How will JWST measure First Light, Reionization, & Galaxy Assembly: New Frontiers after Hubble

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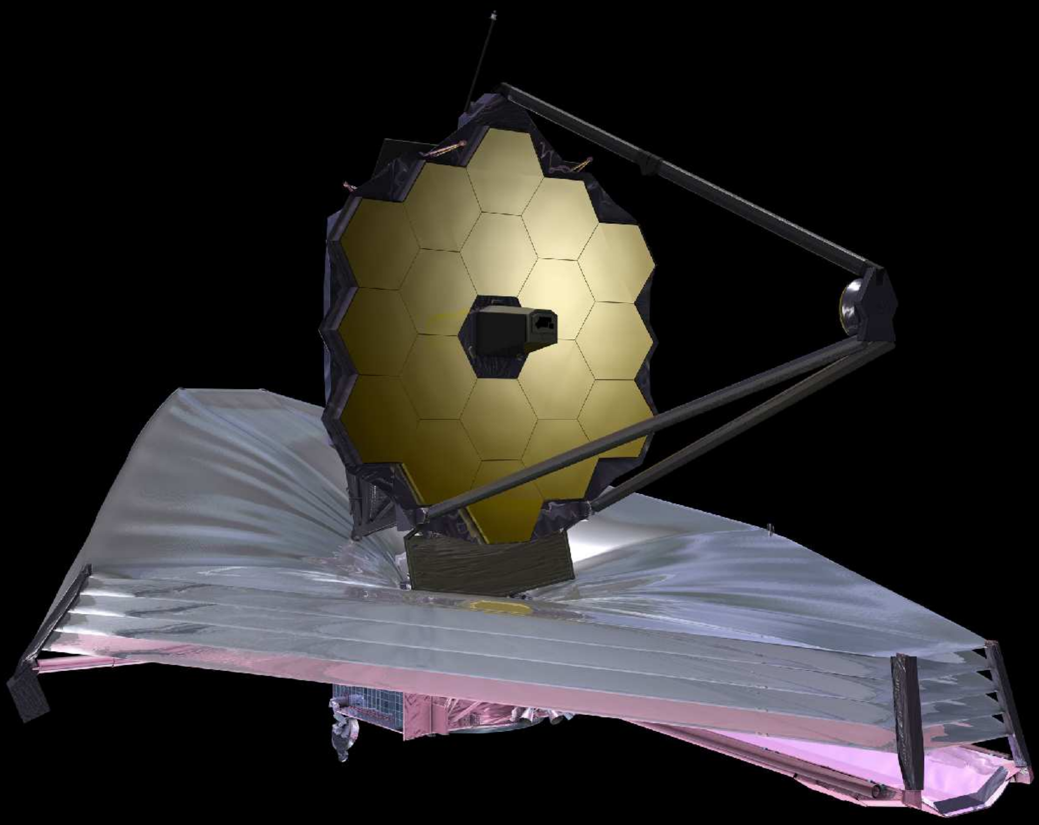


Colloquium at the Physics Department, Technion – Israel Institute of Technology, Thursday May 21 (Haifa, Israel)

All presented materials are ITAR-cleared.

Outline

- (1) Update on the James Webb Space Telescope (JWST), 2015.

- (2) Hubble (Ultra)Deep & Frontier Fields to find z∼9–11 objects:
— Current limitations

- (3) How can JWST measure the Epoch of First Light (using lensing)?

- How many random Webb Deep Fields (WDFs) compared, to the best lensing targets for JWST?

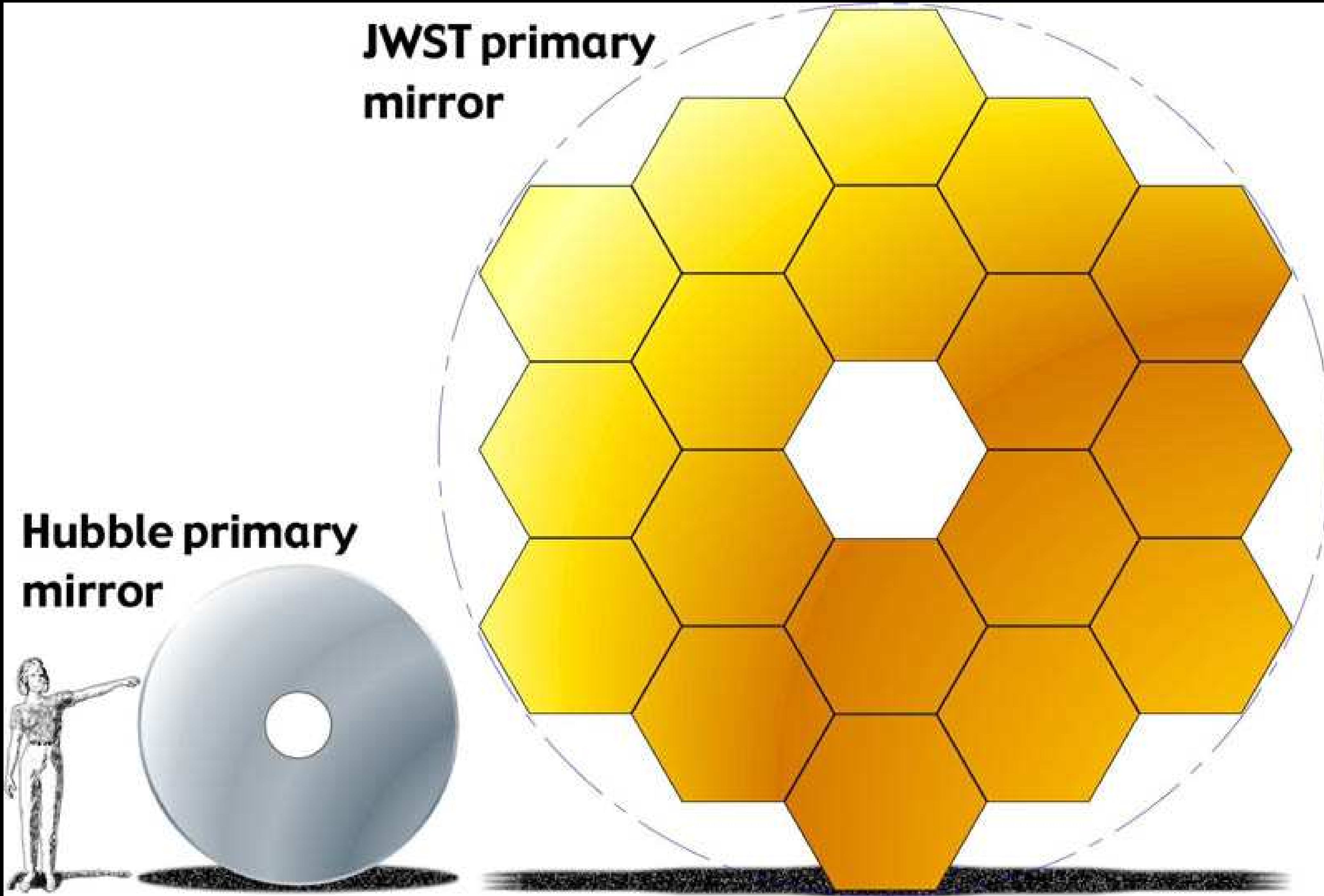
- (4) Summary and Conclusions.

Sponsored by NASA/HST & JWST

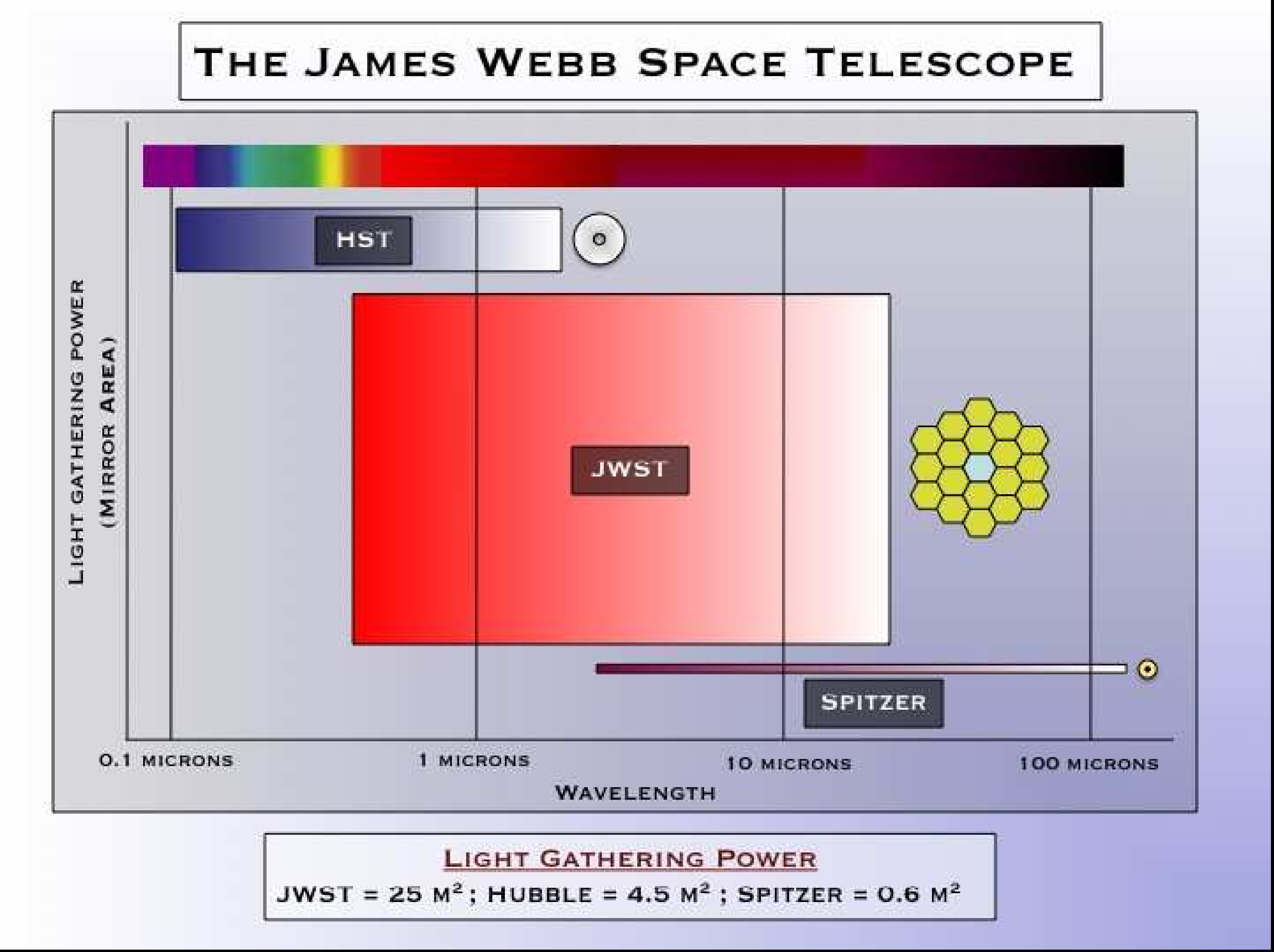
ASU Arizona State University

Talk is on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/israel15technion_hstjwst.pdf

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



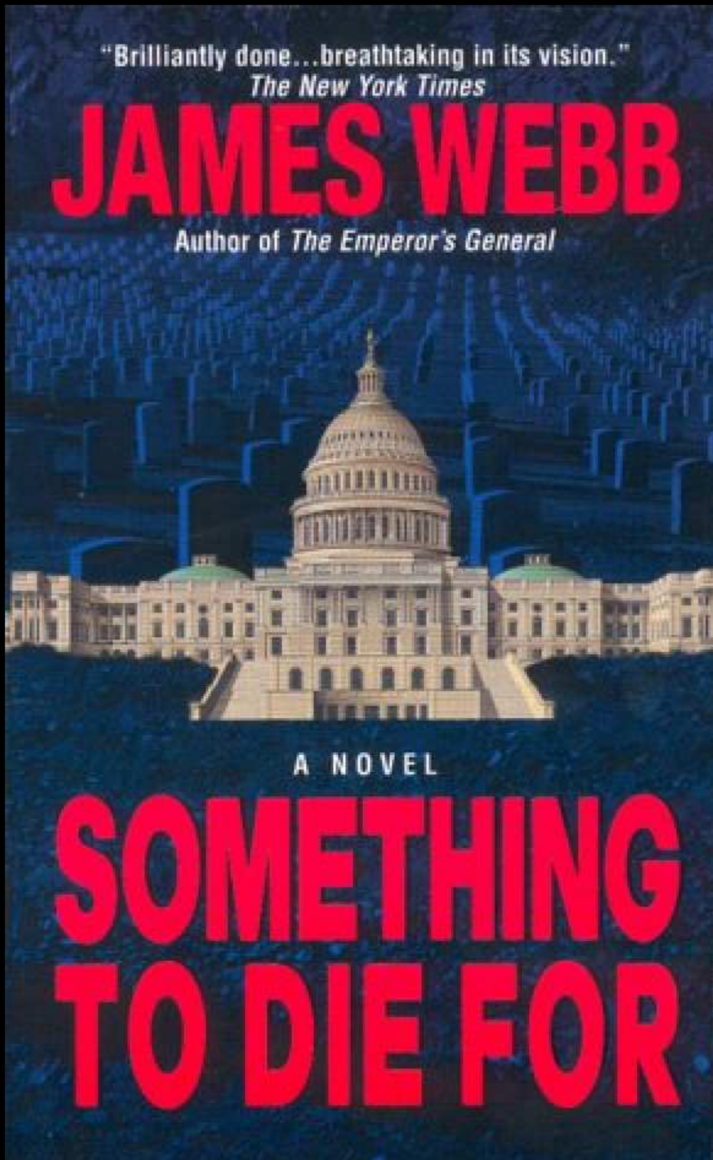
JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.



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

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

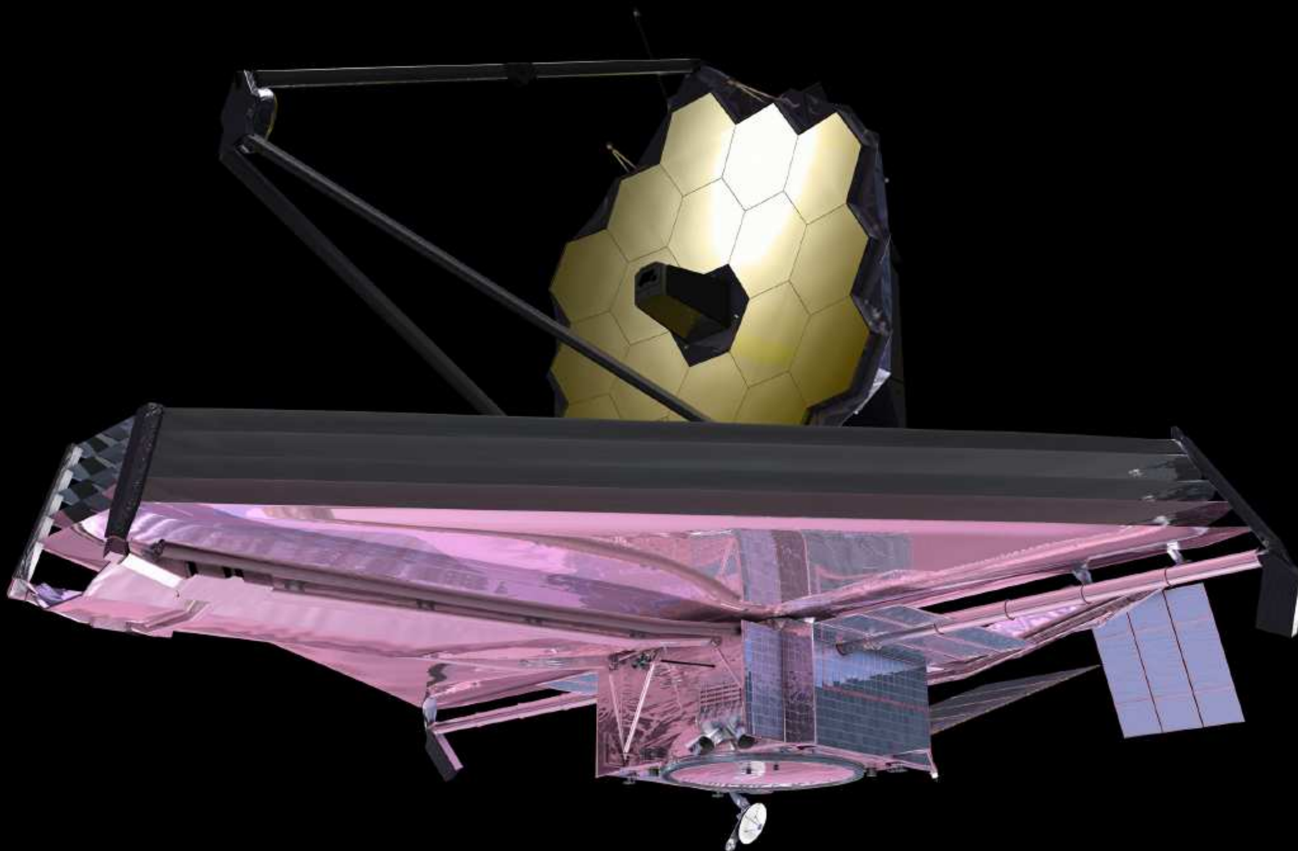
(1) Update of the James Webb Space Telescope (JWST), 2015.



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 2015.

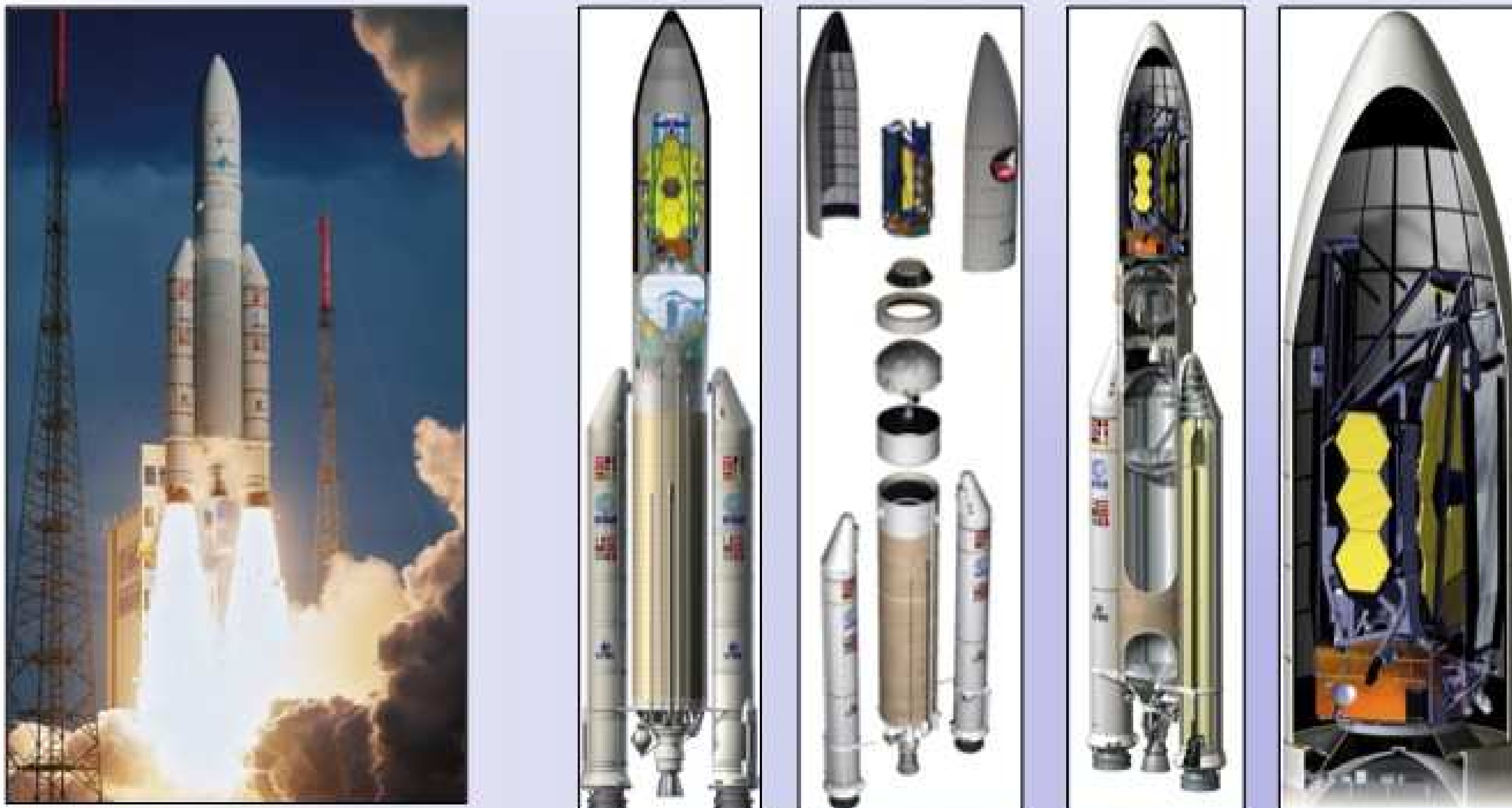


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.

The James Webb Space Telescope

JWST Launch

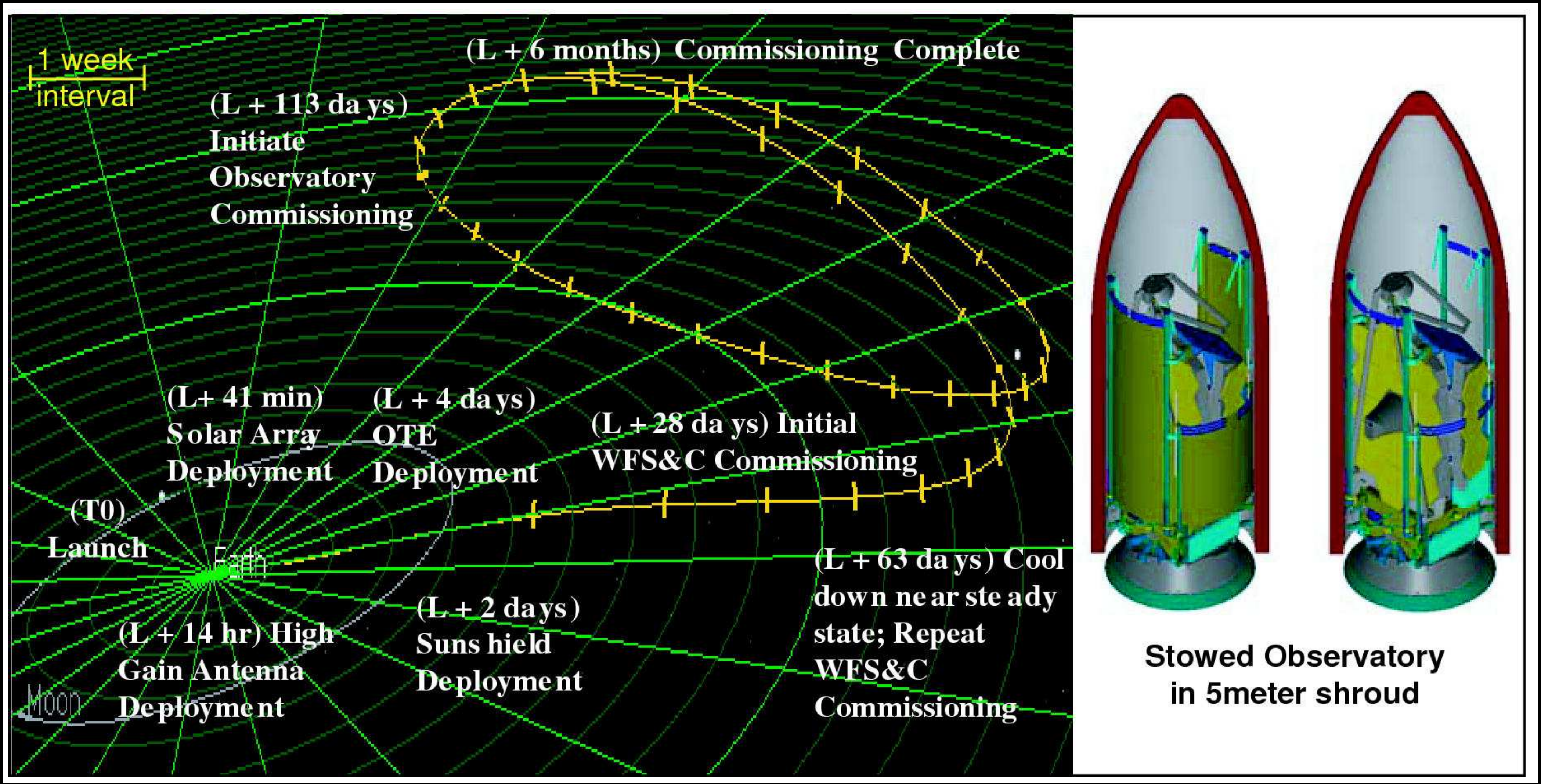
- Launch vehicle is an Ariane 5 rocket, supplied by ESA
- Site will be the Arianespace's ELA-3 launch complex near Kourou, French Guiana



Arianespace – ESA - NASA

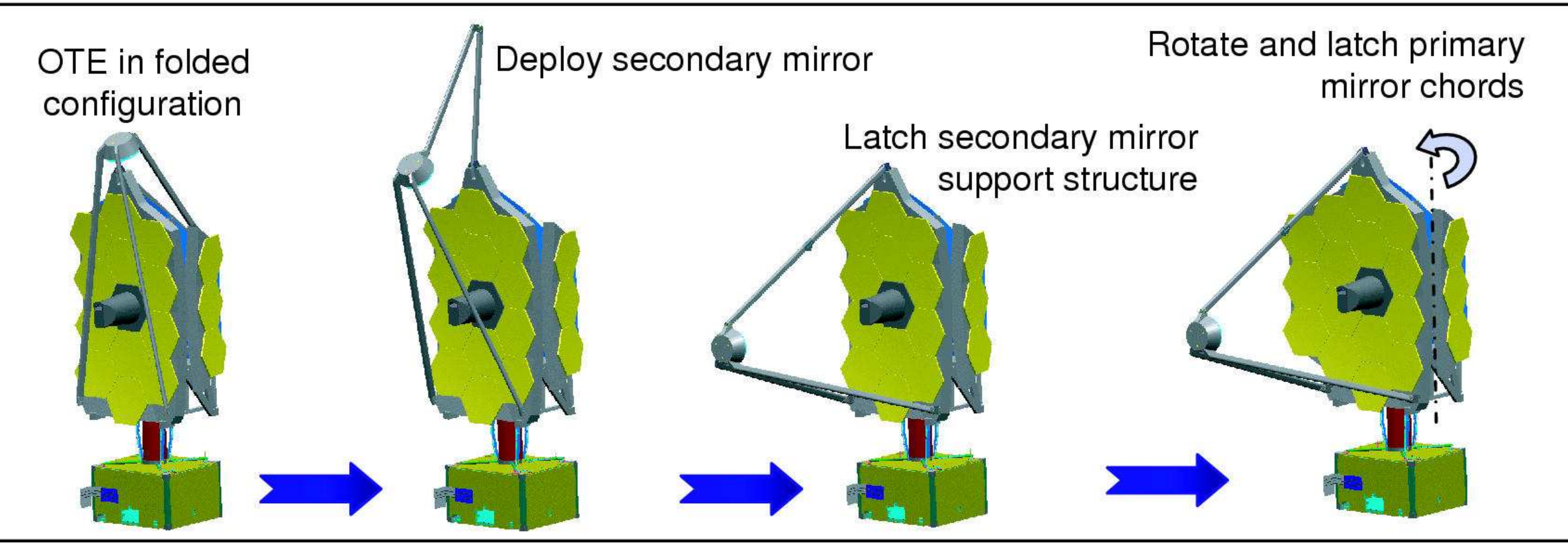
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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



- After launch in (Oct.) 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

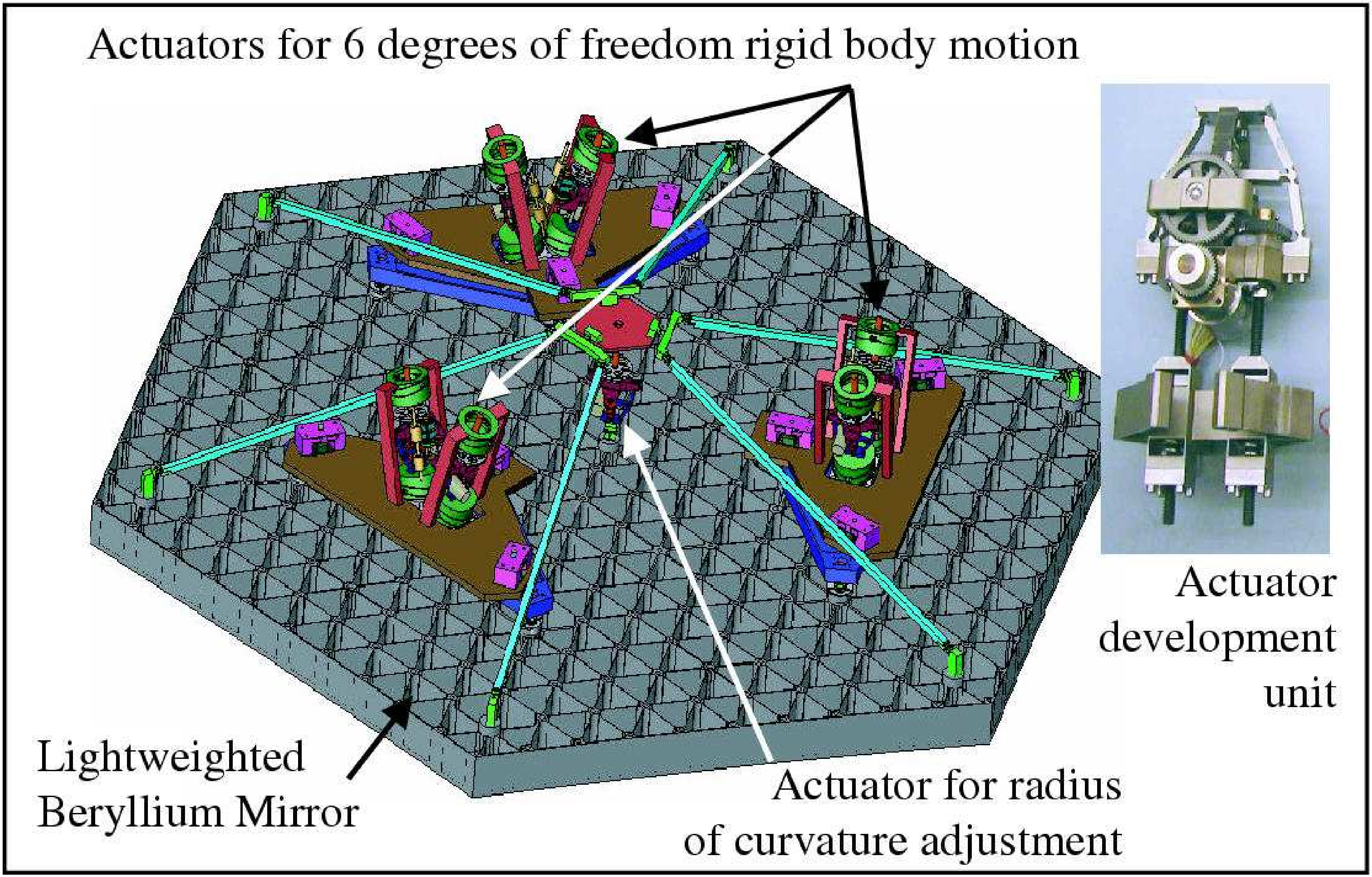
• (1b) How will JWST be automatically deployed?



• During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.

• The entire JWST deployment sequence is being tested several times on the ground — but only in 1-G: component and system tests in 2014–2016 at GSFC (MD), Northrop (CA), and JSC (Houston).

