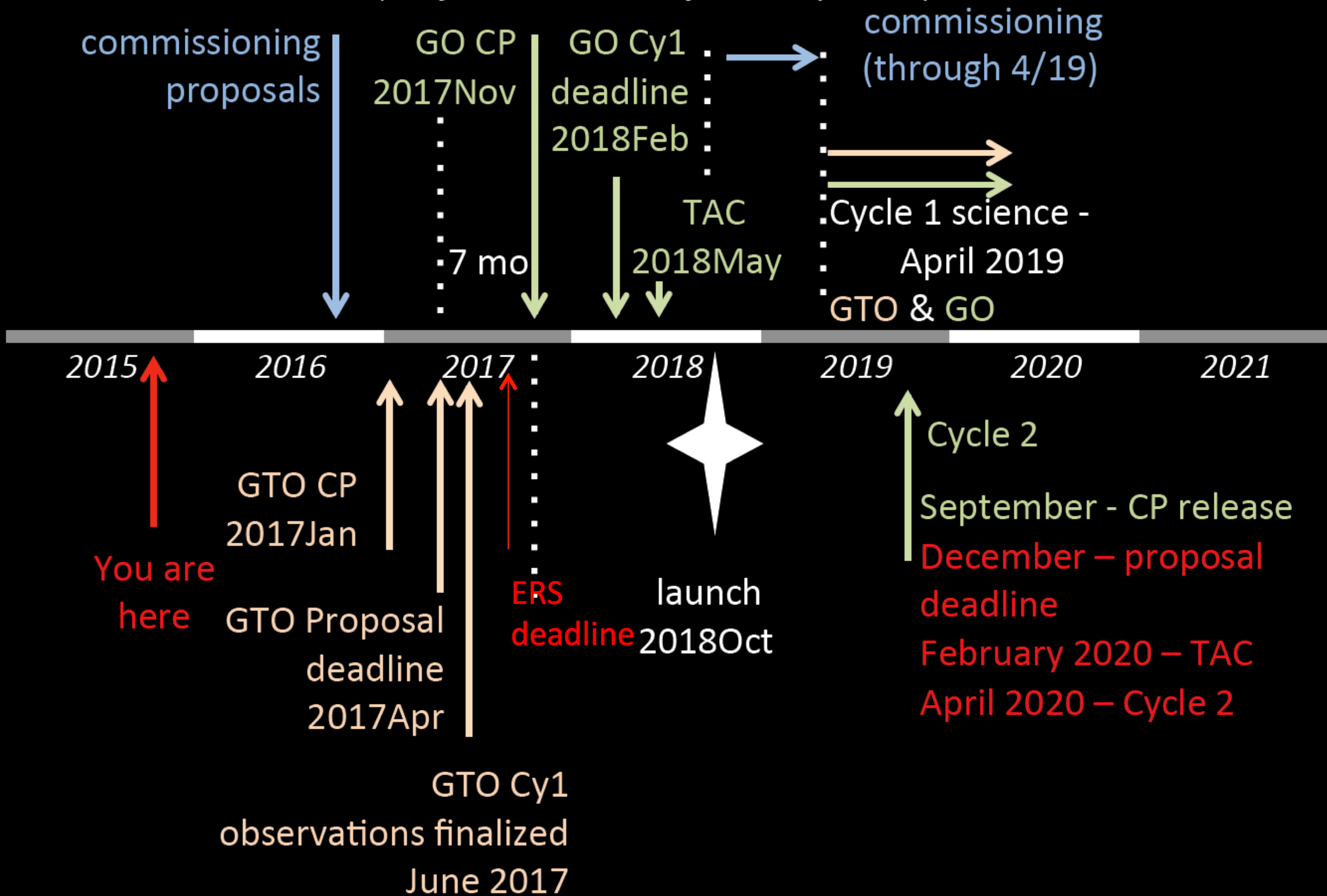
(4) JWST will have a major impact on astrophysics this decade:

- IR sequel to HST after 2018: Training the next generation researchers.
- **Your JWST proposals are due Aug. 2017 (ERS) and Feb. 2018 (Cycle 1 GO)!**

SPARE CHARTS

JWST Science Planning Timeline

(draft schedule as of January 2015)



2017–2018 (Launch) and beyond: When are your ERS & GO proposals due?

- 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

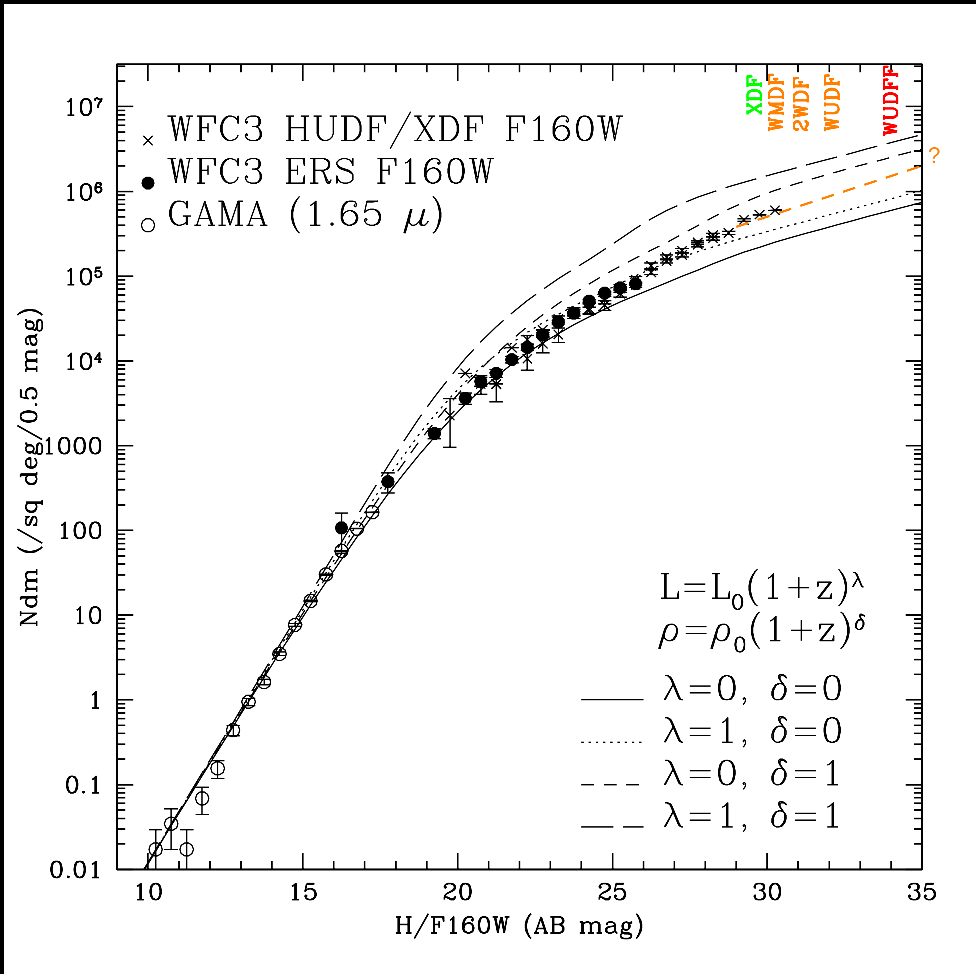
Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

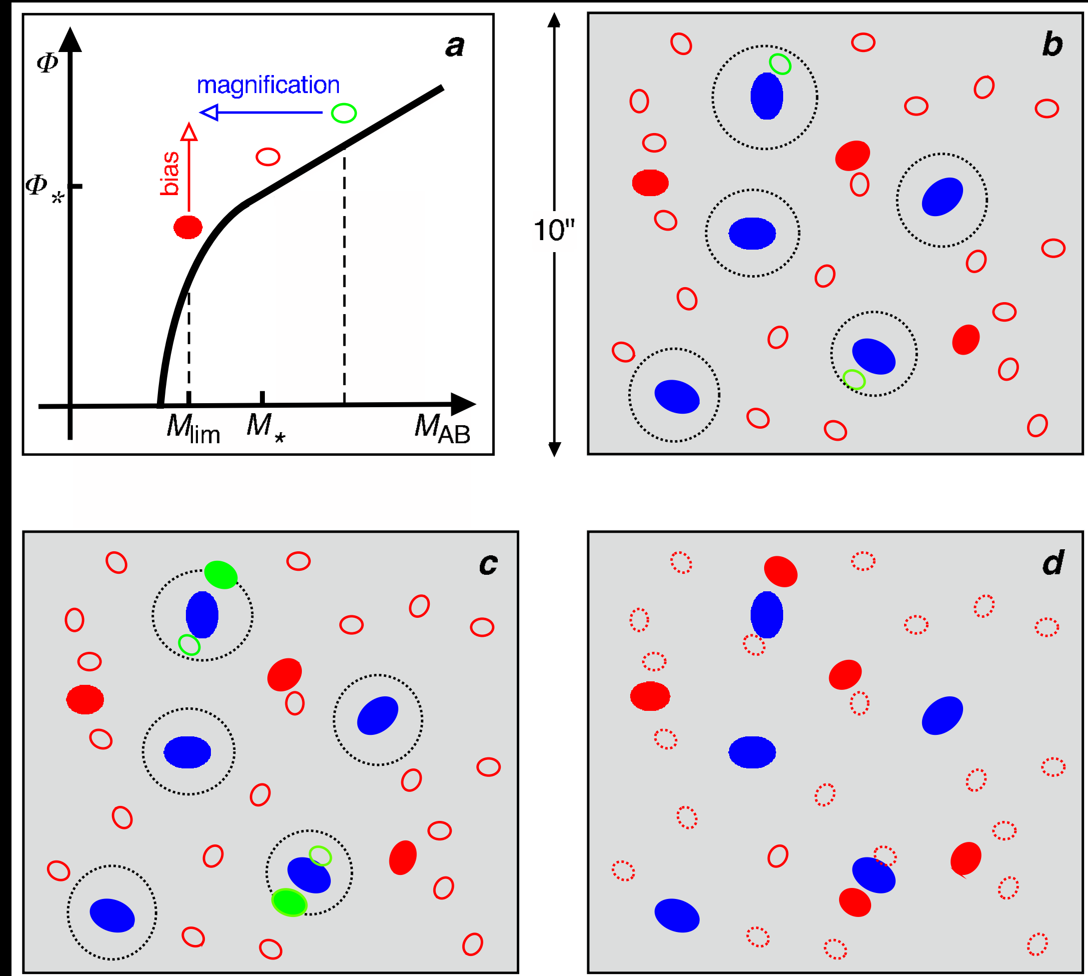
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

