How will JWST measure First Light, Galaxy Assembly & Supermassive Blackhole Growth: New Frontier after HST

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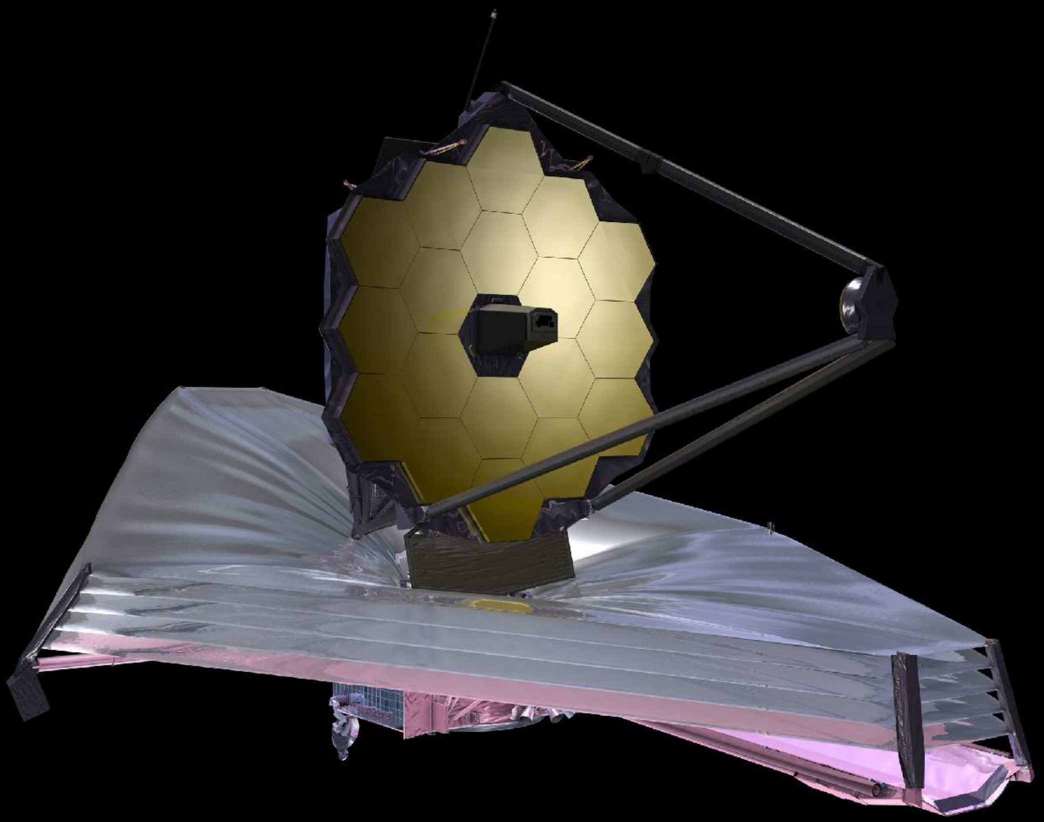


Colloquium at Max Planck Institüt/Landessternwarte, Heidelberg,

Germany, Friday March 14, 2014. All presented materials are ITAR-cleared.

Outline

- (1) Brief Update on the James Webb Space Telescope (JWST)
- (2) What HST WFC3 has done: Measuring Galaxy Assembly and Supermassive Black-Hole Growth, including z$\simeq$6 QSO Host System Detection
- (3) How can JWST measure the Epochs of First Light & Galaxy Assembly, and Supermassive Black-Hole Growth?
- (4) Summary and Conclusions.

Sponsored by NASA/HST & JWST

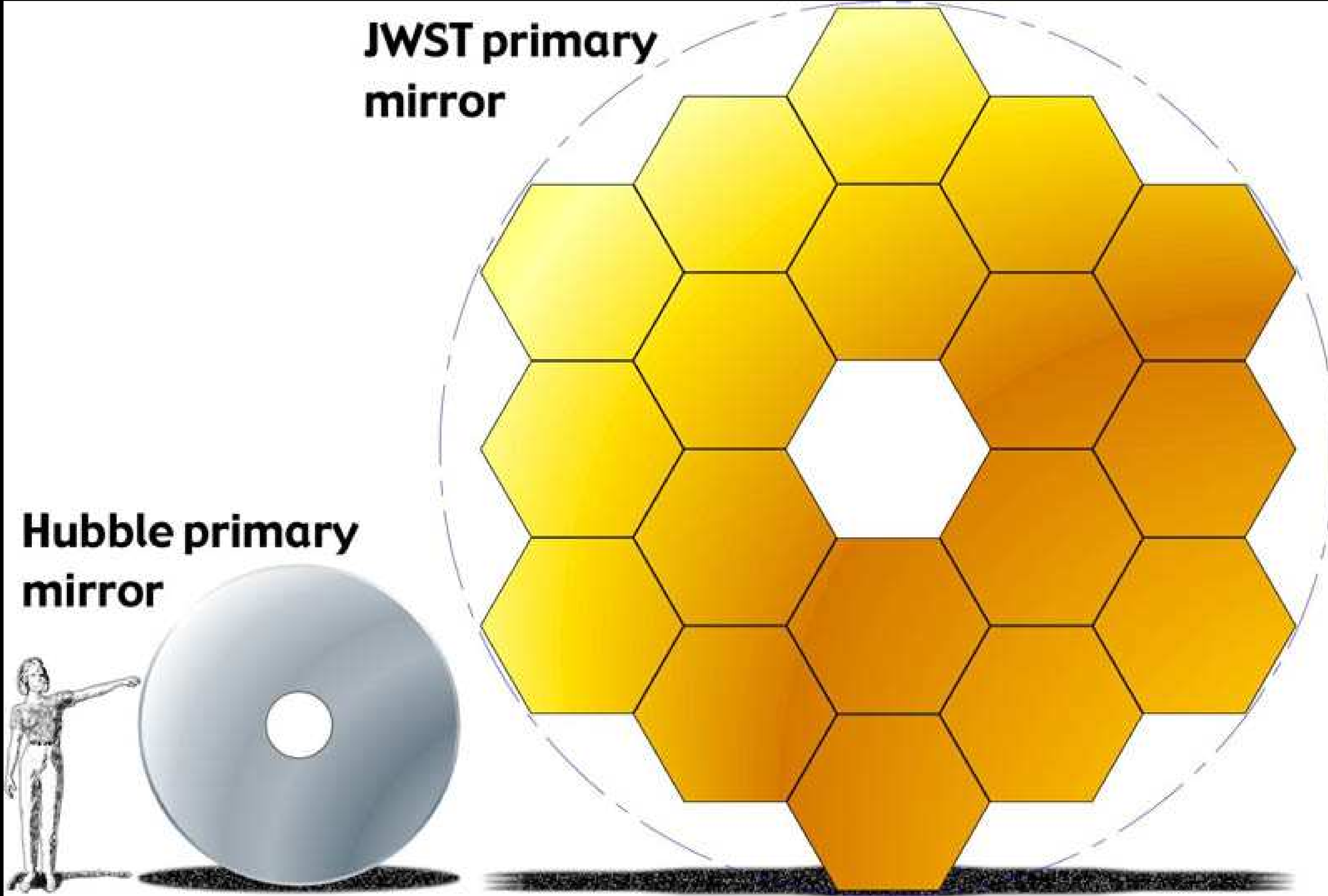
ARIZONA STATE UNIVERSITY

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

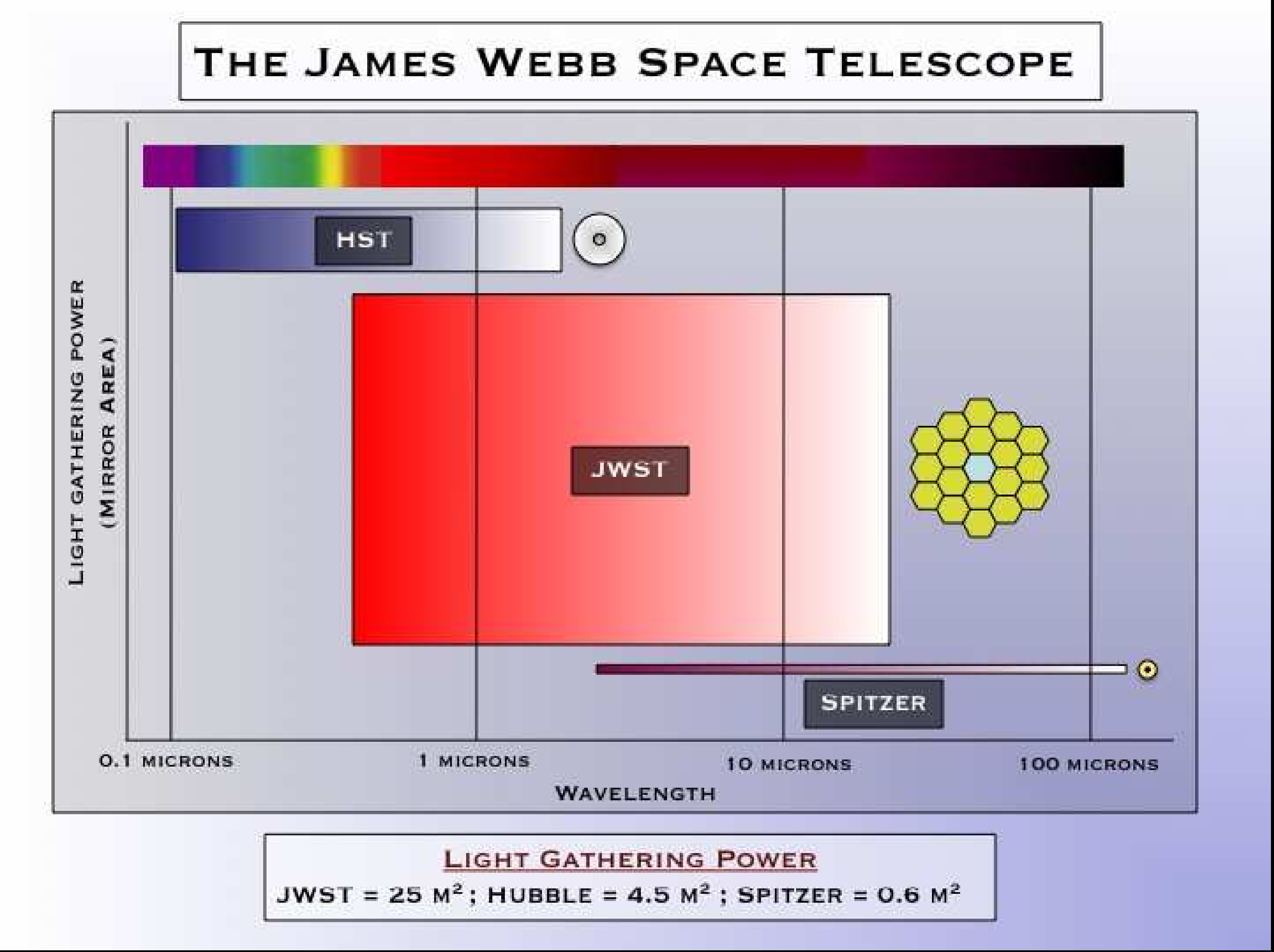
James E. Webb (1906–1992) — Second NASA Administrator

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

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



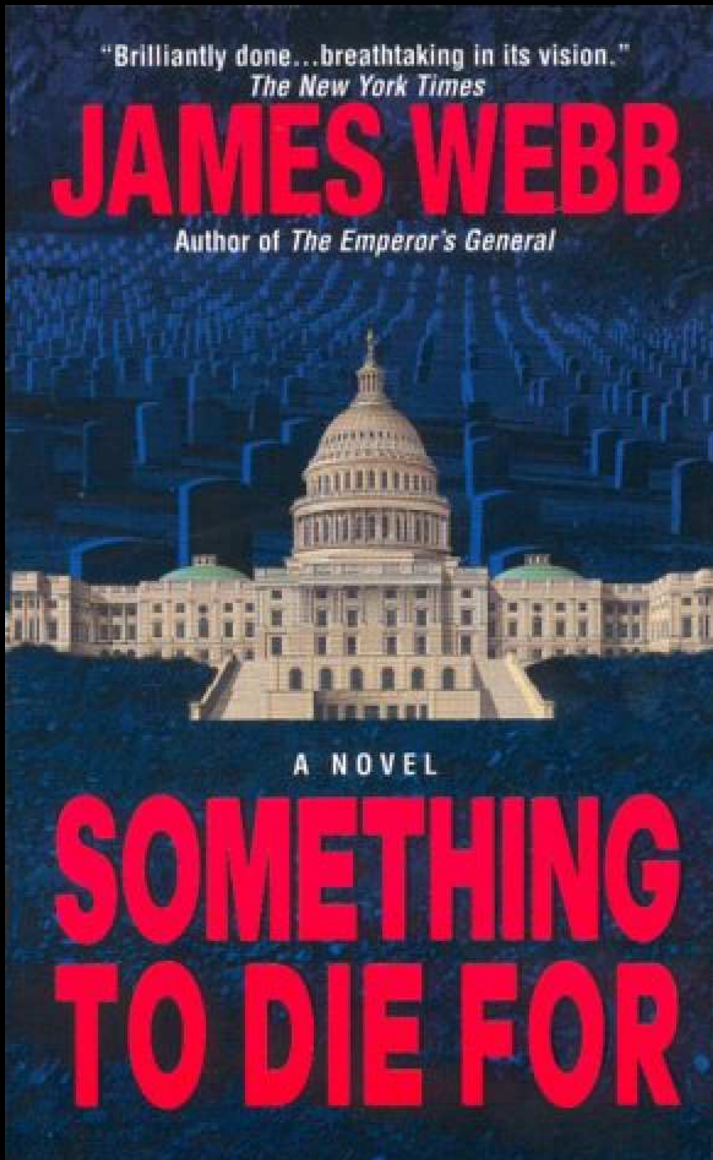
JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.



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

- Vastly larger A($\times\Omega$) than HST in UV-optical and Spitzer in mid-IR.

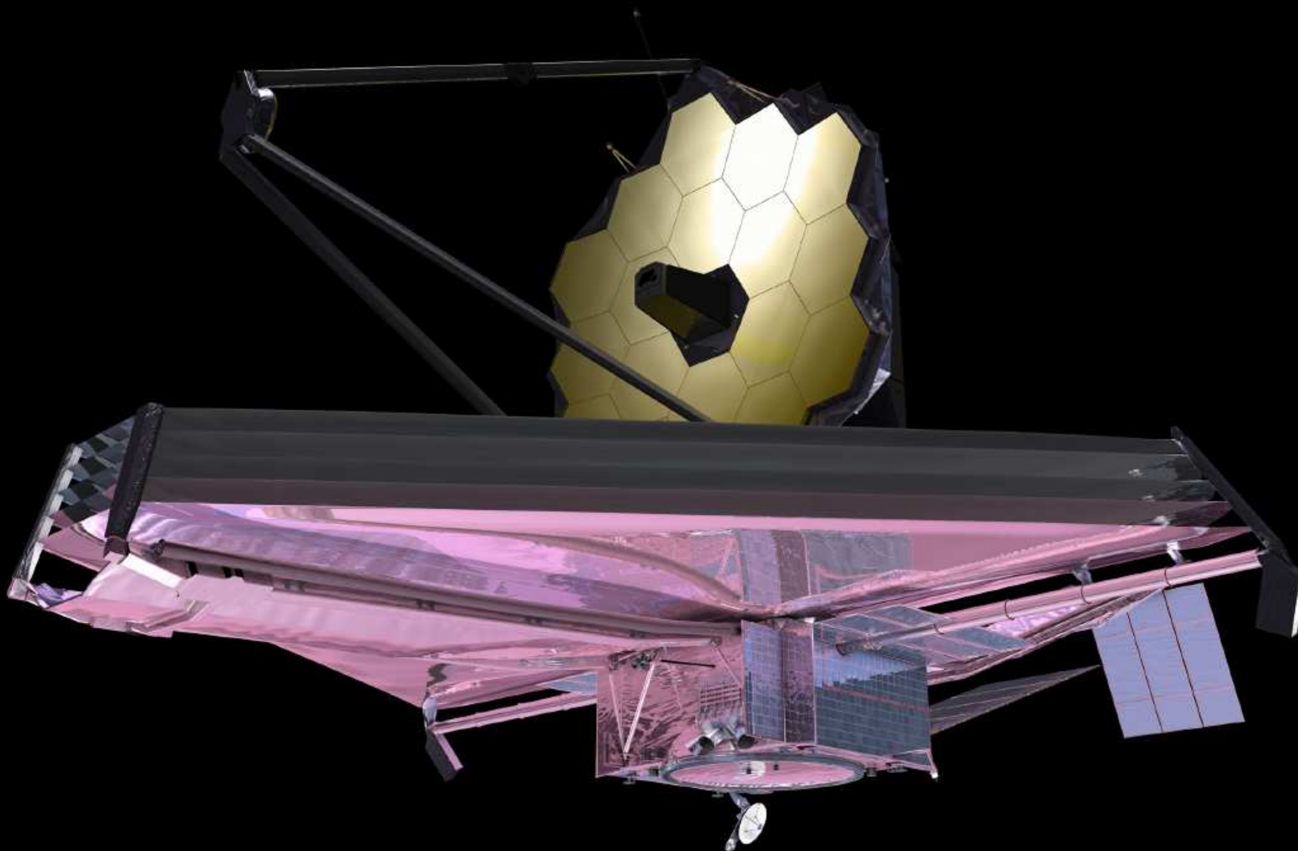
(1) Brief Update of the James Webb Space Telescope (JWST).



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) Brief Update of the James Webb Space Telescope



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

The James Webb Space Telescope

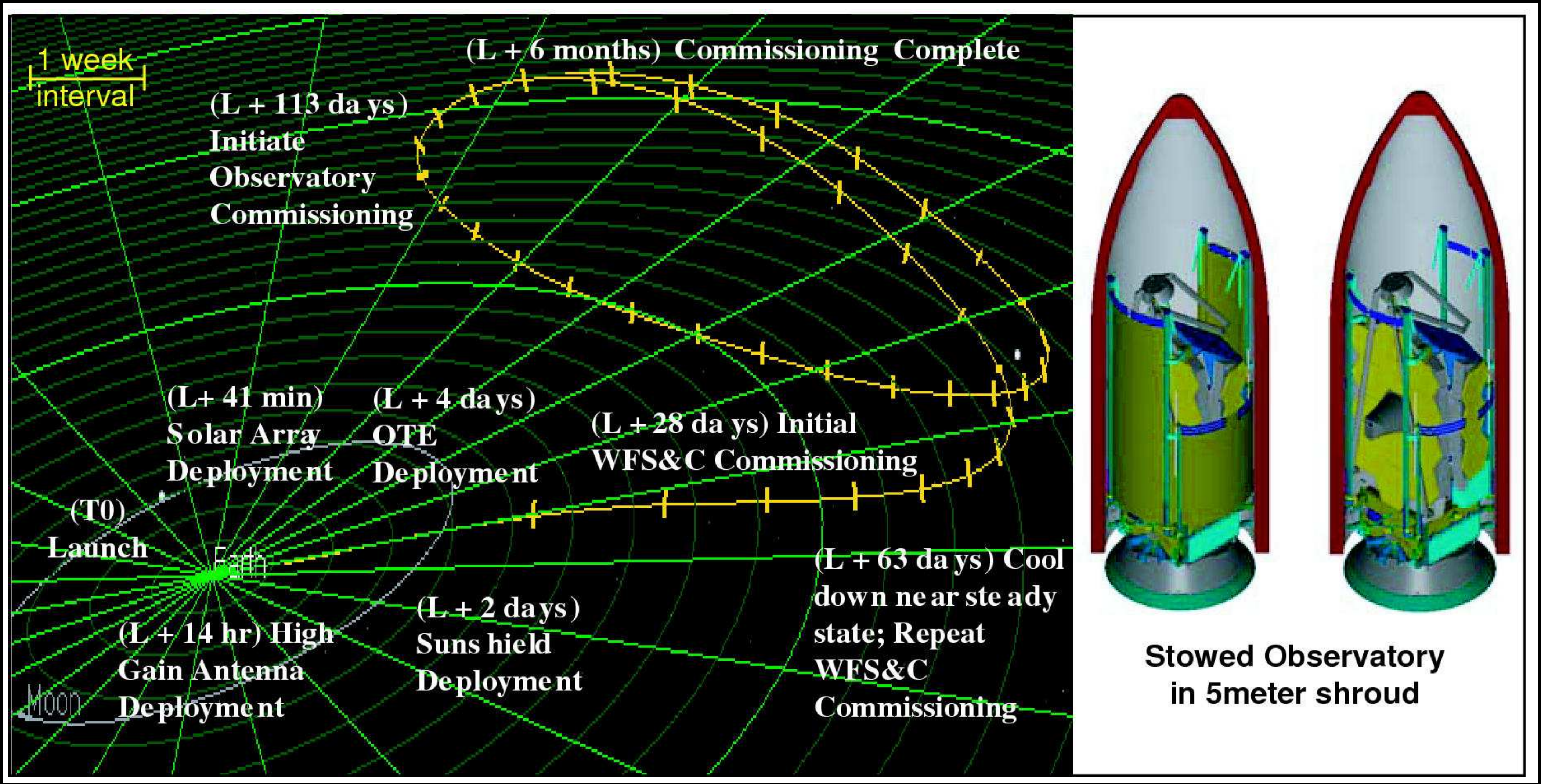
JWST Launch

- Launch vehicle is an Ariane 5 rocket, supplied by ESA
- Site will be the Arianespace's ELA-3 launch complex near Kourou, French Guiana

Arianespace – ESA - NASA

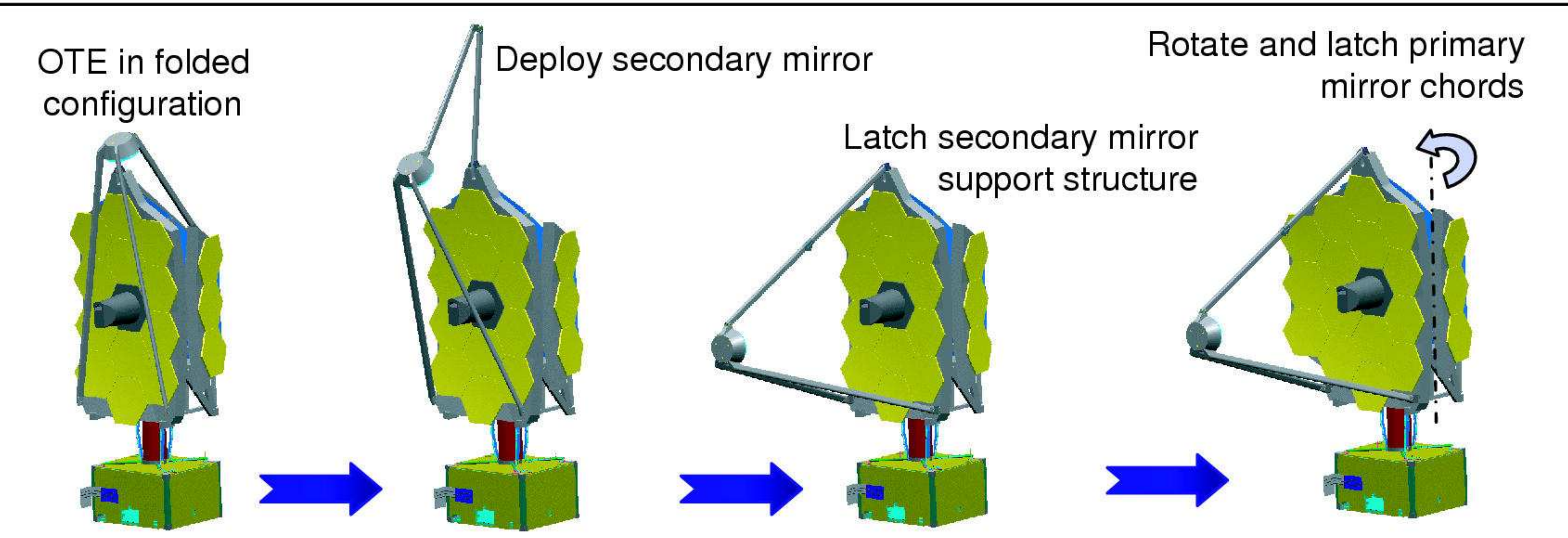
• The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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



- After launch in 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.

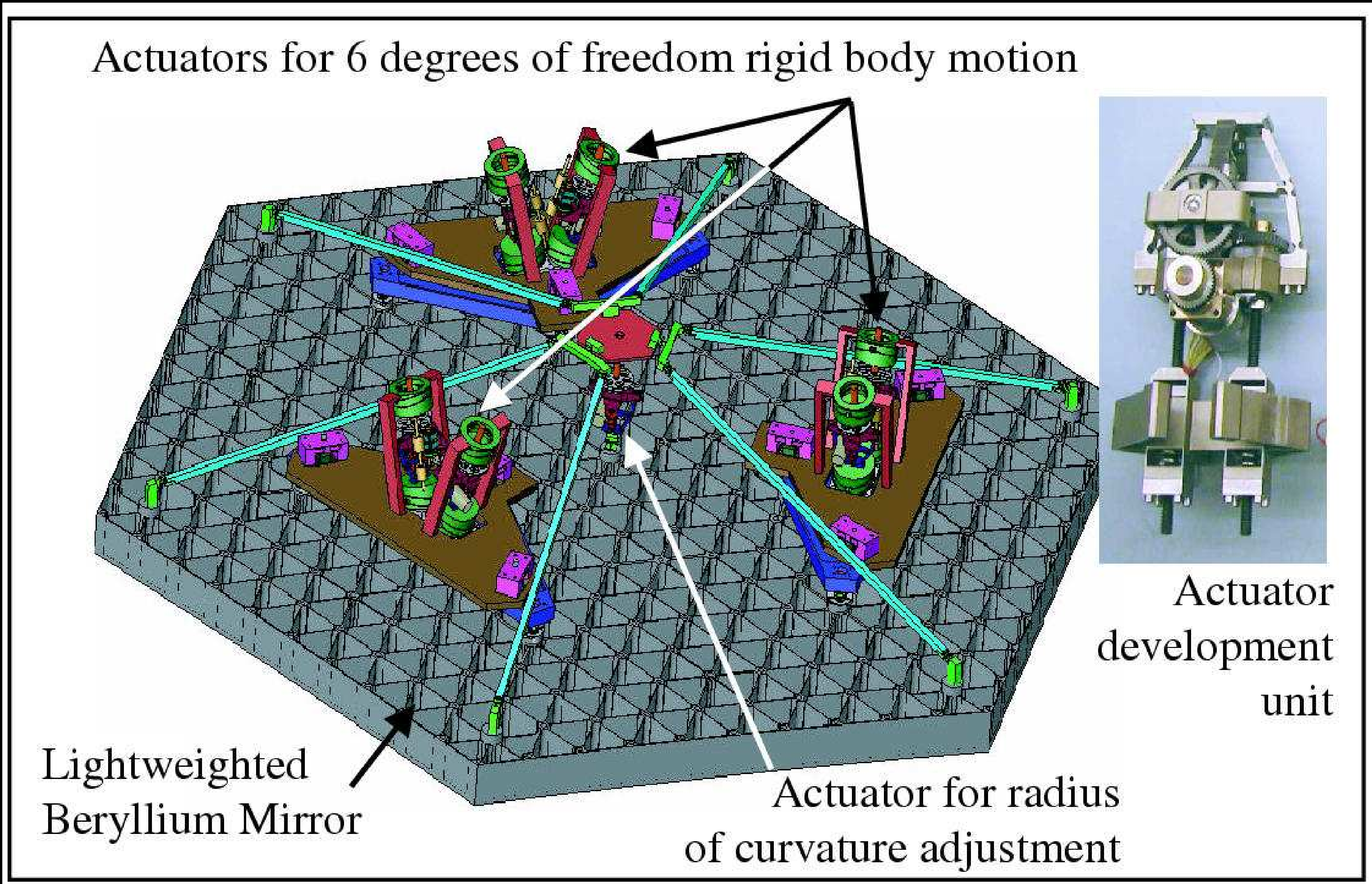
• (1b) How will JWST be automatically deployed?



• 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 will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.