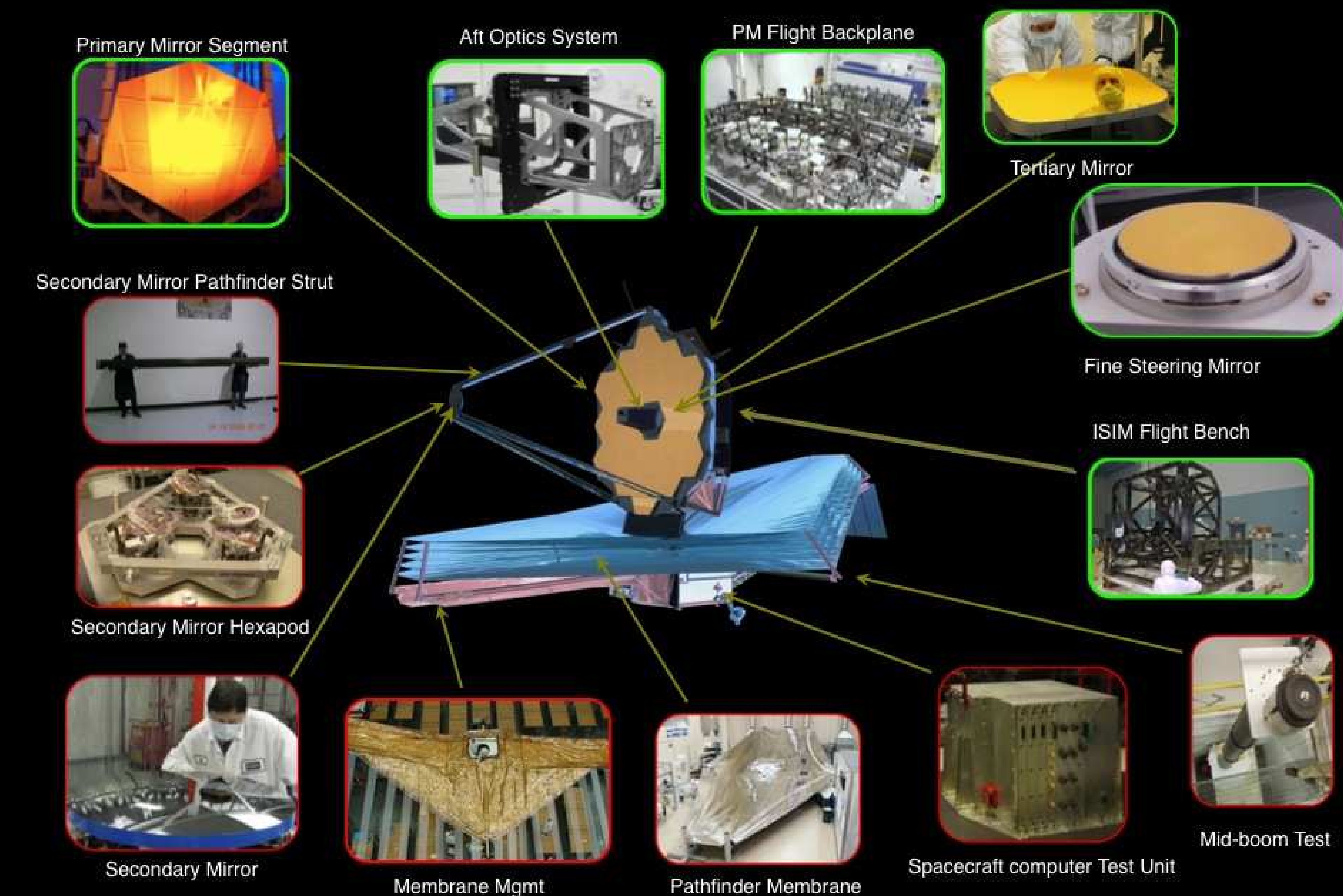
• Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



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

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

JWST Hardware Status

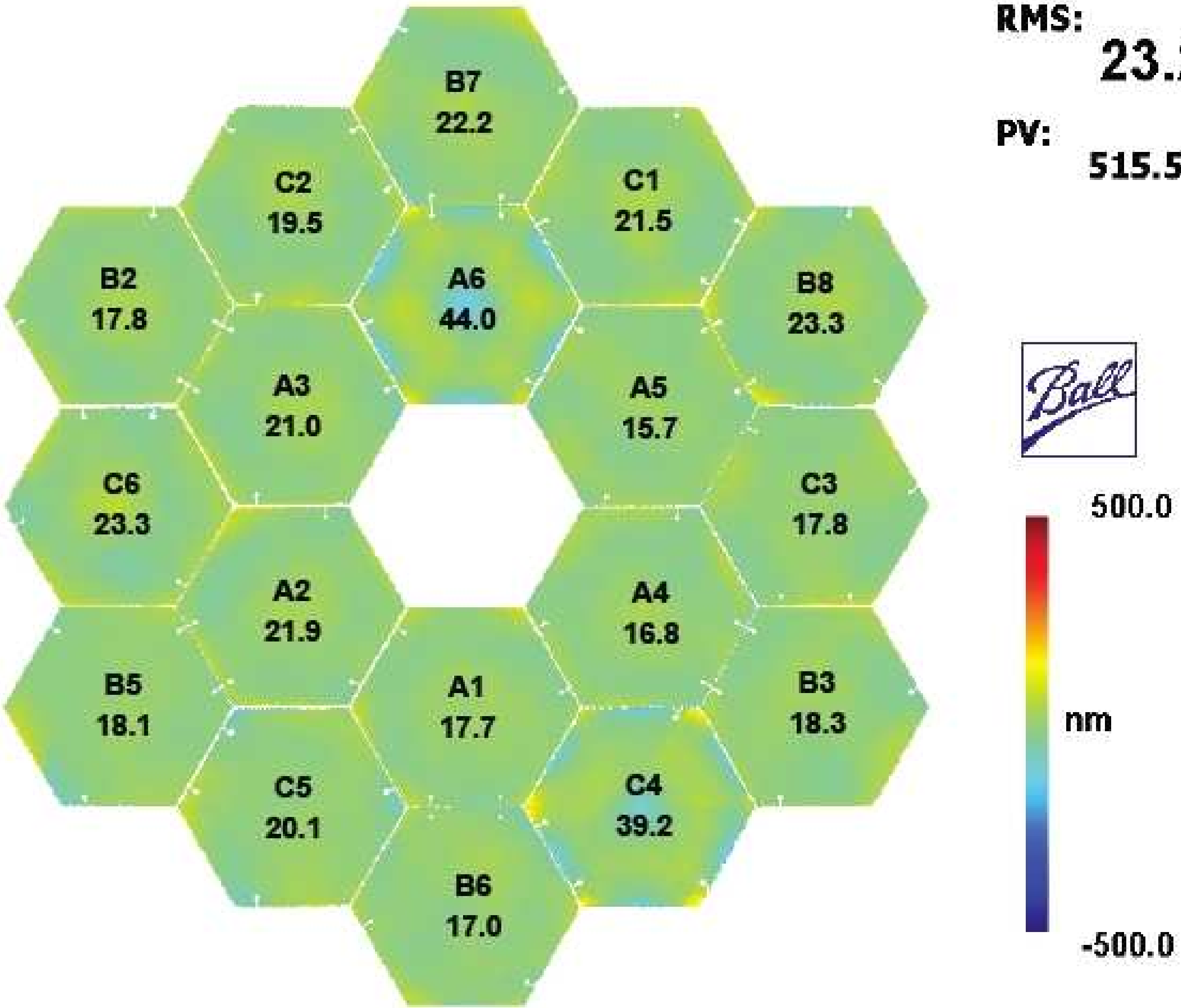


May 2015: $\gtrsim$98% of launch mass designed and built ($\gtrsim$65% weighed).

Mirror Acceptance Testing


Ball

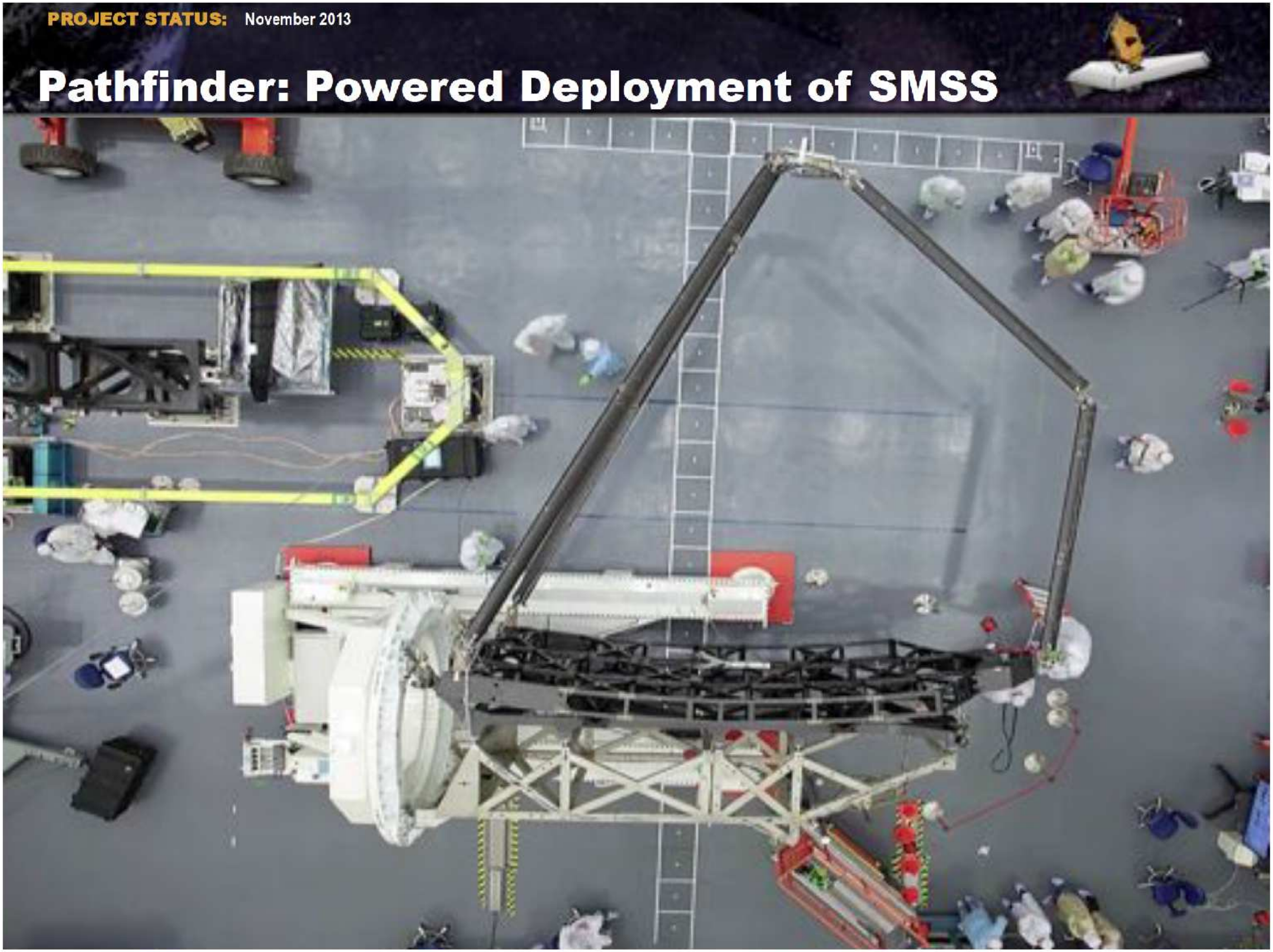
Primary Mirror Composite



Mirror Status

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

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



July 2014: Secondary Mirror Support deployment successfully tested.

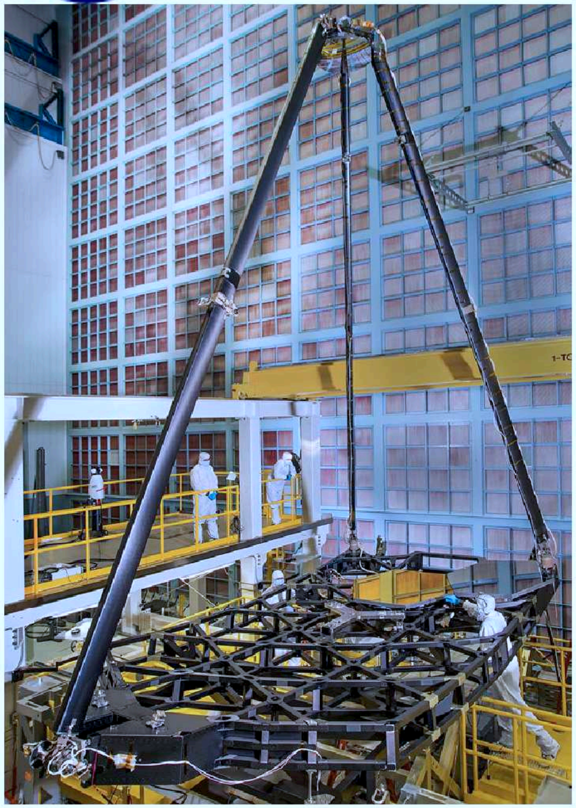
(1) JWST hardware to date, and how to best use it for high redshift lensing.

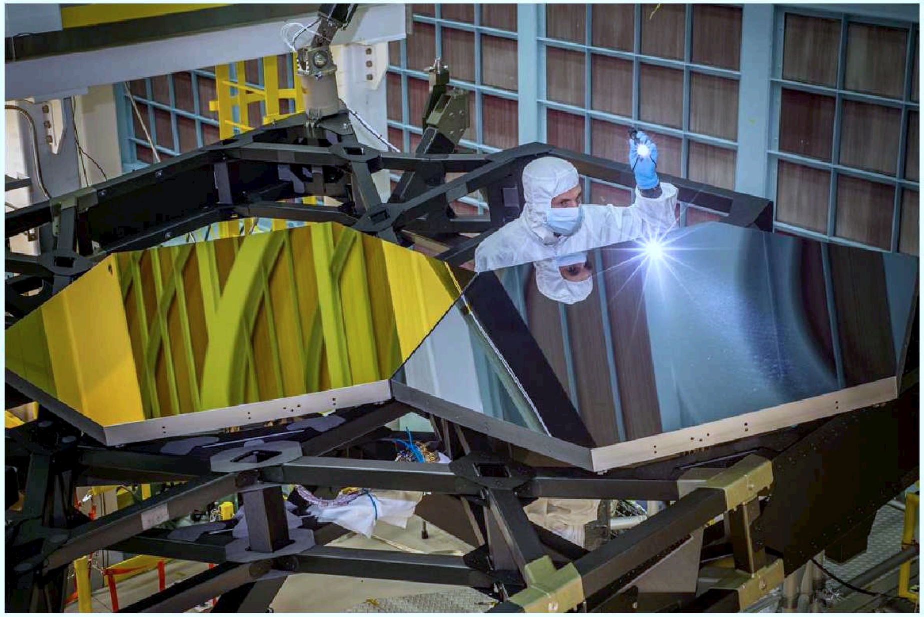
[LEFT]: Aug. 2014: Engineering Kapton Sunshield; 2015: Flight Sunshield.
[RIGHT]: Nov. 2014: First JWST mirrors mounted onto support structure, using Engineering Demo mirrors — Flight mirrors to be mounted in 2015.

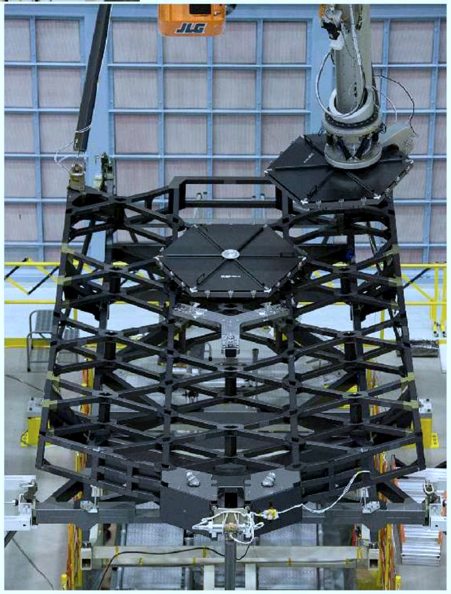
- Our Galaxy is a bright IR source at $\lambda \gtrsim 1$–5μm: In certain directions of sky, some straylight can hit secondary mirror via Sunshield: $\lesssim$40% of Zodi.

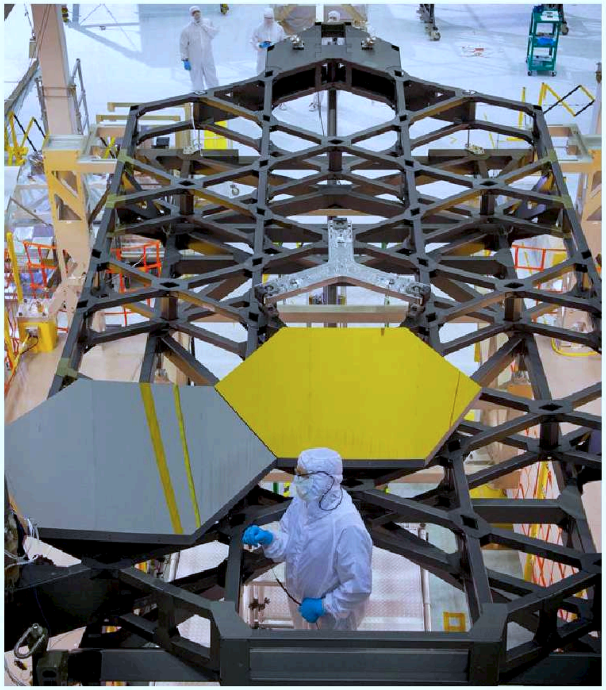
What does this mean for JWST lensing studies of First Light objects?

Telescope Pathfinder – Risk Reduction



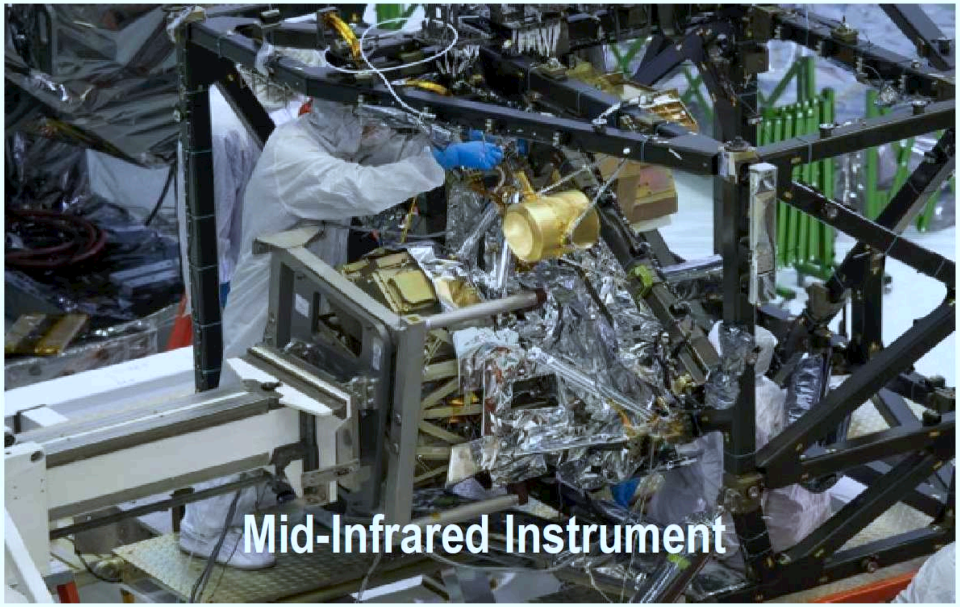


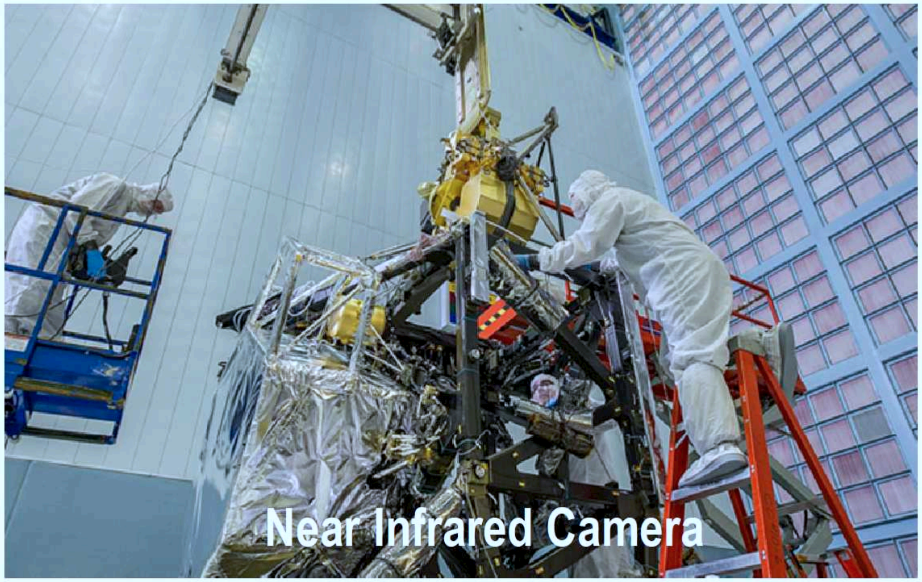


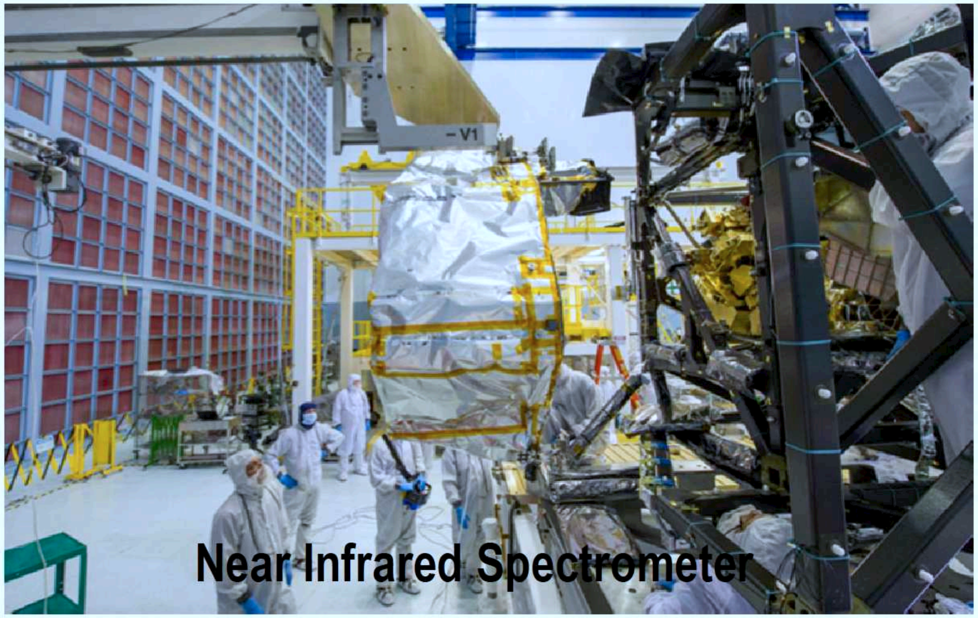


JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

All Instruments Integrated





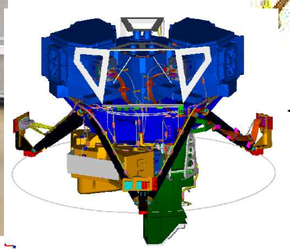


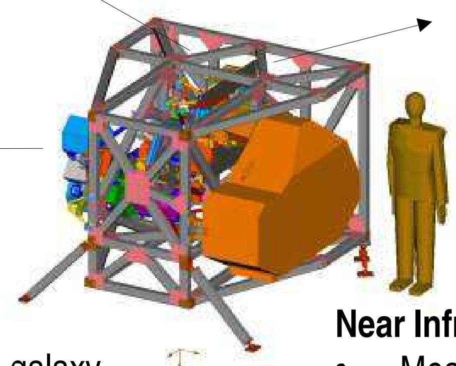
(1c) JWST instrument update: US (UofA, JPL), ESA, & CSA.

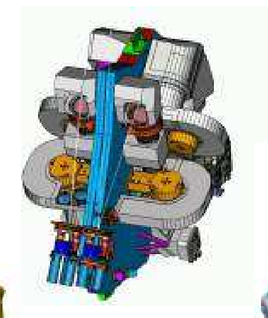
Instrument Overview

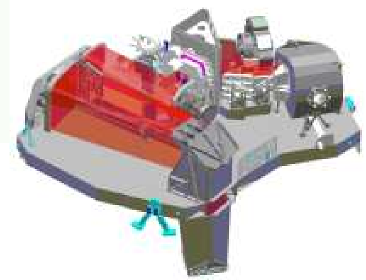
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

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





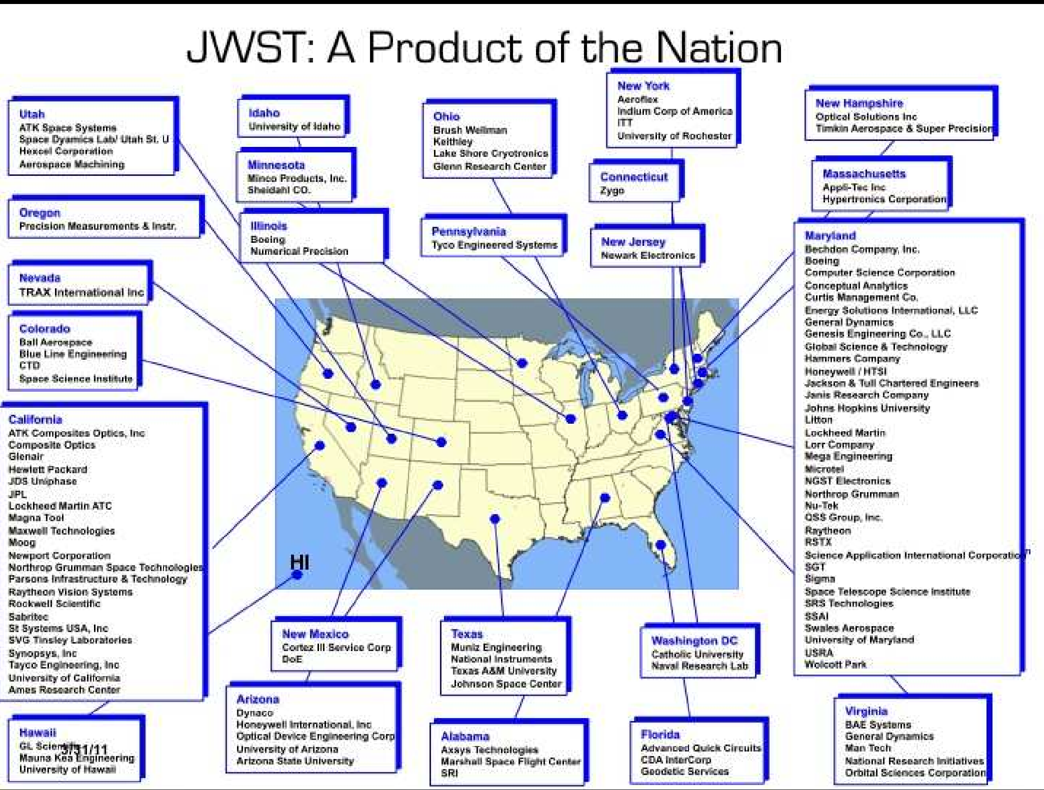


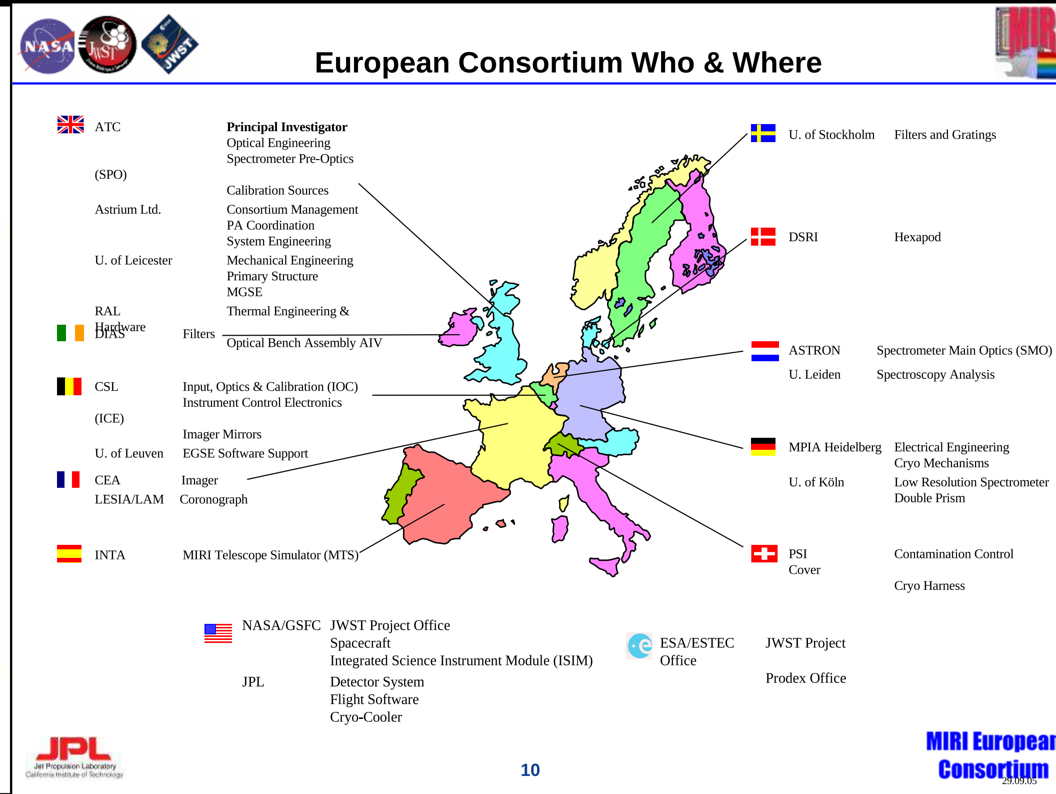


Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

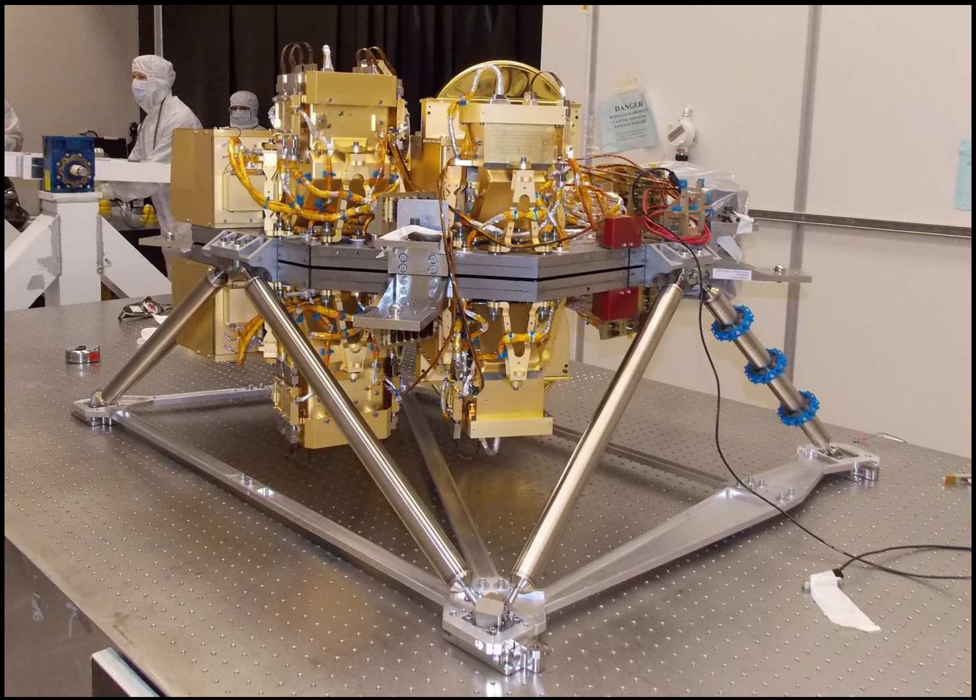
Near Infra-Red Spectrograph (NIRSpec)
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

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



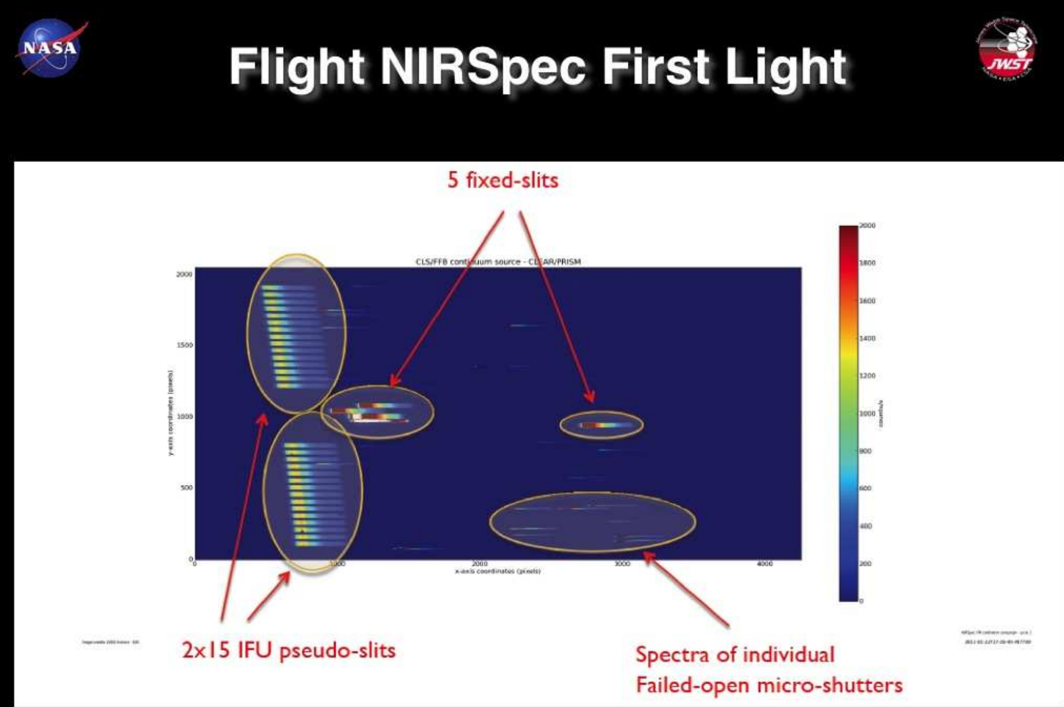


- JWST hardware made in 27 US States: $\gtrsim$98% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.




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 07/13.
- Detectors replaced in 2015 between CryoVacuum tests CV2 and CV3.