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

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

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



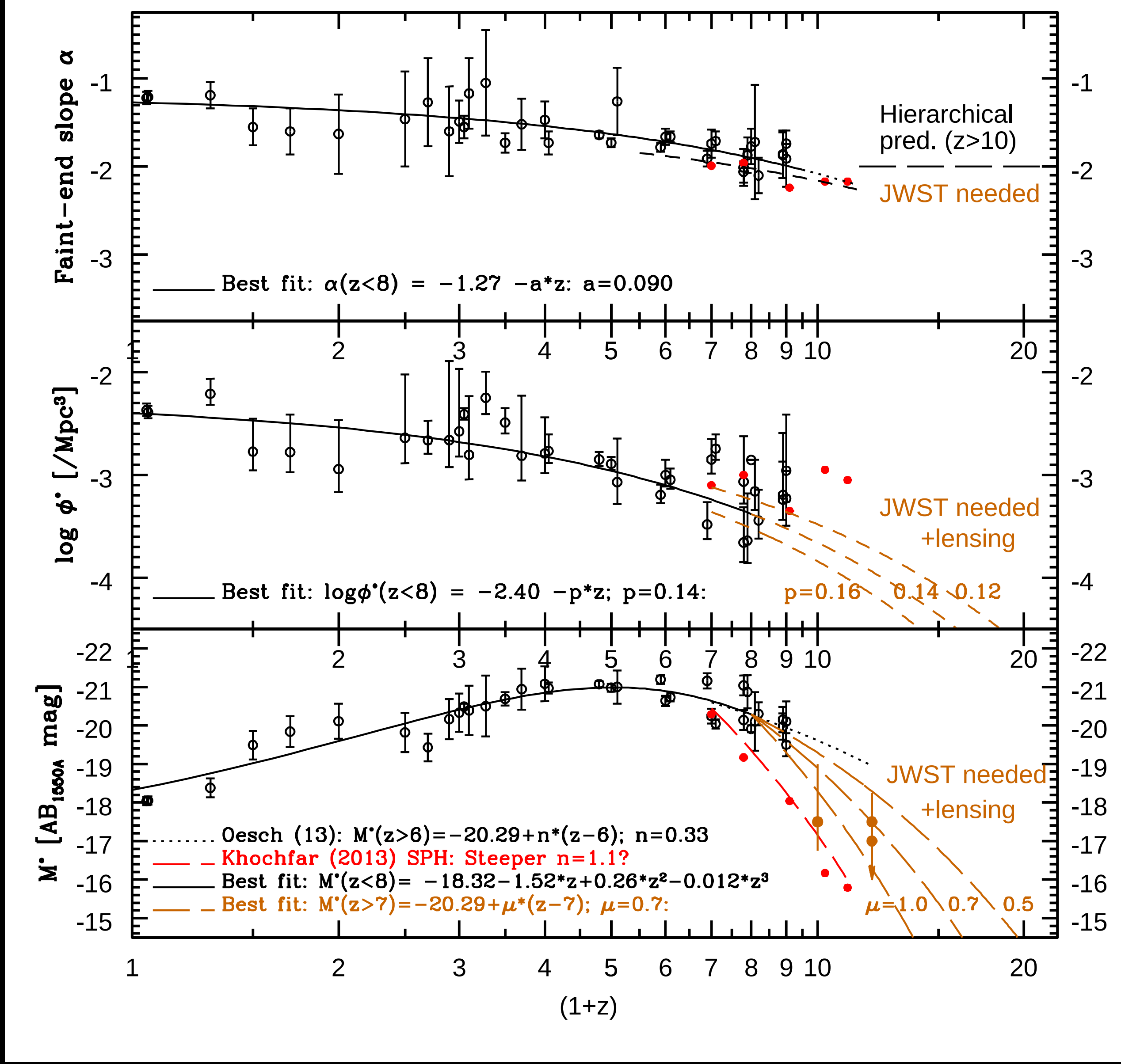


1.6μm counts (Windhorst[+]2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

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

$\Rightarrow$ Faint-end of luminosity function at median redshift is also steep.

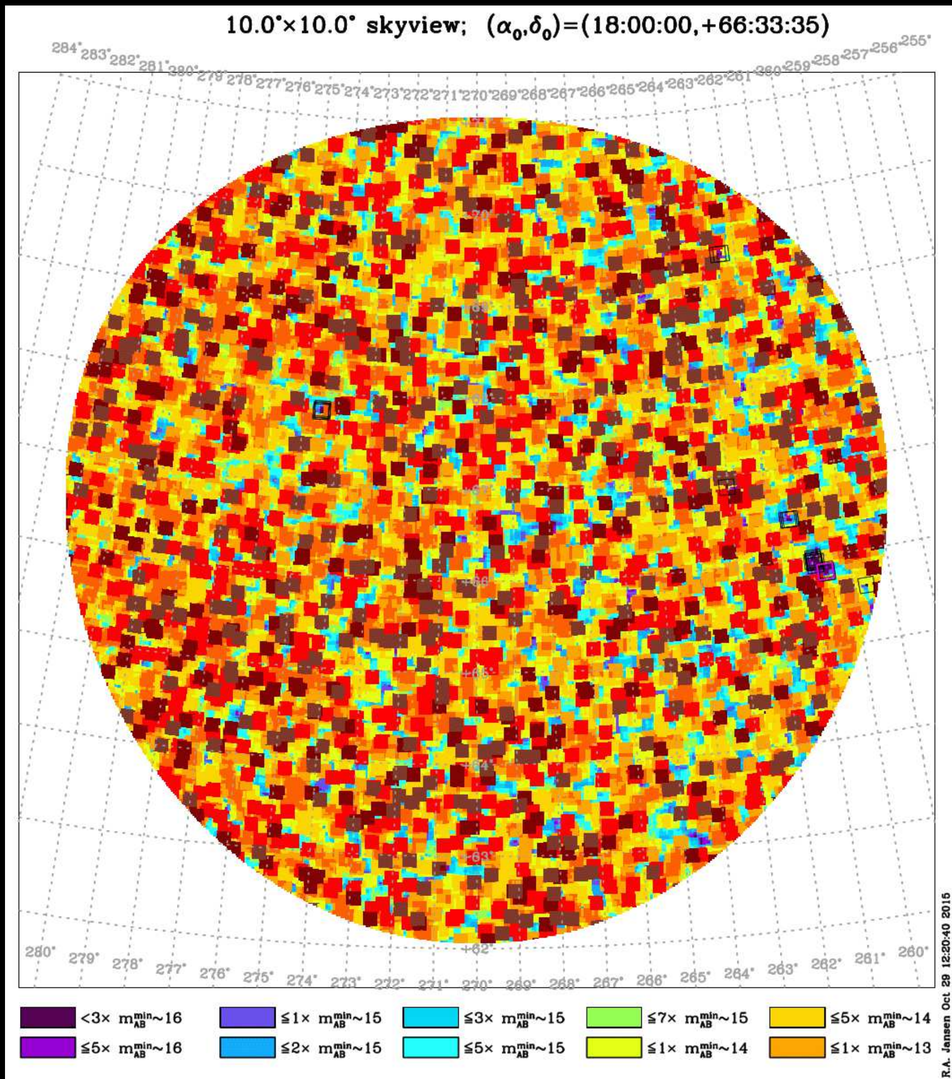
- In 800-hr JWST can see to ∼32 mag: dwarf galaxy at z≃11!
- Lensing will change the landscape for JWST observing strategies.

