The Search for First Light:

James Webb Space Telescope Hardware Update 2016

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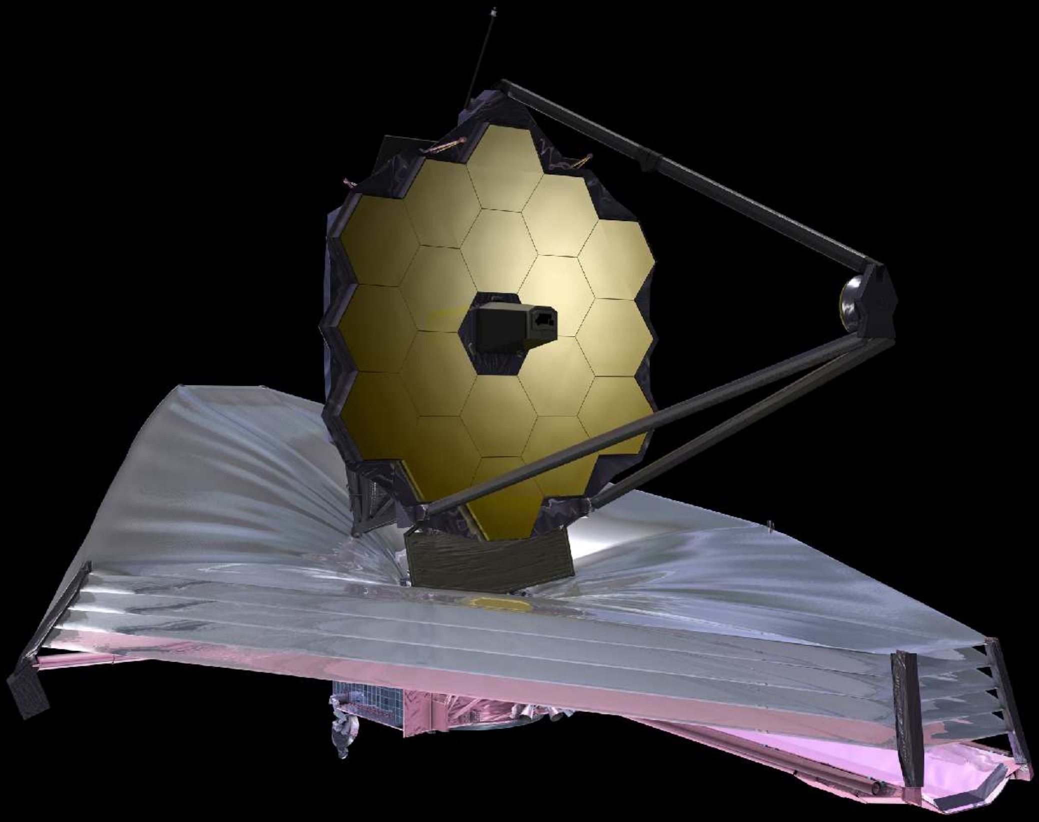


Colloquium at the Department of Physics, University of Oxford,

Oxford, United Kingdom; Monday June 27, 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?

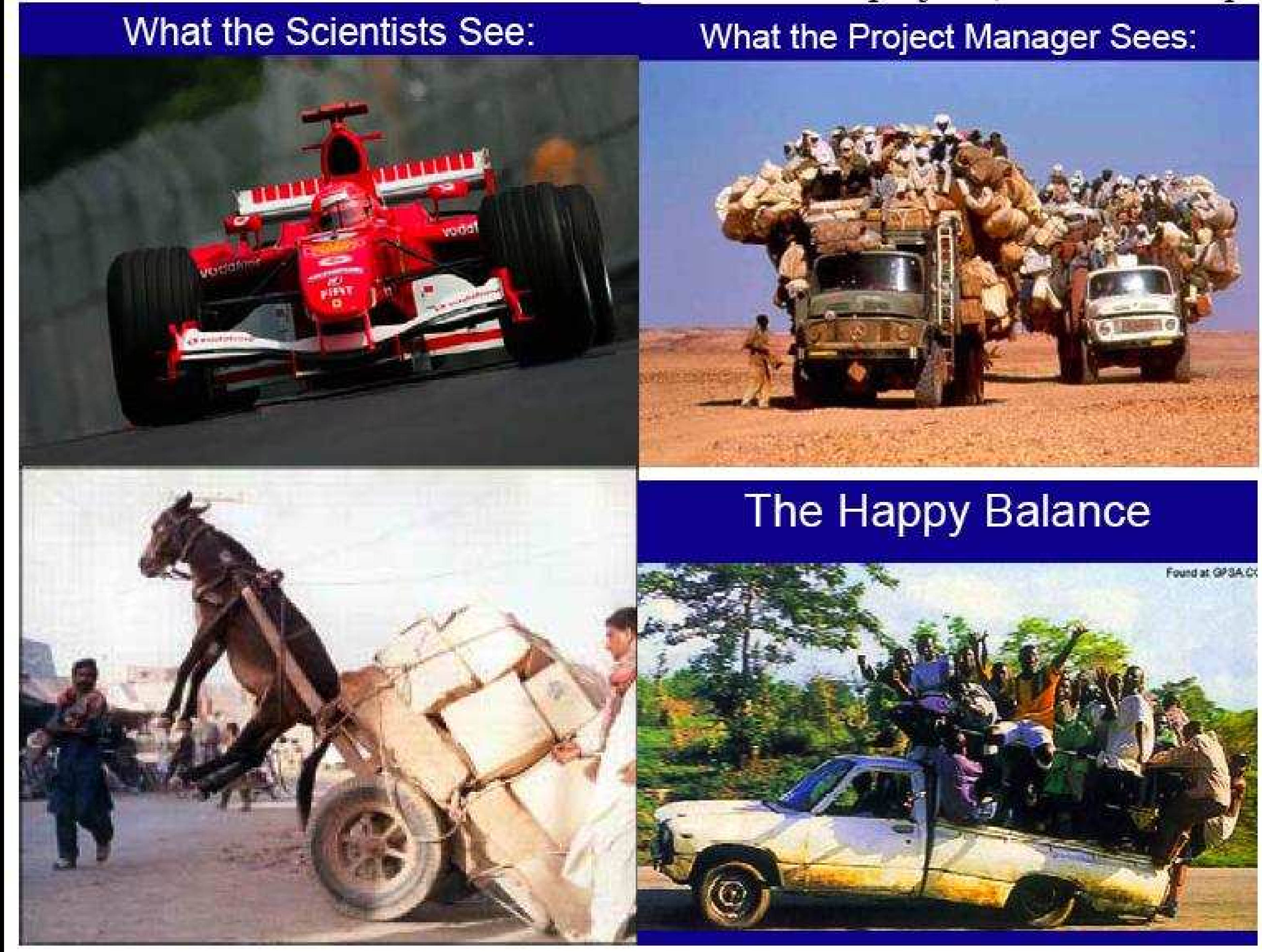
- (3) How will JWST measure the Epoch of First Light (using gravitational lensing) — handshake with Planck 2016 results.

- (4) Summary and Conclusions.

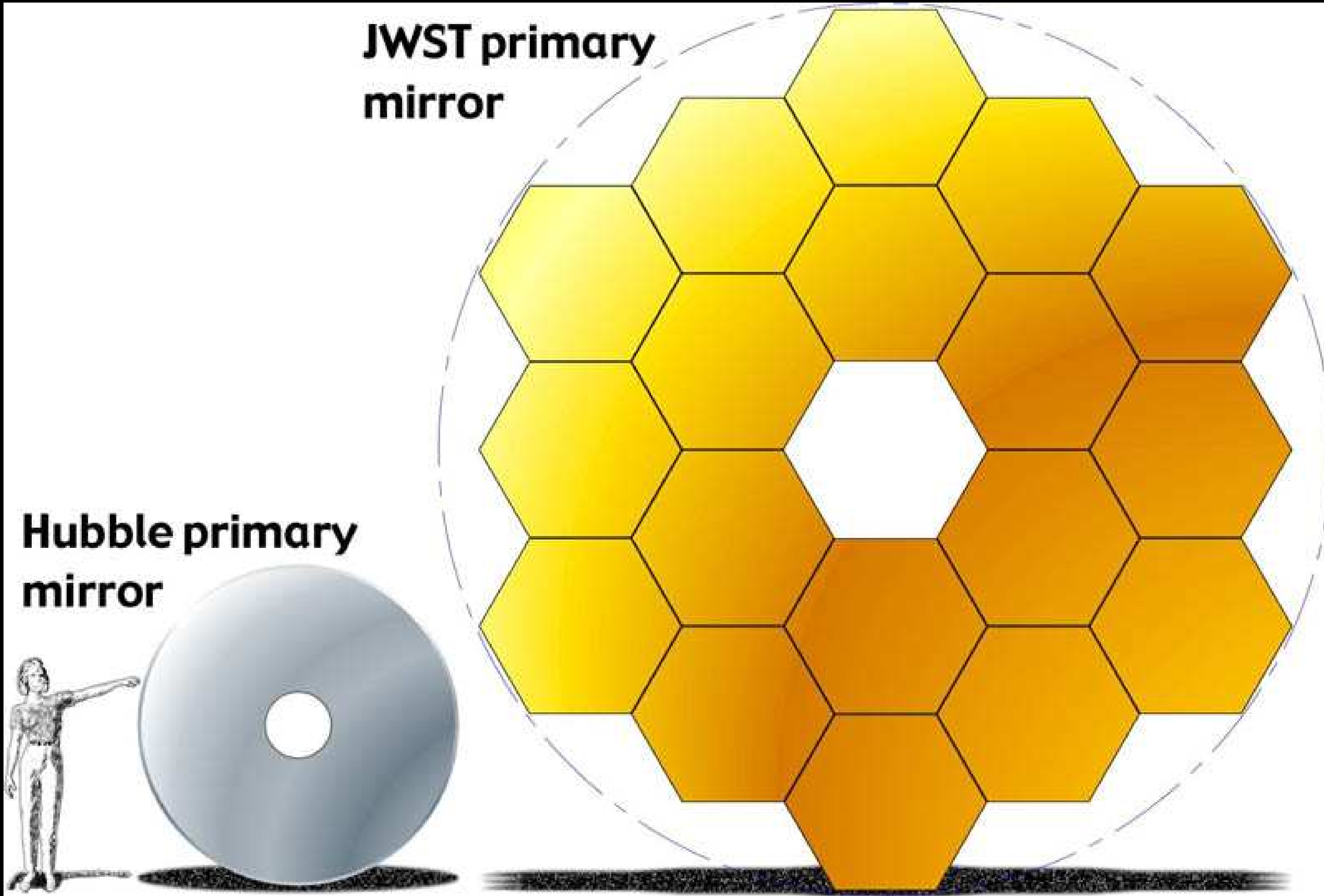
ARIZONA STATE UNIVERSITY

Sponsored by NASA/HST & JWST

Talk is on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/oxford16_jwst.pdf

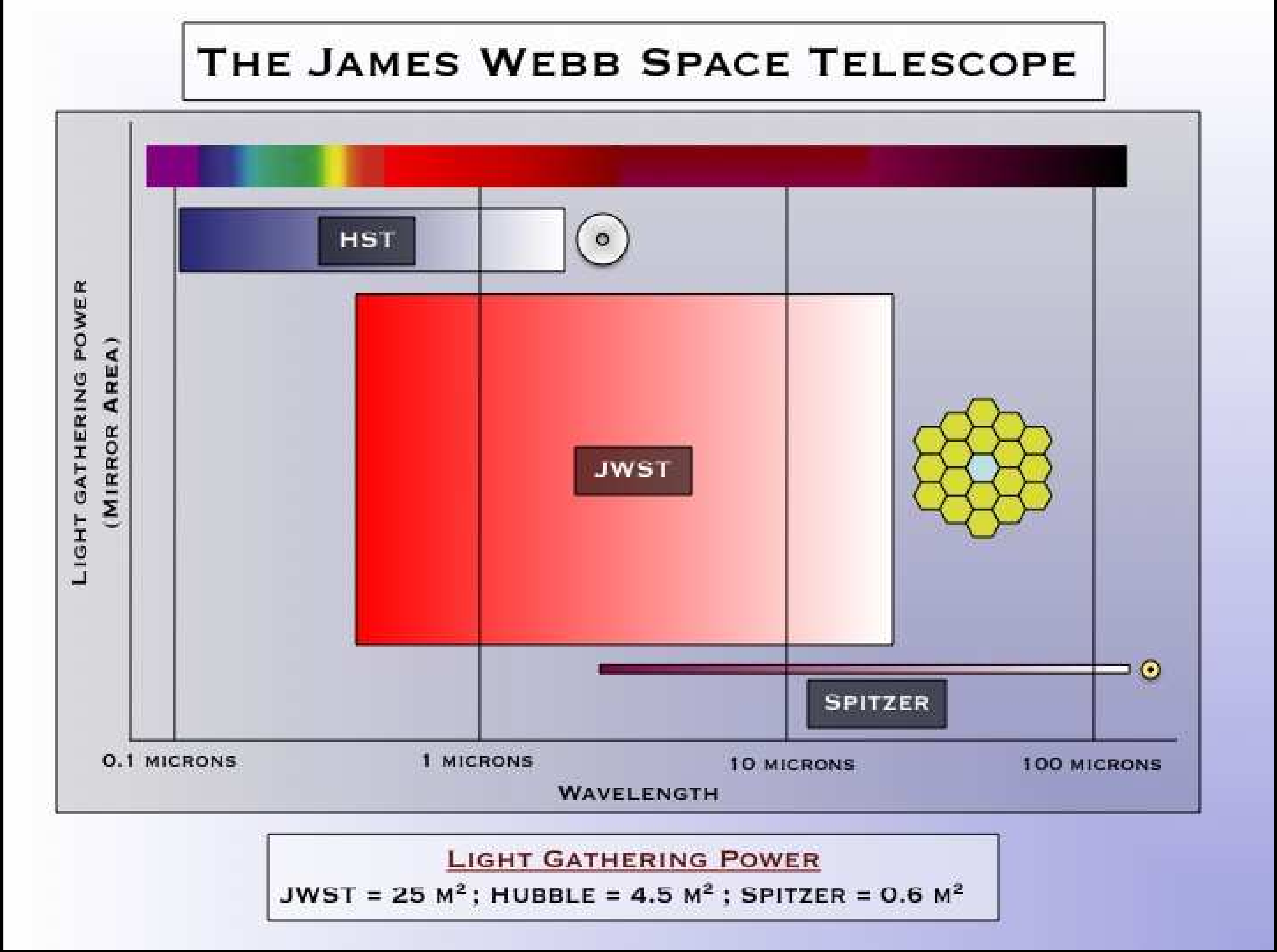


Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).



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

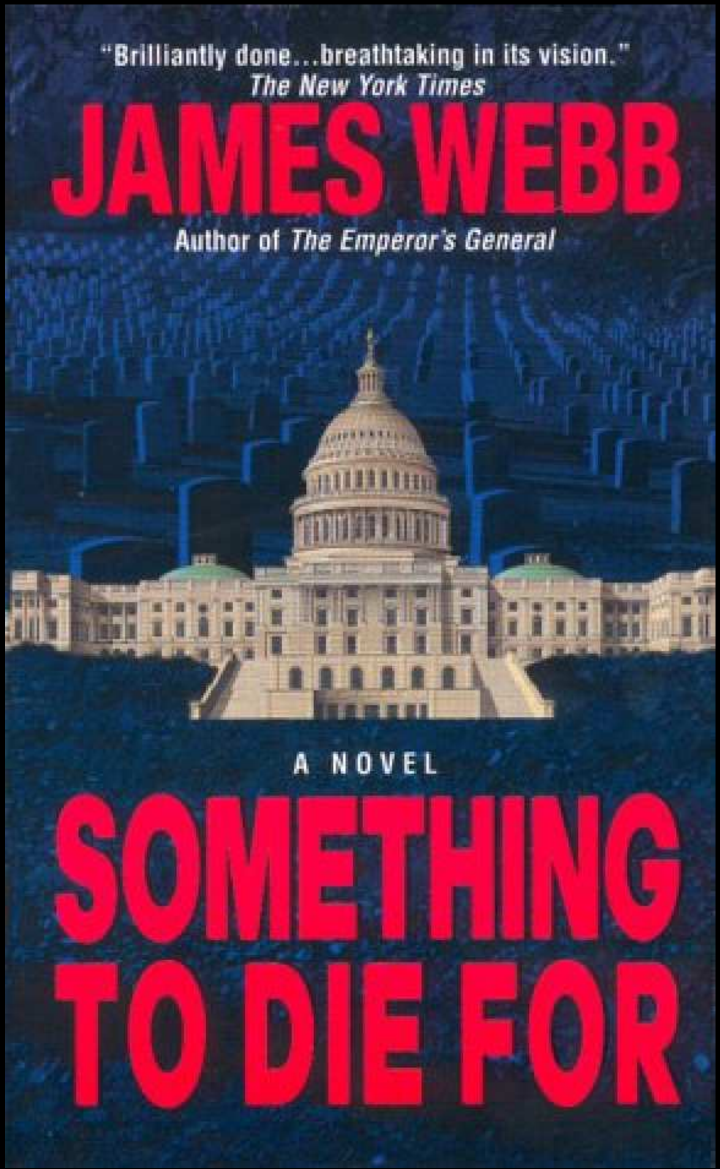
JWST has the same resolution in the near-IR as Hubble in the optical.



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.

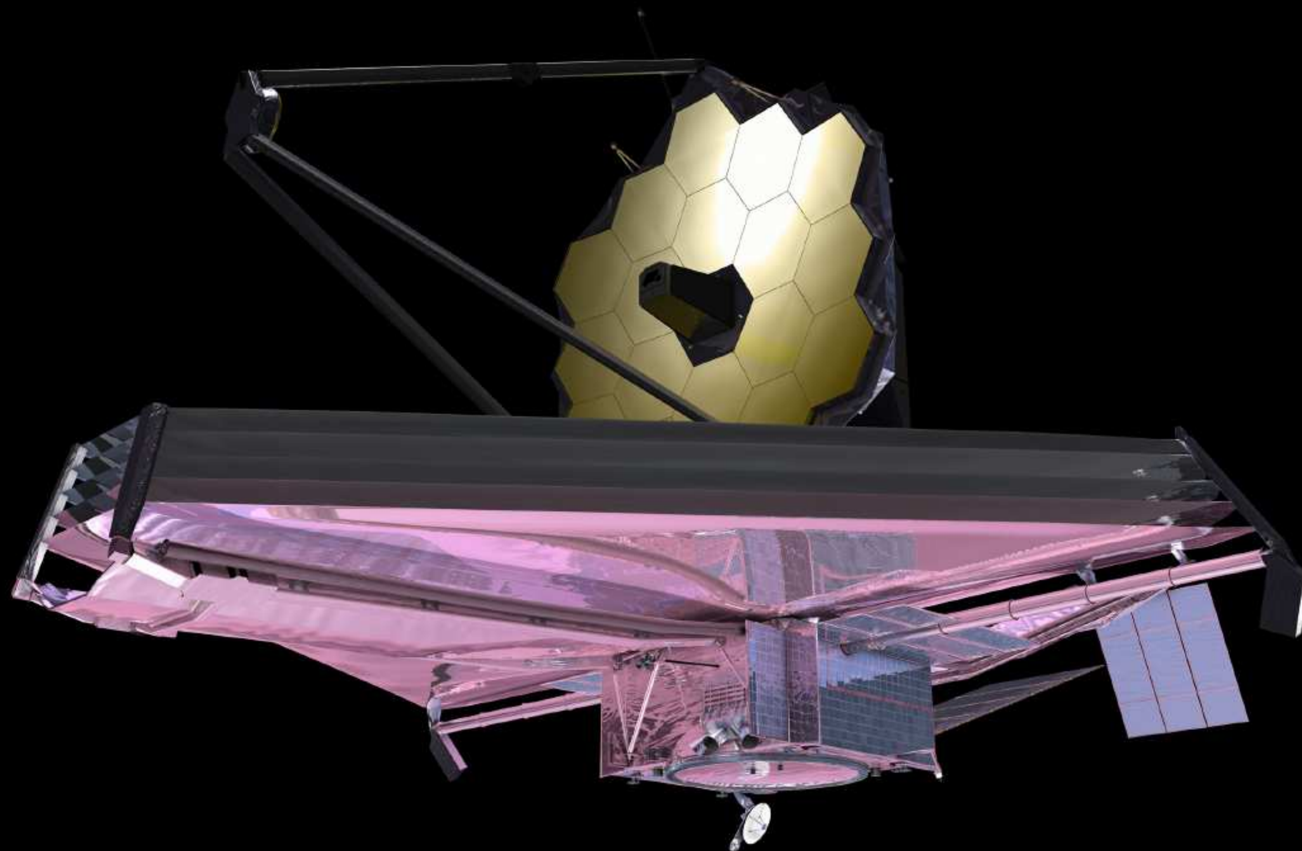
(1) Update of the James Webb Space Telescope (JWST), 2016.



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.

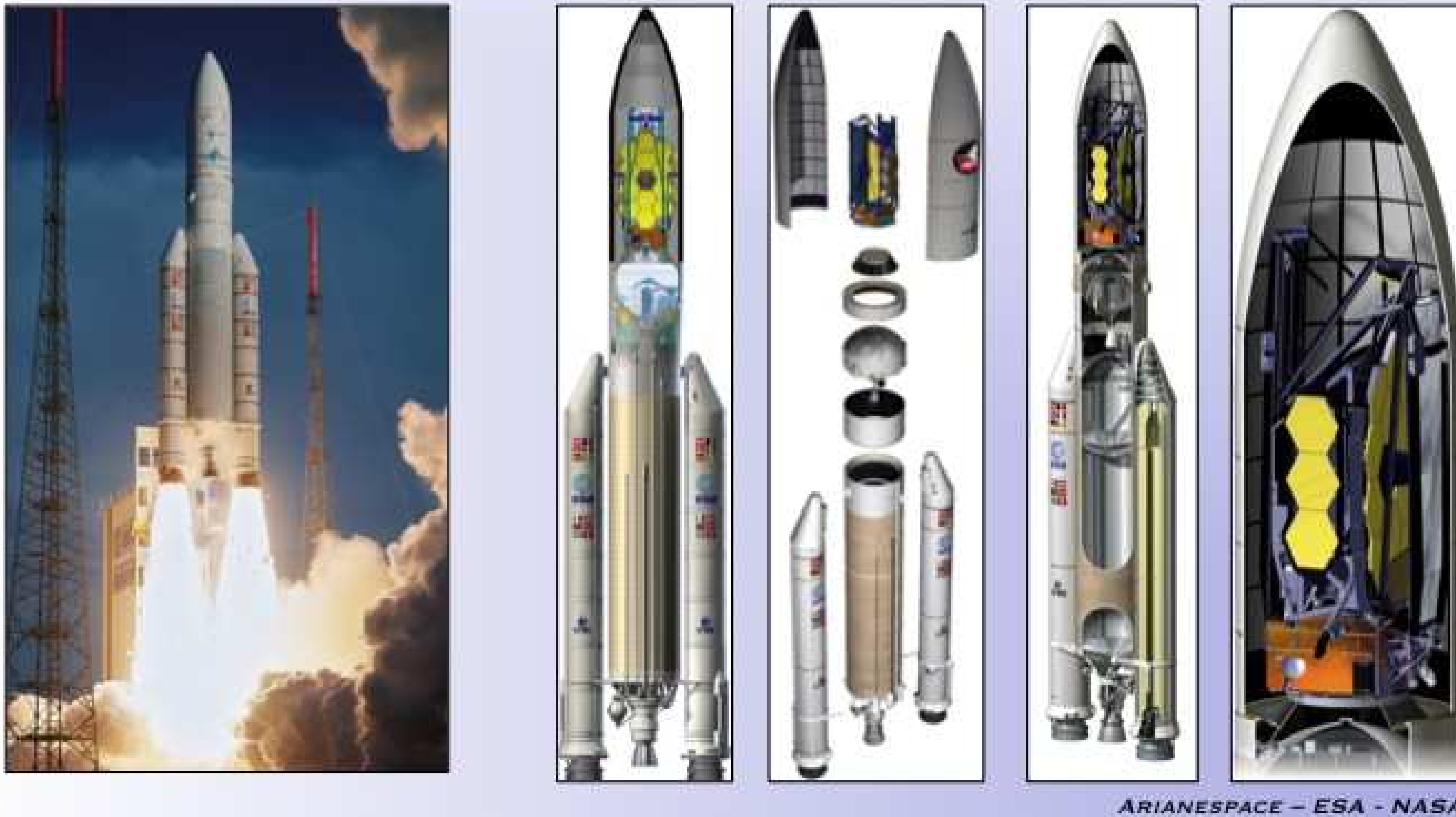


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.

THE JAMES WEBB SPACE TELESCOPE

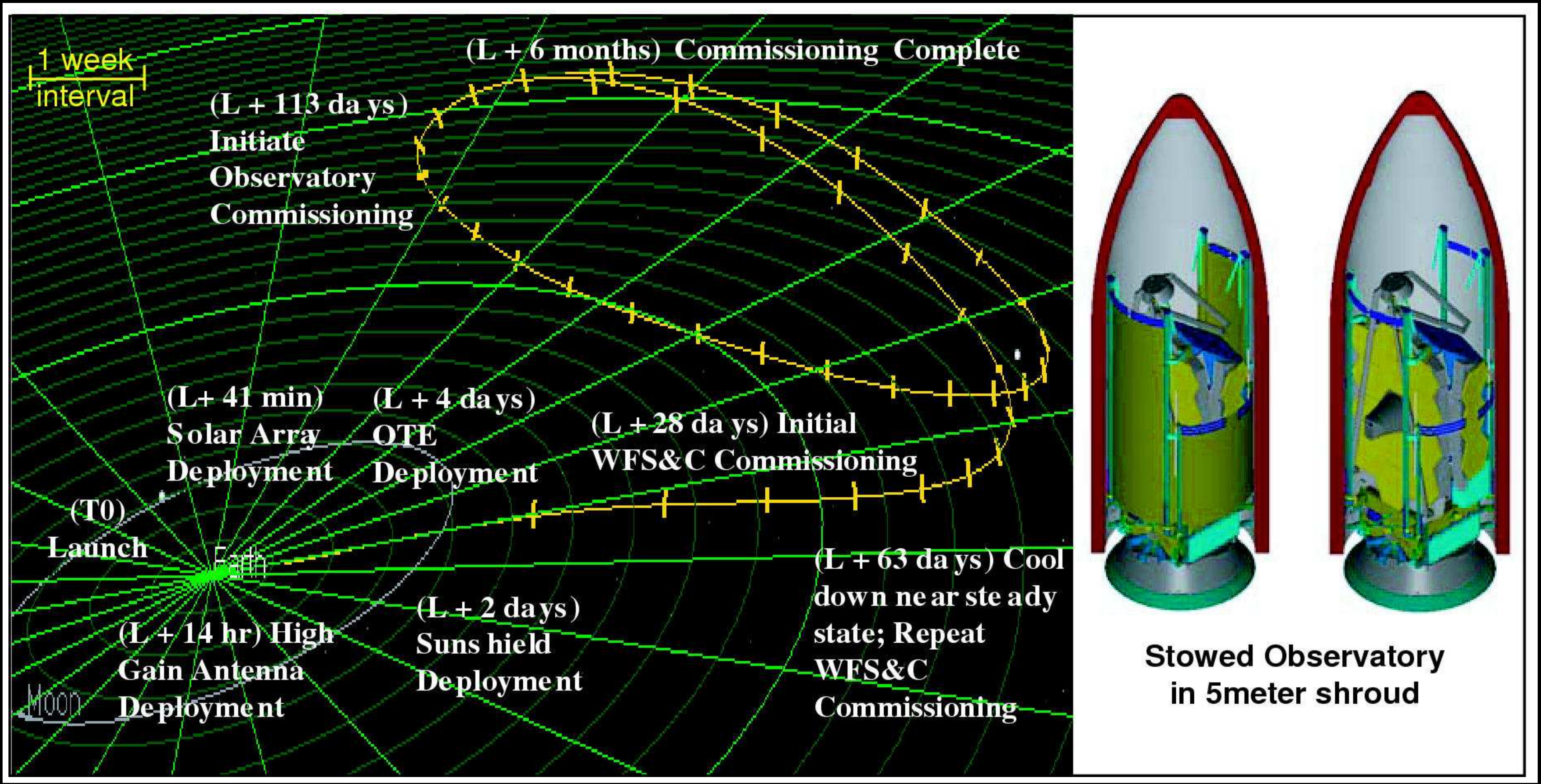
JWST LAUNCH

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



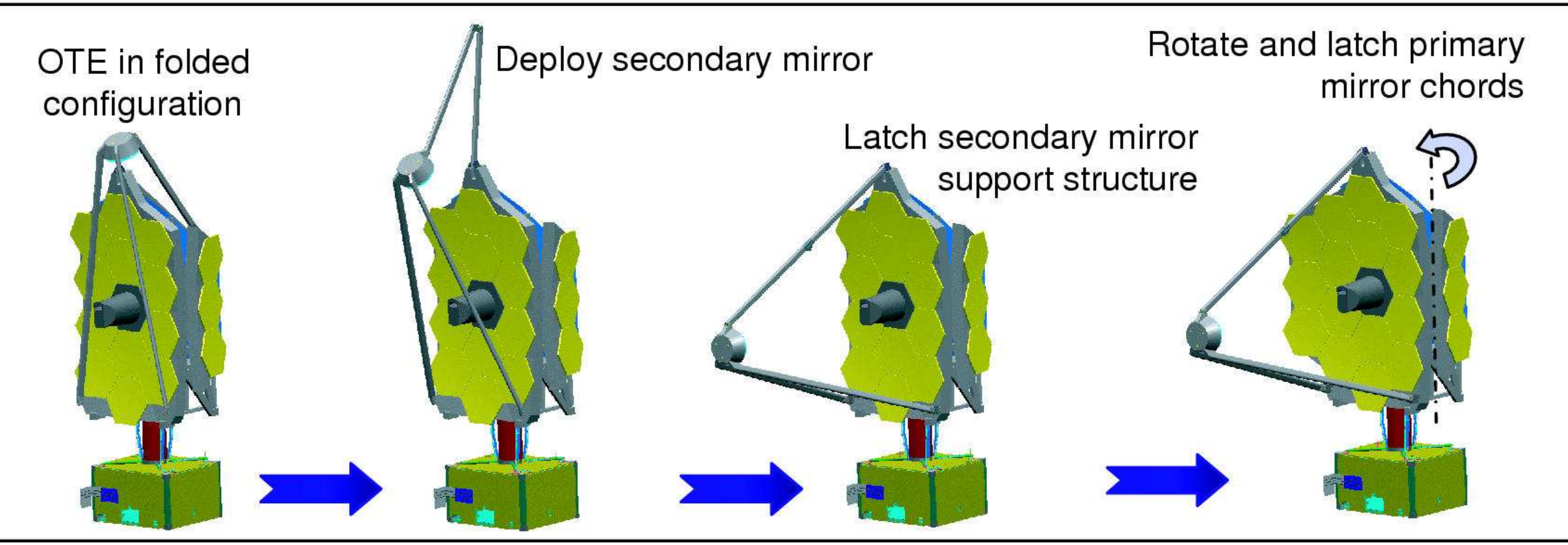
• The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(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.