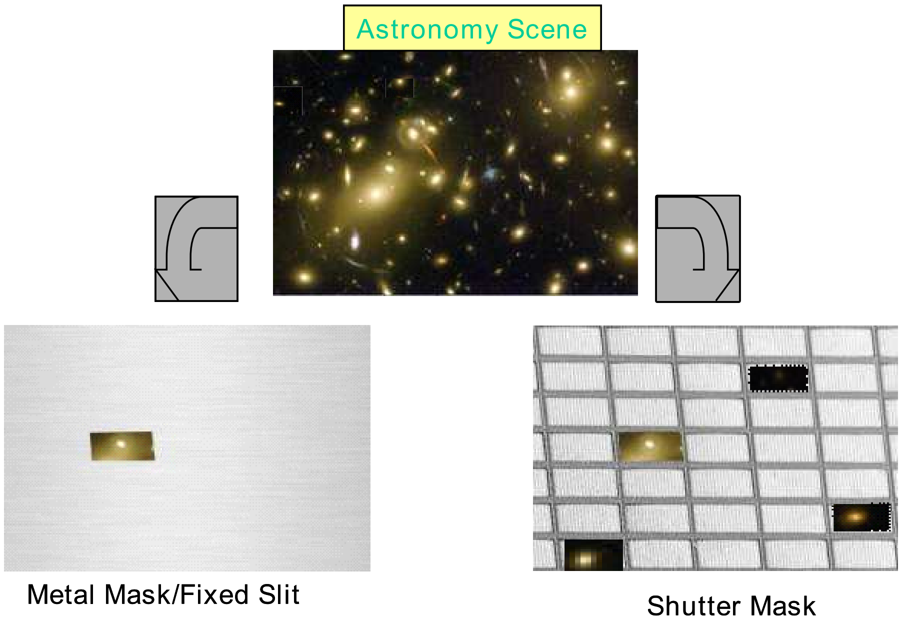
JWST's short-wavelength (0.6–5.0μm) spectrograph:

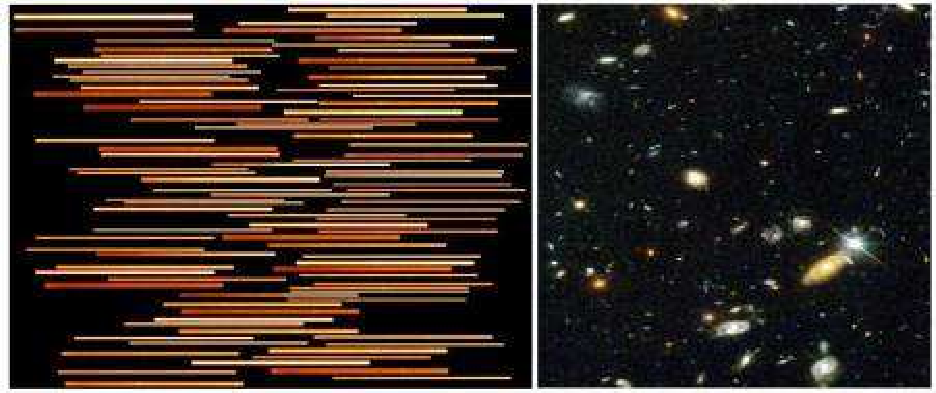
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

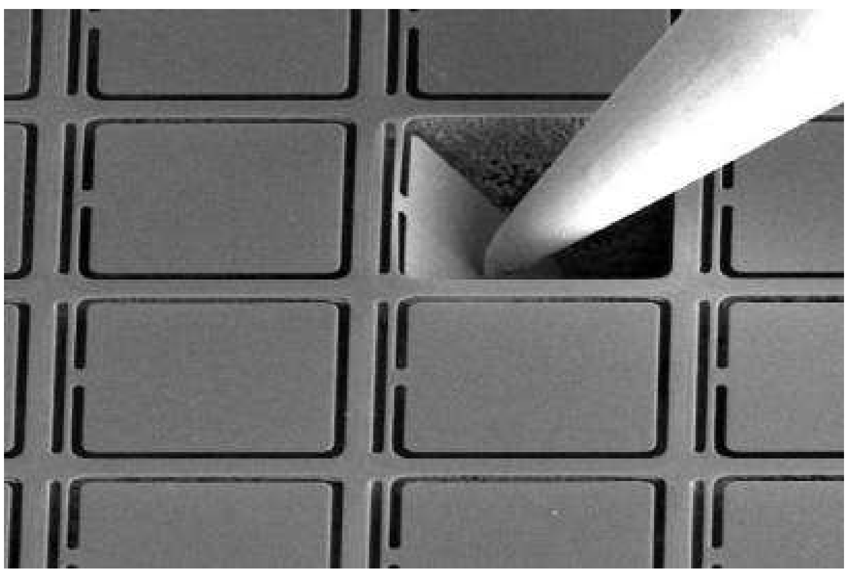
NIRSpec delivered to NASA/GSFC in 09/13.

- Detectors replaced in 2015 between CryoVacuum tests CV2 and CV3.

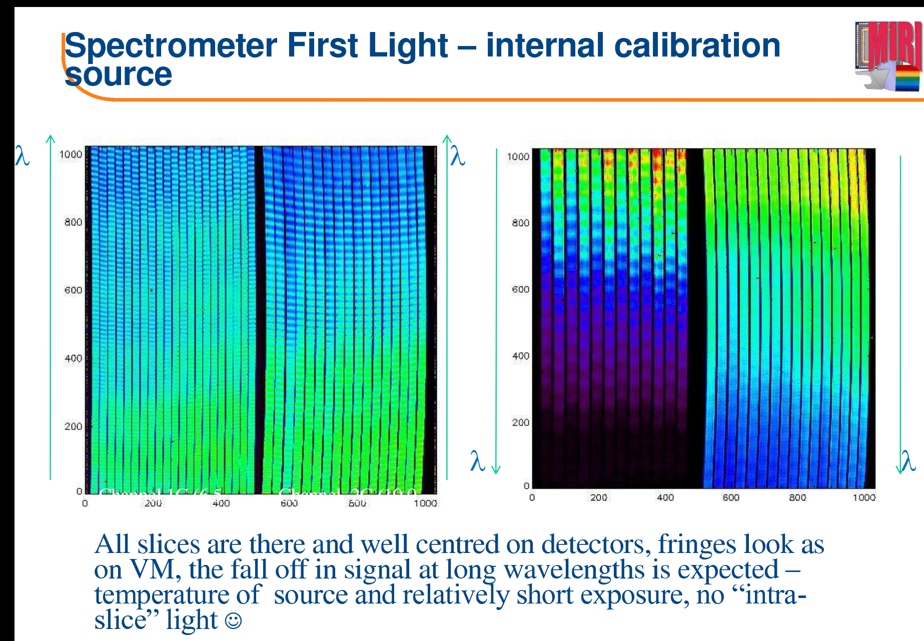
Micro Shutters







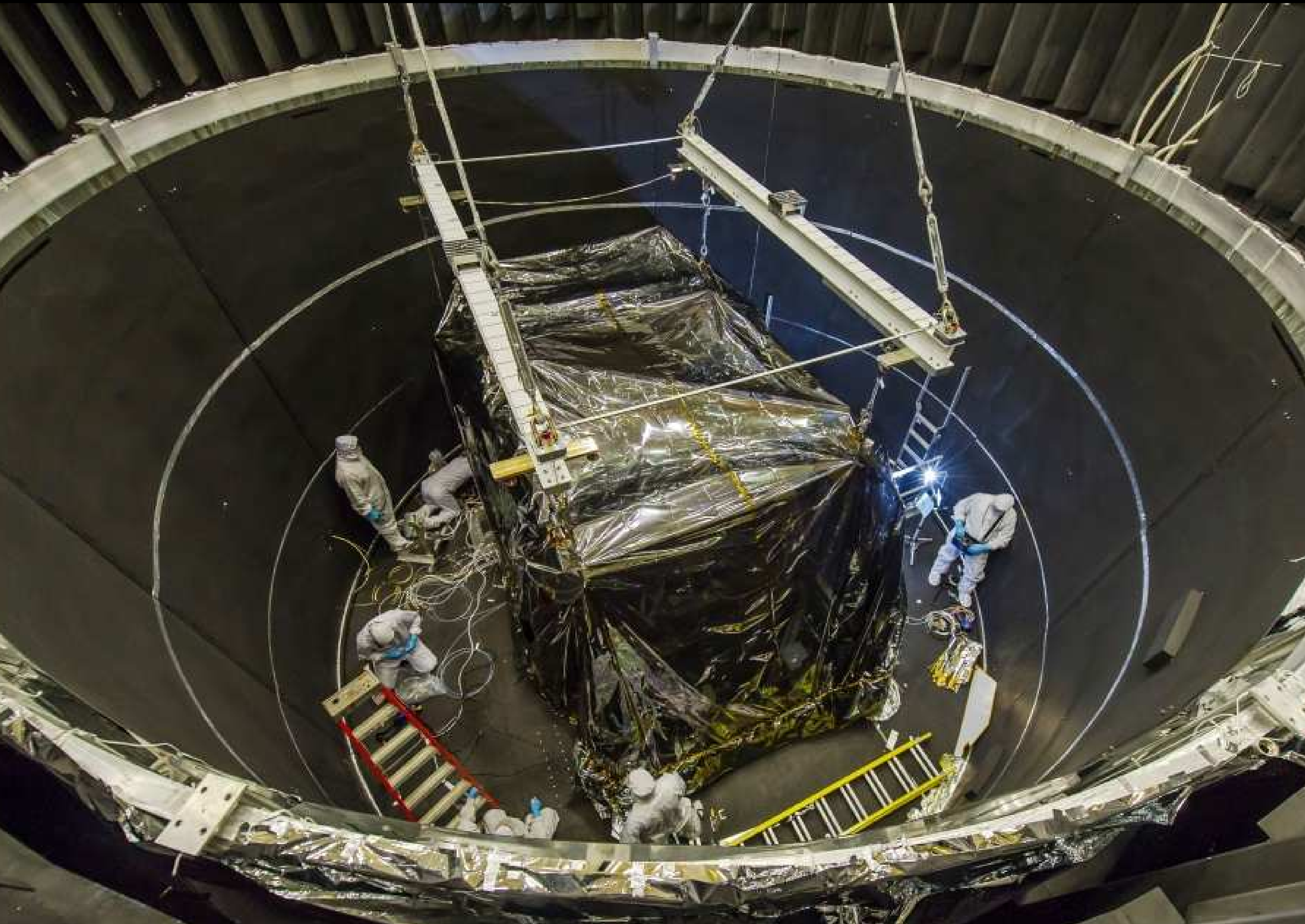
Flight MIRI



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

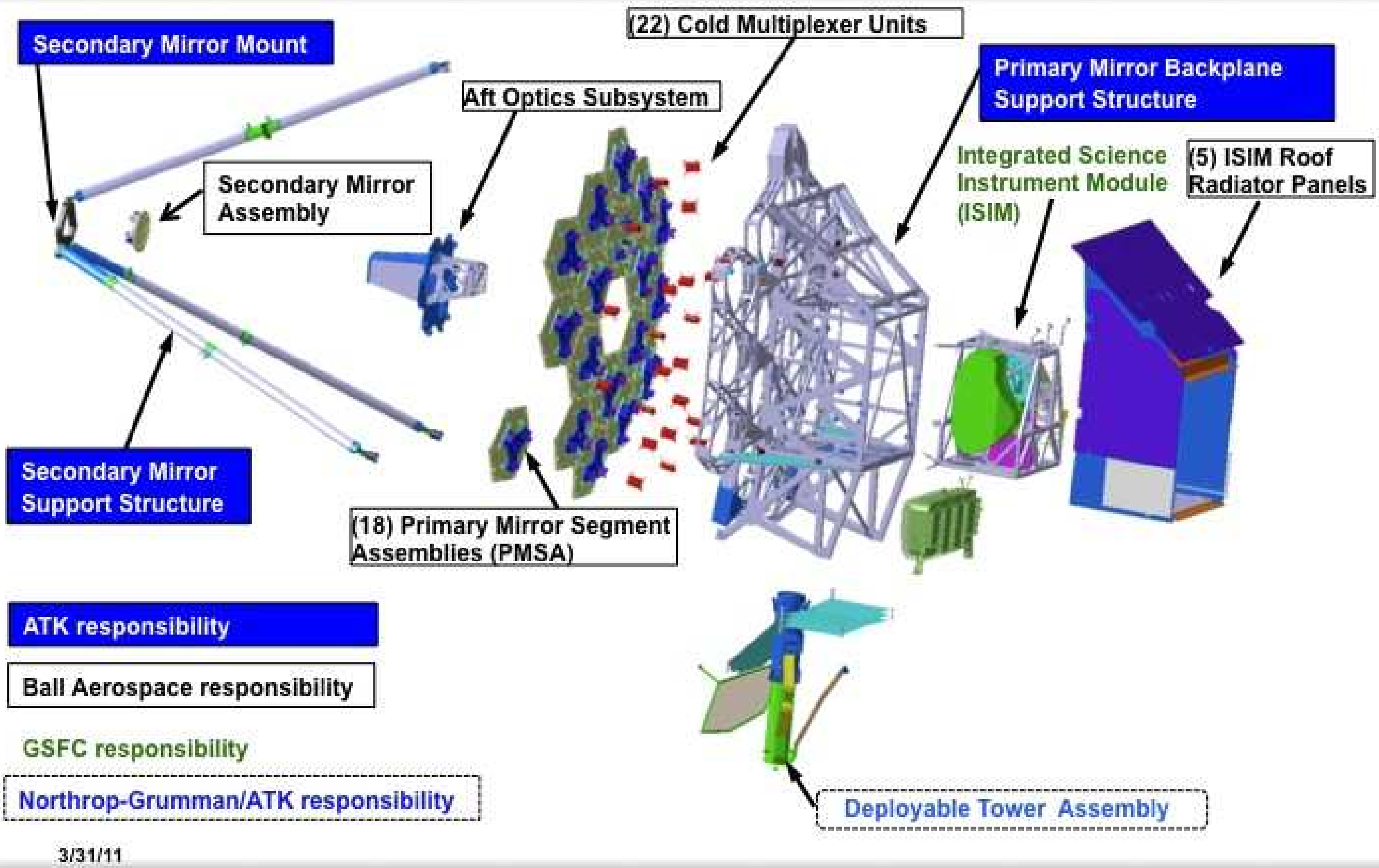
- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in 05/12.

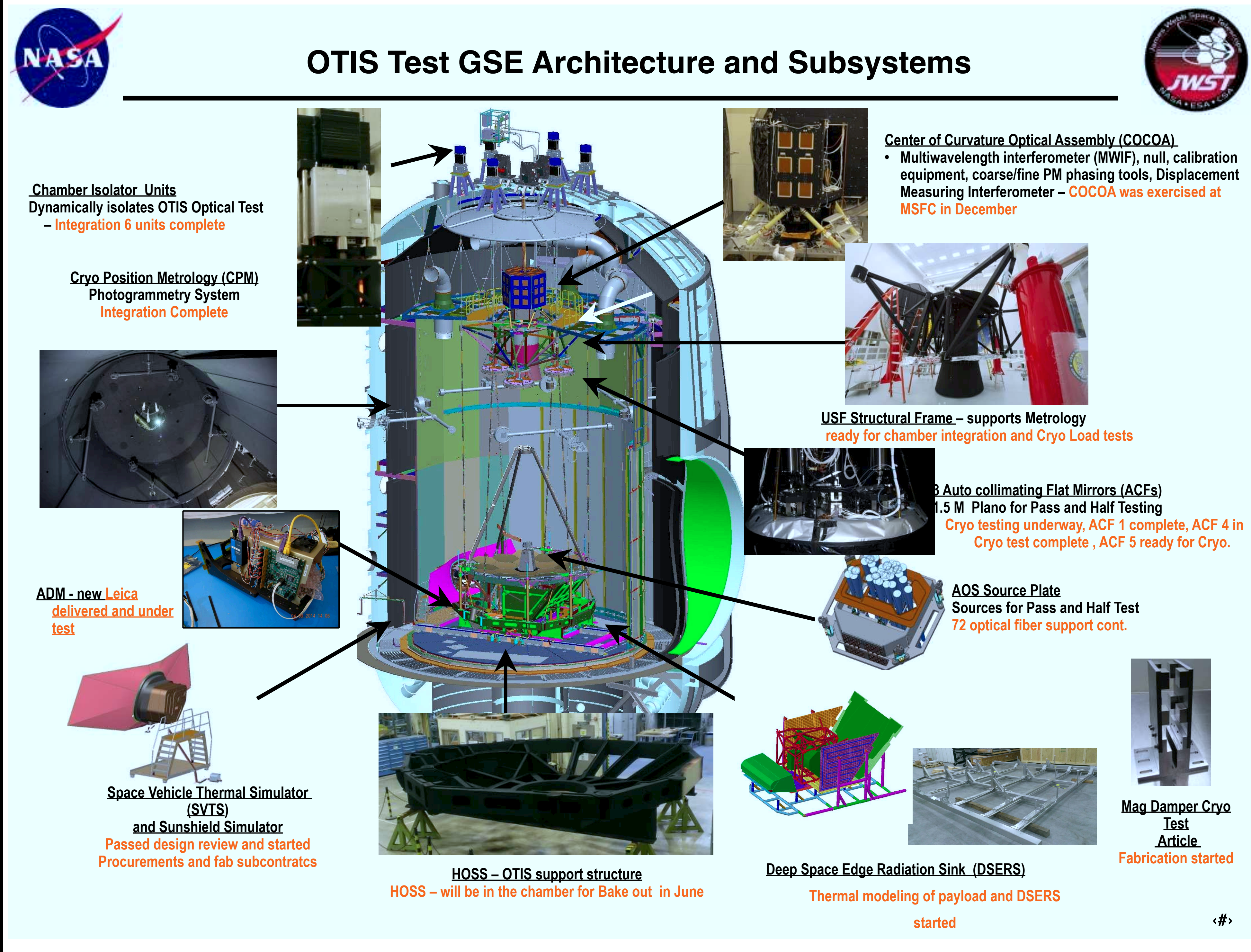


June 2014: Flight ISIM (with all 4 instruments) in OSIM; Aug. 2015: CryoVac3.

TELESCOPE ARCHITECTURE

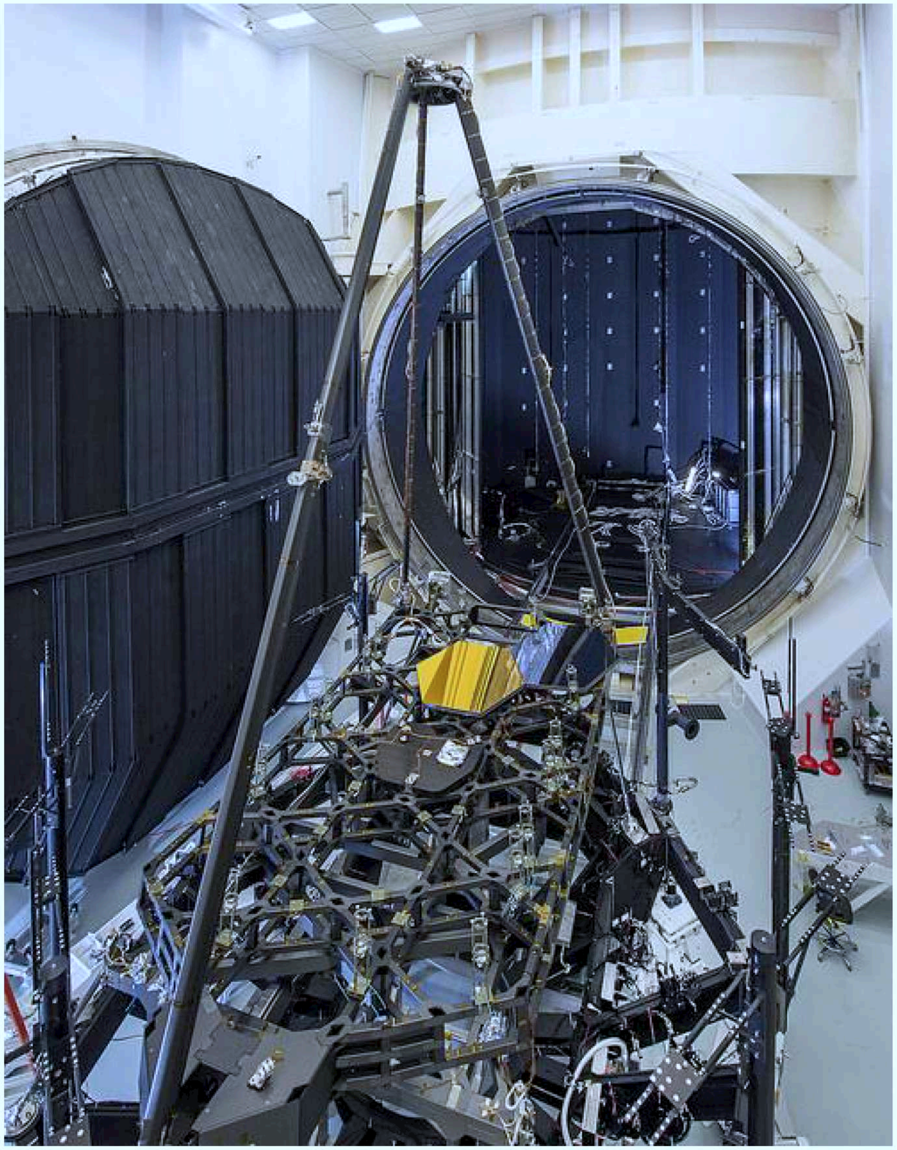


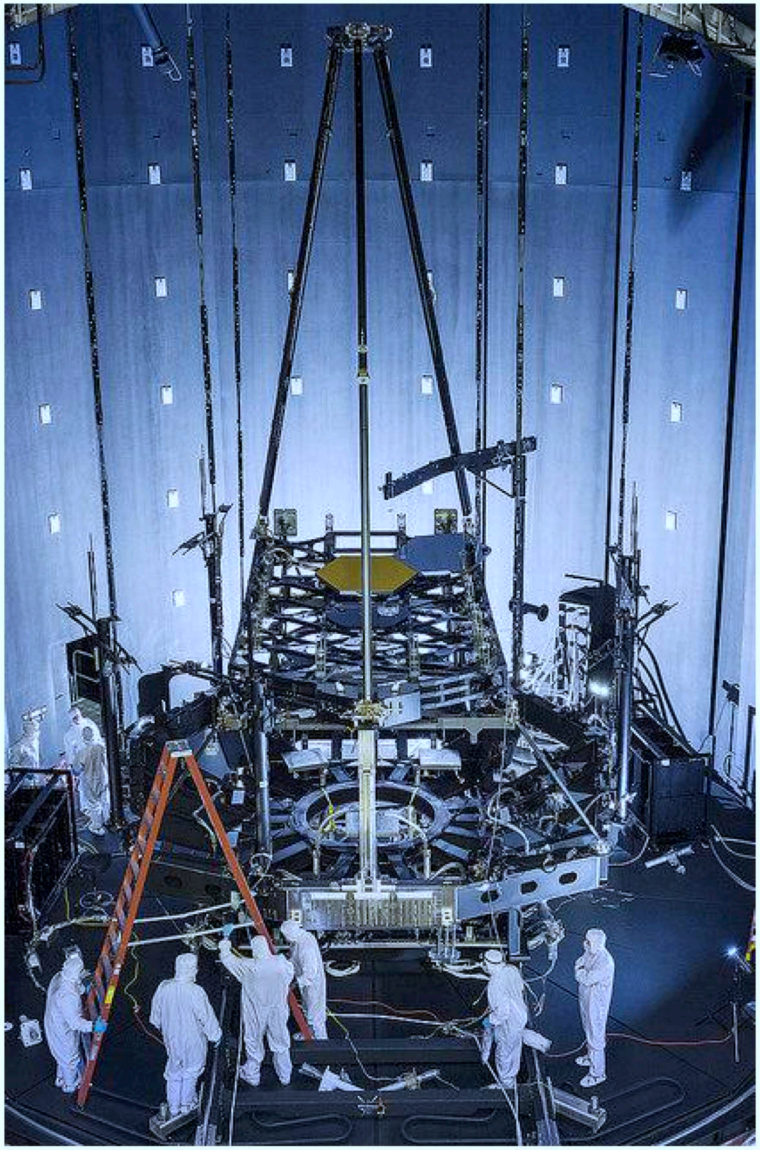
2014–2016: Complete system integration at GSFC and Northrop.



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

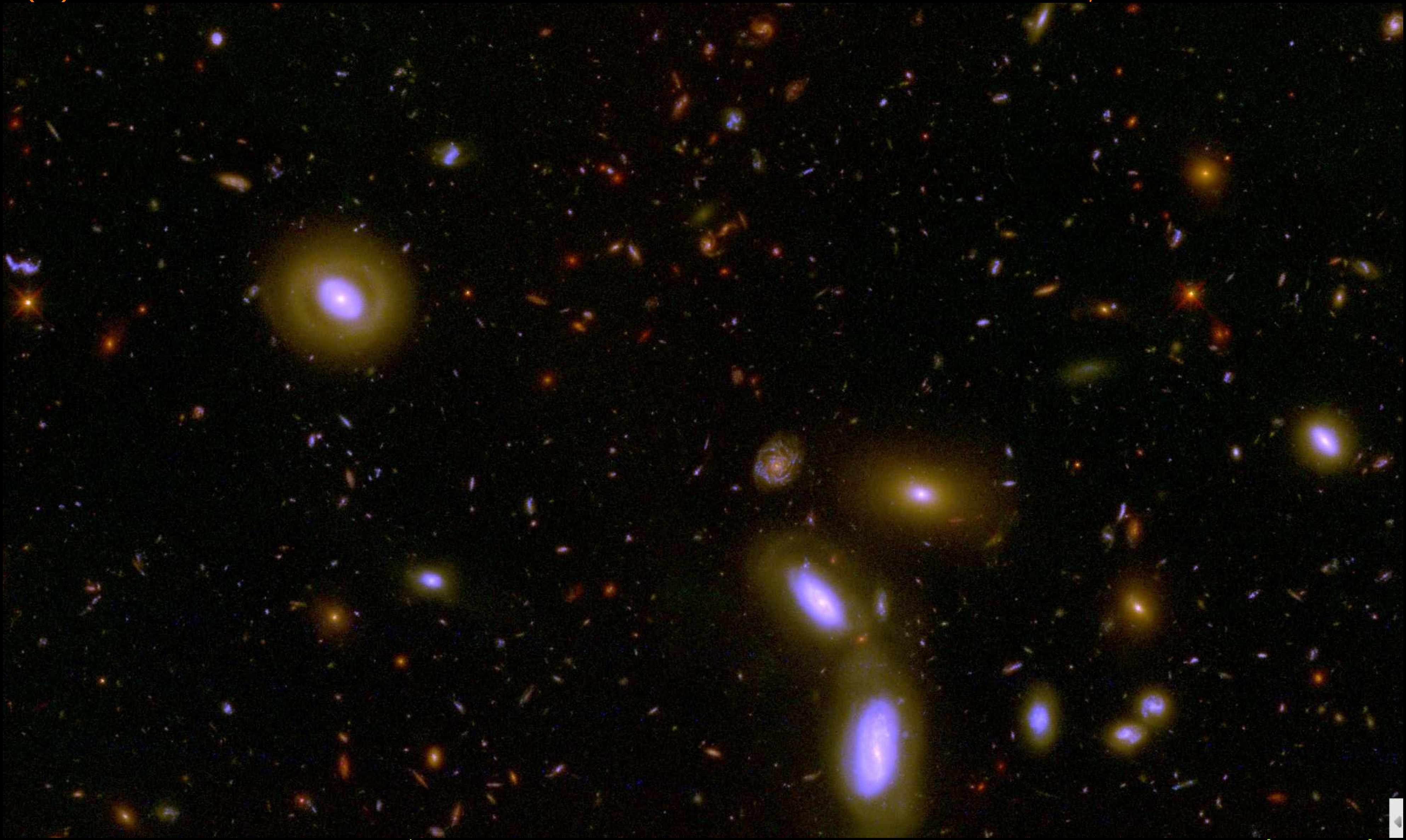
Pathfinder & JSC Chamber A: getting ready for OGSE1 (and eventually OGSE2 & Thermal Pathfinder)





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

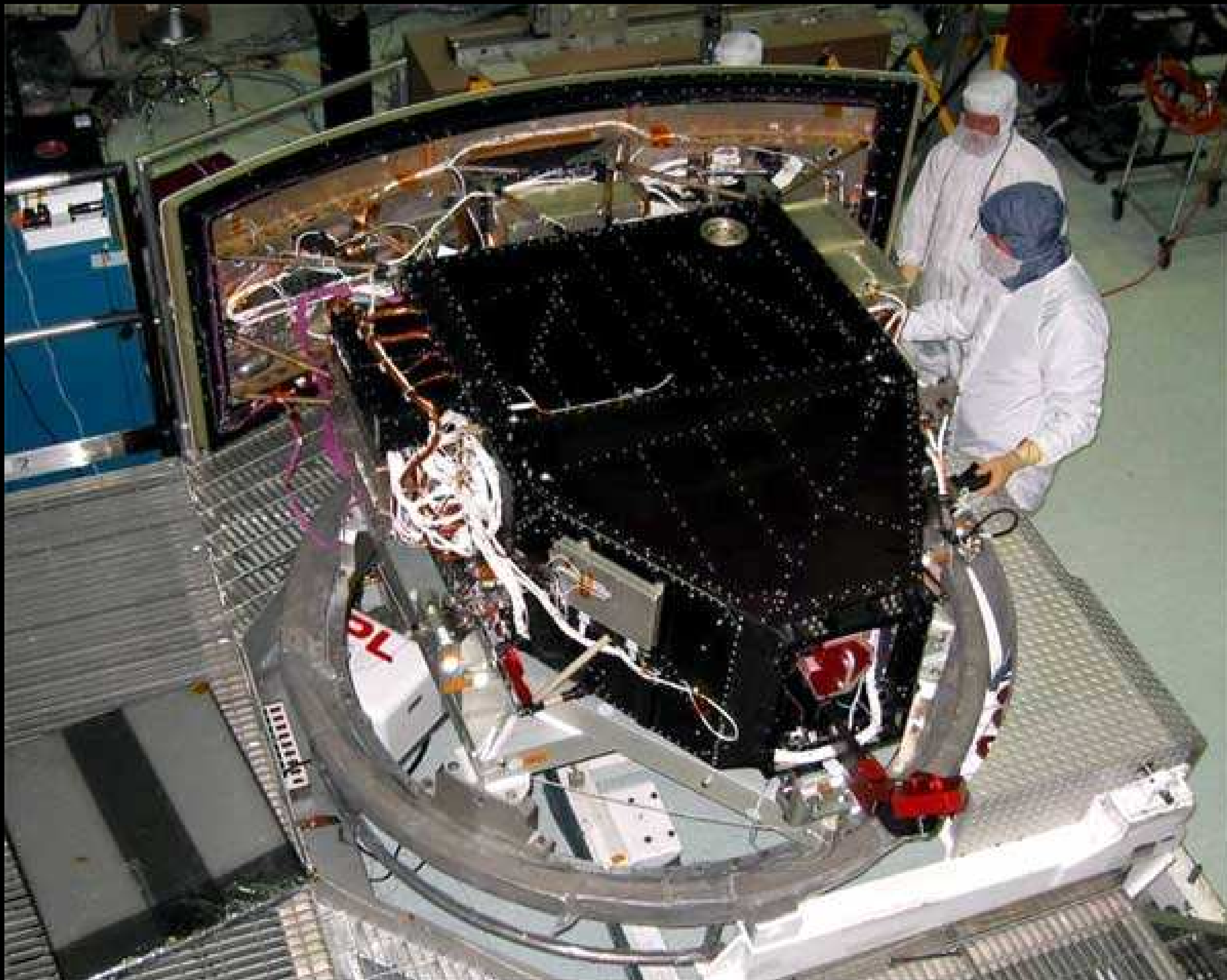
(2) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?



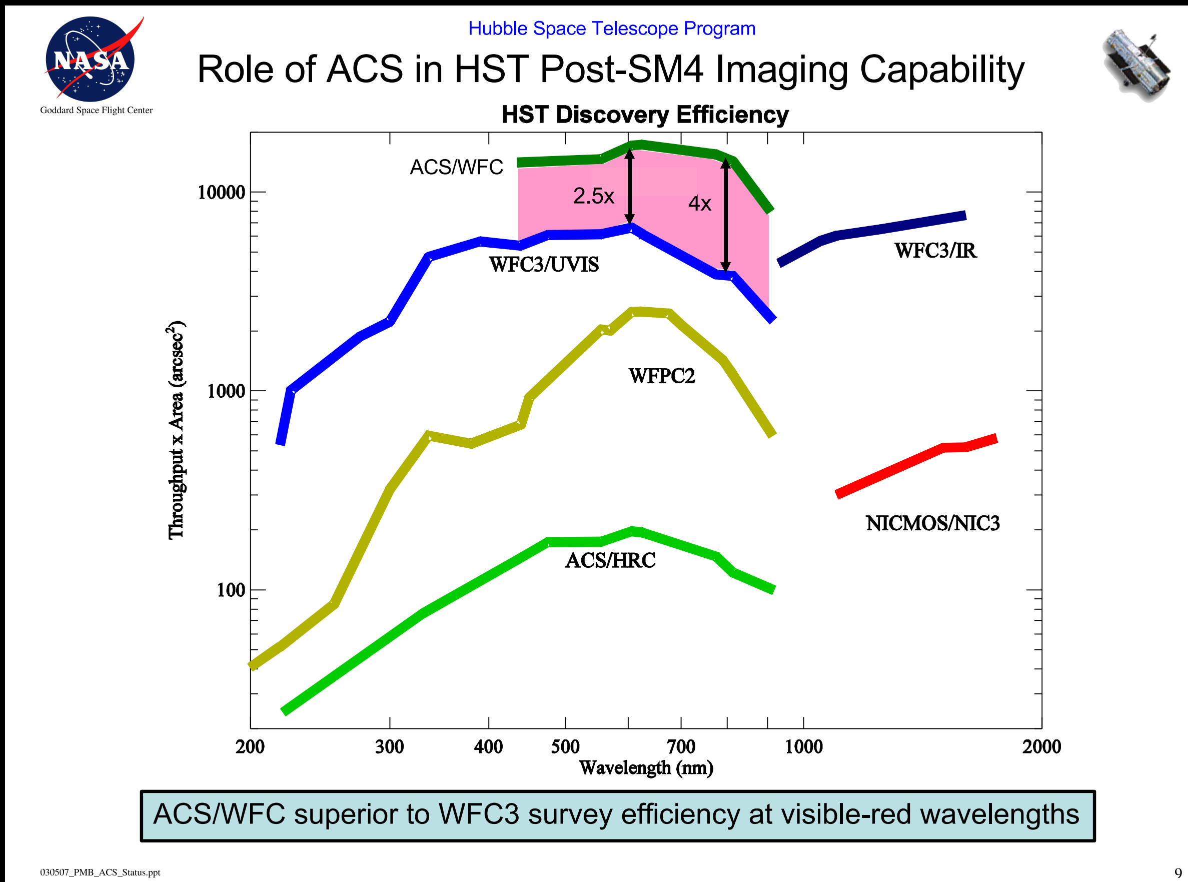
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

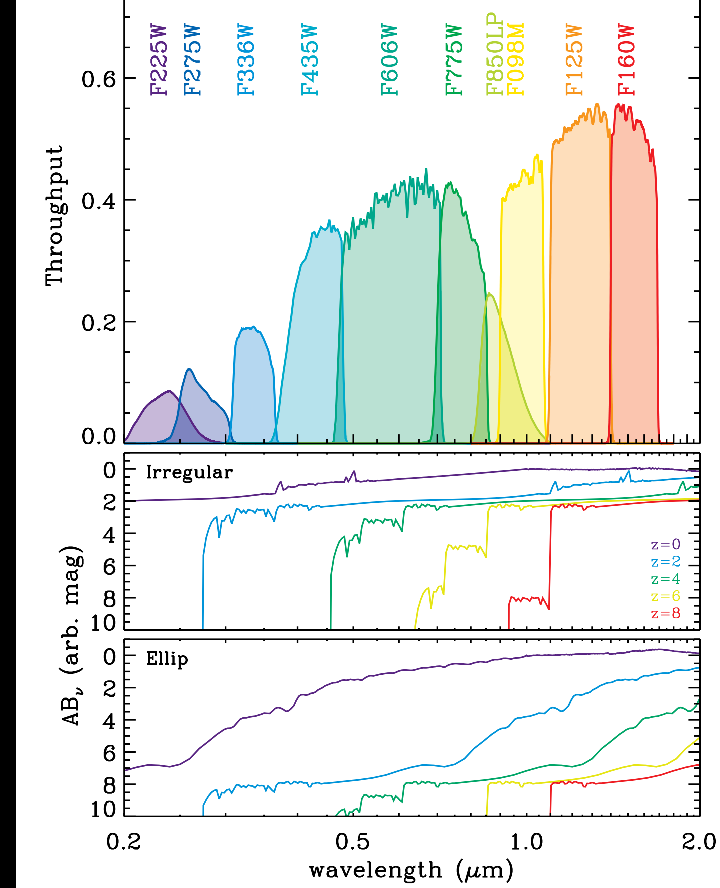
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

(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 $0\farcs04$ pixel, FOV $\simeq 2\farcm67 \times 2\farcm67$.

