# The Search for First Light:

# James Webb Space Telescope Hardware Update 2016


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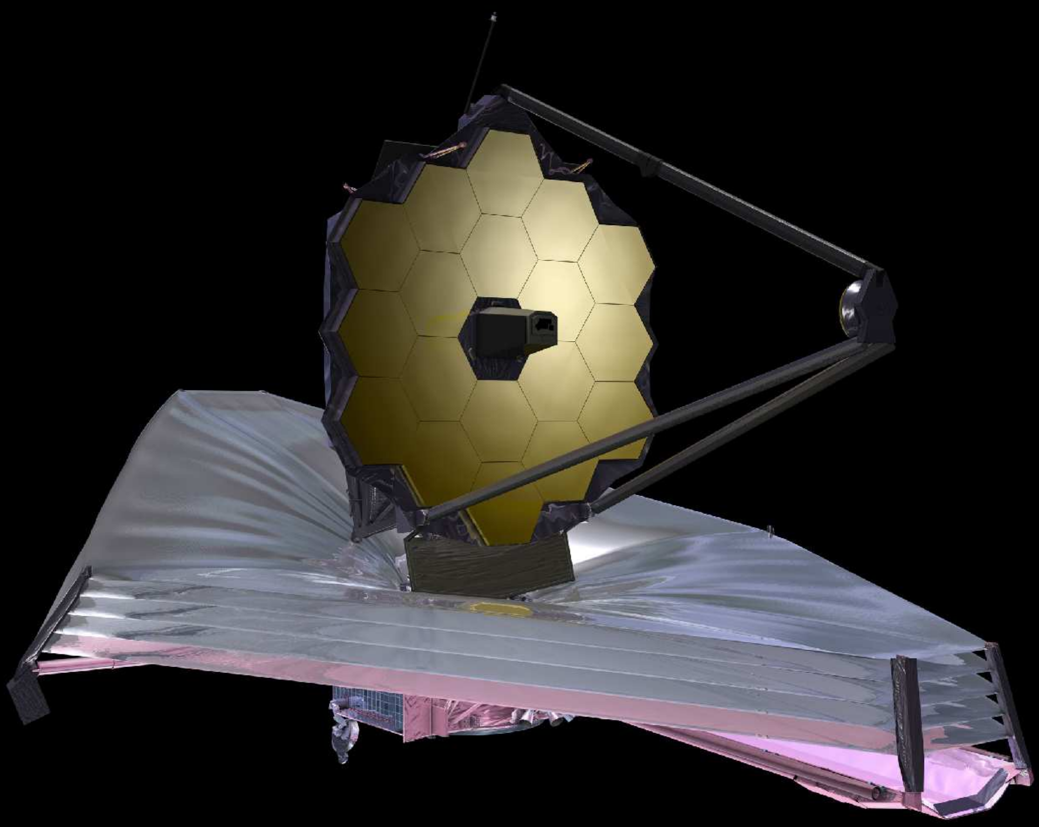


*Colloquium at the Department of Physics and Astronomy, University College London,*

*London, England; Thursday June 30, 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?

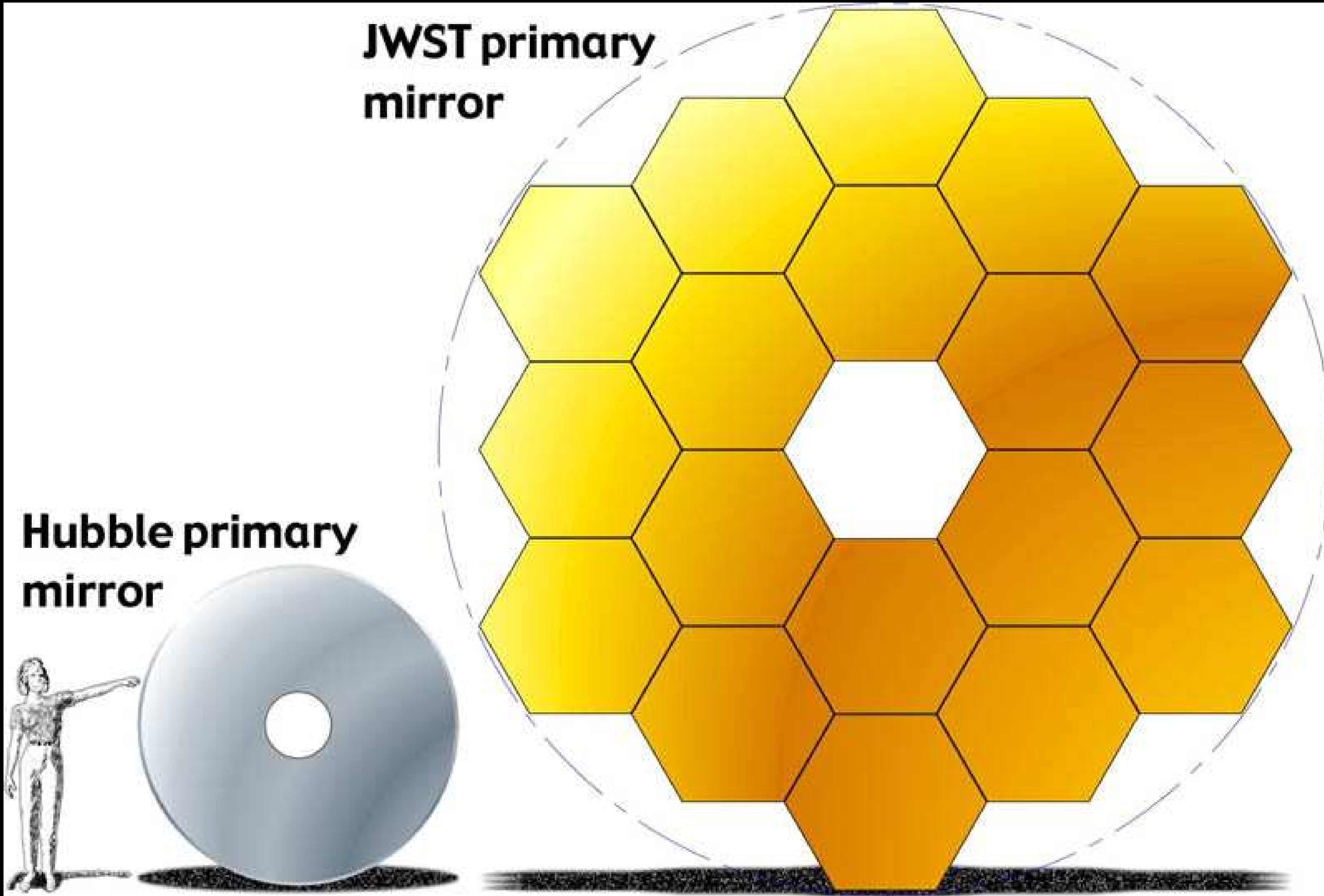
- (3) How will JWST measure the Epoch of First Light (using gravitational lensing) — handshake with Planck 2016 results.

- (4) Summary and Conclusions.

Sponsored by NASA/HST & JWST

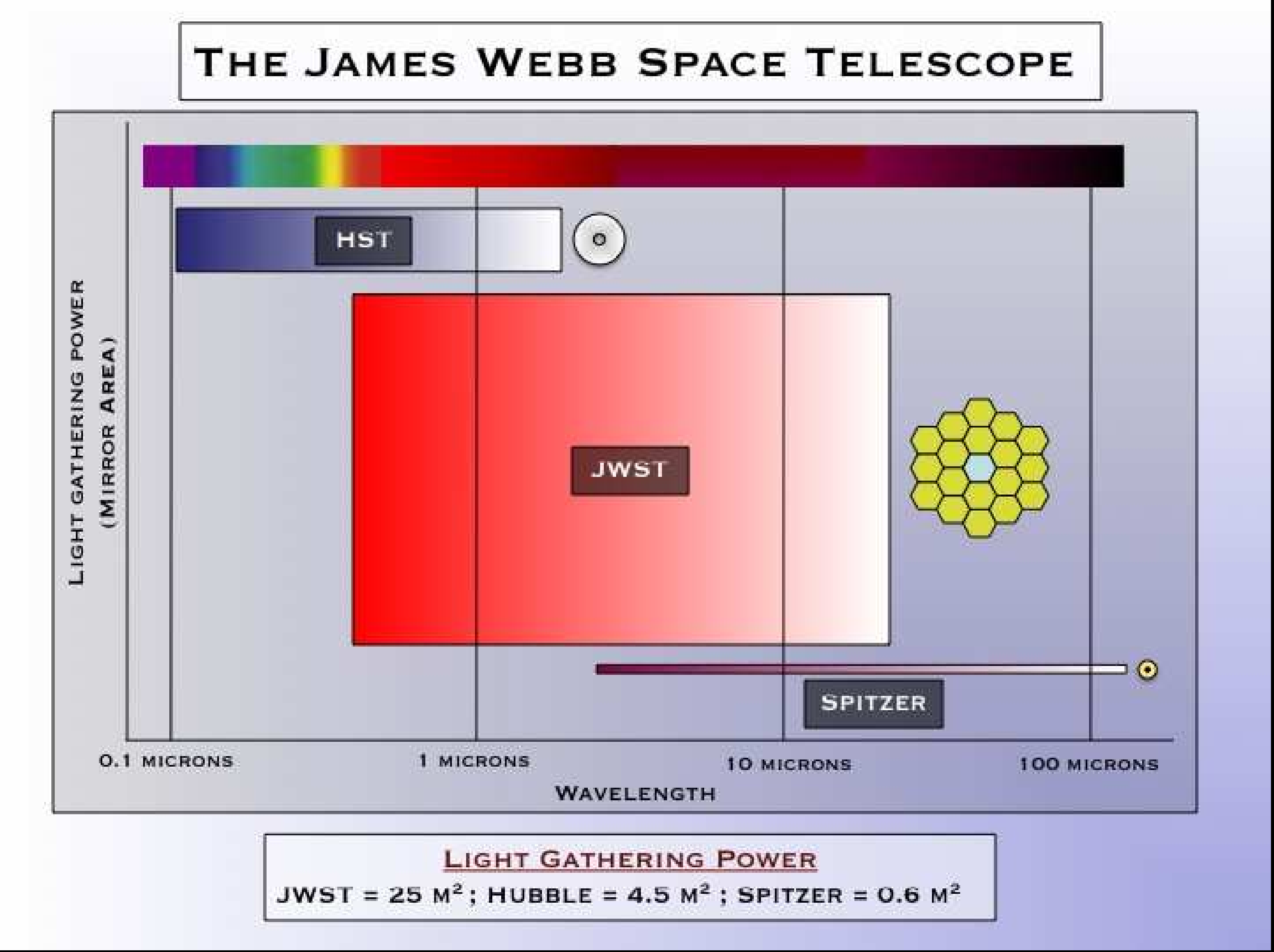
Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/uclondon16_jwst.pdf`


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:

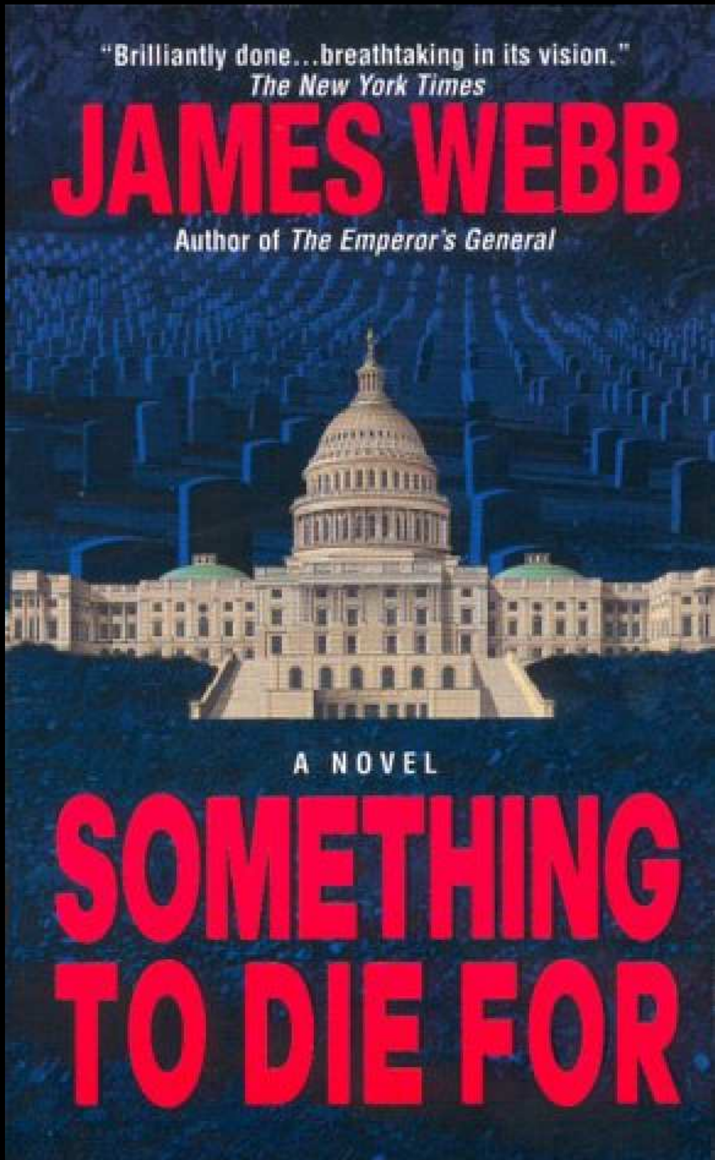
JWST has the same resolution in the near-IR as Hubble in the optical.




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.

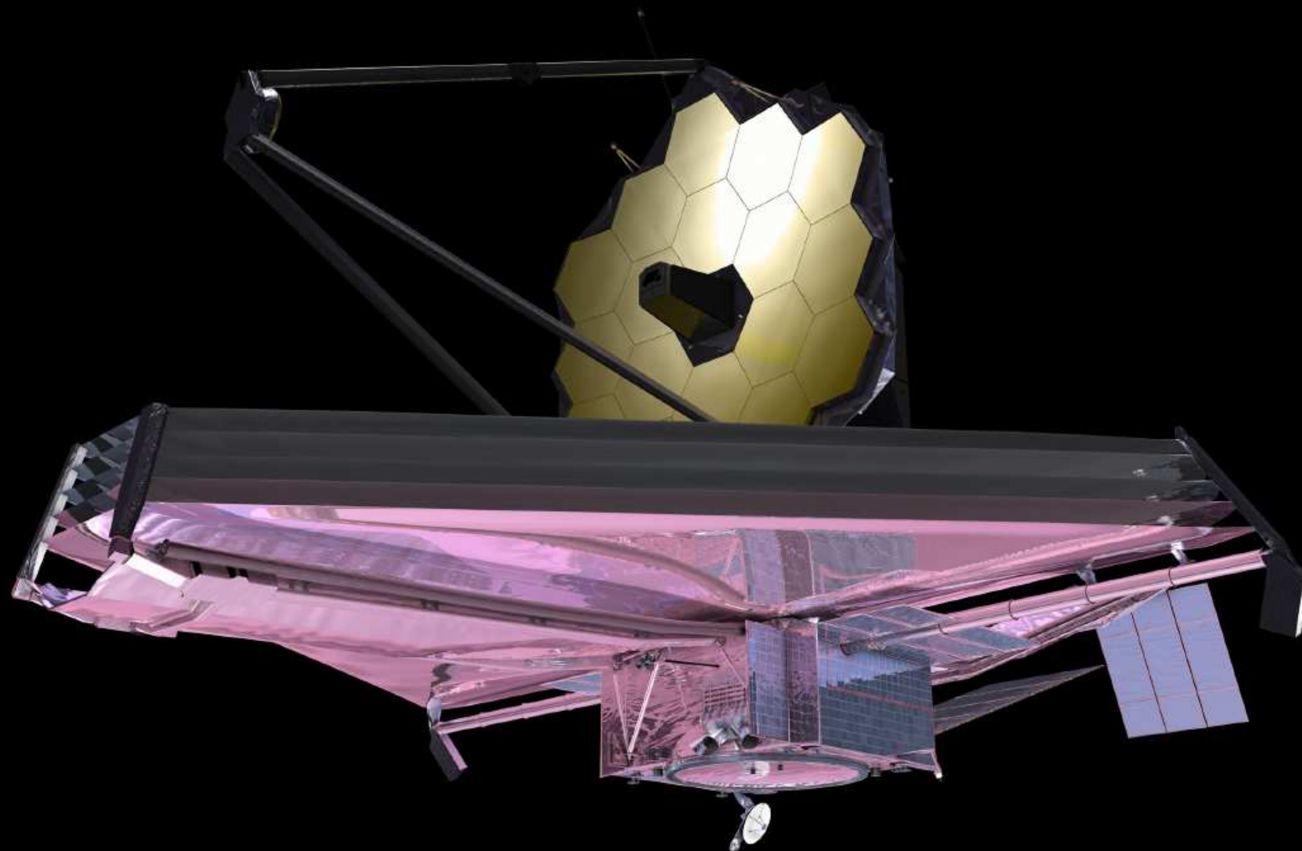
(1) Update of the James Webb Space Telescope (JWST), 2016.



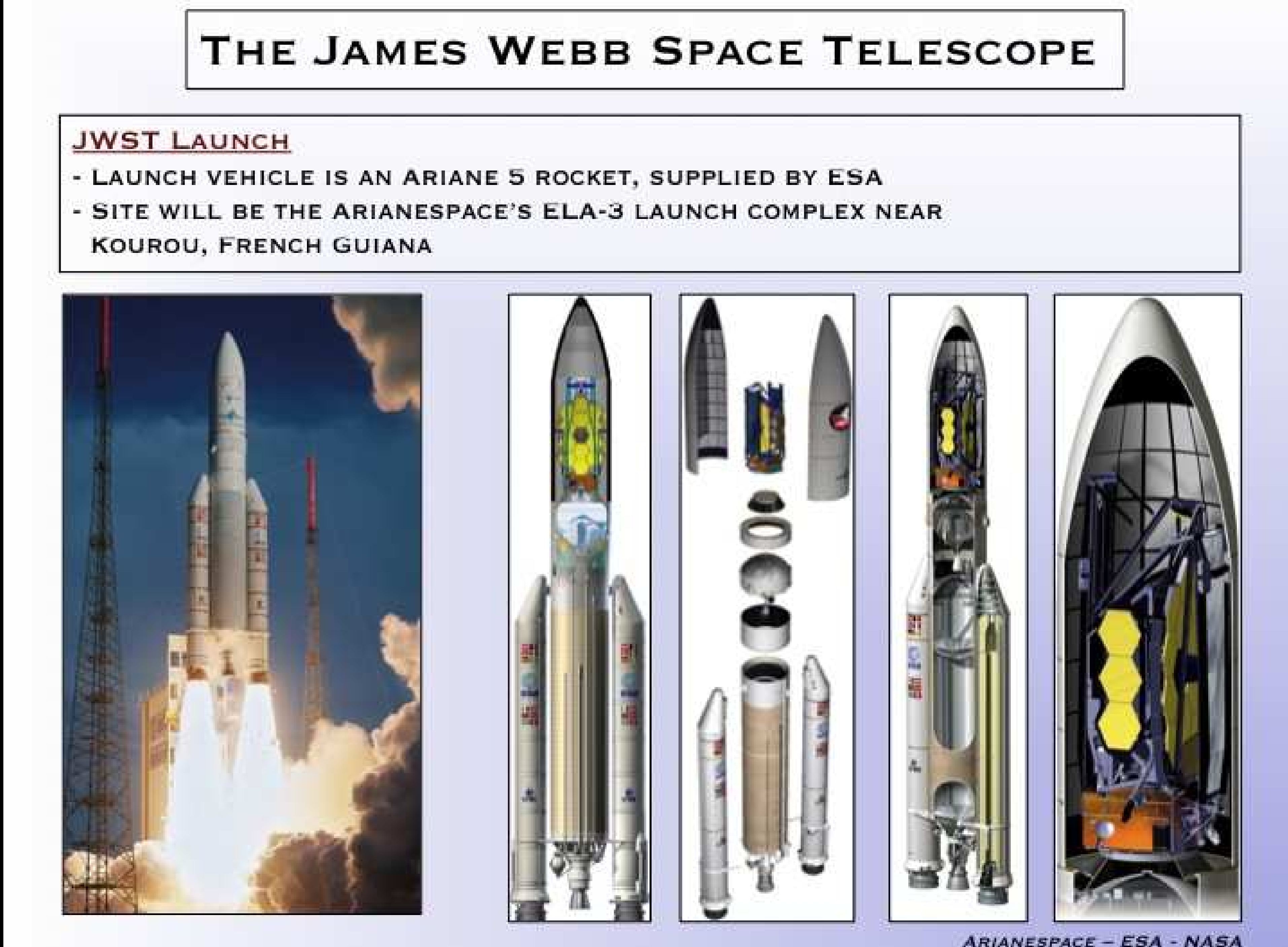

To be used by students & scientists after 2018 ... It'll be worth it.

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

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

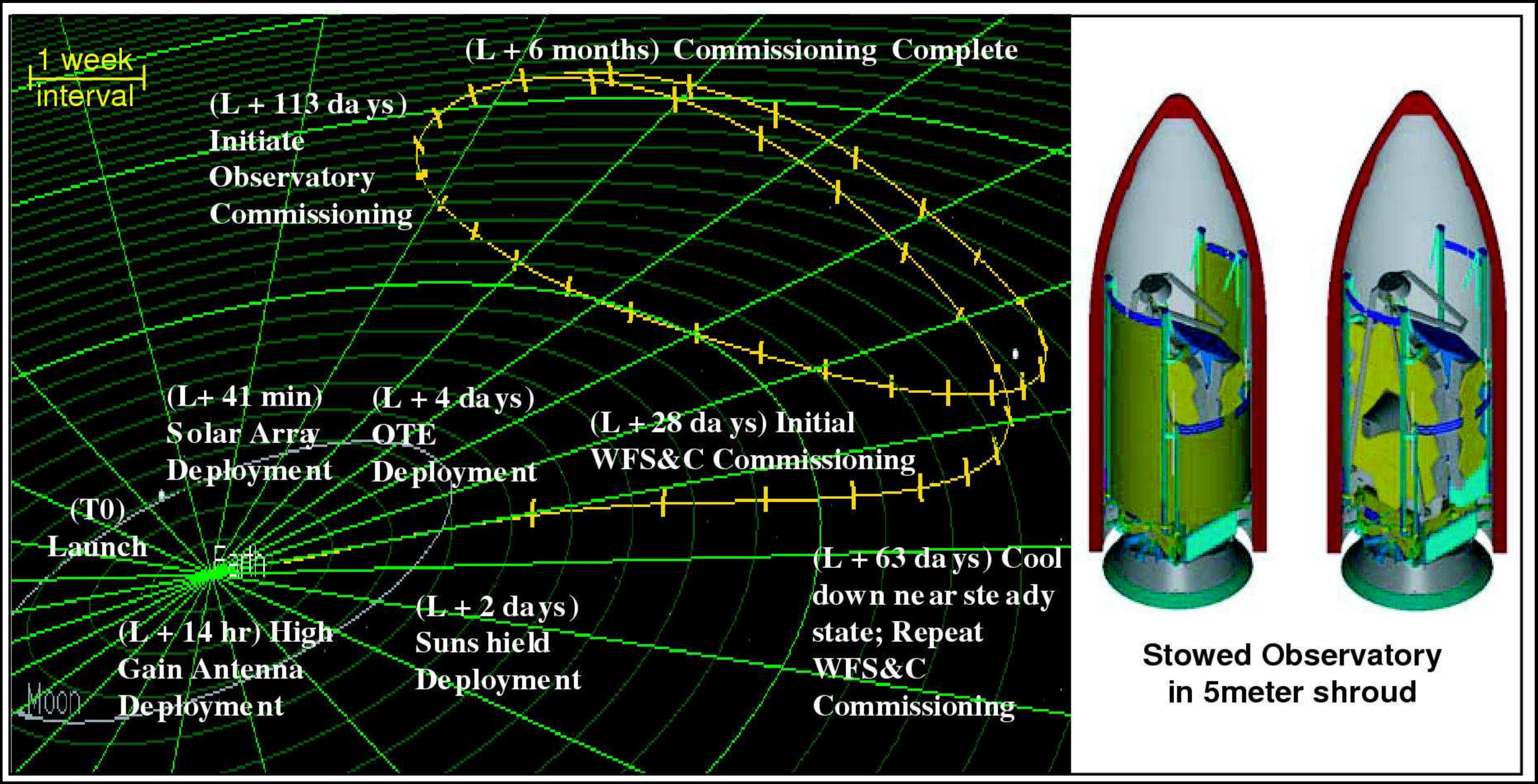


- A fully deployable 6.5 meter (25 $m^2$) segmented IR telescope for imaging and spectroscopy at 0.6–28 $\mu$m wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.



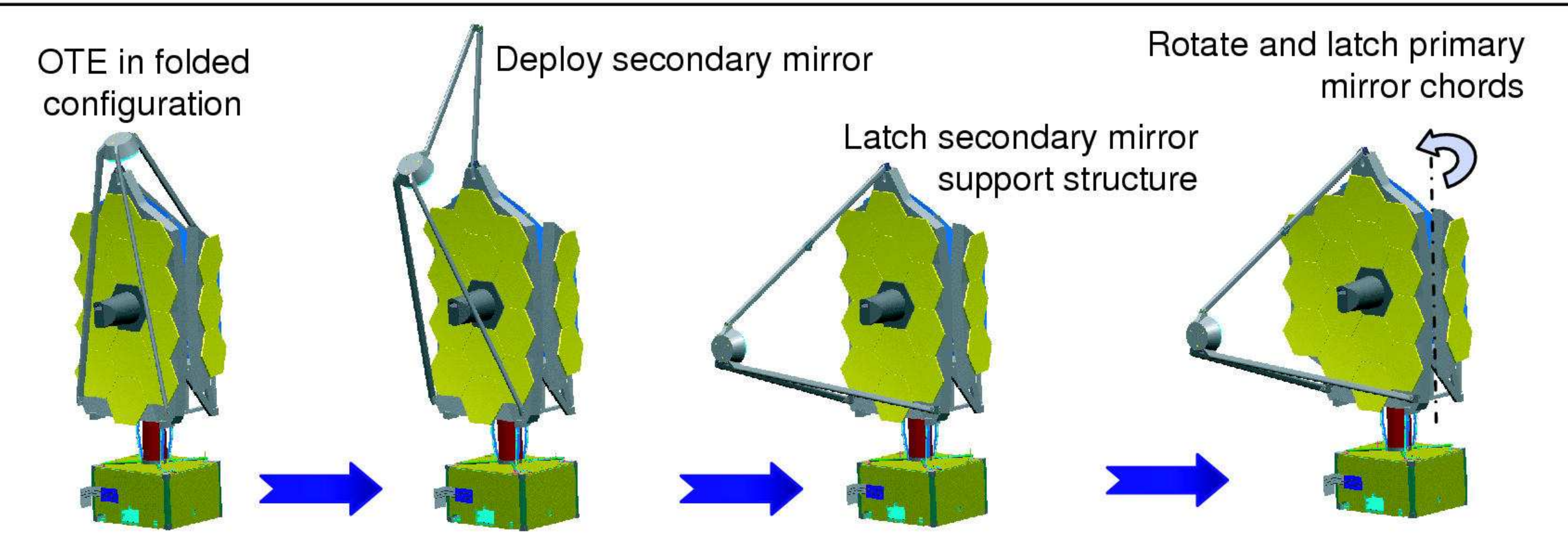

• The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

# (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.

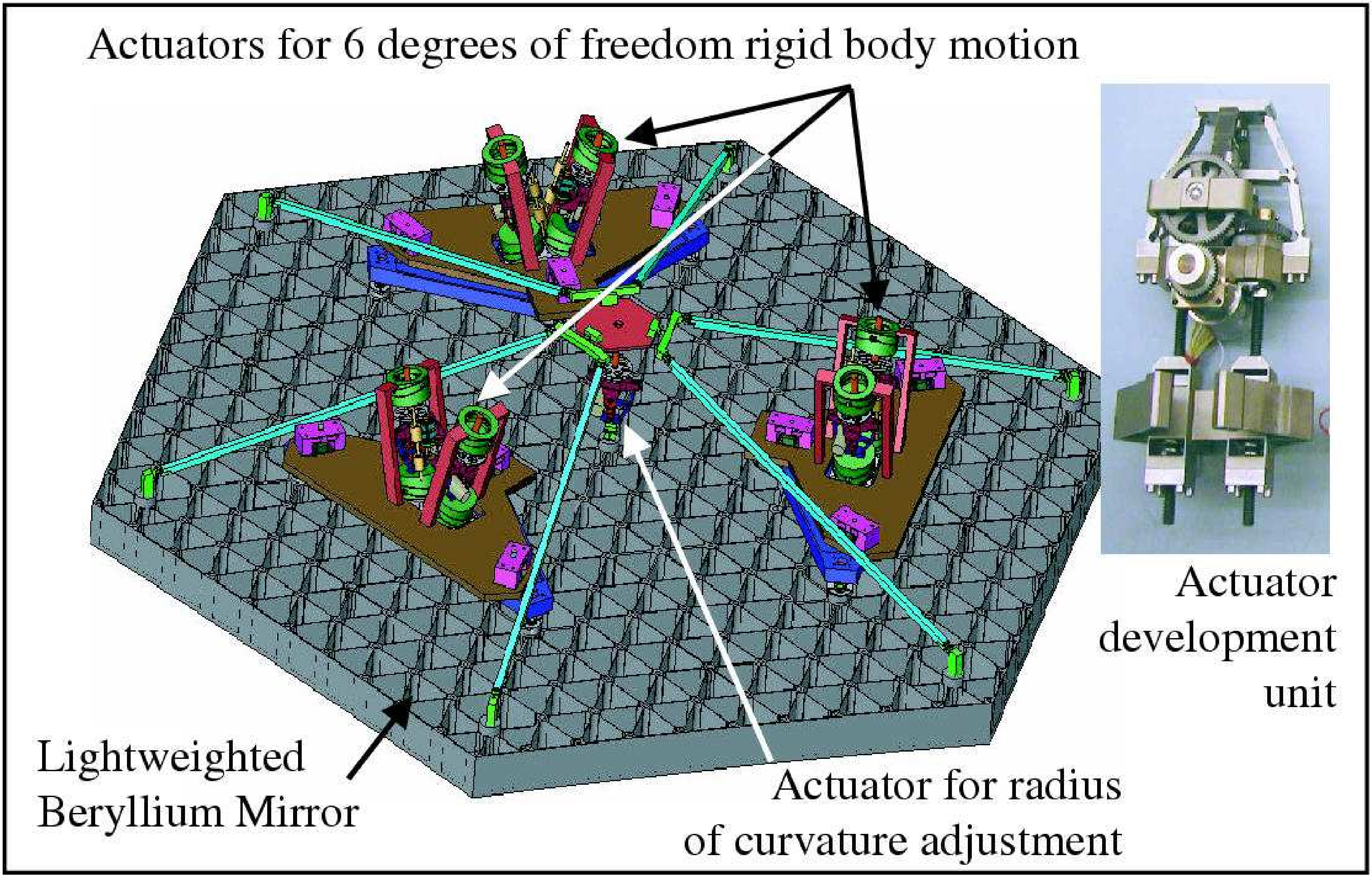
# (1b) How will JWST be automatically deployed?