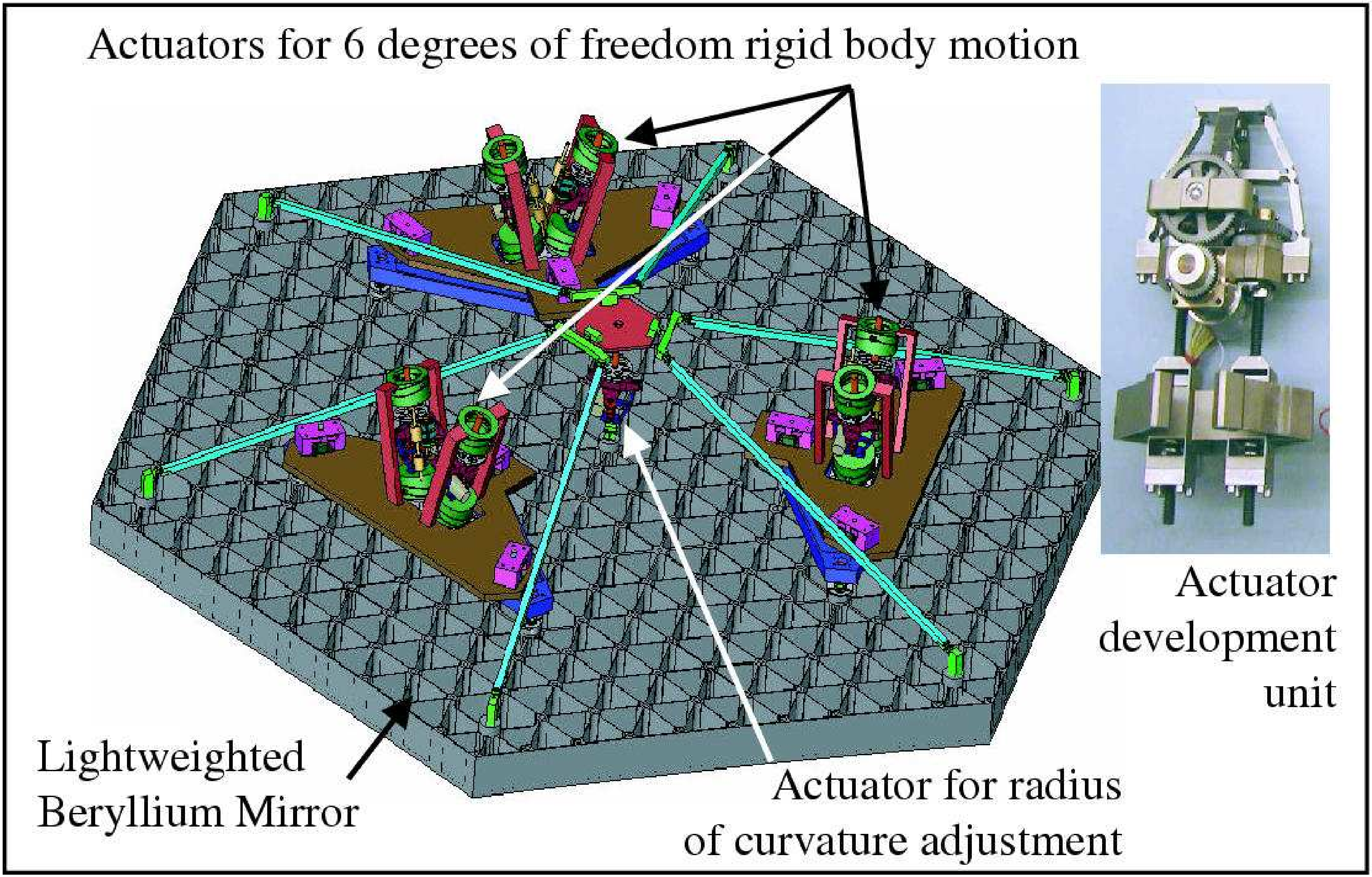
(1b) How will JWST be automatically deployed?



- 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).

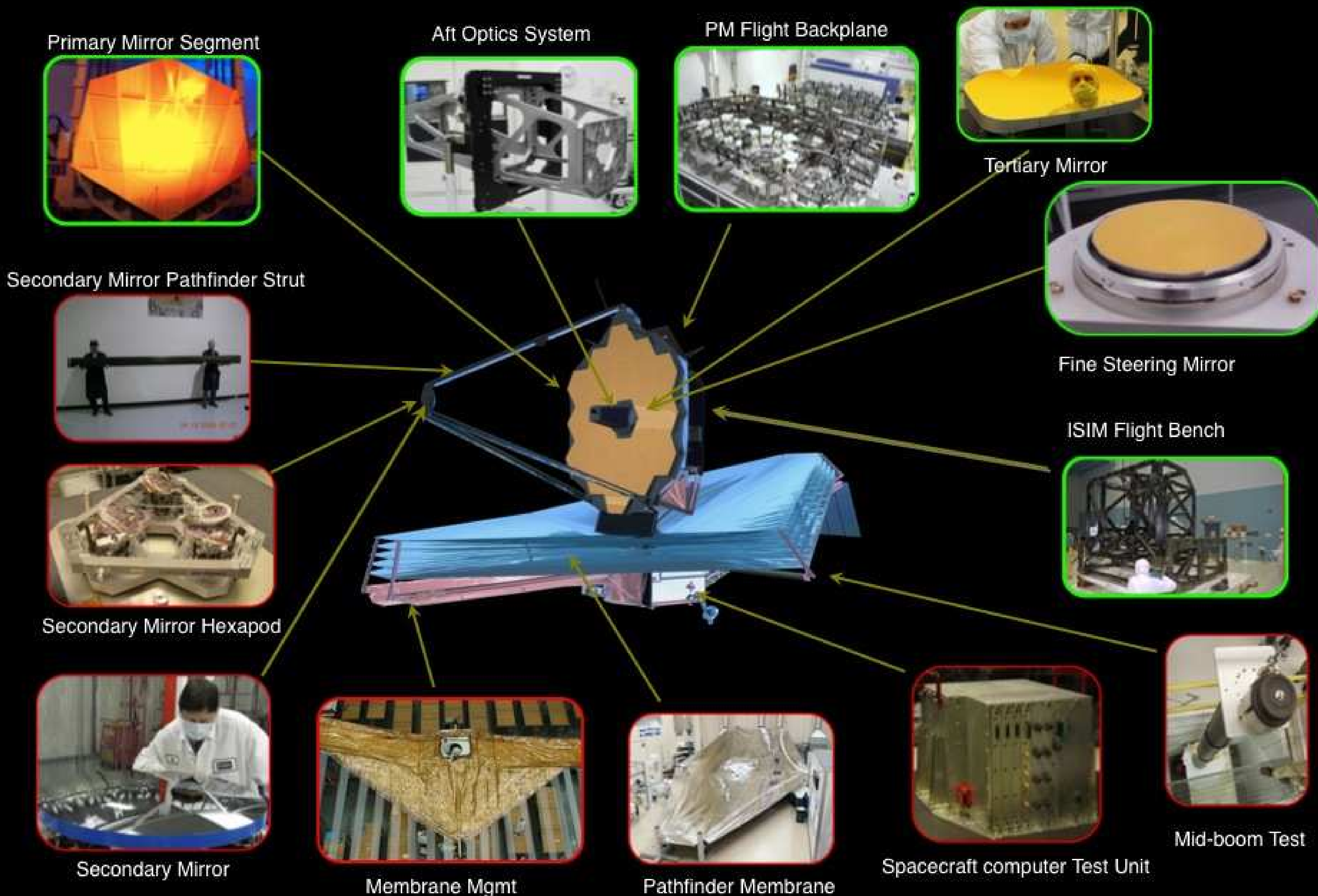
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



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

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

JWST Hardware Status

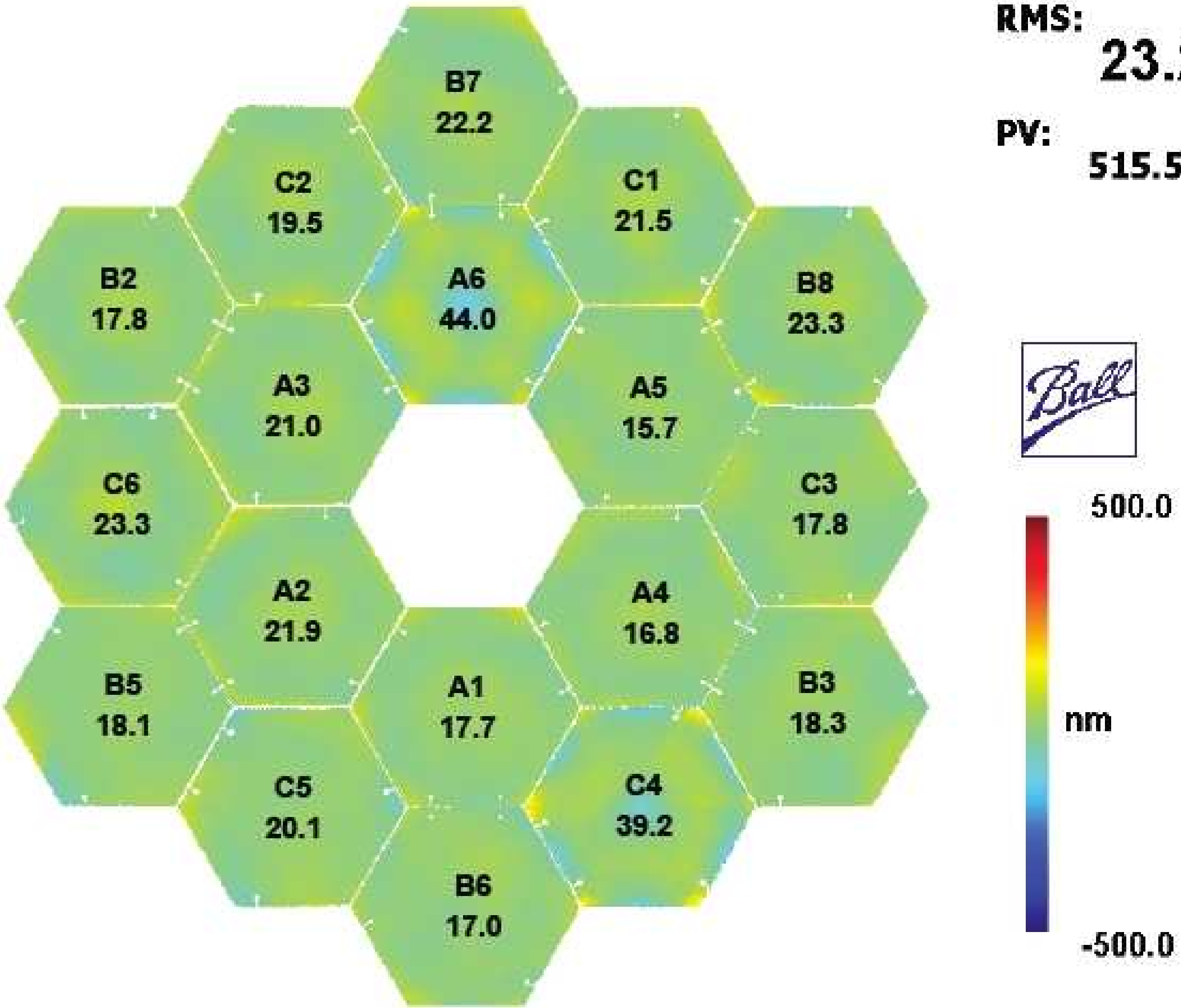


June 2016: $\gtrsim$99% of launch mass designed and built ($\gtrsim$80% weighed).

Mirror Acceptance Testing


Ball

Primary Mirror Composite



RMS: 23.2 nm

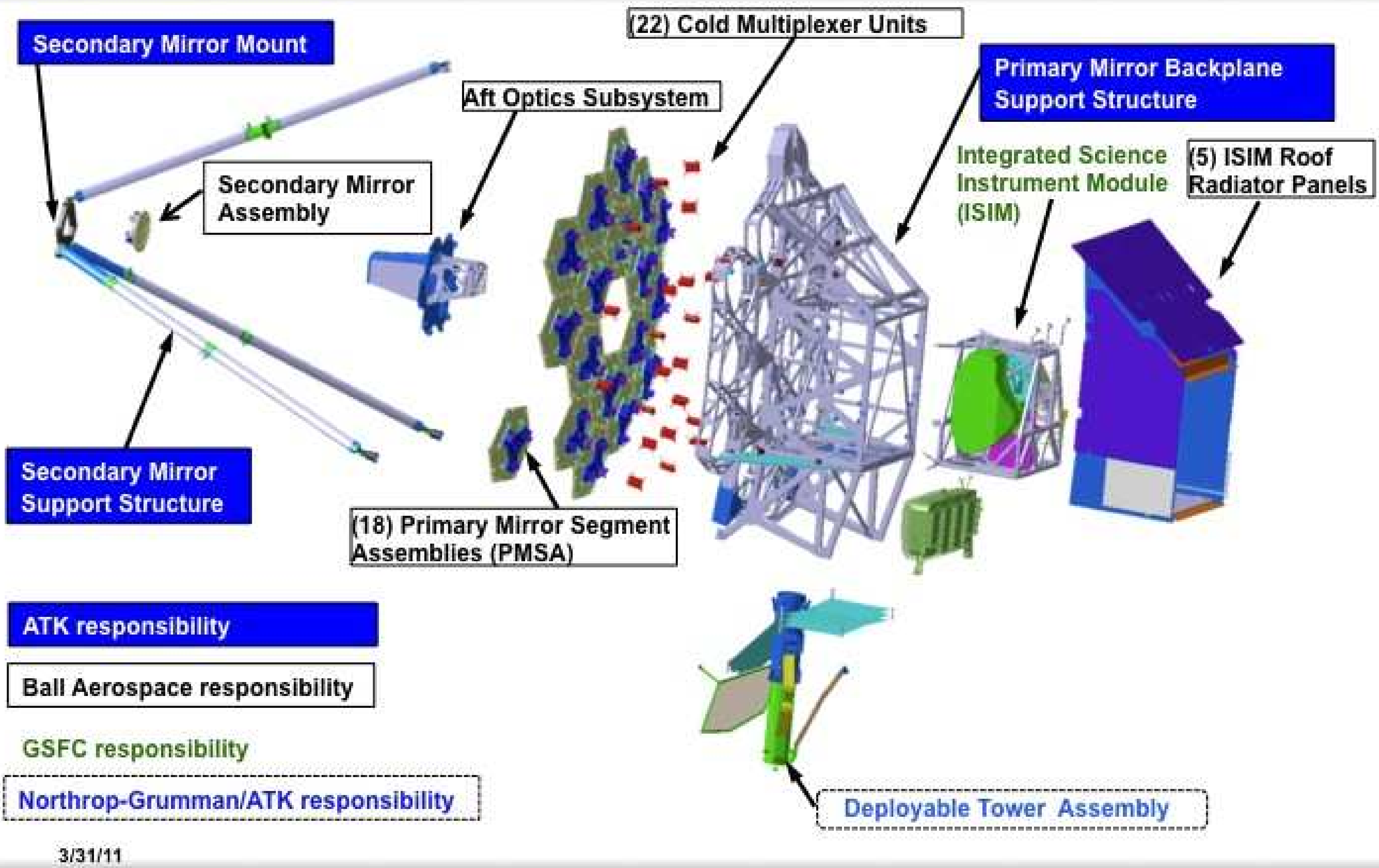
PV: 515.5 nm

Mirror Status

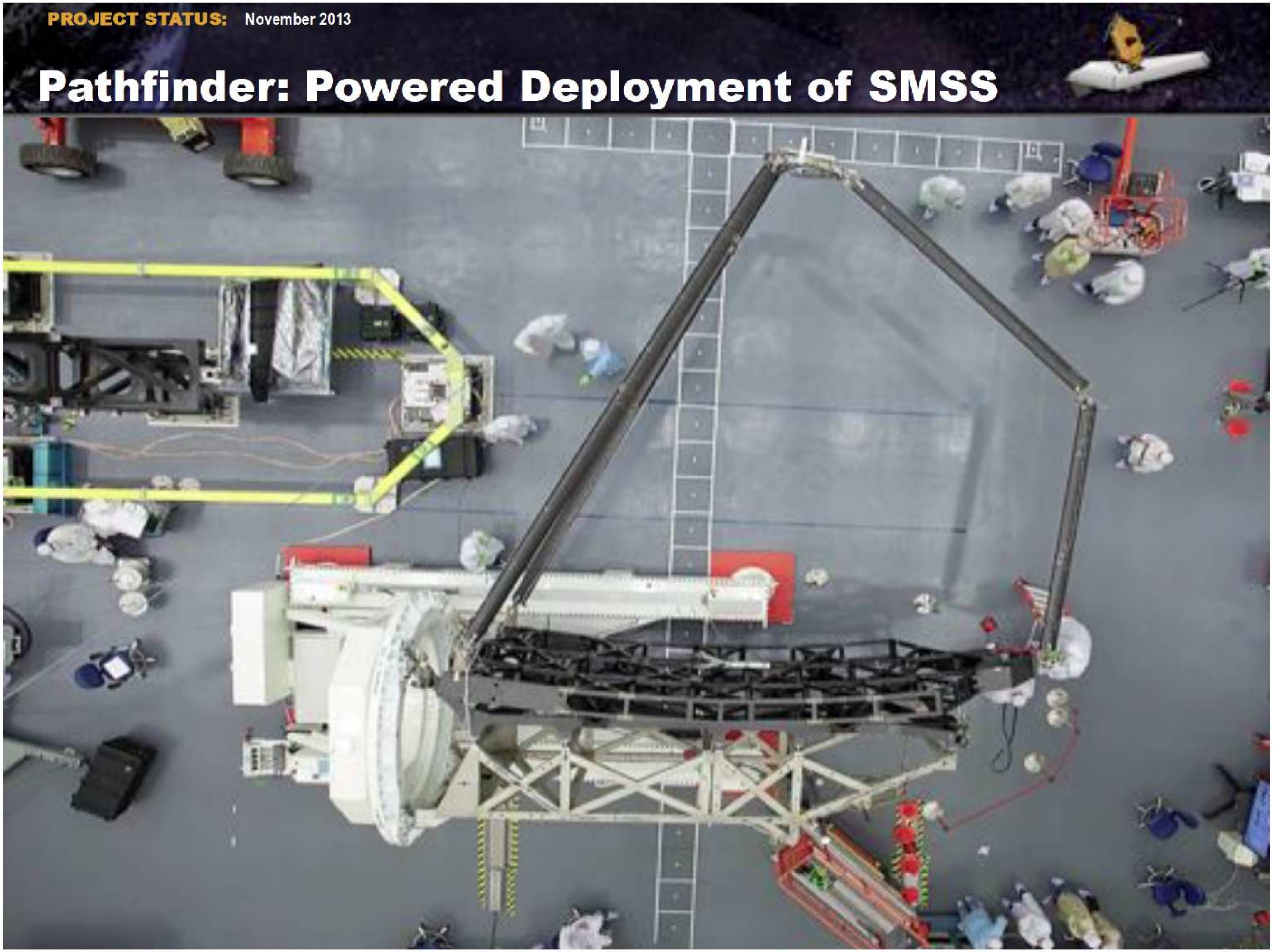
- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC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

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

TELESCOPE ARCHITECTURE



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



July 2014: Secondary Mirror Support deployment successfully tested.

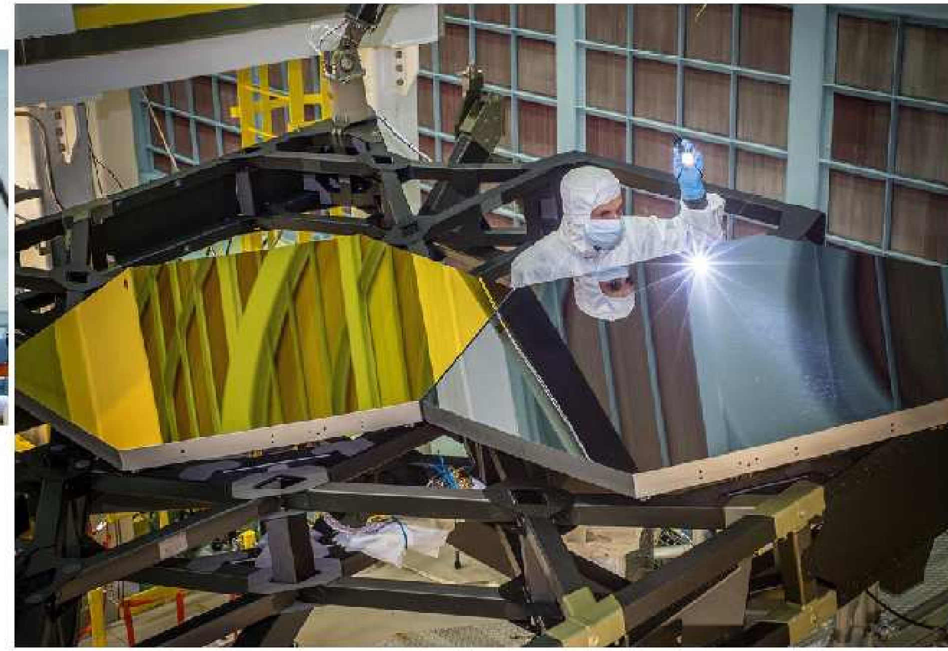
(1c) JWST hardware to date, and how to best use it for high redshift lensing.

[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.

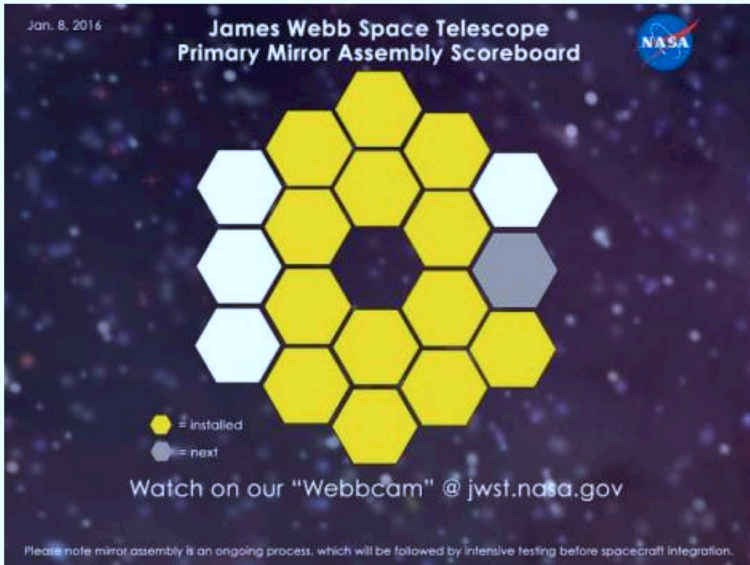
- Our Galaxy is a bright IR source at $\lambda \gtrsim 1$–5μm: In certain directions of the sky, some straylight can hit secondary mirror via Sunshield.
- This can effect JWST (lensing) studies of First Light objects.

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

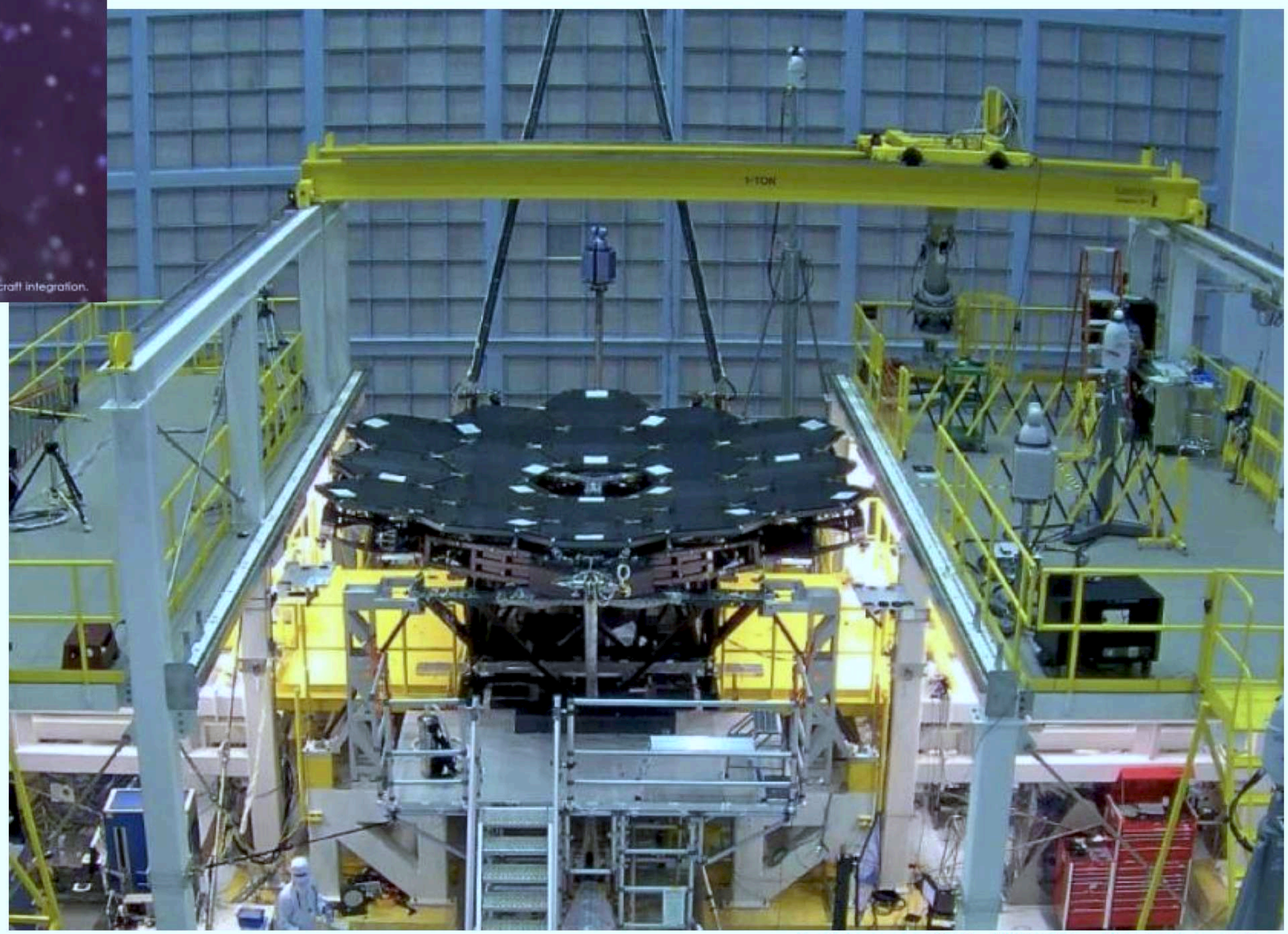
Much progress has been made in OTE integration



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!