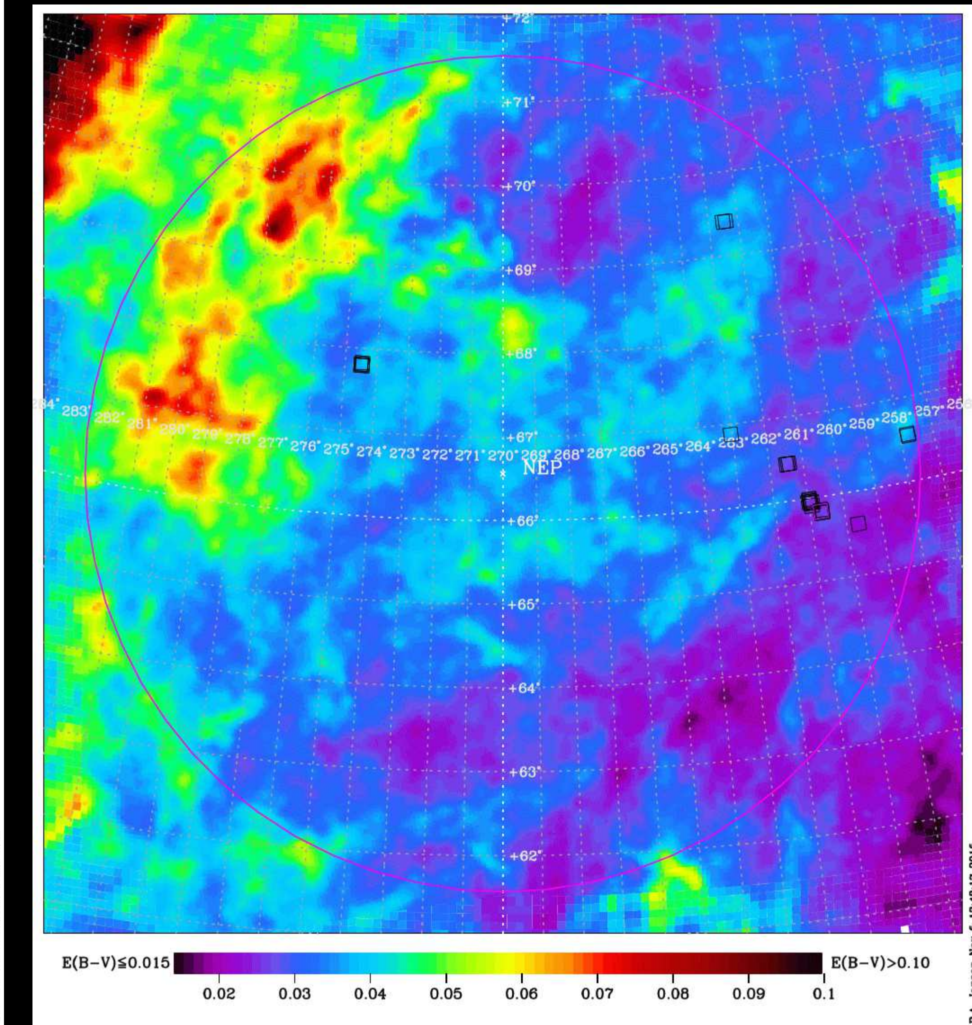


Evolution of Schechter UV-LF: faint-end LF-slope α(z), Φ^* (z) & M^* (z):

- For JWST z$\gtrsim$8, expect $\alpha\lesssim$–2.0; $\Phi^* \lesssim 10^{-3}$ (Mpc^{-3}) (Bouwens$^+$ 15).
- HUDF: Characteristic M^* may drop below –18 or –17.5 mag at z$\gtrsim$10.

$\Rightarrow$ Will have significant consequences for JWST survey strategy.

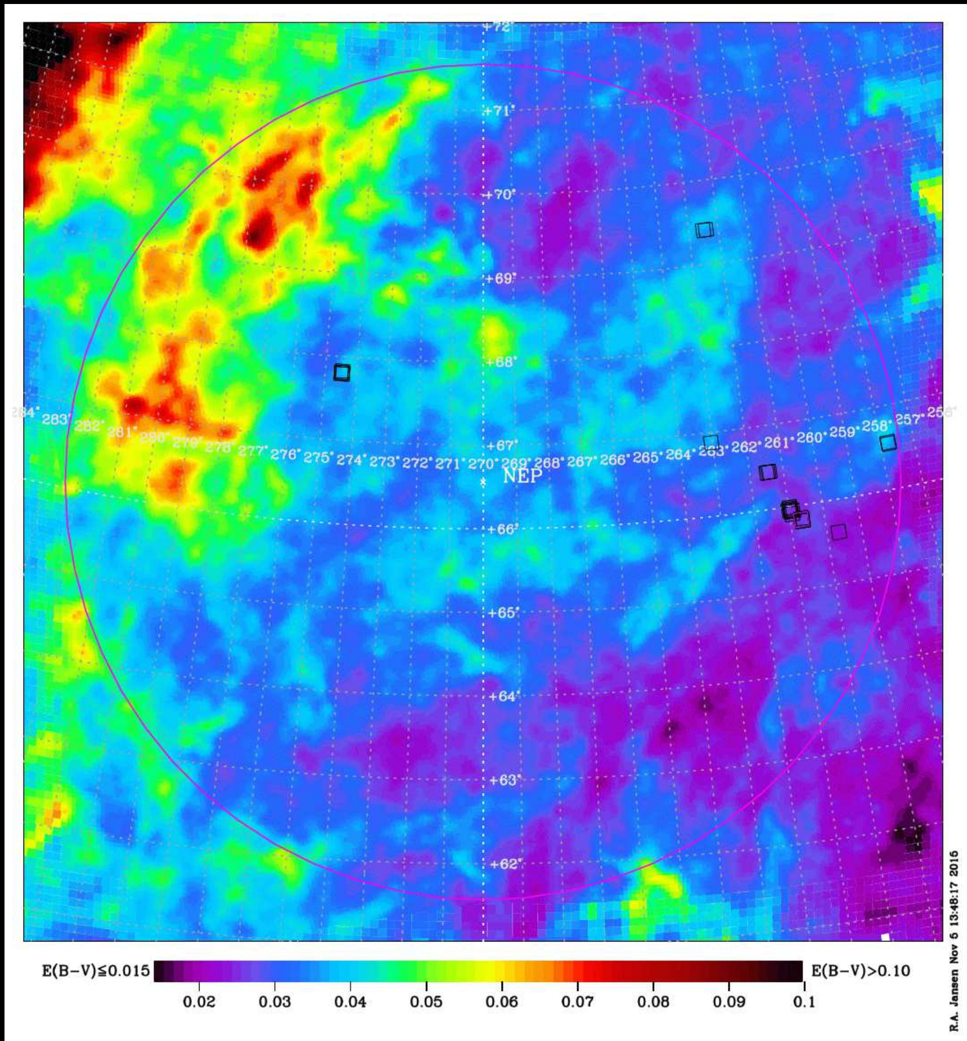


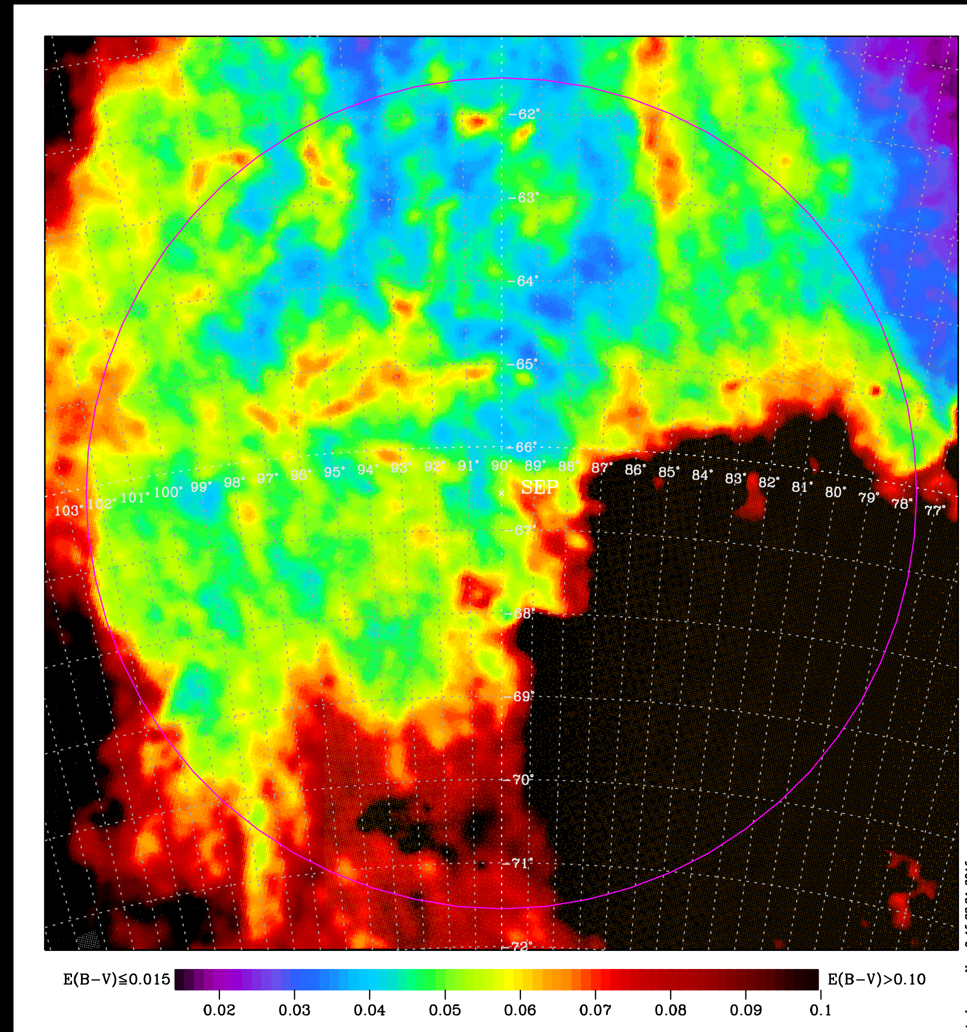


[LEFT]: *WISE* 4μm bright-object penalties in 10′ grid: Very few regions (purple) exist *without bright stars* (AB≲16) to minimize persistence.