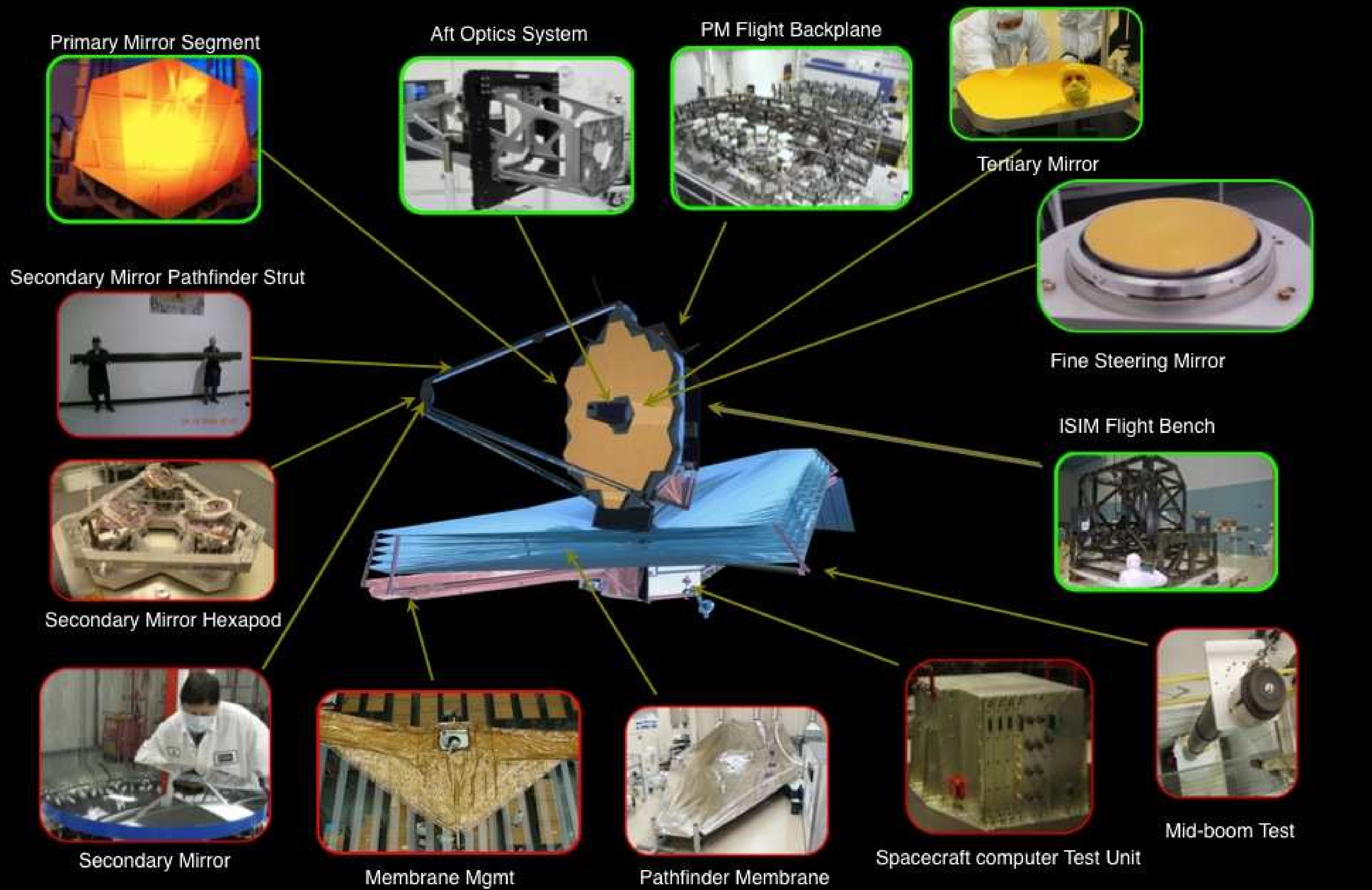
• Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



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

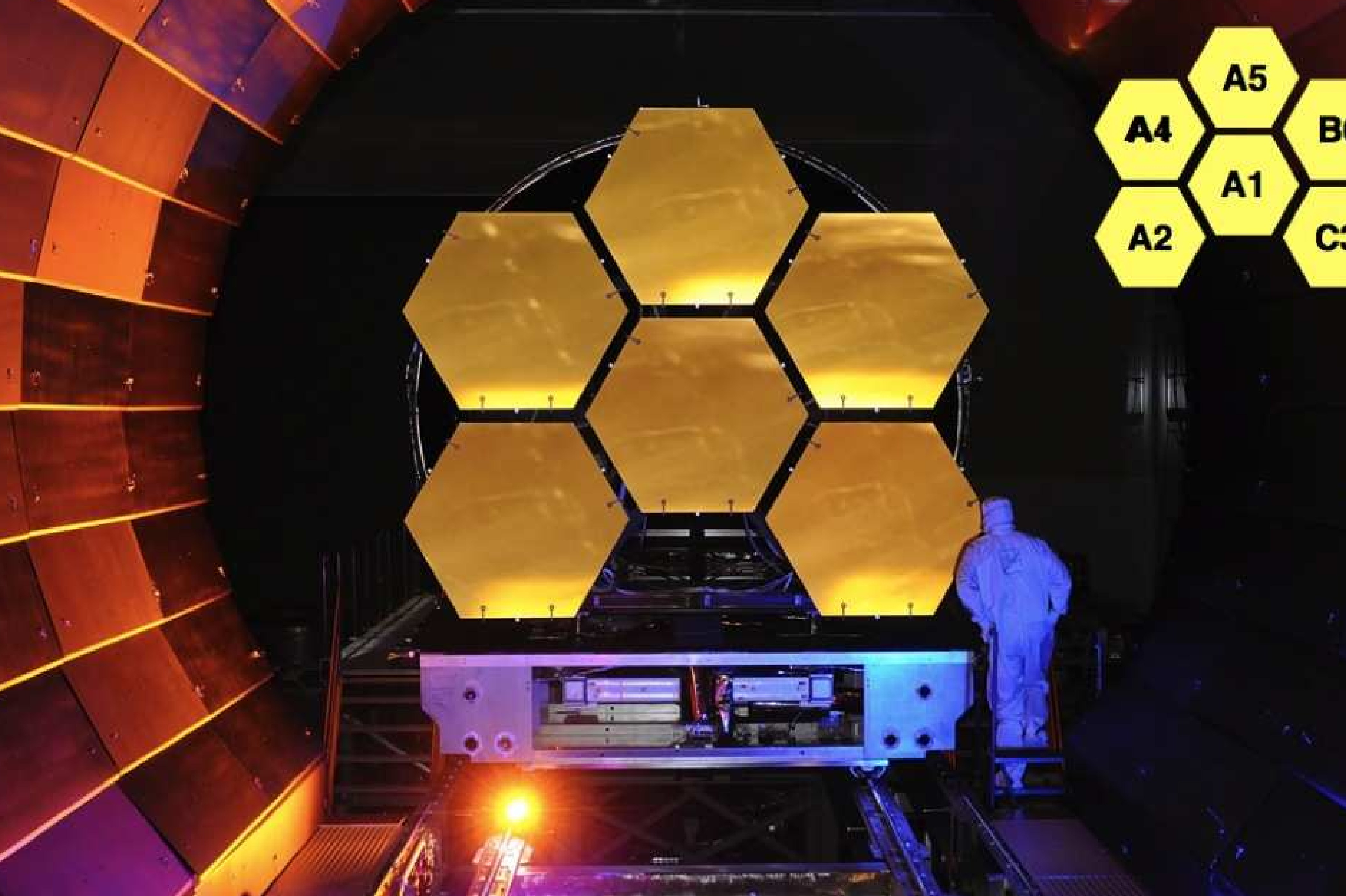
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

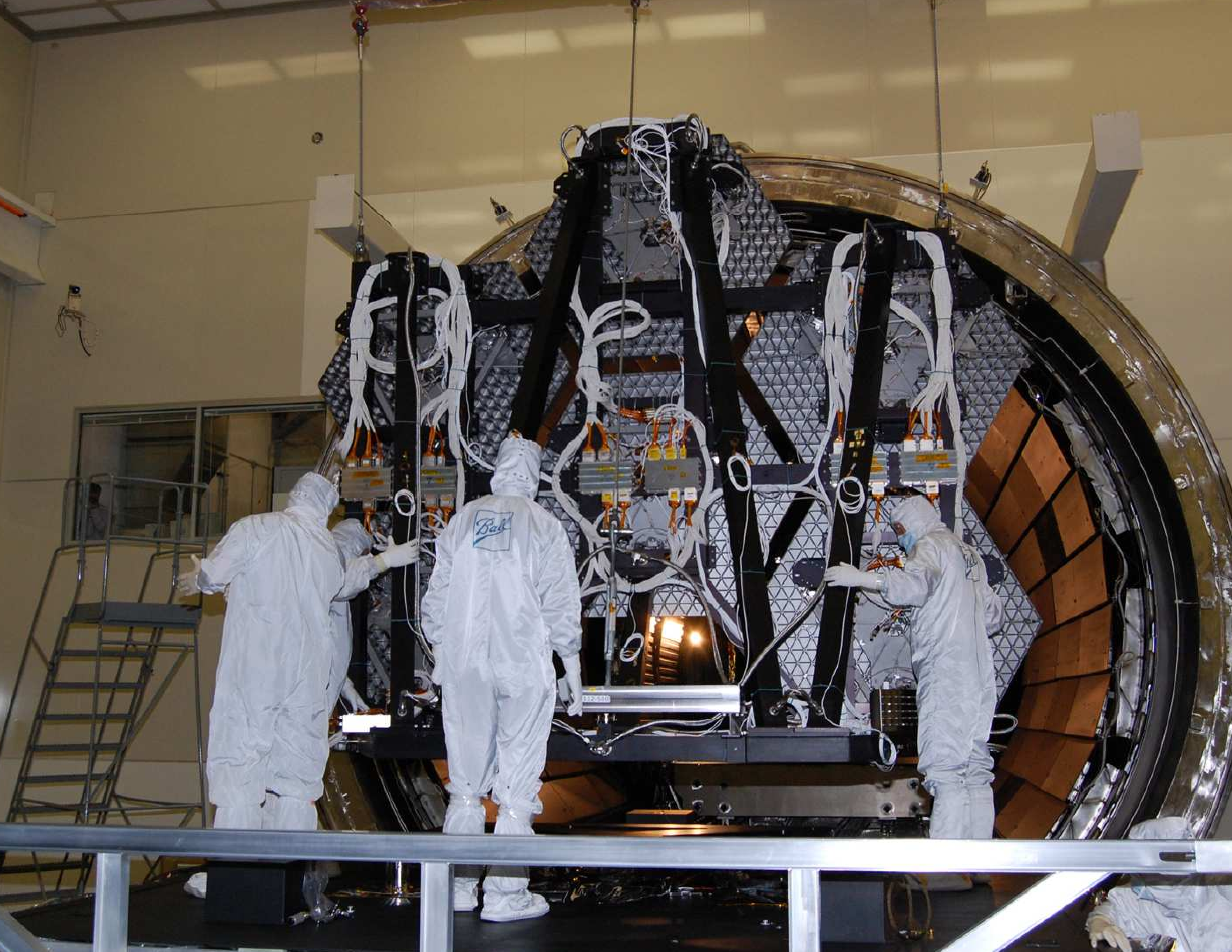
JWST Hardware Status



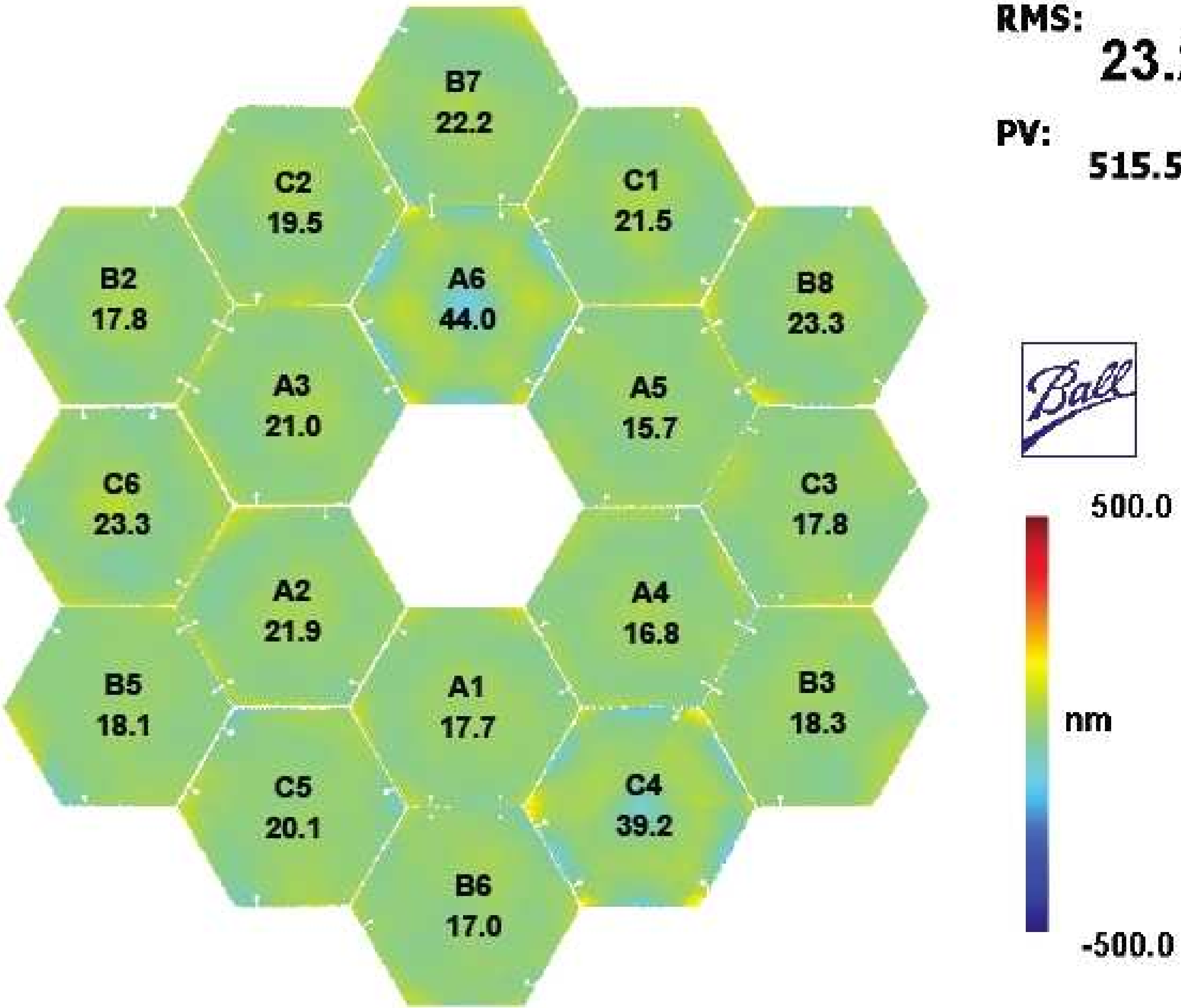
80% of launch mass designed and built as of Jan. 2014.

Mirror Acceptance Testing





Primary Mirror Composite

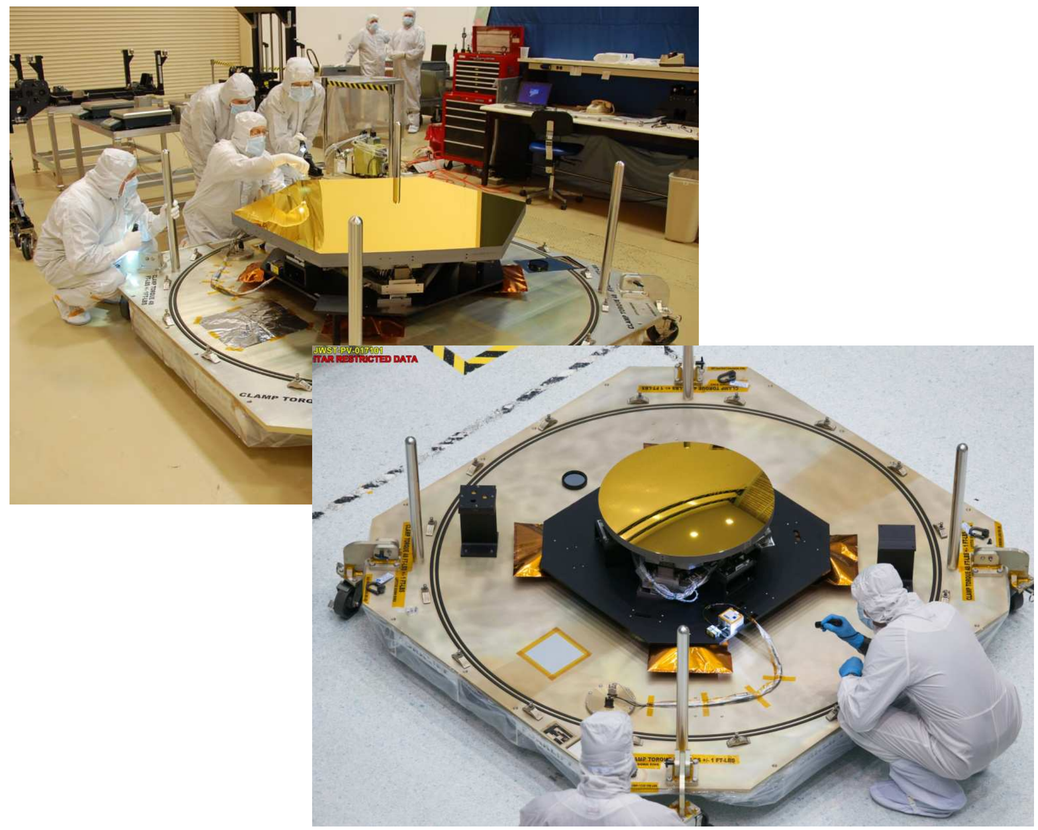


RMS: 23.2 nm

PV: 515.5 nm

Mirror Status

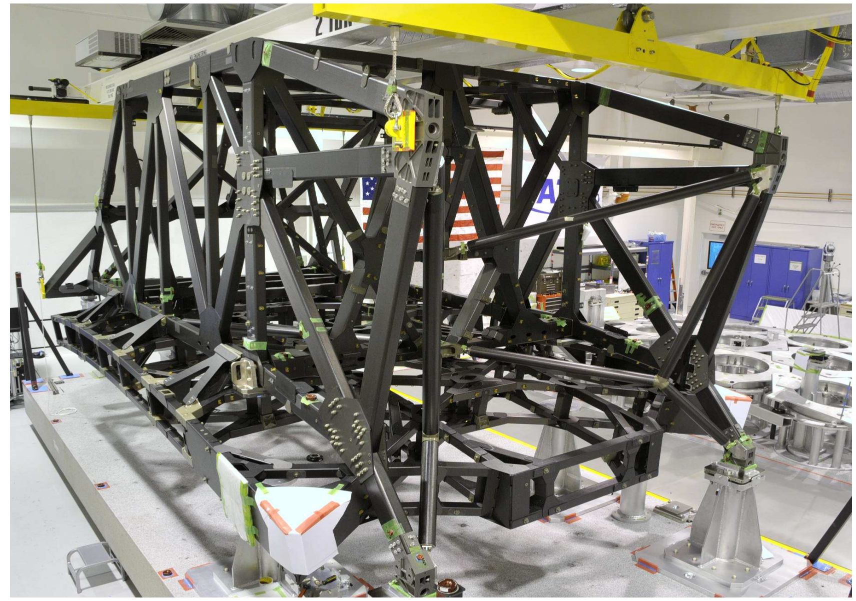
- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC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



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

Backplane Support Frame, Center Section, & Wings

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



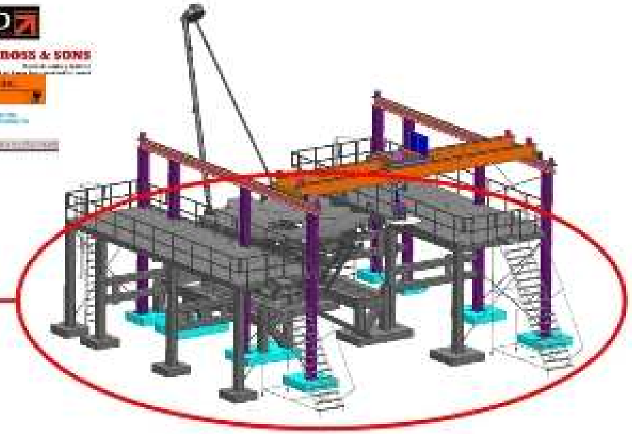
BSF and Center Section

BSF/Center Section coming out of

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

Telescope Assembly Ground Support Equipment

Ambient Optical Alignment Stand Complete



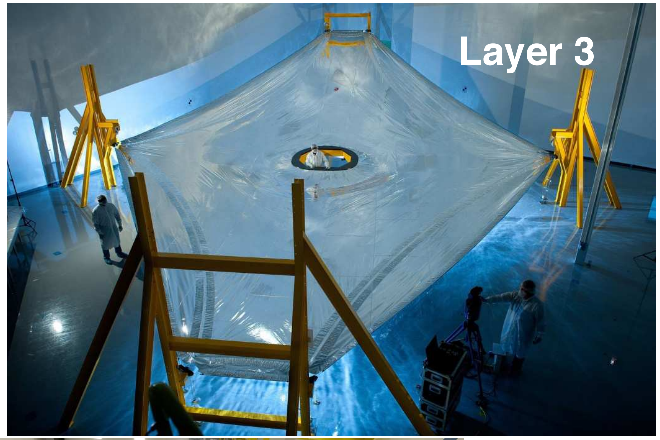
Hardware has been installed at GSFC approximately 8 weeks ahead of schedule

Landing a mirror onto backplane simulator

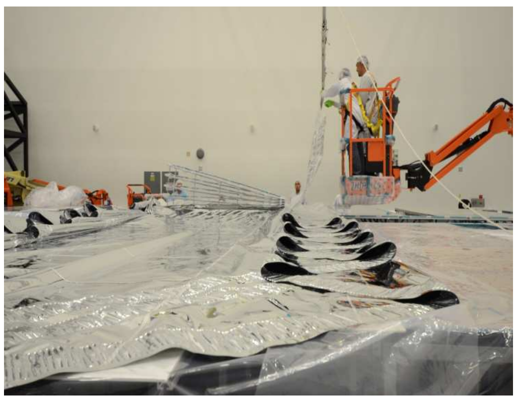
Sunshield Template Membrane Work Completed

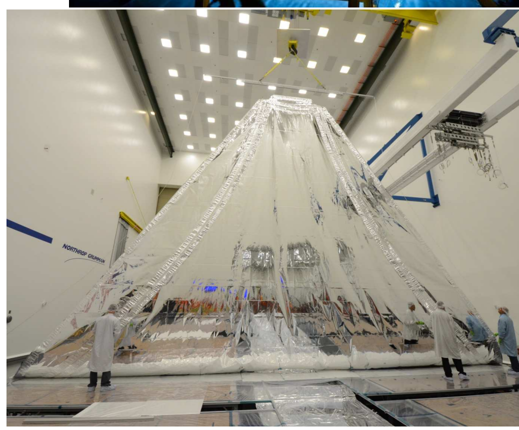
Templates Verify Design/Manufacturing Prior to Flight Build

- All Template Layers Completed
- Preparing for flight article manufacturing
- First two Flight Manufacturing Readiness Reviews Completed
- Membrane pull out test complete

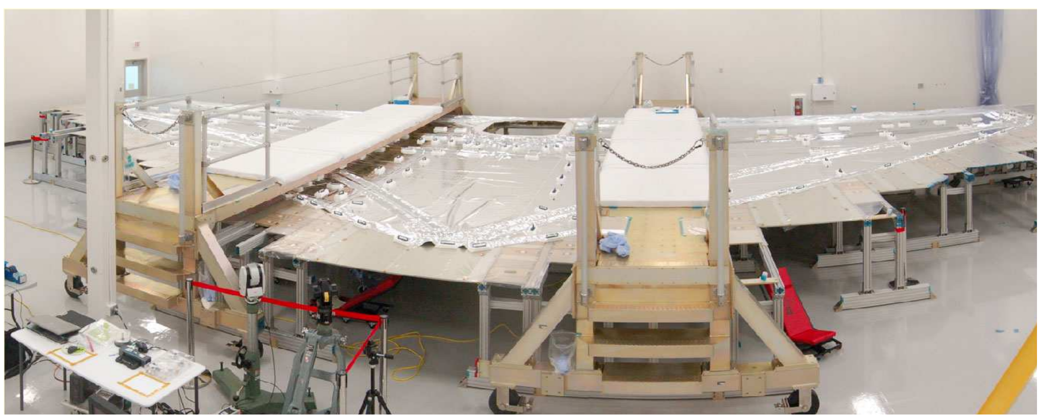


Stringing Operations





Template Layers 3-5



Hole Tool Operations

Flight sunshield to be completed & tested by 2015 at Northrop (CA).

(1c) JWST instrument update: US (UofA, JPL), ESA, & CSA.