- 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).

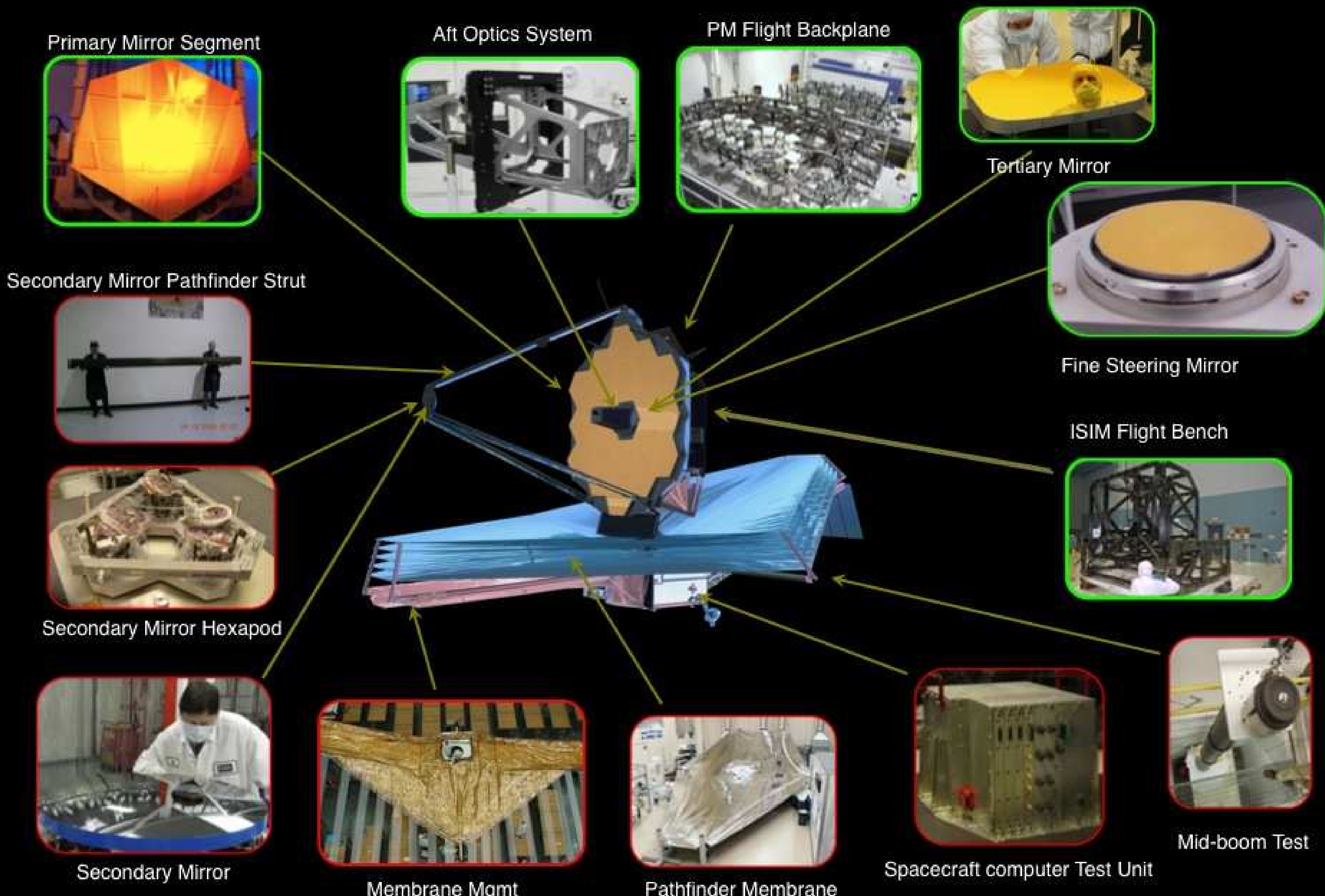
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.




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

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

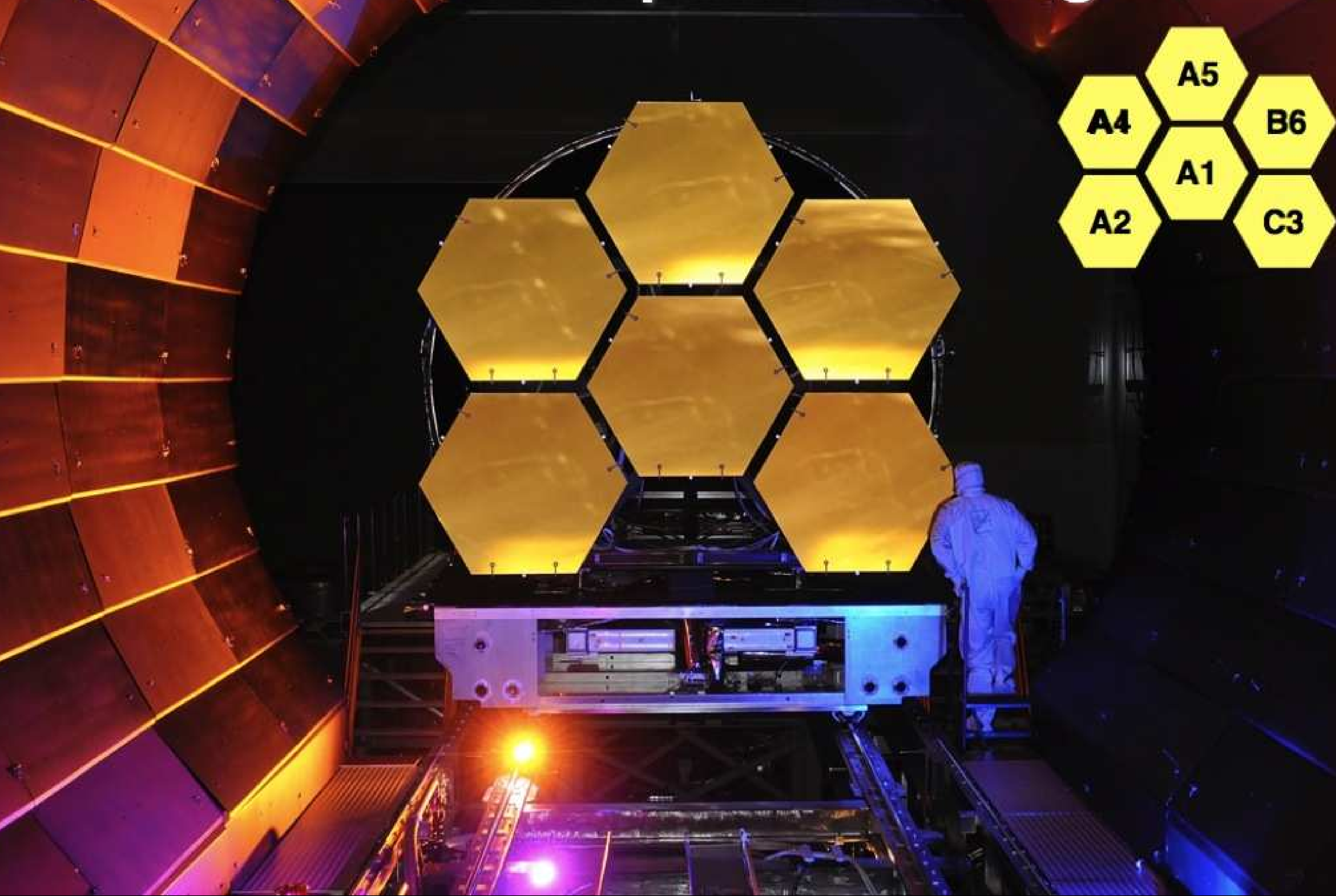
# JWST Hardware Status





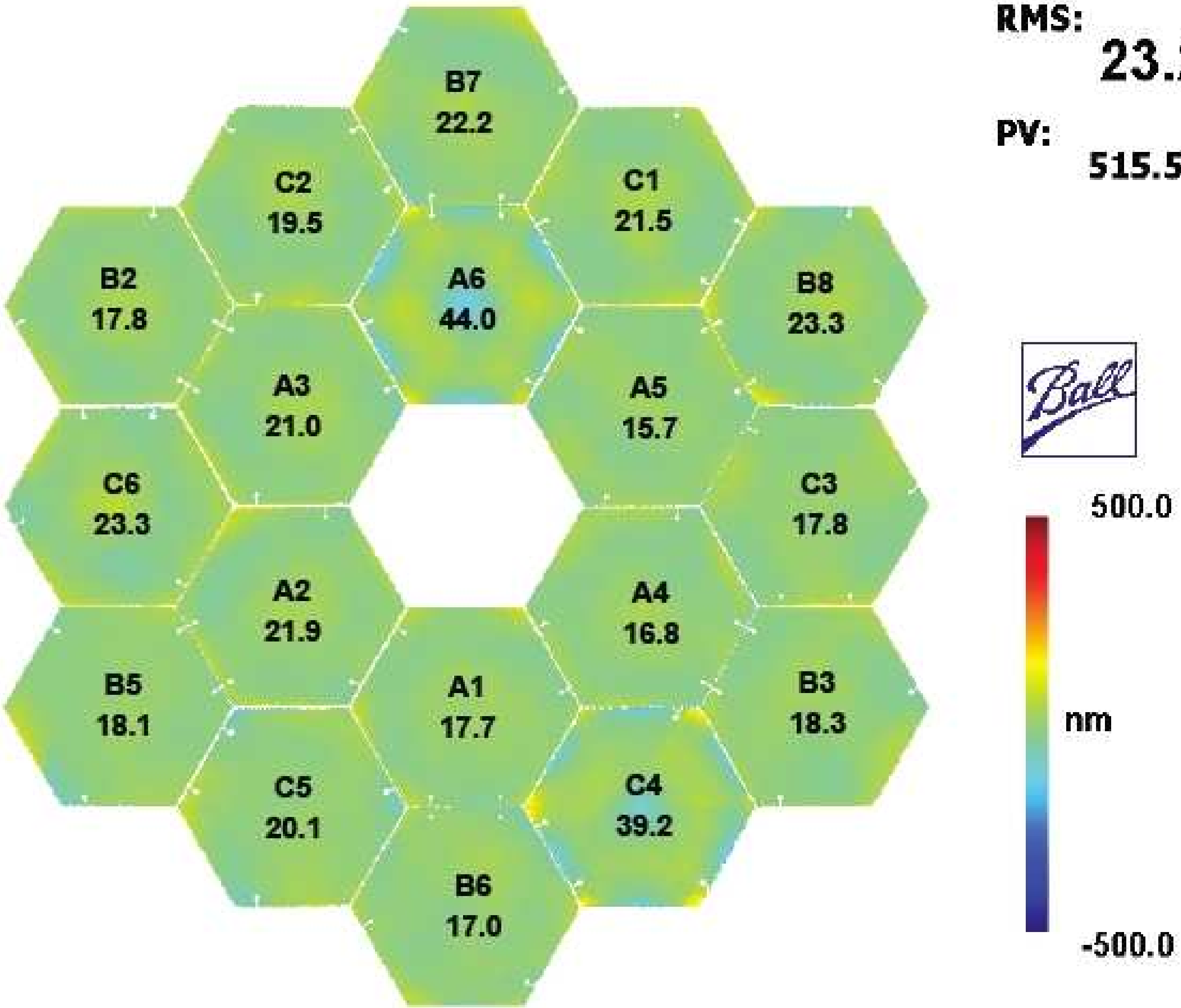

June 2016: $\gtrsim$99% of launch mass designed and built ($\gtrsim$80% weighed).

# Mirror Acceptance Testing




Ball

# Primary Mirror Composite




**RMS:** 23.2 nm

**PV:** 515.5 nm

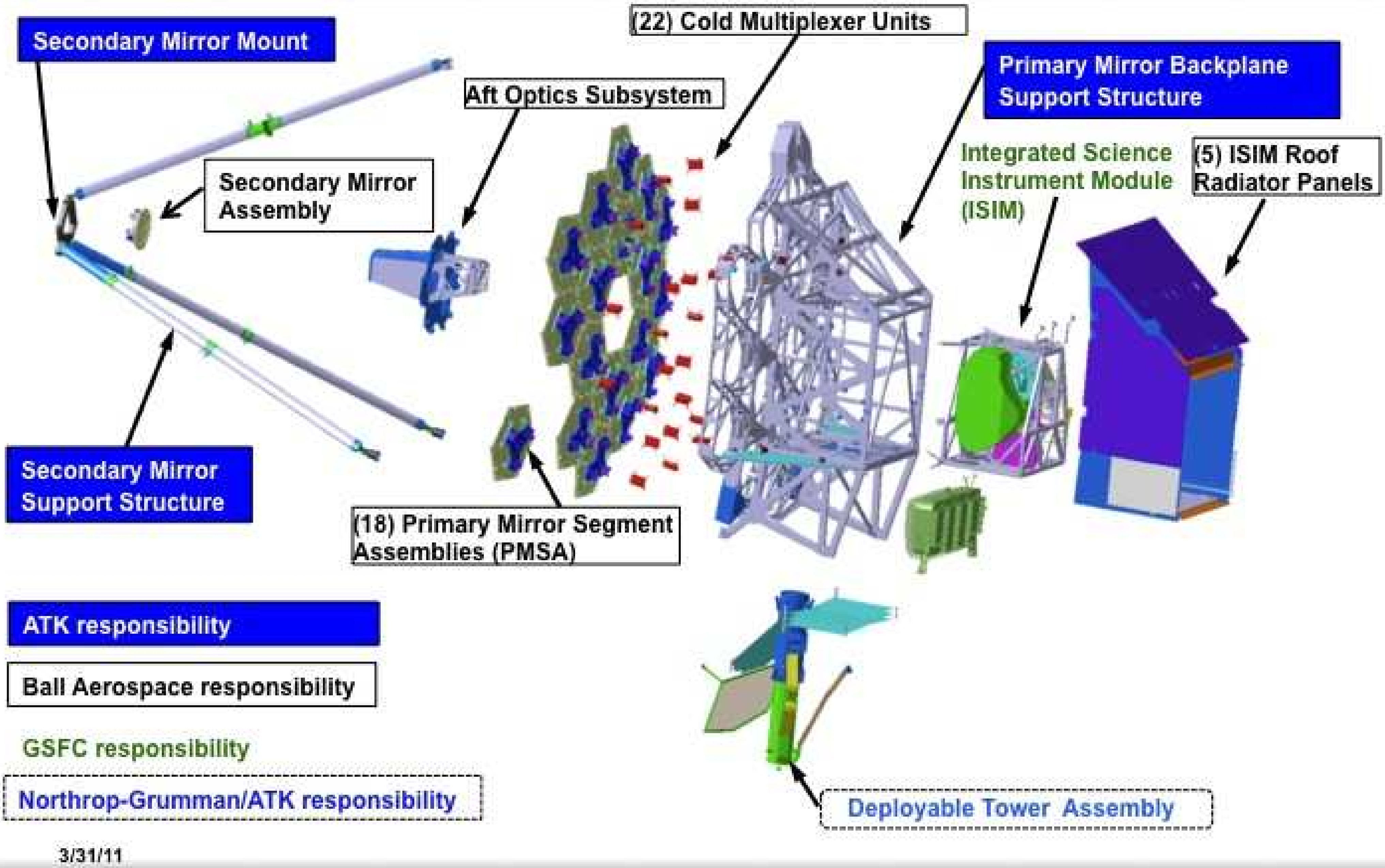
# Mirror Status

- **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

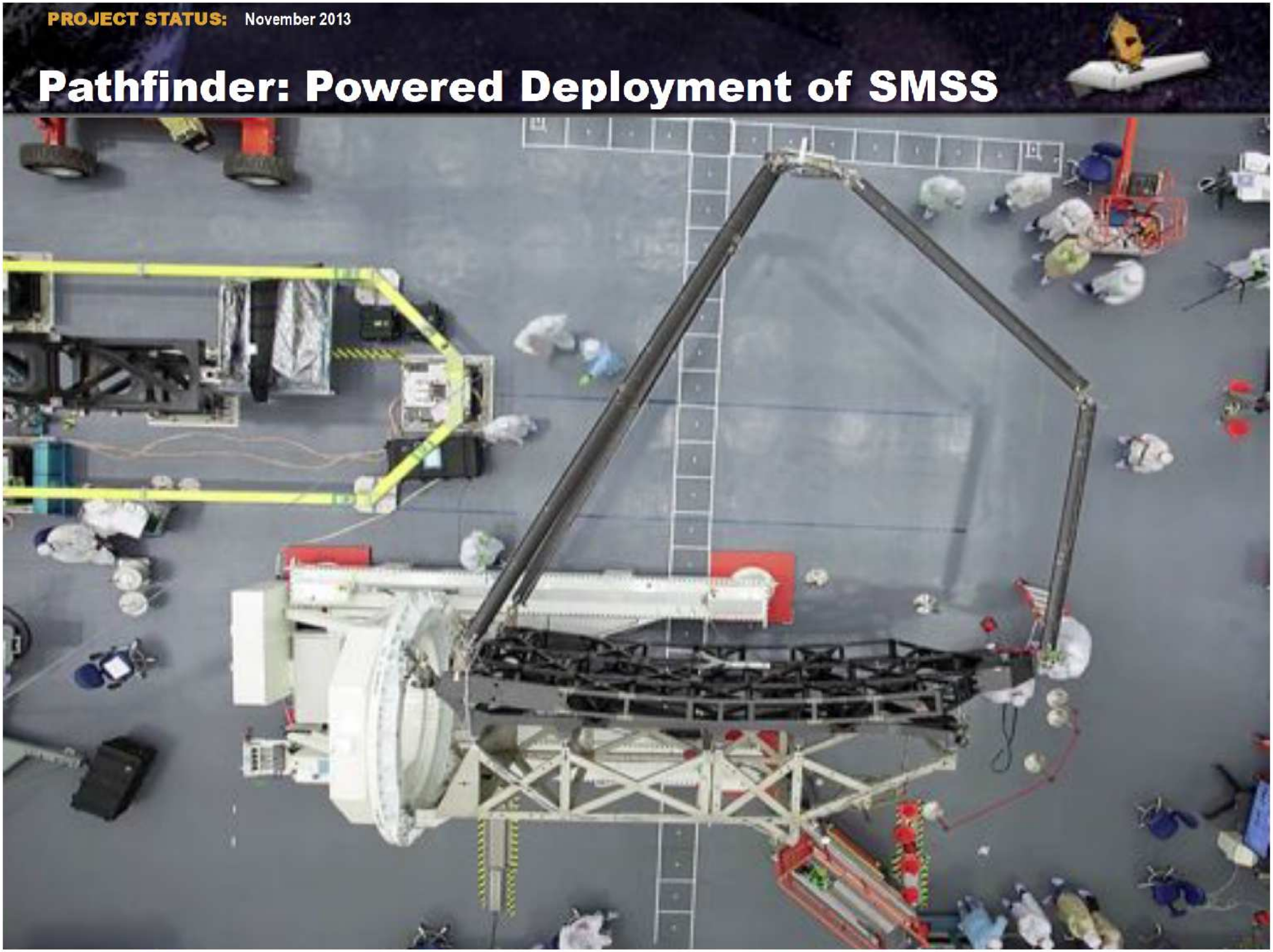


Spring 2014: All 18 flight mirrors delivered to NASA GSFC (MD).

# TELESCOPE ARCHITECTURE




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




July 2014: Secondary Mirror Support deployment successfully tested.

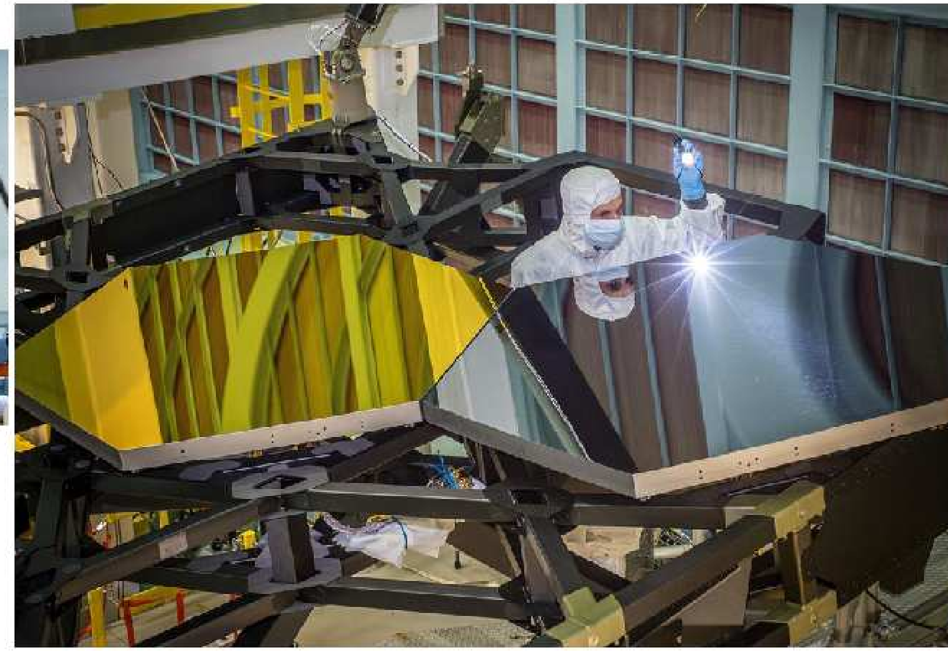
# (1c) JWST hardware to date, and how to best use it for high redshift lensing.

[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.

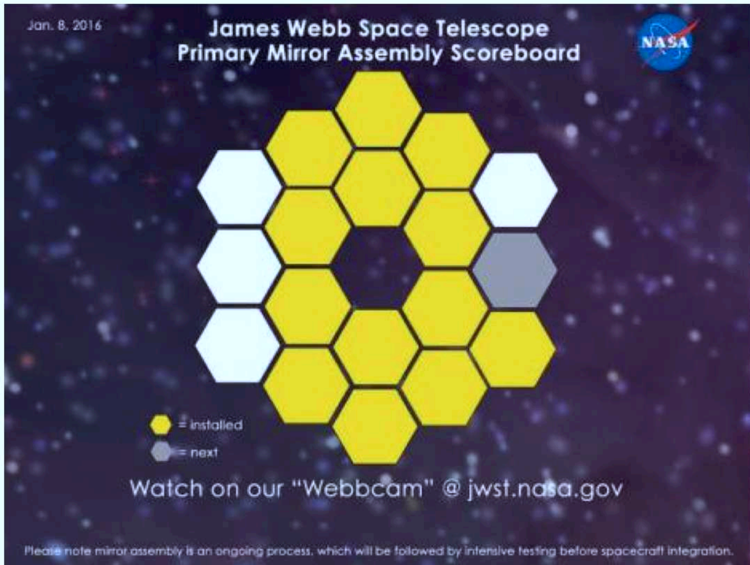
- Our Galaxy is a bright IR source at $\lambda \gtrsim 1$–$5\mu$m: In certain directions of the sky, some straylight can hit secondary mirror via Sunshield.
- This can effect JWST (lensing) studies of First Light objects.