[RIGHT]: *E(B−V)* map (Schlegel et al. 1998) in same NEP-region.

Cleanest 10×10′ region for JWST has modest extinction: *E(B−V)*≲0.028^m.

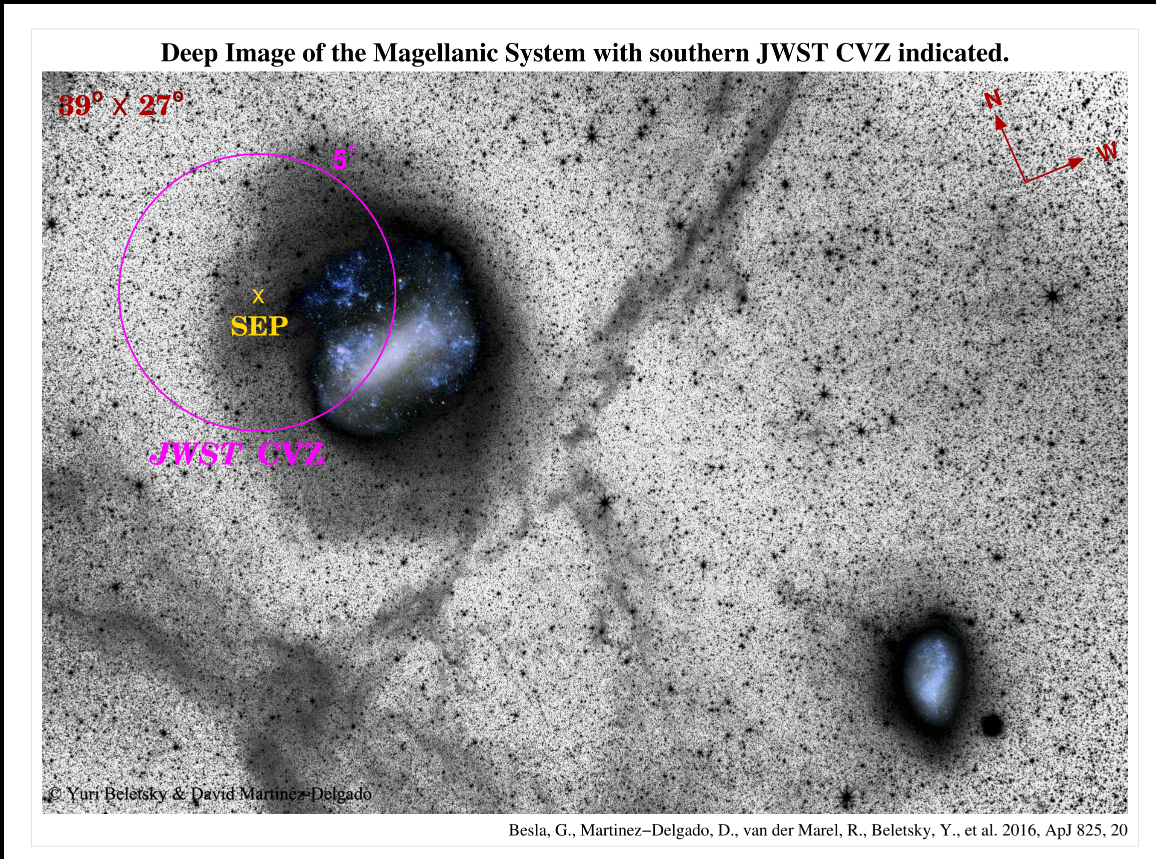


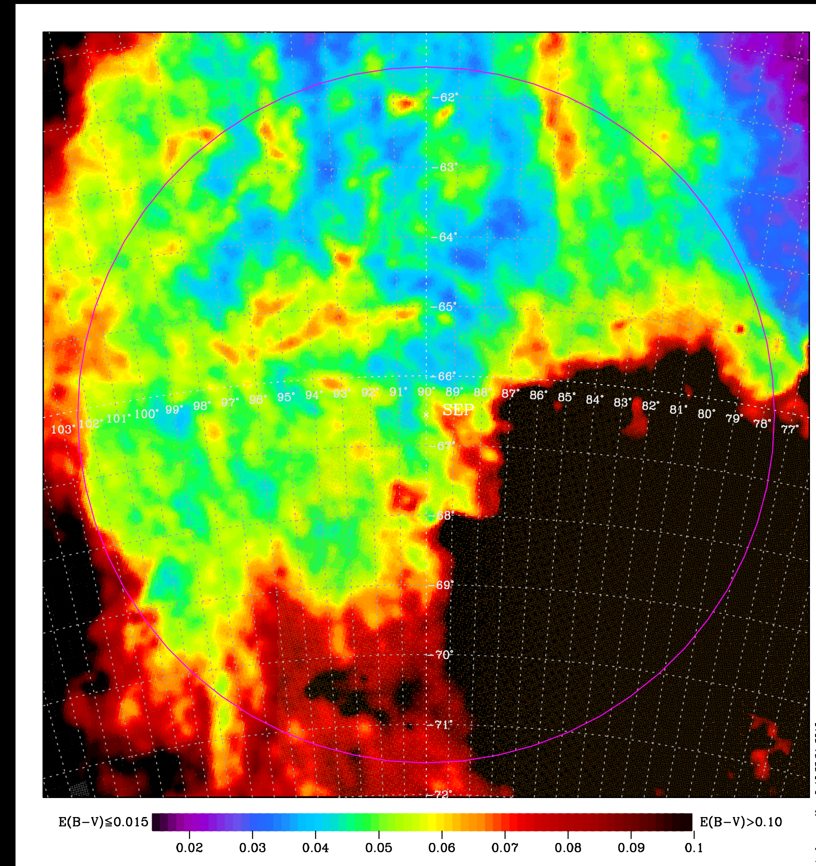


Comparison of *E(B−V)*-maps of NEP [Left] and SEP [Right].

- NEP contains clean $10 \times 10'$ region: no AB$\lesssim$16 stars, *E(B−V)*$\lesssim 0.028^m$.
- SEP contains no clean, bright-star free regions with r$\lesssim 5^\circ$ due to LMC.

Only NEP CVZ can be used for (far-extragalactic) time-domain science.





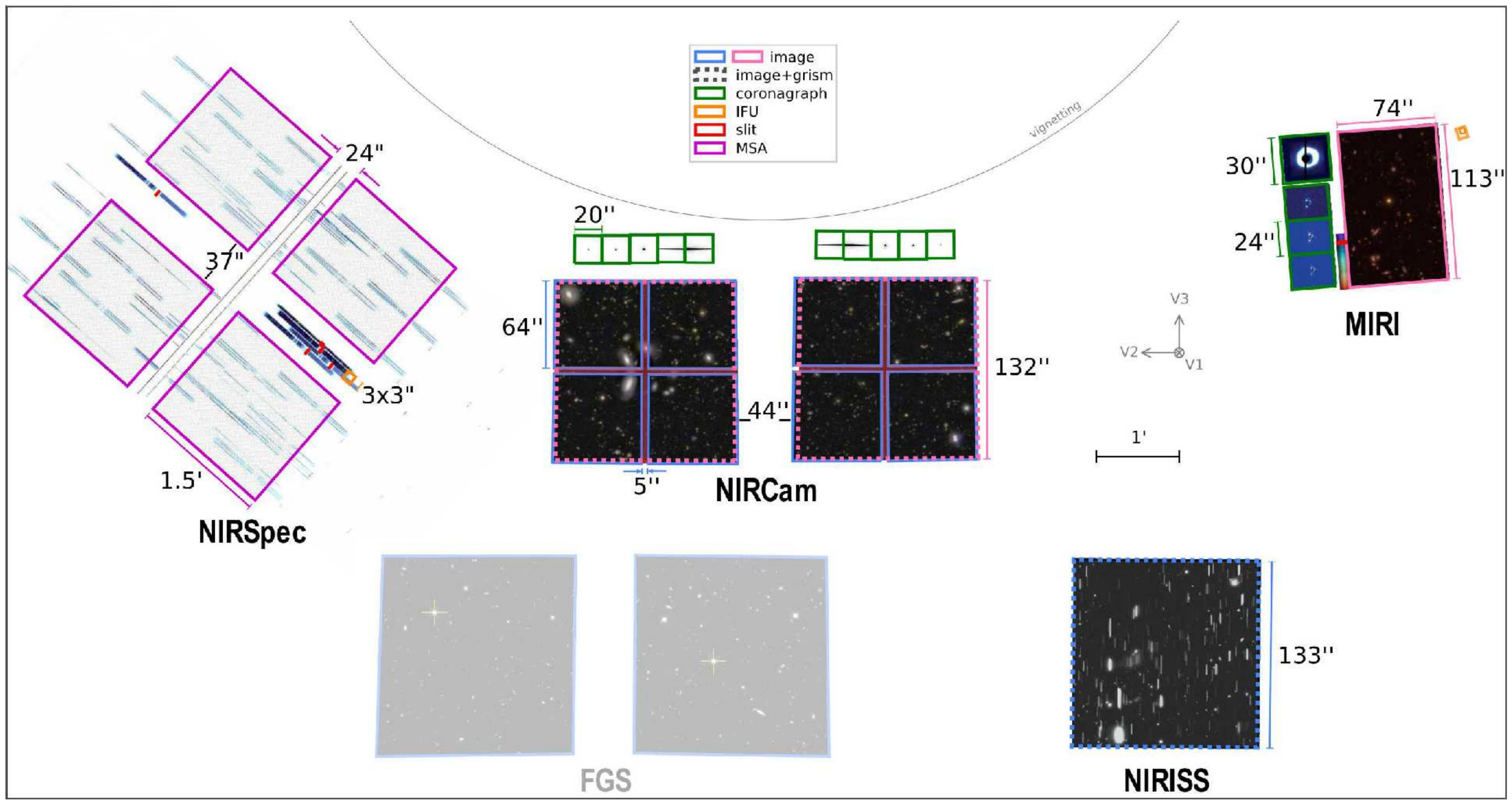
[LEFT] Map of LMC+SMC and spurs (Besla et al. 2016, ApJ, 825, 20).