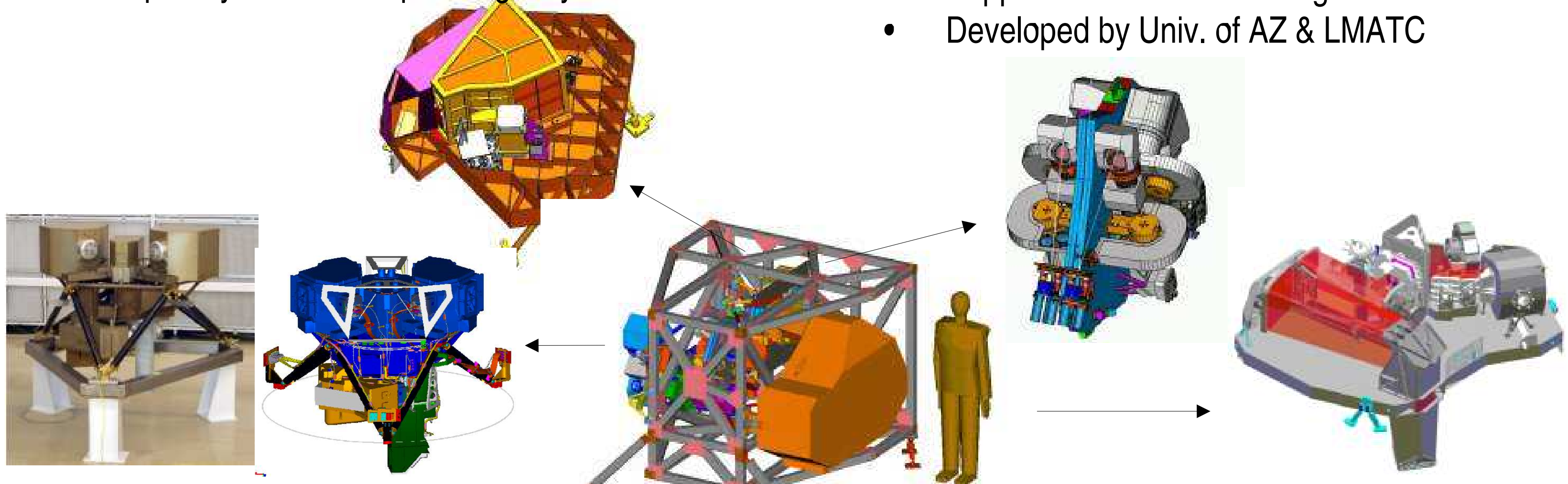
Instrument Overview

Fine Guidance Sensor (FGS)

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

Near Infra-Red Camera (NIRCam)

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



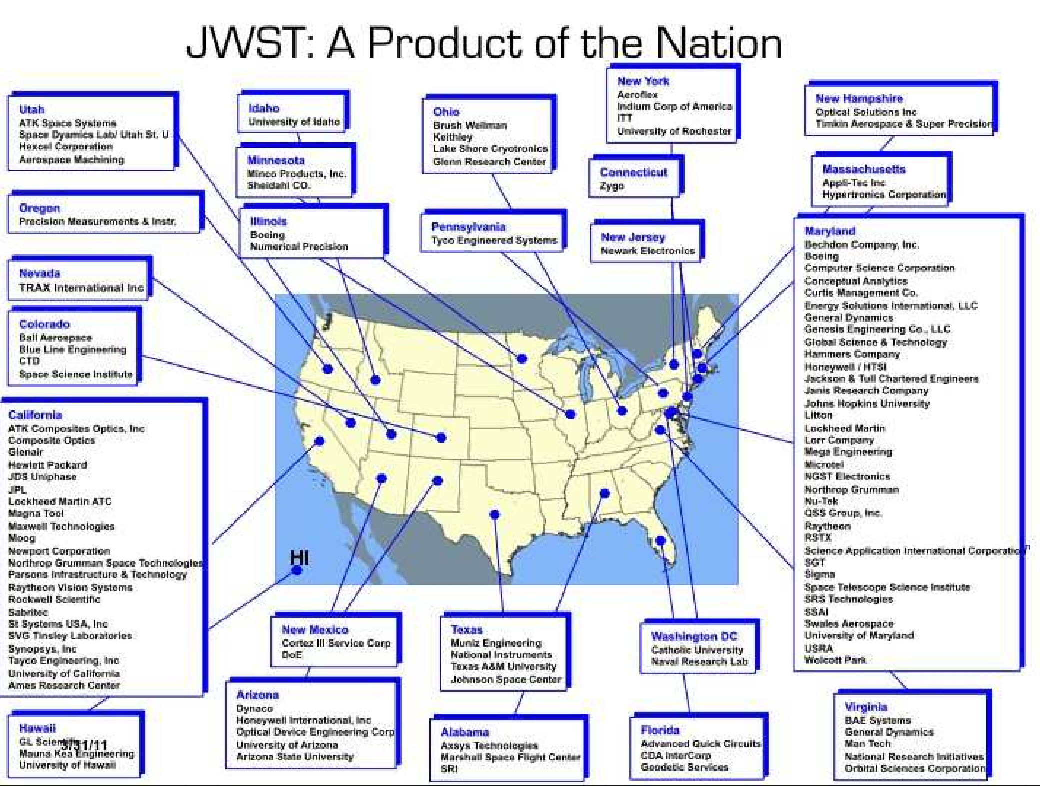
Mid-Infra-Red Instrument (MIRI)

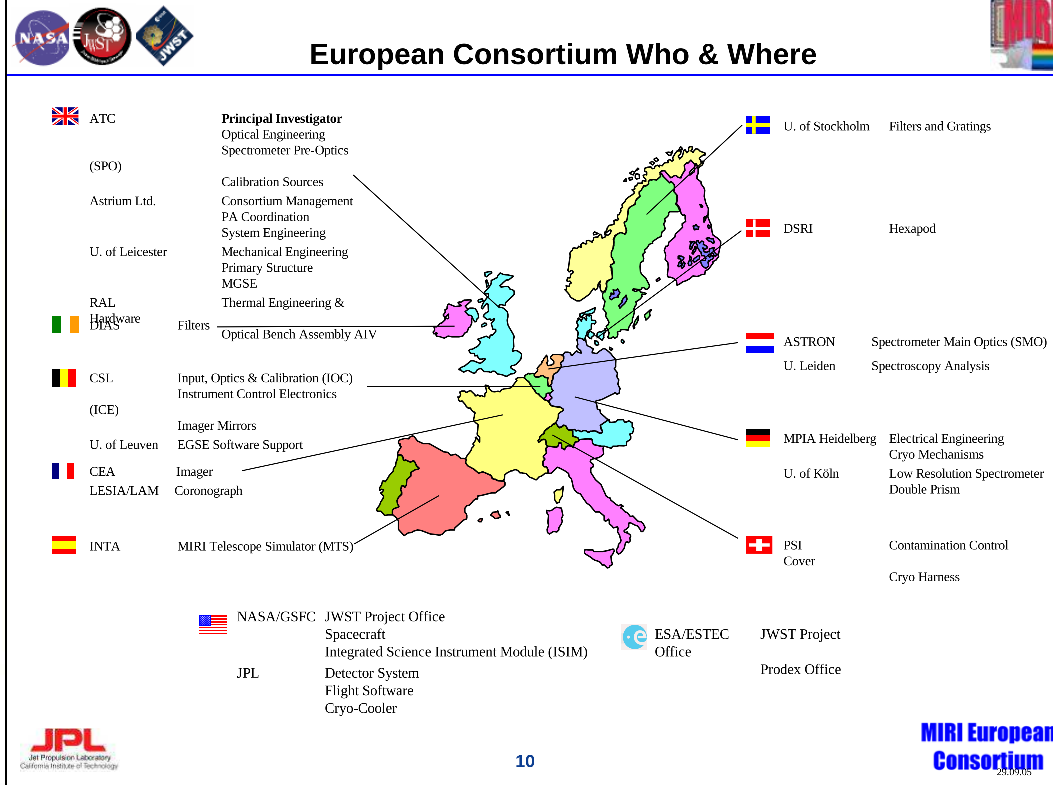
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

Near Infra-Red Spectrograph (NIRSpec)

- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

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





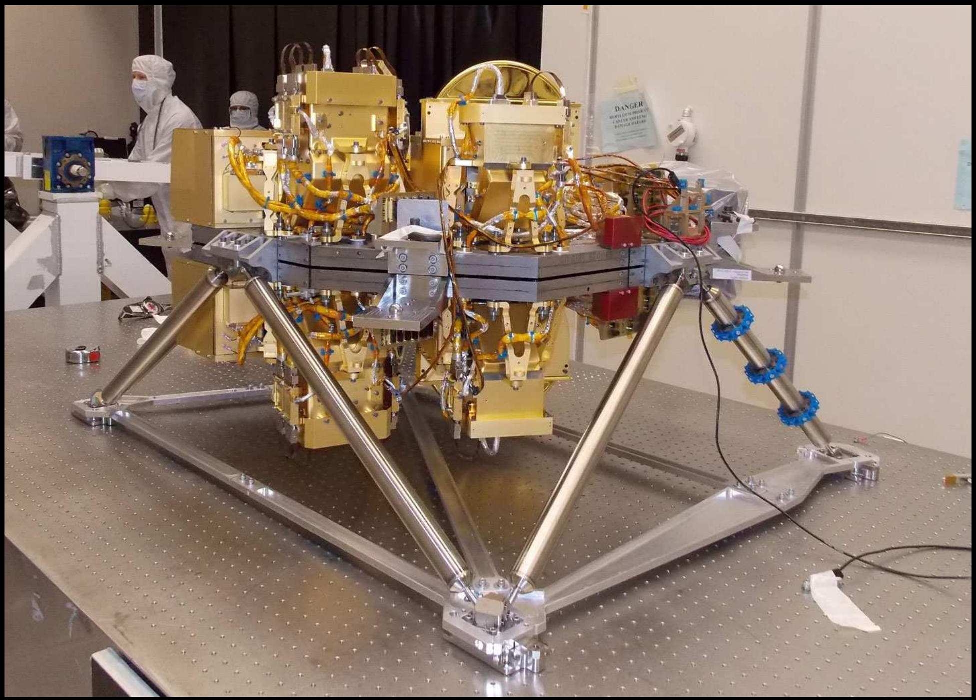
- JWST hardware made in 27 US States: $\gtrsim$80% of launch-mass finished.

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

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

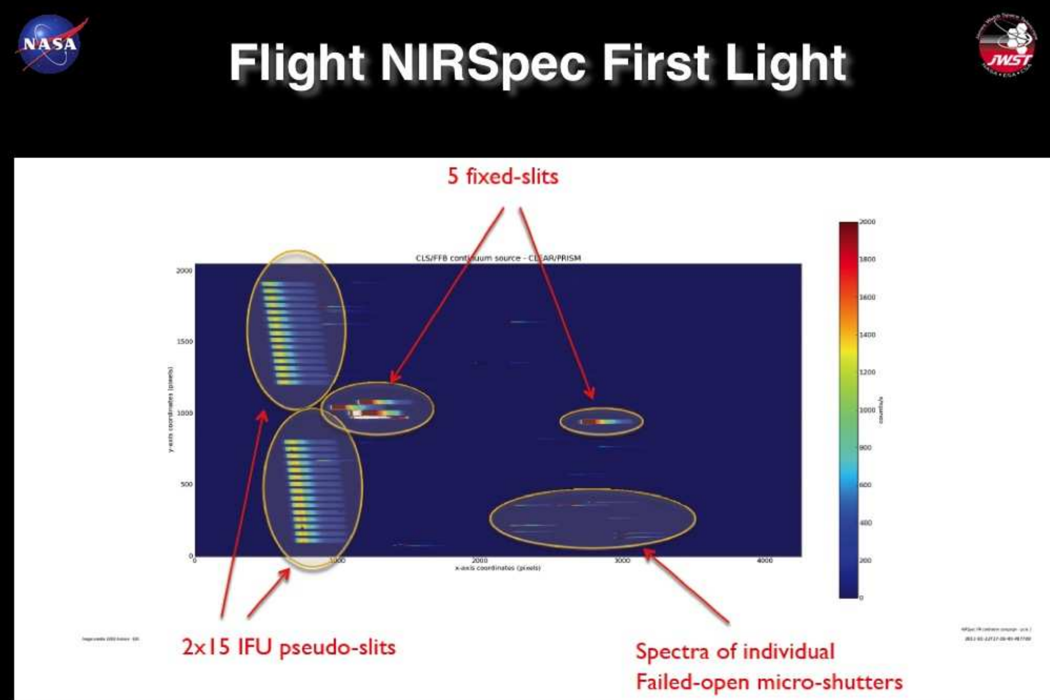
- JWST NIRCam made by UofA and Lockheed.

Thank you, Heidelberg, for your contributions to JWST!

JWST's short-wavelength (0.6–5.0μm) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& 1–5 μm grisms) — built by CSA (Montreal).
- FGS includes very powerful low-res Near-IR grism spectrograph (NIRISS).
- FGS delivered to GSFC 07/12; NIRCam delivered July 28, 2013!

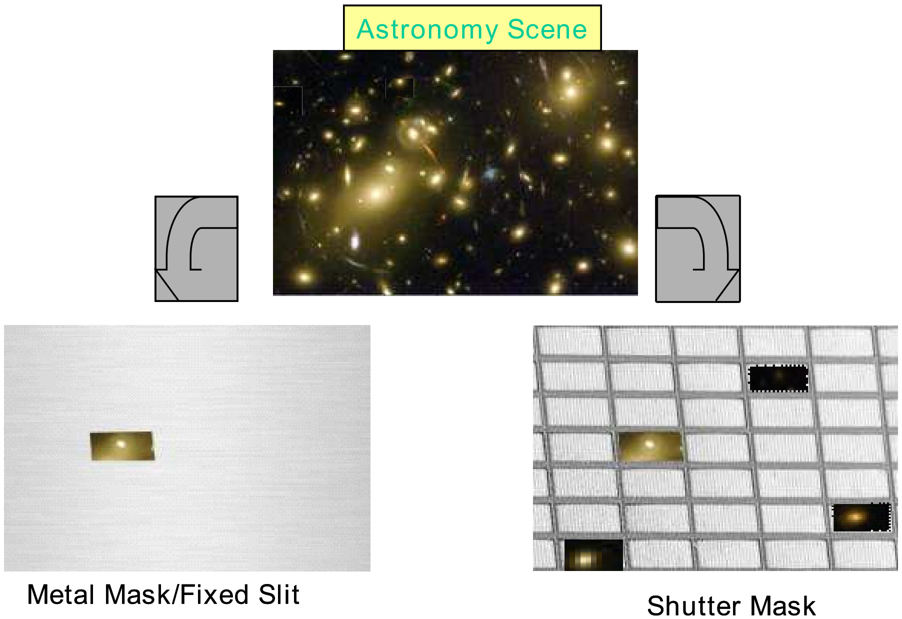


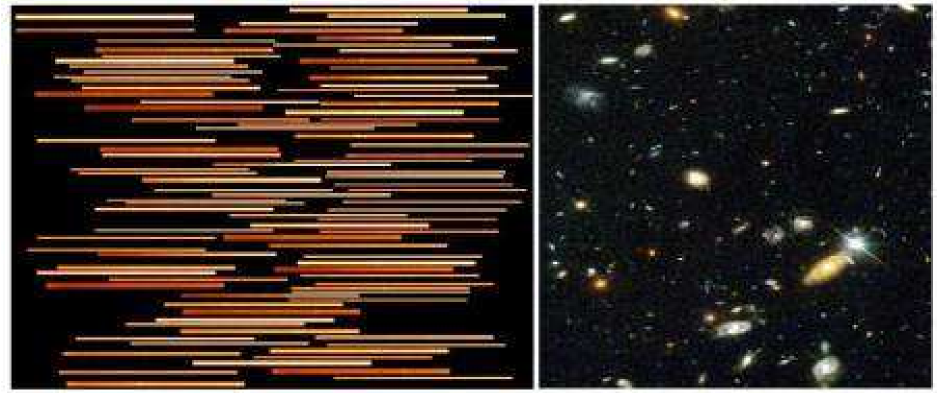
JWST's short-wavelength (0.6–5.0μm) spectrograph:

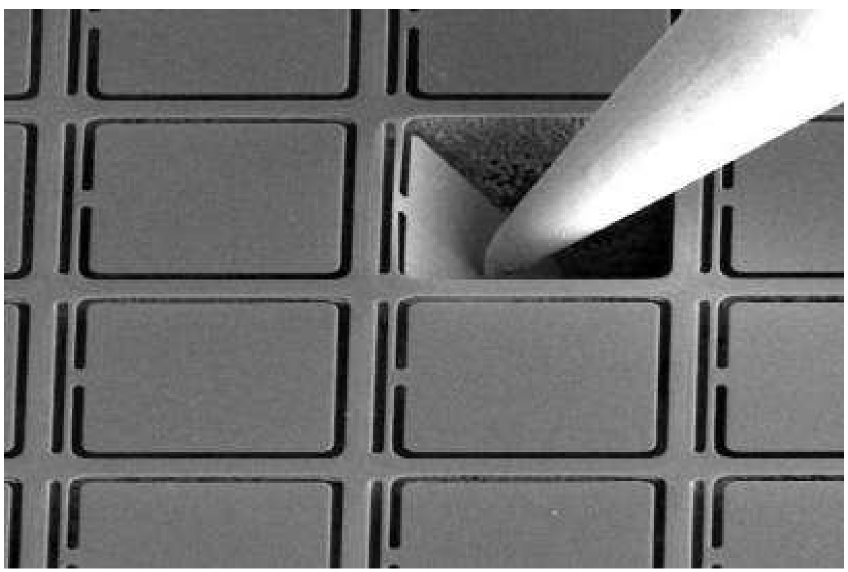
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

NIRSpec delivered to NASA/GSFC in Sept. 2013.

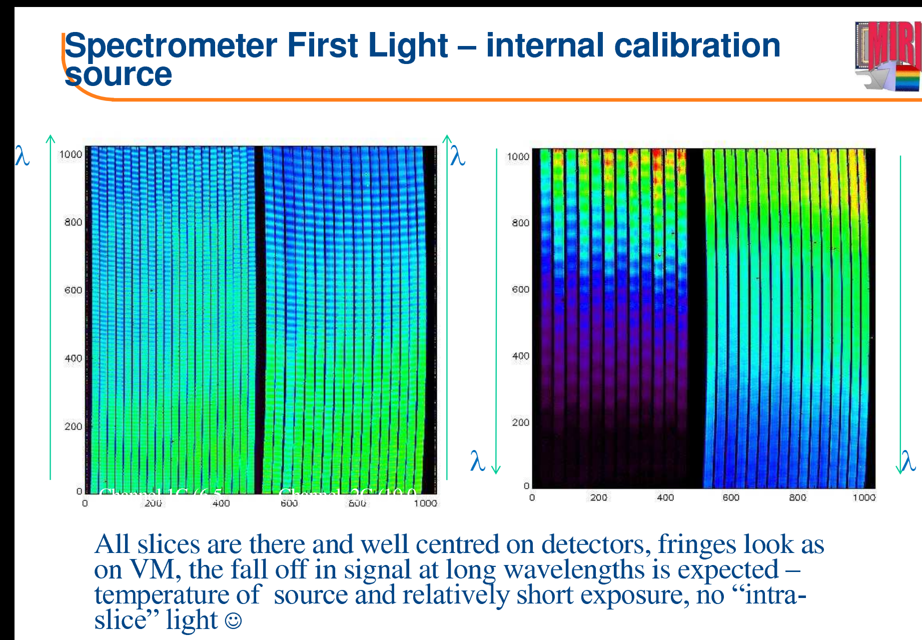
Micro Shutters







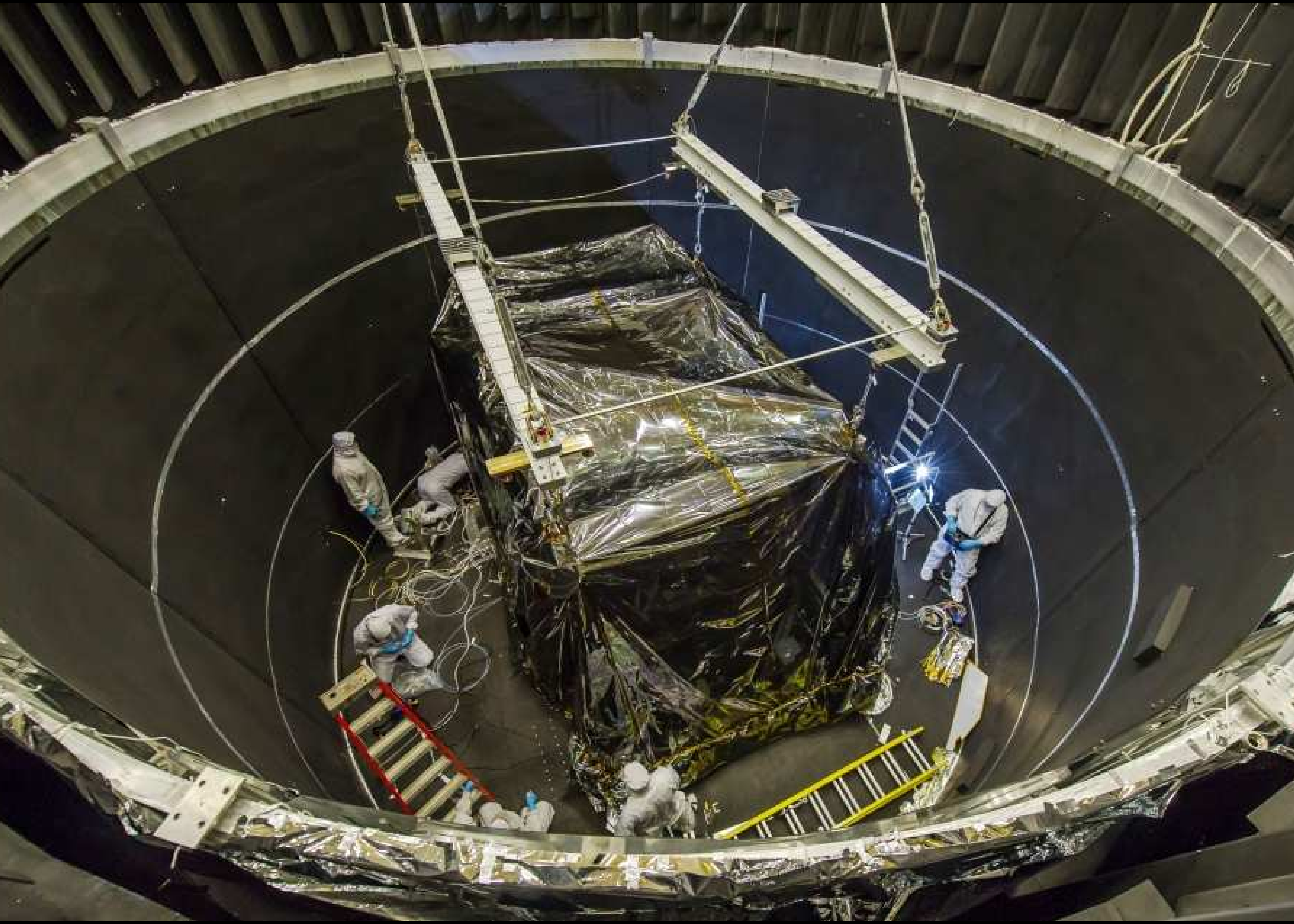
Flight MIRI



JWST’s mid-infrared (5–29μm) camera and spectrograph:

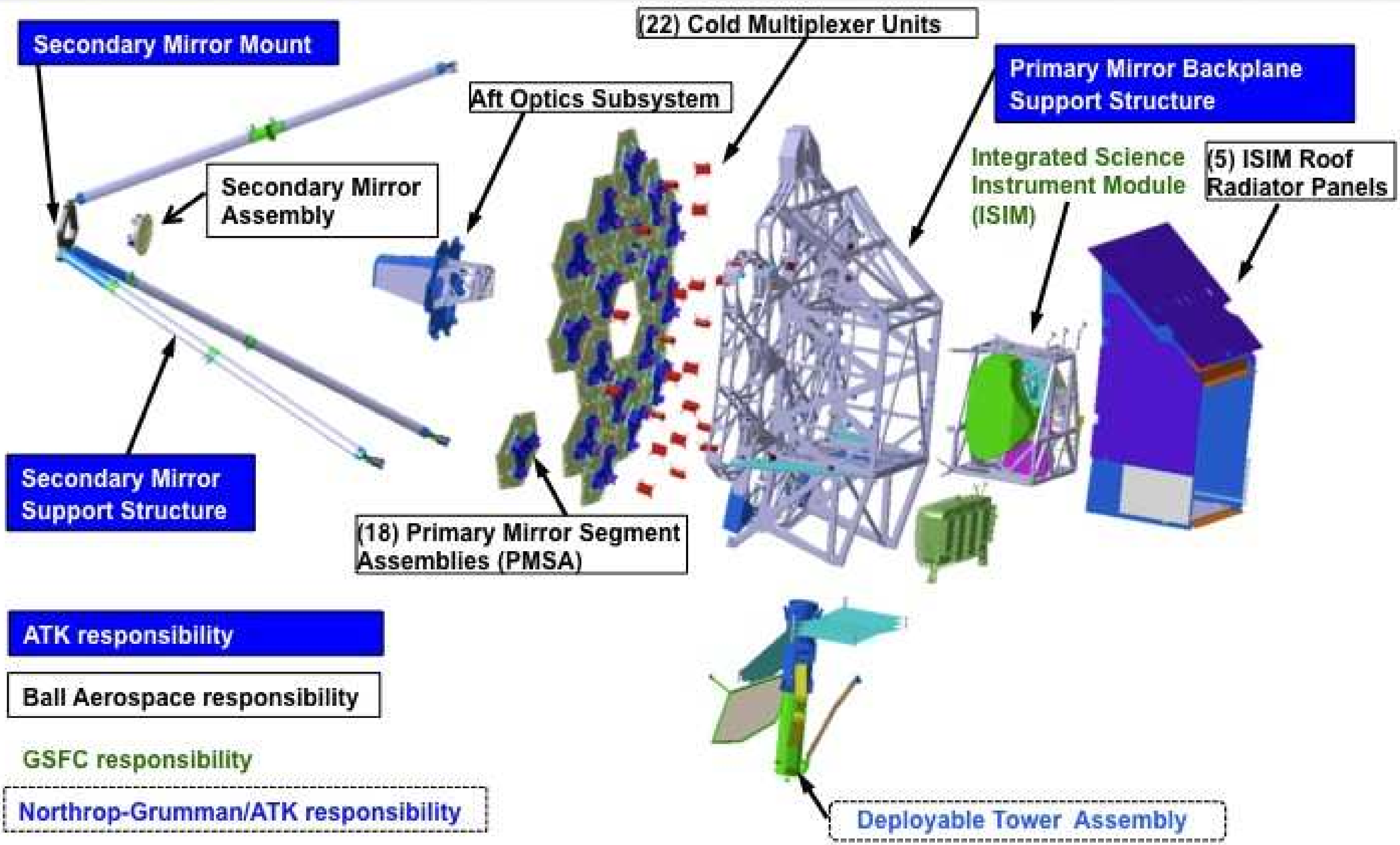
- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012.



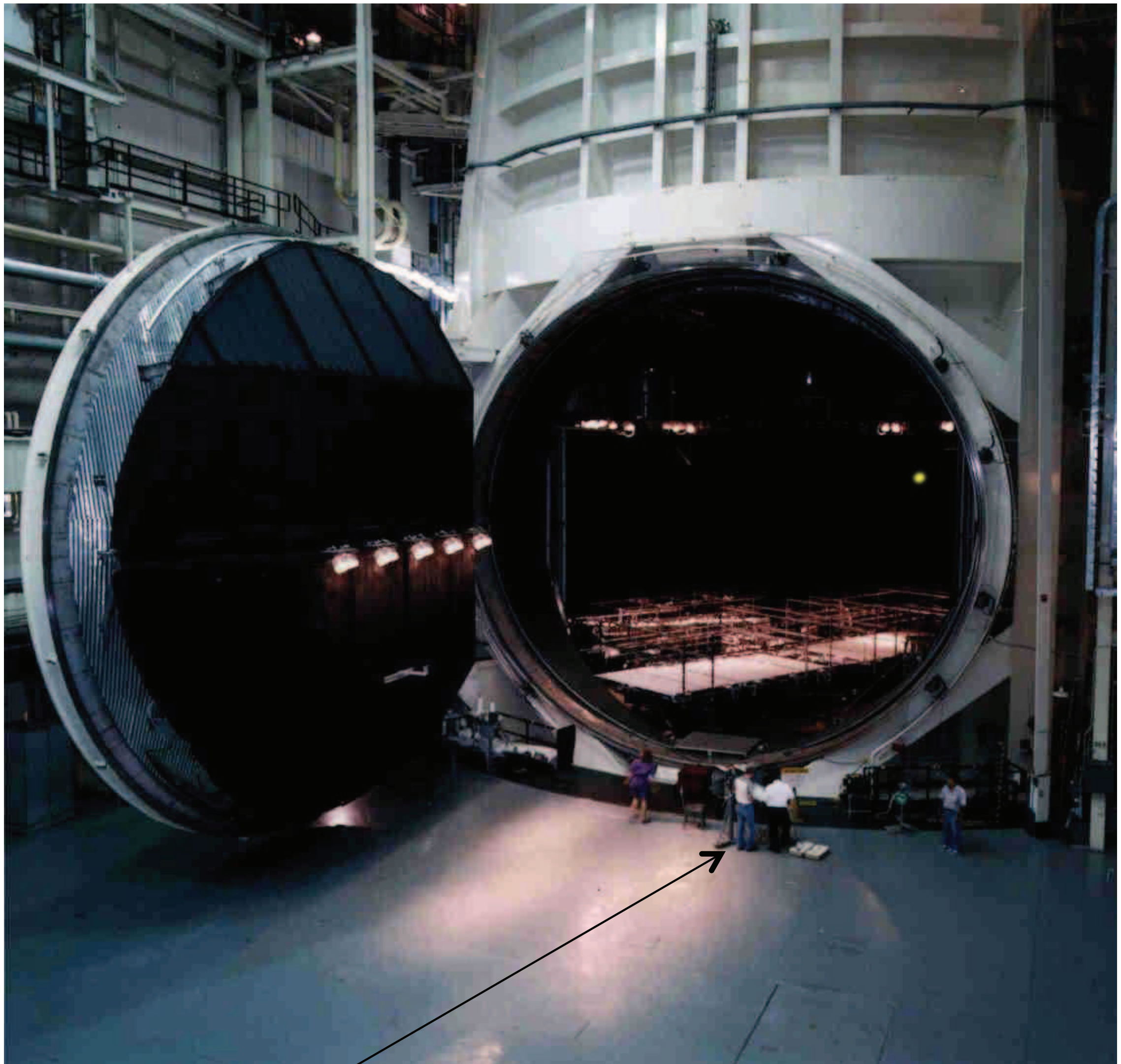
Aug. 2013: Actual Flight ISIM (with MIRI and FGS) lowered into OSIM.