# Telescope Pathfinder – Risk Reduction



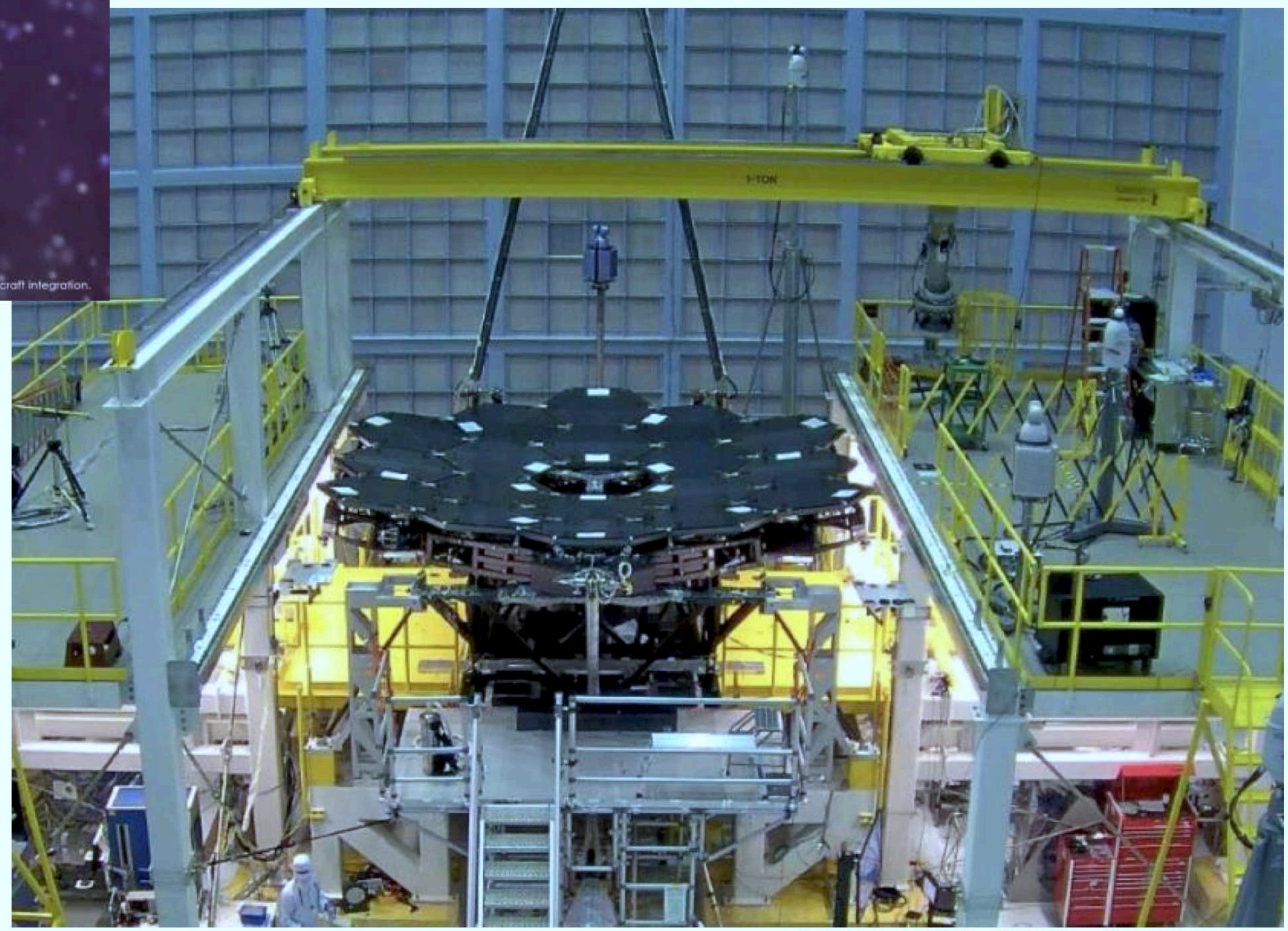
JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

# Much progress has been made in OTE integration




Where we were at last month's call

Current: all 18 PMSAs installed, liquid-shim-cured, & metrologized. Alignments meet specifications, and actuator motions verified
*Big milestone!*



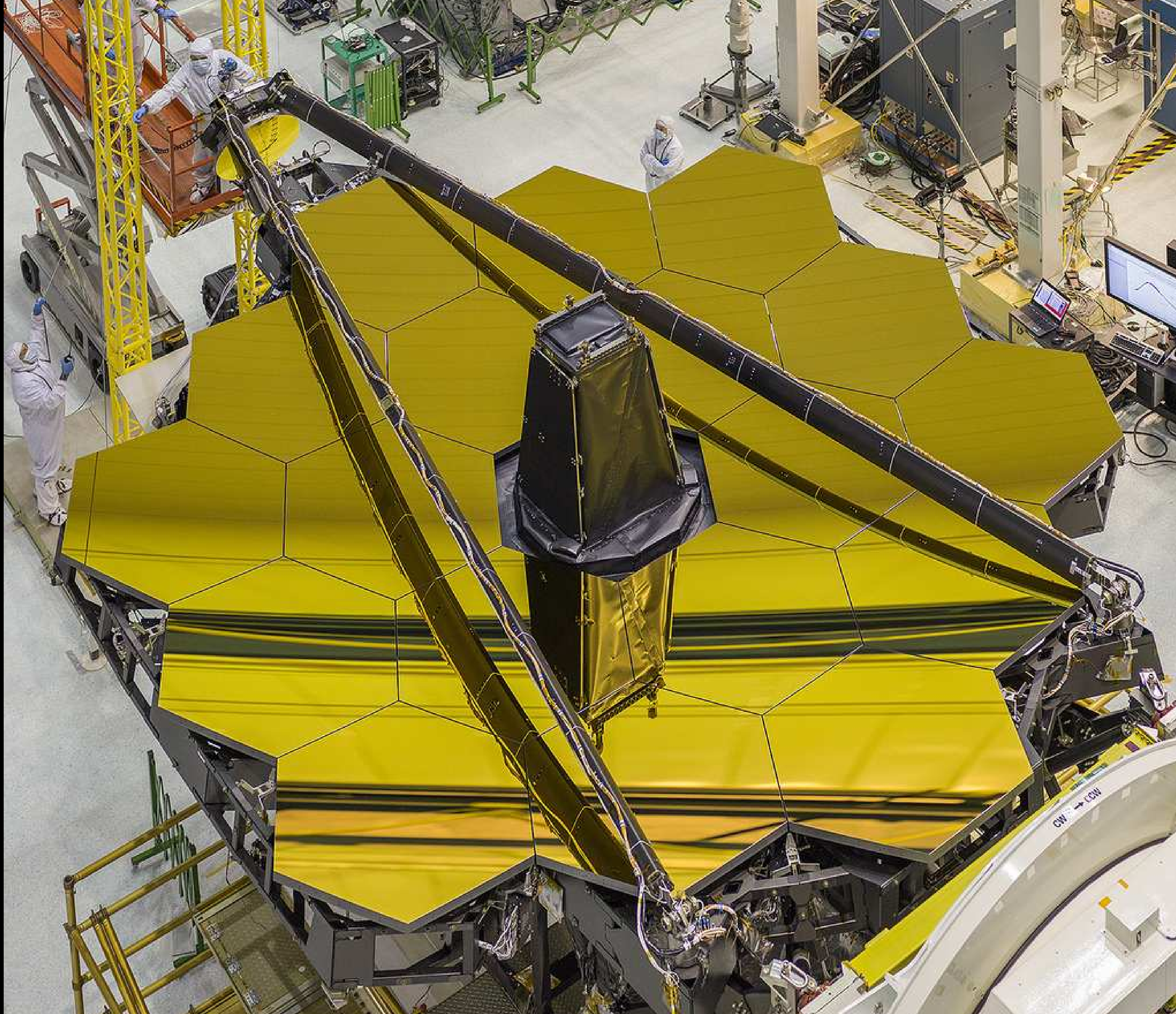


JWST lifetime: Requirement: 5 yrs; Goal: 10 yrs; Propellant: 14 yrs.

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

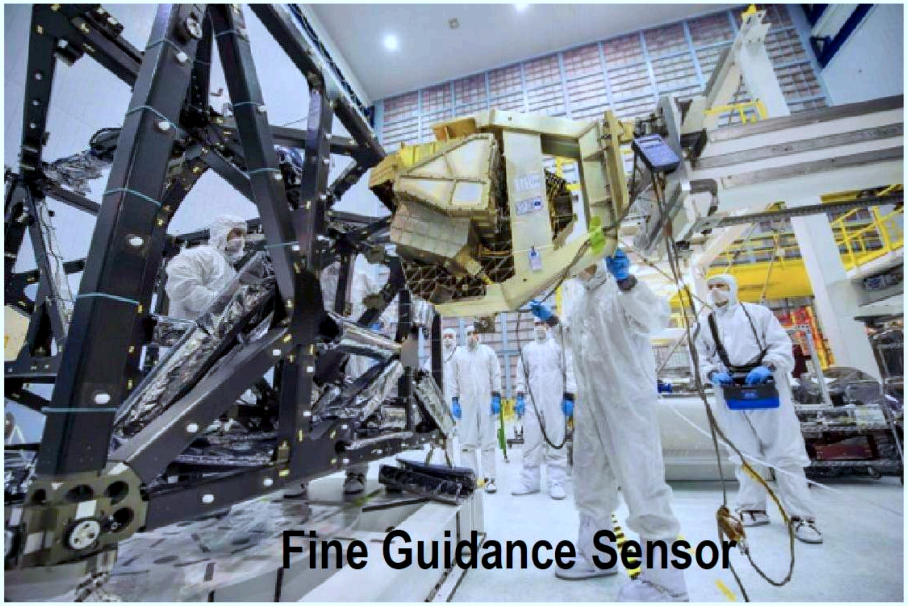

May 2016: JWST being tilted into the right position

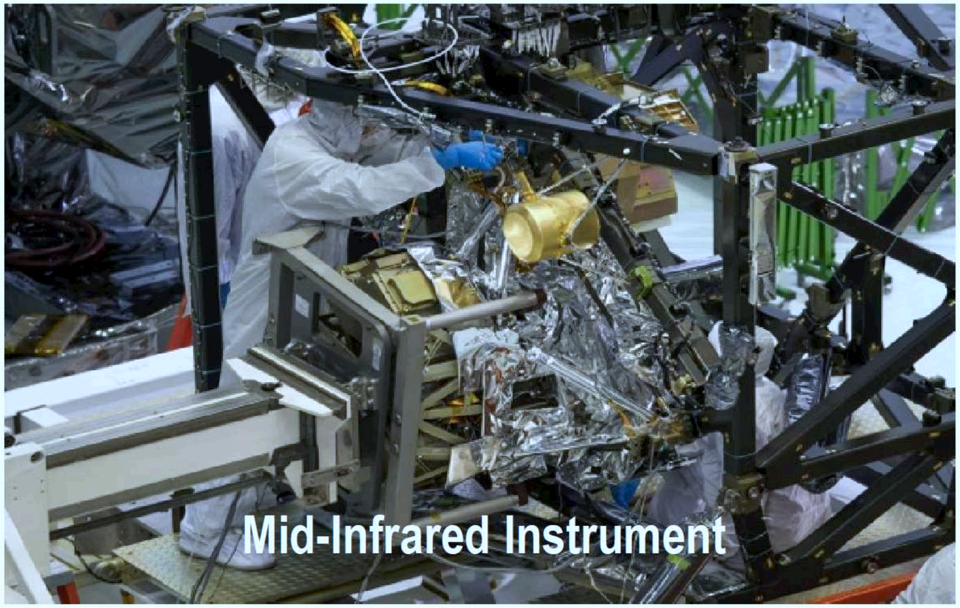
May 2016: Webb mirrors finally mounted and ready!



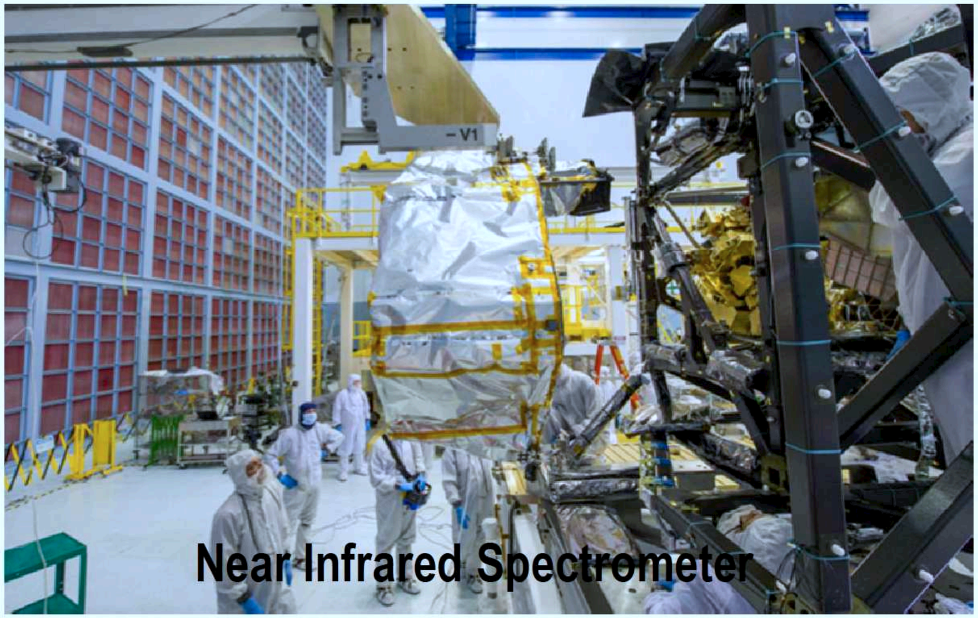
May 2016: JWST stowed for further instrument mounting

# All Instruments Integrated







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

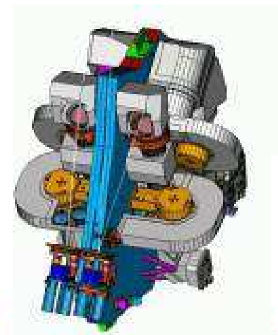
## Instrument Overview

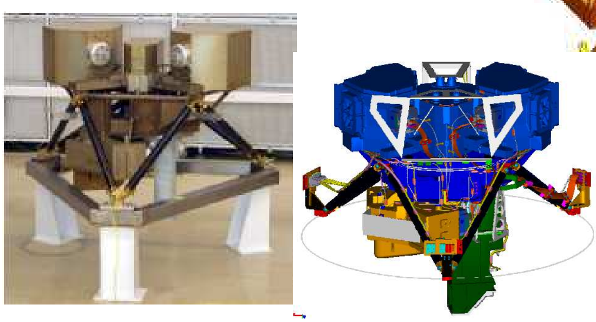
**Fine Guidance Sensor (FGS)**

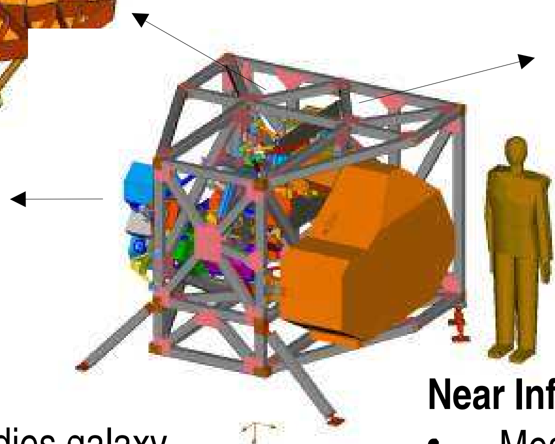
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

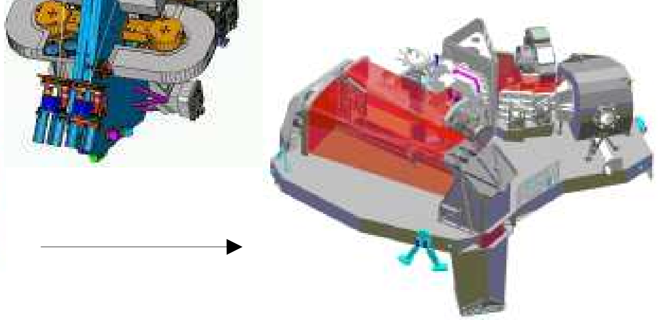
**Near Infra-Red Camera (NIRCam)**

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







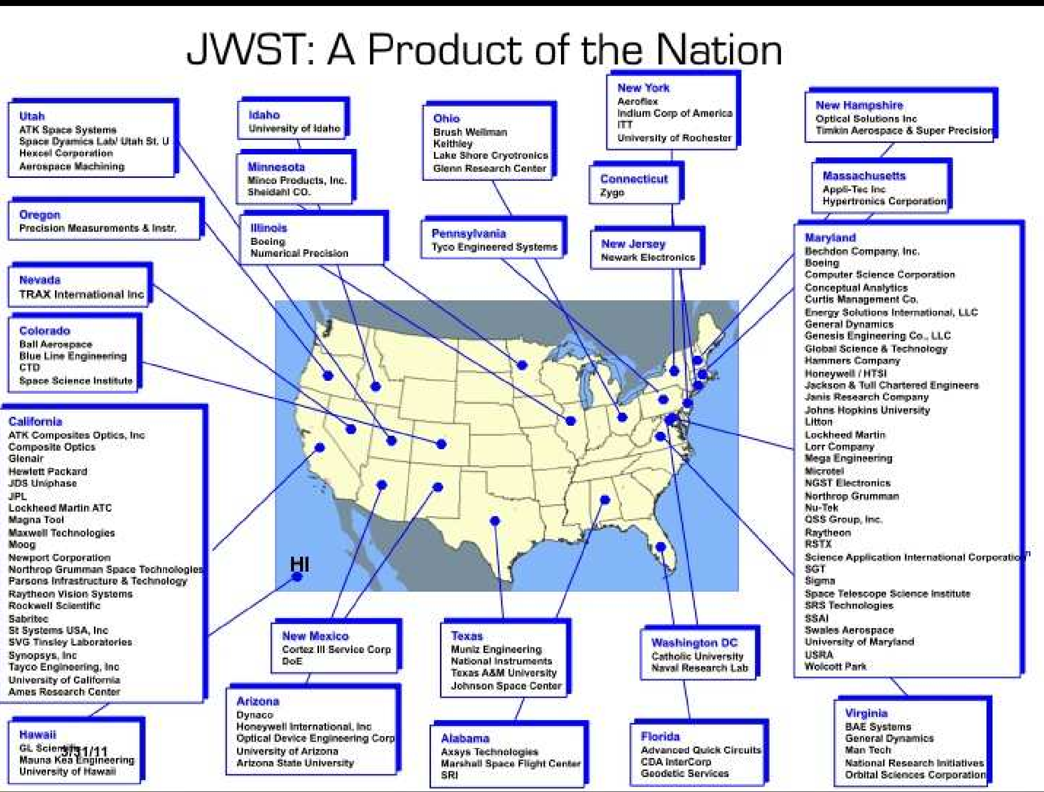


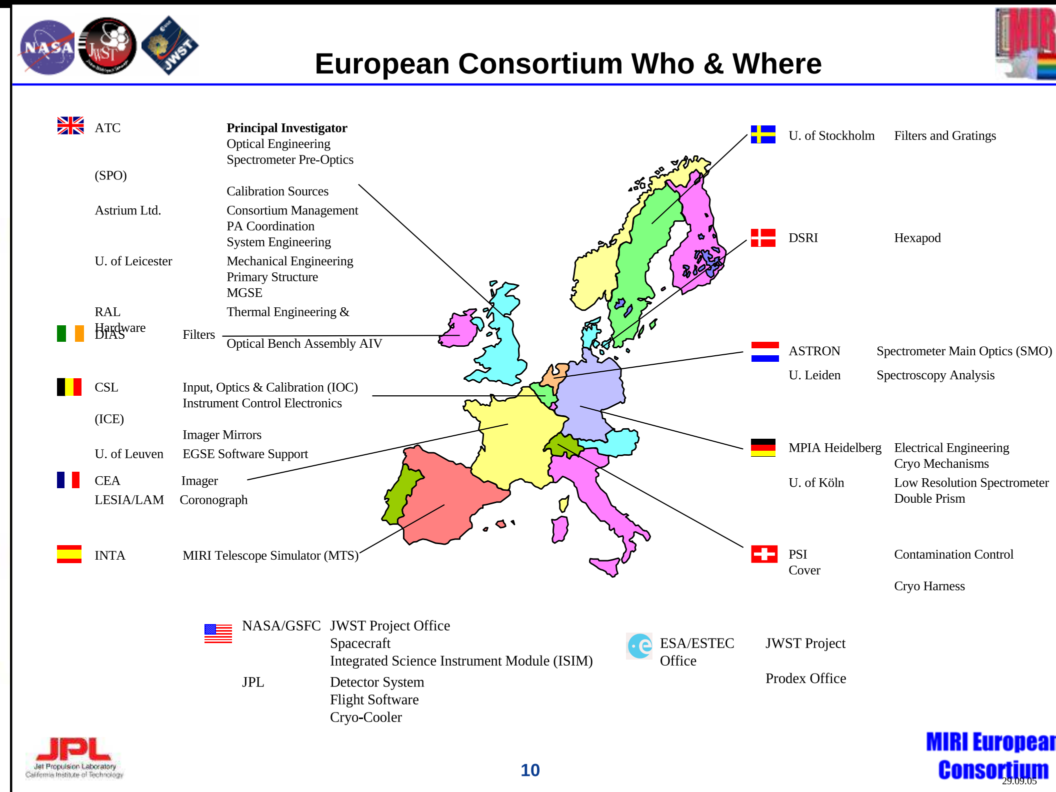
**Mid-Infra-Red Instrument (MIRI)**

- 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.

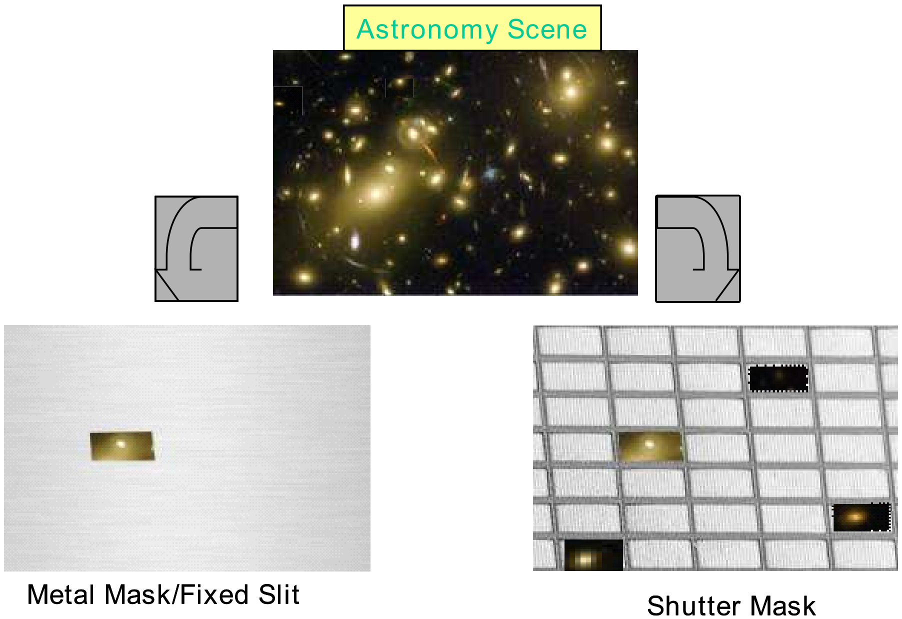
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.

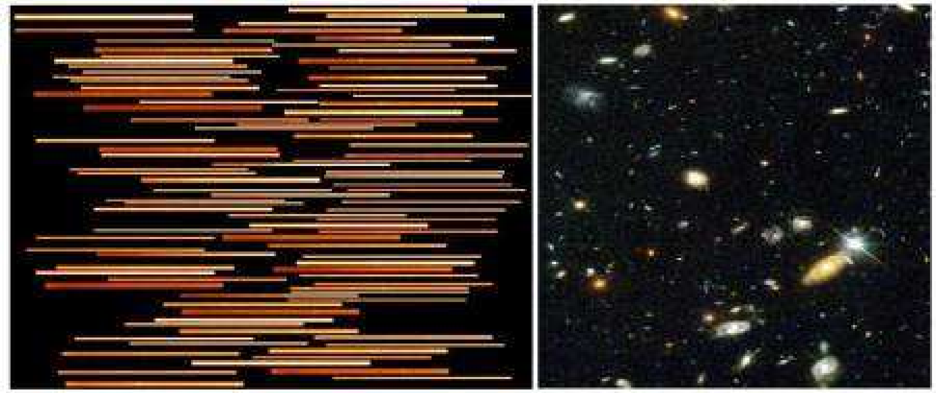
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.

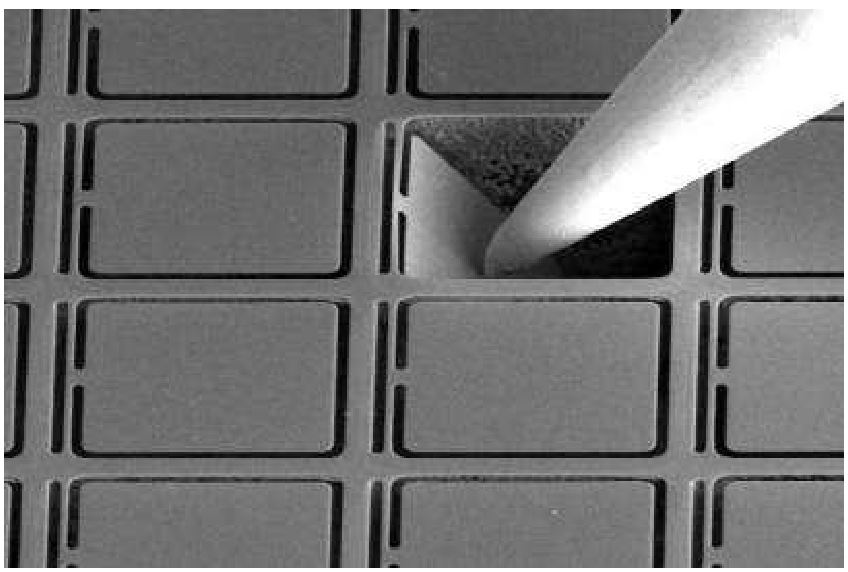
- JWST NIRCam made by UofA and Lockheed.

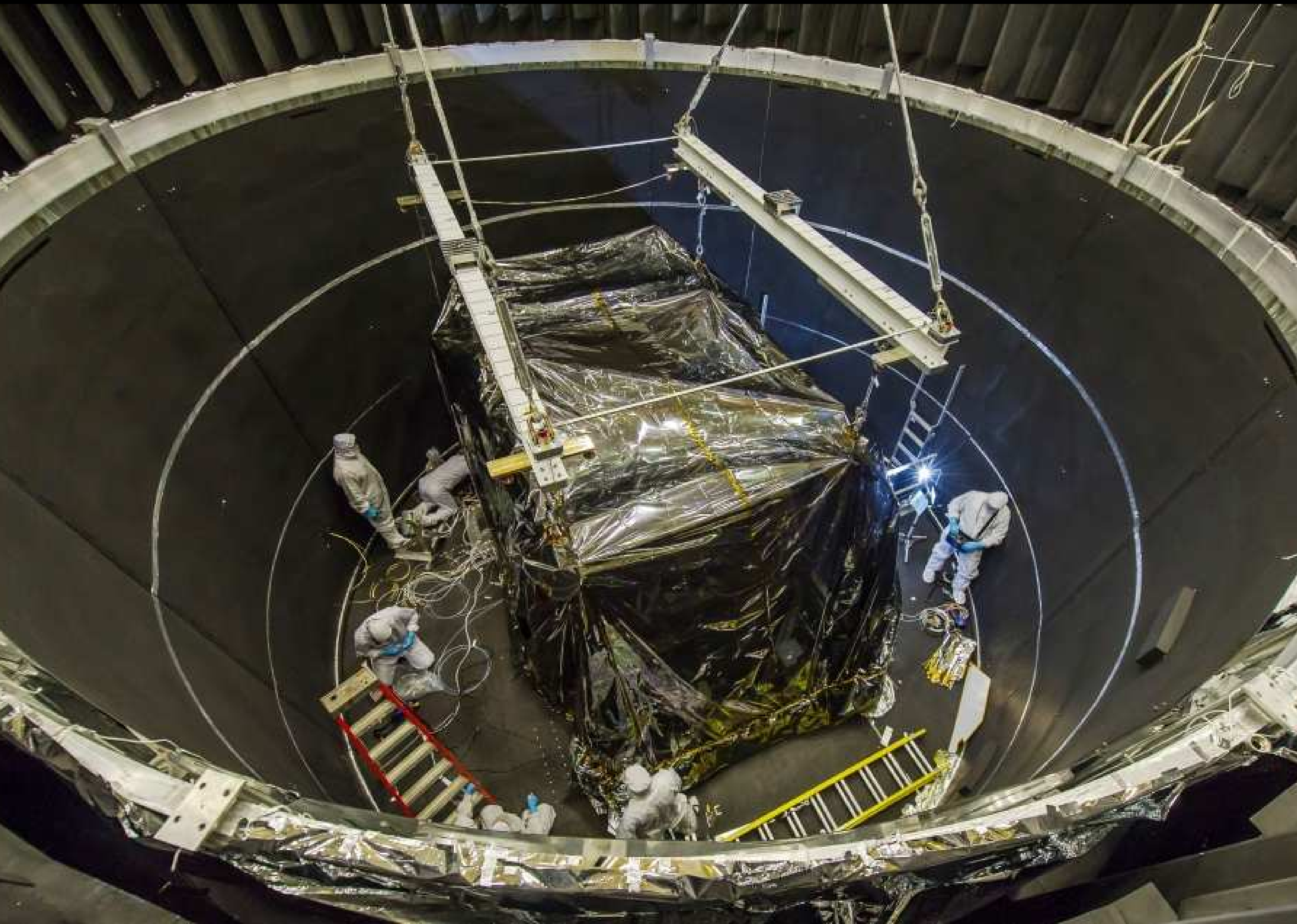
This nationwide + international coalition was critical for project survival!