[RIGHT]: $E(B-V)$ map (Schlegel et al. 1998) in SEP-region.

- SEP will be perfect for CVZ studies of LMC+outskirts (bottom of IMF!).

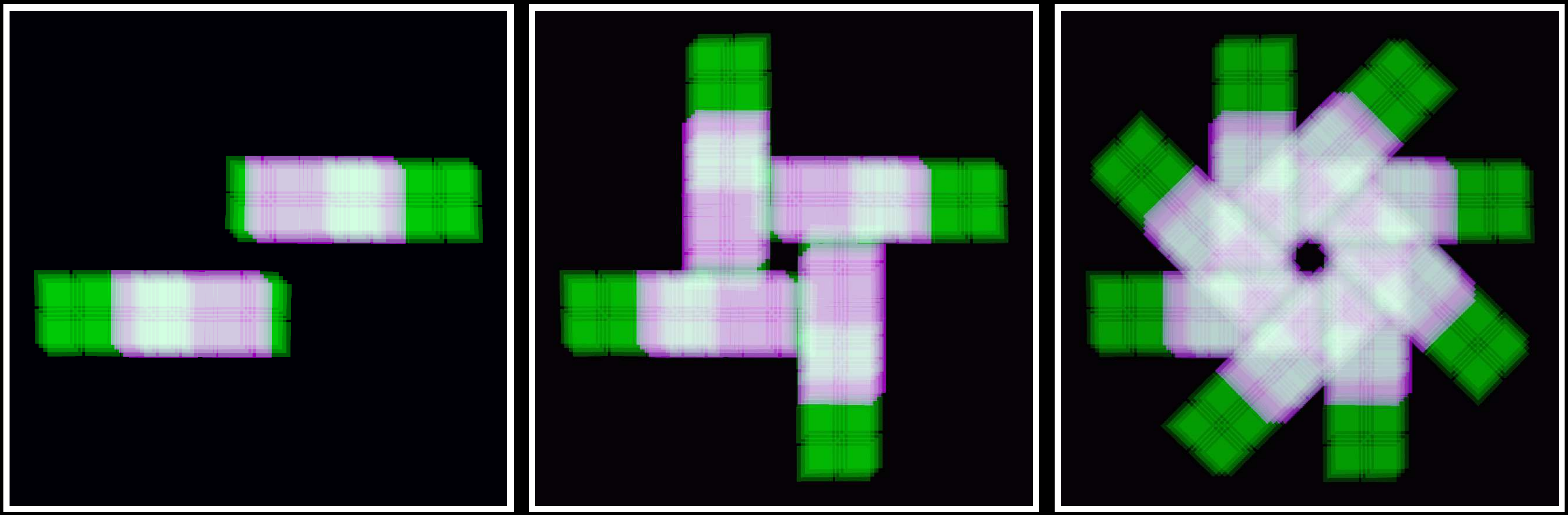
- SEP/LMC can serve as counter-target for NEP surveys: offsets accumulated angular momentum, and so help save JWST propellant/lifetime!

(2) NIRCam + NIRISS-parallels optimally cover the best NEP CVZ field.



- As of FY16, JWST instruments can be used for science parallels.
- Currently being implemented for most-used JWST instrument pairs.
- CVZ enables well-overlapping *dark-sky* NIRCam+NIRISS-parallel mosaics.

Exposure Maps of NEP JWST-Windmill & GO-Extensions:



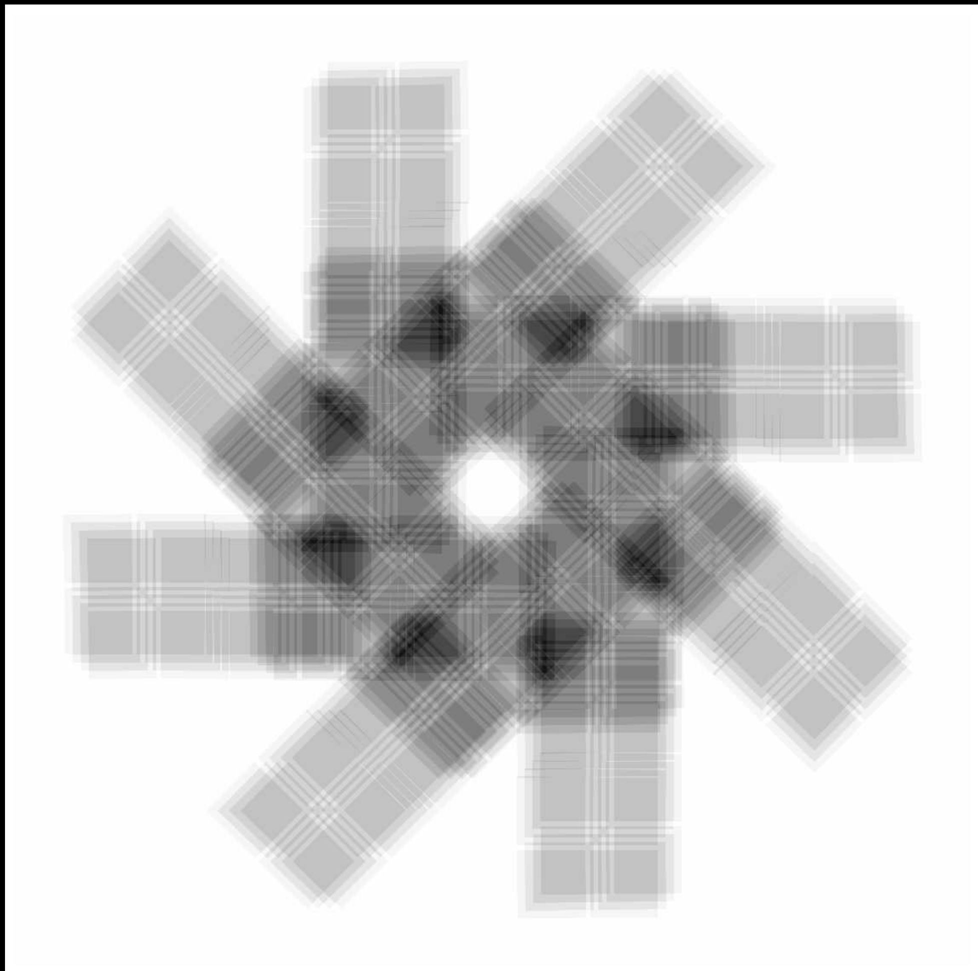
[LEFT]: Parallel NIRISS R150C+R150R grism spectra (purple) observed at ΔPA=0+180°, overlayed on primary NIRCam images (green).

[MIDDLE]: Same with ΔPA=90+270° added: This is our 50-hr GTO plan.