TELESCOPE ARCHITECTURE

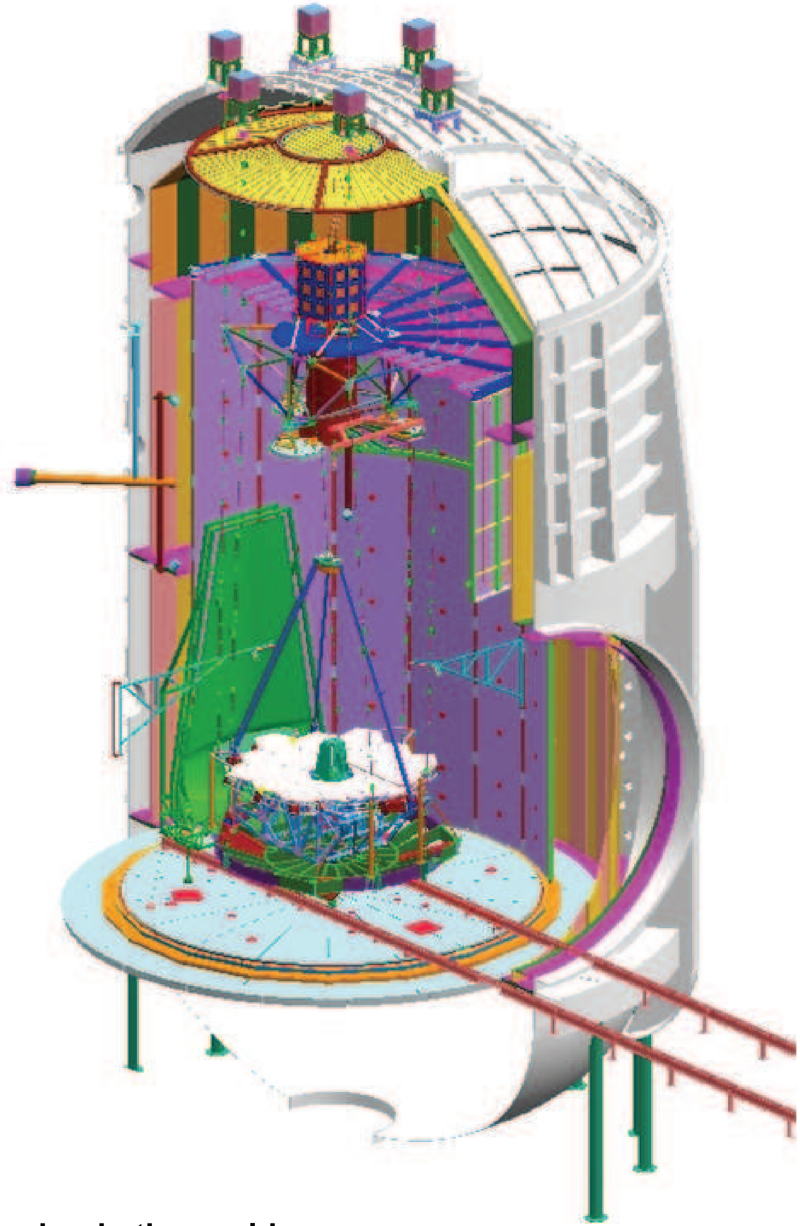


3/31/11

OTE Testing – Chamber A at JSC



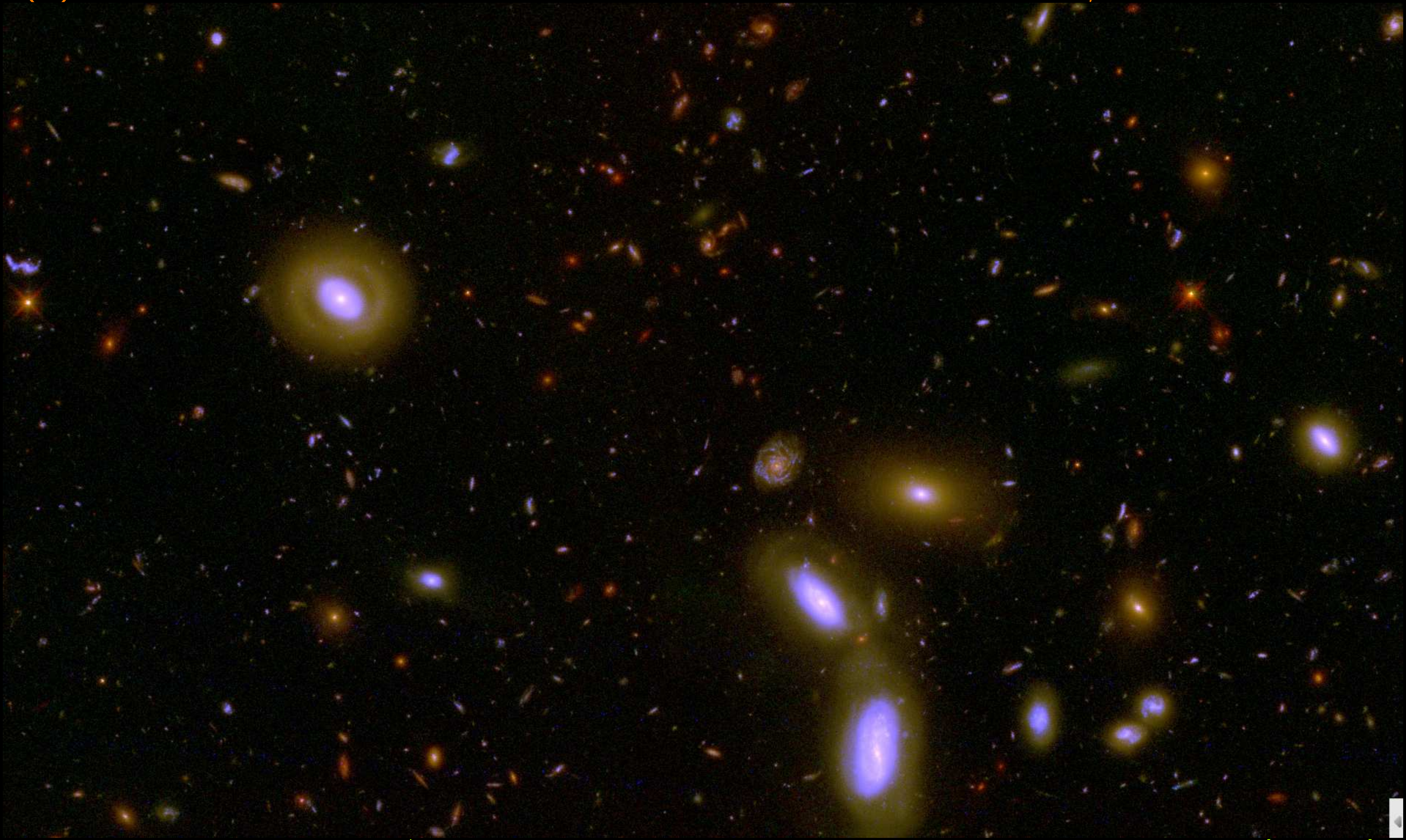
Notice people for scale



Will be the largest cryo vacuum test chamber in the world

OTIS: Largest TV chamber in world: will test whole JWST in 2015–2016.

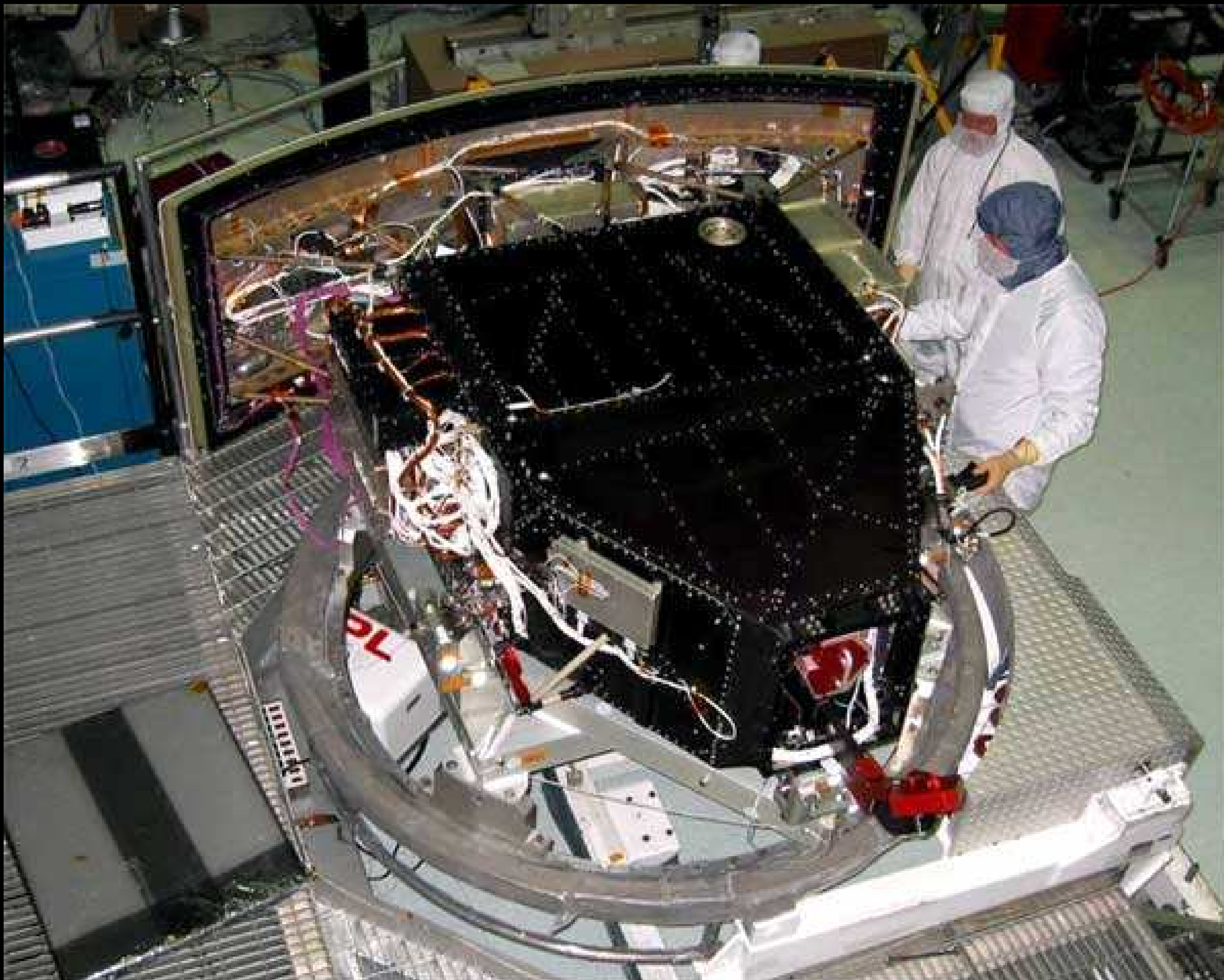
(2) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?



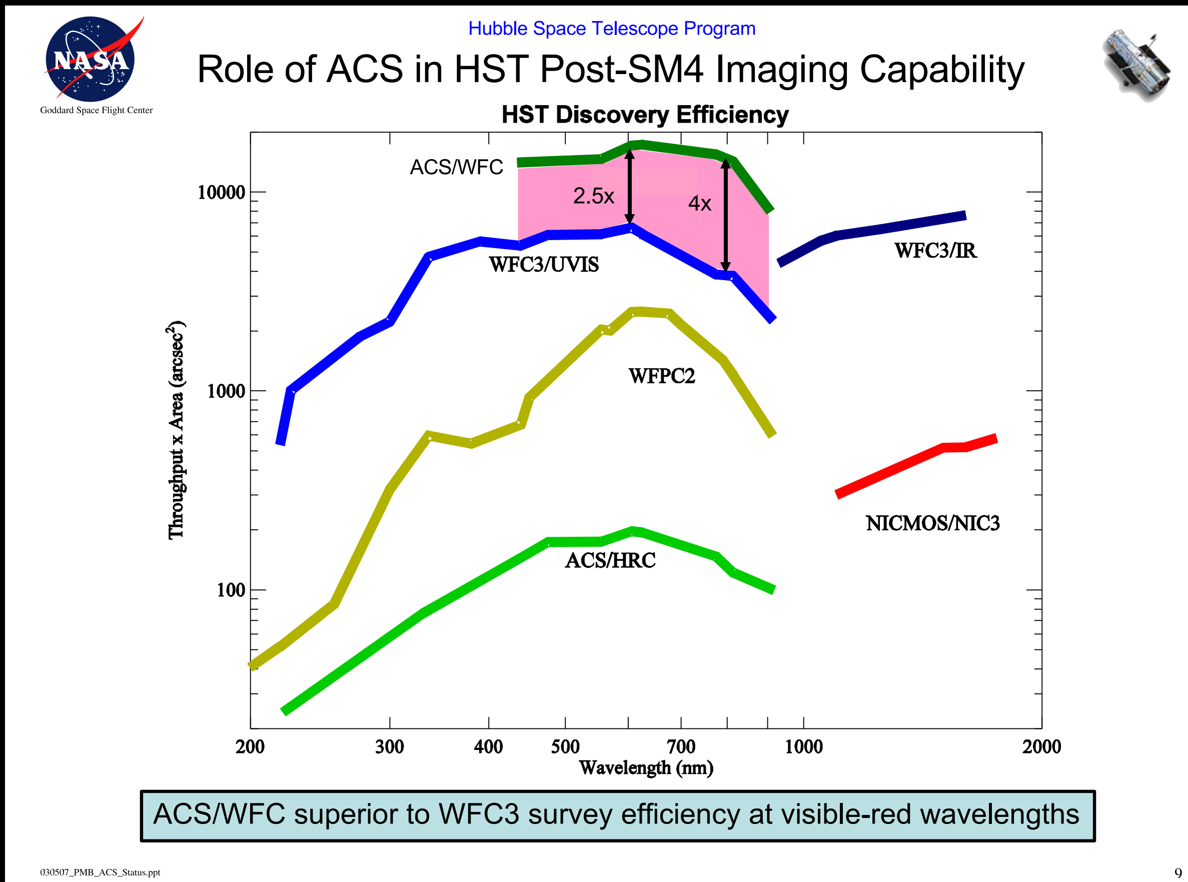
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^{2} at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

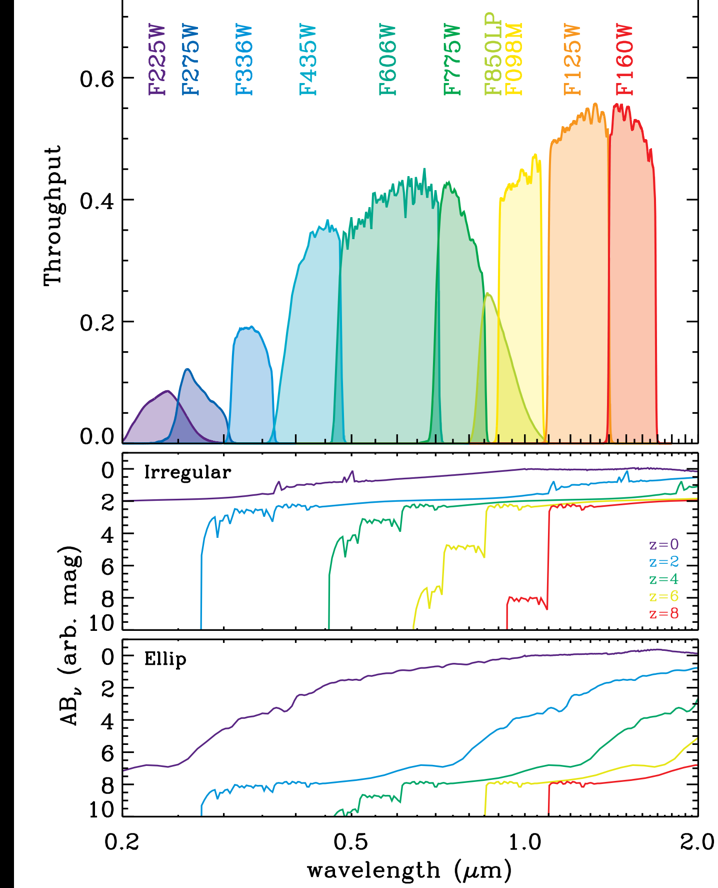
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

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



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





WFC3/UVIS channel unprecedented UV–blue throughput & areal coverage:

- QE$\gtrsim$70%, 4k$\times$4k array of 0.″04 pixel, FOV $\simeq$ 2.′67 $\times$ 2.′67.

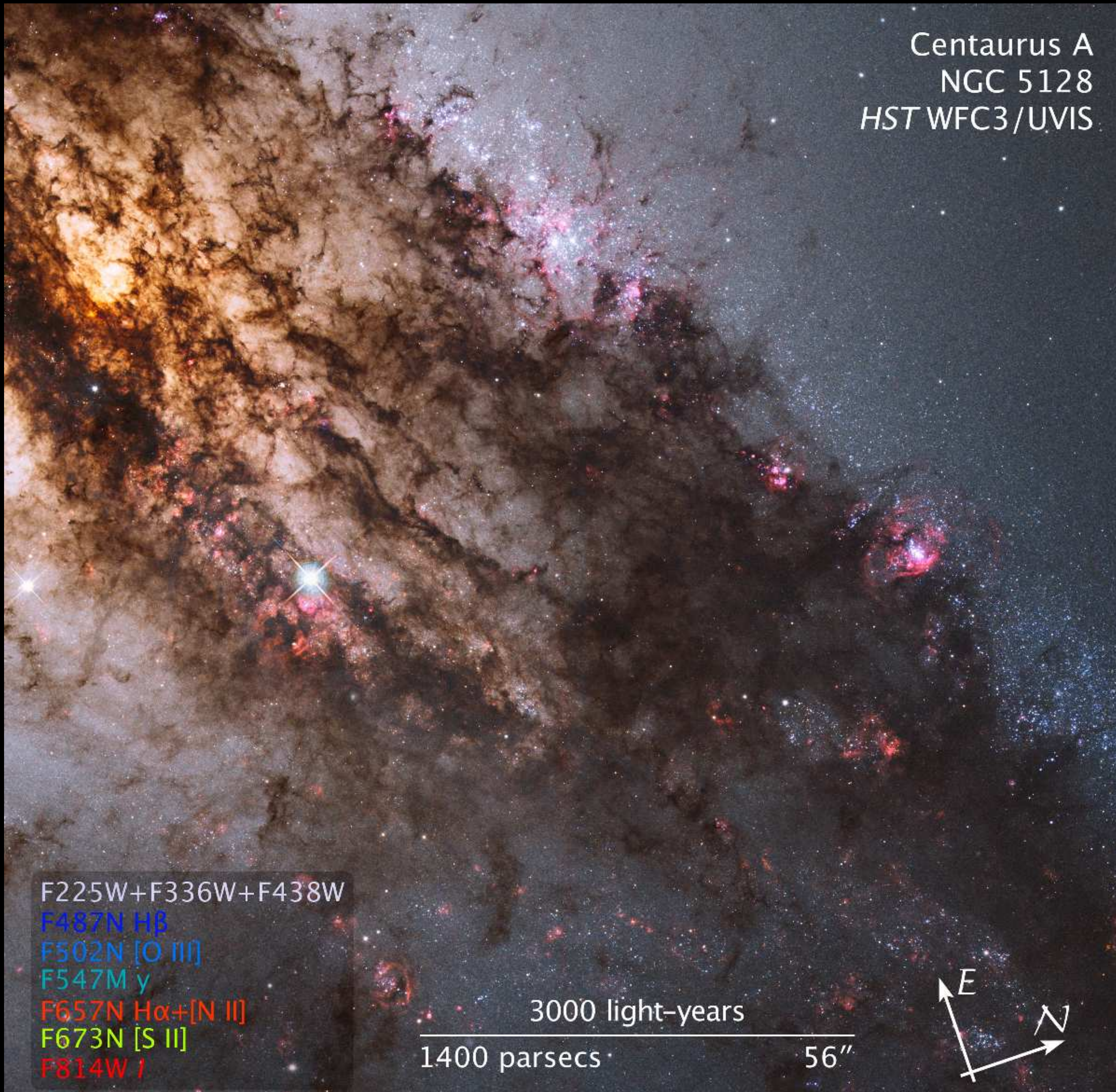
WFC3/IR channel unprecedented near–IR throughput & areal coverage:

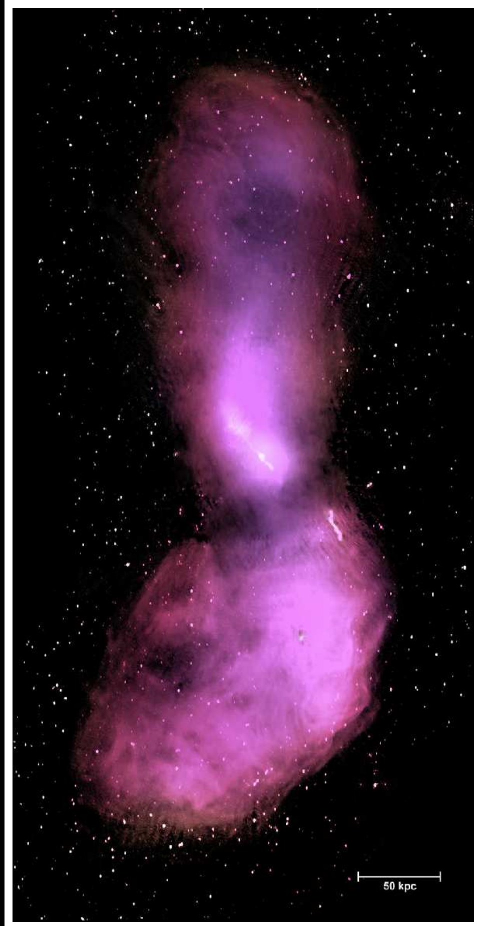
- QE$\gtrsim$70%, 1k$\times$1k array of 0.″13 pixel, FOV $\simeq$ 2.′25 $\times$2.′25.

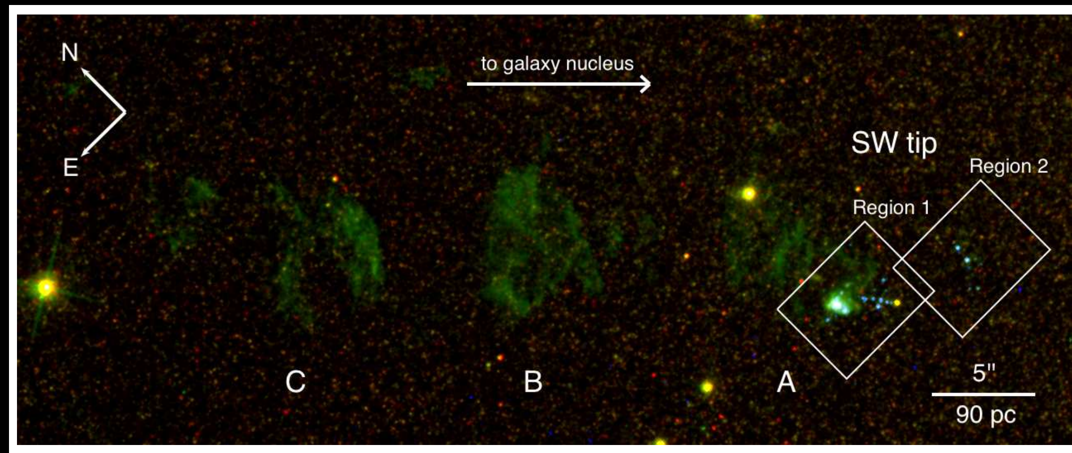
$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:

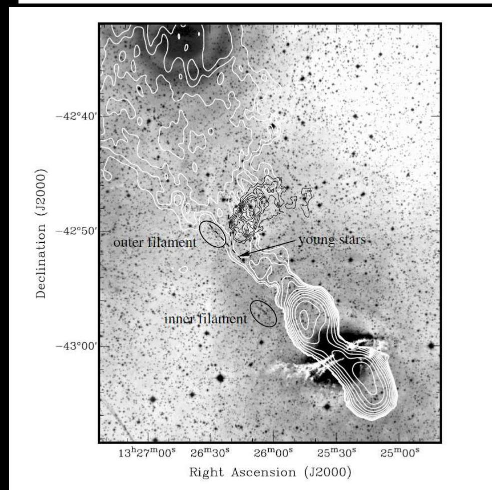
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

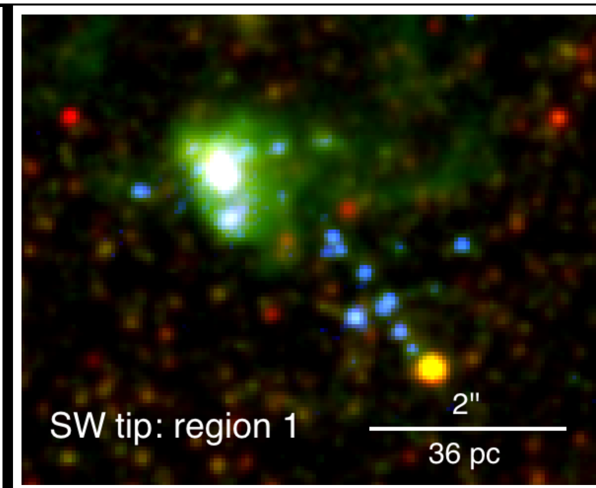
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

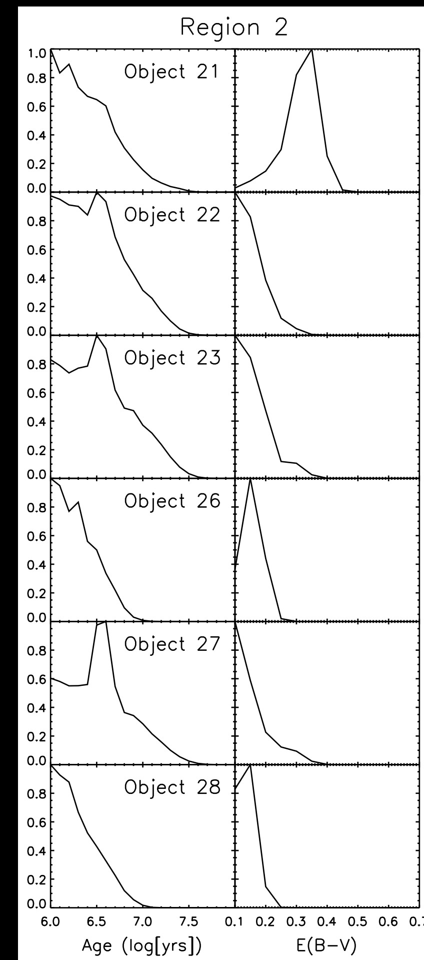

Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W I
3000 light-years
1400 parsecs
56″
E
N











[Left] CSIRO/ATNF 1.4 GHz image of Cen A (Feain+ 2009).

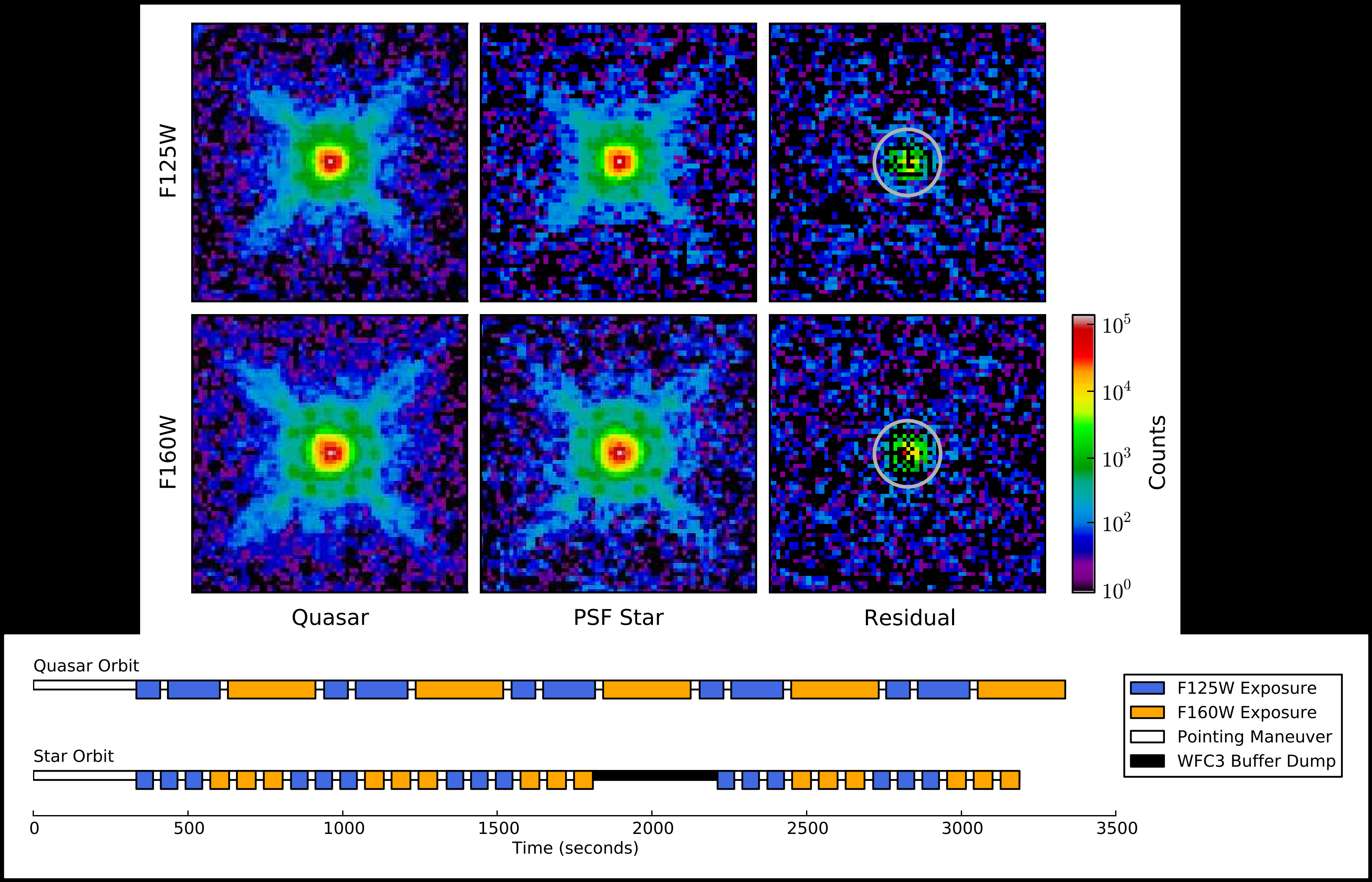
Fermi GeV source (Yang+ 12); & Auger UHE Cosmic Rays (Abreu+ 2010).