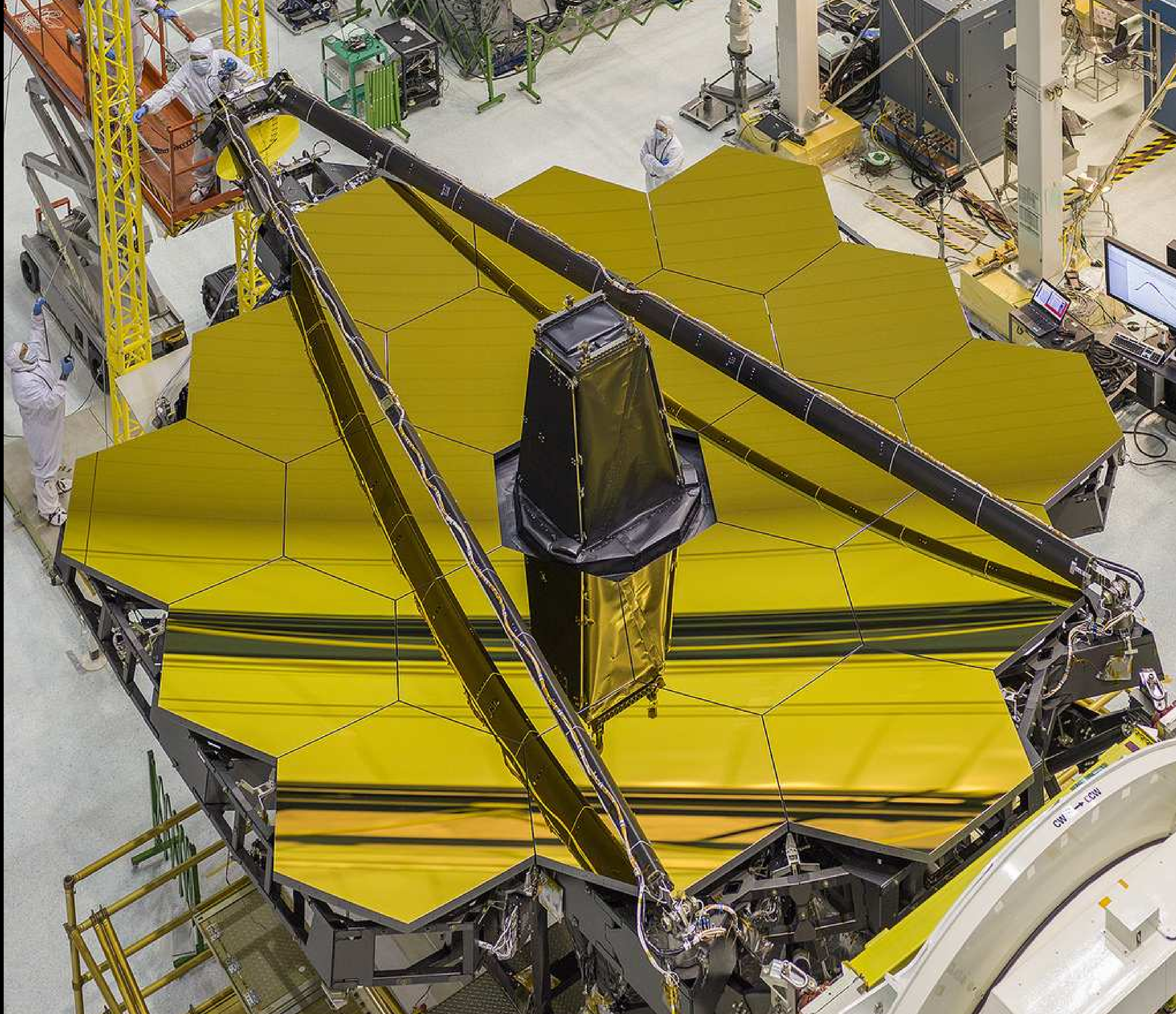


JWST lifetime: Requirement: 5 yrs; Goal: 10 yrs; Propellant: 14 yrs.

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

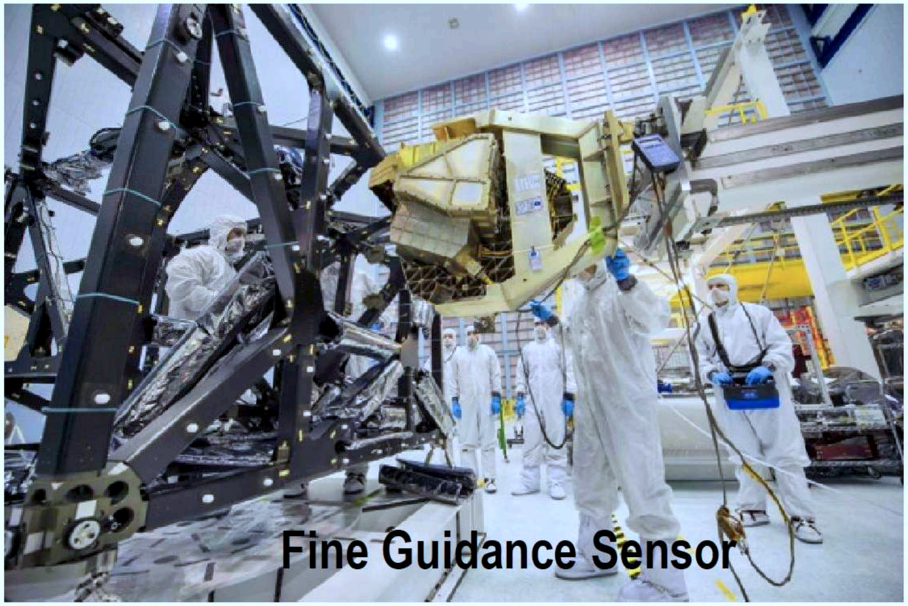
May 2016: JWST being tilted into the right position

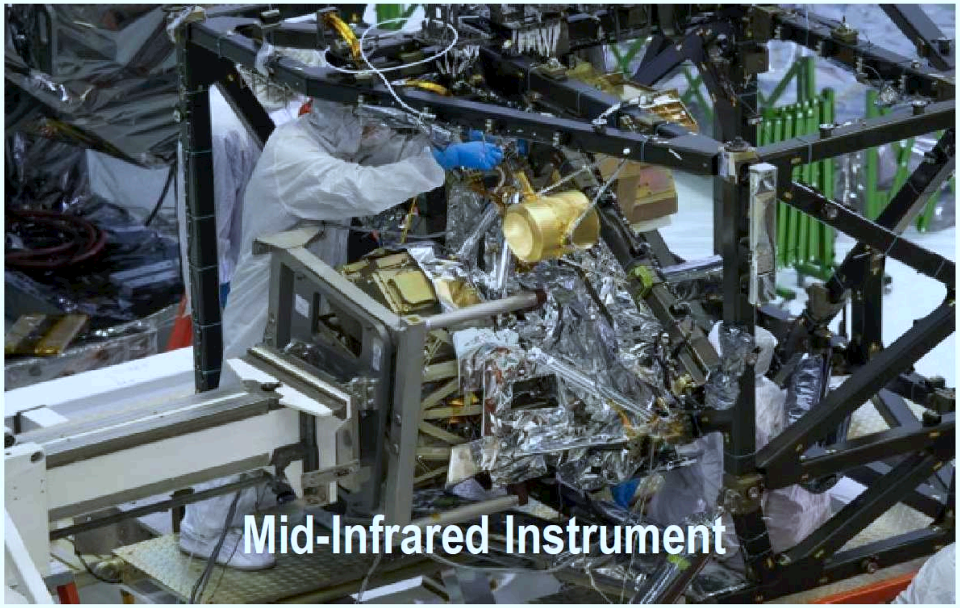
May 2016: Webb mirrors finally mounted and ready!



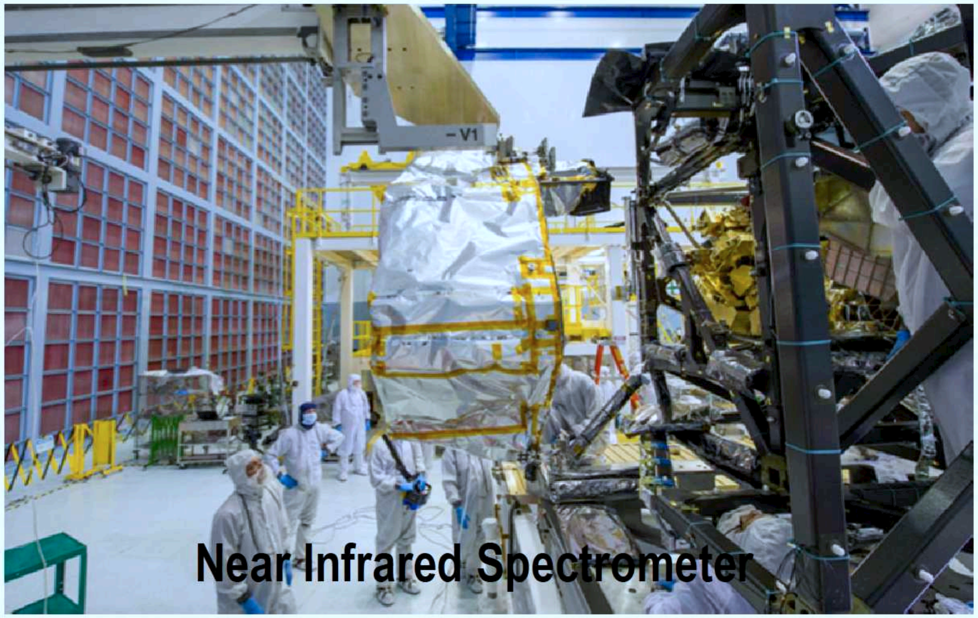
May 2016: JWST stowed for further instrument mounting

All Instruments Integrated


Fine Guidance Sensor


Mid-Infrared Instrument


Near Infrared Camera

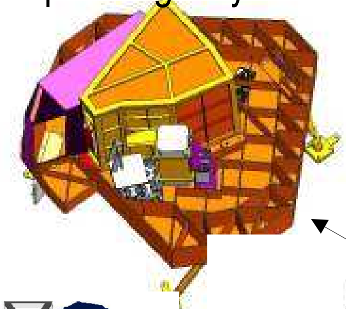

Near Infrared Spectrometer

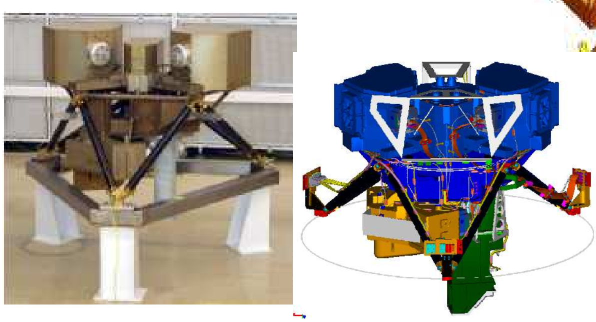
(1d) JWST instruments: USA (UofA, JPL), ESA, & CSA.

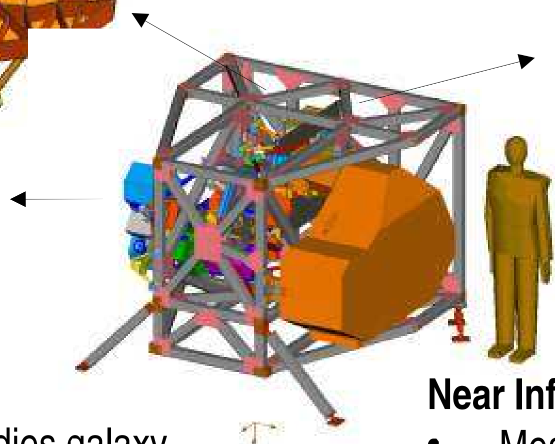
Instrument Overview

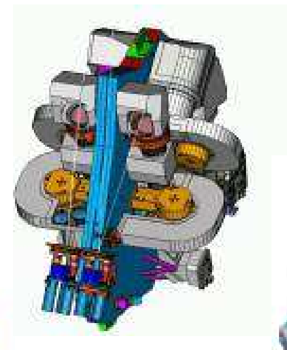
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

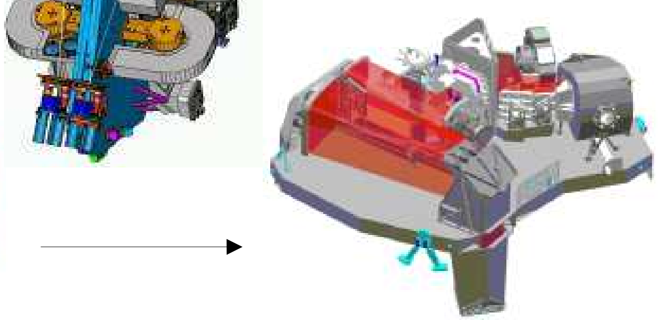
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC





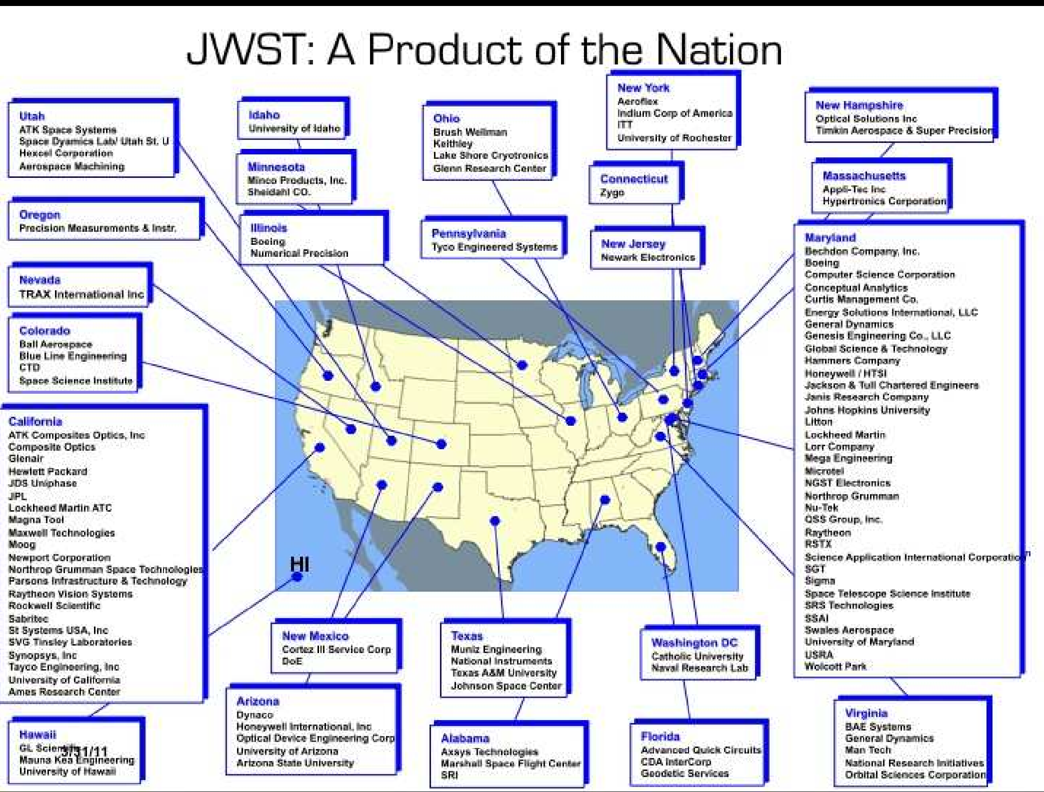


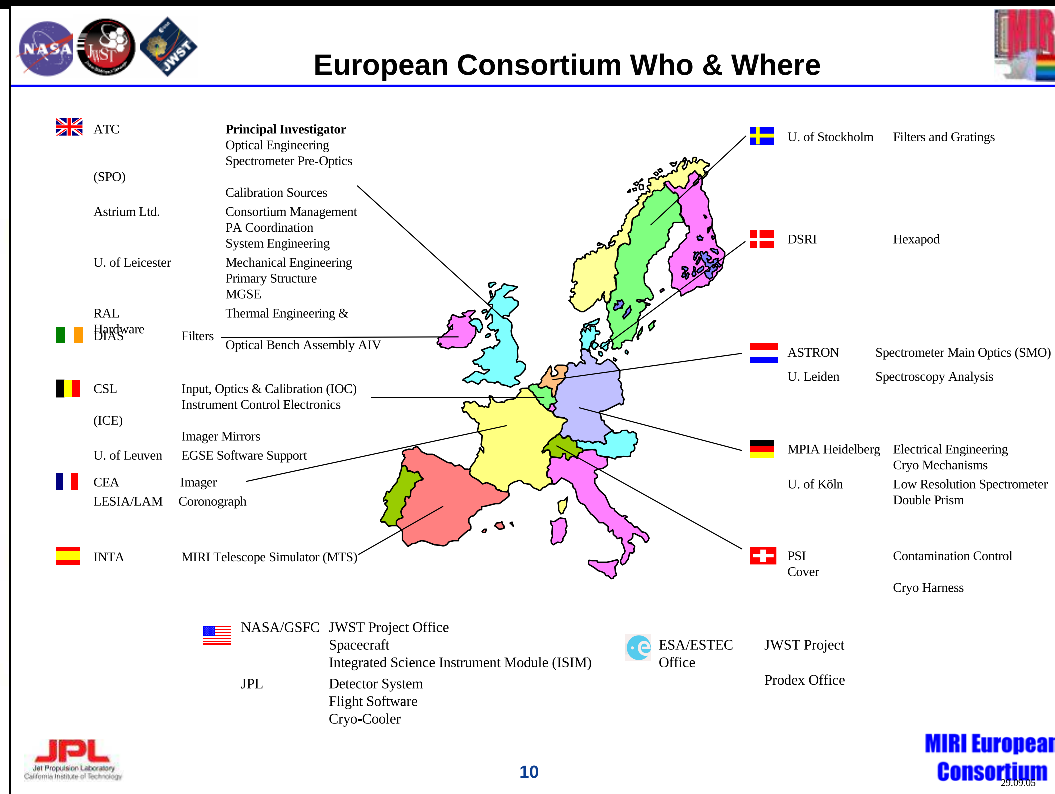




Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

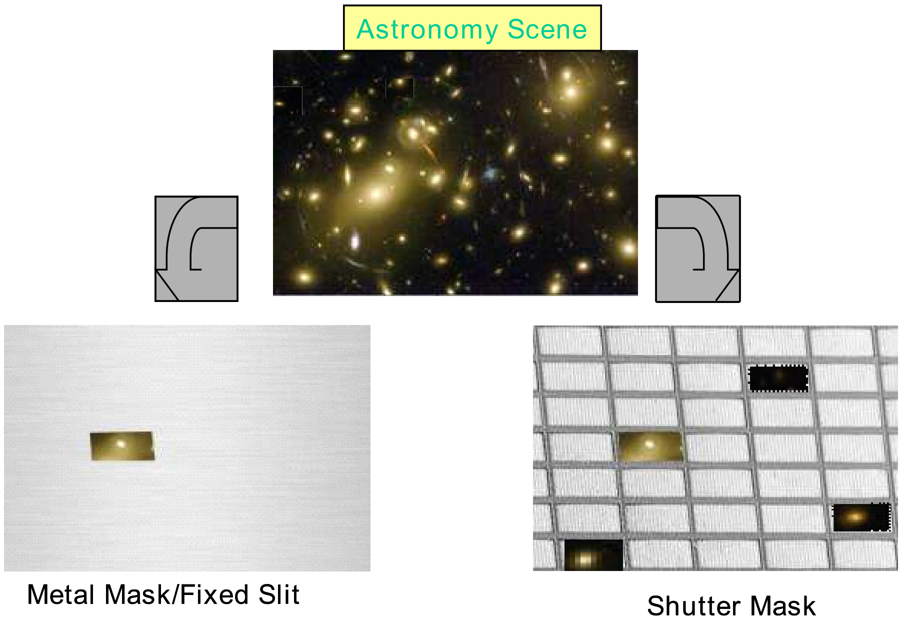


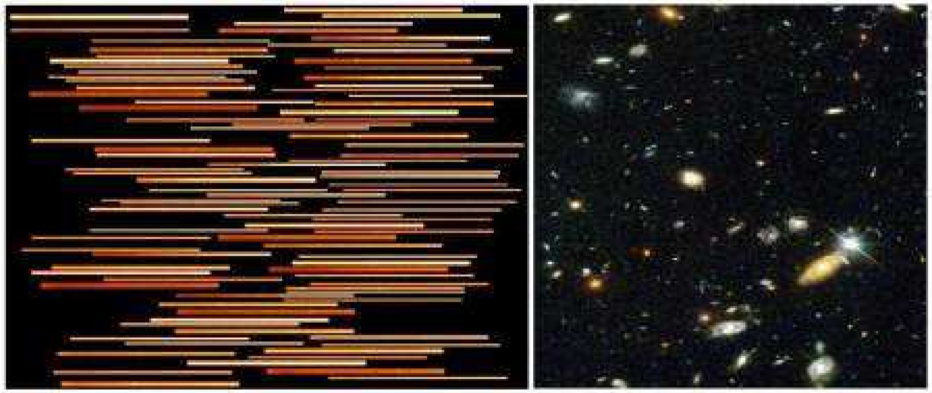


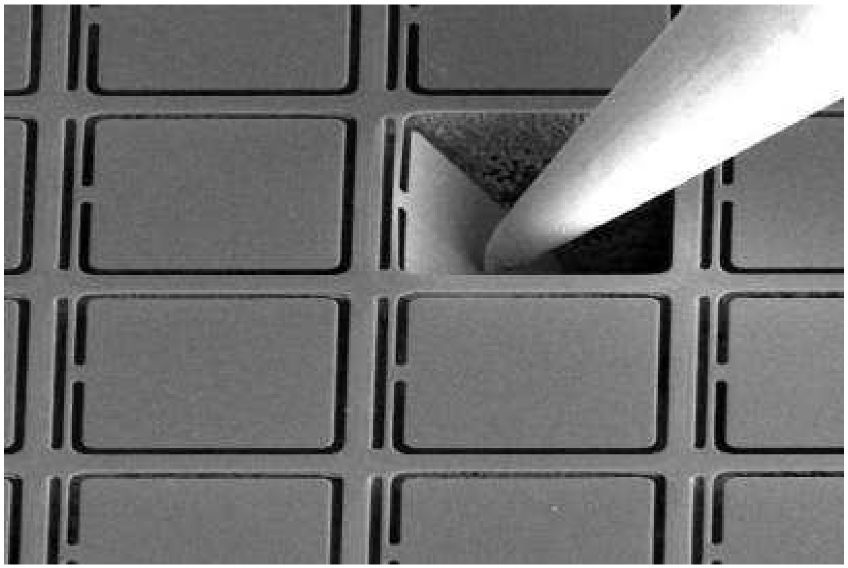
- JWST hardware made in 27 US States: $\gtrsim$99% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

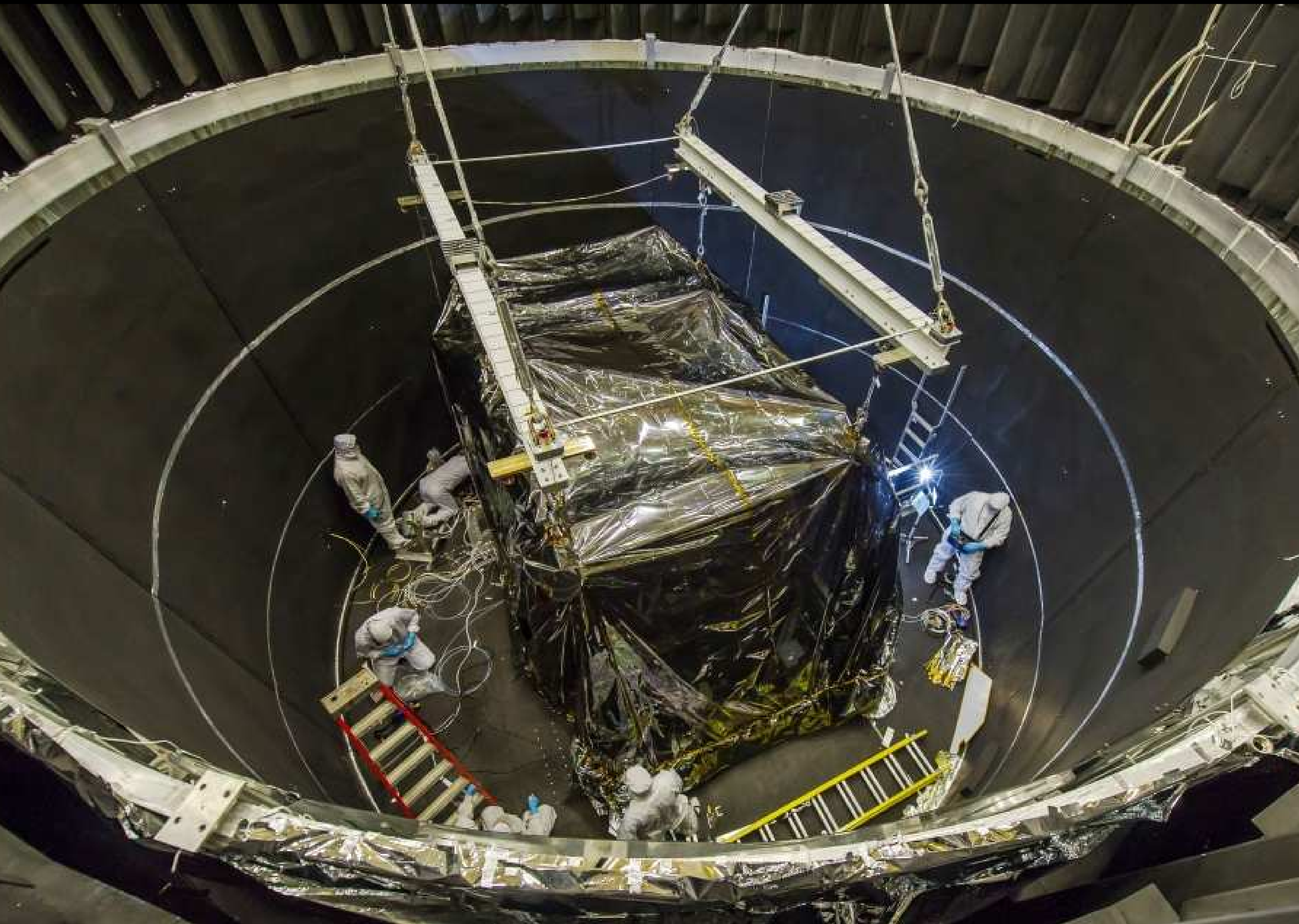
This nationwide + international coalition was critical for project survival!

Micro Shutters





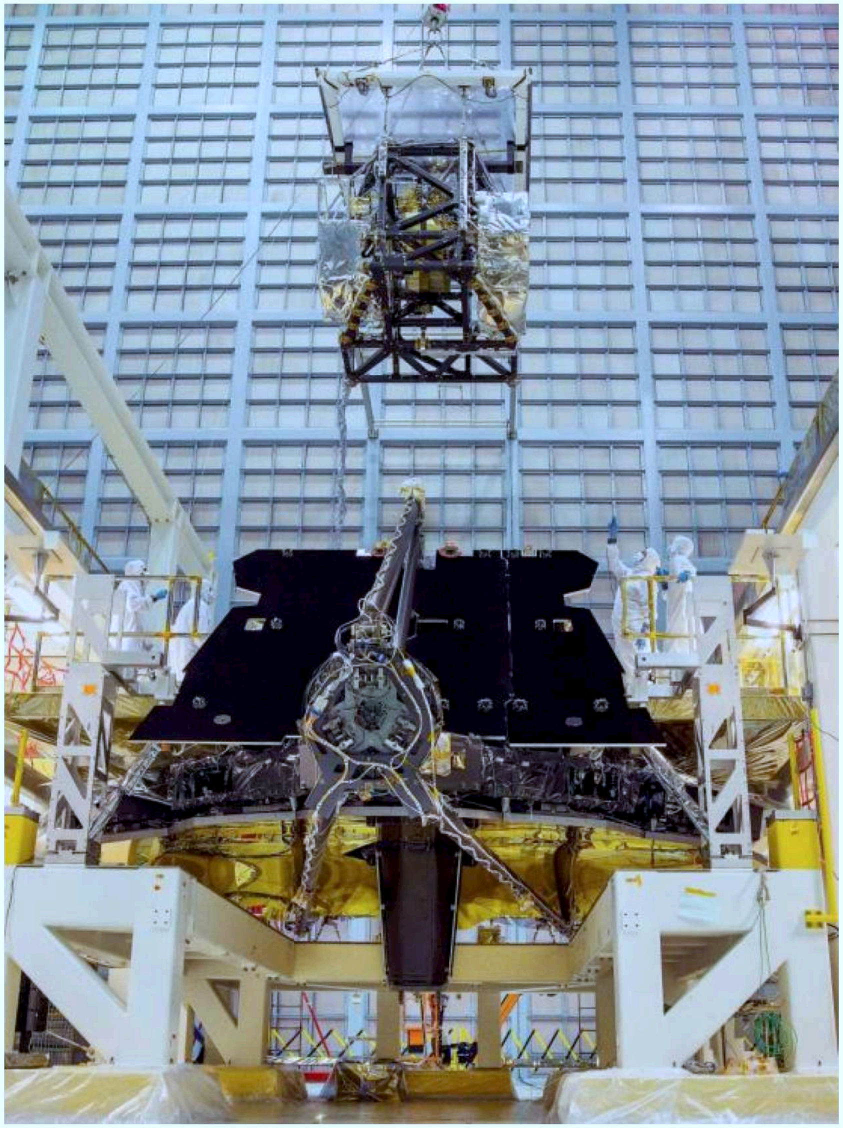


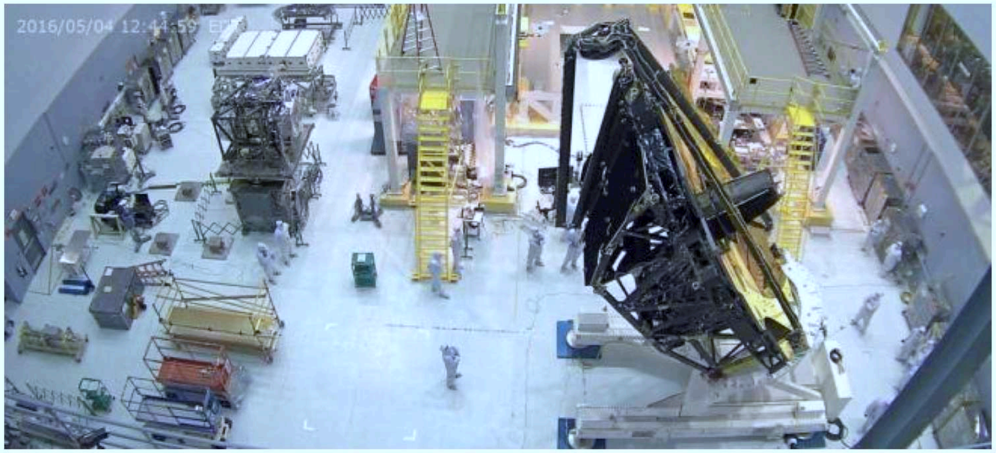


2014: Flight ISIM (all 4 instruments) in test. Oct. 15–Feb. 2016: CryoVac3.