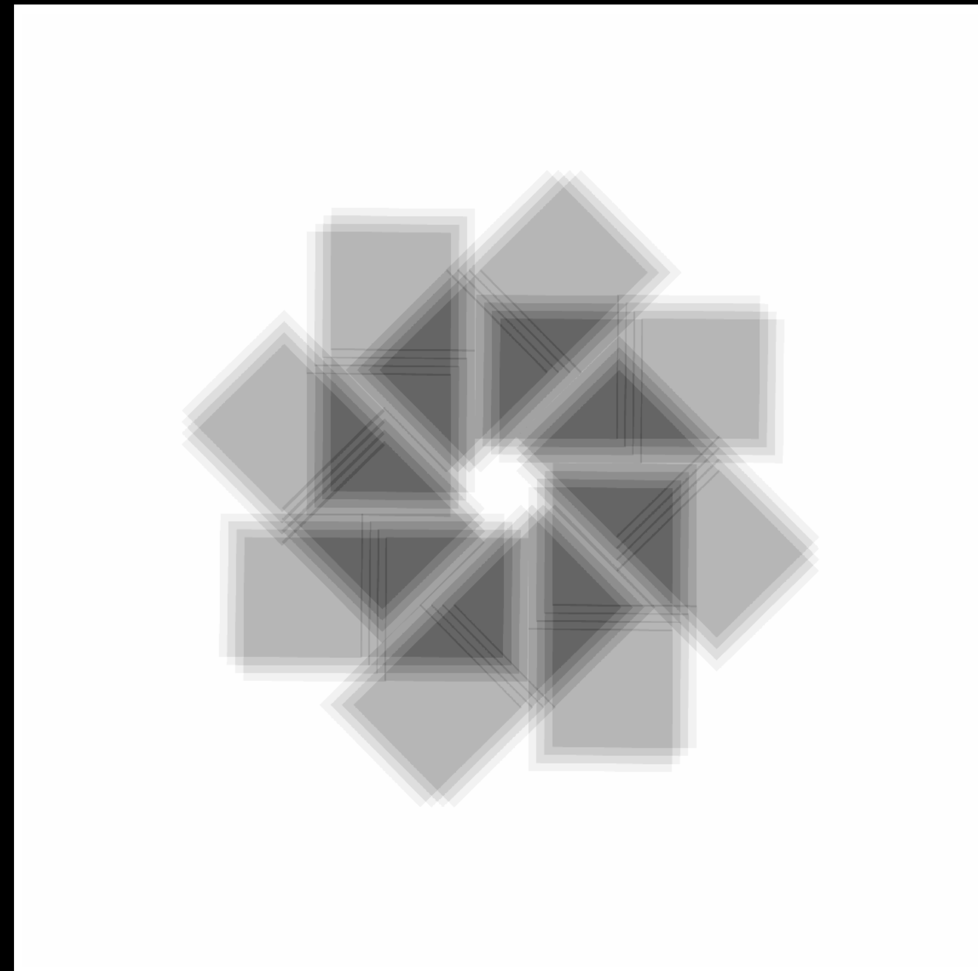
[RIGHT]: Anticipated GO-Community extensions in JWST Cycle $\gtrsim$1.

White regions: NIRCam exposures overlap, reaching $\lesssim$0.75 mag deeper.

- GO's can repeat NIRCam primaries+NIRISS parallels as often as needed during JWST's 5–14 year lifetime at ANY PA!



NIRCam+NIRISS Windmills combined



NIRISS-parallel Windmill alone

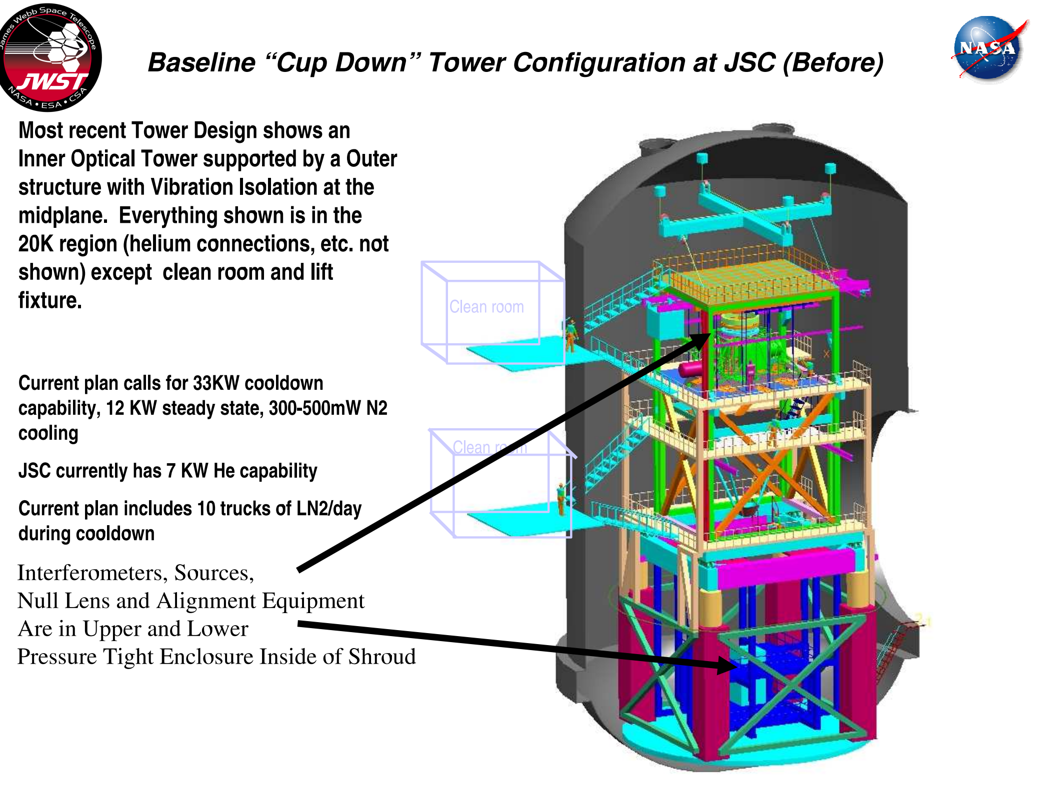
Exposure map of a community-driven GO extension of the JWST-Windmill adds, e.g., relative position angles ΔPA=45, 135, 225, and 315°.

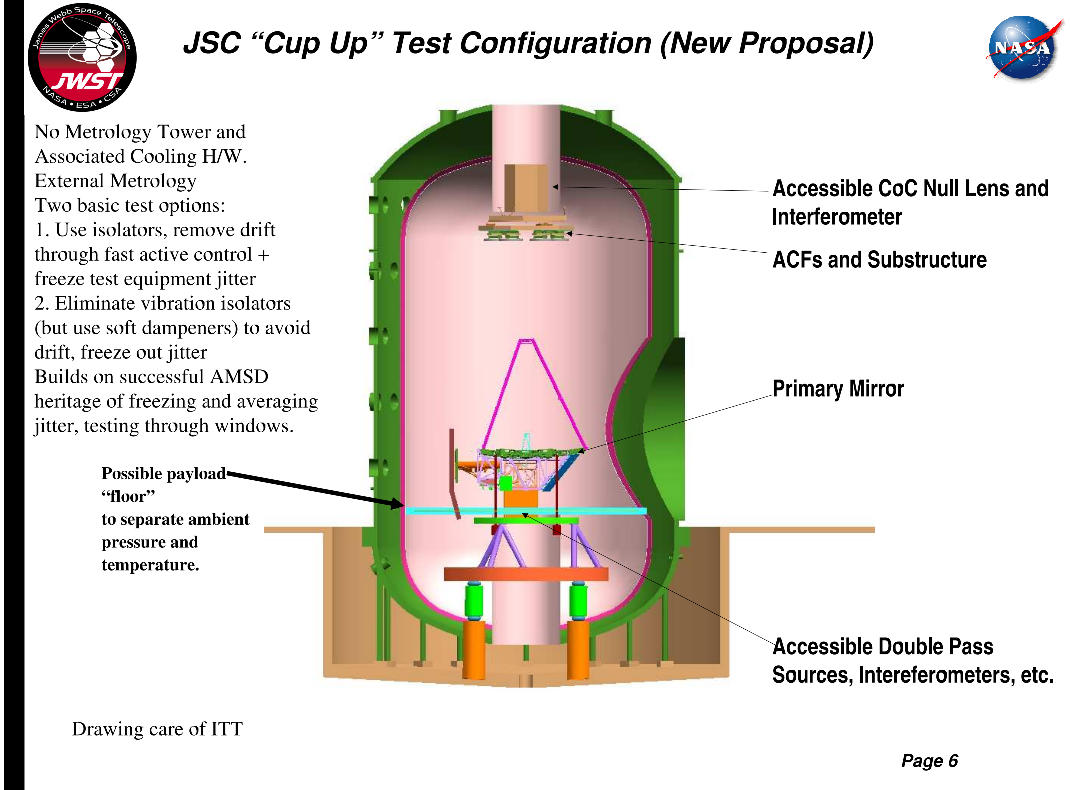
Increases area by ∼60%, provides new epochs, and go $\lesssim$0.75 mag deeper.

- NIRISS parallel grism spectra increase the number of PA's grism angles to robustly disentangle overlapping object spectra to AB$\lesssim$27.5–28 mag.