[Middle] SF in Cent A jet's wake (Crockett+ 2012, MNRAS, 421, 1602).

[Right] Well determined ages for young (∼2 Myr) stars near Cen A's jet.

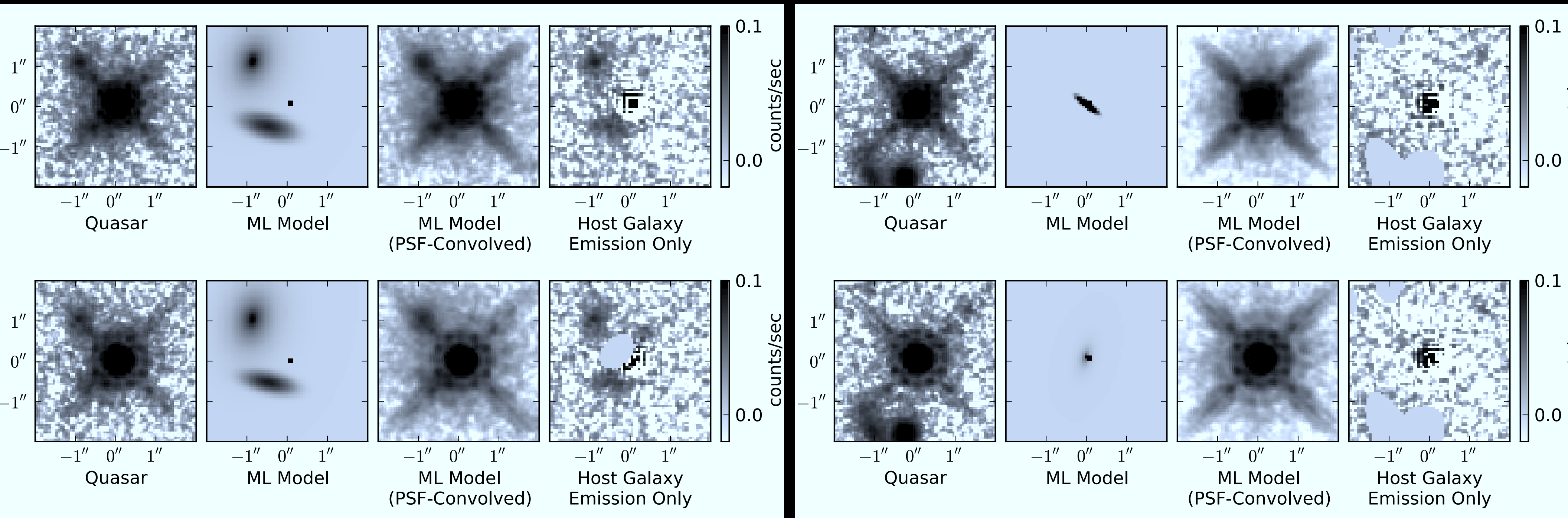
- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV–blue before JWST flies.

(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).

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

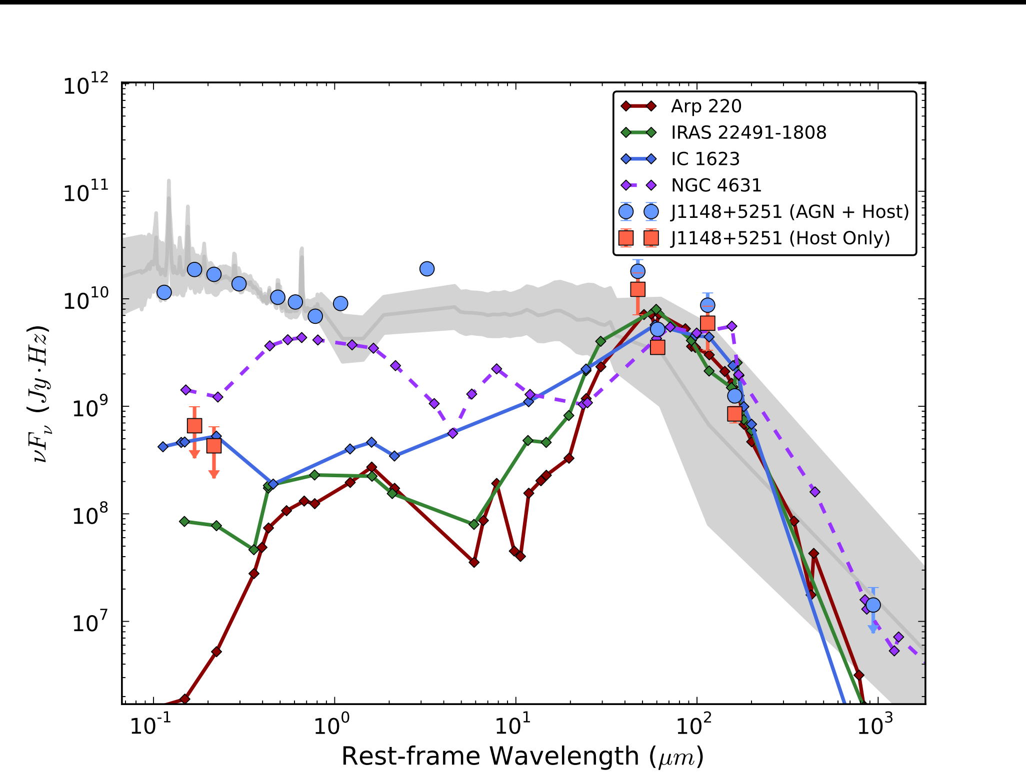


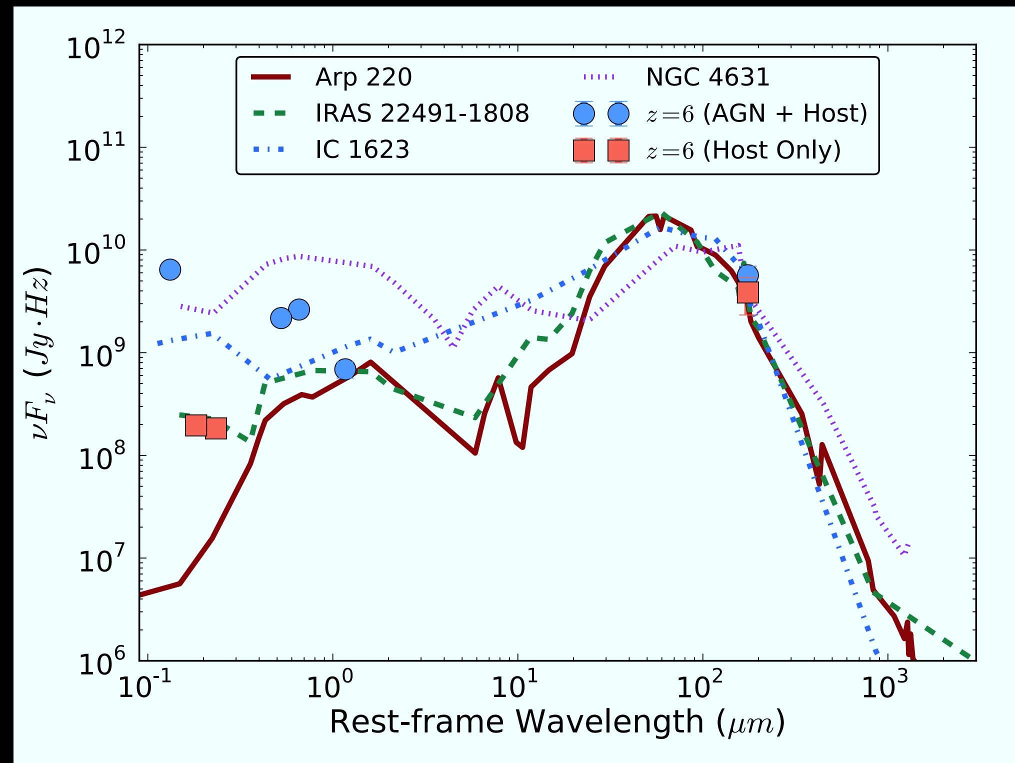
- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO images to pre-select PSF stars (Mechtley+ 2014).
- First detection out of four z≃6 QSOs [2 more to be observed].
- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure??

- Same J+H structure! Blue UV-SED colors: (J–H)≃0.19, constrains dust.
  - IRAS starburst-like SED from rest-frame UV–far-IR, $A_{FUV}\sim 1$ mag.
- $M_{AB}^{host}(z\simeq 6)\lesssim -23.0$ mag, i.e., ∼2 mag brighter than L*(z≃6)!

⇒ z≃6 QSO duty cycle $\lesssim 10^{-2}$ ($\lesssim$10 Myrs); 1/4 QSO's close to Magorrian.

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



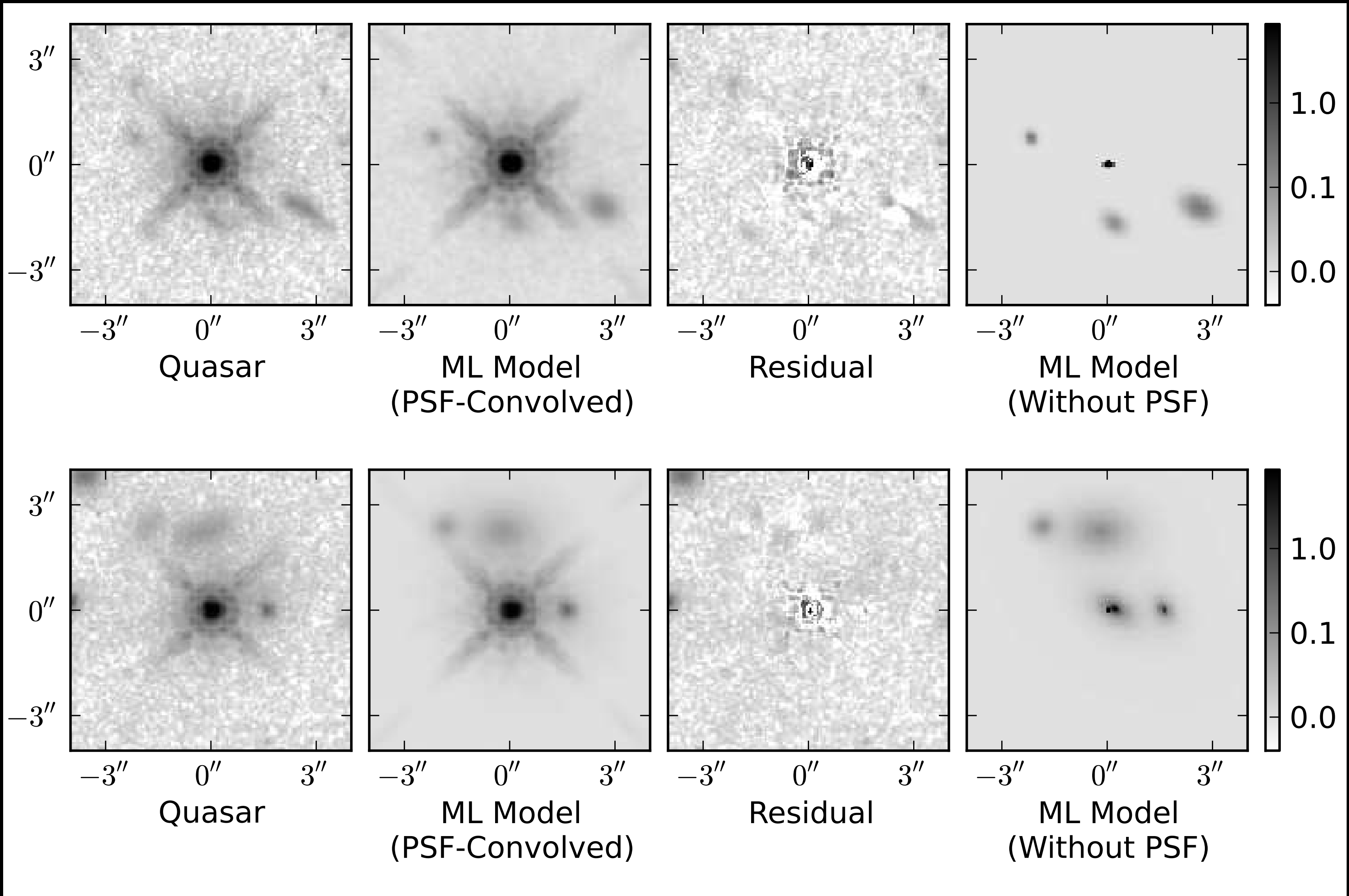


- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5μ). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100μm:

[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. 2014).

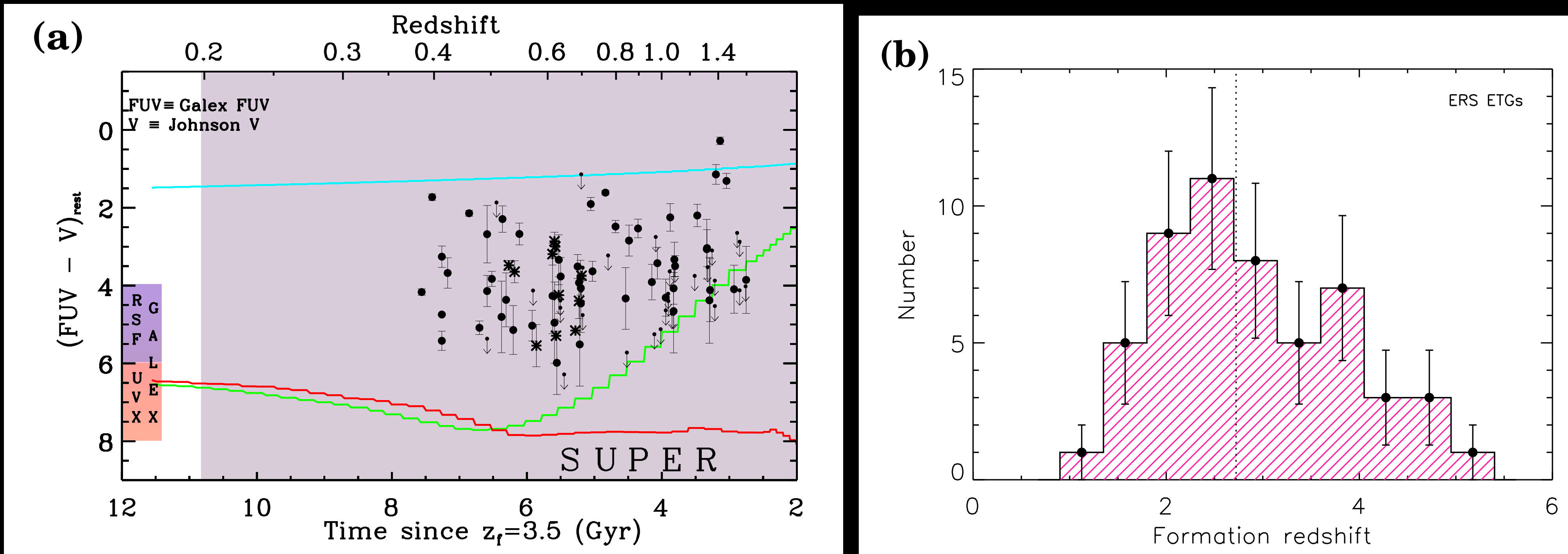
- JWST Coronagraphs can do this 10–100× fainter (& for z≲20, λ≲28μm).

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



- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, MPI, Koekemoer, Windhorst et al. 2014).
- JWST Coronagraphs can do this 10–100× fainter (& for z$\lesssim$20, $\lambda\lesssim28\mu$m).

(2c) Rest-frame UV-evolution of Early Type Galaxies since $z \lesssim 1.5$.

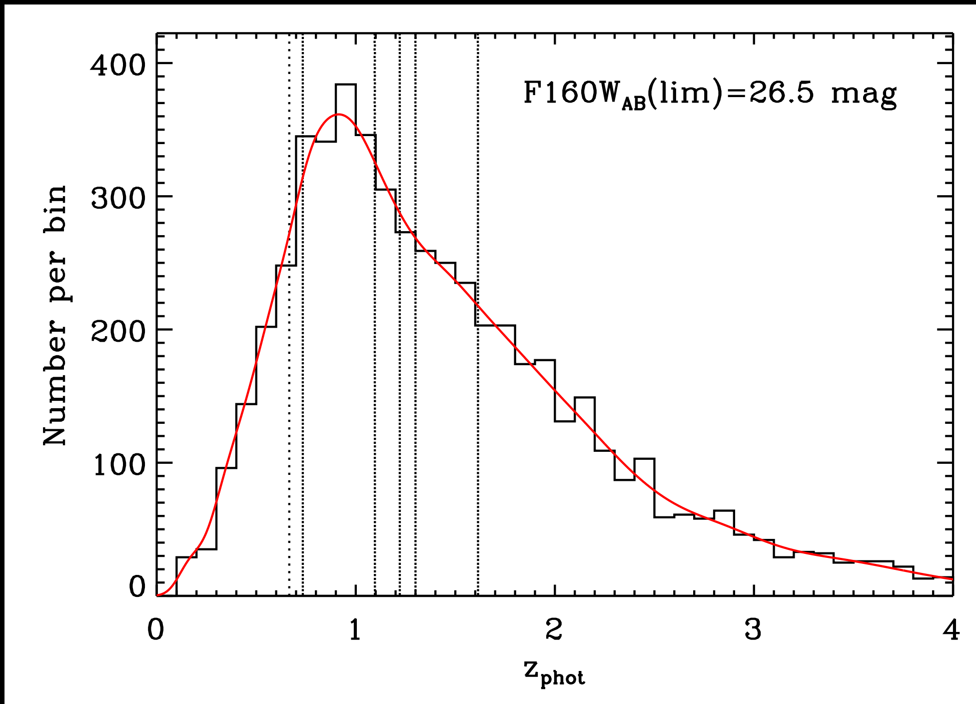


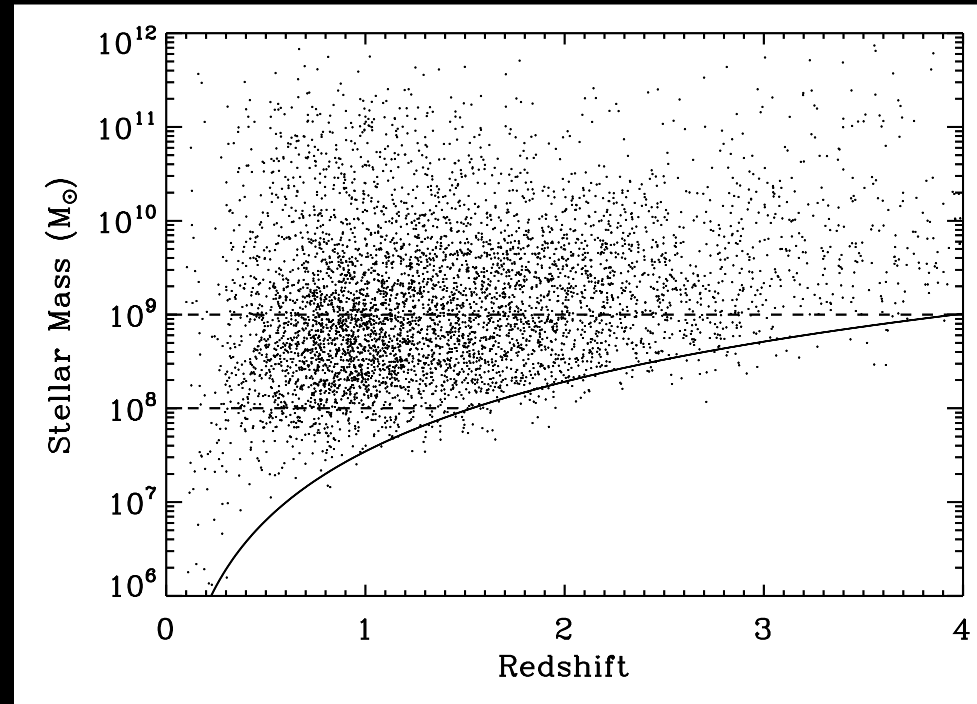
• 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at $0.3 \lesssim z \lesssim 1.5$ (Rutkowski et al. 2012, ApJS, 199, 4).

$\Longrightarrow$ Most ETGs have continued residual star-formation after they form.

• Can determine their $N(z_{form})$, which resembles the cosmic SFH diagram (*e.g.*, Madau et al. 1996). This can directly constrain the process of galaxy assembly and down-sizing (Kaviraj, Rutkowski et al. 2012, MNRAS).

• JWST will extend this to all redshifts with Balmer+4000Å-break ages.





WFC3 ERS 10-band redshift estimates accurate to $\lesssim$4% with small systematic errors (Hathi et al. 2010, 2013), resulting in a reliable N(z).

• Measure masses of faint galaxies to AB=26.5 mag, tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

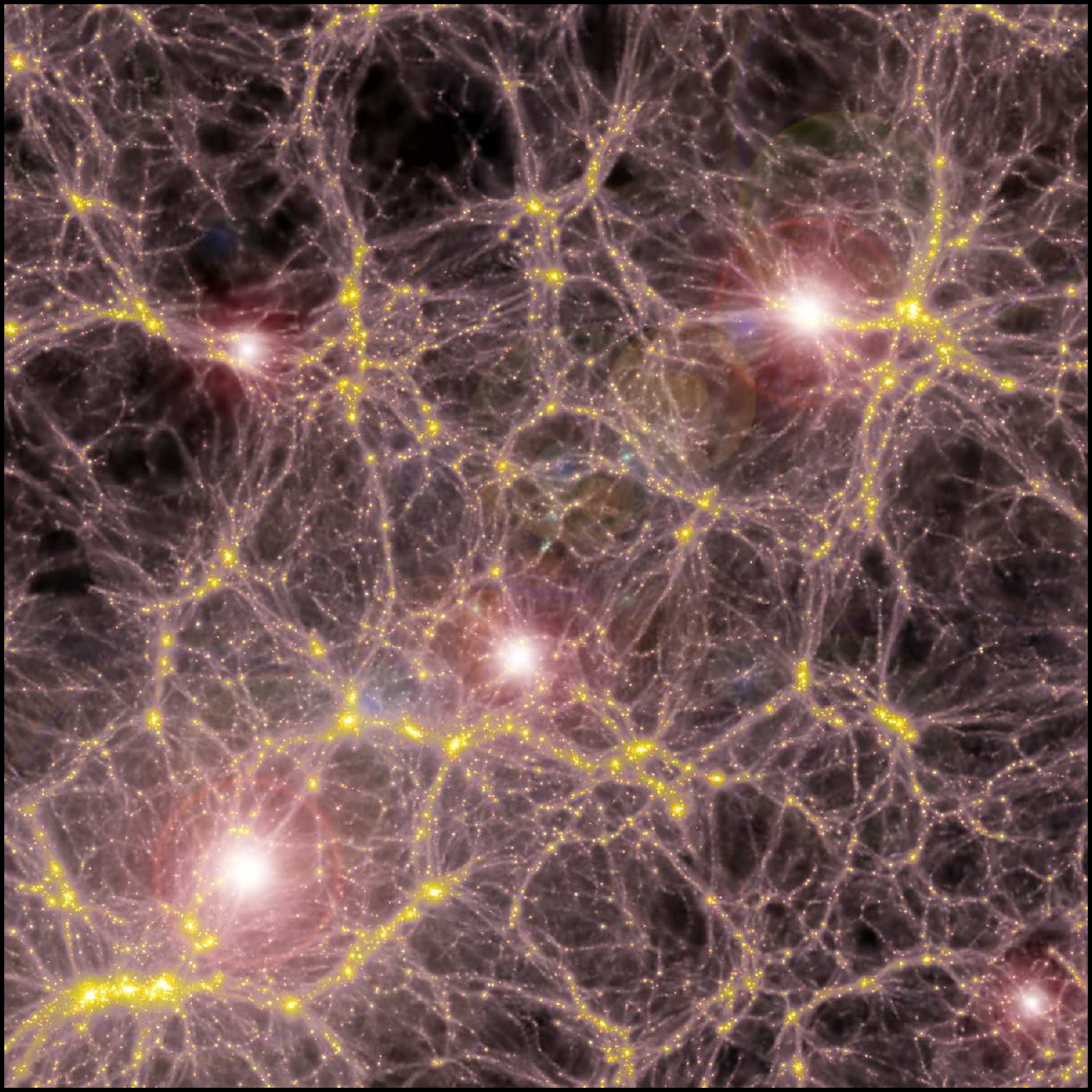
$\Rightarrow$ Median redshift in (medium-)deep fields is z_{med} $\simeq$1.5–2.

ERS shows WFC3's new panchromatic capabilities on galaxies at z$\simeq$0–7.

• HUDF shows WFC3 z$\simeq$7–9 capabilities (Bouwens^{+} 2010; Yan^{+} 2010).

• JWST will trace mass assembly and dust content $\lesssim$5 mag deeper from z$\simeq$1–12, with nanoJy sensitivity from 0.7–5μm.

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

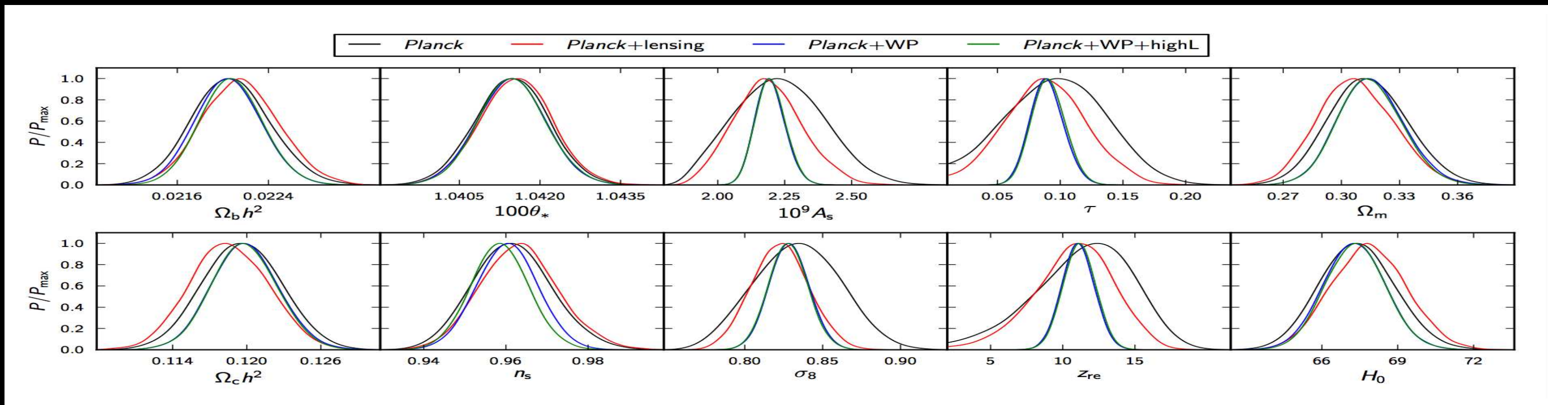


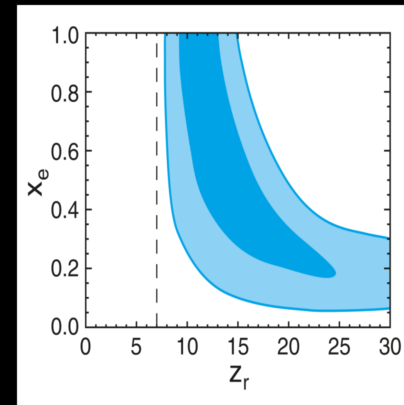
- Detailed Hydrodynamical models (e.g., V. Bromm) suggest that massive Pop III stars may have reionized universe at redshifts $z \lesssim 10$–30 (First Light).

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

We must make sure we theoretically understand the likely Pop III mass-range, their IMF, their duplicity and clustering properties, their SN-rates, etc., with accurate predictions before JWST flies.

Implications of the WMAP year-9 & Planck13 results for JWST science:





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

The year-9 WMAP data provided better foreground removal (Komatsu$^+$ 2011; Hinshaw$^+$ 2012; but see: Planck XVI 2013.)