# Micro Shutters



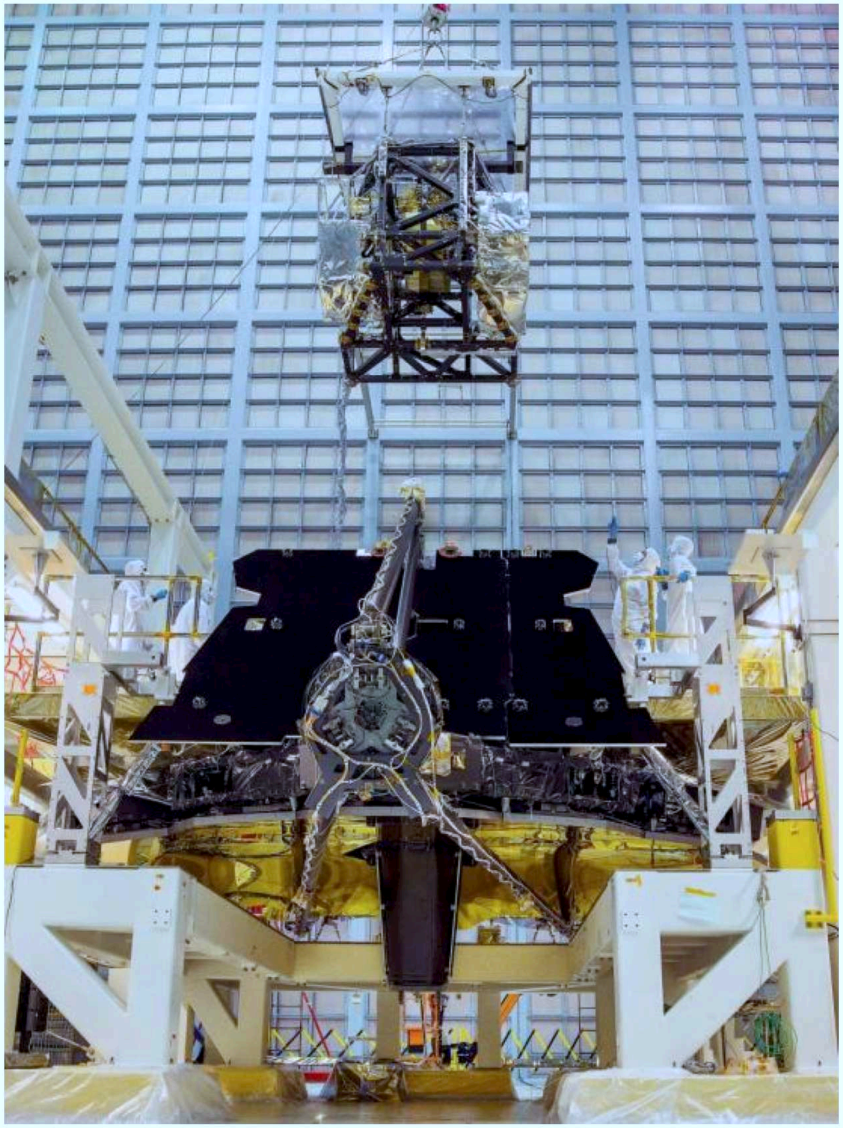


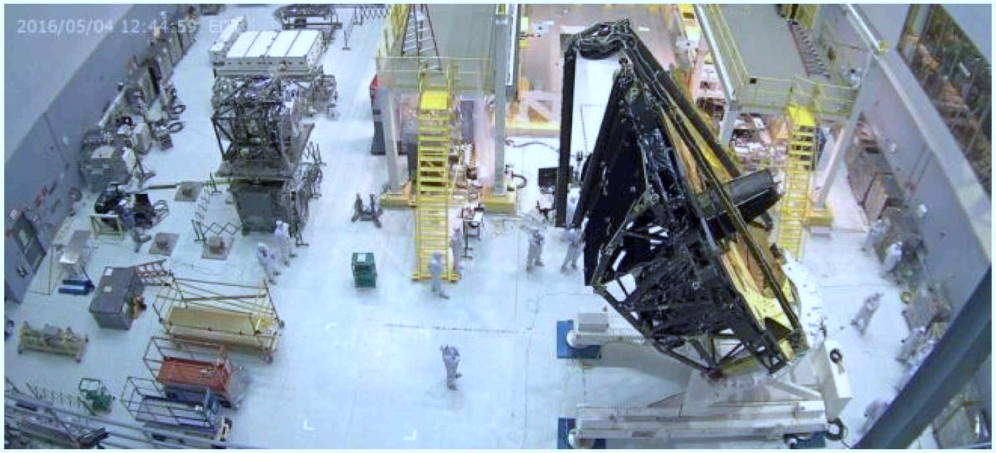


2014: Flight ISIM (all 4 instruments) in test. Oct. 15–Feb. 2016: CryoVac3.

# Program Update: OTE + ISIM = OTIS

NORTHROP GRUMMAN

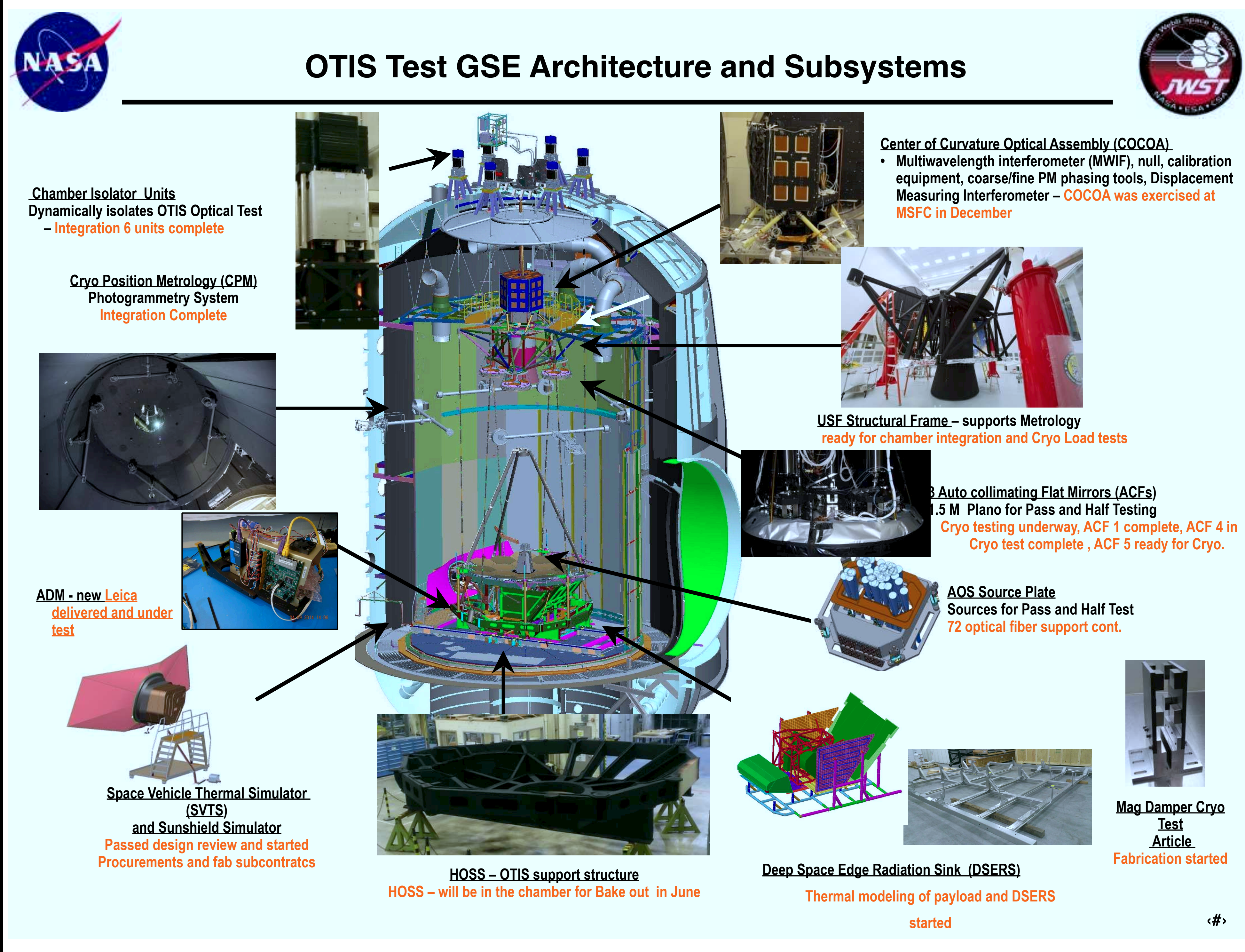






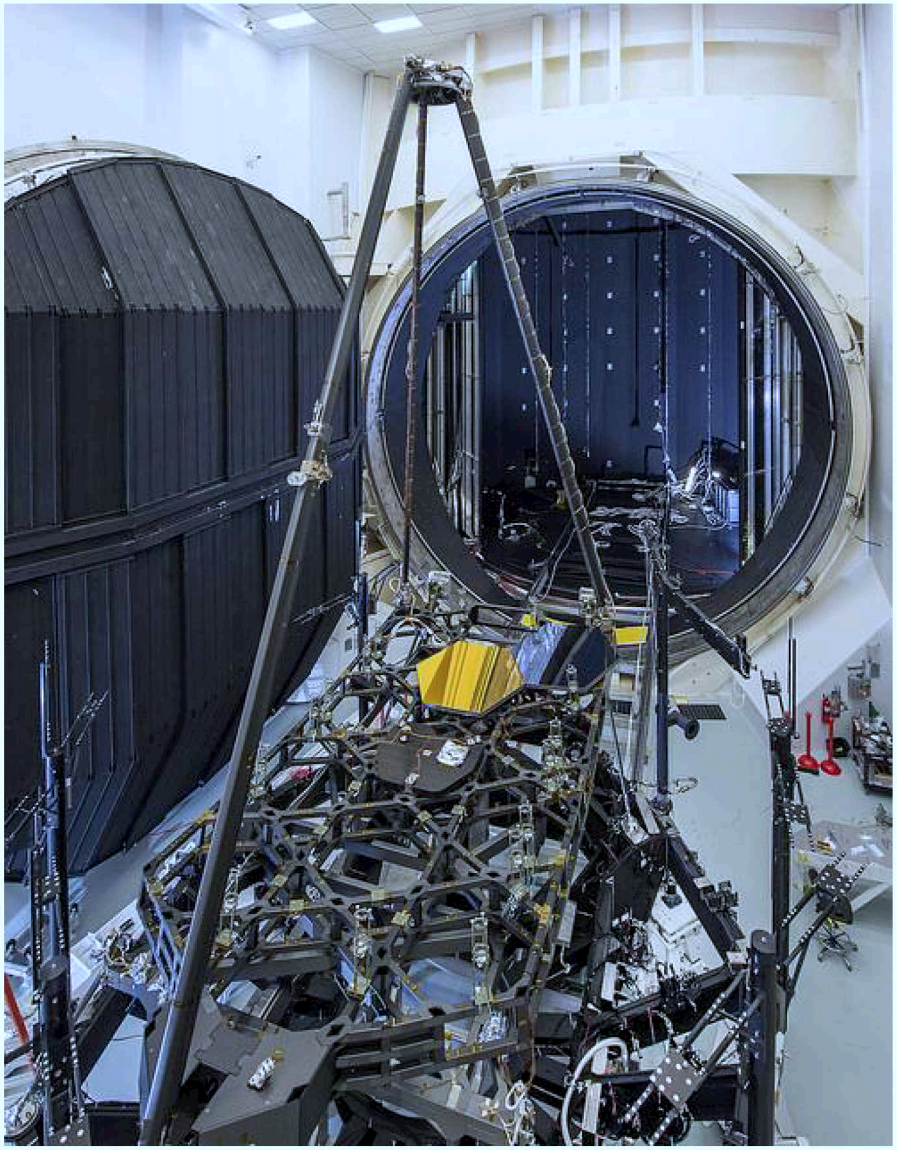


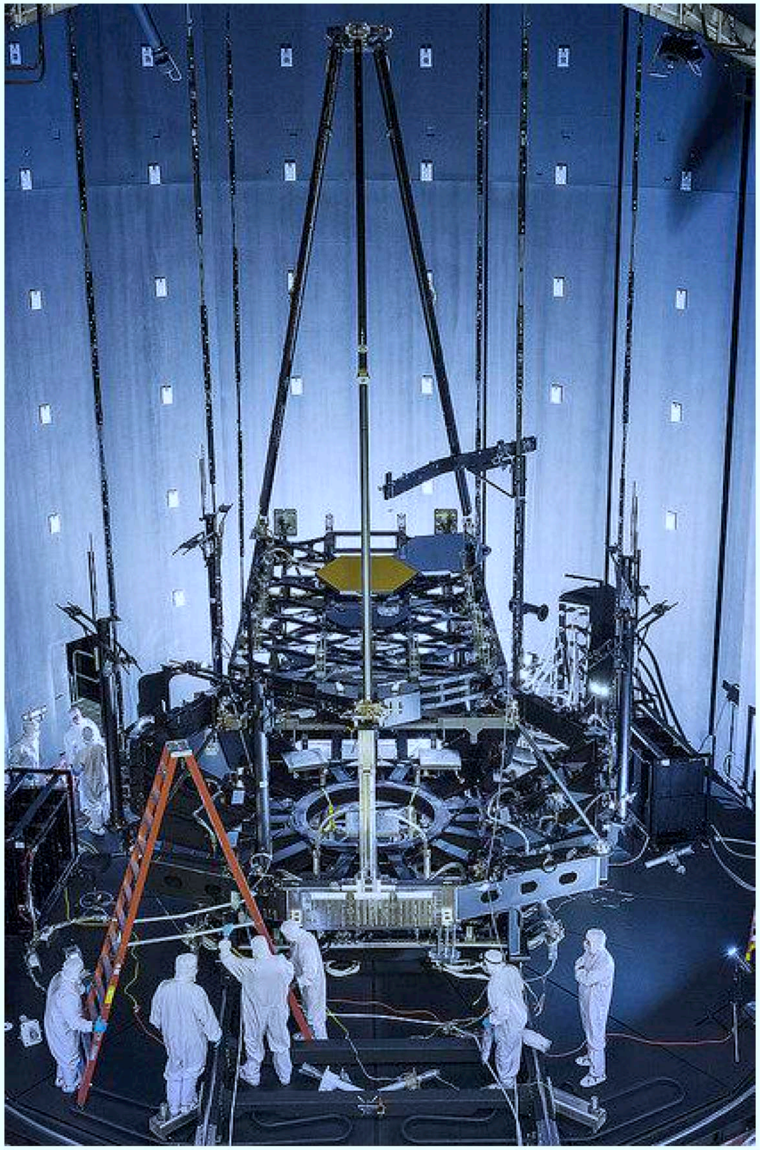
June 2016: Flight ISIM mated with Optical Telescope Element (OTE).
JWST is now a real working telescope (albeit not yet at 40 K & in 0 G)!




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)





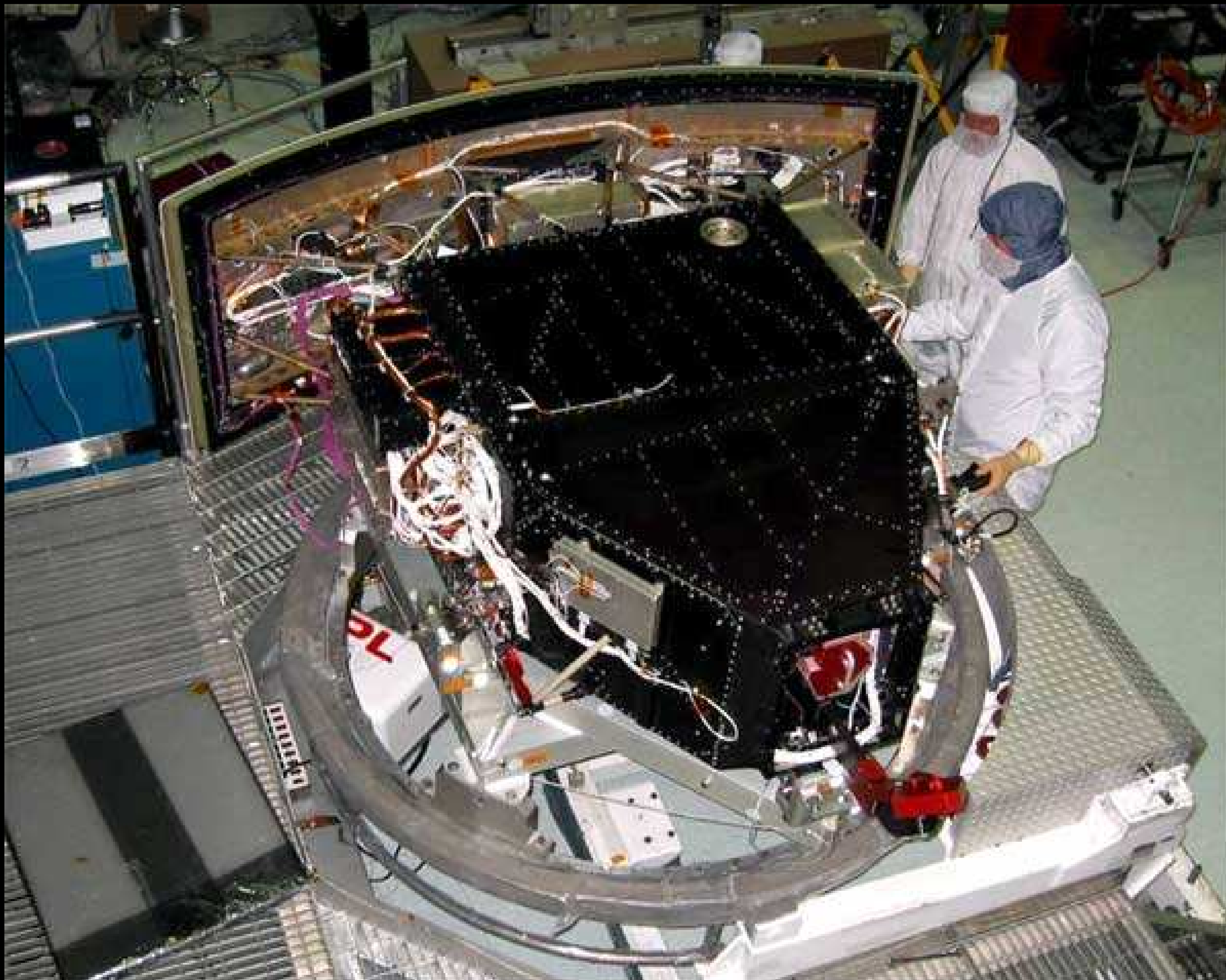
2015–2016: Testing OTIS chamber with the JWST Engineering model.

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

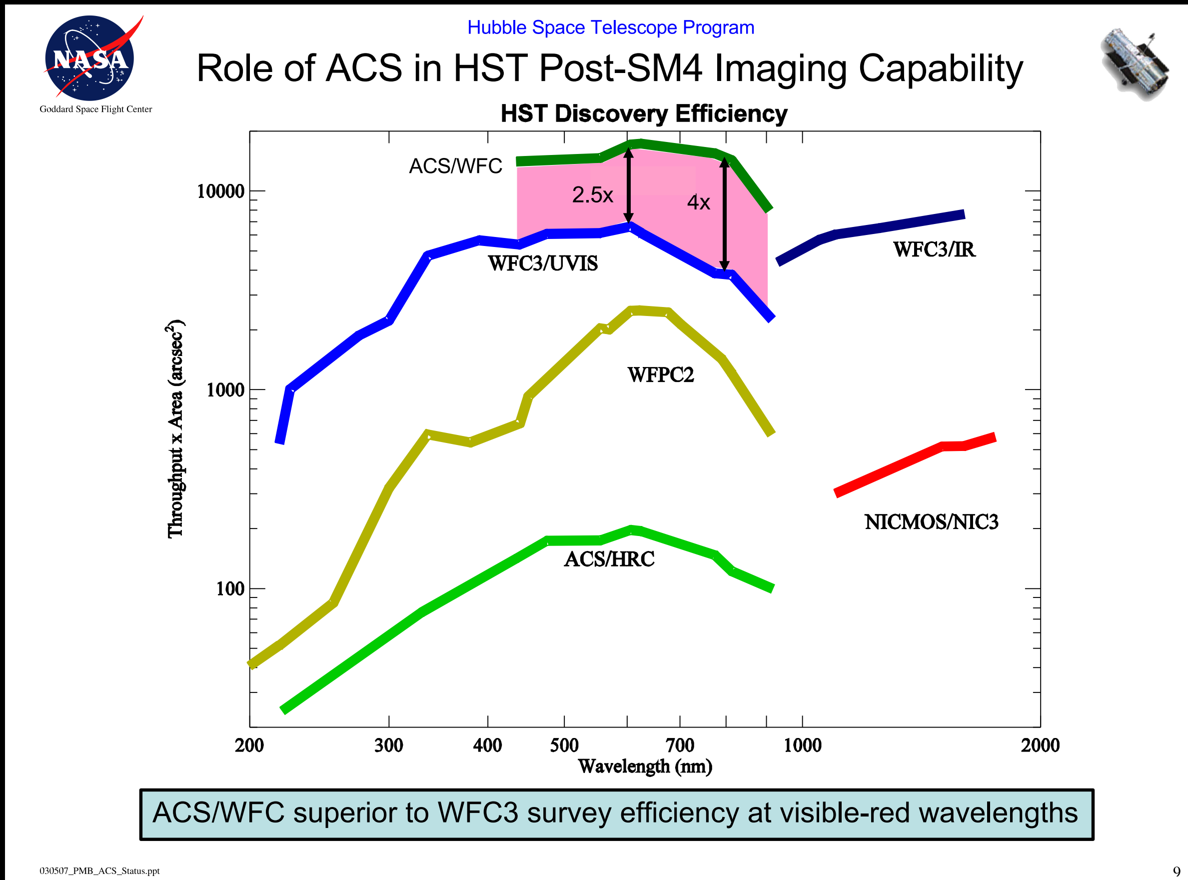
ß10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-$\sigma$) over 40 arcmin$^2$ at 0.07–0.15" FWHM from 0.2–1.7$\mu$m (UVUBVizYJH).

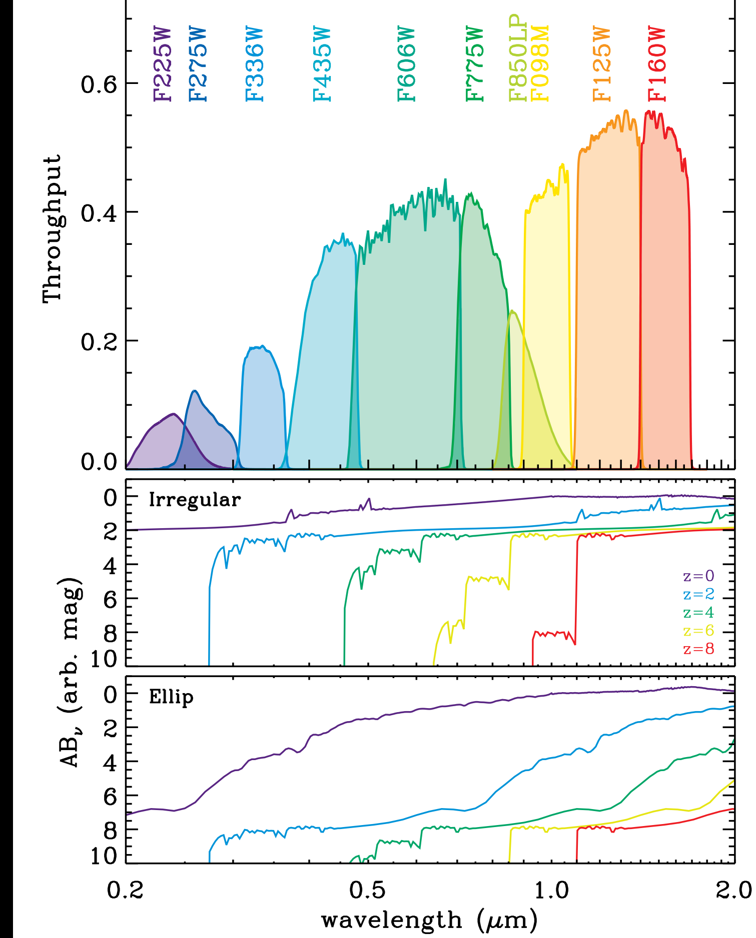
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5$\mu$m, and 0.2–1.2" FWHM at 5–29$\mu$m, tracing young+old SEDs & dust.

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



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



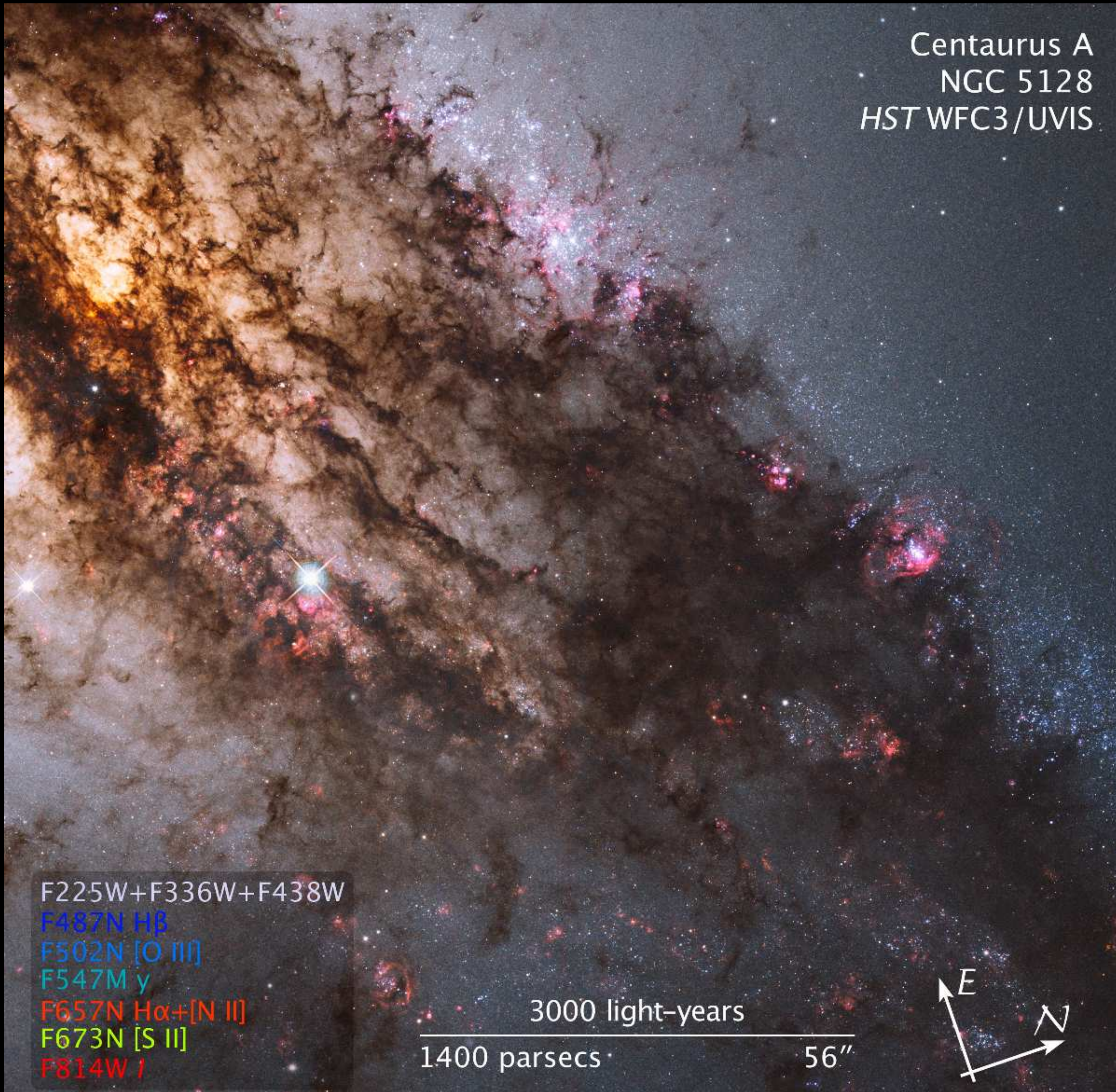

WFC3/UV & IR channels unprecedented throughput & areal coverage:

- 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:

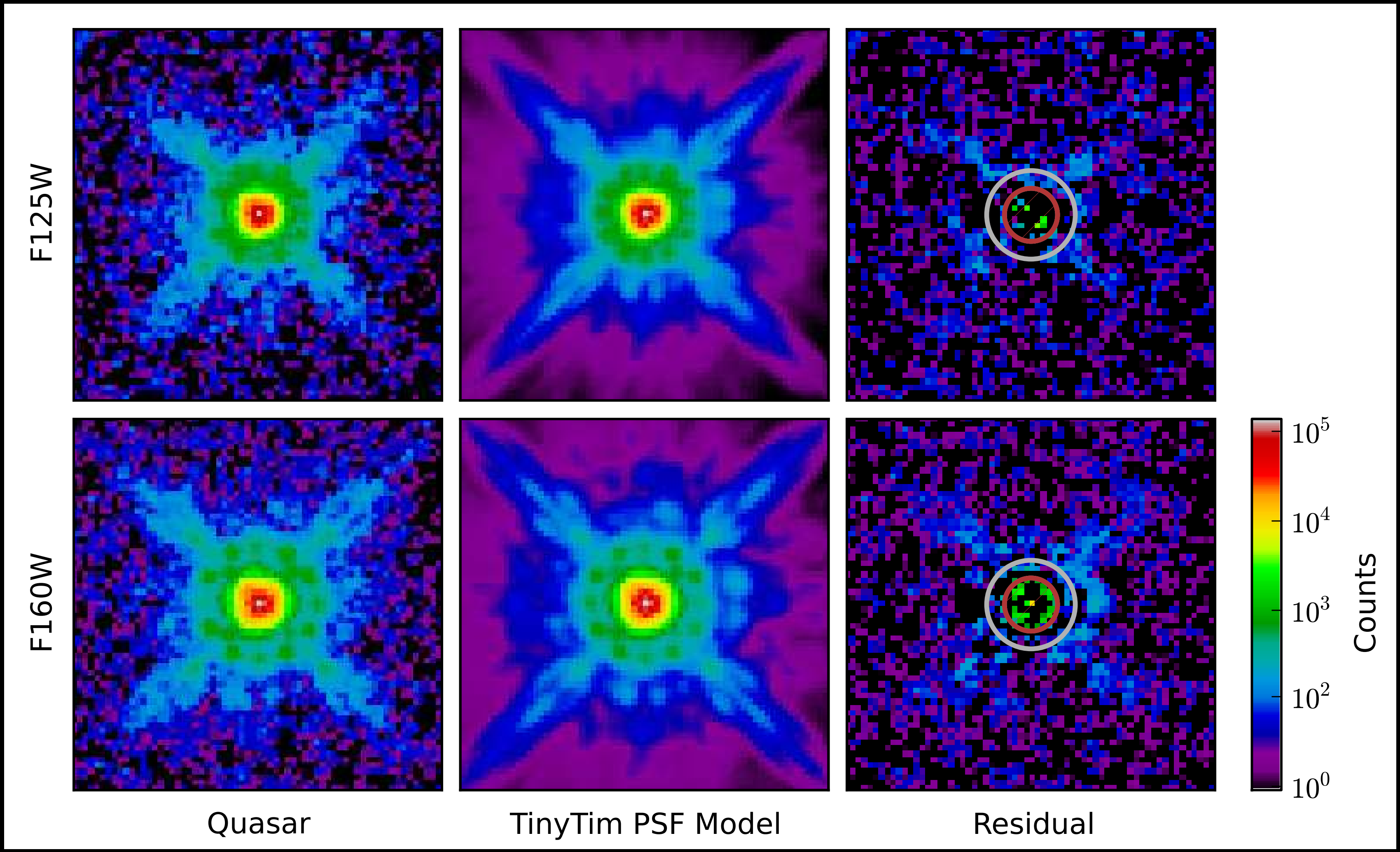
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

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



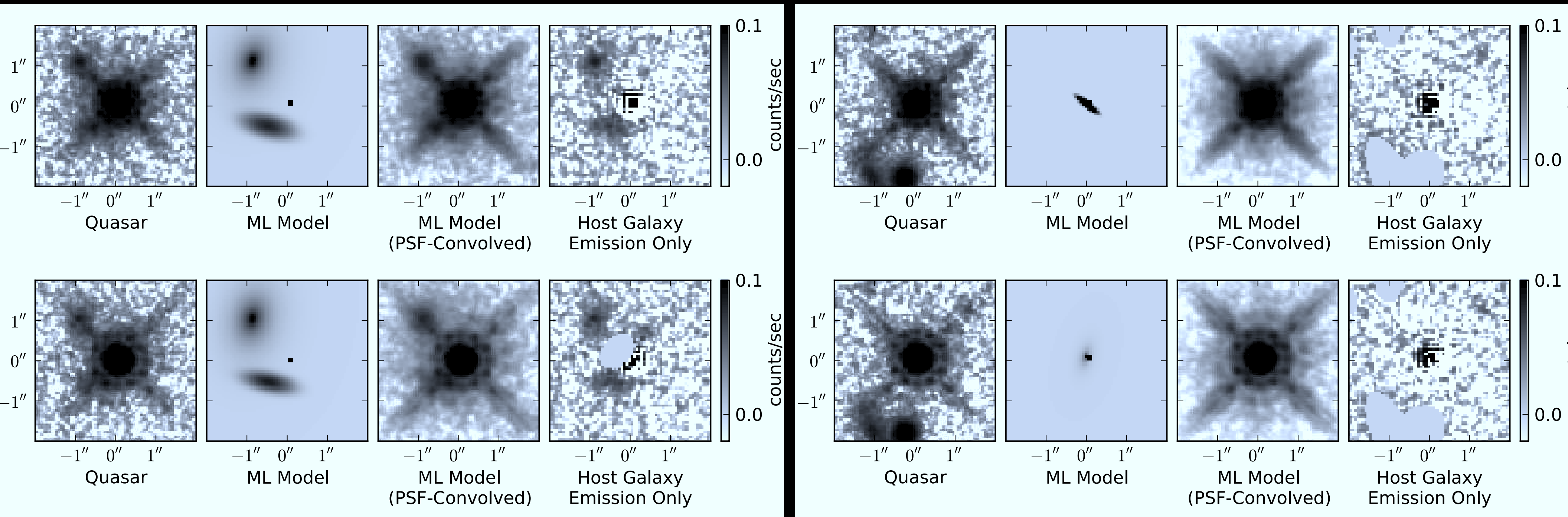
Centaurus A
NGC 5128
*HST* WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N

# (2b) HST WFC3 observations of QSO host systems at z≃6 (age≲1 Gyr)



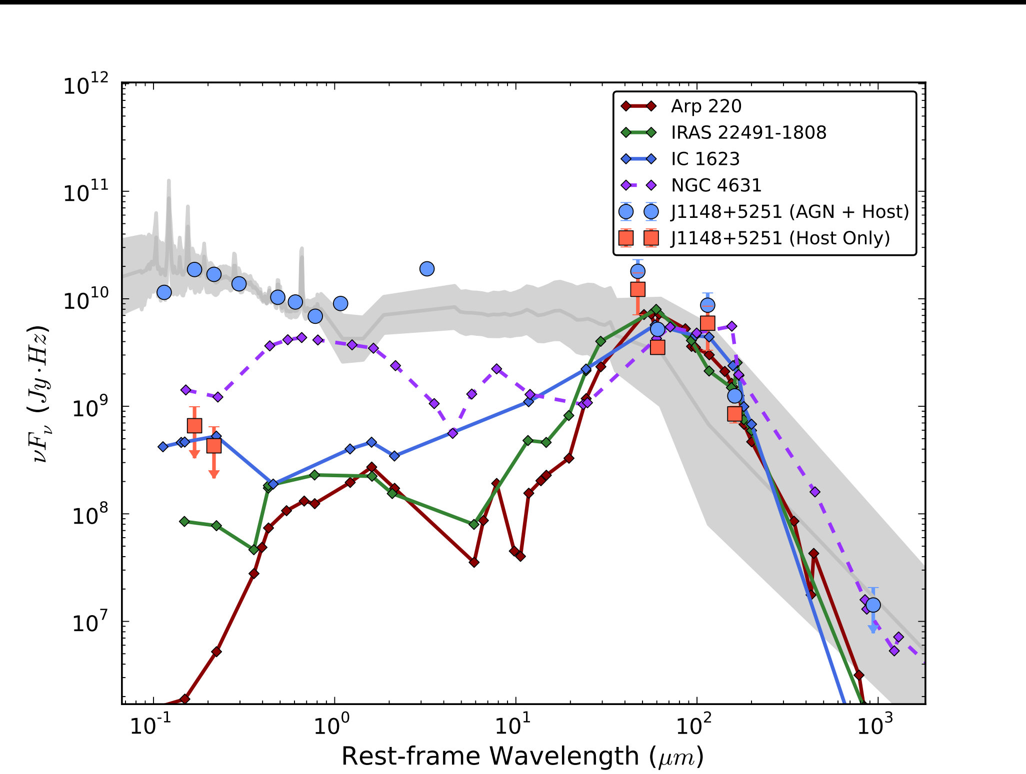

- Careful contemporaneous orbital PSF-star subtraction: Removes most of "OTA spacecraft breathing" effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star (AB≃15 mag) subtracts z=6.42 QSO (AB≃18.5) nearly to the noise limit: NO host galaxy detected 100× fainter (AB≳23.5 at r≳0.″3).
- The most luminous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

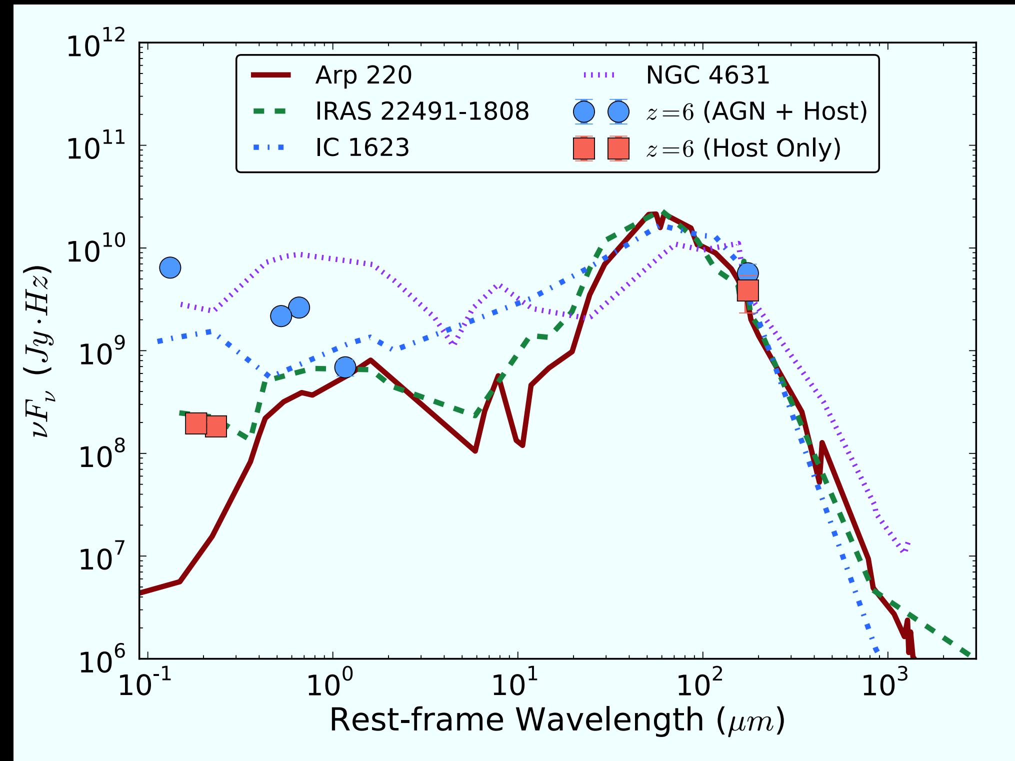
# (2b) WFC3: Detection of one QSO Host System at z≃6 (Giant merger?)




- 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 $\lambda$=1.25 & 1.6 $\mu$m structure. (J–H)≃0.19 color constrains dust.
- IRAS starburst-like SED from rest-frame UV–far-IR: $A_{FUV}\sim$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$28$\mu$m).

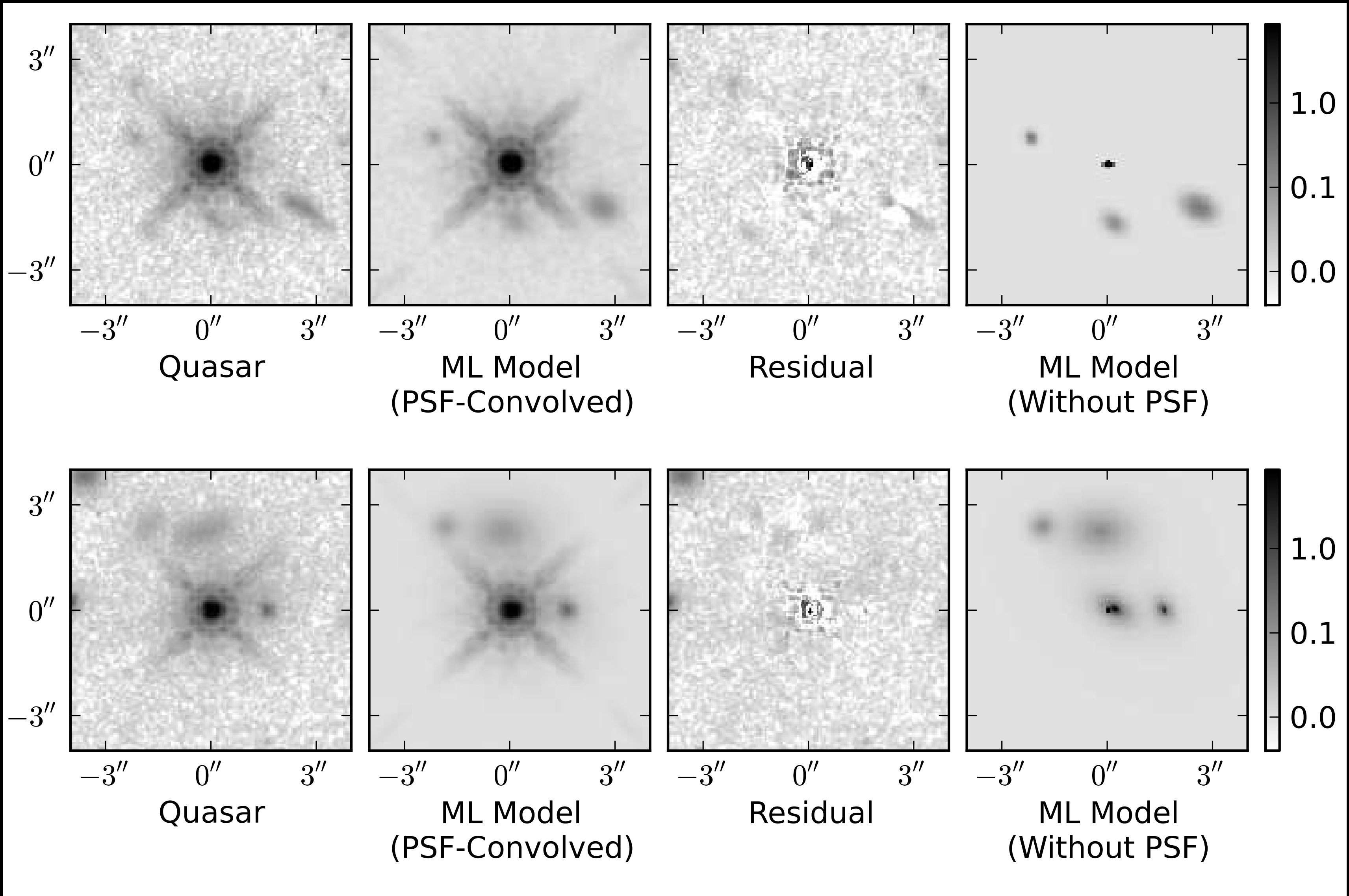
# (2b) HST WFC3 observations of dusty QSO host galaxies at z≃6




- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5$\mu$). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100$\mu$m:
  [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.

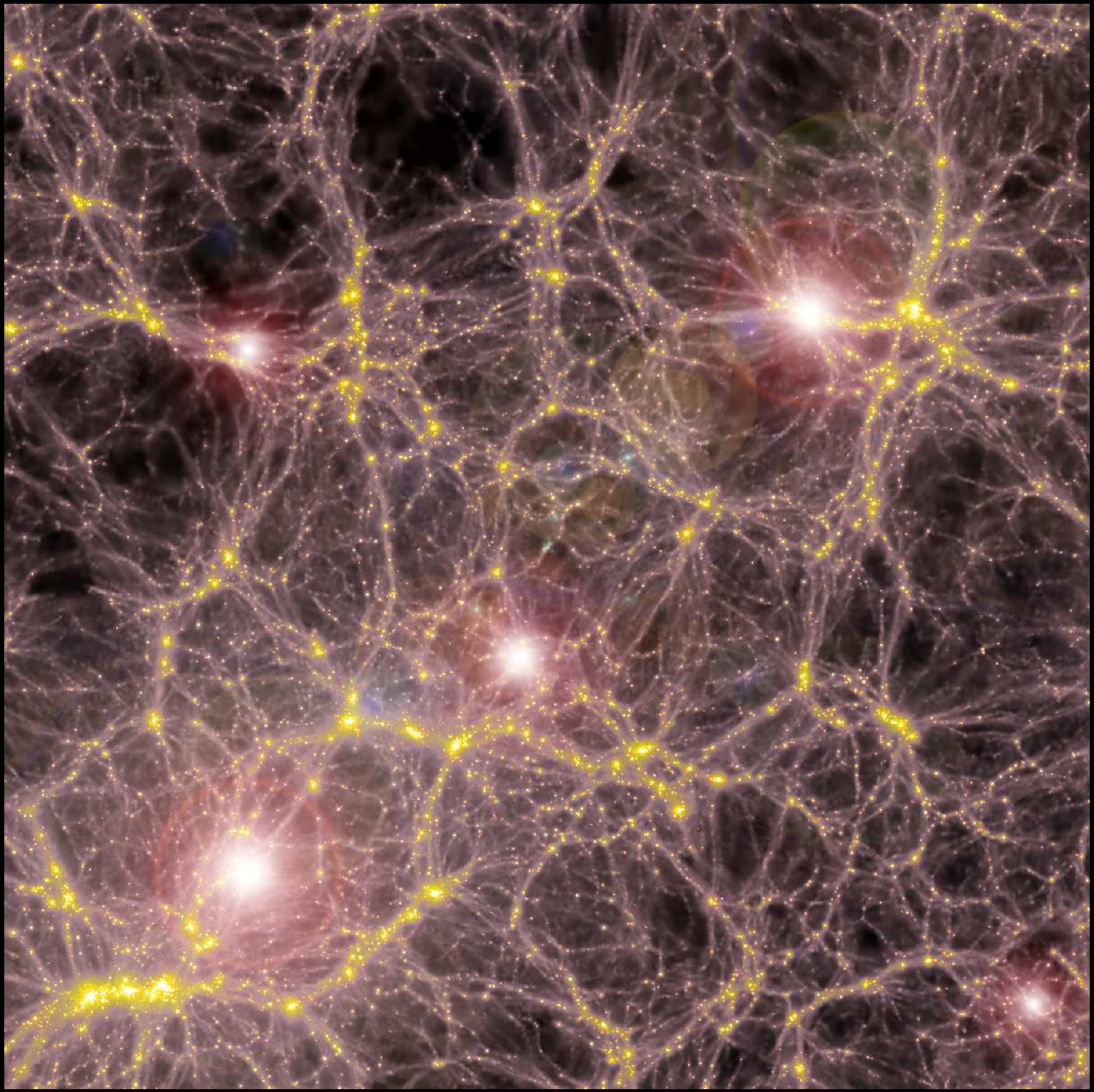
# (2b) WFC3 observations of QSO host galaxies at z$\simeq$2 (evidence for mergers?)




- 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$10$\times$ fainter: in restframe V for z$\gtrsim$6.

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

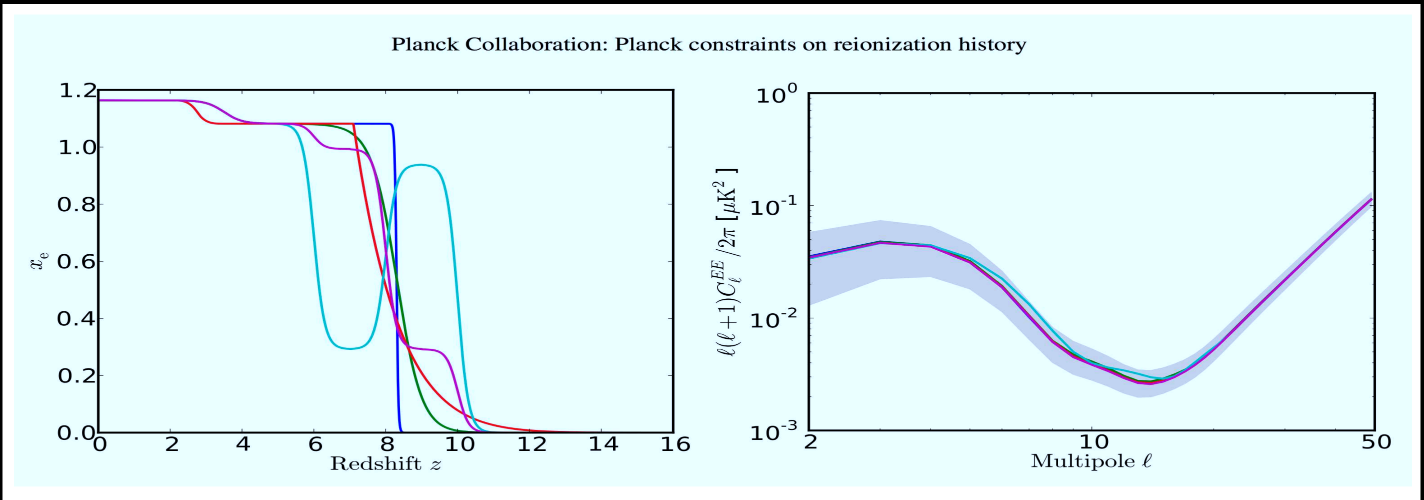


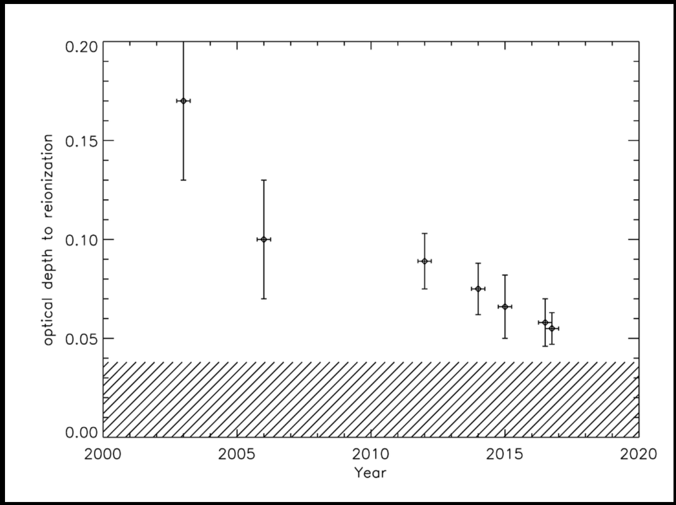
- Detailed cosmological models (V. Bromm) suggest that massive "Pop III" stars ($\gtrsim$100 $M_{sun}$) started to reionize the universe at z$\lesssim$10–30 (0.1–0.5 Gyr; "First Light").

- 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):

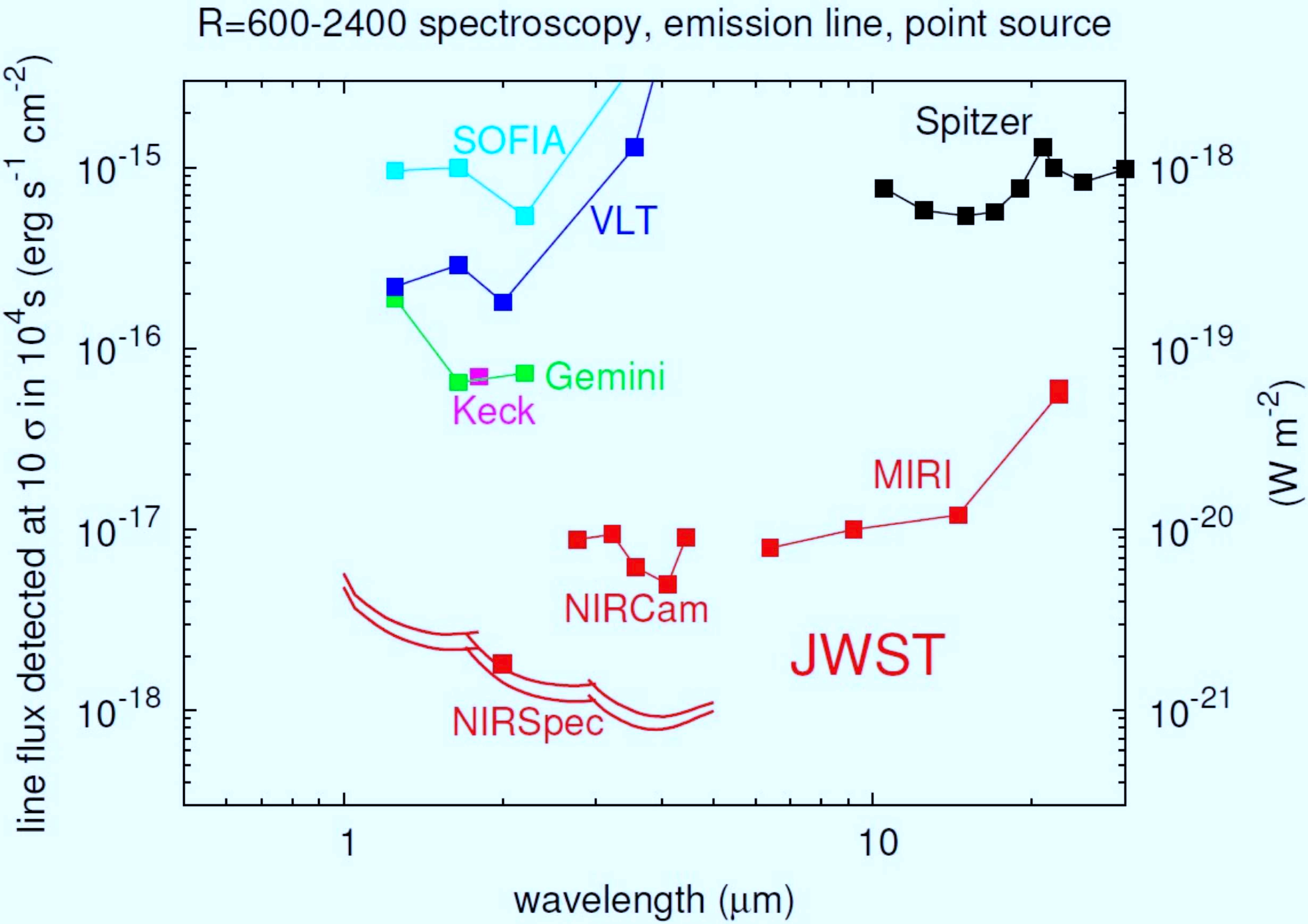
Reionization appears to have occurred between these extremes:

(1) Instantaneous: z$\sim$8.5$\pm$0.9 (optical depth $\tau\simeq$0.055$\pm$0.009; 0.058$\pm$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 $\tau$ has come down considerably ($\tau\simeq$0.055–0.058), how many reionizers will JWST actually see at z$\simeq$10–15?

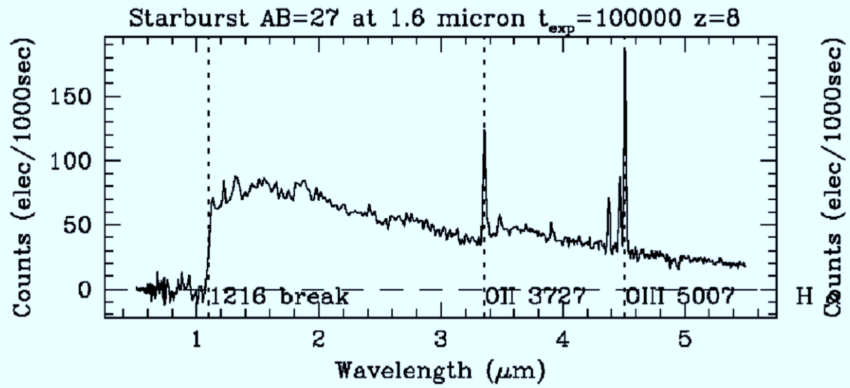
# Sensitivities - spectroscopy

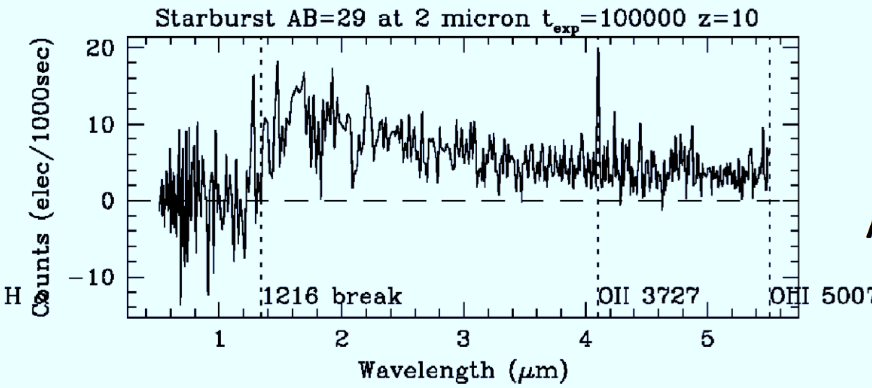



NIRCam, NIRSpec and MIRI sensitivity (cgs) compared to VLT, Keck, Spitzer.