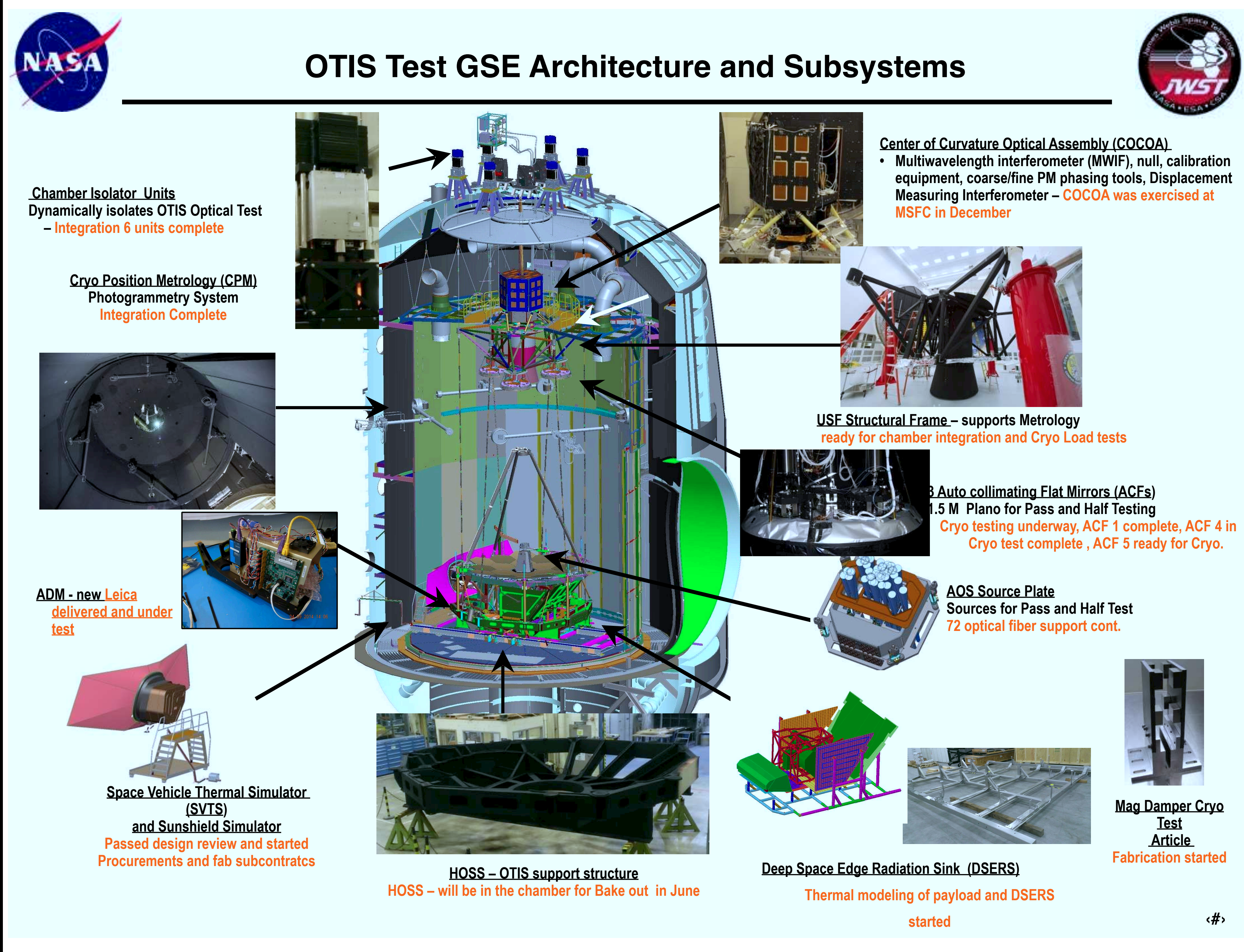
Program Update: OTE + ISIM = OTIS

NORTHROP GRUMMAN



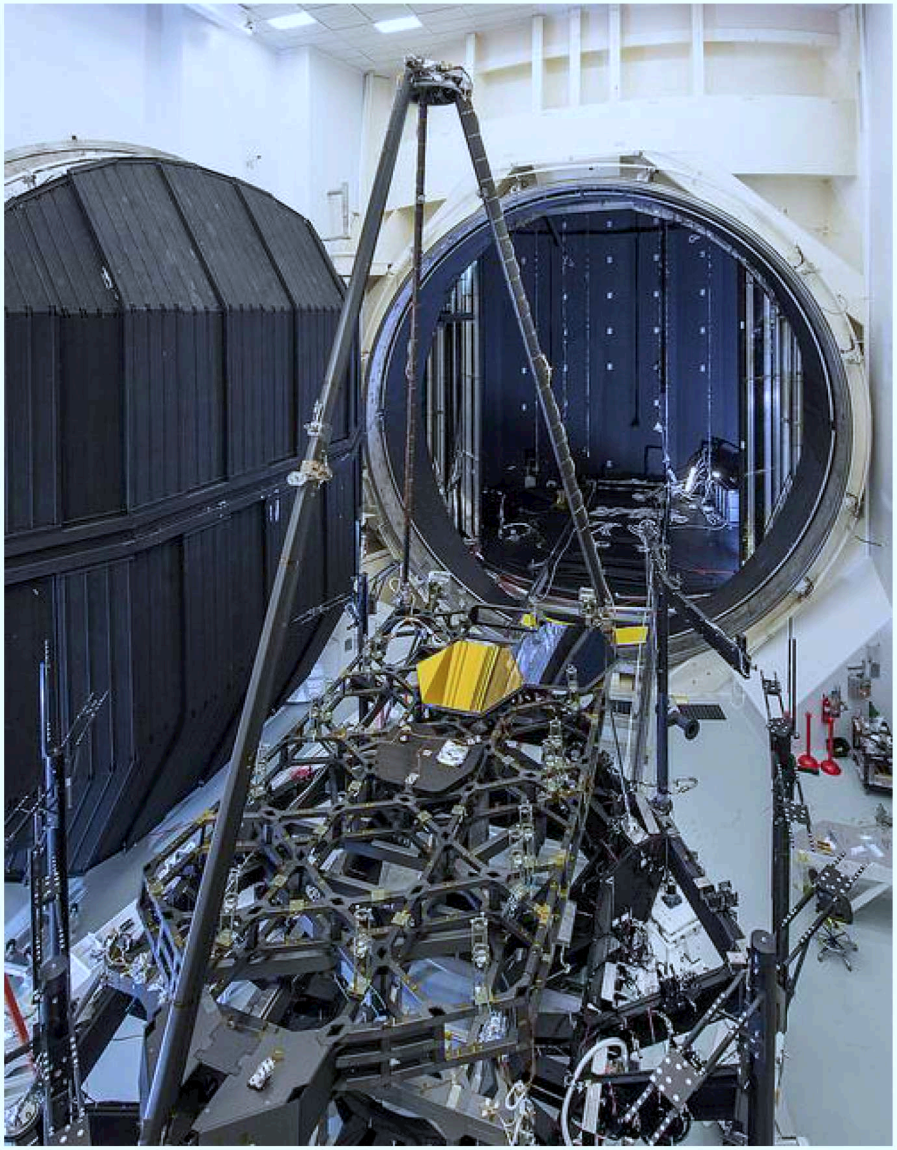


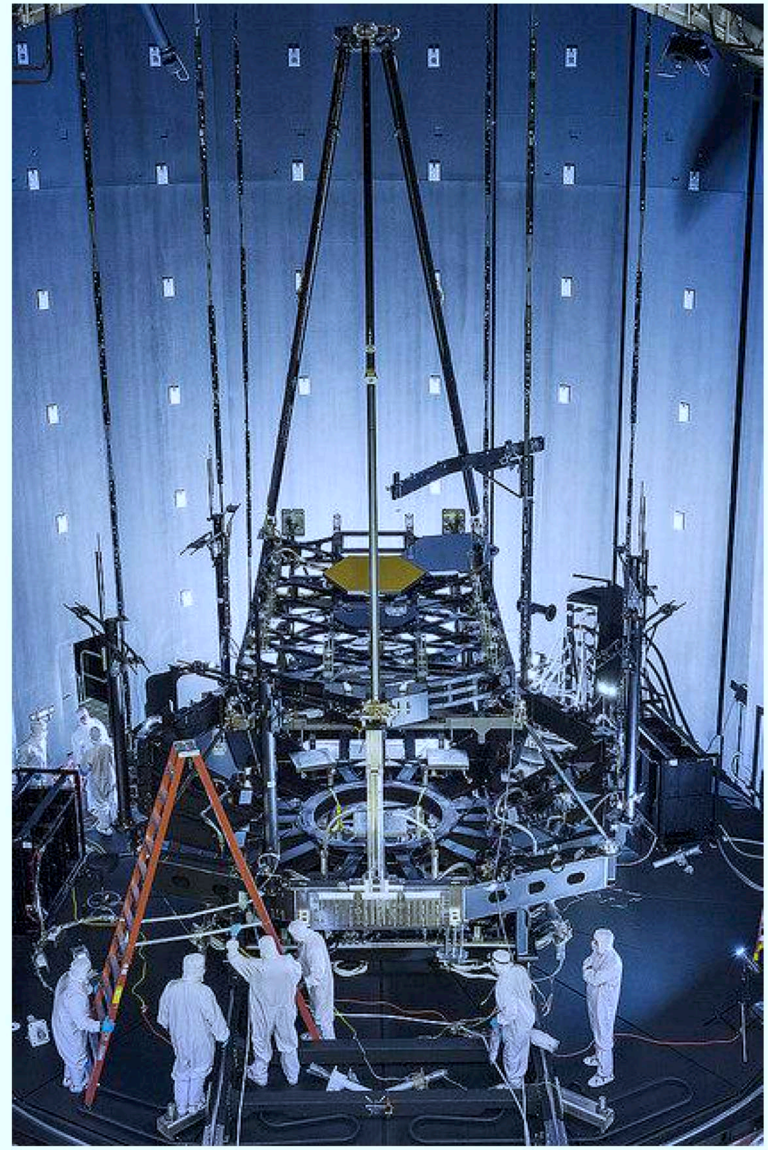
June 2016: Flight ISIM mated with Optical Telescope Element (OTE). JWST is now a real working telescope (albeit not yet at 40 K & in 0 G)!



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

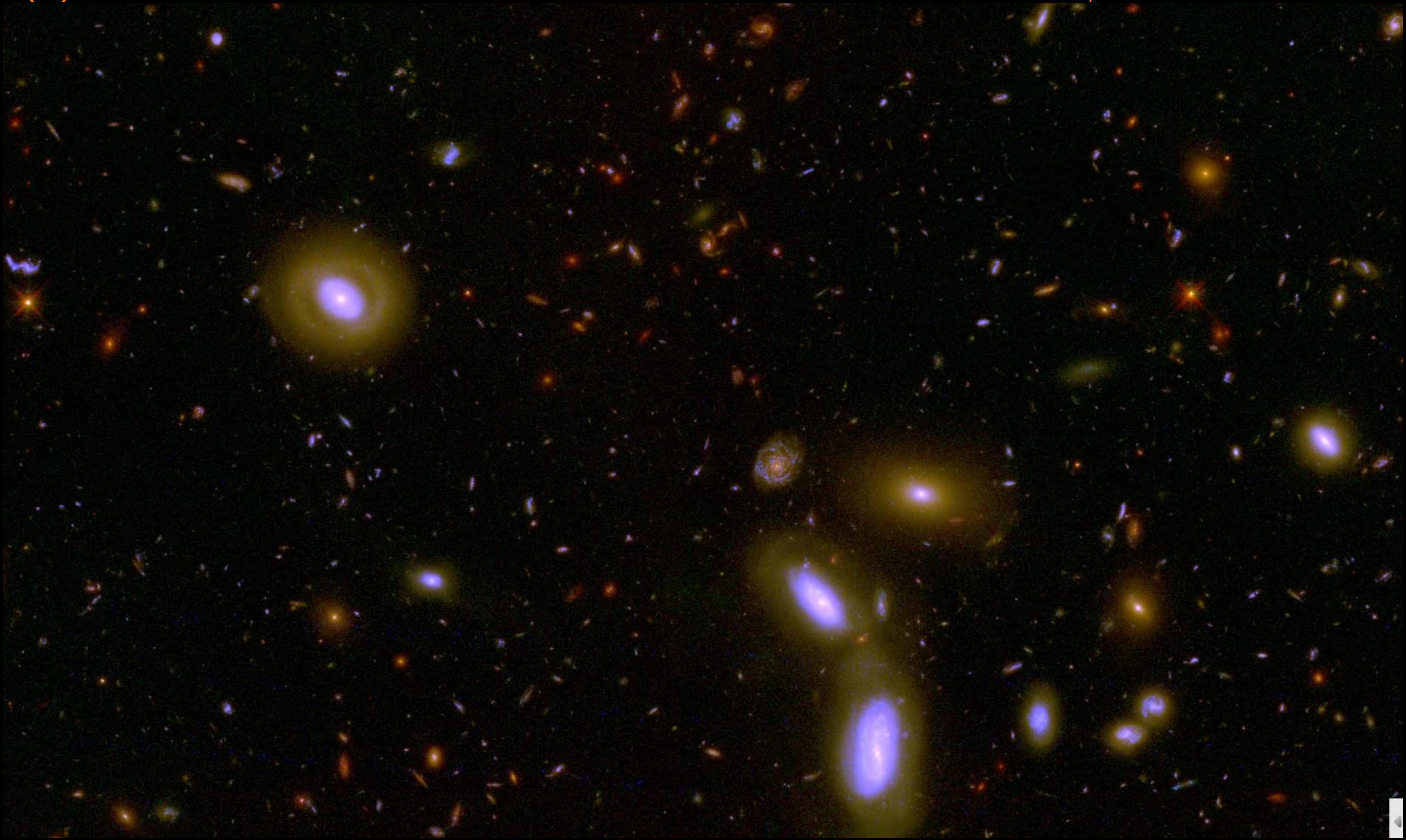
Pathfinder & JSC Chamber A: getting ready for OGSE1 (and eventually OGSE2 & Thermal Pathfinder)





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

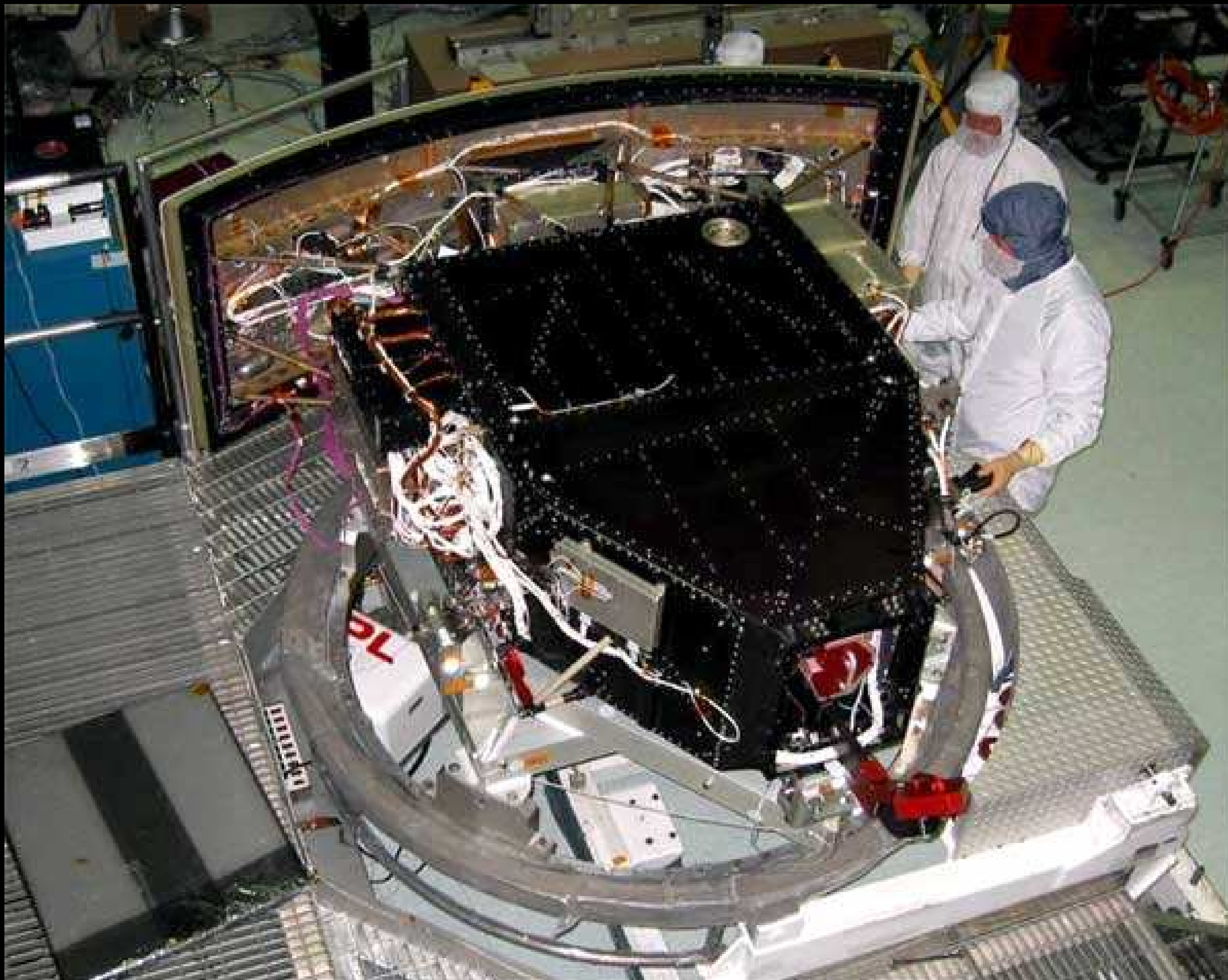
(2) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?



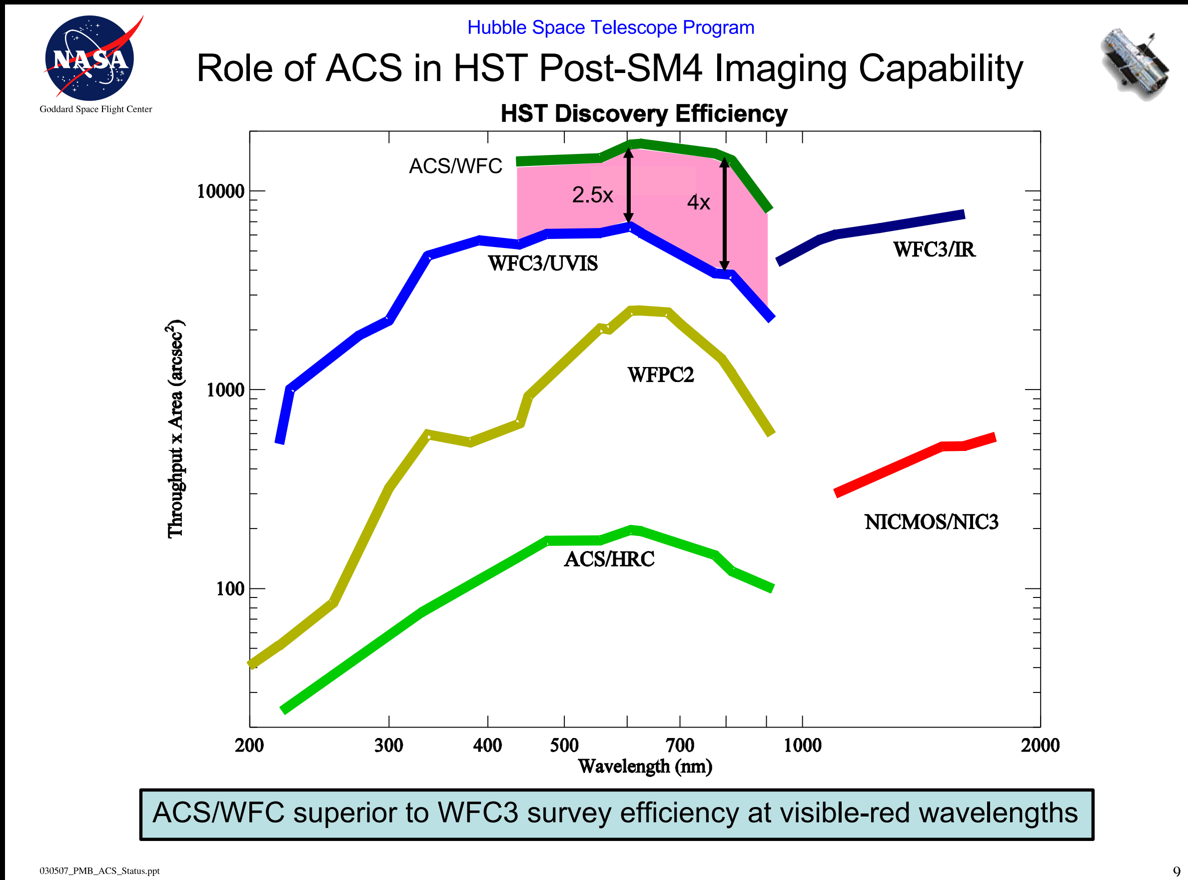
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

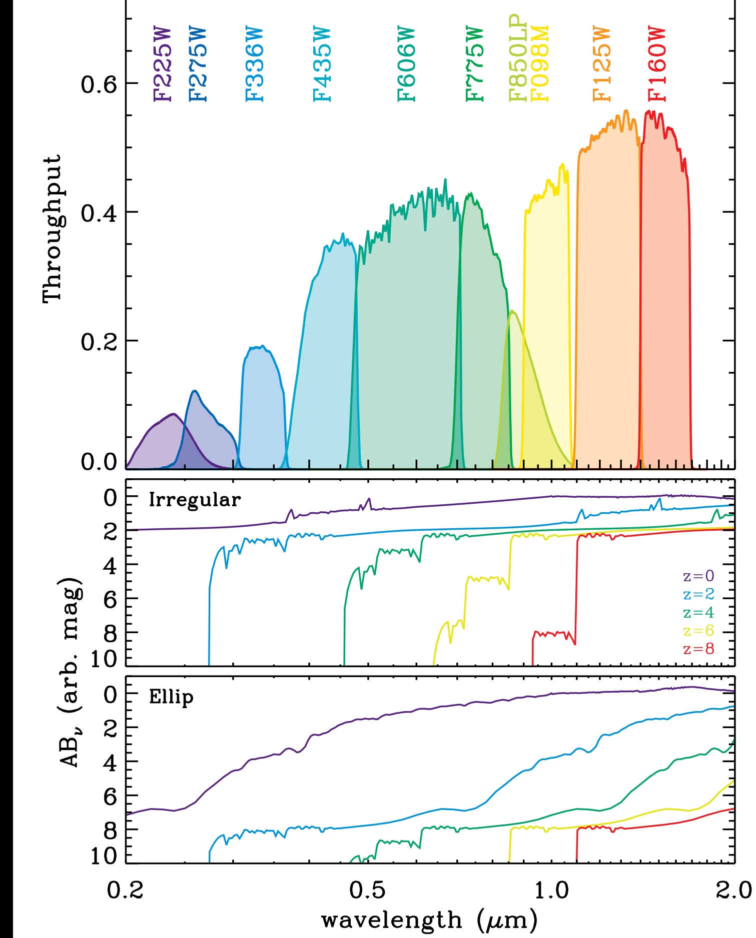
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

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



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



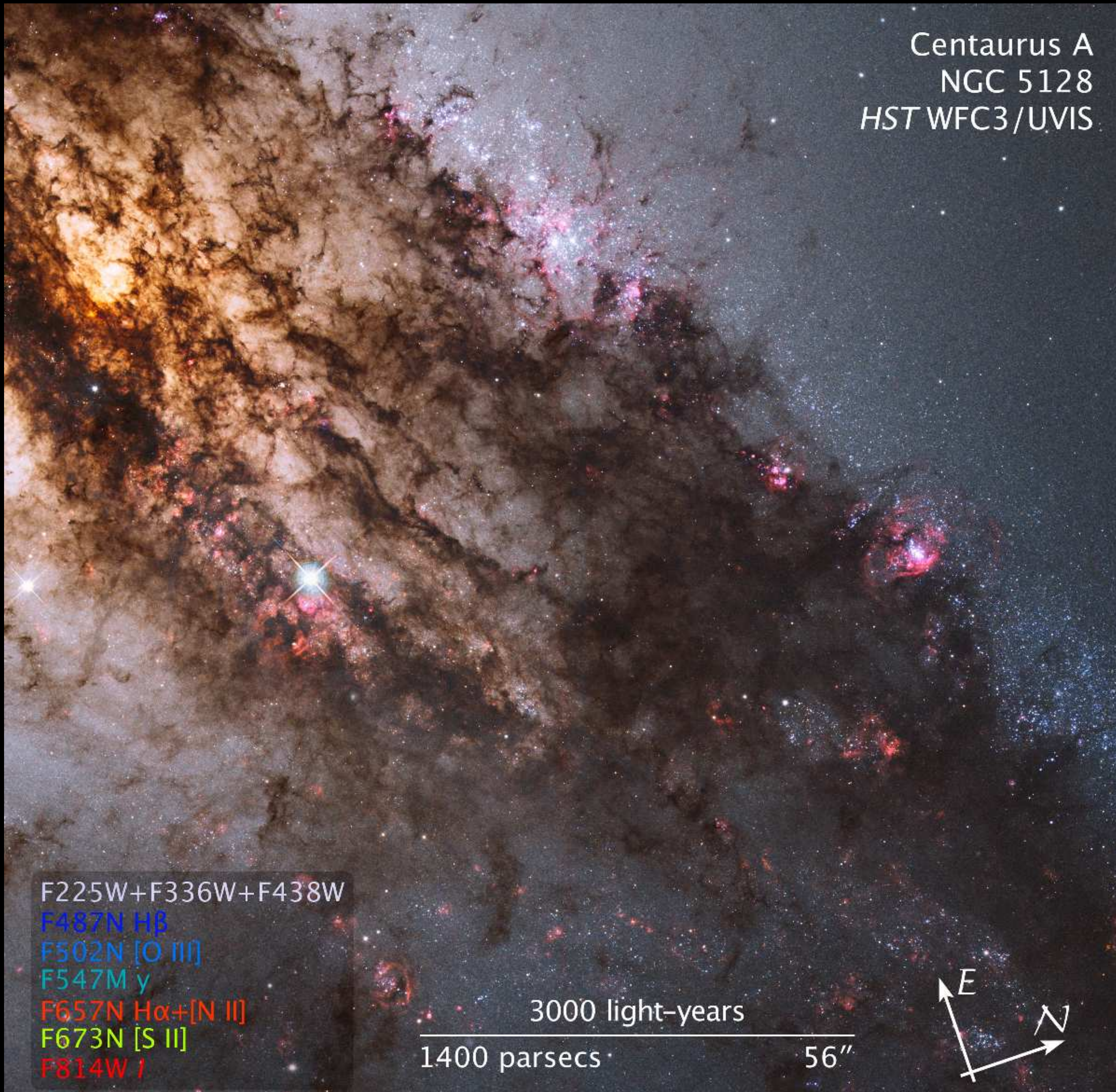


WFC3/UV & IR channels unprecedented throughput & areal coverage:

- QE$\gtrsim$70%, 4k$\times$4k array of $0\farcs04$ pixel, FOV $\simeq 2\farcm67 \times 2\farcm67$.
- QE$\gtrsim$70%, 1k$\times$1k array of $0\farcs13$ pixel, FOV $\simeq 2\farcm25 \times 2\farcm25$.