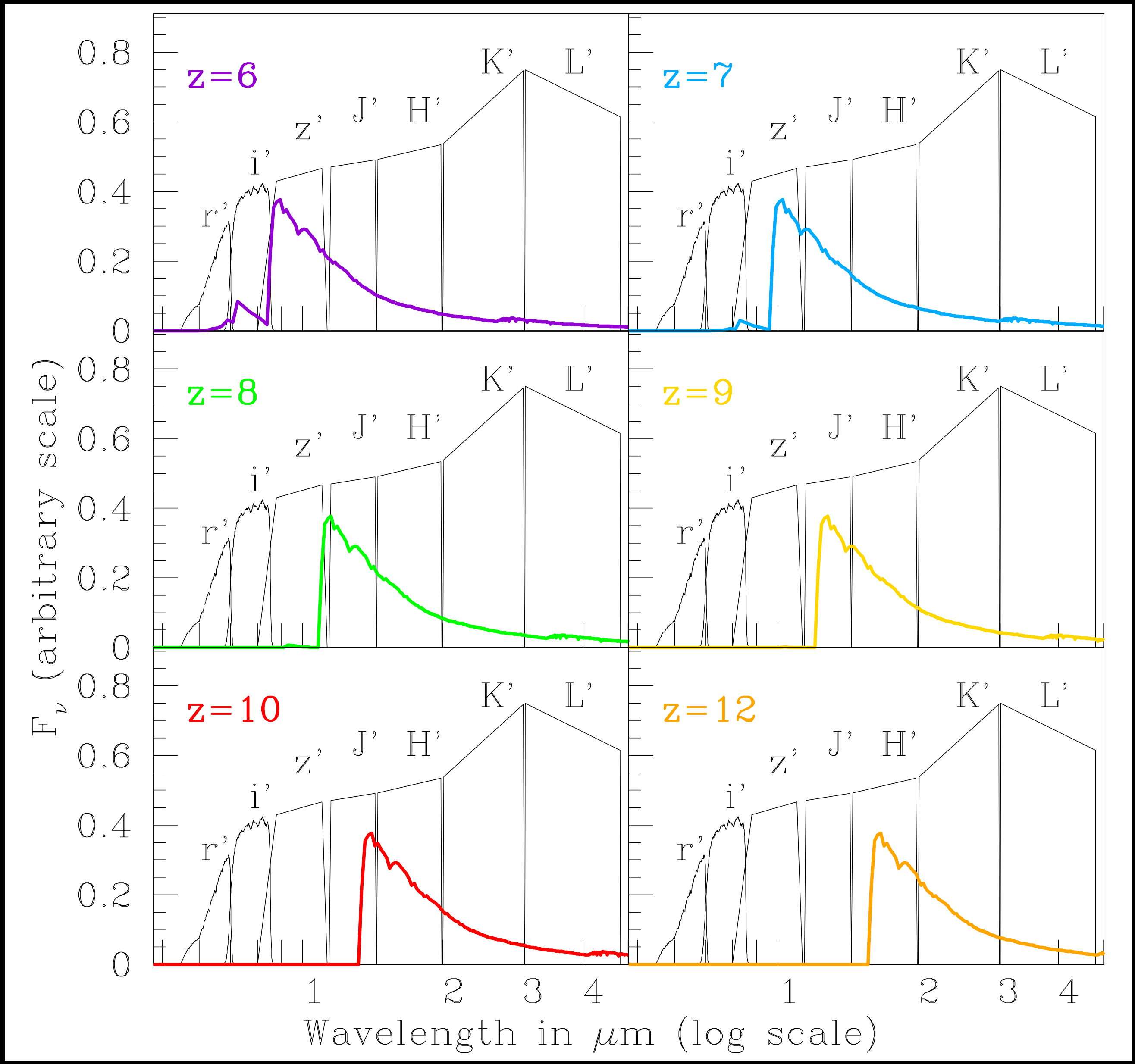
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (1) Instantaneous at $z \simeq 11.1 \pm 1.1$ ($\tau = 0.089 \pm 0.013$), or:
- (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \lesssim 11$, ending at $z \simeq 7$. The implications for HST and JWST are:

- HST/ACS has covered $z \lesssim 6$, and WFC3 is covering $z \lesssim 7$–9.
- For First Light & Reionization, JWST will survey $z \simeq 8$ to $z \simeq 15$–20.

Question: If Planck-$\tau \downarrow \lesssim 0.08$ (TBD, Planck14), then how many reionizers will JWST see at $z \simeq 10$–20?

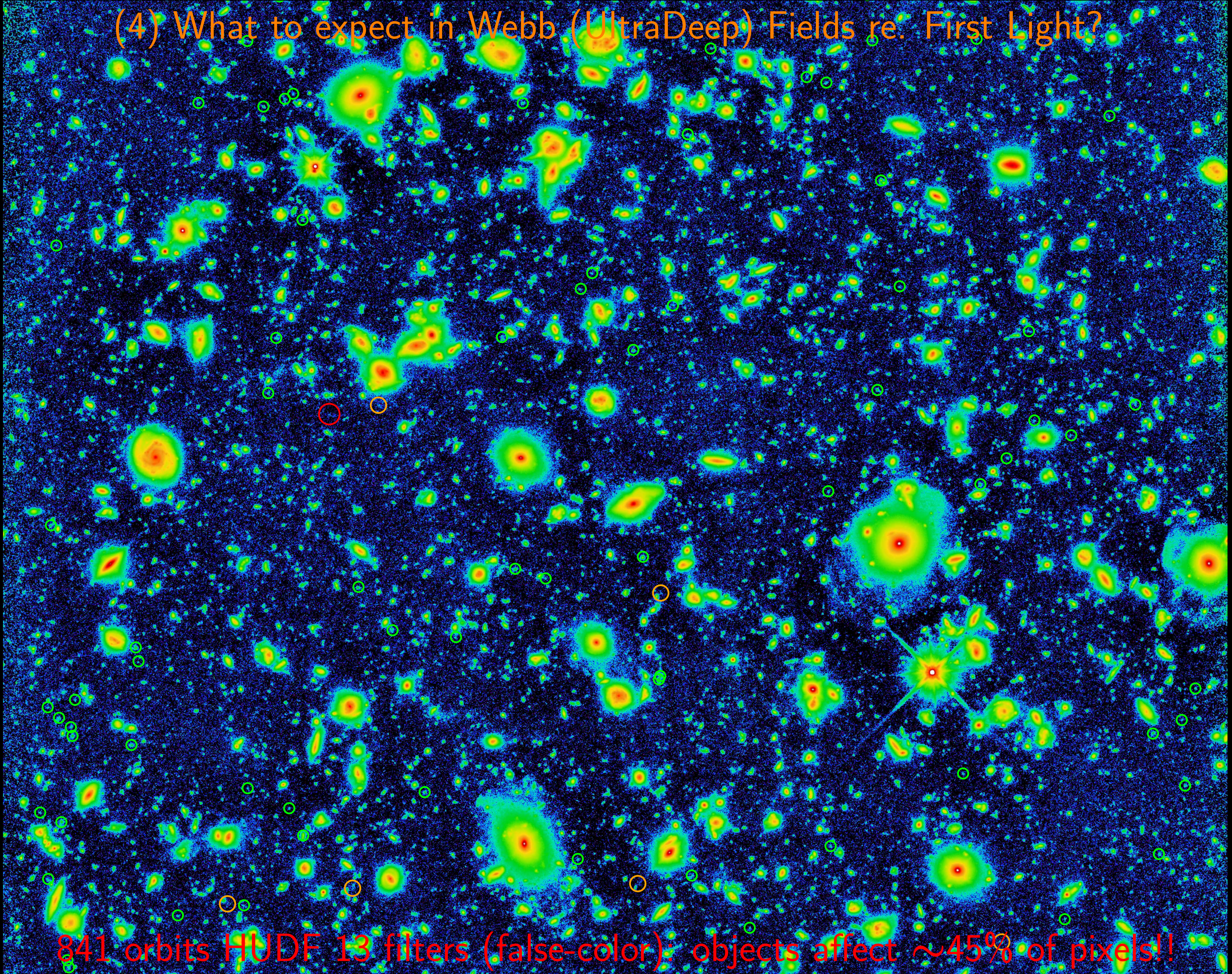
(3) How will JWST measure First Light & Reionization?



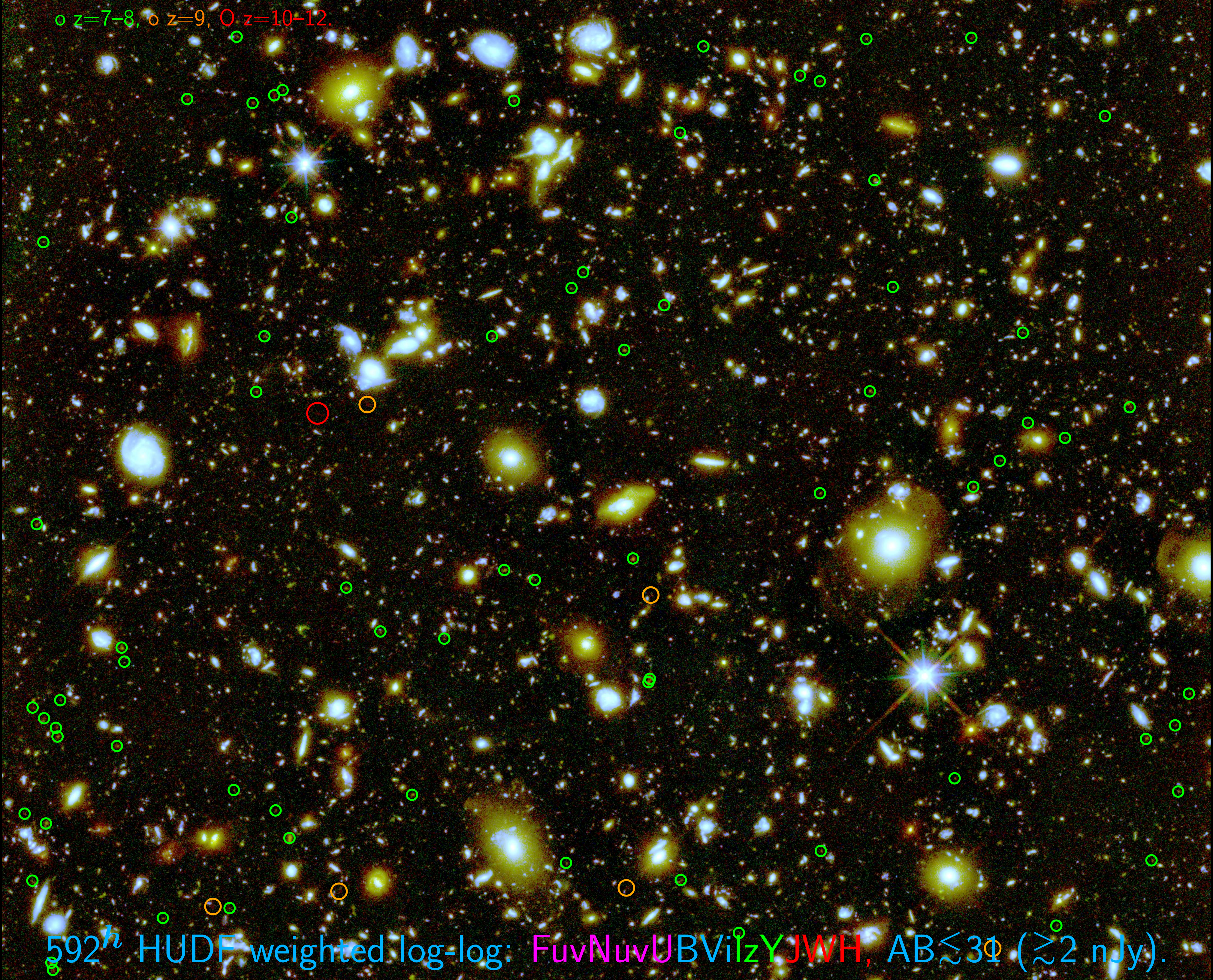
- Can't beat redshift: to see First Light, must observe near–mid IR.

$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

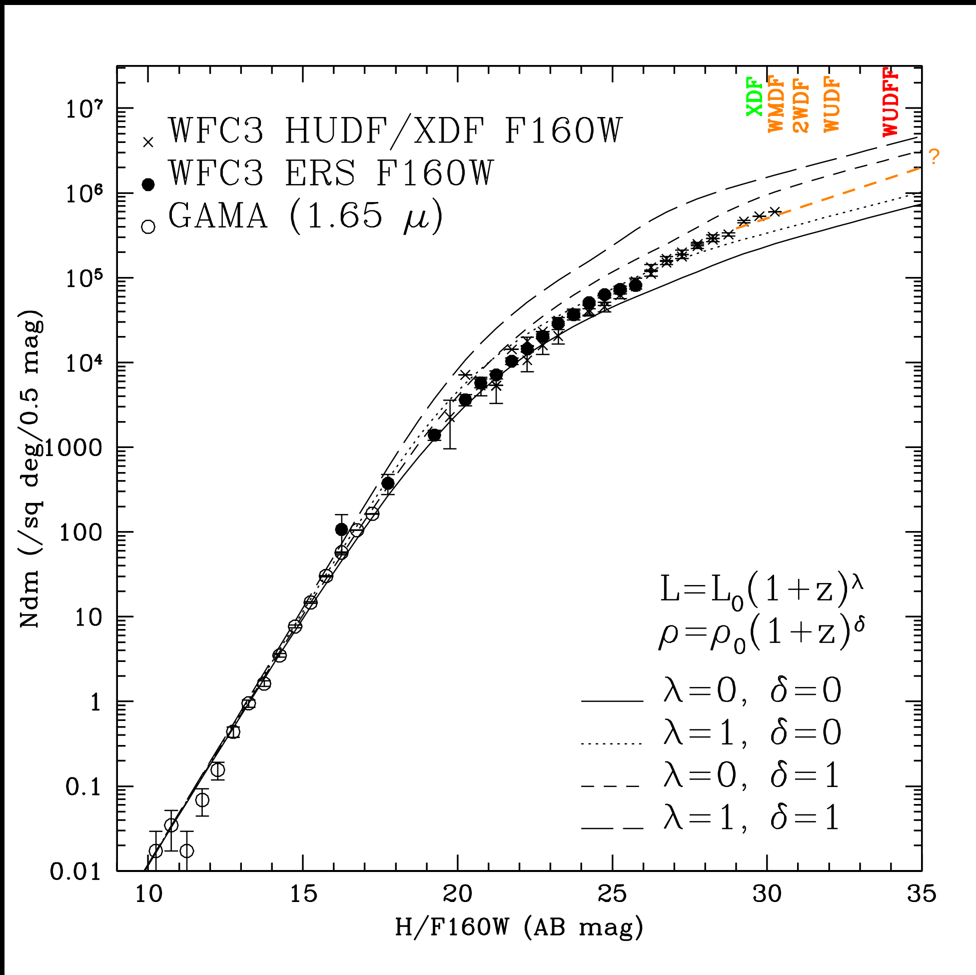
(4) What to expect in Webb (UltraDeep) Fields re. First Light?

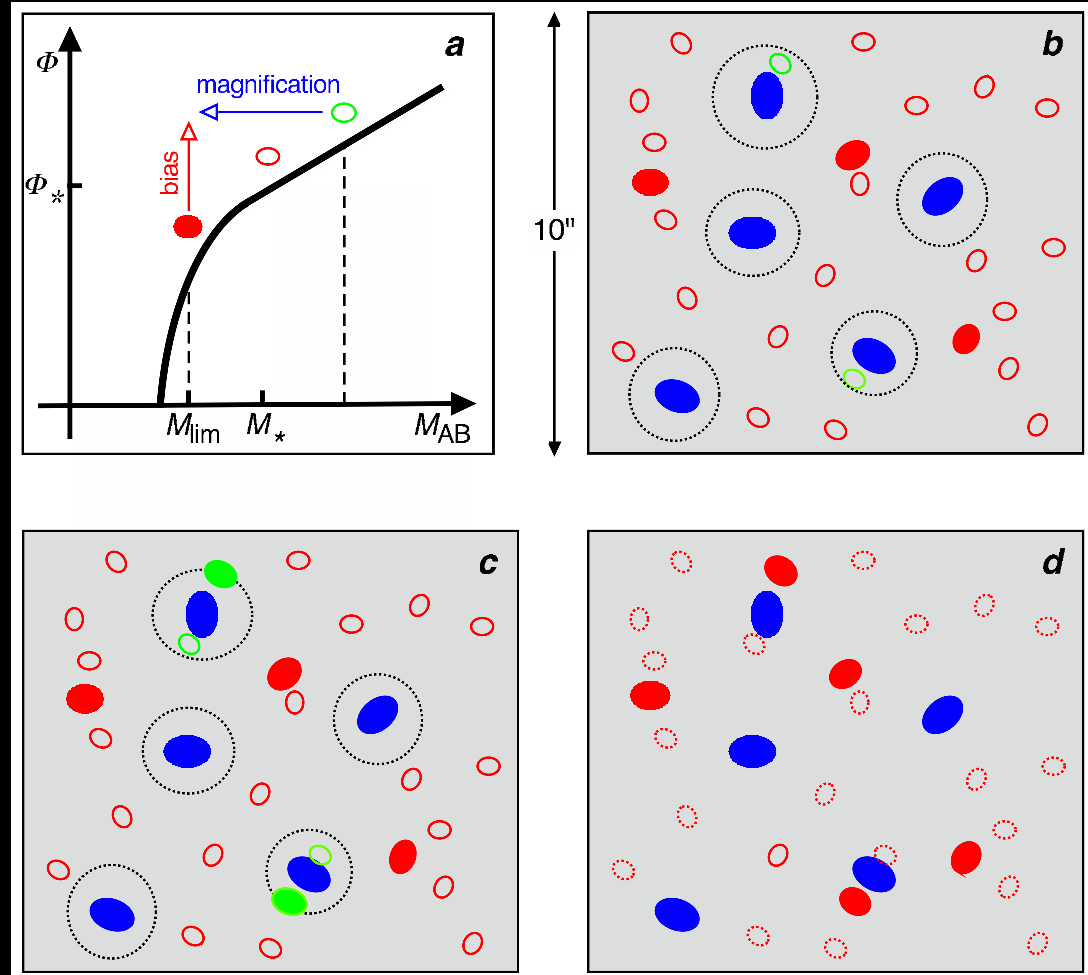


841 orbits HUDF 13 filters (false-color): objects affect ∼45% of pixels!!


o z=7–8, o z=9, O z=10–12.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$31 ($\gtrsim$2 nJy).

HUDF WFC3 IR Galaxy Counts: What to expect in Webb (UltraDeep) Fields?



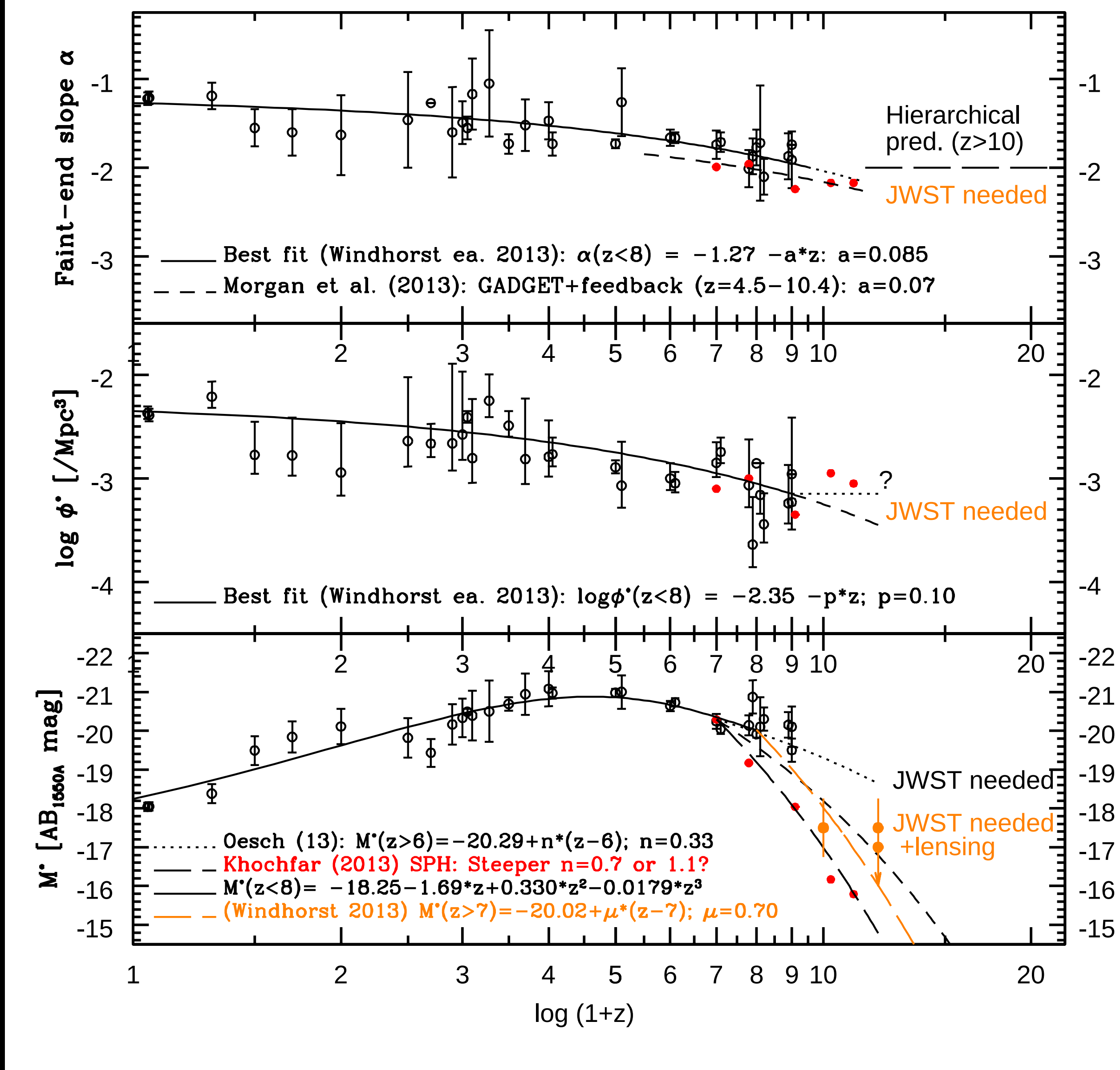


1.6μm counts (Windhorst[+]2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- Faint-end near-IR count-slope$\simeq$0.12$\pm$0.02 dex/mag $\Longleftrightarrow$

Faint-end LF-slope(z_{med} $\simeq$1.6) $\alpha\simeq$–1.4 $\Rightarrow$ reach M$_{AB}\simeq$–14 mag.

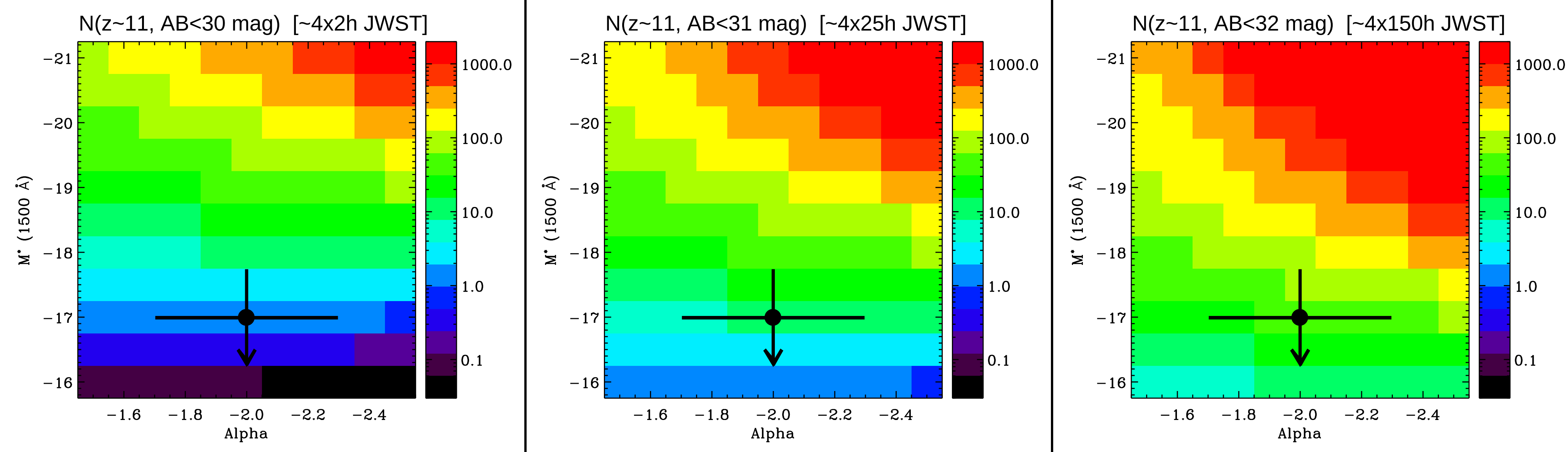
- WUDF (- - -) can see AB$\lesssim$32 objects: M_{AB} $\simeq$–15 (LMCs) at z$\simeq$11.
- Lensing will change the landscape for JWST observing strategies.



Evolution of Schechter 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}) (Oesch$^+$ 11).
- HUDF: Characteristic M^* may drop below –18 or –17.5 mag at z$\gtrsim$10.

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



What do the 6 possible z≃9 and single z≳10 HUDF candidate mean?

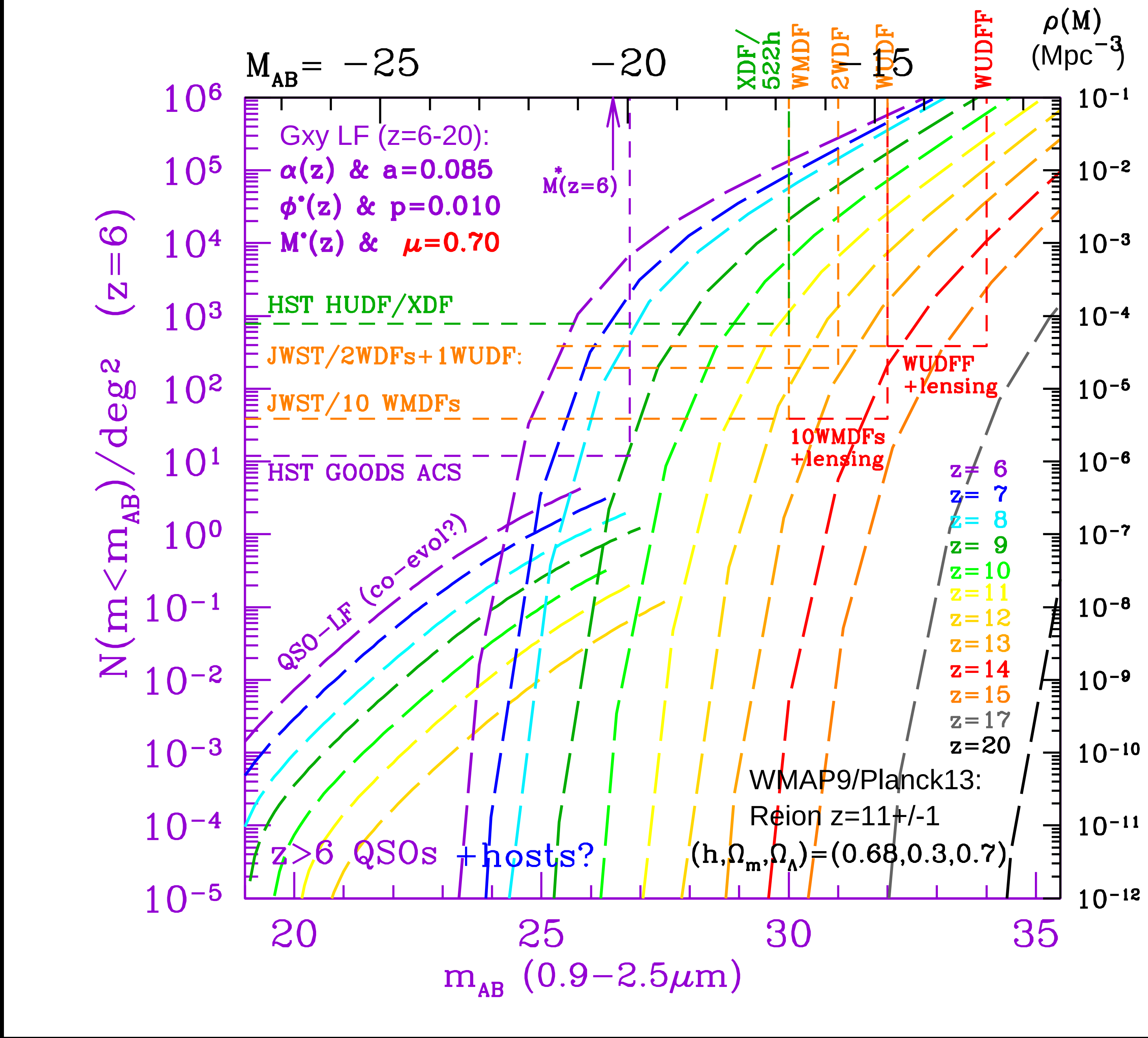
Integrate Schechter LFs with α(z), Φ^* (z) and M^* (z): ≲45% sky-coverage by AB≲30 objects (Koekemoer+13). Cosmic Variance ≳30%.