# What NIRSPEC can do !

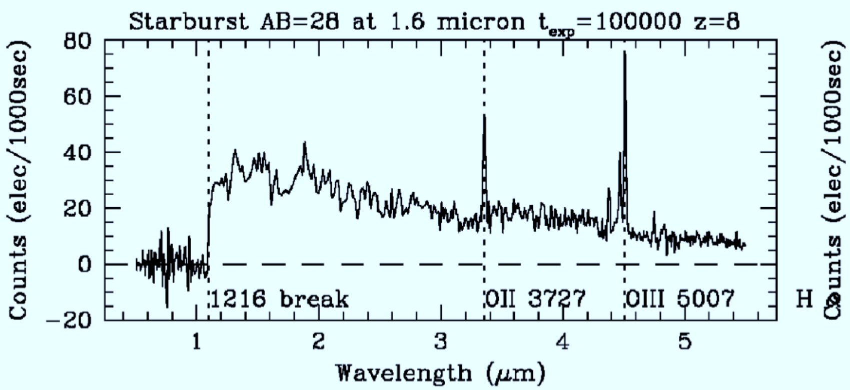
AB=27

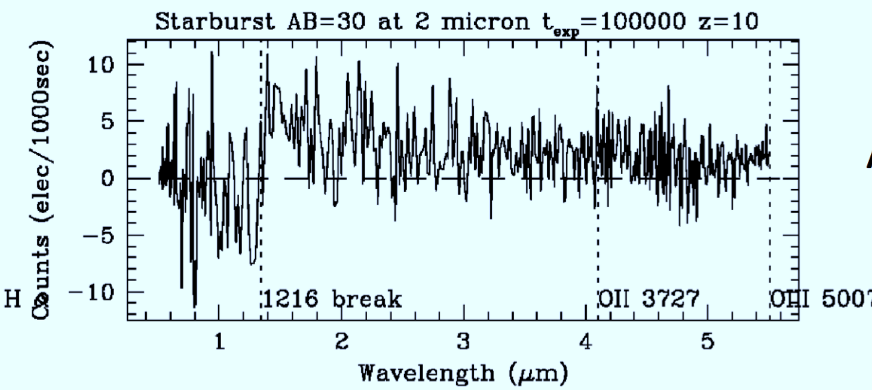



AB=29

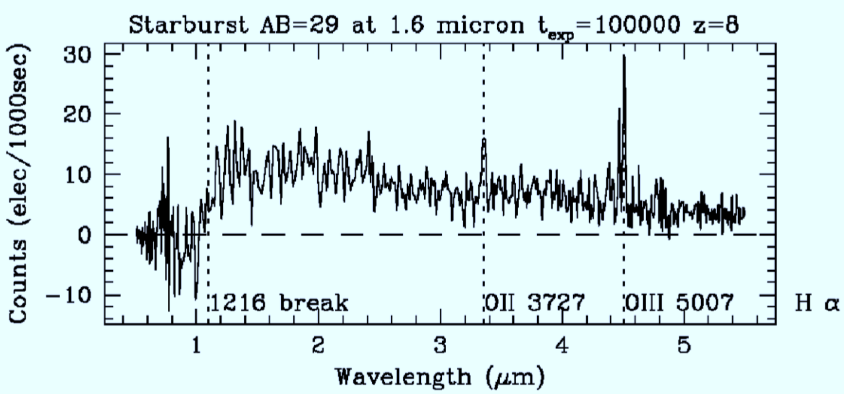
AB=28




AB=30

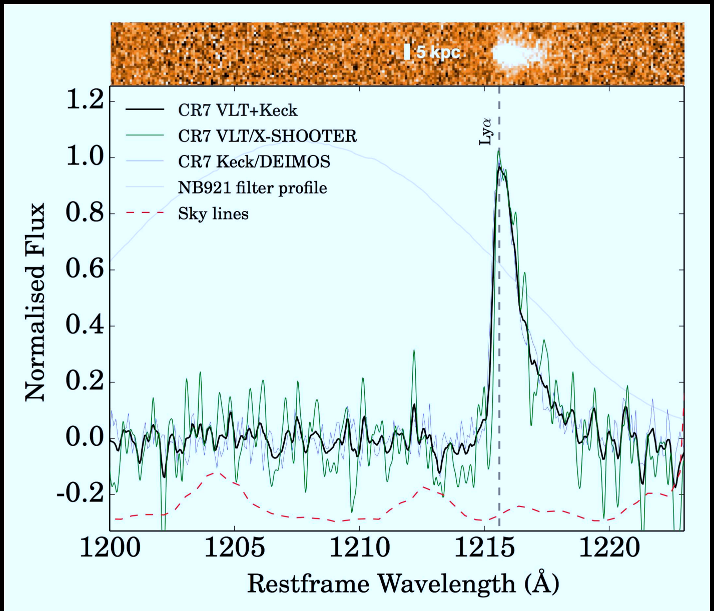
AB=29

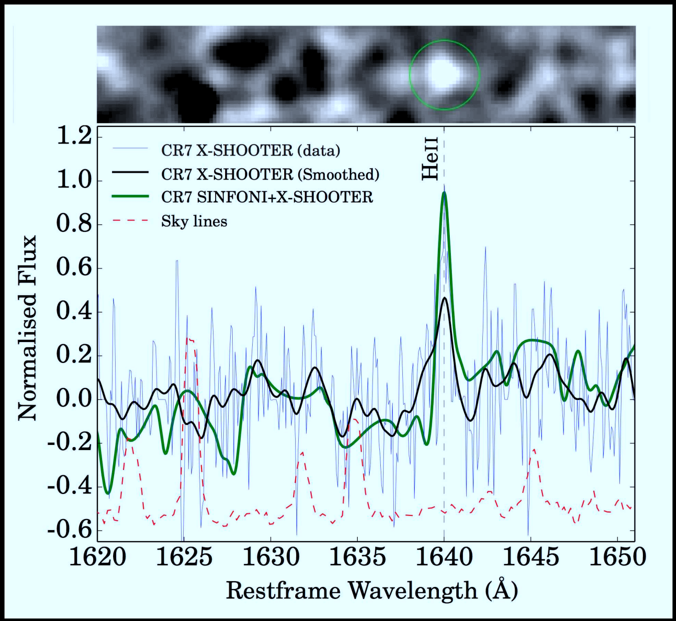



Derive redshifts, stellar masses, stellar ages, gas ionization and metallicities, star formation rates, kinematics, pop III stars, Ly-α LF to z=10, etc.

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

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



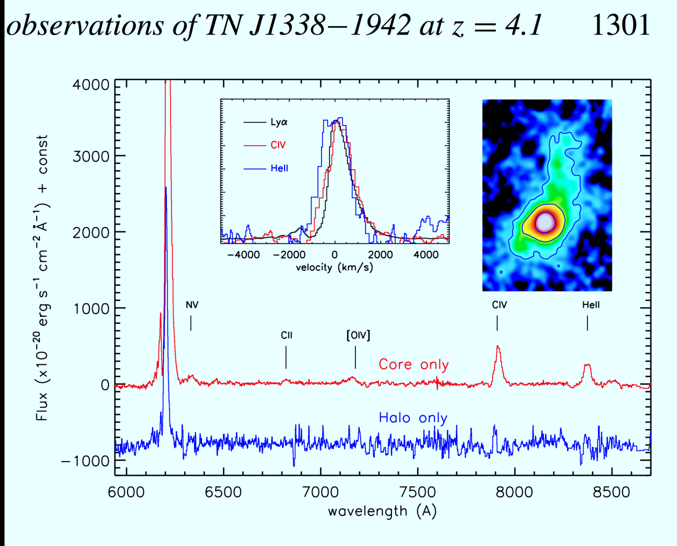




**Figure 2.** The spectrum extracted from the core of the Lyα halo compared to that of the extended halo. The core spectrum shows strong emission lines associated with the AGN activity (e.g. N V, [O IV], C IV and He II). The emis-

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

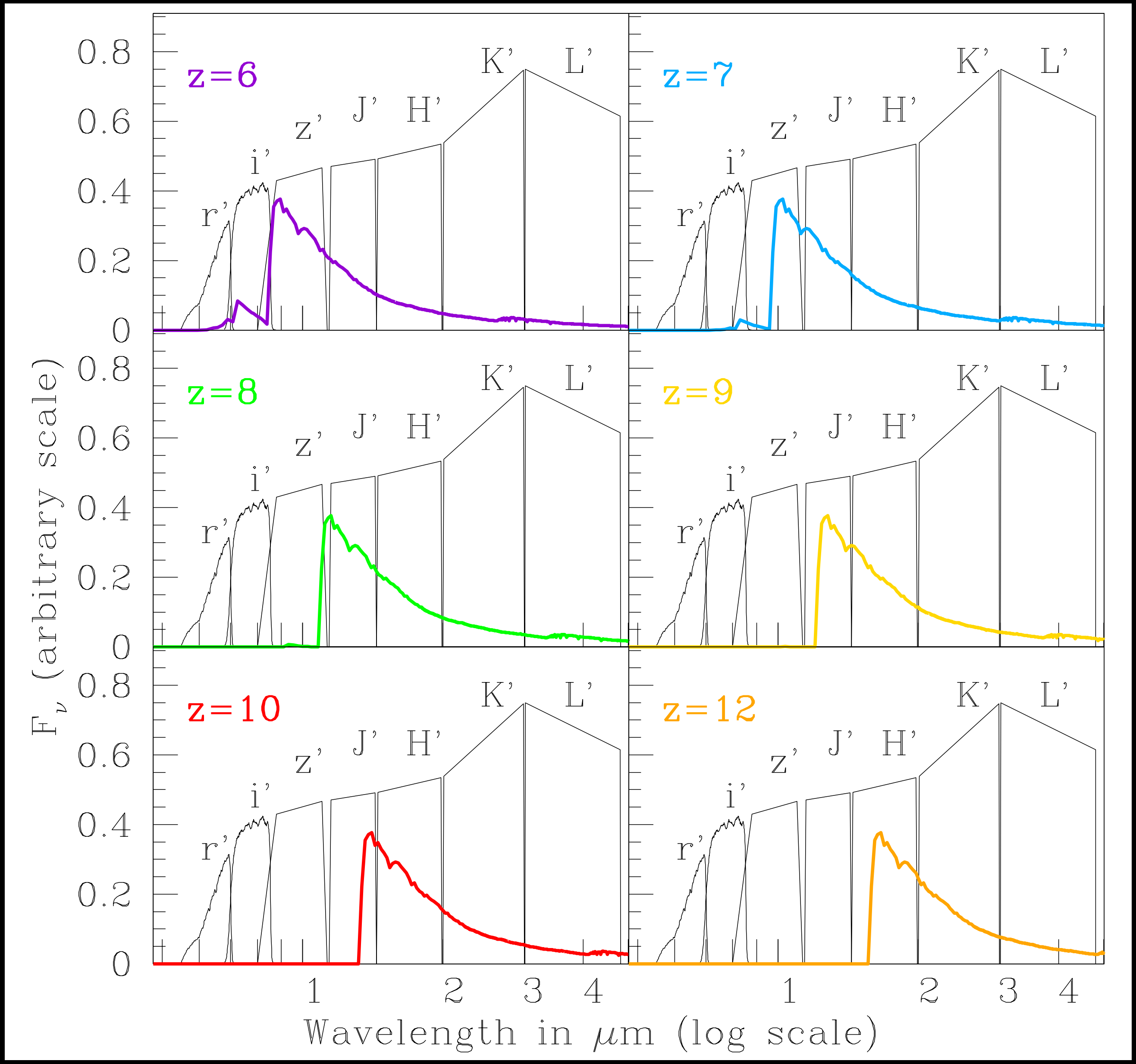
- HeII 1640Å (right) in radio galaxy TN J1338-1942 at z=4.1 (Swinbank et al. 2015, MNRAS 449, 1298).

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

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

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

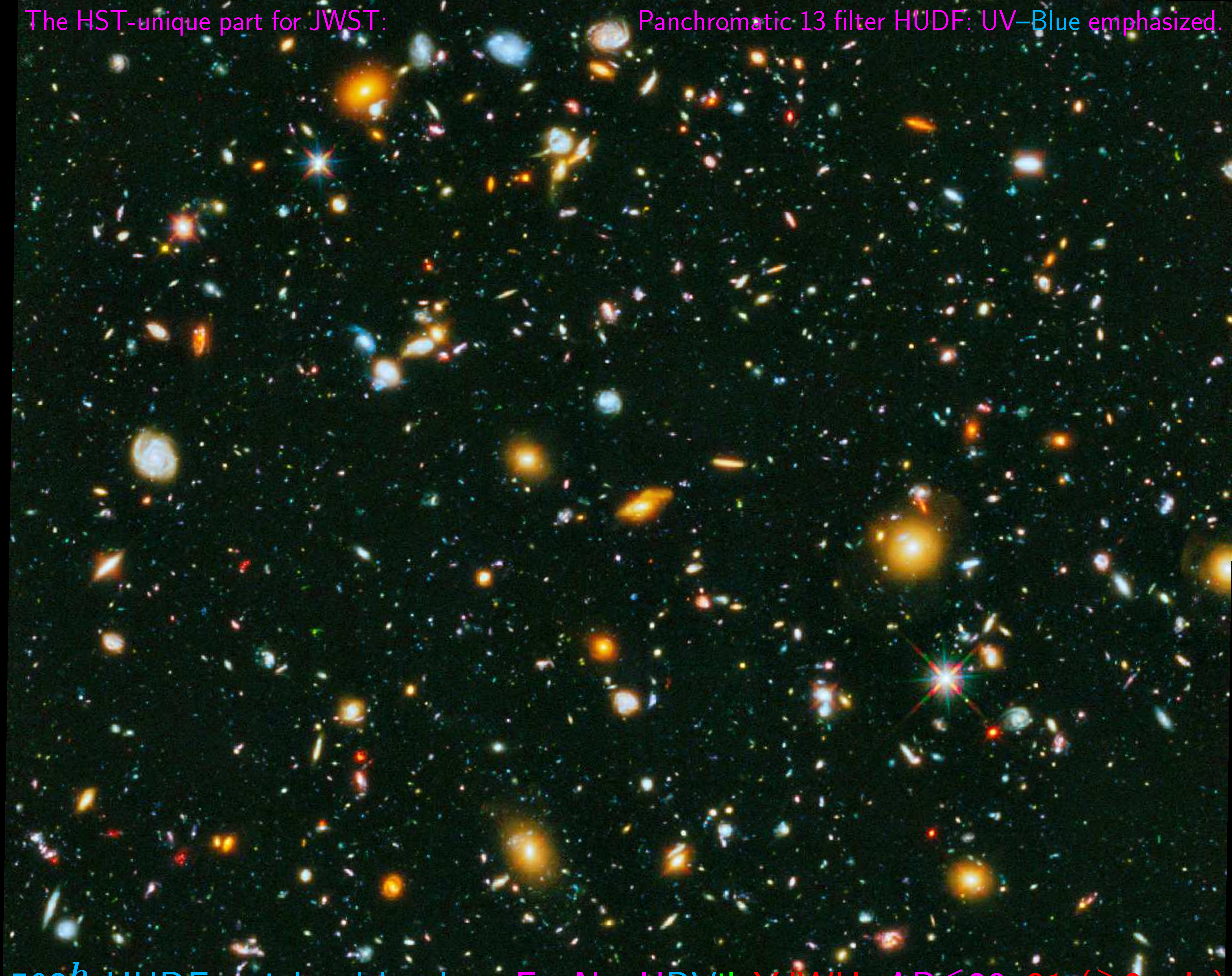
# (3b) How will Webb measure First Light: what to expect in (Ultra)Deep Fields?



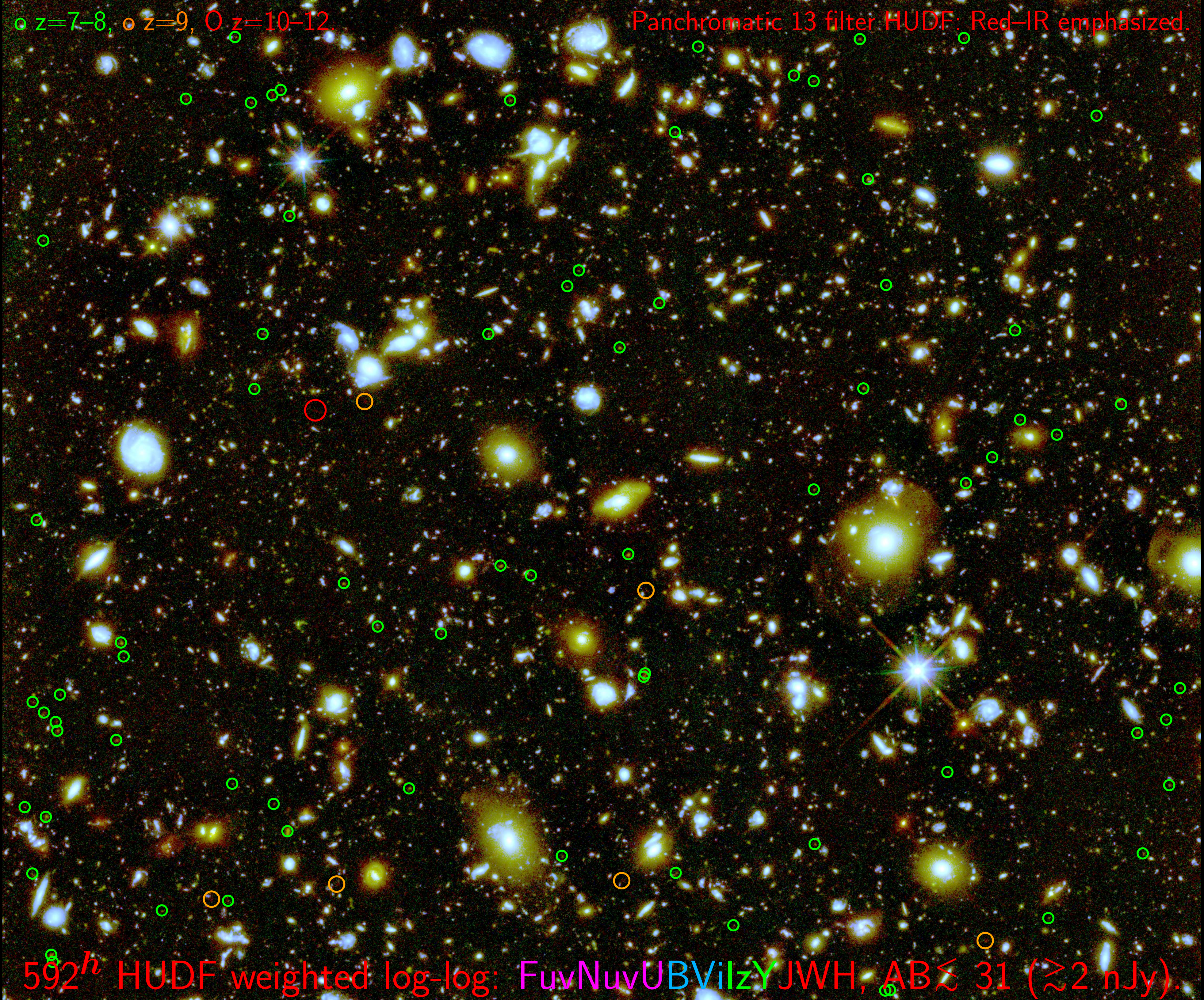

- Can't beat redshift: to see First Light, must observe near–mid IR.

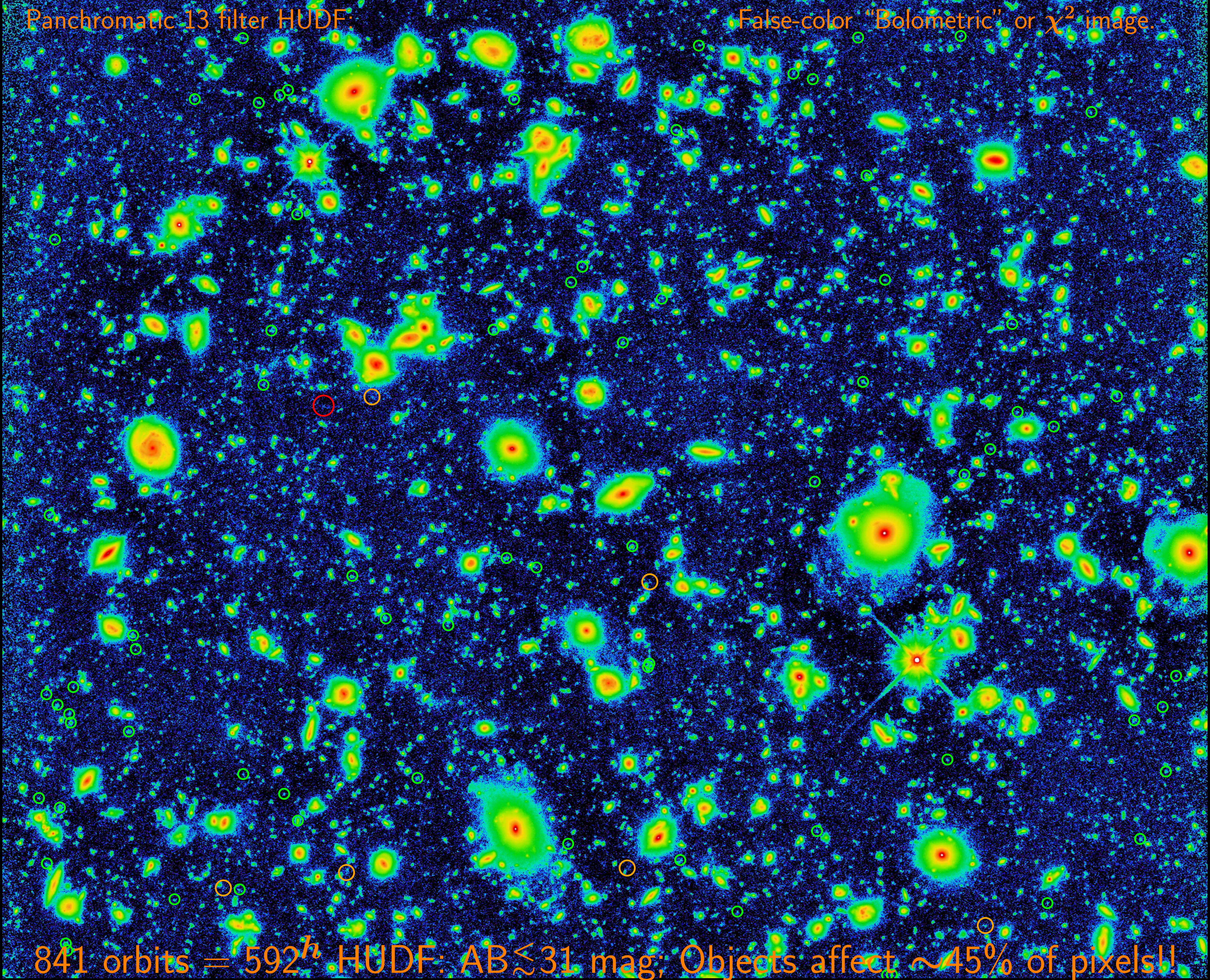
⇒ This is why JWST needs NIRCam at 0.8–5 $\mu$m and MIRI at 5–28 $\mu$m.

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

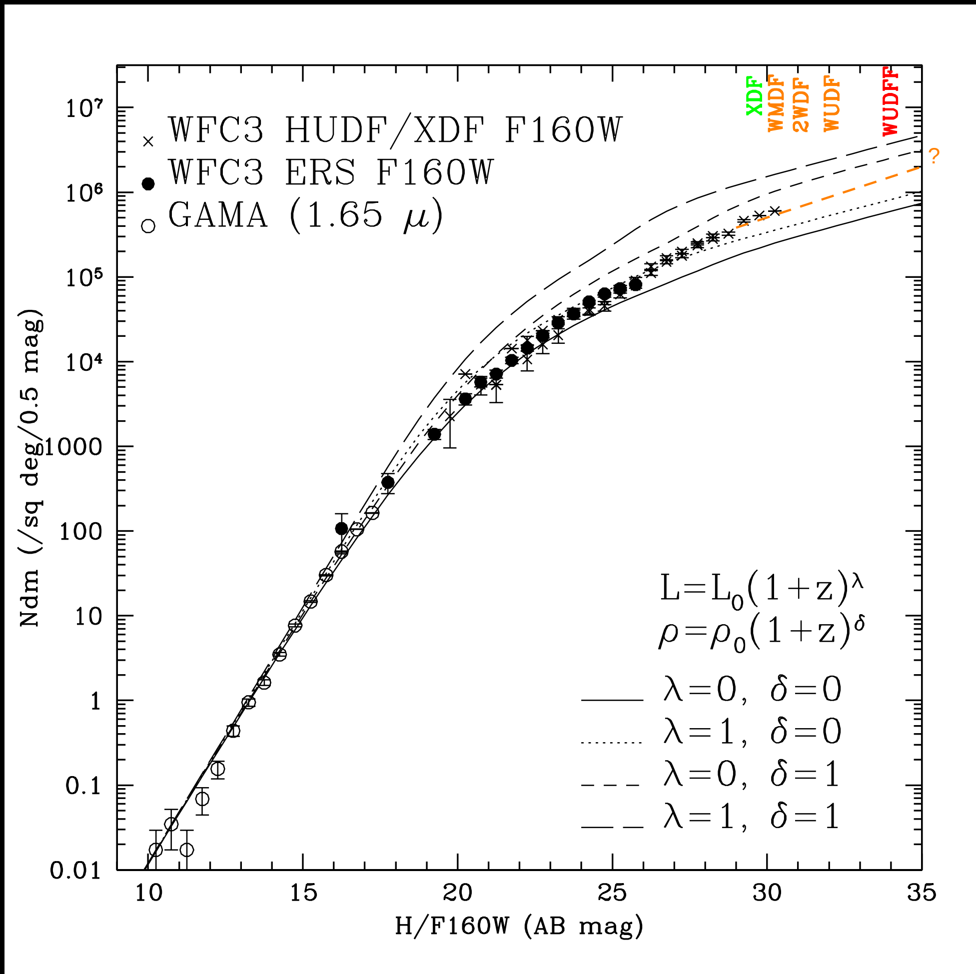


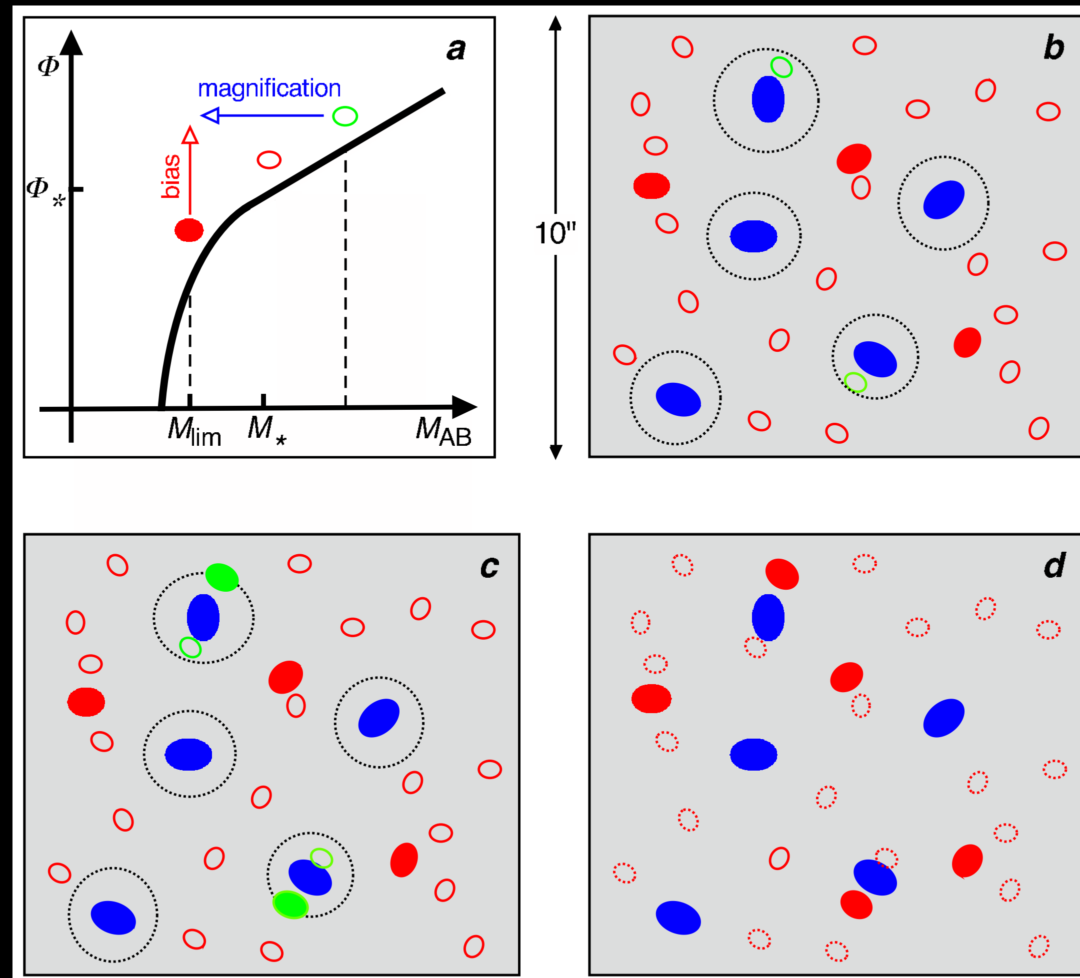
592$^h$ HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).