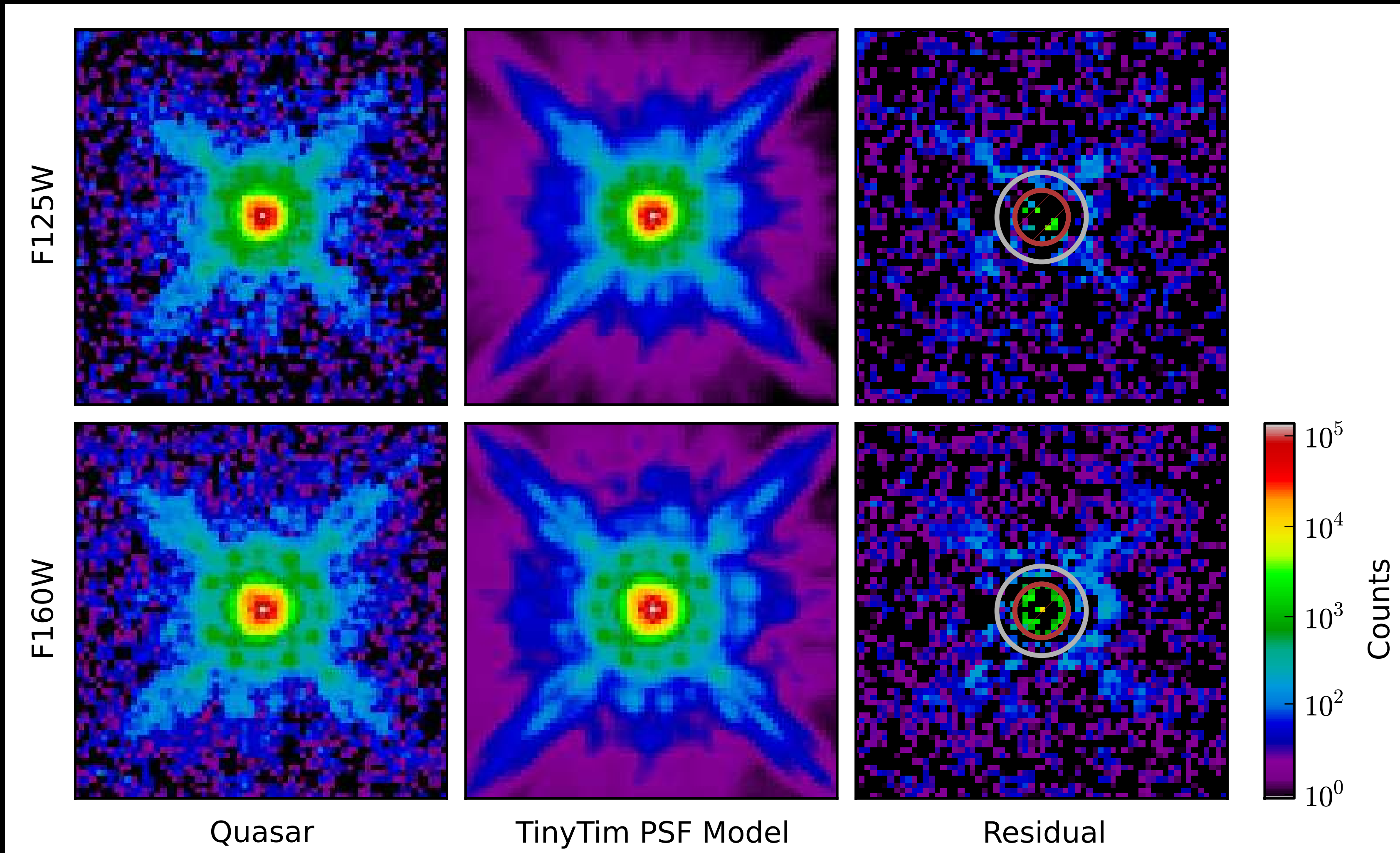
$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

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



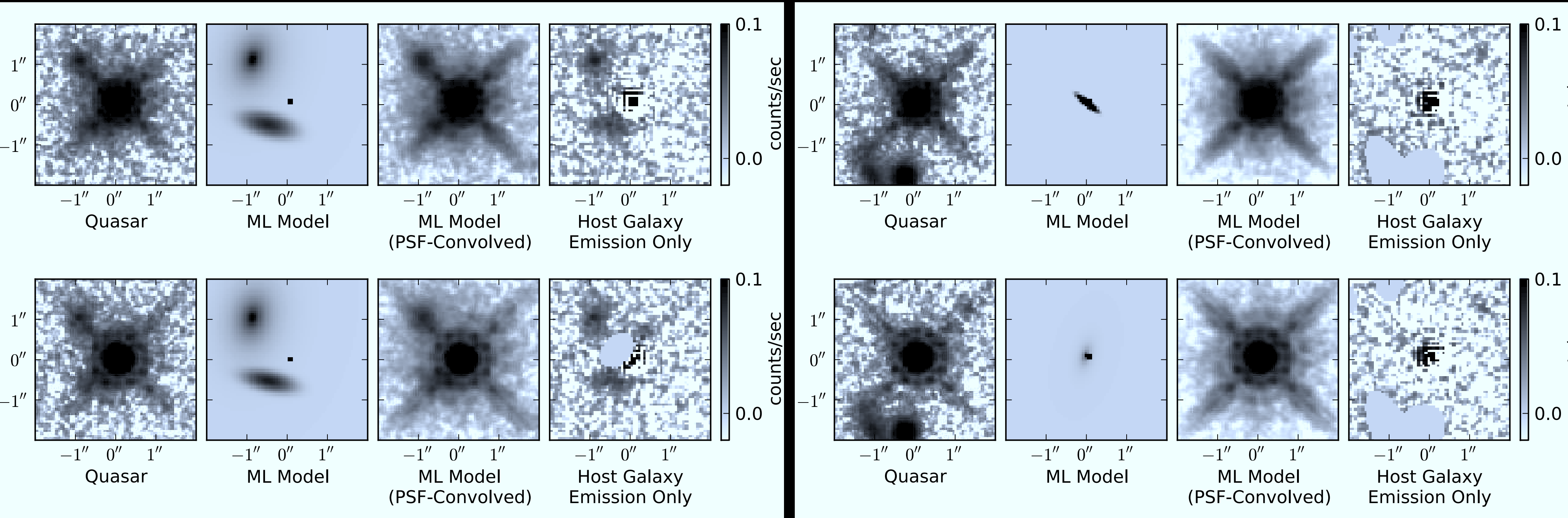
Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N

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



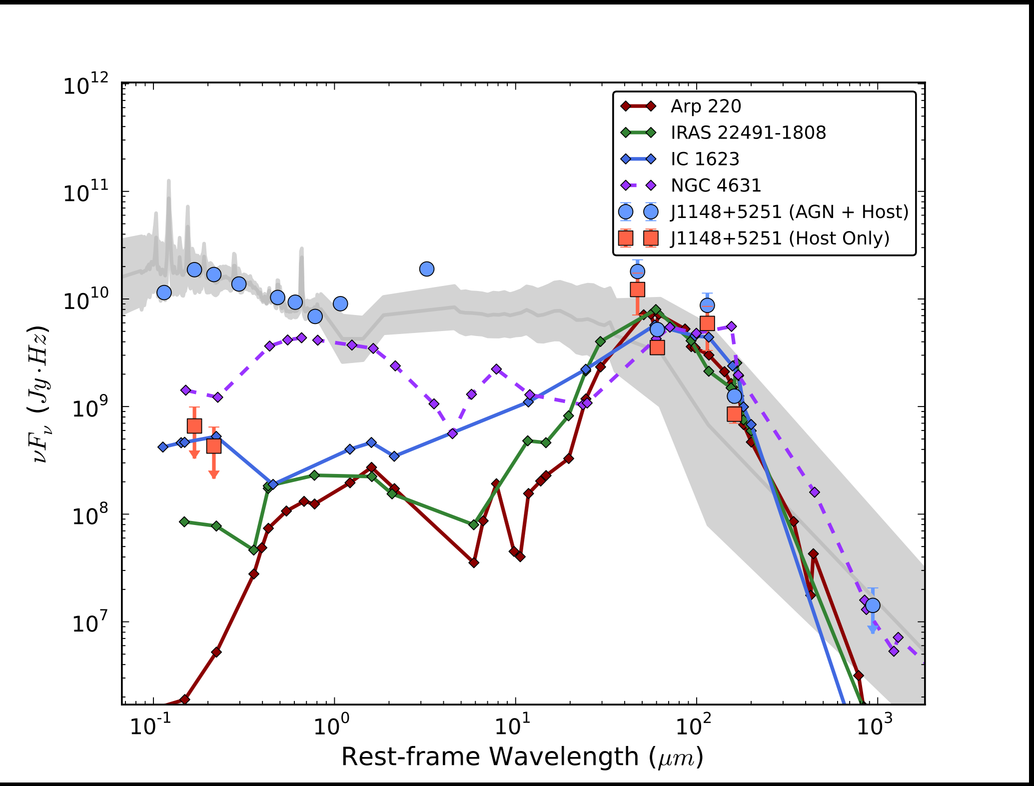
- Careful contemporaneous orbital PSF-star subtraction: Removes most of "OTA spacecraft breathing" effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star (AB$\simeq$15 mag) subtracts z=6.42 QSO (AB$\simeq$18.5) nearly to the noise limit: NO host galaxy detected 100× fainter (AB$\gtrsim$23.5 at r$\gtrsim$0.″3).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

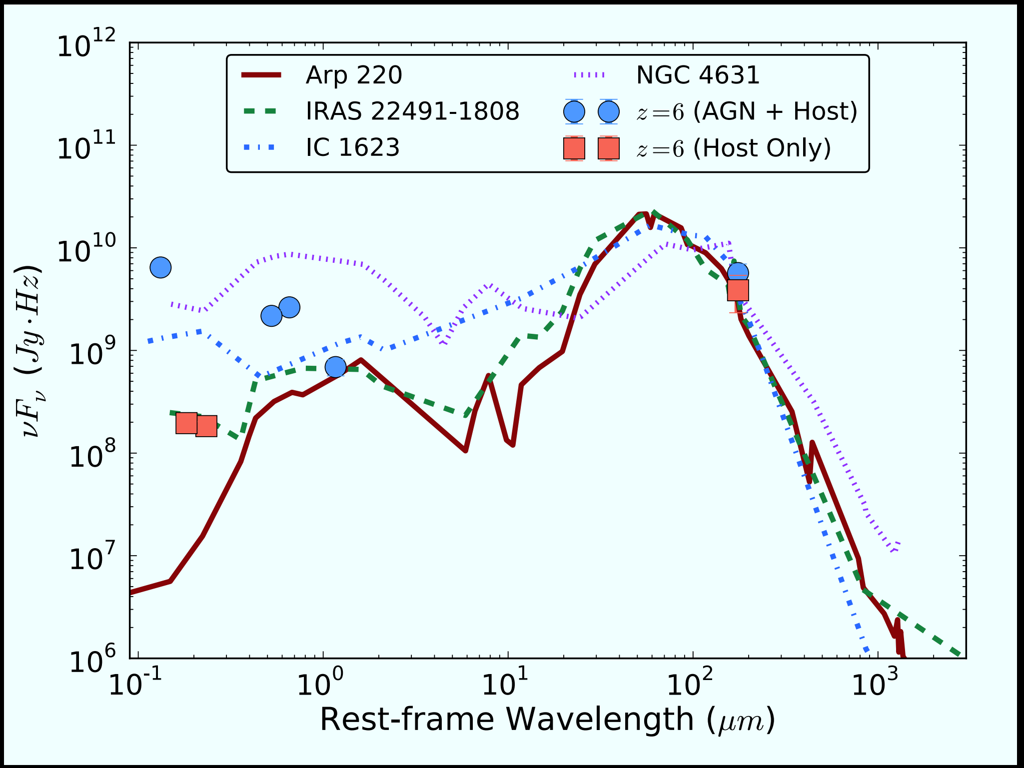
(2b) WFC3: Detection of one QSO Host System at z≃6 (Giant merger?)



- 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)≲–23.0 mag, i.e., ∼2 mag brighter than L*(z≃6).
- JWST can detect 10–100× fainter dusty hosts (for z≲20, λ≲28μm).

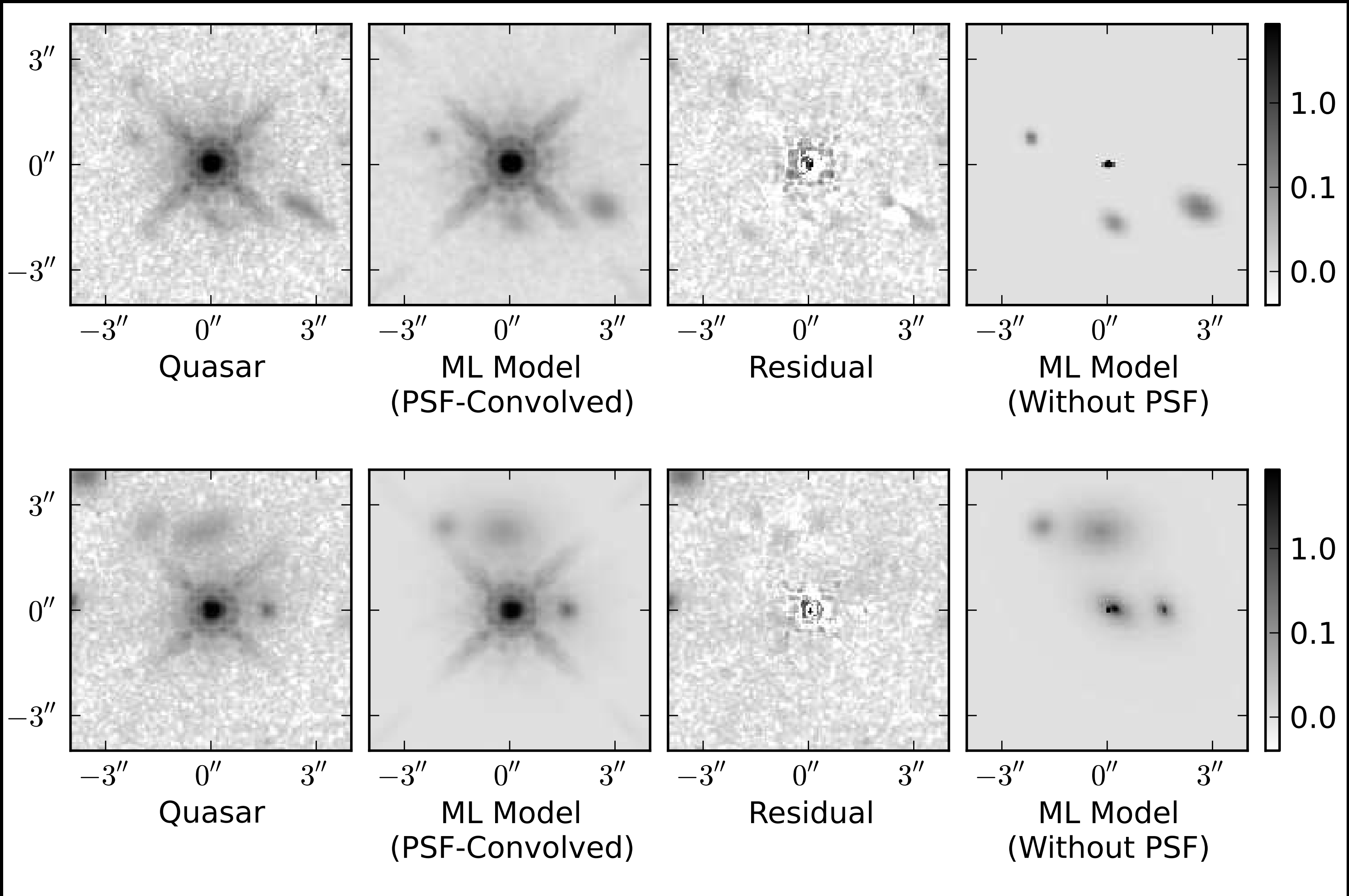
(2b) HST WFC3 observations of dusty QSO host galaxies at z≃6





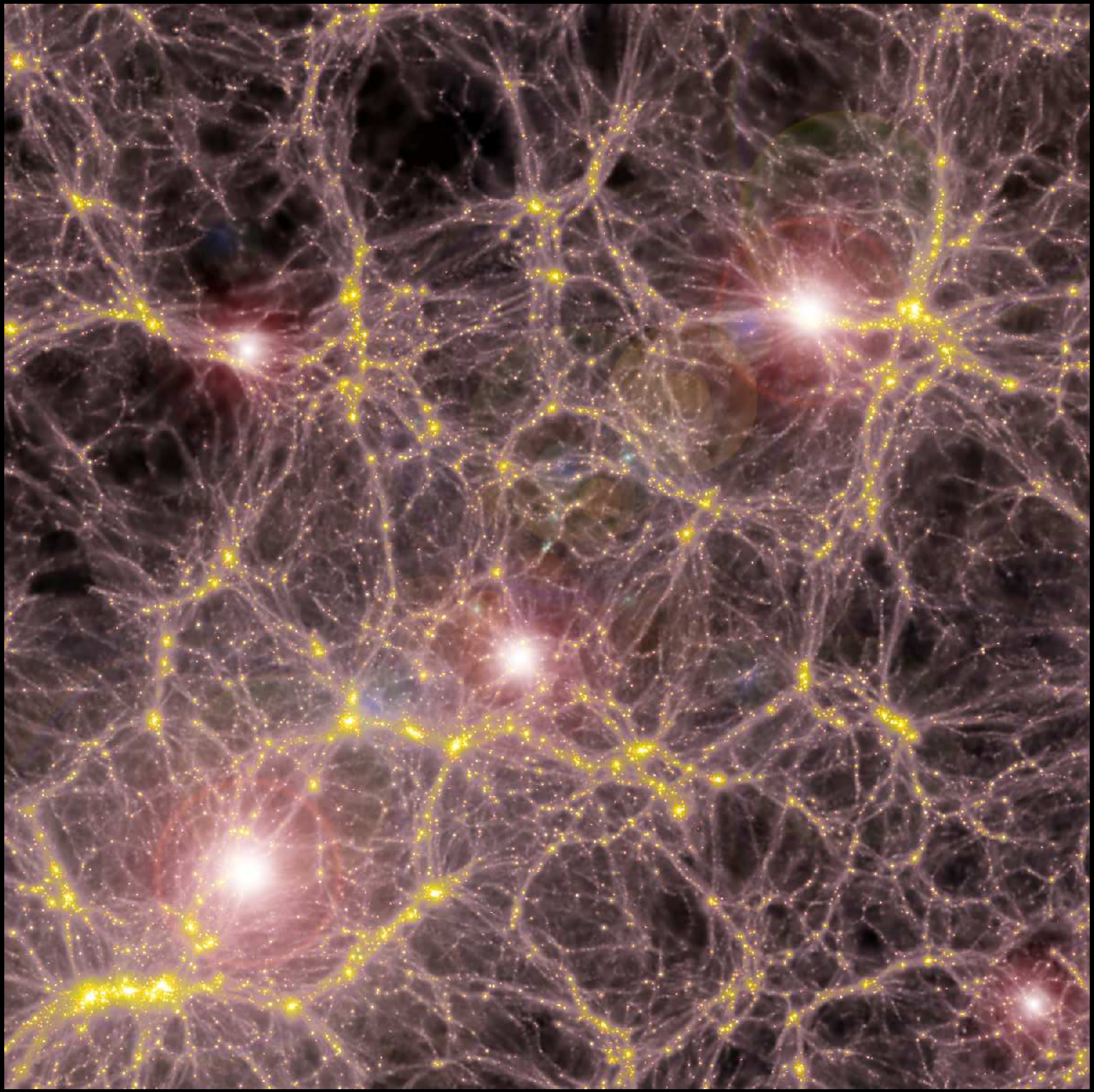
- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5μ). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100μm: [LEFT] Rules out z=6.42 spiral or bluer host galaxy SEDs for 1148+5251. (U)LIRGs & Arp 220s permitted (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, astro-ph/1510.08461).
- JWST (+Coronagraphs) can do this $\gtrsim$10× fainter: in restframe V for z$\gtrsim$6.

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

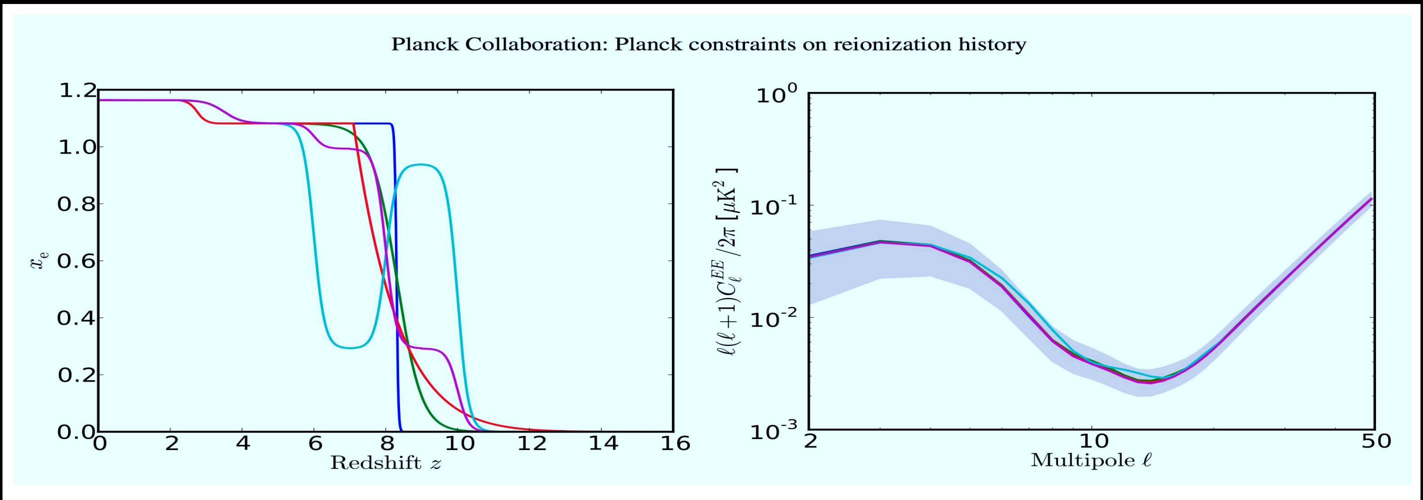


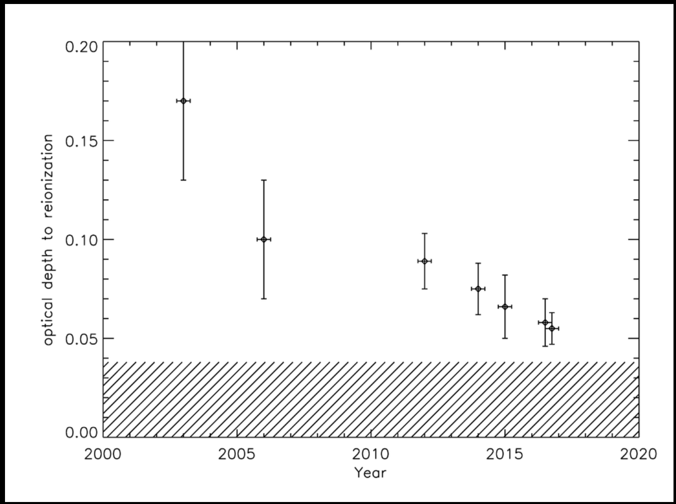
- Detailed cosmological models (V. Bromm) suggest that massive "Pop III" stars ($\gtrsim$100 M_{sun}) started to reionize the universe at z$\lesssim$10–30 (0.1–0.5 Gyr; "First Light").

- 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 ⟵ ⟶ 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):

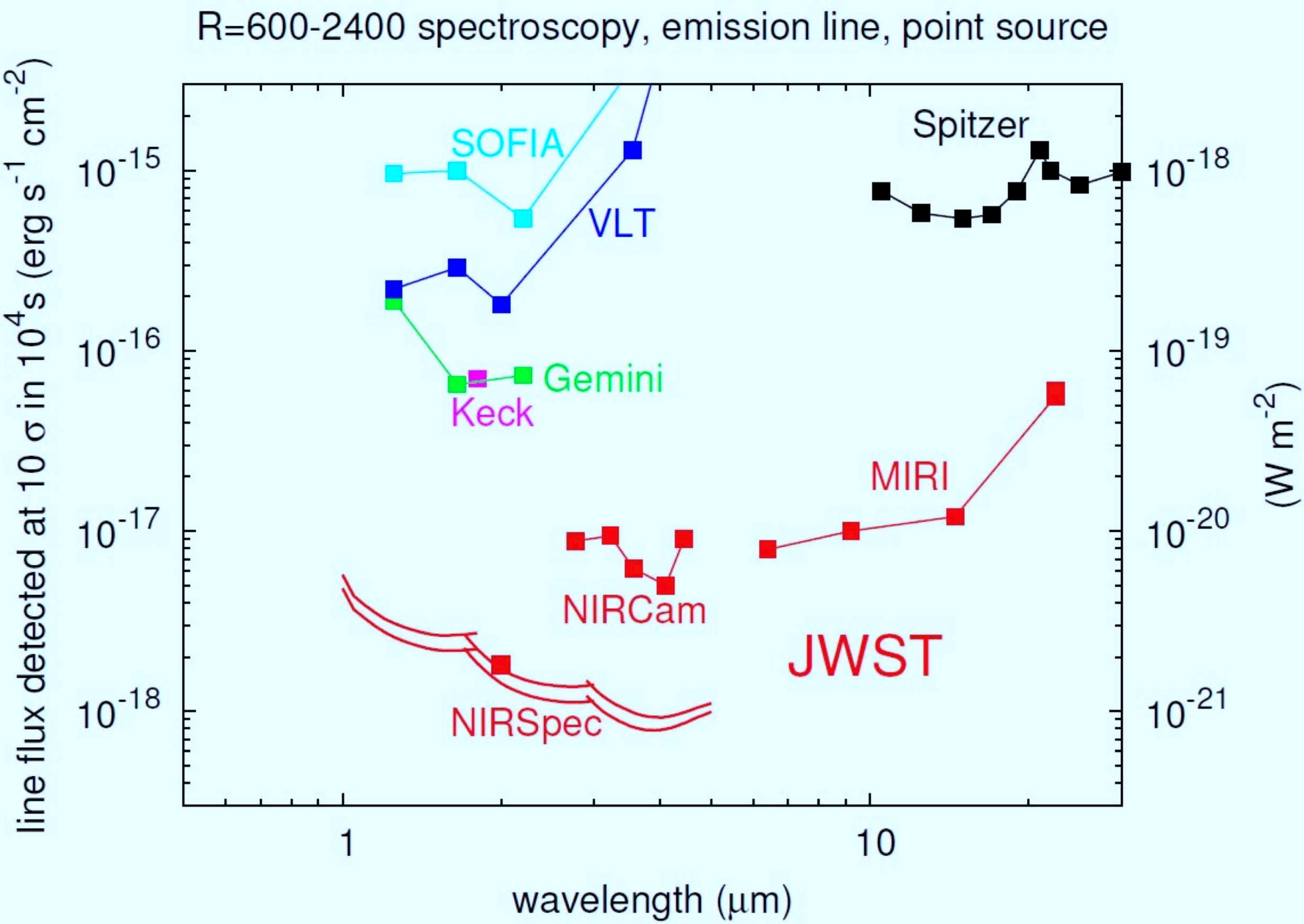
Reionization appears to have occurred between these extremes:

(1) Instantaneous: $z \sim 8.5 \pm 0.9$ (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



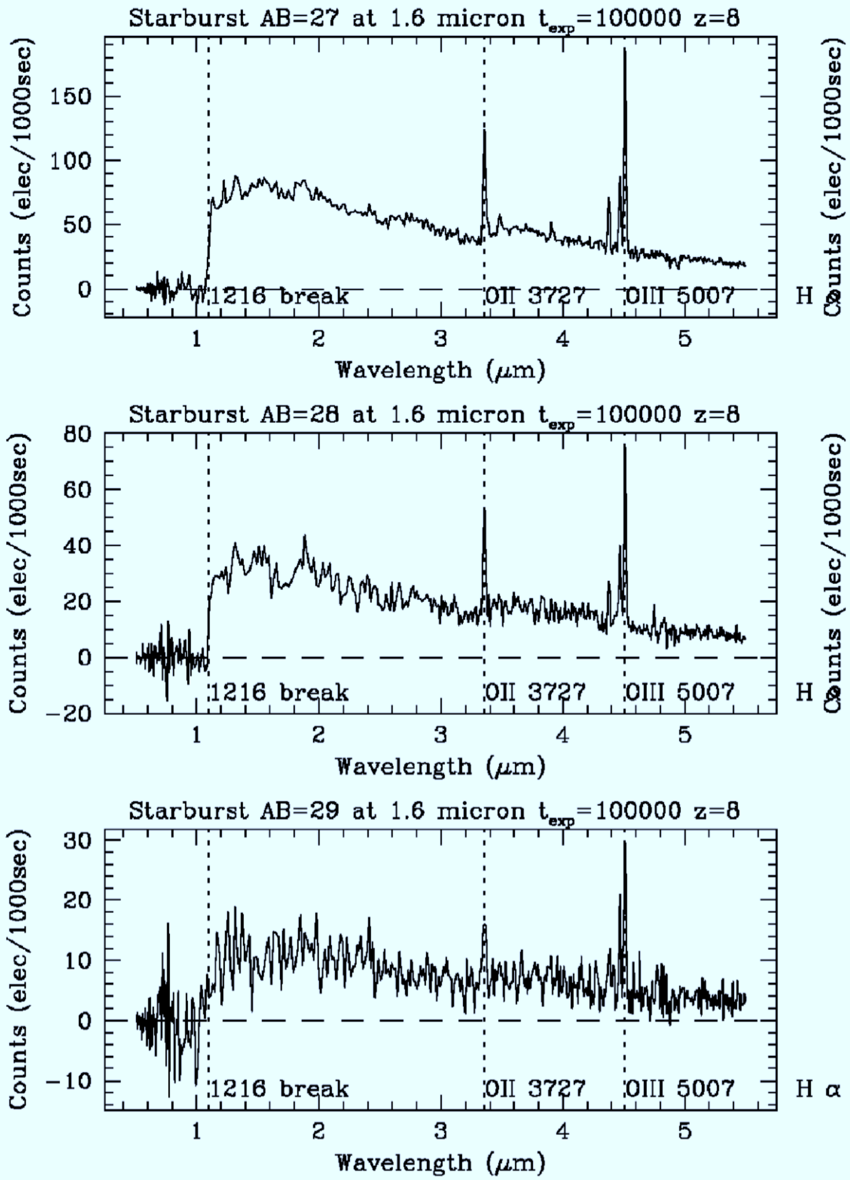
NIRCam, NIRSpec and MIRI sensitivity (cgs) compared to VLT, Keck, Spitzer.

What NIRSPEC can do !