For any α(z≳9–10), implies M^* (z≳10)≳−17.5 mag (fainter!), so plan:

- (1) [Left] Webb “Medium-Deep” Fields (**WMDF**) (10×4×2h RAW): Expect few z≃10–12 objects to AB≲30 mag, so plan lensing targets.

- (2) [Middle] Webb Deep Field (**WDF**) (4×25h 7-filt NIRCam GTO): Expect 8–25 objects at z≃10–12 to AB≲31 mag.

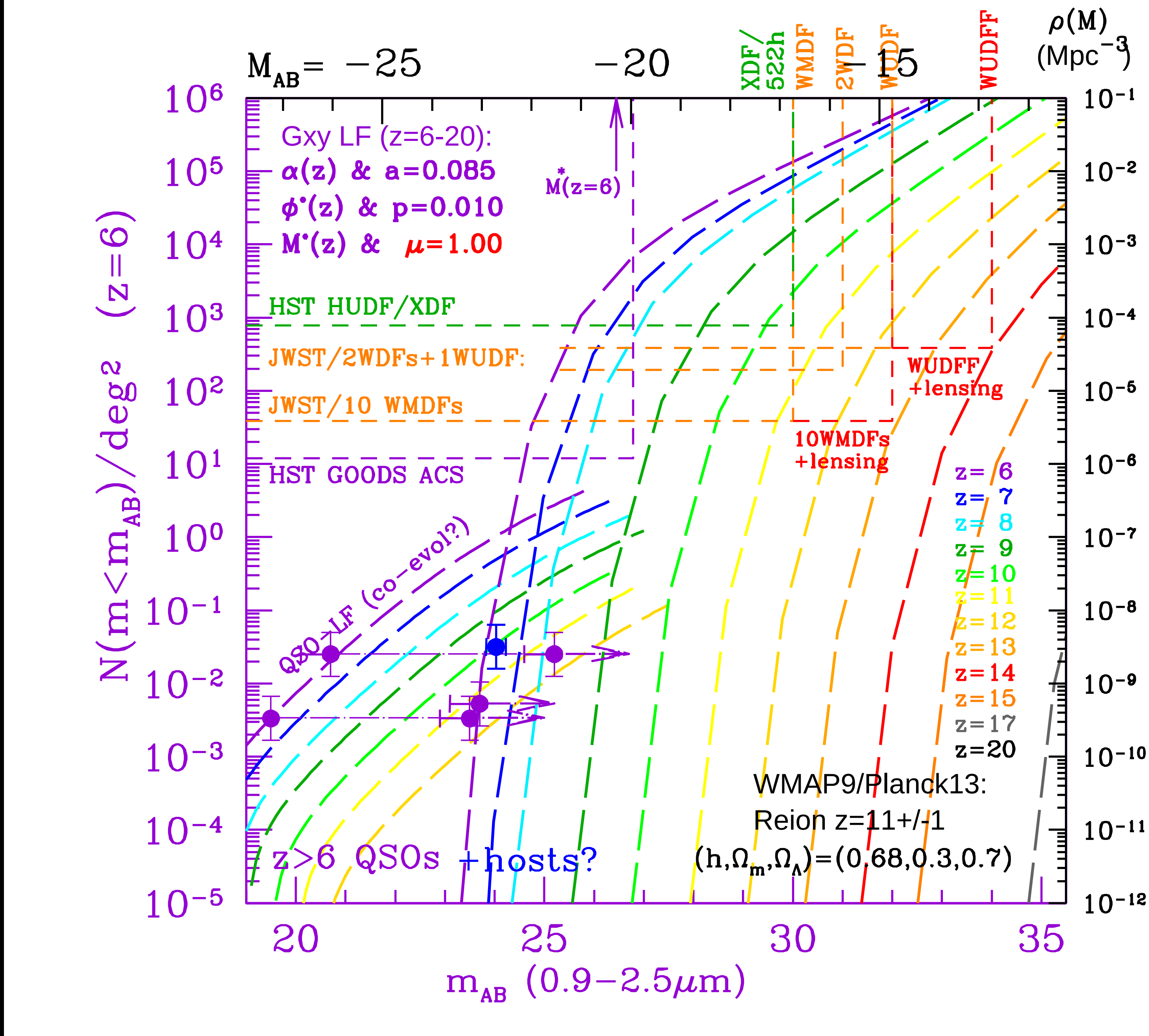
- (3) [Right] Webb UltraDeep Field (**WUDF**) (4×150h; NIRCam DD?]: Expect 30–90 objects to AB≲32 mag, many more if lensing targets.



Schechter LF ($z \lesssim 6 \lesssim 20$) with α(z), Φ^* (z), M^* (z) above & μ=0.70.

Area/Sensitivity for: HUDF/XDF, 10 WMDFs, 2 WDFs, & 1 WUDF.

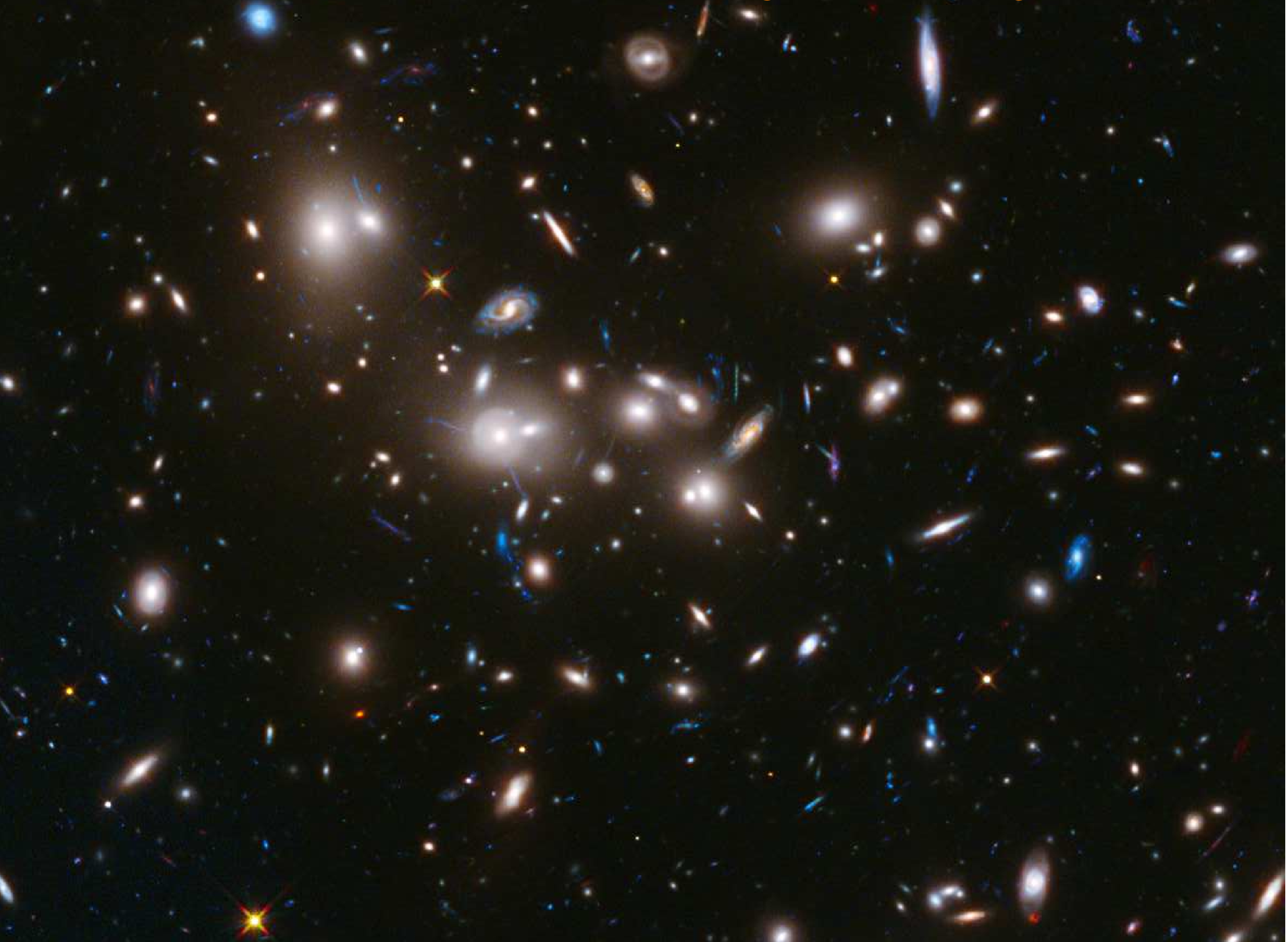
- Will need lensing targets for WMDF–WUDFF to see z≃14–16 objects.



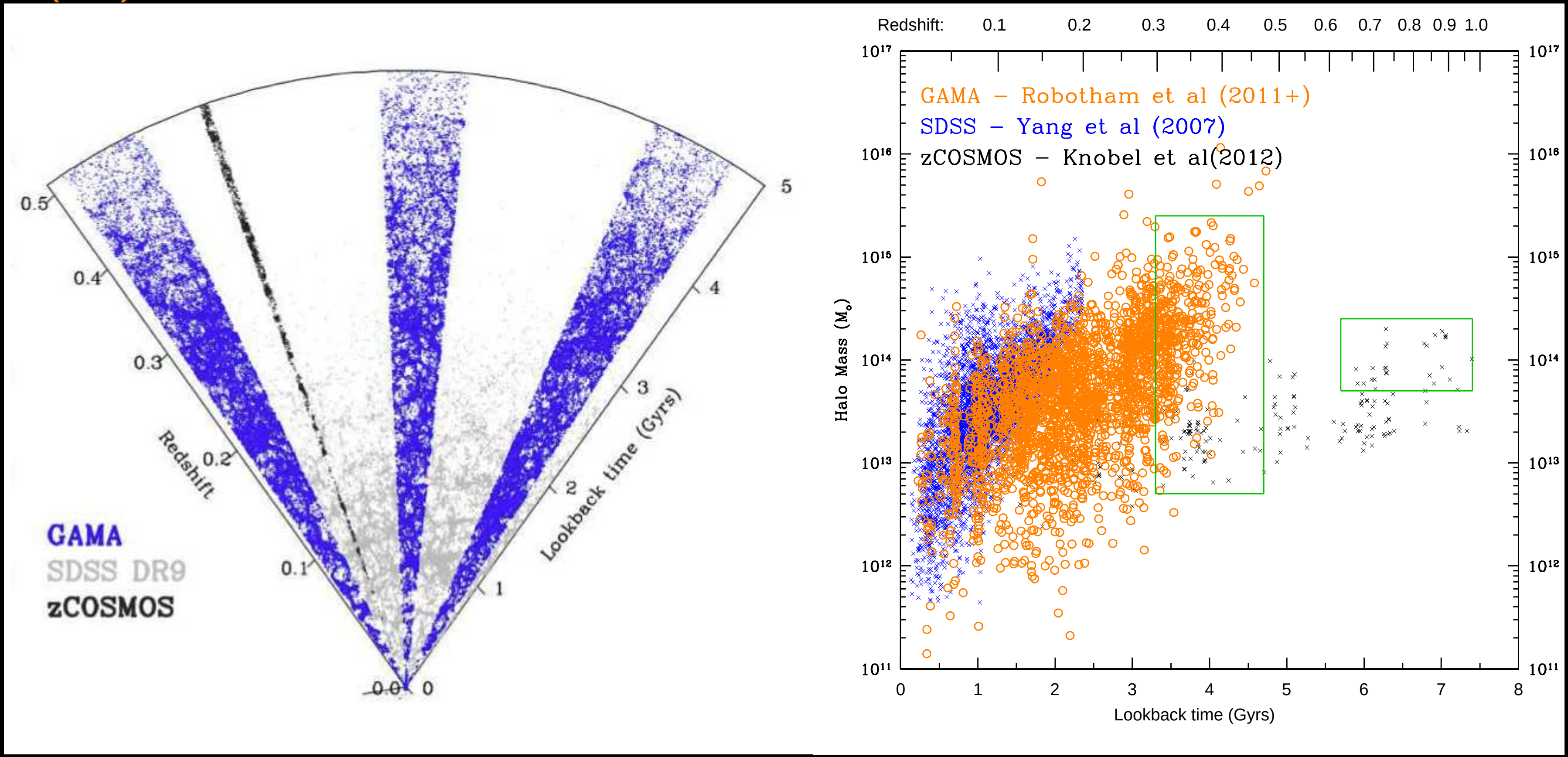
Same as pg. 15, but pessimistic M^* (z) evolution parameter: μ=1.0.

- If so, JWST surveys would need lensing to see most $\gtrsim$11 objects.
- Add z$\simeq$6 QSO host galaxy limits (or fluxes) by Mechtley$^+$ (2012, 2013).

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



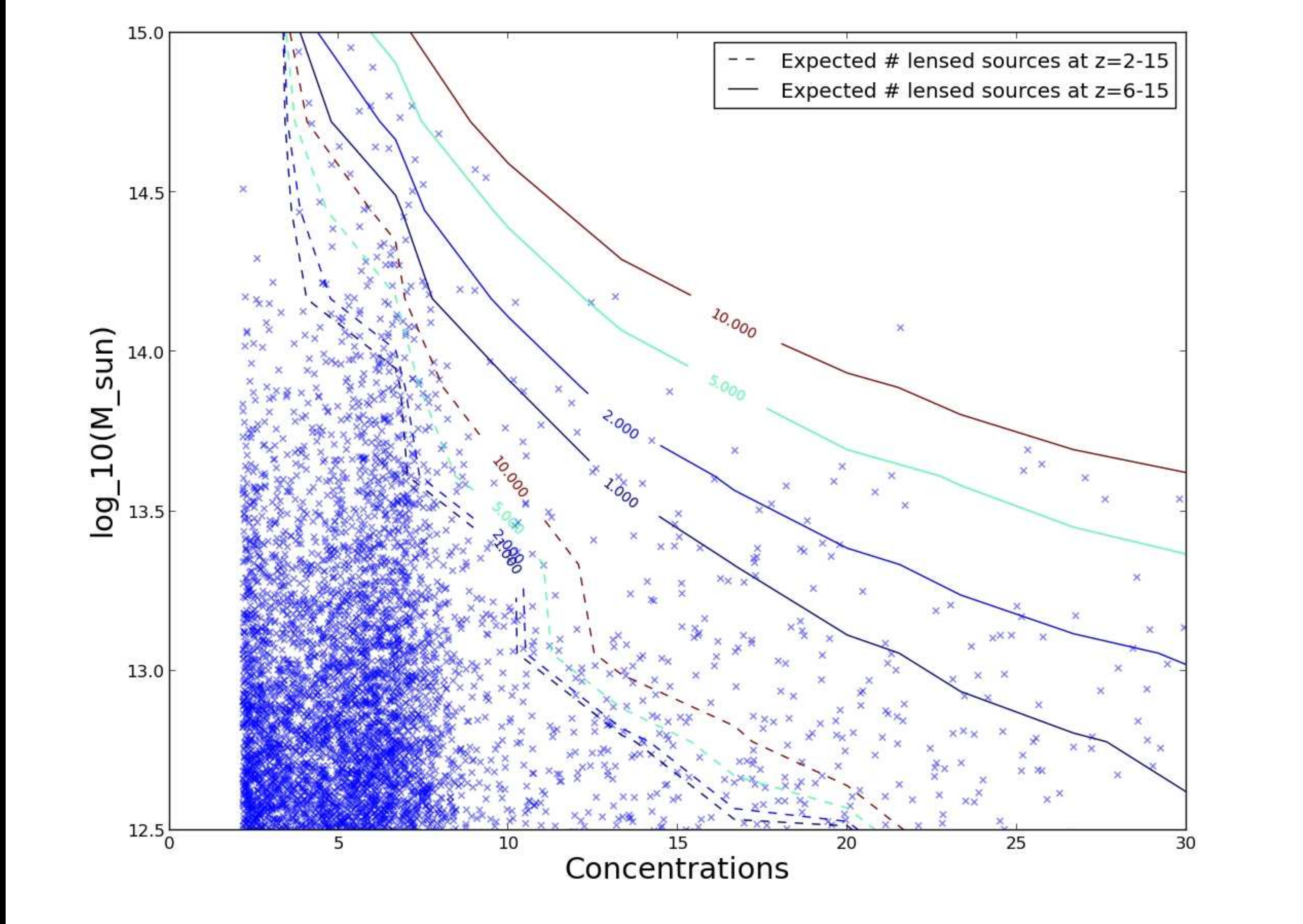
(3b) Gravitational Lensing to see First Light population at z$\gtrsim$10.



What are the best lenses in 2018: Rich clusters or (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$10% of GAMA groups compact for lensing (Konstantopoulos$^+$ 13).
- Large group sample to identify optimal lens-candidates for z$\gtrsim$6 sources.



GAMA group mass versus concentration assuming NFW DM halo profiles.

Contours = Nr of expected lensed sources (Δz=1; Barone-Nugent^{+} 13).

- 10 WMDFs on best GAMA groups add ∼50–100 z≃6–15 sources (AB≲30).
- Also get ≳10× more (≳500) lensed sources at ≃2–15.

WUDFF if pointed at clusters adds ∼6×more (≳3000) sources at 6≲z≲15.

Two fundamental limitations may determine ultimate JWST image depth:

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

Background objects blend into foreground because of their own diameter
$\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ deblending algorithms.

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

$\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ object finder that works on sloped backgrounds

$\Rightarrow$ If $M^*(z \gtrsim 10) \gtrsim -18$, need to use & model gravitational foreground.

(4) Conclusions

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

- Most $z\simeq6$ QSO host galaxies faint (dusty?), with 1 exception: $L>>L^*$.

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

Management replan in 2010-2011. No technical showstoppers thus far:

- More than 80% of JWST H/W built or in fab, & meets/exceeds specs.

(3) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail. JWST will determine:

- Formation and evolution of the first star-clusters after 0.2 Gyr.
- How dwarf galaxies formed and reionized the Universe after 1 Gyr.

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

- IR sequel to HST after 2018: Training the next generation researchers.
- JWST will define the next frontier to explore: the Dark Ages at $z\gtrsim20$.

SPARE CHARTS

- References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool]

http://www.asu.edu/clas/hst/www/ahah/ [Hubble at Hyperspeed Java–tool]

http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/ [Clickable HUDF map]

http://www.jwst.nasa.gov/ & http://www.stsci.edu/jwst/

http://ircamera.as.arizona.edu/nircam/

http://ircamera.as.arizona.edu/MIRI/

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

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

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

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

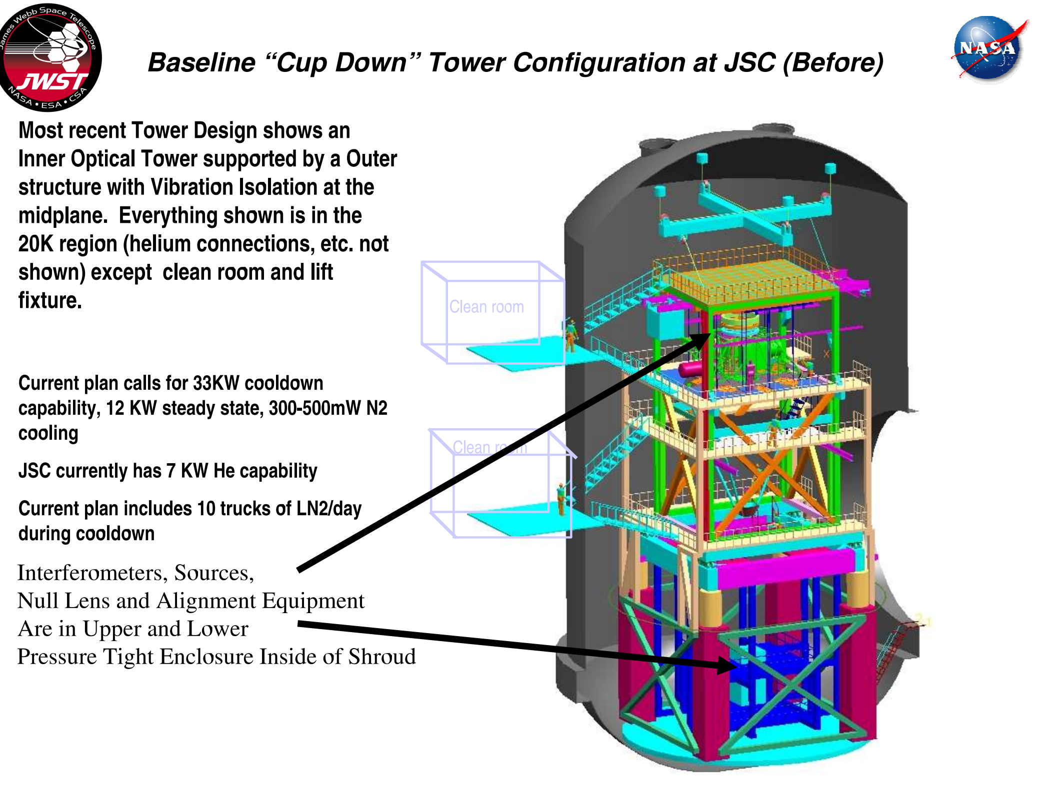
Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

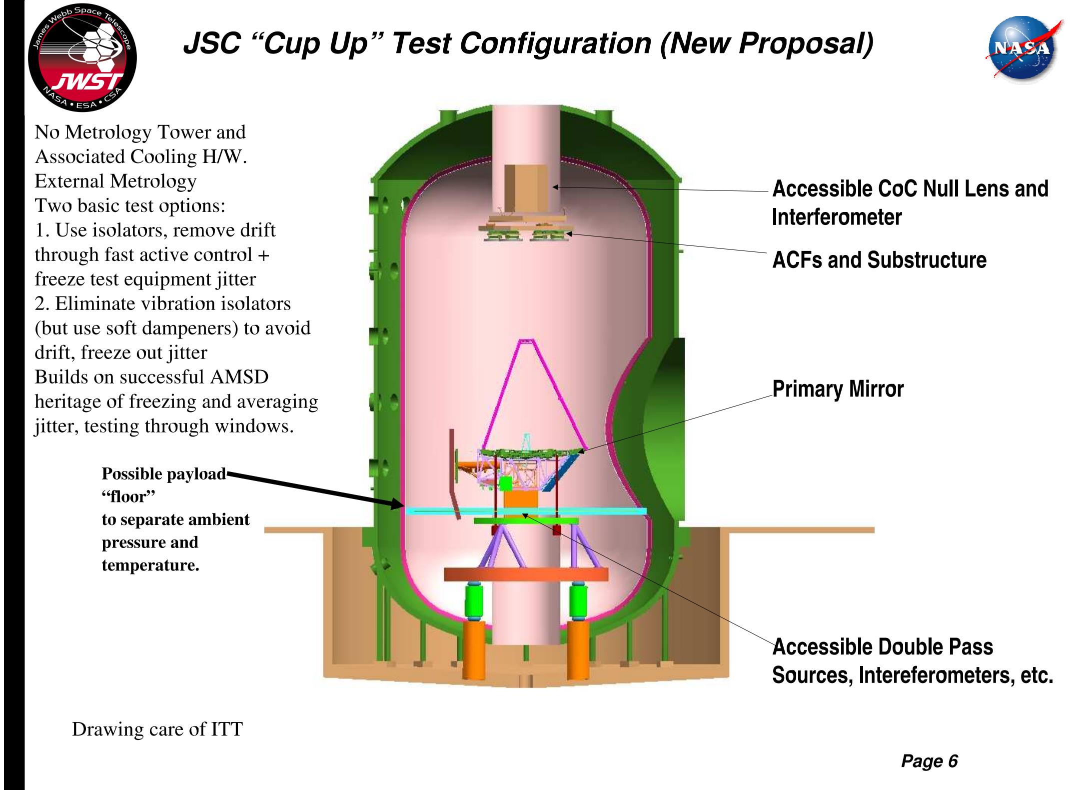
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements







JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.

Fiscal Year 2014 HQ Milestones

Assumes JWST is appropriated in FY2014 the full President's budget request of new obligation authority (NOA).

Month		Milestone	Comment
Oct-13	1	Primary Mirror Backplane Support Structure Cryogenic Testing Readiness Review	Completed 9/10
Nov-13	2	Mirror Deployment Electronics Unit Manufacturing Readiness Review	Completed 10/8
	3	Jet Propulsion Lab. (JPL) Cryogenic Test Chamber Readiness Review	Delayed: pulse tube, cooler shield issues
	4	Johnson Space Center (JSC) Telescope and ISIM support structure fabrication complete	Completed 11/4
Dec-13	5	Spacecraft Critical Design Review Complete	Delayed to 1/14 [shutdown]
	6	MIRI Cryocooler Flight Cold Head Assembly delivered to ISIM	Delayed 1/21/2014
	7	JSC Clean Room ready to receive ground support equipment	Delayed to 1/14 [shutdown]
	8	Complete ISIM cryogenic-vacuum risk reduction test	Concluded 11/13/2013, but not all tests completed because of shutdown
Jan-14	9	Delivery of last Primary Mirror Segment to GSFC	Completed 12/16
	10	Observatory Operations software scripts Build 3 Complete	
	11	New detector focal plane arrays for NIRCam ready for integration into instrument	Completed 11/20
Feb-14	12	Secondary Mirror Mount delivery	
	13	MIRI Cryocooler flight electronics delivered to JPL	
	14	Final Data Management Subsystem Design Review	Completed 11/22
	15	Flight NIRCam and NIRSpec ready for integration into ISIM	Delayed to 3/14 [shutdown]
Mar-14	16	Spacecraft Solar Array Manufacturing Readiness Review	
	17	JSC Chamber A Telescope ground support equipment test #1 design review	
Apr-14	18	Telescope actuators electronics drive unit delivery	
	19	Flight MIRI cryocooler assembly delivered to JPL	
	20	MIRI Cryocooler Flight Refrigerant Line Deployment Assembly delivered to integration and testing	
	21	Sunshield Membrane Cover Assembly Manufacturing Readiness Review	
	22	MIRI cryocooler Test Readiness Review	
May-14	23	Updated Observatory Commissionning Plan (rev C) delivery	
	24	Start acceptance testing of flight cryocooler assembly and associated electronics	
	25	Start cryo-vacuum test with fully integrated ISIM ("CV2")	Delayed to 6/14 [shutdown]
Jun-14	26	Flight spare MIRI cryocooler assembly delivered to JPL	
	27	JSC Chamber A bake-out and cryogenic proof testing complete	
	28	Hardware ready for MIRI cryo cooler test #3: checkout complete	
Jul-14	29	Spacecraft Mid-Course Correction Thruster Final Assembly complete	
	30	Proprosal Planning Subsystem build 9 complete	
Aug-14	31	Sunshield Mid-boom and Stem assembly Manufacturing Readiness Review	
	32	Spacecraft Flight Software Build 2.2 Test Readiness Review	
	33	NIRSpec and FGS/NIRISS new Focal Plane Arrays ready for integration	Delayed to 9/14 [shutdown]
Sep-14	34	JSC cryogenic test telescope and ISIM test ground support equipment integration complete	
	35	Complete cryo-vacuum test of fully integrated ISIM ("CV2")plete	Delayed to 10/14 [shutdown]
	36	NIRSpec new microshutters ready for integration	Delayed to 10/14 [shutdown]

Blue font denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late.