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$\lesssim$ 31 ($\gtrsim$2 nJy).


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

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



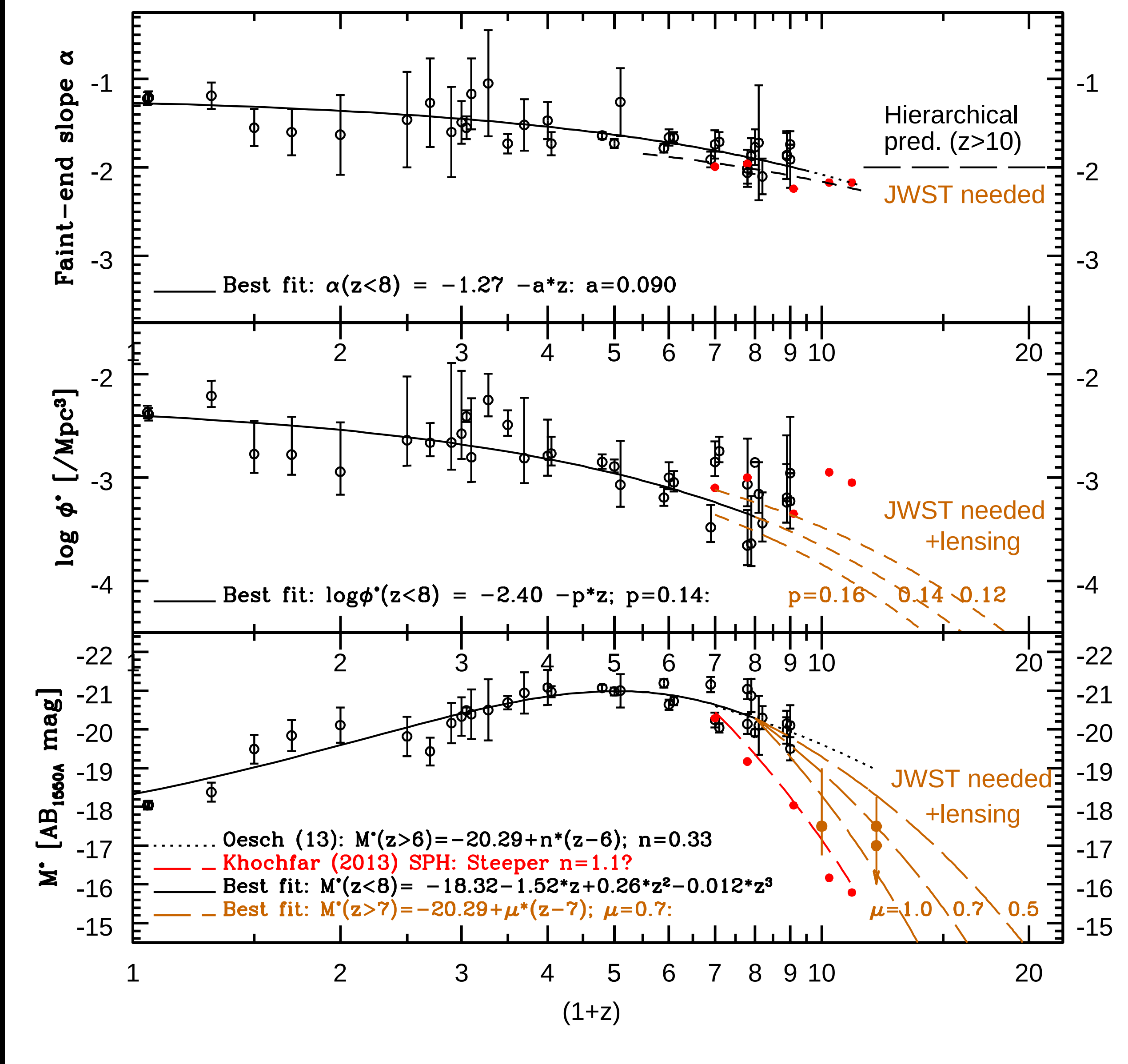

1.6$\mu$m counts (Windhorst[+]2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- 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 $\sim$32 mag: dwarf galaxy at z$\simeq$11!

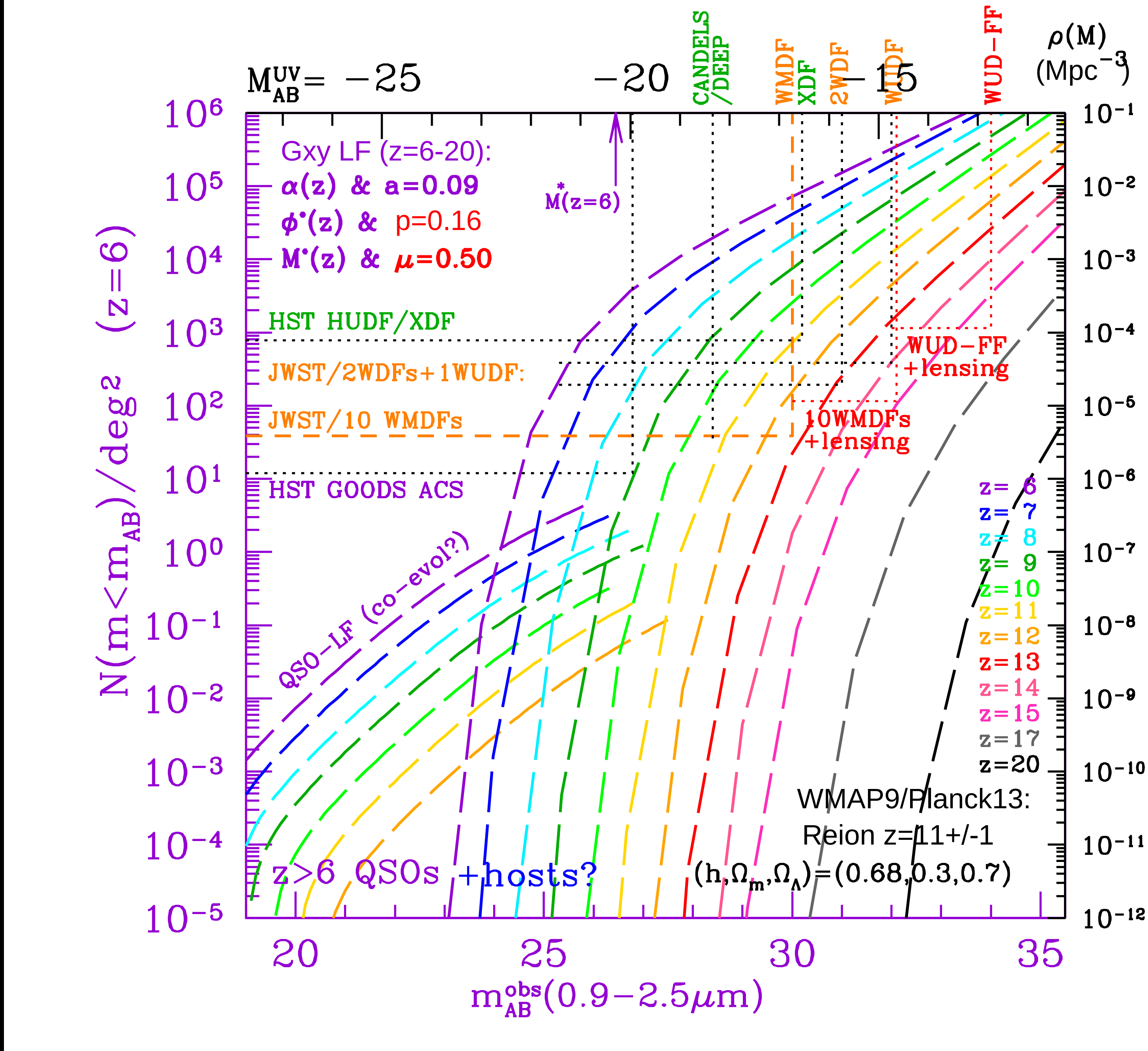
- Lensing will change the landscape for JWST observing strategies.




Evolution of Schechter UV-LF: faint-end LF-slope $\alpha$(z), $\Phi^*$ (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.

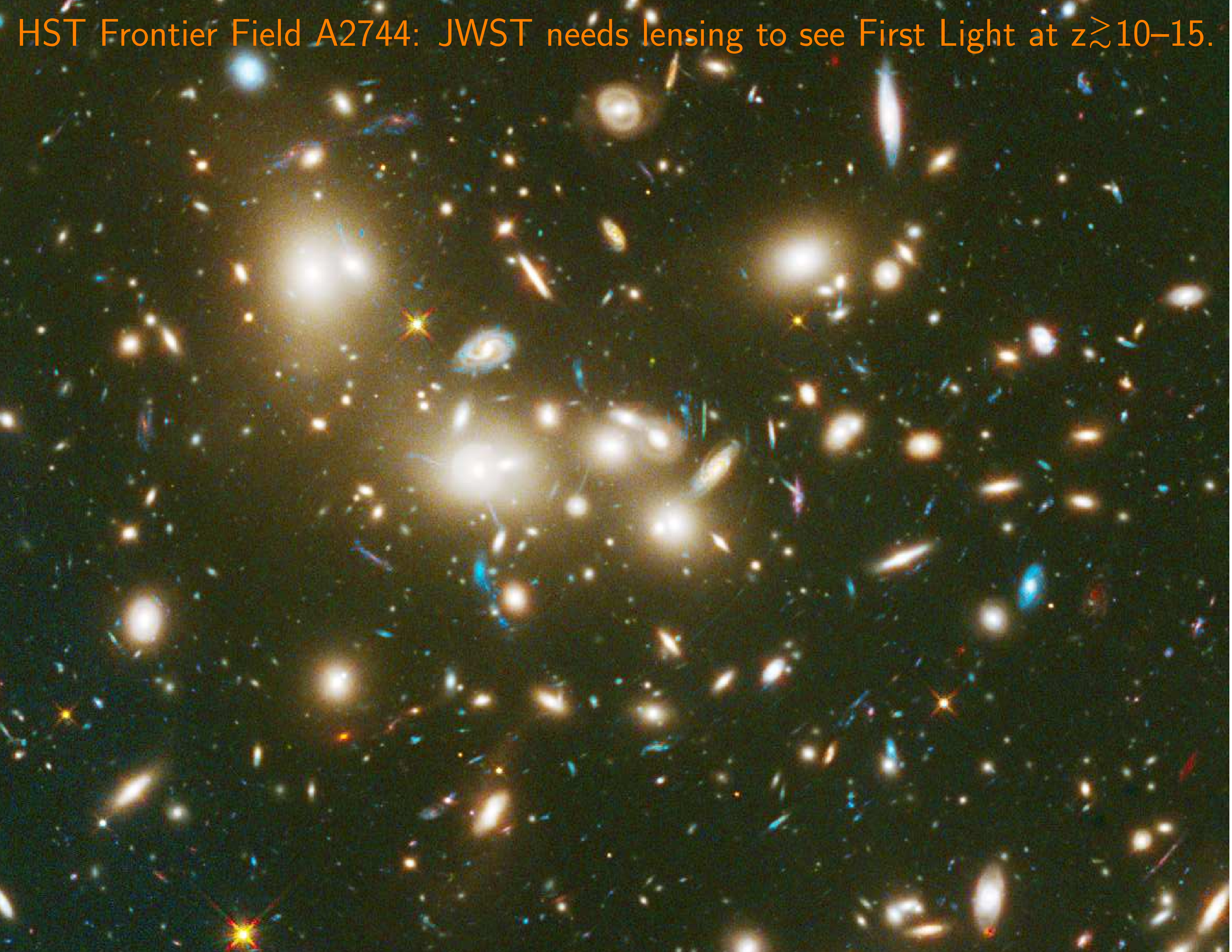



Predicted Schechter Luminosity Function (LF) at redshifts $6 \lesssim z \lesssim 20$:

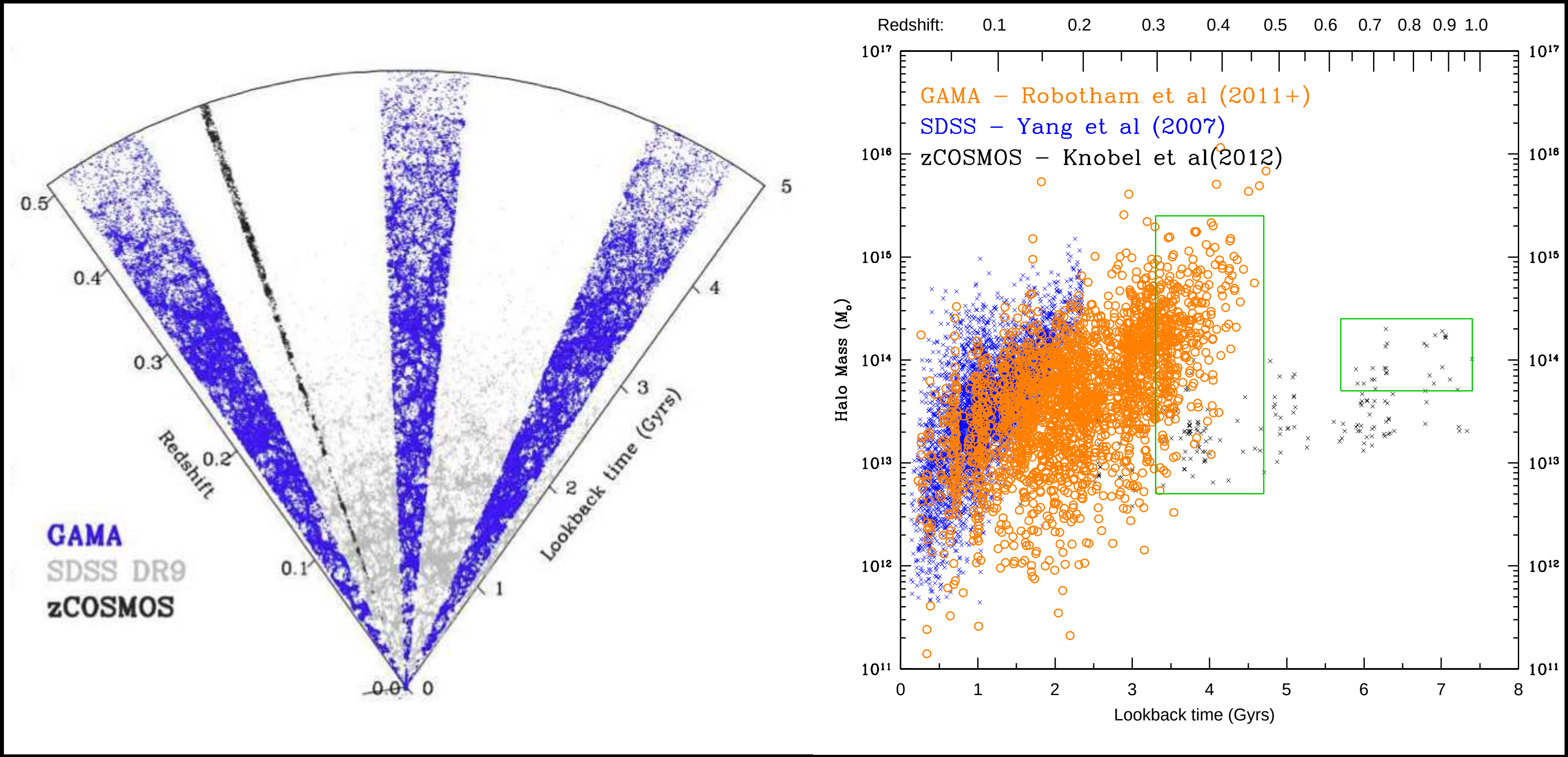
Area/Sensitivity for: Hubble UDF, **Webb: 10 MDFs**, 2 DFs, & 1 UDF.

- 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.



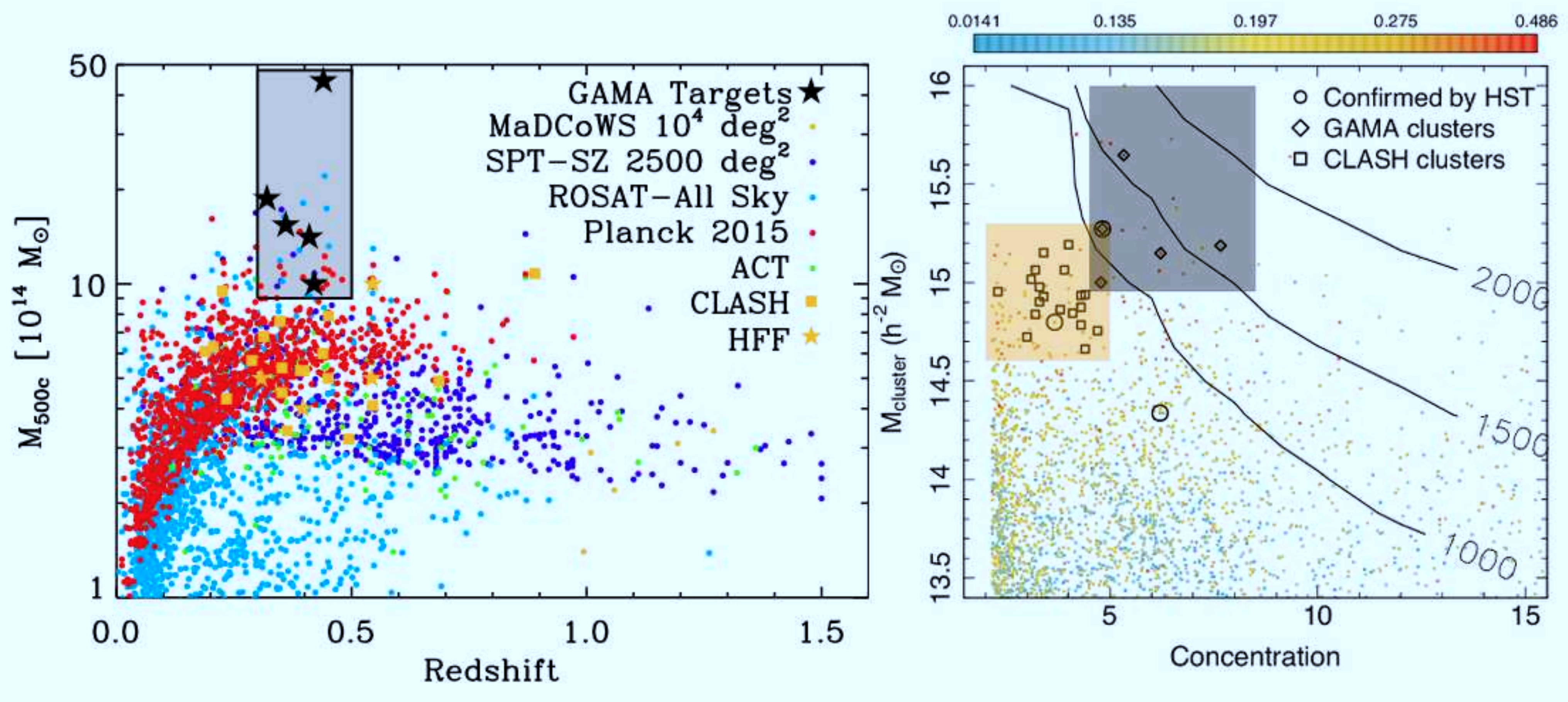
# (3c) Gravitational Lensing to see First Light population at $z \gtrsim 10$.




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 $N_{spec} \gtrsim 5$ (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.

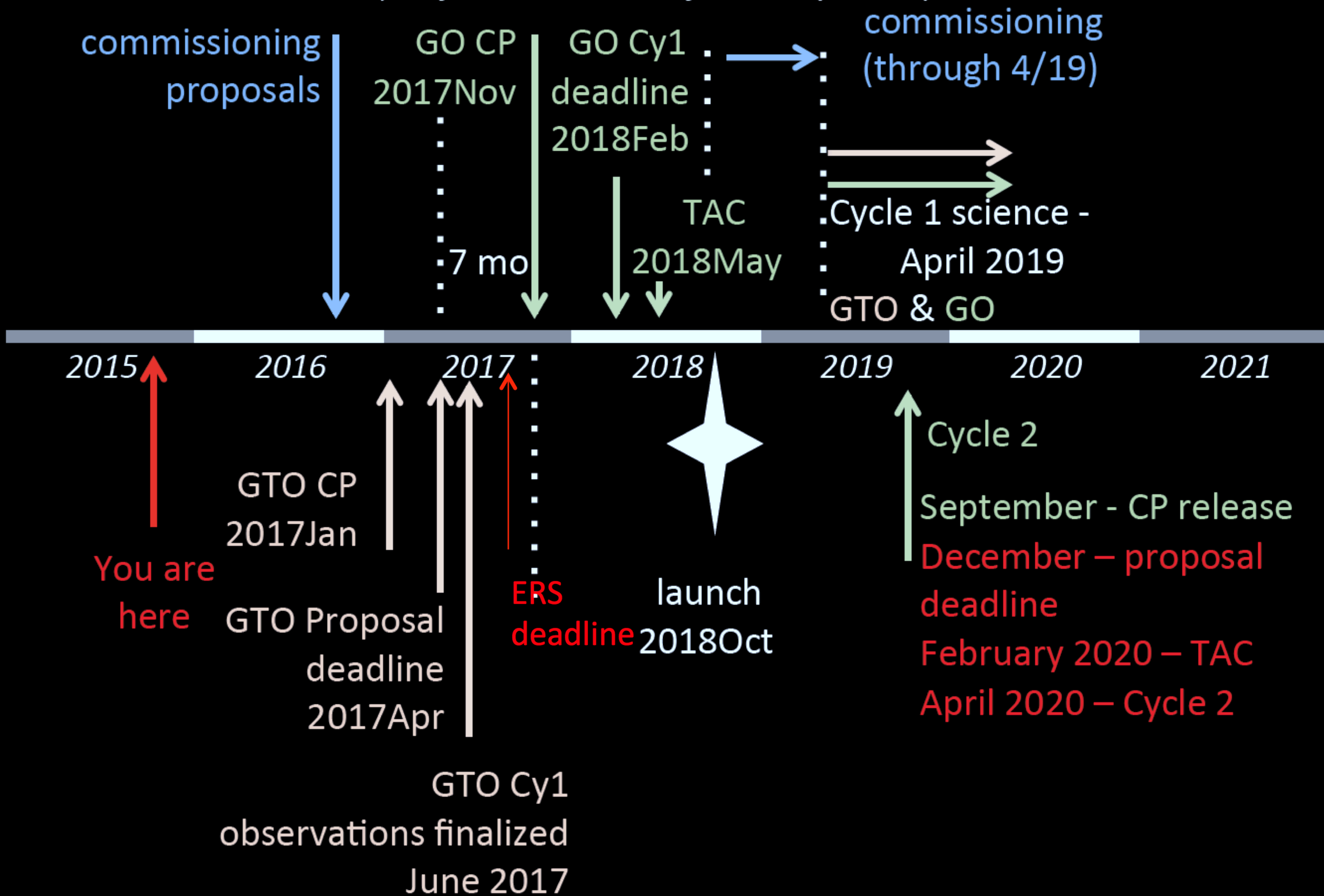
(4) JWST will have a major impact on astrophysics this decade:

- 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/

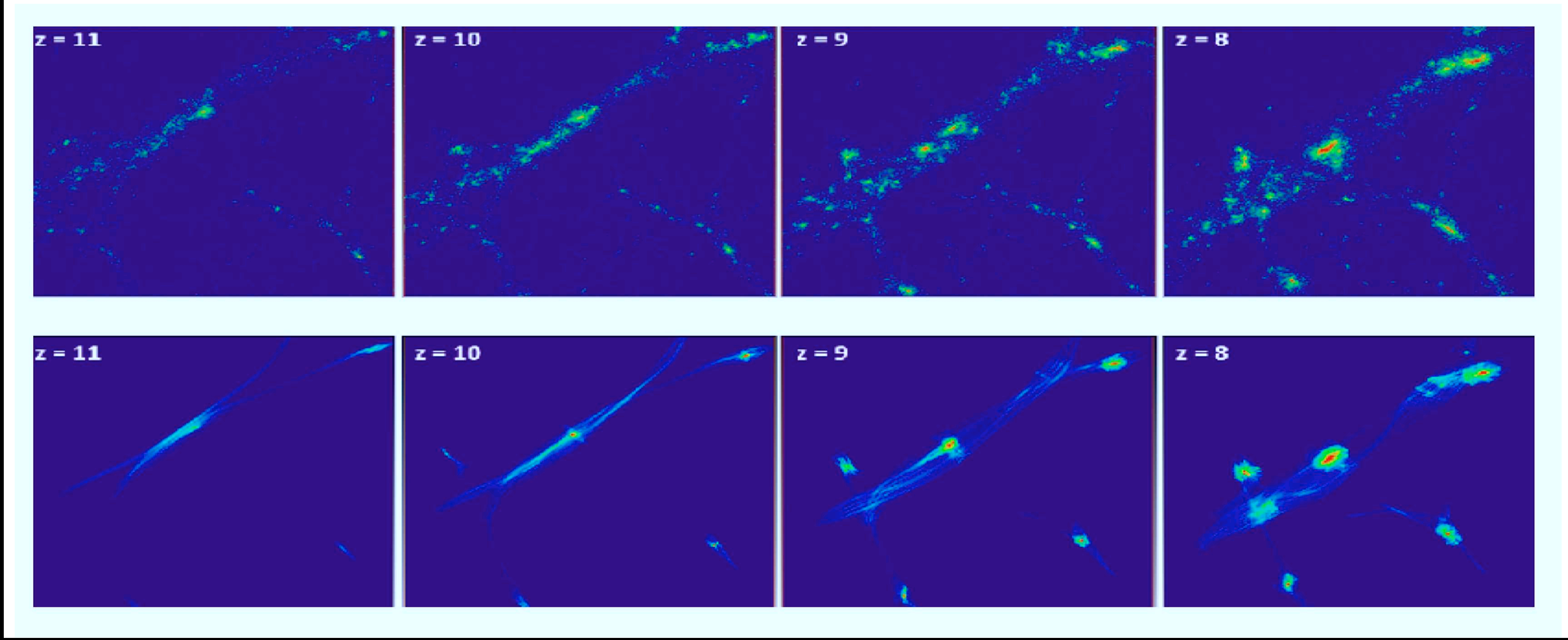
http://www.stsci.edu/jwst/instruments/fgs


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).



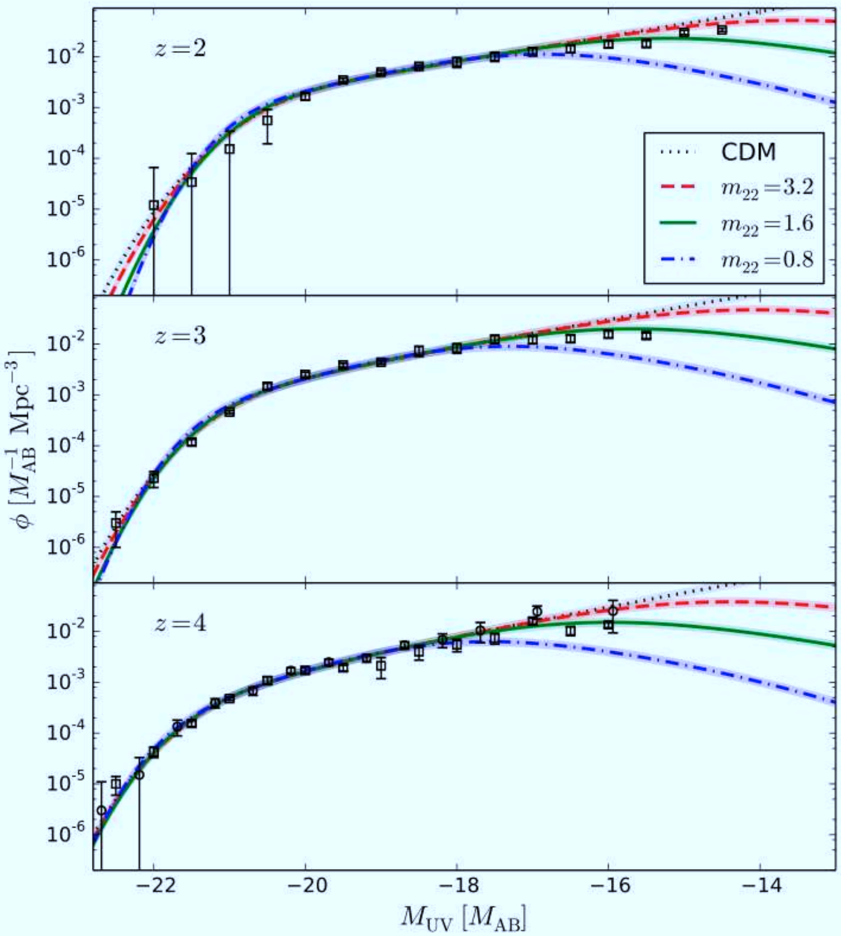

JWST cluster lensing can distinguish between standard $\Lambda$CDM and a new wave-CDM theory ("$\Psi$-CDM", which includes $\Lambda$):

[Top]: Ordinary $\Lambda$CDM simulations of hierarchical clustering:

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

[Bottom]: $\Psi$-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).