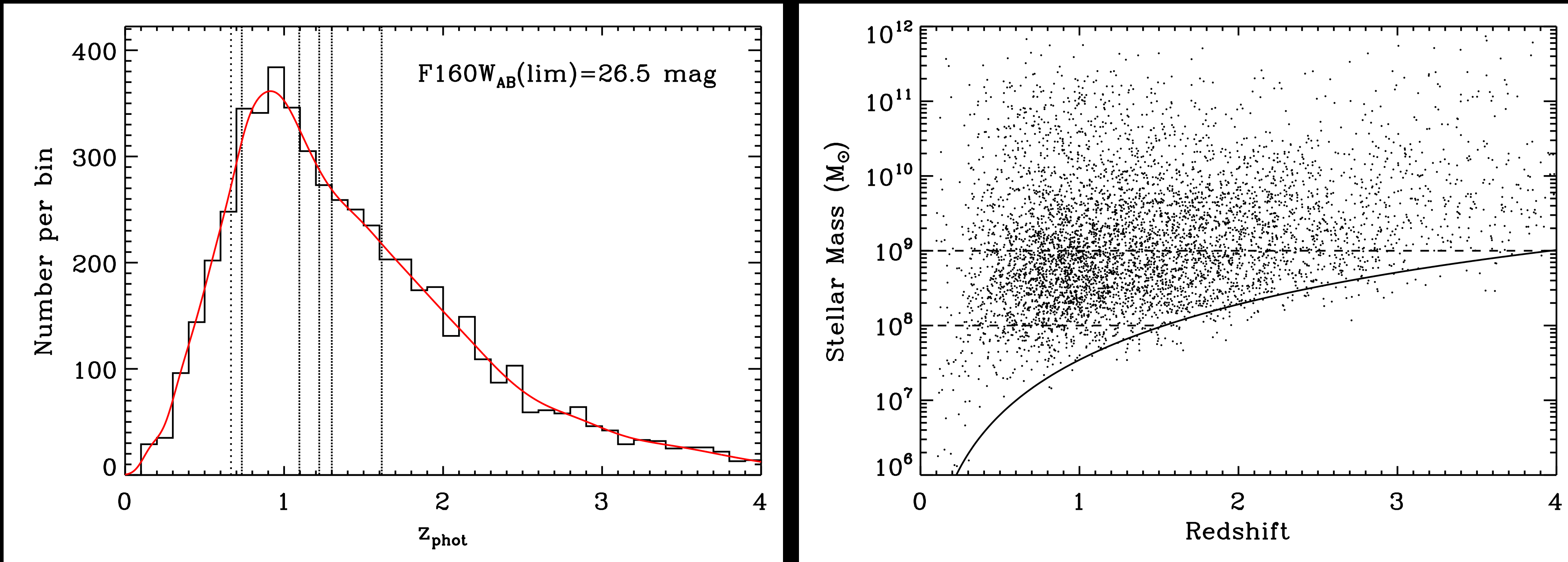
WFC3/IR channel unprecedented near–IR throughput & areal coverage:

- 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.



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).

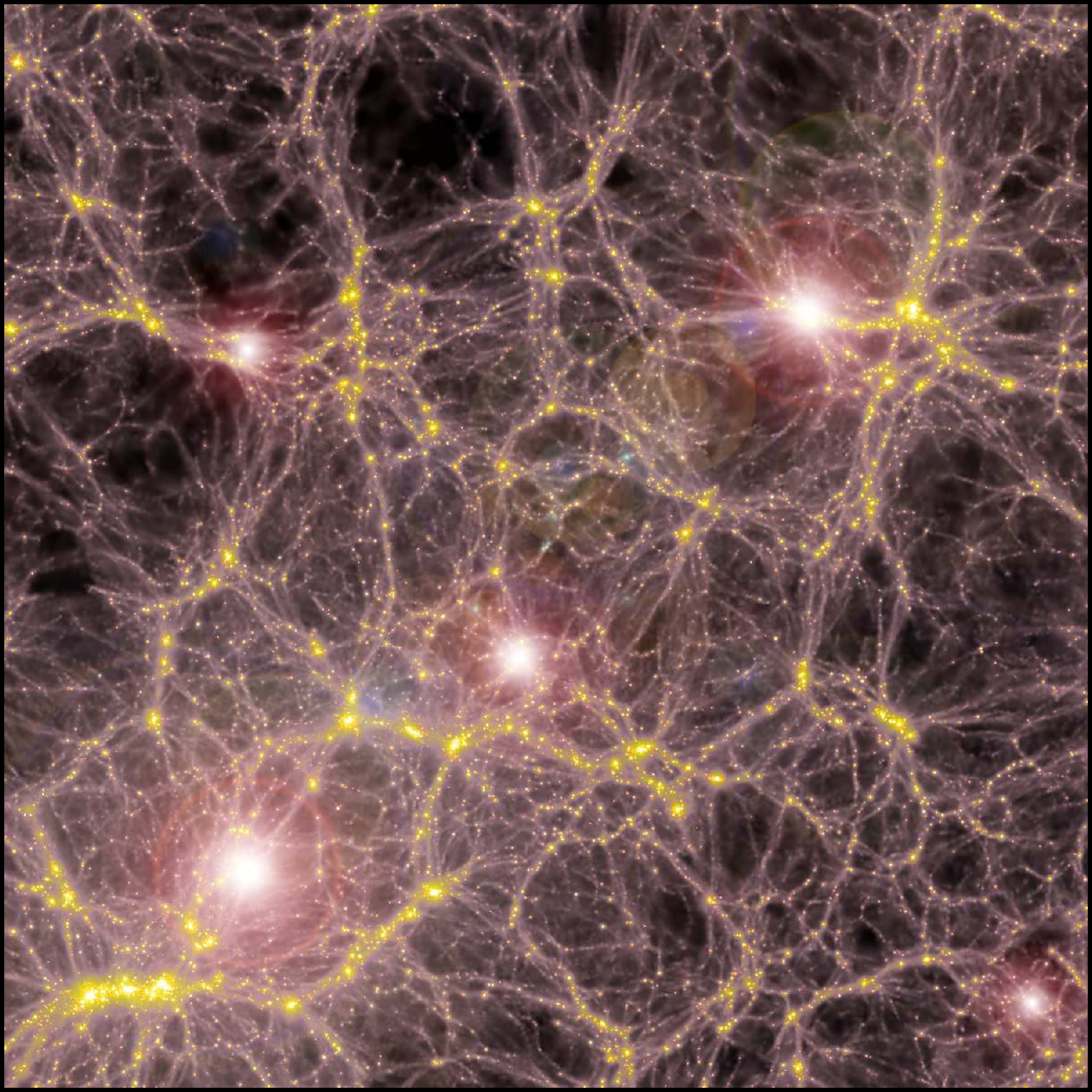
- Measure masses of faint galaxies to AB=26.5 mag, tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

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

- HUDF shows WFC3 z$\simeq$7–9 capabilities (Bouwens$^+$ 2014; 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?

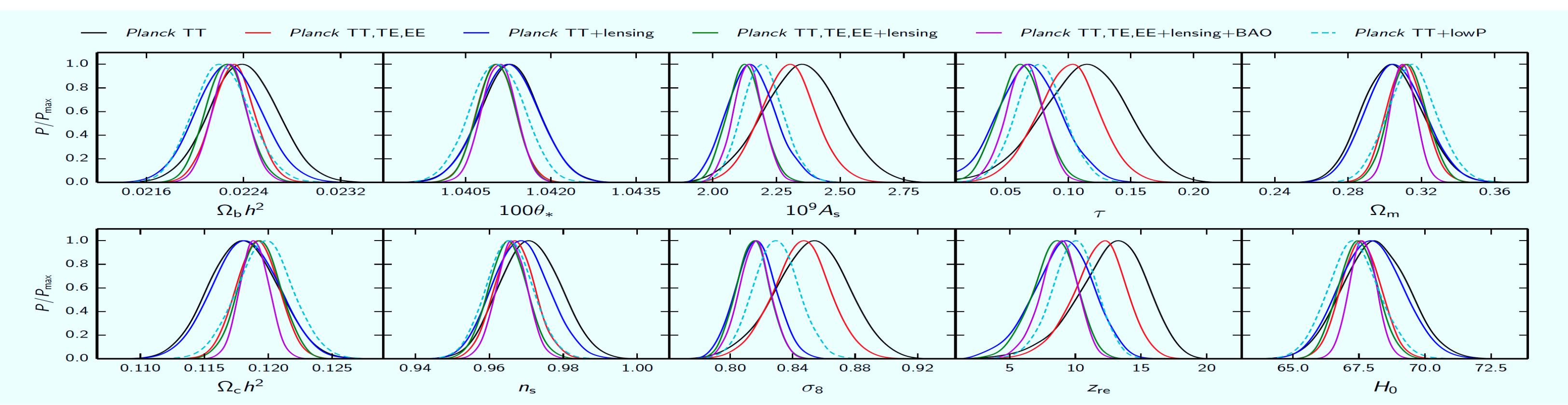


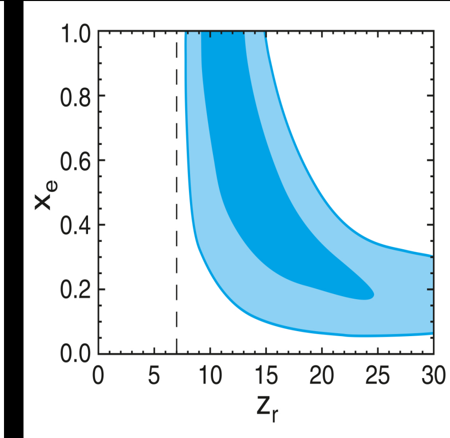
- Detailed cosmological models (V. Bromm) suggest that massive "Pop III" stars ($\gtrsim$100 M_{sun}) started to reionize the universe at z$\lesssim$10–30 (First Light).

- 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 IMF, their duplicity and clustering properties, their SN-rates, etc., before JWST flies, so we know what to look for.

Implications of WMAP year-9 & Planck 2015 results for JWST science:





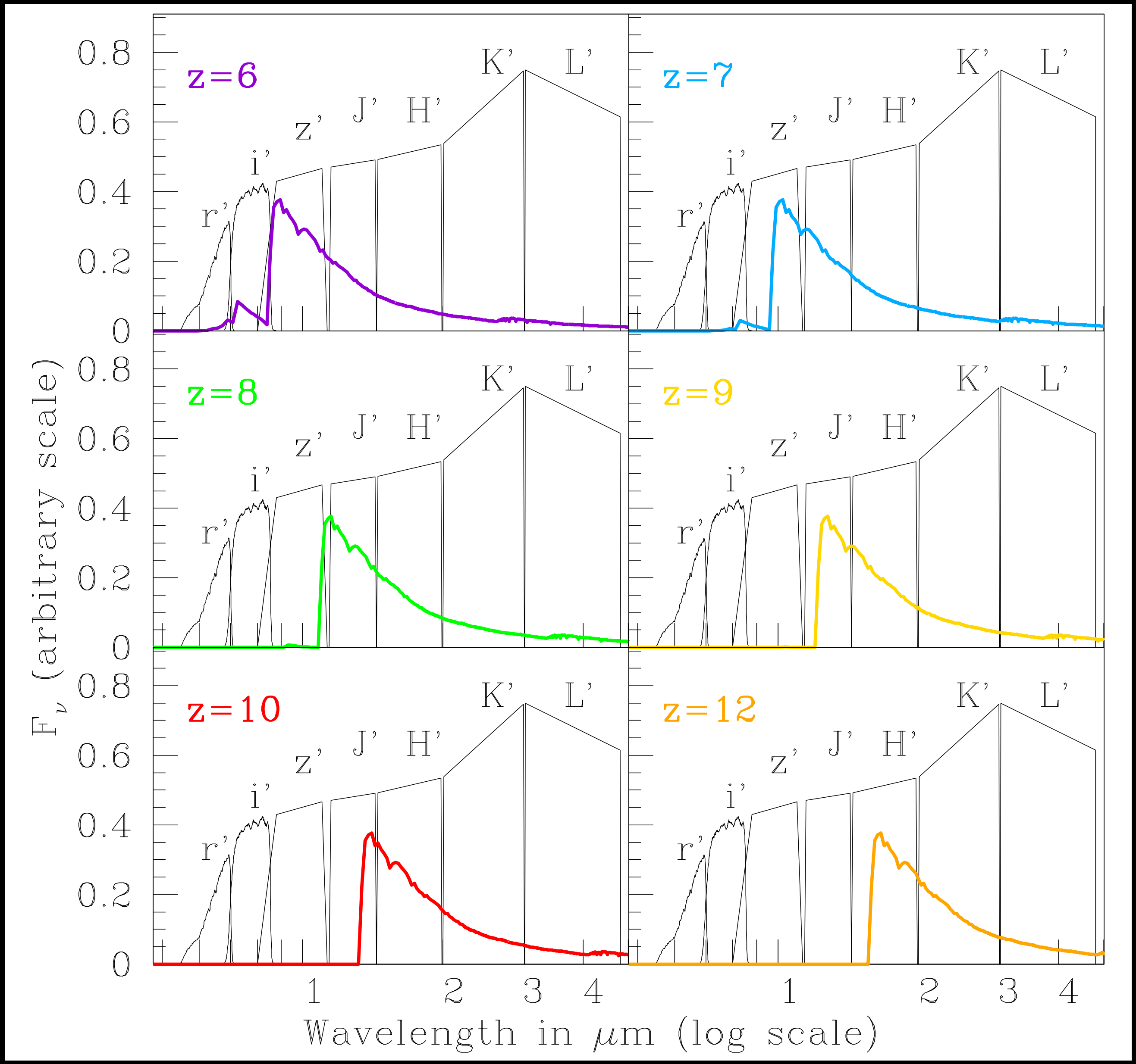
HST/WFC3 z$\lesssim$7–10 ⟵ ⟶ JWST z$\simeq$8–25

The year-9 WMAP and Planck 2015 data provided better foreground removal (Komatsu+ 2011; Hinshaw+ 2012; Planck VIII 2015):

⟹ First Light & Reionization occurred between these extremes:

- (1) Instantaneous: z$\simeq$8.8$\pm$1.5 (pol. optical depth $\tau\simeq$0.066$\pm$0.016), or:
- (2) Inhomogeneous & drawn out: starting at z$\gtrsim$20, peaking at z$\lesssim$9–10, ending at z$\simeq$7. The implications for HST and JWST are:
- HST/ACS has covered z$\lesssim$6, and WFC3 is covering z$\lesssim$7–10.
- JWST designed to survey First Light/Reionization from z$\simeq$8 to z$\simeq$15–20.
- Since Planck 2015's polarization τ has come down considerably ($\tau\simeq$0.066), how many reionizers will JWST actually see at z$\simeq$10–15?

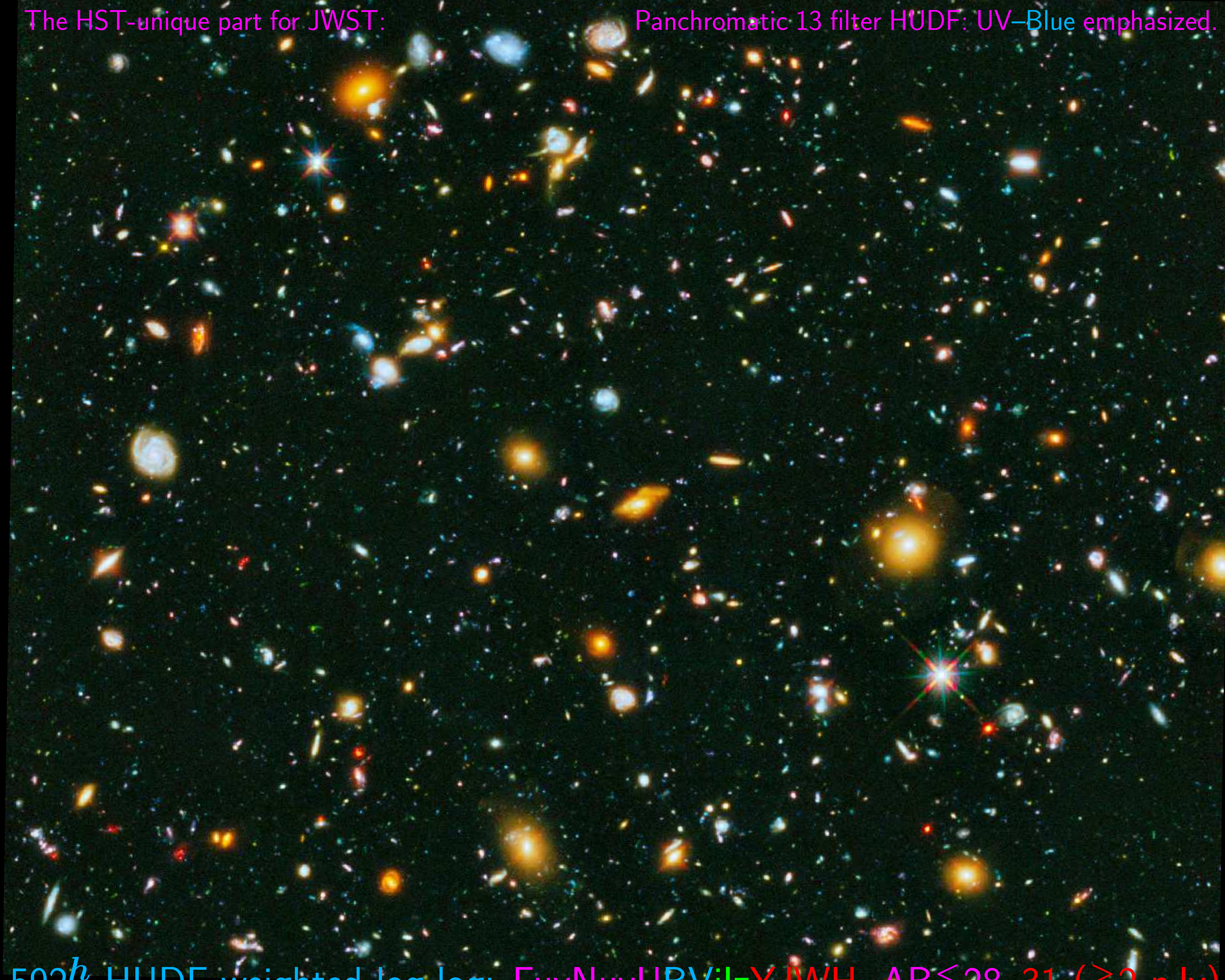
3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



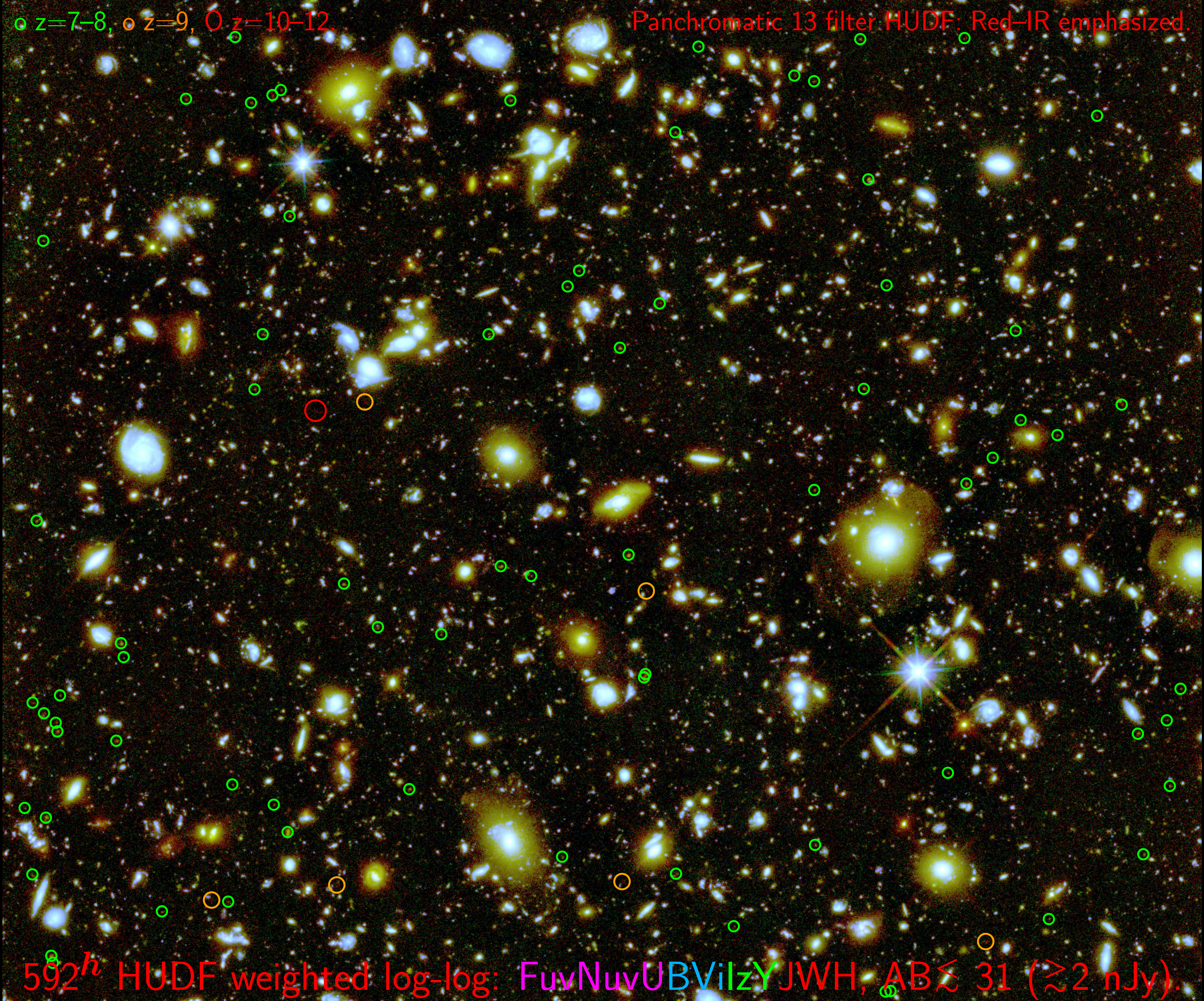
- Can't beat redshift: to see First Light, must observe near–mid IR.

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

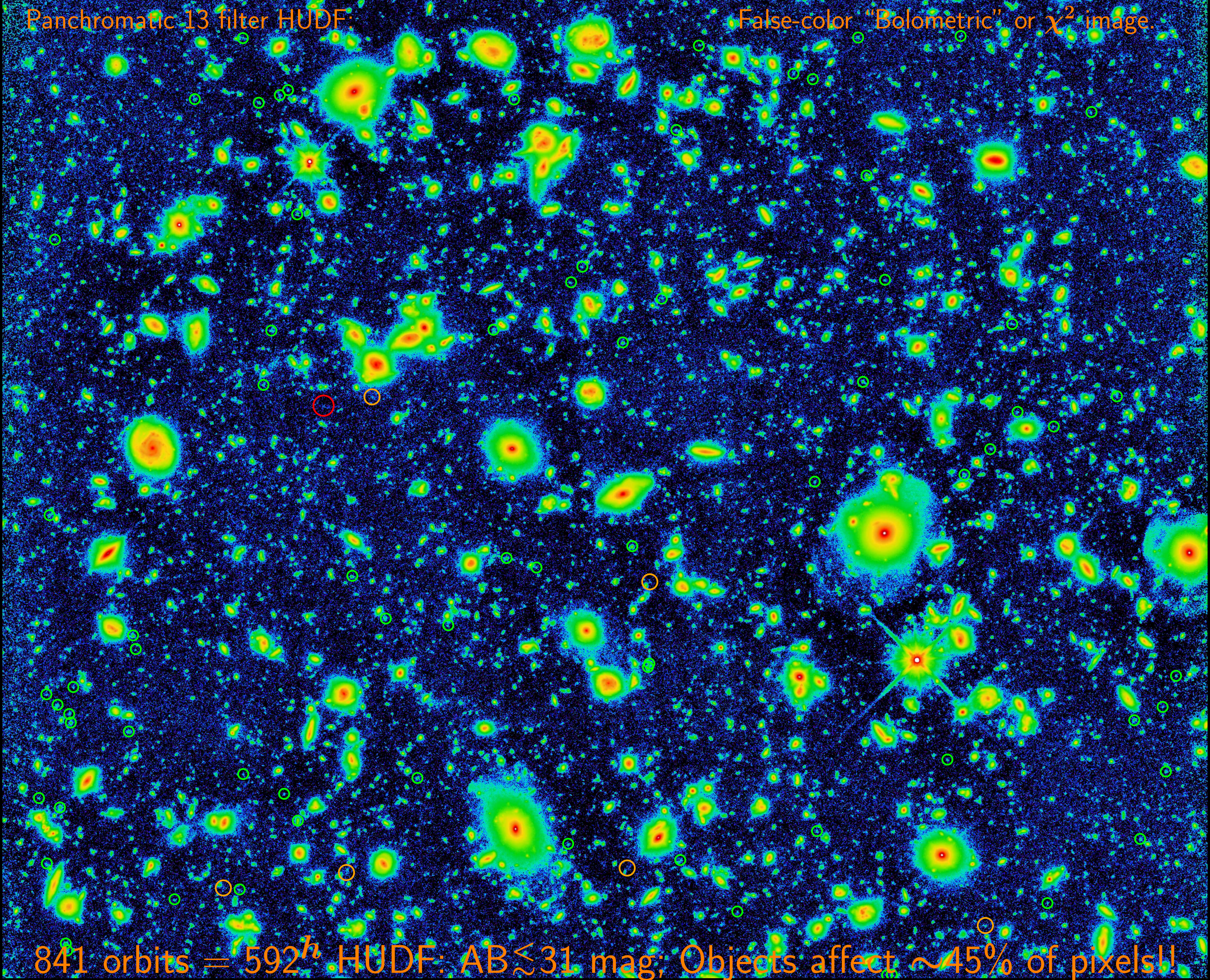
The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.



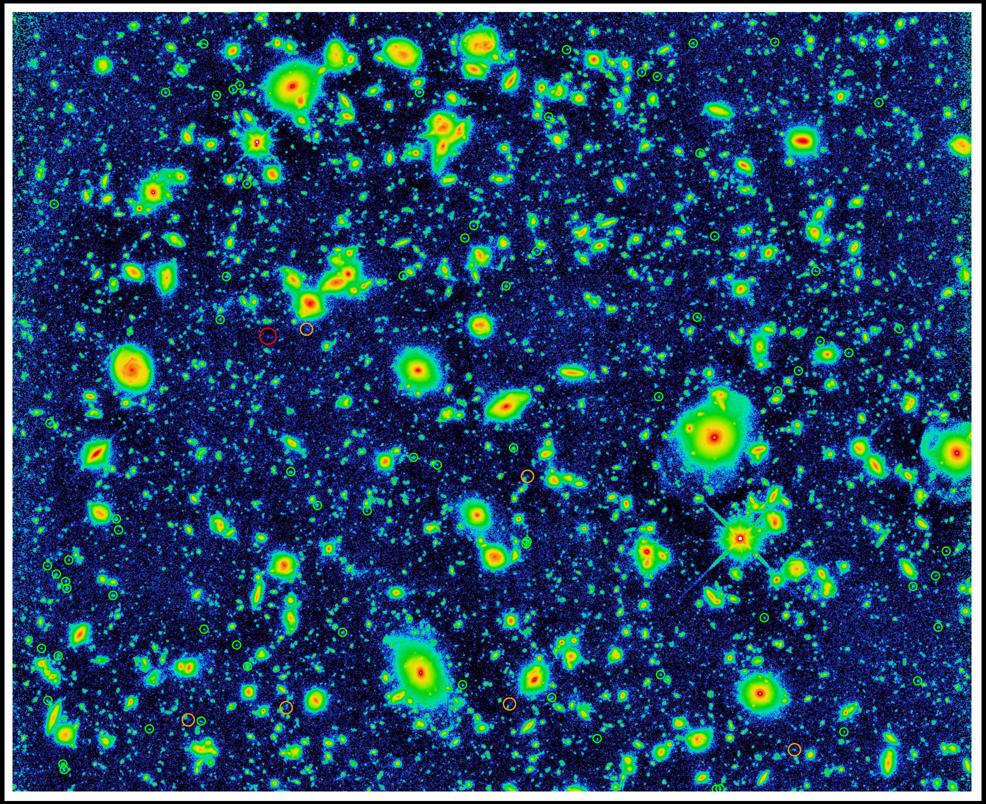
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB≲28–31 (≳2 nJy).

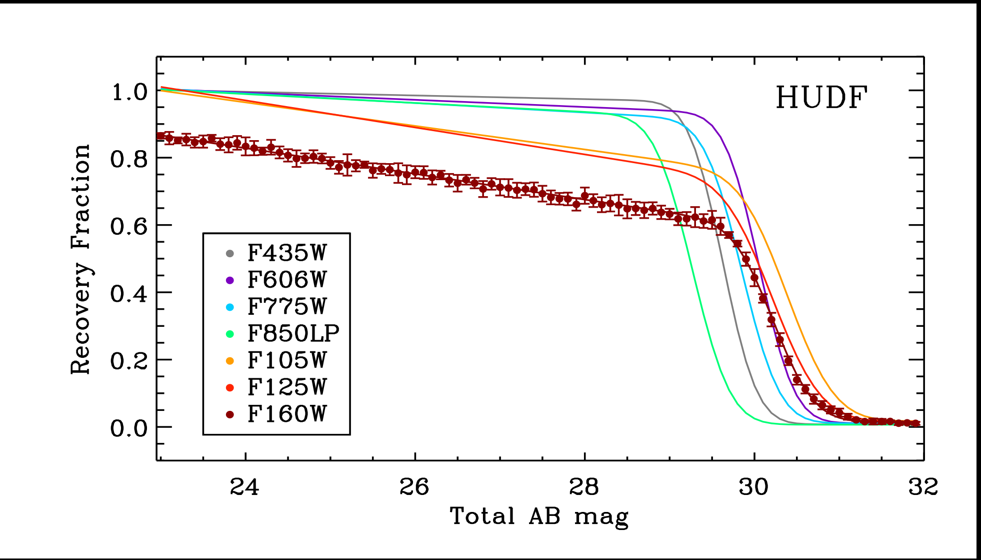


○ z=7–8, ○ z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$ 31 ($\gtrsim$2 nJy).


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

(2a) Current limitations: Wavelength-dependent Deep-Field Completeness limits





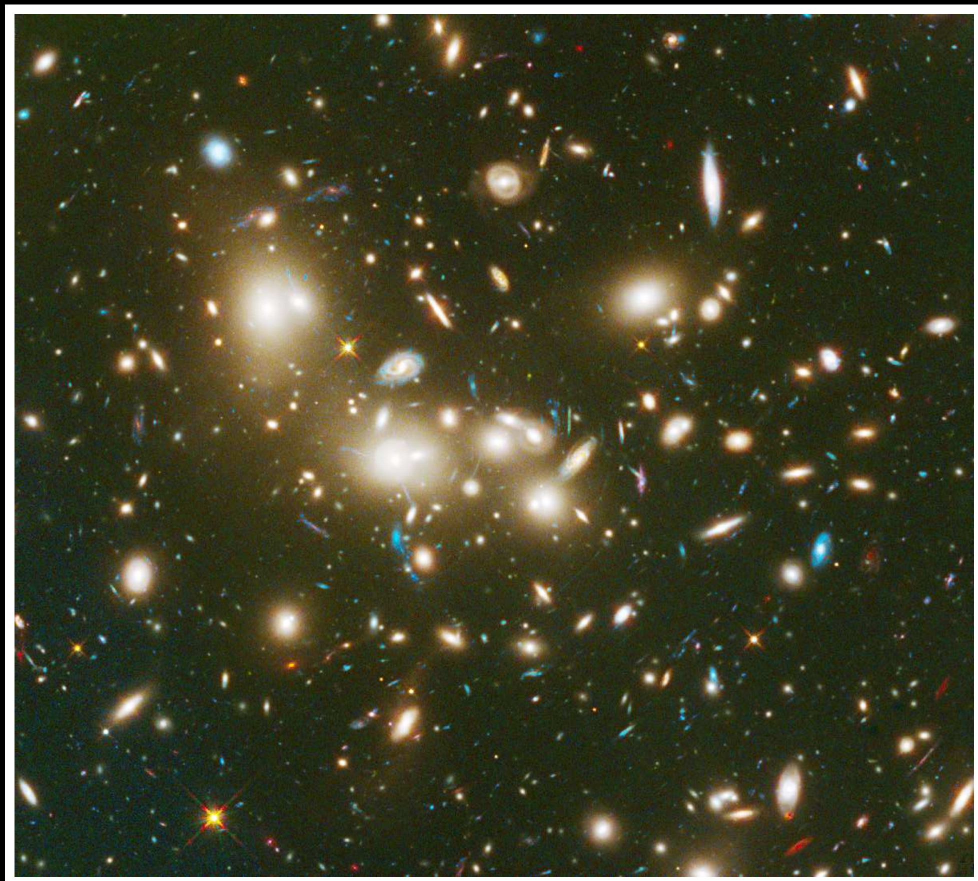
[LEFT]: HUDF bolometric or χ^2-image (false-color log-log stretch): weighted average of 841 orbits (592 hr) in 13 filters reaching AB$\lesssim$31 mag.