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

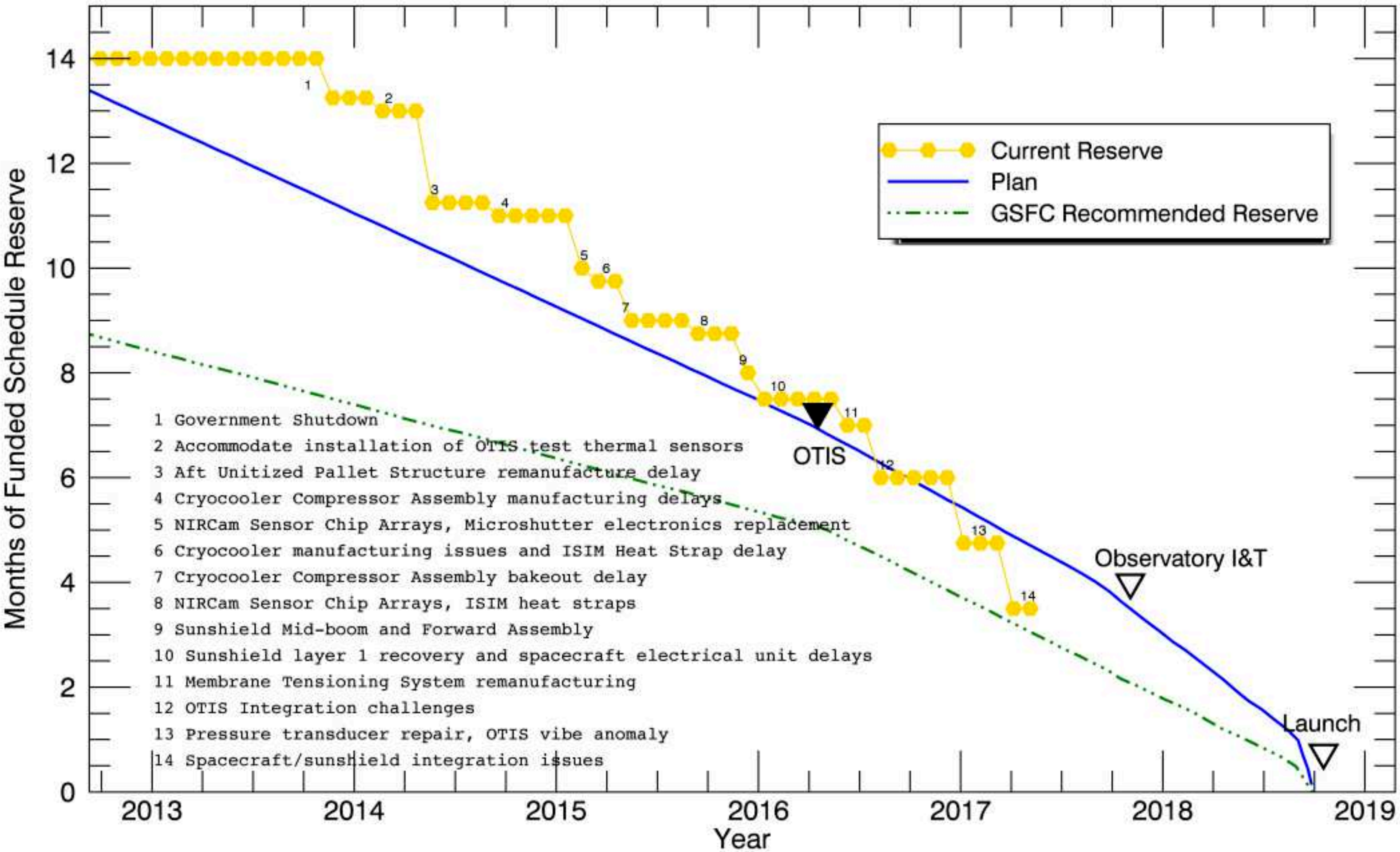




JWST underwent several significant replans and risk-reduction schemes:

- $\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 2017 JWST HQ Milestones

Month		Milestone	FY2016 Deferral	Comment
Oct-16	1	Complete portable clean room for Telescope and Science Instruments (OTIS)		Completed 10/13/16
	2	Complete final checkout of new shaker tables at Goddard Space Flight Center	•	Completed 10/13/16
	3	Begin making electrical connections between spacecraft panels		Completed 10/7/16
	4	Complete Sunshield Mid-Boom Assembly #2 functional test	•	Completed 12/5/16
Nov-16	5	Start optical measurements of OTIS prior to vibration and acoustic tests		Completed 10/24/16
	6	Deliver Science and Operations Center release 1		Completed 9/30/16
	7	Perform Cryocooler installation into the spacecraft bus and begin functional testing		Completed 10/29/16
	8	Complete Aft Unitized Pallet Structure assembly	•	Completed 10/29/16
	9	Deliver Aft Unitized Pallet Structure to Observatory I&T	•	Completed 3/14/17
Dec-16	10	Deliver Forward Sunshield Pallet Structure to Observatory Integration and Test (I&T)	•	Completed 3/28/17
	11	Start OTIS vibration and acoustic testing program		Completed 11/19/16
	12	Complete final test of engineering model of telescope center section at Johnson Space Center (JSC)		Completed 10/31/16
	13	Deliver sunshield flight membranes to Observatory I&T		Completed 12/15/16
Jan-17	14	Complete OTIS vibration and acoustics testing		Completed 3/2/17
	15	Deliver observing proposal and planning subsystem software build that supports launch		Completed 1/12/17
	16	Complete electrical testing of the spacecraft at Northrop-Grumman		Completed 3/7/17
Feb-17	17	Complete OTIS optical measurements after vibration and acoustic tests		Completed 3/31/17
	18	Deliver wavefront and control software that supports launch (controls telescope mirror shape)		Completed 1/20/17
	19	Deliver horizontal deployable radiators to Observatory I&T		Delayed June for release testing
Mar-17	20	Deliver OTIS to the Johnson Space Center		Completed 5/7/17
	21	Deliver the pre-launch Flight Operations System software build		Completed 2/17/17
	22	Delivery of sunshield extension boom #2 membrane attachment assembly to Observatory I&T		Completed 4/13/17

Blue font(underline) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late. "•" denotes 2016 milestones carried forward.

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	45	39	25	7	6	2
FY2017	38	24	11	17*	3	1

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

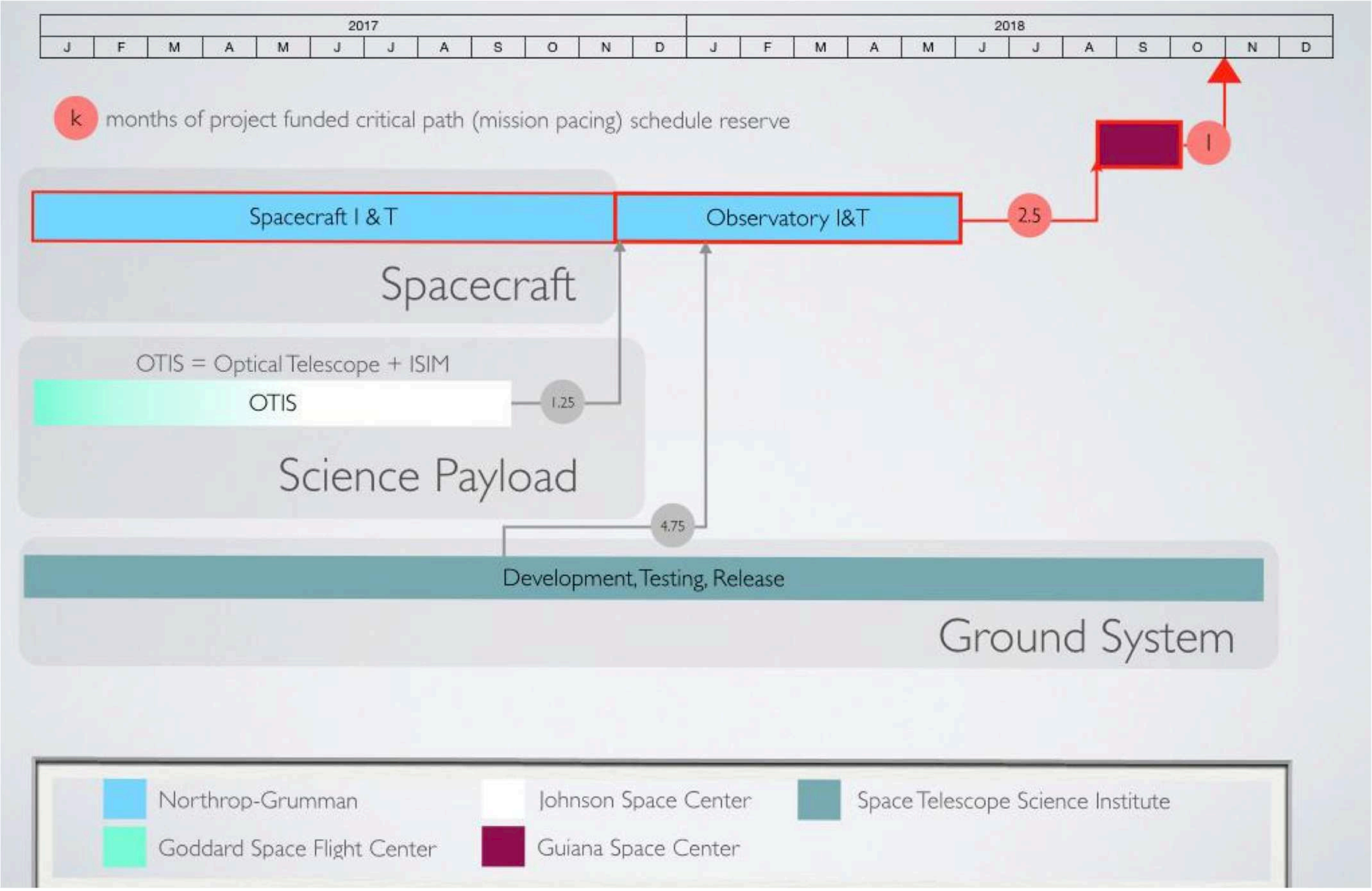
❖ Milestone accounting in FY2014 was complicated by the government shutdown and multicomponent milestones

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

FY15, F16: Most “Lates” not on critical path, nor cause a launch delay.