AB=27

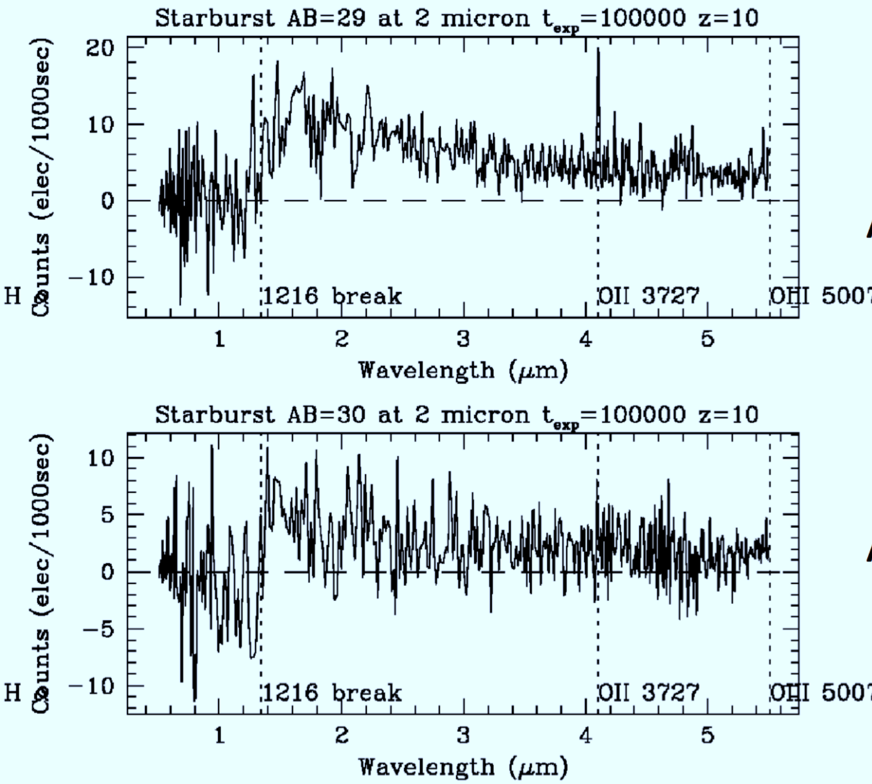
AB=28

AB=29



AB=29

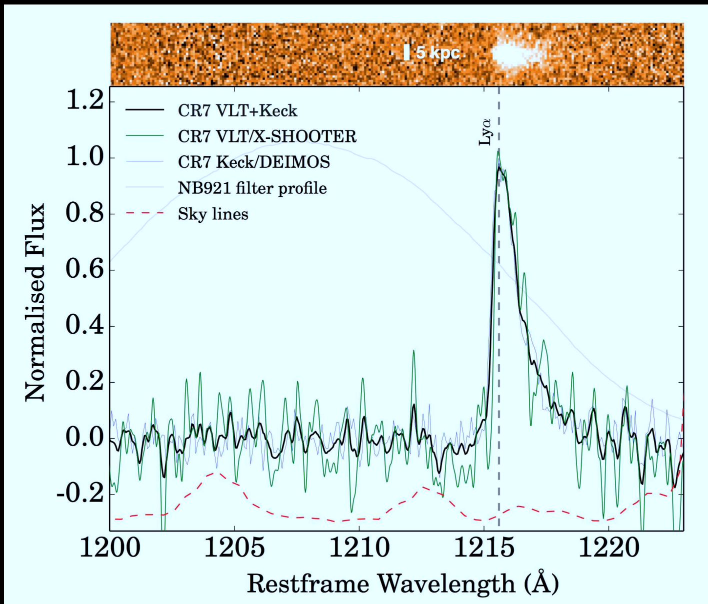
AB=30

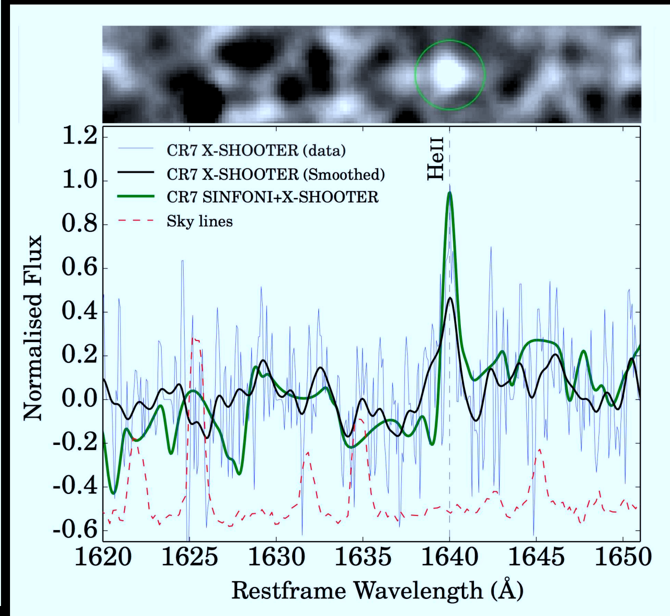


Derive redshifts, stellar masses, stellar ages, gas ionization and metallicities, star formation rates, kinematics, pop III stars, Ly-α LF to z=10, etc.

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

(3a) How can JWST Spectroscopy constrain nature of Reionizing Objects?





observations of TN J1338−1942 at z = 4.1 1301

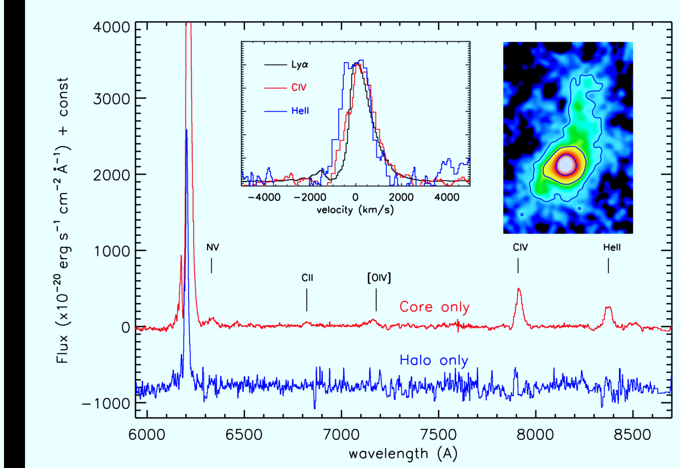


Figure 2. The spectrum extracted from the core of the Lyα halo compared to that of the extended halo. The core spectrum shows strong emission lines associated with the AGN activity (e.g. N V, [O IV], C IV and He II). The emis-

- Lyα 1216Å (left) and He II 1640Å (middle) detections in CR7 at z=6.6 (Sobral et al. 2015): Pop III star signature!?

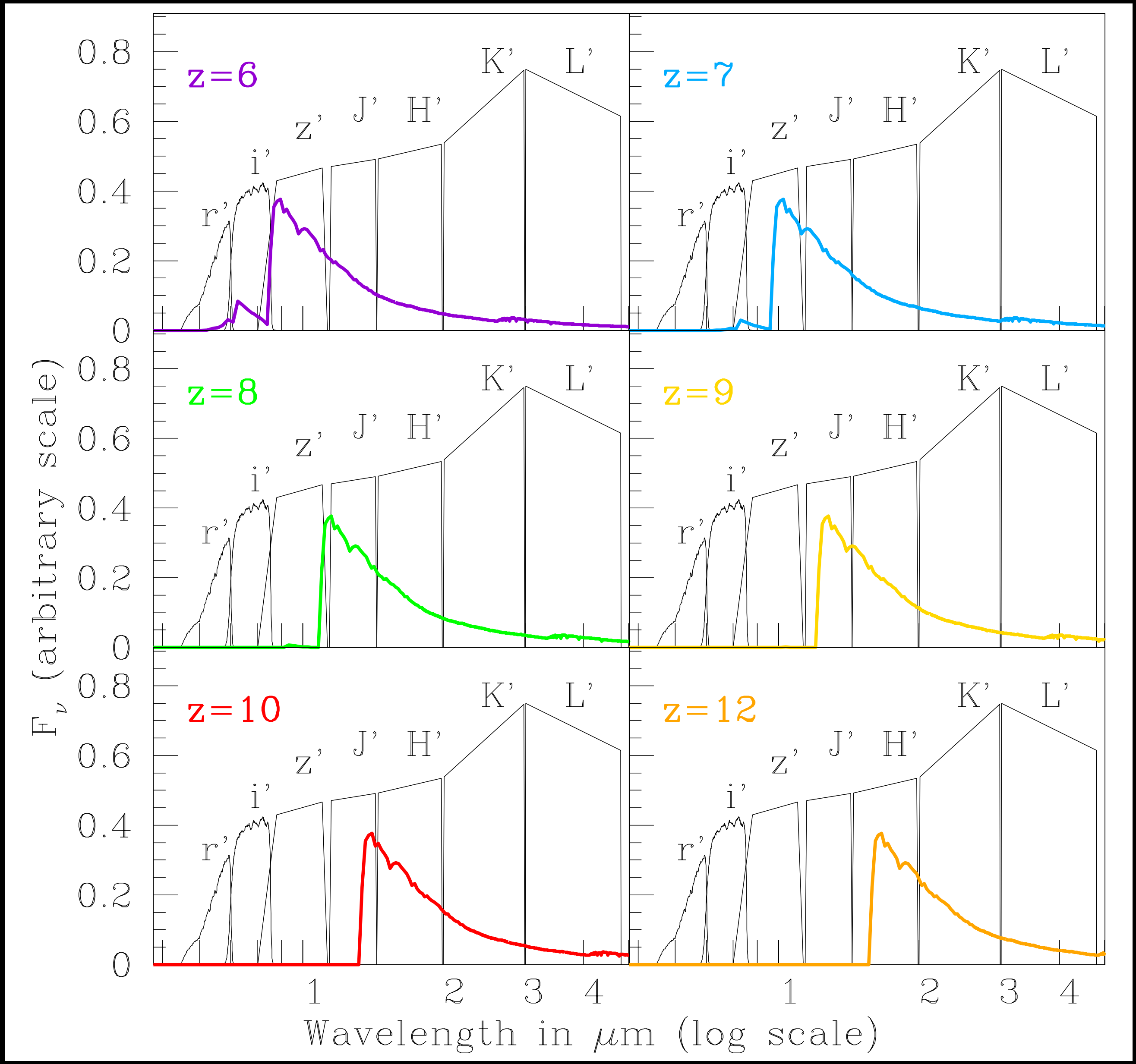
- HeII 1640Å (right) in radio galaxy TN J1338-1942 at z=4.1 (Swinbank et al. 2015, MNRAS 449, 1298).

JWST spectra: NIRSpec/MEMS R∼1000–2700; NIRISS+NIRCam grisms R∼150+2000.

- JWST can see Pop III He II 1640Å to AB≲28–29, z≲30 (if they exist).

(Pop III star activity may not be seen in (small dwarf) galaxies until z≲12).

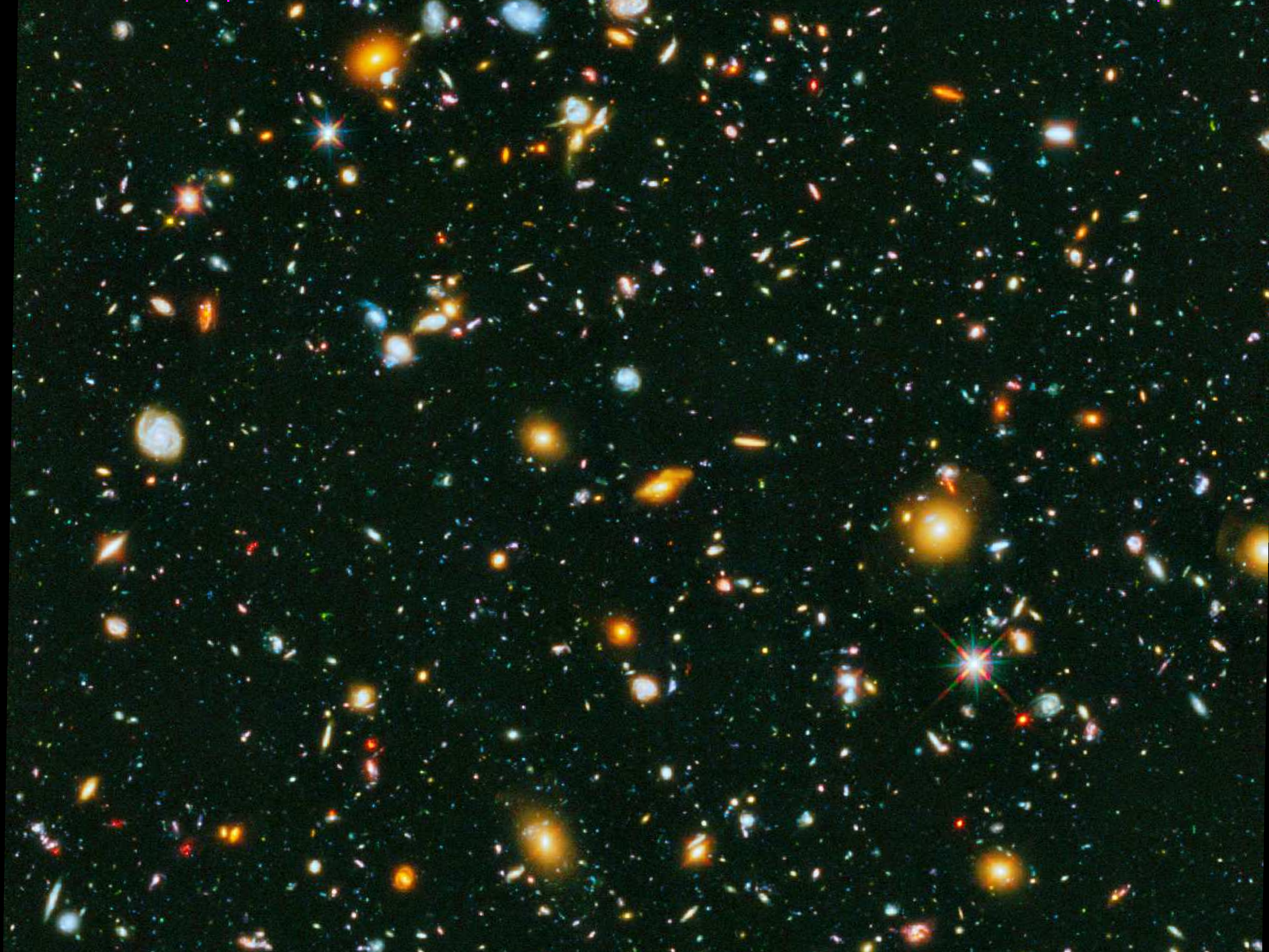
(3b) How will Webb measure First Light: what to expect in (Ultra)Deep Fields?



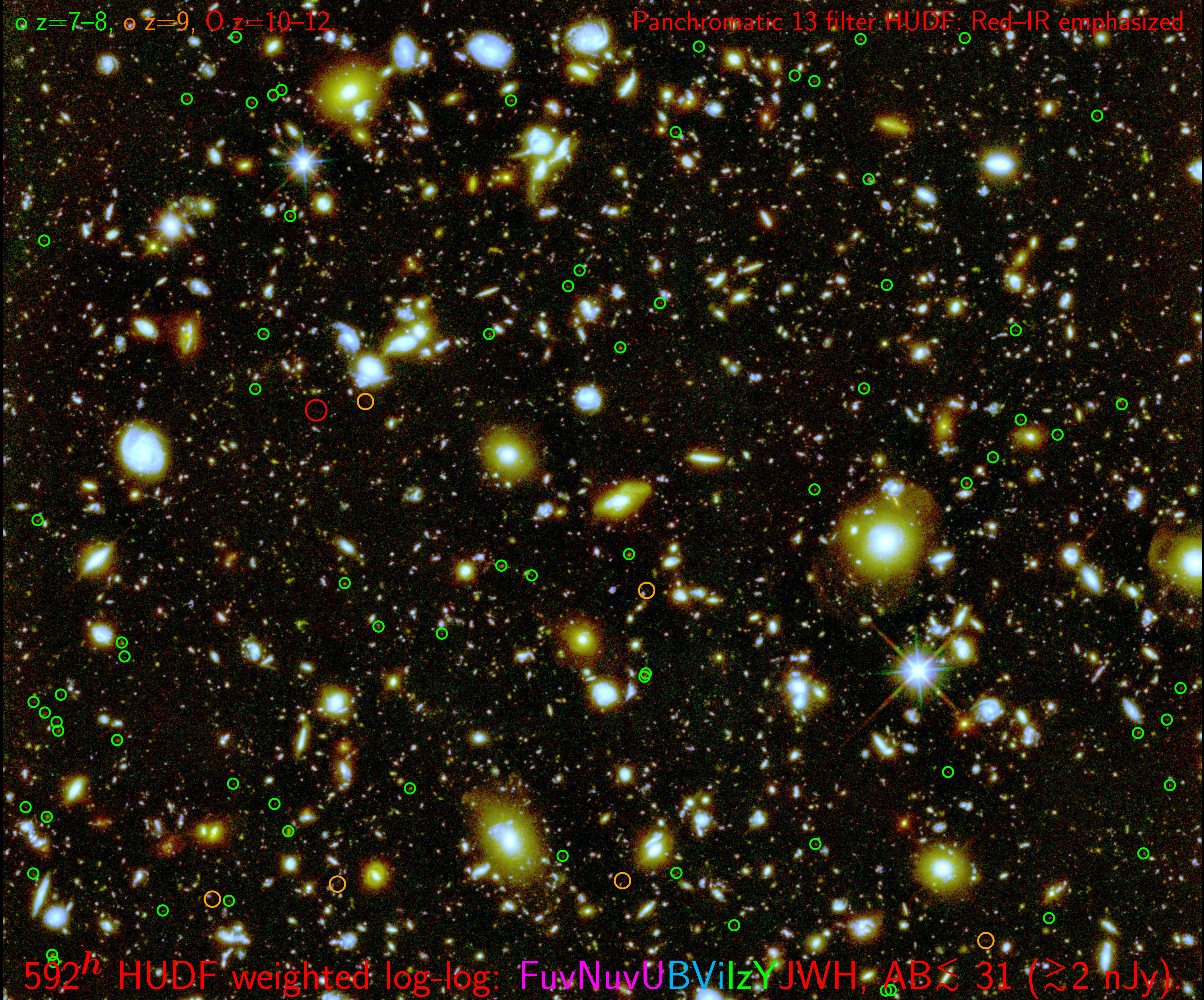
- Can't beat redshift: to see First Light, must observe near–mid IR.

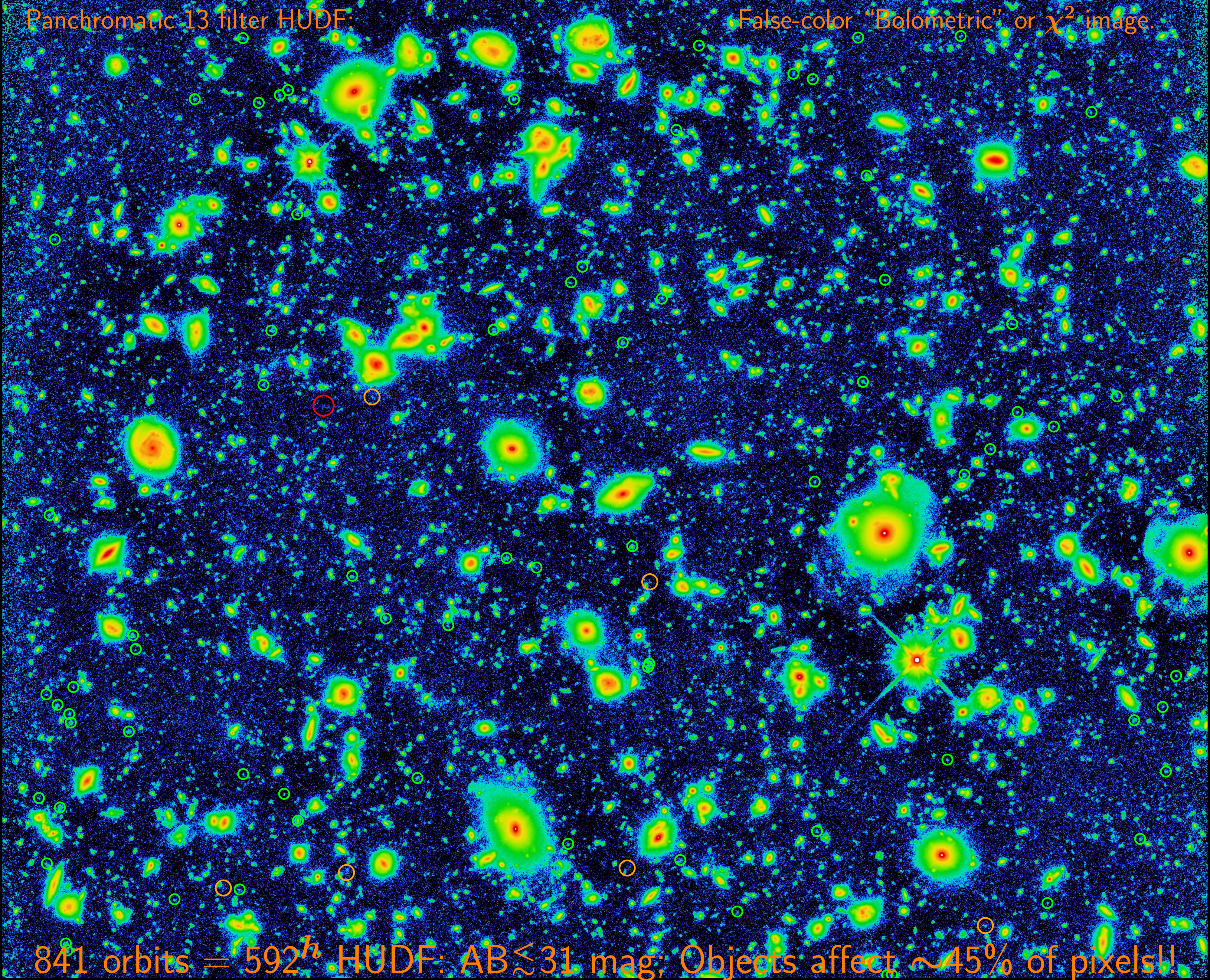
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

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

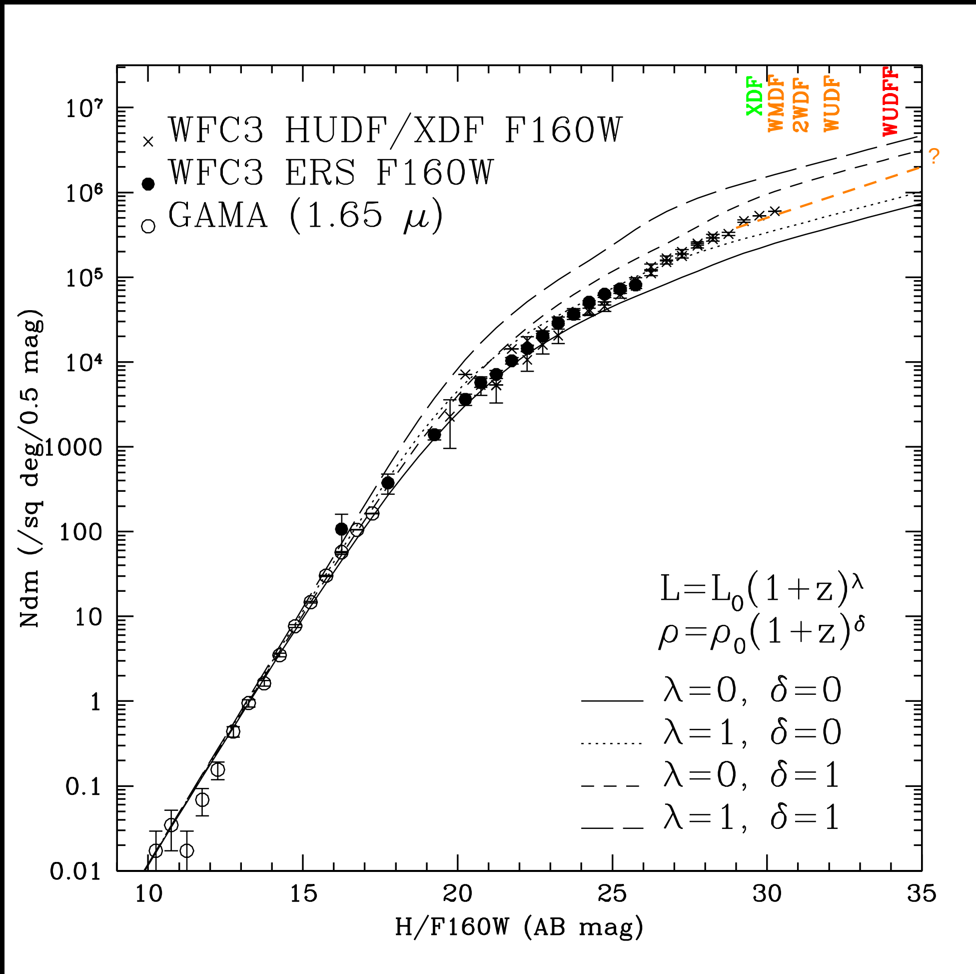


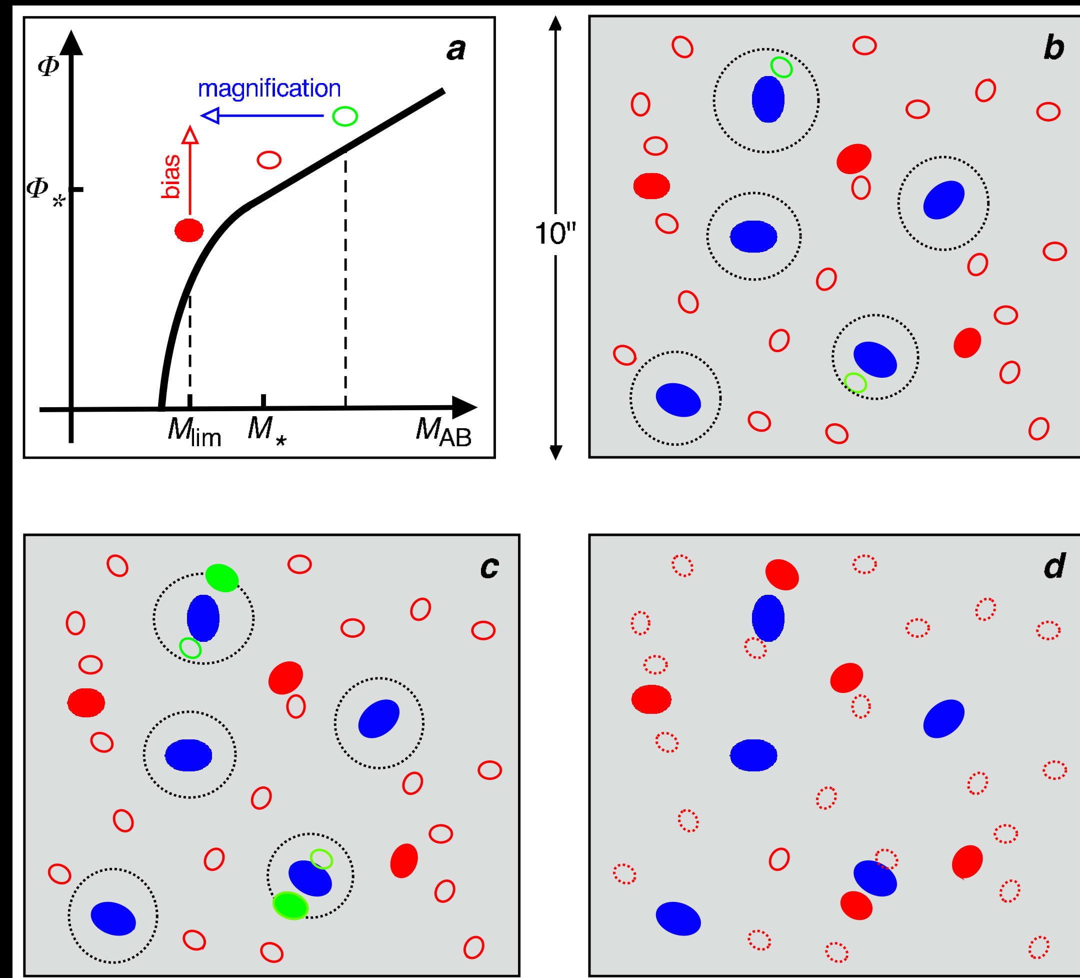
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).


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!!