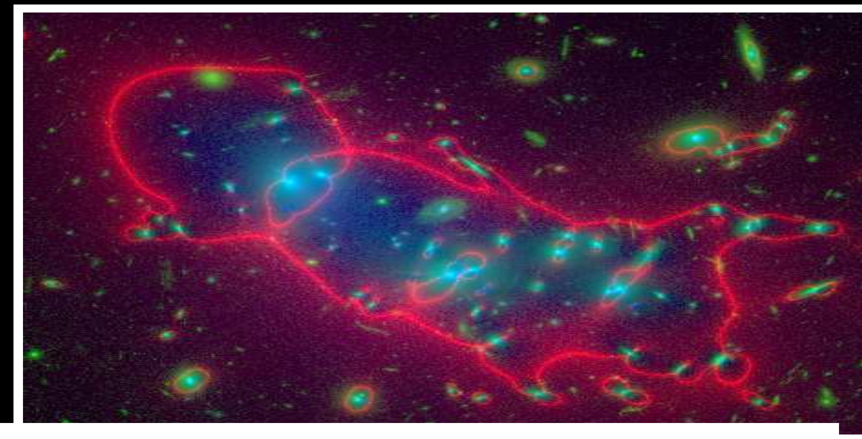
- Faint object wings cover ∼45% of all pixels (Koekemoer et al. 2013)!

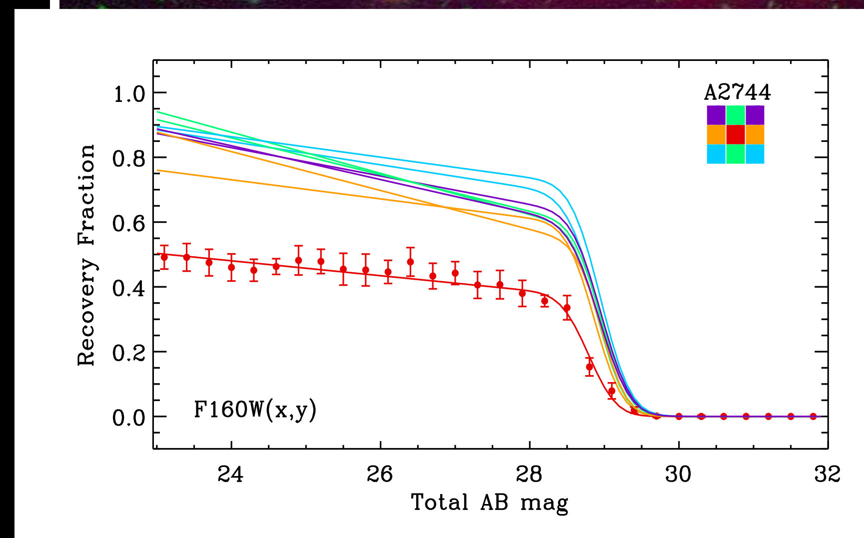
[RIGHT]: HUDF *wavelength-dependent* completeness functions from Monte Carlo (MC) insertions:

- Faint-end recovery fractions drop to ∼60% at longer wavelengths.
- Even the bright-end at H$\simeq$23 AB-mag is ∼15% incomplete!

(2b) Cluster-Position Dependence of Deep-Field Completeness limits







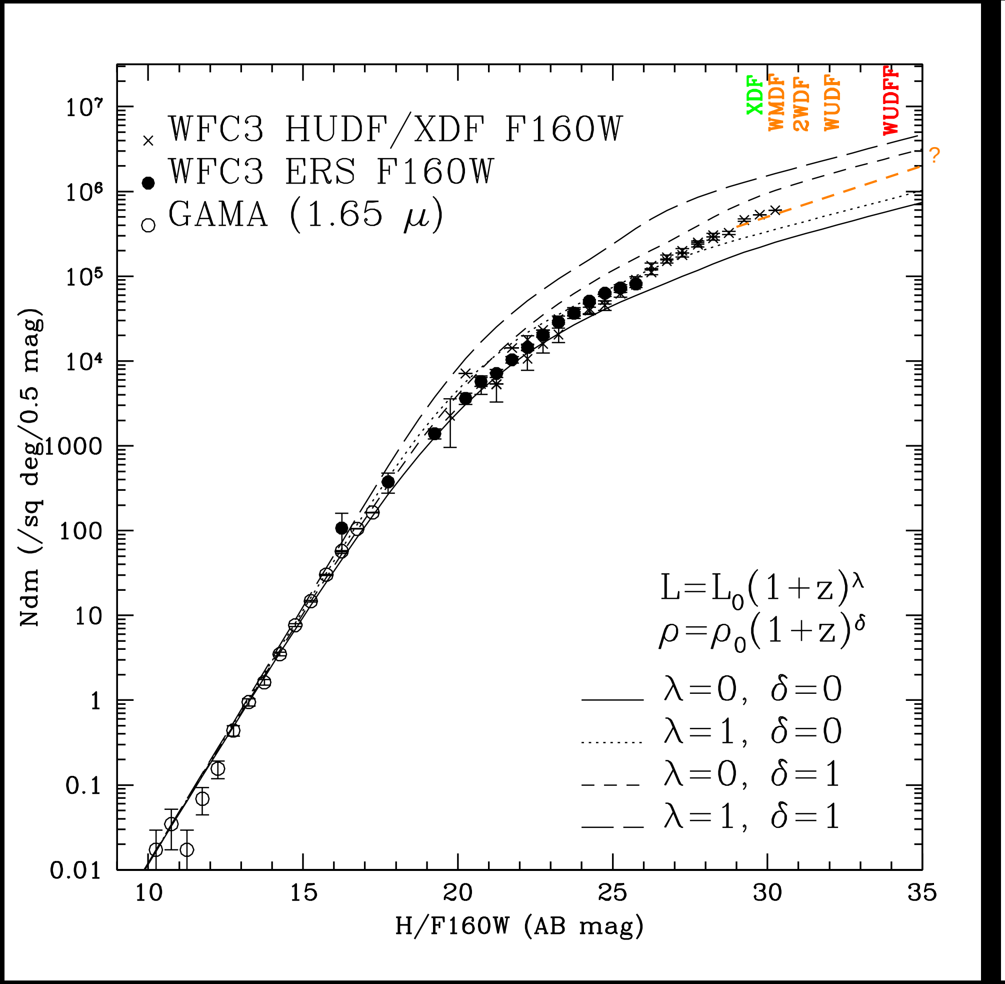
[LEFT]: HFF cluster A2744 in: F435W+F606W, F814W+F105W, F125W+F140W+F160W.

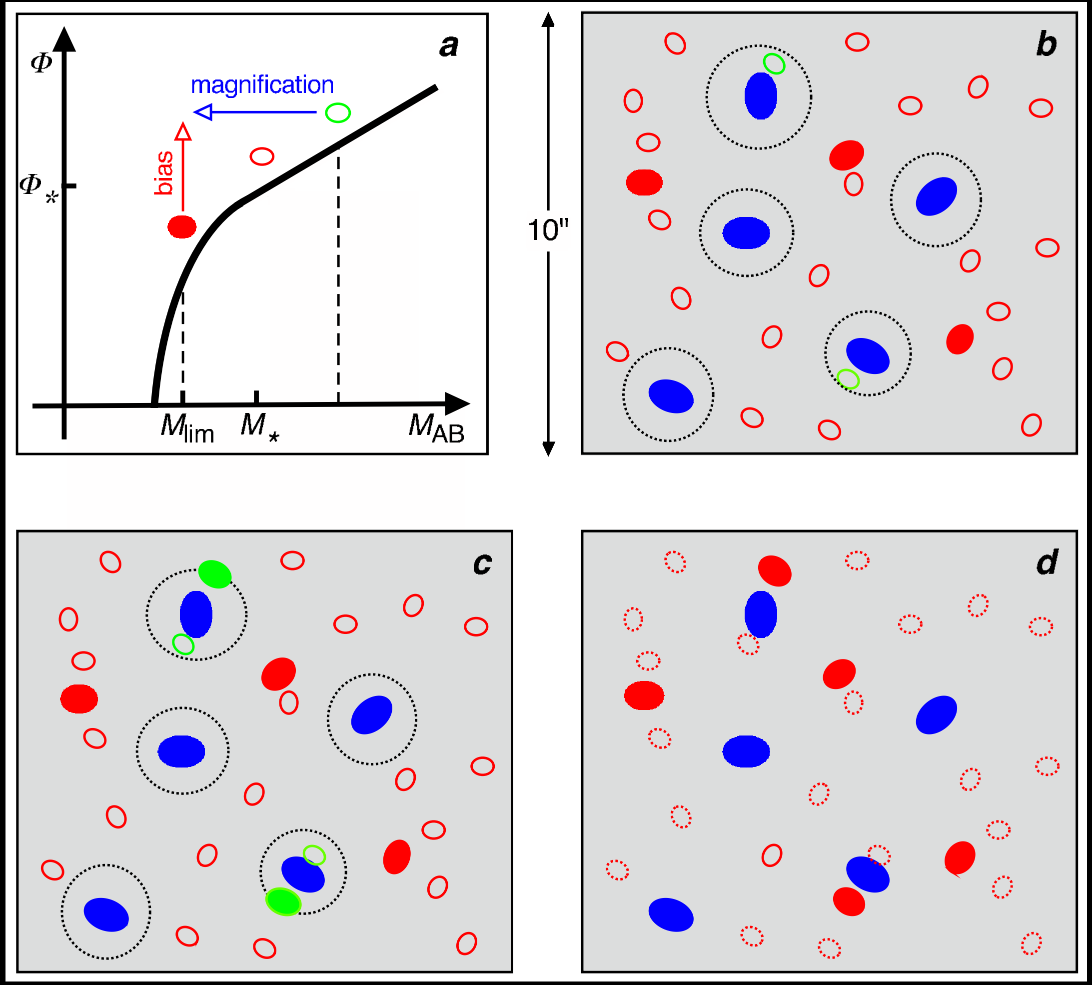
[RIGHT, TOP]: Lensing map for A2744 from Ebeling et al. (2014) [see updated models this Workshop].

[RIGHT BOTTOM]: *Position-dependent* completeness in a 3×3 MC-grid.

- Faint-end lensing sample *incompleteness* increases from ∼10–40% in the cluster outskirts/corners to ∼50–65% in cluster center [but see MUSE results!].
- Even bright-end of the cluster image is incomplete at the 5–50% level.

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





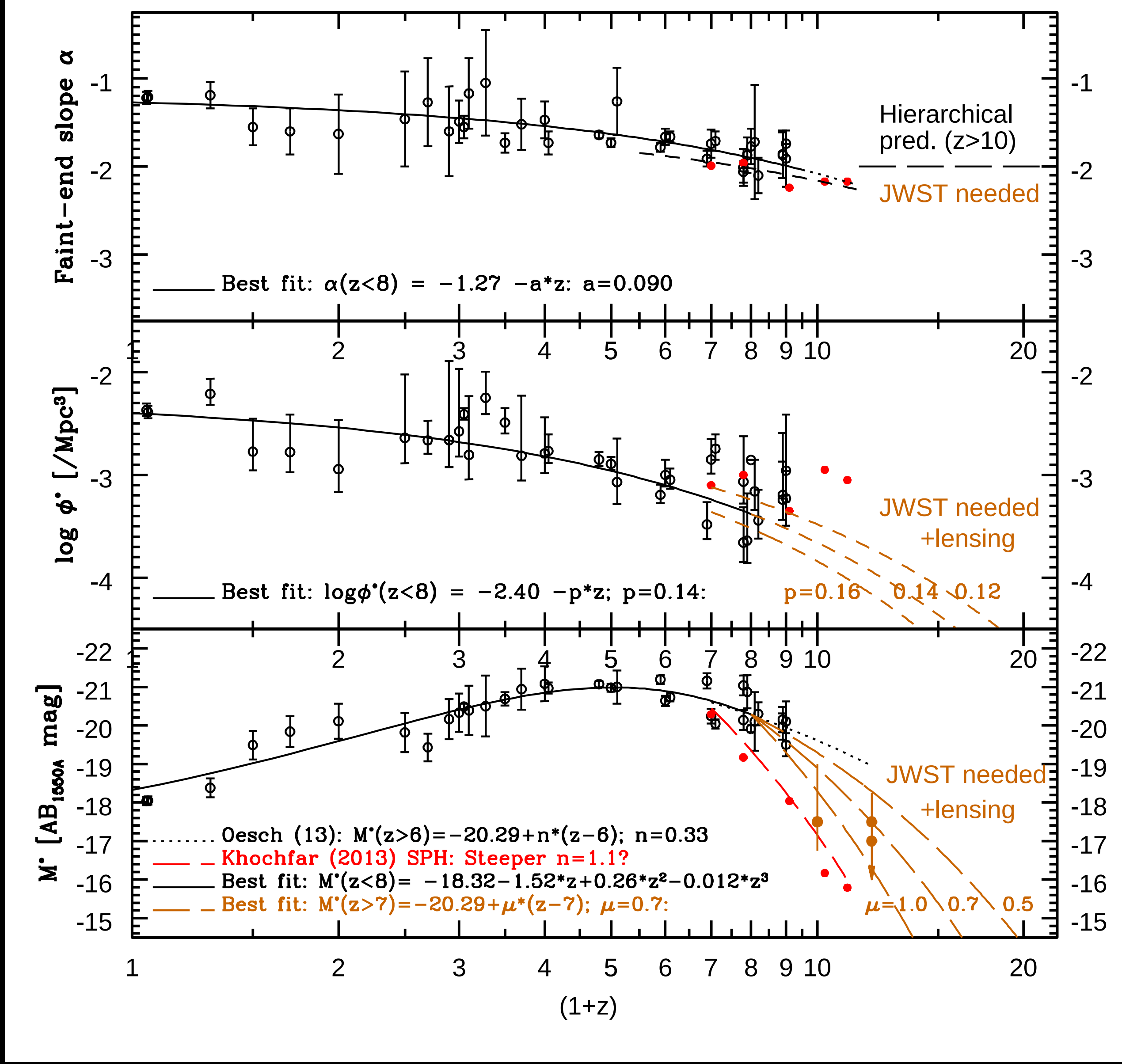
1.6μm counts (Windhorst[+]2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- Faint-end near-IR count-slope≃0.16±0.02 dex/mag ⟺

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

- 800-hr WUDF can see AB$\lesssim$32 objects: $M_{AB} \simeq -15$ (LMCs) at z≃11!

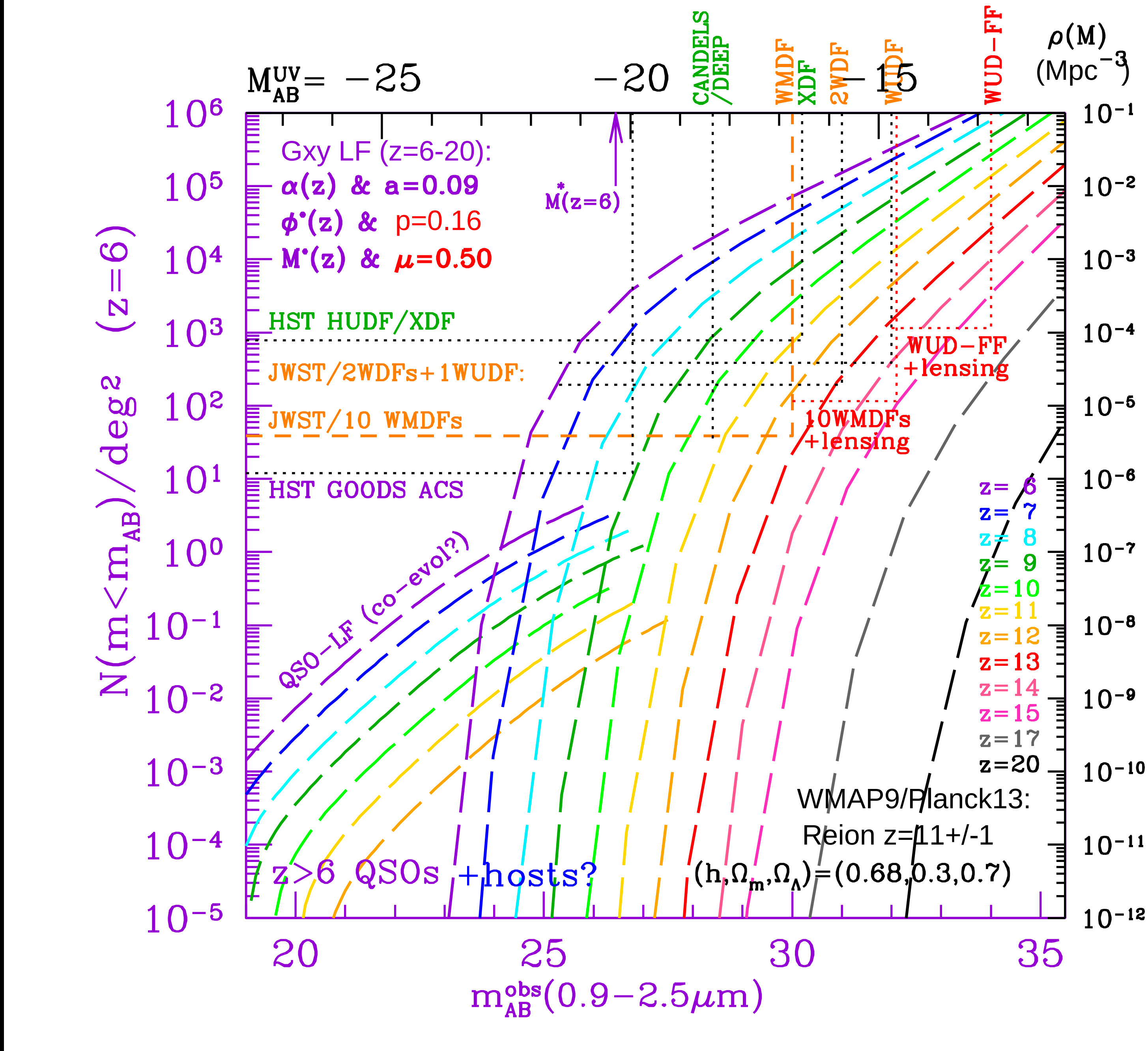
- Lensing will change the landscape for JWST observing strategies (WUDFF).



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$^+$ 14).
- HUDF: Characteristic M^* may drop below –18 or –17.5 mag at z$\gtrsim$10.

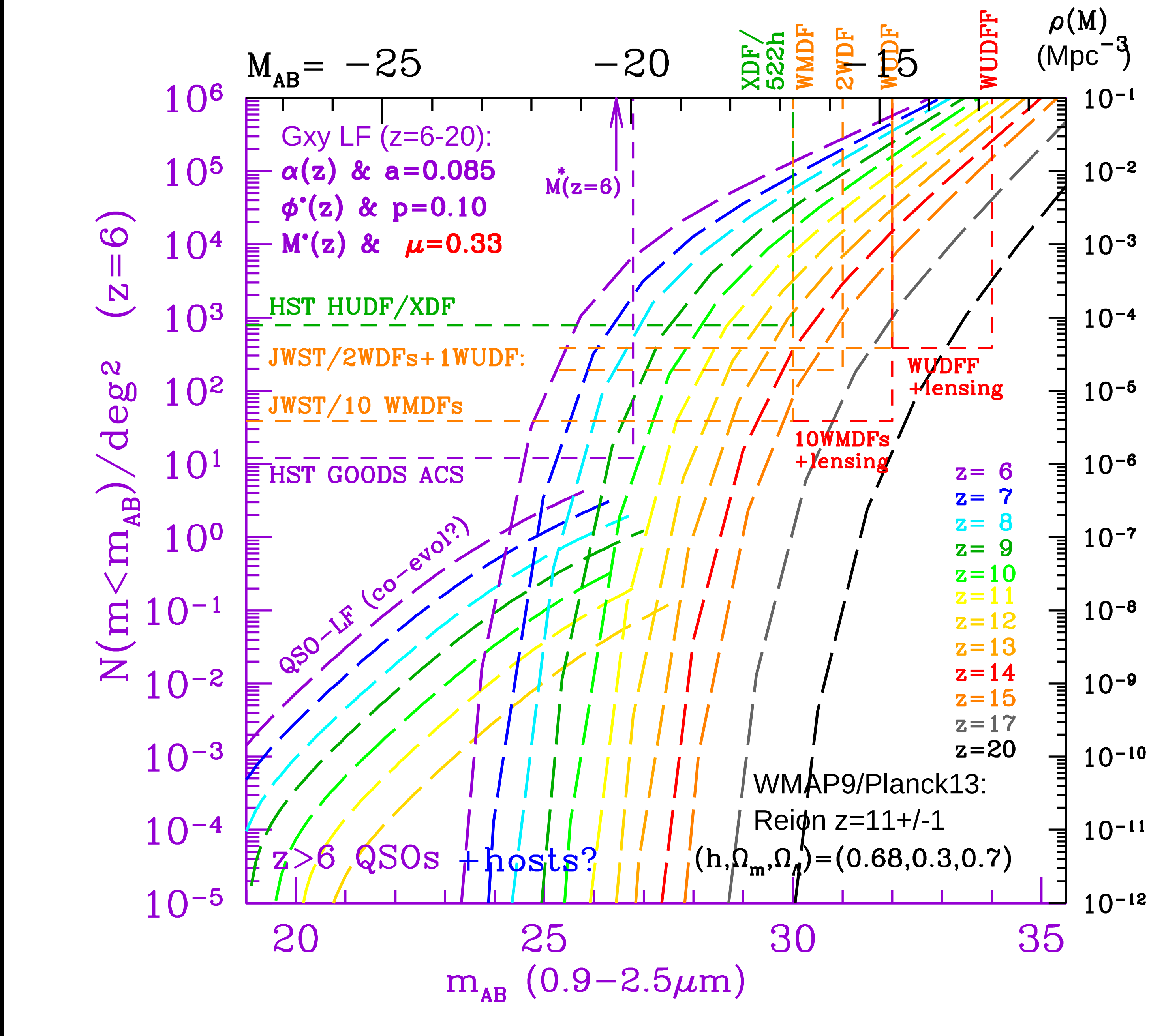
$\Rightarrow$ Will have significant consequences for JWST survey strategy.



Schechter LF (6≲z≲20) with best-fit α(z), Φ^* (z), M^* (z) & μ=0.50.

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

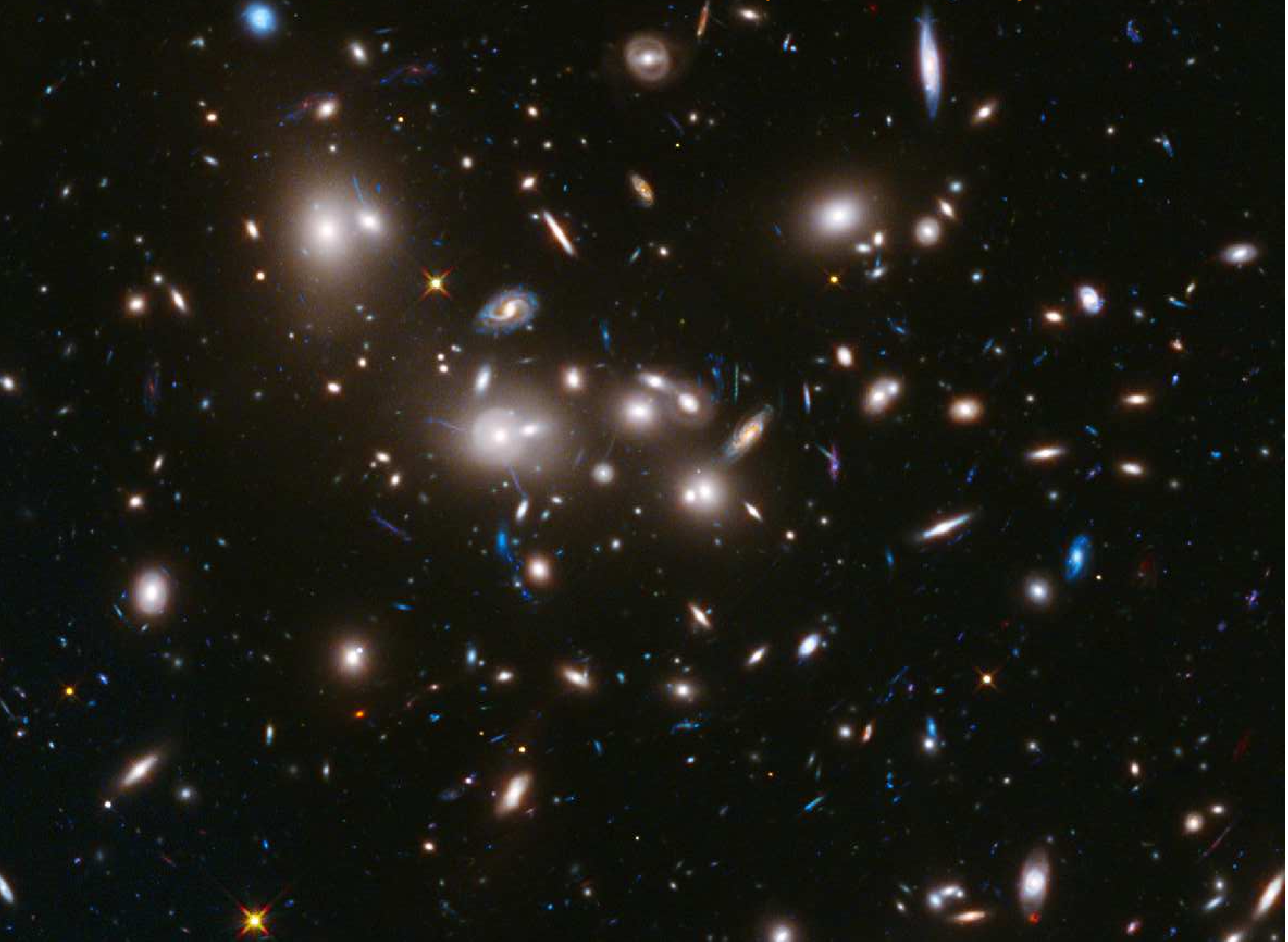
- Will need lensing targets for WMDF–WUDFF to see z≃12–15 objects.



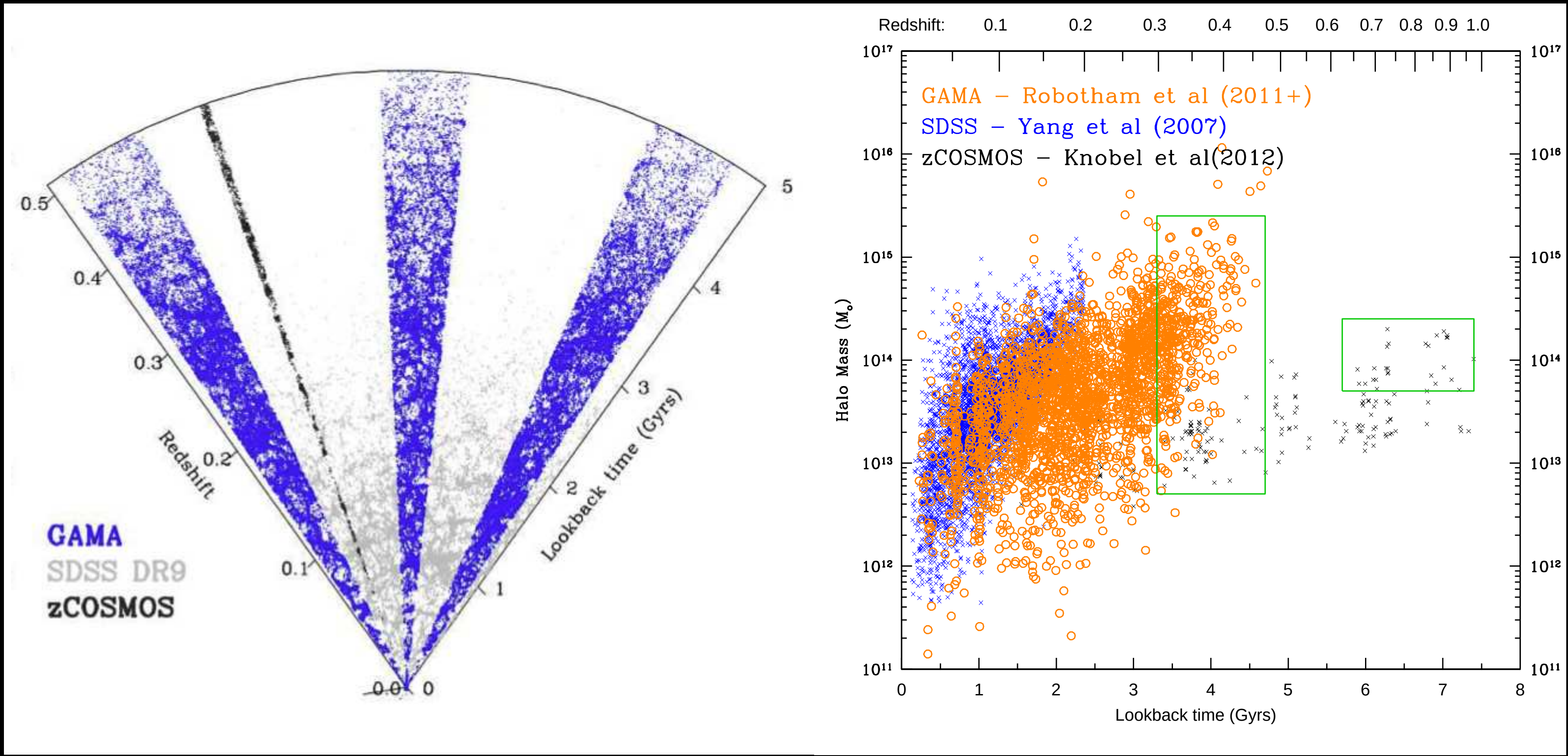
Same as p. 15, but optimistic M^* (z) drop: μ=0.33 (Oesch et al. 2013).

• If so, far more 9≲z≲12 objects expected in XDF, even though N(6≲z≲8) remains the same $\Longleftrightarrow$ M^* (z≃11) fainter than –18±0.5 mag?

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



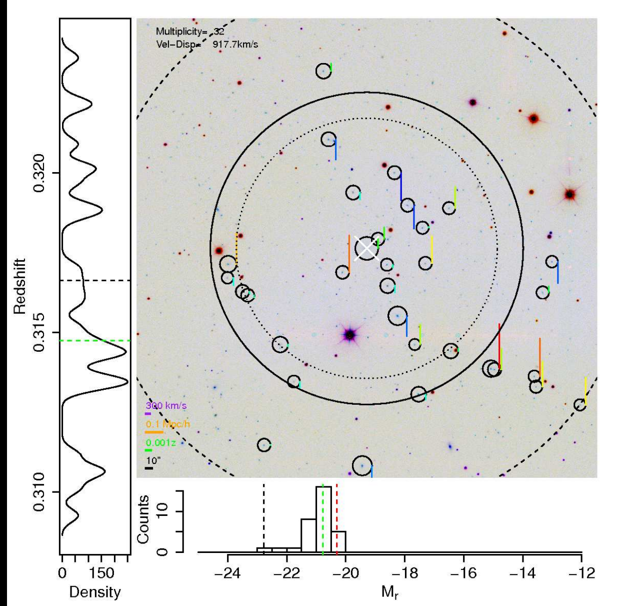
(3) What are the best lensing targets for JWST to see First Light?

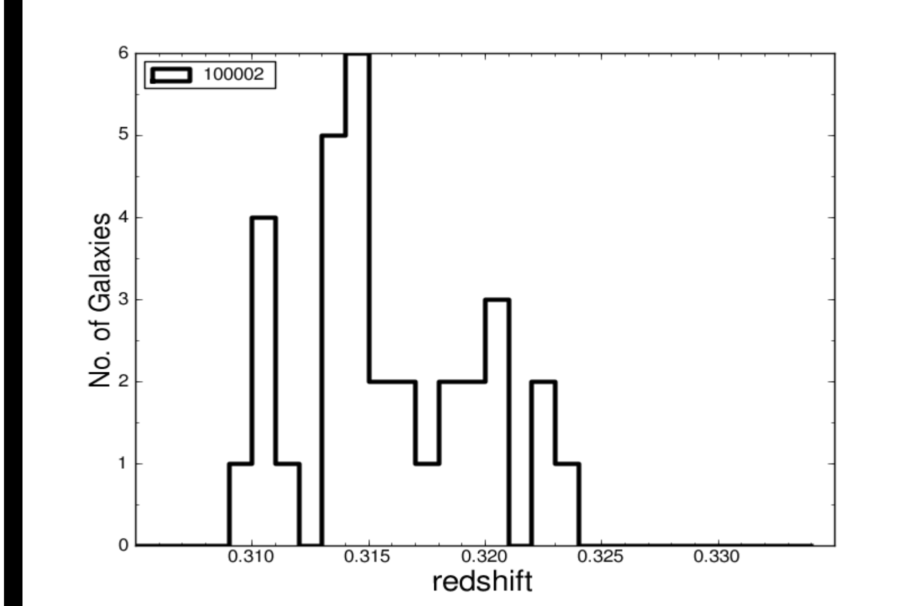


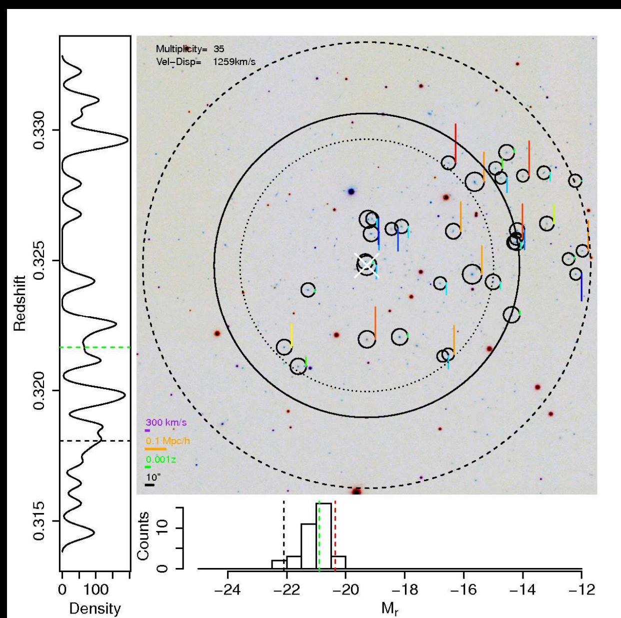
For JWST, use the best lenses in 2018: Rich clusters of high compactness!