FY17: “Lates” anticipated to finish with FY, not causing launch delay.

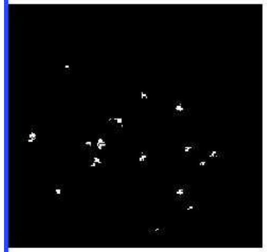
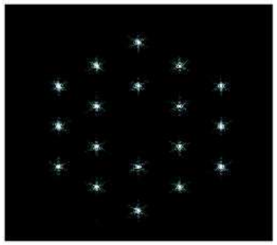
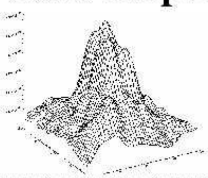
Simplified Schedule



170612 JWST Monthly Telecon 5

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

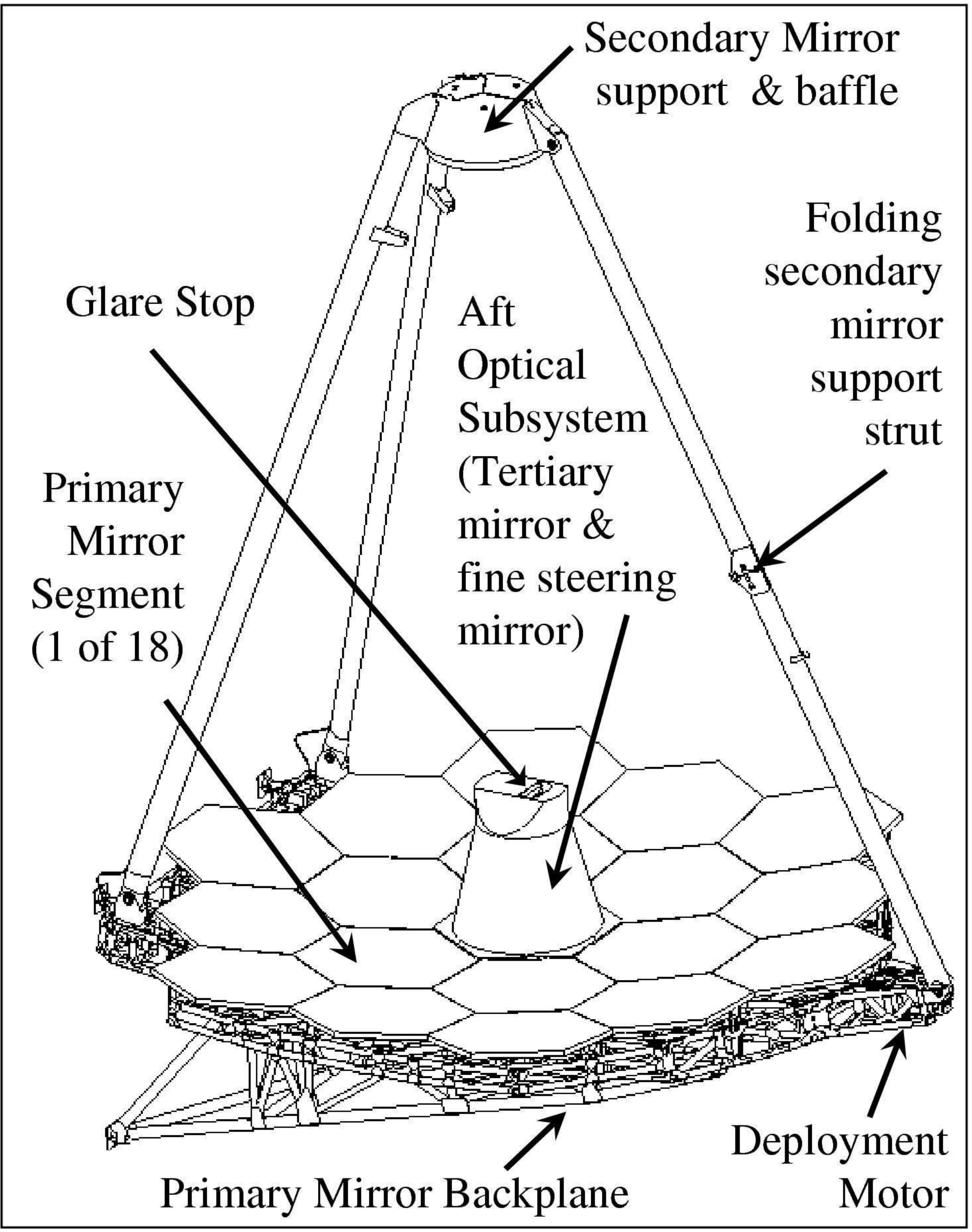
Instruments+detectors & Optical Telescope Element remain on critical path.

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.

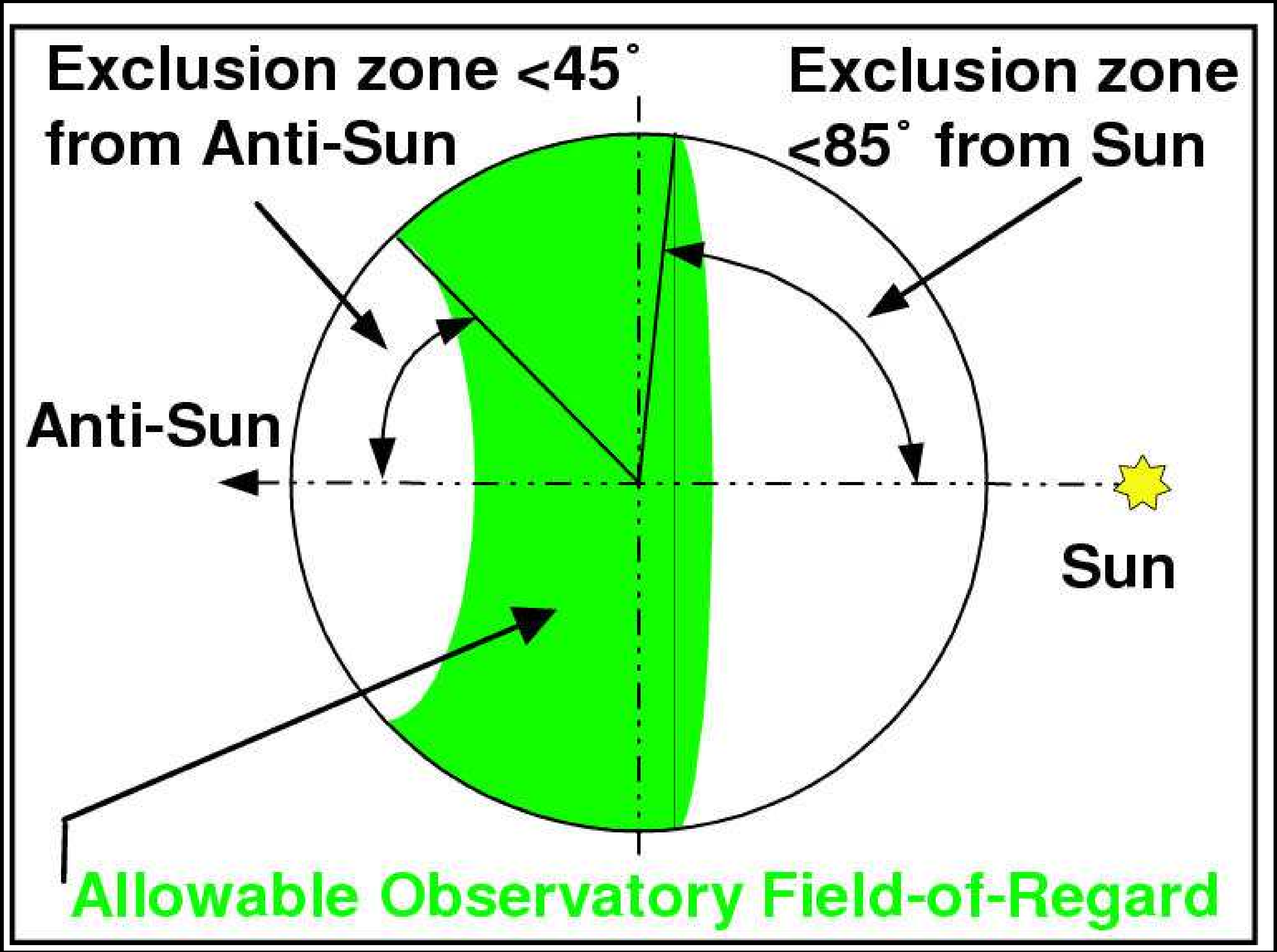
Redundant & doubly-redundant mechanisms, quite forgiving against failures.



Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2017.

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

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



JWST can observe North/South Ecliptic pole targets continuously:

- 1000-hr JWST projects swap back/forth between NEP/SEP targets.