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



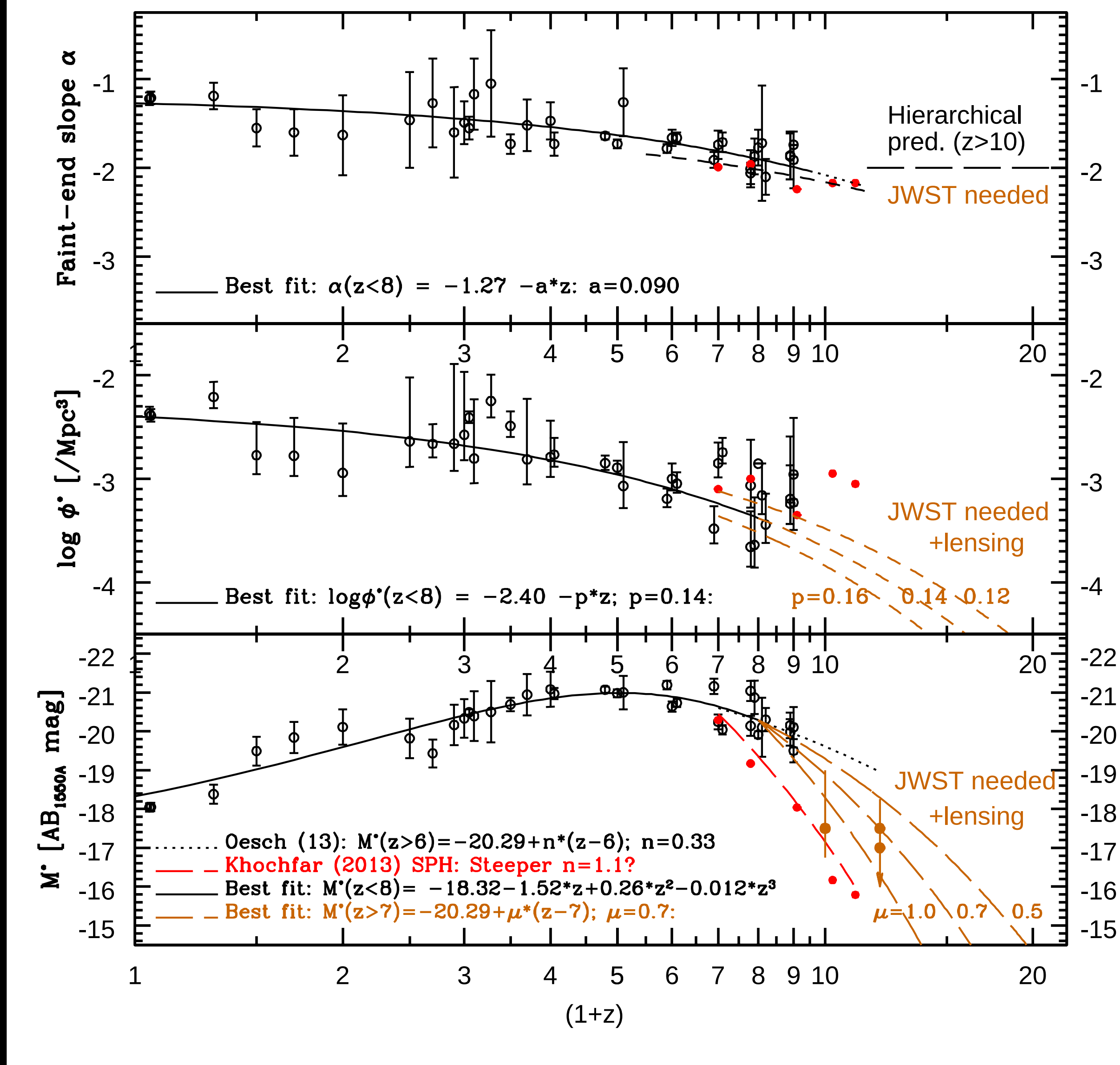


1.6μm counts (Windhorst+2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

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

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

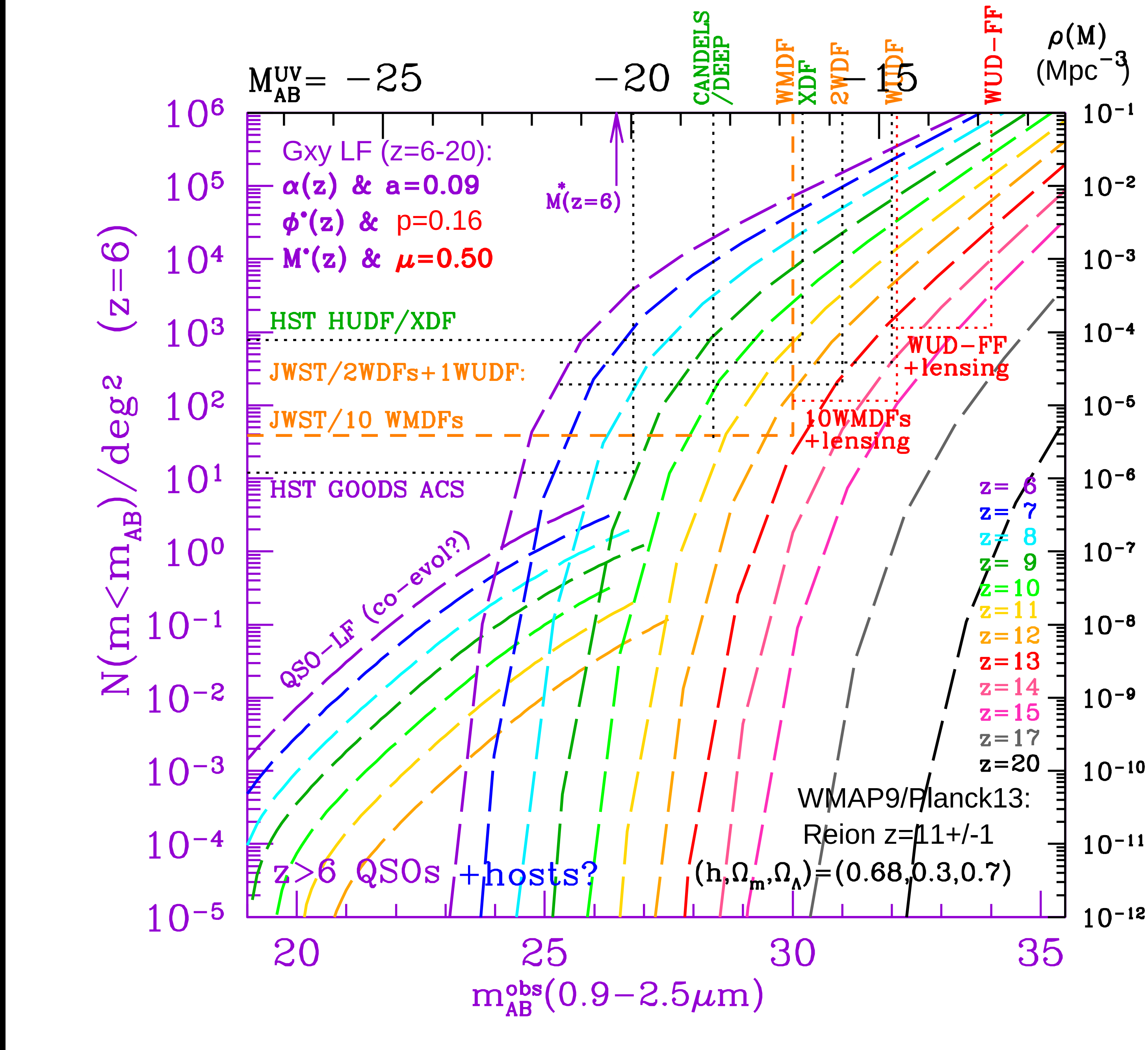
- In 800-hr JWST can see to ∼32 mag: dwarf galaxy at z≃11!
- Lensing will change the landscape for JWST observing strategies.



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.

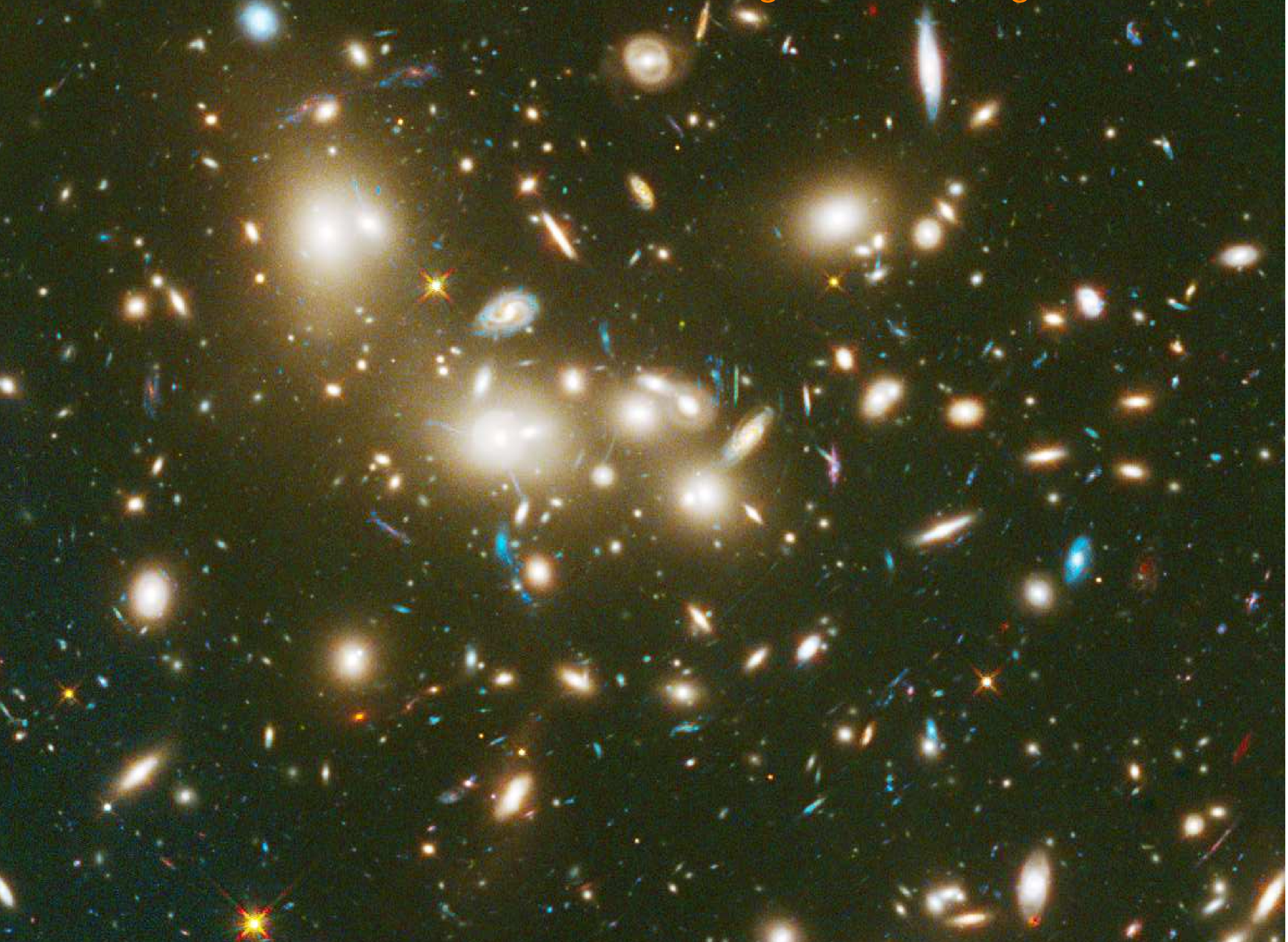


Predicted Schechter Luminosity Function (LF) at redshifts $6 \lesssim z \lesssim 20$:

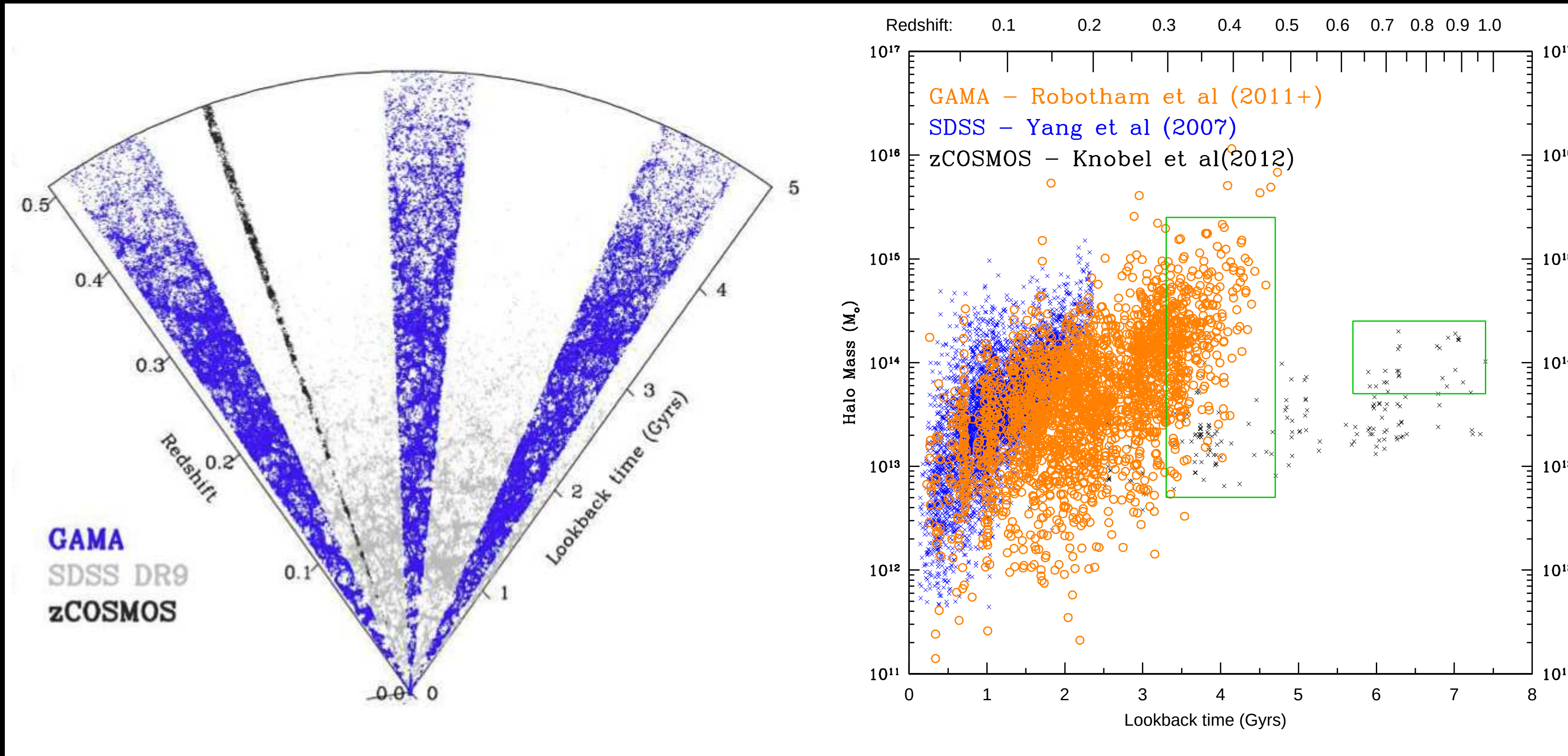
Area/Sensitivity for: Hubble UDF, **Webb: 10 MDFs**, 2 DFs, & 1 UDF.

- 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.



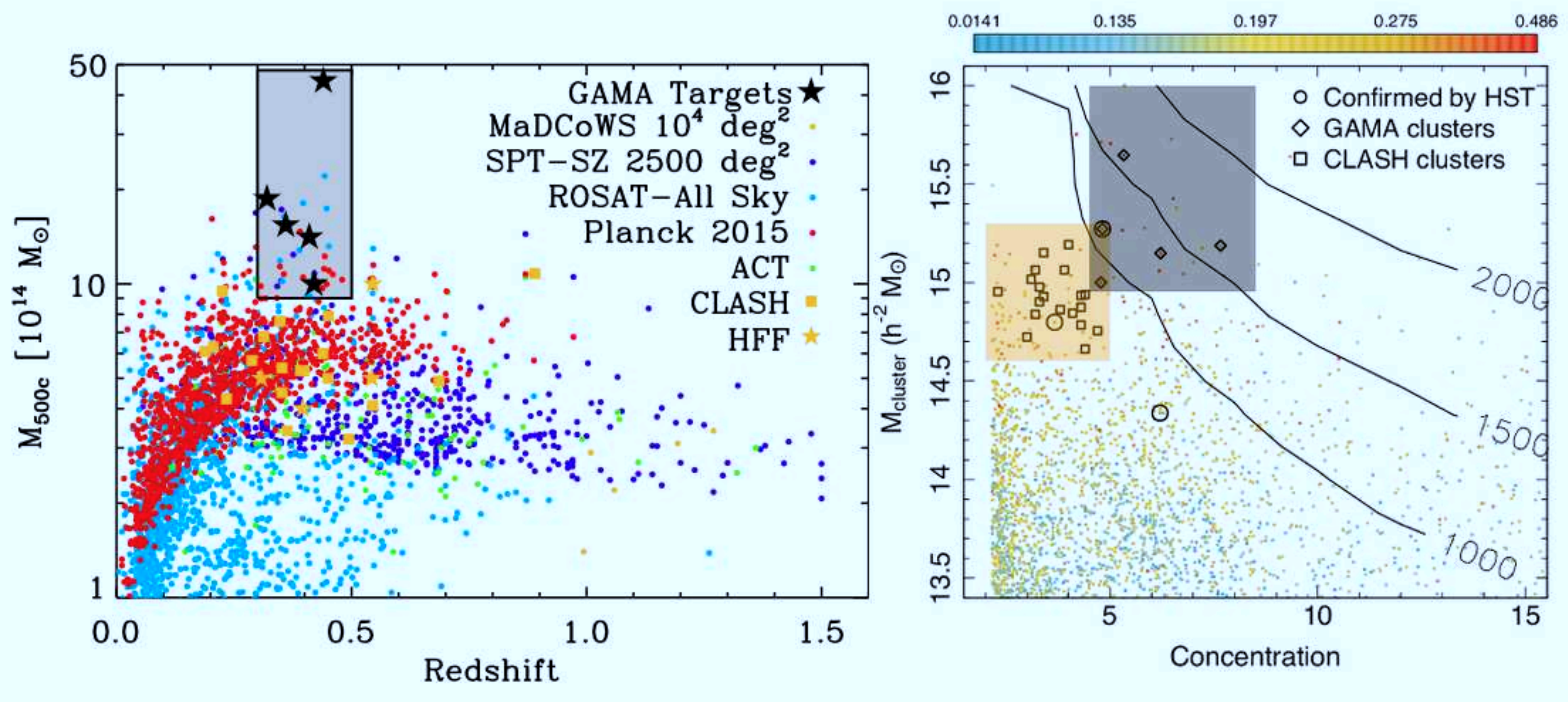
(3c) Gravitational Lensing to see First Light population at z$\gtrsim$10.



Use the best available lenses: Rich clusters and (compact) galaxy groups.

[Left] Redshift surveys: SDSS z$\lesssim$0.25 (Yang+ 2007), GAMA z$\lesssim$0.45 (Robotham+ 2011), and zCOSMOS z$\lesssim$1.0 (Knobel+ 2012).

- GAMA: 22,000 groups z$\lesssim$0.45; 2400 with $N_{spec}\gtrsim5$ (Robotham+ 11).
- $\lesssim$10% of GAMA groups compact enough for lensing (Wyithe et al.).
- Large cluster sample to identify optimal lens-candidates for z$\gtrsim$6 sources.



[LEFT] Best lensing GAMA clusters vs. ROSAT, Planck, SPT, MaDCoWS.
[RIGHT] Best lensing GAMA clusters vs. CLASH/HFF clusters.
(Contours: Number of lensed JWST sources at z$\simeq$1–5 to AB$\lesssim$27 mag).

- Resulting sweet spot for JWST lensing of First Light Objects (z$\gtrsim$10):
Redshift: 0.3$\lesssim$z$\lesssim$0.5; Mass: $10^{15-15.6}$ $M_{\odot}$; Concentration: 4.5$\lesssim$C$\lesssim$8.5

- GAMA clusters confirmed w/ $\gtrsim$24 z_{spec}'s, removing chance projections.

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.

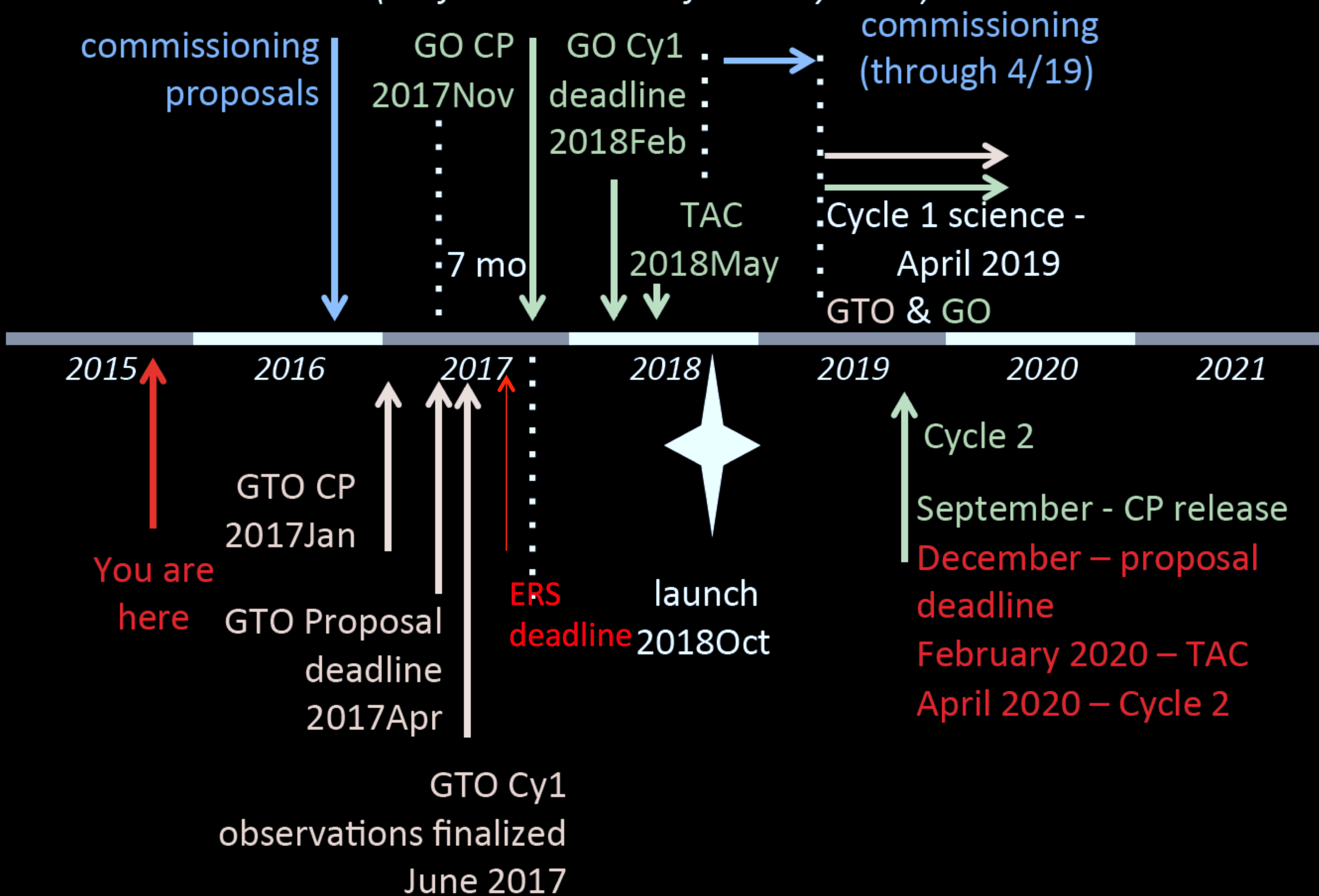
(4) JWST will have a major impact on astrophysics this decade:

- IR sequel to HST after 2018: Training the next generation researchers.
- **Your JWST proposals are due $\lesssim$1.7 years from today!**

SPARE CHARTS

JWST Science Planning Timeline

(draft schedule as of January 2015)



2016–2018 (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/

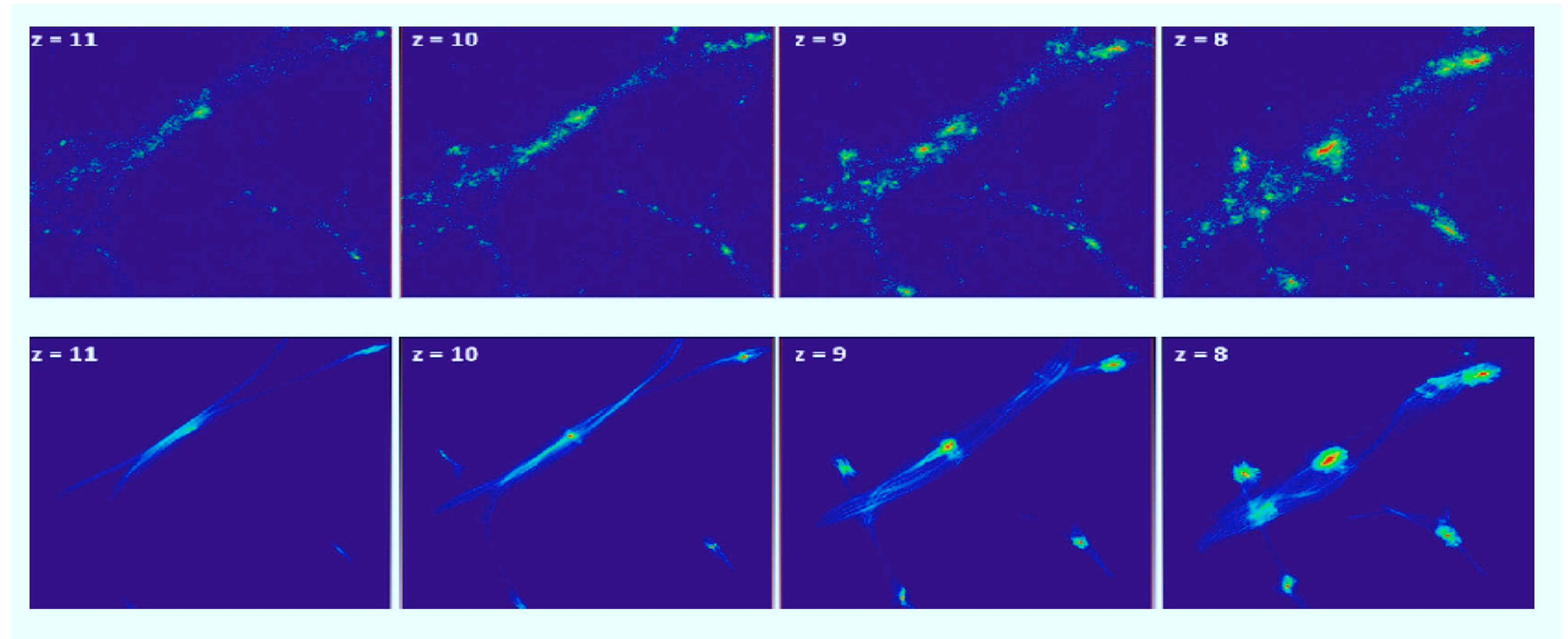
http://www.stsci.edu/jwst/instruments/fgs

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).



JWST cluster lensing can distinguish between standard ΛCDM and a new wave-CDM theory ("Ψ-CDM", which includes Λ):

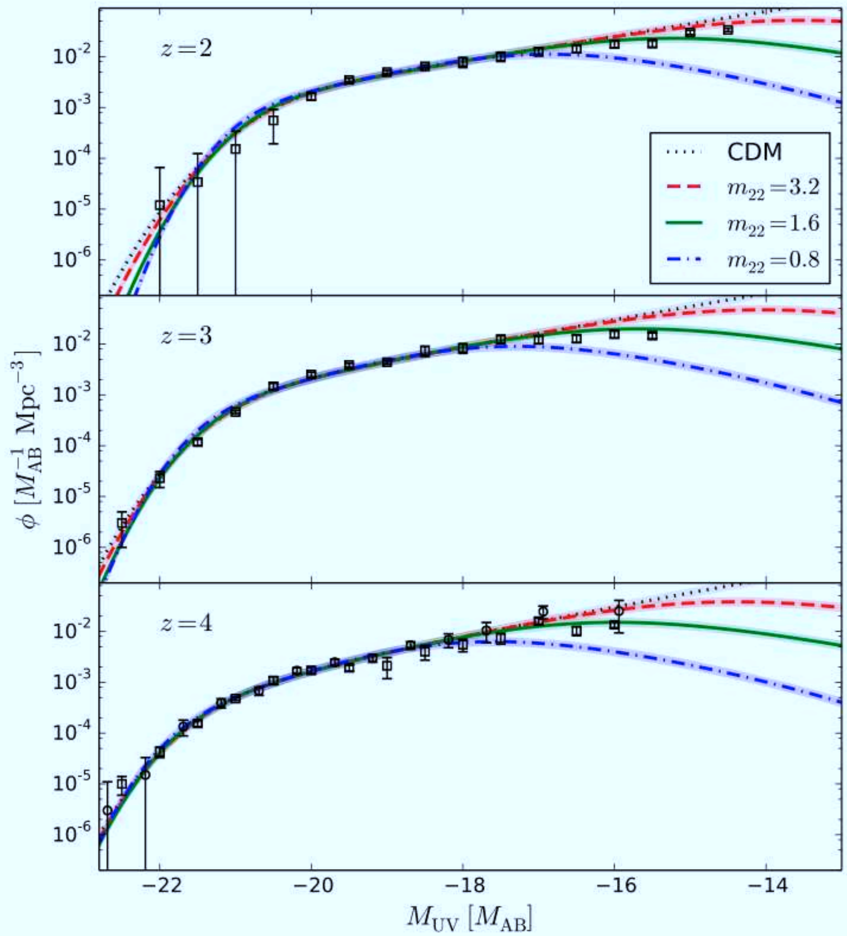
[Top]: Ordinary ΛCDM simulations of hierarchical clustering:

- ΛCDM has no lower limiting scale $\Rightarrow$ expect galaxies at $\gtrsim$20.