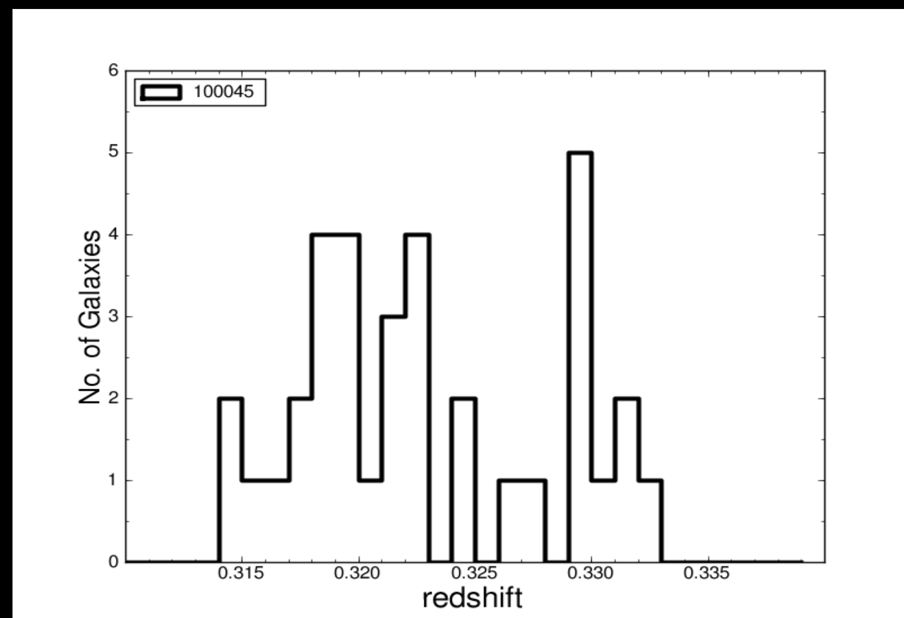
[Left] Redshift surveys: SDSS z$\lesssim$0.25 (Yang+ 2007), GAMA z$\lesssim$0.45 (Robotham+ 2011), and zCOSMOS z$\lesssim$1.0 (Knobel+ 2012).

- GAMA: 22,000 groups z$\lesssim$0.45; 2400 with $N_{spec}\gtrsim$5 (Robotham+ 11).
- $\lesssim$10% of GAMA clusters compact for lensing (Konstantopoulos+ 13).
- Need large sample to identify best lenses to find z$\sim$6–15 sources.





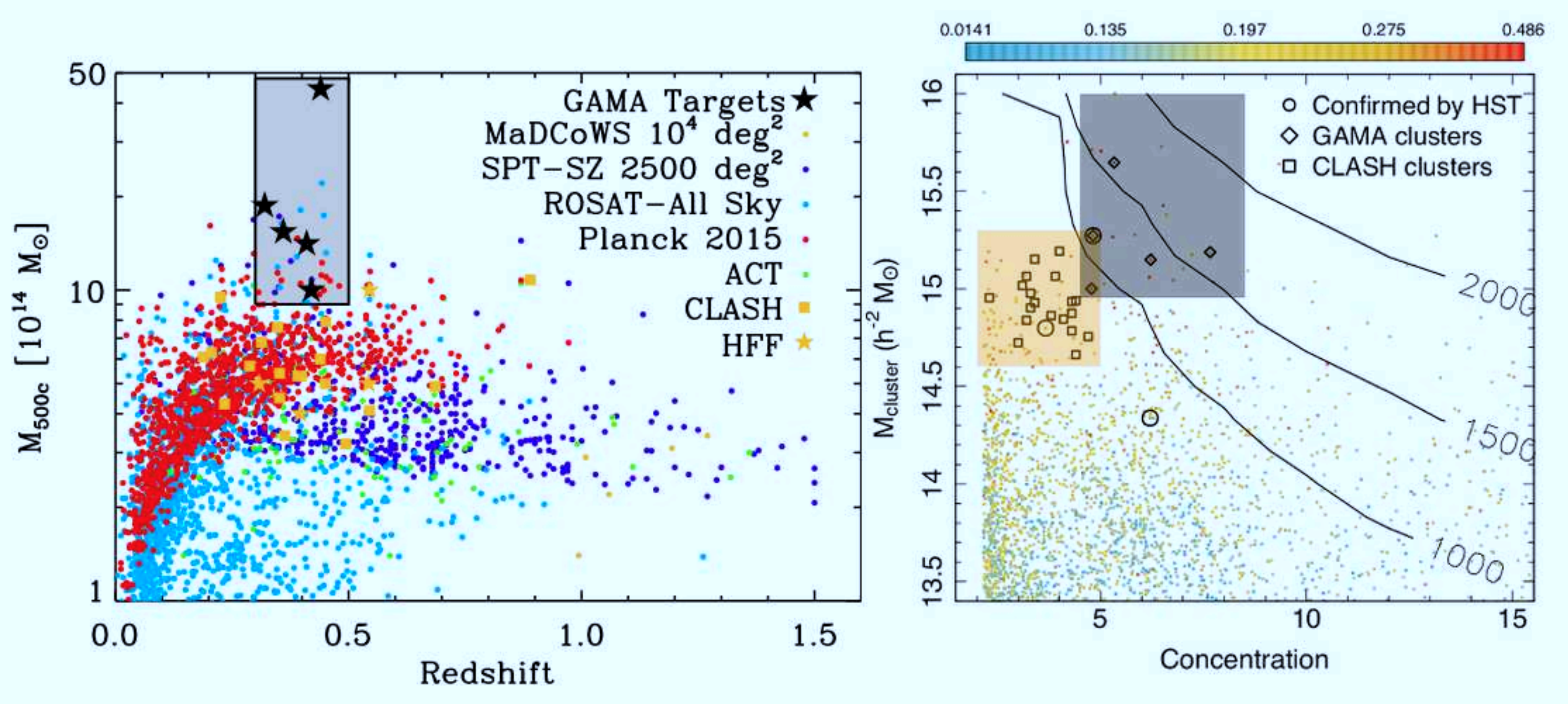




[Left] GAMA clusters with secure AAT redshifts for R$\lesssim$19.8 AB-mag. Also show redshift probability and absolute magnitude (M_r) distributions.

[Right] Measured redshift distribution for two GAMA clusters.

- Will select our WMDF IDS targets on best-lensing compact clusters.



GAMA compact clusters compared to other cluster samples:

[LEFT] Best lensing GAMA clusters vs. ROSAT, Planck, SPT, MaDCoWS.

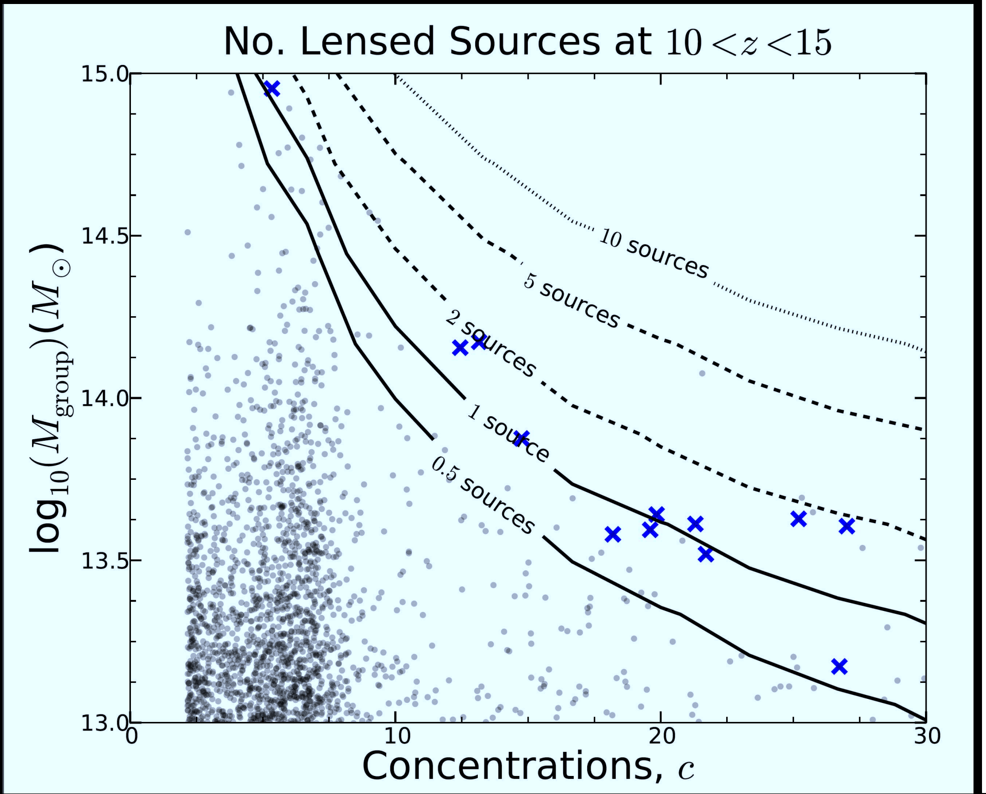
[RIGHT] Best lensing GAMA clusters vs. CLASH clusters.

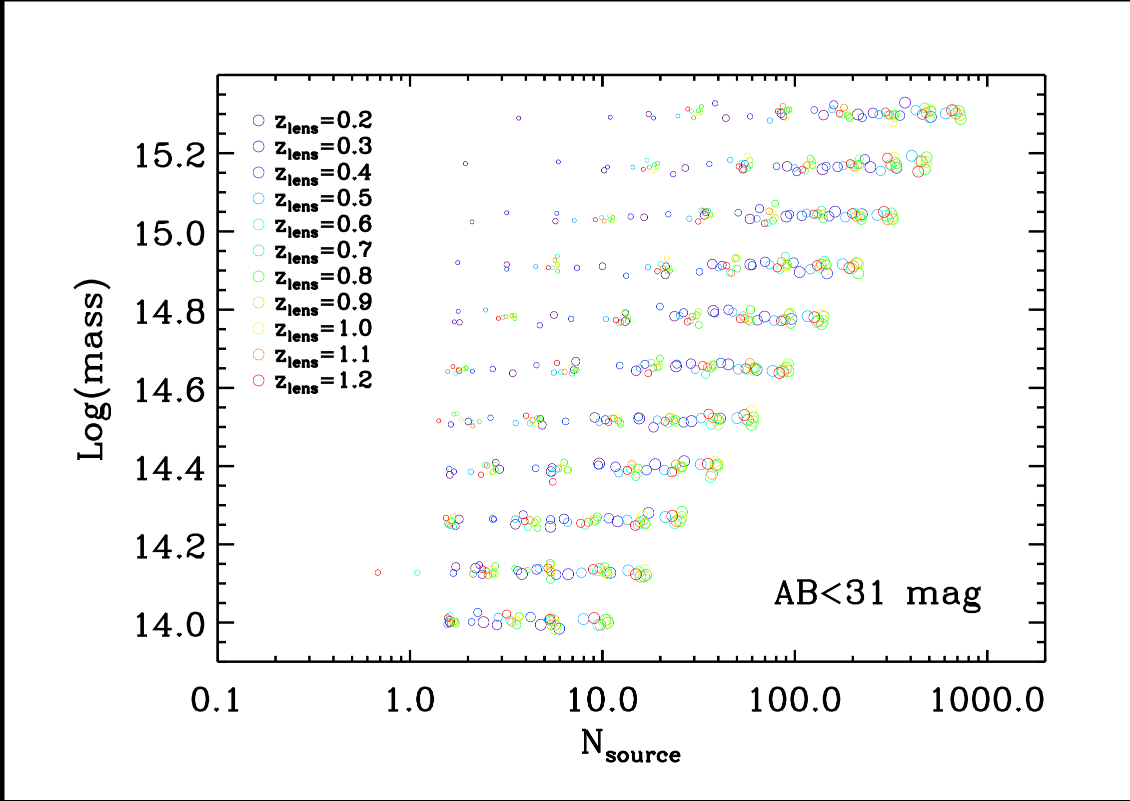
(Contours: Number of lensed JWST sources at z≃1–5 to AB≲27 mag).

- Resulting sweet spot for JWST lensing of First Light Objects (z≳10):

Redshift: 0.3≲z≲0.5; Mass: $10^{15-15.6}$ $M_\odot$; Concentration: 4.5≲C≲8.5

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





GAMA group/cluster mass vs. Concentration, fitted with NFW DM-halo profiles (Barone-Nugent$^+$ 15).

[LEFT] = Nr of expected lensed sources at 10$\lesssim$z$\lesssim$15 (AB$\lesssim$30 mag).

[RIGHT] = Nr of expected lensed sources at 6$\lesssim$z$\lesssim$15 (AB$\lesssim$31 mag).

- 10 WMDFs on best 10^{15} $M_\odot$ clusters: $\sim$100 z$\simeq$6–15 sources (AB$\lesssim$30).
- WDF (AB$\lesssim$31 mag) will get $\sim$250 lensed sources at z$\simeq$6–15.

WUDFF (AB$\lesssim$32) on best cluster yields $\sim$800 lensed sources at 6$\lesssim$z$\lesssim$15!

Conclusion: JWST First Light strategy must consider three aspects:

(1) The rapid drop in the LF Φ^* (z) and/or M^* (z) 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 $\Rightarrow$ Need multi-λ deblending algorithms & object subtraction (e.g., wavelets).

(3) Gravitational Lensing: JWST will need to find most First Light objects at z$\gtrsim$10–15 through the best lensing compact clusters.

- Need multi-λ object-finders that works on sloped backgrounds.
- If M*(z$\gtrsim$10)$\gtrsim$–18 or Φ^* $\lesssim 10^{-3.5}$, must image, (subtract,) & model the entire gravitational foreground, and remove the (rogue-path) straylight.

(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.

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

- More than 98% 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.

- To see the most First Light, JWST must cover the best lensing clusters!
- Need to consider brightness of — and low-level gradients in — IntraCluster Light (ICL). May need a majority of gravitational lensing targets.

(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$3 years from today!**

SPARE CHARTS

- References and other sources of material shown:

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

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

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

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

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

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

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

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

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

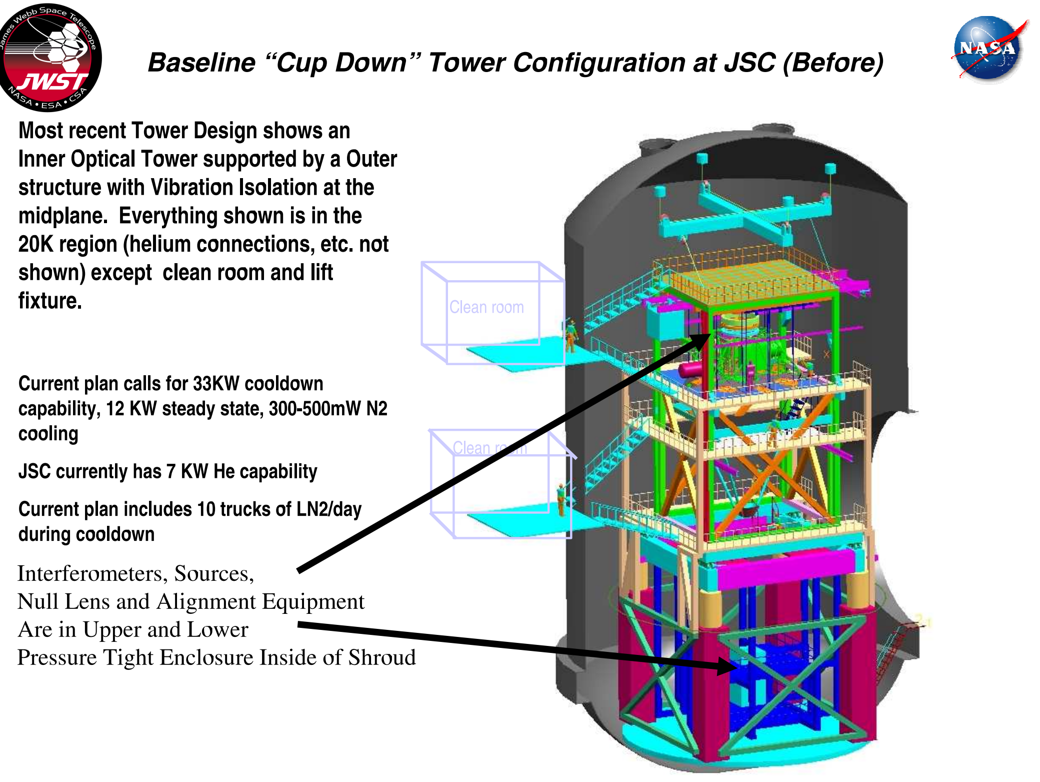
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

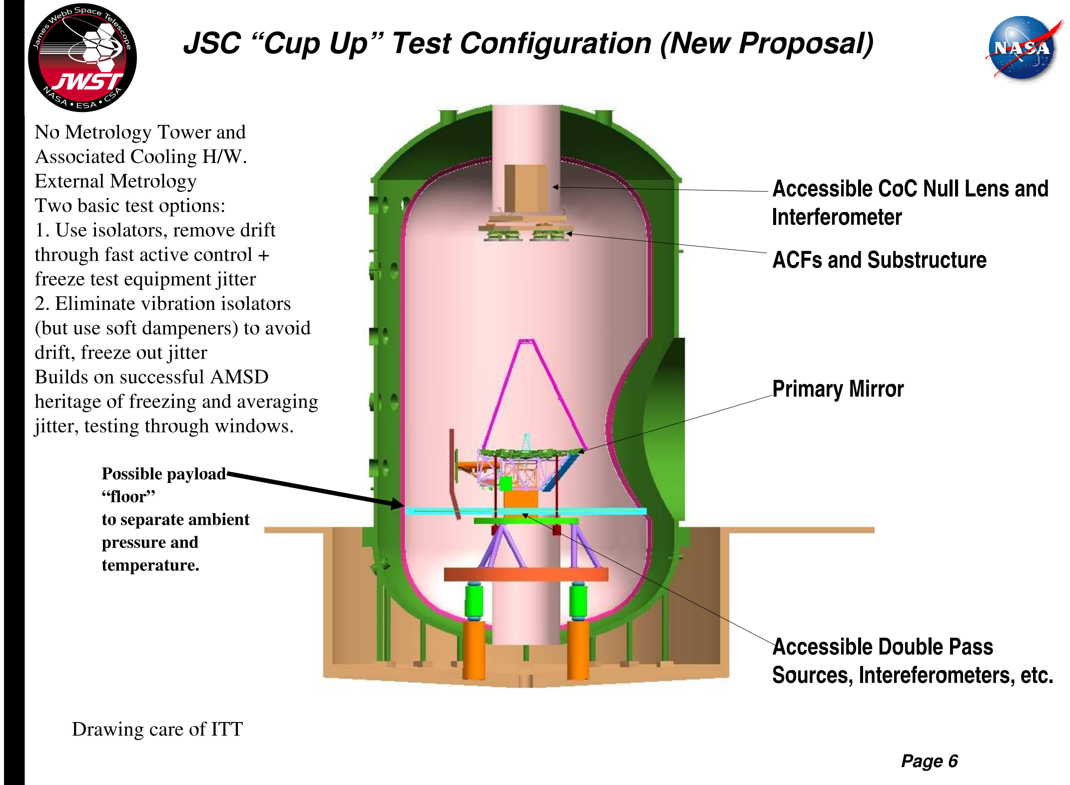
Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

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

Northrop Grumman Expertise in Space Deployable Systems

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

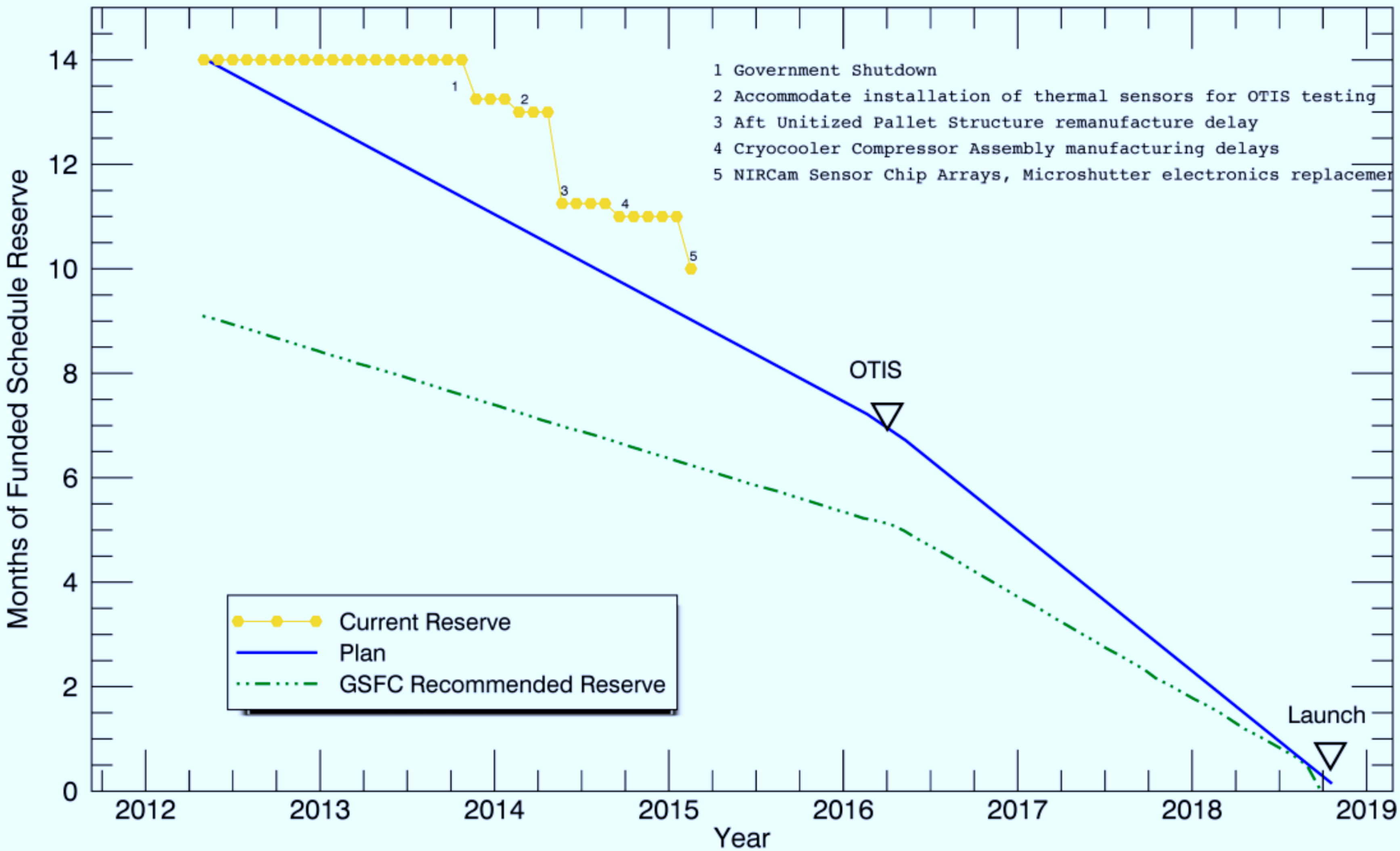




JWST underwent several significant replans and risk-reduction schemes:

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

Project Funded Schedule Reserve



Keys to stay on schedule: 1) Sufficient Project contingency (≳25% of total).

2) Well replanned and managed Project (starting late summer 2011).

Fiscal Year 2015 JWST HQ Milestones

Month		Milestone	FY2014 Deferral	Comment
Oct-14	1	Secondary Mirror Structure dynamics Test Readiness Review		Completed 11/20/14
	2	ISIM Cyo-vacuum Test #2 complete	•	Completed 9/23/14
	3	Flight and flight spare MIRI Cryocooler Electronics Assembly delivered to JPL	•	Completed 10/6/14
	4	Johnson Space Center Optical Ground Support Equipment integration complete	•	Completed 10/10/14
Nov-14	5	Install Engineering Development Unit Secondary Mirror Assembly onto Pathfinder		Completed 10/10/14
	6	Johnson Space Center (JSC) Chamber A commissioning test start		Completed 10/18/14
	7	Data Management Subsystem software Build 3 delivery		Completed 9/30/14
Dec-14	8	Demonstration model Mid-Boom Assembly thermal vacuum test start		Completed 11/19/14
	9	Transfer Telescope Pathfinder structure ownership to GSFC		Completed 10/31/14
	10	Flight Operations Subsystem Build 1 System Design Review		Completed 11/20/14
	11	Proposal Planning Subsystem Build 10 delivery		Completed 11/3/14
	12	Deliver flight Cold Head Assembly to ISIM for Cryo-vacuum test #3	•	Completed 11/10/14
	13	Fine Guidance Sensor focal plane arrays ready for integration	•	Completed 12/9/14
Jan-15	14	Deliver Spacecraft Simulator handbook, Rev B (flight software build 1) to GSFC		Completed 12/11/14
	15	JSC Chamber A Commissioning complete		Completed 11/27/14
Feb-15	16	Start formal Engineering Model Test Bed electrical integration		Completed 11/13/14
	17	Sunshield Mid-boom Manufacturing Readiness Review	•	Completed 2/9/15
	18	Sunshield Flight Layer 3 delivered to Northrop-Grumman (NGAS)		Completed 2/16/15
	19	Deliver Telescope Pathfinder Structure to JSC		Completed 2/4/15
	20	Observatory Operations Scripts Subsystem Build 4 delivery		Completed 1/16/15
	21	Wavefront Sensing and Control Software Build 4 delivery		Completed 12/30/14
Mar-15	22	Qualification Sunshield Membrane Retention Device thermal vacuum test start		Completed 3/12/15
	23	Deliver Cryocooler Jitter Attenuator Assembly to Optical Telescope Element		Delayed to April, ground support equipment issue
	24	NGAS Acceptance of Spacecraft propellant tank		Delayed to June due to test unit welding issue, no schedule impact
	25	Near Infrared Instrument Detector changeouts complete		Completed 4/3/2014
Apr-15	26	Start acceptance testing of flight Cryocooler Assembly and Electronics	•	
	27	Flight Observatory Deployment Tower Assembly complete		Completed 3/12/15
	28	ISIM Vibration Testing complete		
	29	Start Optical Ground Support Equipment test #1 at JSC		
May-15	30	Flight Cryocooler Compressor Assembly to JPL for Acceptance Test #3	•	
		~~Dual Thruster Module Test Readiness Review~~		Milestone deleted, due to change in thruster design, new milestone in June (#36).
	31	Spacecraft Flight Software Build 2.2 Test Readiness Review	•	
	32	Sunshield Forward Cover Assemby shipped to NGAS		Moved to July, reprioritizing work for efficiencies at Nexolve
	33	Deliver Flight Aft Optics System to Telescope Pathfinder		
	34	Data Management Subsystem Build 4 delivery		
Jun-15	35	Attitude Control System test set delivery to Observatory Integration and Test		Completed 2/6/15
	36	Propellant Mid-Course Correction testing complete	•	(modified milestone to include testing post build of hardware)
	37	Delivery of new Vibration Test System to GSFC		
	38	ISIM Acoustic testing complete		
	39	Proposal Planning Subsystem Build 11		
	40	Thruster Module Test Readiness Review		Completed 2/23/15
Jul-15	41	Flight spare cryo-cooler assembly to JPL for Acceptance Test #4	•	
	42	Aft Deployable ISIM Radiator build complete		
	43	ISIM Electro-Magnetic testing complete		
Aug-15	44	Deliver Spacecraft Side Equipment Panels to Observatory integration and testing		
	45	Deliver Reaction Wheel Assemblies to Observatory integration & testing		
	46	Start ISIM Cryo-vacuum Test #3		
	47	Start Optical Ground Support Equipment Test #2 at JSC		
Sep-15	48	Deliver Communications Antenna Bi-Axial Gimbal Assembly to Observatory integration and testing		

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

Milestone Performance

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

	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year
FY2011	21	21	6	3	0
FY2012	37	34	16	2	3
FY2013	41	38	20	5	3
FY2014 ❖	36	23	10	8	11
FY2015	48	25	16	5*	0

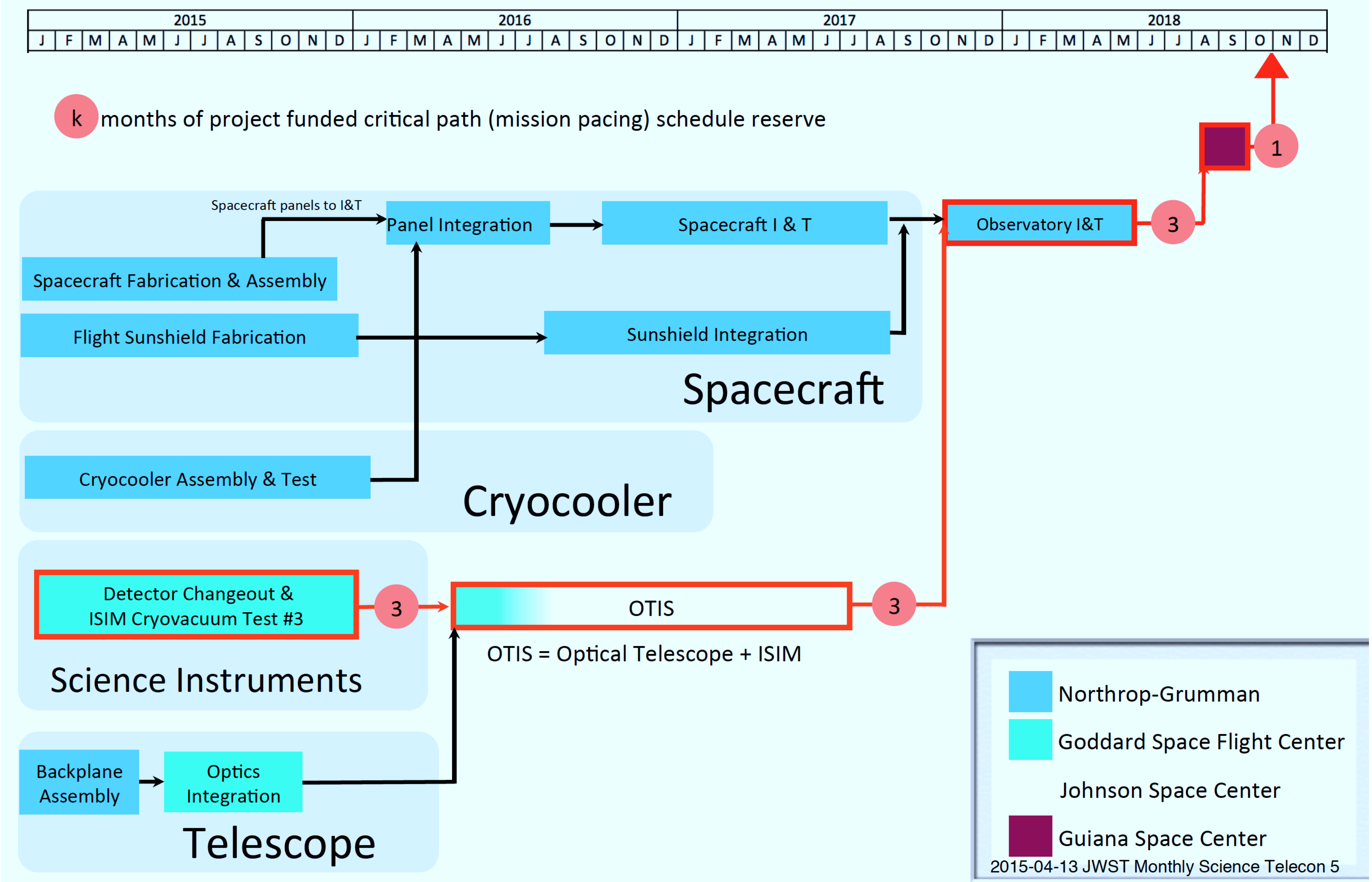
*Late milestones have been or are forecast to complete within the year. Deferred milestones are not included in the number-completed-late tally.

❖ 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: 4/5 of the “Lates” not on critical path, causing no launch delay.

Simplified Schedule

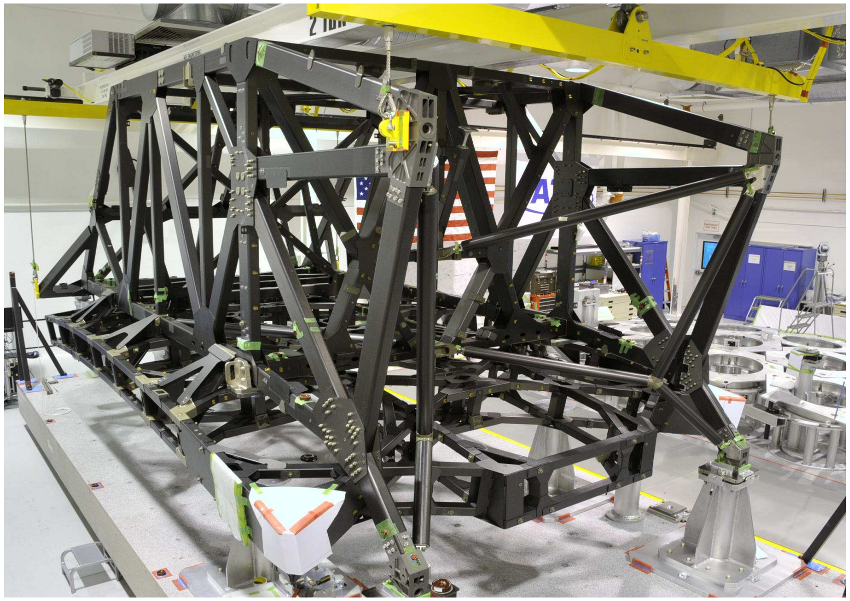


Path forward to Launch (in Oct. 2018): 10 months schedule reserve.