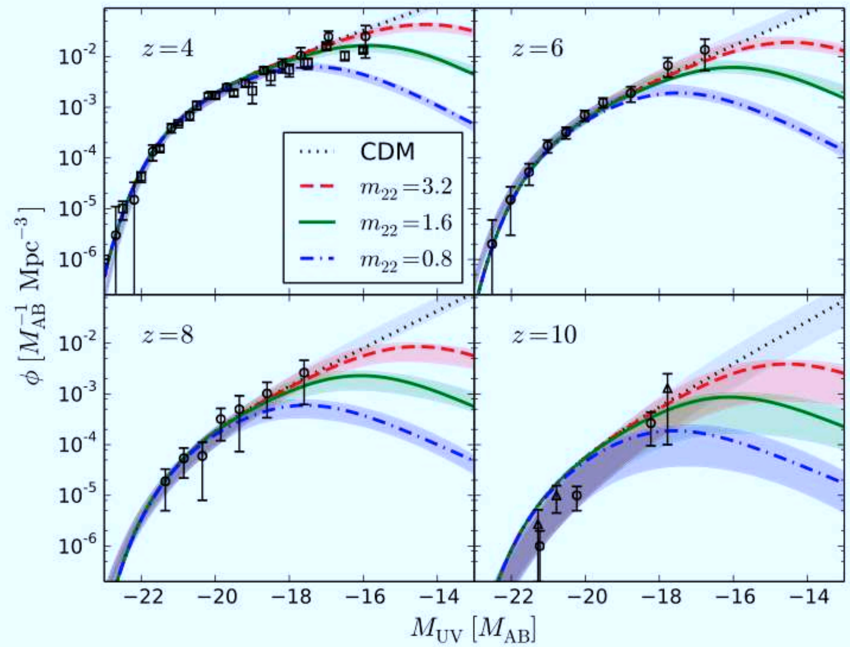




**Figure 8.** Luminosity function (LF) at $z = 4$–10 obtained by a single analytic formula similar to the Schechter function (Equations (11)–(13); central lines). The shaded regions are the same as Figure 6, showing the LF predicted by the conditional LF model within $2\sigma$. Error bars show the observed LFs ($2\sigma$ at $z = 4-8$ and $1\sigma$ 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 $\Lambda$CDM has *straight power-law* LFs at the faint end.
- $\Psi$-CDM better predicts declining numbers near the current HST limits.

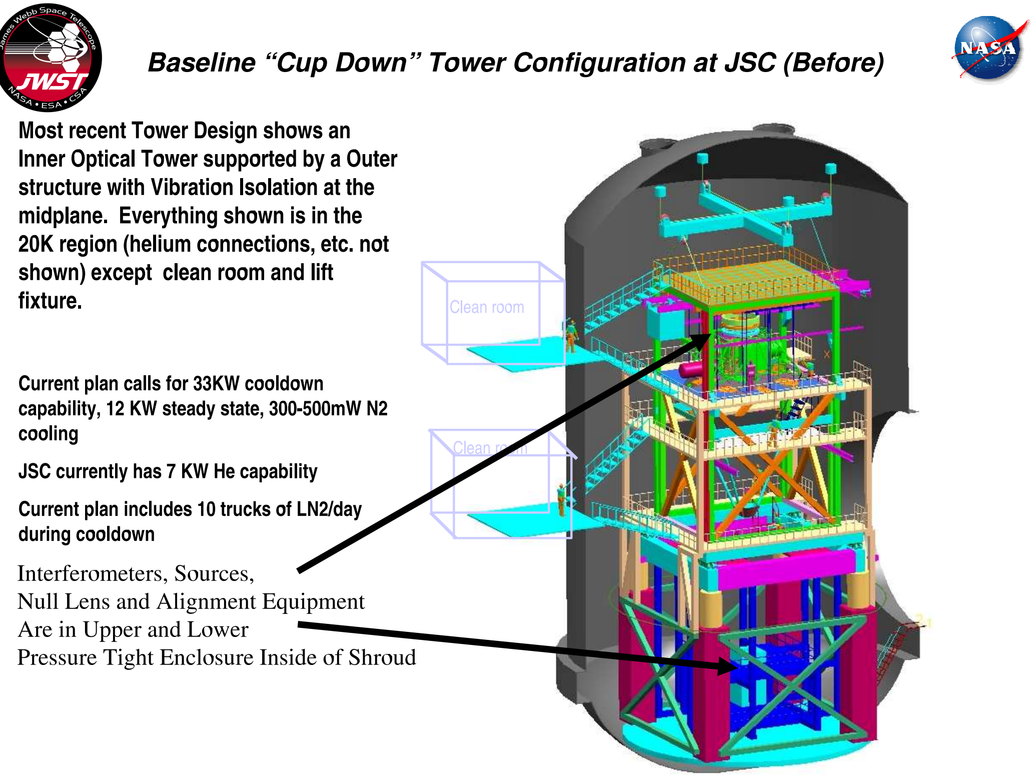
($\Psi$-CDM bosonic "axion" mass in units of $10^{-22}$ eV or $\lambda_{deB}$~0.4 pc).

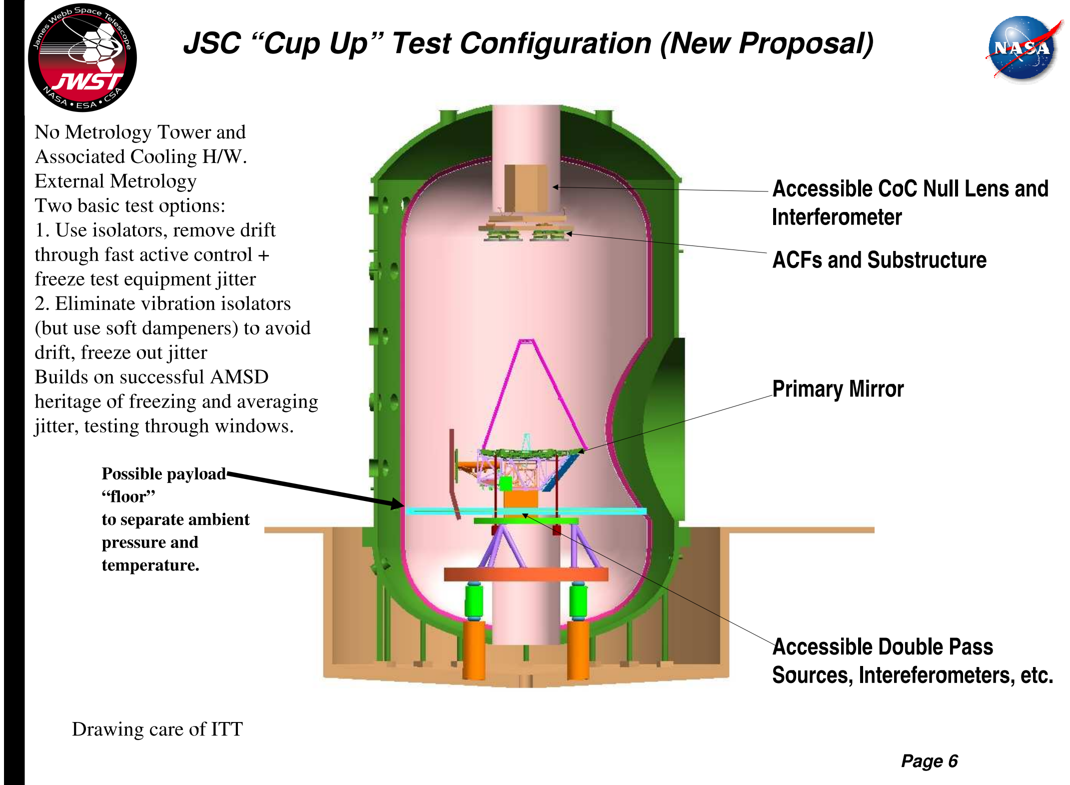
- JWST cluster lensing can distinguish between $\Lambda$CDM and $\Psi$-CDM.

# 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



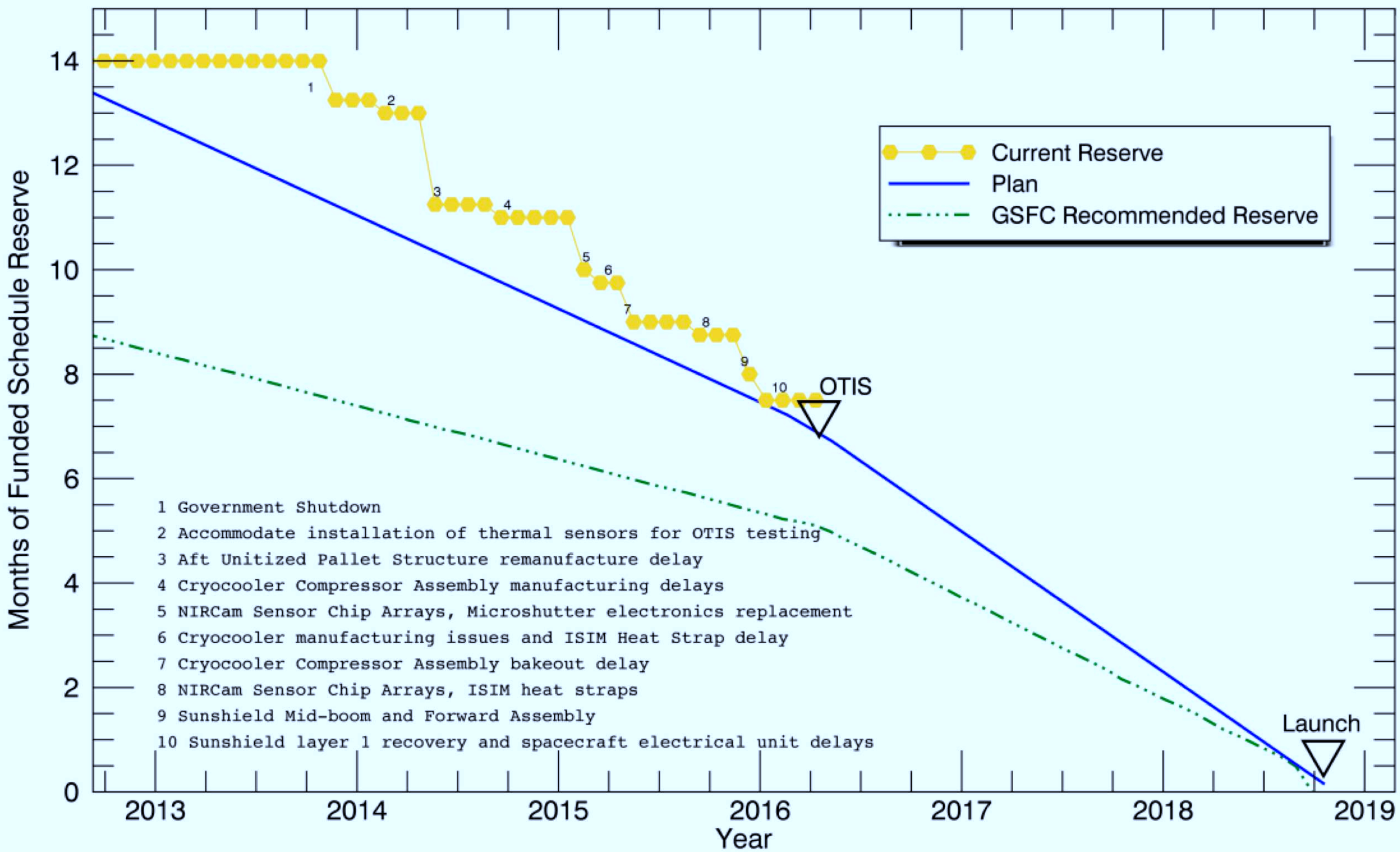



JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 $\mu$m performance specs (kept 2.0 $\mu$m).
- 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.

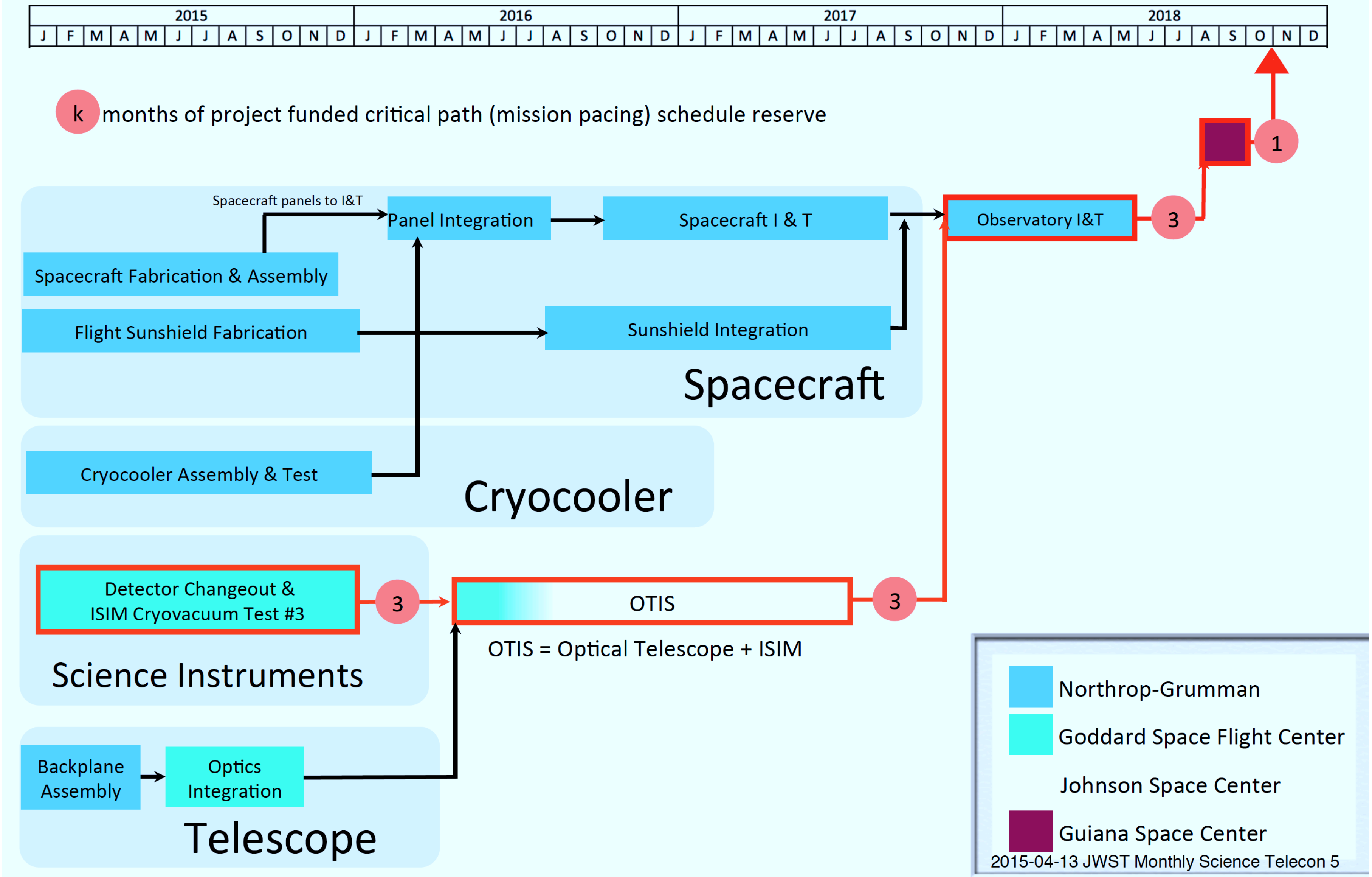
❖ Milestone accounting in FY2014 was complicated by the government shutdown and multicomponent milestones



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

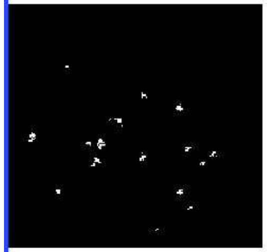
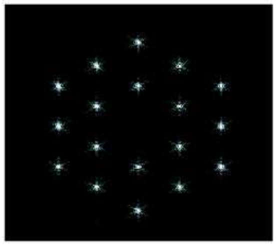
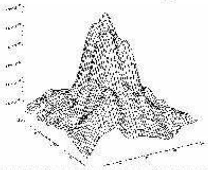
FY15, F16: Most "Lates" are not on critical path, nor cause a launch delay.

# Simplified Schedule




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

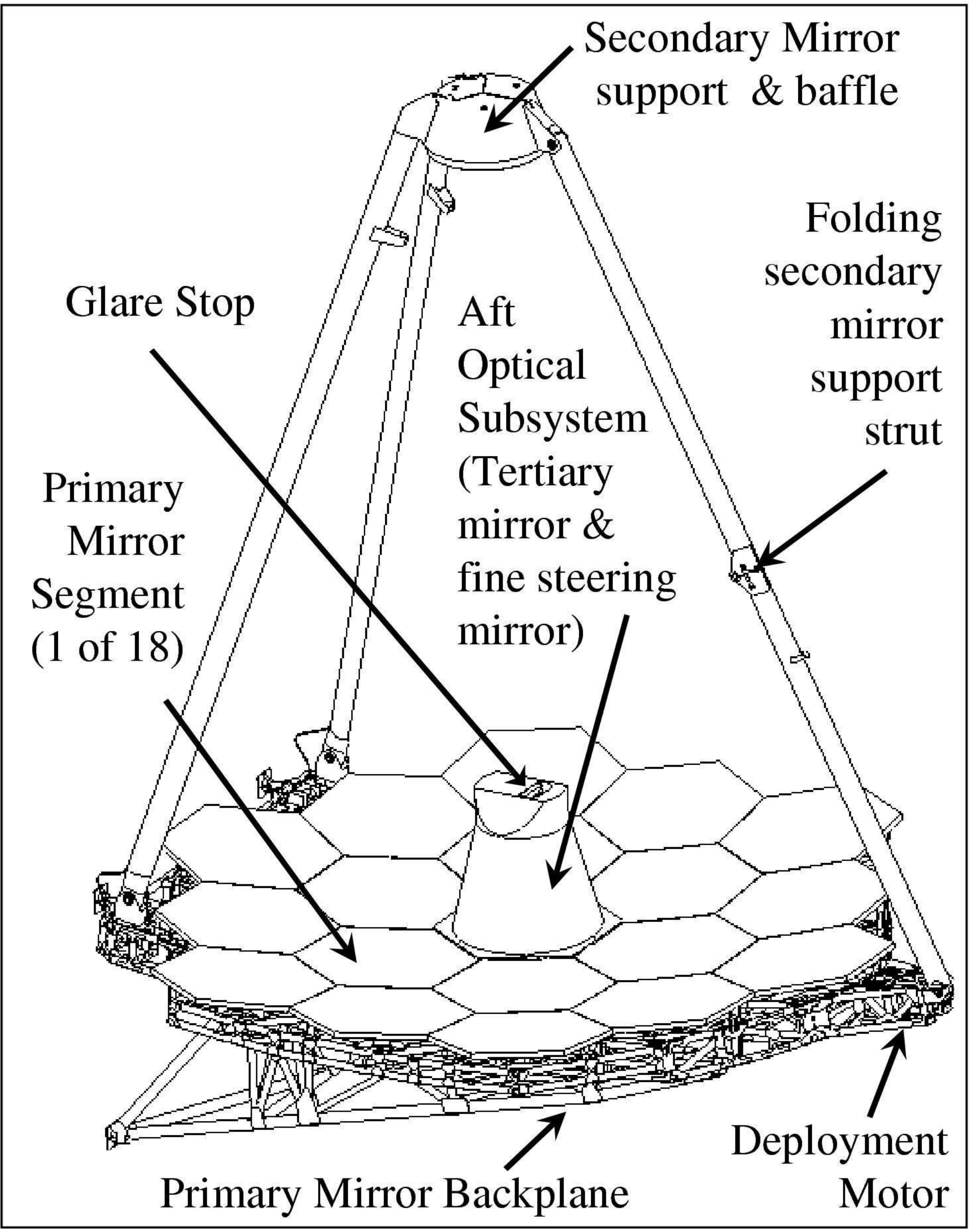
Instruments+detectors & Optical Telescope Element remain on critical path.

| 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<br>PM segments: < 1 mm, < 2 arcmin tilt<br>SM: < 3 mm, < 5 arcmin tilt | PM segments: < 100 μm, < 2 arcsec tilt<br>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<br>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.

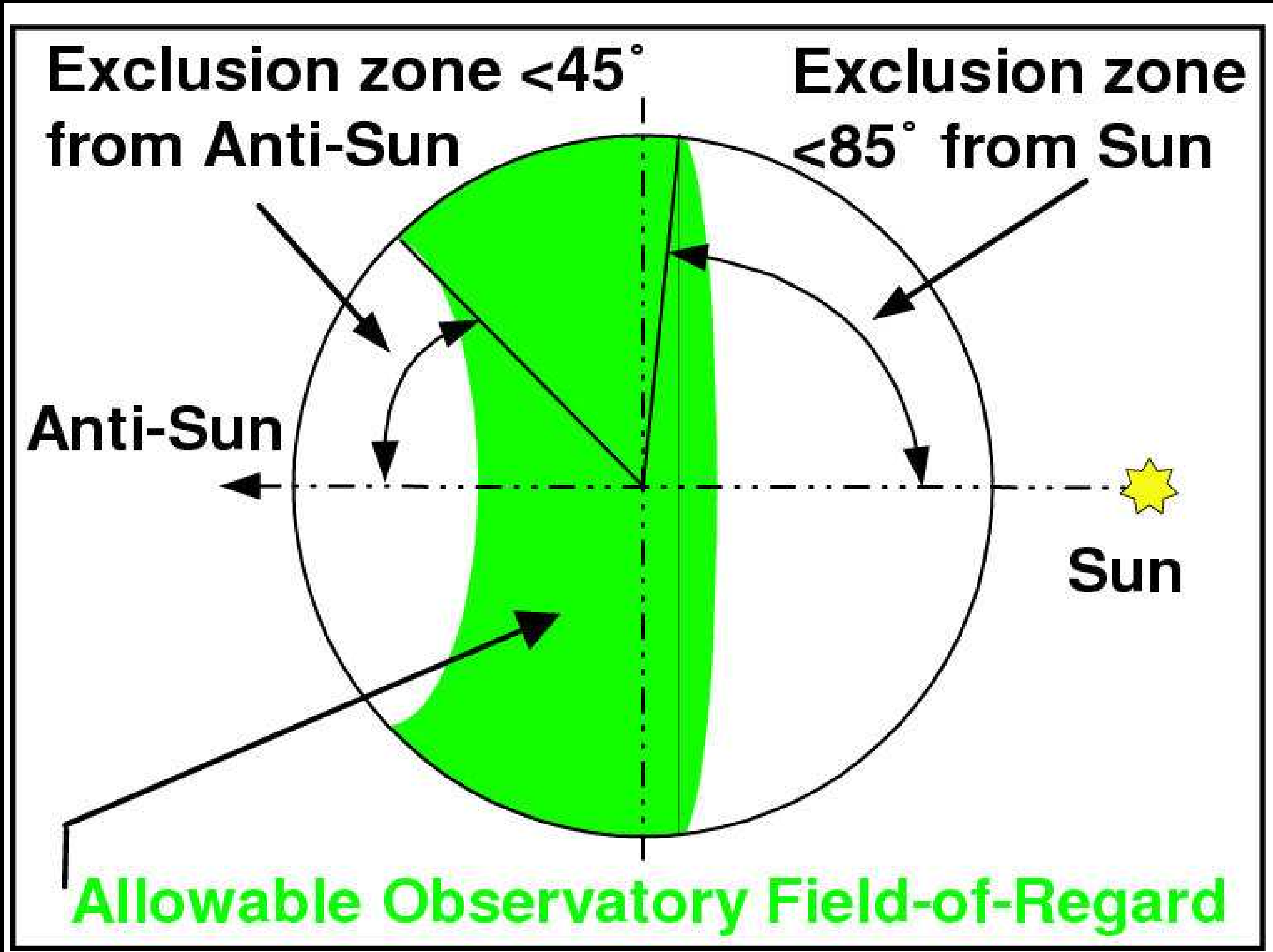
Redundant & doubly-redundant mechanisms, quite forgiving against failures.




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 $\mu$m images.

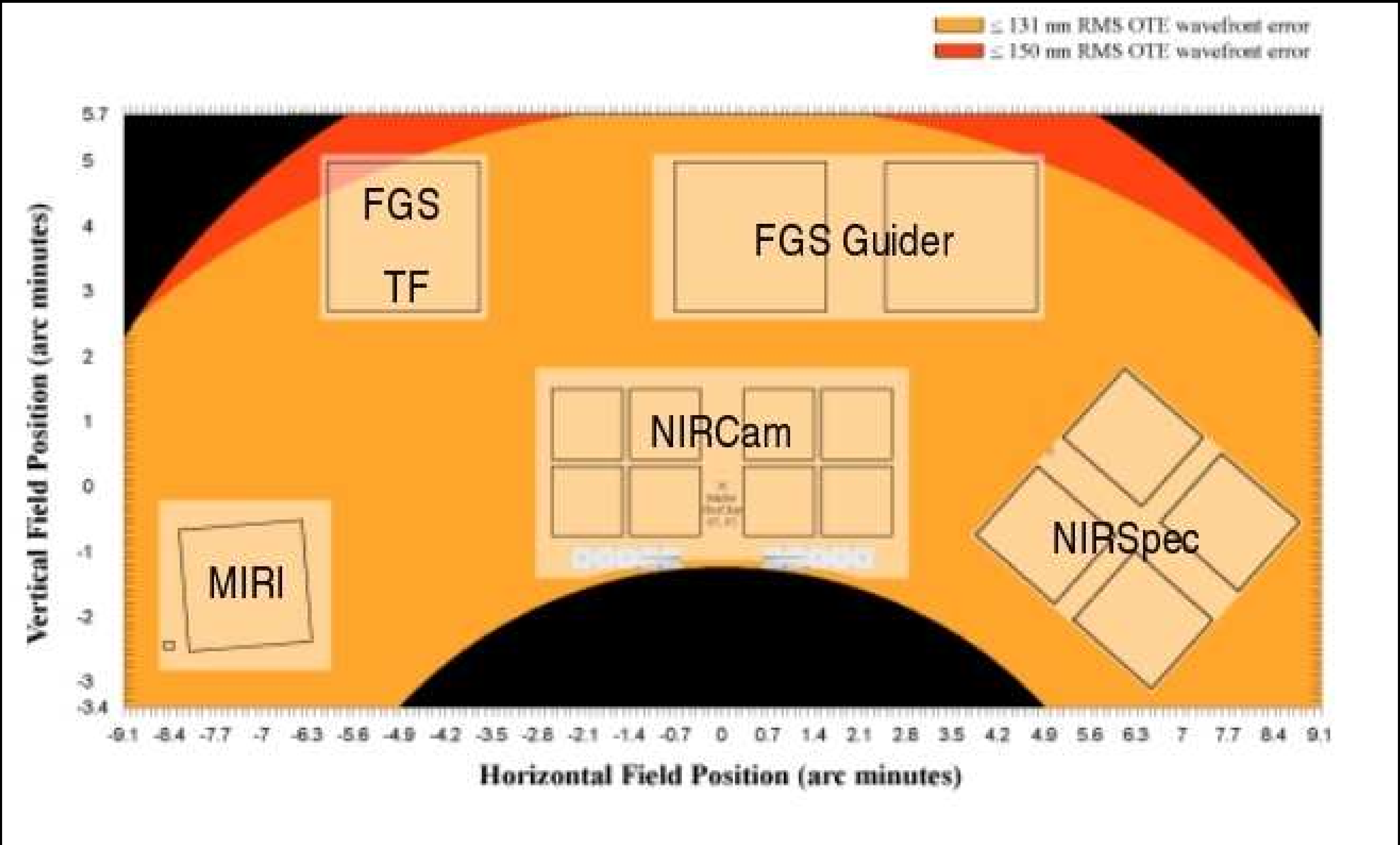
In L2, WFS updates every 10 days depending on scheduling/ SC-illumination.




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.