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

Milestone Performance

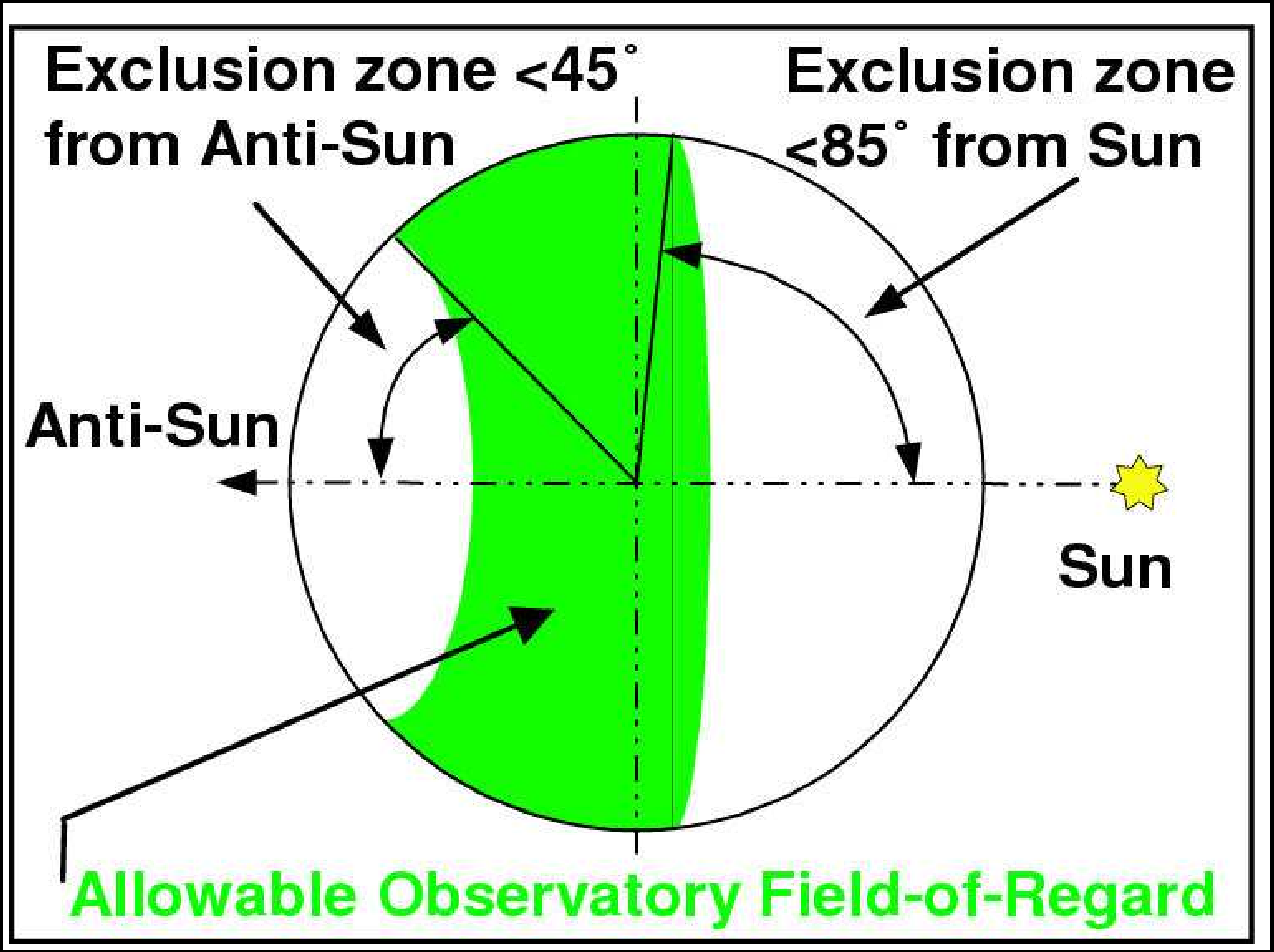
- Since the September 2011 replan JWST reports high-level milestones monthly to numerous stakeholders

	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year
FY2011	21	21	6	3	0
FY2012	37	34	16	2	3
FY2013	41	38	20	5	3
FY2014	36	7	5	10*	0

*Late milestones have been or are forecast to complete within the year. Shutdown related delayed milestones included in this tally

7 out of 10 FY14 milestones late by 1 month due to Government shutdown.

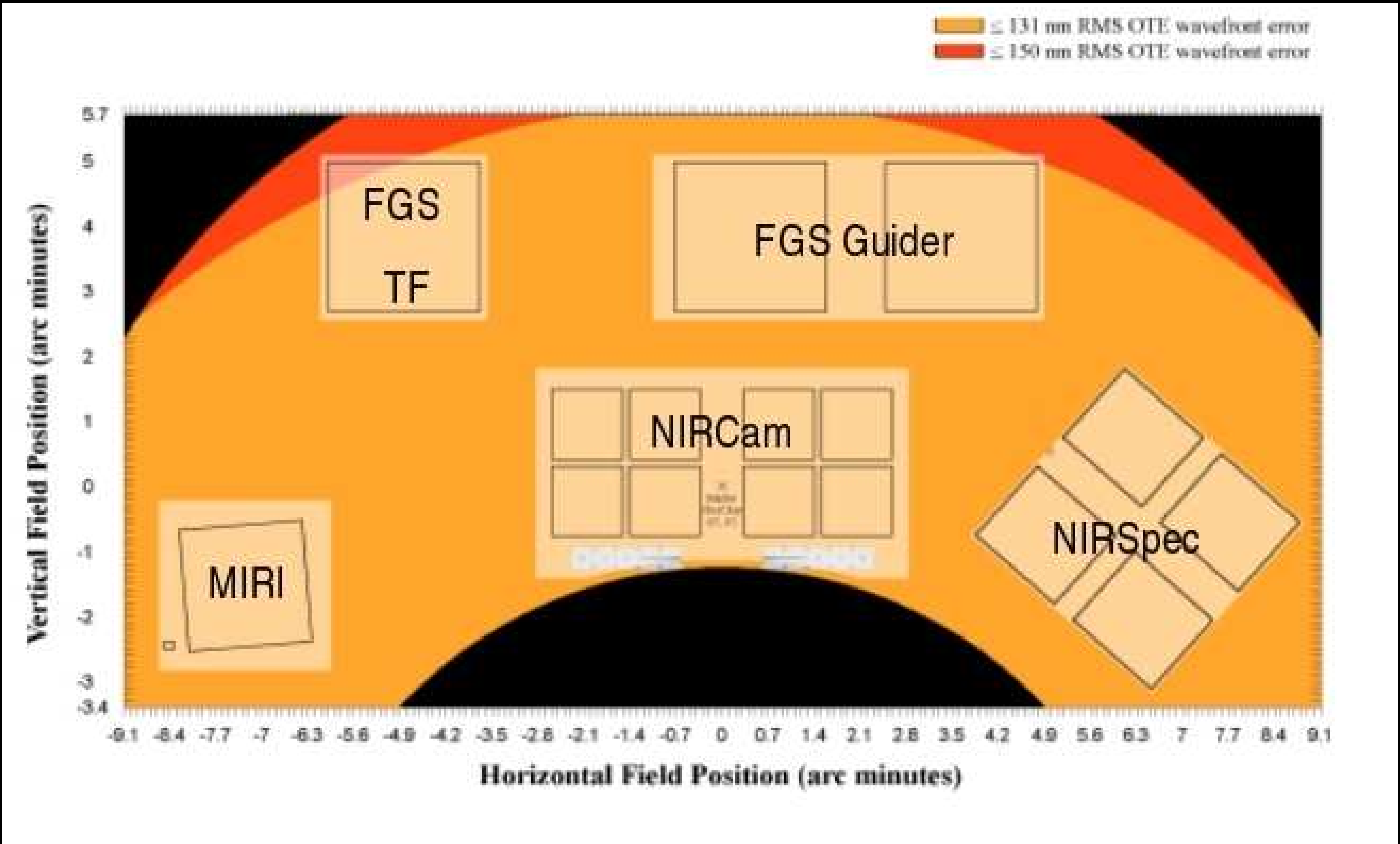
None of these are on the critical path, so caused no launch delay.



JWST can observe North/South Ecliptic pole targets continuously:

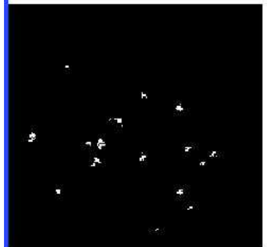
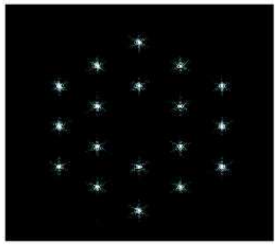
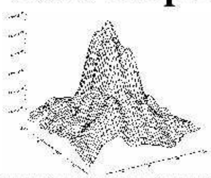
- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- They will rely a lot on Rockwell Collins reaction wheels!

• (3c) What instruments will JWST have?



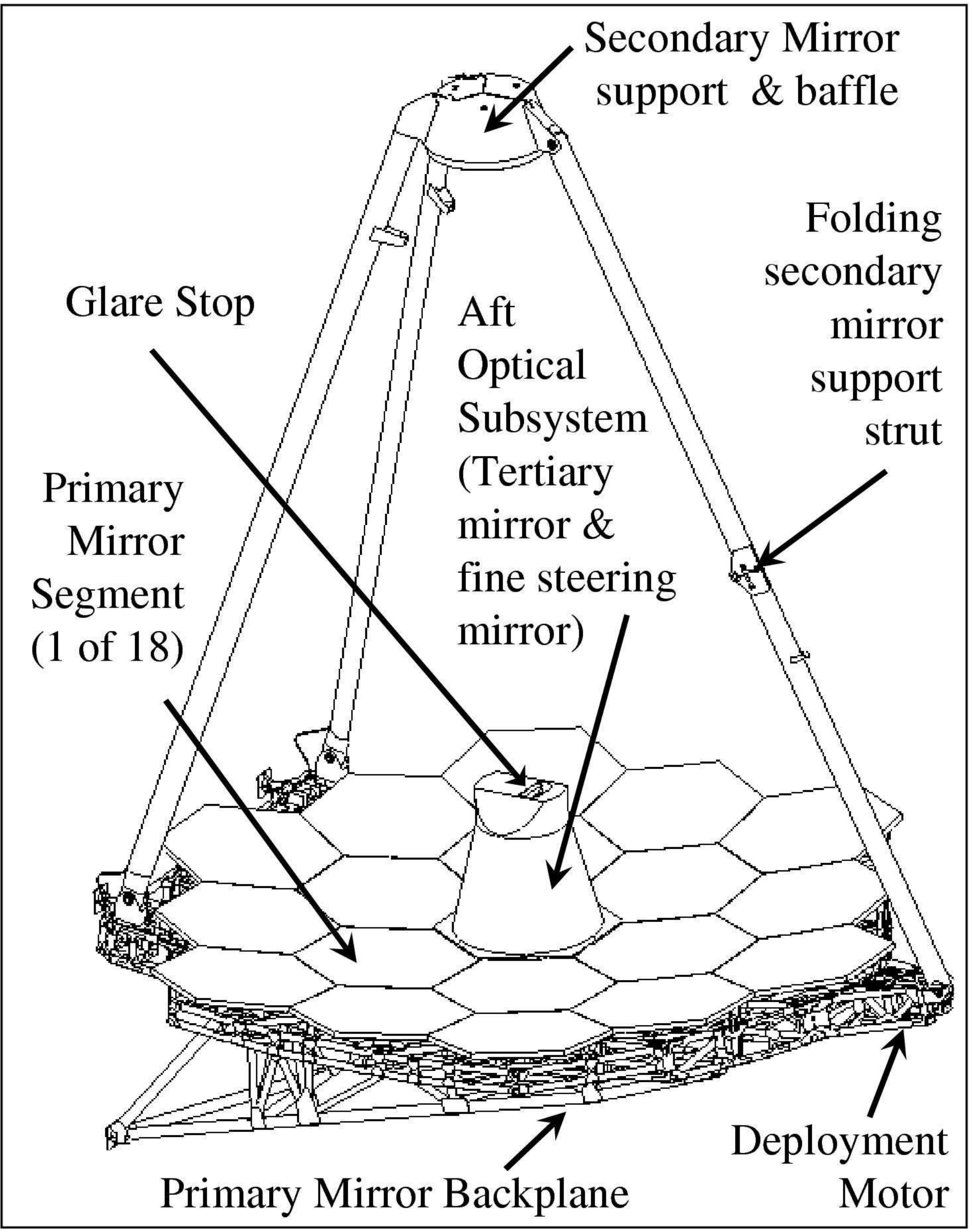
All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations.*

Step		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	**After Step 1** 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted	**After Step 2** 	Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 μm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)	**After Step 3** 	WFE: < 250 μm rms	WFE < 1 μm (rms)
4. Fine Phasing	**After Step 4** 	WFE: < 5 μm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring	**After Step 5** 	WFE: < 150 nm (rms)	WFE < 110 nm (rms)

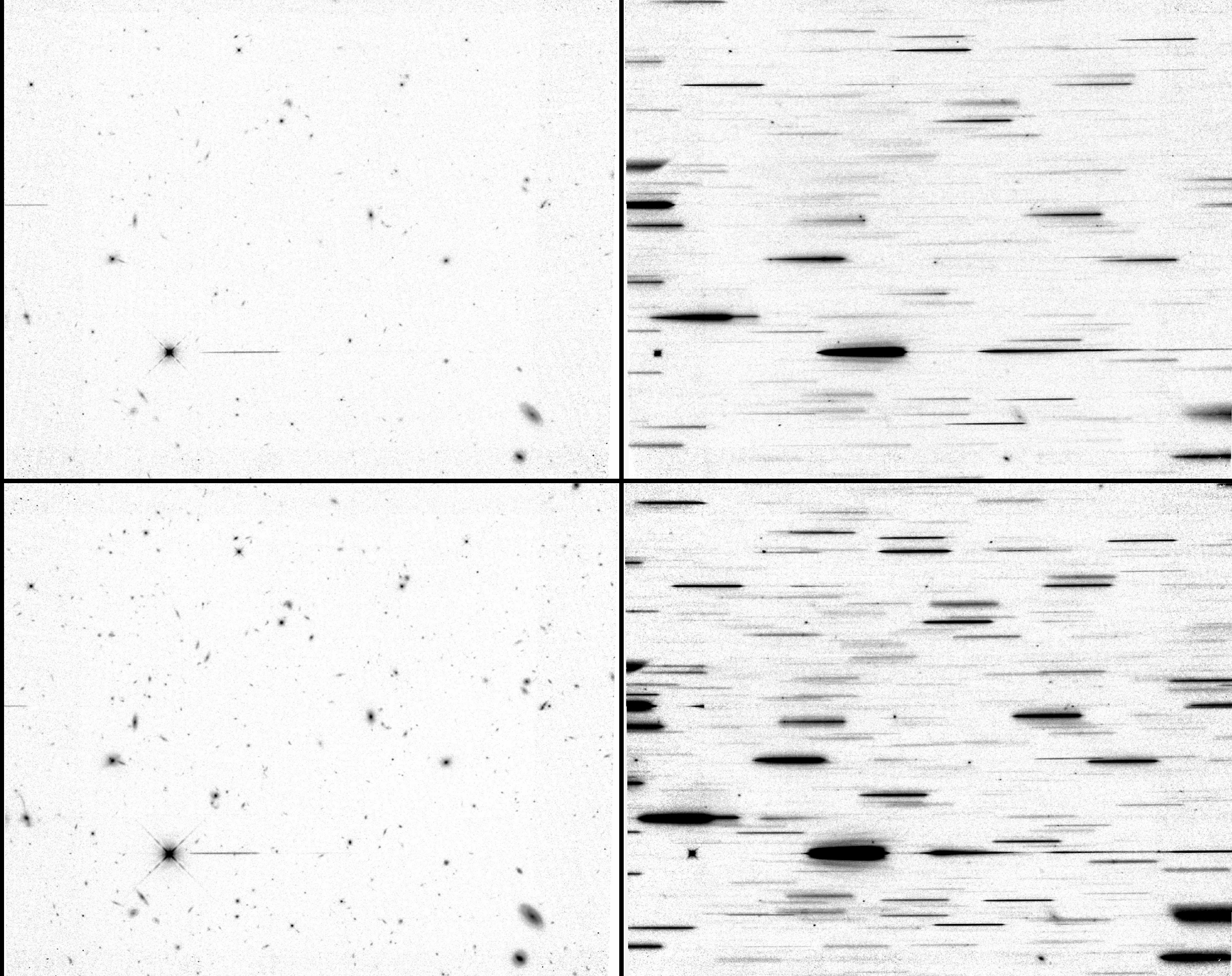
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

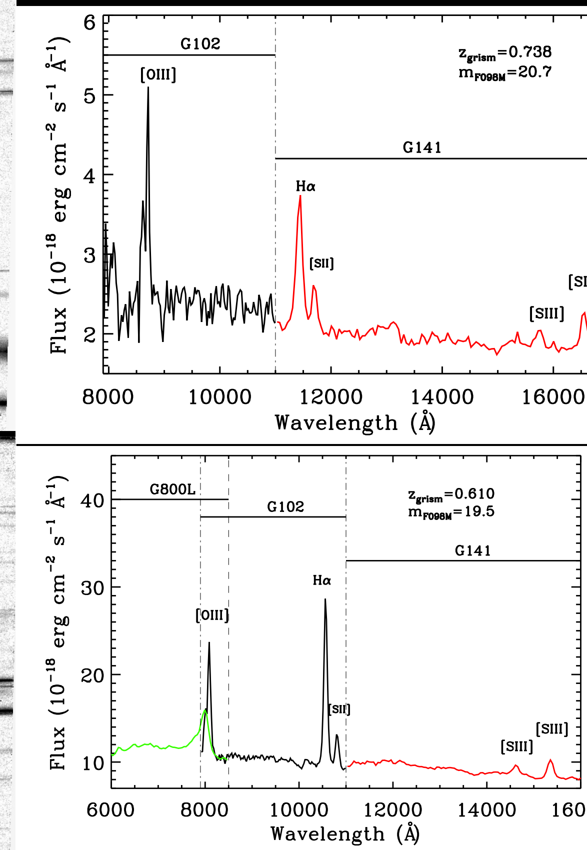
In L2, need WFS updates every 10 days depending on scheduling/illumination.



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

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





HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn^{+} 2010)

IR grism spectra from space: unprecedented new opportunities in astrophysics.

- JWST will provide near-IR grism spectra to AB$\lesssim$29 mag from 2–5.0 μm.

One day we will need a UV-optical sequel to Hubble:

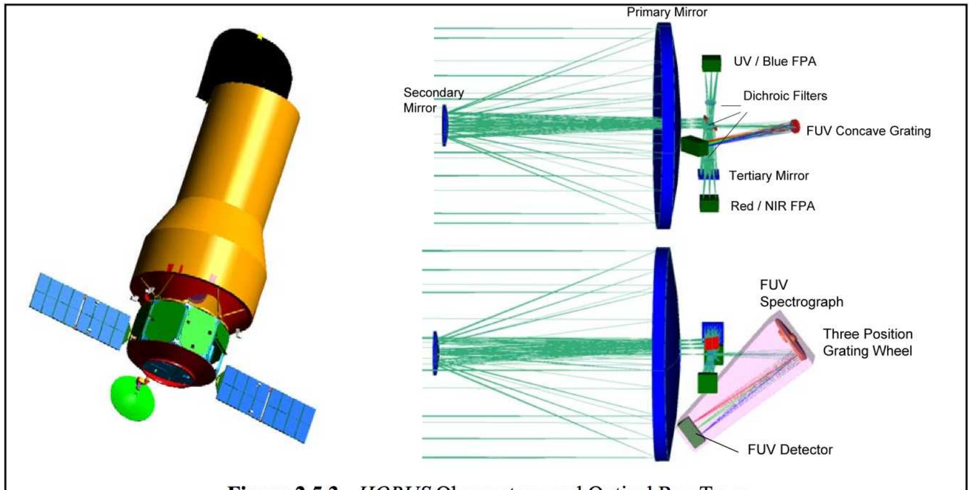
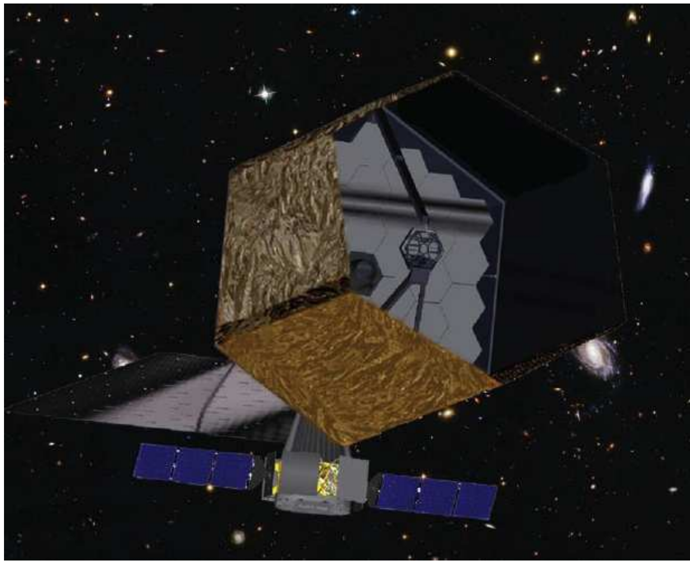


Figure 2.5.3 - *HORUS* Observatory and Optical Ray Trace



[Left] One of two spare 2.4 m NRO mirrors: one will become WFIRST.

- NASA may look for partners to turn 2nd NRO into UV-opt HST sequel.

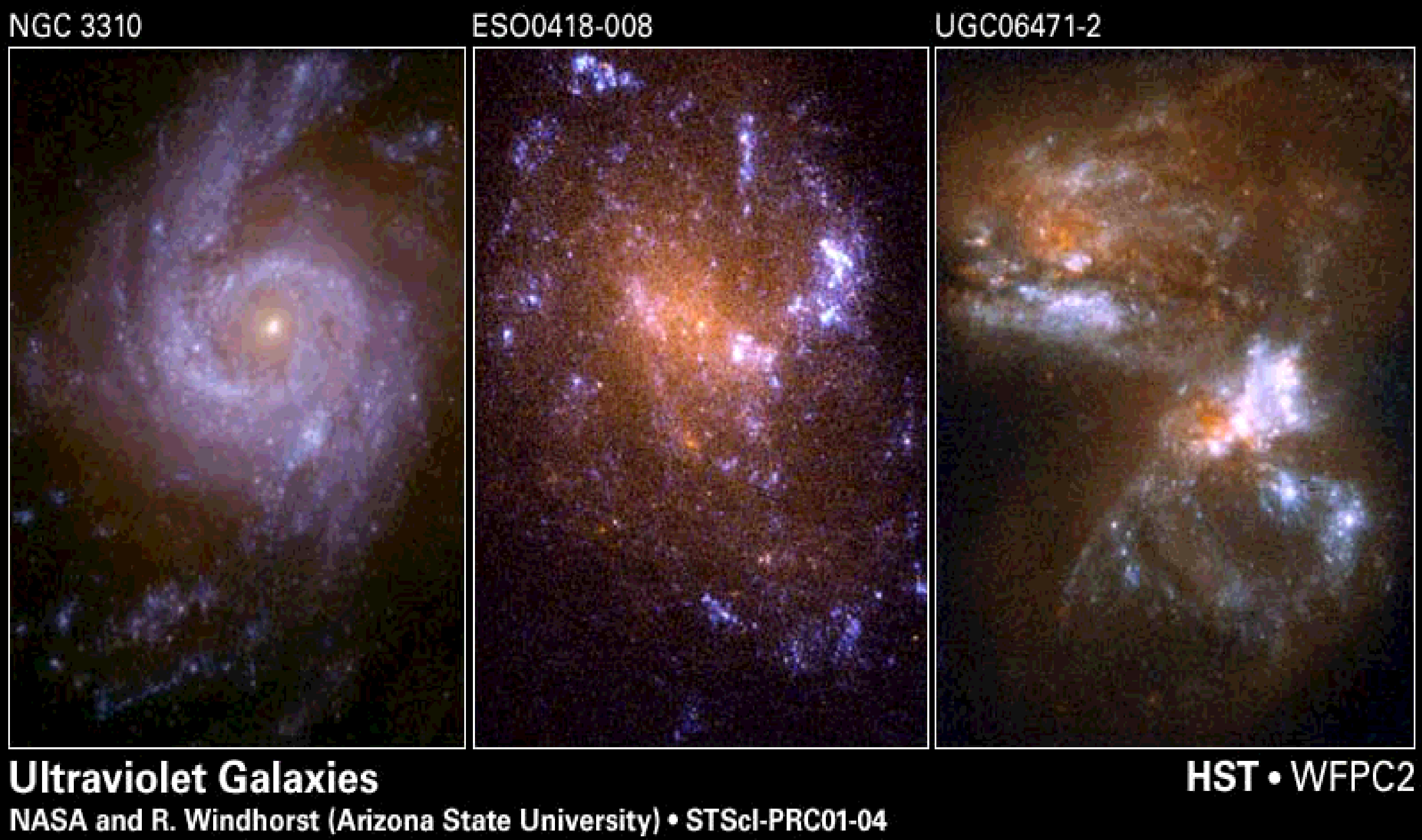
[Middle] HORUS: 3-mirror anastigmat NRO as UV-opt HST sequel.

- Can do wide-field ($\sim$0.25 deg) UV-opt $0\farcs06$ FWHM imaging to AB$\lesssim$29-30 mag, and high sensitivity (on-axis) UV-spectroscopy.

[Right] ATLAST: 8–16 m UV-opt HST sequel, with JWST heritage.

- Can do same at 9 m.a.s. FWHM routinely to AB$\lesssim$32-34 mag, [and an ATLAST-UDF to AB $\lesssim$38 mag $\sim$1 pico-Jy].

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

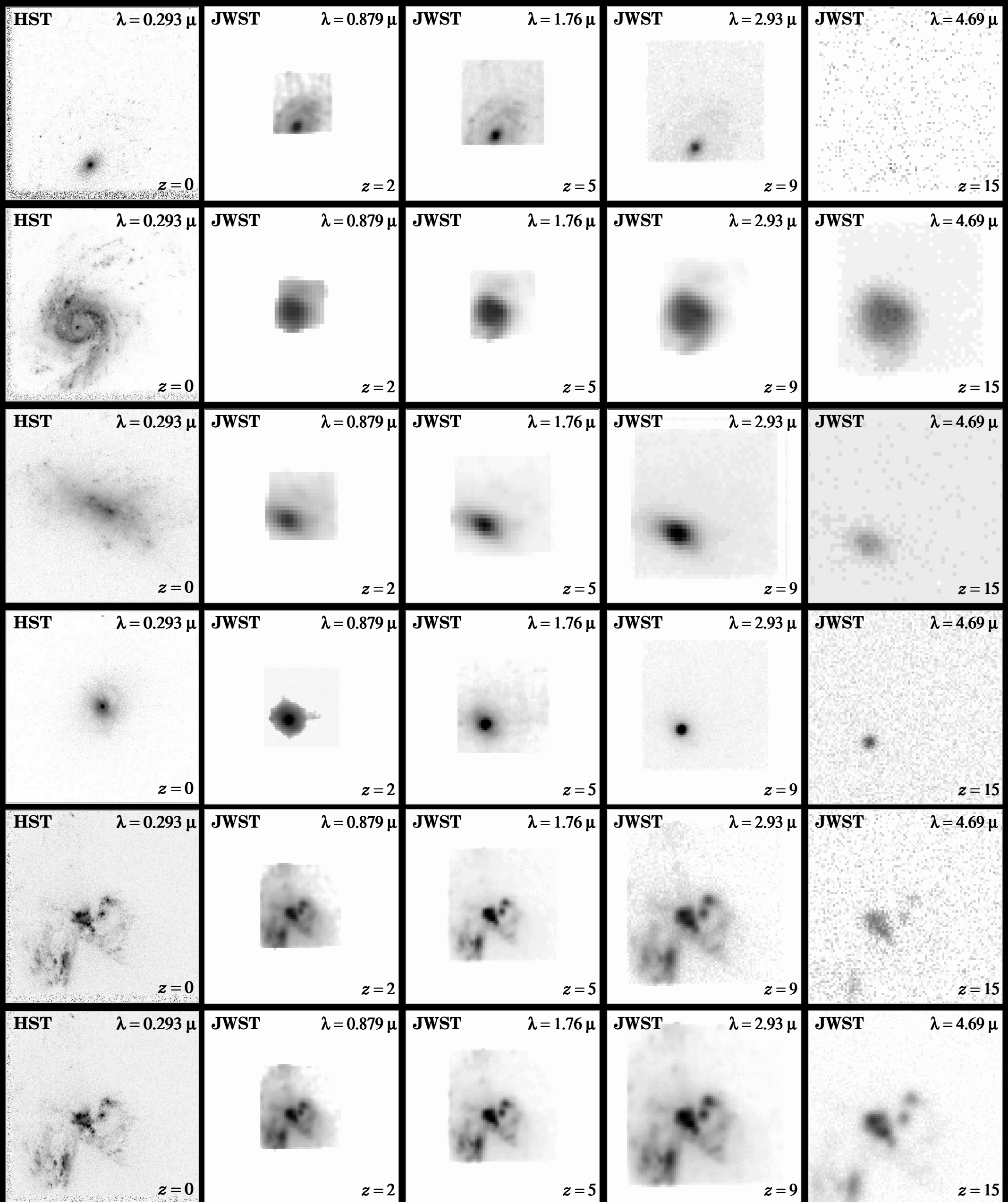


- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

- High-resolution HST ultraviolet images are benchmarks for comparison with very high redshift galaxies seen by JWST.

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

HST z=0 JWST z=2 z=5 z=9 z=15



With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most spiral disks will dim away at high redshift, but most formed at z$\lesssim$1–2.

Visible to JWST at very high z are:

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

B, I, J AB-mag vs. half-light radii r_e from RC3 to HUDF limit are shown.

All surveys limited by by SB (+5 mag dash)

Deep surveys bounded also by object density.

Violet lines are gxy counts converted to to natural conf limits.

Natural confusion sets in for faintest surveys (AB$\gtrsim$25). Will update for JWST.