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

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

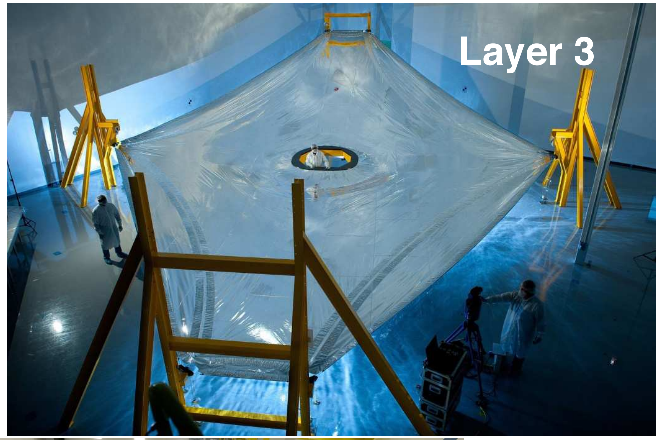
BSF/Center Section coming out of XRCF

Flight back-plane ready to receive mirrors, starting in Fall 2014.

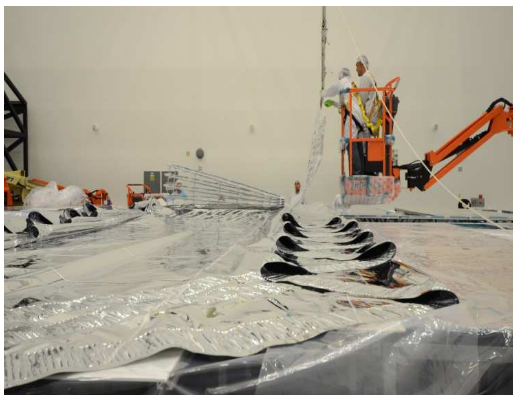
Sunshield Template Membrane Work Completed

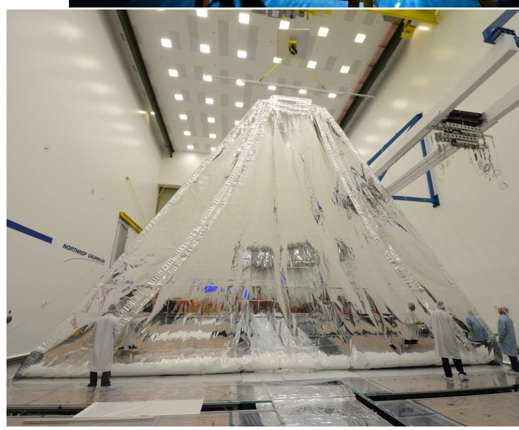
Templates Verify Design/Manufacturing Prior to Flight Build

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

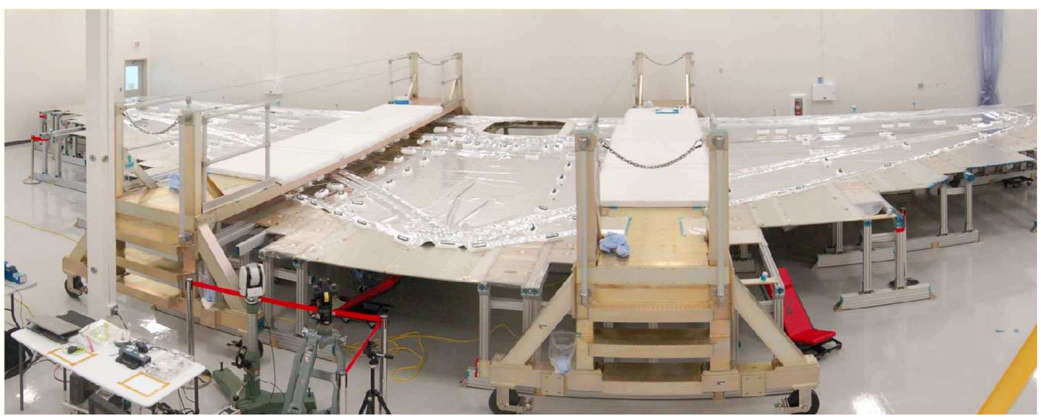


Stringing Operations





Template Layers 3-5

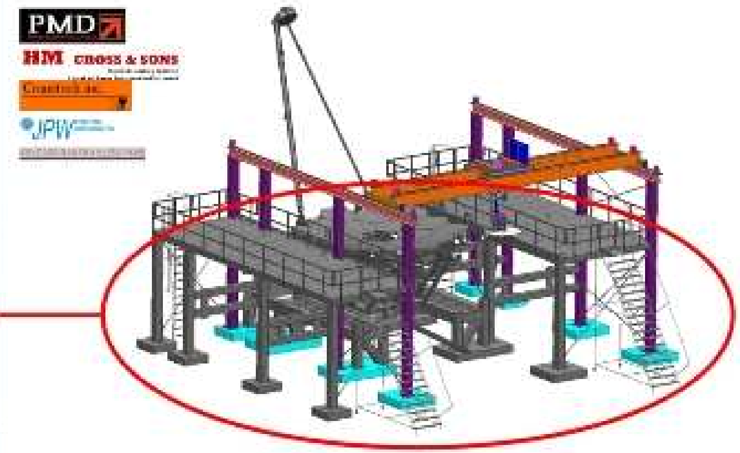


Hole Tool Operations

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

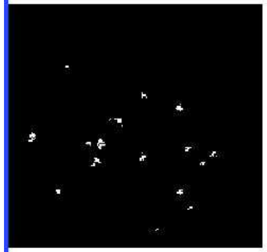
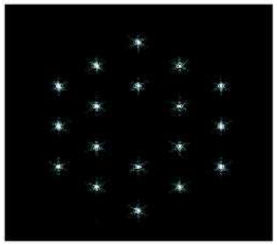
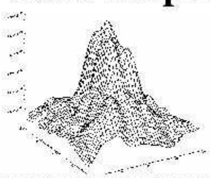
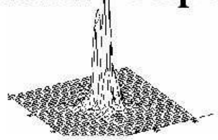
Telescope Assembly Ground Support Equipment

Ambient Optical Alignment Stand Complete



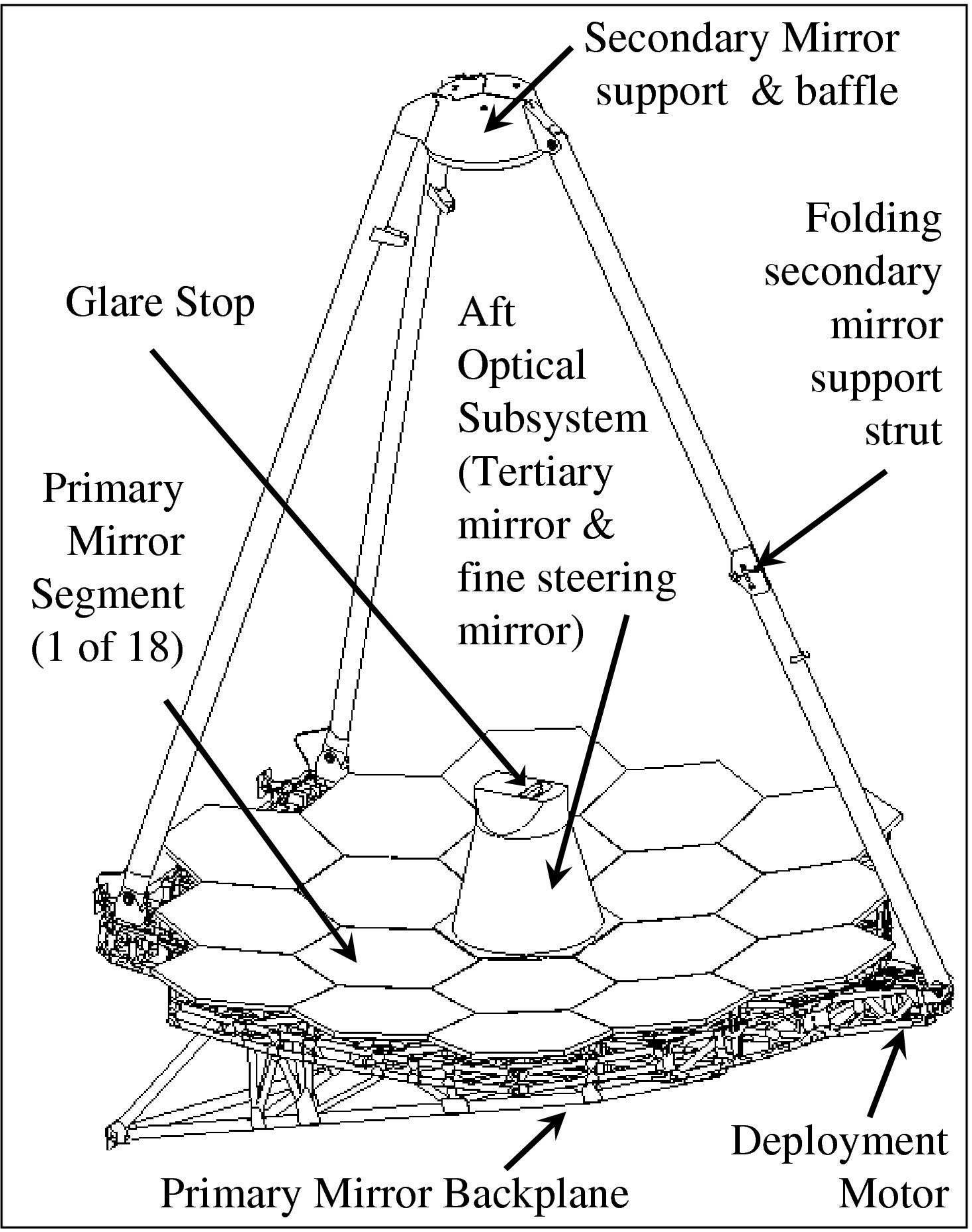
Hardware has been installed at GSFC approximately 8 weeks ahead of schedule

Landing a mirror onto backplane simulator

Step	Result	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)

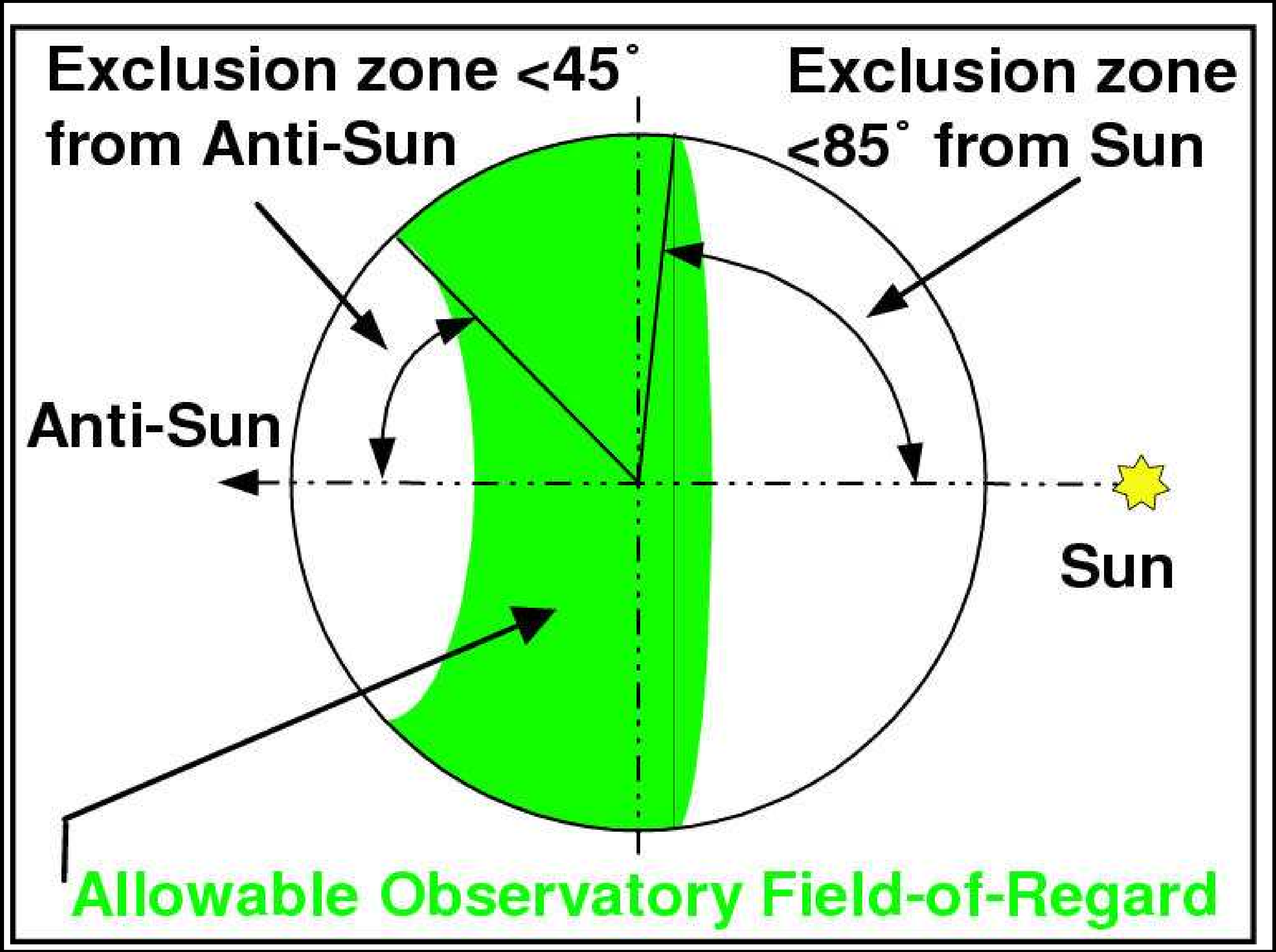
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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.

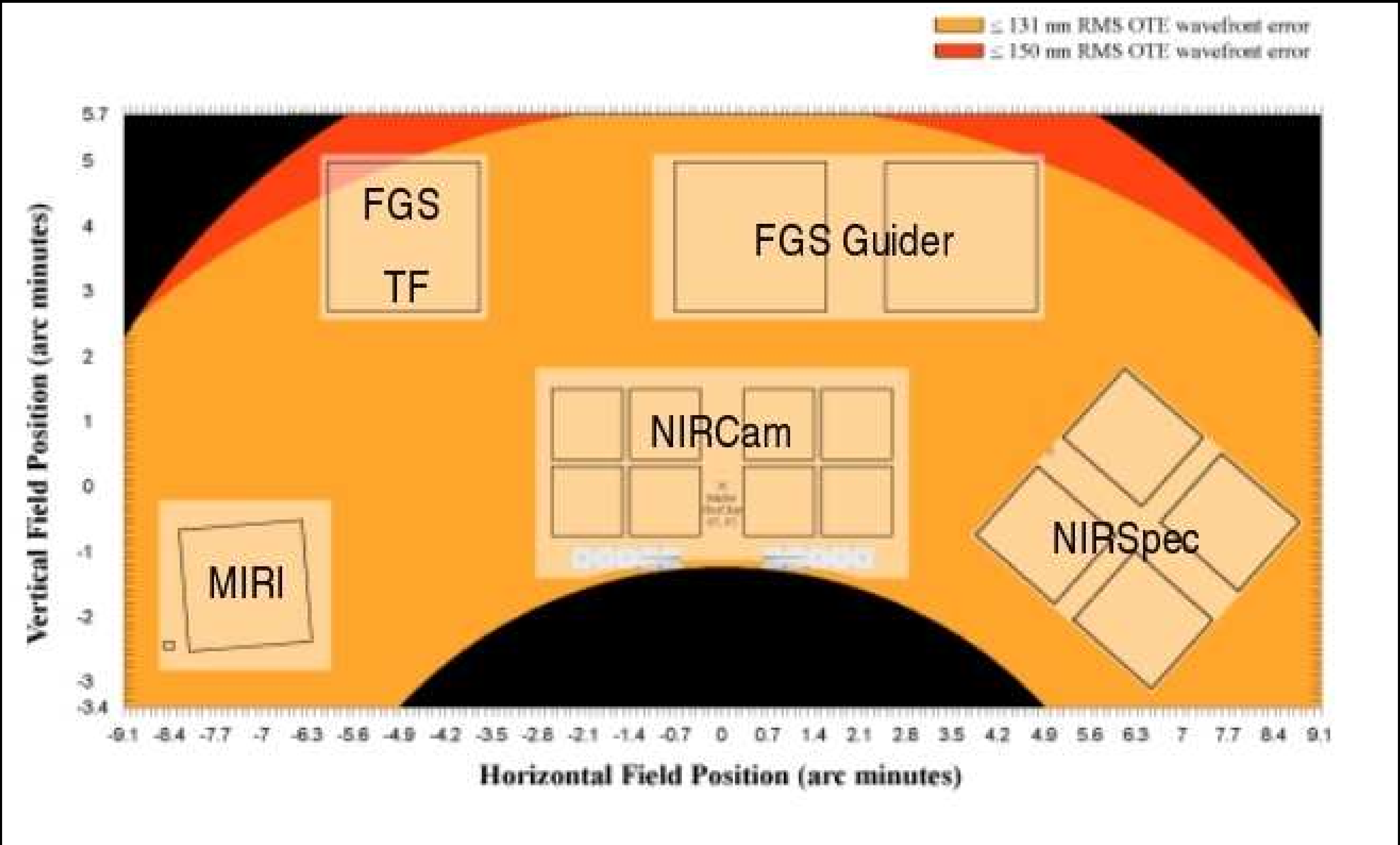
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.



JWST can observe North/South Ecliptic pole targets continuously:

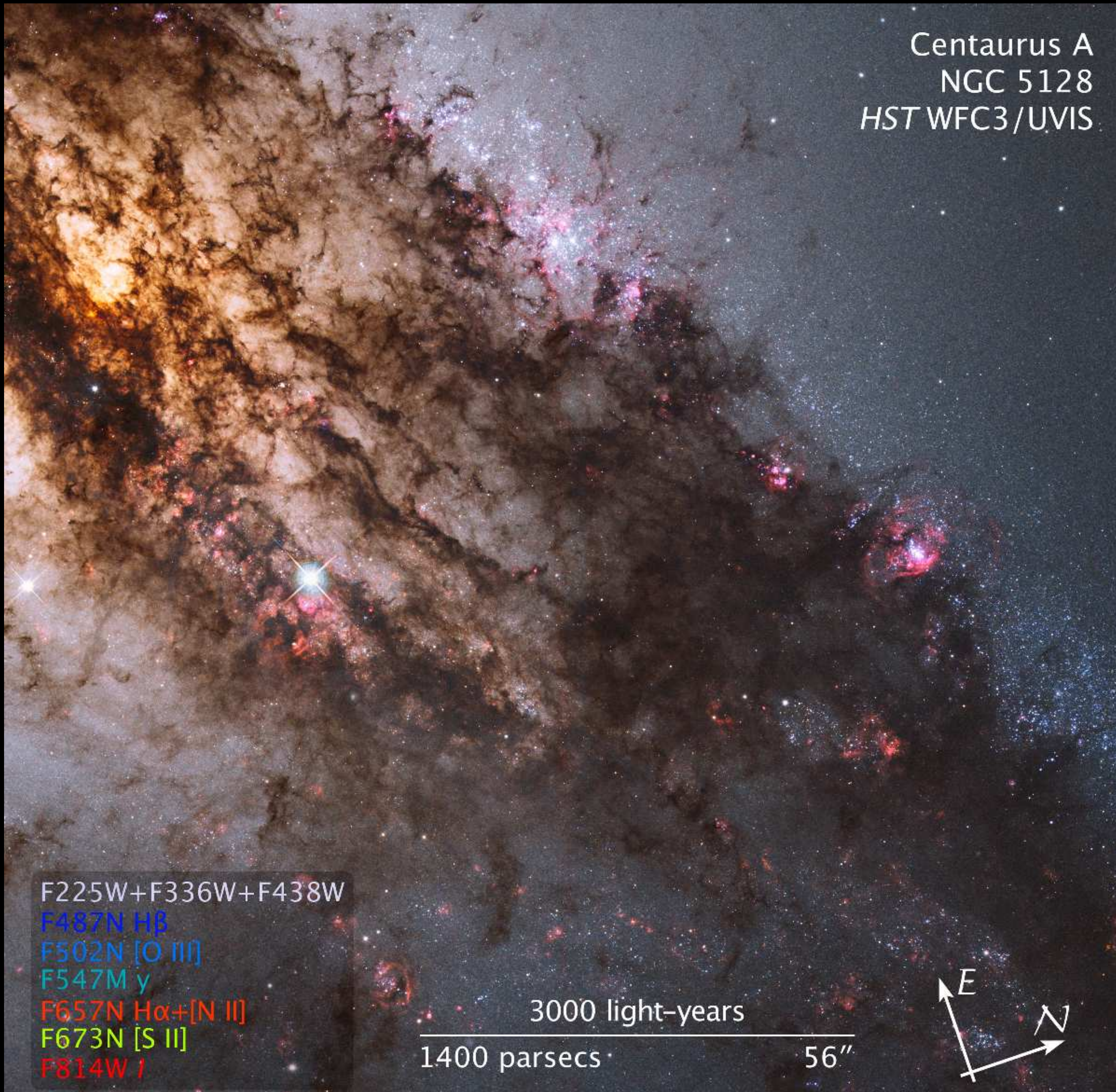
- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- They will rely a lot on Rockwell Collins' (Heidelberg) reaction wheels.

• (3c) What instruments will JWST have?

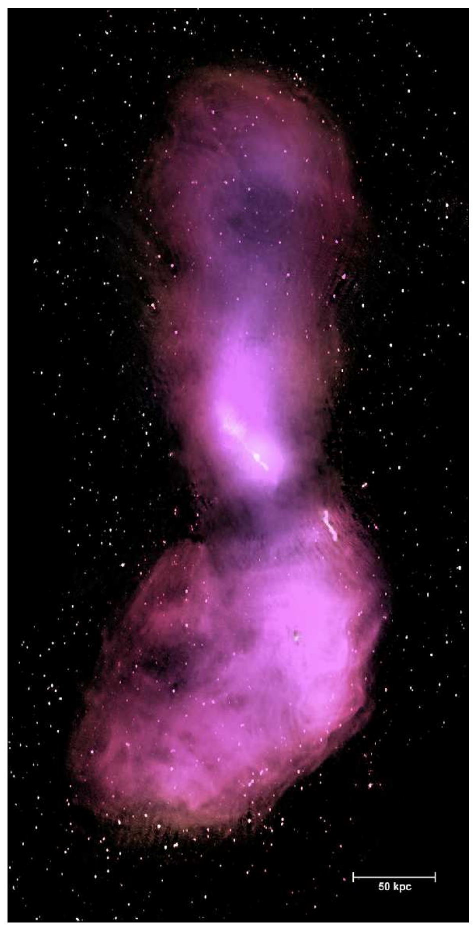


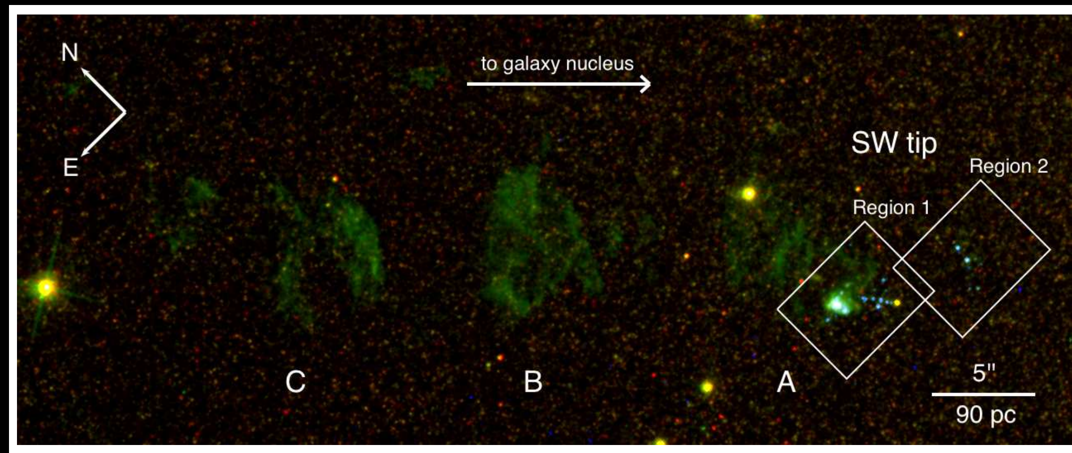
All JWST instruments can in principle be used in parallel observing mode:

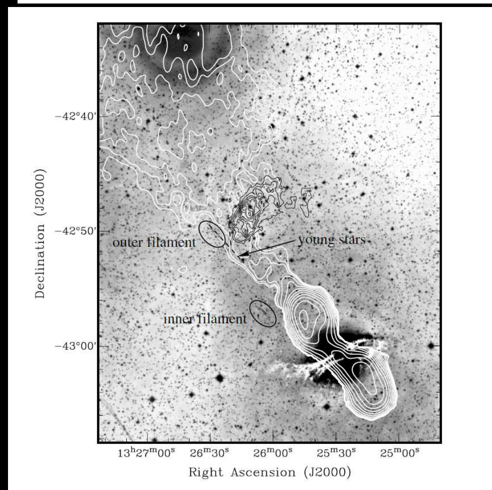
- Currently only being implemented for parallel *calibrations.*

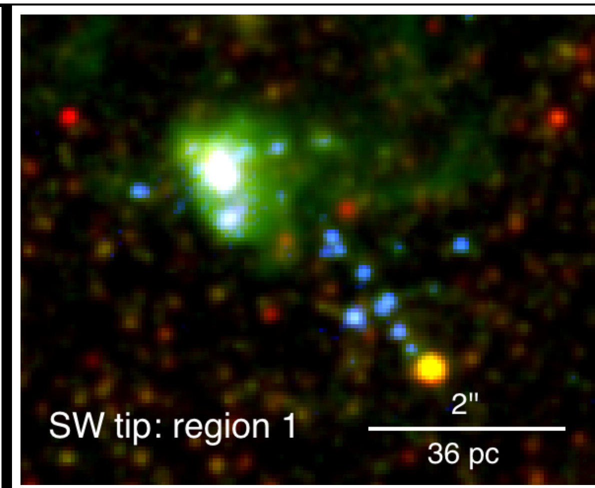


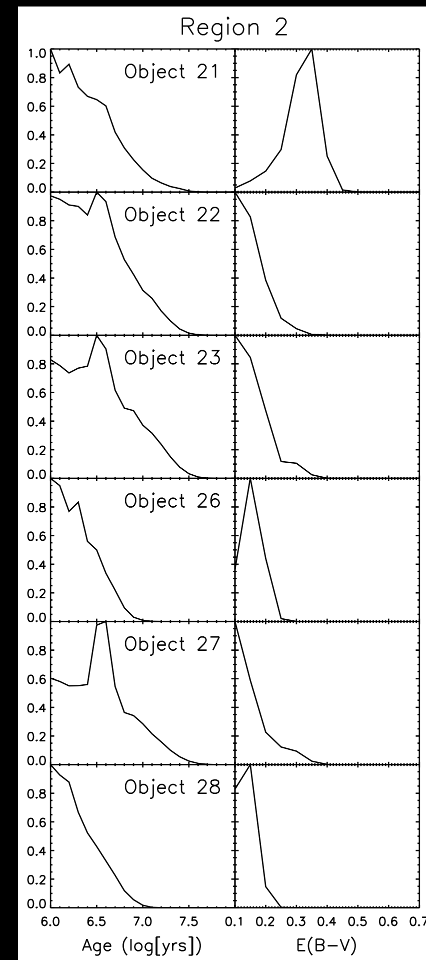
Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N











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

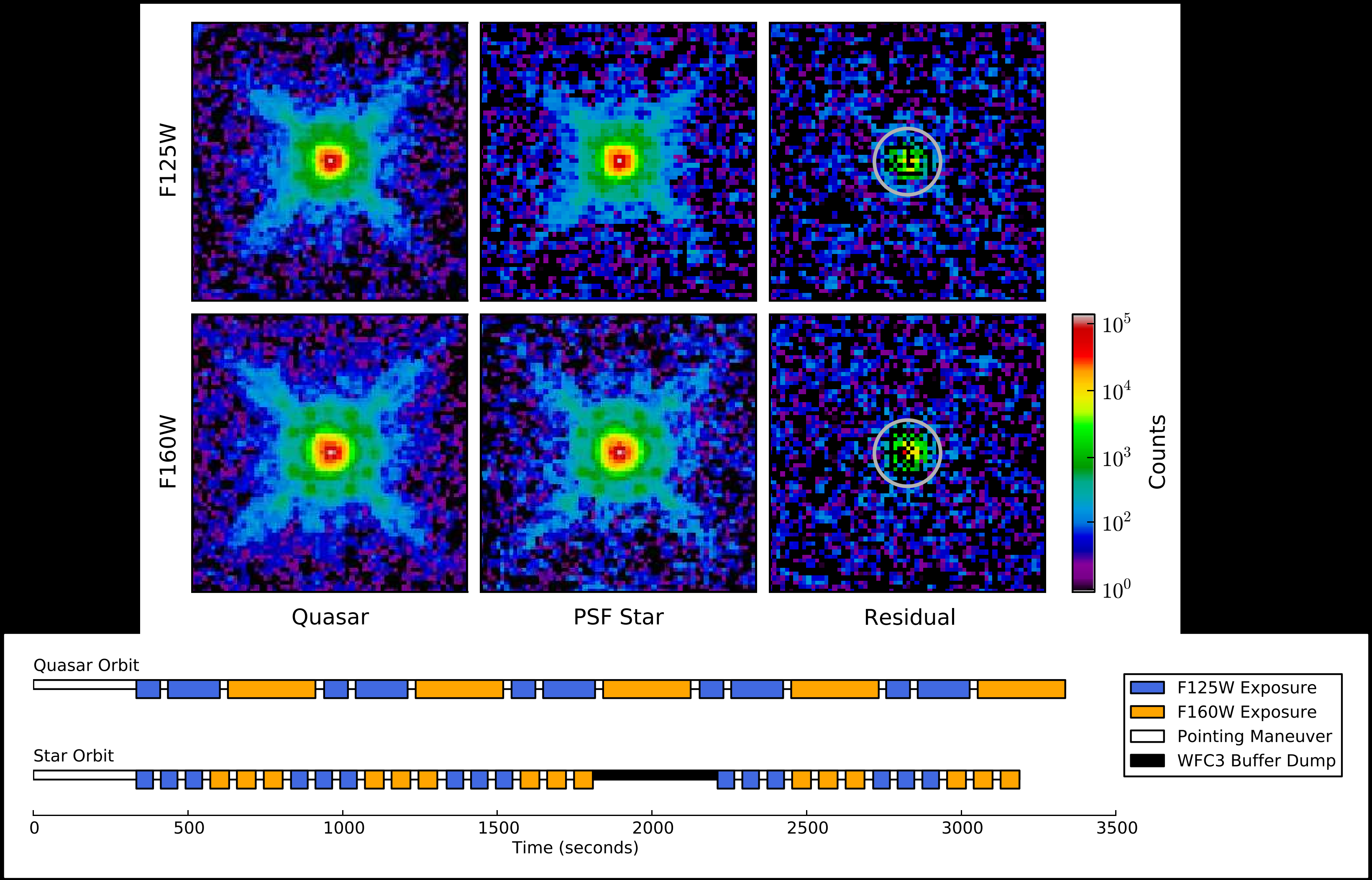
Fermi GeV source (Yang$^+$ 12); & Auger UHE Cosmic Rays (Abreu$^+$ 2010).

[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.

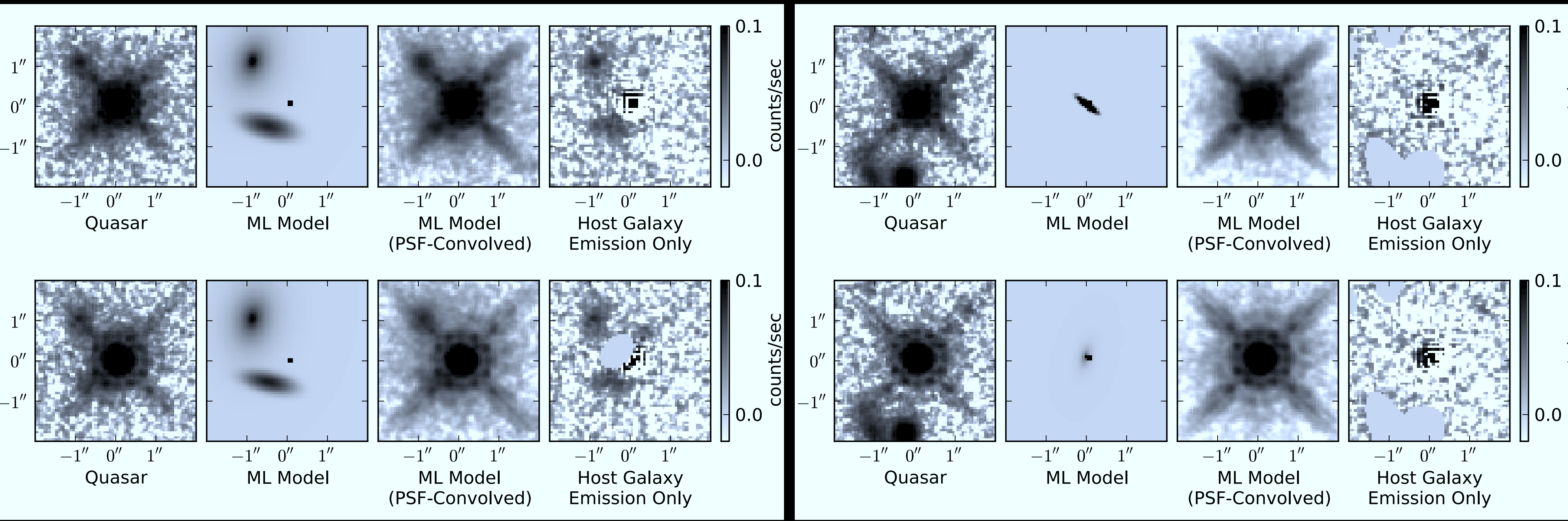
- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV–blue before JWST flies.