[Bottom]: Ψ-CDM better predicts density & profiles of dwarf galaxies:

- Wave-CDM cannot form objects below the de Broglie wavelength tuned to fit the solitonic cores of dwarf Spheroidal galaxies ($\sim$ 1 pc).
- Wave-CDM delays galaxy formation with a deficit at z$\gtrsim$8, yielding only filaments at z$\gtrsim$11 (Schive et al. 2016, ApJ, 818, 89).

THE ASTROPHYSICAL JOURNAL, 818:89 (14pp), 2016 February 10 SCHIVE ET AL.



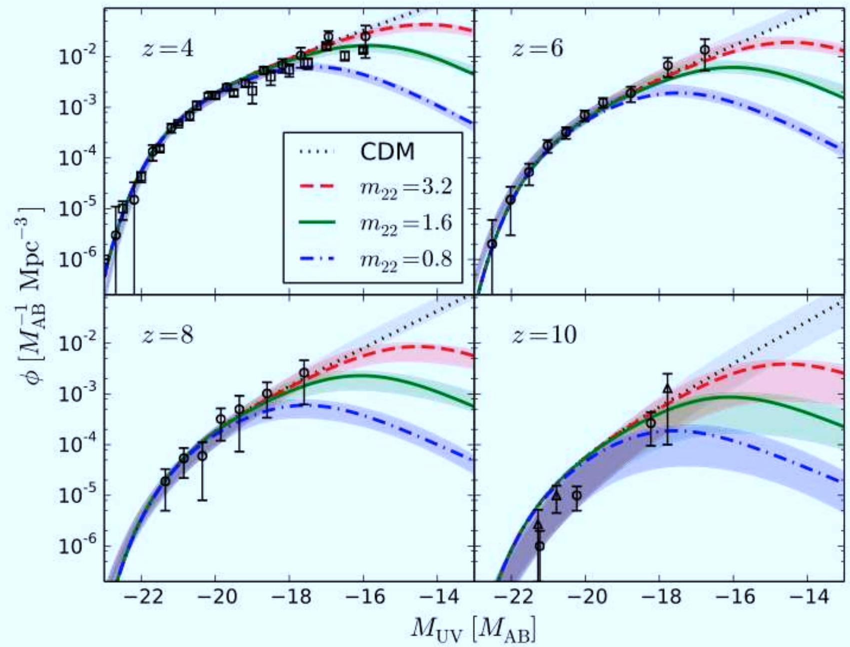


Figure 8. Luminosity function (LF) at $z = 4$–10 obtained by a single analytic formula similar to the Schechter function (Equations (11)–(13); central lines). The shaded regions are the same as Figure 6, showing the LF predicted by the conditional LF model within 2σ. Error bars show the observed LFs (2σ at $z = 4-8$ and 1σ at $z = 10$) of Parsa et al. (2015, open squares), B15b (open circles), and Oesch et al. (2014, open triangles). The analytic formula well reproduces the conditional LF results at $z = 4-8$, while at $z = 10$ it slightly outnumbers the observed galaxies and is marginally consistent with the conditional LF model.

Wave-CDM predicts the LF at z≃2–10 (Schive et al. 2016, ApJ, 818, 89):

- Ordinary ΛCDM has *straight power-law* LFs at the faint end.
- Ψ-CDM better predicts declining numbers near the current HST limits.

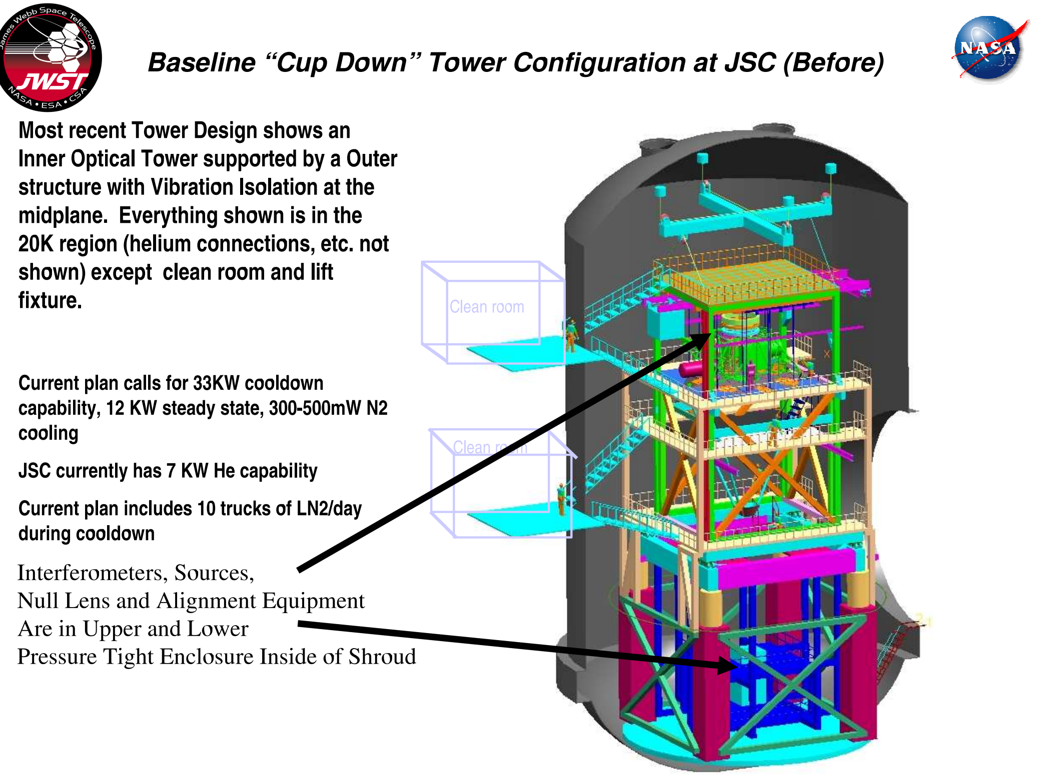
(Ψ-CDM bosonic "axion" mass in units of 10^{-22} eV or $\lambda_{deB}\sim$0.4 pc).

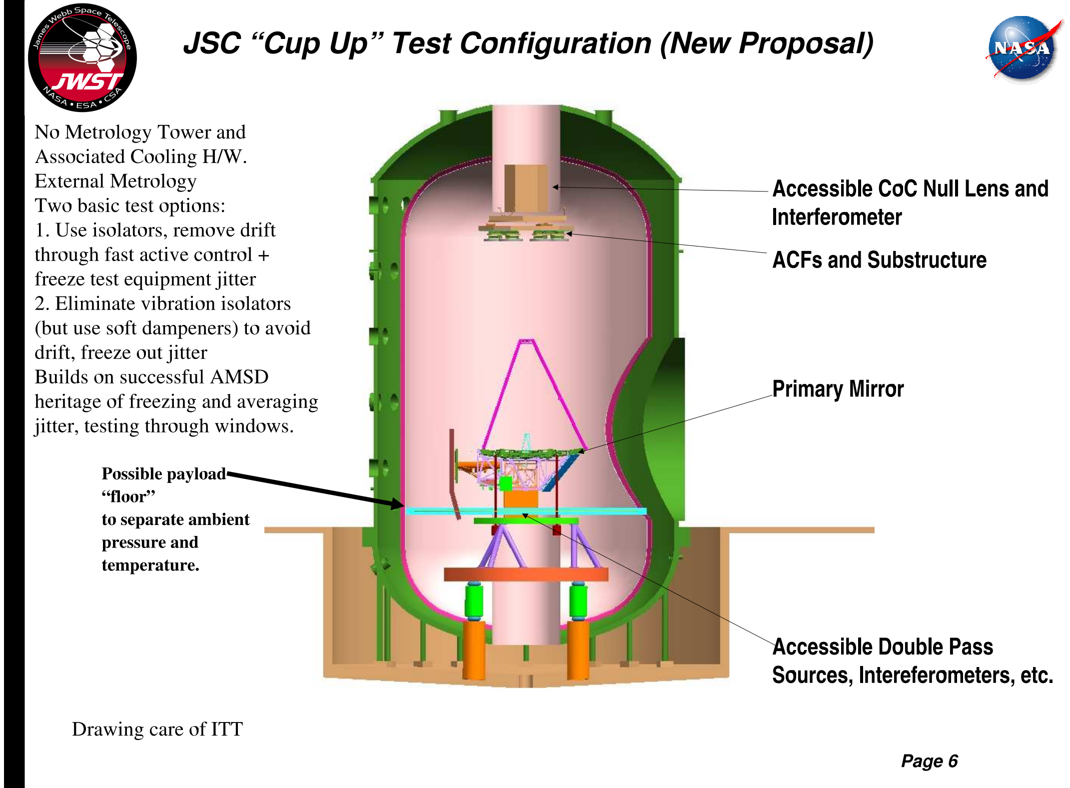
- JWST cluster lensing can distinguish between ΛCDM and Ψ-CDM.

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



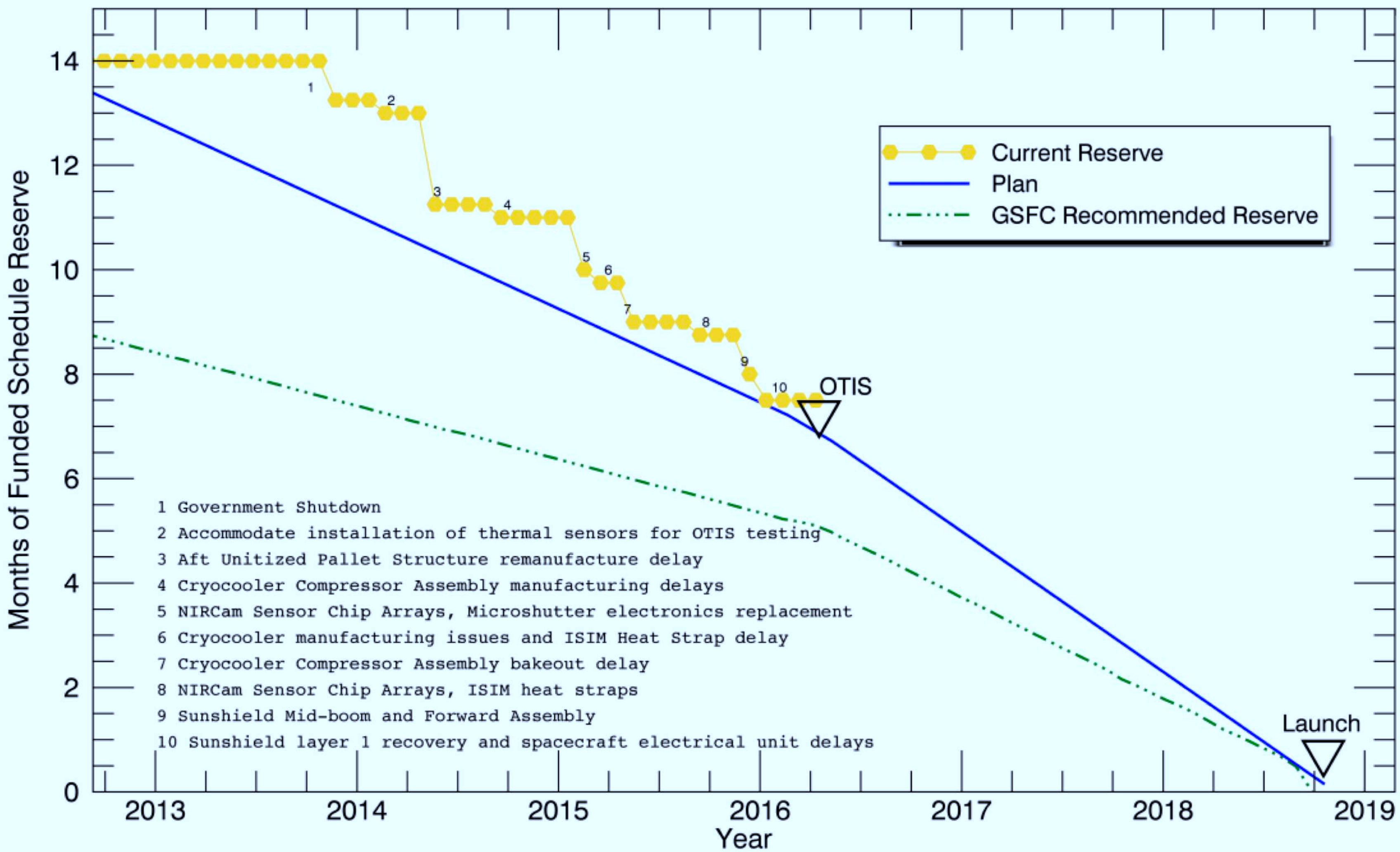




JWST underwent several significant replans and risk-reduction schemes:

- $\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 May 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 June, 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		Horizontal shaker table accepted 3/3/2016, Vertical shaker acceptence delayed to May
	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		Completed 2/15/16
	17	Deliver Command & Telemetry computer to Observatory I&T		Completed 4/11/16
	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	•	Delayed to May 2016, no schedule impact
Mar-16	21	Start Spacecraft Panel Integration		Completed 10/26/15
	22	Complete Sunshield Mid-Boom Assembly #2 functional test		Forecasting July completion date due to latch and detent pin redesign and tubessegment rebuild
	23	Complete cryocooler thermal performance acceptance testing		Completed 3/5/16

Blue font(underline) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late. "•" denotes 2015 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	46	24	19	10*	0	0

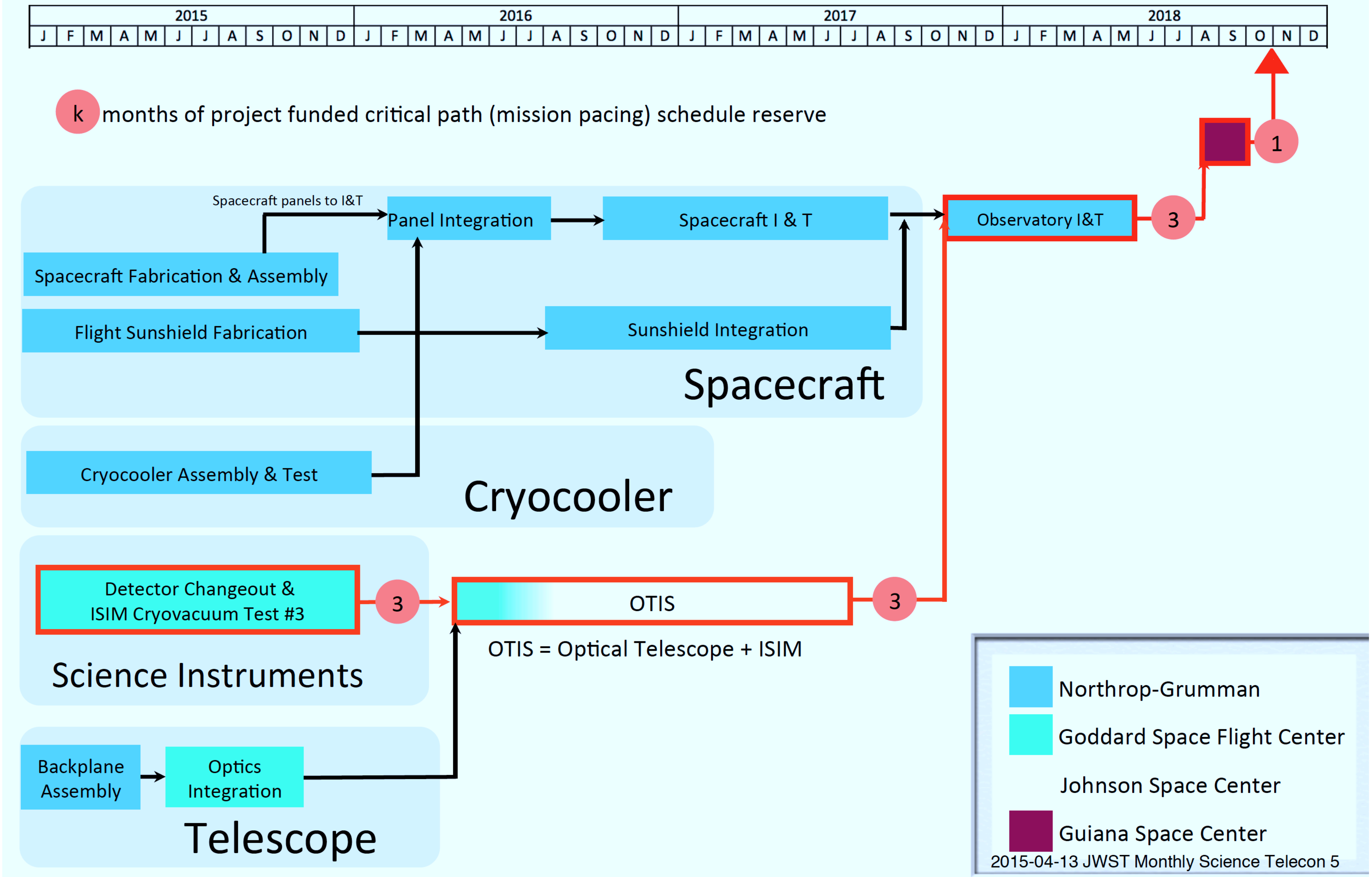
*Late milestones have been or are forecast to complete within the year. Deferred milestones are not included in the number-completed-late tally.

❖ 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.

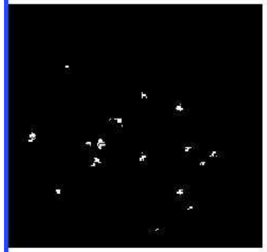
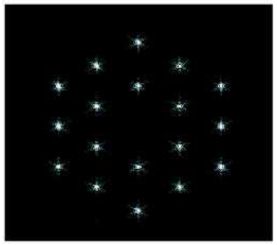
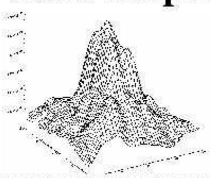
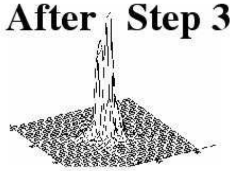
FY15, F16: Most "Lates" are not on critical path, nor cause a launch delay.

Simplified Schedule



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

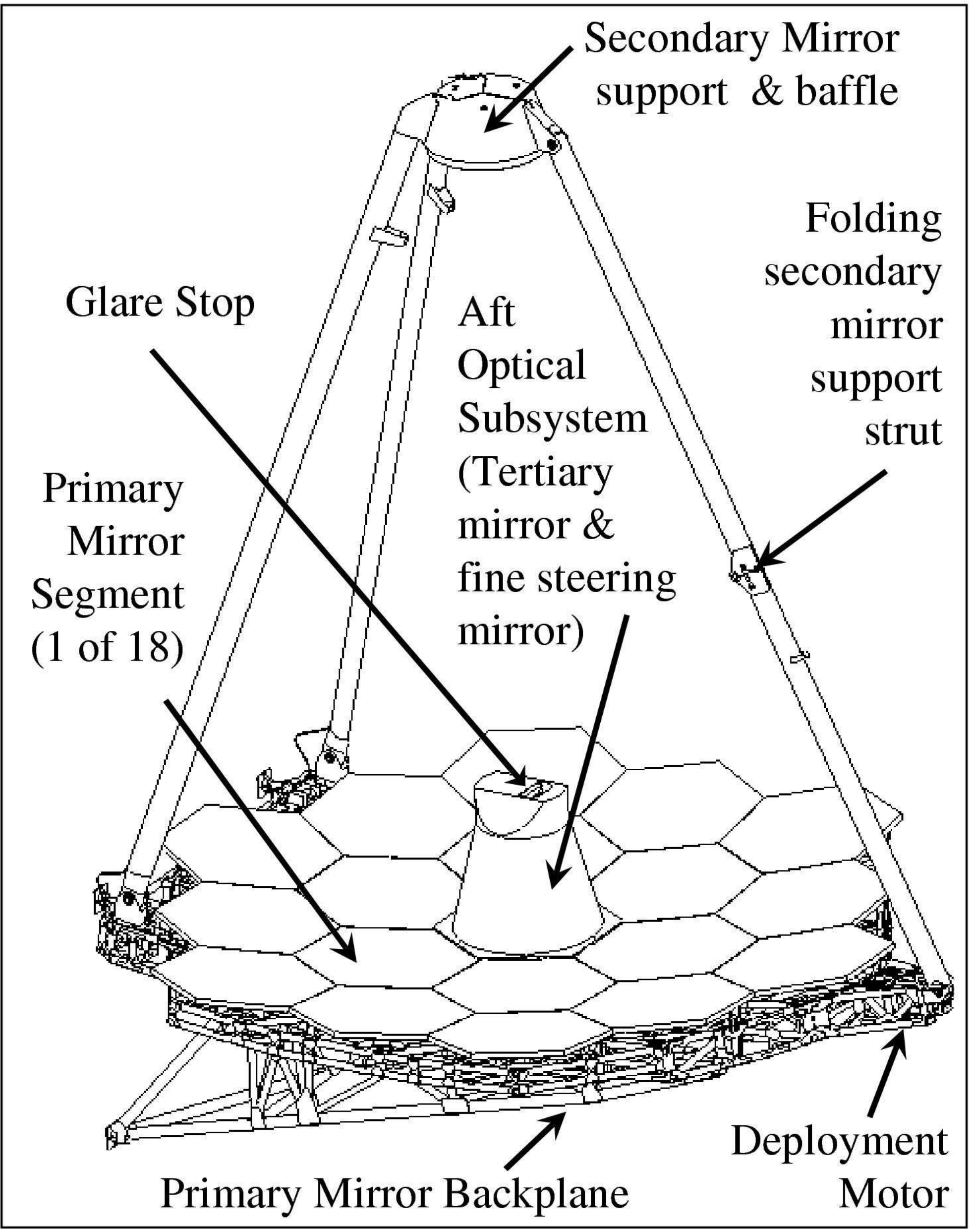
Instruments+detectors & Optical Telescope Element remain on critical path.

		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.

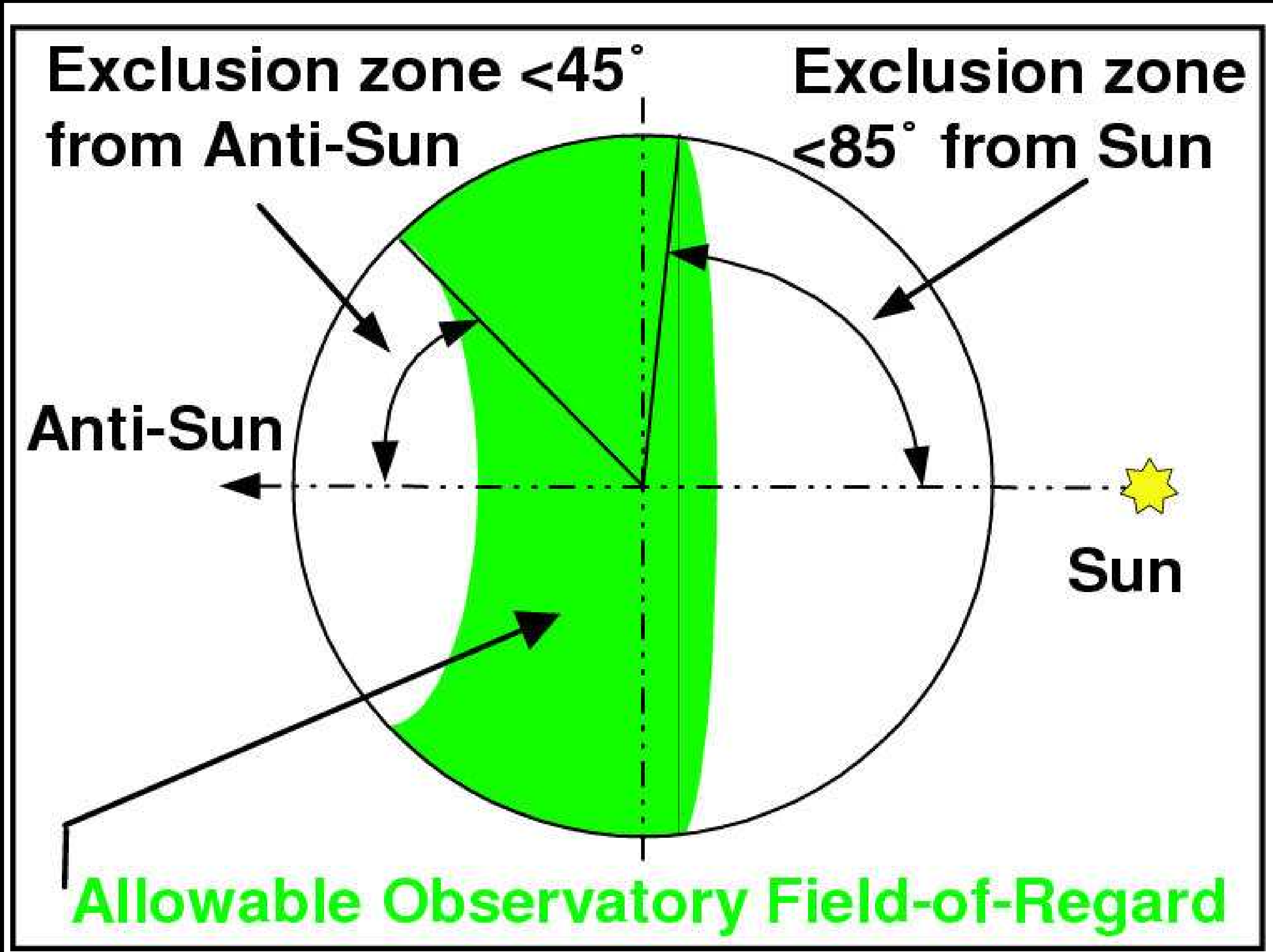
Redundant & doubly-redundant mechanisms, quite forgiving against failures.



Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2016–2017.

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

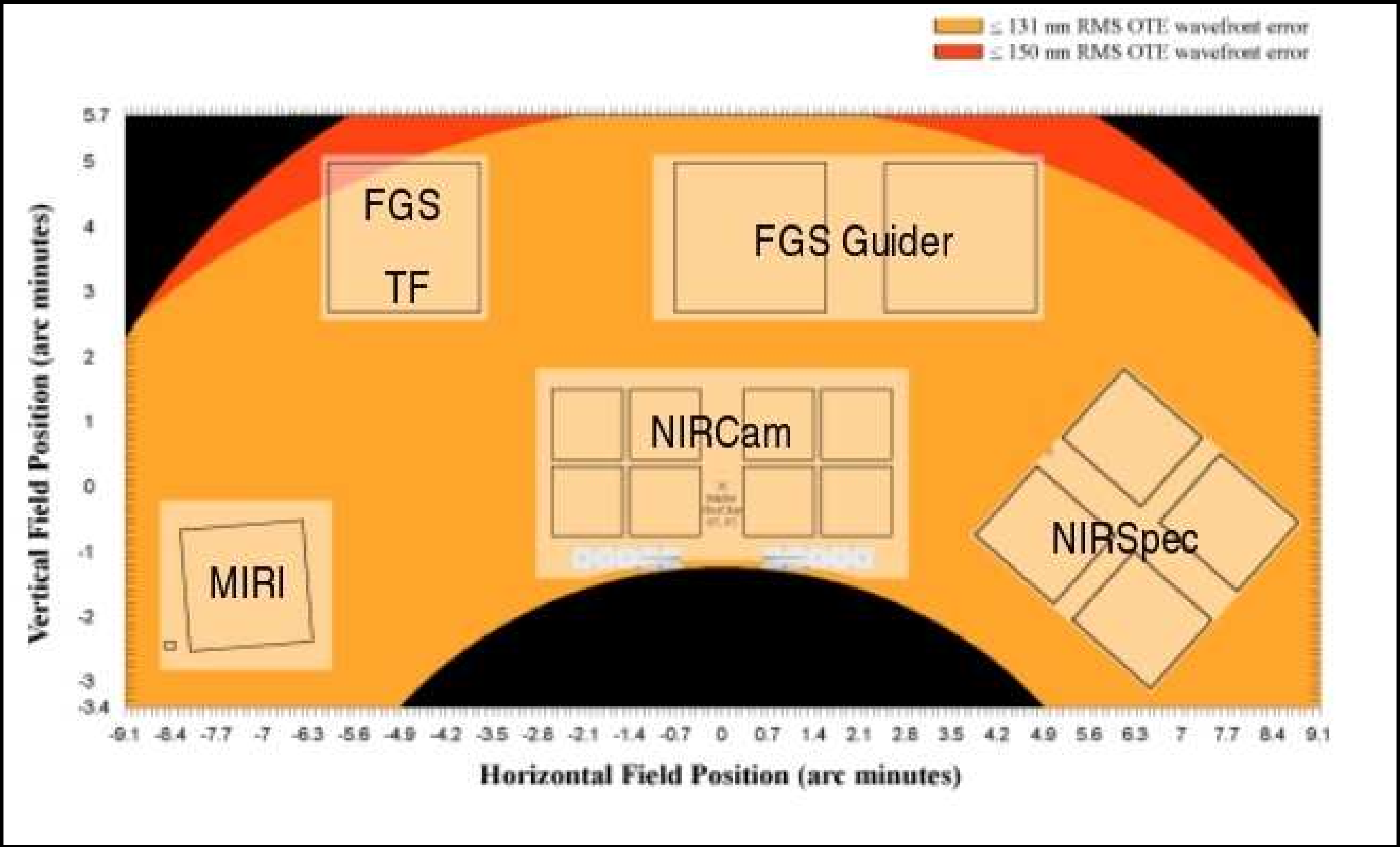
In L2, WFS updates every 10 days depending on scheduling/ SC-illumination.



JWST can observe North/South Ecliptic pole targets continuously:

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

• (3c) What instruments will JWST have?



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

• As of 2015, now also implemented for parallel *science* observations.