(2b) HST WFC3 observations of QSO host systems at z≃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).

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



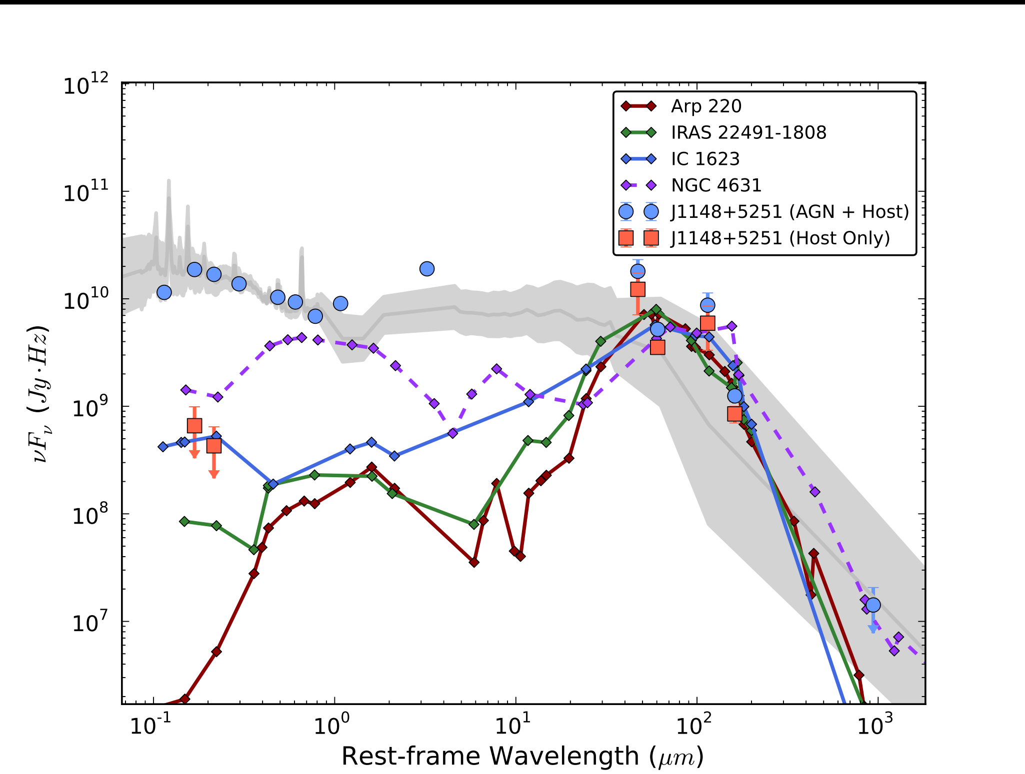
- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO images to pre-select PSF stars (Mechtley$^+$ 2014).
- First detection out of four z≃6 QSOs [2 more to be observed].
- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure??

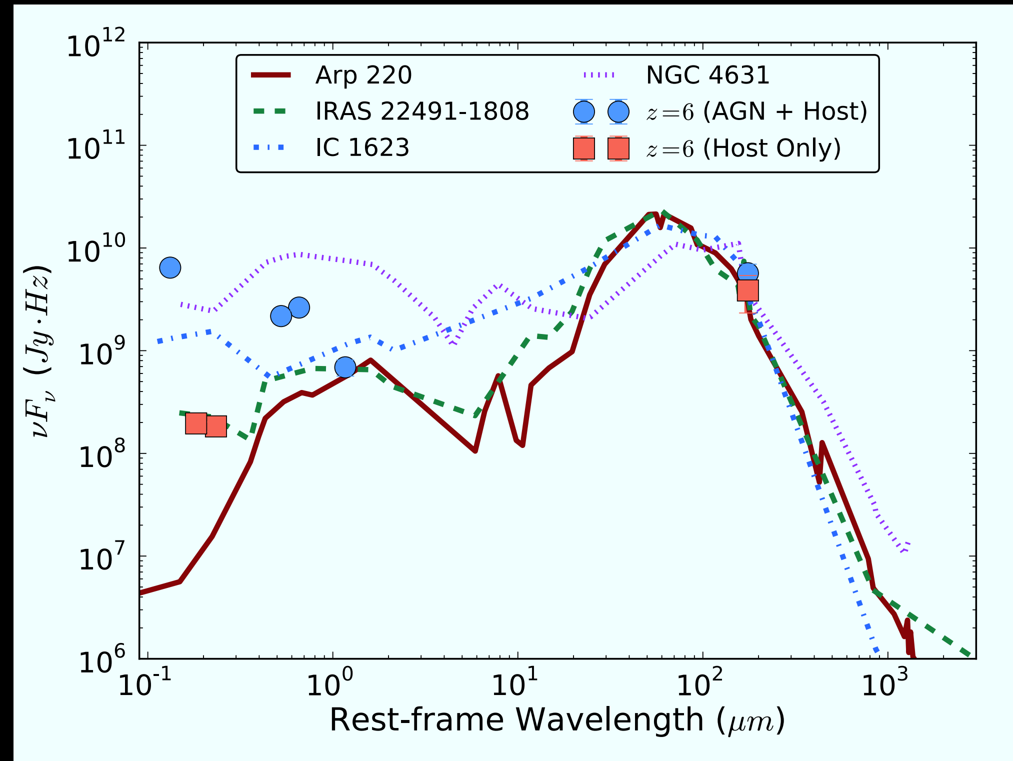
- Same J+H structure! Blue UV-SED colors: (J–H)≃0.19, constrains dust.
- M_{AB}^{host}(z≃6)$\lesssim$–23.0 mag, i.e., ∼2 mag brighter than L*(z≃6)!

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

- JWST Coronagraphs can do this 10–100× fainter (& for z$\lesssim$20, $\lambda \lesssim 28\mu$m).

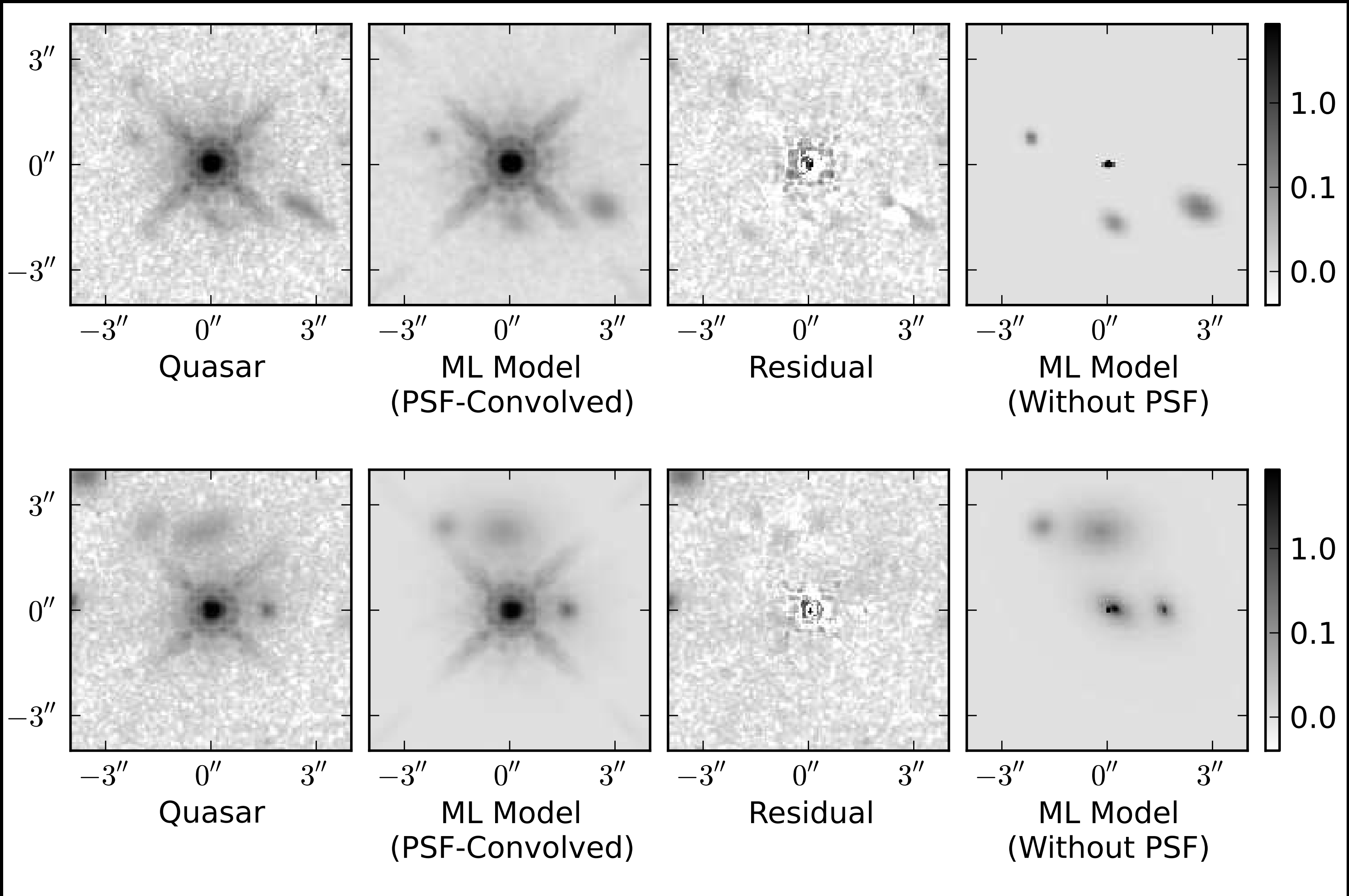
(2b) HST WFC3 observations of dusty QSO host galaxies at z≃6



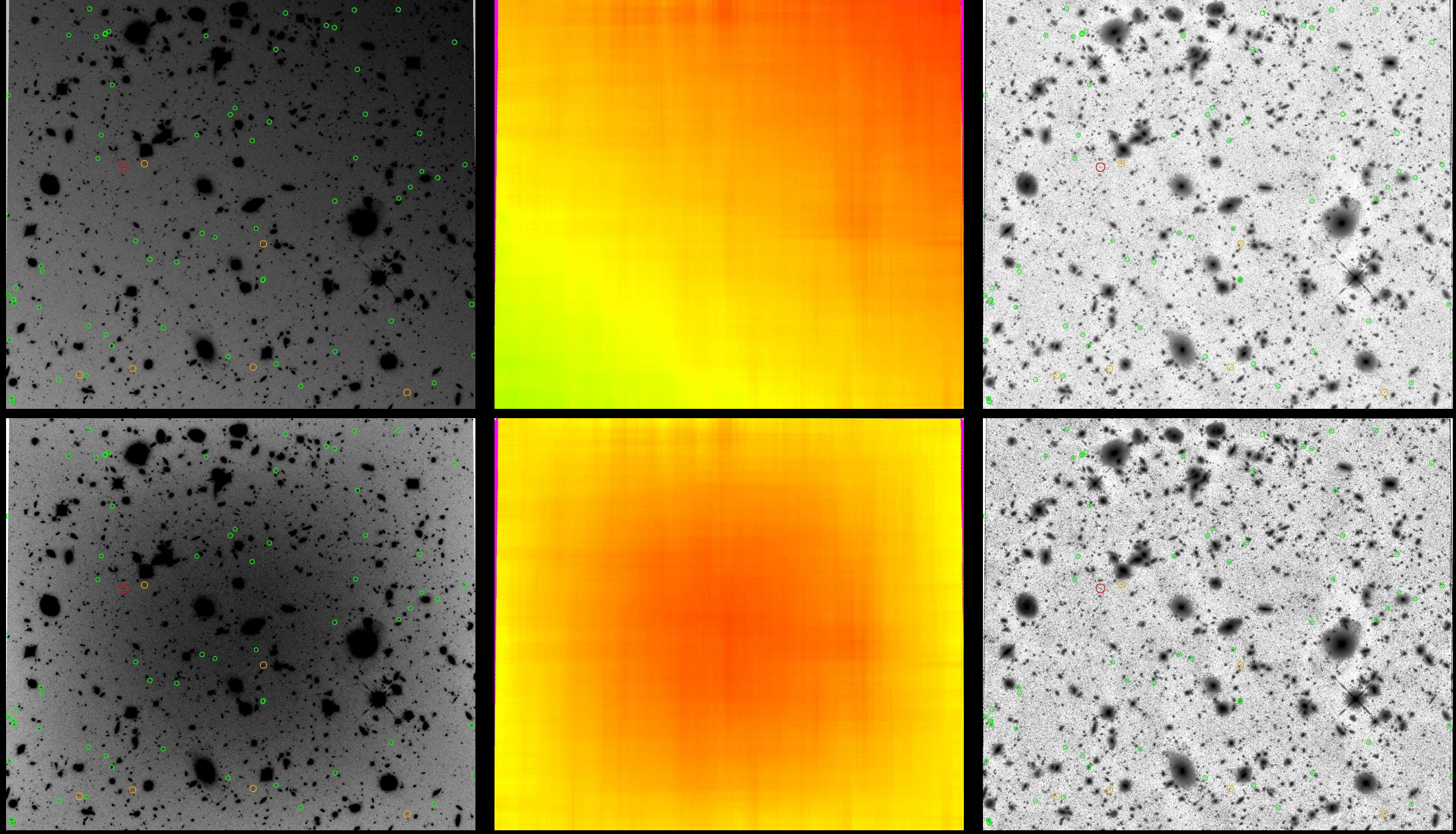


- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5μ). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100μm: [LEFT] Rules out z=6.42 spiral or bluer host galaxy SEDs for 1148+5251. (U)LIRGs & Arp 220s permitted (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, $\lambda\lesssim 28\mu$m).



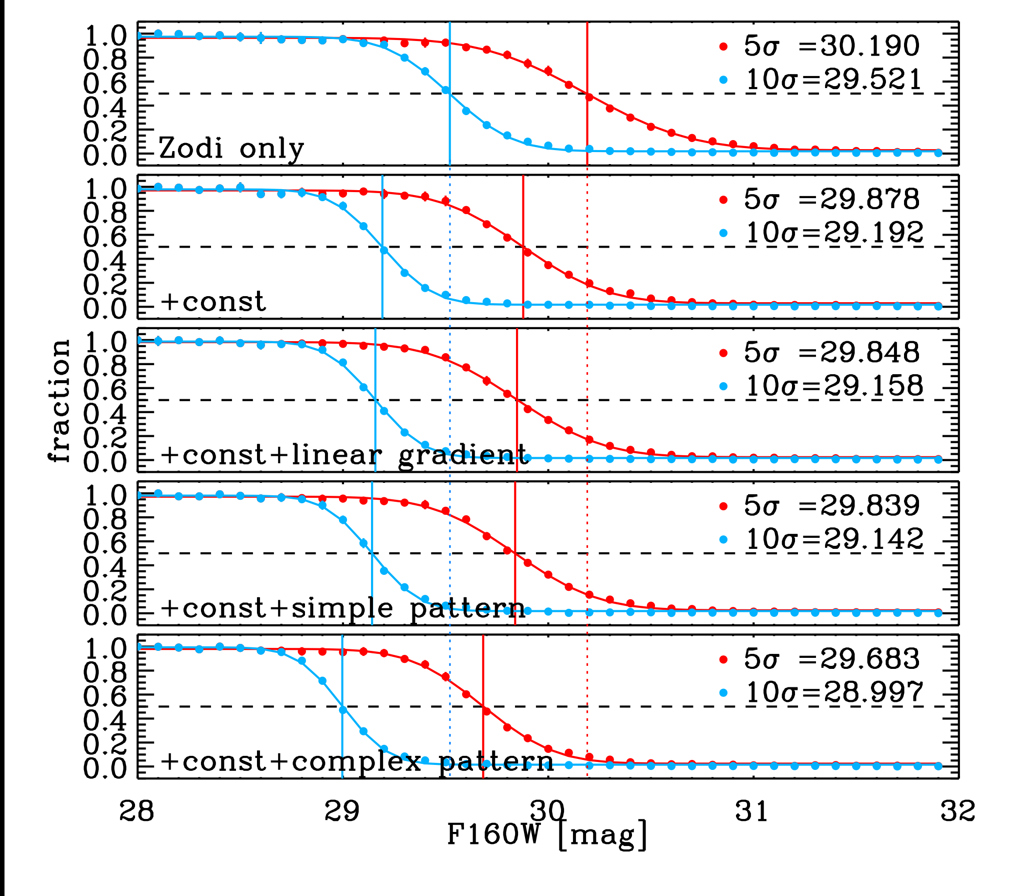
[TOP]: [Left] HUDF F160W image with *worst case* (95% of Zodi) rogue-path amplitude imposed $\pm$ a 4% *linear gradient* from corner-to-corner.

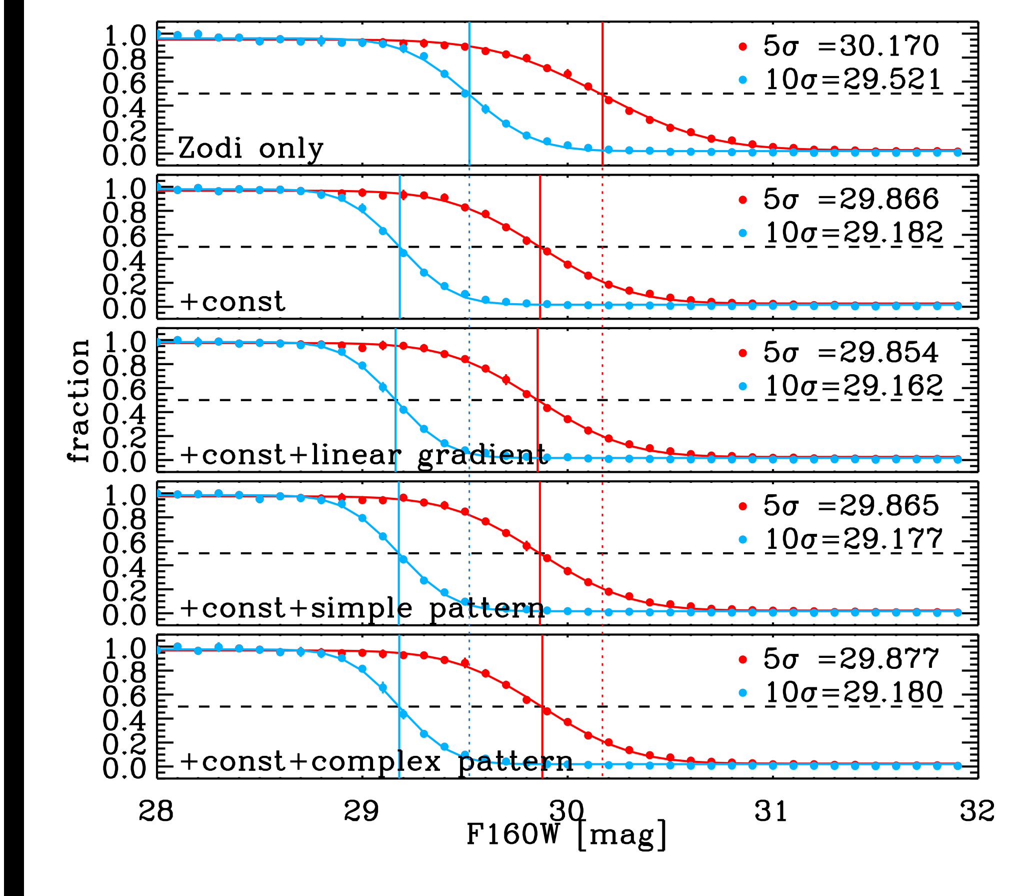
[Middle]: Best fit to sky-background with R. Jansen's "rjbgfit.pro".

[Right]: HUDF image from left with best-fit sky-background subtracted.

[BOTTOM]: Same as top row, but with a *single-component simple 2D pattern* superimposed, modeled and removed, respectively.

• If JWST rogue-path straylight has slight or complex gradients, we must carefully plan JWST imaging of lensing clusters with strong ICL.



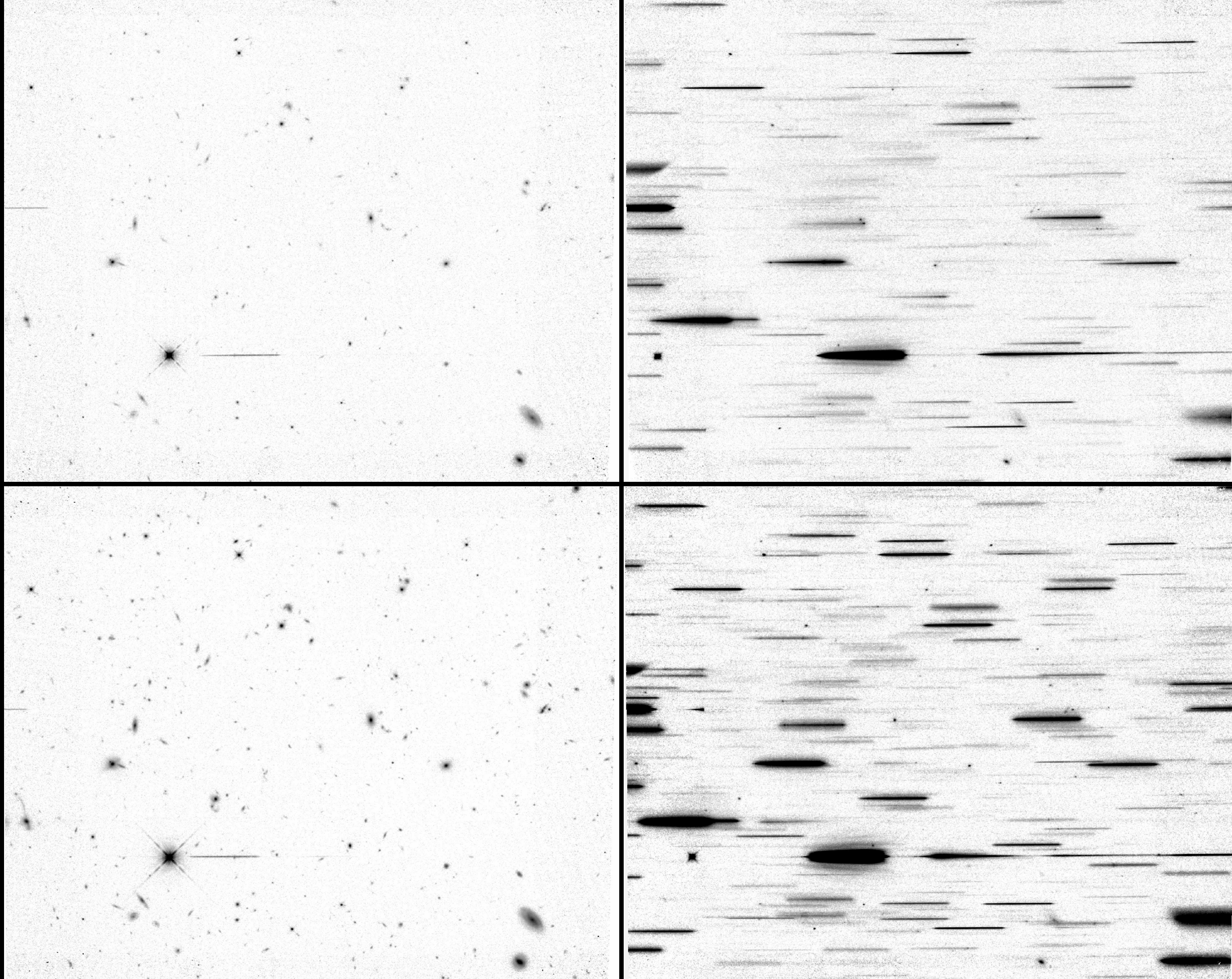


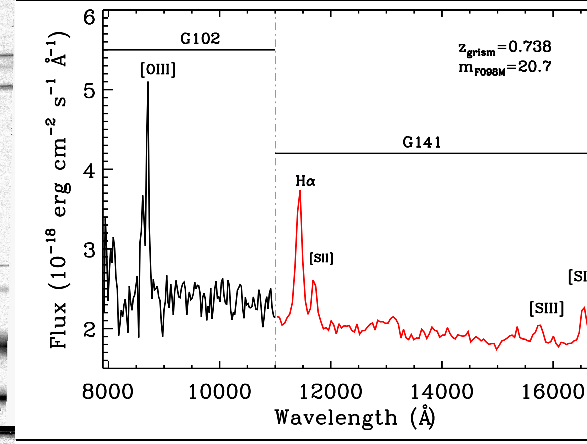
[LEFT]: Completeness tests in HUDF F160W image *before* imposing on top of Zodi (=22.70 H-mag arcsec^{-2}; Petro 2001) [2nd–5th row]: *Constant 95% of Zodi amplitude*; *+ a ±4% linear gradient*; or *simple 2D pattern of ±4%*; or *a more complex pattern*.

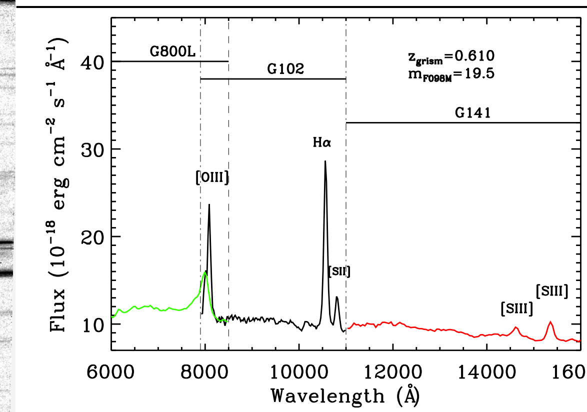
[RIGHT]: Same as left *after* best fit to + removal of image sky-background.

Red and blue lines: 50% 5-σ and 10-σ AB-completeness limits, resp.

• Simple low-frequency rogue-path gradients can be removed from "random" deep fields, without much extra loss in sensitivity. Clusters: TBD.





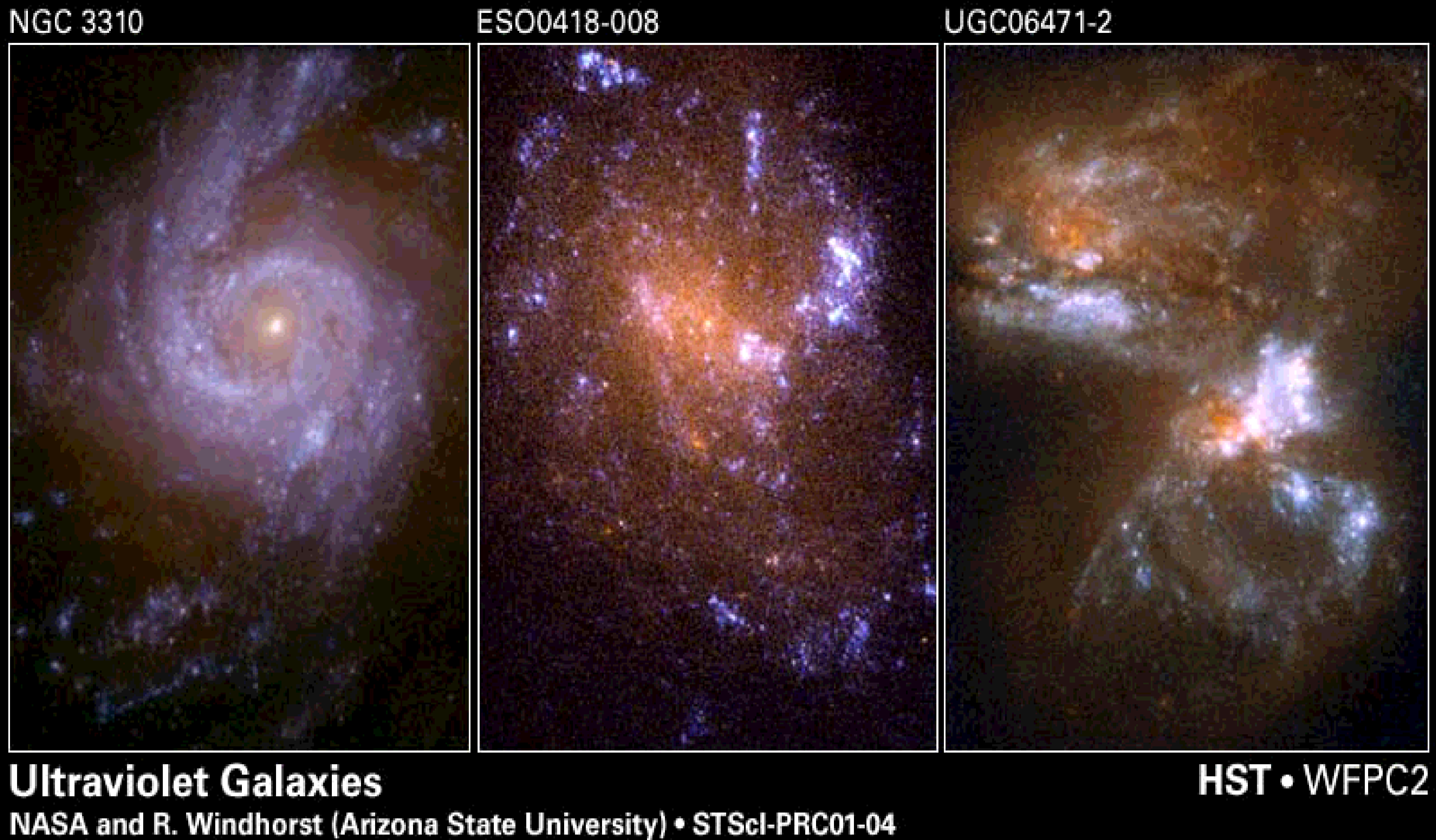


HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn+ 2010)

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.

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

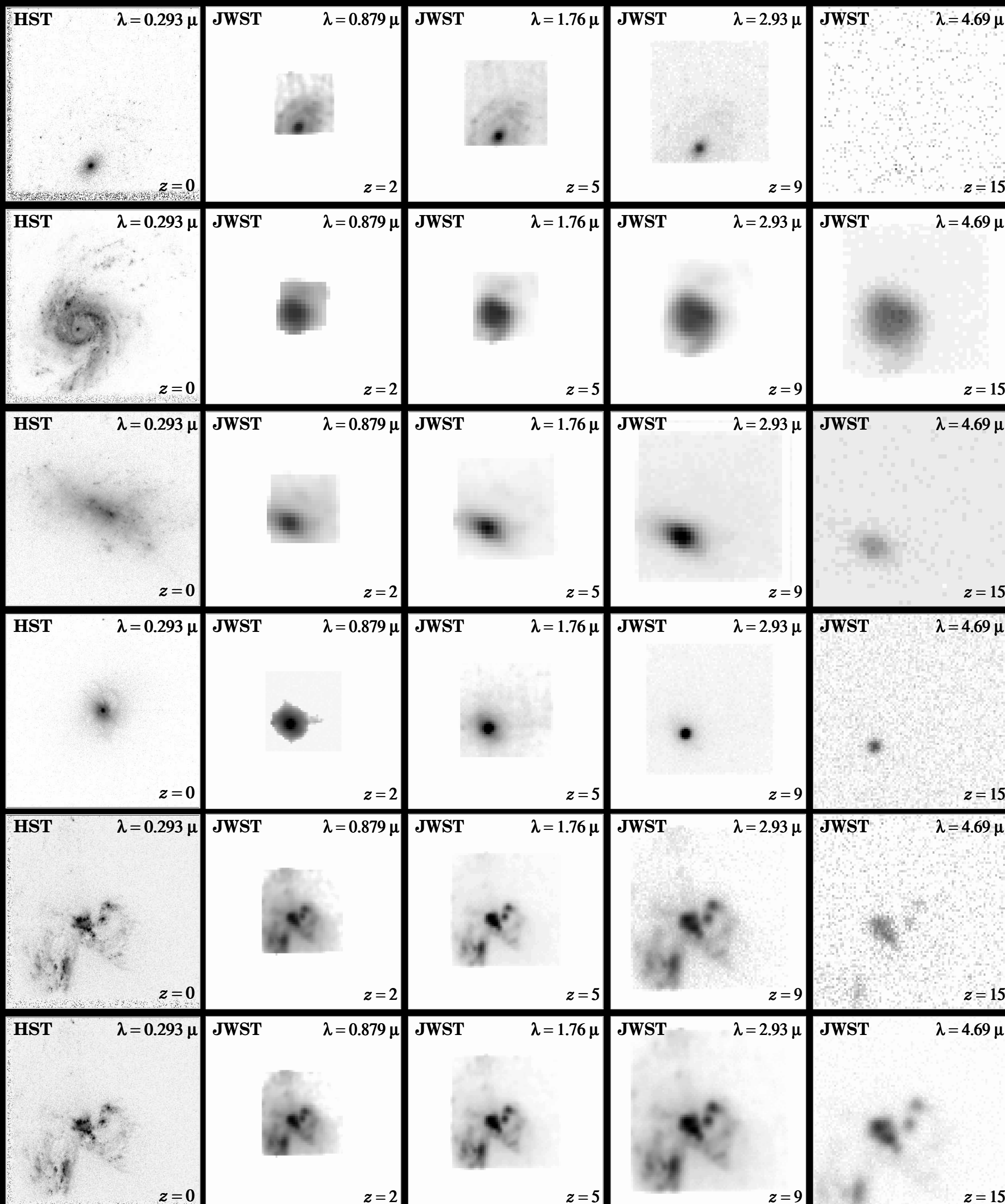


- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

- 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≲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.